SOME PHYSICAL PROPERTIES OF HIGH ENERGY DENSITIES PLASMA WORTH INVESTIGATING BY INTENSE HEAVY ION BEAMS

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Plasmas at high pressure. Nonideality

Generations and Diagnostics

Metallizations

Plasma Phase Transitions

Dielectrizations

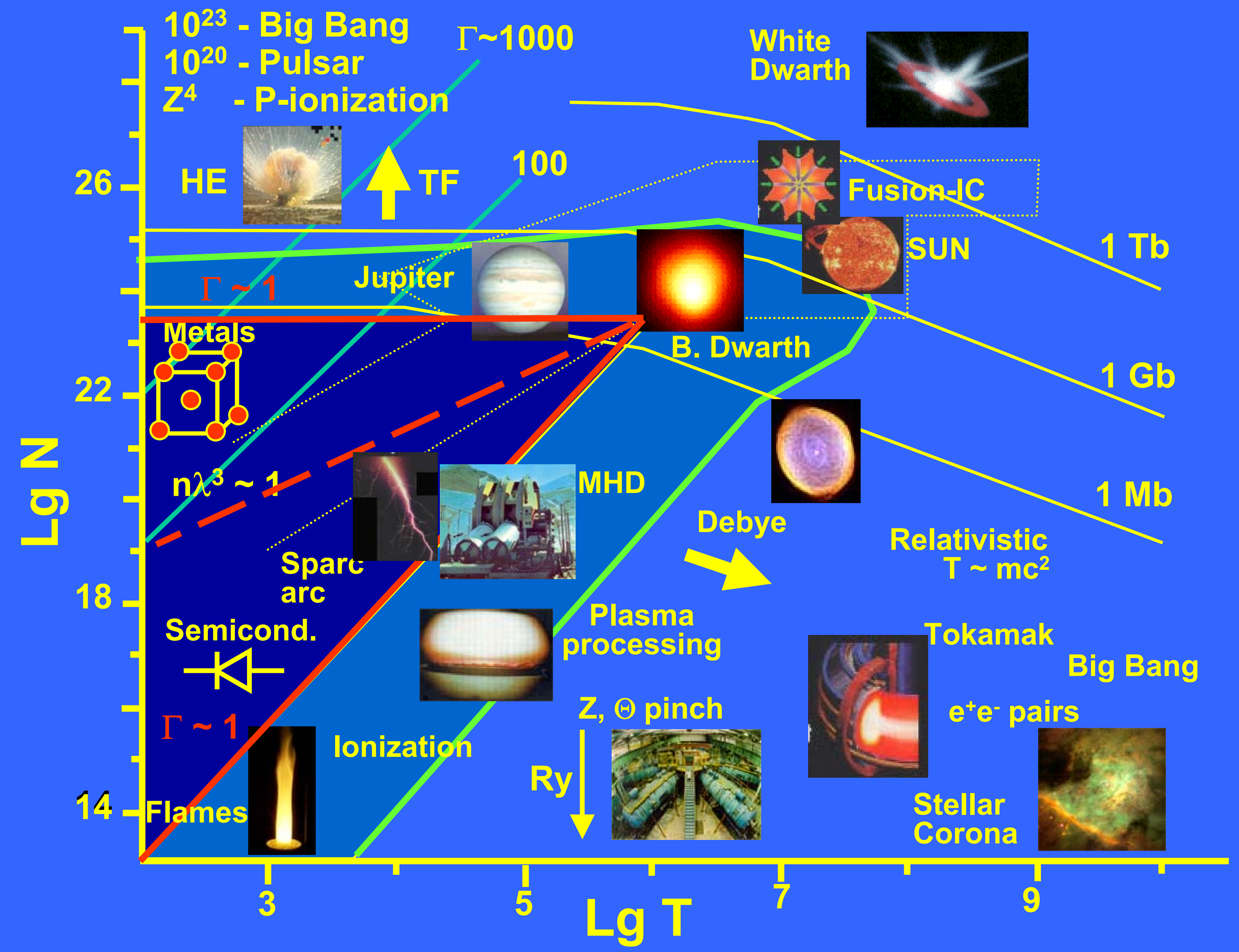
Rarefaction Waves-Evaporation

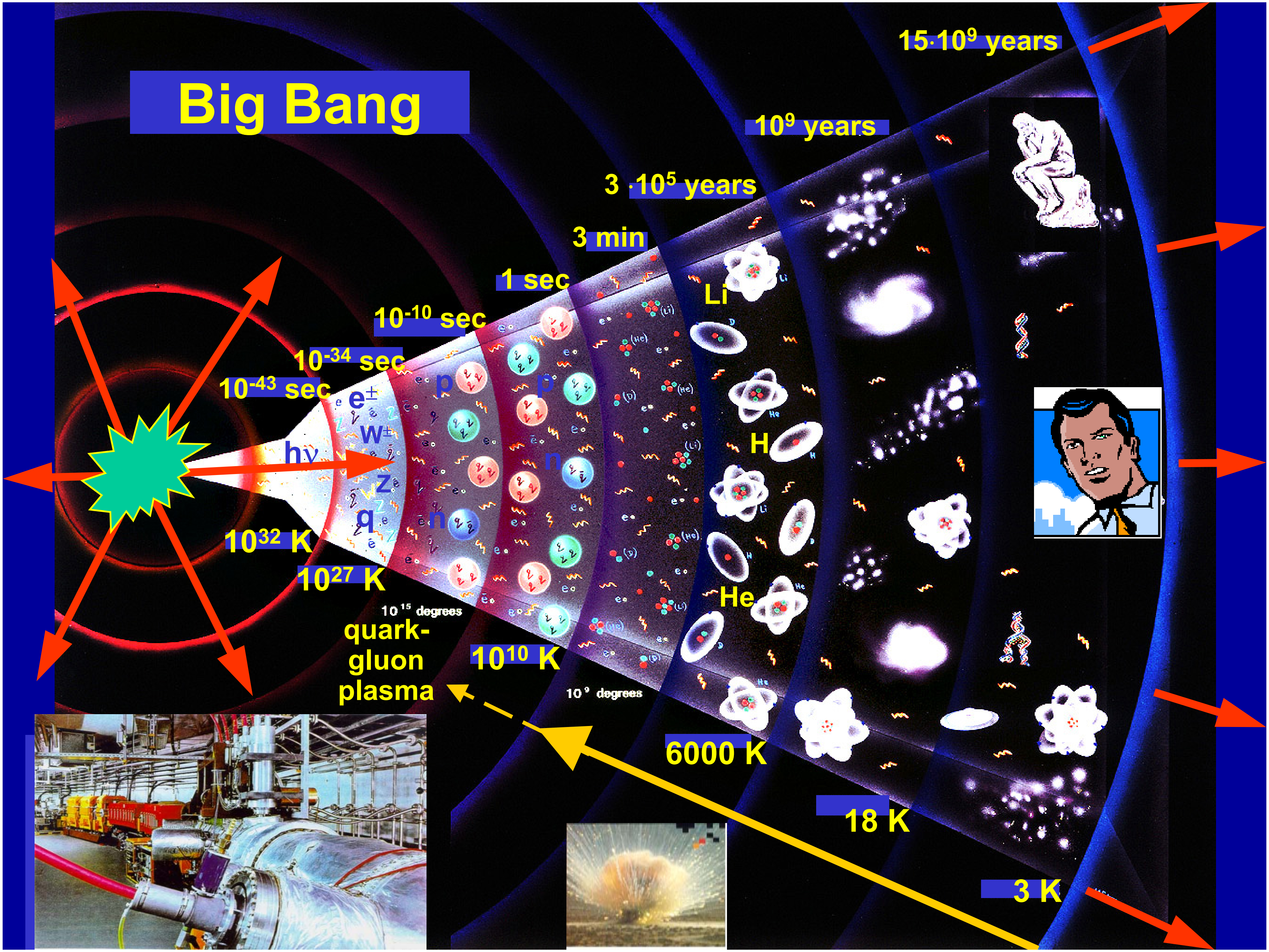
Non-Congruent evaporation

High Strain Rate Effects

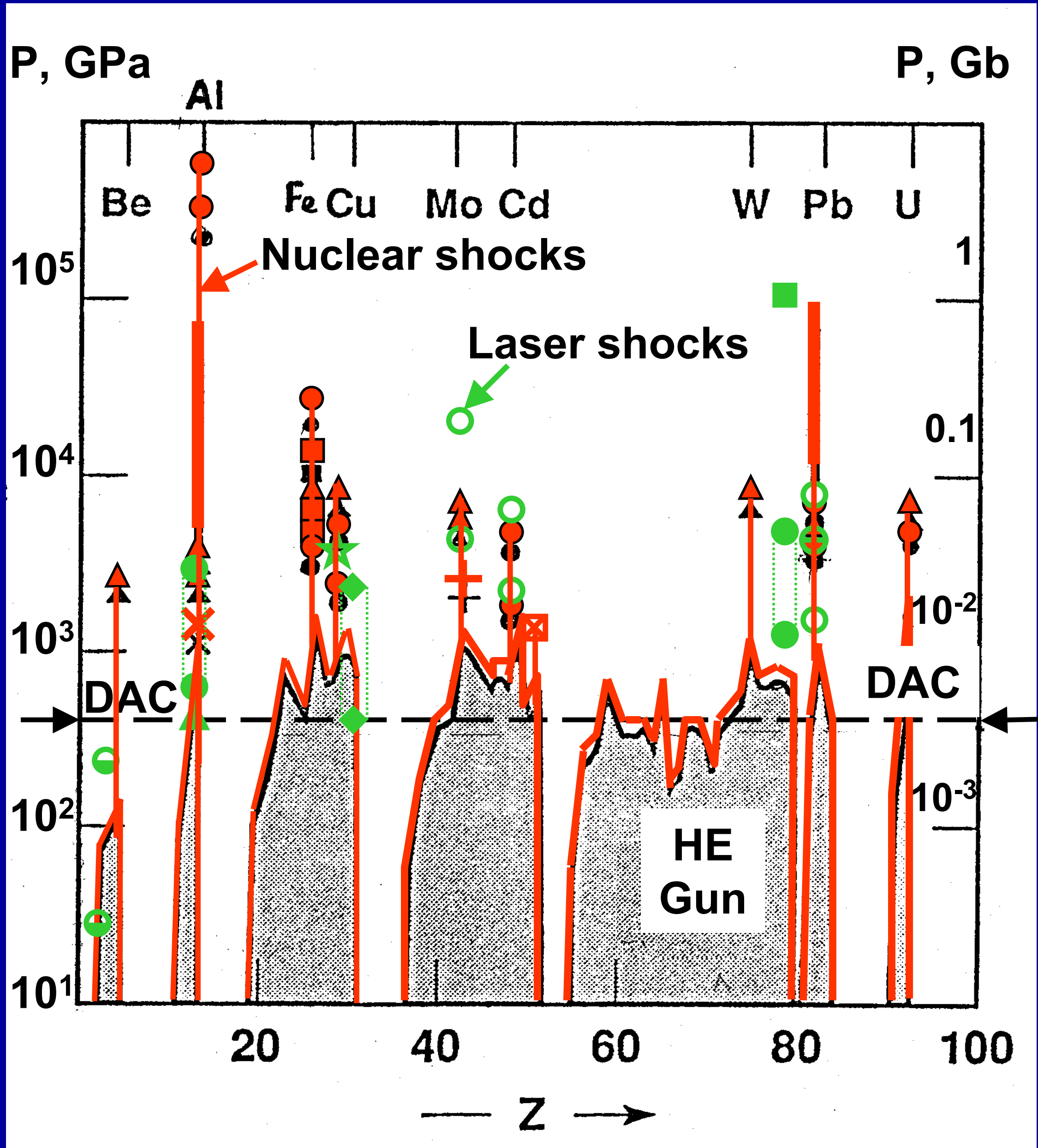
Kinetics

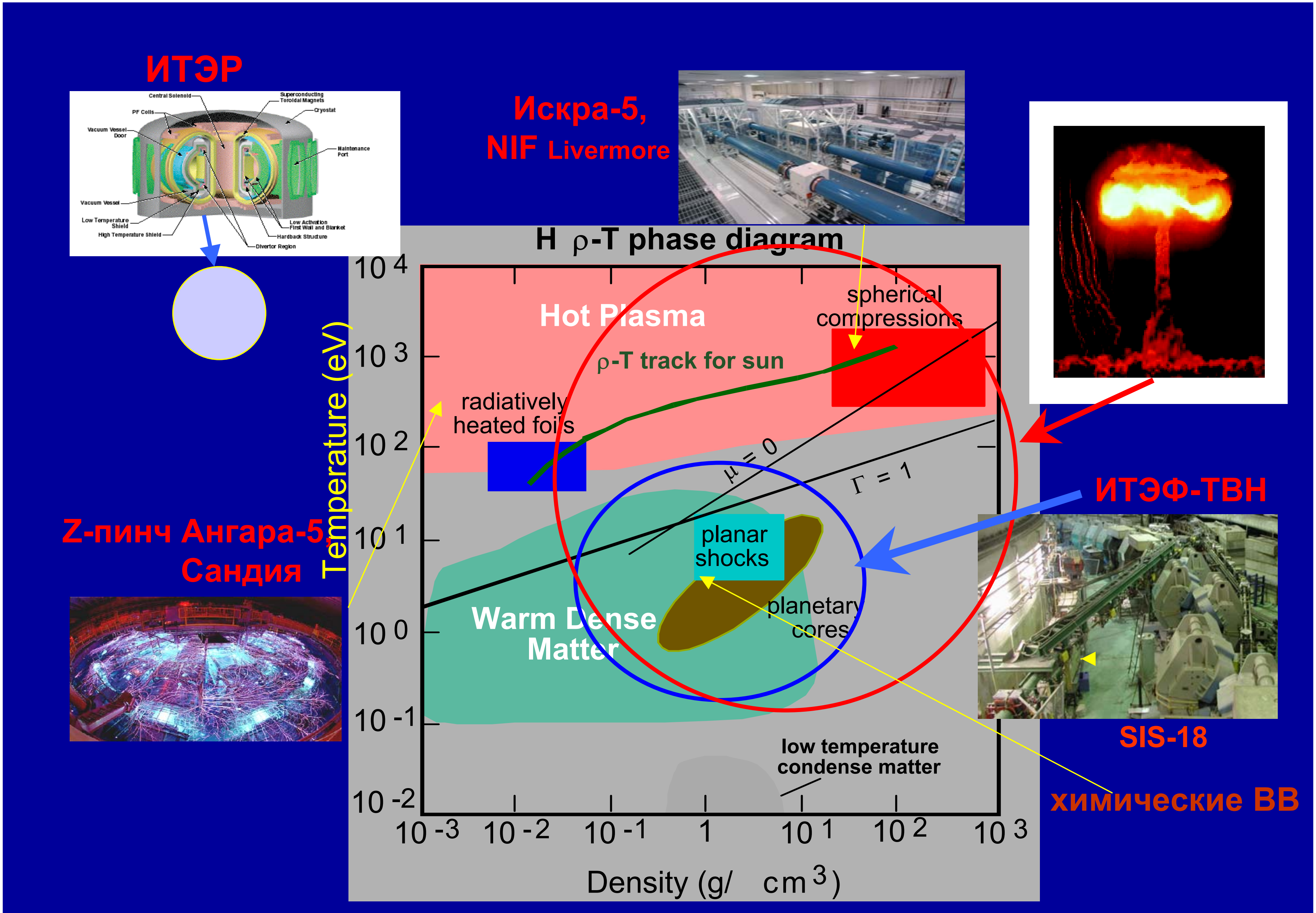
PHASE DIAGRAM OF PLASMA




Big Bang
$15 \cdot 10^{9}$ years
10^{9} years
$3 \cdot 10^{5}$ years
3 min
1 sec
10^{-10} sec
10^{-34} sec
10^{-43} sec
hγ
e±
W±
Z
q
p
n
Li
H
He
10^{32} K
10^{27} K
10^{15} degrees
quark-gluon plasma
10^{10} K
10^{9} degrees
6000 K
18 K
3 K

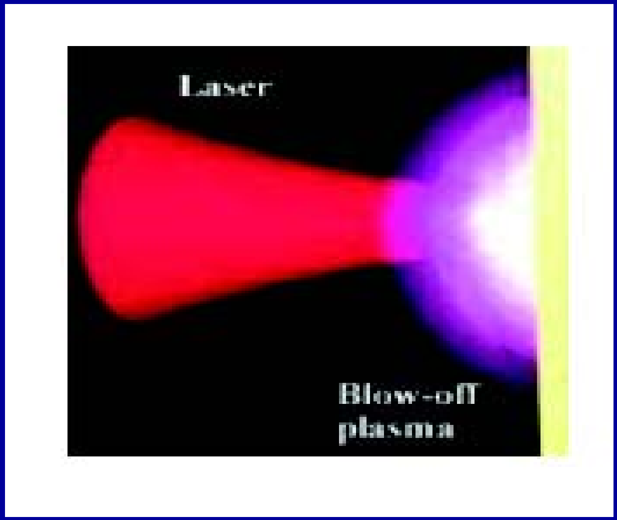
MAXIMUM PLASMA PRESSURES IN THE "LABORATORY"

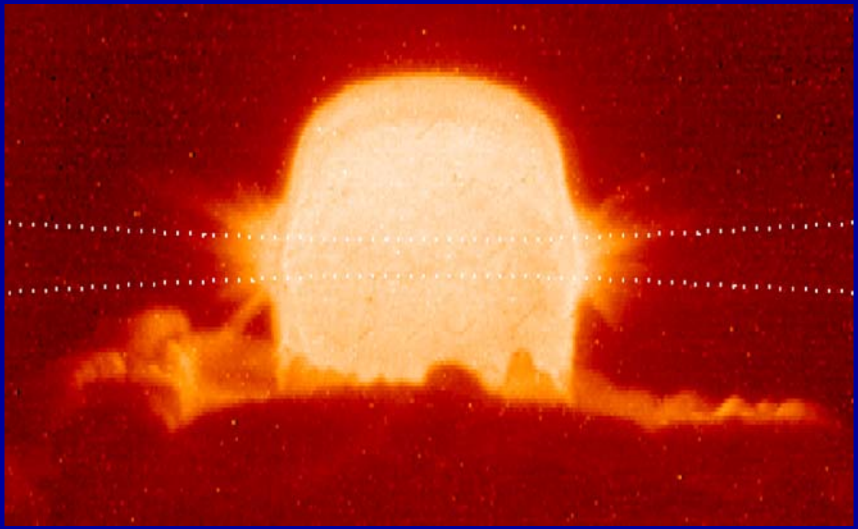




Phase Diagram of Matter

Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of plasma <u>in reproducible experimental conditions</u>





Powerful Lasers

NIF, Omega, Gekko XII, LMG, ISKRA-6, X-FEL….

