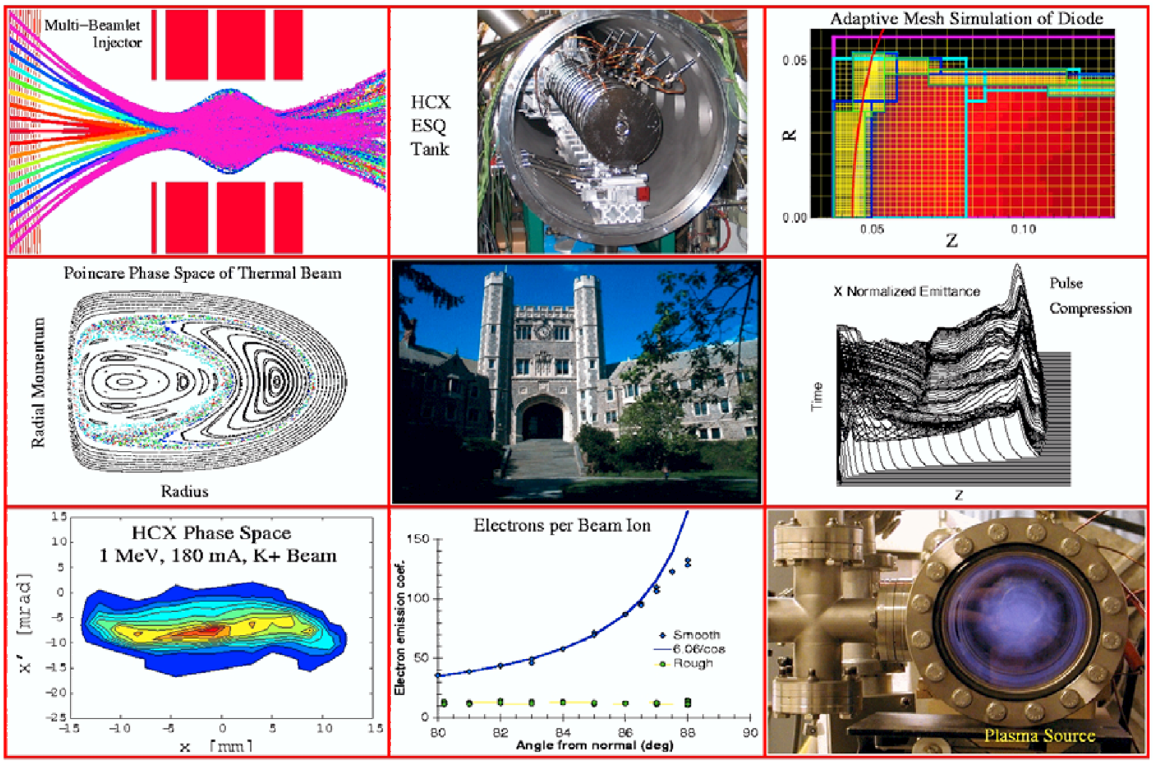
15th International Symposium on Heavy Ion Inertial Fusion

Princeton Plasma Physics Laboratory
Princeton University, Princeton, New Jersey, USA
June 7-11, 2004



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15^{th} International Symposium on Heavy Ion Inertial Fusion
Program Outline
07-11 June, 2004, Princeton University, New Jersey, USA

Sunday, June 6
17:00 – 19:00 Registration and Welcoming Reception

Monday, June 7 Morning
I. Opening Statements and Program Reviews
8:30 - 8:45 Opening Remarks
8:45 – 10:45 Program Reviews: 30,30,30,30 min
10:45 - 11:00 *Coffee Break*
11:00 - 11:30 Overview: 30 min

II. Targets for Fusion Energy and High Energy Density Physics - Part I
11:30 - 12:30 Targets: 30,30 min

12:30 - 14:00 *Lunch*

Monday, June 7 Afternoon
II. Targets for Fusion Energy and High Energy Density Physics - Part II
14:00 – 15:20 Targets and Fabrication: 25,30,25 min
15:20 - 15:35 *Coffee Break*
15:35 – 17:30 Fast Ignition: 30,30,30,25 min

Tuesday, June 8 Morning
III. Atomic Physics and Ion and Laser Interactions with Matter
8:30 - 9:00 HEDP, Beam Stopping and Beam-Plasma: 30,30,20,20,20 min
10:30 - 10:45 *Coffee Break*
10:45 - 11:15 Cross-Sections, WDM Equations of State, Beam-Plasma, Resistivity: 30,25,25,25 min

12:30 - 14:00 *Lunch*

Tuesday, June 8 Afternoon
V. Accelerators and Beam Physics - Part I
14:00 - 14:30 GSI Project, Beam Stability: 30,25,25 min
15:50 - 16:05 Coffee Break
16:05 - 16:35 Ion Sources, ITEP Project, Beam Science: 30,25,25 min

Tuesday, June 8 Evening
18:30 - 21:00 *Banquet*

Wednesday, June 9 Morning

IV. Fusion Chamber

8:30 - 10:30 5 HIF Chamber, Recycling, Neutronics, Vapor Condensation:
30,30,20,20,20 min

10:30 - 10:45 *Coffee Break*

10:45 - 11:05 Salt Chemistry: 20 min

V. Accelerators and Beam Physics - Part II

11:05 - 11:35 Space-Charge Experiments, Beam Simulations: 30,30,25 min

12:30 - 14:00 *Lunch*

Wednesday, June 9 Afternoon

V. Accelerators and Beam Physics - Part II (continued)

14:00 - 14:30 PPPL Paul Trap, Maryland e- Ring, Solenoidal Transport: 30,30,30 min

Poster Session I and PPPL Tour

15:30 - 17:30 Poster Presentations

16:30 - 18:30 Tour of PPPL to run concurrently with poster session

Thursday, June 10 Morning

V. Accelerators and Beam Physics - Part III

8:30 - 10:05 Electron-Cloud, Final Focus, Drift and Bunch Compression:
30,20,20,25 min

10:05 - 10:20 *Coffee Break*

10:20 - 10:50 30,25,25,25,25 min

12:30 - 14:00 *Lunch*

Thursday, June 10 Afternoon

V. Accelerators and Beam Physics - Part III (continued)

14:00 - 15:35 Diagnostics, Modulators, Laser-Ion Source, Superconducting Magnets:
25,25,25,20 min

Poster Session II

15:35 - 17:35 Poster Presentations

Friday, June 11 Morning

VI. System Studies and Alternates

8:30 - 9:00 HIF Point Designs, Laser IFE, Z-Pinch IFE, Systems, IBX Options:
30,30,30,25,25,25 min

11:15 - 11:30 *Coffee Break*

Summaries and Closing Remarks

11:30 - 12:45 Summaries: Target, Atomic, Chamber, Accelerators, Systems 15 min each

12:45 - 13:00 Closing Remarks

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Welcome to the 2004 International Symposium on Heavy Ion Fusion

It is a great pleasure to welcome all participants and companions to the 15th International Symposium on Heavy Ion Fusion. The Symposium is being held on June 7 – 11, 2004, on the campus of Princeton University in historic Princeton, New Jersey. The 2004 Symposium is hosted by the Princeton Plasma Physics Laboratory, organized by the Princeton Plasma Physics Laboratory, Lawrence Berkeley National Laboratory and Lawrence Livermore National Laboratory, and sponsored by the U.S. Department of Energy.

The International Symposium on Heavy Ion Fusion has been held approximately on a biannual basis since 1976, and provides an important international forum for researchers from around the world to discuss recent scientific advances and future plans in heavy ion fusion and beam-driven high energy density physics. The week-long opportunity to exchange technical information and develop collaborative ties among international researchers at these Symposia have provided a key stimulus for the significant technical advances in the field, with strong participation by scientists from France, Germany, Japan, Russia, Spain, the United States and other countries

The Program Committee for the 15th International Symposium has developed a very exciting technical program for the Symposium, with 60 invited oral presentations, and 50 poster presentations. The program for the 15th International Symposium covers a broad range of topics, including overviews of national programs, target physics and design, high energy density physics, target fabrication, fast ignition, ion beam production by intense lasers, beam-plasma interaction physics, atomic physics and cross sections, warm dense matter physics, accelerator and intense beam physics, collective instabilities, ion source and injector experiments, beam transport, fusion chamber technology, electron cloud effects, neutralized transport, drift compression and final focus, induction module development, system studies and driver point designs.

Again, on behalf of the Organizing Committee, welcome to the 2004 International Symposium on Heavy ion Fusion. I hope you find the conference stimulating, and enjoy your stay in Princeton.

Ronald C. Davidson, 2004 HIF Symposium Coordinator
Princeton Plasma Physics Laboratory
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Princeton, New Jersey, 08543-0451, USA
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General Information

Symposium Location

Princeton University, Princeton, New Jersey, USA
Physics Department, Jadwin Hall, Room A - 10

Conference Hotel

Nassau Inn, 10 Palmer Square
Princeton, New Jersey, USA 08542
Telephone: 609-921-7500
http://www.nassauinn.com

Registration

Registration starts on Sunday, 17:00 – 18:00 and then each morning from 8:00. The regular on-site registration fee is $400 US. The student registration fee is $ 175 US. You will receive a name badge upon registration. Please wear it to attend all sessions and events.

Oral Presentations

The oral sessions include all invited papers. An overhead projector will be available for showing viewgraphs. A Windows PC, a Macintosh PC, and a LCD projector will be available for electronic presentations. It is strongly recommended that electronic presentations be submitted in advance using a portable memory device, and individuals making electronic presentations verify that their visual materials are compatible with the computers and the LCD projector provided. A microphone and a laser pointer will also be available. Requests for additional audio-visual equipment should be made in advance with Hong Qin (hqin@pppl.gov). Speakers should allow 5 minutes at the end of their presentation time for questions and should attend the full session in case changes in speaking order are needed. Limited space will be available on a first-come first-served basis in the poster sessions for speakers who wish to post their oral talks for further discussion.

Poster Presentations

Poster sessions of contributed papers are on Wednesday and Thursday afternoon. Posters should be prepared for display in the morning of the day of presentation and removed after the session. The Poster boards are two-sided with each side measuring 3 ft x 4 ft (0.91 m x 1.22 m). If necessary, both sides of a board can be used for each individual presentation. At least one author of the poster is expected to be present at their poster for all of the session. Posters have been grouped by topic and then distributed between Wednesday and Thursday. This should allow those making presentations time to communicate with those presenting similar topics and aid attendees searching for specific topics.

Proceedings

All attendees making oral and poster presentations at the Symposium are requested to submit papers for a peer-reviewed special issue to be published in Nuclear Instruments and Methods in Physics Research, Section A. Journal page limits are 6 pages for invited (oral) presentations and 4 pages for contributed (poster) presentations. Manuscripts are due at the Symposium and can be turned in at the registration desk. More information on the proceedings including preparation instructions can be found on the Symposium web site: http://nonneutral.pppl.gov/HIF04/.

Tour

A tour of Princeton Plasma Physics Laboratory will be held on Wednesday, June 9, 16:30 - 18:30. Bus transportation will be provided from the conference center to the Princeton Plasma Physics Laboratory and back at the end of the tour. Please observe the following rules:

Passport or picture ID required for identification
No smoking
No high-heeled or open-toed shoes, or sandals
No briefcases or packages
Children should be over 10 years of age
People with pacemakers will not be permitted in experimental areas
Radiation monitoring will be performed on the group per DOE requirements
(radiation areas will not be entered)
Areas may be entered where hardhats are required
Cameras are permitted

2004 International Symposium on Heavy Ion Inertial Fusion
Scientific Program

Monday, 07 June Morning
I. Opening Statements and Program Reviews
(150 min, 5 30 min talks ... not including opening remarks)

Chair: R. Davidson

8:30 - 8:45 Opening Remarks, R. Davidson
8:45 - 9:15 25+5 M.I-01 G. Logan (LBNL - USA)
"Overview of US Heavy-Ion Fusion Progress and Plans"
9:15 - 9:45 25+5 M.I-02 D. Hoffmann (GSI - Germany) M.I-02
"European Program Overview"
9:45 - 10:15 25+5 M.I-03 B. Sharkov (ITEP - Russia)
"Russian HIF Program Overview"
10:15 - 10:45 25+5 M.I-04 T. Katayama (RIKEN - Japan)
"Japanese Program Overview"

10:45 - 11:00 *Coffee Break*

Chair: D.H.H. Hoffmann

11:00 - 11:30 25+5 M-I-05 M. Campbell (General Atomics - USA)
"Future Prospects for Heavy Ion Fusion"

II. Targets for Fusion Energy and High Energy Density Physics - Part I
(60 min, 2 30 min talks)
A. Physics

11:30 - 12:00 25+5 M.I-06 D. Callahan (LLNL - USA)
"Heavy Ion Target Physics and Design in the USA"
12:00 - 12:30 25+5 M.I-07 N. Tahir (GSI - Germany)
"Studies of High-Energy-Density States in Matter at the
GSI Darmstadt Using Intense Beams of Energetic Heavy Ions"

12:30 - 14:00 *Lunch*

Monday, 07 June Afternoon

II. Targets for Fusion Energy and High Energy Density Physics - Part II

(195 min, 7 talks: 4 30 min, 3 25 min)

A. Physics

B. Fabrication and Technology

Chair: S. Kawata

14:00 - 14:25 20+5 M.I.-08 A. Piriz (University of Castilla-La Mancha - Spain)
"Target Design for the Cylindrical Compression
of Matter Driven by Heavy Ion Beams"
14:25 - 14:55 25+5 M.I-09 D. Goodin (General Atomics - USA)
"Progress in Heavy Ion Driven Target Fabrication and Injection"
14:55 - 15:20 20+5 M.I-10 A. Nikroo (General Atomics - USA)
"Fabrication of Capsules with Angle Dependent Gold Shims
for Hohlraum Drive Symmetry Correction"

15:20 - 15:35 *Coffee Break*

C. Fast Ignition

Chair: P. Velarde

15:35 - 16:05 25+5 M.I-11 M. Tabak (LLNL - USA)
"Models of Gain Curves for Fast Ignition"
16:05 - 16:35 25+5 M.I-12 M. Geissel (SNL - USA, TU - Darmstadt)
"Short Pulse Laser Generated Ion Beams for Fast Ignition"
16:35 - 17:05 25+5 M.I-13 R. Town (LLNL - USA)
"Simulations of Electron Transport for
Fast Ignition Using LSP"
17:05 - 17:30 20+5 M.I-14 M. Murakami (ILE Osaka - Japan)
"A New Twist to Inertial Confinement Fusion -- Impact Ignition"

Tuesday, 08 June Morning

III. Atomic Physics and Ion and Laser Interactions with Matter

(225 min, 9 talks: 3 30 min, 3 25 min, 3 20 min)

A. Beam Stopping in Matter and Beam-Plasma Interaction

B. Cross Sections for Beam and Chamber Physics

C. Warm Dense Matter Physics

Chair: G. Logan

8:30 - 9:00 25+5 Tu.I-01 V. Fortov (RAS - Russia)
"Some Physical Processes at High Energy Densities,
Worth Investigating by Intense Heavy Ion Beams"
9:00 - 9:30 25+5 Tu.I-02 D. Varentsov (GSI - Germany)
"High Energy Density Physics Experiments with Intense Heavy Ion Beams"

9:30 - 9:50 15+5 Tu.I-03 A. Blazevic (TU Darmstadt - Germany)
"Ion Beam Interactions with a Dense, Laser Produced Plasma"
9:50 - 10:10 15+5 Tu.I-04 Y. Oguri (TIT - Japan)
"Stopping of Low-Energy Highly-Charged Ions in Dense Plasma"
10:10 - 10:30 15+5 Tu.I-05 G. Maynard (LPGP UParis XI Orsay - France)
"Isochoric Heating of DT fuels Through PW-Laser
Produced Non Relativistic Ion Beams"

10:30 - 10:45 *Coffee Break*

Chair: C. Deutsch

10:45 - 11:15 25+5 Tu.I-06 I. Kaganovich (PPPL - USA)
"Ionization Cross Sections for Ion-Atom Collisions in
High Energy Ion Beams"
11:15 - 11:40 20+5 Tu.I-07 I. Lomonosov (RAS - Russia)
"Equation of State of Warm Dense Matter Generated by Heavy Ions"
11:40 - 12:05 20+5 Tu.I-08 A. Golubev (ITEP - Russia)
"Experiments on Beam-Plasma Interaction Physics"
12:05 - 12:30 20+5 Tu.I-09 S. Udrea (GSI - Germany)
"Electrical Resistivity Measurements of Ion Driven
High Energy Density Matter"

12:30 - 14:00 *Lunch*

Tuesday, 08 June Afternoon
V. Accelerators and Beam Physics - Part I

(160 minutes, 6 talks: 2 30 min, 4 25 min)
A. Sources and Injectors
B. Transport and Acceleration
C. Pulse Compression Methods

Chair: H. Klein

14:00 - 14:30 25+5 Tu.I-10 P. Spiller (GSI - Germany)
"Accelerator Plans at GSI and Plasma Physics Applications"
14:30 - 15:25 20+5 Tu.I-11 R. Davidson (PPPL - USA)
"Survey of Collective Instabilities and Beam-Plasma
Interactions in Intense Heavy Ion Beams"
15:25 - 15:50 20+5 Tu.I-12 E. Startsev (PPPL - USA)
"Three-Dimensional Simulation Studies of the
Temperature Anisotropy Instability
in Intense Charged Particle Beams"

15:50 - 16:05 *Coffee Break*

Chair: M. Pusterla

16:05 - 16:35 25+5 Tu.I-13 J. Kwan (LBNL - USA)
"Ion Source and Injector Experiments at the HIF VNL"
16:35 - 17:00 20+5 Tu.I-14 P. Zenkevich (ITEP - Russia)
"Beam Physics in the ITEP-TWAC Synchrotron Rings"
17:00 - 17:25 20+5 Tu.I-15 C. Celata (LLNL - USA)
"Scientific Issues in Future Accelerators for Heavy Ion Fusion"

Tuesday, 08 June Evening
Banquet

18:30 - 21:00 *Dinner*

Wednesday, 09 June Morning
IV. Fusion Chamber

(140 min, 6 talks: 2 30 min, 4 20 min)
A. Beam Transport
B. Technology and Power Plant Considerations

Chair: G. Miley

8:30 - 9:00 25+5 W.I-01 P. Peterson (Berkeley - USA)
"HIF Chamber Phenomena and Design"
9:00 - 9:30 25+5 W.I-02 S. Kawata (Utsunomiya Univ. - Japan)
"Final Beam Transport and Target Illumination"
9:30 - 9:50 15+5 W.I-03 L. El-Guebaly (Univ. of Wisconsin at Madison - USA)
"Recycling Issues Facing Target and RTL Materials of Inertial Fusion Designs"
9:50 - 10:10 15+5 W.I-04 J. Latkowski (LLNL - USA)
"Neutronics of Heavy Ion Fusion Chambers"
10:10 - 10:30 15+5 W.I-05 P. Calderoni (UCLA - USA)
"Vapor Condensation Study for HIF Liquid Chambers"

10:30 - 10:45 *Coffee Break*

Chair: TBA

10:45 - 11:05 15+5 W.I-06 Dai-Kai Sze (UCSD - USA)
"Molten Salt Chemistry Control for Fusion Chambers"

V. Accelerators and Beam Physics - Part II

(175 minutes, 6 talks: 5 30 min, 1 25 min)

A. Sources and Injectors
B. Transport and Acceleration
C. Pulse Compression Methods

11:05 - 11:35 25+5 W.I-07 L. Prost (LBNL - USA)
"Experimental Study of the Transport Limits of Intense Heavy Ion Beams in the High Current Transport Experiment"
11:35 - 12:05 25+5 W.I-08 A. Friedman (LLNL - USA)
"Simulation of Intense Beams for Heavy Ion Fusion"
12:05 - 12:30 20+5 W.I-09 E. Sonnendrucker (Univ. of Strasbourg - France)
"Adaptive Numerical Vlasov Simulation of Intense Beams"

12:30 - 14:00 *Lunch*

Wednesday, 09 June Afternoon

Chair: D. Rose

14:00 - 14:30 25+5 W.I-10 E. Gilson (PPPL - USA)
"Simulation of Long-Distance Beam Propagation in the Paul Trap Simulator Experiment"
14:30 - 15:00 25+5 W.I-11 R. Kishek (Univ. of Maryland - USA)
"HIF Research on the University of Maryland Electron Ring"
15:00 - 15:30 25+5 W.I-12 E. Lee (LBNL - USA)
"Solenoidal Transport for Heavy Ion Fusion"

Wednesday, 09 June Afternoon
Poster Session I and PPPL Tour

(120 minutes)
15:30 - 17:30 Poster Presentations (See Poster Program)

16:30 - 18:30 Tour of PPPL to run concurrently with poster session

Thursday, 10 June Morning

V. Accelerators and Beam Physics - Part III

(315 minutes, 12 talks: 3 30 min, 6 25 min, 3 20 min)
D. Final Focus
E. Electron Production and Interactions
F. Technology

