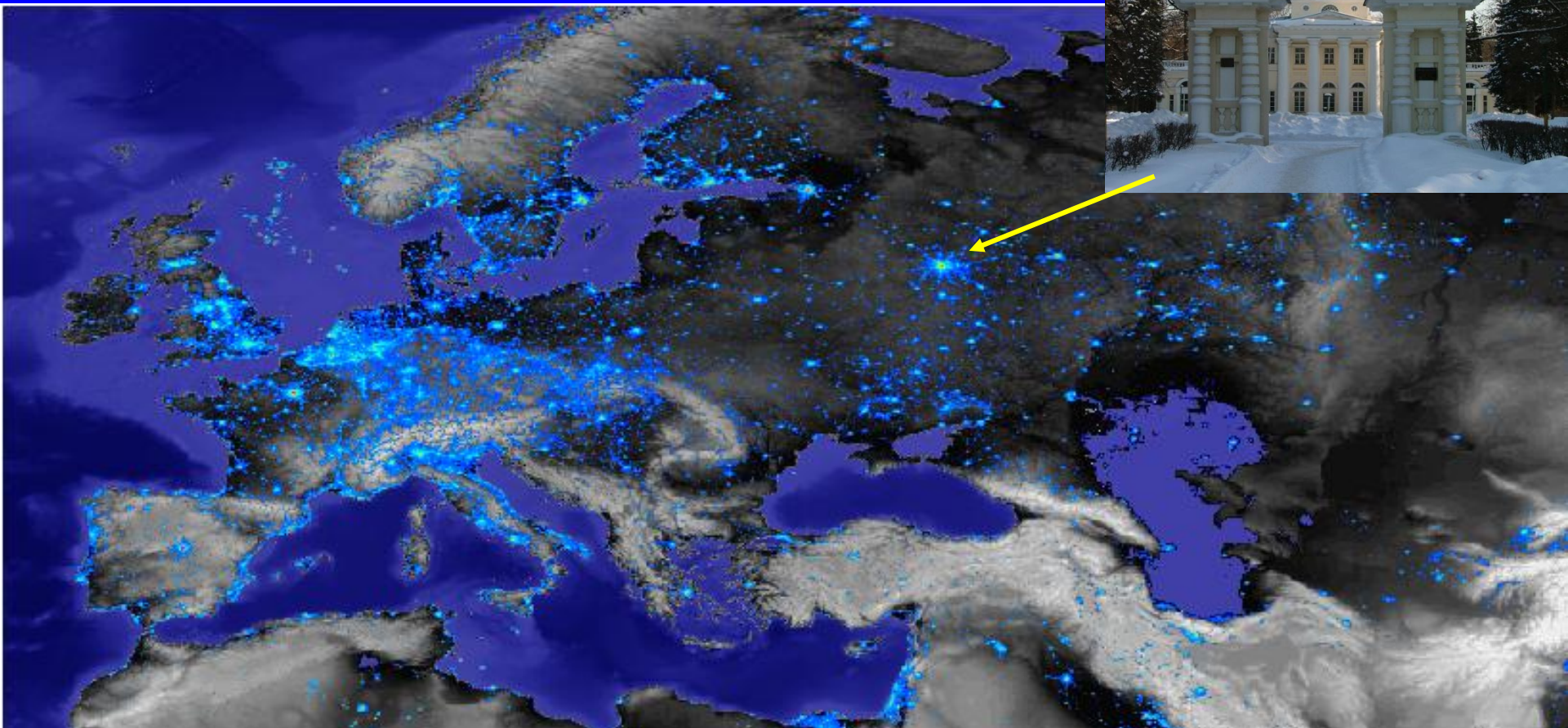
Intense Heavy Ion Beams for Research into Extreme State of Matter

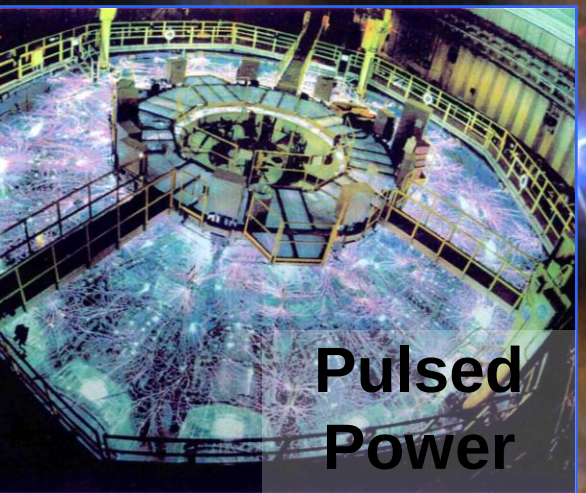
Boris Sharkov
ITEP-Moscow



EXTREME STATES OF MATTER

98% of VISIBLE MATTER

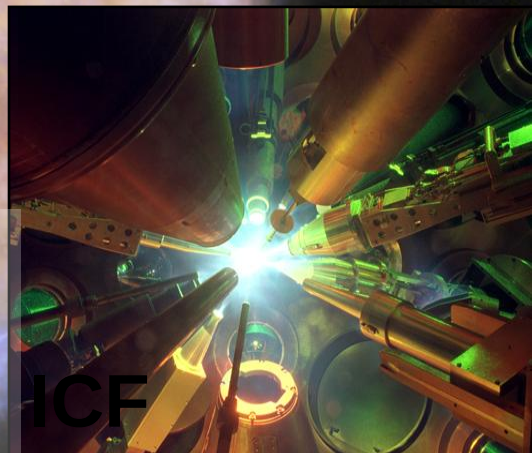
SUPERNOVA EXPLOSION



Pulsed Power

"Today we understand all the physical processes in the Universe, except extreme ones."

S.Hawking, A Briefer History of Time

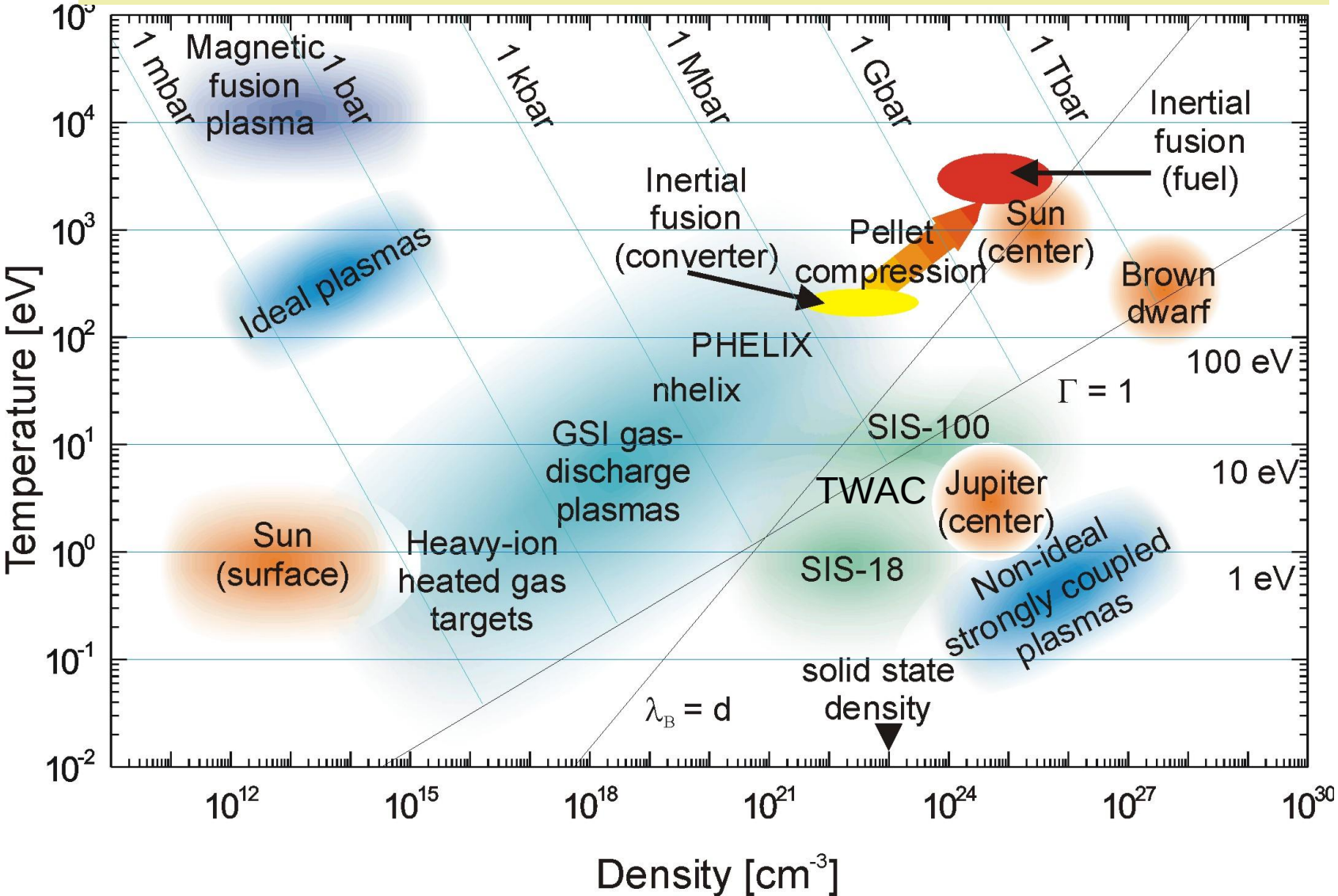


ICF

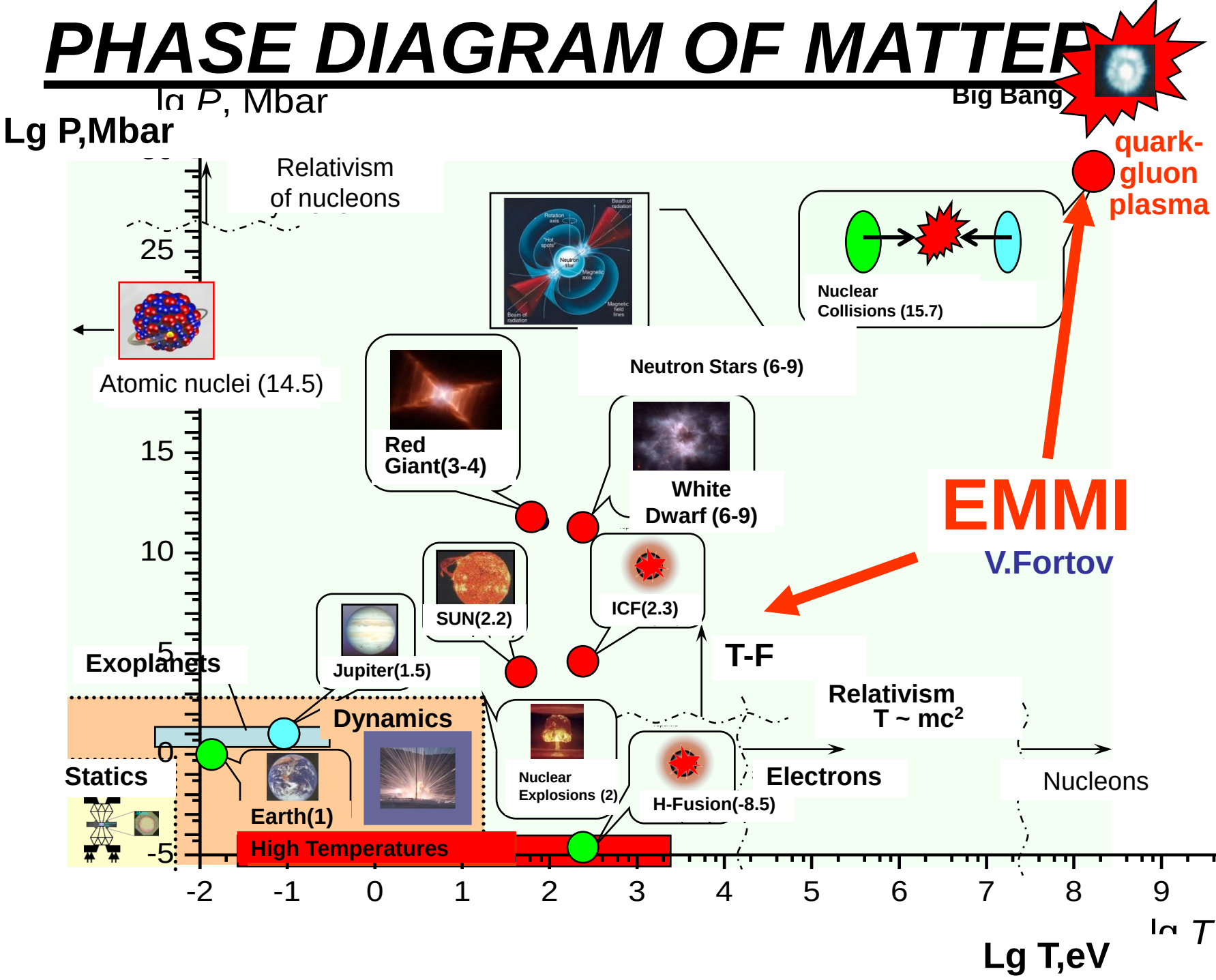
HED - ESM

- Astrophysics
- Planetary physics
- IC Fusion
- MHD, FC Generators
- Plasma processing
- Microelectronics Tech.
- Metals, semiconductors
- Beam-matter interactions
- Hypervelocity impact
- Electrical, high explosion
- etc.

The collective interaction of the matter with itself, particle beams, and radiation fields is a rich, expanding field of physics called high energy density physics. It is a field characterized by *extreme states* of matter previously unattainable in laboratory experiments



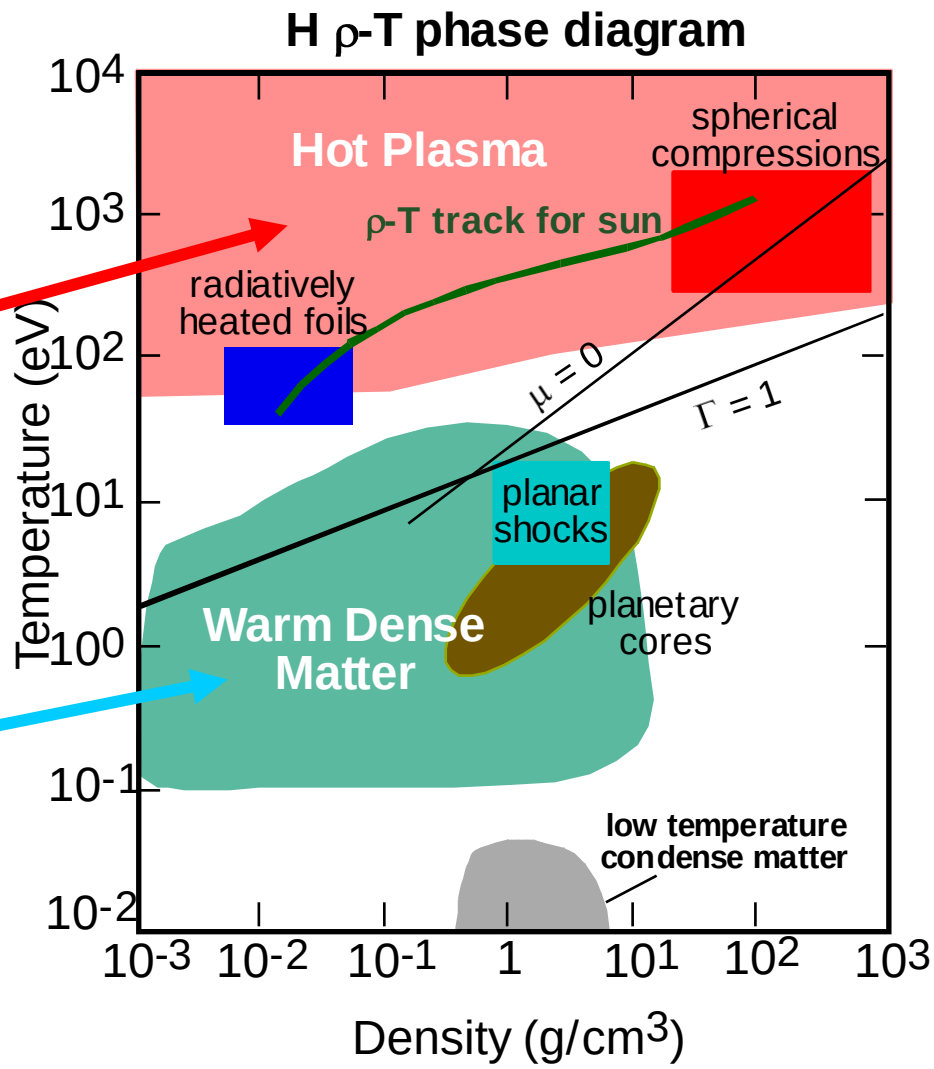
PHASE DIAGRAM OF MATTER



HEDP is defined as an energy density of 10^5 J/cm^3 that is equivalent to a pressure of 1 Mbar*

High Energy Density matter is interesting because it occurs frequently in Nature

- **Hot Dense Matter (HDM) occurs in:**
  - Supernova, stellar interiors, accretion disks
  - Plasma devices: laser produced plasmas, Z-pinches, i-beams
  - Directly driven inertial fusion plasma
- **Warm Dense Matter (WDM) occurs in:**
  - Cores of large planets
  - Systems that start solid and end as a plasma
  - X-ray driven inertial fusion implosion

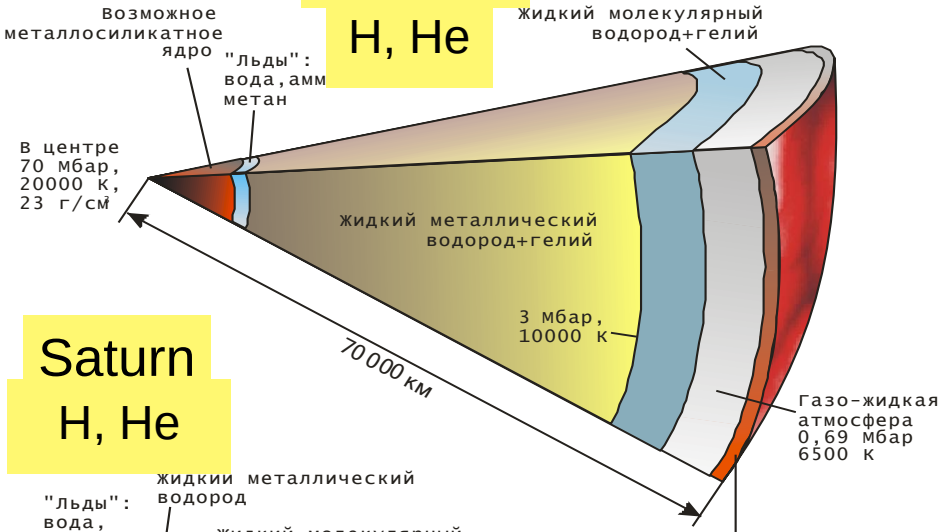


ASTROPHYSICAL APPLICATIONS

Население Солнечной системы

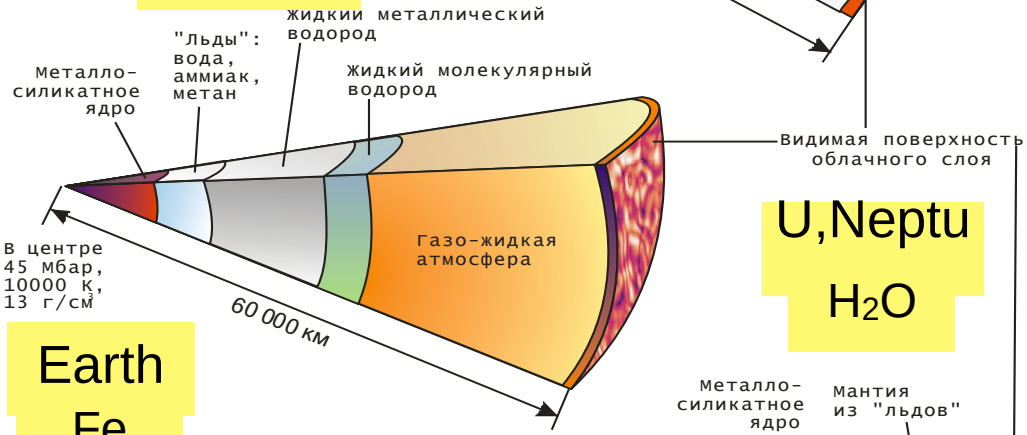
Jupiter

H, He



Saturn

H, He

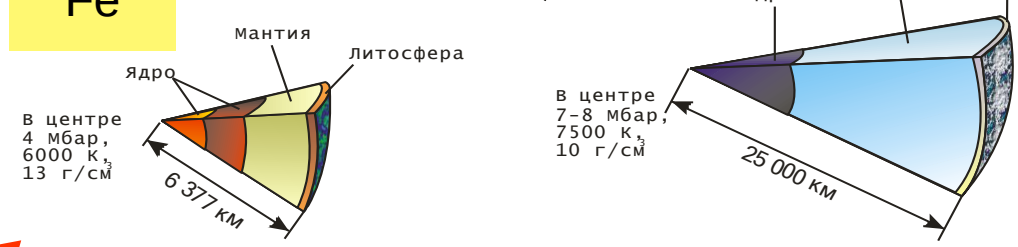


U,Neptu

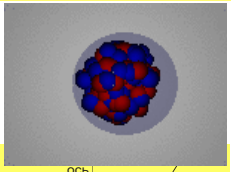
H_2O

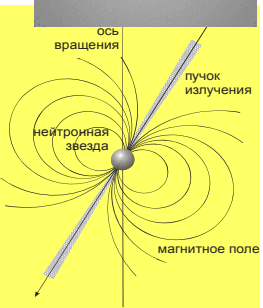
Earth

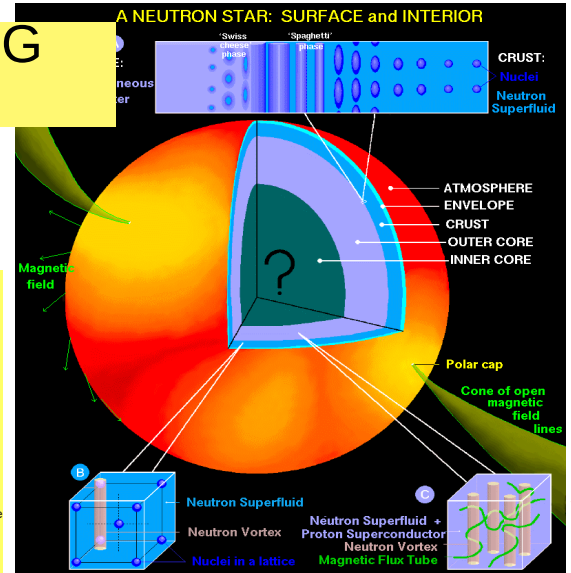
Fe



Neutron-QG Stars





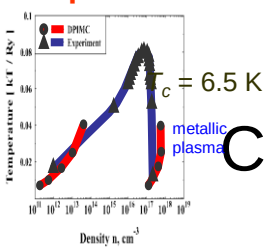


10^8-10^{11} K, 10^{14}-5.10^{15} g/cc, 10^{25}-10^{27} Bar

PHASE STATES OF MATTER

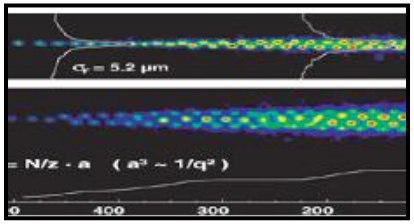
- Quark-gluon plasma
- Plasma
- Gas
- Liquid
- Crystal