- low repetition rate
- small volumes
- large gradients
- short life time

Intense Heavy Ion Beams,*GSI*

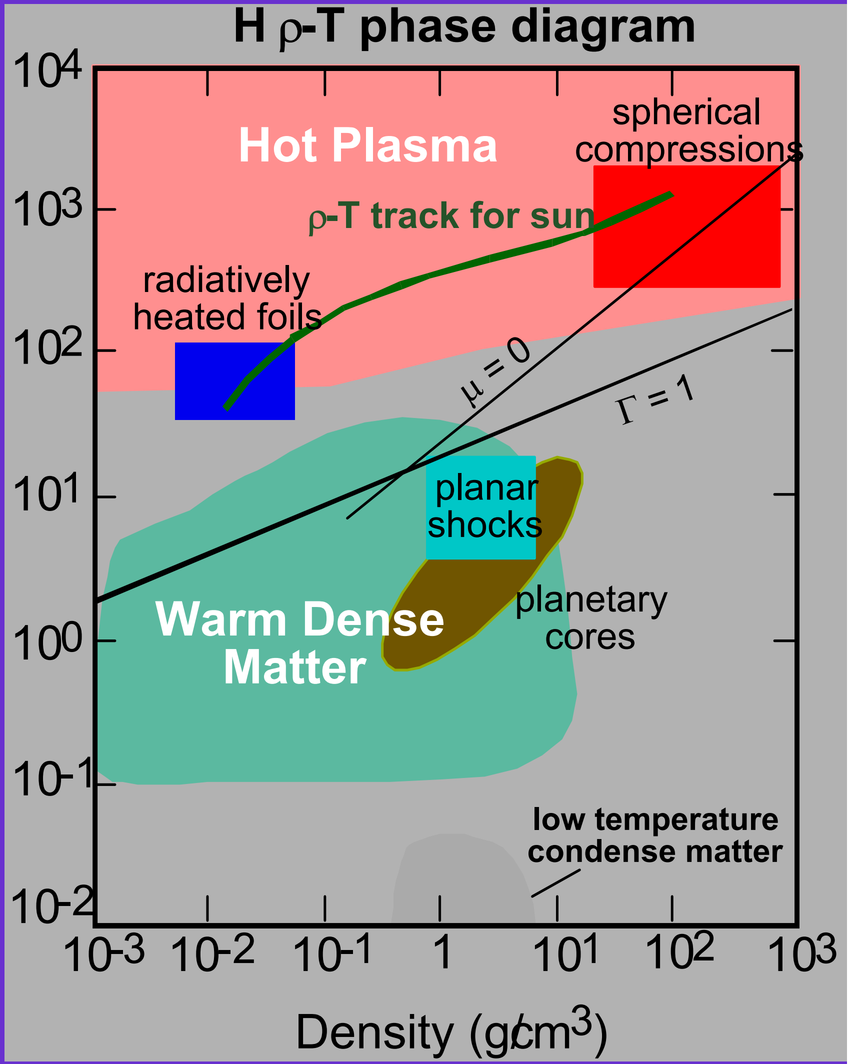
- large volume of sample (N mm3)
- fairly uniform physical conditions
- high entropy @ high densities
- extended life time

HI : high entropy states of matter - without shocks !

Main Directions of Coupled Plasma Research

High Energy Density Plasma

Es ~ 10 – 1000 kJ/g
T ~ 0.5 – 20 eV
ρ ~ 10-3 - 10 g/cm3
P ~ kbar – Mbar



Properties of matter under extreme conditions
(EOS, plasma phase transitions, critical points, strongly coupled plasmas, atomic physics, transport properties: conductivity, r-transport

Non-ideal dense plasma physics
Non-congruent phase transitions (U02) stimulated by plasma non-ideality- phase equilibrium in 2-phase region

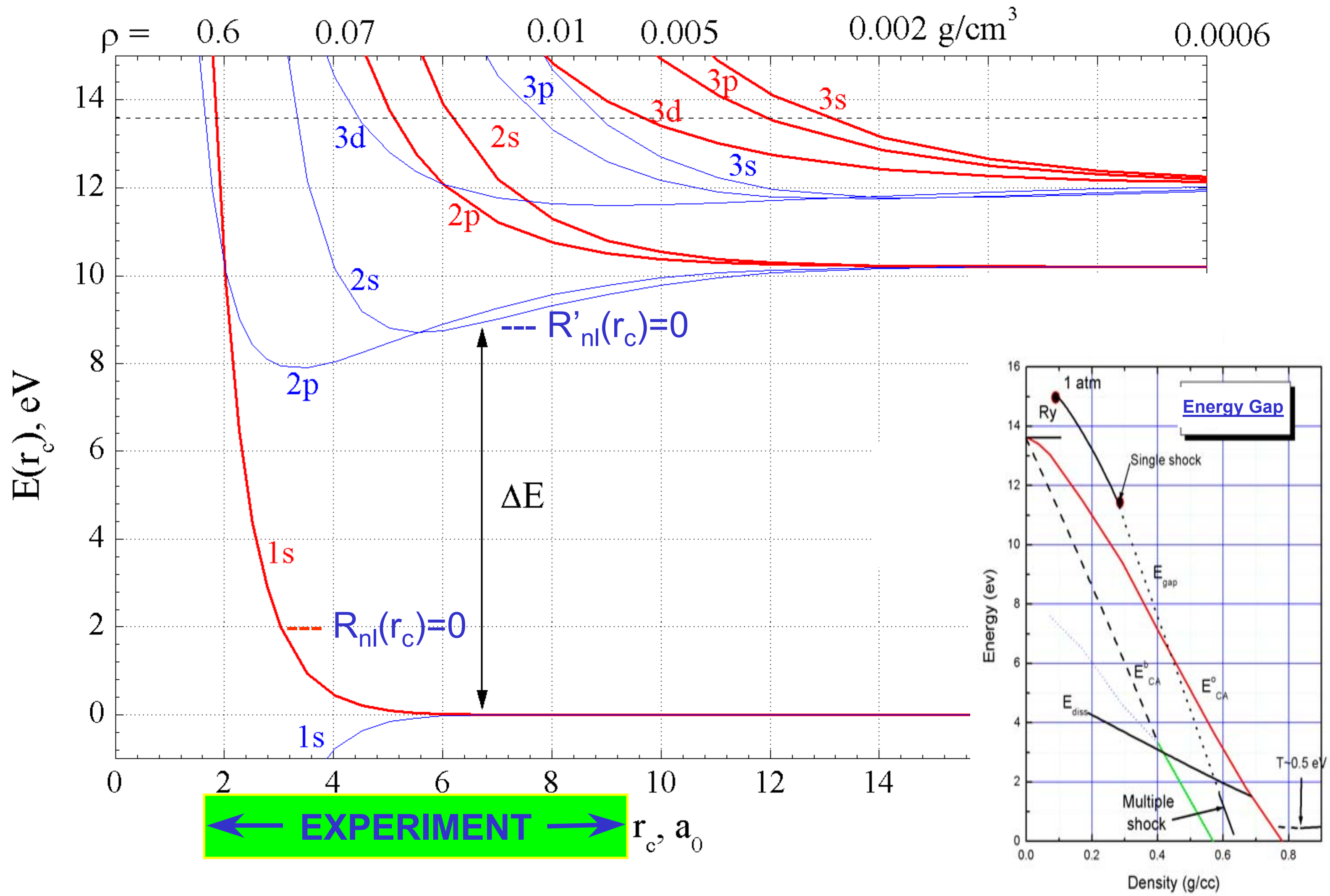
Applic.:IFE research, safety of nuclear reactors space technologies, geophysics, planetary science, plasma technology.

What type of beams will be needed :

- **Intensity** **> 10^12** *of 0.4-2 GeV* **U28+ ions/pp**
- **Pulse length :** **~ 50 ns – 100 ns – strong bunch compression**
- **Pulse shaping :** **temporal , transversal**
  (parabolic, gaussian, box-shape…)
- **Focusing system:** **strong focusing** ***(~1 mm FWHM)***
  annular focal spot
- **Beam diagnostic:** **intensity, temporal, transversal**

Requirements – at the limit of technical feasibility

ELECTRONIC SPECTRUM OF COMPRESSED HYDROGEN PLASMA



“SHELL” PHASE TRANSITIONS IN STRONGLY COUPLED PLASMA

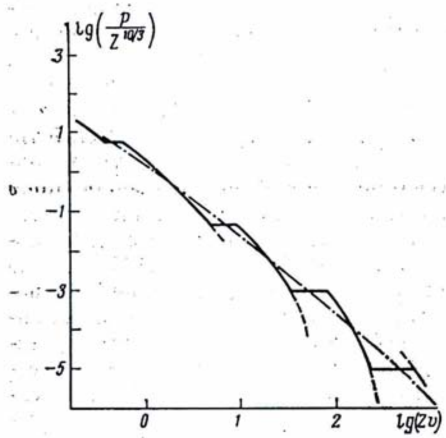


Рис. 1. Уравнение состояния по квазиклассической модели с учетом оболочечных эффектов по [7, 12].

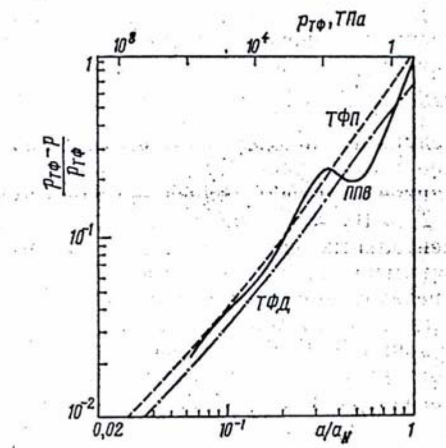


Рис. 2. Уравнение состояния алюминия по модели Томаса — Ферми — Дирака (ТФД), Томаса — Ферми с квантовыми и обменными поправками (ТФП) и модели присоединенных плоских волн (ППВ) [9].

a — параметр решетки, $a_N = 7{,}65\, a_0$; a_0 — параметр при нормальных условиях.

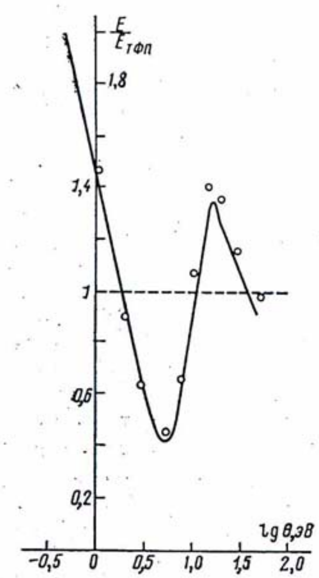


Рис. 3. Отношение величин энергий в модели Хартри — Фока — Слэтера [13] (ХФС), Томаса — Ферми с квантовыми и обменными поправками (ТФП) и в «химической» модели плазмы (точки) в зависимости от температуры при давлении 1 кбар [13].

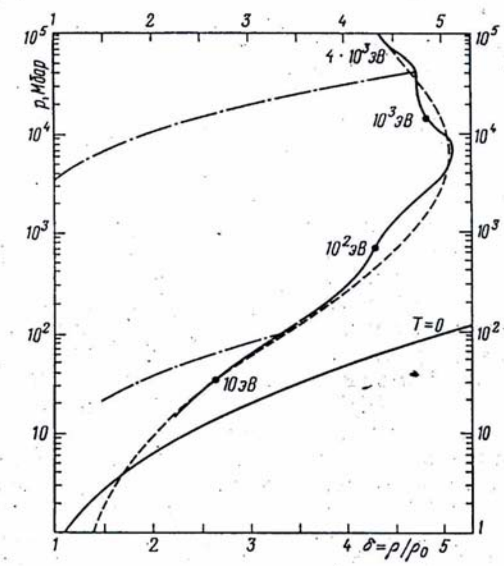
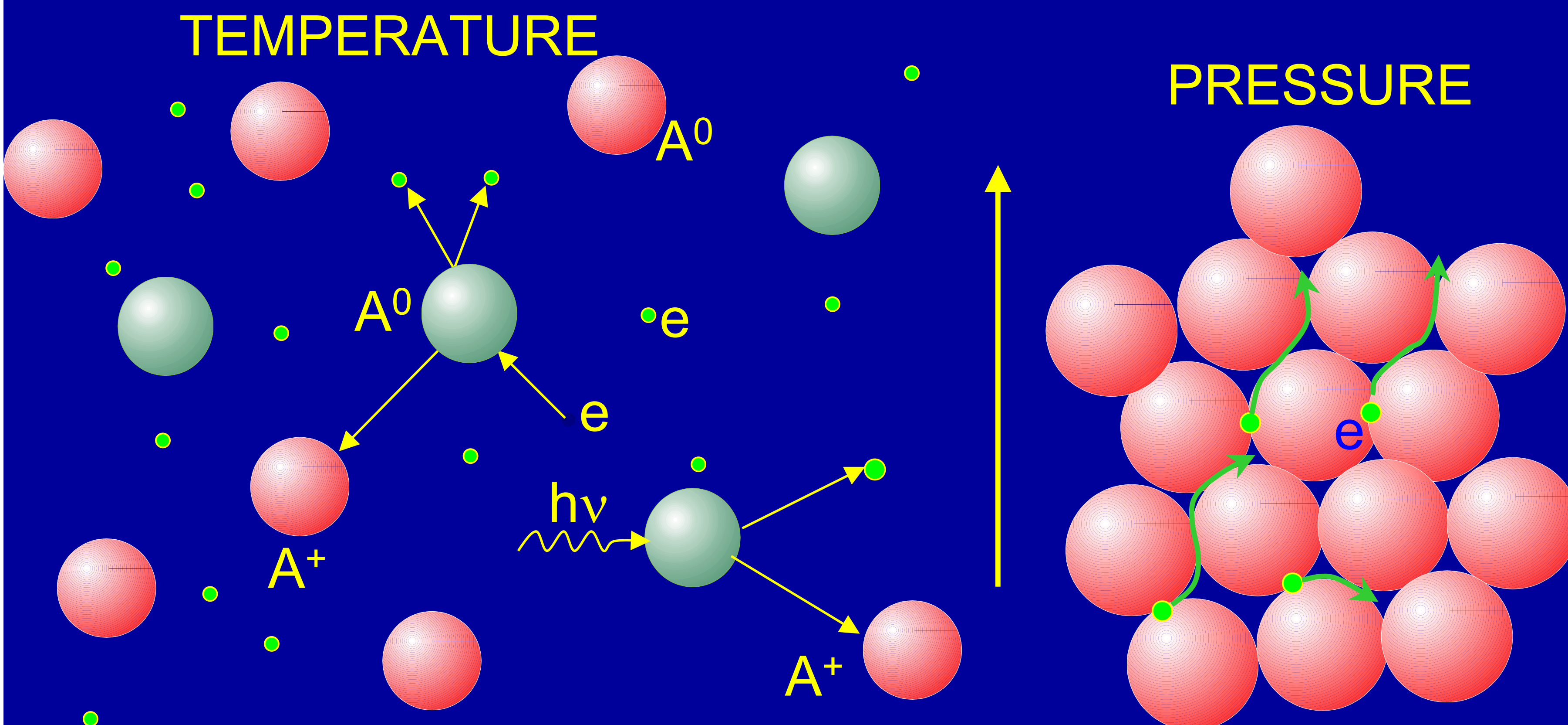


Рис. 4. Ударная адиабата железа [75] $\rho_0 = 7{,}85$ г/см^3 и кривая холодного сжатия $T_0 = 0$ К с учетом оболочечных эффектов (сплошные кривые).