Chair: A. Schempp

8:30 - 9:00 25+5 Th.I-01 A. Molvik (LLNL - USA)
"Experimental Studies of Electrons in a Heavy-Ion Beam"
9:00 - 9:20 15+5 Th.I-02 A. Lifschitz (LPGP UParis XI Orsay - France)
"Dynamics of Neutralizing Electrons and the Focusability of Intense Ion Beams in HIF Accelerating Structures"
9:20 - 9:40 15+5 Th.I-03 R. Cohen (LLNL - USA)
"Simulating Electron Cloud Effects in Heavy-Ion Accelerators"
9:40 - 10:05 20+5 Th.I-04 L. Grisham (PPPL - USA)
"Experimental Evaluation of a Negative Ion Source for a Heavy Ion Fusion Negative Ion Driver"

10:05 - 10:20 *Coffee Break*

Chair: G. Turchetti

10:20 - 10:50 25+5 Th.I-05 P. Roy (LBNL - USA)
"Neutralized Transport Experiment"
10:50 - 11:15 20+5 Th.I-06 D. Welch (Mission Research Corp - USA)
"Simulations of Neutralized Final Focus"
11:15 - 11:40 20+5 Th.I-07 J. Barnard (LLNL - USA)
"A Final Focus Model for Heavy Ion Fusion Driver System Codes"
11:40 - 12:05 20+5 Th.I-08 H. Qin (PPPL - USA)
"Drift Compression and Final Focus Options for Heavy Ion Fusion"
12:05 - 12:30 20+5 Th.I-09 T. Kikuchi (Univ. of Tokyo - Japan)
"Beam Dynamics and Emittance Growth During Final Beam Bunching in HIF Driver Systems"

12:30 - 14:00 *Lunch*

Chair: G. Westenskow

14:00 - 14:25 20+5 Th.I-10 F. Bieniosek (LBNL - USA)
"Diagnostics for Intense Heavy Ion Beams"
14:25 - 14:50 20+5 Th.I-11 K. Horioka (TIT - Japan)
"Development of Induction Modules for High Power Accelerators"

14:50 - 15:15 20+5 Th.I-12 T. Cowan (U. Nevada Reno - USA)
"Ultra-Low Emittance, High Current Proton Beams Produced with a Laser-Virtual Cathode Sheath Accelerator"
15:15 - 15:35 15+5 Th.I-13 G-L. Sabbi (LBNL - USA)
"Development of Superconducting Magnet Systems for HIF"

Thursday, 10 June Afternoon
Poster Session II

(120 minutes)

15:35 - 17:35 Poster Presentations (See Poster Program)

Friday, 11 June Morning
VI. System Studies and Alternates

(165 min, 7 talks)

Chair: E. Lee

8:30 - 9:00 25+5 F.I-01 S. Yu (LBNL - USA)
"HIF Driver Point Designs"
9:00 - 9:30 25+5 F.I-02 J. Sethian (NRL - USA)
"Laser Fusion Energy"
9:30 - 10:00 25+5 F.I-03 C. Olson (SNL - USA)
"Progress on Z-Pinch IFE and HIF Target Work on Z"
10:00 - 10:25 20+5 F.I-04 S. Medin (IHT RAS - Russia)
"Power Plant Conceptual Design for Fast Ignition Heavy Ion Fusion"
10:25 - 10:50 20+5 F.I-05 W. Meier (LLNL - USA)
"Systems Analysis for Modular Versus Multi-Beam HIF Drivers"
10:50 - 11:15 20+5 F.I-06 M. Leitner (LBNL - USA)
"Options for an Integrated Beam Experiment"

11:15 - 11:30 *Coffee Break*

Chair: R. Davidson

11:30 - 12:45 Summaries

Target	15	R. Bangerter
Atomic	15	C. Deutsch
Chamber	15	P. Peterson
Accelerator	15	P. Seidl
Systems	15	W. Meier

12:45 - 13:00 Closing Remarks
R. Davidson

2004 International Symposium on Heavy Ion Inertial Fusion
Poster Presentations

Wednesday, 09/06 Afternoon
Poster Session I and PPPL Tour

15:30 - 17:30 Poster Presentations
16:30 - 18:30 Tour of PPPL to run concurrently with poster session

W.P - 01 D. Clark, M. Tabak
"Nonlinear Rayleigh-Taylor Growth in Converging Geometry"
W.P - 02 G. Dolgoleva, A. Gorbunov, V. Kechin, V. Nechpai, P. Pevnaya, L. Sizova, S. Kholin, "Heavy-Ion Target with a Disc Converter"
W.P – 03 K. Starikov, C. Deutsch
"Stopping of Relativistic Electrons in Partially Generate Electron Fluid"
W.P – 04 P. Velarde, F. Ogando, S. Eliezer
"Fast Ignition Heavy Ion Fusion Target by Jet Impact"
W.P – 05 R. Olson,
"Electron Loss Cross Sections for Low Charge State Ions"
W.P – 06 A. Konkachbaev, N. Morley, M. Abdou,
"3D Modeling of Liquid Jets, Used in Heavy Ion Fusion for Beam Line Protection"
W.P – 07 C. Debonnel, S. Yu, P. Peterson
"Progress Towards a Detailed Tsunami Modeling of the Heavy Ion Fusion Modular Point Design"
W.P – 08 J-L. Vay, P. Colella, J. Kwan, P. McCorquodale, D. Serafini, A. Friedman, D. Grote, G. Westenskow, J-C. Adam, A. Héron, I. Haber, "Application of Adaptive Mesh Refinement to PIC Simulations in Inertial Fusion"
W.P – 09 W. Lee, R. Davidson, E. Startsev, H. Qin,
"The Electromagnetic Darwin Model for Intense Charged Particle Beams"
W.P – 10 D. Grote,
"Simulation of Integrated Beam Experiment Designs"
W.P – 11 H. Li, S. Bernal, T. Godlove, I. Haber, R. Kishek, B. Quinn, M. Reiser, M. Walter, M. Wilson, Y. Zou, P. O'Shea, "Beam Control and Matching on the University of Maryland Electron Ring (UMER)"
W.P. – 12 M. Walter, D. Lamb, S. Bernal, T. Godlove, I. Haber, R. Kishek, H. Li, P. O'Shea, B. Quinn, M. Reiser, "Experimental Tests of the Injection Y on the University of Maryland Electron Ring.
W.P – 13 P. Efthimion, E. Gilson, L. Grisham, R, Davidson, S. Yu, B. Logan
"Development of a One-Meter Plasma for Heavy Ion Beam Charge Neutralization"
W.P –14 I. Kaganovich, E. Startsev. R. Davidson, D. Welch
"Theory of Ion Beam Pulse Neutralization by a Background Plasma in a Solenoidal Magnetic Field"
W. P – 15 D. Rose, T. Genoni, D. Welch,
"Two-Stream, Stability Assessment of Intense Heavy Ion Beam Propagating in Preformed Plasmas"

W.P – 16 D. Ho, S. Brandon
“Is Laser Calling for Heavy-Ion Fusion Feasible”
W.P - 17 T. Kikuchi, T. Katayama, S. Lund,
“Bunch Compression in a Ring in Future Riken Projects”
W.P – 18 J. Harris, S. Bernal, D. Feldmen, I. Haber, T. Godlove, R. Kishek, H. Li, B. Quinn, M. Reiser, M. Walter, M. Wilson, Y. Zou, P. O’Shea, “Longitudinal Drift Experiments at the University of Maryland Electron Ring”
W.P – 19 W. Sharp, J. Barnard, D. Grote, C. Celata, S. Yu, D. Rose, D. Welch,
“Simulation of Drift-Compression for Heavy-Ion- Fusion”
W.P – 20 J. Hasegawa, T. Mawatari, Y. Oguri, M. Ogawa, K. Horioka,
“Dynamics of Plasma Channels for Chamber Transport”
W.P – 21 H. Zimmermann, U. Bartz, N. Mûller, A. Schempp, J. Thibus
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Poster Session II

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Th.P - 01 M. Rosen, J. Hammer,
“Analytic Expression for Optimal Hohlraum Wall Density”
Th.P – 02 T. Someya, S. Kawata, T. Kikuchio, A. Ogoyski,
“HIB Illumination on a Target in HIF”
Th.P – 03 A. Aksenov,
“Cylindrical Targets in HIF”
Th.P – 04 G. Dolgoleva, V. Ermolovich,
“Numerical Evaluation of the Influence of Non-Stationary State and Heterogeneity of the Rotated Ion Beam on the Irradiated Cylindrical Target Compression Parameters”
Th.P – 05 S. Bouchigny, C. Commeaux, J-P. Didelez, G. Rouillé,
“Progress in the Polarization of HD”
Th.P – 06 V. Nechpai, L. Potapkina, S. Smirnov, S. Kholin,
“2-D Model of a Concentrated Shell with Magnetic Field”
Th.P – 07 A. Bret, M. Firpo, C. Deutsch,
“Between Filamentation and Two Stream Instabilities”
Th.P – 08 M. Velarde, J. Perlado, J. Abascal
“The Role of Organically Bound Tritium After Ingestion in Normal and Accidental Scenarios in Inertial Fusion Reactors”
Th.P – 09 J. Perlado, M. Caturla, E. Domínguez, D. Lodi, J. Marian, F. Mota, M. Salvador, G. Velarde, J. Abascal., “Review of Structural and Ceramic Materials under Irradiation in Inertial Fusion Reactors: Comparison of Multi-Scale Modeling and Experiment”
Th.P – 10 A. Fertman, A. Golubev, B. Sharkov, M. Prokouronov, G. Fehrenbacher, R. Haase, I. Hofmann, D. Hoffmann, E. Mustafin, D. Schardt, K. Weyrich
“Residual Radioactivity of Copper Induced by Argon Beam Irradiation”
Th.P – 11 J. Kwan, F. Bieniosek, W. Waldron, J-L. Vay, G. Westenskow, E. Halaxa, I. Haber, “Production of a High Brightness Beam from a Large Surface Source”

Th.P – 12 G. Westenskow, D. Grote, E. Halaxa, J. Kwan, J. Kapica, W. Waldron,

Th.P – 13 E. Henestroza, J. Kwan, E. Lee, S. Yu, R. Briggs, "Extraction and Acceleration of High Line Charge Density Beams"

Th.P – 14 I. Haber, S. Bernal, R. Kishek, P. O'Shea, B. Quinn, M. Reiser, Y. Zou, A. Friedman, D. Grote, J-L. Vay, "Measurement and Simulation of the UMER Beam in the Source Region"

Th.P – 15 O. Meusel, A. Bechtold, J. Pozimski, U. Ratzinger, A. Schempp, H. Klein, "Low Energy Beam Transport Using Space Charge Lenses"

Th.P – 16 R. Bhatt, C. Chen, E. Henestroza, J. Zhou, "The Path to Ideal High-Intensity Beams in Alternating-Gradient Focusing Systems"

Th.P - 17 M. Pusterla, "Unconventional Theoretical Methods Applied to High Intensity Ion Beams in Circular and Linear Accelerators"

Th.P – 18 S. Hudson, H. Qin, R. Davidson, "Chaotic Particle Trajectories in High Intensity Finite-Length Charge Bunches"

Th. P – 19 G. Benedetti, G. Turchetti, "Collision Effects and Dynamic Aperture in High Intensity Storage Rings"

Th.P - 20 S. Lund, D. Grote, R. Davidson, "Simulation of Beam Emittance Growth from the Collective Relaxation of Space-Charge Nonuniformities"

Th.P – 21 F. Bieniosek, A. Faltens, L. Prost, P. Roy, P. Seidl, S. Eylon, E. Henestroza, W. Waldron, S. Yu, "Experimental Study of Space-Charge Waves in Intense Heavy Ion Beams"

Th.P – 22 P. Seidl, D. Baca, G. Ritchie, G. Sabbi, D. Shuman, M. Covo, A. Molvik, "Magnetic Field Measurements of Quadrupoles in the High Current Experiment"

Th.P - 23 J. Zhou, C. Chou, B. Qian "Beam Halo Formation and Bean Loss Induced by Image-Charge Effects in a Small-Aperture Alternating-Gradient Focusing System"

Th.P – 24 R. DuBois, A. Santos "Scaling Laws for Electron Loss from Ion Beams"

Th.P – 25 P. Stoltz, S. Veitzer, R. Cohen, A. Molvik, J.L.-Vay "Electron Effects Due to Grazing Collisions Between Heavy Ions and Walls"

Th.P. – 26 S. Eylon, E. Henestroza, P. Roy, S. Yu "Electron Effects in the Neutralized Transport Experiment (NTX)"

Th.P – 27 M. Chung, E. Gilson, R. Davidson, P. Efthimion, R. Majeski, E. Startsev "Laser Induced Fluorescence Diagnostic of Barium Ion Plasmas in the Paul Trap Simulator Experiment"

Th.P – 28 P. Roy, S. Yu, S. Eylon, E. Henestroza, J. Ludvig, D. Shuman, W. Greenway, D. Vanecek, W. Waldron, R. Hannink, "Study of a Non Intercepting Beam Diagnostic for Beam Density Profile"

Th.P – 29 Y. Cui, Y. Zou, M. Reiser, R. Kishek, I Haber, S. Bernal, P. O'Shea, "Resolution Study of a Retarding Energy Analyzer"

Th.P – 30 Y. Zou, Y. Cui, M. Reiser, K. Tian, M. Walter, I. Haber, R. Kishek, S. Bernal, P. O'Shea, "Progress on Experimental Study of Beam Energy in the Space-Charge Dominated Beams"

Th.P – 31 L. Wu, G. Miley, H. Momota, "Space-Charge Neutralization of Heavy Ion Beams via Electron Injection

Abstracts
Oral Presentations
Monday, 07 June, 2004

Program Overviews
Targets for Fusion and High Energy Density Physics

Listed in Program Order
One Per Page

OVERVIEW OF US HEAVY- ION FUSION RESEARCH*

B. Grant Logan

Heavy Ion Fusion Virtual National Laboratory (HIF-VNL)+

Significant experimental and theoretical progress has been made in the U.S. heavy ion fusion program on high-current sources, transport, final focusing, chambers and targets for inertial fusion energy (IFE) driven by induction linac accelerators. The program seeks to provide the scientific and technical basis for the Integrated Beam Experiment (IBX), an integrated source-to-target physics experiment recently included in the list of future facilities planned by the U.S. Department of Energy. To optimize the design of IBX and future inertial fusion energy drivers, current HIF-VNL research is addressing several key issues (representative, not inclusive): gas and electron cloud effects which can exacerbate beam loss at high beam perveance and magnet aperture fill factors; ballistic neutralized and assisted-pinch focusing of neutralized heavy ion beams; limits on longitudinal compression of both neutralized and un-neutralized heavy ion bunches; and tailoring heavy ion beams for uniform target energy deposition for high energy density physics (HEDP) studies.

Recent progress highlights: *The Source Test Stand (STS)*: High brightness beamlets of Ar^{+1} ions have been measured with current density (100 mA/cm^2 @ 5 mA), emittance (T_{eff} < 2 eV), charge state purity (> 90%) and energy spread (< 0.01%) supporting future merging-beamlet injectors for heavy ion fusion. Sixty-one beamlets have been extracted through 4 Einzel lens arrays with good uniformity across the array. *The High Current Experiment (HCX):* Beam loss from transport of 180 mA, 1 MeV K^+ beams over five electric-quadrupole lattice periods has been reduced by a factor of three by flattening the injector extraction voltage waveform [flatter $I_b(t)$], improved matching (smaller envelope oscillations), and better beam centroid control. Experiments with transport through four pulsed quadrupole magnets began in May 2003 to study gas and electron effects. Work in progress includes a variety of new diagnostics and use of electron clearing electrodes, as well as addition of small induction gaps to expel electrons. *The Neutralized Transport Experiment (NTX)*: a very high brightness ion beam (ε_n < 0.05 πmm-mr at 25 mA, 300 keV K^+), supports small neutralized focal spots, RF and MEVVA plasma sources have been characterized, and initial experiments focusing high perveance (3×10^{-4}) beams show that plasma neutralization reduces focal spot radii from ~ 1.1 cm (vacuum focus) to <0.14 cm (neutralized focus) consistent with particle-in-cell calculations. In addition, transport physics experiments relevant to long-path heavy ion fusion drivers have begun with the University of Maryland Electron Ring, and with the Paul Trap Simulator Experiment at PPPL. Recent heavy ion fusion theory and simulation research has developed 3D time-dependent simulations of HCX and IBX, new insights have been gained on electron cloud effects by including electron cloud models in WARP simulations, new Adaptive Mesh Refinement capabilities in WARP are yielding better injector simulations, and the behavior of anisotropy and two-stream modes have been explored with the nonlinear perturbative BEST δf code.

A multi-beam induction linac driven power plant study (9-03) shows detailed requirements for distributed radiator targets (spot size, power, symmetry and pulse shape) can be met with ballistic neutralized focusing of a 120 beam array over 6 meter focal lengths. Provided neutralized drift compression and focusing onto larger-spot hybrid targets can be experimentally validated, preliminary studies indicate that modular induction linac driver systems with ~ 20-40 linacs may be cost-competitive. Methods to accommodate or correct chromatic aberrations with neutralized drift compression are being investigated in this new study. Combinations of tangential liquid injection and ejection allow controlled and flexible liquid cavity geometry, giving rise to new large vortex-liquid protection chamber concepts without oscillating jets.

The above research by the U.S Heavy Ion Fusion –Virtual National Laboratory, and associated heavy ion fusion chamber and target research, by the Virtual Laboratory for Technology supports the scientific and technical basis for heavy ion induction-linac-driven inertial fusion energy and high energy density physics.

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Berkeley and Lawrence Livermore National Laboratories under Contract Numbers DE-AC03-76SF00098 and W-7405-Eng-48, and by the Princeton Plasma Physics Laboratory under Contract Number DE-AC02-76CH03073.

+ Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory, and Princeton Plasma Physics Laboratory

M.I-02

EUROPEAN PROGRAM OVERVIEW

Basic Physics for Inertial Fusion Energy in High Energy Density Physics with Intense Heavy Ion and Laser Beams

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By definition there is no European program on Inertial Fusion and definitely no HIIF program. There are, however, basic science issues which are studied at universities and research centers throughout Europe that contribute to improve the understanding of fundamental inertial fusion issues, like:

- Beam Plasma Interaction Processes
- Interaction of intense Laser fields with matter
- Accelerator physics
- Beam transport and focusing

In this talk, emphasis will be given to the development of the understanding of beam plasma interaction phenomena relevant to inertial fusion physics.
Intense beams of ions and photons interacting with matter transform the interacting zone into transient plasma. The system, then generally consists of a mixture of electrically charged ions, electrons and neutral particles as well. In this situation collective effects, determine the statistical properties of the sample. Atoms and ions immersed in a plasma environment experience perturbations from the plasma. As a result the atomic and ionic states turn out to be mixed, and strongly different from pure, unperturbed atomic states and they are different as well from the situation of a cold matter environment. Consequently not only the spectral characteristics of radiation emission and absorption by the atoms and ions in plasma are substantially different from spectra of the unperturbed species, but also bulk matter properties. These can be expressed in terms of an equation-of-state, relating pressure and temperature to the matter density of the sample, by the electrical, and thermal conductivity, and radiation transport properties. In general these properties turn out to be vastly different from those of matter under ordinary conditions. The physics of such dense, and strongly coupled plasmas is closely related to those states of matter with a high energy density and high pressure above 1 megabar. Examples are the interior of planets, giant planets and stars or even compact astrophysical objects or the converter of an inertial fusion target. The knowledge of the behaviour of matter under extreme conditions, especially at ultrahigh pressures in the megabar region, is of fundamental importance for inertial fusion energy research as well as improved models for the planetary and stellar structure. Future perspective of intense ion and laser beams for inertial fusion physics will be discussed from a European perspective

RUSSIAN HIF PROGRAM OVERVIEW

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Studies of heavy ion driven inertial fusion aiming at energy production have been pursued with increasing activities in Russian HIF community. The emphasis of the related studies on Heavy Ion Fusion Energy were centered on the

- fusion targets design,
- experimental and theoretical study of heavy ion beam-plasma interaction,
- theoretical and experimental investigations of the state of matter under extreme conditions,
- critical issues of the physics and technology of intense heavy ion accelerators-drivers,
- critical issues of the fast ignition heavy ion driven power plant concept.

Overview of the joint activities of numerous institutes of Russia is presented.

JAPANESE PROGRAM OVERVIEW

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Fundamental issues for HIF research are intensively studied at several universities and institutes as collaborating works of domestic and international forms.

Beam dynamics in the final beam bunching from 1.6 kA to 40 kA with induction modulators and FODO transverse focusing structure, is simulated using a PIC code. Emittance growth of 20% is observed which is independent of the initial particle distribution. The emittance growth during the bunch compression is attributed to the flute perturbation instability for the KV and Waterbag distributions. The other activity on the beam dynamics is the study of high current bunch compression in the storage ring project at RIKEN which is presently under the discussion stage.

Heavy-ion beam irradiation onto the fuel targets is simulated to study the influence of non-uniformity of energy deposition on the target implosion. The calculation is carried out as a function of beam non-uniformity such as Gaussian shape or semi-Gaussian shape, beam number, reactor-chamber radius and so on. The RMS non-uniformity of beam irradiation is reduced when the calculation includes the beam temperature.

