Talk Outline

Basics
- Why do Heavy Ion Fusion?
- What do we have to do?
- A bit about the accelerator and the beams

Program
- Past Accomplishments
- Present Program
- Future Plans

Physics of Ion Beam Plasma Interaction
- Degree of charge and current neutralization
- Self electric and magnetic fields
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Introduction to Heavy Ion Fusion

- Inertial fusion is based on H-bomb design

- Who built the h-bomb? Debate revives

- By WILLIAM J. BROAD, April 24, 2001
**Bomb Basics**

**PRIMARY**
Conventional explosives compress plutonium in the primary, creating a critical mass in which atoms begin to split apart and release nuclear energy.

**SECONDARY**

**SECONDARY**
The radiation vaporizes the lining of the casing and radiates back toward the secondary, compressing it and heating it to fusion temperature.

**SECONDARY**
Radiation from the primary flows down the length of the bomb casing ahead of the primary blast.
Heavy Ion Fusion Concept

Source, Injector -> Accelerator -> Final Focus
How IFE Targets Work
Heavy Ion Fusion Requirements

Target requirements

3 - 7 MJ × ~ 10 ns ⇒ ~ 500 Terawatts

(hand grenade) (Forty times the averaged world-wide electric power consumption)

Ion Range: 0.02 - 0.2 g/cm² ⇒ 1- 10 GeV
Peaceful Power -- An Artist’s Conception of a HIF Power Plant
Why Heavy Ion Fusion?
Advantages of Heavy Ion Fusion Approach

- Driver is separate from the fusion chamber
  - accelerator not exposed to fusion environment
  - can protect 1st wall

- High electrical efficiency

- Takes advantage of decades of worldwide investment in accelerators & defense-funded target design
Heavy Ion Accelerators are a Good Choice for a Fusion Driver

High Energy Physics accelerators already have:

- Long life
- High pulse repetition rates
- High efficiency (~ 30%)
- Present systems comparable to requirements in:
  - complexity
  - cost
  - ion energy

But: much higher charge-per-unit-length is needed. Induction is not used in HEP accelerators.
The First Wall is Protected by Neutron-thick Molten Salt (FLiBe)

(one half cut away)
Fusion Pocket Formed by Liquid Jets

Flibe (Li2BeF4), is a molten salt with twice the density of water, and roughly the same viscosity, desired for making high-pressure steam for driving turbines.

Flibe absorbs neutrons.
Why Not Laser Drivers?

Lasers:
- Easy to focus
- Much more money in program
- Easier development path

but:
- Problem protecting final optics
- Problem protecting first wall
- Target gets damaged (hot)
- Low repetition rate (a few/day)
- Low electrical efficiency (a few - 10%)

Glass

All
Features of the Accelerator

3 - 7 MJ / 1- 10 GeV ions ⇒ ~ 10^{16} ions / 100 beams

⇒ 1-2 kA / beam => Space-charge-dominated beams (non-neutral plasma)

For accelerator design:

Focusability ⇒ Multiple beams
Efficiency ⇒ Induction acceleration
Stability ⇒ Linear accelerator
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Present Experiments

Present experiments – higher current (larger radius)
similar to the driver at low energy
⇒ high space charge potential.

0.1 - 0.5 A, 0.4 - 1 MeV, space charge potential ~ few kV

High Current Experiment (HCX) –
how much beam can be transported?

Neutralized Transport Experiment (NTX) –
neutralization by plasmas after the final focus
The Present Experimental Program: HCX and NTX experiments

Many, but not all, issues experimentally explored

Very complete experimental understanding
The High Current Experiment (HCX)

Issues to be resolved:

- Dynamic aperture (usable aperture set by dynamics)
- Halo production
- Effect of desorbed gas on tail
- Electron production & orbits (magnetic transport)
- Mismatch, misalignment

How much beam can be transported?

Parameters:
- $K^+$ or $Cs^+$
- $\sim 0.2 - 0.5$ Amp
- $1 - 1.7$ MeV
- $4.5 - 7 \mu$s

Quadrupoles:
- 10 (30-40 later) electrostatic
- 4 pulsed normal magnetic
- a few superconducting
High Current Experiment (HCX) operation since January, 2002

Transport
- aperture limits
- electrons
- gas effects
- halo formation
- steering

Marx
ESQ injector
matching
diagnostics
10 ES quads
diagnostics
Chamber Transport
Neutralization competes with stripping in the target chamber.
Neutralized Transport Experiment

- 400 kV injector
- Final-focusing optical system
- FY02: characterize ion & plasma sources
- FY03: study beam aberrations
- FY04: complete initial neutralization experiments
Beam Focusing with Plasma Plug
(operation since September, 2002)

Magnetic section  

Without Plasma  

With Plasma  

Pulsed arc plasma source  
Drift tube  
Scintillating glass
Beam simulations and theory span a variety of processes