Пунктир — результаты гладкой сшивки эксперимента и расчетов по модели Томаса — Ферми с поправками. Штрих-пунктир — изэнтропы расширения.

NONIDEAL PLASMAS

IONIZATION BY:



Coulomb: $W_c \sim Z^2 e^2 n^{1/3}$

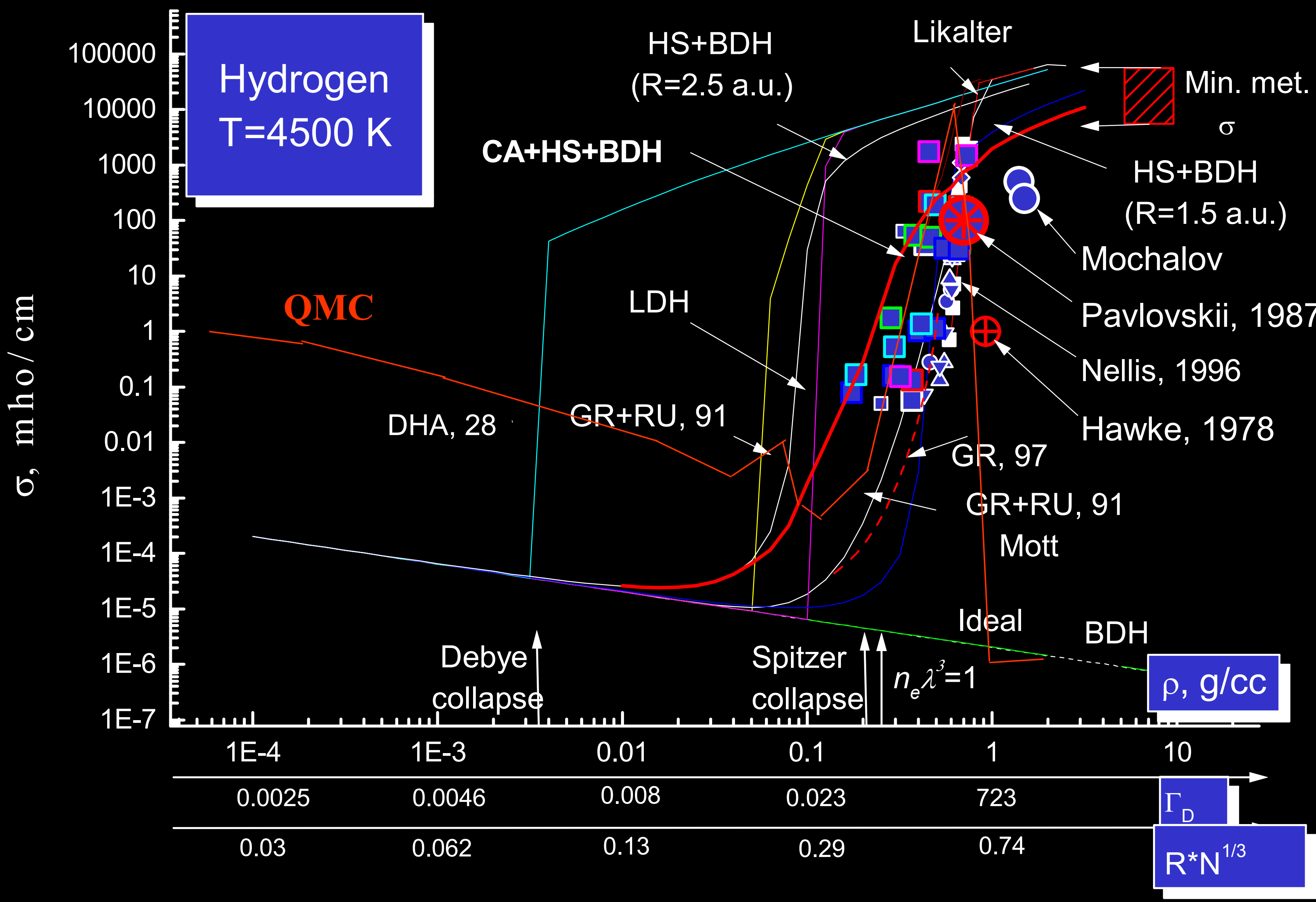
$\Gamma = W_c / W_{th} < 1$

$n\lambda^3 << 1,\ W_{th} \sim kT$

$\Gamma = W_c / W_{th} \geq 1$

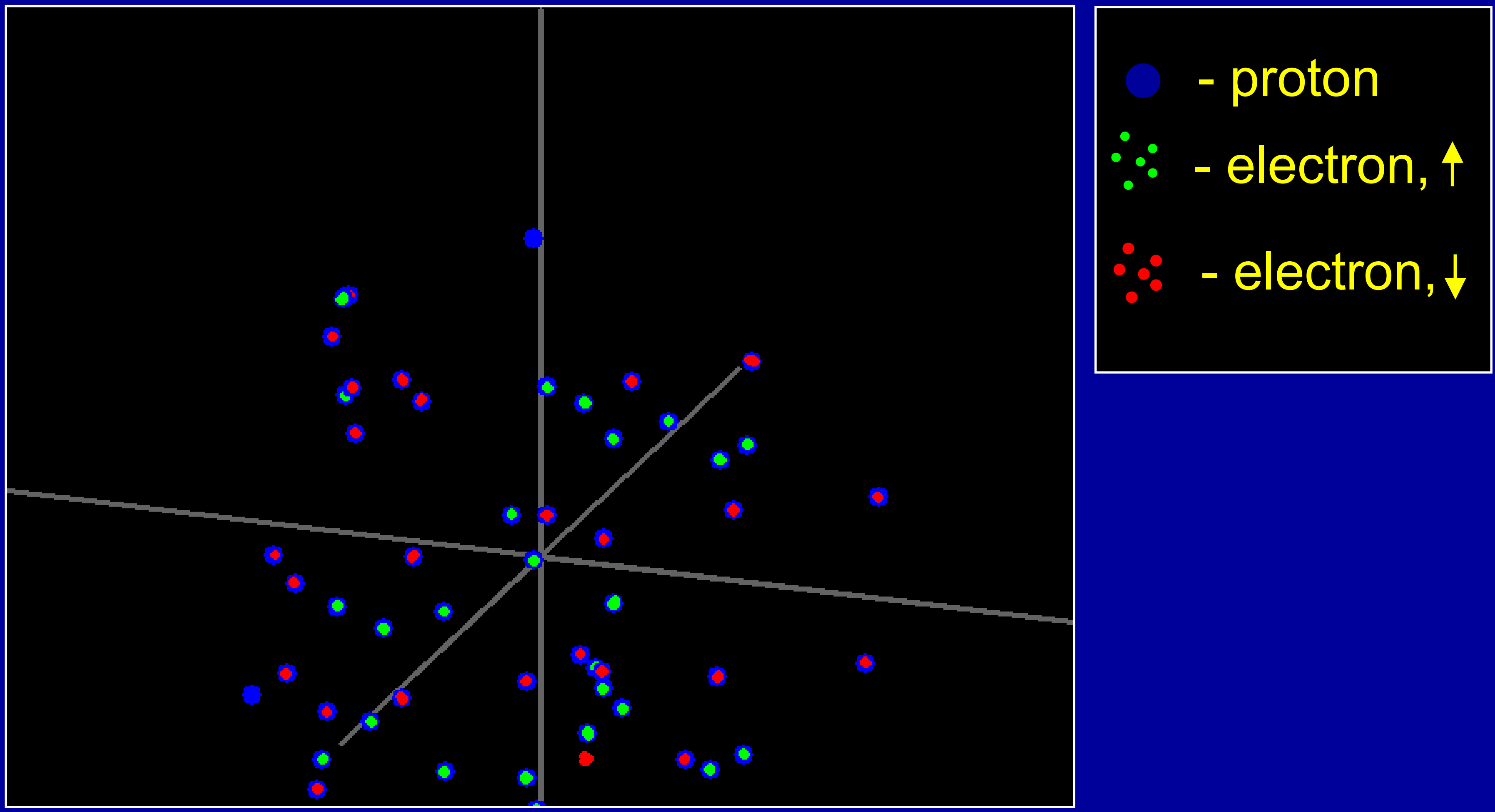
$n\lambda^3 \sim 1,\ W_{th} = h^2 n^{2/3}/2m$

HYDROGEN PRESSURE IONIZATION



PLASMA QUANTUM MONTE-CARLO SIMULATIONS

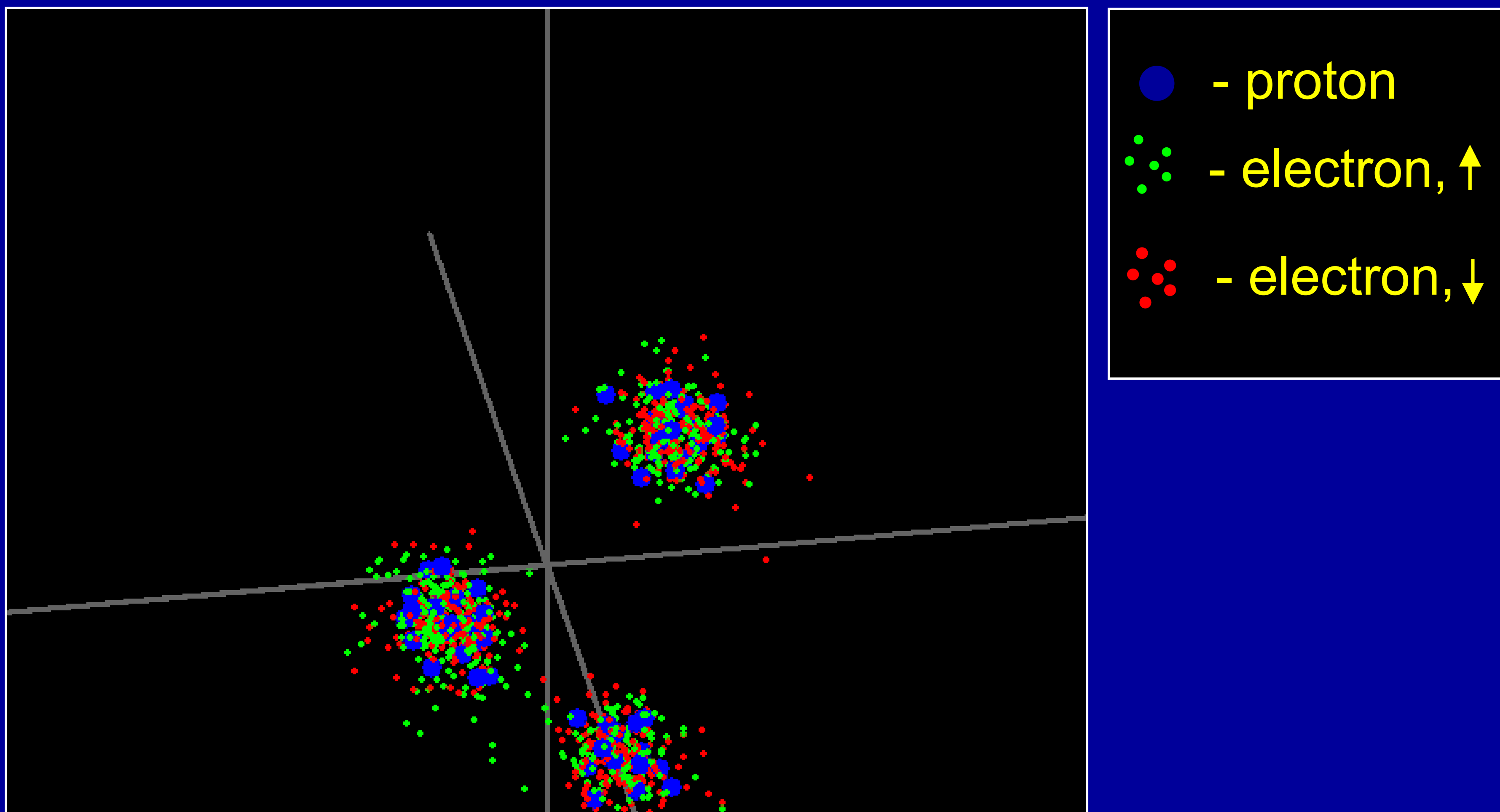
Hydrogen, dissociation



T = 10000 K, n = 10^{18} cm^{-3}, ρ = 1.67·10^{-6} g/cm^{3}

PLASMA QUANTUM MONTE-CARLO SIMULATIONS

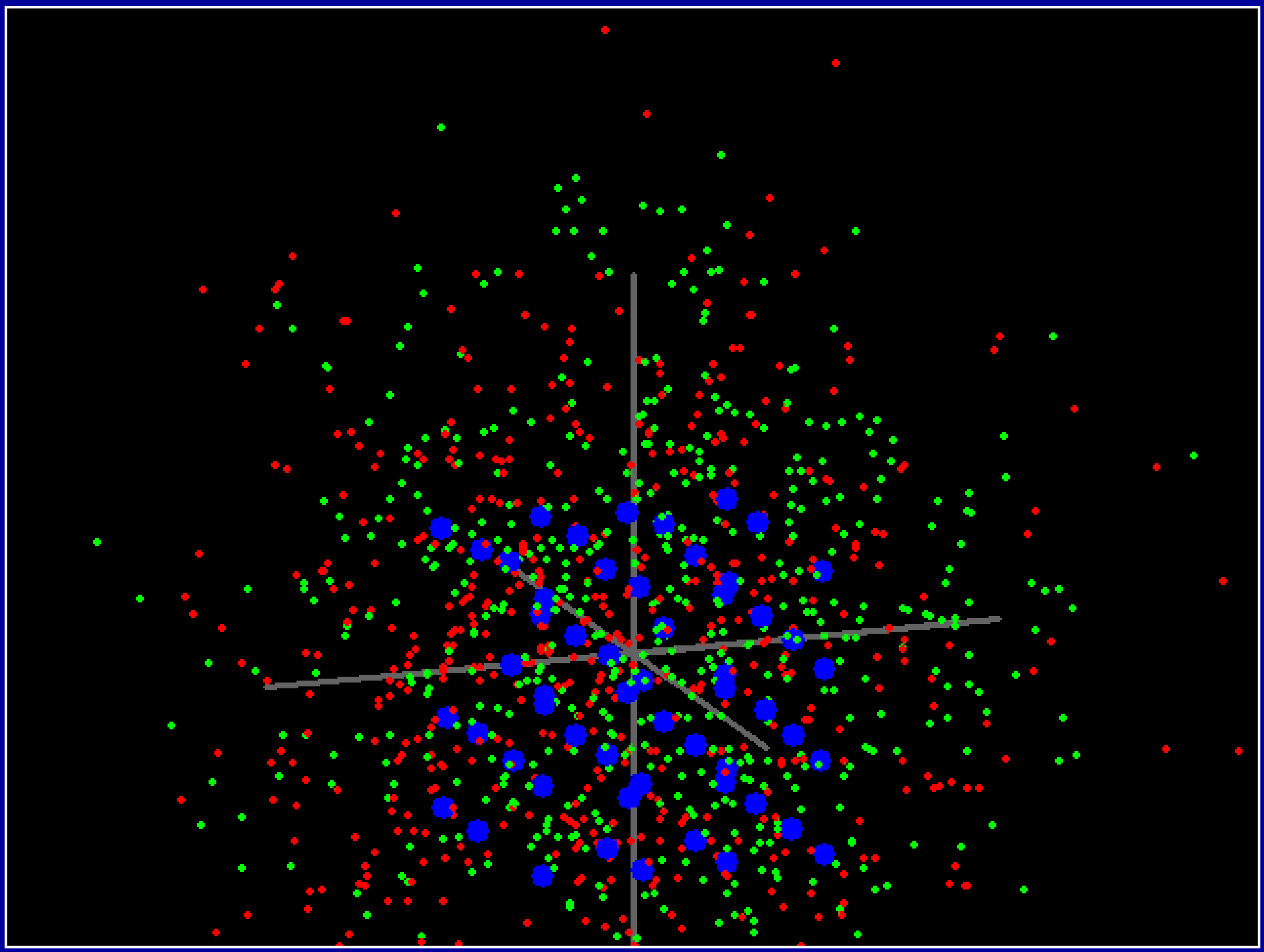
Hydrogen, phase transition

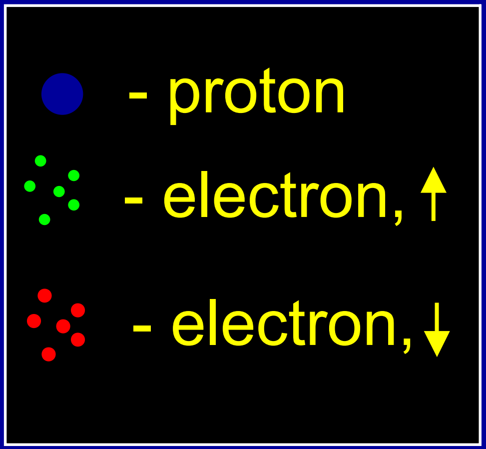


T = 10000 K, n = $3 \cdot 10^{22}$ cm^{-3}, ρ = 0.05 g/cm^{3}

PLASMA QUANTUM MONTE-CARLO SIMULATIONS

Hydrogen, protons ordering





T = 10000 K, n = $3 \cdot 10^{25}$ cm^{-3}, ρ = 50.2 g/cm^3

HIERARHY OF PHASE TRANSITIONS

Li (T<200 K): cF4 (12) —39→ [hR1 (6) + {cI16}] —42→ {cI16} (11)

