



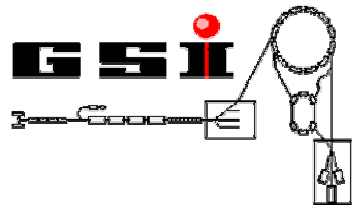
Basic Physics for Inertial Fusion Energy in High Energy Density Physics with Intense Heavy Ion and Laser Beams.

***“Present and future prospects of high energy
density in matter research at GSI”***

*Dieter HH Hoffmann
GSI & TU Darmstadt*



High Energy Density Physics with Intense Heavy Ion and Laser Beams at GSI- Darmstadt



Plasma Physics Group
at GSI & TU Darmstadt

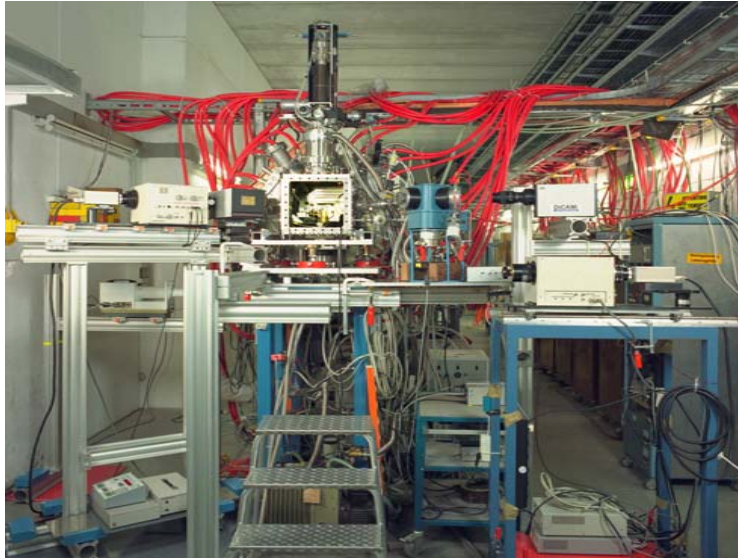


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Collaborators and Collaborations



V. Arsov, A. Blazevic, R. Bock, E Brambrink
C. Constantin, E. Dewald, E. Gaul, M. Geißel
S. Hakuli, J. Jacoby, R. Knobloch, A.
Kozyreva, Th. Kühl, T. Merz, C. Niemann, V.
Orsic, D. Penache, P. Pirzadeh, F. Rosmej,
G. Rodriguez –Prieto, O. Rosmej, M. Roth, T.
Schlegel, S. Samek, G. Schaumann, B.
Schuster, M. Schollmeier, F. Schrader, I.
Strachnov N. Tahir, A. Tauschwitz, S. Udrea,
D. Varentsov, H. Wahl, K. Weyrich, J. Wieser,
P. Wiewior, M. Youssef, E. Zouzouris

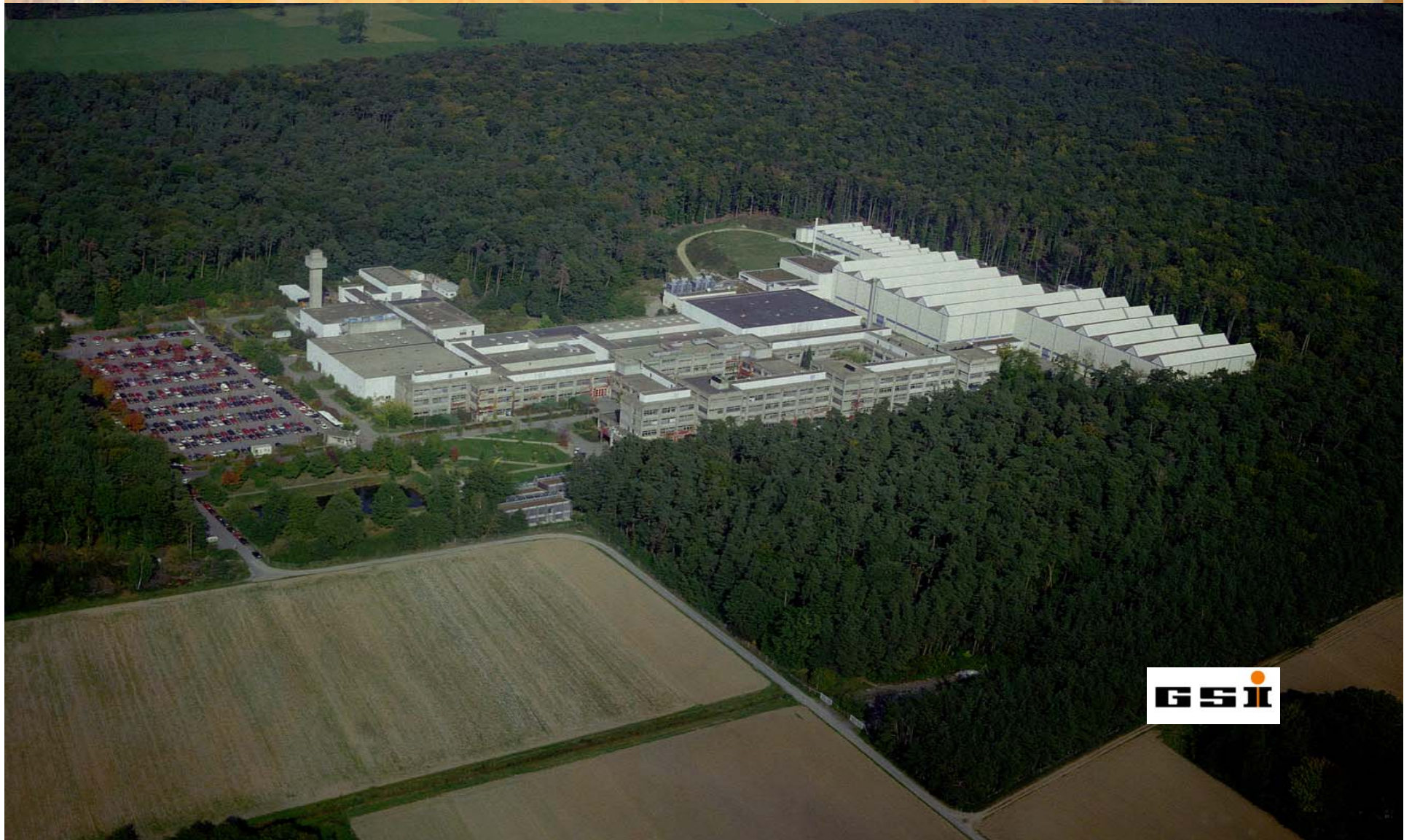


Collaborations:

TU Darmstadt, Univ. Erlangen, Univ.
Frankfurt, Univ. Jena, Univ. Rostock
Univ. Greifswald, Univs. München, Univ.
Naples, Univ. Castilla La Mancha, MPQ
Garching, HMI Berlin, MBI Berlin, LBNL,
Berkeley, VHIFNL Berkeley, LLNL
Livermore, TITech Tokyo, ITEP, Moskau
IPCP Chernogol., VNIIEV Sarov, LULI
Paris, CLRC Rutherford, Weizmann Inst
Israel, Queens Univ. Belfast, Univ.
Marseille,

Gesellschaft für Schwerionenforschung GSI

in der Helmholtz-Gemeinschaft



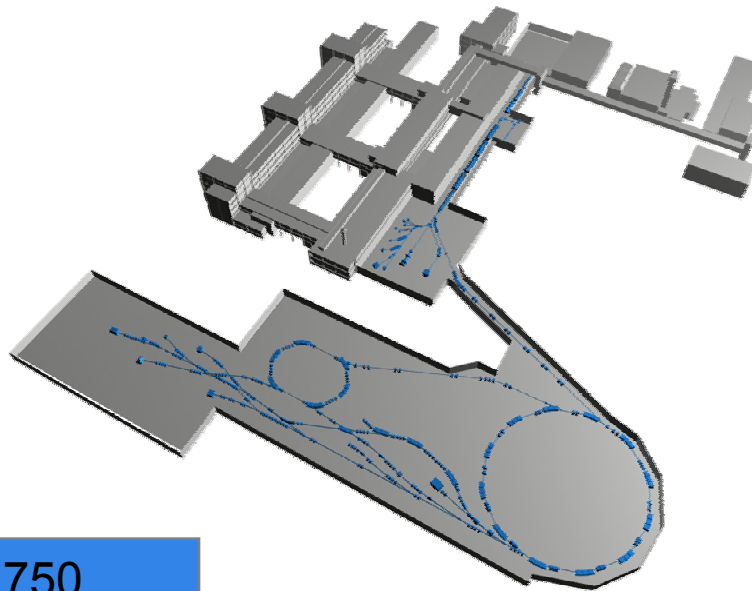
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GSI Overview

Budget: 70 Mio €
90% Federal, 10% State
Hessen

External Users: 1000
600 Germany, 400 abroad

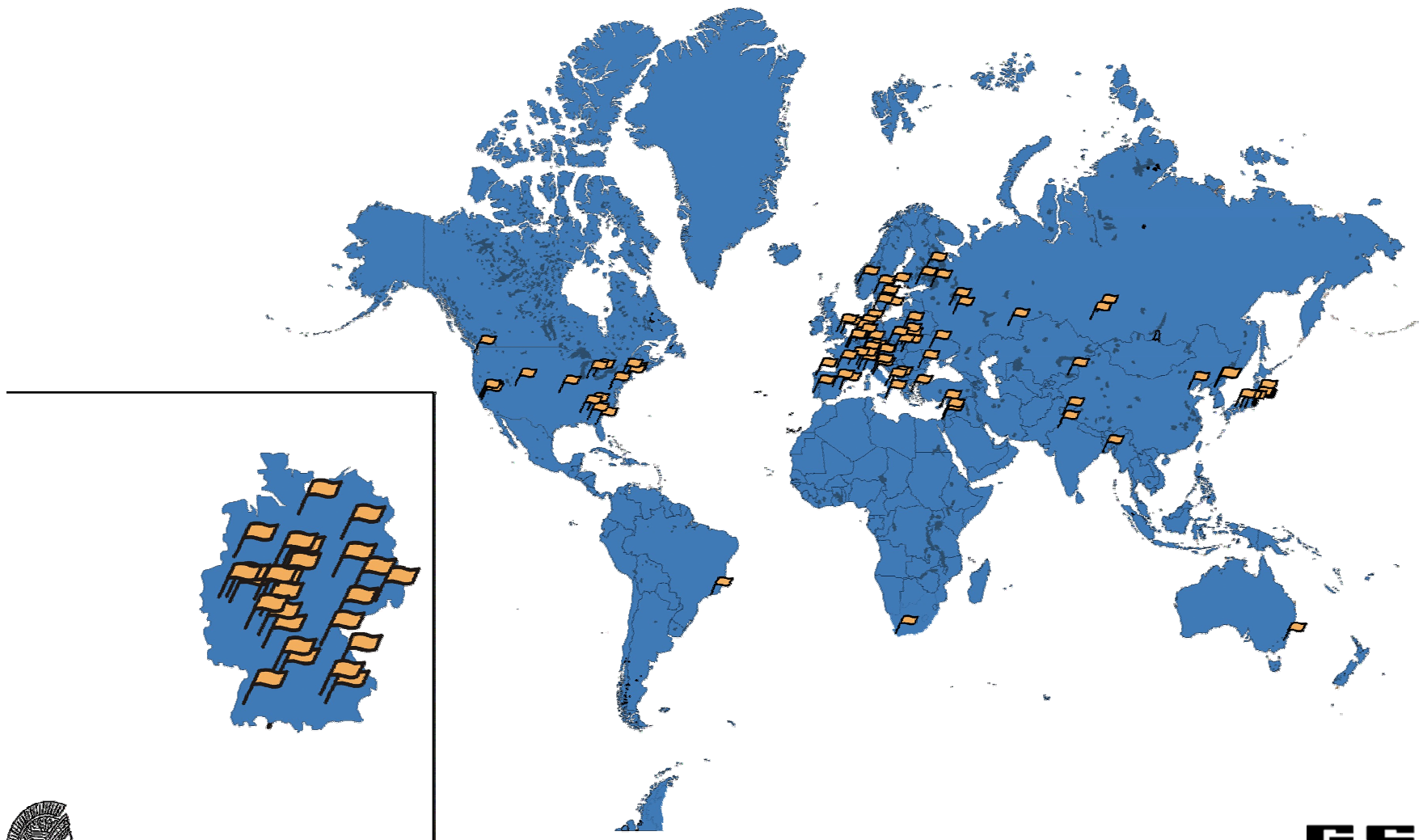


Employees: 750
(300 Scientists and
Engineers)

Large scale facility:
Accelerator
25 Expts. sites



Worldwide GSI Cooperations



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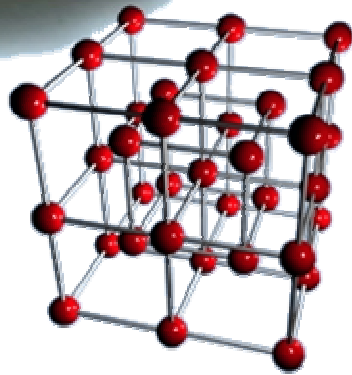


Building blocks of matter

Materie



Kristall



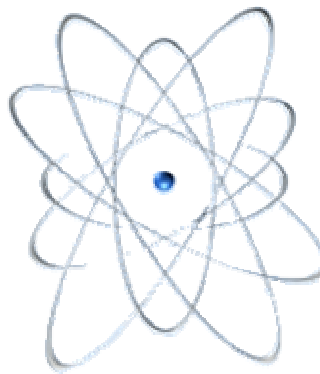
10^{-3} m
(makroskopisch)