- Acceleration in 3-D structure
- Two-stream instability
- Halo generation
- Electrons during neutralization
- Beam ions, Flibe ions, electrons
- Chamber propagation

![Diagram](Image)
Integrated Beam eXperiment Short-Pulse Source-to-Focus Experiment

- **Injector**: 2 m, 250 ns
- **Drift Compression/Bend section**
- **Shaping/matching section**
- **Velocity tilt section**
- **Final Focus**: 7 m, 25 ns

- **Ion**: K⁺
- **Pulse duration**: 250 ns → 25 ns
- **Final energy**: 5 - 10 MeV
- **Total half-lattice periods**: 148
- **Total length**: 64 m
- **Cost**: ~ 70 M$

$50 - 70 M TEC over 5 yrs + $15 M R&D

The Heavy Ion Fusion Virtual National Laboratory
Heavy Ion Fusion Summary

- Because of the separation of accelerator from fusion chamber, the heavy ion fusion concept is able to protect the 1st wall, and the driver, from fusion products.
- HIF benefits from large U.S. and worldwide investments in accelerators and defense-funded target research.
- Past and present experiments have demonstrated production, acceleration, compression, and focusing of beams at lower energy and current.
- The Integrated Beam Experiment would be a proof-of-principle experiment with a rich physics mission: to explore longitudinal physics and test integrated source-to-focus transport.
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Means of Investigation

- Nonlinear theory
- Numerical simulation:
  - Particle in cell
  - Fluid
- Neutralization experiment (VNL)
Results of 2D PIC-MC Code

- Beam propagation in the y-direction,
- beam length $7.5 \frac{c}{\omega_p}$;
- beam radius $1.5 \frac{c}{\omega_p}$;
- beam density equal to the half of the plasma density;
- beam velocity $c/2$.

- Shown are electron density and the current.
beam length \(30. \frac{c}{\omega_p}\);
beam radius \(0.5 \frac{c}{\omega_p}\);
• beam density is 5 of plasma density;
• beam velocity \(0.5c\).
System of Equations

\[ \frac{\partial n_e}{\partial t} + \nabla \cdot (n_e \vec{V}_e) = 0, \]

\[ \frac{\partial \vec{p}_e}{\partial t} + (\vec{V}_e \cdot \nabla) \vec{p}_e = -\frac{e}{m} \left( \vec{E} + \frac{1}{c} \vec{V}_e \times \vec{B} \right), \]

\[ \nabla \times \vec{B} = \frac{4\pi e}{c} \left( Z_b n_b V_{bz} - n_e V_{ez} \right) + \frac{1}{c} \frac{\partial \vec{E}}{\partial t}, \]

\[ \nabla \times \vec{E} = -\frac{1}{c} \frac{\partial \vec{B}}{\partial t}. \]
Beam propagates in the $y$-direction, beam half length $l_b = 15 \frac{c}{\omega_p}$; beam radius $r_b = 1.5 \frac{c}{\omega_p}$; beam density $n_b$ is equal to the background plasma density $n_p$; beam velocity $V_b = \frac{c}{2}$.

Shown are the normalized electron density $n_e/n_p$ and the vector fields for the current.

FOR MORE INFO...

http://hifnews.lbl.gov/hifweb08.html
Beam propagates in the y-direction, 
\[ l_b = 15 \frac{c}{\omega_p} \]; 
\[ r_b = 1.5 \frac{c}{\omega_p} \]; 
\[ n_b = n_p \]; 
\[ V_b = c/2 \].

Shown are the normalized electron density \( n/e_n p \) and the vector fields for the electric force on electrons.

FOR MORE INFO...
http://hifnews.lbl.gov/hifweb08.html
Steady-State Results

normalized electron current $j_y/(ecn_p)$

http://www.trilobites.com
Analytic theory of chamber transport: excitation of plasma waves by beam depends on bunch length

\[ \beta_b = 0.5, \quad l_b/r_b = 10, \quad n_b/n_p = 0.5 \]

- a) \( l_b = 2 V_b/\omega_p \)
- b) \( l_b = 6 V_b/\omega_p \)
- c) \( l_b = 20 V_b/\omega_p \)

Red line: ion beam size, brown lines: electron trajectory in beam frame
Important issues:
- Finite length of the beam pulse,
- Arbitrary value of $n_b/n_p (n_b >> n_p)$,
- 2D.

Approximations:
- Fluid approach,
- Conservation of generalized vorticity,
- Long dense beams $l_b >> r_b, V_b/\omega_p$.