A driver system based on controllable repetitive induction modulators is studied to accelerate and bunch the intense heavy-ion beams. A basic concept proposed is to synthesize the desired shape of voltage pulse from sinusoidal waveforms. A small-scale test has successfully proved to operate the module elements with a rep-rate of 1 MHz at 2.5 kV.

The beam-plasma interaction experiments are to be extended to the non-ideal target plasma. Calculation with a particle code predicts that the non-linearity effect in the stopping power is observable even for the plasma of coupling constant $\Gamma<1$ if the low-energy (~ 100 keV/u) and highly-charged (> 25+) ions are available. The non-linearity of the stopping power can be discussed by introducing a beam-plasma coupling constant. To perform the interaction experiments, plasma targets based on the shockwave drive and the exploding wire are developed. As a fundamental experiment of the interaction of heavy ion beam with the laser induced plasma, Xe and Kr beams are used at RIKEN linear accelerator facility. The enhancement of stopping power was observed comparing with ones at cold matter case.

FUTURE PROSPECTS FOR HEAVY ION FUSION*

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Despite growing concerns about climate modification due to human activities, the rapidly growing economies of China and India, and the increasing volatility of the MidEast, there is presently no real national commitment today to the development of Fusion energy. The present location of the Office of Fusion Energy within the Office of Science also naturally emphasizes nearer term scientific objectives particularly in the the areas of Plasma Physics and High Energy Density Physics rather than the broad science and technology needs of Fusion energy development. The Heavy Ion Fusion program must find a way to navigate through these issues-dealing with today's focus while not forgetting the mission and unifying objective of the program. The challenges and opportunities facing HIF will be discussed as well as possible strategies to move the program forward.

*Work supported by the U.S. Department of Energy under Contract DE-AC03-98ER54411.

HEAVY ION TARGET PHYSICS AND DESIGN IN THE USA*

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Over the past few years, the emphasis in heavy ion target design has moved from the distributed radiator target [1,2] to the "hybrid" target [3] because the hybrid target allows a larger beam focal spot than the distributed radiator (~ 5 mm radius rather than ~ 2 mm radius). The beam focusing requirements were one of the motivations for going to a large number of beams (120 beams) in the "Robust Point Design" [4]. The large beam spot of the hybrid target may also allow lower energy, lower mass ions which should reduce the driver cost and size and possibly even allow a modular driver with a small number of separate accelerators. The hybrid target introduces some new target physics issues, however. Most notable is the use of shims to correct asymmetries that result from the ion beam geometry. Since heavy ion accelerators that are capable of experimentally testing these concepts are years away, we are using x-rays produced by a z-pinch on the Sandia Z machine [5] to test the concept of shims.

In addition to our hohlraum work, we continue to work on capsule design using calculations in both 2-d and 3-d [6] as well as analytic theory to guide the calculations. Gaining a better understanding of the capsule performance is critical if we want to trade capsule margin for lower peak power from the driver.

*This work performed under the auspices of the U.S Department of Energy by University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48.

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2. D. A. Callahan-Miller and M. Tabak, Nuclear Fusion, 39, 883 (1999).
3. D. A. Callahan, M. C. Herrmann, and M. Tabak, Laser and Particle Beams, 20, 405 (2002).
4. S. S. Yu, et. Al, Fusion Science and Technology, 44, 266 (2003).
5. G. R. Bennett, et. Al, Phys of Plasmas, 10, 3717 (2003).
6. A. E. Koniges, M. M. Marinak, M. Tabak, M. C. Herrmann, proceedings of the 3rd International Conference on Inertial Fusion Sciences and Applications, Sept 2003, Monterey, CA.

STUDIES OF HIGH-ENERGY-DENSITY STATES IN MATTER AT THE GSI DARMSTADT USING INTENSE BEAMS OF ENERGETIC HEAVY IONS

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The Gesellschaft für Schwerionenforschung (GSI) Darmstadt, is a unique laboratory worldwide that has a heavy ion synchrotron (SIS18) that delivers intense beams of energetic heavy ions. Currently this facility delivers a uranium beam that deposits about 0.7 kJ/g specific energy in solid matter. This facility is being upgraded and numerical simulations show that the the uranium beam generated at this upgraded facility will deposit about 50 kJ/g energy in solid targets [1]. GSI is also in the process of constructing a new bigger synchrotron ring, SIS100 that will deliver a much more intense uranium beam which will lead to a specific energy deposition of 200 kJ/g [2]. Availability of such high specific energy deposition will open up the possibility to study the equation-of-state (EOS) and transport properties of high-energy-density (HED) matter and access those parts of the phase diagram that are not accessible with other techniques.

An intense heavy ion beam can be used in two different schemes to achieve the above goals. One scheme involves isochoric heating of matter by the beam and subsequent isentropic expansion of the heated material [3]. In the second scheme one achieves a low-entropy compression of a sample material, like hydrogen that is imploded in a multi-layered cylindrical target [4,5]. In this paper we present novel designs for current and future EOS experiments using two-dimensional hydrodynamic simulations.

1 N. A. Tahir et al., Phys. Rev. E, **61** (2000) 1975.

2 N. A. Tahir et al., PR ST AB, **6** (2003) 020101.

3 D. H. H. Hoffmann et al., Phys. Plasmas , **9** (2002) 3651.

4 N. A. Tahir et al., Phys. Rev. E, **63** (2001) 016402.

5 A. R. Piriz et al., Phys. Rev. E, **66** (2002) 056403.

TARGET DESIGN FOR THE CYLINDRICAL COMPRESSION OF MATTER DRIVEN BY HEAVY ION BEAMS

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The compression of a cylindrical sample of cryogenic hydrogen contained in a hollow shell of Pb or Au has been analyzed in the framework of the experiments to be performed in the heavy ion synchrotron SIS100 to be constructed in the Gesellschaft für Schwerionenforschung (GSI) Darmstadt [1,2]. The target implosion is driven by an intense beam of heavy ions and, in order to avoid the direct heating of the sample, it has a ring shaped focal spot.

In this work we report the results of a parametric study of the final state of the compressed matter in terms of the target and beam parameters [3]. Then we consider the generation of the annular focal spot by means of a radio frequency wobbler that rotates the beam at extremely high frequency and we determine the required frequency in order to accommodate symmetry constraint [4,5]. Besides, the sample parameters that can be achieved with a Gaussian focal spot (non rotating beam) has also been studied as well as the possibility to use a mask as an alternative way to avoid the direct heating of the sample [6]. Finally we report the analysis of the hydrodynamic instabilities that affect the implosion and the mitigating effects of the elastoplastic properties of the shell [7].

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[2] N. A. Tahir et al. Phys Rev. E **63**, 016402 (2001).
[3] A. R. Piriz et al. Phys Rev. E **66**, 056403 (2002).
[4] A. R. Piriz et al. Plasma Phys. Contr. Fusion **45**, 1733 (2003).
[5] M. Temporal et al. Laser Part. Beams **21**, 605 (2003).
[6] M. Temporal et al, submitted to Plasma Phys.
[7] J. J. Lopez-Cela et al, submitted to EPJ-AP.

PROGRESS IN HEAVY ION DRIVEN TARGET FABRICATION AND INJECTION

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The target for an Inertial Fusion Energy (IFE) power plant introduces the fusion fuel to the chamber, where it is compressed and heated to fusion conditions by the driver beams. The "Target Fabrication Facility" of an IFE power plant must supply over 500,000 targets per day. The target is then injected into the target chamber at a rate of 5–10 Hz and tracked precisely so the driver beams can be directed to the target. The feasibility of developing successful fabrication and injection methodologies at the low cost required for energy production (about $0.25/target, about 10^4 less than current costs) is a critical issue for inertial fusion.

The technologies for producing Heavy Ion Fusion (HIF) targets have significant overlaps and synergisms with current day inertial fusion experimental targets and with laser fusion (direct drive) IFE targets. Capsule formation and characterization, permeation filling, and layering of the DT using a cryogenic fluidized bed are common methodologies shared between laser fusion and HIF. Specific to HIF targets are the techniques for fabricating and assembling the hohlraum components. We will report on experimental progress with the Laser-assisted Chemical Vapor Deposition (LCVD) technique to produce "micro-engineered" low density metallic foams for the hohlraum, and calculations of hohlraums materials performance during handling. Fiber growth by LCVD in arrays has been demonstrated for the first time, important to achieve the volume production needed for IFE. We have also evaluated a variety of hohlraum material selections, with consideration of target physics, cost, ES&H, activation, and compatibility with the molten salt coolant. These materials include selections for once-through and for re-cycle scenarios. We have performed a cost analysis for an "nth-of-a-kind" Target Fabrication Facility using our current assumptions about the production processes. Some of these scenarios result in future target manufacturing costs consistent with economical electricity production.

*Work supported by the U.S. Department of Energy under Contract DE-AC03-98ER54411, DE-FC02-04ER54698, and W-7405-ENG-36.

FABRICATION OF CAPSULES WITH AN ANGLE DEPENDENT GOLD SHIMS FOR HOHLRAUM DRIVE SYMMETRY CORRECTION

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Sandia National Laboratory's (SNL) Z-pinch facility can generate a tremendous amount of x-rays suitable for compression of ICF capsules in the several millimeter diameter range. In particular, the double Z-pinch scheme driving a sandwiched hohlraum, closely mimics the indirect laser or heavy ion drives and can be used as a test bed for innovative target design and fabrication for overcoming some of the driver related issues. One specific study on Z involves compensating for the asymmetries of the hohlraum drive by shimming the target itself. These targets are typically ~ 5 mm in diameter and 25 µm in wall thickness, with a gold coating, ~ few tenth of micron in thickness, which varies as a function of the polar angle in a specified manner. We have recently produced such targets for the first experiments testing the viability of the target shimming concept. The developmental effort for producing and characterizing the proper gold thickness profile as well as the fabrication issues involved in producing the targets recently fielded at Z will be discussed in this talk.

*This work performed under General Atomics' internal research and development funds, number 40011.265.70000.

MODELS OF GAIN CURVES FOR FAST IGNITION *

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We consider gain curves for Fast Ignition that have the following ingredients: hydrodynamic efficiency of the implosion for a range of drive intensities, density of the assembled fuel resulting from the reflected shock produced at the culmination of the implosion, effective particle range produced in the laser-plasma interaction as well as the heat capacity of the ignition region as determined by Atzeni. The dependence of the gain curves on the coupling efficiency from ignition laser to fuel, allowed in-flight-aspect-ratio, compressed fuel density profile and fraction of implosion energy in the compressed fuel is shown. In addition the fraction of the total driver energy devoted to the ignition driver that maximizes the gain is shown. These estimates will be made for systems where the implosion is directly driven with a laser of various colors or indirectly with various drivers.

*This work was performed under the auspices of the U.S. Department of Energy
by the University of California Lawrence Livermore National Laboratory
under contract No. W-7405-Eng-48.

SHORT PULSE LASER GENERATED ION BEAMS FOR FAST IGNITION *

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The generation of highly collimated, ultra-intense ion beams at laser intensities beyond 10^{19} W/cm^2 is proposed as an alternative driver for fast ignition of compressed fuel pellets in Inertial Fusion Energy scenarios. The energy deposition characteristics and the ability to propagate through plasmas exceeding the critical density of common high intensity lasers are the major beneficial properties of ion beams to enhance the energy density in the hot and compressed core of a fuel pellet.

A series of experiments at the 100 TW laser facility of the Laboratoire pour l'Utilisation des Lasers Intenses (LULI) in Palaiseau, France, was performed to investigate the generation mechanisms and to shape the properties of laser generated ultra-intense ion beams. It could be shown that ions in the MeV regime are created by "Target Normal Sheath Acceleration" (TNSA), which is an effect of a space charge layer on the back surface of a foil, caused by Laser-target-interaction electrons, which penetrate the target[1]. Furthermore, the geometrical properties of the target back surface strongly influence the resulting ion beam[2].

A summary of the results achieved in Palaiseau will be presented along with an outlook on upcoming experiments at Sandia National Laboratories, which will address this interesting research field.

1. J. Fuchs, et al., *Phys. Rev. Lett*. 91 (2003), p. 255002.
2. M. Roth, et al., *Phys. Rev. ST- AB* 5 (2002), p. 061301.

* This work was supported by the European Union program HPRI CT 1999-0052.

† Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

SIMULATIONS OF ELECTRON TRANSPORT FOR FAST IGNITION USING LSP*

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A crucial issue for the viability of the fast ignition approach [1] to inertial fusion energy is the transport of the ignition pulse energy from the critical surface to the high-density compressed fuel. Experiments have characterized this transport through the interaction of short pulse, high intensity lasers with solid-density targets containing thin K_α fluorescence layers [2]. These experiments show a reasonably well-collimated beam, although with a significantly larger radius than the incident laser beam. We have previously reported LSP calculations that showed reasonable agreement with these experiments, but used an ad-hoc prescription for the fast electron source. We are coupling the particle distribution from Z3 (a massively parallel explicit 3D PIC code based on Zohar [3]) to our LSP calculations. The LSP code uses a direct implicit particle-in-cell (PIC) algorithm in 2 or 3 dimensions to solve for beam particle transport, while treating the background particles as a fluid [4]. The implications for fast ignition will be discussed.

*This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under contract No. W-7405-Eng-48. UCRL-ABS-202062.

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A New Twist to Inertial Confinement Fusion – Impact Ignition -

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Abstract

A new scheme for fast ignition is proposed, in which the compressed DT main fuel is ignited by impact collision of another fraction of separately imploded DT fuel. The second DT shell is ablatively driven in the hollow conical target to hyper-velocities ~ 10^8 cm/sec corresponding to temperatures > 5 keV on the collision with the main fuel, and this self-heated portion plays the role of igniter. The cone shell is irradiated at intensities > 10^{15} W/cm^2 to exert ablation pressures > 100 Mbar at laser wavelength of 0.35 μm. A preliminary two-dimensional hydrodynamic simulation shows the generation of a dense hot core and thus the feasibility of the new scheme. Application of the scheme to heavy ion fusion is also discussed.

Abstracts
Oral Presentations
Tuesday, 08 June, 2004

Atomic Physics and Ion and Laser Interactions with Matter
Accelerator and Beam Physics – Part I

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SOME PHYSICAL PROCESSES AT HIGH ENERGY DENSITIES, WORTH INVESTIGATING BY INTENSE HEAVY ION BEAMS

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High energy densities in matter can be generated by different methods. Review of modern experimental techniques, such as methods of shock compression, multi-step shock compression, isochoric heating and others is given. A special attention is pointed out to possibilities of intense heavy ion beams in high-energy-density matter research. Due to the unique feature of energy deposition process of heavy ions in dense matter (volume character of heating) it is possible to generate high entropy states in matter without necessity of shock compression. Previously, such high entropy states could only be achieved by using most powerful shock wave generators like nuclear explosions or powerful lasers. This novel technique of heavy ion heating and expansion [1] allows one to explore new fascinating regions of the phase diagram including liquid phase, evaporation region with the critical point and strongly coupled plasmas.

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HIGH ENERGY DENSITY PHYSICS EXPERIMENTS WITH INTENSE HEAVY ION BEAMS*

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Intense beam of energetic heavy ions is an excellent tool to create large samples of high energy density (HED) matter with fairly uniform physical conditions. This paper presents an overview of the current experimental research that has been done at GSI-Darmstadt in the field of heavy-ion beam generated HED matter. Special attention is given to the most recent experiments at GSI with an emphasis on developed ion-beam and target diagnostic techniques as well as on new target designs for such experiments. Some prospects on the future work planned at GSI in this direction are also discussed.

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ION BEAM INTERACTIONS WITH A DENSE, LASER PRODUCED PLASMA

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The combination of intense heavy ion beams and a powerful laser makes the Gesellschaft für Schwerionenforschung (GSI) a unique place for the investigation of the interaction of swift heavy ions with dense plasmas ($n_e \approx 10^{21} e/cm^3$) [1]. After the upgrade of the *nhelix* laser the plasma group at GSI is in a position to heat up a target foil to a plasma of above 100 eV temperature by depositing more then 100 J in 13 ns on a spot of 1,5 mm diameter. This plasma serves as target to investigate the stopping and charge exchange processes of ions penetrating it. The plasma is diagnosed by a X-ray streak camera, laser interferometry, spectroscopic detectors and visible imaging to gain as much information as possible and use them as benchmarks for PIC simulations of the laser-plasma interaction.
We will report on energy loss measurements of Ar ions with an energy of 4 MeV/u interacting with a carbon plasma. The measured plasma properties will be compared with a PIC simulation, dealing for the calculation of the energy loss. Complementing experiments of charge state dependent stopping powers and charge exchange cross sections of Ar ions in solid carbon foils were done at the Hahn-Meitner-Institute in Berlin (analogical to [2]). Those data can be used to specify the main processes leading to an enhanced stopping in plasmas compared to solids.

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STOPPING OF LOW-ENERGY HIGHLY-CHARGED IONS IN DENSE PLASMAS

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Heavy ion stopping in dense plasmas was numerically analyzed to find realistic parameters of the experiments on nonlinear interactions between the plasma targets and 10-100 keV/u beams delivered by a small electrostatic accelerator. We investigated interactions between the beams and highly-ionized hydrogen plasmas with coupling constants $\Gamma \approx 0.1\text{-}2$. To evaluate the energy loss we applied a simple particle code, in which the equations of motion were integrated for the projectile and all particles in the plasma contained in a cylinder. If the projectile charge was sufficiently high, nonlinear stopping was clearly observed even for plasmas with $\Gamma < 1$. The evaluated nonlinearity was explained comprehensively by introducing a projectile-plasma coupling constant. However we found that such a high projectile charge is not realistic for the low-energy ions at least during the passage through cold targets. Possibility of attaining high charge states needed for successful observations of the nonlinearity is discussed by considering the charge-changing processes of the projectile in target plasmas with different ionization degrees.

ISOCHORIC HEATING OF DT FUELS THROUGH PW-LASER PRODUCED NON RELATIVISTIC ION BEAMS*

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Several experiments have demonstrated that a short pulse of a high current well collimated proton beam can be generated by irradiation of a thin solid target by a high intensity sub-picosecond laser. Due to the large proton/electron mass ratio, a proton beam is much less affected by instabilities. It has lead M. Roth et al. [1]) to propose a proton beam Fast Ignitor Scenario (FIS). This scenario is quite attractive, in particular because the Laser generated Proton Source (LPS) is put outside the indirect driven target and so has no interference with the evolution of the target during the main pulse irradiation. To investigate this scenario in more details, and also for application such that the proton imaging of plasma targets, we have constructed a numerical code that describes the transport and energy deposition of high current energetic proton beams, as those generated by a LPS, through complex targets. Energy loss and dispersion together with angular diffusion due to multiple scattering have been included in our model.

For ion beams generated by standard accelerators, the transverse dispersion is not of fundamental importance to predict the interaction of the beam with dense targets, so more efforts have been put previously on the determination of the longitudinal force (stopping) induced mainly by the interaction of the beam with the plasma electron. However, due to the specific properties of LPS, the transverse dispersion becomes a central quantity to accurately determine the density of deposited energy by the proton beam.

Inside a target, the transverse spreading of a beam generated by a LPS is related mainly to the low frequency (ionic) part of the microfield, whereas the high frequency (electronic) part produces the longitudinal force. We are thus here in a quite stimulating case, from a theoretical point of view, where a large domain of frequencies of the fluctuating field inside a dense plasma has to be investigated. Together with our code results for FIS applications we will describe at the conference the present state of our modeling on this field.

* This work was support by CEA-EURATOM (under grant V.3094.003). M. D. B-C thanks Fundacion Séneca for a post-doctoral grant.

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IONIZATION CROSS SECTIONS FOR ION-ATOM COLLISIONS IN HIGH ENERGY ION BEAMS*

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Knowledge of ion-atom ionization cross sections is of great importance for many accelerator applications. We have recently investigated theoretically and experimentally the stripping of more than 18 different pairs of projectile and target particles in the range of 3-38 MeV/amu to study the range of validity of both the Born approximation and the classical trajectory calculation. In most cases, both approximations give similar results [1,2]. However, for fast projectile velocities and low ionization potentials, the classical approach is not valid and can overestimate the stripping cross sections by neutral atoms by an order-of-magnitude [3]. We have developed a hybrid approach, which automatically chooses between the Born approximation and the classical mechanics approximation depending on the parameters of the collision.

When experimental data and theoretical calculations are not available, approximate formulas are frequently used. Based on experimental data and theoretical predictions, a new fit formula for ionization cross sections by fully stripped ions is proposed. The resulting plots of the scaled ionization cross sections of hydrogen by fully stripped ions are presented. The new fit formula has also been applied to the ionization cross sections of helium [4]. Again, the experimental and theoretical results merge close together on the scaled plot.

* This research was supported by the U. S. Department of Energy.