e-h plasma

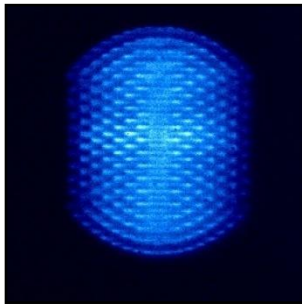


- Non-ideal plasma
- «Liquid» plasma
- «Crystalline» plasma

CRISTALLINE BEAMS

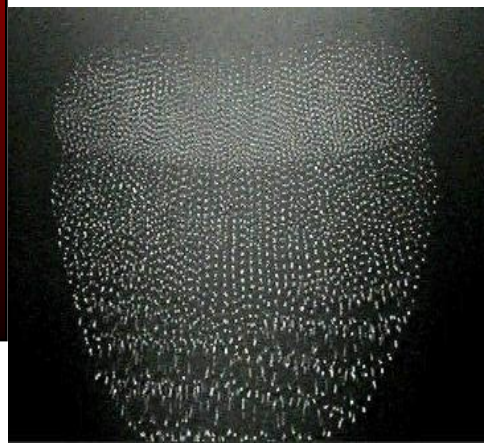


NONNEUTRAL PLASMA



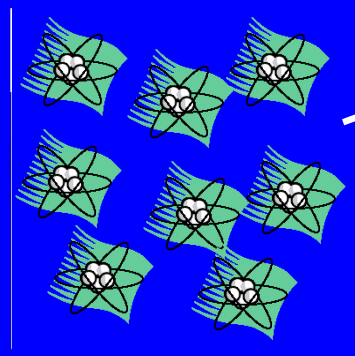
rise temperature, disorder, entropy

DUSTY PLASMA CRYSTAL



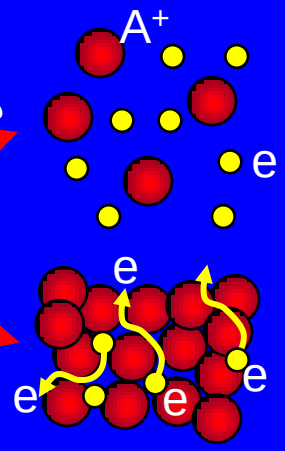
Compress matter to form new states

ATOM

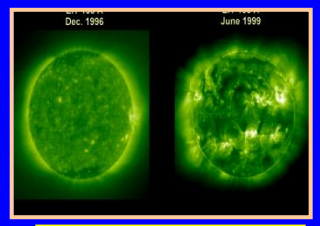


$T > Ry = e^2/a_b$

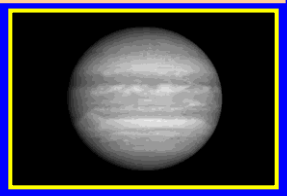
$P > e^2/a_b^4$



PLASMA

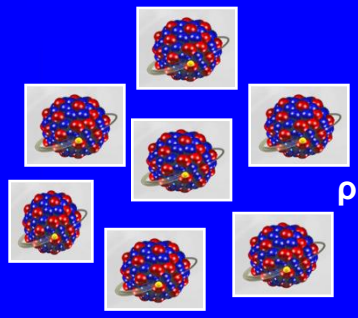


Sun

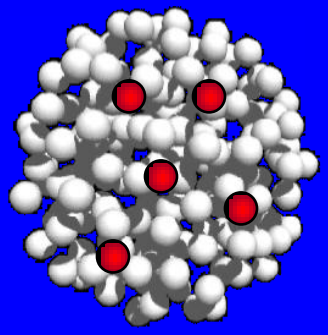


Jupiter

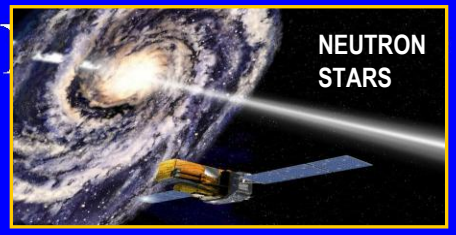
NUCLEI



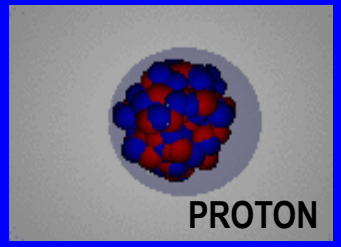
$\rho \sim 2.5\times10^{14}$ g/cm^3
P ~ 10^{25} Mbar

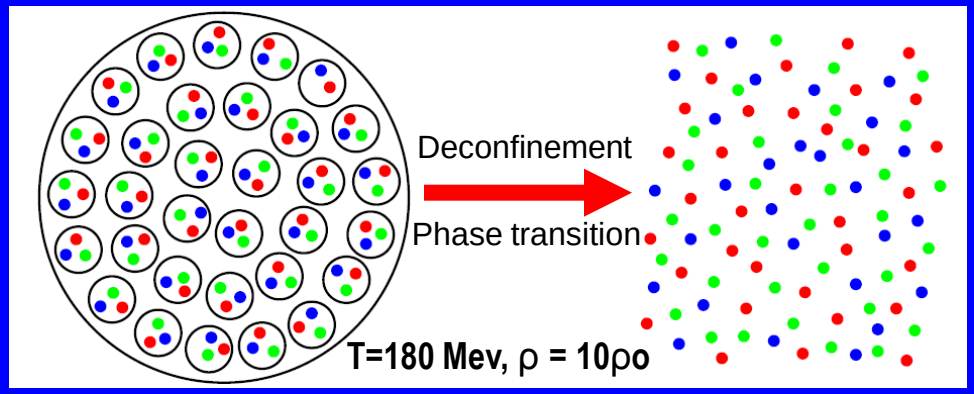


NUCLEAR MATTER

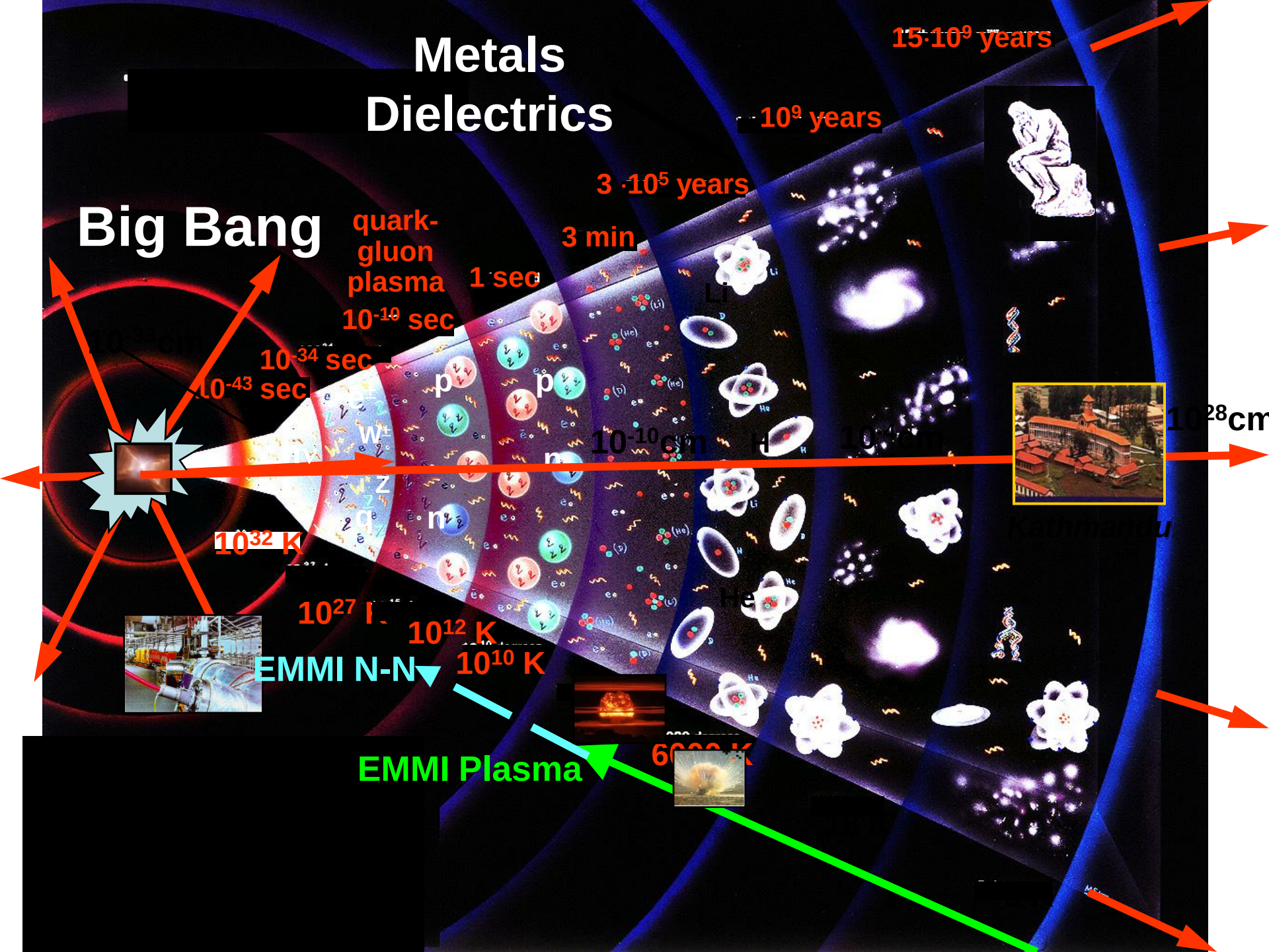


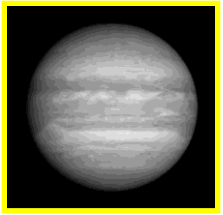
HADRONS





QUARK-GLUON PLASMA


Metals
Dielectrics
15·10^9 years
10^9 years
3 ·10^5 years
Big Bang
quark-gluon plasma
3 min
1 sec
10^-10 sec
10^-34 sec
10^-43 sec
10^-10 cm
10^28 cm
10^32 K
10^27 K
10^12 K
10^10 K
EMMI N-N
EMMI Plasma
Li
He
H



Coulomb interaction

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

strong coupling, if $\Gamma = \frac{W_c}{W_{th}} \geq 1$

Nonideality boundary:

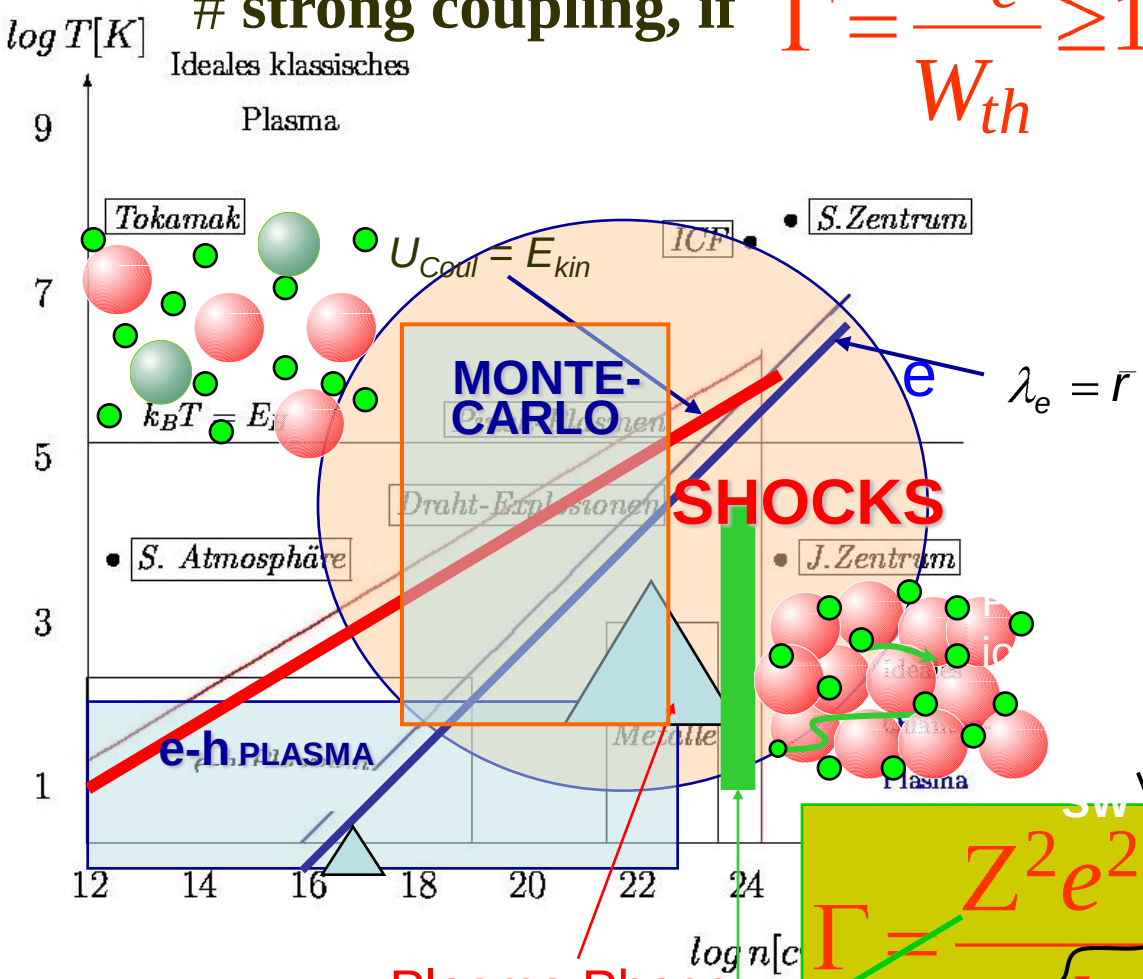
$\langle U_{Coul} \rangle = \langle E_{Kin} \rangle$

Statistics:

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

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

$\lambda_e = \bar{r}$



Pressure dissociation and ionization, Mott effect

Plasma Phase Transition!

$\Gamma = \frac{Z^2 e^2 n^{1/3}}{kT}$

DUST

10^5

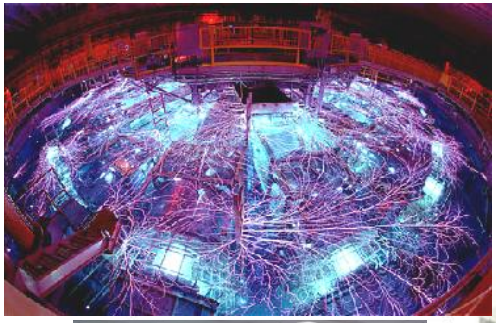
10^2

10^2

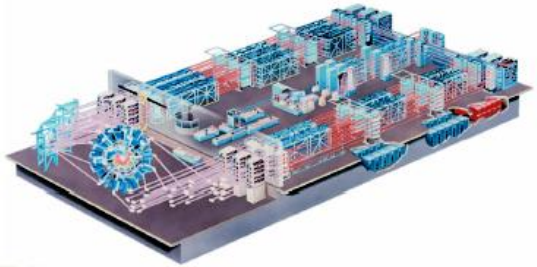
i,e cristals

Recent advances in extending the energy, power and brightness of lasers, particle beams, and Z-pinch generators make it possible to create matter with extremely high energy density in the laboratory

20 MA Sandia (SNL) Z facility



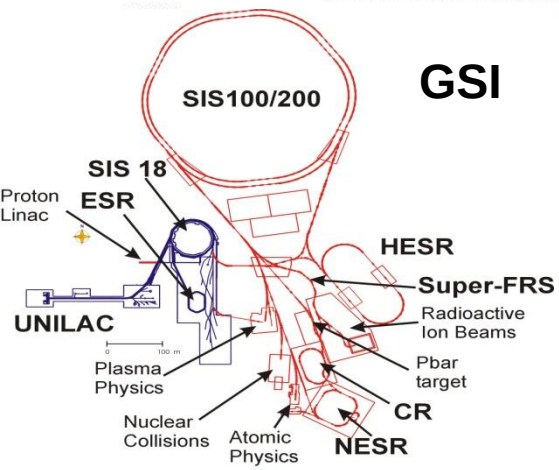
30-kJ OMEGA laser (UR-LLE)

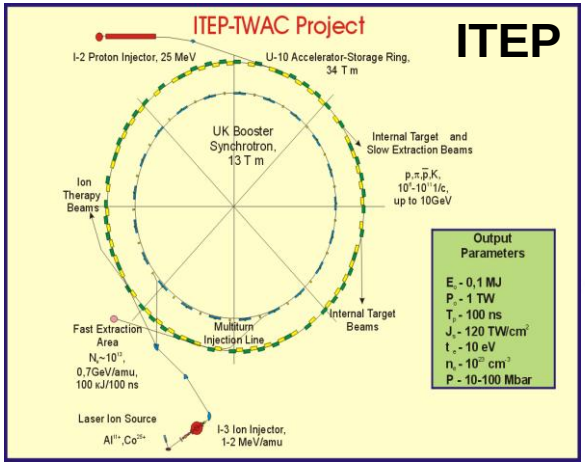


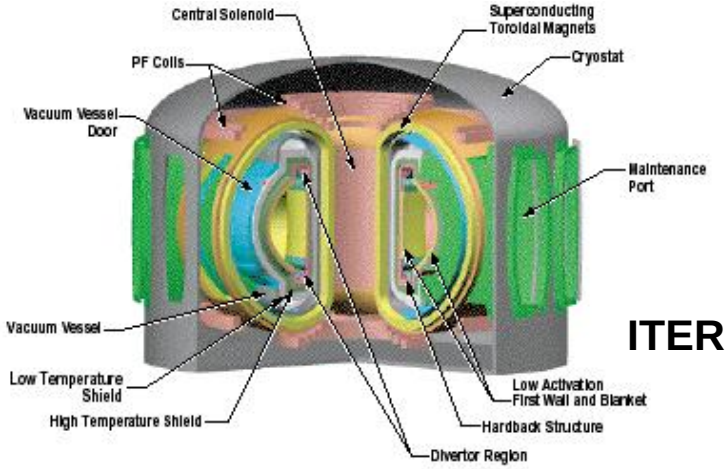
10 kJ &10kJ (PW)
FIREX1

LMJ

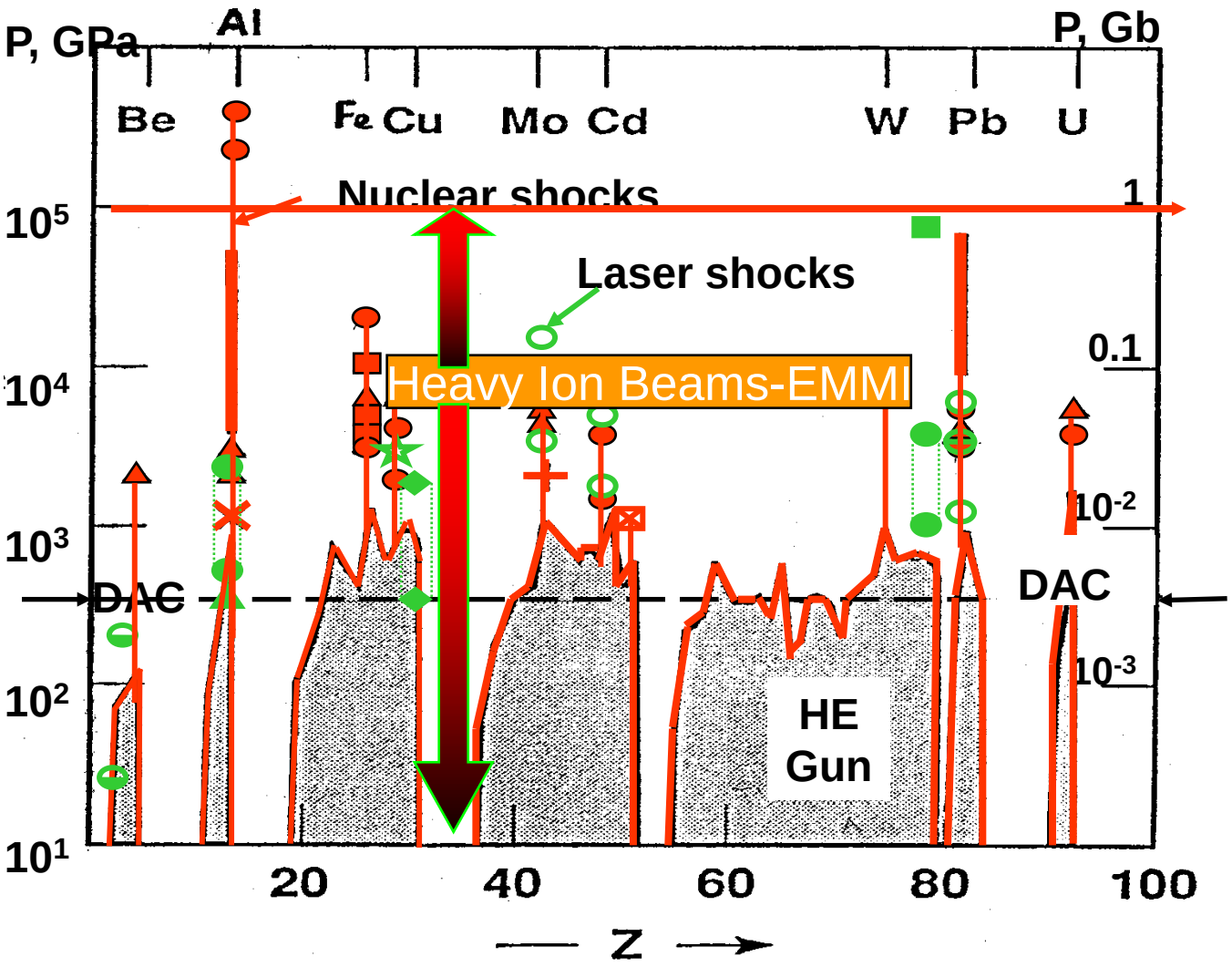
2-MJ National Ignition Facility, under construction at LLNL