Zelle



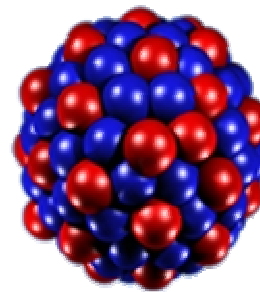
10^{-5} m

Atom



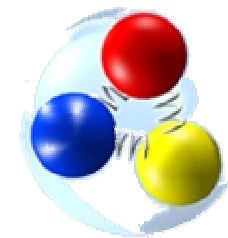
10^{-10} m

Kern



10^{-14} m

Nukleon



10^{-15} m

Elektron



Quarks



$< 10^{-18}$ m

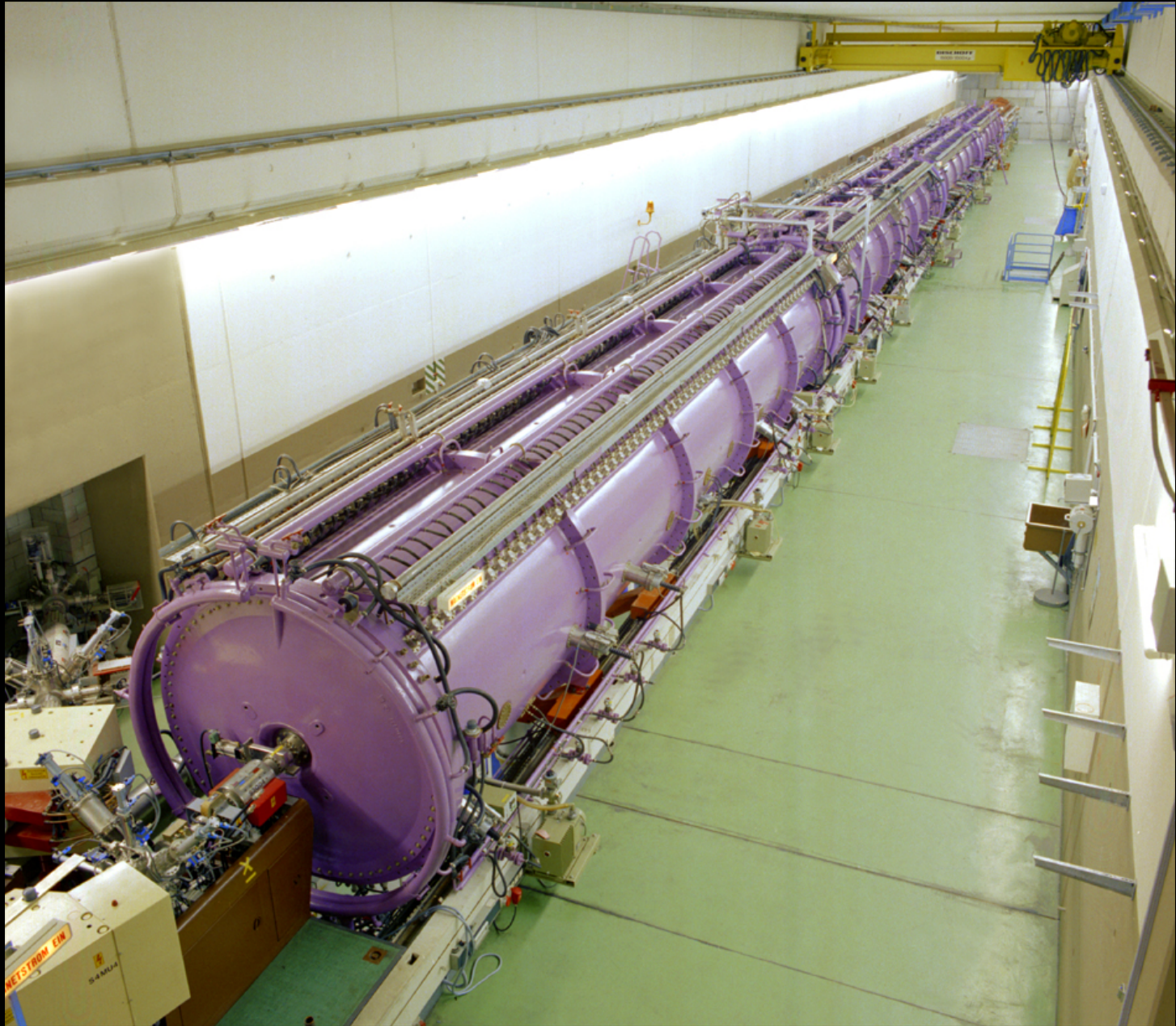


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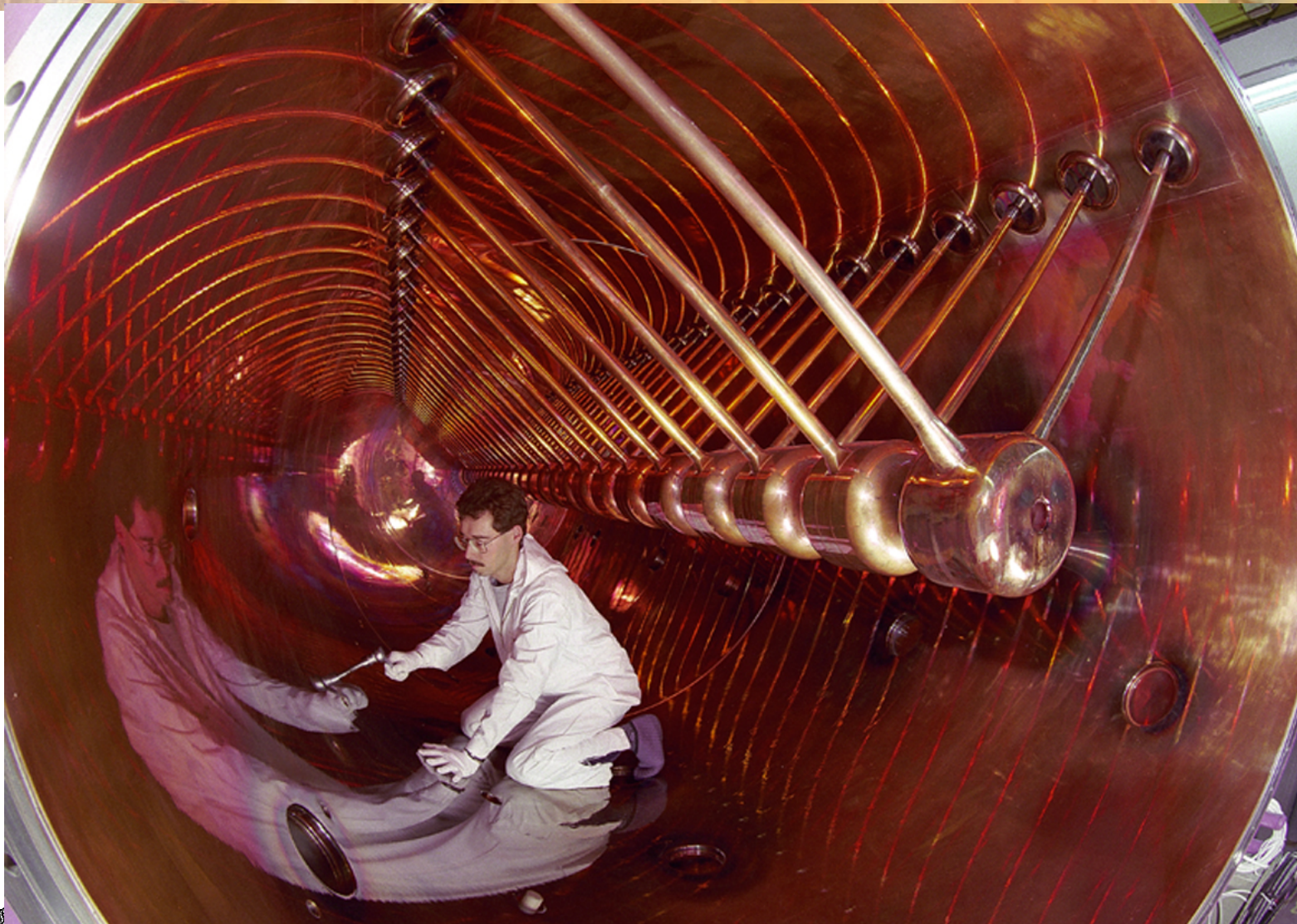
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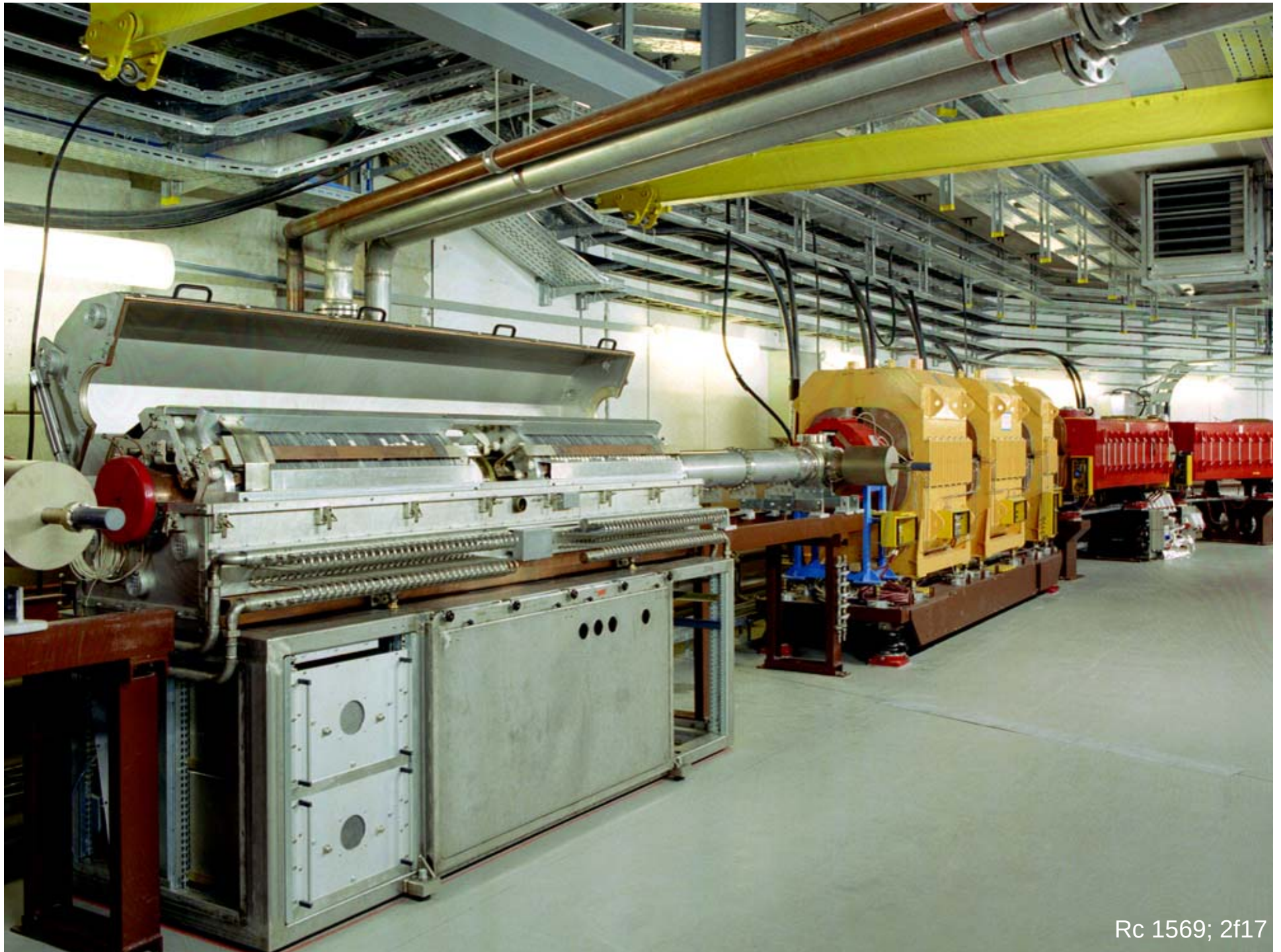
GSI

Rc 259; 2f11

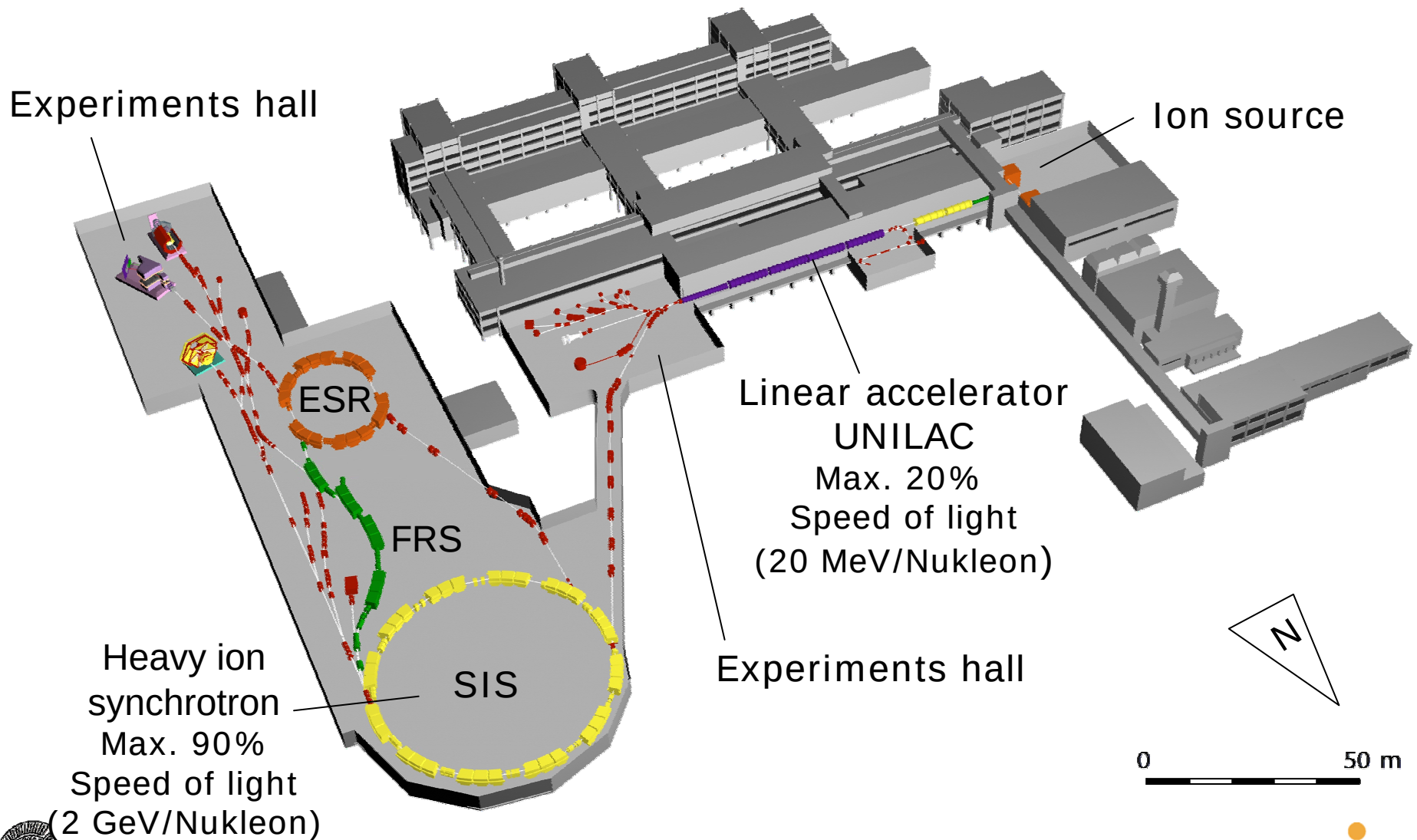








Existing Accelerator Facility



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GSI

Elements periodic system

I																	VIII						
H 1																			He 2				
Li 3	Be 4																	B 5	C 6	N 7	O 8	F 9	Ne 10
Na 11	Mg 12																	Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36						
Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54						
Cs 55	Ba 56	La* 57	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86						
Fr 87	Ra 88	Ac+ 89	Rf 104	Db 105	Sg 106	Bh 107	Hs 108	Mt 109	Ds 110	111 111	112 112		114 114		116 116								

+Actinoide

Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	No 102	Lr 103
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*Lanthanoide

Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
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 natürlich,
stabil