Rb: cI2 (8) —7→ cF4 (12) —14→ ? —17→ {tI19*} (7-8\2-6) —20→ tI4 (4+4) —46→ {oC16} (10\11)

Cs: cI2 (8) —2,3→ cF4 (12) —4,2→ cF4' (12) —4,4→ tI4 (4+4) —12→ {oC16} (10\11) —72→ hP3 (6+6)

Sr: cF4 (12) —3,5→ cI2 (8) —24→ cI4 (4+2) —35→ ? —46→ {tI11*} (9\6-11)

Ba: cI2 (8) —5,5→ hP3 (6+6) —12,6→ {tI11*} (9\6-11) —45→ hP3 (6+6)

Si: cF8 (4) —11,7→ tI4 (4+2) —13→ oI4 (2+2+2) —15,4→ hP1 (2+6) —38→ {oC16} (10\11) —40→ hP3 (6+6) —78→ cF4 (12)

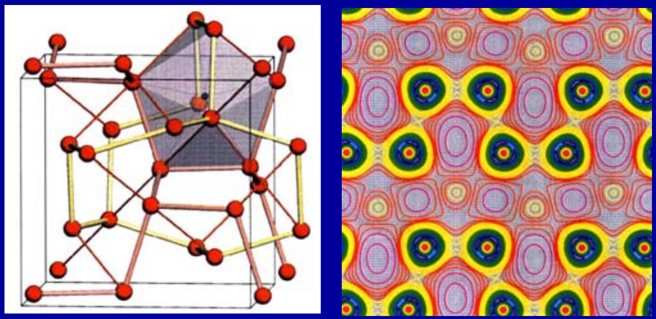
As: hR2 (8+3) —25→ cP1 (3) —48→ {tI11*} (9\6-11) —97→ cI2 (8)

Sb: hR2 (8+3) —6,4→ cP1 (3) —8,6→ {tI11*} (9\6-11) —28→ cI2 (8)

Bi: hR2 (8+3) —2,54→ mC4 (5+4) —2,7→ {tI11*} (9\6-11) —8,8→ cI2 (8)

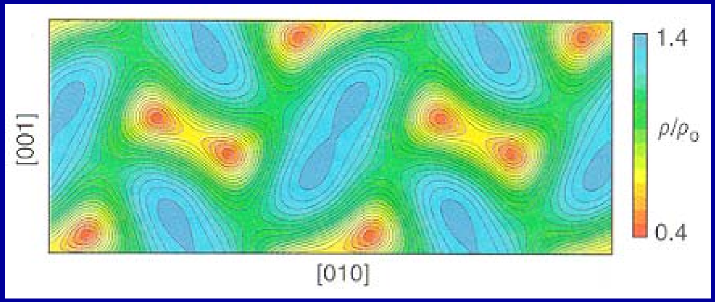
Solid state Li plasma AT HIGH PRESSURE

cI16 structure

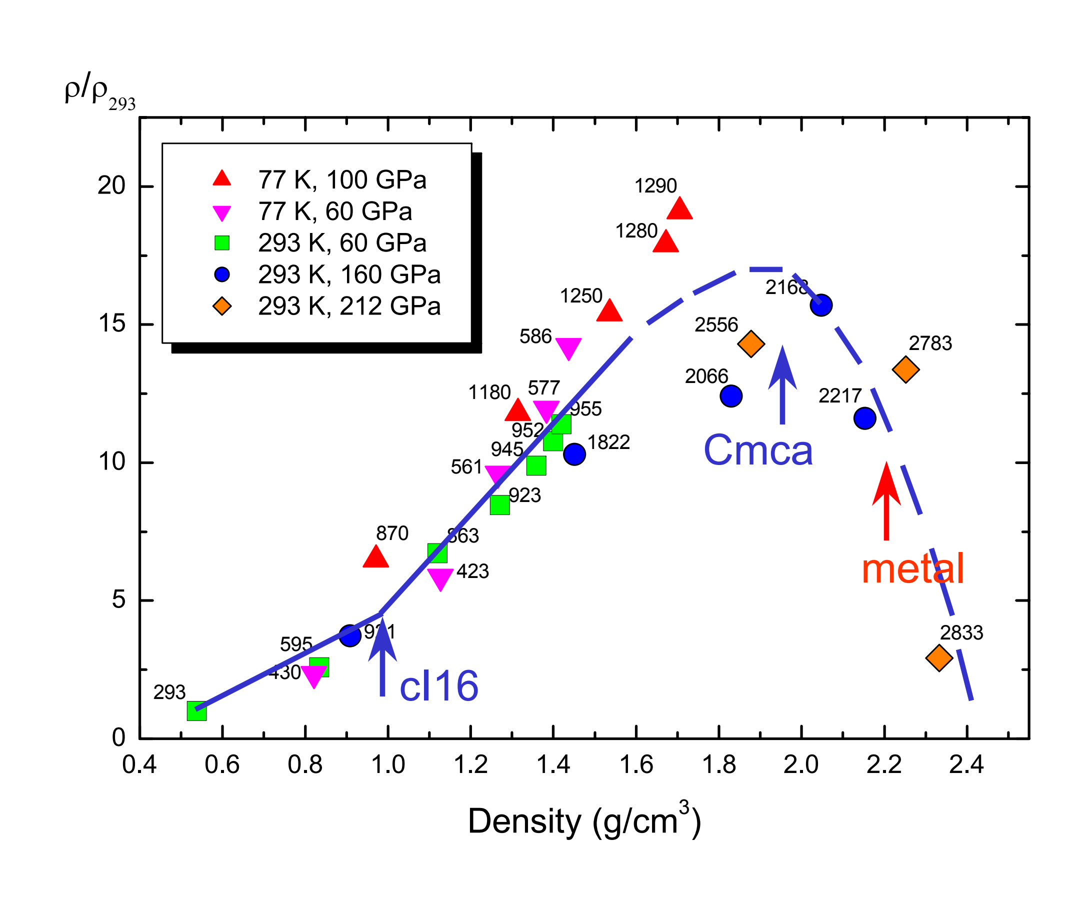


Hanfland et al.,
Nature, 408, 174, 2000

Cmca structure



J. Neaton, N. Ashcroft
Nature, 400, 141, 1999



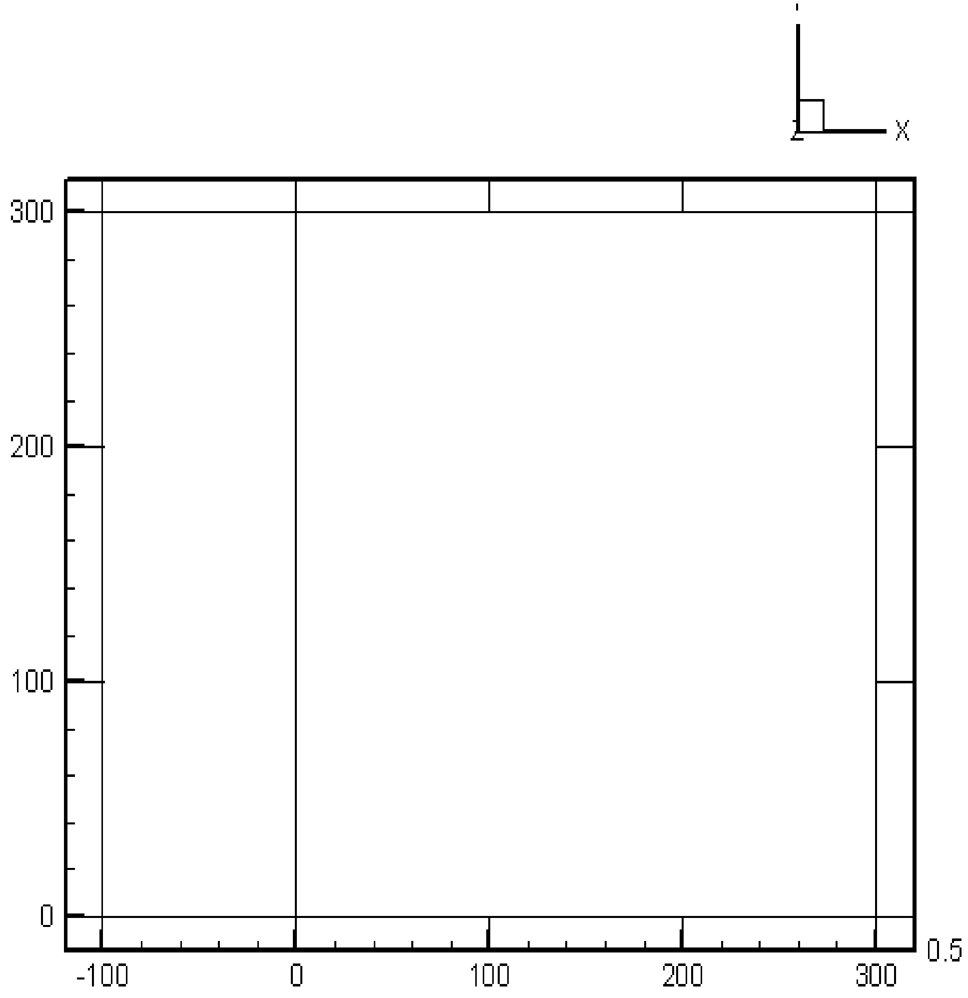
Fortov et al., 2001

bcc → 16GPa → fcc → 41GPa → hR1 → 48GPa → cI16 → 165GPa → Cmca

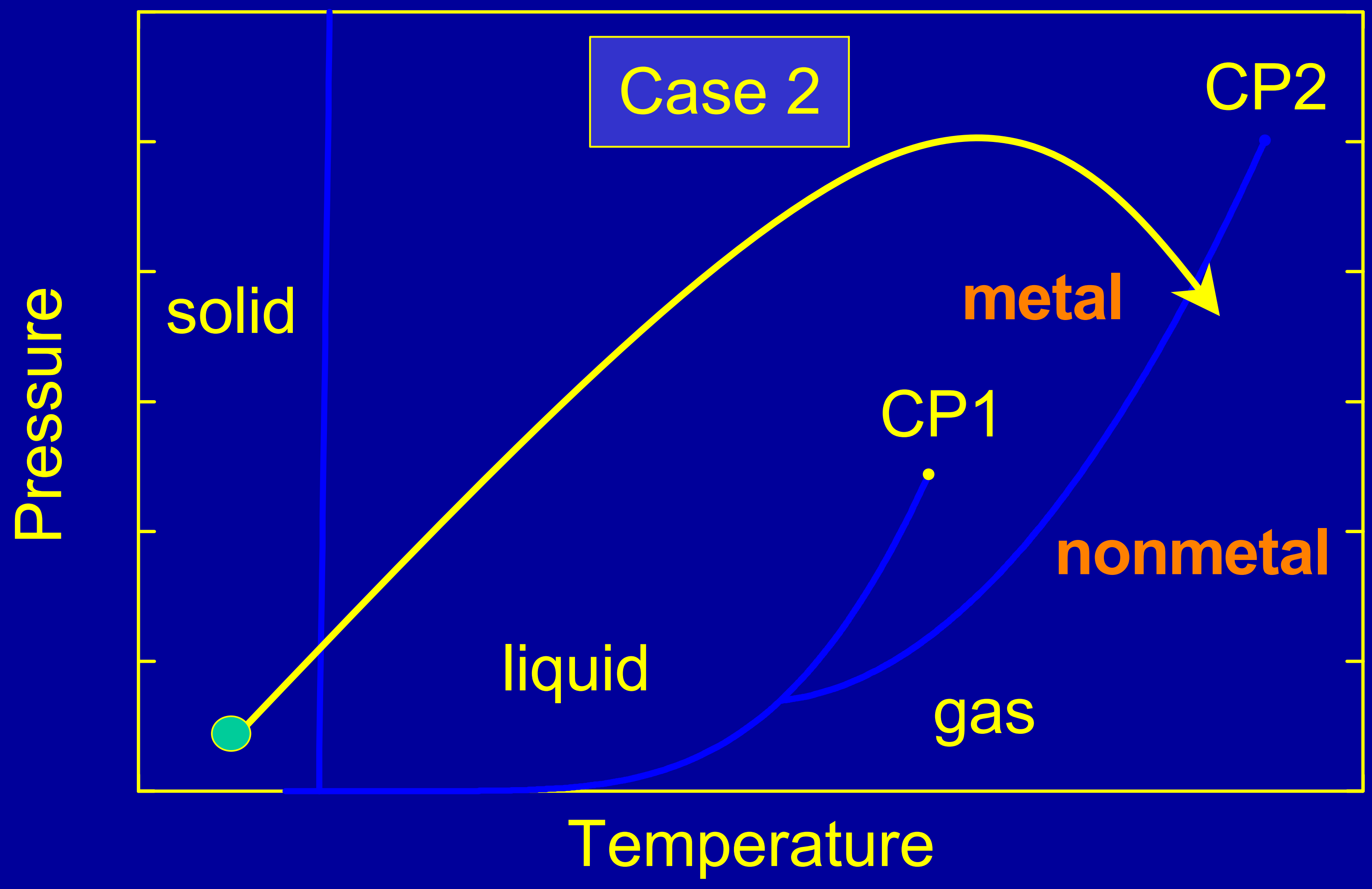
Hanfland et al., Nature, 408, 174, 2000

Акустическая неустойчивость замыкающей УВ в полной комбинированной волне

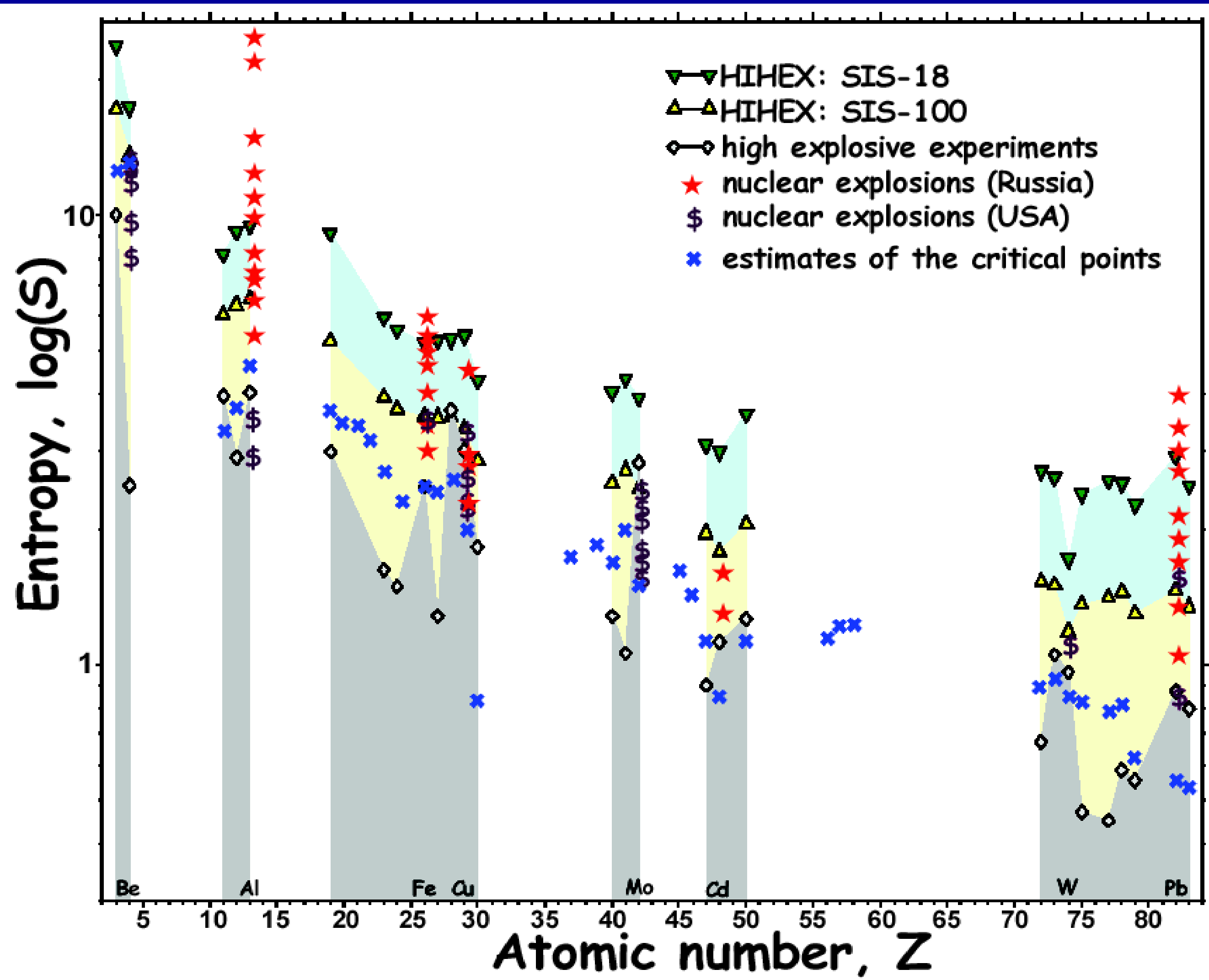
(модельное УРС, точечное возмущение скорости (1%) в потоке перед исходной УВ)