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EQUATION OF STATE OF WARM DENSE MATTER GENERATED BY HEAVY IONS*

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Physical states of warm dense matter (WDM) resulting from action of intense energy fluxes on condensed media include hot compressed liquid, dense plasmas, liquid-gas region with the critical point and quasi-ideal gas. The available equation-of-state (EOS) information of WDM for most materials is limited by knowledge of the principal shock adiabat and several evaluations of the critical point. The idea to create and to investigate states of WDM through isochoric heating is very promising [1-3]. The possibilities of intense heavy ion beams to generate WDM are discussed. We used in the present analysis a wide-range multi-phase EOS for metals and 3D parallel particles-in-cells gas dynamic code. Discussed are results obtained for SIS18 and SIS 100 heavy ion beams at GSI, Darmstadt.

*This work has been supported by GSI-INTAS contract, No. 03-54-4254.

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Tu.I-08

EXPERIMENTS ON BEAM-PLASMA INTERACTION PHYSICS

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Investigation of heavy ion beam interaction physics with dense plasma is one of key issues for Inertial Confinement Fusion (ICF) driven by powerful heavy ion beams. In fact it determines the requirements to the output parameters of powerful ion beams, final focusing system, number of beamlets in reactor chamber, beam transport through the reactor chamber, target positioning and the design of the target geometry itself. The detailed modeling of the heavy ion beam driven ICF conditions requires adequate quantitative description of the interaction processes of heavy ion beams with dense plasmas in a wide range of parameters.

Since 2001 at the UNILAC accelerator at GSI an experimental set-up exists for measuring the interaction of heavy ions with non-ideal plasmas. [1] The experimental results of energy loss measurements of C, Ne, Ar and Xe ions in energy range 5.9 – 11.4 MeV/u and charge state distribution in a shockwave-driven, strongly-coupled (non-ideal) Ar plasma with a variation of the plasma parameters are present.

New experimental setup for stopping power measurements based on a 27 MHz RFQ-linac has been designed and assembled at ITEP, Moscow. Energy losses of 101 keV/n Cu ions in nitrogen and hydrogen have been measured for subsequent comparison with the energy losses of the same ions in plasma. The plasma was generated by igniting a 3 kA electric discharge in two 78 mm long collinear quartz tubes of 6 mm in diameter [2]. It is closed at both sides by 1 mm diameter diaphragms. This set-up allows producing plasma with linear electron density of up to $5{\cdot}10^{17}$ cm^{-2}.

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ELECTRICAL RESISTIVITY MEASUREMENTS OF ION DRIVEN HIGH ENERGY DENSITY MATTER*

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The high intensity heavy ion beams provided by the accelerator facilities of the Gesellschaft für Schwerionenforschung (GSI) Darmstadt are an excellent tool to produce large volumes of high energy density (HED) matter. The thermophysical properties of such systems are of interest for fundamental as well as for applied research. The development of a new diagnostic technique allowed for first measurements of the electrical conductivity of heavy ion driven HED matter. The targets consisted of 10 mm long, 0.25 mm diameter, lead, copper or silver wires. Oxygen and argon ion beam pulses with a duration of 1 μs, intensities up to $6 \cdot 10^{10}$ particles and energies of 200 and 300 AMeV, respectivelly have been used as drivers. High energy density deposition (up to 1 kJ/g) has been achieved by focussing the ion beams with a high current plasma lens down to a diameter of $0.7 - 1.0$ mm FWHM. The measurements are compared with results obtained by 2D simulations of the hydrodynamic response of the target material and electrical current flow calculations.

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ACCELERATOR PLANS AT GSI AND PLASMA PHYSICS APPLICATIONS

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In November 2001 the Conceptual Design Report presented the concepts for "An International Accelerator Facility for Beams of Ions and Antiprotons".

The main accelerator stage of the proposed facility is the synchrotron complex SIS100/300 consisting of two separate synchrotron accelerator rings with a maximum rigidity of 100 and 300 Tm at the same circumferences of 1083m, which shall provide beams of protons and heavy ions with high intensities and at high energies. The existing GSI accelerators UNILAC and SIS18 will serve as injector facility for the SIS100/300.

The SIS100 will be used for the acceleration of high intensity heavy ion beams to deliver up to $1\text{-}2\cdot10^{12}$ U^{28+} - ions with energies ranging from 400 to 2700 MeV/u with one machine cycle every second. These beams of heavy and also of lighter ions shall be used for the production of secondary beams of radioactive ions, but may also provide unique properties for high energy density in matter experiments.

The status of the technical planning and the design studies will be presented. Special emphasis will be on the experiences with intermediate charge-state operation of heavy ions gained by preparing the SIS18 as a booster for SIS100.

Survey of Collective Instabilities and Beam-Plasma Interactions in Intense Heavy Ion Beams*

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This paper presents a survey of the present theoretical understanding of collective processes and beam-plasma interactions affecting intense heavy ion beam propagation in heavy ion fusion systems. In the acceleration and beam transport regions, the topics covered include: discussion of the conditions for quiescent beam propagation over long distances; the electrostatic Harris-type instability and the transverse electromagnetic Weibel-type instability in strongly anisotropic, one-component nonneutral ion beams; and the dipole-mode, electron-ion two-stream instability driven by an (unwanted) component of background electrons. In the plasma plug and target chamber regions, collective processes associated with the interaction of the intense ion beam with a charge-neutralizing background plasma are described, including: the electrostatic electron-ion two-stream instability, the electromagnetic Weibel instability, elecron plasma oscillation excitations, and the resistive hose, sausage, and hollowing instabilities. Particular emphasis is placed on identifying operating regimes where the possible deleterious effects of collective processes on beam quality are minimized.

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Three-Dimensional Simulation Studies of the Temperature Anisotropy Instability in Intense Charged Particle Beams*

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In plasmas with strongly anisotropic distributions ($T_{||b}/T_{\perp b} \ll 1$) a Harris-type collective instability may develop if there is sufficient coupling between the transverse and longitudinal degrees of freedom. Such anisotropies develop naturally in accelerators and may lead to a detoriation of beam quality. The instability may also lead to an increase of longitudinal velocity spread, which would make the focusing of the beam difficult and impose a limit on the minimum spot size achievable in heavy ion fusion experiments. Our previous studies [1] clearly show that moderately intense beams with $s_b = \widehat{\omega}_{pb}^2/2\gamma_b^2\omega_{\beta\perp}^2 \geq 0.4$ are linearly unstable to short wavelength perturbations with $k_z^2 r_b^2 \geq 1$, provided the ratio of longitudinal and transverse temperatures is smaller than some threshold value. This paper reports the results of recent simulations of the temperature anisotropy instability using the Beam Equilibrium Stability Transport (BEST) code for space-charge-dominated, low-emittance beams with $s_b \to 1$. Such high-intensity beams are relevant to the Integrated Beam Experiment (IBX) which would serve as proof-of-principal experiment for heavy ion fusion.

*Research supported by the U. S. Department of Energy.

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Ion Source and Injector Experiments at the HIF/VNL*

Tu.I-13

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Heavy ion fusion requires ion sources that can produce high current, but the beams must have low emittance in order to achieve high brightness. Furthermore the injector must be able to transport and match the severely space-charge dominated beam into an induction linac channel.

The traditional approach is to use large diameter surface ionization sources that produce ions with low thermal velocities. In this case, the maximum current density is determined by the space-charge limit of a large extraction diode. At low ion "temperature" the beam emittance can be dominated by spherical aberrations. An experiment is set up on a 500-kV test stand to study the beam optics and to find ways for improvement. The finite ion transit time in a large diode can be a problem for injectors that try to produce short pulses with fast rise time. Fortunately, our simulations have shown that a proper waveform can be constructed to produce a rise time as short as 50-ns beam. We have conducted an experiment to benchmark the simulation results.

Simulation has also shown that by merging a large number of high current density beamlets, a high current beam can be formed with an acceptable low emittance. In our experiment, we have tested an RF-driven argon plasma source to produce an array of 61 beamlets. We have reached our goal of producing 100 mA/cm^2 current density (= 4.9 mA per beamlet) with 90% of the ions in the single charged Ar^+ state. Other beamlet parameters will be reported in the symposium. At present, the schedule is to complete the Merging-Beamlets Experiment in FY05. Design of the apparatus is in progress and the experiment is expected to begin in the summer of 2004.

There are other innovative injector concepts being developed in the VNL, e.g., using an accel-decel scheme to reach high line charge density, or using negative ion beams to prevent the secondary electrons problem in beam transport. These proposed experiments along with data from the present experiments will be discussed.

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BEAM PHYSICS IN ITEP-TWAC SYNCHROTRON RINGS.

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For plasma physics experiments in TWAC accelerator facility there are essential the following parameters of the extracted beam: kind of ions, beam energy and beam power, beam momentum spread and beam emittances (these parameters define specific energy and specific power dissipated in the experimental target). We have proposed three stages of complex upgrade directed on an improvement of the beam parameters: 1) change of the laser source on a new more powerful one; 2) development of a new linac; 3) enhancement of the booster repetition rate up to 20 Hz. For modified complex, it is considered beam physics phenomena limiting beam intensity and beam quality: space charge effects, intra-beam scattering, beam induced pressure growth in the vacuum chambers and electron cloud effects. The corresponding cures for suppression of these effects have been described. It is marked that achievement of design TWAC parameters requires significant technical and intellectual efforts.

SCIENTIFIC ISSUES IN FUTURE ACCELERATORS FOR HEAVY ION FUSION*

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The U.S. and wordwide heavy ion fusion programs have made a large amount of progress over almost three decades of research on the intense beam physics and driver concepts needed for our concept. In the 1970's, '80's, and '90's, most experiments used driver parameters scaled to low energy and low line charge in order to study, most often with a single beam, the physics of high-perveance beams. More recently, the U.S. program has introduced higher line-charge experiments, where the beam space charge potential is significant. This allows investigation of the production, and effect on the beam, of stray electrons. Increasingly, the possibilities for neutralizing plasmas are also being investigated, both just upstream, and in, the target chamber. This talk will outline the scientific issues which remain to be examined. These include issues of longitudinal compression, dynamic aperture, electron/ion instabilities, effect of electrons and gas on the beam, longitudinal emittance evolution, halo production, inductive effects at high energy, multiple beams, innovative final focus approaches, and driver issues for solenoid transport. A outline of future experiments to address these issues will be presented and discussed.

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Fusion Chamber
Accelerator and Beam Physics – Part II

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HIF CHAMBER PHENOMENA AND DESIGN*

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A strong linkage exists between chamber conditions and the propagation and focusing of heavy ion beams for the production of inertial fusion energy. Heavy-ion fusion (HIF) adapts well to the use of liquids, like the molten salt flibe, in chambers. Liquids protect the surfaces of chamber structures from ablation by target x rays, and attenuate and stop fusion neutrons, reducing damage to structural materials. HIF chamber research has identified a wide variety of liquid configurations that can be applied for chamber protection. This presentation summarizes recent progress in research on HIF chambers, including x-ray ablation, debris venting and condensation, liquid response and regeneration, and chamber reliability and safety. Novel liquid configurations that have been developed, including very smooth jets, oscillating porous liquid structures, and vortex flows, are also discussed.

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FINAL BEAM TRANSPORT AND TARGET ILLUMINATION*

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Key issues in heavy ion beam (HIB) inertial confinement fusion (ICF) include an accelerator design for an intense HIB, an efficient HIB transport, a HIB-target interaction, a reactor design and so on. At the final transport region in HIF the HIB space charge should be neutralized and several effective methods for the HIB space charge neutralization have been already proposed. In our study, an insulator annular tube guide has been proposed at the final transport part, through which a HIB is transported, in order to neutralize the HIB space charge [1]. After the HIB final transport, HIBs enter the fusion reactor and should illuminate a fuel target. Therefore, in our study three-dimensional computer simulations are performed for a HIB irradiation onto a direct-driven spherical fuel pellet in HIB ICF in order to clarify a dependence of multi-HIB illumination non-uniformity on parameter values of HIB illumination. If HIBs are not well neutralized, the HIB energy may not be used effectively and the present-designed fuel pellet may not lead a high gain. Therefore we employ this reasonable assumption that HIBs are neutralized well in our calculation of HIB irradiation. For various beam parameters and reactor chamber radii we investigate the energy deposition non-uniformity using 12, 20, 32, 60, 92 and 120-beam irradiation systems. In this study, effects of HIB temperature, HIB illumination systems, HIB emittance and pellet temperature on the HIB illumination non-uniformity are also evaluated. In addition, the non-uniformity growth due to a little pellet displacement from a reactor chamber center is investigated. The calculation results demonstrate that we can realize a rather low non-uniform energy deposition: for example, less than 2.0 % even for a 32-beam irradiation system.

*This work has been partly supported by JSPS (Japan Society for the Promotion of Science). We would like to present our thanks to Prof. K. Tachibana for his fruitful discussions on this subject.

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RECYCLING ISSUES FACING TARGET AND RTL MATERIALS OF INERTIAL FUSION DESIGNS

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Designers of heavy ion (HI) and Z-pinch inertial fusion power plants have explored the potential of recycling the target and recyclable transmission line (RTL) materials as an alternate option to disposal in a geological repository. The choice between disposal and recycling primarily depends on the volume of the target/RTL waste relative to the nuclear island waste and the economics of the recycling process. Although the physics basis of the HI and Z-pinch concepts is widely different, many of the recycling issues facing both designs are quite similar. This work represents the first time a comprehensive recycling assessment was performed on both machines with an exact pulse history. The irradiation schedule begins with inserting the target/RTL into the nearly spherical chamber at a design-specific repetition rate and generating x-rays of sufficient energy and intensity to indirectly heat the DT capsule to ignition and burn. During burn, the target/RTL materials are irradiated by the energetic source neutrons and after burn, the debris is pumped out of the chamber for disposal or recycling. We examined two extreme irradiation approaches and assessed their impact on multi-disciplinary design requirements, such as the waste level, economics, and design complexity. The open-cycle, once-through approach irradiates the target/RTL materials a single time and then disposes of them in a repository. In the closed-cycle recycling approach, the target/RTL materials are remanufactured, spending a few days outside the chamber in an on-site factory, and reused for the entire life of the plant. The main goal of the latter approach is to lower the target/RTL inventory and minimize the waste stream at the expense of more radioactive end products and a more severe radiation environment at the target/RTL fabrication facility. Our results offer two divergent conclusions on the target/RTL recycling issue. For the HI concepts, target recycling is not a “must” requirement and the preferred option is the one-shot use scenario as target materials represent a small waste stream, less than 1% of the total nuclear island waste. We recommend using low-cost hohlraum materials once-through and then disposing of them instead of recycling expensive materials such as Au and Gd. On the contrary, RTL recycling is a “must” requirement for the Z-pinch concept in order to minimize the RTL inventory and enhance the economics. The initial activation results showed that the steel-based RTLs could meet the low level waste and recycling dose requirements with a wide margin when the RTLs are recycled for the entire plant life even without a cooling period. The incremental cost associated with the recycling scheme and the timeline of the remote remanufacturing process using robotic or similar technology should be investigated during the course of the Z-pinch power plant study.

W.I-04

NEUTRONICS OF HEAVY ION FUSION CHAMBERS*

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The leading candidate for a Heavy Ion Fusion (HIF) chamber is the thick-liquid wall concept, where a liquid (usually a lithium molten-salt) is used to attenuate neutrons and protect the solid structures from radiation damage, therefore lengthening the lifetime of components. This thick-liquid wall is also used to remove the heat from the fusion chamber and to breed the tritium fuel that is consumed during the fusion process. A very important advantage of the thick-liquid concept resides in the fact that the neutron spectrum at the chamber first wall (FW) has lower energy and intensity than that experienced in a dry wall system. Therefore, an HIF chamber could be built with materials that have already been developed and tested for neutron damage using currently available fission irradiation sources.

In this paper we investigate the nuclear characteristics of an HIF thick-liquid wall chamber in terms of neutron attenuation capability for FW protection. Starting with the HIF target output spectra, we have used a Monte Carlo neutron transport code to calculate the chamber spectra for various candidate liquids and thicknesses. We have used available radiation damage data from fission reactor testing to evaluate the performance of various steels as potential FW material. It is found that while some transmutant generation and temperature history effects may require further investigation, the development path for HIF chambers may not require the construction of a 14 MeV neutron source for chamber material testing.

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VAPOR CONDENSATION STUDY FOR HIF LIQUID CHAMBERS*

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The condensation rate of flibe vapors under conditions relevant to a HIF system is experimentally assessed and reported. An HIF system involves using liquid flibe to absorb the energy released by the fusion reaction (x-ray, debris, and neutrons). As a consequence, part of the liquid material vaporizes. Because of the high repetition rates necessary to keep the IFE power plant economically competitive, the issue of chamber vapor clearing plays an important role in demonstrating the feasibility of the concept. In the laboratory experiment, the prototypical dynamic characteristics of the excited vapor are obtained by rapidly passing a large current generated from a pulsed electric arc to a pool of molten flibe. The excited vapor expands inside a chamber that has been scaled to reproduce IFE conditions, and condenses as it comes in contact with the chamber walls, in which are maintained at a controlled temperature. The pressure history in the chamber and the residual gas composition are recorded to characterize condensation rates. The experiment results show that chamber clearing can be characterized by an exponential decay with a time constant of 6.58 milliseconds. The resulting period for chamber clearing for IFE systems requirements is 60 milliseconds. The conclusion is that condensation rates are sufficiently fast to allow the required repetition rates, but that the problem of the feasibility of the use of flibe in IFE systems lies in the control of the impurities dissolved in the salt.

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W.I-06

Molten Salt Chemistry Control

for Fusion Chambers

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The molten salt of Lif-BeF2 is an attractive coolant breeding material for fusion applications. This was the coolant salt used for the molten salt reactor experiment (MSRX). Many engineering issues were studied in the development of the MSRX. One of the key issues for the molten salt is the development a process for chemistry control. Due to the transmutation of Li and Be, the F is the molten salt would be freed to form either free fluorine or hydrogen fluorine. Both F2 and TF can be very corrosive toward the structural materials.

A REDOX process, based on the following chemical reaction, was developed for the MSRE. (REDOX means REDuction and Oxidation, which indicates the chemical state of the molten salt.)

$$TF + UF_3 \rightarrow 0.5T_2 + UF_4$$

This process controlled the TF activities successfully. In the fusion chamber, there is no U for this chemistry control process. However, we will have Be in the fusion chamber for neutron multiplication. Since BeF_2 is very stable, we can use the following reaction for the chemistry control,

$$2TF + Be \rightarrow T_2 + BeF_2$$

Based on thermodynamics, this reaction will process toward the left side of the reaction. However, while this reaction will be fast enough to control the chemical state of the molten salt remains to be demonstrated. As a part of JUPITER-II collaboration between us and Japan, an experimental program has been established at INEL to study this process. The results will be available during the earlier part of 2005.

EXPERIMENTAL STUDY OF THE TRANSPORT LIMITS OF INTENSE HEAVY ION BEAMS IN THE HCX*

W.I-07

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The High Current Experiment (HCX) at Lawrence Berkeley National Laboratory is part of the US program to explore heavy-ion beam transport at a scale representative of the low-energy end of an induction linac driver for fusion energy production. The primary mission of this experiment is to investigate aperture filling factors acceptable for the transport of space-charge-dominated heavy-ion beams at high space-charge intensity (line charge density up to ~ 0.2 μC/m) over long pulse durations (>4 μs) in alternating gradient electrostatic and magnetic quadrupoles. The experiment also contributes to the practical baseline knowledge of intense beam manipulations necessary for the design, construction and operation of a heavy ion driver for inertial fusion. This experiment is testing -- at driver relevant scale -- transport issues resulting from nonlinear space-charge effects and collective modes, beam centroid alignment and beam steering, matching, image charges, halo, electron cloud effects, and longitudinal bunch control. We first present the results for a coasting 1 MeV K^+ ion beam transported through the first ten electrostatic transport quadrupoles, measured with optical beam-imaging and double-slit phase-space diagnostics. This includes studies at two different radial filling factors (60% and 80%), for which the beam transverse distribution was fully characterized. Additionally, longitudinal phase space and halo measurements will be shown. We then discuss the first results of beam transport through four pulsed room-temperature magnetic quadrupoles (located downstream of the electrostatic quadrupoles), where the beam dynamics become more sensitive to the presence of secondary electrons.

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W.I-08

SIMULATION OF INTENSE BEAMS FOR HEAVY ION FUSION*

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Computer simulations of intense ion beams play a key role in the Heavy Ion Fusion research program. Simulations, coupled with analytic theory, are used to develop plans for future experiments, to guide ongoing experiments, and to aid in the analysis and interpretation of experimental results. They also afford access to regimes not yet accessible in the experimental program. The U. S. Heavy Ion Fusion Virtual National Laboratory and its collaborators have developed state-of-the art computational tools, related both to codes used for stationary plasmas and to codes used for traditional accelerator applications, but necessarily differing from each in important respects. The simulation packages in use model the beam or beams in varying levels of detail and at widely varying computational cost. They include moment models (envelope equations and fluid descriptions), particle-in-cell methods (electrostatic and electromagnetic), nonlinear-perturbative descriptions ("delta-f"), and continuum Vlasov methods. Increasingly, it is becoming clear that it is necessary to simulate not just the ion beams themselves, but the environment in which they exist, be it an intentionally-created plasma or an unwanted cloud of electrons and gas. In this paper, an overview of recent progress in the development of computational models of intense ion beams will be presented, and examples of the application of simulation tools to problems of current interest will be described.