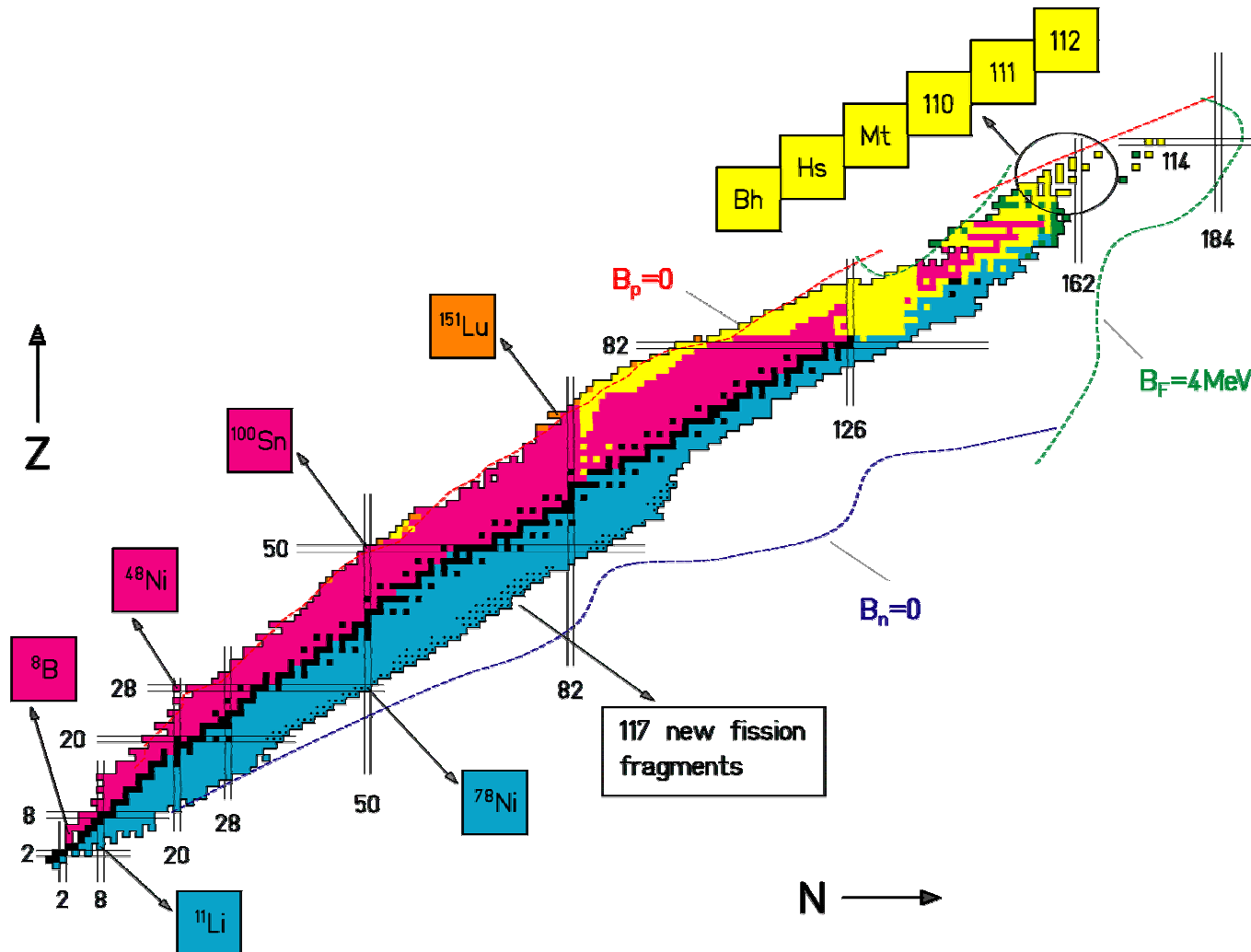
 natürlich,
instabil

 künstlich,
instabil

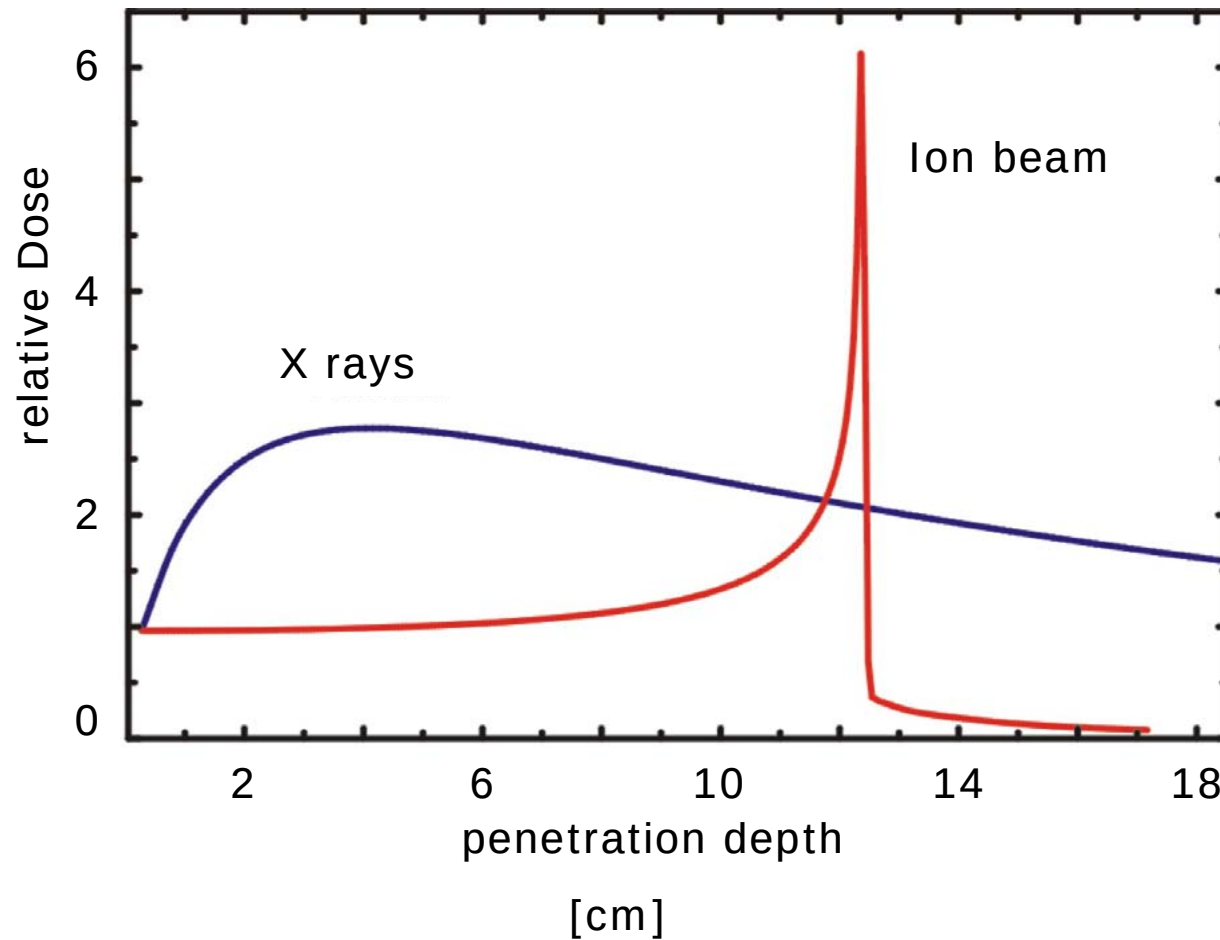
 bei GSI erzeugt,
instabil

☐ nicht bestätigt

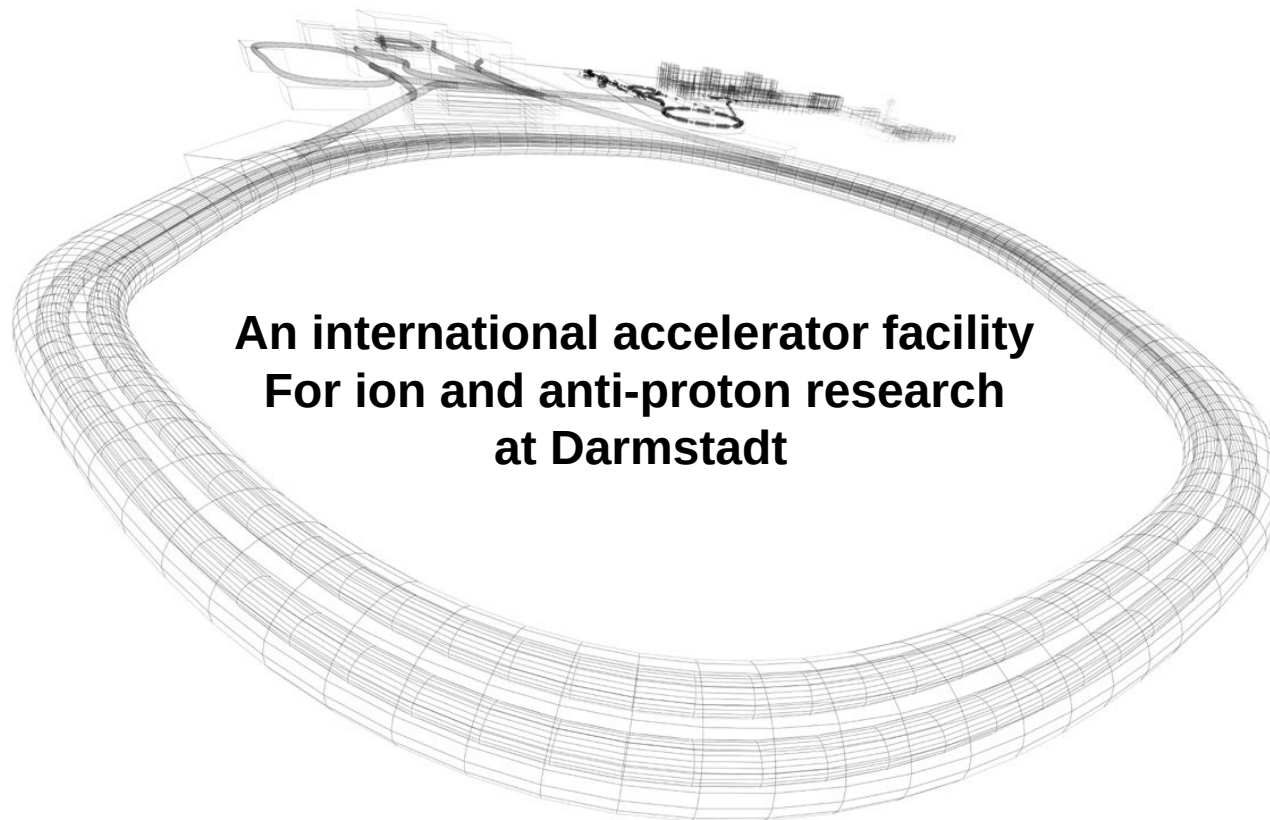
Chart of Nuclei



Radiation therapy – Dose comparison



Future Project of GSI

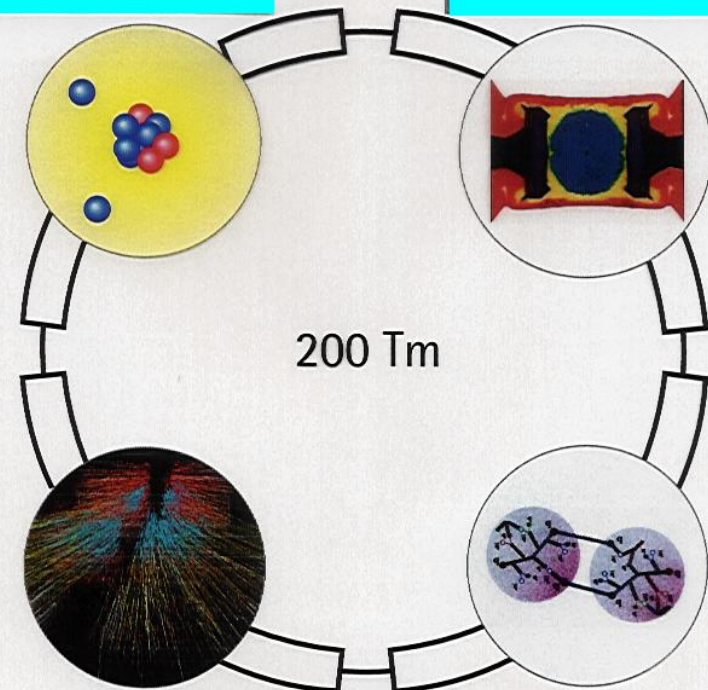


An International Accelerator Facility for Beams of Ions and Antiprotons

Conceptual Design Report

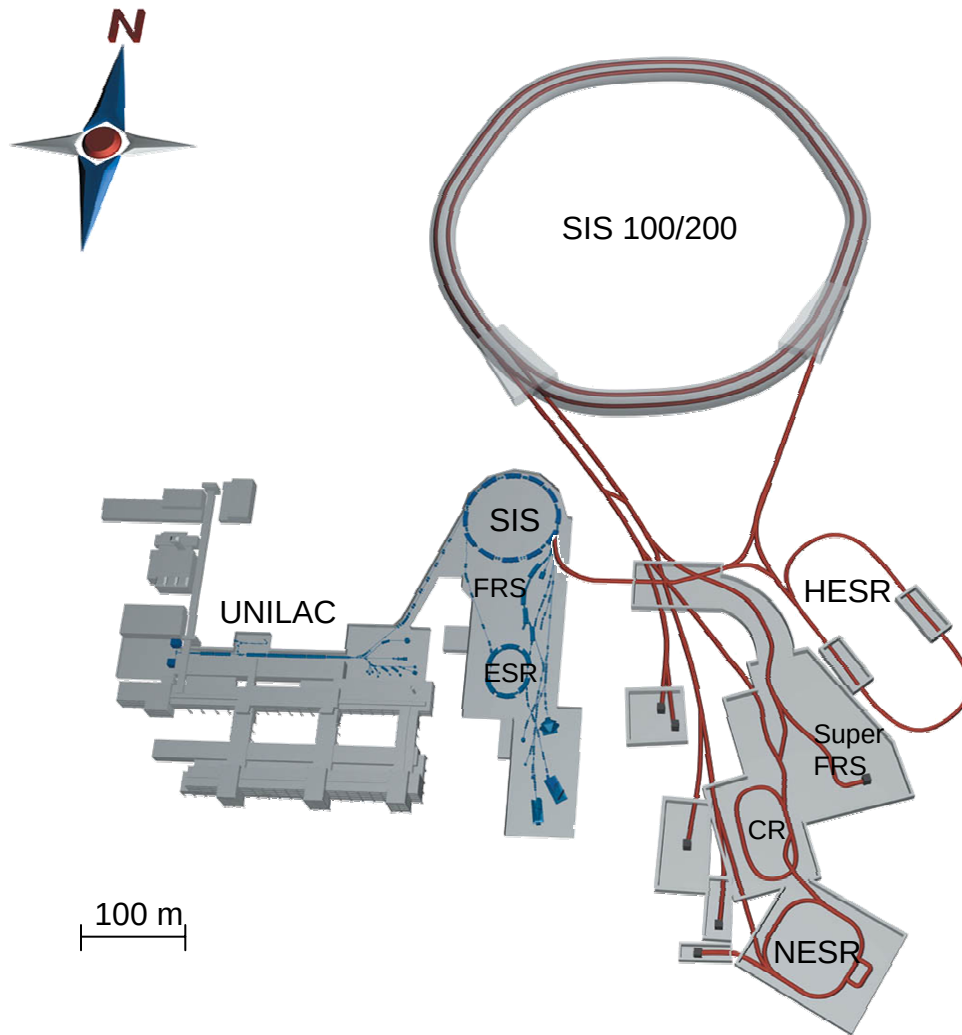
**Nuclear structure
with
intense beams of
short**

**High energy density
in
matter with intense
heavy ion beams**



**High energy
heavy ion
reactions
30 GeV/u**

**Intense proton
(30 GeV) and
cooled
antiprotons**



Novel beams

Exotic nuclei

Anti protons

Novel beam quality

Beam intensity

beamI-Precision

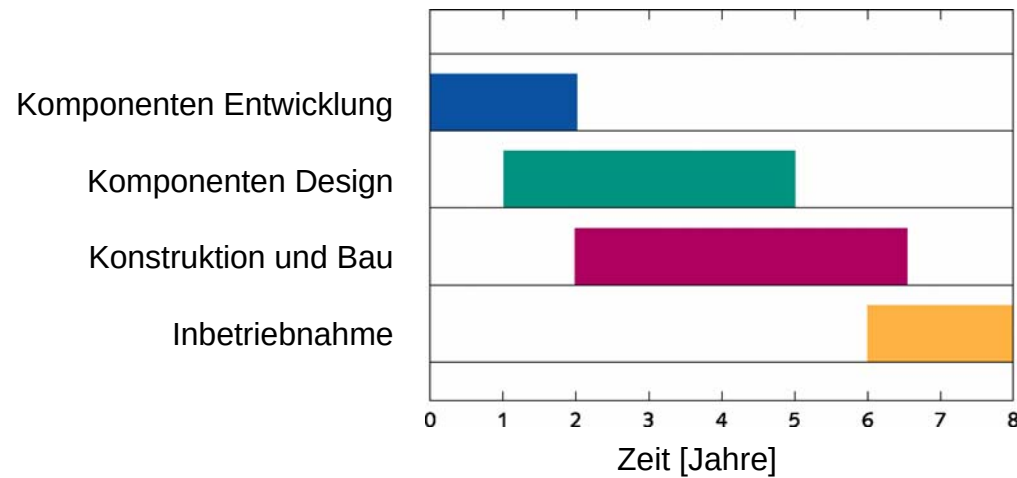




Costs

Building and infrastructure:	225 Mio. €
Accelerator:	265 Mio. €
Experiments / Detektors:	185 Mio. €
Total:	675 Mio. €

Time table



**An international accelerator facility for research
with ion- und antiproton beams**



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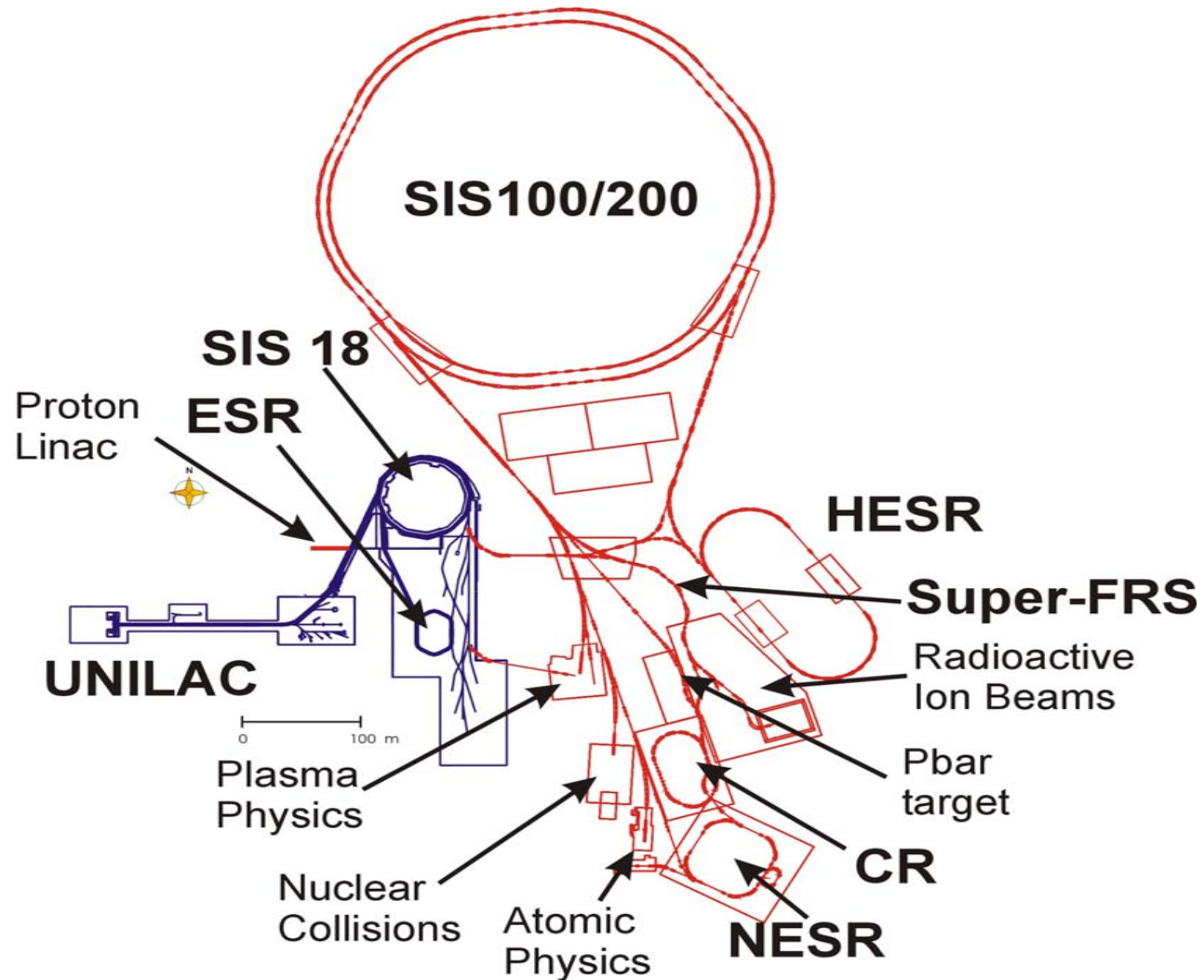


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Set-up of the new facility



Present and Future Facilities at GSI



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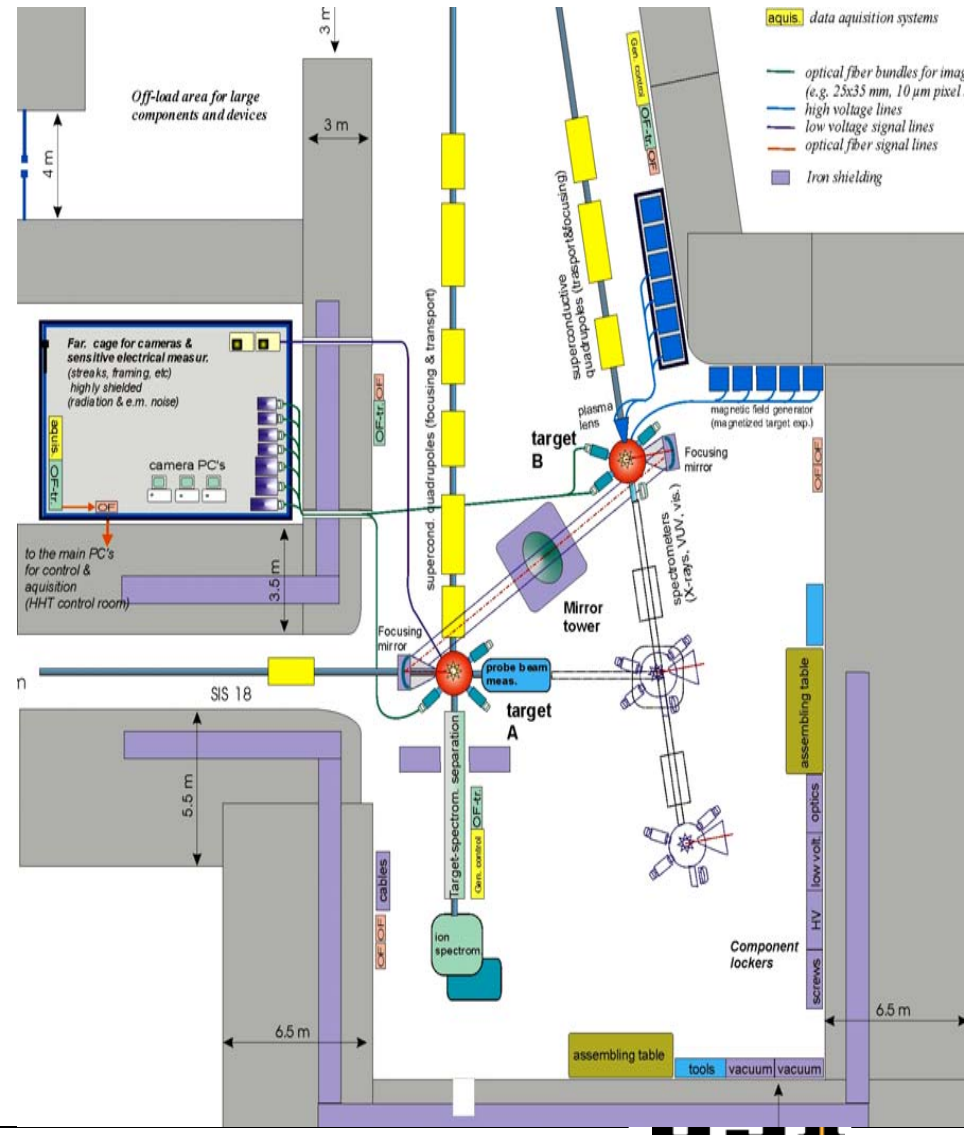
New Plasma Physics experimental area at SIS 100

**Ion beam intensity: 10^{12} U $^{28+}$ / ~ 50 ns
concentrated in $\sim 10^{-2}$ cm 3 $\rightarrow$ ~ 300 kJ/g**

supplemented by physics of beam-matter interaction, making possible the homogeneous volumetric isochoric heating regime

2. Combination of powerful PW laser + heavy ion beam

3. Advanced diagnostic methods



Expected Beam Parameters

SIS 100 (GSI)