PHASE DIAGRAMS OF METAL PLASMA ACCORDING TO LANDAU AND ZEL'DOVICH (1943, ACTA PHYS. CHIM. USSR)

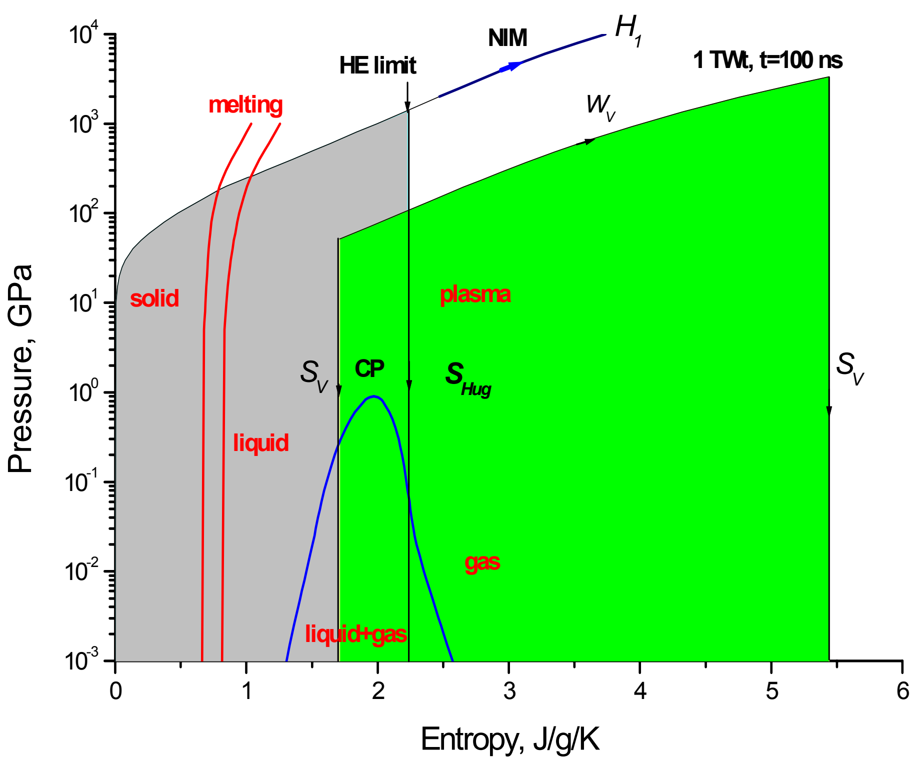


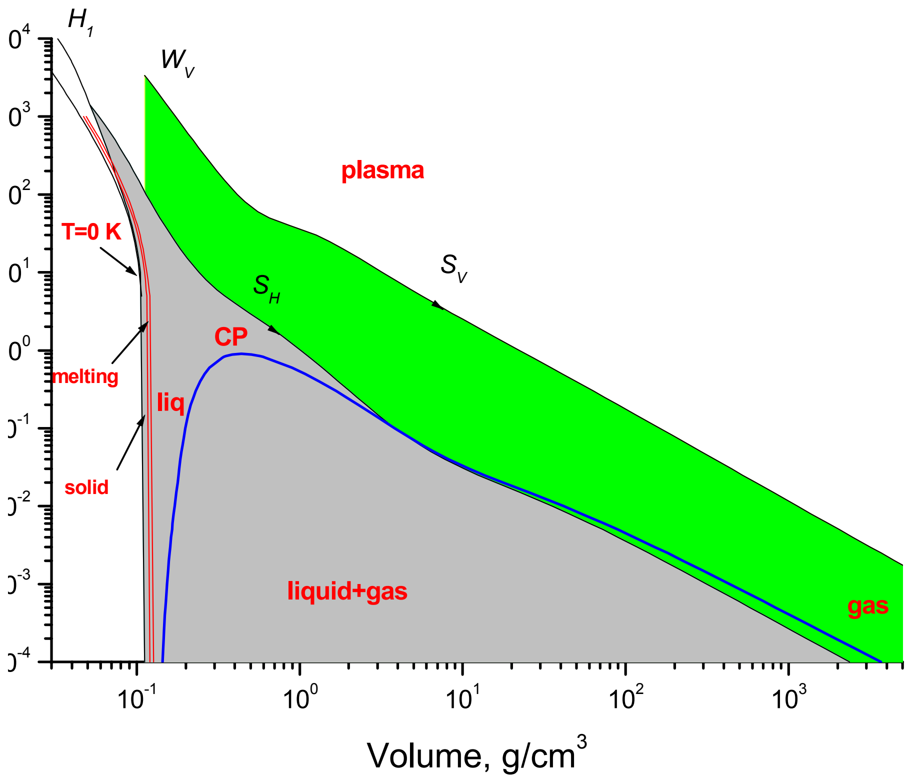
Entropy levels accessible by intense heavy-ion beams and other drivers for metals



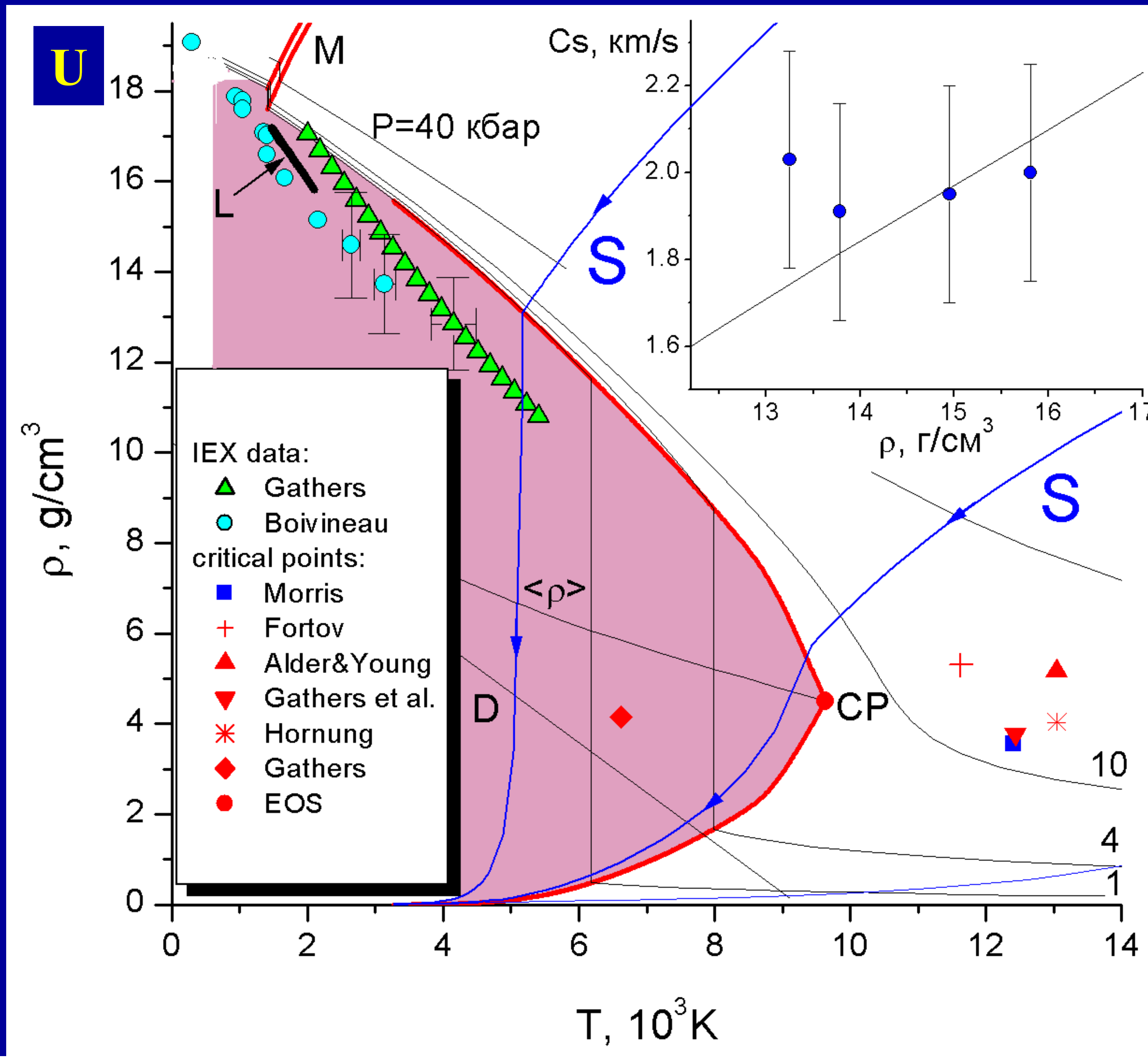
D.H.H. Hoffmann, V.E. Fortov et al. Phys. Plasmas 9 (2002) 3651.

HEAVY ION BEAM – COPPER PLASMA



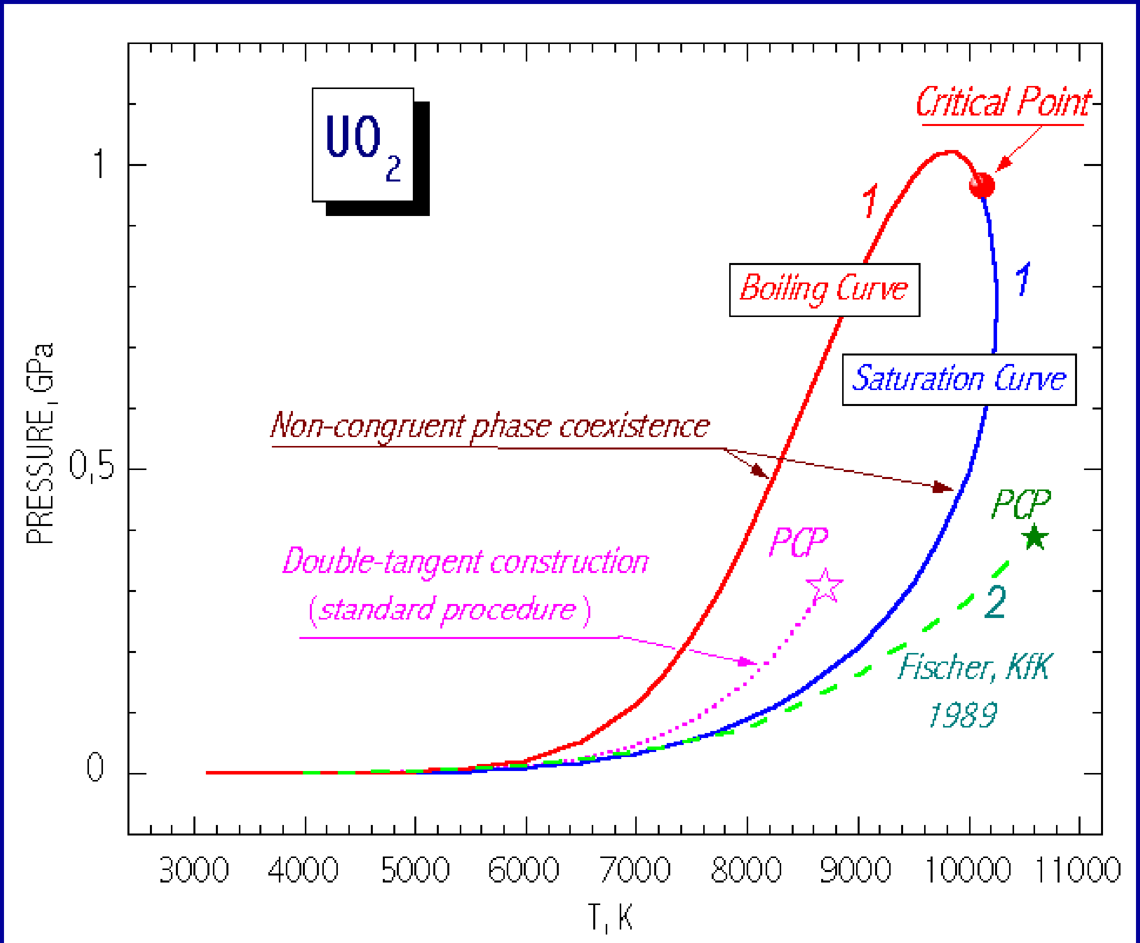


HIGH PRESSURE EVAPORATION



EQUATION OF STATE OF URANIUM DIOXIDE UP TO THE CRITICAL POINT

1 - Gas-liquid coexistence in PCE-mode (BC=SC)
BC - Boiling curve (total equilibrium(EOS "IN TAS-99")
SC - Saturation curve (total equilibrium(EOS "IN TAS-99")
2 - Total vapour pressure calculated by E.Fischer (KfK-1989)
PCP - Two pseudo-critical points: - that of E.Fischer and PCP presently calculated in PCE-mode
CP - Critical point (CP) presently calculated in total equilibrium



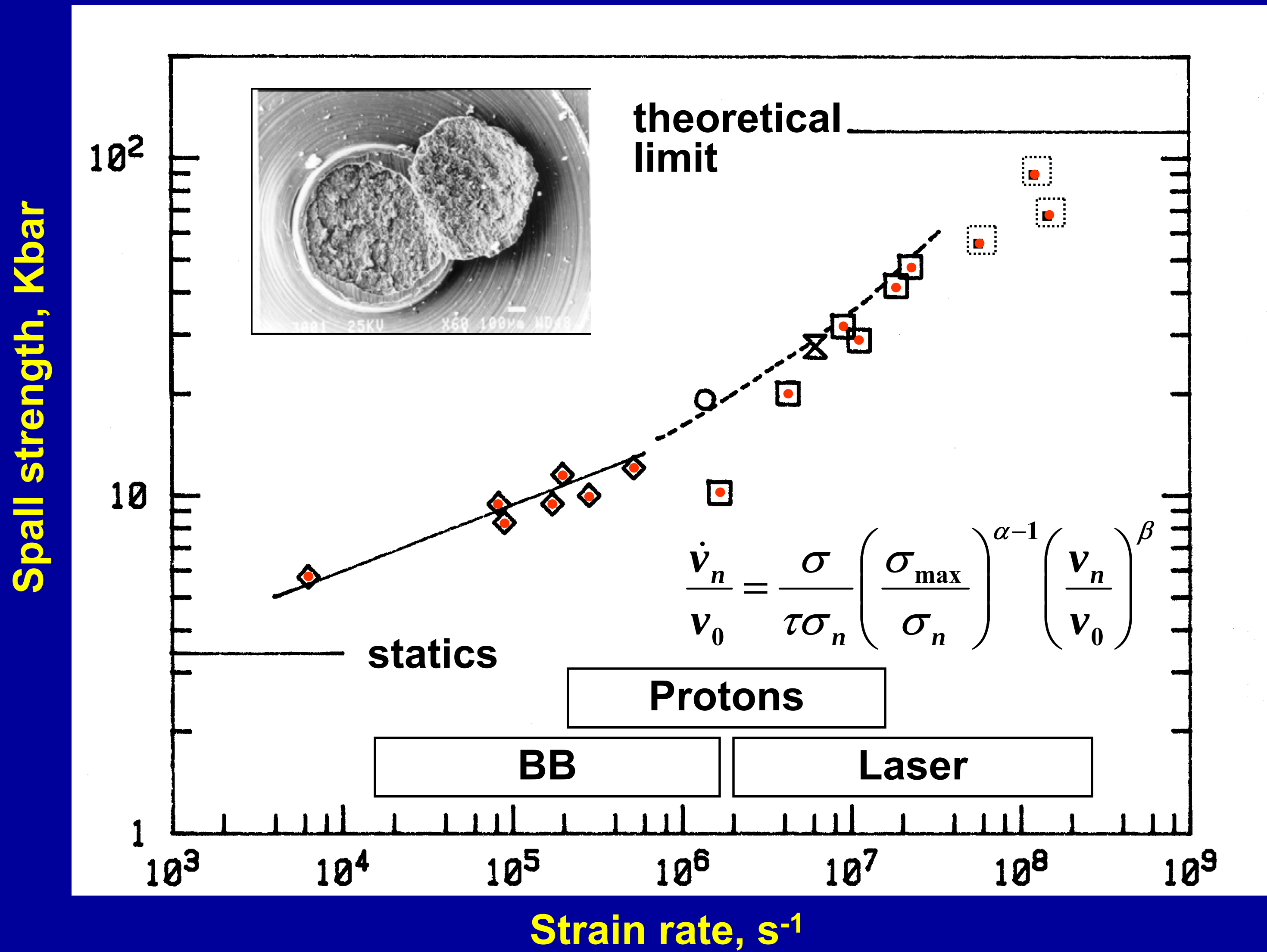
Фазовая P-T диаграмма неконгруэнтного испарения диоксида урана (UO2.0)