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Adaptive Numerical Vlasov Simulation of Intense Beams

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Numerical simulation of intense beams studied for heavy ion fusion are often based on the Vlasov-Poisson equations and involve strongly nonlinear phenomena. In such regimes a direct simulation of the Vlasov equation can be more efficient than a PIC method especially when a precise description of the tail of the distribution function is needed.

One of the drawbacks of Vlasov solvers in the context of beam simulation is that they are in general based on a uniform mesh of phase space that needs to cover the whole phase-space that will be reached by the particles during the entire simulation. In configurations like periodic focusing or alternating gradient focusing the beam envelope can move considerably so that one needs to grid enormous regions of phase space that are inoccupied at any given moment. In order to overcome this kind of inefficiencies inherent to Vlasov solvers we investigate different kind of methods based on a grid of phase space which moves during time. The first kind of method is based on the use of a uniform logical grid that is mapped to the envelope of the beam at each time step. The second kind of method uses a fully adaptive grid which is automatically determined at each time step according to the local variations of the distribution function.

In this talk, we shall describe both these approaches and their application to beam simulation.

SIMULATION OF LONG-DISTANCE BEAM PROPAGATION IN THE PAUL TRAP SIMULATOR EXPERIMENT*

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The Paul Trap Simulator Experiment (PTSX) simulates the propagation of intense charged particle beams over equivalent distances of many kilometers through magnetic alternating-gradient (AG) transport systems by making use of the similarity between the transverse dynamics of particles in the two systems. Plasmas have been trapped that correspond to normalized intensity parameters $\hat{s} = \omega_p^2(0)/2\omega_q^2 \leq 0.8$, where $\omega_p(r)$ is the plasmas frequency and ω_q is the average transverse focusing frequency in the smooth-focusing approximation. The PTSX device confines one-component cesium ion plasmas for hundreds of milliseconds, which is equivalent to over 10 km of equivalent beam propagation. Detailed comparisons are made with WARP 3D simulations, and initial results are presented for experiments in which the confining voltage waveform has been modified so that it is no longer purely sinusoidal. Results using a cesium ion source and a barium ion source are presented, and the development of a laser-induced fluorescence diagnostic system is discussed.

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HIF RESEARCH ON THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)*

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The understanding of collective interactions of particles in an intense beam by means of long range forces is crucial for successful development of heavy ion inertial fusion. Designs for a heavy ion fusion drivers call for beam brightness and intensity surpassing traditional limits. Collective effects such as halo formation and emittance growth impose stringent limits on the driver and can raise the costs of the machine. The University of Maryland Electron Ring (UMER), currently near completion, is designed to be a scaled model (3.6-m diameter) for exploring the dynamics of such intense beams. The ring configuration permits the investigation of dispersion and other effects that would occur in bends and a recirculator machine, in addition to those occurring in a straight lattice. Using a 10 keV electron beam, other parameters are scaled to mimic those of much larger ion accelerators, except at much lower cost. An adjustable current in the 0.1-100 mA range provides a range of intensities unprecedented for a circular machine. By design, UMER provides a low-cost, well-diagnosed research platform for driver physics, and for beam physics in general. UMER is augmented with a separate setup, the Long Solenoid Experiment (LSE) for investigating the longitudinal beam dynamics and the evolution of energy spread due to Coulomb collisions in a straight geometry.

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SOLENOID TRANSPORT FOR HEAVY ION FUSION*

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Solenoidal transport for high perveance heavy ion beams is considered for several stages of a fusion driver. In general this option is more efficient than magnetic quadrupole transport at sufficiently low kinetic energy and/or large e/m, and for this reason it has been employed in electron induction linacs. Ideally an ion beam would be transported in a state of Brillouin flow, i.e. cold in the transverse plane and spinning at one half the cyclotron frequency. The equilibrium and stability of such a beam are discussed along with details of application to injection, acceleration, drift compression, and final focus. A modular driver architecture based on linacs using solenoidal transport is described.

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NONLINEAR RAYLEIGH-TAYLOR GROWTH IN CONVERGING GEOMETRY*

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The early nonlinear phase of Rayleigh-Taylor (RT) growth is typically described in terms of the classic models of Layzer [1] or Davies & Taylor [2] in which bubbles of light fluid rise into the heavy fluid at a constant rate determined by the bubble radius and the gravitational acceleration. However, these models are strictly valid only for planar interfaces and hence ignore any effects which might be introduced by the spherically converging interfaces of interest in ICF. The work of G. I. Bell [3] and M. S. Plesset [4] introduced the effects of spherical convergence on RT growth but only for the linear regime. Here, a generalization of the Layzer nonlinear bubble rise rate is given for a spherically converging flow of the type studied by Kidder [5]. A simple formula for the bubble amplitude is found showing that, while the bubble initially rises with a constant velocity similar to the Layzer result, during the late phase of the implosion, an acceleration of the bubble rise rate occurs. Analytical results are compared with numerical simulations using the Hydra code [6].

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W.P-02

HEAVY-ION TARGET WITH A DISC CONVERTER

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Performance features of a heavy-ion target with 10 MJ ion beam energy and 2mm* 6mm beam cross section are studied. The ions are decelerated in a disc converter, in which high energy concentration is ensured by superposition of a few beams near the disc axis. When the beam energy is high, no impulse shape profiling is required. In the calculation, the thermonuclear mixture solid phase ignites in the capsule without "gas spark", with which the ignition reliability is higher.

STOPPING OF RELATIVISTIC ELECTRONS IN PARTIALLY DEGENERATE ELECTRON FLUID

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The stopping mechanisms of relativistic electron beams (REB) in superdense and partially degenerate electron fluid targets are investigated in the framework of the fast ignitor concept for inertial confinement fusion. ln order to comply with specific demands in this area, we focus attention on the target partial degeneracy parameter $\theta = T_e/T_f$, in terms of thermal to Fermi temperature ratio. Target electron fluid (TEF) is thus modelled very accurately with a RPA dielectric function. Stopping results are shown very weakly θ-dependent. However, a quantum target description is needed to recover their correct and increasing trend with increasing projectile energy.

Ranges and effective penetration depths in precompressed thermonuclear fuels are shown to be nearly a factor of two shorter compared to earlier classical estimates in same conditions. Overall conclusions pertaining to the feasibility of fast ignition thus remain unchanged.

W.P-04

FAST IGNITION HEAVY ION FUSION TARGET BY JET IMPACT*

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Fast ignition[1] targets usually require two energy sources, one for the compression of the target and the other to start the ignition in the compressed target. We present a design based on the same principles as the laser driven fast ignition but only using one drive, either laser or heavy ion beam. The idea is to transform part of the X ray energy from the hohlraum cavity to generate a high speed, medium density jet[2]. This jet will collide with the compressed target starting the ignition of the DT fuel. The design is composed by two cones, one to produce the jet by cumulative effect, and the other to guide spherically the target.

Several configurations are studied in order to increase the efficiency of the process, and other designs based on this will be presented and briefly analyzed. We have performed numerical simulations of these designs with the Arwen code[3], an AMR Radiation Transport code.

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ELECTRON LOSS CROSS SECTIONS FOR LOW CHARGE STATE IONS

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Projectile electron loss cross sections have been calculated for a series of systems using large multi-electron, two-center basis sets within the classical trajectory Monte Carlo method. Studied is U^{28+} colliding with H, N and Ar targets. Here, 39-, 45- and 54-body calculations are used to represent the collision systems, respectively. These electron loss cross sections are central to the design of the SIS-100 cyclotron ring at GSI-Darmstadt. The present calculations predict a constant beam lifetime between 10 and 150 MeV/amu which leads to very stringent vacuum requirements, especially at the highest energies.

Multi-electron calculations have also been performed for Ar and Xe isoelectronic ions colliding with nitrogen. These systems include K^+ and Cl^-, and Cs^+ and I^- at energies from 10 keV/amu to 30 MeV/amu. At all energies, the negative ion electron removal cross section is approximately a factor of three larger than its isoelectronic positive ion.

In the above cases the calculated cross sections are compared to available experimental data. The agreement between theory and experiment is reasonable. However, for all systems our multi-electron based cross sections depart significantly from those predicted by one-electron theories such as the binary encounter and first Born calculations. The inclusion of multiple electron removal, Auger losses, and preserving unitarity in the calculations is essential for an accurate description of the scattering processes.

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W.P-06

3D MODELING OF LIQUID JETS, USED IN HEAVY ION FUSION FOR BEAM LINE PROTECTION*

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Current designs for thick liquid protection of heavy ion inertial fusion reactors utilize banks of liquid jets to protect sensitive beam line components from neutrons and debris following target explosions. IFE designers must have knowledge of the surface quality of these jets in order to determine the distance between the jets and the ion beams that must propagate through the void spaces between them. Here numerical simulations of such jet flows performed with the customized Flow3D solver are reported. 3-D unsteady flow simulations are qualitatively verified by comparison to several jet flow experiments. These numerical simulations predicted no significant jet breakup in region of interest, but did show surface and shape deformation that may end up determining the minimum standoff distance between jets and driver beams. The simulations also show small droplet ejection that may adversely affect beam propagation characteristics. The intrusion distance of liquid into the beamlines was determined to be below 10% of the original jet thickness throughout computational domain (up to 1 meter downstream from the nozzle). A discussion of the relative effect of turbulence level and direction, and velocity profile is given. Recommendations on how to avoid or minimize unwanted hydrodynamic phenomena (surface rippling and droplet ejection) by upstream conditioning and nozzle design are developed for free surface jets in vacuum in the context of qualitative understanding of the physical mechanisms at play.

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PROGRESS TOWARDS A DETAILED TSUNAMI MODELING OF THE HEAVY ION FUSION MODULAR POINT DESIGN

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The "robust point design" (RPD) [1] describes a self-consistent heavy-ion inertial fusion power plant based on a single linear accelerator and the neutralized ballistic beam transport scheme. The heavy-ion fusion community is exploring the feasibility of a modular power plant, with several, smaller accelerators---this approach has the potential to offer a faster and cheaper development path to a viable fusion power plant. The Berkeley hydrodynamics code TSUNAMI is being used to model x-ray ablation and gas venting in the target chamber and beam tubes of the yet-to-be-finalized modular point design. Gas dynamics simulations are presented along with a comparison to a previous RPD modeling [2]. The need for this modeling stems from strict requirements on background gas density set to achieve proper beam and target propagation; differences between limits imposed by various beam propagation schemes are highlighted.

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W.P-08

APPLICATION OF ADAPTIVE MESH REFINEMENT TO PIC SIMULATIONS IN INERTIAL FUSION*

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We have recently merged AMR with the Particle-In-Cell (PIC) method for simulation of plasmas and particle beams. The application of AMR to plasma modeling poses significant challenges, including the introduction of spurious forces on simulation particles. We have carried out a detailed analysis of the coupling of the two methods and, in collaboration with the developers of the popular Chombo package for AMR, have developed practical methods and demonstrated their effectiveness on electrostatic Particle-In-Cell simulations of intense ion beams [1]. Initial successes include major savings of computational effort in simulations of time-dependent space-charge-limited flow (in a 5-D phase space); and demonstrations of numerical convergence. Most recently, the merger of the PIC code WARP (developed for Heavy Ion Fusion studies) and Chombo has been accomplished. The application of AMR to electromagnetic plasma modeling is even more challenging; we have introduced a new methodology using recently developed Absorbing Boundary Conditions, and are beginning to employ it on laser-plasma interaction in the context of fast-ignition.

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The Electromagnetic Darwin Model for Intense Charged Particle Beams*

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The theoretical and numerical properties of the electromagnetic Darwin model [1] for intense charged particle beams are investigated. The model neglects the transverse displacement current in Ampere's law and results in the elimination of high-frequency transverse electromagnetic waves and the associated retardation effects in the Maxwell-Vlasov equations. In this paper, two numerical schemes are presented for the purpose of circumventing the numerical instabilities associated with the presence of $\mathbf{E}^T(\equiv \partial \mathbf{A}/\partial t)$ in the equations of motion for particle codes [2], where $\mathbf{A}$ is the vector potential. The first relies on higher-order velocity moments for closure [3,4], and the other replaces the mechanical momentum, $\mathbf{p} = \gamma m \mathbf{v}$, by the canonical momentum, $\mathbf{P} = \mathbf{p} + (q/c)\mathbf{A}$, as the phase-space variable [2]. The properties of these simulations schemes in the laboratory frame as well as in the beam frame are also discussed. These new numerical methods are most suitable for studying Weibel [5] and two-stream [6] instabilities in heavy ion fusion research.

*This work performed under the auspices of the U.S Department of Energy.

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SIMULATION OF INTEGRATED BEAM EXPERIMENT DESIGNS*

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Simulation of designs of an Integrated Beam Experiment (IBX) class accelerator have been carried out using the WARP[1] particle-in-cell code. These simulations are an important tool for validating such designs. Issues such as envelope mismatch and emittance growth can be examined in a self-consistent manner, including the details of injection, accelerator transitions, long-term transport, and longitudinal compression. The simulations are three-dimensional and time-dependent, and begin at the source. They continue up through the end of the acceleration region, at which point the data is passed on to a separate simulation of the drift compression. Various aspects of the lattice design were examined - for example, the frequency of accelerating gaps. Results will be presented.

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BEAM CONTROL AND MATCHING ON THE UNIVERSITY OF MARYLAND ELECTRON RING (UMER)*

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The transport of intense beams for heavy-ion inertial fusion demands tight control of beam characteristics from the source to the target. The University of Maryland Electron Ring (UMER), which uses a low energy (10 keV), high current (∼100 mA) electron beam to model the transport physics of a future recirculator driver, employs real time beam characterization and control in order to optimize beam alignment and envelope matching throughout the strong-focusing lattice. We describe in this paper the main components and operation of the diagnostics/control system in UMER, which employs phosphor screens, real-time image analysis and iterative beam steering and quadrupole-current scans. The procedure is not only indispensable for optimum single-turn transport (over ∼ 12 m, or 36 FODO periods), but also provides important insights into the beam physics involved. Some of the issues discussed are: quadrupole rotation errors, mechanical alignment, rms envelope matching, halo formation and emittance growth. Understanding of the single-turn physics provides the basis for multi-turn operation in UMER.

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EXPERIMENTAL TESTS OF THE INJECTION Y ON THE UNIVERSITY OF MARYLAND ELECTRON RING*

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The injection Y has been designed and built for the University of Maryland Electron Ring (UMER). The design incorporates a combination of two unique printed circuit magnet designs. The dipole component of an offset quadrupole and a pulsed dipole are used to achieve the 10 degree bend required from the injection line. The current for each magnet is supplied by its own pulse-forming network (PFN). The dipole PFN is designed as a long pulse (300 V, 15 A, 20 μs duration) for multiple beam passes with a short pulse (2 kV, -30 A, 100 ns flat top duration) superimposed for beam extraction. To accommodate field penetration a glass gap covers the area near the pulsed dipole. The glass gap has a thin conductive coating on the inner surface to minimize perturbations on the beam due to changing boundary conditions. The completed Y assembly has been installed on the downstream end of the beam line to facilitate experimental tests before closure of the ring. Initial experimental results of the testing of this design will be presented.

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Development of a One-Meter Plasma Source for Heavy Ion Beam Charge Neutralization*

W.P-13

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Highly ionized plasmas are being employed as a medium for charge neutralizing heavy ion beams in order to focus to a small spot size. Calculations suggest that plasma at a density of 1 - 100 times the ion beam density and at a length ~ 0.1-1.0 m would be suitable for achieving a high level of charge neutralization. An electron cyclotron resonance (ECR) source was constructed at the Princeton Plasma Physics Laboratory (PPPL) in support of the joint Neutralized Transport Experiment (NTX) at the Lawrence Berkeley National Laboratory (LBNL) to study ion beam neutralization. Pulsed operation of the source enabled operation at pressures in the 10^{-6} Torr range with plasma densities of 10^{11} cm^{-3}. Near 100% ionization was achieved. The source was integrated with the NTX facility and used in the plasma neutralization experiments. The plasma was approximately 10 cm in length in the direction of the beam propagation, but future experiments require a source 1m long. The present ECR source does not easily scale to that length. Consequently, large-volume plasma sources based upon ferroelectric ceramics are being considered.[1] These sources have the advantage of being able to increase the length of the plasma and operate at low neutral pressures. The source will utilize the ferroelectric ceramic $BaTiO_3$ to form a metal plasma. A 1 m long section of the drift tube inner surface of NTX will be covered with the ceramic. A high voltage (~ 1-5 kV) is applied between the drift tube and the front surface of the ceramic by placing a wire grid on the front surface. A current density of ~ 0.5 A/cm^2 is required. Pulsed plasma densities of 10^{12} cm^{-3} and neutral pressures ~ 10^{-6} Torr are expected. A test stand to produce a 20 cm long plasma in a drift tube is being constructed and will be tested before a 1 m long source is developed. Experimental results from the source development are presented.

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W.P-14

THEORY OF ION BEAM PULSE NEUTRALIZATION BY A BACKGROUND PLASMA IN A SOLENOIDAL MAGNETIC FIELD*

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Ion beam pulse propagation through a background plasma in a solenoidal magnetic field has been studied analytically. The neutralization of the ion beam pulse current by the plasma has been calculated using a fluid description for the electrons. This study is an extension of our previous studies of beam neutralization without an applied magnetic field [1,2]. The high solenoidal magnetic field inhibits radial electron transport, and the electrons move primarily along the magnetic lines. For high-intensity ion beam pulses propagating through a background plasma with pulse duration much longer than the electron plasma period, the quasineutrality condition holds, $n_e = n_p + n_b$, where n_e is the electron density, n_b is the ion density of the ion beam pulse, and n_p is the ion density of the background ions (assumed unperturbed by the beam). For one-dimensional electron motion, the charge density continuity equation $\partial\rho/\partial t + \nabla \cdot \mathbf{j} = 0$ combined with the quasineutrality condition $[\rho = e(n_p + n_b - n_e) = 0]$ yields $\mathbf{j} = \mathbf{0}$. Therefore, in the limit of a strong solenoidal magnetic field, the beam current is completely neutralized. Analytical studies show that the solenoidal magnetic field starts to influence the radial electron motion if $\omega_{ce} \gtrsim \omega_{pe}\beta$, (where $\omega_{ce} = eB/m_e c$ is the electron gyrofrequency, ω_{pe} is the electron plasma frequency, and $\beta = V_b/c$ is the ion beam velocity relative to the speed of light). The condition already holds for relatively small magnetic fields; for example, for a $100MeV$ Ne^+ $1kA$ ion beam $(\beta = 0.1)$ and plasma density of $10^{11}cm^{-3}$, B corresponds to a magnetic field of $100G$.

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TWO-STREAM STABILITY ASSESSMENT OF INTENSE HEAVY ION BEAMS PROPAGATING IN PREFORMED PLASMAS*

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A recent analysis [1] of the stability of intense ion beams propagating in unmagnetized, preformed plasmas is being applied to heavy ion fusion (HIF) reactor chamber parameters. An earlier analysis carried out for heavy ion beams propagating in an evacuated chamber [2] predicted stability over a range of beam parameters. That analysis invoked a temporally evolving, maximum unstable wavenumber to detune two-stream unstable growth for a focusing beam. This conclusion is presently being re-examined using particle-in-cell simulations.

The modular accelerator concept for HIF is presently being evaluated. The concept uses solenoid transport with high line-charge densities [3,4]. Propagating ion beams are time-of-flight compressed in a magnetized plasma, which fills the transport sections upstream of the reactor chamber. The analysis presented in [1] has been extended to include the impact of applied axial magnetic fields on the growth and saturation of the two-stream instability.

*This work is support by the US DOE through Lawrence Berkeley National Laboratory and the Princeton Plasma Physics Laboratory.

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Is Laser Cooling for Heavy-Ion Fusion Feasible?

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Heavy-ion beams, each with current in the kiloampere range and particle energy in the gega-electronvolt range, must be focused onto a millimeter-size spot to provide the power required for ignition of high-gain targets for inertial confinement fusion. However, the focal spot size is always enlarged by chromatic aberration generated by the thermal spread of the beam ions in the direction of beam propagation. Enlarged focal spot degrades the target performance. For high-current beams, conventional remedy for chromatic aberration using sextupole magnets has shown to be ineffective.[1] If novel correction schemes can be found, then the spot size can be reduced to below that previously believed possible. Smaller spots can mean lower pulse energy targets and the heavy-ion fusion scenario can look more attractive. Success in laser cooling of ion beams in storage rings has led us to explore the feasibility of applying laser cooling for heavy-ion fusion, and the recirculator configuration proposed for heavy-ion fusion appears to be well suited for this purpose. However, using particle-in-cell simulations and theoretical arguments, we demonstrate in this paper that although laser cooling of heavy-ion beams is feasible in principle, the rapid velocity-space diffusion of ions in the bump-in-tail distribution, set up by the cooling lasers, limits the velocity-space compressibility of the thermal spread along the beam. Consequently, laser cooling is impractical for high-current, heavy-ion beams for the proposed recirculator configuration. Nevertheless, if the recirculator architecture or the target requirement can reduce the beam current, then the cooling scheme described here should work.