$$N = 2 \cdot 10^{12} \text{ Uran} \quad \tau = 50 \text{ ns}$$

$$E_0 = 1 \text{ GeV/u} \quad E_{\text{tot}} = 80 \text{ kJ}$$

Range (Pb) $\approx 1.55 \text{ cm}$ beam radius $\approx 0.05 \text{ cm}$

$$E_s = 600 \text{ kJ/g} \quad P_s = 12 \text{ TW/g}$$



Heavy Ion Beams at GSI



SIS18



200-1000 MeV/u

$4 \times 10^9 - 10^{10}$

~300 ns

~1-3 kJ/g

SIS100



400-2700 MeV/u

10^{12}

<100 ns

300 kJ/g

2×10^{11}

<100 ns

20-30 kJ/g

uniform volume heating



Specific Energy Deposition E_s

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

Effective Heating Time t_H

$$t_H \propto \left(\frac{L^2}{P} \right)^{1/3}$$

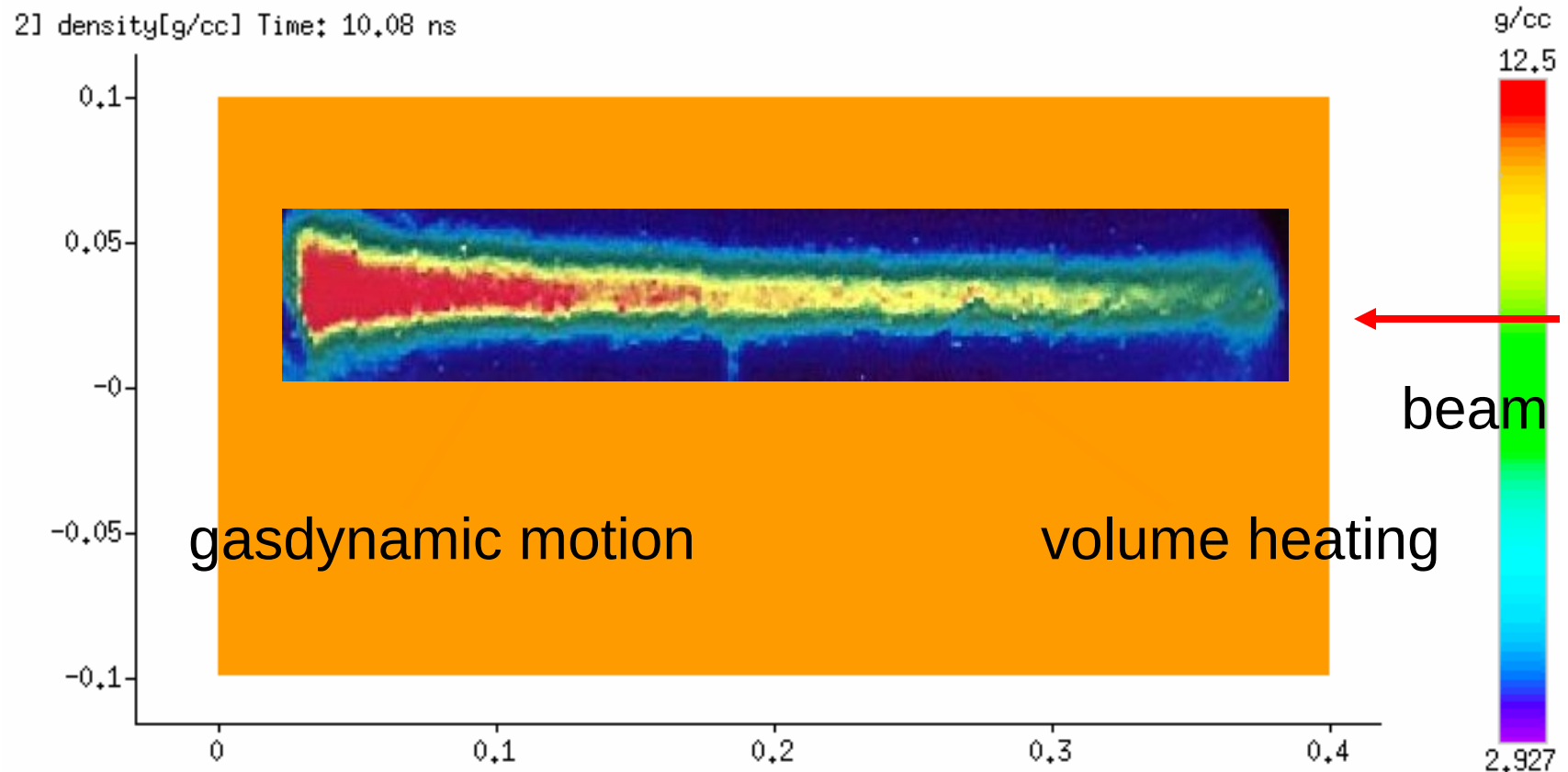
Specific Power Deposition P_s

$$P_s = E_s / t_H$$

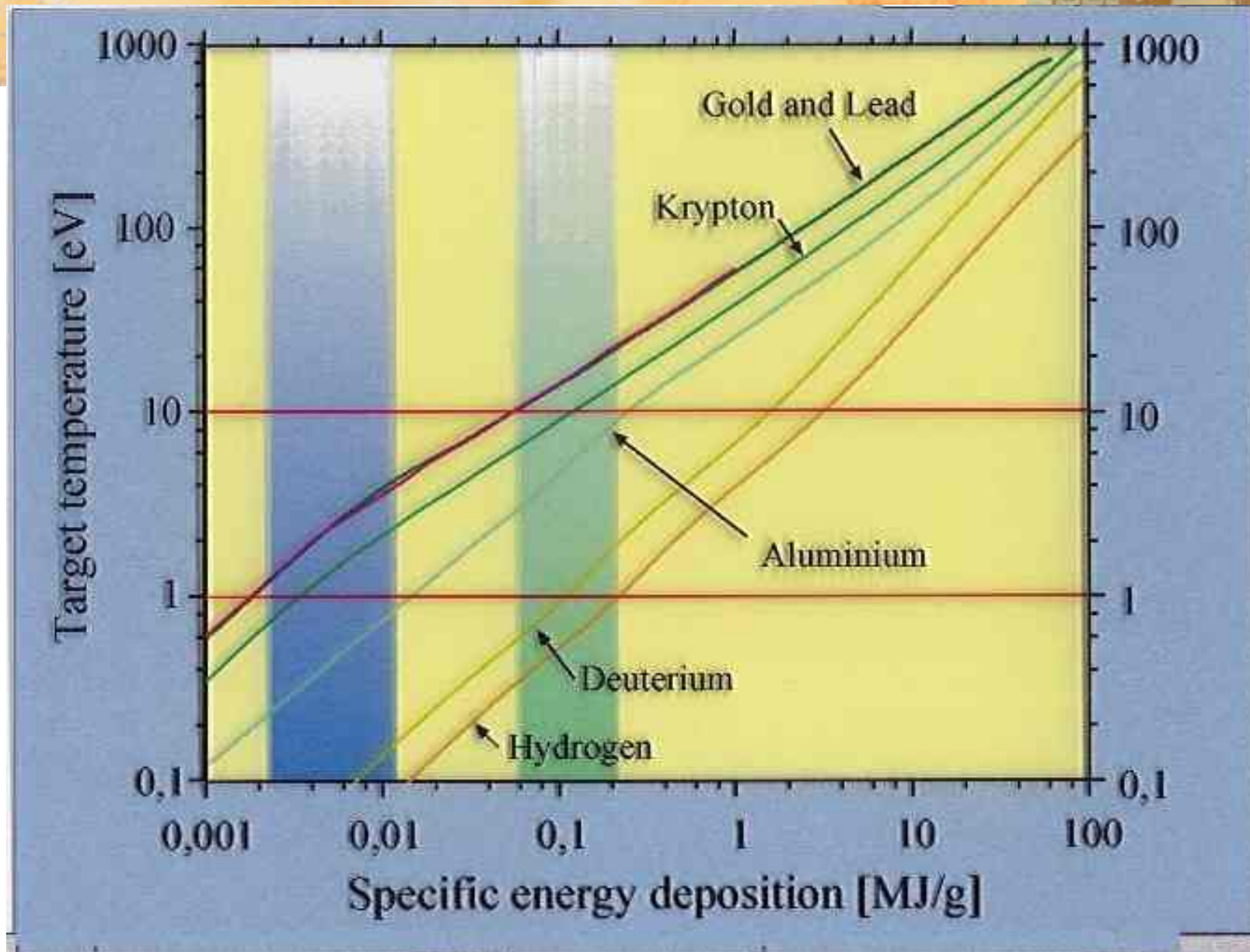


Heavy ion beam & target

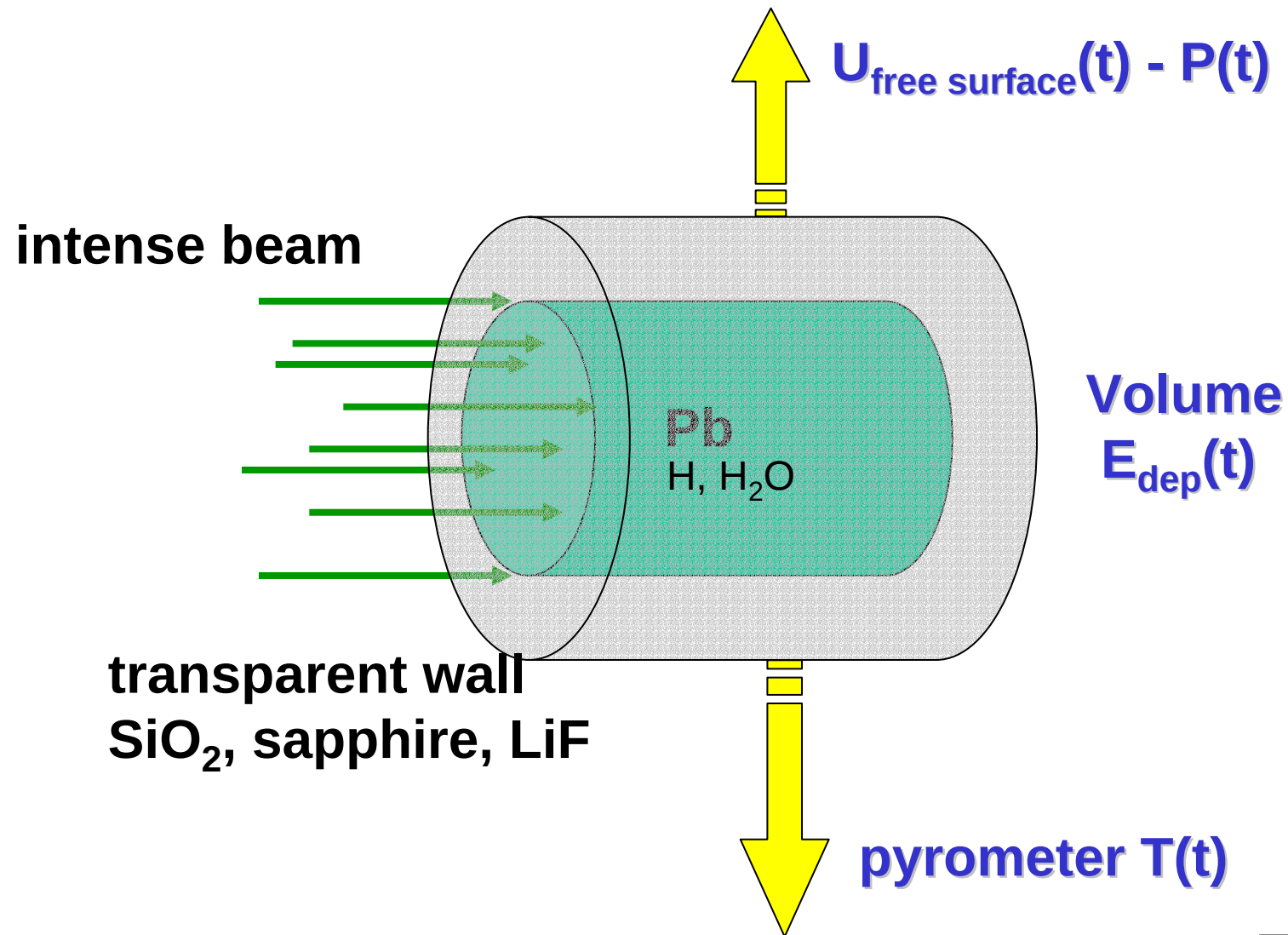
target



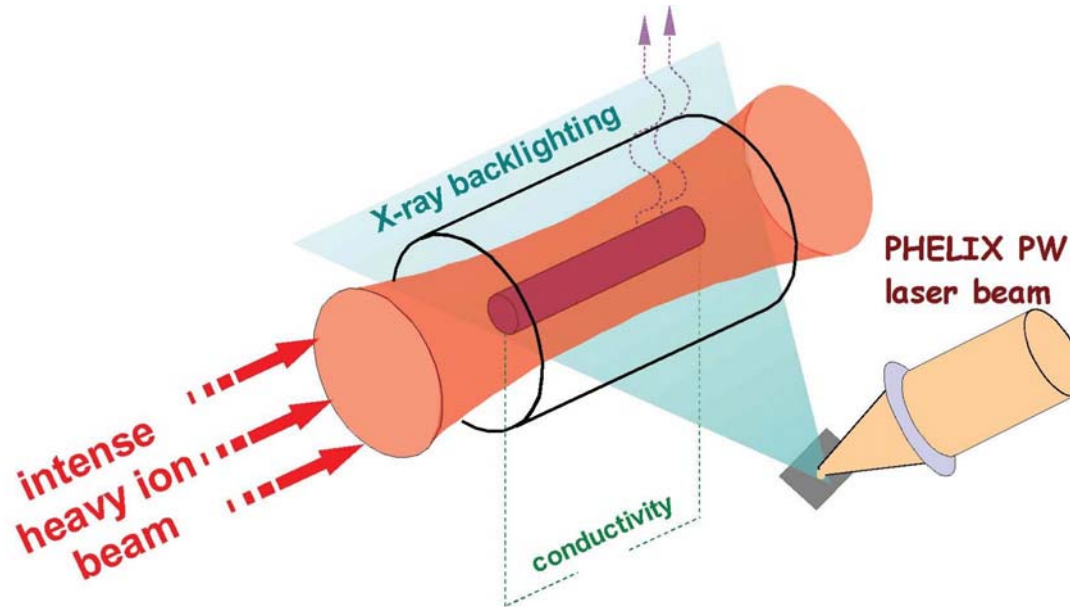
Heating Matter with Heavy Ion Beams



Diagnostics



Future experiments



Parameter:

- temperature

- density/volume

- mass velocity/pressure

- conductivity

- deposited energy

Diagnostics:

⇐ fast 6-channel radiation pyrometer

⇐ shadowgraphy, γ & p radiography
(with PHELIX backlighting)

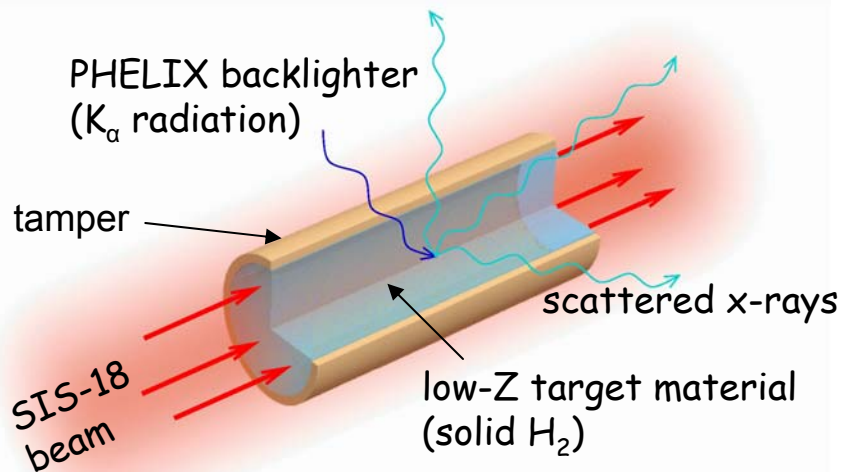
⇐ interferometry/VISAR

⇐ multi-probe & non-contact methods

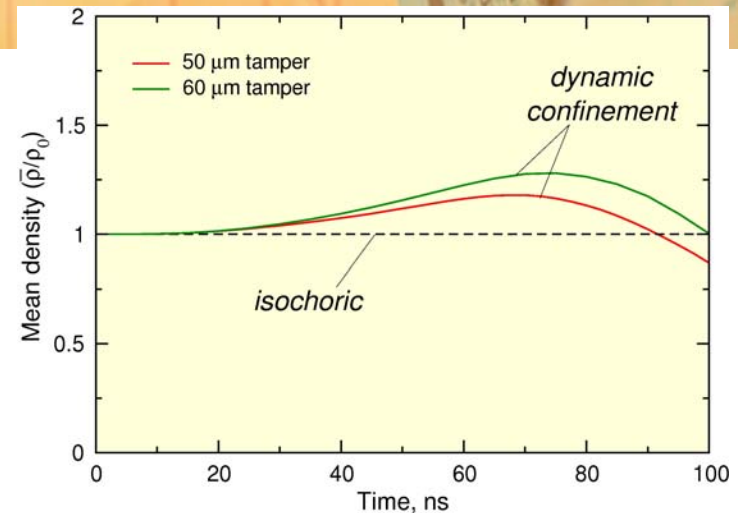
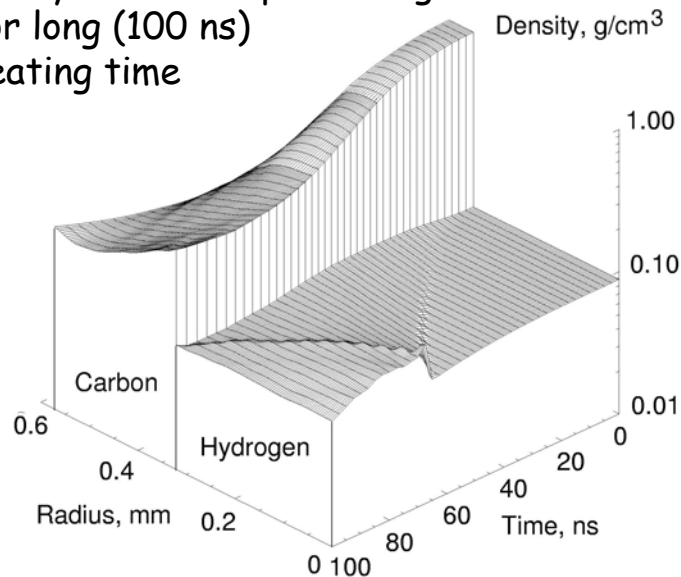
⇐ precision beam diagnostics & alignment



Dynamic Target Confinement for EOS Measurements using X-Ray Scattering



nearly static tamper / target interface even for long (100 ns) heating time



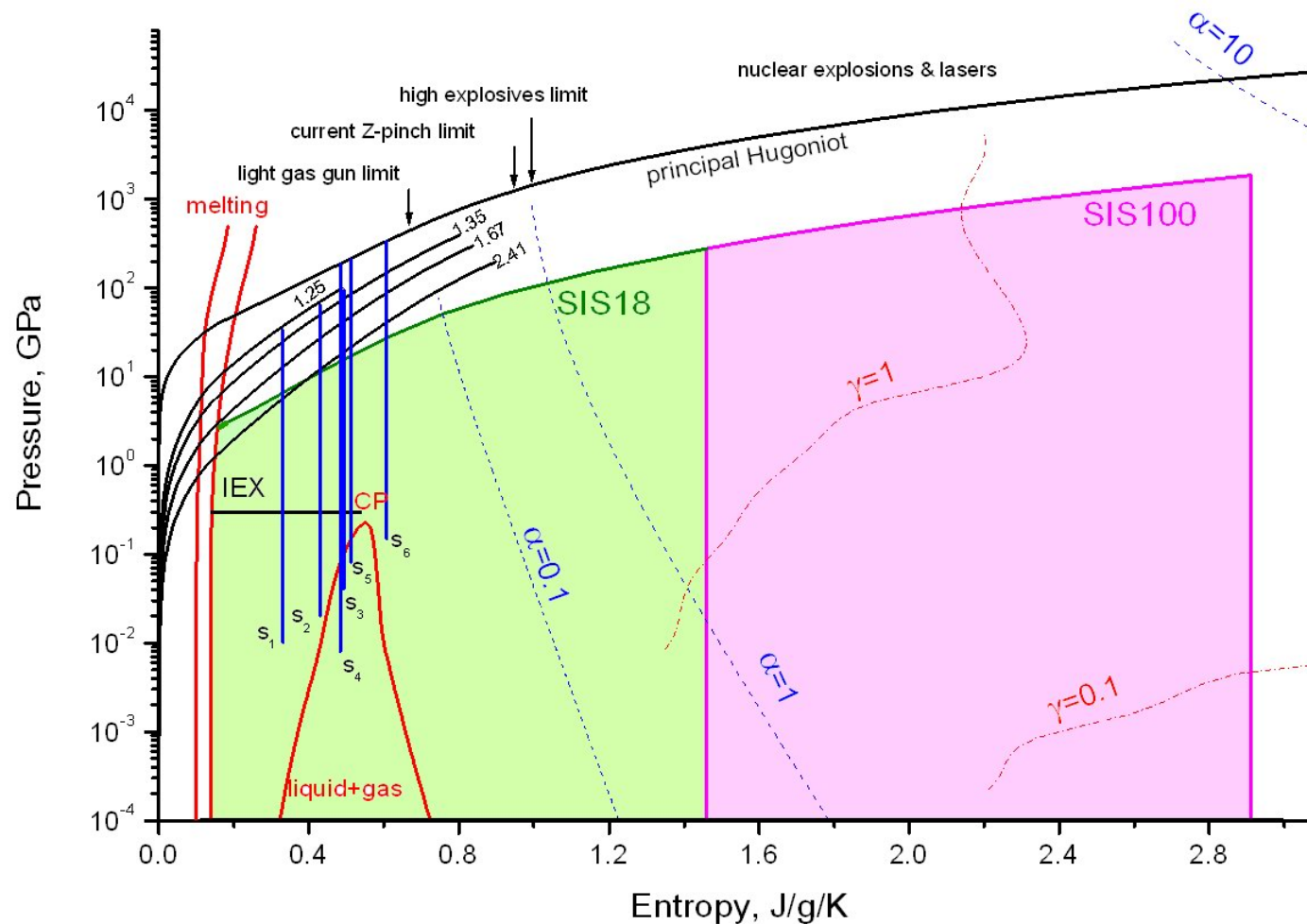
Tamper thickness can be optimized to yield:

- smallest density variation during beam heating
- initial target density at the bunch end

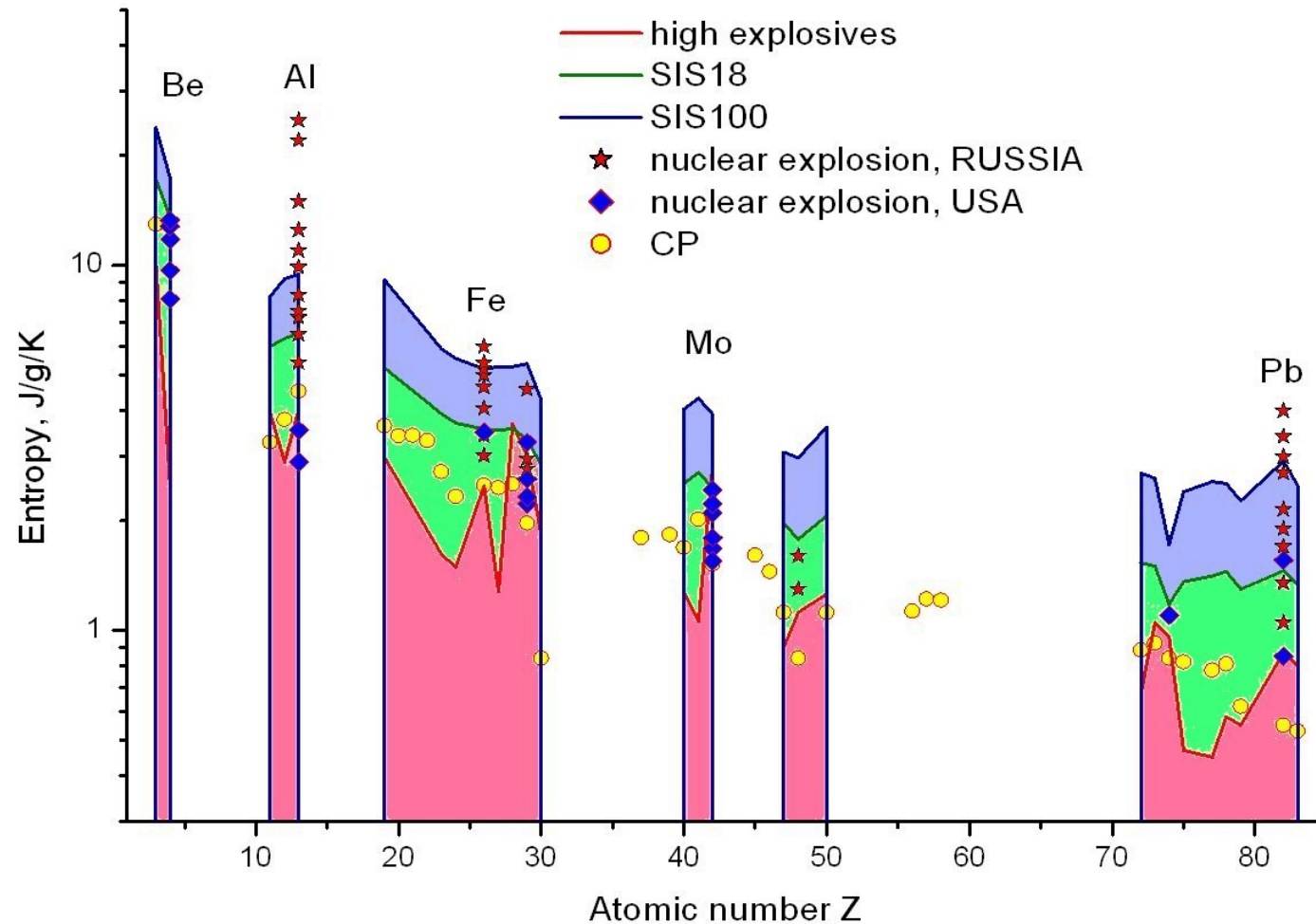
Dynamic Confinement:

- uses a x-ray transparent tamper (50 μm carbon)
- x-ray scattering provides information on density and temperature of electrons, degree of ionization, and ion-ion correlations