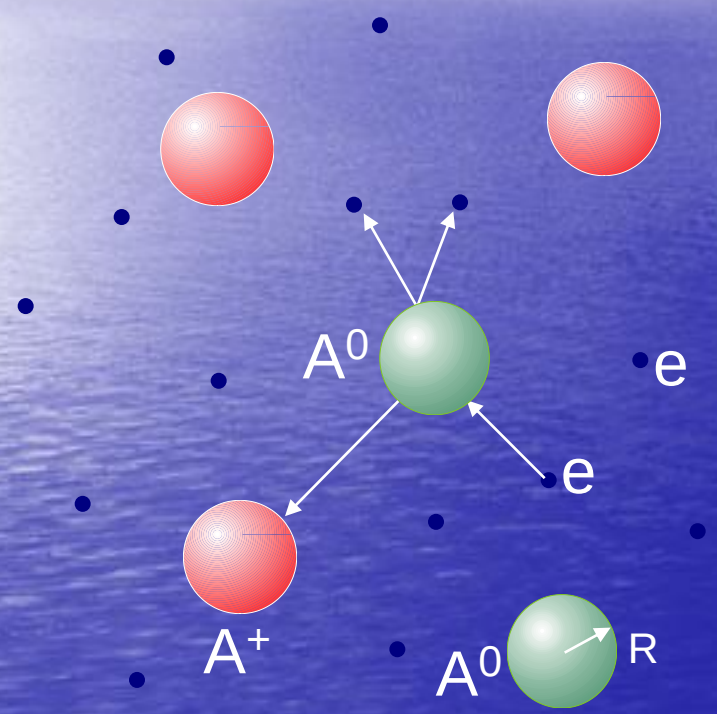


MAXIMUM PRESSURES IN THE "LABORATORY"



IONIZATION BY

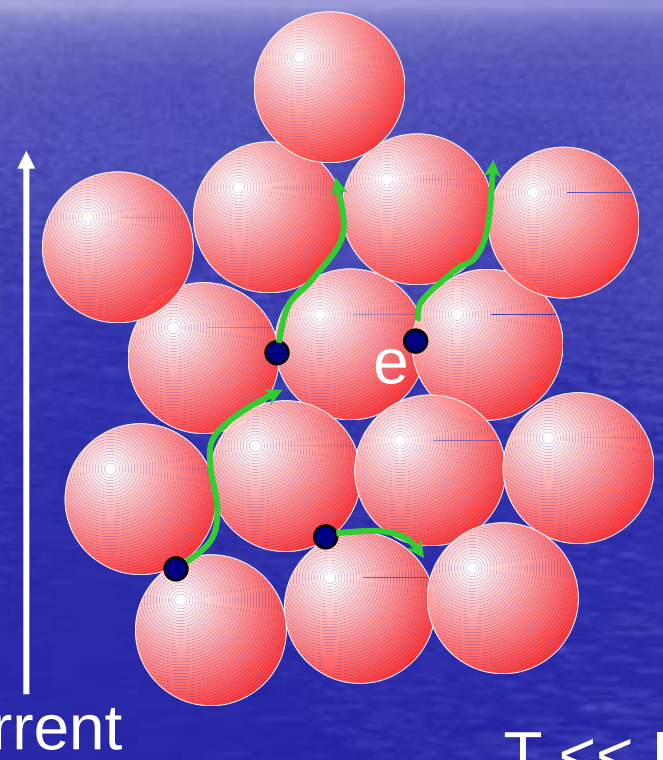
TEMPERATURE



$T \sim I$

$R << n^{-1/3}$

PRESSURE



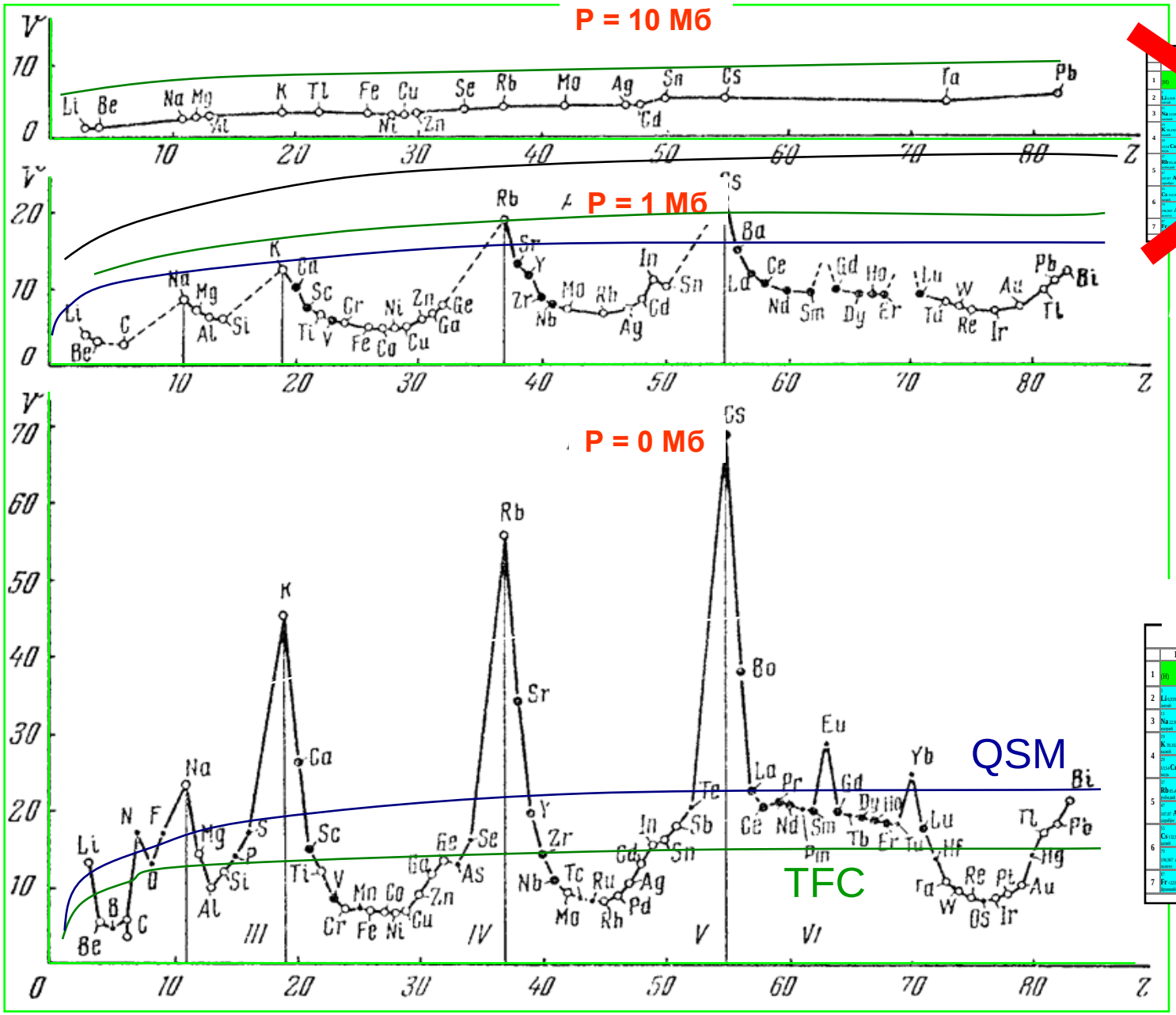
$T << I$

$R \sim n^{-1/3}$

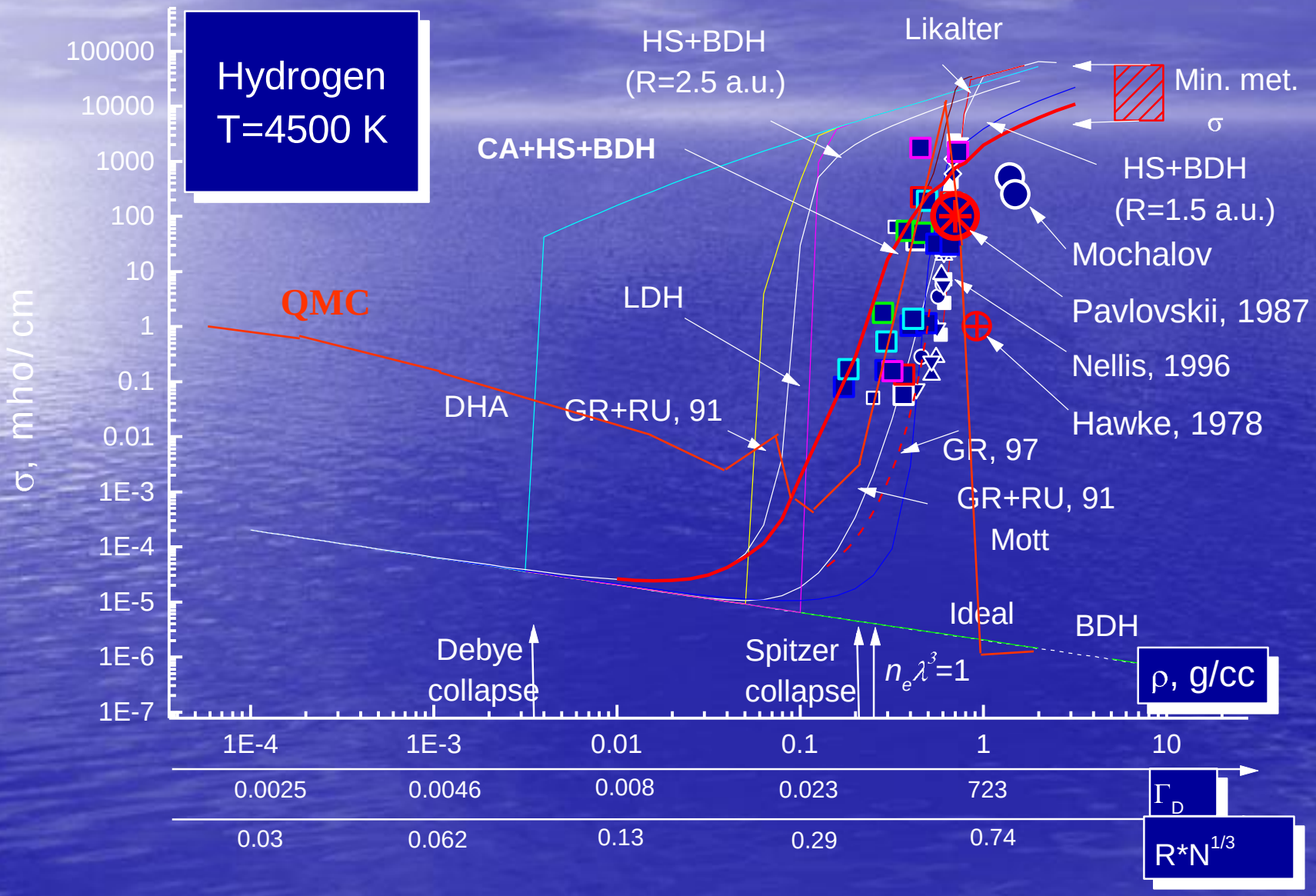
$$A^0 + e^- \rightarrow A^+ + e^- + e^-$$

$$\mu_a + \mu_e = \mu_+ + \mu_e + \mu_e$$

MATTER «SIMPLIFICATION» AT HIGH PRESSURE



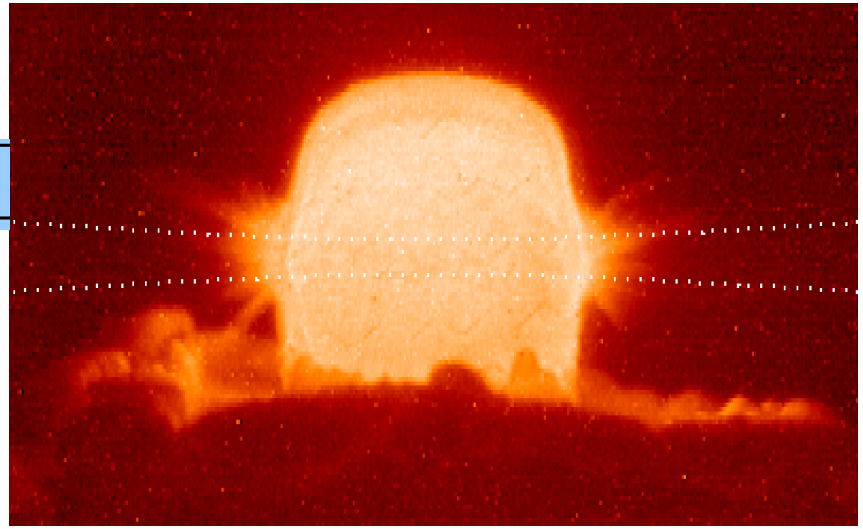
HYDROGEN "METALLIZATION"



Intense beams of energetic heavy ions are an excellent tool to create and investigate extreme states of matter in reproducible experimental conditions

$$E_s = (1.6 \cdot 10^{-19}) \cdot \frac{dE/\rho dx}{\pi \cdot r^2} \cdot N \; [J/g]$$

$$dE/dx \sim -\rho \frac{Z_{эф}^2}{E_i} \ln \Lambda$$



Intense Heavy Ion Beams

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 !

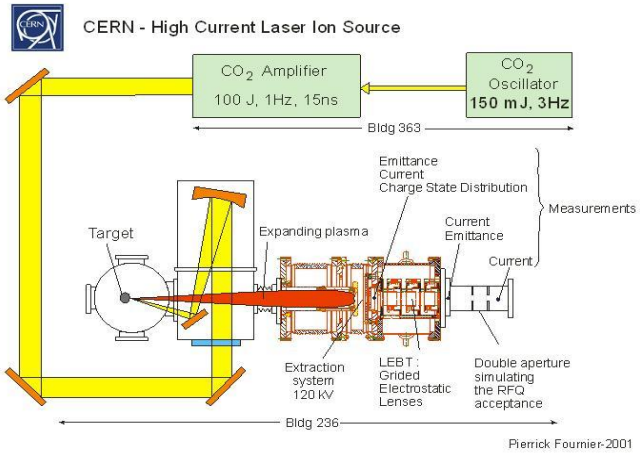
ITEP Solutions

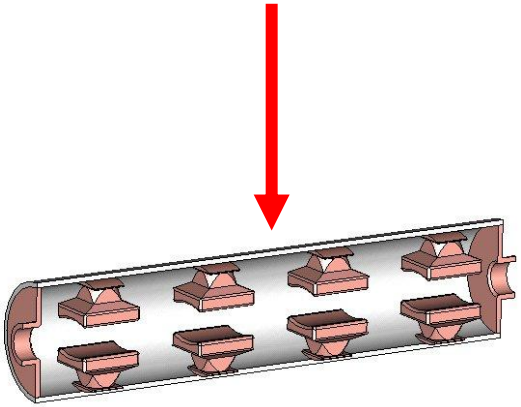
1:Laser ion source

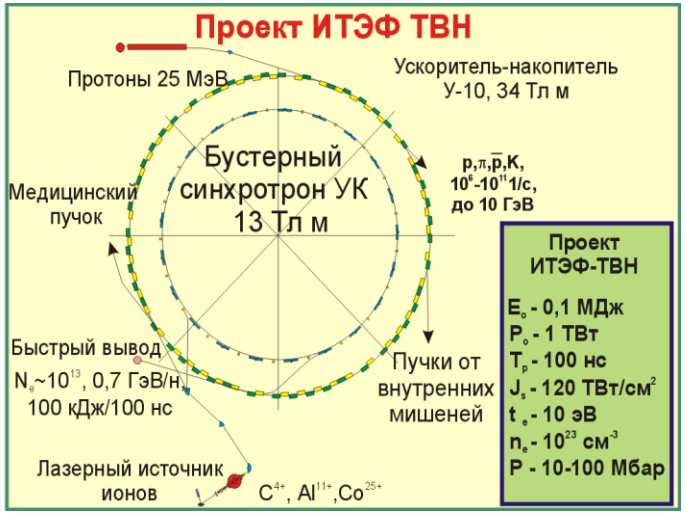
2: RFQ accelerator

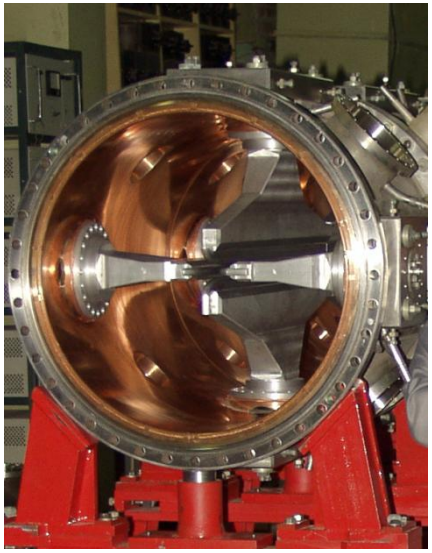
3: Non-Liouvillian stacking

4. RF wobbler technique

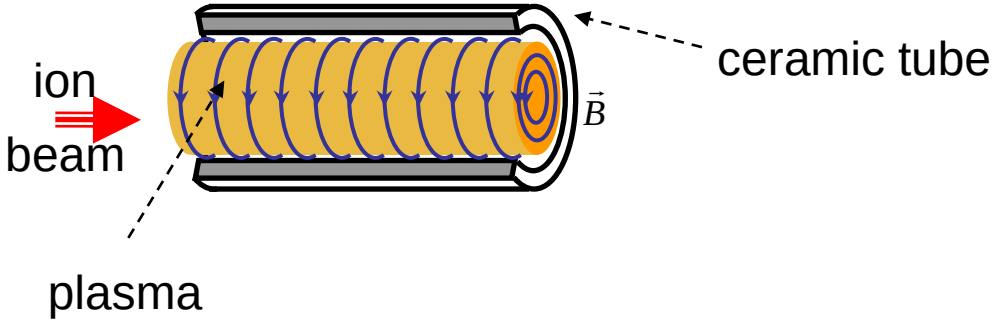








Plasma lens focusing – at GSI



$$F = Zev_z B_\phi(r)$$

$$B = \frac{\mu_0}{2} jr$$

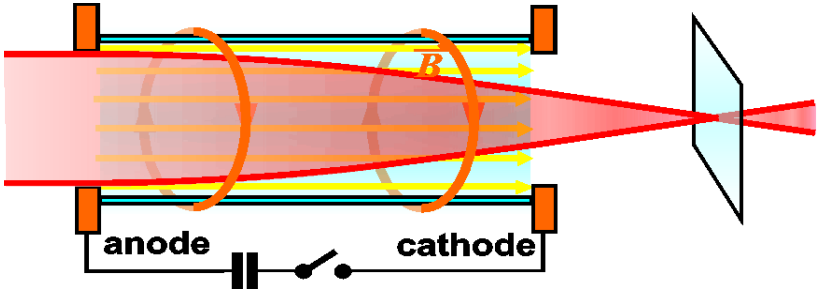
$$d_{min} \sim \varepsilon I^{-1/2}$$

Advantages of plasma lens :

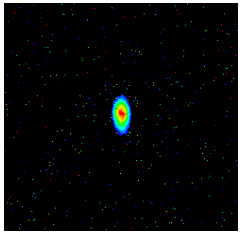
- **focusing area has symmetric first order focusing;**
- **there is no limit for the magnitude of the magnetic field connected with saturation;**
- **charge neutralization of ion beam into the plasma lens ;**
- **beam rigidity decreases by the reason of the stripping of electrons from not fully ionized ions;**

Disadvantages:

- **a plasma lens system doesn't have necessary stability in contrast to a quadrupole magnetic systems;**
- **very strong electromagnetic noise and inducing .**