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BUNCH COMPRESSION IN A RING IN FUTURE RIKEN PROJECTS

W.P-17

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Facilities of a heavy ion accelerator system, which are primarily for nuclear physics researches associated with a radio isotope beam, are constructed at RIKEN. Although the site facilities including buildings are presently under construction, studies for generating high-current heavy-ion beam and for High Energy Density Physics applications are planned as part of the MUSES project [1]. Parts of TARN2 ring [2] are being moved to RIKEN, and may be possible to rebuild as the bunch accumulation ring for these applications. The rebuilt TARN2 ring is filled from new superconducting ring cyclotrons, and beam cooling is carried out after the accumulation. The filled bunches are merged into a single superbunch by longitudinal compression. For such bunch compression, fast rotation of the longitudinal phase-space using rf or induction technology is carried out [3]. The bunch is compressed longitudinally, and is kicked out of the ring near peak compression into an extraction line for the final transport and focusing onto a target. While the fast compression scheme in the ring requires the control of space-charge and dispersive effects to achieve maximum performance at the target, the rms emittance will be increased due to these effects. We employ theory and more detailed particle-in-cell (PIC) simulations to investigate potential parameters in the system. The PIC simulations are carried out using the WARP code [3] developed to study strong space-charge effects in Heavy Ion Inertial Fusion.

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W.P-18

LONGITUDINAL DRIFT EXPERIMENTS AT THE UNIVERSITY OF MARYLAND ELECTRON RING*

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An understanding of the longitudinal behavior of intense beams is key for the successful design of a heavy ion fusion driver. Experiments to improve this understanding are now underway at the University of Maryland Electron Ring (UMER), an intense, low energy (10 keV, 100 mA) dispersive beam transport system now nearing completion. UMER features a sophisticated set of diagnostics, which include the capability to measure the transverse beam profile at different positions (times) along the bunch and the ability to produce various longitudinal beam distributions from the electron gun. In preparation for multi-turn operation, longitudinal experiments are concentrating on the free expansion of the beam. In this paper, we describe these experiments and future plans for UMER.

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SIMULATION OF DRIFT-COMPRESSION FOR HEAVY-ION-FUSION *

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Beams for heavy-ion fusion (HIF) must be compressed lengthwise by a factor of more than ten between an induction accelerator and the final-focus magnets. The compression scenario favored by the US HIF program is to impose a head-to-tail velocity increase or “tilt”, so the beam tail approaches the head in a “drift-compression” section. The beam current and velocity must be accurately tailored before drift-compression in order that the longitudinal space-charge field removes the velocity tilt just as the beam traverses the final-focus lattice. Transverse focusing in the drift-compression lattice must also be carefully designed to ensure that all parts of the beam remain approximately matched as the beam expands to the larger radius needed for final focusing. The principle physics questions posed by this section are how much the total emittance grows, whether a beam halo develops, and how these processes scale with beam and lattice parameters. A second broad area of research is optimizing the initial pulse-shaping schedule to minimize the bandwidth and volt-seconds requirements of the pulsed power.

This paper presents recent theoretical work to model the final longitudinal compression of HIF beams. Pulse-shaping fields are first calculated using a fluid/envelope dynamics model, and these fields are then used in the three-dimensional electrostatic particle-in-cell (PIC) code WARP3d to study beam transport in the pulse-shaping and drift-compression sections. Possible low-energy near-term experiments are investigated, as well as full-scale fusion drivers, and for each accelerator category, we examine how emittance growth and sensitivity to errors scale with the major beam and lattice parameters.

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DYNAMICS OF PLASMA CHANNELS FOR CHAMBER TRANSPORT

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Plasma-channel-based transport is one of the attractive schemes for delivering space-charge-dominated beams to a fuel target in a reactor chamber. It relaxes the requirements for beam quality and may decrease the cost of driver accelerators. Recently, a final focusing scheme using Z-pinch plasma channels has been proposed with a combination of adiabatic plasma lenses [1] and a proof-of-principle experiment also has been performed [2]. The discharge parameters of the plasma channels, however, were limited because those analyses and experiments were based on the specific reactor designs. Particularly the dynamics of the plasma channel strongly depends on the background gas pressure and the required discharge current for beam confinement and it also determines the design of the discharge circuit. To discuss the applicability of plasma channels for chamber transport, the dynamics of the channel must be examined in a wide range of discharge parameters. Thus, we performed numerical analyses of the plasma channel using a one-dimensional magneto-hydrodynamic (MHD) code. This report discusses the realistic parameter range of the channel discharge and shows the results from the numerical calculations. We also show the results on the beam trajectory obtained by a two-dimensional particle code.

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THE FRANKFURT FUNNELING EXPERIMENT

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The Frankfurt Funneling Experiment is a scaled version of the first funneling stage of a HIF driver to demonstarte the funneling technique, a procedure to multiply beam currents at low energies in several stages. In each stage two beam lines are combined into a common beam line. Funneling is required for proposed high current accelerator facilities like HIDIF. The main goal is to prevent emittance growth during the funneling process. Our set-up is scaled to He^+ instead of Bi^+ of the first funneling stage of a HIIF driver. The progress of our experiment and the results of the simulations will be presented.

Abstracts
Oral Presentations
Thursday, 10 June 2004

Accelerators and Beam Physics –- Part III

Listed in Program Order
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EXPERIMENTAL STUDIES OF ELECTRONS IN A HEAVY-ION BEAM*

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Electron cloud effects, ECEs, are normally a problem only in ring accelerators. However, heavy-ion induction linacs for inertial fusion energy have an economic incentive to fit beam tubes tightly to intense beams. This places them at risk from electron clouds produced by emission of electrons and gas from walls. We have measured electron and gas emission from 1 MeV K^+ impact on surfaces near grazing incidence on the High-Current Experiment (HCX) at LBNL and are making similar measurements below 500 KeV on the injector test stand STS-500 at LLNL. Electron emission scales with 1/cos consistent with emission from a thin layer, whereas gas desorption varies much more slowly with angle indicating sources other than adsorbed gas layers. Mitigation techniques are being studied: A bead-blasted rough surface reduces electron emission by a factor of 10 and gas desorption by a factor of 2. A biased cylindrical mesh on the Neutralized Transport Experiment (NTX) at LBNL prevents electron emission from the beam-tube. Diagnostics are installed on HCX, between and within quadrupole magnets, to measure the beam halo loss, net charge and expelled ions, from which we infer gas density, electron trapping, and the effects of mitigation techniques. We have also installed clearing electrodes between magnets to remove electrons, and a suppressor electrode after the magnets to block secondary electrons off the end wall from entering the magnets. The effects of electrons on ion beams are determined with slit scanners. These data will be compared with predictions of theory and simulations.

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Th.I-02

DYNAMICS OF NEUTRALIZING ELECTRONS AND THE FOCUSABILITY OF INTENSE ION BEAMS IN HIF ACCELERATING STRUCTURES*

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In most of the proposals for HIF reactors, the beams propagate ballistically through the containment chamber. To get the required final radius (~ 3 mm), the charge of the beam must be neutralized to some extent. Several neutralization schemes are possible, as co-injection of negative-ions beams, inclusion of external sources of electrons, or it can be provided by electrons coming from ionization of the background gas. In this work, we study the role of the electron dynamic on the neutralization and final radius of the beam. This is done by performing fully-electromagnetic PIC simulations of the beam ballistic transport using the BPIC code[1]. We have considered for the atomic processes both ion-ion and electron-ion collisions. Differences in the behaviour of the electron populations (electrons coming from gas ionization, from beam ionization and co-injected at the chamber entrance) and their screening properties are presented, for beams of Pb and Xe moving in FLIBE gas.

*One of us (A.F.L.) is grateful to the French Research Ministry for a post-doctoral grant.

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SIMULATING ELECTRON CLOUD EFFECTS IN HEAVY-ION ACCELERATORS*

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Heavy-ion fusion (HIF) accelerators, like other positive-charge accelerators, are subject to contamination by stray electrons. HIF economics dictates working with the largest possible beam-pipe fill factor, and stray electrons can be a determinant in setting that limit. For parameters of HIF induction accelerators, the predominant source is ionization of neutral gas released from the beam pipe upon ion bombardment; direct release of secondary electrons can also play a role. Because the beam pipes (and hence electron sources) are localized to the magnet regions, modeling of electron accumulation must take into account ion reflections off the beam pipe. Another consequence is that self-consistent simulation requires bridging timescales ranging from the electron cyclotron period to ion transit times. We present results from several studies: electron clouds formed from direct release of electrons upon ion bombardment of the beam pipe, and from ionization of released neutrals; and effects of various types of model electron cloud distributions on ion beam quality. We also describe a model for averaged electron dynamics which enables bridging electron and ion timescales for both magnetized and unmagnetized electrons, and will present first simulation results using this model.

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EXPERIMENTAL EVALUATION OF A NEGATIVE ION SOURCE FOR A HEAVY ION FUSION NEGATIVE ION DRIVER*

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Negative halogen ions have recently been proposed as a possible alternative to positive ions for heavy ion fusion drivers because electron accumulation would not be a problem in the accelerator, and if desired, the beams could be photodetached to neutrals [1]. To test the ability to make suitable quality beams, an experiment was conducted at Lawrence Berkeley National Laboratory using chlorine in an RF-driven ion source. Without introducing any cesium (which is required to enhance negative ion production in hydrogen ion sources) a negative chlorine current density of 45 milliamperes per square centimeter was obtained under the same conditions that gave 53 milliamperes per square centimeter of positive chlorine, suggesting the presence of nearly as many negative ions as positive ions in the plasma near the extraction plane. The negative ion spectrum was 99.5% atomic chlorine ions, with only 0.5% molecular chlorine, and essentially no impurities. Although this experiment did not incorporate the type of electron suppression technology that is used in negative hydrogen beam extraction, the ratio of co-extracted electrons to negative chlorine ions was as low as 7 to 1, many times lower than the ratio of their mobilities, suggesting that few electrons are present in the near-extractor plasma. This, along with the near-equivalence of the positive and negative ion currents, suggests that the plasma in this region was mostly an ion-ion plasma. The negative chlorine current density was relatively insensitive to pressure, and scaled linearly with RF power. If this linear scaling continues to hold at higher RF powers, it should permit current densities of 100 milliamperes per square centimeter, sufficient for present heavy ion fusion injector concepts.

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NEUTRALIZED TRANSPORT EXPERIMENT*

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Final focusing has been a subject of intense study from the very early days of heavy ion fusion (HIF). Neutralized ballistic transport (NBT)[1] is presently being studied for propagating intense heavy ion beams inside a reactor chamber to an inertial confinement fusion (ICF) target. A recent HIF driver study[2] demonstrates that stringent final-focus requirements[3] can be met provided that active neutralization is implemented to overcome the formidable space charge of the intense ion beams. To quantitatively ascertain the various mechanisms for neutralization, the Neutralized Transport Experiment (NTX) was constructed at Lawrence Berkeley National Laboratory. In this experiment a high quality beam is passed through well-characterized plasma sources to neutralize space charge of the beam. Here we describe NTX beam line system, techniques to control stray electrons in vacuum transport, measurements of current transmission, phase space, beam spot size, beam halos, and preliminary results of beam neutralization along with detailed comparisons with theory.

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SIMULATIONS OF NEUTRALIZED FINAL FOCUS*

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In order to drive an inertial fusion target with heavy ion beams, the beam radius must be focused to < 3 mm and the pulselength must be compressed to < 10 ns. The typical scheme for temporal pulse compression makes use of a head-to-tail ion velocity tilt to compress the beam as it drifts and beam space charge to stagnate the compression. Beam compression in a neutralizing plasma does not require stagnation of the compression enabling a much more robust method. A final pulse shape at the target can be programmed by an applied energy tilt. In this paper, neutralized drift compression is investigated with a particle-in-cell code. The sensitivity of compression to beam momentum spread, plasma and magnetic field conditions is studied. Representative examples will be shown, such as neutralized drift compression in the Integrated Beam Experiment (IBX) accelerator. Application to a driver final focus system for an accelerator using modular solenoid technology[1] and assisted pinched transport [2] is discussed. Using the 3-D parallel LSP[3] code, we discuss issues associated with self-field generation, stability and the vacuum-to-neutralized transport transition.

*This work is supported by the Virtual National Laboratory for HIF, the Department of Energy through Princeton Plasma Physics Laboratory and Lawrence Berkeley National Laboratory.

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A FINAL FOCUS MODEL FOR HEAVY ION FUSION DRIVER SYSTEM CODES*

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The need to reach high temperatures in an inertial fusion energy (IFE) target (or a target for the study of High Energy Density Physics, HEDP) requires the ability to focus ion beams down to a small spot. Systems models indicate that within the accelerator, the beam radius will be of order centimeters, whereas at the final focal spot on the target, beam radii of order millimeters are required, so radial compression factors of order ten are required. The IFE target gain (and hence the overall cost of electricity) and the HEDP target temperature are sensitive functions of the final spot radius on target. Because of this sensitivity, careful attention needs to be paid to the spot radius calculation.We review our current understanding of the elements which enter into a systems model (such as emittance growth from chromatic, geometric, and non-linear space charge forces) for the final focus based on a quadrupolar magnet system. We also outline how the systems model may be extended to axisymmetric focusing (such as solenoidal and plasma lens focusing).

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Th.I-08

DRIFT COMPRESSION AND FINAL FOCUS OPTIONS FOR HEAVY ION FUSION*

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In the currently envisioned configurations for heavy ion fusion, it is necessary to longitudinally compress the beam bunches by a large factor after the acceleration phase. A one-dimensional warm fluid model in the longitudinal direction has been developed to study the self-similar drift compression schemes and pulse shaping methods. In the transverse direction, the beam size will increase in a periodic quadrupole lattice due to the increasing space-charge force as the beam is compressed. To actively control the beam size, a non-periodic quadrupole lattice has been designed to provide a larger focusing force along the beam path. Four time-dependent magnets are introduced in the upstream of drift compression to focus the entire pulse onto the same focal spot. Drift compression and final focusing schemes are developed for a typical heavy ion fusion driver and for the Integrated Beam Experiment (IBX) currently being designed by the Heavy Ion Fusion Virtual National Laboratory.

* This research was supported by the U.S. Department of Energy under the auspices of the Heavy Ion Fusion Virtual National Laboratory.

BEAM DYNAMICS AND EMITTANCE GROWTH DURING FINAL BEAM BUNCHING IN HIF DRIVER SYSTEMS

Th.I-09

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Research efforts on a heavy ion fusion (HIF) have been concentrated on the control and transport of space-charge-dominated beams in the accelerator system. In particular, the beam dynamics in the final section is expected to involve a lot of unclarified physical problems. For an efficient implosion of a fuel pellet, the intense heavy-ion beam should be longitudinally compressed in the final stage of HIF driver system. While the longitudinal compression is carried out in the final buncher, the beam must be transported without significant emittance growth and excessive non-uniformity. Using particle simulations, we have investigated the beam dynamics during the final bunching [1-2]. The space charge oscillation may induce instability in the beam transport [1], thereby emittance growth and modulation of transverse distribution during the final beam bunching. The emittance growth accompanied by the longitudinal compression is estimated by the numerical simulation with various initial particle distributions. After the final bunching, particle distributions inside the beam are evaluated in the uniformity on the transverse cross section of the beam [2]. Obtained results should provide us a useful information for design of the fuel pellet, for study of beam transport in a rector chamber, and for consideration of optimum scheme of multi-beam illumination onto the target.

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2 T. Kikuchi, M. Nakajima, K. Horioka, T. Katayama, *to be published by* Journal of Plasma and Fusion Research, **80** (2004).

DIAGNOSTICS FOR INTENSE HEAVY ION BEAMS *

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Modern diagnostic techniques provide detailed information on beam conditions in injector, transport, and final focus experiments in the HIF-VNL. Parameters of interest include beam current, beam energy, transverse and longitudinal distributions, emittance, and space charge neutralization. Imaging techniques, based on kapton films and optical scintillators, complement and in some cases, may replace conventional techniques based on slit scans. Time-resolved optical diagnostics that provide 4-D transverse information on the experimental beams are in operation on the existing facilities. Current work includes a folded, compact optical diagnostic suitable for insertion in transport lines, improved algorithms for data analysis and interpretation, and a high-resolution electrostatic energy analyzer. A longitudinal diagnostic kicker has been implemented for generating longitudinal space-charge waves that travel on the beam. Time of flight of the space charge wave and an electrostatic energy analyzer provide an absolute measure of the beam energy. Special diagnostics to detect secondary electrons and gases desorbed from the wall have been developed.

The diagnostics currently in use are suitable for low kinetic energy, but high intensity and integrated experiments will require increasing emphasis on non-intercepting diagnostics, such as beam current transformer and capacitive pickup. One new non-intercepting diagnostic under development is the electron beam potential probe. We will discuss the techniques, results, and plans for implementation of these and other new diagnostics.

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DEVELOPMENT OF INDUCTION MODULES FOR HIGH POWER ACCELERATOR

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Research activities for high power induction accelerator system in the TIT-KEK-JAERI-RIKEN group are presented including a research effort for high flux ion injector, and R&Ds on induction voltage modulators for repetitive operation and precise voltage modulation. Using an induction modulator, high flux beams are directly extracted from a laser ablated expanding plasma. A proof-of-principle experiment on basic module shows that the module elements are successfully operated up-to MHz with good re-producibility[1]. The first experiment on the induction synchrotron is scheduled this year using the KEK 12-GeV proton synchrotron. For the experiments, a proto type induction modulator has been developed. One of the serious problem for beam modulation is some droop in the acceleration voltage because of a finite length of the transmission cable between the voltage driver and the induction cell[2]. In order to precisely control the accelerating voltage, a method is proposed for power transport without any load mismatching through the long transmission line. Efforts for the component technologies of the induction accelerator along with a consideration on high power accelerator system will be discussed.

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ULTRA-LOW EMITTANCE, HIGH CURRENT PROTON BEAMS PRODUCED WITH A LASER-VIRTUAL CATHODE SHEATH ACCELERATOR*

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High current multi-MeV protons and ions can be produced by irradiating thin foils with short-pulse, ultra-high intensity lasers (τ<ps, $I\lambda^2$ >10^{18} W/cm^2 μm^2). For many potential new applications, the high degree of beam laminarity is an important aspect, for example for table-top ion accelerators, high-resolution charged-particle radiography, or production of high energy density matter by isochoric heating. We understand the high laminarity, or low emittance, of these beams stems from the fact the acceleration process takes place on the cold rear (i.e. non-irradiated) surface of the thin foils. There, a dense relativistic electron sheath is formed by the laser-accelerated electrons that have propagated through the foil. This sheath produces an electrostatic field >10^{12} V/m that ionizes the surface atoms almost instantaneously, forming a ~1 nm thick ion layer which, together with the electron sheath, resembles a virtual cathode.

By structuring the rear surface of this foil, we have succeeded to produce modulations in the transverse phase space, which resemble fiducial "beamlets" within the envelope of the expanding plasma. This allows us to map the expansion of the beam envelope during the latter, sheath expansion phase. Using this technique that allows to directly image the initial accelerating sheath, and we fully reconstruct the transverse phase space for protons of different energy. We find that for protons of up to 10 MeV, the transverse emittance is less than 0.004 mm.mrad [1], i.e. 100-fold better than typical RF accelerators and at a substantially higher ion current (kA range).

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1. T.E. Cowan, J. Fuchs, H. Ruhl *et al*., *Phys. Rev. L*ett. (2004), in press.

DEVELOPMENT OF SUPERCONDUCTING MAGNET SYSTEMS FOR HIF *

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A collaboration of LBNL, LLNL, MIT and Advanced Magnet Lab (AML) is developing superconducting focusing quadrupoles for near-term HIF experiments and future driver accelerators. Following the fabrication and testing of several prototypes, a baseline quadrupole design was selected and further optimized. The first model of the optimized design has achieved a conductor-limited gradient of 132 T/m in a 70 mm bore, with measured field harmonics within 10 parts in 10^4. In parallel, a compact focusing doublet was fabricated and tested using two of the first-generation quadrupoles. After assembly in the cryostat, both magnets reached their conductor-limited quench current. Further optimization steps are currently underway to improve the performance of the magnet system and reduce its cost. They include the fabrication of a new prototype quadrupole with field quality at the 10^{-4} level, as well as improvements of the cryostat design for the focusing doublet. The prototype units could eventually be installed in the HCX beamline at LBNL, to perform accelerator physics experiments and gain operational experience.

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Abstracts
Poster Presentations
Thursday, 10 June 2004

Poster Session II

Listed in Program Order
One Per Page

ANALYTIC EXPRESSION FOR OPTIMAL HOHLRAUM WALL DENSITY*

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We apply recent analytic solutions [1] to the radiation diffusion equation to problems of interest for ICF hohlraums. The solutions provide quantitative values for absorbed energy which are of use for generating a desired radiation temperature vs. time within the hohlraum. Comparison of supersonic and subsonic solutions (heat front velocity faster or slower, respectively, than the speed of sound in the x-ray heated material) suggests that there may be some advantage in using high Z metallic foams as hohlraum wall material to reduce hydrodynamic losses, and hence, net absorbed energy by the walls. Analytic and numerical calculations suggest that the loss per unit area might be reduced ~ 20% through use of foam hohlraum walls and that this reduction factor is "universal" – independent of drive and pulse-length. We derive an explicit expression for the optimal density (for a given drive temperature and pulse-length) that will achieve this reduction factor. Since heavy ion hohlraums naturally involve such high Z foams, this work may be of some use to this HIF/IFE community.