Heavy ion beam as generator of high-S states in Pb

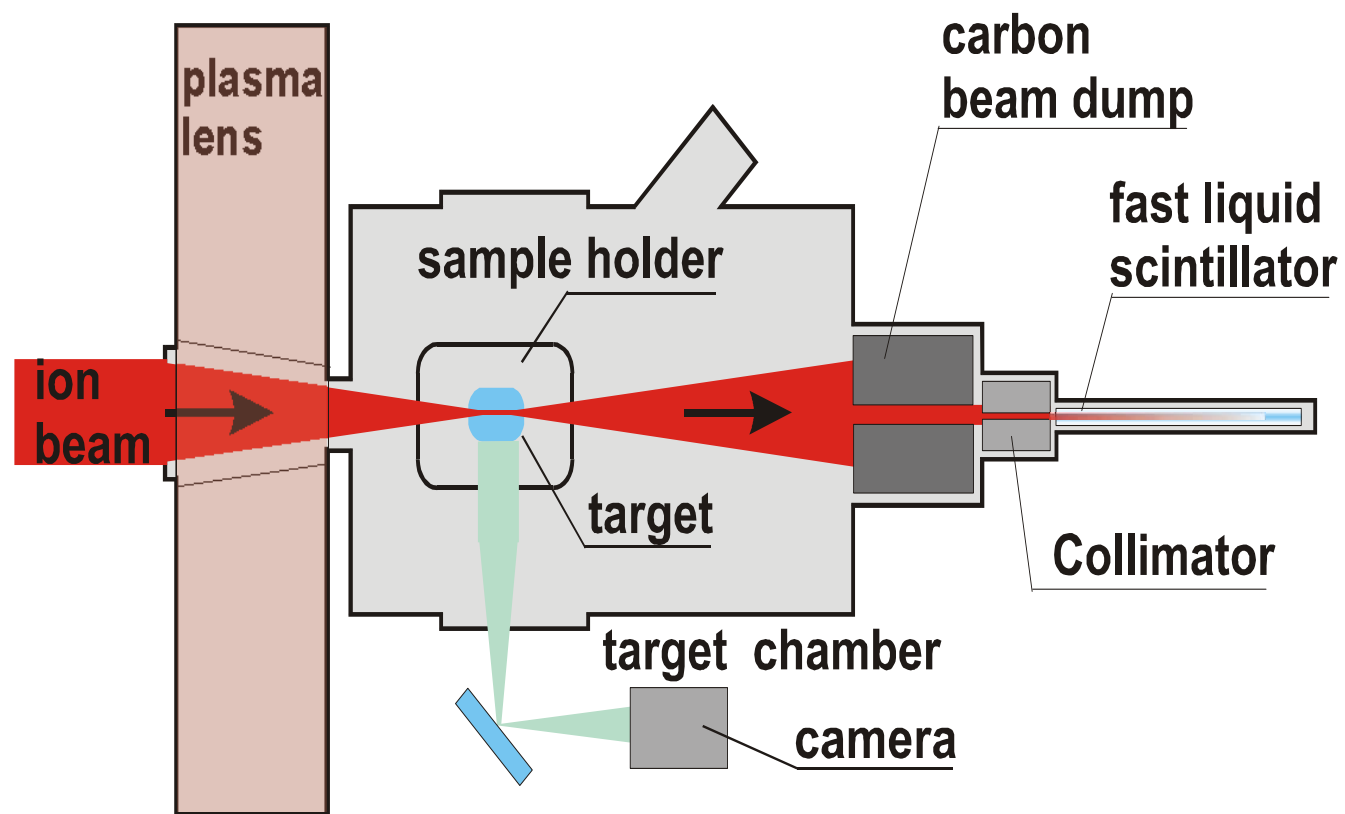


Heavy ion beam as generator of high-S states in metals



Time Resolved Energy Loss Spectrometry

D. Varentsov



Transmitted beam ions carry the information on the state of matter inside the target volume

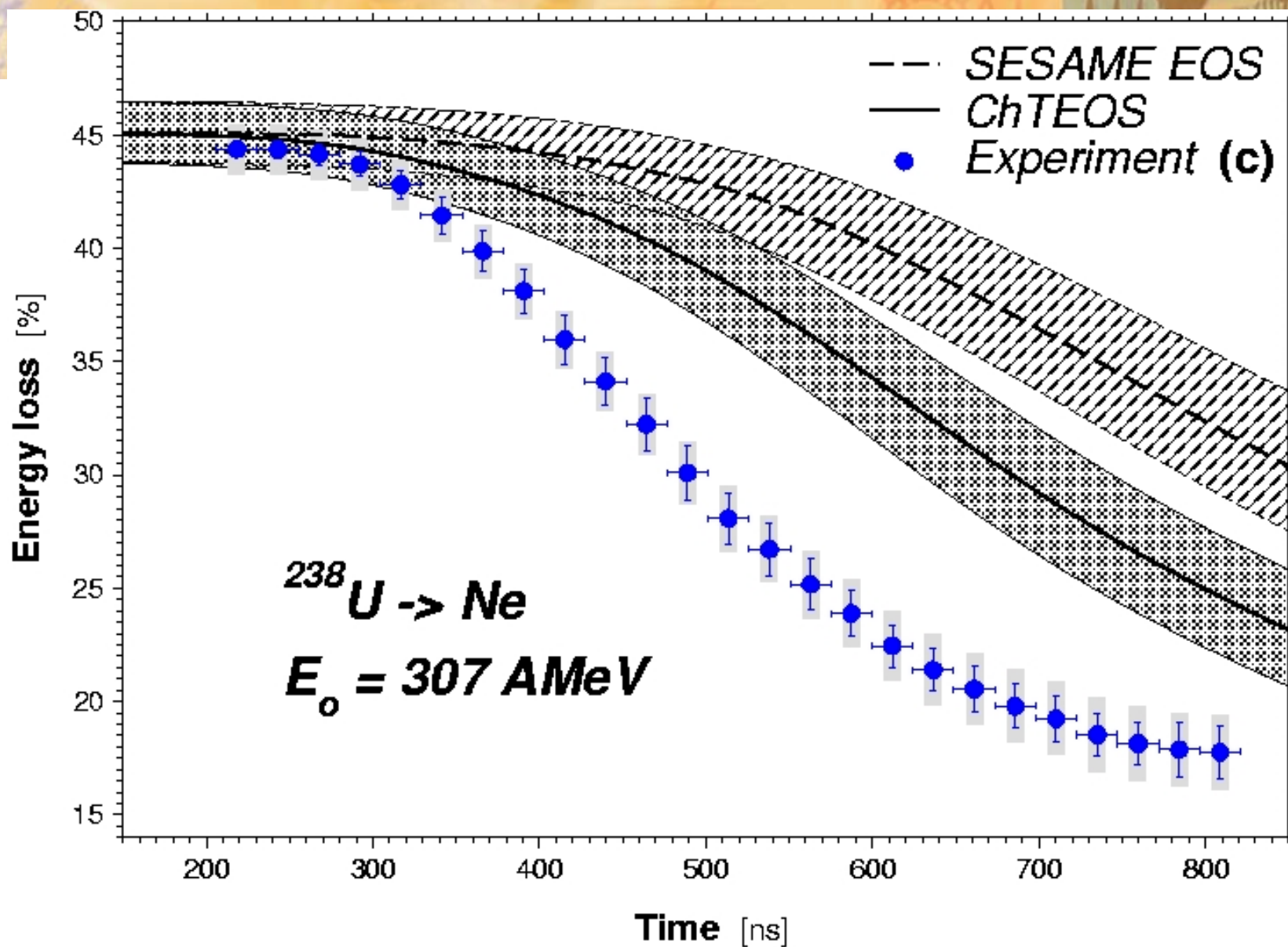


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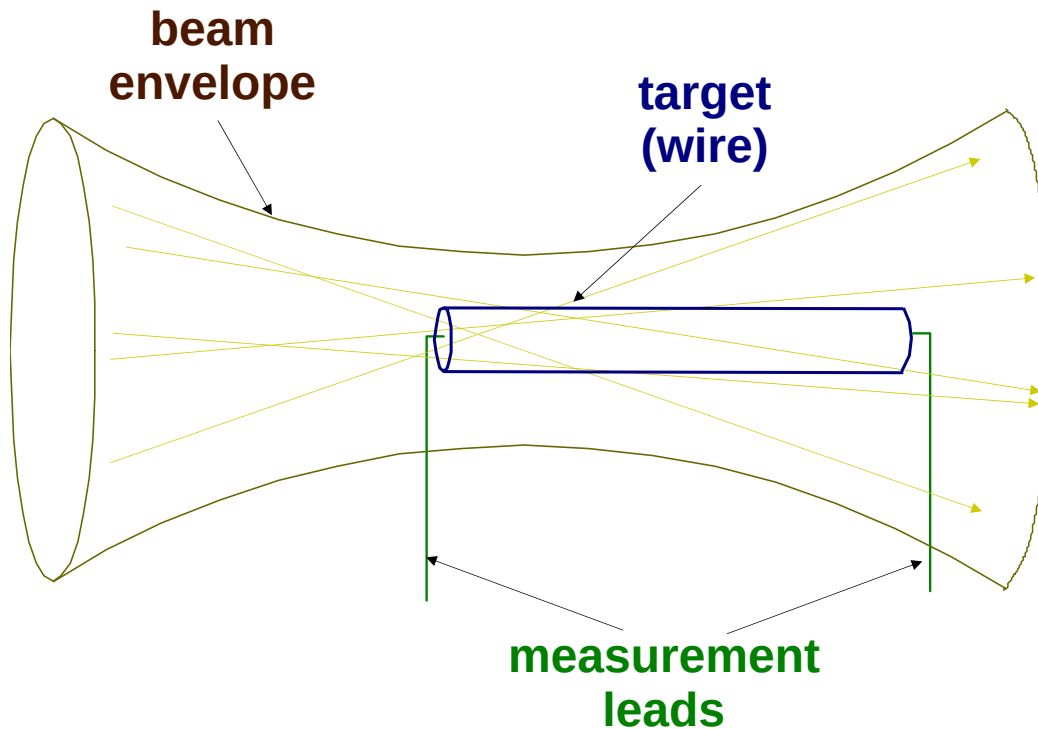
GSI

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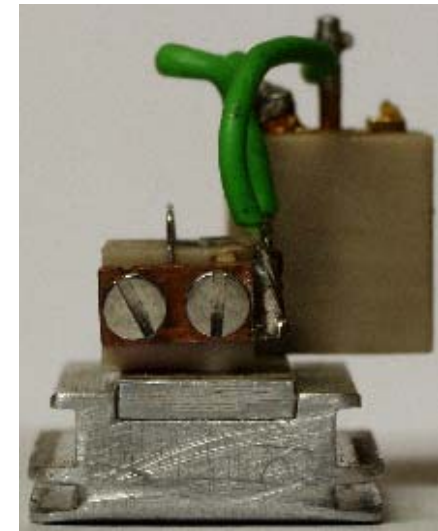
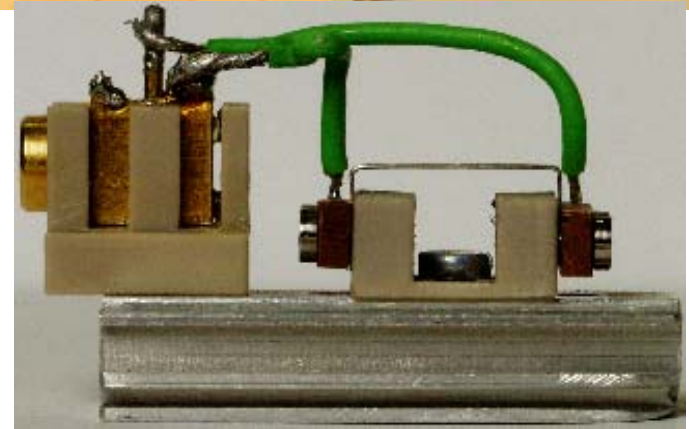


Transport Properties of Beam Heated Matter

First measurements of **electrical conductivity** of metallic targets



Target dimensions: $\varnothing 0.25 \times 10$ mm
Beam focal spot: 0.5 - 1 mm (FWHM)



S. Udrea, Laser and Part. Beams 20 (2002) 399

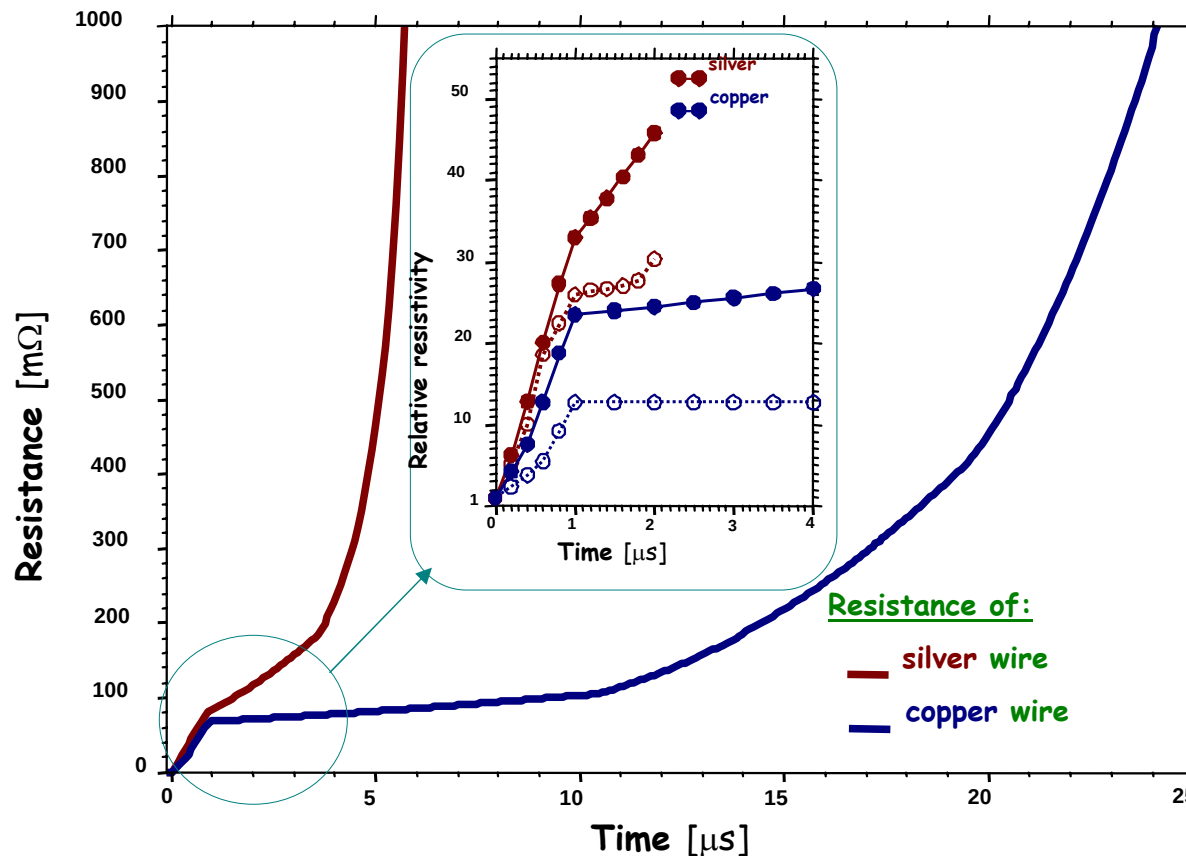
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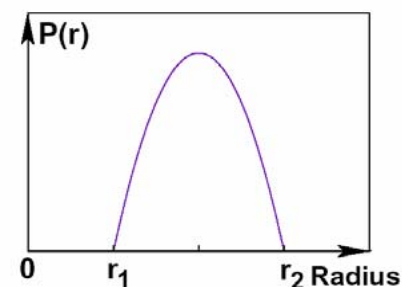
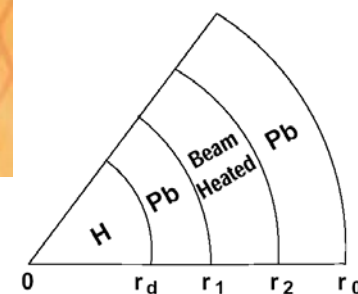
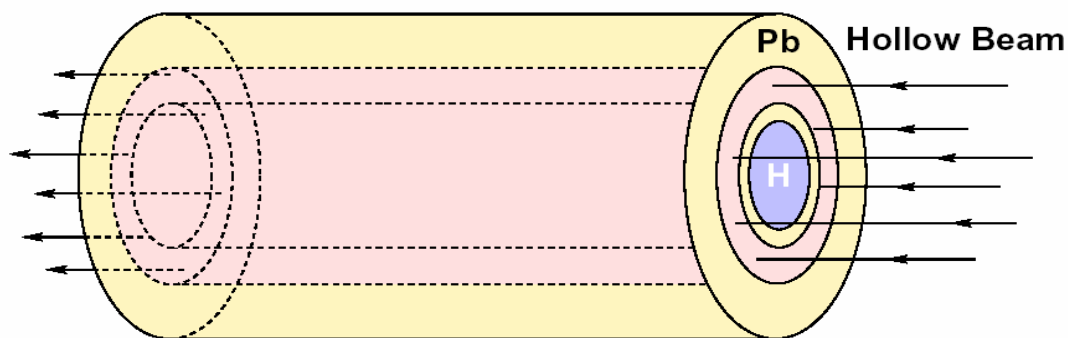


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First measurements of **electrical conductivity** of metallic targets



Low entropy compression



Target Parameters

$$r_d = 0.4 \text{ mm}$$

$$r_1 = 0.6 \text{ mm}$$

$$r_2 = 2.1 \text{ mm}$$

$$r_0 = 3.5 \text{ mm}$$

$$L = 1.0 \text{ cm}$$

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

Beam Parameters

$$2.7 \text{ GeV/u Uranium}$$

$$N = 0.2 - 1.5 \times 10^{12}$$

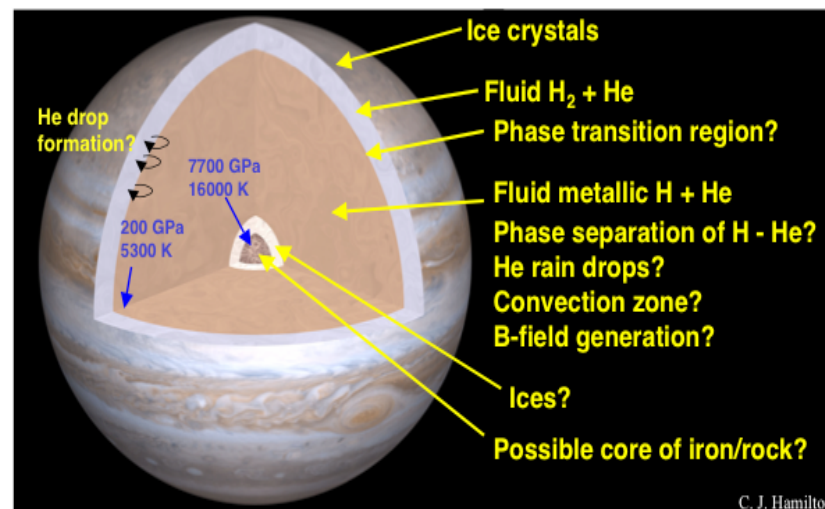
$$\tau = 20 \text{ ns}$$

$$E_b = 21 - 155 \text{ kJ}$$

$$R_{\text{ion}} = 5.9 \text{ cm}$$

$$P = 2 - 10 \text{ Mbar}$$

$$T = 0.2 - 0.6 \text{ eV}$$



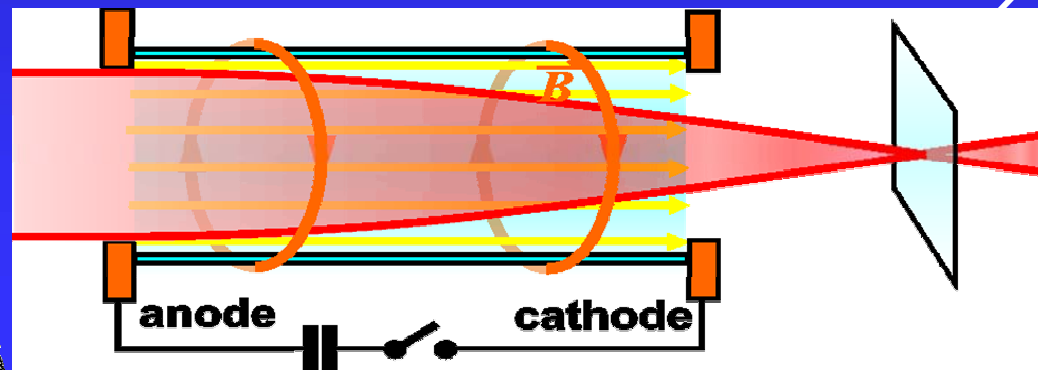
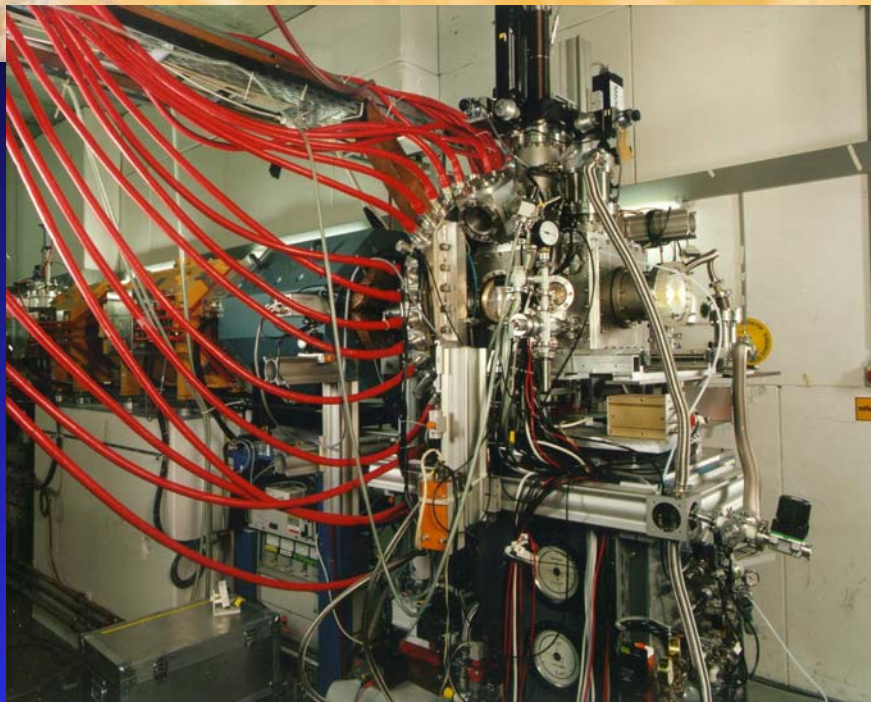
C. J. Hamilton