TIME-DEPENDENT PHENOMENA:
YIELDING, FRACTURE, POLYMORPHOUS TRANSFORMATIONS, AND CHEMICAL REACTIONS

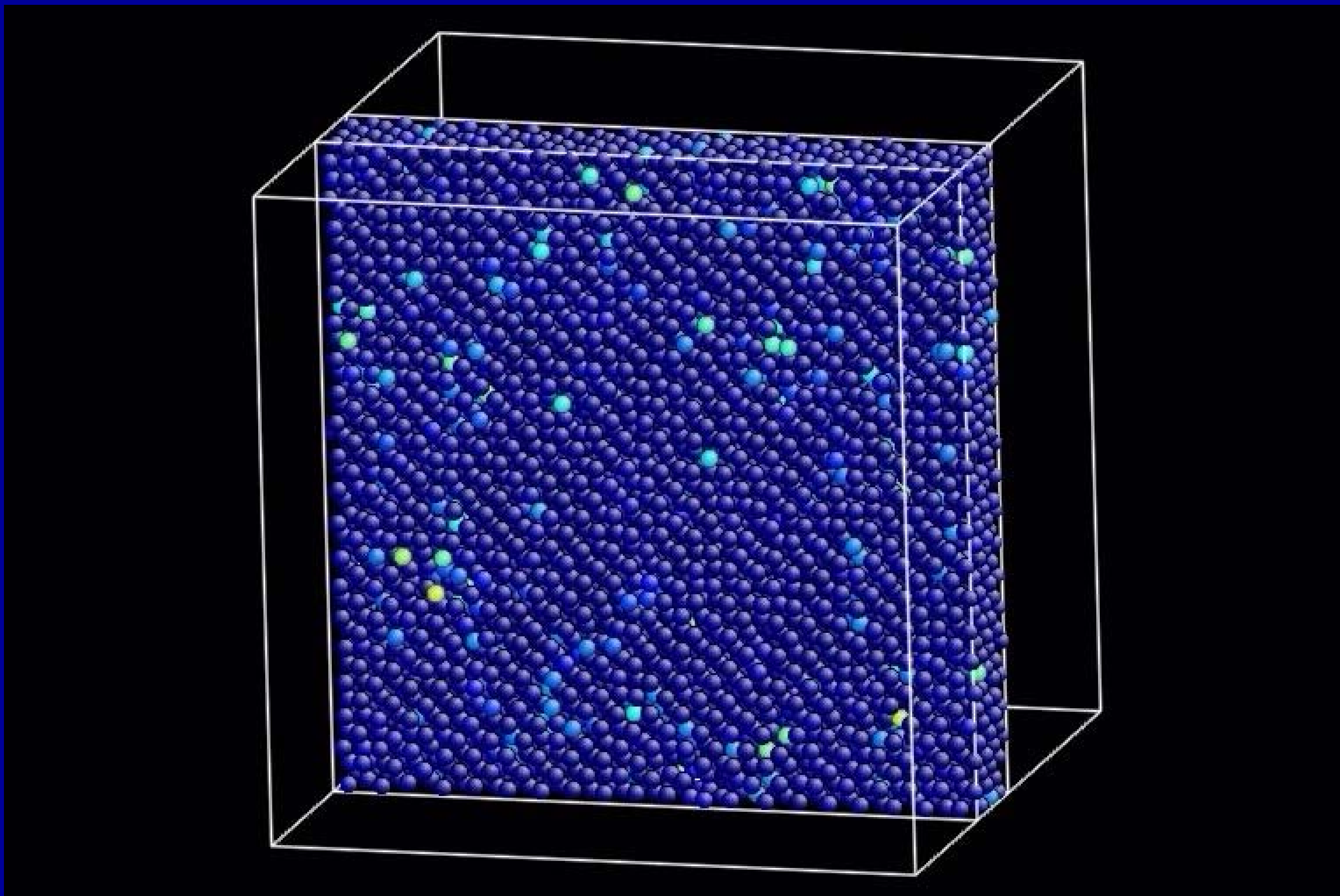
Goals:

- **Fundamental strength properties of a matter; approaching the ideal strength;**
- **Extremely rapid rearrangements of crystal structures and metastable (superheated) states;**
- **Catastrophic fractures under compression;**
- **Chemical-Detonation phenomena.**

APPROACHING THE ULTIMATE TENSILE STRENGTH, AMг6



РЕЛАКСАЦИЯ РАСТЯНУТОГО КРИСТАЛЛА



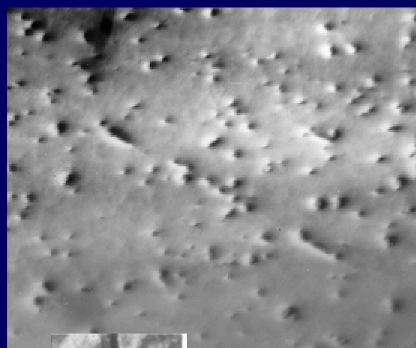
c = 0 (Параметр симметричности, c) c ≥ 0.5

Г.ц.к. решетка — Аморфная структура

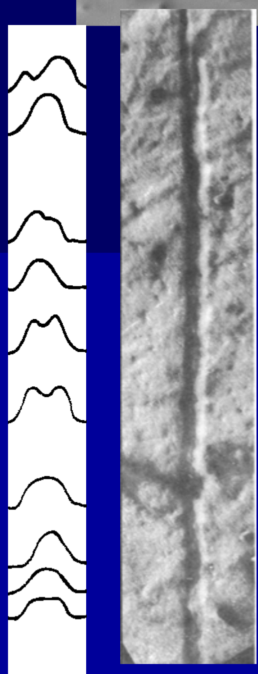
FROM FISSION ENERGY TO THERMAL ENERGY:

1 µm

Foil thickness

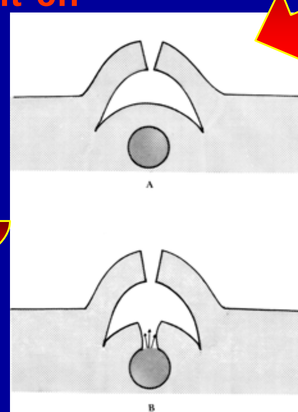


Surface track (REM)

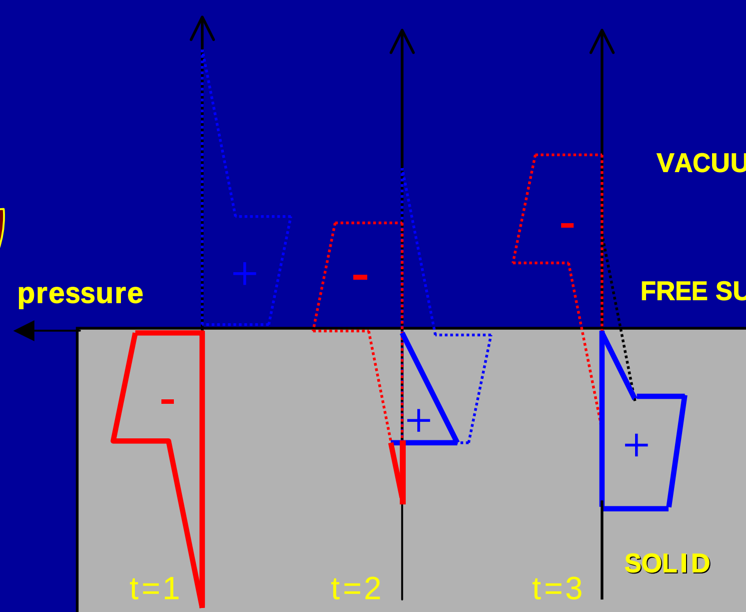


30 nm

Split-off

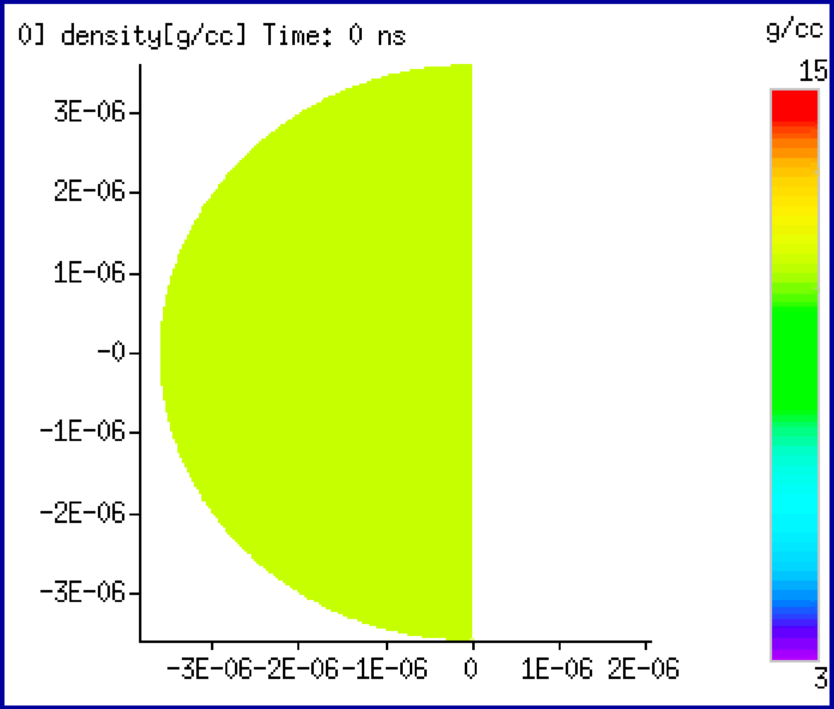


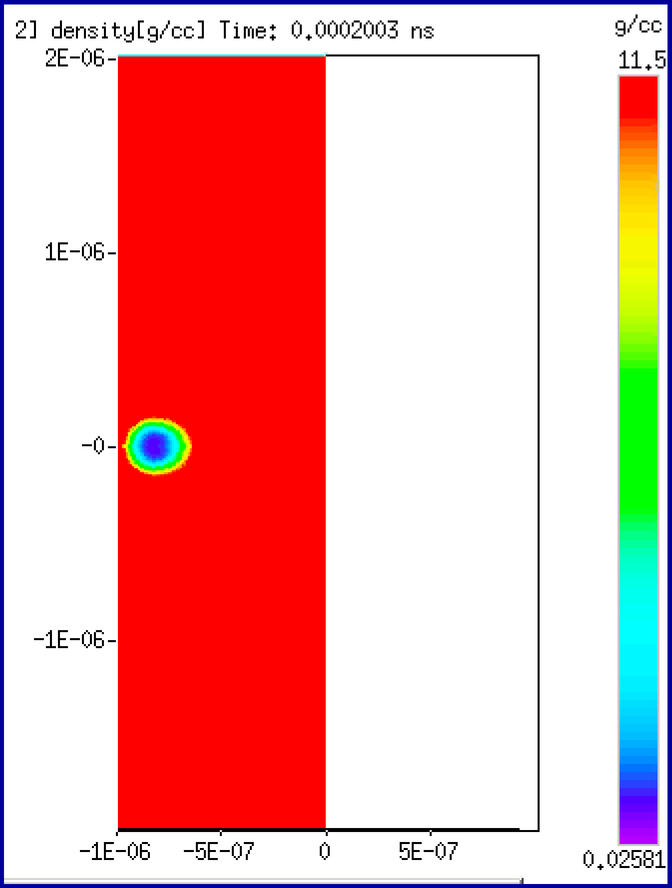
Relaxation of a fission spike: shock-wave and surface-track formation in uranium dioxide