Exact analytical solution.
Conservation of Generalized Vorticity

\[\tilde{\Omega}_e = \nabla \times \tilde{p}_e - e\tilde{B} / c,\]

\[\frac{\partial \tilde{\Omega}_e}{\partial t} - \nabla \times (\tilde{V}_e \times \tilde{\Omega}_e) = 0,\]

\[\oint \tilde{\Omega}_e \cdot dS = \oint (\tilde{p}_e - \frac{e}{c} \tilde{A}) \cdot \delta \tilde{r} = \text{const.},\]

\[\tilde{\Omega}_e = 0 \Rightarrow \nabla \times \tilde{p}_e = e\tilde{B} / c.\]

FOR MORE INFO... I. Kaganovich, et.al, Physics of Plasmas 8, 4180 (2001).
Approximate System of Equations

\[ l_b >> r_b, \]

\[ (V_{ey} - V_b) \frac{\partial n_e}{\partial y} + \frac{1}{r} \frac{\partial}{\partial r} (r n_e V_{er}) = 0, \]

\[ \nabla \times \vec{p}_e = \frac{e}{c} \vec{B}, \]

\[ \frac{1}{r} \frac{\partial}{\partial r} E_r = 4\pi e (Z_b n_b + n_p - n_e), \]

\[ K_e = m_e \vec{V}_e^2 / 2, \]

\[ (V_{ey} - V_b) \frac{\partial p_{er}}{\partial y} + \frac{\partial K_e}{\partial r} = -eE_r, \]

\[ -\frac{1}{r} \frac{\partial}{\partial r} r \frac{\partial}{\partial r} p_{ey} = \frac{4\pi e}{c} (Z_b n_b V_{by} - n_e V_{ey}). \]
Approximation of long beams:
- Beam length is much longer than beam radius;
- Therefore, beam can be described by a number of weakly interacting slices.
- The electric field is found from radial Poisson’s equation.
- As a result of the simplification the second code is hundreds times faster than the first one and can be used for most cases, while the first code provides benchmarking for the second.
Comparison of Theory and Simulation: Electron Density

Electron density
Left – PIC,
Right - fluid

\[ l_b = \frac{1}{\omega_p}, \quad r_b = \frac{0.1}{\omega_p} \]
\[ n_b = 0.5n_p, \quad V_b = 0.5c \]

Brown lines: electron trajectory in the beam frame.
Red line: ion beam size.

FOR MORE INFO...
I. Kaganovich et.al,
Comparison of Theory and Simulation: Electron Density

Key parameter $\omega_p l_b / V_b$

Quasineutrality $l_b >> V_b / \omega_p$

$l_b = 30c/\omega_p$

$r_b = 1.5c/\omega_p$

$n_p = n_b$

$V_b = 0.5c$

Ion Bunch Density

$y = 25c/\omega_p$
Comparison of Theory and Simulation: Current Neutralization

Key parameter $\omega_p r_b/c$, Current neutralization $r_b >> c / \omega_p$.

$l_b = 30c/\omega_p$
$r_b = 1.5c/\omega_p$
$n_p = n_b$
$V_b = 0.5c$

Ion Bunch Density

(b) $y=0$ $y=25c/\omega_p$

$\frac{i_y}{en_p}$ $x_\omega_p/c$ $y_\omega_p/c$
Comparison of Theory and Simulation: Magnetic Field

Key parameter $\omega_p r_b/c$

Magnetic field neutralization $r_b > c/\omega_p$

$l_b = 30c/\omega_p$
$r_b = 1.5c/\omega_p$
$n_p = n_b$
$V_b = 0.5c$

I. Kaganovich, et.al, Physics of Plasmas 8, 4180 (2001).
Results and Conclusions

- Developed a nonlinear fluid theory for the quasi-steady-state propagation of an intense ion beam pulse in a background plasma under the assumption of a long beams $l_b \gg r_b$.
  - The analytical formulas can provide an important benchmark for numerical codes.
  - The analytical solutions form the basis of a hybrid semi-analytical approach, used for calculations of beam propagation in the target chamber.

- The simulations of current and charge neutralization performed for conditions relevant to heavy ion fusion showed:
  - very good charge neutralization: key parameter $\omega_p l_b / N_b$,
  - very good current neutralization: key parameter $\omega_p r_b / c$.

- Plasma wave breaking heats electrons $n_b > n_p$. 
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• beam density equal to the half of the plasma density;
• beam velocity $c/2$.

• Shown is the electron current.
Plasma Wave Breaking Heats the Electrons when $n_b < n_p$

Electron phase space shown for $l_b=30 V_b/\omega_p$; $n_b = 2n_p$. Times after entering the plasma plug are: (a) $113/\omega_p$, and (b) $245/\omega_p$. 
**Fluid approximation is good for**

\[ n_b \leq n_p \]

Electron current and phase space  
\[ l_b = \frac{15c}{\omega_p} ; \quad n_b = n_p ; \quad V_b = \frac{c}{2}. \]
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- Beam propagation in the y-direction,
- beam half length $30 \frac{c}{\omega_p}$;
- beam radius $0.5 \frac{c}{\omega_p}$;
- beam density is equal to 5 of the plasma density;
- beam velocity $c/2$.

- Shown is the electron density.