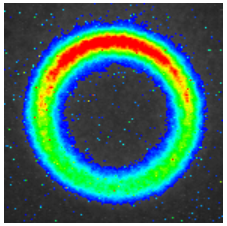


focal beam spots

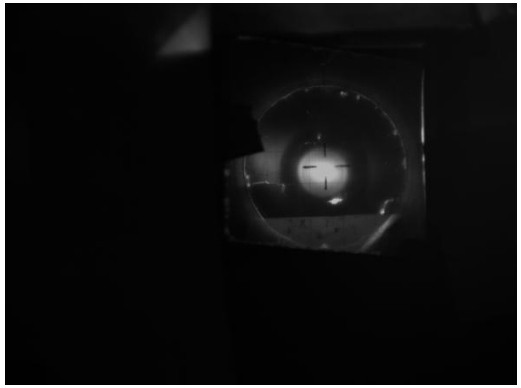


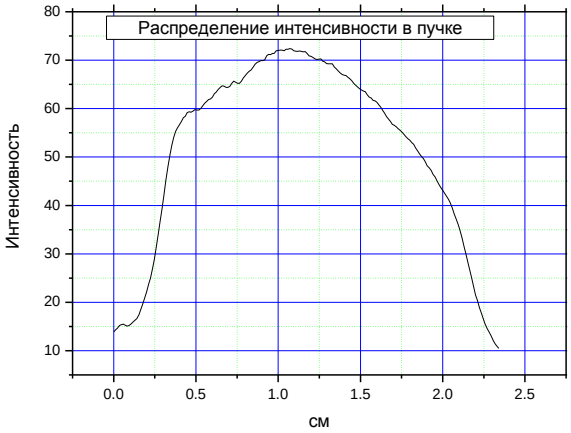
linear B-field

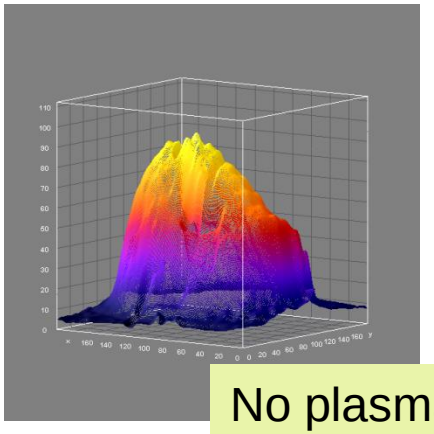
nonlinear B-field



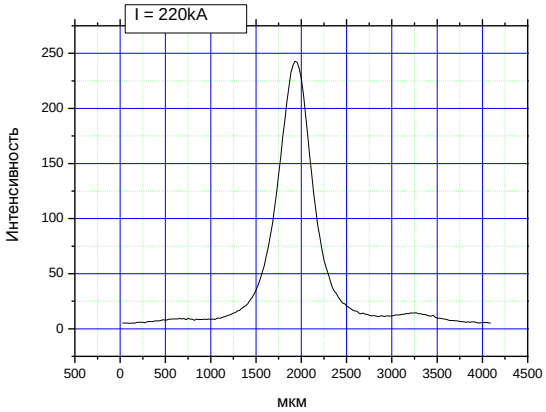
Beam Focusing by Plasma Lens ITEP

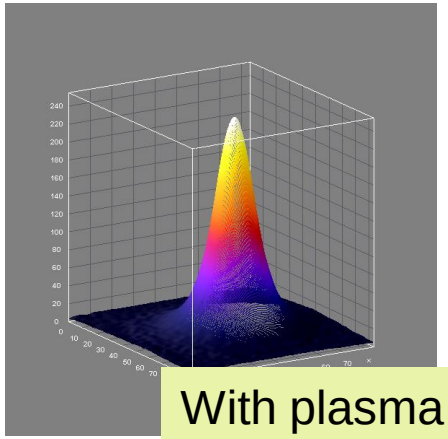






No plasma lens





With plasma lens

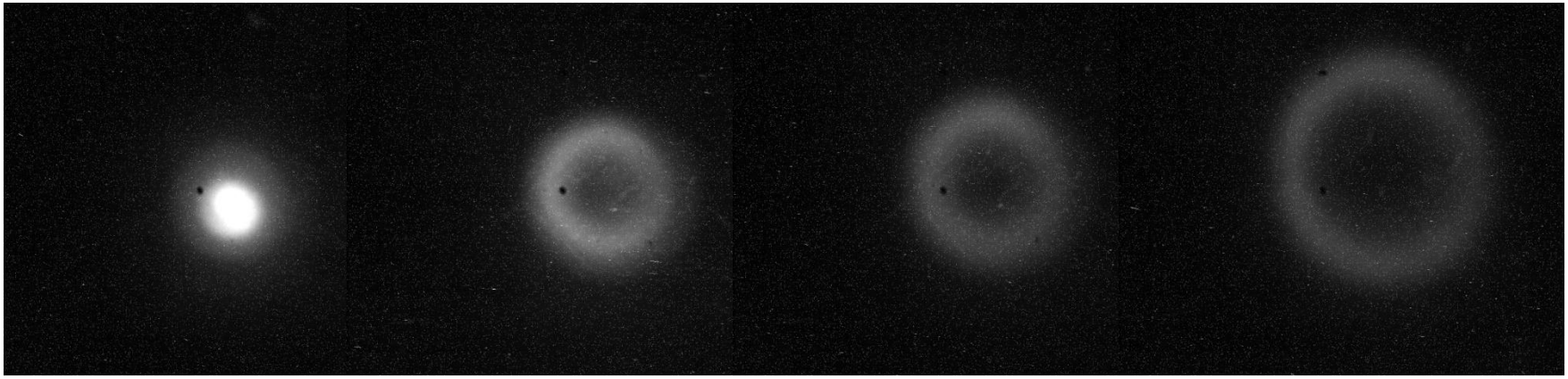
Изображение пучка ионов C^{6+} с энергией 200 МэВ/н и поперечное распределение плотности частиц без фокусировки и с фокусировкой при помощи плазменной линзы: ток в линзе 220 кА, фокусное расстояние 30 см, размер пятна (на полувысоте) 350 мкм

C6+ 200 MeV/u, F= 30 cm, D (FWHM = 350 mkm)

Plasma lens - Hollow beam

Beam Radius

4 mm | 8 mm | 10 mm | 15 mm



0.2 m | 0.3 m | 0.35 m | 0.45 m

Distance from the end of the discharge tube to scintillator →

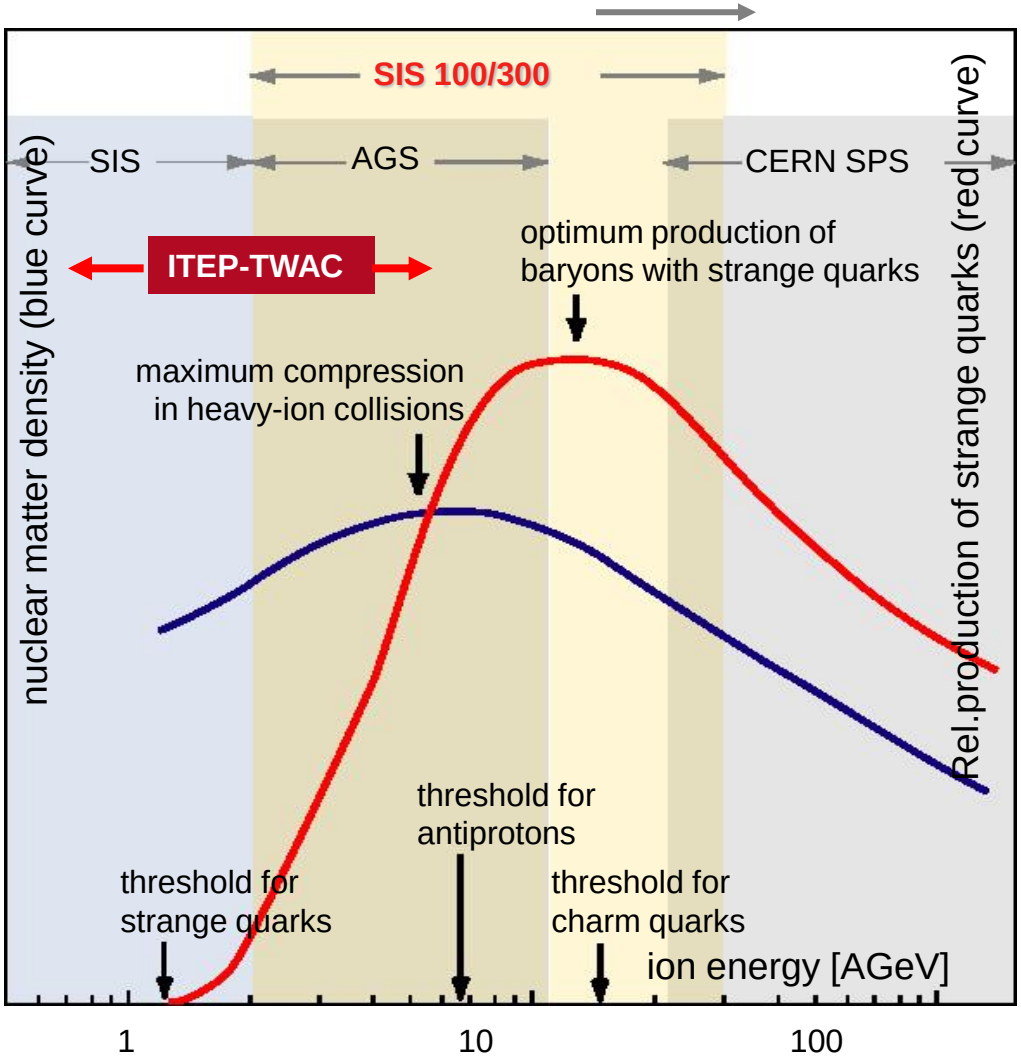
Plasma lens parameters:

I_{max} = 130 kA, p_{Ar} = 6.8 mbar

Relativistic Nuclear Physics

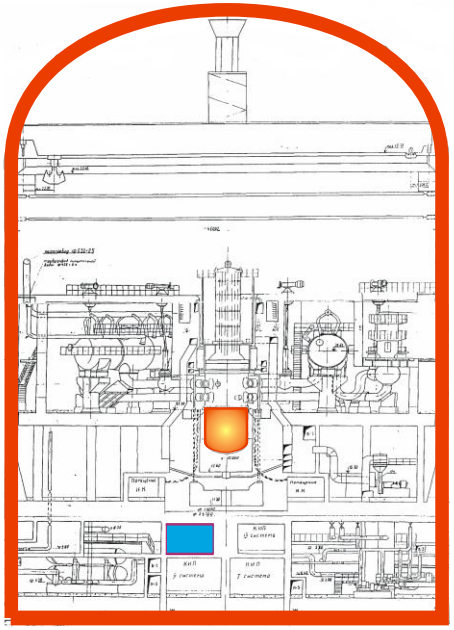
Studies of hadronic matter at high densities

Motivation for NN collisions at 2-40 AGeV



Нейтринная диагностика реакторов

Калининская АЭС блок №3



Позволяет контролировать:

1. *Тепловую мощность реактора с точностью ~ 0.5%;*

2. *Пространственную неоднородность выгорания топлива в активной зоне – томографию активной зоны реактора с точностью 1-5 см -* ν - томография

3. *Изотопный состав топлива в ходе кампании:* *наработку* ^{239}Pu *выгорание* ^{235}U *с точностью ~ 5%;*

10E4 нейтринных события в сутки, Срок – 1,5 - 2 года

P+ терапия

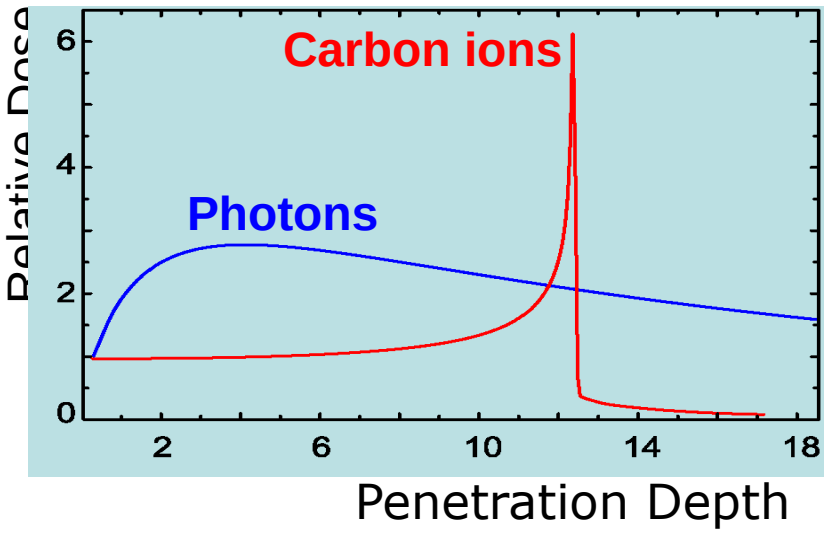
В.Хорошков

Радиобиология на ионах

А.Голубев

Physical and Biological Properties of Ion Beam Irradiation

Clinical Studies at the Pilot Facility



Центр ядерной медицины – ИТЭФ – Росатом- ФМБА

Разработка методов и испытания воздействия ионизирующих излучений космического пространства на электронную компонентную базу оборонного и гражданского назначения

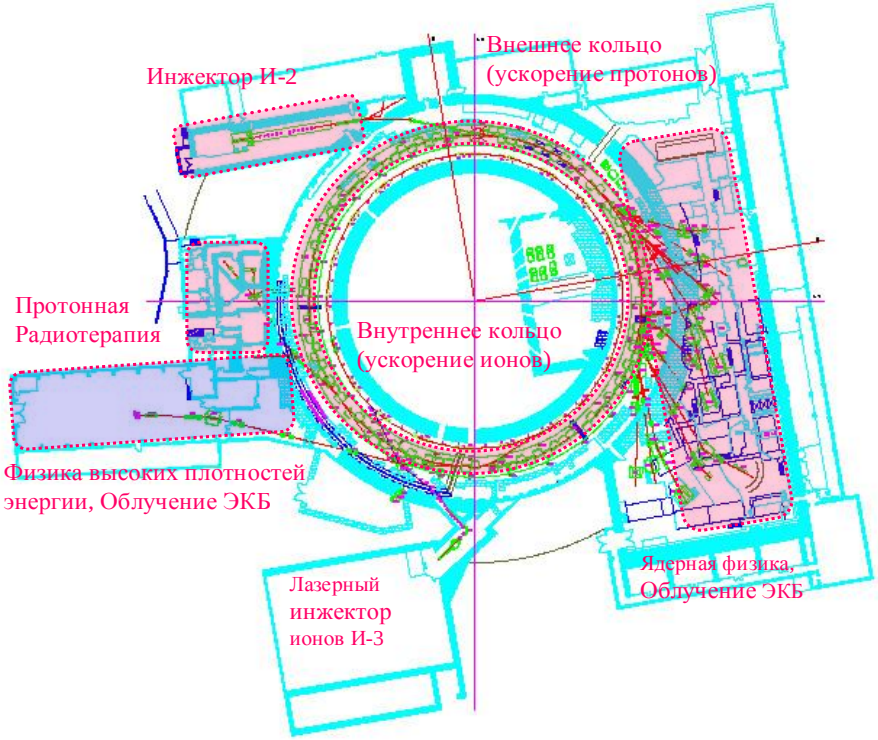
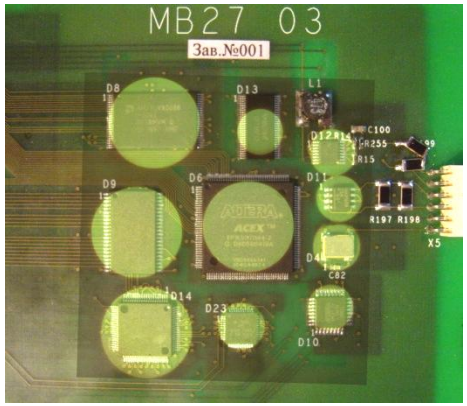
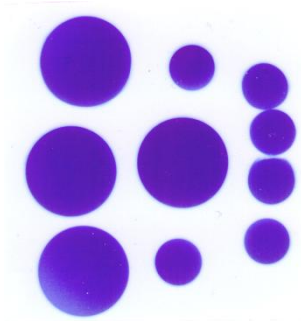


Схема ускорительного комплекса ТВН-ИТЭФ

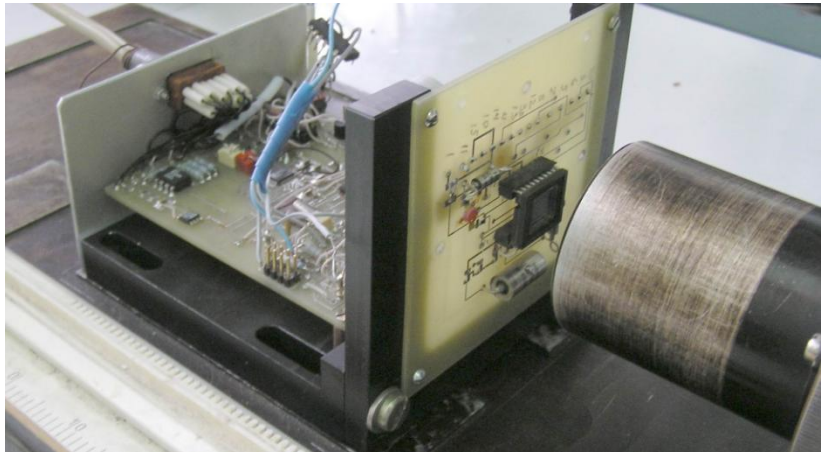
Примеры проведенных испытаний



Фрагмент платы с испытуемыми элементами и наложенным просканированным изображением радиохромной дозиметрической пленки.

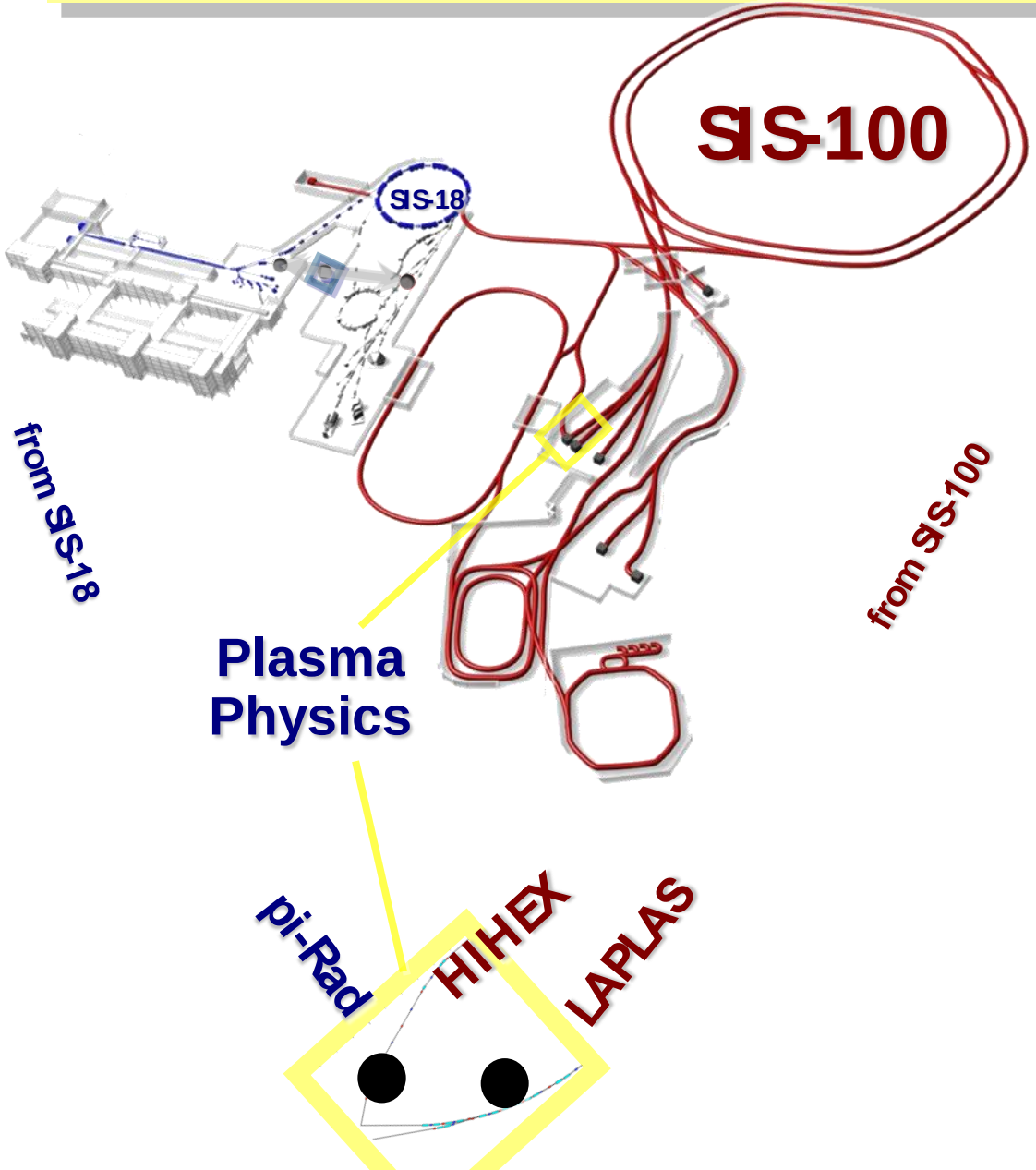


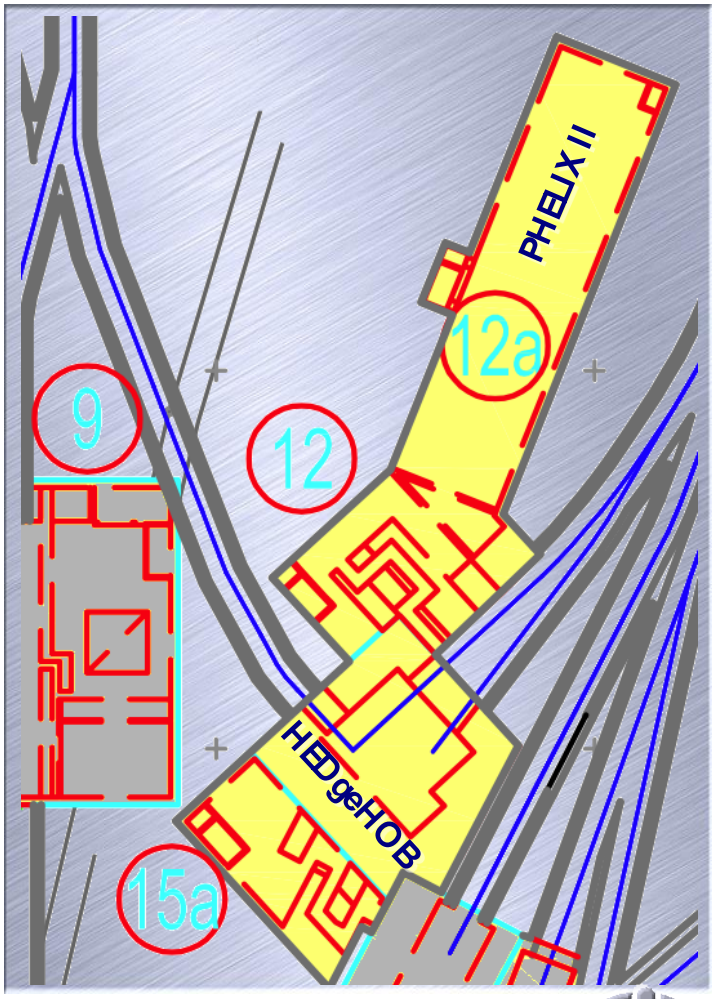
Изображение радиохромной дозиметрической пленки