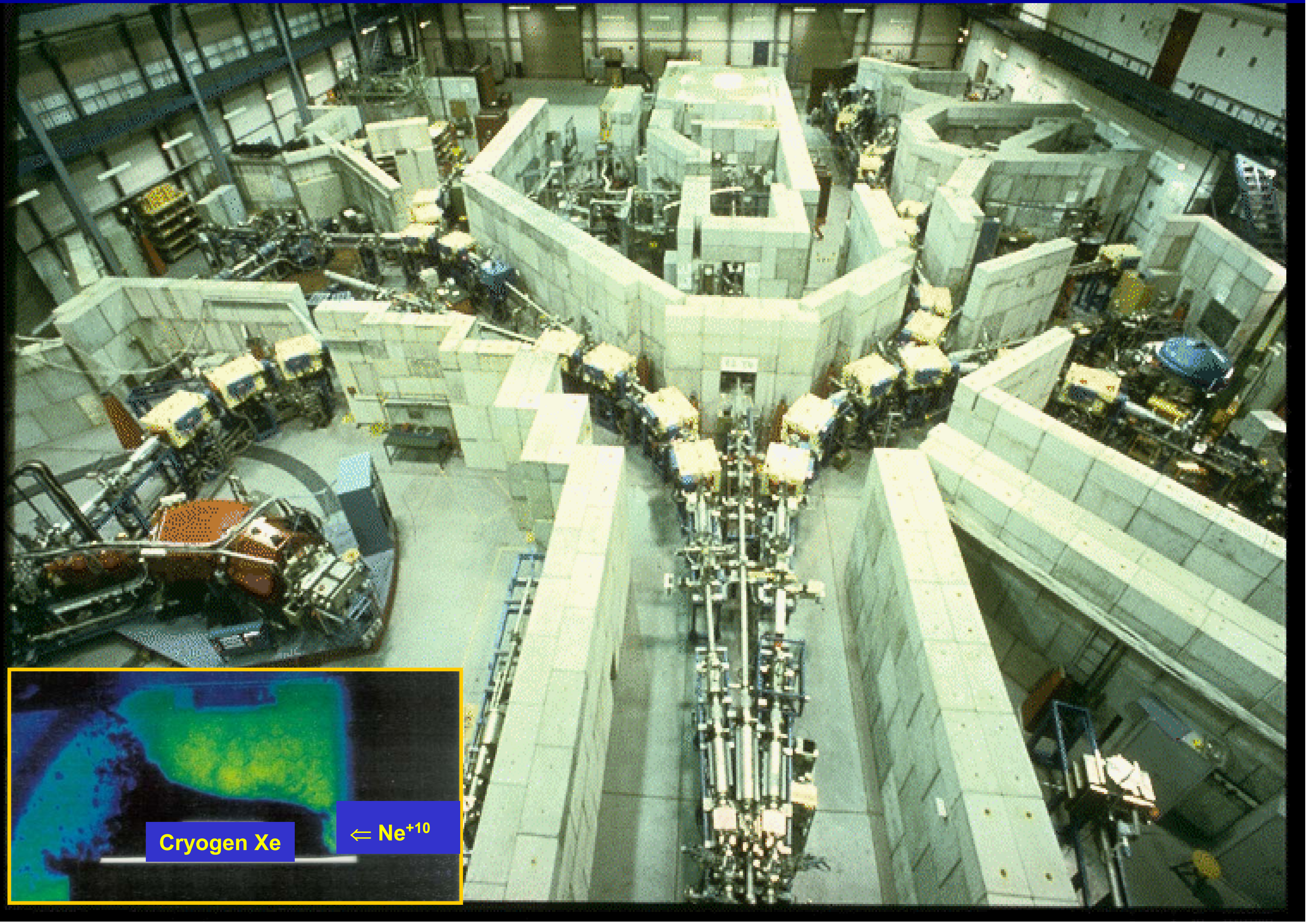
EUROPEAN COMMISSION, ITU Karlsruhe

ОБРАЗОВАНИЕ ТРЕКА, БЕЗ УЧЕТА ТЕПЛОПРОВОДНОСТИ

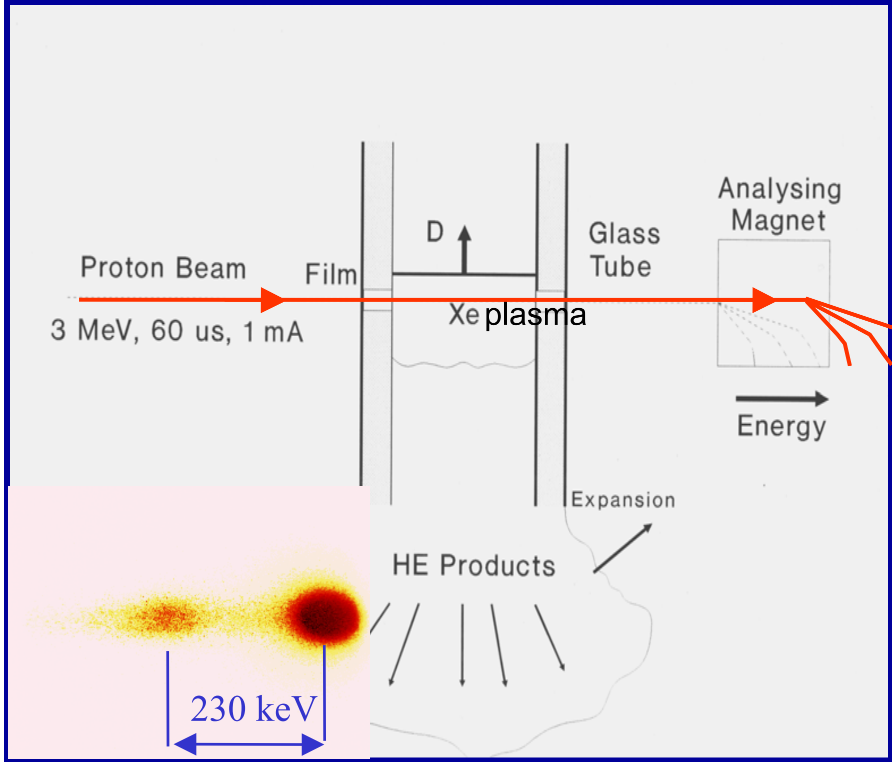


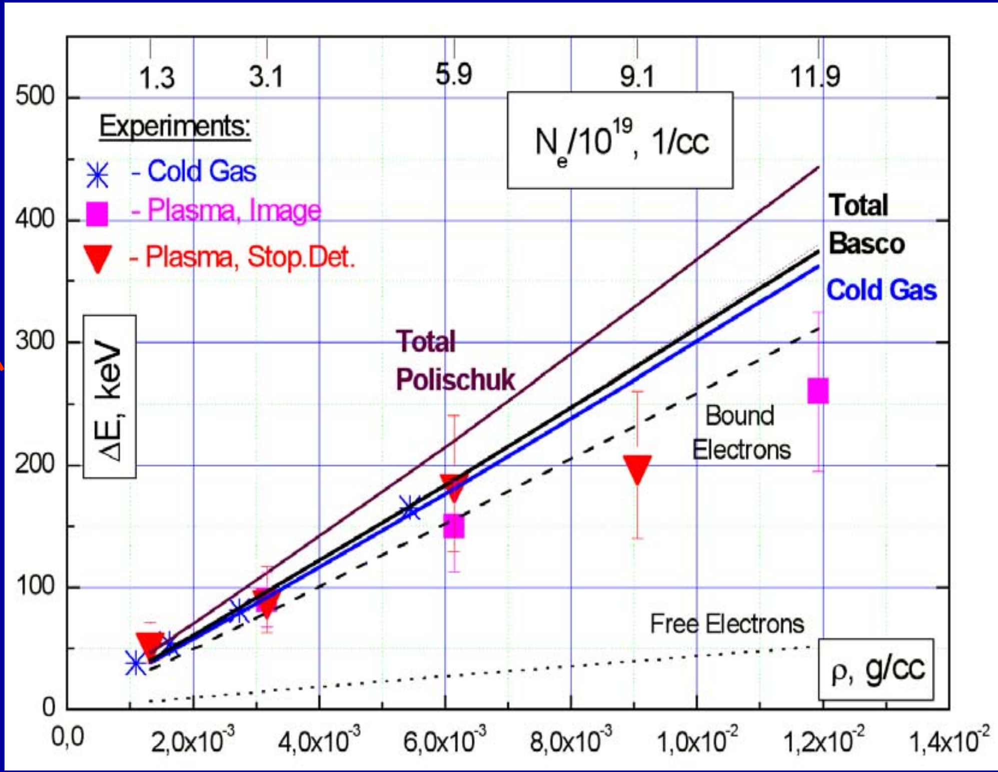


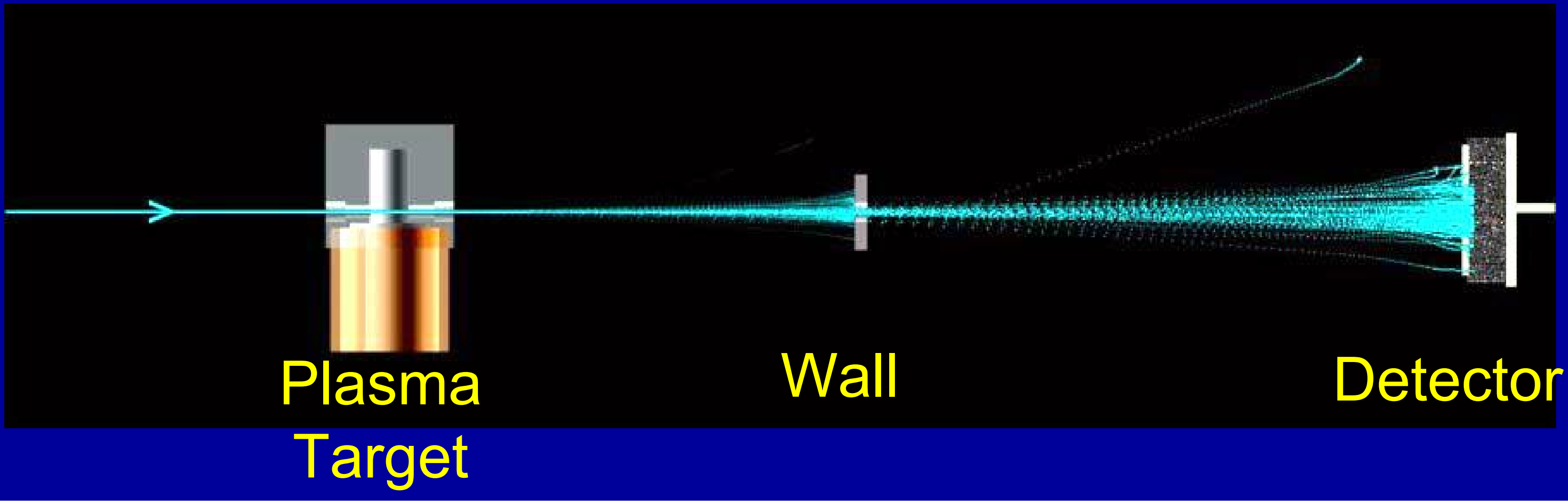
GSI,Relativistic Ion Beam-Plasma Interaction at 4 GeV



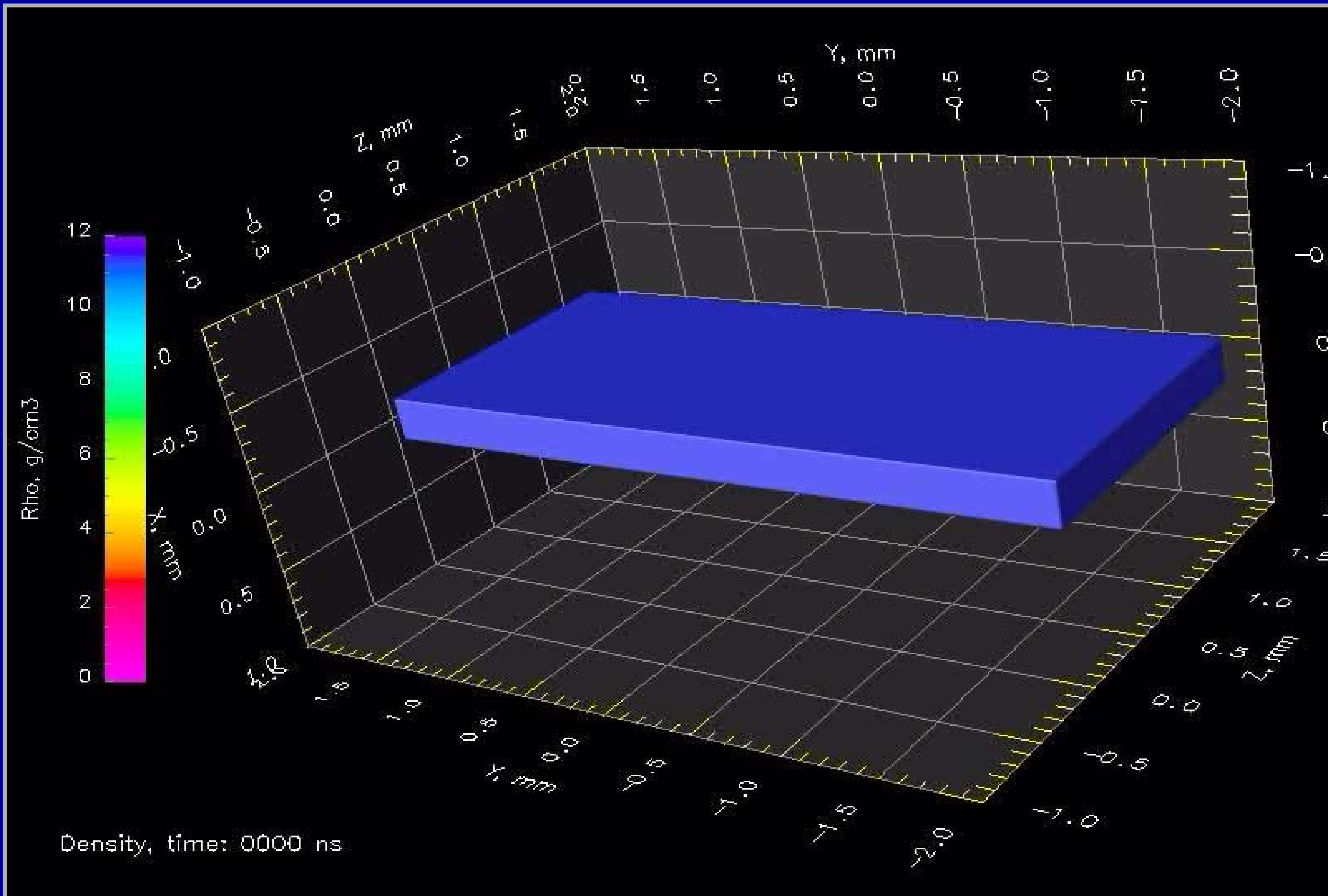
PROTON STOPPING POWER IN Xe PLASMA







Heavy ion beam & target: 3D simulation



0.25 mm Pb foil, Beam :U^{28+} $4x10^9$ 500 MeV/u FWHM=1.5 mm 250 ns

Collaborators

Gesellschaft für Schwerionenforshung (GSI) – Darmstadt, Germany

Technische Universität (TU) – Darmstadt, Germany

Universität Frankfurt - Germany

Institute of High Energy Density RAS – Moscow, Russia

Institute of Problems of Chem. Physics RAS – Chernogolovka, Russia

Institute of Theoretical and Experimental Physics – Moscow, Russia

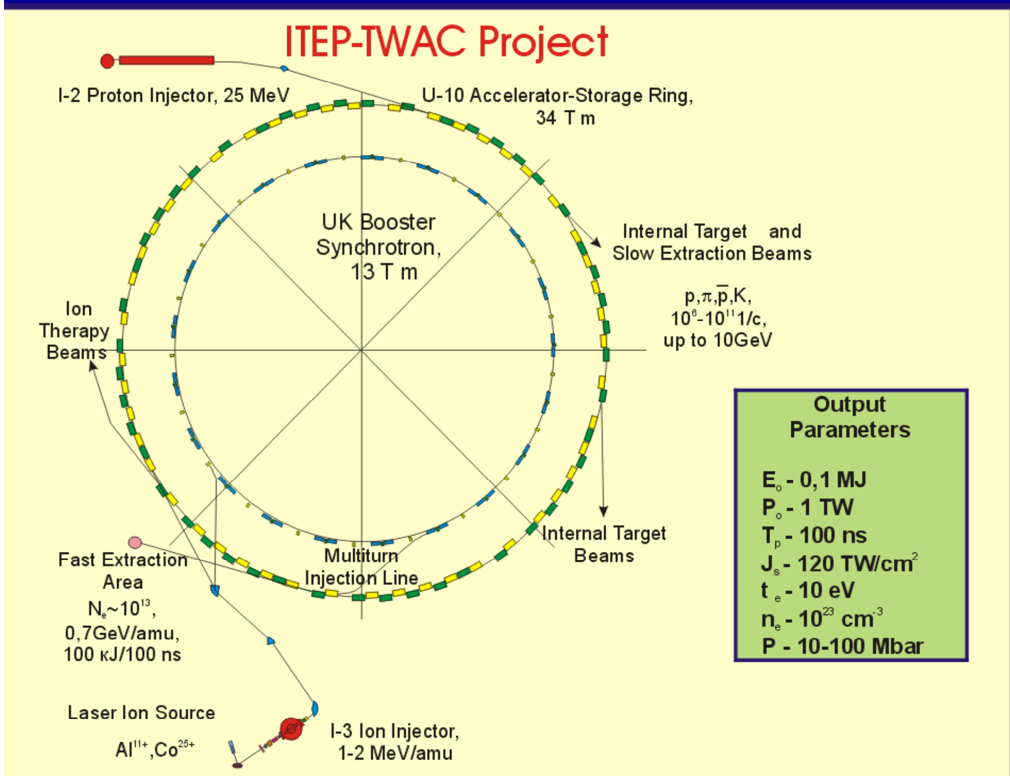
University of Castilla-La Mancha (UCLM) – Ciudad Real, Spain

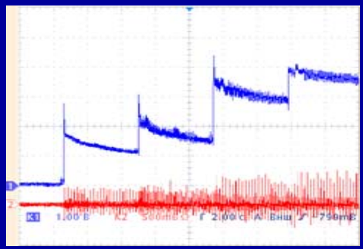
LPGP - Orsay, France

Polytechnical University of Valencia - Spain

University of Rostock - Germany

ITEP-TWAC PROJECT IN PROGRESS





- $>10^{10}$ C6+ accumulated
- accelerated up to 4 GeV/u

- Ion **accumulation mode** - 300-700 MeV/u and 10^{12} – 10^{13} particles per ~100 ns pulse;

- Ion **acceleration mode** - up to 4.3 GeV/u and up to 10^{11} particles/s;

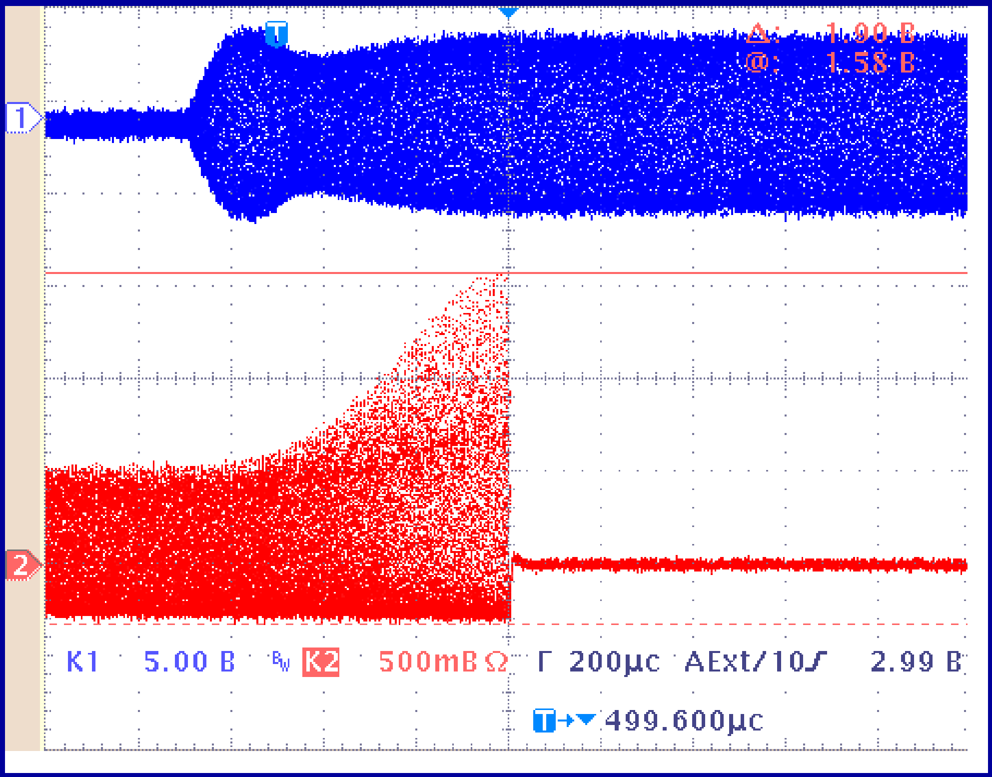
- **Medical application** mode - ~ 250 MeV/u, 10^{9} - 10^{10} particles/s C^{6+}.