*This work performed under the auspices of the U.S Department of Energy by University of California, Lawrence Livermore National Laboratory under contracts No. W-7405-Eng-48.

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HIB ILLUMINATION ON A TARGET IN HIF*

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In direct-driven pellet implosion, HIB illuminates a spherical target and deposits its energy on a target after a HIB final transport. In our study, we develop a three-dimensional HIB illumination code for direct-driven pellet in HIF [1]. We calculate the deposition energy on the spherical target according to a stopping power. The main object of our study is to clarify a dependence of multi-HIB illumination non-uniformity on parameter values of HIB illumination in HIF. The HIB ions impinge the target surface, penetrate relatively deep into the deposition layer and deposit their energy in a rather wide region in the deposition layer: this HIB deposition feature influences the beam illumination non-uniformity. The HIB temperature and emittance effects are also evaluated. During the HIB illumination the temperature of the energy deposition layer increases to a few hundred eV. We also investigate the pellet temperature effect on the HIB illumination non-uniformity. We also investigate the relationship between a chamber radius and the HIB illumination non-uniformity, and study the effect of the total HIB number on the HIB illumination non-uniformity. In an ICF power plant, a position of fuel pellet may shift from a reactor center, because a pellet may be injected from a pellet injection port at a reactor wall. The HIB illumination non-uniformity may be influenced by a little pellet displacement from the chamber center. In our study we also investigate the relation between the pellet displacement and the HIB illumination non-uniformity. For the evaluations of the illumination non-uniformity on the target, we compute the root mean square (RMS) non-uniformity on the spherical target. In addition, we also perform mode analyses of the HIB deposition energy on the spherical fuel target using the Legendre polynomial and the Fast Fourier Transfer (FFT). The calculation results demonstrate that we can realize a rather low energy deposition non-uniformity. Moreover from the investigation of the non-uniformity growth due to the little pellet displacement, we confirm that the pellet displacement is a serious problem in HIF.

*This work has been partly supported by JSPS (Japan Society for the Promotion of Science). We would like to present our thanks to Prof. K. Tachibana for his fruitful discussions on this subject.

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Cylindrical Targets in HIF.

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Annotation:

"Fast ignition" of the DT fuel by a superpower heavy ion beam (Jm ~ 4.10^6 TW/g) was a main peculiarity of the ITEP prospects for HIF system at HIF-2002 Symposium (Moscow). Low entropy compression of the DT fuel (ρ_{DT} ~ 100 g/cc) was achieved by direct irradiation with a heavy ion pulse: ion energy ε ~ 100 GeV, target energy input Eo ~ 10 MJ [1]. The next step of the investigations to obtain the more reliable system may be in an employment of the relativistic heavy ion driver proposed by D.G.Koshkarev [2]. Ion energy ε ~ 1000 GeV creates new possibilities in the HIF system without a superpower ignition beam, but with a high level of the energy input Eo ~ 100 MJ. A complex but a reliable form of the irradiation is employed to compress the fuel to the density ρ_{DT} ~ 100 g/cc and to ignite DT. The perfectly well results of the Zabrodins group in Keldysh IAM (Moscow) with the "low entropy compression" [3] were as a starting-point to consider a multi-layered design of the cylindrical target. Energy gains ≥ 50 were obtained in the two-dimensional simulations by MDMT code for this DT cylindrical target. Some set of the investigations was fulfilled also for the deuterium fuel by the driver energy at the level Eo ~ 1000 MJ.

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Th.P-04

NUMERICAL EVALUATION OF THE INFLUENCE OF NON-STATIONARY STATE AND HETEROGENEITY OF THE ROTATED ION BEAM ON THE IRRADIATED CYLINDRICAL TARGET COMPRESSION PARAMETERS

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Higher compression ratios in targets can be achieved, if the target cores remain cold, i.e. if they are not exposed to ion beams. One of the methods used to provide such conditions is to rotate an ion beam with speed w around the target axis (Fig). The principal requirement of achieving high compression ratios is to provide homogeneous irradiation that is assumed to be resultant from ion beam rotation at high speeds. The efforts described consist in evaluation (in 1D approximation) of the requirements imposed on temporal and spatial characteristics of the ion beam rotated around the cylindrical target axis to gain high compression ratios.

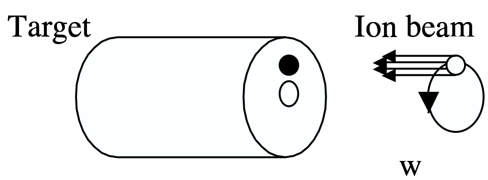

Fig. Scheme of the irradiated cylindrical target by rotated ion beam

PROGRESS IN THE POLARIZATION OF HD

Th.P-05

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The static polarization of HD samples has been achieved using "brute force", for HD samples purified by double distillation. Proton polarization in excess of 60% and deuteron vector polarization higher than 14% have been reached. It has been demonstrated that the ageing technique allows to get relaxation times at 1.5 K and 1 T larger than a week [1]. It is advocated that the conventional dynamic polarization of HD should be feasible for the proton and the deuteron contained in the HD molecule. This would simplify considerably the machinery presently necessary to perform nuclear physics experiments with HD targets polarized by the static method. On the other hand, if feasible, the dynamic polarization of HD would open the possibility to polarize DT, which has the same magnetic structure as HD and is the ideal fuel for Inertial HIF. According to Kulsrud [2], the full polarization of D and T nuclei should increase the reactivity of the DT fuel by 50%.

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Th.P-06

2-D MODEL OF A CONCENTRATED SHELL WITH MAGNETIC FIELD

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Both electron heat conductivity factor and alpha particle range are known to decrease in magnetic field, so thermonuclear mixture ignition is feasible at lower densities, which reduces the target sensitivity to the temperature field asymmetry on the capsule surface. As known, the 1D ultra fine shell model can be used to estimate the new density level. This paper estimates a 2D perturbation level that does not impede the ignition in the presence of magnetic field.

BETWEEN FILAMENTATION AND TWO STREAM INSTABILITIES

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In the realm of beam-plasma interaction, filamentation as well as double-stream instabilities represent key issues in various physical settings ranging from astrophysical scenarii to the fast ignition scheme for inertial confinement fusion. These instabilities have been investigated for a long time and the corresponding growth rates are well documented including temperature, relativistic and collisions effects. The wave vector orientation however has always been considered strictly parallel or normal to the beam although reality is found back summing over every possible wave vector in the $(\mathbf{k}, \omega)$ Fourier space.

We present an analytical study of unstable electromagnetic modes with arbitrarily oriented wave for a beam passing through a hot plasma with return current. We make the bridge between usual two-stream and filamentation instability across the $\mathbf{k}$ space, and prove the existence of an intermediate orientation with important growth rates.

Th.P-08

The Role of Organically Bound Tritium after Ingestion in Normal and Accidental Scenarios in Inertial Fusion Reactors

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In the future design of Inertial Fusion Reactors (IFE), the potential environment contamination by tritium emissions to the atmosphere could be relevant when considering ingestion by tritiated foods. In this case, the most important chemical forms of tritium, elemental tritium (HT) and tritiated water (HTO) derive in special form of tritium: Organically Bound Tritium (OBT). The behavior of tritium after chronic or accidental releases is that of being deposited on soil and vegetation via dry and wet deposition processes during pass of the tritiated plume or due to being re-emitted to the atmosphere in form of HTO (from HT form) to the air. Depending on the different types of soil, the tritium incorporates to the soil water and it is absorbed to subwater, roots of plants and drinking of animals. These processes are now considered in our calculations with more precise calculations and first conclusions of their real significance, and those conclusions will be exposed and explain in this work. The role of HT versus HTO and importance of re-emission process will be remarked.

In early time, one week after the emission, the contribution to the Effective Dose Equivalent is mainly due to both forms HT and HTO, but at long time, the OBT contributes at total doses by ingestion more than HT or HTO. New updated consequences appear in this continuous uptake of tritium after that secondary phase because OBT forms live for a long time in the human body. Those conclusions and the diffusion process is study and analyzed in this paper.

Review of Structural and Ceramic Materials under Irradiation in Inertial Fusion Reactors: comparison of Multiscale Modeling and Experiment

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Long term research on Reduced Activation Ferritic Alloys (RAFM steels) is being pursued in Fusion Programs, and an efficient lifetime is actually envisioned that will be here compared with that estimated in IFE reactor. However, from our simulations, comprehension of basic mechanisms of radiation damage is not understood to obtain predictive consequences. Multiscale simulation at the microscopic level will be compared with experiments, and results on the simplest material representing steels (Fe) will be reported as a function of impurity contents, temperature and dose. In addition, results using Molecular Dynamics allow us to identify stress-strain curve of FeCr ferritic steels under irradiation, and macroscopic conclusions can be advanced using simple models.

Radiation damage in amorphous ceramic Silica results in point defects that can lead to obscuration; that is, degradation of the optical properties of these materials. Atomistic threshold displacement energies of the components have been calculated using Molecular Dynamics, and cascade analysis for recoils of energies larger than 5 keV will be presented for working temperatures.

Research on radiation damage in SiC composite is being pursued at macroscopic level. However, results from theory and simulation to explain that physics is being slowly progressing. The systematic identification of the type of stable defects is the first task to perform, that will presented after verification of new tight binding techniques reported in the past. The different level of knowledge between simulation and experiments will be remarked.

RESIDUAL RADIOACTIVITY OF COPPER INDUCED BY ARGON BEAM IRRADIATION*

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Results of the measurement of the residual radioactivity produced by Argon beam with energies of E = 300,500,800 MeV/u in the copper target are presented. The spatial distributions of residual nuclei along the ion beam trajectory were obtained by measuring the gamma-ray activities of 1 mm thick foils inserted in the target with a high purity Ge detector. Long-time prediction of dose rates around the accelerator equipment is calculated on the base of the experimental data.

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Production of a High Brightness Beam from a Large Surface Source *

Th.P-11

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In today's HIF experiments, e.g. the HCX, the typical K^+ ion current density at the alumino-silicate ion source is about 7 mA/cm^2. This corresponds to an ion source diameter of 10 cm in order to produce 500 mA of beam current. Previous HCX data have indicated that spherical aberrations could degrade the emittance, so an experiment was set up on a 500-kV test stand to study the beam optics and to find ways for improvement. One of the experiments that we plan to do is to aperture the high current beam to enhance its brightness.

Beam diagnostics measurements from Faraday cup, emittance scanner, kapton and optical imaging will be compared with the 3-D WARP simulation in order to benchmark the computer code and confirm the beam optics.

We have also used the large diode to study the physics of controlling beam pulse rise time. Fast rise time is desirable because many potential near-term HIF experiments will require short beam pulses, and this can only be realized if the beam has a fast rise-time. According to a one-dimensional model, the beam head can propagate through the extraction diode with a sharp front edge by applying a special voltage waveform to the diode. Our simulation results showed that a proper waveform can be constructed to produce a 50-ns beam rise time for a real 3-D diode.

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Th.P-12

RF PLASMA SOURCE FOR HEAVY ION FUSION*

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We are developing high-current ion sources for Heavy Ion Fusion applications. Heavy ion driven inertial fusion requires beams of high brightness to deposit the necessary high energy in the target to obtain high gain. Our proposed RF plasma source starts with an array of high current density mini-beamlets (of a few mA each at ~100 mA/cm^2) that are kept separated from each other within a set of acceleration grids in order to minimize the space charge expansion. After they have gained sufficient kinetic energy (~1 MeV), the mini-beamlets will be allowed to merge together to form a high current beam (about 0.5 A) with low emittance. Simulations have been done to maximize the beam brightness within the physical constraints of the source.

We have performed a series of experiments on an RF plasma sources. A 80-kV 20-μs source has produced up to 5 mA of Ar^+ in a single beamlet. The emission current density was over 100 mA/cm for this case. We have measured the emittance of a beamlet, energy spread, and the fraction of ions in higher charge states. The plasma chamber has 26-cm inner diameter with multicusp permanent magnets to confine plasma. RF power (~11 MHz, >10 kW) is applied to the source via a 2-turn, 11-cm diameter antenna inside the chamber. We have tested a 80-kV 61-hole multi-beamlet array designed to produce a total current >200 mA. In these experiments the beamlets were not merged into a single beam. We are preparing hardware for a test of the extraction gap and first 4 Einzel Lens at the full gradient proposed for an injector. This experiment should produce a 0.5 A beam. The design of a full system with merged beamlets is also underway. It will be tested at one-quarter the normal gradient proposed for an injector. It should produce a low-emittance 40-mA beam. Details will be presented.

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EXTRACTION AND ACCELERATION OF HIGH LINE CHARGE DENSITY BEAMS

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HEDP applications and the modular linac systems approach to HIF, a lower-cost development path for a driver, require high line charge density (λ) ion beams. An efficient method to obtain high line charge density beams is to extract a long pulse, high current beam from an ion gun at high energy, and let the beam pass through a decelerating field to compress it, thus obtaining a high line charge density beam. The low energy beam bunch is loaded into a solenoid and matched to a Brillouin equilibrium flow. Once the beam is loaded, the Brillouin equilibrium is independent of the energy if the relationship between the beam size (a), solenoid magnetic field strength (B) and line charge density (λ) is such that λ/(Ba)^2 is constant. Thus it is possible to accelerate a matched beam at constant λ. We call this scheme the Accel-Decel-Load-and-Fire Solenoid Bunching Injector. Two experiments, NDCX-1 and NDCX-2 are being designed to test the feasibility of this type of injectors. NDCX-1, a proof-of-principle experiment, will extract a 500 ns, 12 mA, potassium beam at 285 keV, decelerate it to 30 keV (λ ~0.03 μC/m), and load it into a 3 T solenoid where it will be accelerated to 80—130 keV (head to tail) at constant λ to a final current of 24 mA and 250 ns pulse length. NDCX-2, an HEDP application injector experiment, will extract a 1 μs, 1 A, helium beam at 300 keV, decelerate it to 10 keV (λ ~1.4 μC/m), and load it into a 1.7 T solenoid where it will be accelerated to 70—210 keV (head to tail) at constant λ to a final current of 5 A and 200 ns pulse length. The head-to-tail velocity tilt can be used to increase bunch compression and to control longitudinal beam expansion. We will present the physics design and numerical simulations of the proposed experiments.

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MEASUREMENT AND SIMULATION OF THE UMER BEAM IN THE SOURCE REGION*

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As the beam propagates in the University of Maryland Electron Ring (UMER) complex transverse density structure, including halos, has been observed. A primary objective of the experiment is to understand the evolution of a space-charge-dominated beam as it propagates over a substantial distance. It is therefore important to understand which details of the beam structure result from propagation of the beam in the ring and which characteristics result from the specific details of the initial distribution. Detailed measurements of the initial beam characteristics have therefore been performed. These include direct measurement of the density using a phosphor screen, as well as pepper pot measurements of the initial transverse distribution function. Detailed measurements of the distribution function have also been obtained by scanning a pinhole aperture across a beam diameter, and recording phosphor screen pictures of the beam downstream of the pinhole.

Simulations using of the beam characteristics in the gun region have also been performed using the WARP P.I.C. code. From these simulations, the observed behavior has been attributed to a combination of perturbations to the transverse distribution by a cathode grid that is used to modulate the beam current, as well as the complex transverse dynamics that results from the combination of the nonlinear external focusing fields of the gun structure and the nonlinear space charge forces.

* This work supported by the United States Department of Energy.

LOW ENERGY BEAM TRANSPORT USING SPACE CHARGE LENSES *

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Gabor lenses provide strong cylinder symmetric focusing for low energy ion beams using a confined nonneutral plasma [1]. They need drastically reduced magnetic and electrostatic field strength or a reduced installation length to provide a given focal length compared with conventional LEBT – systems like quadrupoles and magnetic solenoids. The density distribution of the enclosed space charge is given by the enclosure conditions in transverse and longitudinal direction [2]. For homogeneous charge density distribution the resulting electrostatic field and therefrom the focusing forces inside the space charge cloud are linear. Additionally in case of a positive ion beam the space charge of the confined electrons causes compensation of the ion beam space charge forces. Hence all resolving forces on the beam ions are linear and thus the transformation is linear as well and the aberrations are minimal. Therefore space charge lenses are a serious alternative to inject space charge dominated low energy heavy ion beams into a RFQ.
To study the capabilities of a Gabor double lens system to match an ion beam into a RFQ a testinjector was installed at IAP and put into operation successfully. Furthermore to verify the beam focusing of bunched beams using this lens type at beam energies up to 500 keV a new high field Gabor lens was build. It will be installed behind the RFQ.
The first experimental results will be presented together with numerical simulations.

*Work supported by GSI and BMBF under contract no. 06 F 133.

1. J.A.Palkovic Measurement on a Gabor lens for neutralising and focusing a 30keV Proton beam., University of Wisconsin, Madison, 1982
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THE PATH TO IDEAL HIGH-INTENSITY BEAMS IN ALTERNATING-GRADIENT FOCUSING SYSTEMS*

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A persistent challenge in high-intensity accelerator design is the optimization of matching conditions between a beam injector and a focusing system in order to minimize non-laminar flows, envelope oscillations, emittance growth, and halo production. It has been shown [1] that the fluid motion of a thin space-charge dominated beam propagating through a linear magnetic focusing channel consisting of any combination of uniform or periodic solenoidal fields and alternating gradient quadrupole fields can be solved by a general class of corkscrewing elliptic beam equilibria. The present work extends this discussion to asymmetric PPM focusing and derives conditions under which a uniform density elliptical beam can be matched to such a focusing channel by considering the fluid equilibrium in the paraxial limit. Methods of constructing such a beam are also discussed, with particular attention devoted to analytic electrode design for Pierce-type gun diodes of elliptical cross-section. A case of special interest for heavy-ion fusion applications is the realization of an ideal KV beam in an AG focusing channel.

* This work was performed under the auspices of the U.S Department of Energy and the Air Force Office of Scientific Research.

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UNCONVENTIONAL THEORETICAL METHODS APPLIED TO HIGH INTENSITY ION BEAMS IN CIRCULAR AND LINEAR ACCELERATORS

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Abstract

A theoretical approach based on a formalism which is similar to quantum theory, with a new suitable interpretation of the fundamental parameters, is proposed and applied to high intensity ion beams with the purpose of finding their stationary profiles, stability conditions and halos.

Th.P-18

CHAOTIC PARTICLE TRAJECTORIES IN HIGH-INTENTSITY FINITE-LENGTH CHARGE BUNCHES*

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A Vlasov-Maxwell equilibrium for a charged particle bunch is given by the distribution function that is a function of the single-particle Hamiltonian $f = f(H)$, where in an axisymmetric cylinder $H = \mathbf{p}^2/2m + \kappa_\perp r^2/2 + \kappa_z z^2/2 + q\phi(r, z)$, the kinetic energy is $\mathbf{p}^2/2m$, $\kappa_\perp$ and κ_z are the external focussing coefficients in the transverse and longitudinal directions, and ϕ is the self-field potential determined self-consistently from Poisson's equation

$$\nabla^2\phi = -4\pi q \int d^3p f(H). \qquad (1)$$

The self-field potential ϕ introduces a coupling between the otherwise independent r and z motions. Under quite general conditions, this leads to chaotic motion. Poisson's equation is solved using a spectral method in z and a finite-difference method in r, and a Picard iteration method is used to determine ϕ self-consistently. For the thermal equilibrium distribution $f = A\exp(-H/T)$, the single-particle trajectories display chaotic behavior. The properties of the chaotic trajectories are characterized.

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COLLISIONAL EFFECTS AND DYNAMIC APERTURE IN HIGH INTENSITY STORAGE RINGS

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We analyze the dynamic aperture in presence of strong sextupolar errors for a high intensity beam. The scaling laws for the short term dynamic aperture are examined and its dependence on the perveance is discussed in a mean field approximation for a coasting beam. The collisional effects of Coulombian interaction are estimated for a linear lattice using a scaling law for the relaxation time. The collisional effects on the long time dynamic aperture are discussed by comparing the results of full Hamiltonian integration with a mean field theory. An application to a storage ring with the HIDIF parameters is briefly outlined.

Th.P-20

SIMULATIONS OF BEAM EMITTANCE GROWTH FROM THE COLLECTIVE RELAXATION OF SPACE-CHARGE NONUNIFORMITIES*

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In ideal linear focusing systems of space-charge-dominated beams, the transverse space-charge distribution of an ion beam tends to be nearly uniform within an elliptical envelope boundary. This produces linear transverse self-field forces within the beam that preserve beam phase space area (emittance). Non-ideal forces from aberrations of the applied focusing system and other sources can result in transverse density profiles that have strongly nonuniform charge density. This creates nonlinear self-field forces that can launch a broad spectrum of collective modes internal to the beam. There have been concerns that the free energy of such space-charge waves could lead to a loss of beam control and excessive emittance growth from oscillating nonlinear self-field forces. Here we employ the two-dimensional module of the WARP electrostatic particle in cell code to simulate this process. We find that collective relaxation processes tend to drive an initial nonuniform density beam to a final, relaxed state that is equilibrium-like with a more uniform, smoothed density profile and low-order residual oscillations. These relaxations appear driven by nonlinear wave interactions and phase-mixing associated with broad mode spectrums. This process is investigated for continuous focusing channels and periodic quadrupole focusing channels, both for rms matched and mismatched beam envelopes. It is found that surprising degrees of initial nonuniformity can be tolerated with modest emittance growth and that rms beam control can be maintained. Cases where the relaxation is fast and slow are analyzed. Simulation results are contrasted to earlier analytical theories[1] that should provide an upper bound on emittance growth if excessive halo is not generated. This work suggests that a surprising degree of initial space-charge nonuniformity can be tolerated in intense beams.