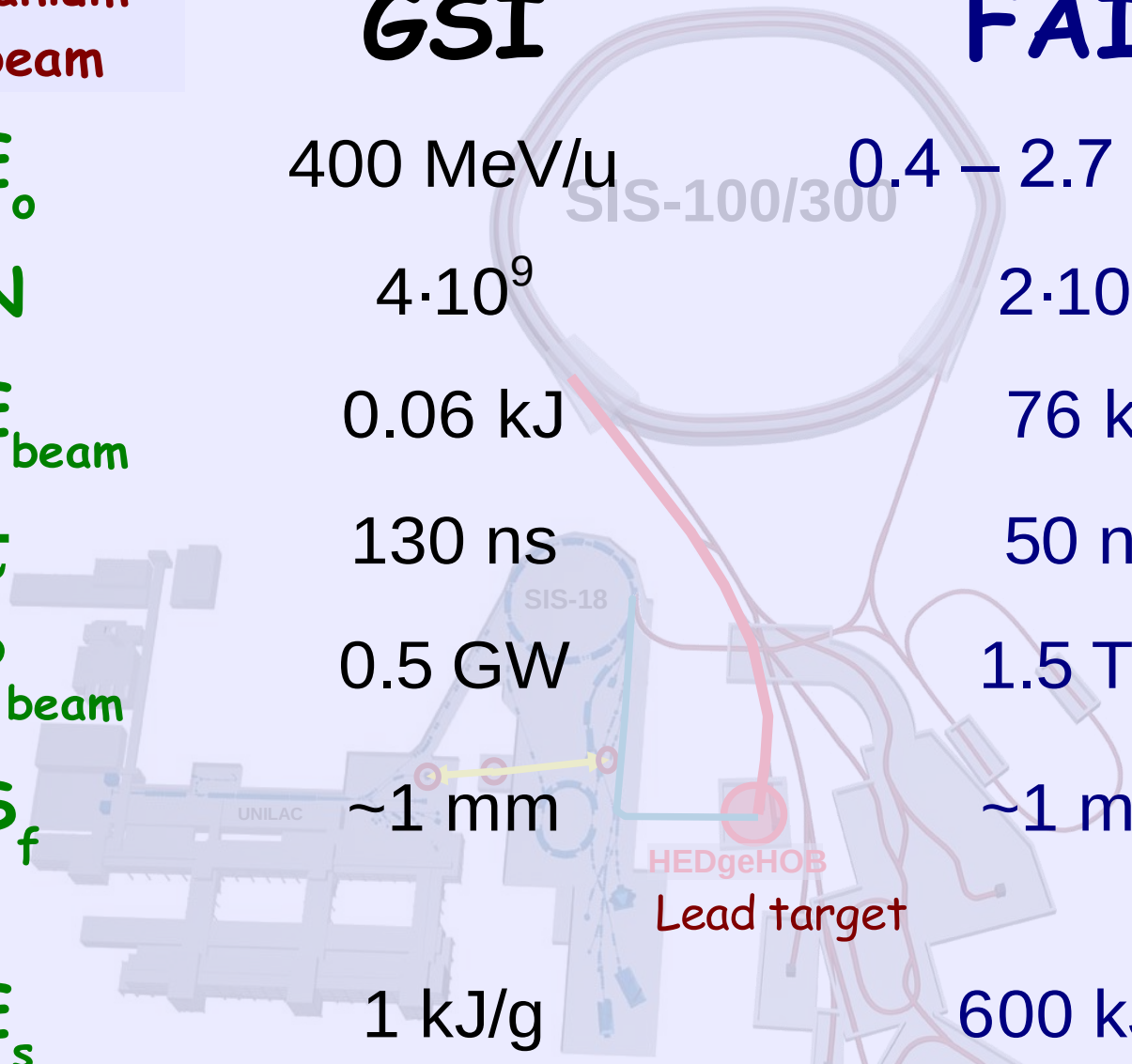
Проведение испытаний:
видео матрицы CCD SONY ICX429ALL,
видео процессора AD9844A,
видео-драйвера CXD1267AN,
синхро-генератора CXD1261AR

HEDgeHOB beam lines and cave



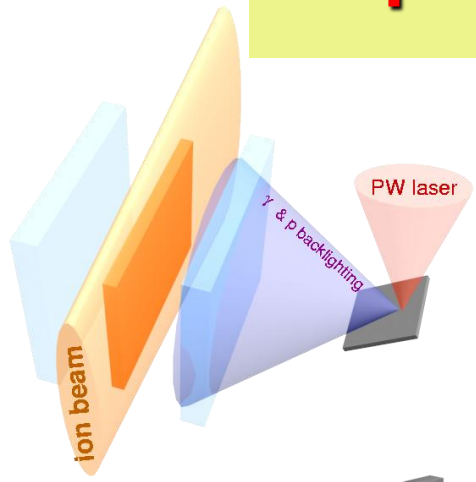


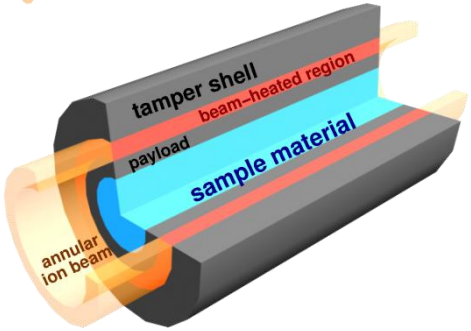
Uranium beam	GSI	FAIR	
E_o	400 MeV/u	0.4 – 2.7 GeV/u	
N	$4 \cdot 10^9$	$2 \cdot 10^{12}$	×500
E_{beam}	0.06 kJ	76 kJ	
τ	130 ns	50 ns	
P_{beam}	0.5 GW	1.5 TW	×3000
S_f	~1 mm	~1 mm	
E_s	1 kJ/g	600 kJ/g	×600
P_s	5 GW/g	12 TW/g	×2400

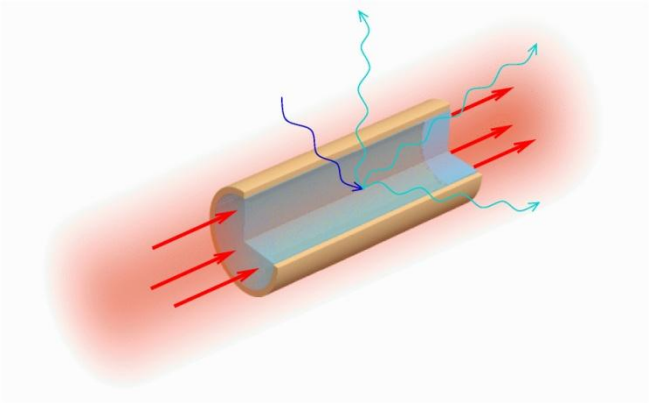


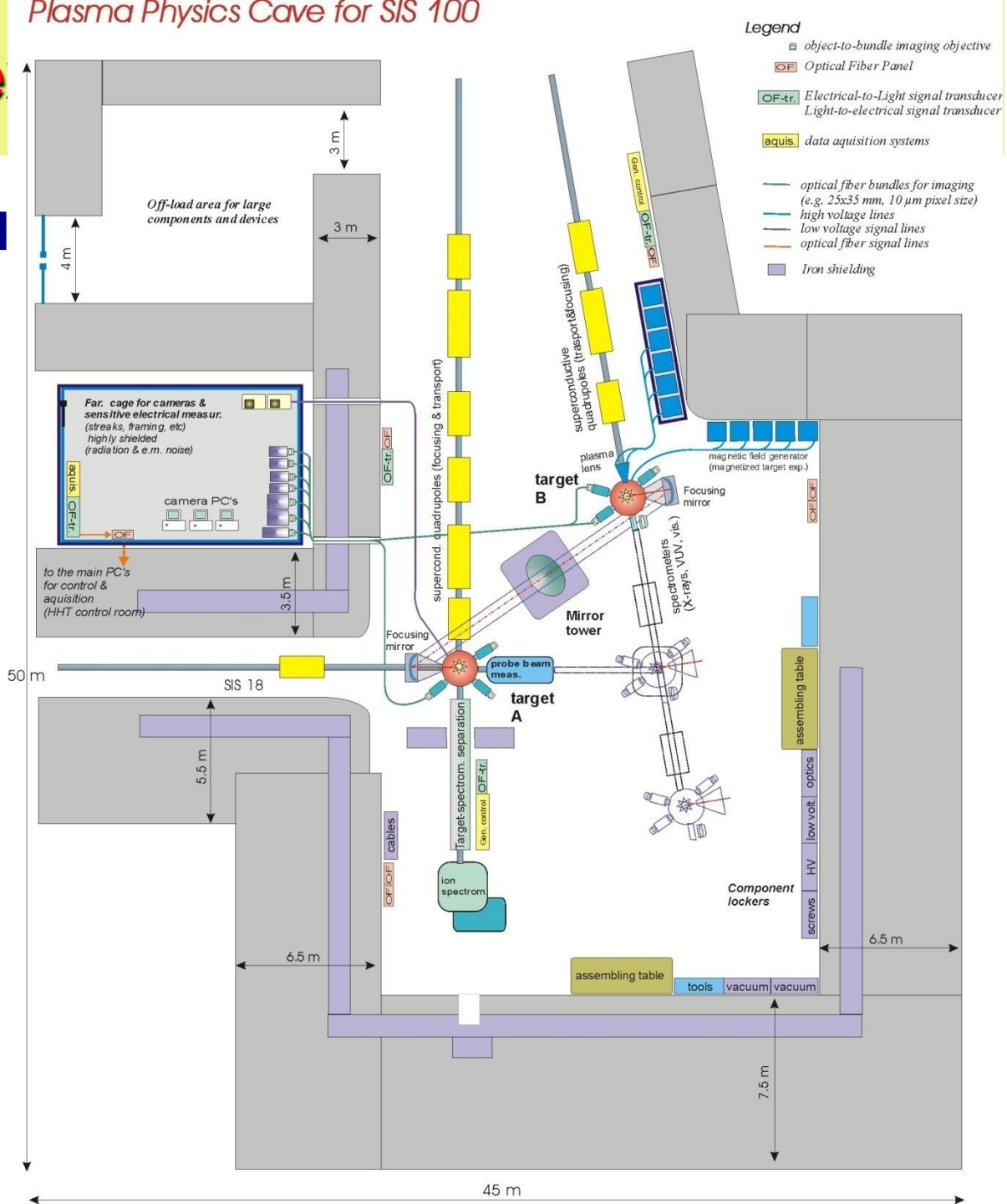
Proposed e

HIH

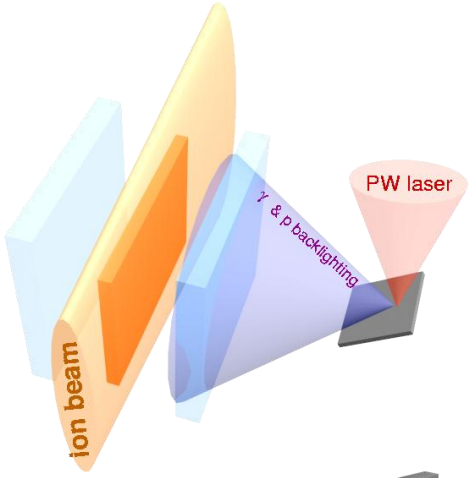




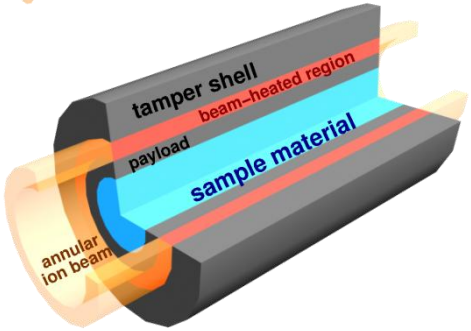




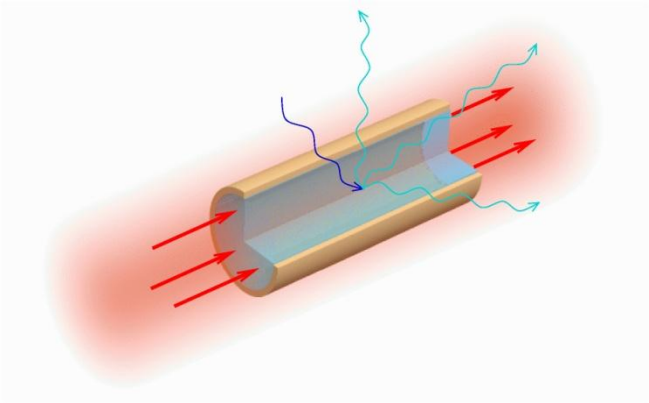
Proposed **HEDgeHOB** experiments



HIHEX: Heavy Ion Heating and Expansion

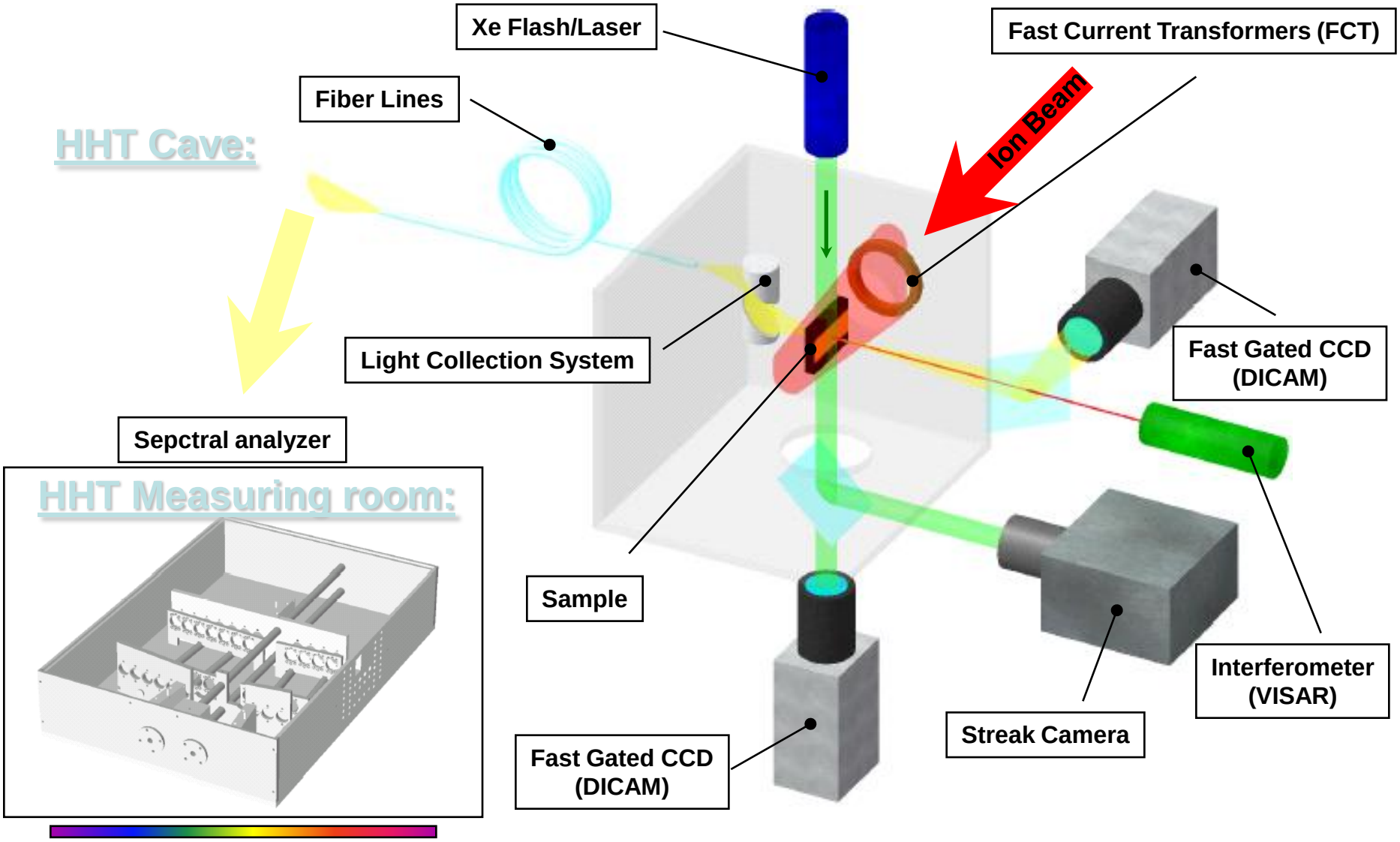


LAPLAS: Laboratory Planetary Sciences

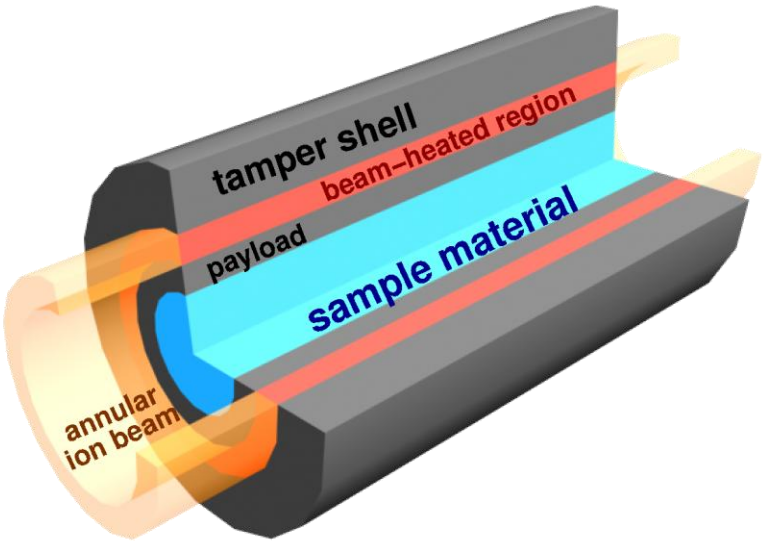


WDM: Warm Dense Matter

HHT Experimental Setup



Wobbler development for experiments at ITEP and LAPLAS (Laboratory Planetary Sciences) FAIR project



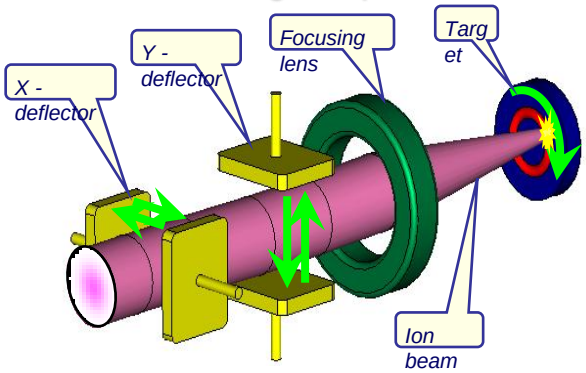
- hollow *(ring-shaped)* beam heats a heavy tamper shell
- cylindrical implosion and low-entropy compression of the sample
  - Mbar pressures @ moderate temperatures
    interior of Jupiter and Saturn, hydrogen metallization

An intense ion beam can be used very efficiently to achieve low-entropy compression of a sample material like hydrogen or ice that is enclosed in a heavy cylindrical tamper shell. Such a target will be driven by a hollow beam with a ring shaped (annular) focal spot. In this experiment it will be possible to achieve physical conditions that exist in the interior of giant planets, Jupiter and Saturn. Another goal of the LAPLAS experiment will be to study the problem of hydrogen metallization.

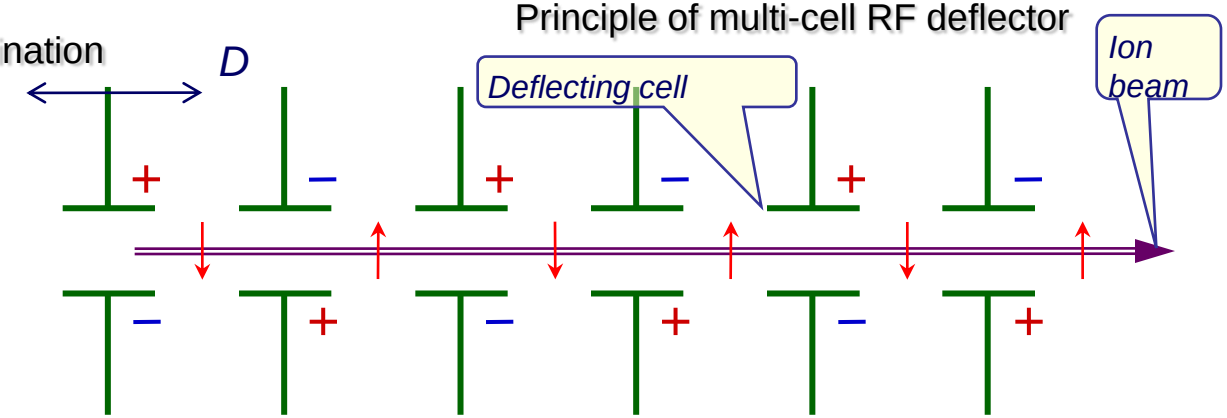
Implosion asymmetries induced by a rotating ion beam

Cylindrical implosions with high radial convergence require high degree of azimuthally uniformity of the beam irradiation, especially when a cold pusher is used to compress the sample material in the central cavity. To ensure the required symmetry of beam irradiation, it was proposed to rotate the ion beam around the cylindrical target axis by means of a corresponding beam wobbler. An idea is to deflect the parallel beam by RF electric field in both transverse directions and then to focus it to the small rotating spot, illuminating the ring-shaped area on the target.