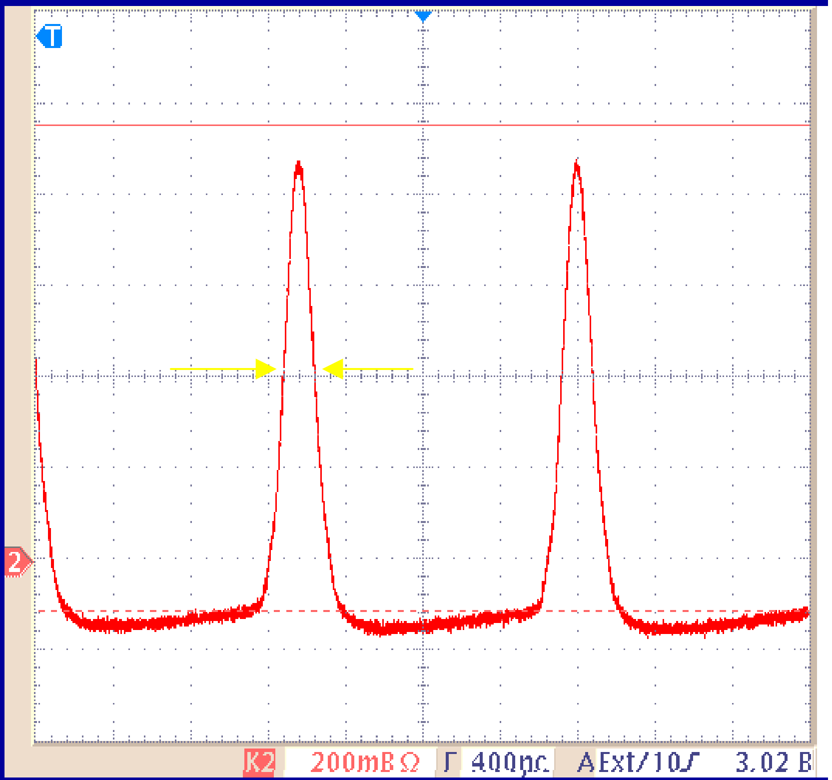
27.05.03

RF pulse compression for C6+
213 MeV/u

(fo = 695 кHz, 10 кV) ITEP

170 ns FWHA

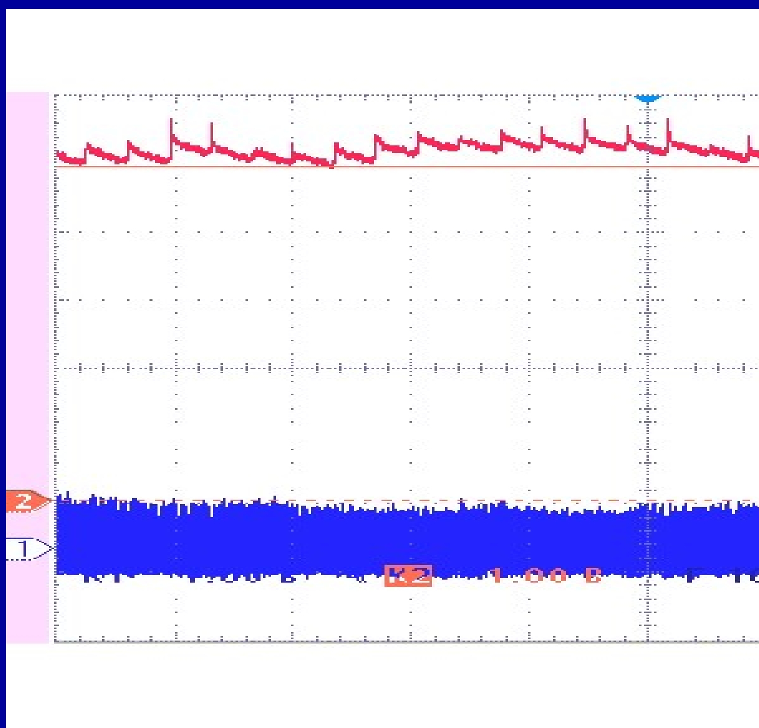




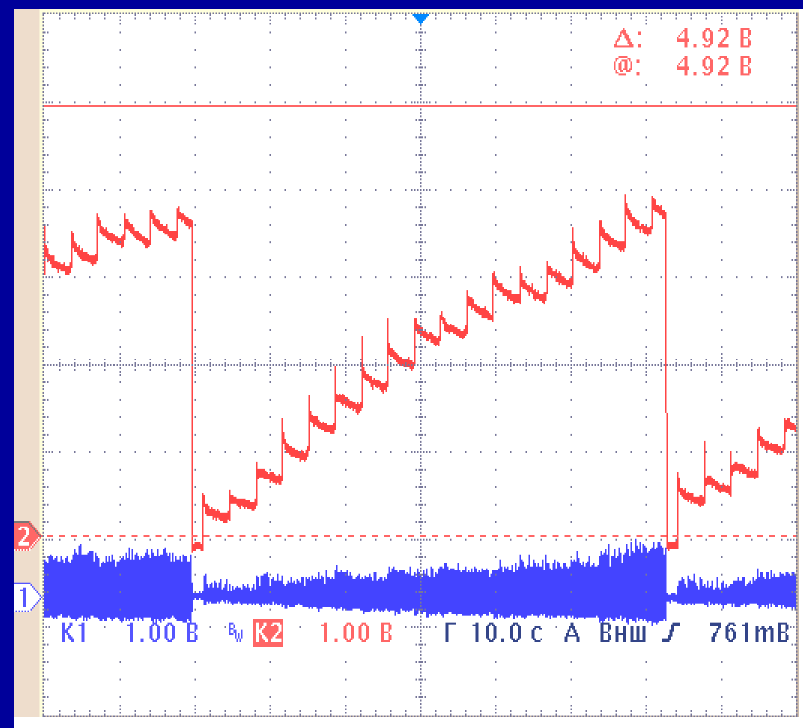
B.Sharkov ITEP

RECENT PROGRESS IN BEAM INTENSITY

Accumulation of 200 MeV/n C6+ ion in U-10 ring

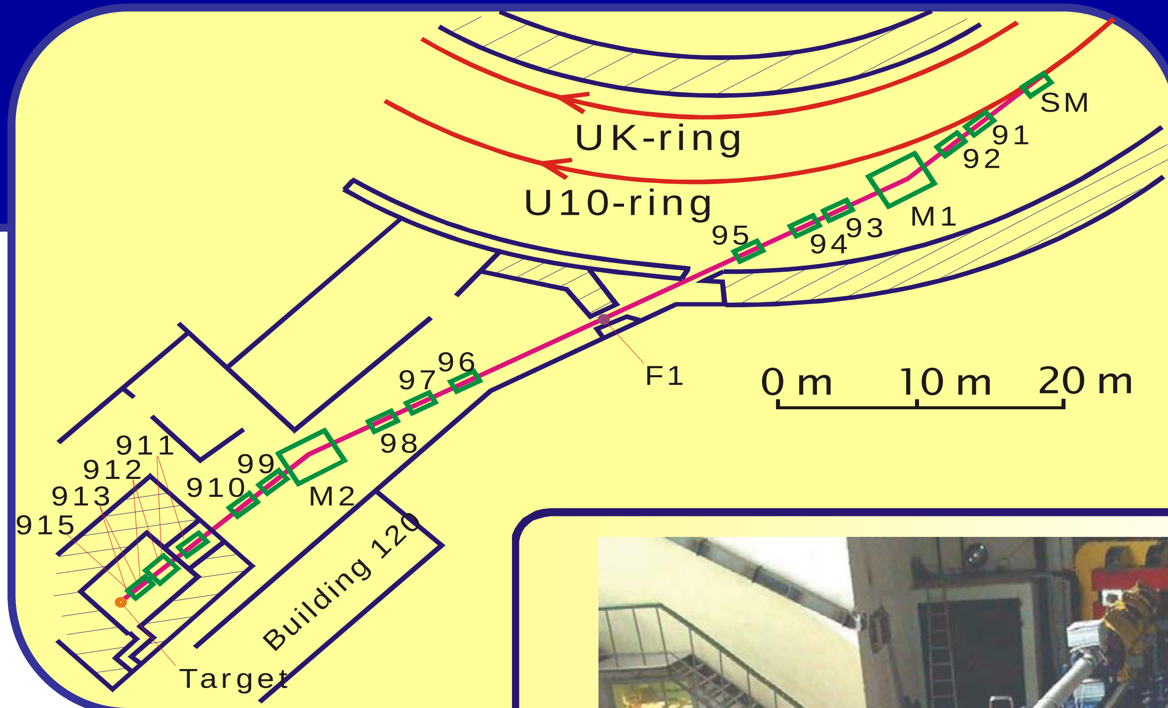


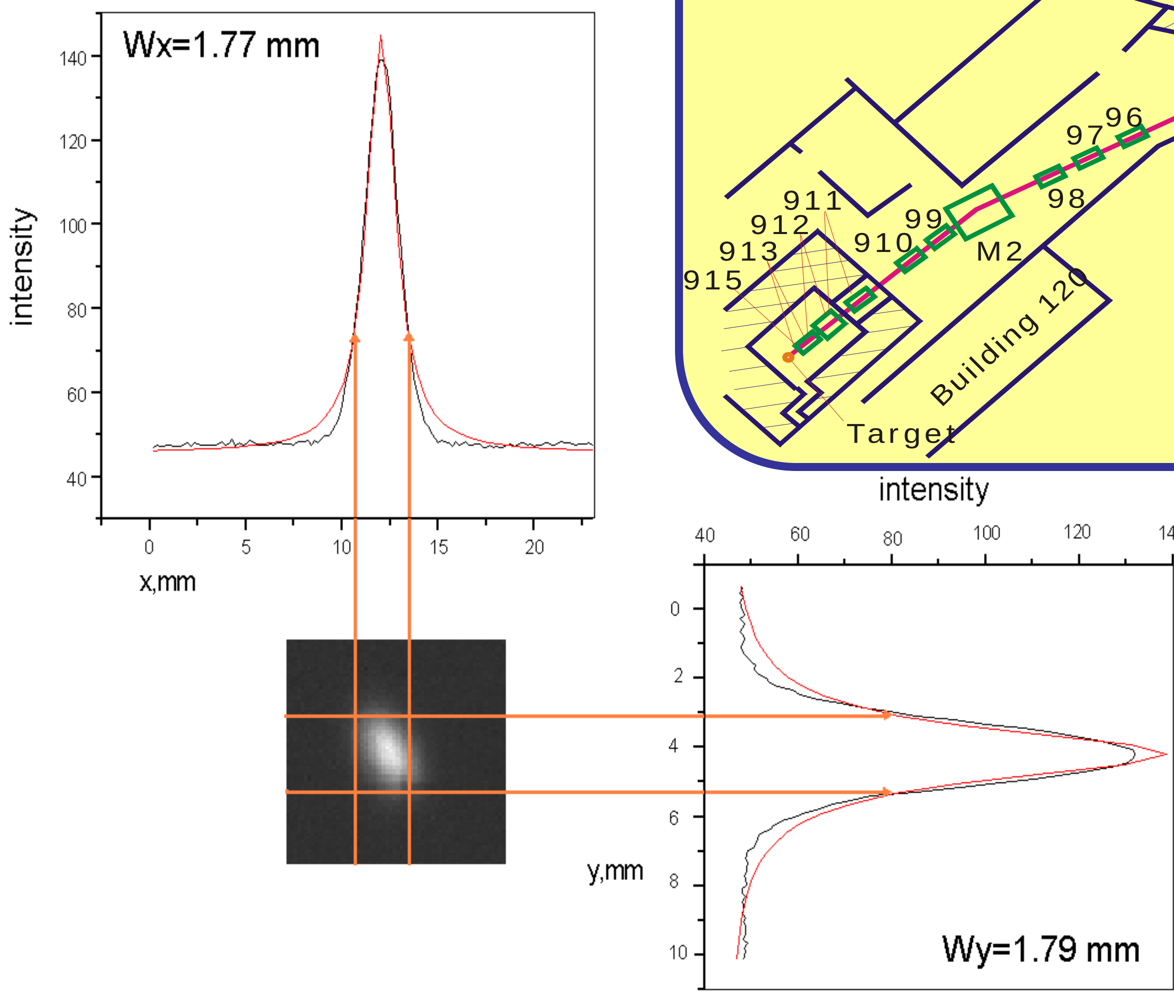
Fast extraction of accumulated beam



High energy density experimental area

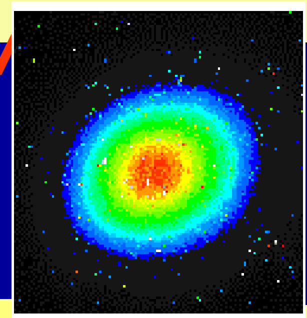
ITEP-TWAC



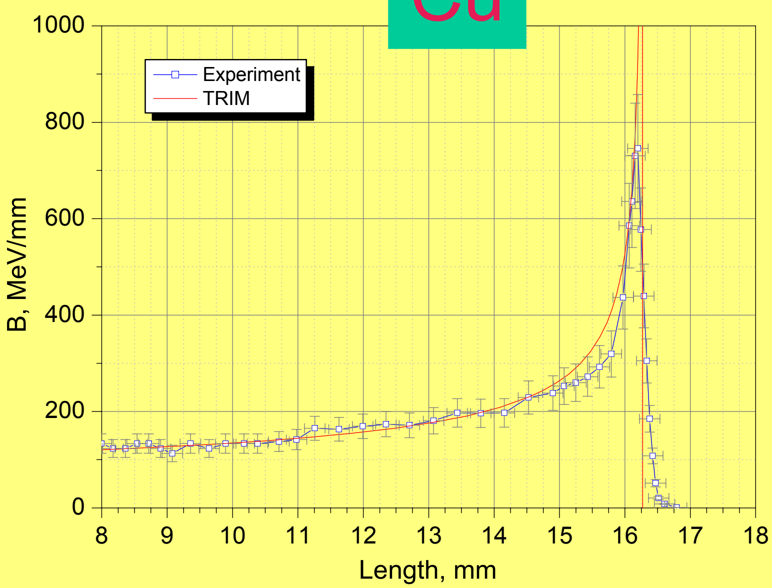


Energy Deposition profile Measurements

$_{12}C$ 6+, 214 M **ITEP-TWAC**



Cu



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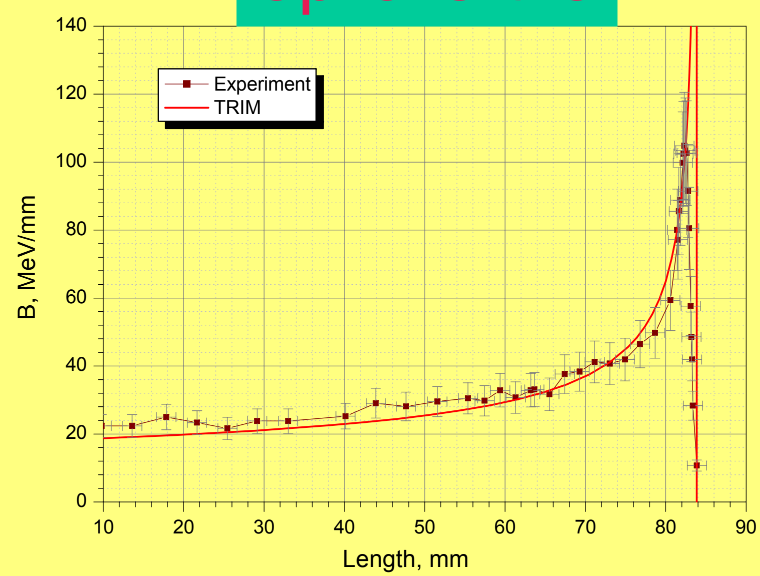

B.Sharkov ITEP

Thank You....!