GSII

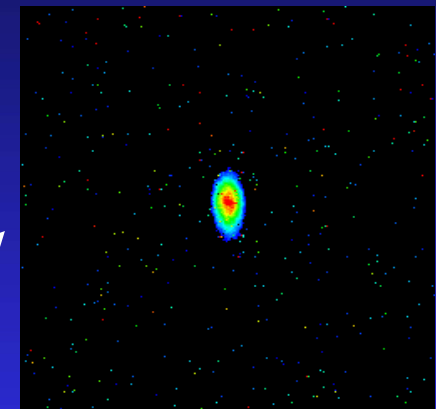


Plasma Linse

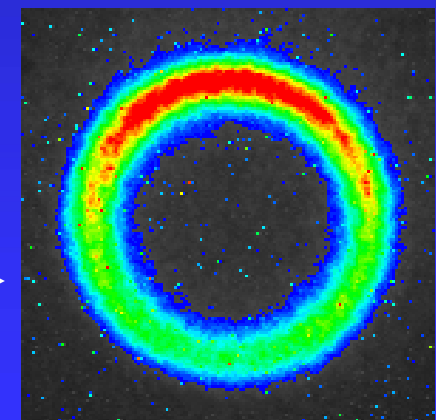
(U. Neuner et al)



focal beam spots



linear B-field



nonlinear B-field





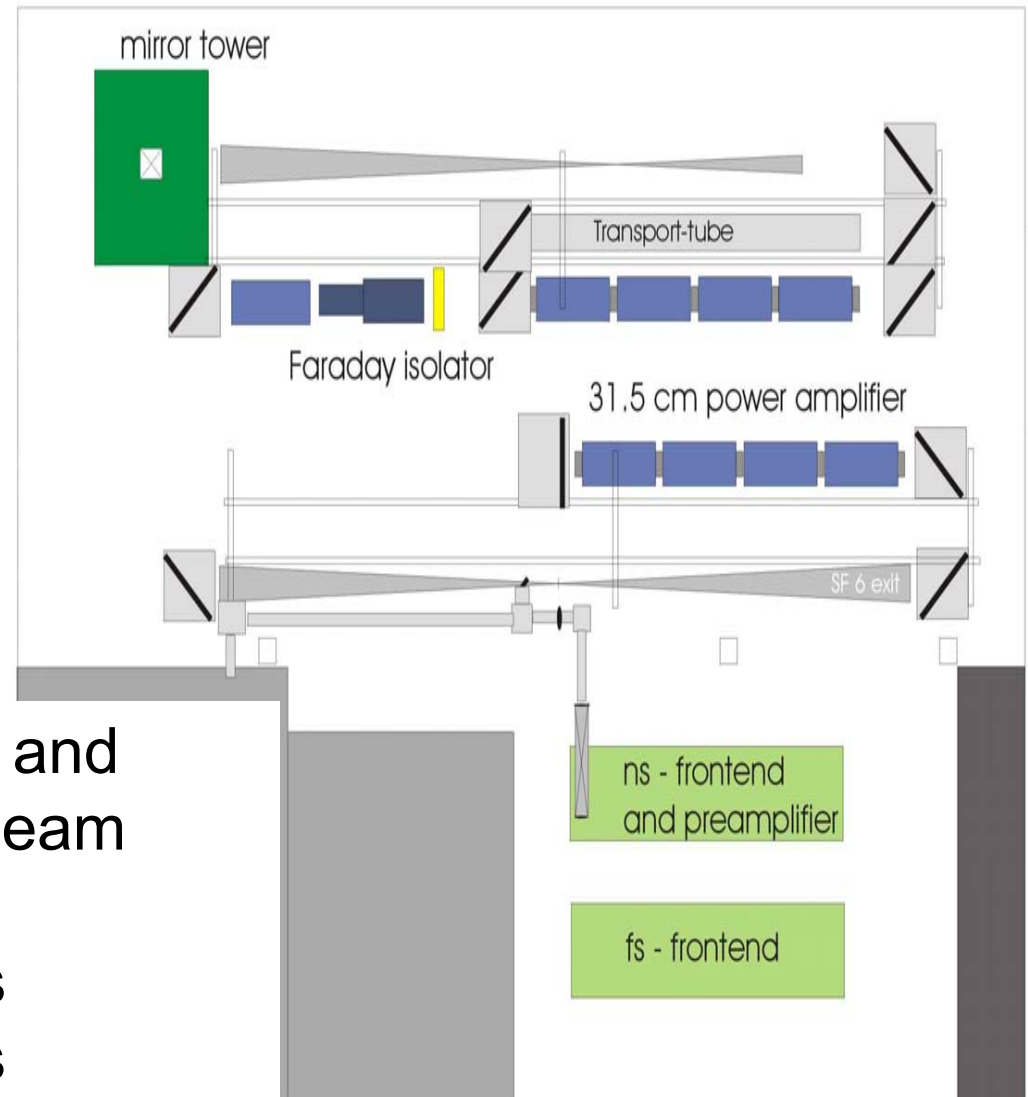
Petawatt High Energy Laser for Heavy Ion Experiments



Nd:Glass Laser Double-pass and
Booster Geometry, 31.5cm Beam
diameter:

4-6 kJ Pulse Energy @ 10 ns

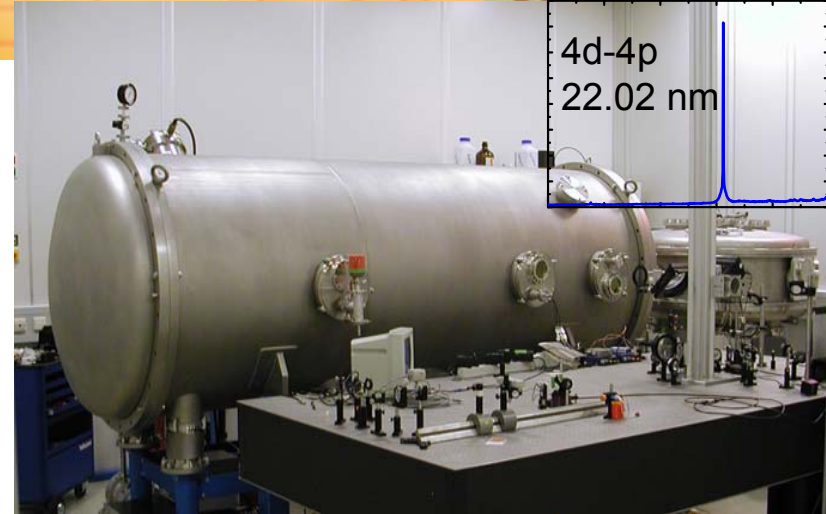
500 J Pulse Energy @ 0.5 ps



Status of the PHELIX Laser Project



The 31.5 cm double-pass amplifier, using Nova and PHEBUS disk amplifiers, is in commissioning (1kJ in 0.5 - 10 ns)



First successful x-ray laser experiments (Ni-like Zirconium) using the frontend beam (5J in 350 fs)

PHELIX Physics Program:

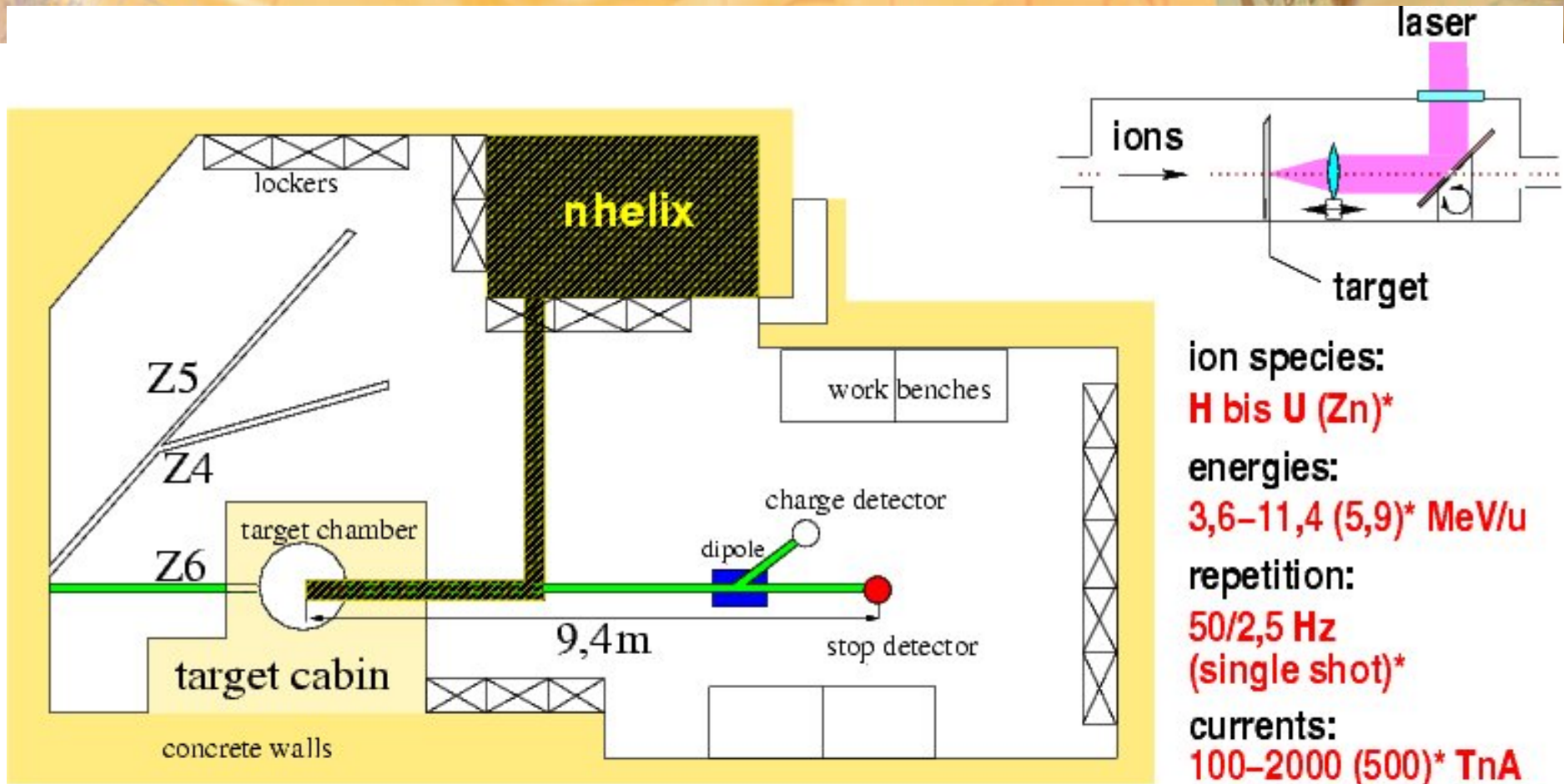
- diagnostics for WDM studies
- spectroscopy and interaction with radioactive isotopes from the accelerator
- ion stopping in laser plasmas
- x-ray laser experiments
- ion acceleration experiments / fast ignitor
- laser induced nuclear physics

PHELIX Timeline:

- 2003/4: experiments with UNILAC beam (1 kJ in 0.5 - 10 ns)
- 2004: experiments with SIS-18 beam (1 kJ in 0.5 - 10 ns)
- 2004/5: PW compressor installation (500J in 500 fs)
- 2005: Booster amplifier installation (4 kJ 10 ns)



nhelix laser system at GSI



ion species:

H bis U (Zn)*

energies:

3,6–11,4 (5,9)* MeV/u

repetition:

**50/2,5 Hz
(single shot)***

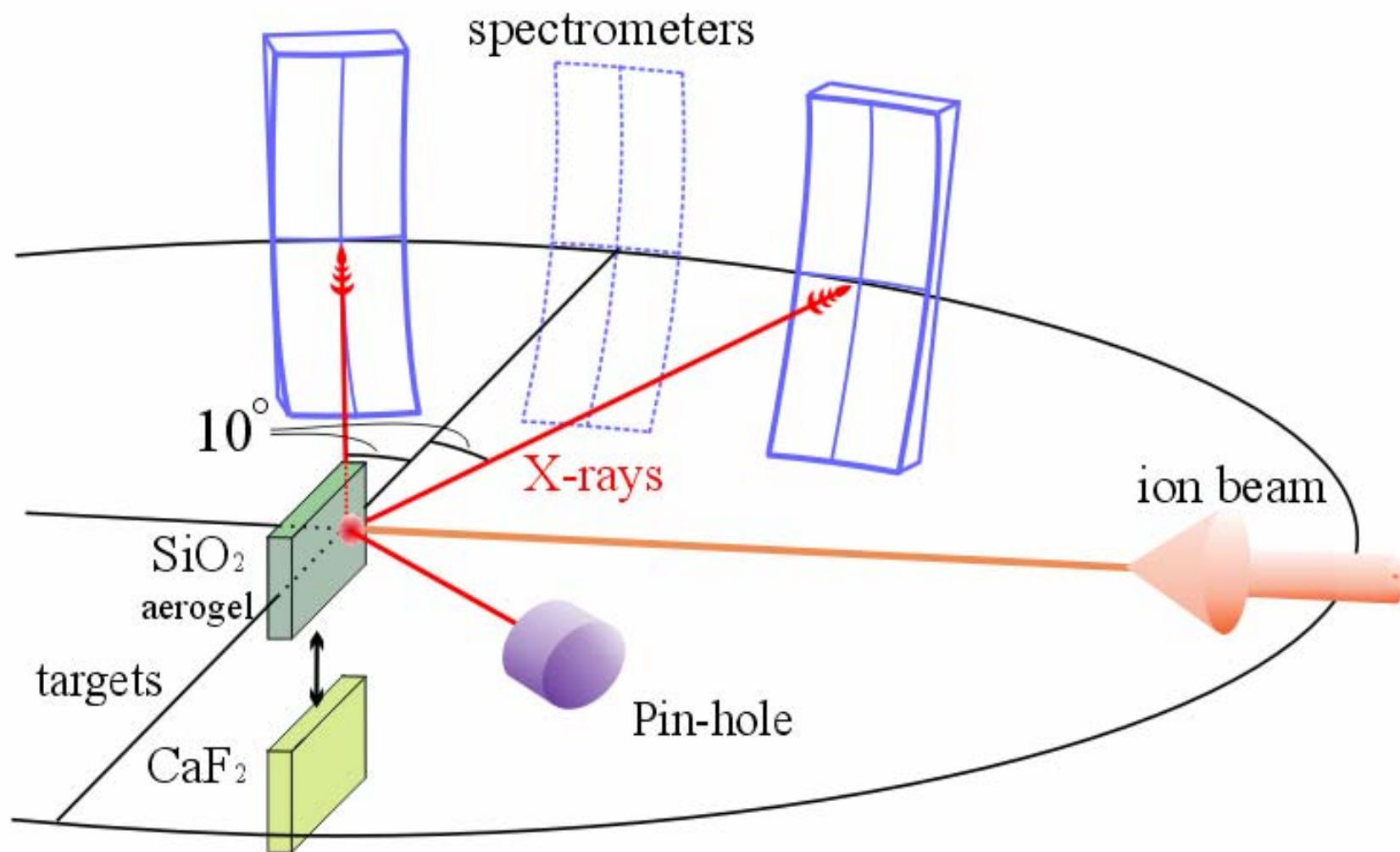
currents:

100–2000 (500)* TnA

***typical data**

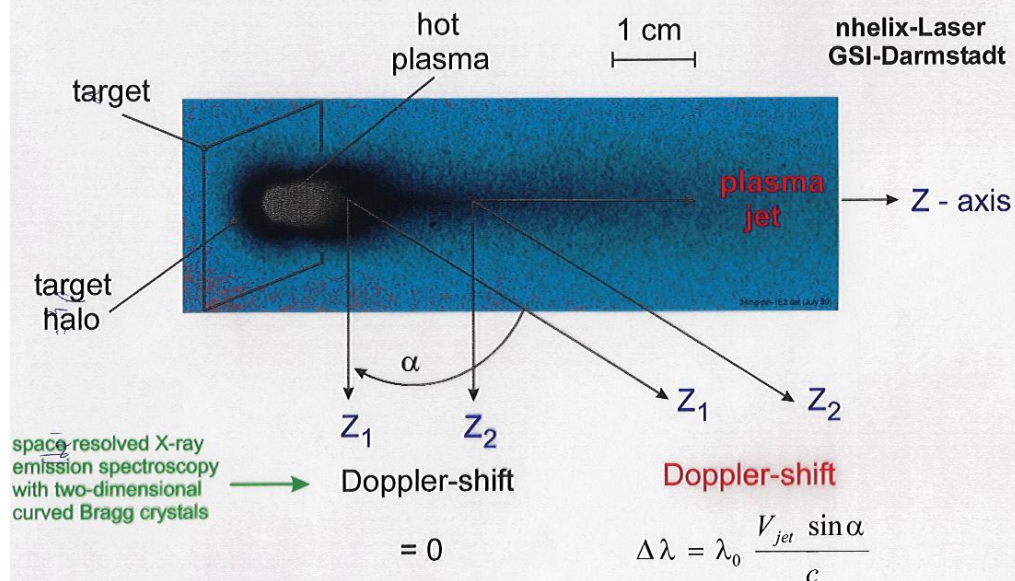


Experimental Scheme

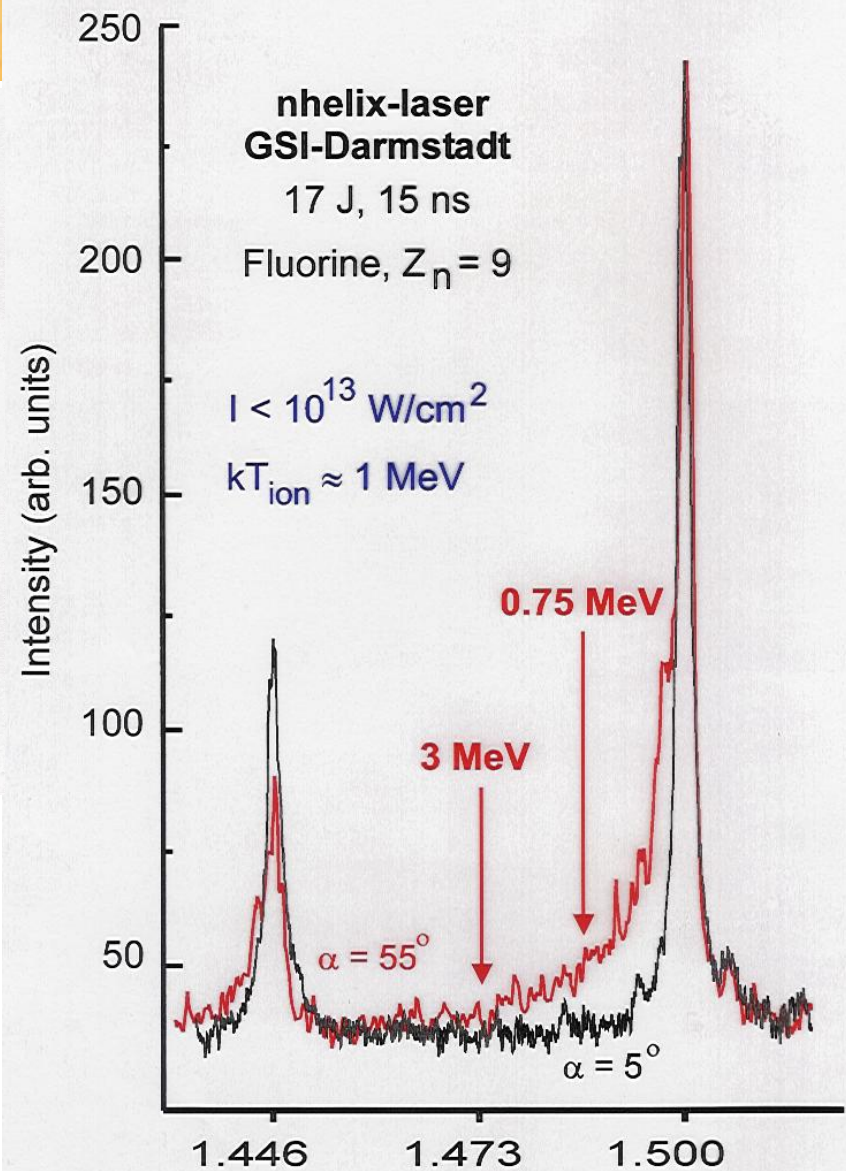


High Energy Ions in Laser Plasma

Space Resolved Observation of MeV-Ions



Rosmej, Hoffmann, Süß et al. 1999, JETP Lett. 70, 270



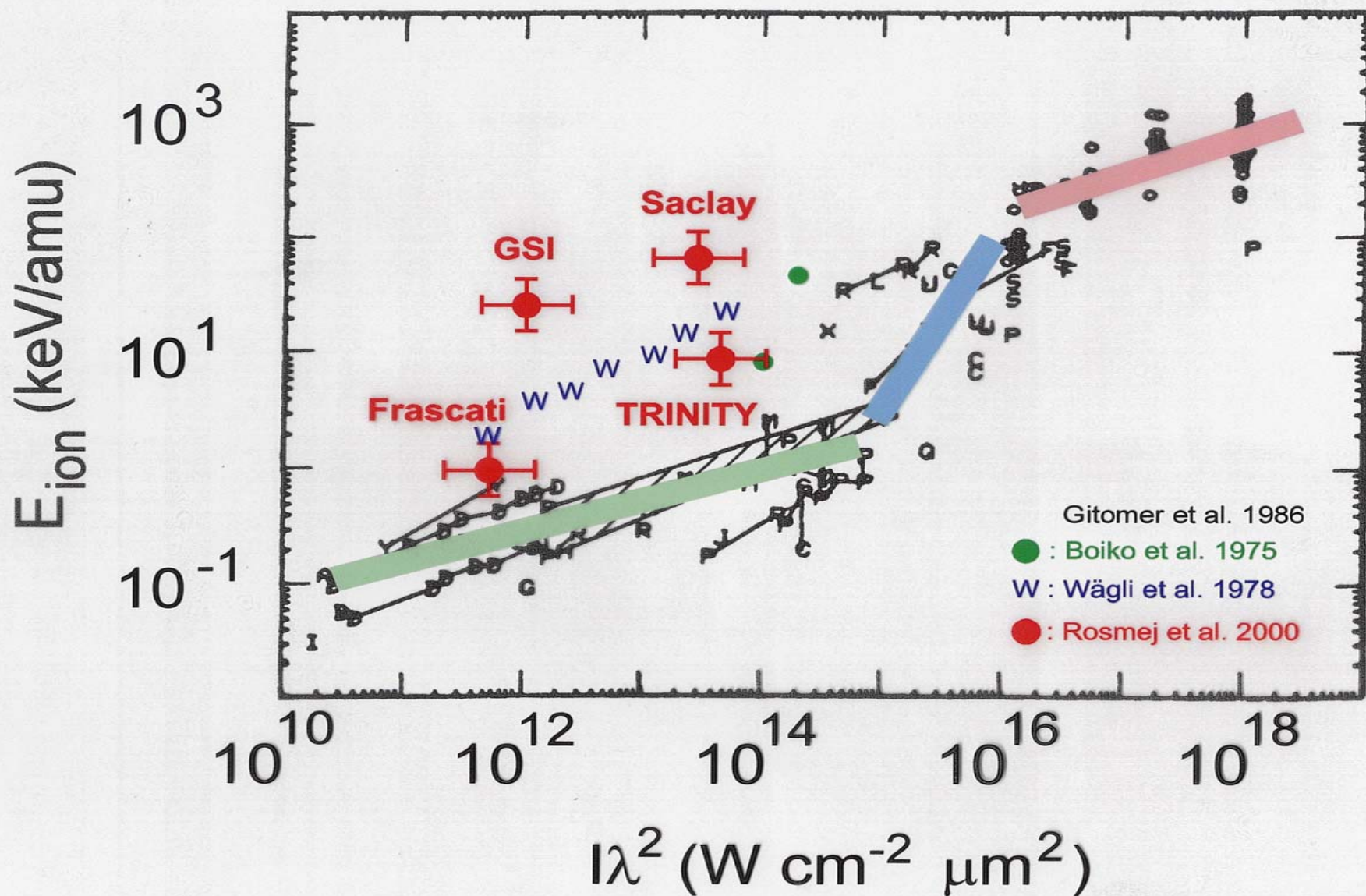
Rosmej, Hoffmann, Süß et al 1999, JETP Lett. 70, 270



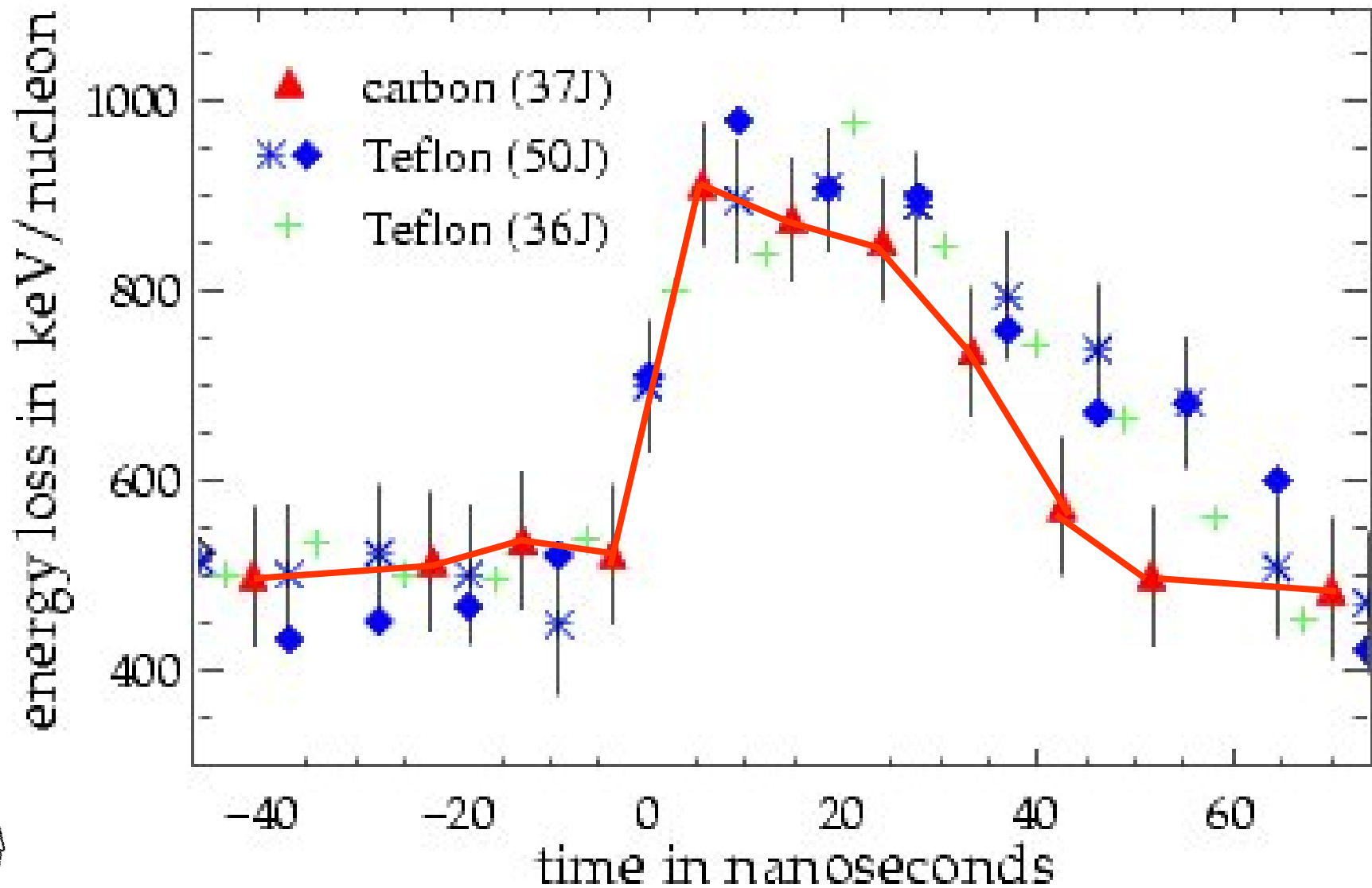
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High Energy Ions in Laser Plasma



Energy loss of $^{64}\text{Ni}^{9+}$ -ions at 5.9 MEV/u



Energy loss of heavy ions in plasma

Energieverlust von Schwerionen in Plasmen:

$$-\frac{dE}{dz} = \frac{16\pi a_0^2 I_H^2 Z_p^2}{m_e v_p^2} \left[\sum_{Z=0}^{Z_K} (Z_K - Z) n_z \ln \left(\frac{2m_e v_p^2}{I_Z} \right) + n_e \ln \left(\frac{2m_e v_p^2}{\hbar \omega_P} \right) \right]$$

- Projectile charge
- Bound electron contribution
- Free electron contribution

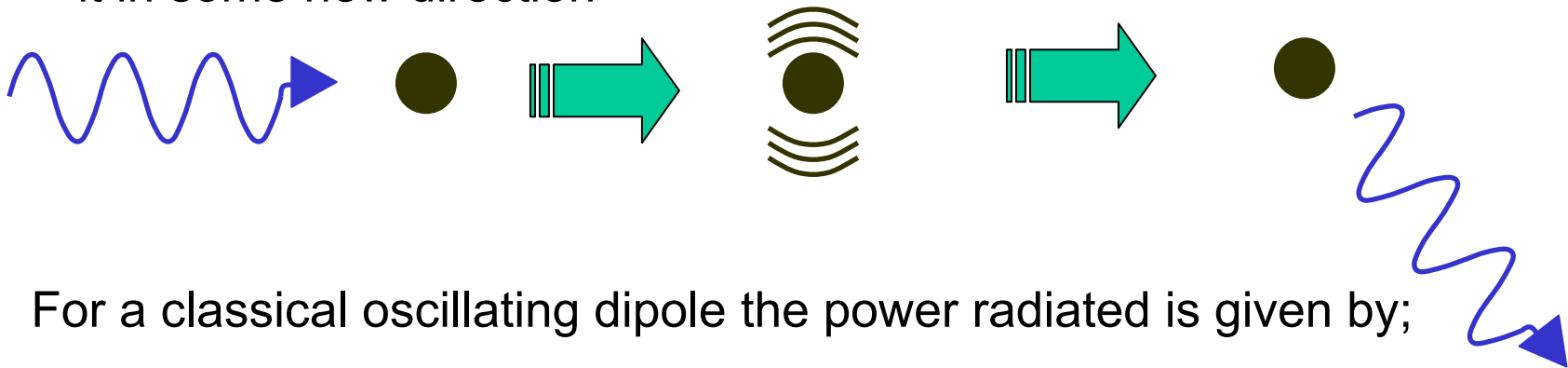
$$I_Z > \hbar \omega_p \rightarrow dE_{Plasma} > dE_{Folie}$$



Review of Thomson Scatter-1

The free electron

Thomson scatter is essentially the scattering of a photon from an electron. An electron “absorbs” the photon and re-radiates it in some new direction



For a classical oscillating dipole the power radiated is given by;

$$\langle P \rangle = \frac{\omega^4 p_0^2}{12\pi\epsilon_0 c^3} \quad \text{W}$$

where p_0 is the magnitude of the dipole



Review of Thomson Scatter-2 cross-section



By dividing the time averaged scatter power by the averaged incident power we can get the total scatter cross-section which we note is independent of wavelength and small- *so we need lots of photons.*

$$\sigma_T = \frac{\langle P \rangle}{\langle I \rangle} = \frac{e^4}{6\pi\epsilon_0^2 m_e^2 c^4} \sim 6.66 \times 10^{-29} \text{ m}^2$$

For unpolarised radiation the angular scatter depends on the angle between the laser direction and the scatter direction

$$\frac{d\sigma}{d\Omega} = \frac{1}{2} \left(\frac{e^2}{4\pi\epsilon_0 m_e c^2} \right)^2 (1 + \cos^2 \theta)$$

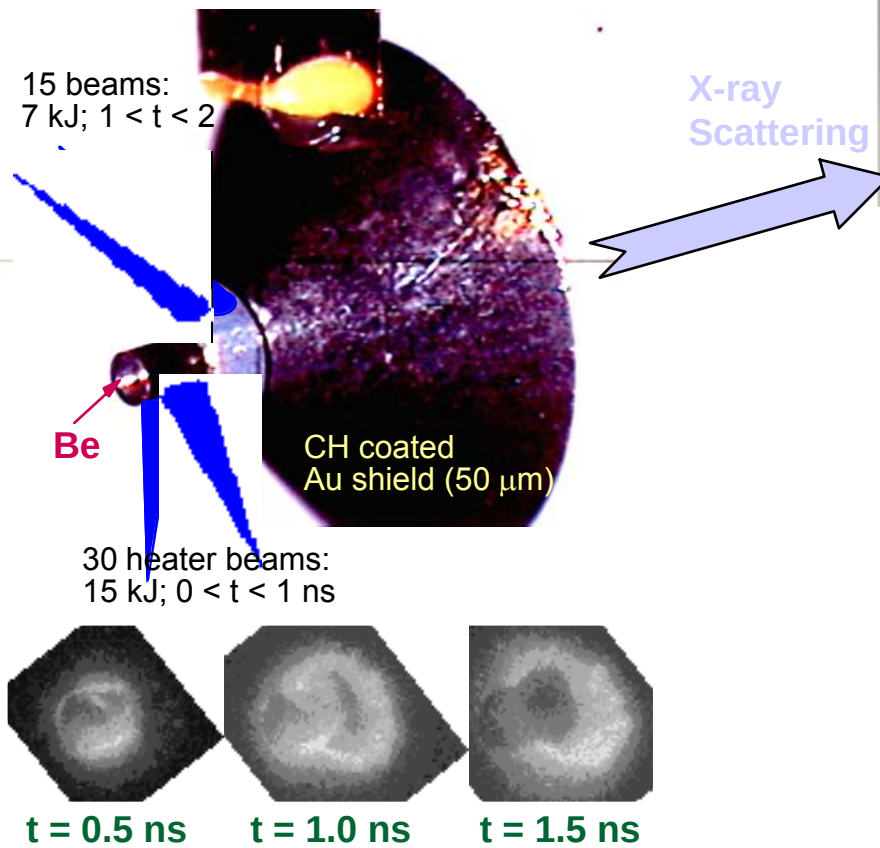


Results

Experiments on solid density Be plasmas provided the first spectrally resolved x-ray Thomson scattering data



Gated HOPG spectrometer

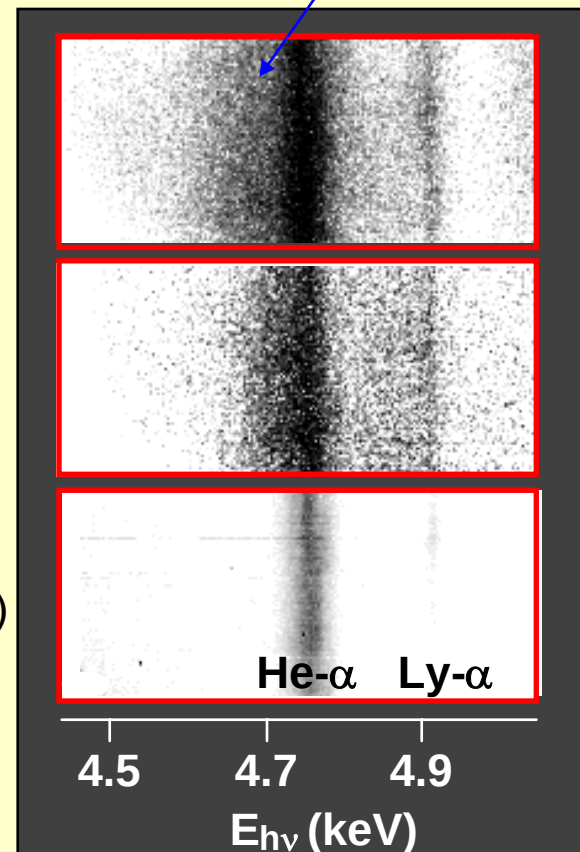


Compton downshifted and Doppler broadened Thomson spectrum observed as expected

Heated Be

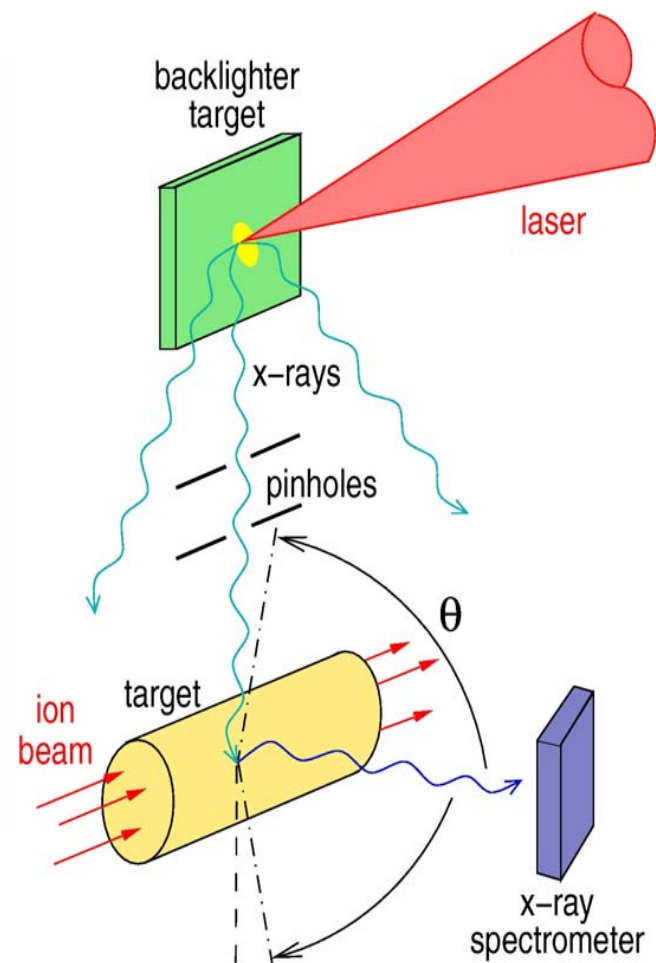
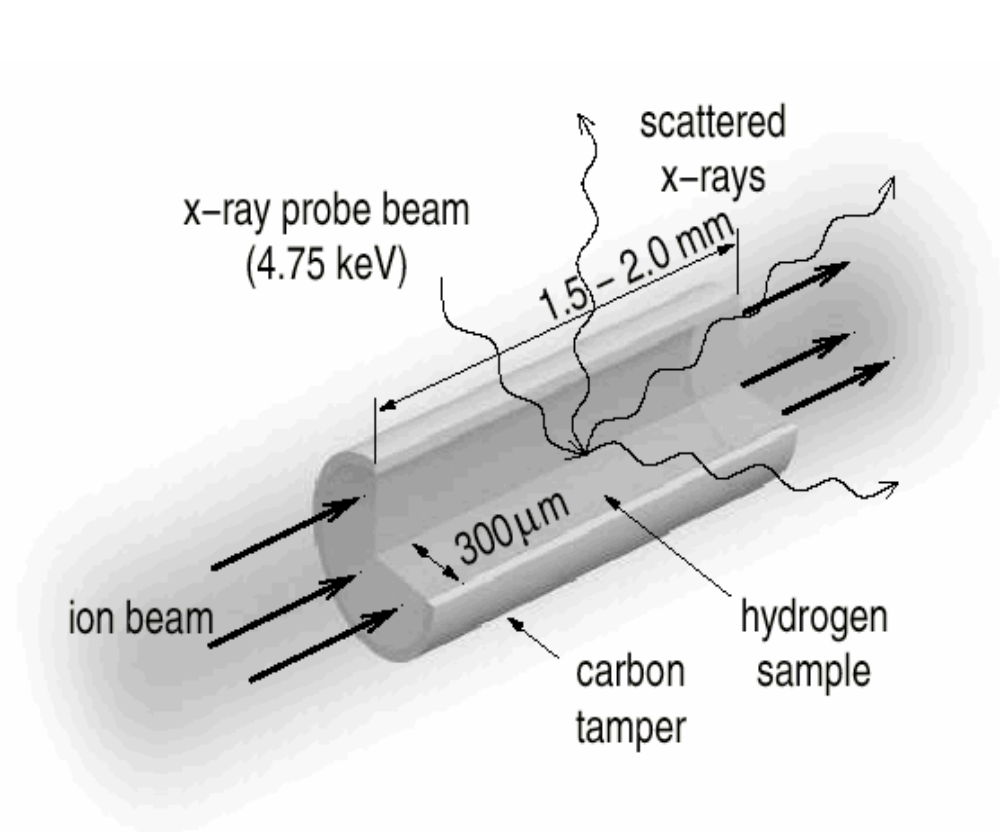
Cold Be

Ti disk
($g=10^{-4}$)



This slide supplied from SG Glenzer *et. al.* (PRL 90(17) art. 175002, 2003) kindly sent by O. Landen.