Mechanism of ring-shaped area illumination



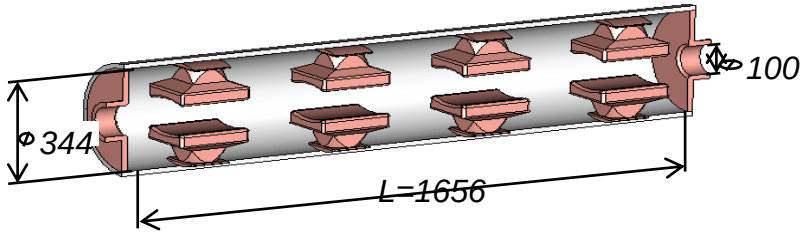
Principle of multi-cell RF deflector



In order to keep the resonant interaction of the beam with the electric field, every cell must be as long as ***βλ/2***, where ***β*** is the normalized beam velocity and ***λ*** is the ***rf*** wavelength. When this condition is satisfied, particle crosses all the cell centers at the same phase, regularly increasing the transverse momentum dependently on the phase value

Example of deflecting cavity parameters for 700MeV/u Co+25 beam TWAC-ITEP facility

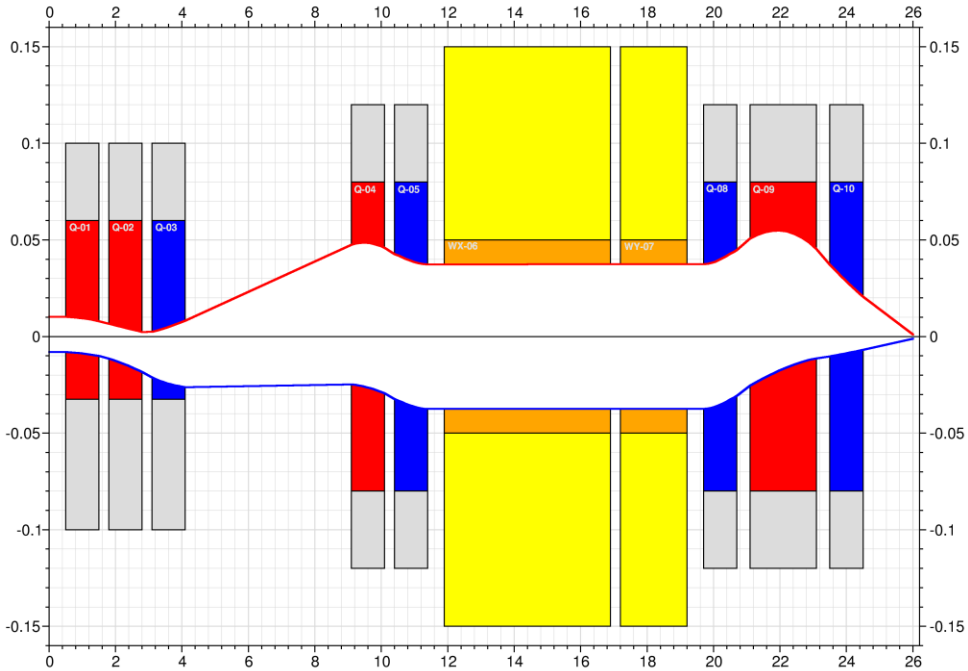
Operating frequency	*MHz*	*300*
Number of cells		*4*
Aperture diameter	*mm*	*100*
Cavity diameter	*mm*	*344*
Cavity length	*mm*	*1656*
Plate-plate RF voltage	*MV*	*1*
Quality factor		*1400*
*Maximum **rf** peak power*	*MW*	*1.5*



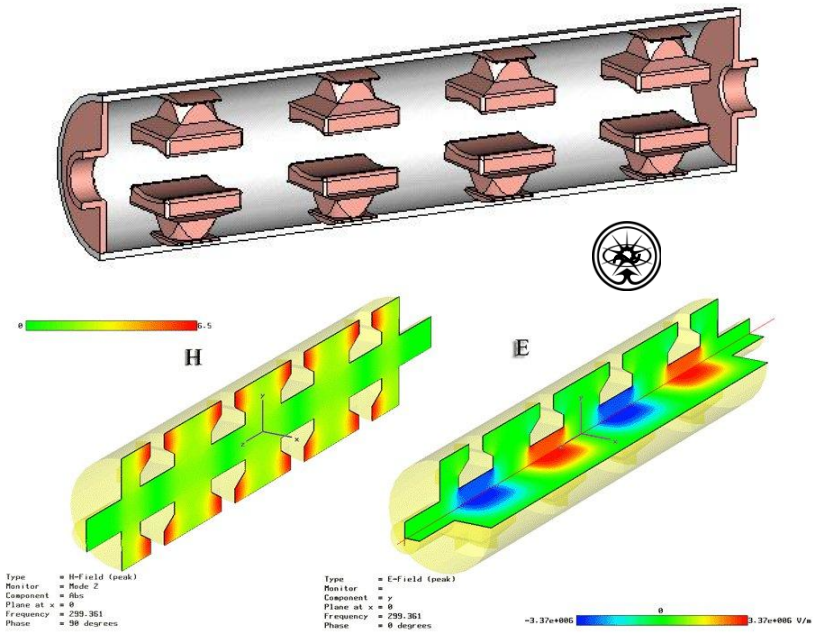
Two resonant multi-cell deflecting rf cavities are proposed to obtain the necessary beam deflection in both directions. Rotation frequency of 300 MHz is the minimum possible value allowed by the experiment requirements.

P6.1&6.2: Ion optical design of the **LAPLAS** beam line: focusing and rf beam deflector (wobbler)

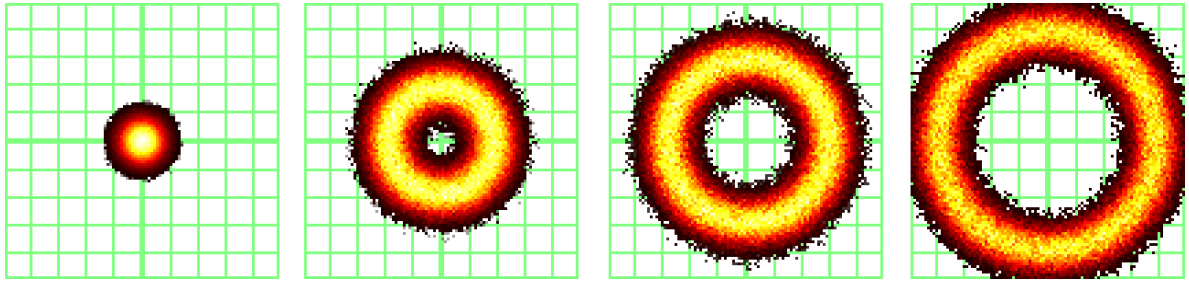
Layout of the **LAPLAS** beam line



Design of rf beam deflector (wobbler)



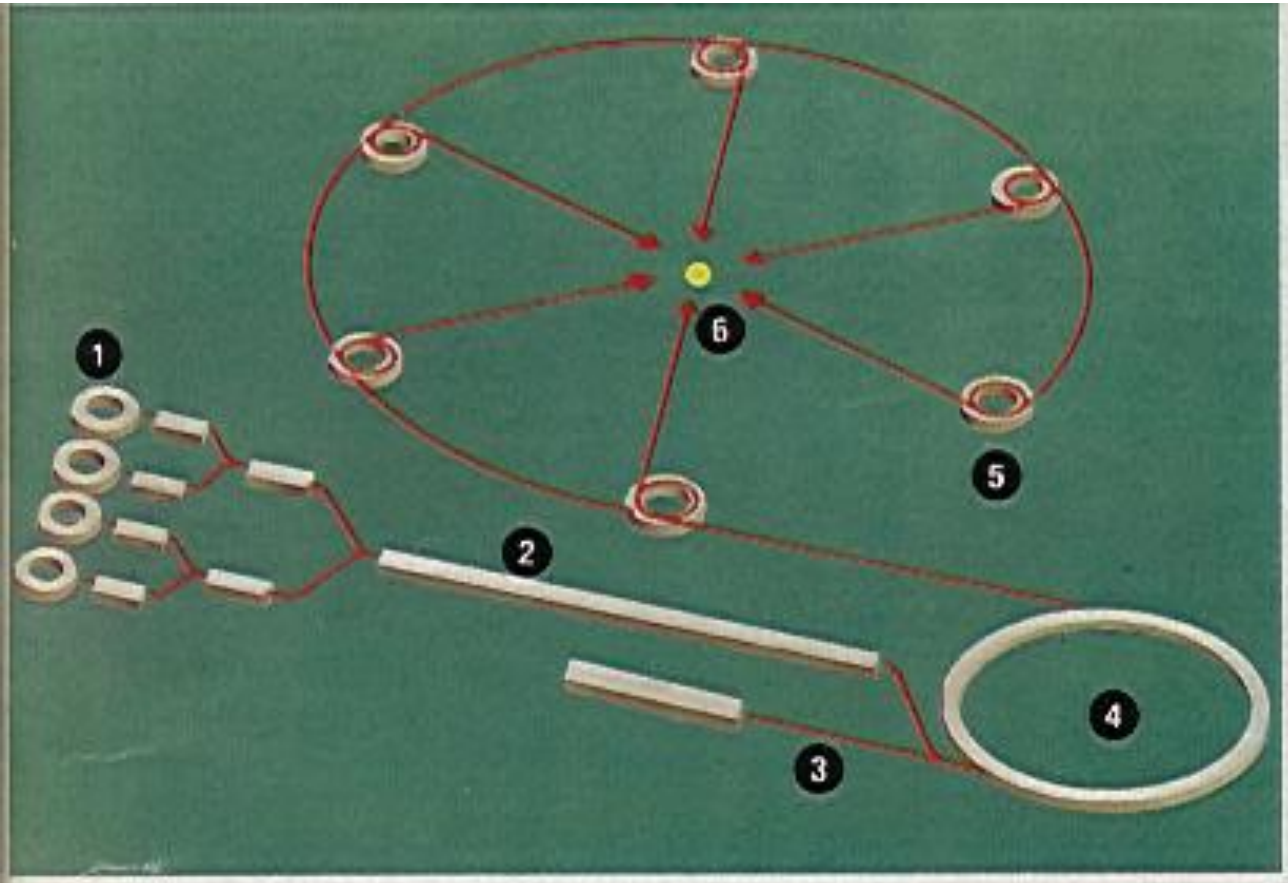
Transverse beam intensity distribution in the focal spot

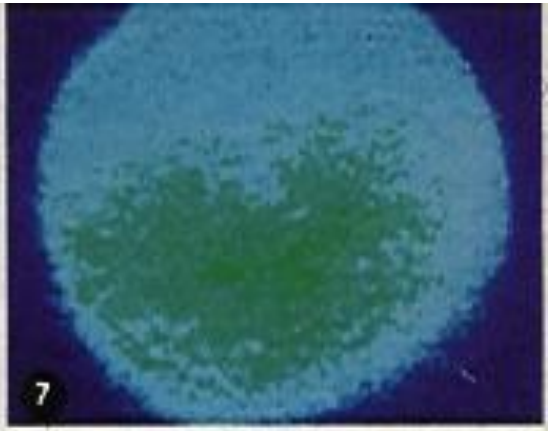


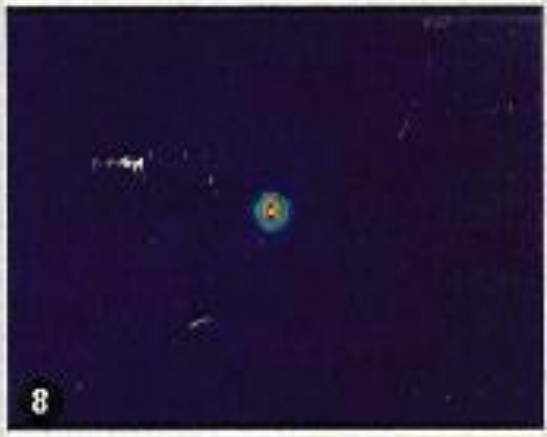
Heavy Ion driven Inertial Fusion Energy

high efficiency
high repetition rate

1 : Ion source
2: Low energy Beam Transpt.
3,4: Beam Intensity

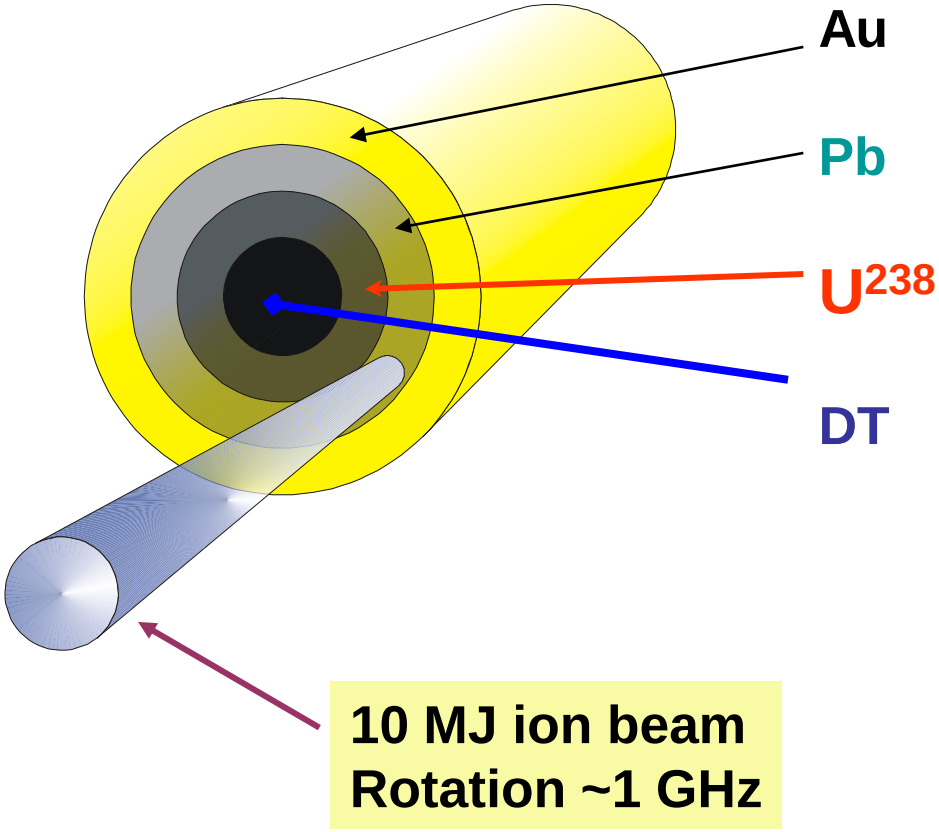






Fusion – Fission - Fusion

- **10 MJ Heavy Ion Driver -> directly driven cylindrical target**
- **Cylindrical implosion of DT fuel -> DT-neutrons generation**
- **DT-neutrons -> fission of U_{238} pusher material**
- **Better confinement, additional compression of DT**
- **Burn fraction & energy gain enhancement**



Энергетическая установка, сочетающей процессы синтеза и деления на основе микромишеней прямого действия и мощного тяжелоионного драйвера

(*ИТЭФ им.А.И.Алиханова, ИПМ им.М.В.Келдыша*)
Алексеев Н.Н., Баско М.М., Долголева Г.В., Жуков В.Т., Забродин А.В., Забродина Е.А., Имшенник В.С., Кошкарев Д.Г., Масленников М.В., Орлов Ю.Н., Субботин В.И., Чуразов М.Д., Шарков Б.Ю

Энерговклад – 10 МДЖ

Ионы ^{196}Pt – 100 ГэВ

Энергия пучка - 10 МДж

Мощность – 2 х 160 ТВт

Коэф.Т.Я. Усиления – 50

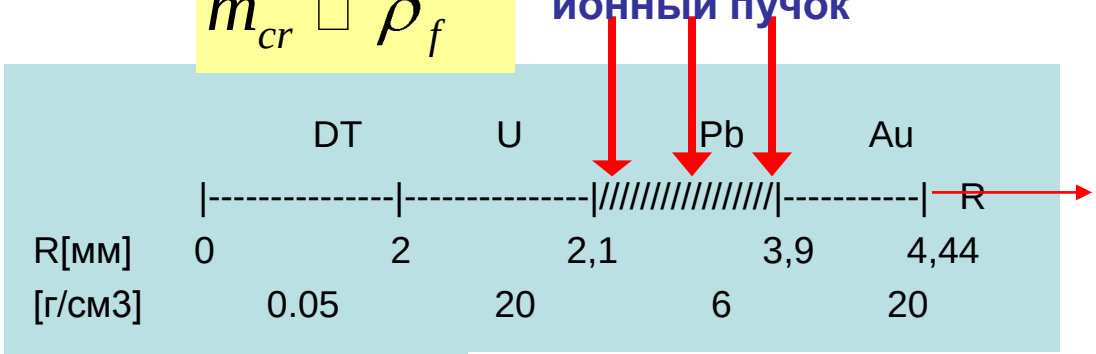
Загорание DT~ 1000 г/см3)

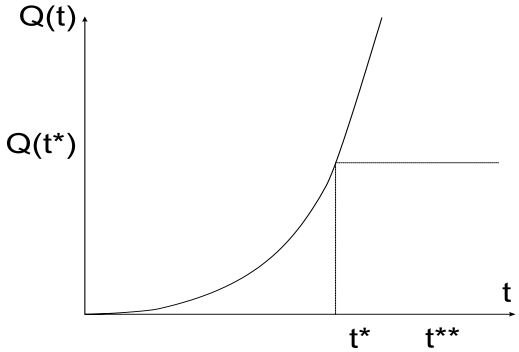
Режим безударного сжатия топлива

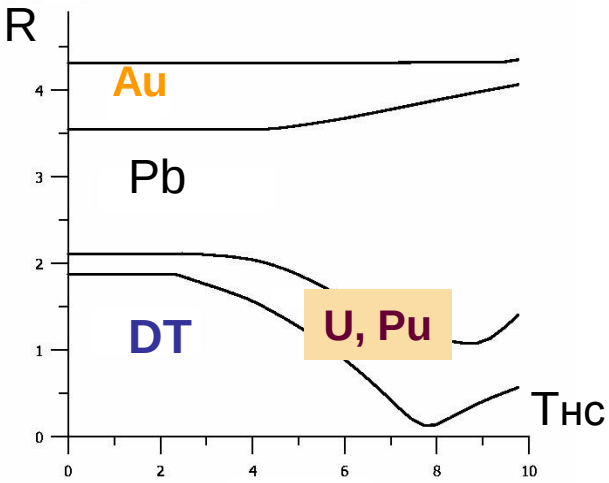
Разрез цилиндрической мишени

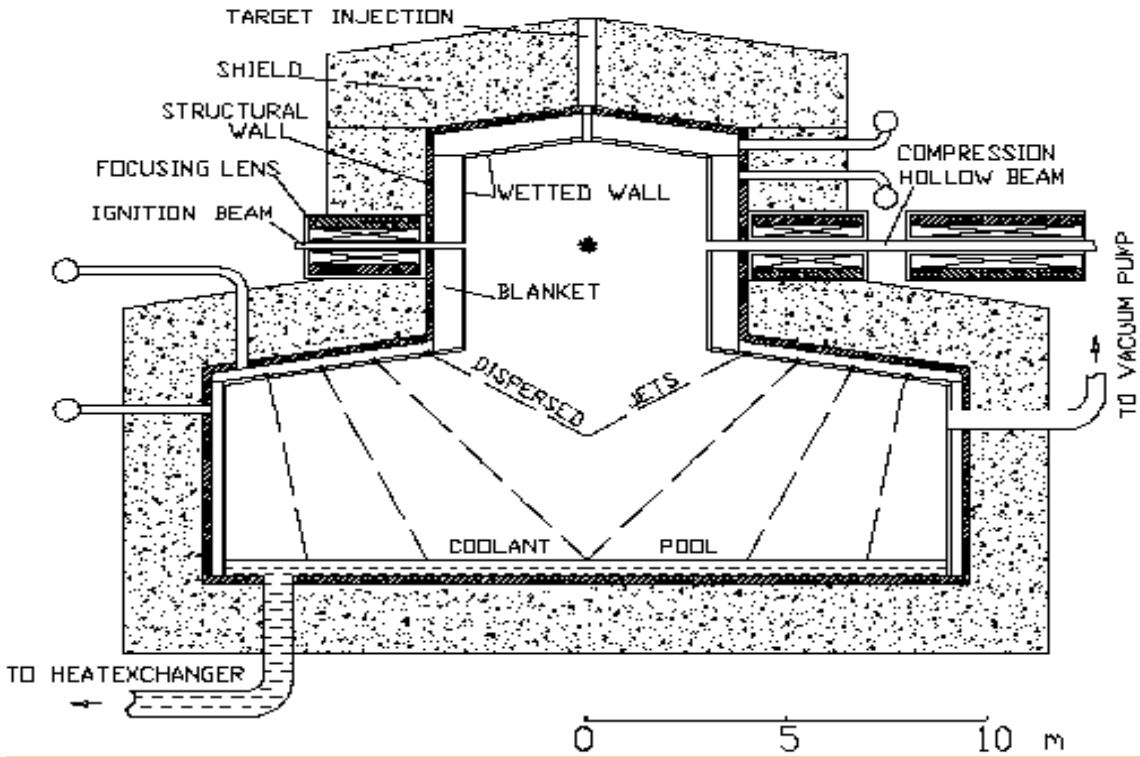
$$m_{cr} \square \rho_f^{-2}$$

ионный пучок

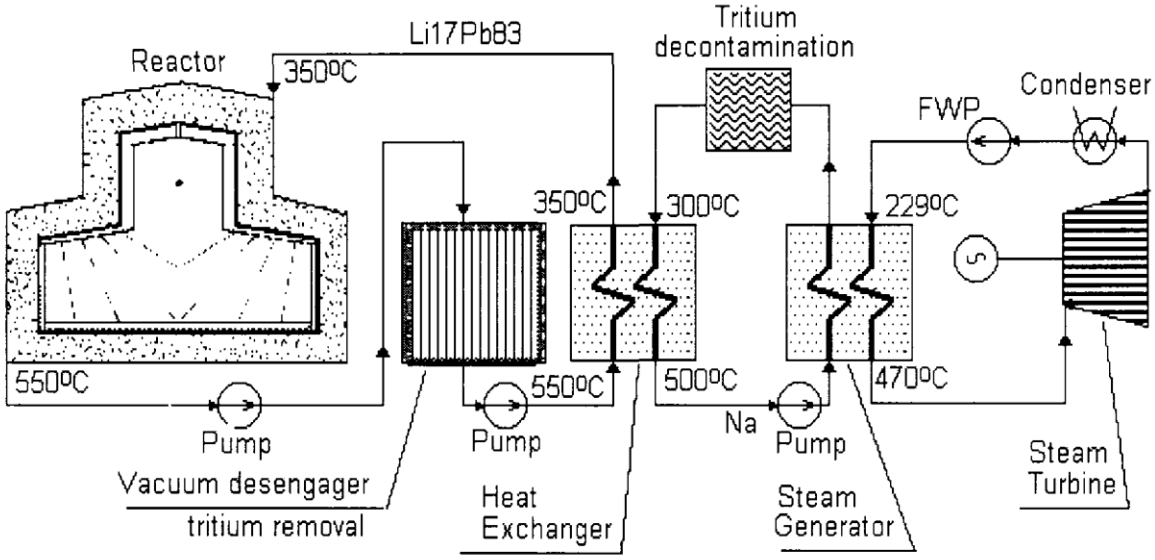








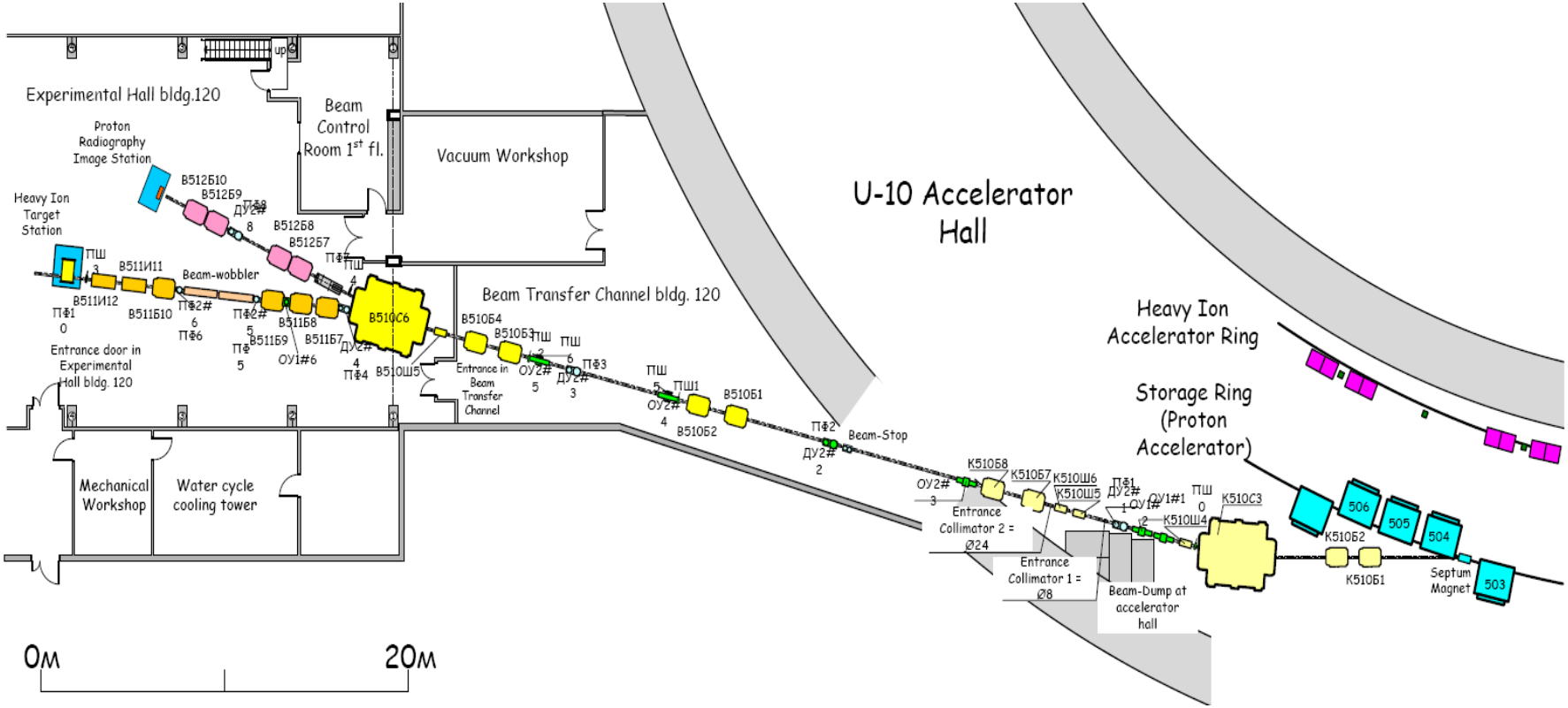
Электростанция ИТС 1 ГВт + драйвер 100 ГэВ Pt+