*This work performed under the auspices of the U.S Department of Energy by University of California, Lawrence Livermore and Lawrence Berkeley National Laboratories under contracts No. W-7405-Eng-48 and DE-AC03-76SF00098.

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EXPERIMENTAL STUDY OF SPACE-CHARGE WAVES IN INTENSE HEAVY ION BEAMS *

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When a short-duration, small-amplitude energy perturbation is applied to an intense heavy-ion beam, positive- and negative-going longitudinal space charge waves are generated on the beam [1]. Longitudinal diagnostic kickers that provide ~1% energy perturbation have been implemented for generating space-charge waves on HCX and NTX beams. The kickers consist of specially-designed fast pulse generators combined with an existing aperture or ESQ structure to provide the longitudinal perturbation to the beam. The amplitudes of the resulting density waves are ~10%, measured a few meters downstream of the kicker. The time of flight of the wave provides an accurate measure of the beam energy. The time of flight measurements will be described. Comparison of measured waves with a simple 1-D fluid model [2] of the beam will be presented.

[1] Martin Reiser, Theory and Design of Charged Particle Beams, Wiley Interscience, 1994.
[2] John Barnard, HIF Note 96-12, LLNL Internal Memo, Sept. 26, 1996.

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Th.P-22

MAGNETIC FIELD MEASUREMENTS OF QUADRUPOLES IN THE HIGH CURRENT EXPERIMENT*

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Abstract

The High Current Experiment (HCX) at Lawrence Berkeley National Laboratory is part of the US program to explore heavy-ion beam transport at a scale representative of the low-energy end of an induction linac driver for fusion energy production. Four pulsed magnetic quadrupoles are being used to study gas and electron effects with a 0.2 A, 1-MeV K^+ beam. The magnets, originally designed and built for a prototype pulsed magnetic quadrupole array, have an elliptical beam tube (6 x 10 cm) and iron boundary. The magnet coil and field length are ≈ 31 cm, and operating gradients are 10-40 T/m. To establish that the field quality of the prototype quadrupoles is satisfactory for the experiments, a <1 cm pickup loop was used to measure the flux $B_r(\theta)$ at the magnet mid-plane and also at the lead and return ends. A longer probe was used to measure the integrated flux $B_\theta(\theta)$ along the magnet. The probe measurements will be compared to model calculations of the field, and the implications for the beam experiments will be discussed.

* This work performed under the auspices of the U.S Department of Energy by University of California, Lawrence Livermore and Lawrence Berkeley National Laboratories under contracts No. W-7405-Eng-48 and DE-AC03-76SF00098.

BEAM HALO FORMATION AND BEAM LOSS INDUCED BY IMAGE-CHARGE EFFECTS IN A SMALL-APERTURE ALTERNATING-GRADIENT FOCUSING SYSTEM*

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The image-charge effects on an intense charged-particle beam propagating through an alternating-gradient focusing channel with a small aperture, circular, perfectly conducting pipe are studied using a test-particle model. For a well-matched elliptical beam with the Kapchinskij-Vladimirskij (KV) distribution, it is found that halo formation and beam loss is induced by nonlinear fields due to image charges on the wall. The halo formation and chaotic particle motion dependent sensitively on the system parameters: filling factor of the quadrupole focusing field, vacuum phase advance, beam perveance, and the ratio of the beam size to the aperture. Furthermore, the percentage of beam loss to the conductor wall is calculated as a function of propagating distance and aperture. The theoretical results are compared with PIC code simulation results.

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Th.P-24

SCALING LAWS FOR ELECTRON LOSS

FROM ION BEAMS*

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Heavy Ion Fusion requires accelerating intense beams of low-charge-state, heavy ions to high energies, transporting them over long distances, and focusing them on a small target in a target chamber. All along the beam path interactions between the beam particles and background gases generate charge and energy straggled beam components which are lost to the walls. This degrades the beam quality, erodes vacuum walls or lens elements, and increases radiation levels. Minimizing such problems requires information about interaction probabilities, particularly for single and multiple electron loss from fast, low-charge-state, heavy ions interacting with many-electron targets. Unfortunately, direct experimental information is not possible since existing acclerators cannot provide low-charge-state heavy ion beams at the high energies of interest. Therefore, available information must be extrapolated to the regions of interest. Theory can be used for this purpose but is complicated since multi-electron transitions resulting from intereactions between two highly complex particles must be modeled.

To aid in this problem we have used available experimental information to extract empirical scaling laws for projectile electron loss resulting from collisions with a many-electron target. It was found that a single universal curve can be used to fit single and multiple electron loss from virtually any projectile. The same curve can be used for loss from negative ions, neutral particles, and singly or multiply charged positive ions. We have applied the scaling to projectiles ranging from hydrogen to uranium and collision energies ranging from sub keV/u to hundreds of MeV/u. At high energies, existing data are consistent with a v^{-1} impact velocity dependence for scaled velocities less than 10. Above 10, limited data imply that the velocity dependence becomes v^{-2}. Using our fitted curve and a few input parameters such as the ionization potentials and number of outer shell electrons, absolute cross sections can be extracted for single and multiple electon loss from any arbitrary ion; from these total loss cross sections and the average number of electrons lost can be determined. Examples and predictions for electron loss from several possible ions of interest to the HIF program will be presented.

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ELECTRON EFFECTS DUE TO GRAZING COLLISIONS BETWEEN HEAVY IONS AND WALLS*

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In a heavy ion fusion accelerator, halo ions collide with the beampipe walls at grazing incidence. Standard theories for interactions between ions and wall materials break down at these highly-grazing angles. Effects that are typically neglected, such as surface roughness and ion scattering, become important. We present models of ion-wall interactions that take into account surface roughness and ion scattering, and we show how these factors effect electron production and neutral gas desorption. We compare electron production with experimental data from the High Current Experiment and from an experiment at Brookhaven National Laboratories and show how these models help explain a deficit in the electron yield compared with standard theories. Also, we combine these models with WARP simulations to help predict the magnitude of electron effects in the High Current Experiment.

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Th.P-26

ELECTRON EFFECTS IN THE NEUTRALIZED TRANSPORT EXPERIMENT (NTX) *

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The NTX experiment at the Heavy Ion Fusion Virtual National Laboratory is exploring the performance of neutralized final focus systems for high perveance heavy ion beams. To focus a high intensity beam to a small spot requires a high brightness beam. In the NTX experiment, a potassium ion beam of up to 400 keV and 80 mA is generated in a Pierce type diode and transported through 4 quadrupole magnets up to a distance of 2. 5m. The beam can be neutralized and focused using a MEVVA Plasma plug and RF plasma source. We shall report on effects of electrons, generated at beam aperture, along the magnetic section and on the focusing beam in the drift tube. Furthermore we shall describe ways to mitigate the effects of unwanted electrons.

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LASER INDUCED FLUORESCENCE DIAGNOSTIC OF BARIUM ION PLASMAS IN THE PAUL TRAP SIMULATOR EXPERIMENT*

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The Paul Trap Simulator Experiment (PTSX) is a cylindrical Paul trap whose purpose is to simulate the nonlinear dynamics of intense charged particle beam propagation in alternating-gradient magnetic transport systems. To investigate the ion plasma microstate in PTSX, including the ion density profile and the ion velocity distribution function, a laser induced fluorescence diagnostic system is being developed as a non-destructive diagnostic. Instead of cesium, which has been used in the initial phase of the PTSX experiment, barium has been selected as the preferred ion for the laser induced fluorescence diagnostic. A feasibility study of the laser induced fluorescence diagnostic using barium ions is presented with the characterization of a tunable dye laser. The installation of the barium ion source and the development of the laser induced fluorescence diagnostic system are also discussed.

*Research Supported by the U.S. Department of Energy.

STUDY OF A NON INTERCEPTING ION BEAM DIAGNOSTIC FOR BEAM DENSITY PROFILE*

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Measurement of the charge distribution and phase space of an ion beam using conventional intercepting diagnostics such as a Faraday cup, slit cup, pepperpot, or scintillator is highly perturbative, and often completely disrupts the ion beam itself. This is presently unavoidable for phase space measurements, though total beam charge can be measured non-perturbatively using a Rogowski coil or other similar inductive probes located around the beam. Such devices cannot quantify the cross sectional charge distribution in the beam. An electron beam diagnostic system for measuring the charge distribution of an ion beam without changing its properties is presently under development. In this new diagnostic a low energy, low current electron beam is moved transversely across the ion beam; the measured electron beam deflection is used to calculate the line-integrated charge density of the ion beam. The conceptual basis of the diagnostic, the design and setup of the system, characterization of the mechanical construction, electron beam transport and its trajectory is presented. Extraction of electric field from electron beam deflection is also presented to represent effectiveness of the diagnostic.

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Resolution Study of a Retarding Energy Analyzer

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Abstract: A novel cylindrical retarding electrostatic field energy analyzer for low-energy beams has been designed, simulated, and tested with electron beams of several keV, in which space charge effects play an important role. A cylindrical focusing electrode is used to overcome the beam expansion inside the device due to space-charge forces, beam emittance, etc. In this paper, we present the resolution study of this energy analyzer with single particle simulation and beam envelope equation including space charge. The study shows that this energy analyzer can achieve very high resolution (with relative error of around 10^{-5}). The theoretical analysis is compared with experimental results.

* This work is sponsored by US Dept. of Energy.

PROGRESS ON EXPERIMENTAL STUDY OF BEAM ENERGY SPREAD IN THE SPACE-CHARGE DOMINATED BEAMS*

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Many applications with intense charged particle beams, such as the ion drivers for Heavy Ion Fusion (HIF), require a small beam energy spread. It is believed that coupling between transverse and longitudinal direction due to coulomb collisions, instabilities and other mechanisms will cause an increase of the beam longitudinal energy spread. Characterization of beam energy spread is very important to understanding the physics of beam energy spread growth in the intense beams. So far, little experiments have investigated this problem in a systematic way. Low-energy, intense electron beams provide an economic way to study this problem in a small-scaled experimental setup. The results obtained with low-energy electron beams can be scaled to high-energy ion beams with appropriate scaling. At the University of Maryland, experiments with space-charge-dominated electron beams are being carried out to study the energy evolution in such beams. In order to measure the energy spread, a high-resolution retarding field energy analyzer has been developed and tested. A one-meter long linear system with solenoidal focusing is being set up and commissioned. In this paper, some preliminary experimental results and progresses on this topic will be presented.

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SPACE-CHARGE NEUTRALIZATION OF HEAVY ION BEAMS VIA ELECTRON INJECTION

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One key issue in heavy ion beam fusion (HIBF) is how to effectively focus high-current and high-perveance ion beams onto a small target area, usually with a radius of several mms. Space charge neutralization must be achieved to prevent defocusing as the ion density compresses during focusing. The present study is concerned with the physics of space-charge neutralization by use of various concepts for injection of electrons into the ion beam in addition to plasma neutralization. To date the most widely studied approaches employ a preformed plasma or ionize a background gas in the beam line. However, these schemes face difficulties due to local non-uniformities in charge neutralization due to beam dynamic/focusing effects. Thus, two supplemental techniques are under study and will be discussed here. One involves axial injection of electrons created in a thin foil in the beam path. The other uses a magnetic field to guide the electrons into the direction of the beam path. Both techniques would be used in combination with a conventional background plasma, providing added control. A preliminary analysis these schemes using computer simulations will be presented. Also, possible components that could be added onto an existing HIBF experiment such as NTX at LBL to provide a test of this type of electron injection will be discussed.

Abstracts
Oral Presentations
Friday, 11 June 2004

System Studies and Alternates

Listed in Program Order
One Per Page

HIF DRIVER POINT DESIGNS

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In 2002, the Robust Point Design of an HIF driver based on a driver with one induction linac transporting multiple beams and a distributed radiator target was completed. The main objective was to demonstrate the existence of a self-consistent solution that met in a robust manner all the requirements of the target, a thick liquid wall chamber, neutralized beam transport through the chamber, final focus magnet lifetime and driver architecture. In 2004, a program was launched to study an alternate Modular Point Design based on multiple identical induction linac modules and a hybrid target. The modular point design has significant payoffs in the driver development path. It also takes us into new regimes of physics related to beams with high line charge densities. These two point design studies will be presented and compared.

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LASER FUSION ENERGY*

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We are developing the science and technologies for laser fusion energy. The main components are developed in concert with one another to develop Laser Fusion Energy as an integrated system. The lasers [krypton-fluoride (KrF) and diode-pumped solid-state laser], the chamber, final optics, target fabrication and target injection are developed under the HAPL program. Target designs and experiments are carried out largely through the DOE ICF program.

Recent advances include: Target designs, backed with 2D simulations, show sufficient gain (>150) for fusion energy. The KrF laser produces 650 J/pulse at 1 Hz and 5 Hz, and the individual components meet the efficiency and beam smoothing requirements. The durability of the electron beam window is the major outstanding issue. The DPSSL produces 35 J/pulse in 5 Hz runs of over 10^5 shots, with efficiency and beam smoothing the main outstanding issues. A chamber "operating window" has been established that avoids first wall vaporization and allows target injection. A model has been developed to study how the chamber evolves between shots. The remaining issue of long term material behavior is being addressed with experiments that expose first wall materials to relevant ions and x-rays. Final optics studies have shown that a grazing incidence aluminum mirror meets the reflectivity requirements and exceeds the required laser damage threshold. For the targets: IFE sized foam shells have been mass produced, the required target specifications for DT ice smoothness has been met (but not on a mass production basis); and the cost of target production and injection has been modeled to be about $0.16 each. A facility to accelerate, inject and track targets has demonstrated the concept of a separable sabot and met the required injection velocity. The pointing accuracy is within a factor of five of the IFE requirement.

We propose to develop laser fusion energy in three phases. The present Phase I program is developing the critical science and technologies. Phase II would develop and integrate full size components. Phase III, the Engineering Test Facility (ETF), would: 1) optimize laser-target and target-chamber interactions, 2) develop materials and components; and 3) generate net electricity from fusion. We could be prepared to start construction of the ETF within ten to twelve years.

*Work sponsored by US Department of Energy, NNSA

This is a summary of work performed by researchers from over 20 institutions. For a detailed list of collaborators, see: J.D. Sethian, et al, "Fusion Energy Research with Lasers, Direct Drive Targets, And Dry Wall Chambers," Nucl. Fusion, **43, 1693-1709 (2003).

PROGRESS ON Z-PINCH IFE AND HIF TARGET WORK ON Z*

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The long-range goal of the Z-Pinch IFE program is to produce an economically-attractive power plant using high-yield z-pinch-driven targets (~3GJ) with low rep-rate per chamber (~0.1 Hz). The present mainline choice for a Z-Pinch IFE power plant uses an LTD (Linear Transformer Driver) repetitive pulsed power driver, a Recyclable Transmission Line (RTL), a dynamic hohlraum z-pinch-driven target, and a thick-liquid wall chamber. The RTL connects the pulsed power driver directly to the z-pinch-driven target, and is made from frozen coolant or a material that is easily separable from the coolant (such as low activation ferritic steel). The RTL is destroyed by the fusion explosion, but the RTL materials are recycled, and a new RTL is inserted on each shot. The Z-Pinch IFE program includes research on all aspects of the RTL, repetitive pulsed power, shock mitigation (due to the large fusion yields), automated RTL operation, z-pinch-driven targets, and power plant technology development (thick-liquid wall chambers, target fabrication, activation and waste stream analysis, etc.). Recent progress in all of these areas will be discussed.

HIF and Z-Pinch IFE have several closely-related development areas, including indirect-drive targets, thick liquid walls, repetitive driver pulsed power, target fabrication issues, waste stream analysis, etc. Active collaborations have been formed between the HIF program and the Z-Pinch IFE program to address several of these common issues. Progress in all of these areas will be discussed, with special emphasis on P4 target symmetry experiments on Z.

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POWER PLANT CONCEPTUAL DESIGN FOR FAST IGNITION HEAVY ION FUSION

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A conventional way of implementation of HIF energy is based on indirect target drive. This is motivated by large stopping ranges of heavy ions. A direct drive can be well adjusted to cylindrical targets. The concept of fast ignition heavy ion fusion (FIHIF) suggests a detonation burning of precompressed DT fuel as a basic scenario for target ignition. The cylindrical target composed of concentric massive shell and inner cylinder of fuel is driven by the two high power heavy ions beams of 100-GeV ions. The first beam of hollow tube geometry deposits its energy into the shell causing compression of fuel by imploding shell material. The second sharply focused beam impacts on the front end of the high density cord of fuel, thus initiating a detonation wave propagating along the cord. The compression beam of Pt^{+}_{192} ions is arranged by rotation of a single beam. The ignition beam of high power is composed of Pt ions of four different masses and plus/minus one charge states. The efficiency of the driver of RF linac type is evaluated as 0.25.

The energy released in the target microexplosion is partitioned in 546 MJ for neutrons, 187 MJ for debris and 17 MJ for X-rays. The X-ray pulse is characterized by very long duration of about 0.7 ms and by mean temperature of 30 eV. A wetted wall design is chosen for the reactor chamber. The chamber consists of the two adjacent sections: the upper section is the explosion section itself and the lower section is an expansion volume for the condensation of vapor on sprayed jets.

The response of the reactor chamber to the microexplosion is started by the X-ray impact. This results in evaporation of 5.4 kg of coolant from the liquid film at the first wall and generation of recoil pressure of 700 bar.

The neutron heating of the blanket is determined for a design, which is modeled by a multilayer cylinder. The energy deposition at the first wall is determined as 22 MJ/m^3 for liquid film and 20 MJ/m^3 for SiC porous structure. This should result in pressure pulse generation, the maximum amplitude of which is evaluated for isochoric heating as 400 bar that does not exceed the yield strength of silicon carbide. Tritium breeding ratio for the blanket is 1.05 and blanket multiplication factor is 1.1.

The energy conversion system consists of three loops. The maximum temperature of $Li_{17}Pb_{83}$ in the first loop is taken as 823 K. The inlet temperature in the reactor chamber is 623K. The initial steam pressure is taken as 180 bar. The efficiency of the steam cycle is equal to 0.417. The resulting net efficiency of the power plant is 0.37, providing the net power for one reactor chamber of 670 MW.

SYSTEMS ANALAYSIS FOR MODULAR VERSUS MULTI-BEAM HIF DRIVERS*

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Previous modeling for HIF drivers has concentrated on designs in which 100 or more beams are grouped in an array and accelerated through a common set of induction cores [1,2]. The total beam energy required by the target is achieved by the combination of final ion energy, current per beam and number of beams. Economic scaling favors a large number of small (~1 cm dia.) beams. An alternative architecture has now been investigated, which we refer to as a modular driver. In this case, the driver is subdivided into many (>10) independent accelerators with one or many beams each. A key objective of the modular driver approach is to be able to demonstrate all aspects of the driver (source-to-target) by building a single, lower cost module compared to a full-scale, multi-beam driver. We consider and compare several design options for the modular driver including single-beam designs with solendoid instead of quadrupole magnets in order to transport the required current per module in a single beam. Multi-beam, quad focus modules and solenoid/quad combinations are also evaluated. The drivers are designed to meet the requirements of the hybrid target, which can accommodate a larger spot size than the distributed radiator target that was used for the Robust Point Design [2]. We compare the multi-beam and modular driver configuration for a variety and assumptions and identify key technology advances needed for the modular design.

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OPTIONS FOR AN INTEGRATED BEAM EXPERIMENT*

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The Heavy Ion Fusion Virtual National Laboratory (HIF-VNL), a collaboration among LBNL, LLNL, and PPPL, is presently focused on separate smaller-scale scientific experiments addressing key issues of future Inertial Fusion Energy (IFE) or High Energy Density Physics (HEDP) drivers: the injection, transport and focusing of intense heavy ion beams at currents from 25 mA to 1 A.

As a next major step in the HIF-VNL program, we aim for a complete "source-to-target" experiment, the Integrated Beam Experiment (IBX). By combining the experiences gained in the current separate beam experiments, IBX would allow the integrated scientific study of the evolution of a high current (~1 A) single heavy ion beam through all sections of a possible heavy ion fusion driver: the injection, acceleration, compression, and beam focusing.

This paper describes the main parameter and technology choices of the proposed IBX experiment. Present designs call for a K^+ beam accelerated in an induction linac to 5-10 MeV. Different accelerator cell options are described in detail. In addition, recent innovative IBX design alternatives are introduced, which would allow ion-driven energy deposition into targets for HEDP studies.

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