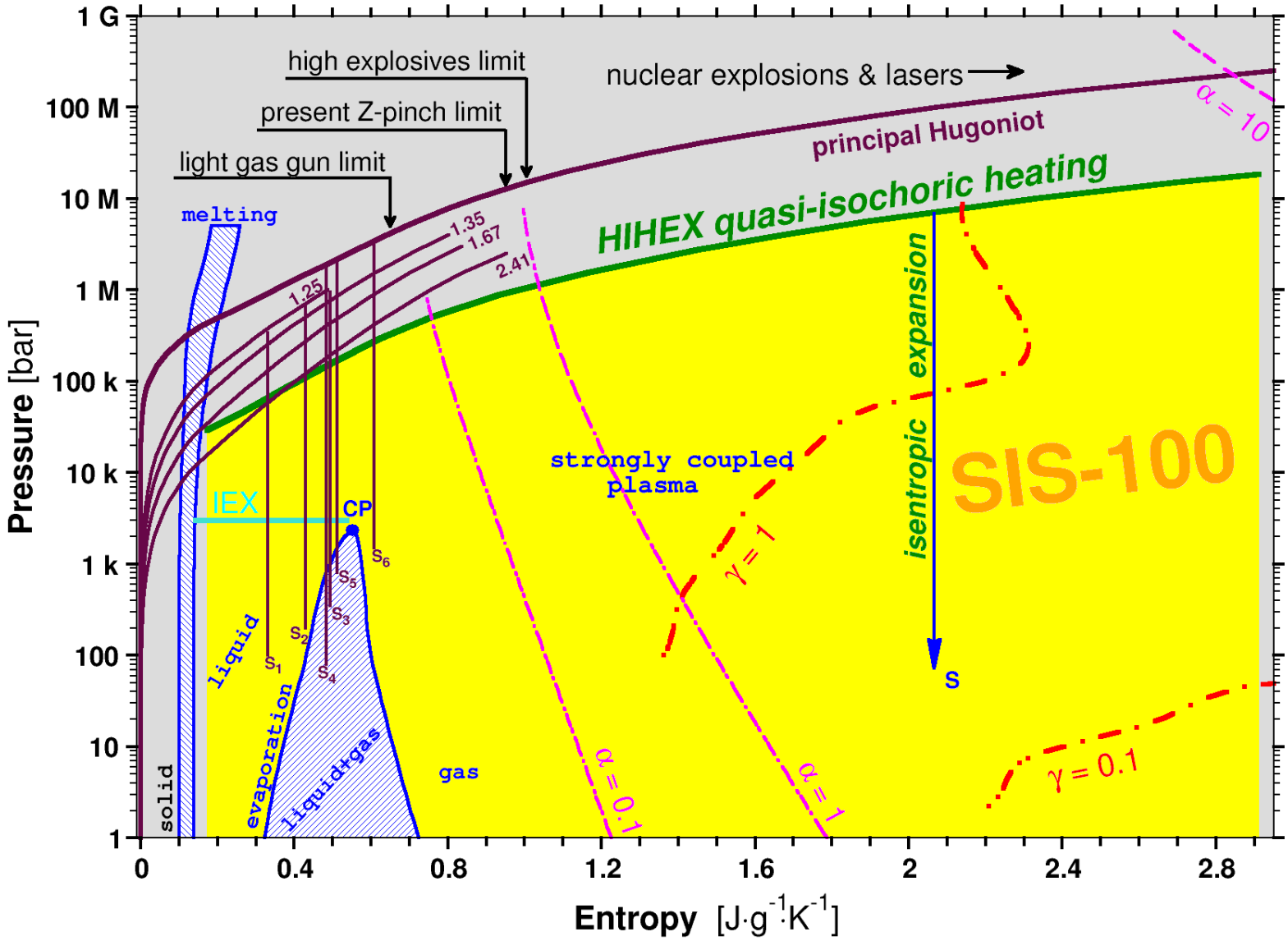
WDM Experimental Area on ITEP-TWAC Facility

Developed and constructed at present time in ITEP project of the TeraWatt ACcelerator complex (TWAC) has unique possibility to accelerate and accumulate intense proton and heavy ion beams in energy regime of the hundred of the MeV/u [Alexeev N.N., Koshkarev D.G., Sharkov B.Yu., First start-up of the ITEP-TWAC accelerator, ZhTPh Lett., vol.6, 2002.].

For carrying out experiments on the Warm Dense Matter (WDM) research program and for investigations in a field of the radiation and medical physics was designed and assembled ion-transport channel with exacting requirements on the vacuum and on the transporting ion beam quality.

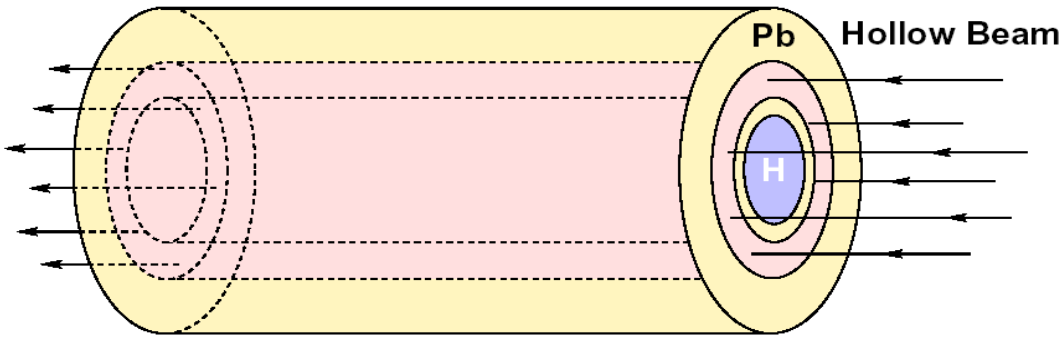


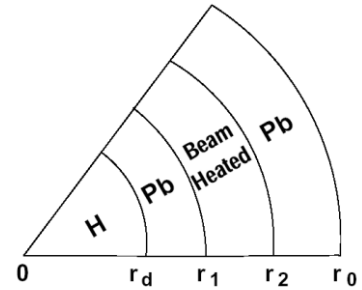
"Terra Incognita" regions of the phase diagram accessible in **HEDgeHOB** experiments at FAIR

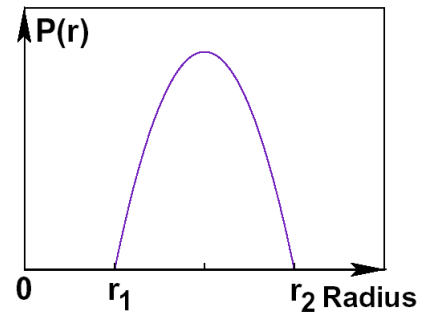


D.H.H. Hoffmann, V.E. Fortov et al. Phys. Plasmas 9 (2002) 3651.

Low entropy compression





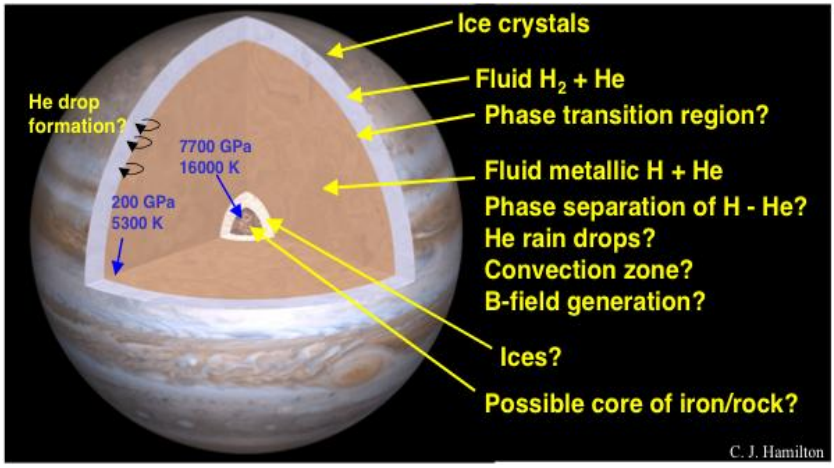


Target Parameters	Beam Parameters
r_d = 0.4 mm	2.7 GeV/u Uranium
r_1 = 0.6 mm	N =0.2 – 1.5 x 10^{12}
r_2 = 2.1 mm	τ = 20 ns
r_0 = 3.5 mm	E_b = 21 – 155 kJ
L = 1.0 cm	R_{ion} = 5.9 cm

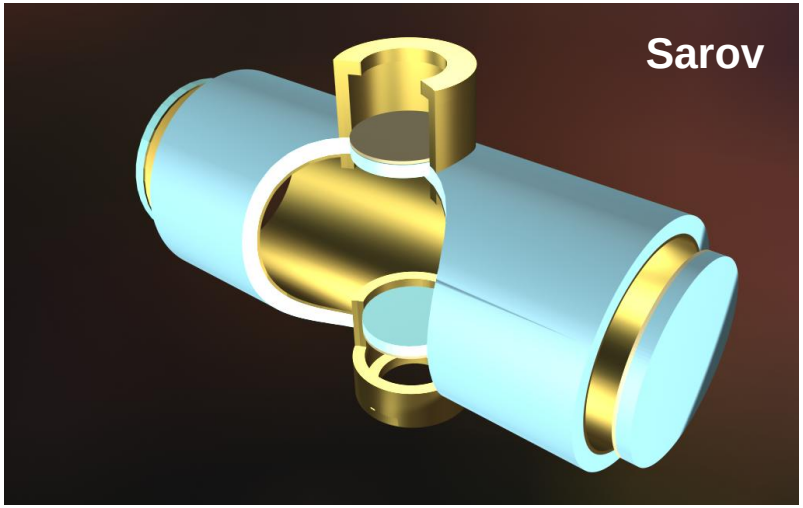
$\rho = 1 - 2\ g/cm^3$

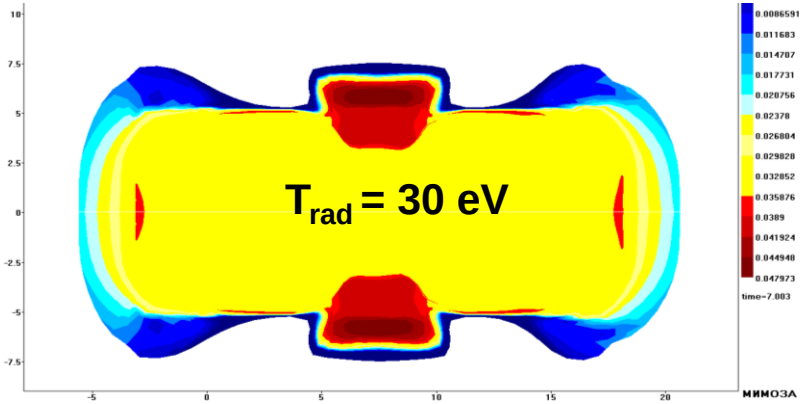
P = 2 – 10 Mbar

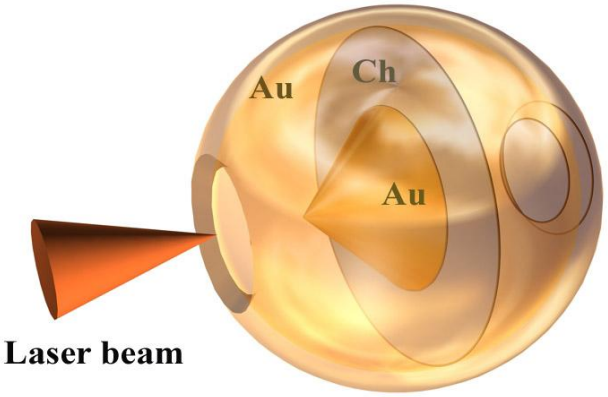
T = 0.2 – 0.6 eV



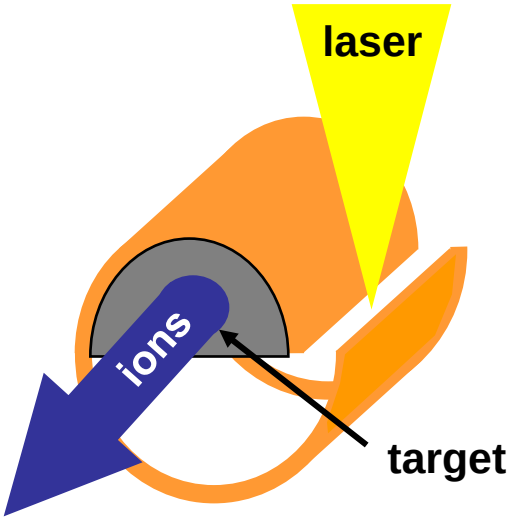
Various design of Hohlraum targets







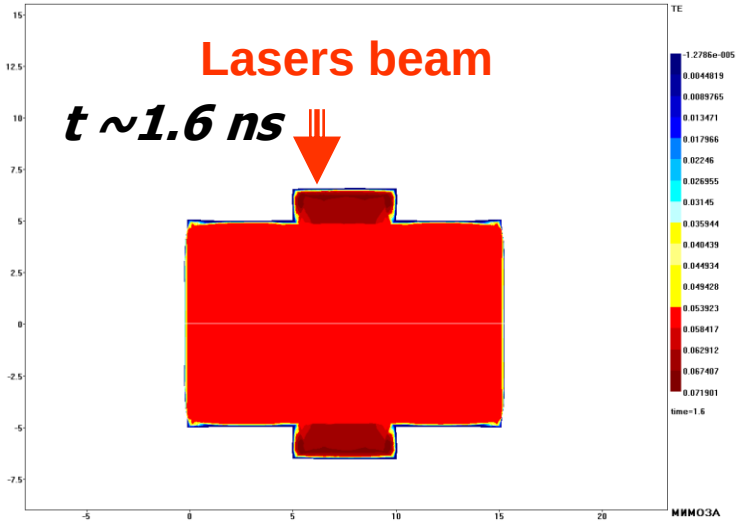
Type of Asterix target as x-ray source for Hohlraum target (GSI proposal)

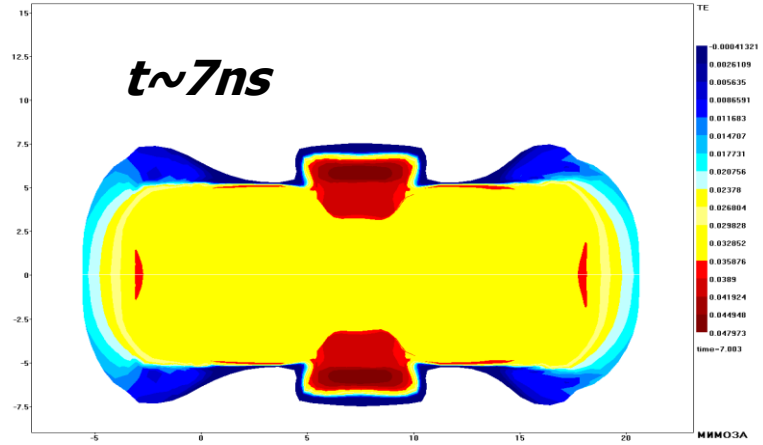


Basko

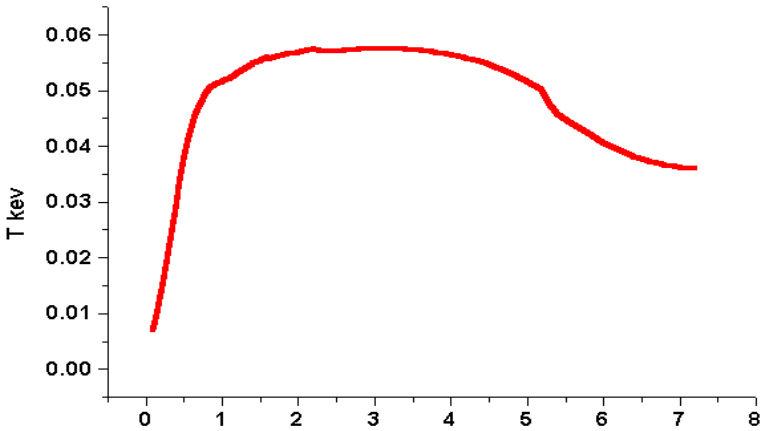
Numerical simulations: Y.Belyakov et al., Sarov
Maruhn, Frankfurt
Basko, Moscow

Results of 2D calculations (O. Vinokurov) for Phelix conditions (E_{laser}~1 kJ, dt~ 1 ns, ρ_{CH}~0.02 g/cm^3)

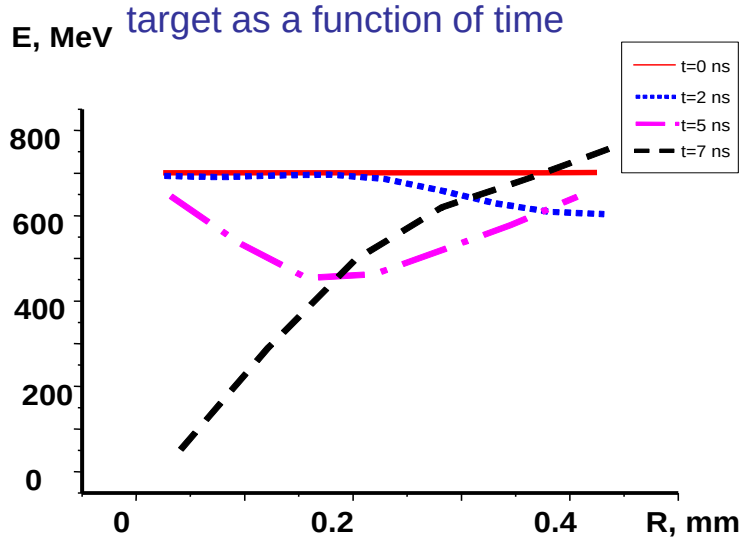




Temperature distribution inside the target



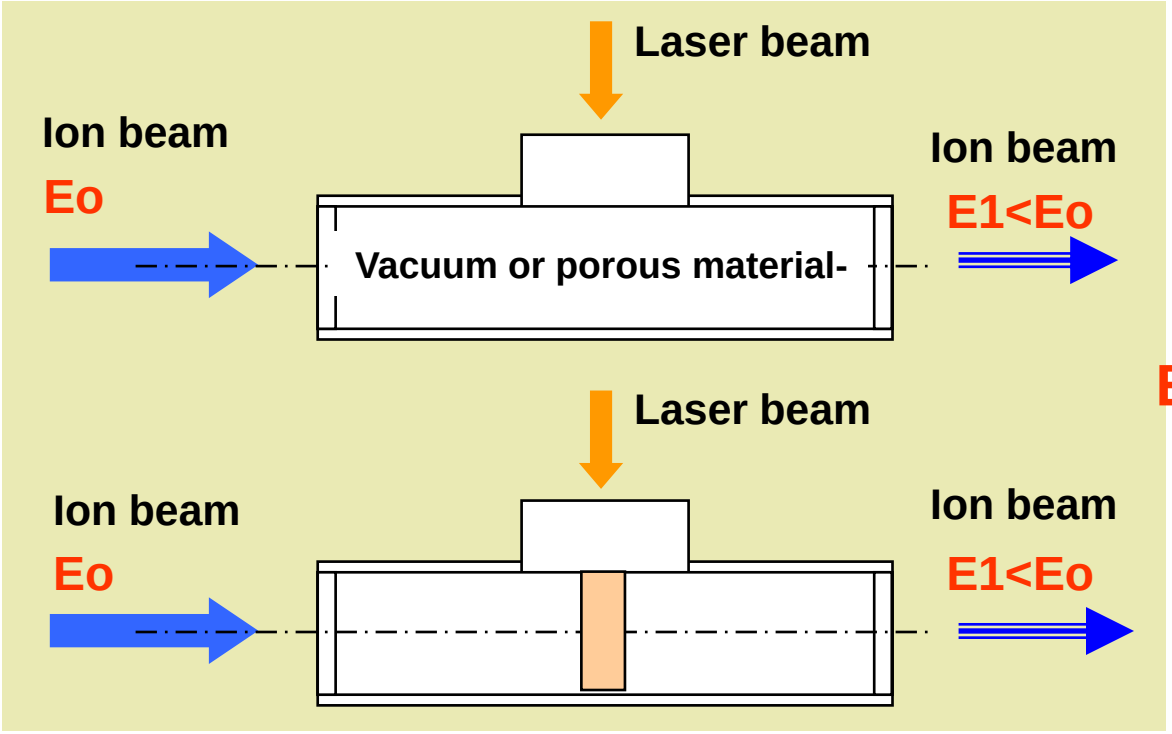
Plasma temperature inside the target as a function of time



Ion energy behind the target as a function of the target radius for different moments

Indirect target design for investigation of ion stopping in plasma targets (V. Vatulin, VNIIEF,1999)

In order to get clear experimental evidence of temperature effect on ion stopping in dense plasma, it is desirable that the target density is uniform and $\rho \cdot l$ *target* conserved going from cold to plasma target. It is also very important to determine plasma parameters accurately.

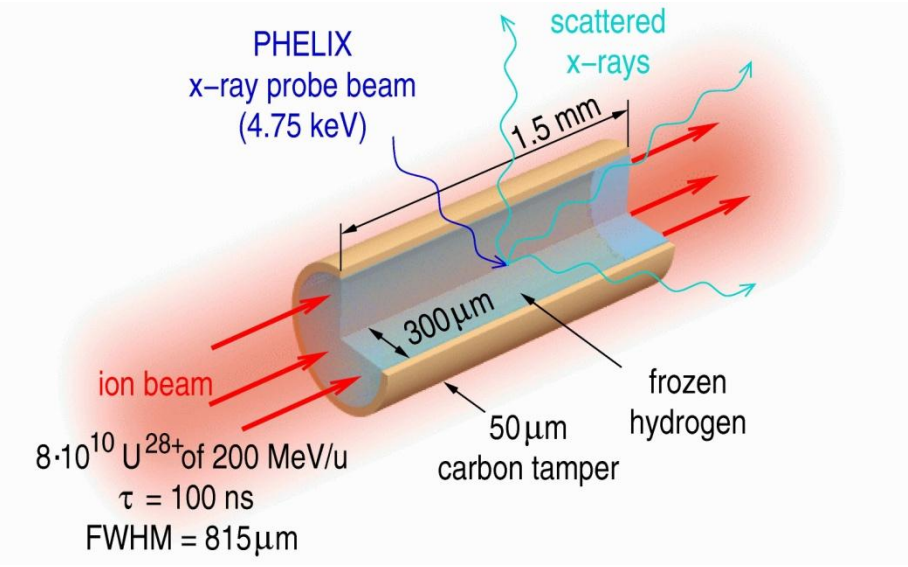


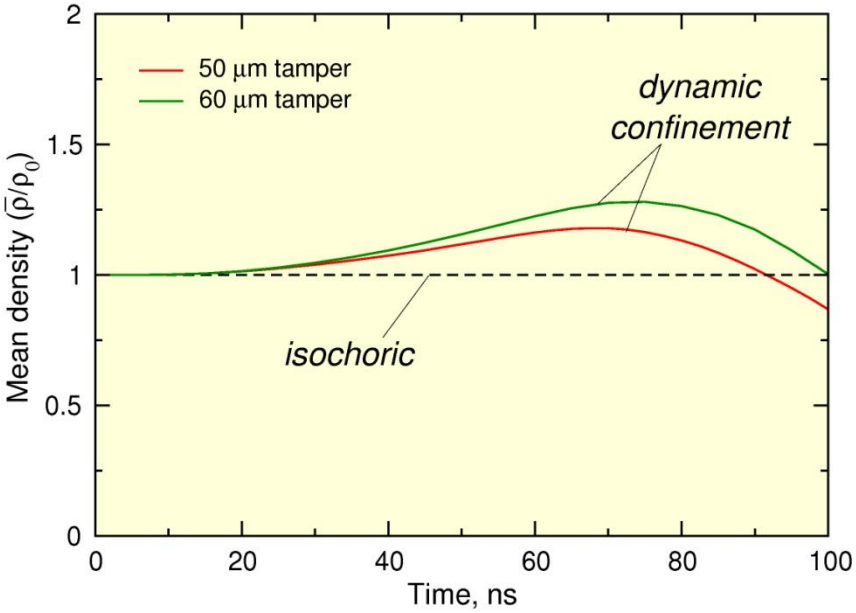
E1/Eo=?

X-rays generated by Phelix laser heat the main volume of the target.

Dynamic confinement of targets heated quasi-isochorically with heavy ion beams

A. Kozyreva[1], M. Basko[2], F. Rosmej[3], T. Schlegel[1],
A. Tauschwitz[3] and D.H.H. Hoffmann[1,3]



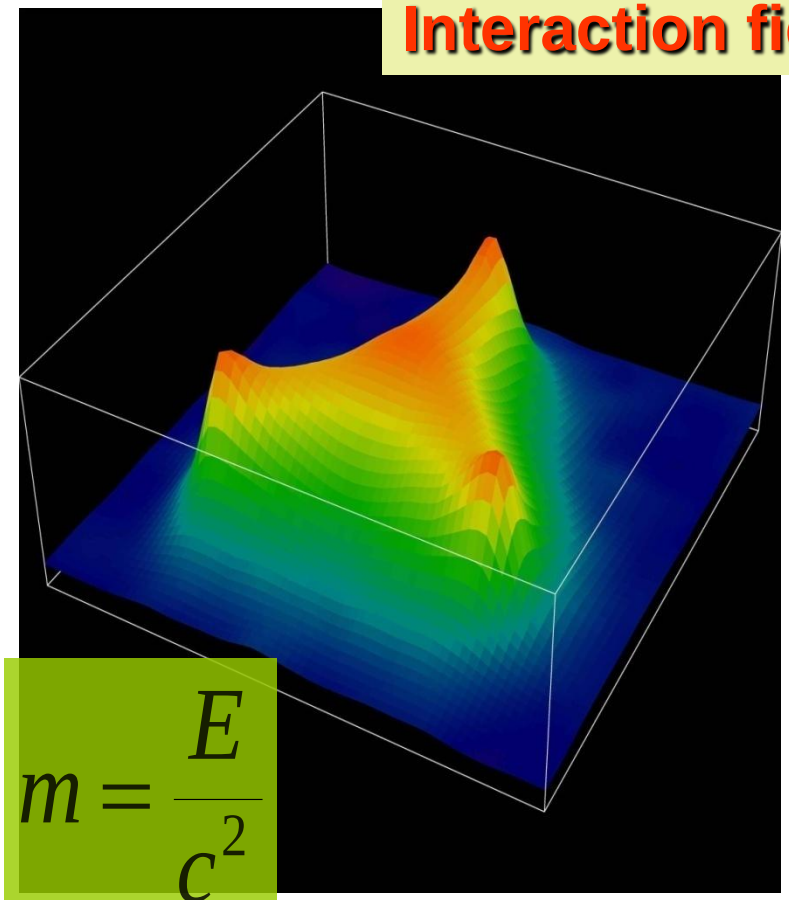


Target: Solid (cryogenic) hydrogen
For isochoric heating in at ε = 130 kJ/g → T = 0.64 eV (Warm Dense Matter regime)

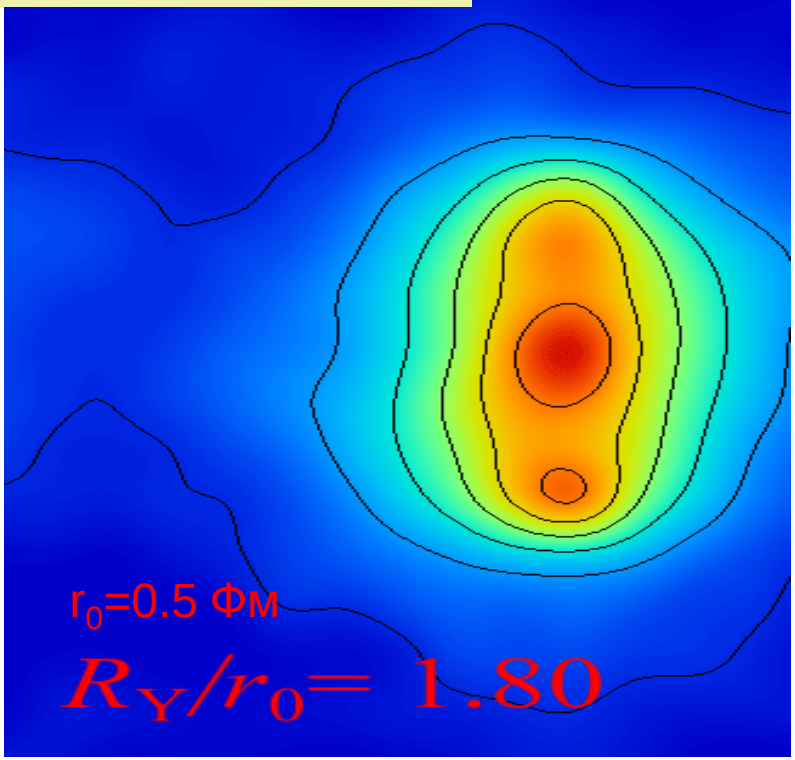
Фундаментальные исследования мирового уровня :

Кварк-глюонная плазма, структура “элементарных” частиц, «Невылетание цвета»

Interaction field inside a Hadron



$$m = \frac{E}{c^2}$$



Расчеты на Российских суперкомпьтерах МВС1000 и МВС15000, 10 Терафлоп*лет

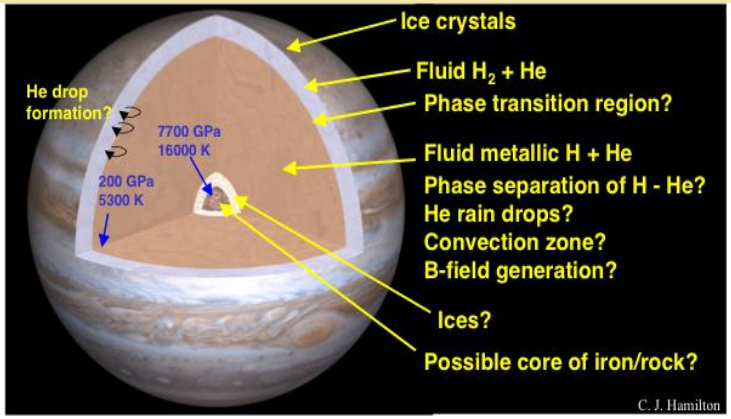
Extreme State of Matter for FAAE (Rosatom)

Mission :

to make AE more safe,

economically advantageous,

environmentally friendly



Matter in Universe: planetary and stellar structure

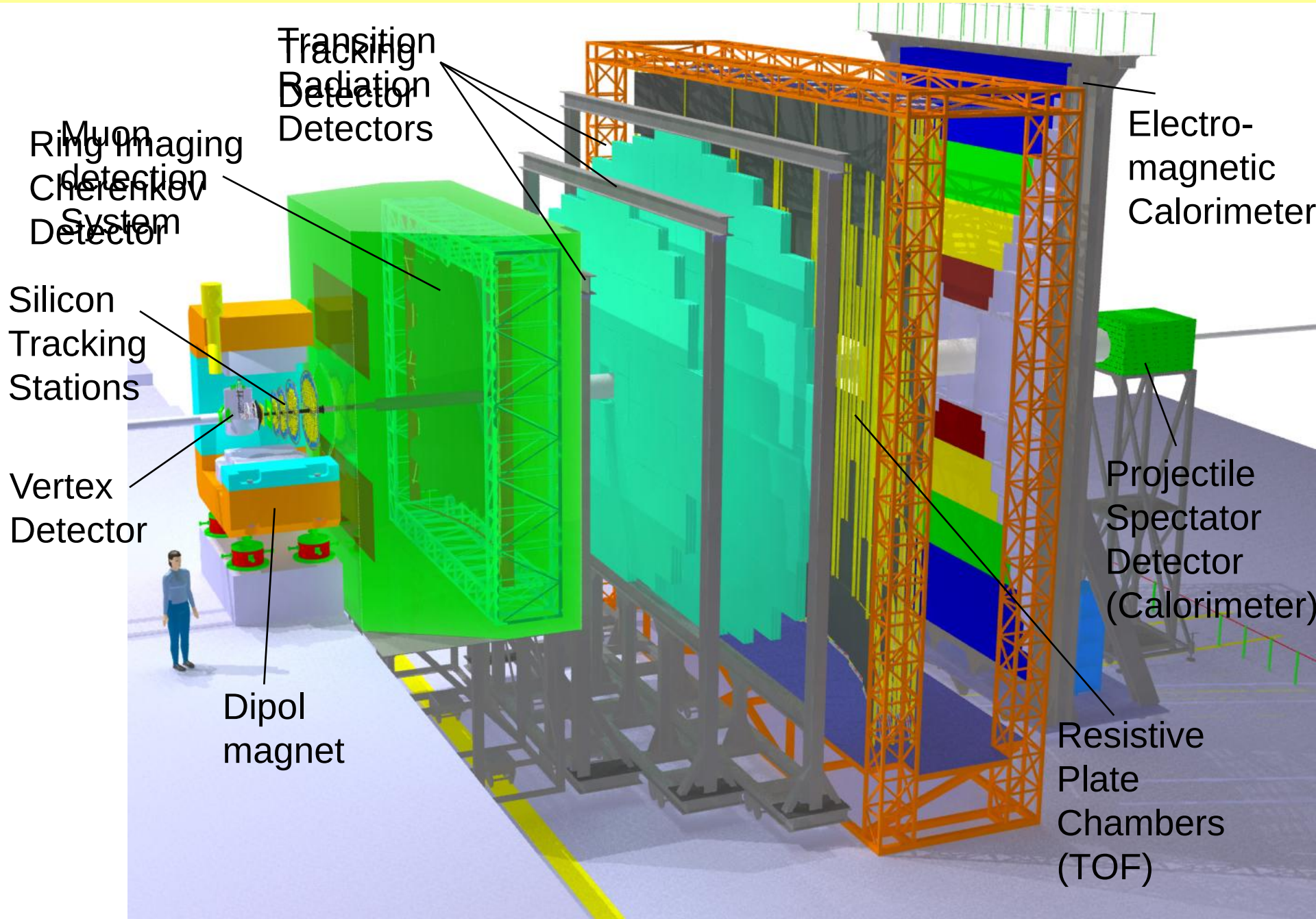
Atomic energy

Stockpile stewardship

"We have to know at least ten times more in basic physics than it's pragmatically necessary to resolve technical problems".

acad. Y.Khariton

The Compressed Baryonic Matter Experiment



Mass Modification in Medium

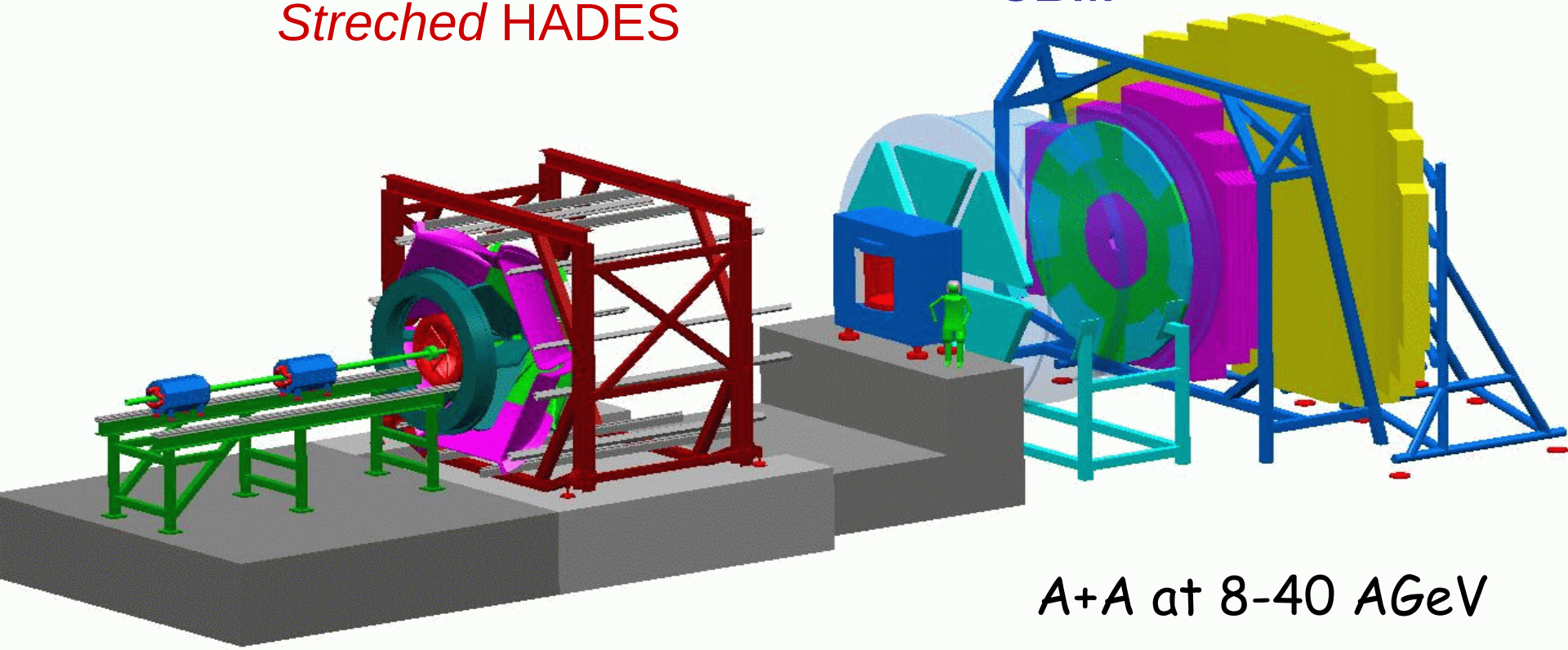
CBM - >400 уч.,15 стран
54 (12) инст,

The nuclear reaction experiments at the future facility at GSI

ITEP,IHEP,JINR…

CBM

Streched HADES

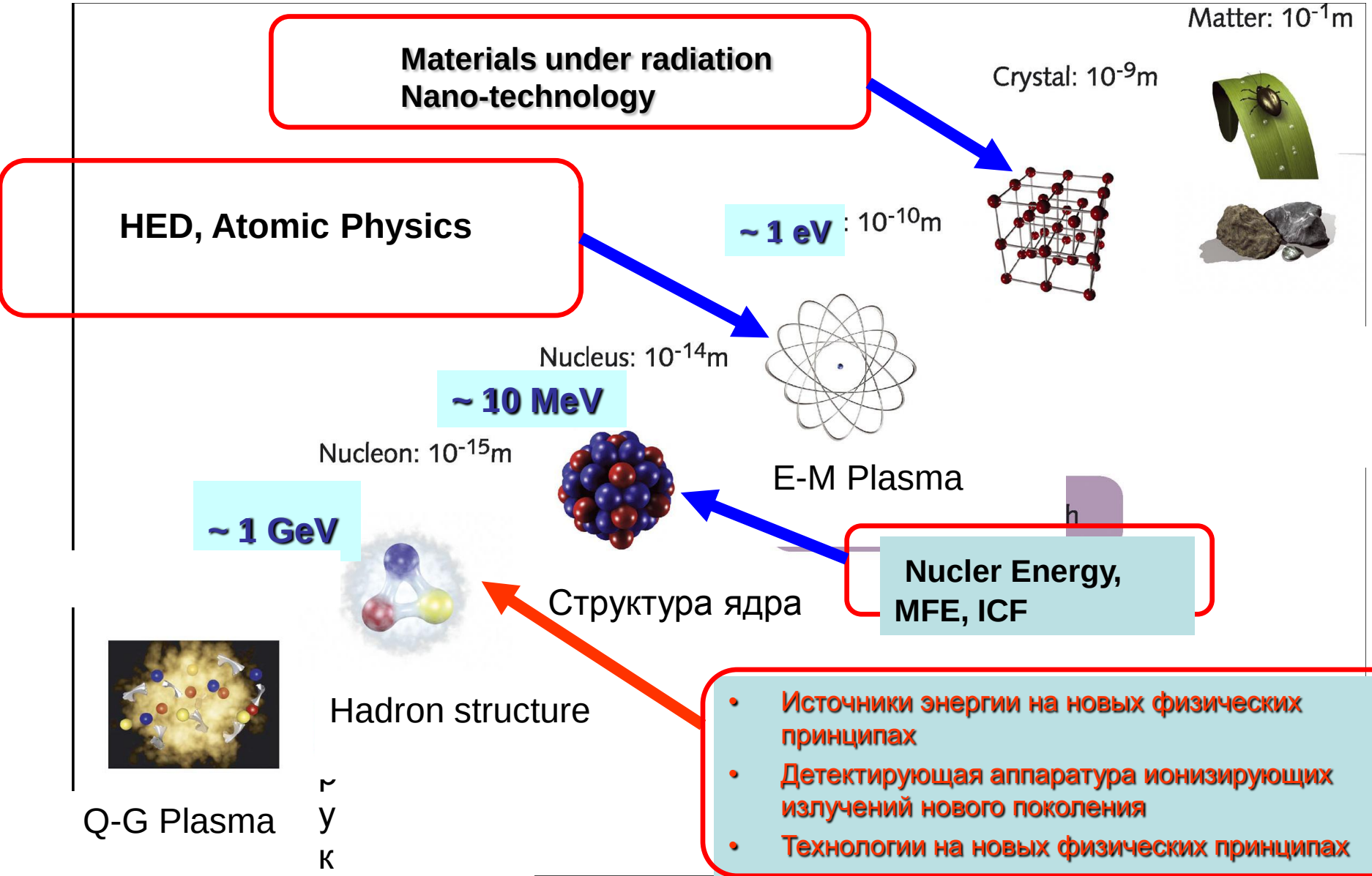


A+A at 8-40 AGeV

A+A at 2-8 AGeV

At 10^7 interactions per second!!

Basis for technology break-through



- Источники энергии на новых физических принципах
- Детектирующая аппаратура ионизирующих излучений нового поколения
- Технологии на новых физических принципах

Power Plant Design and Accelerator Technology for Heavy Ion Inertial Fusion Energy Nucl. Fus. 45 (2005) 5291-5297