Proposals for XRTS-1 PHELIX is a promising test-bed



Target Diagnostics by X-ray Scattering

Backlighter options:

- Long pulse (1 ns):
 $E_L \sim 1 \text{ kJ}$, $\varnothing \sim 100 \mu\text{m}$, $I_L \sim 10^{16} \text{ W/cm}^2$
Ti : thermal ionization, He_α : $E_x = 4.75 \text{ keV}$
- Short pulse (1 ps):
 $E_L \sim 100 \text{ J}$, $\varnothing \sim 100 \mu\text{m}$, $I_L \sim 10^{18} \text{ W/cm}^2$
Mo: inner shell ionization by hot electrons, K_α : $E_x \cong 20 \text{ keV}$

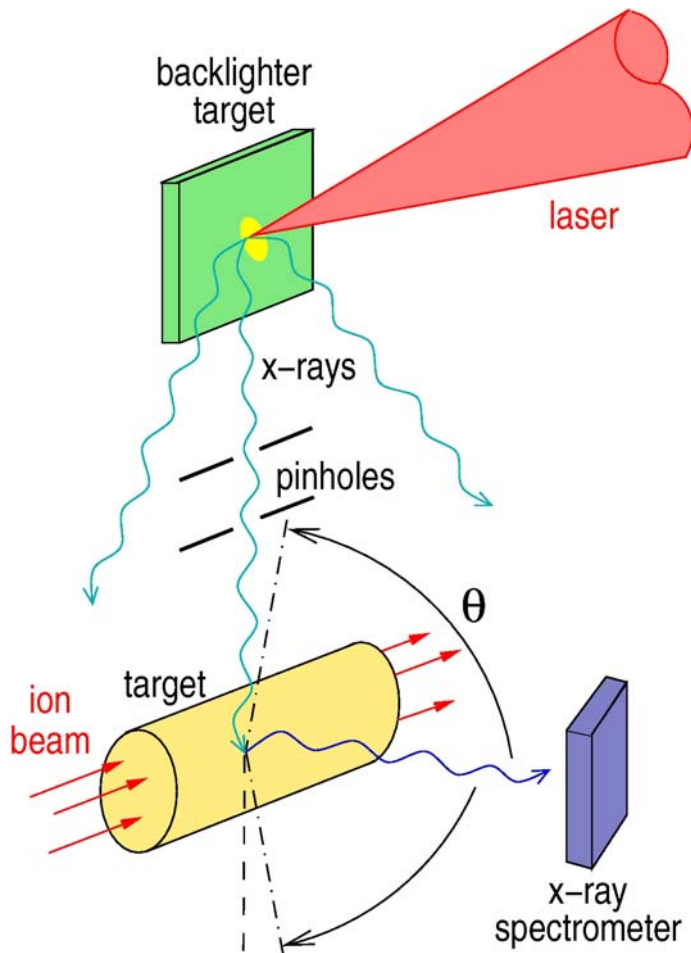
Diagnostics possibilities:

Spectrally resolved (nearly backscattering geometry)

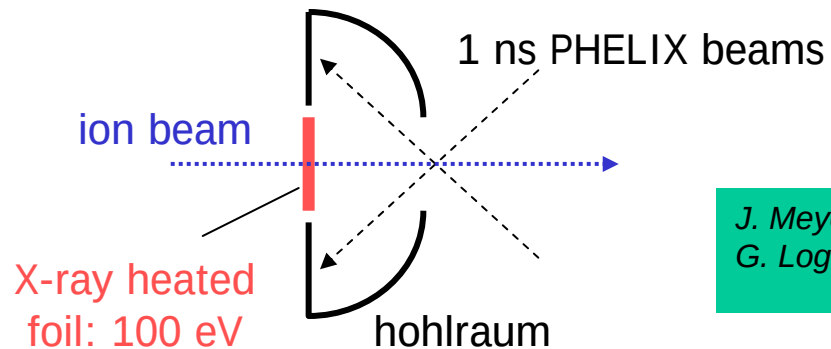
- density
- temperature
- ionization degree

Spectrally unresolved (scanning the scattering angle)

- ion – ion correlations

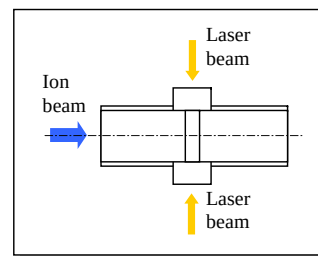
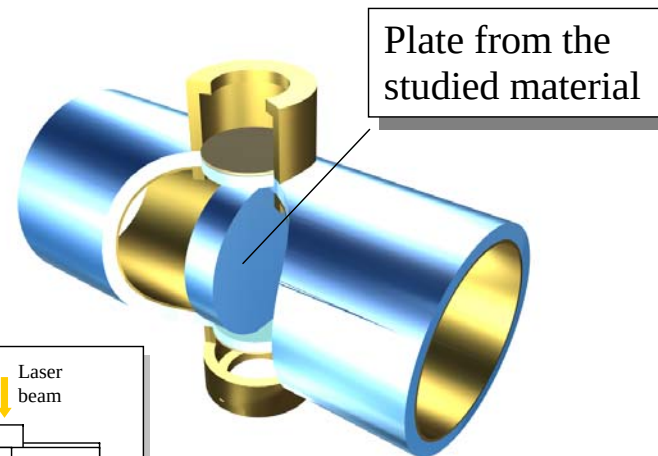


Laser beam generates dense plasma for ion interaction experiments



*J. Meyer-ter-Vehn (MPQ), A. Pukhov (HHUD)
G. Logan (LBL), H. Ruhl (GA), D. Habs (LMU)*

- Radiation transport
- Hohlraum experiments related to Heavy Ion Fusion targets
- Ion stopping in hot dense plasma



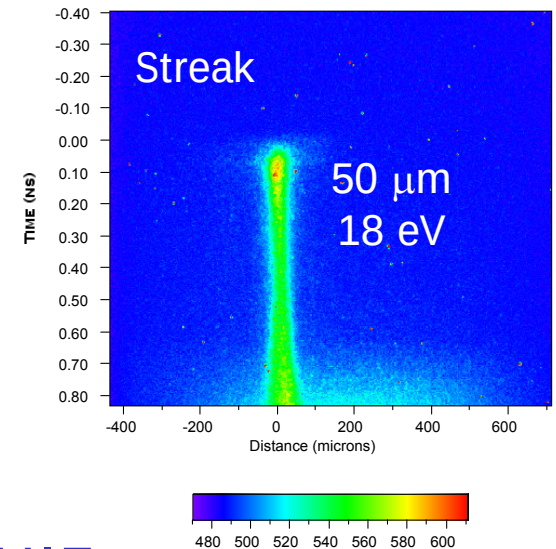
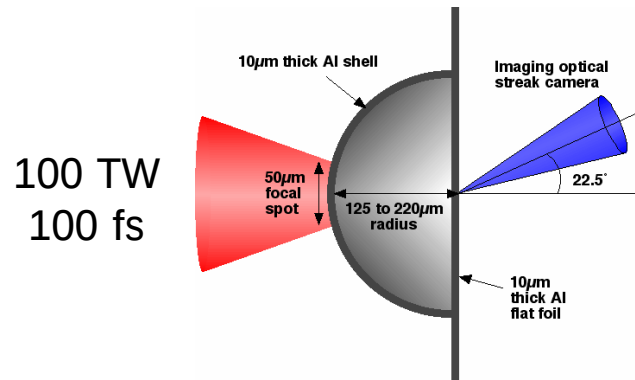
(V. Vatulina, VNIIEF)



Physics with PHELIX Petawatt Pulse

071802#4 Hemisphere

Example: Laser generated ion beams



Beam densities close to what is needed for HIF

laser generated proton beam:

$$n_p = 10^{16} - 10^{17} / \text{cm}^3$$

$$E_p = 1 - 50 \text{ MeV}$$

$$I = \text{few kA}$$

$$P = 10 \text{ TW/cm}^2$$

HIF driver beam:

$$n_p = \text{few } 10^{15} \text{ ions /cm}^3 (A=200)$$

$$E_p = 50 \text{ MeV/amu}$$

$$I = 40 \text{ kA}$$

$$P = 400 \text{ TW/cm}^2$$



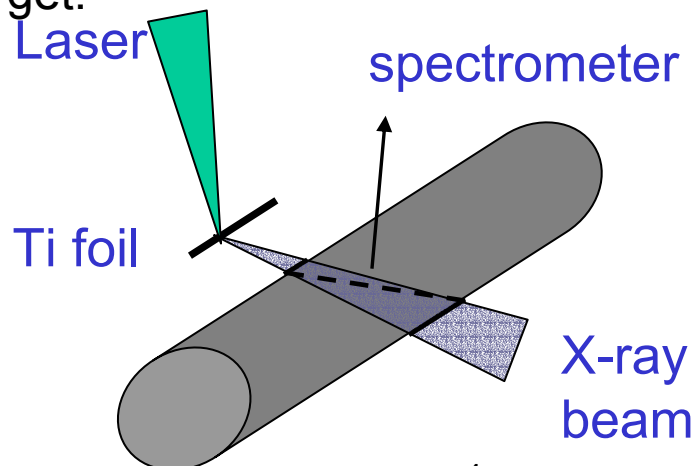
Proposals for XRTS-3 Consider some numbers

- We may get $\sim 1\text{kJ}$ in 1ω on target, thus we get $\sim 10^{15}$ photons in $\sim 1\text{ns}$ compared to $\sim 100\text{ns}$ plasma lifetime.
- Using pinhole collimation from 1cm away onto a $400\mu\text{m}$ spot gives a solid angle of $1.25 \times 10^{-3} \text{ Sr}$, resulting in $\sim 10^{11}$ photons on target.
- The cross-section is $\sim 4 \times 10^{-26} \text{ cm}^2$ and the target has $\sim 3 \times 10^{21} \text{ electrons/cm}^2$ and so $\sim 10^7$ photons/Sr are scattered.
- 2-D focusing crystal geometry can give collection efficiency of 10^{-2} Sr and so $\sim 10^5$ photons per shot are collected, enough to make a decent spectrum.
- Having source closer (3mm) means 10^6 photons and α varies by $\pm 15\%$ only



Proposals for XRTS-4 Consider some more numbers

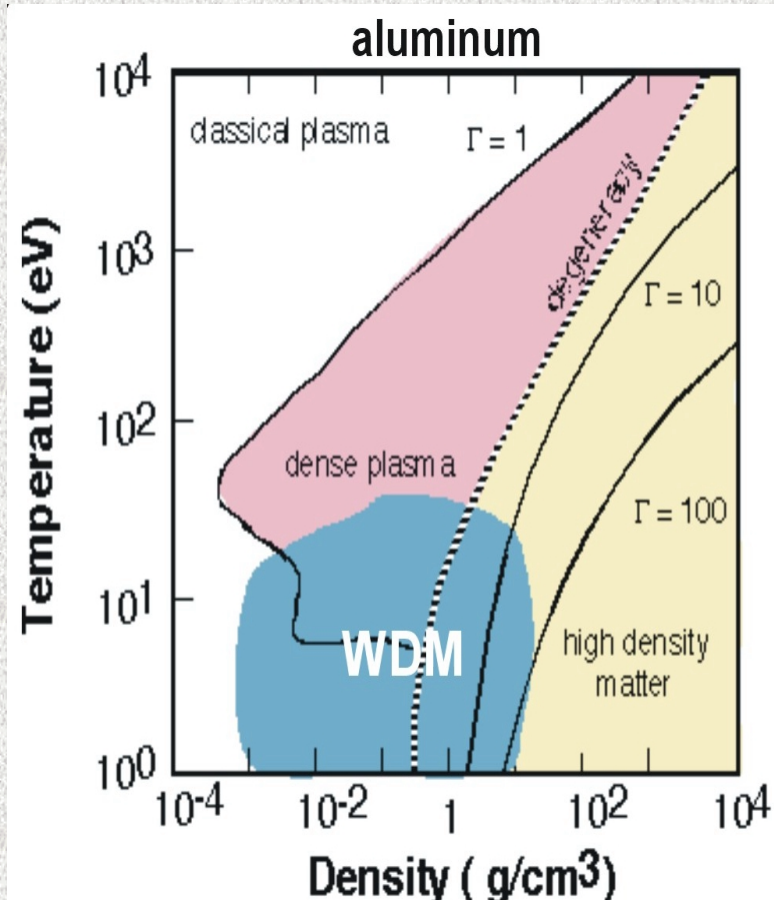
We can use spatial resolution on crystal set-up to image scatter from a volume in the centre, thus avoiding problem with scatter from the resin shell of the tamped target.



- In this case collection may only be $\sim 10^{-4}$ Sr and so only $\sim 10^4$ photons are collected per spectrum. Still enough for some useful data.
- For H at ~ 0.5 eV and ~ 0.05 g/cc the strong coupling factor is $\Gamma \sim 14Z^2$ thus we are in the moderate coupling regime for which theory has begun (e.g. Gregori *et. al.* J. Phys. A **36** 5971 2003)



Atomic Physics in Warm Dense Matter

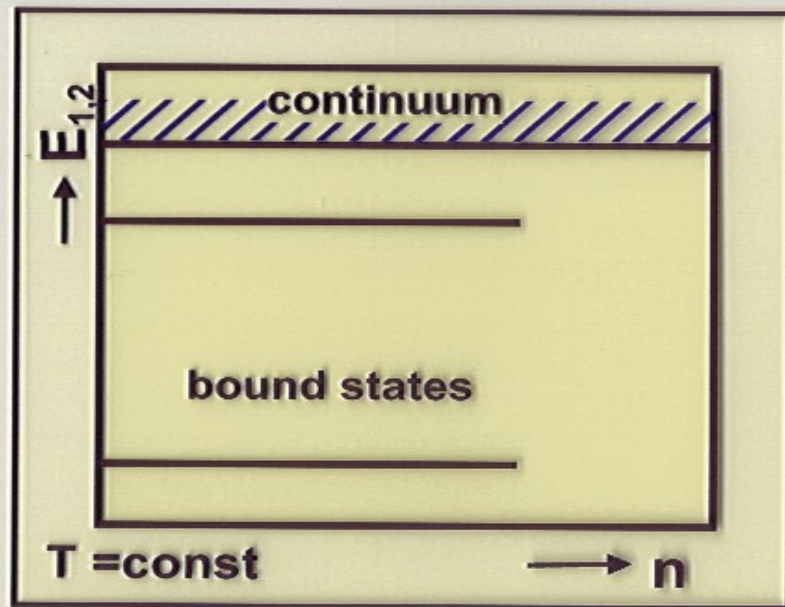


R. Lee: Laser and Part Beams
Vol. 20 Nr 3

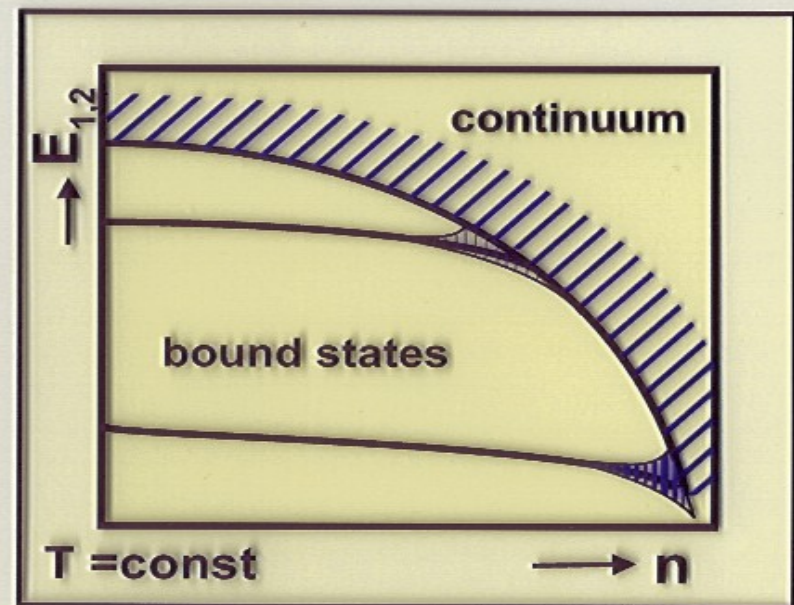


Mott-Effect

Ideal Plasma



Nonideal Plasma



lowering of the continuum edge reduces number and energy of bound states



Atomic physics in Warm Dense Matter (WDM): background and justification



- WDM = strong coupling between atoms and plasmas :
 - Photons are radiated in WDM by a compound system “ATOM + PLASMA”
 - The coupling parameter Γ is the ratio of interparticle potential energy to the thermal energy

$$\Gamma = Z^2 e^2 / r_0 k T, \quad r_0 = (3Z / 4\pi N_e)^{1/3} \quad \text{or} \quad N_e \rho_D^3$$

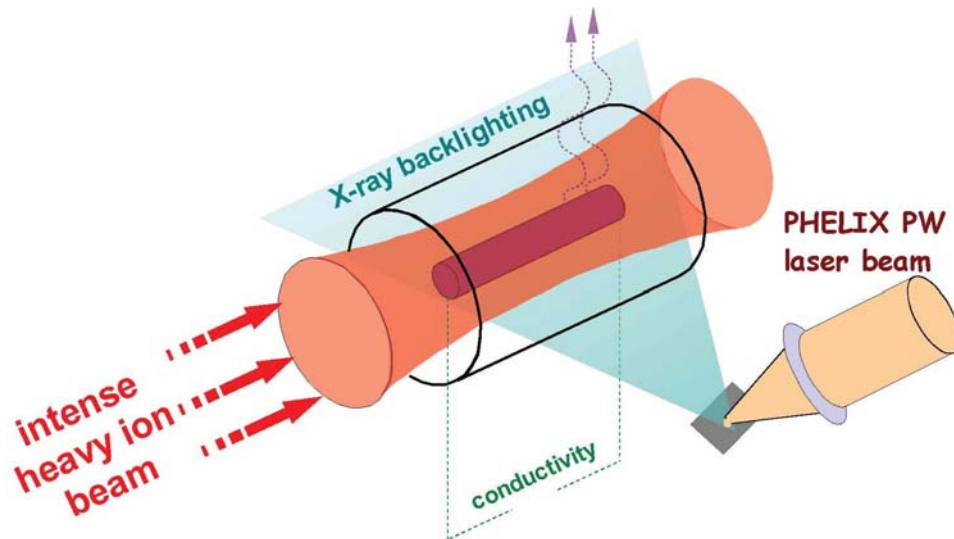
Z is the ion charge , r_0 is the interparticle spacing in terms of the electron density N_e , ρ_D is the Debye radius

Weakly coupled ($\Gamma \ll 1$) and strongly coupled ($\Gamma > 1$) plasmas



Atomic physics in Warm Dense Matter (WDM): background and justification

- WDM = strong coupling between atoms and plasmas :
 - WDM production by means of heavy ions beams at GSI
- from SIS 18 to SIS 100 from weakly to strongly coupled plasmas**



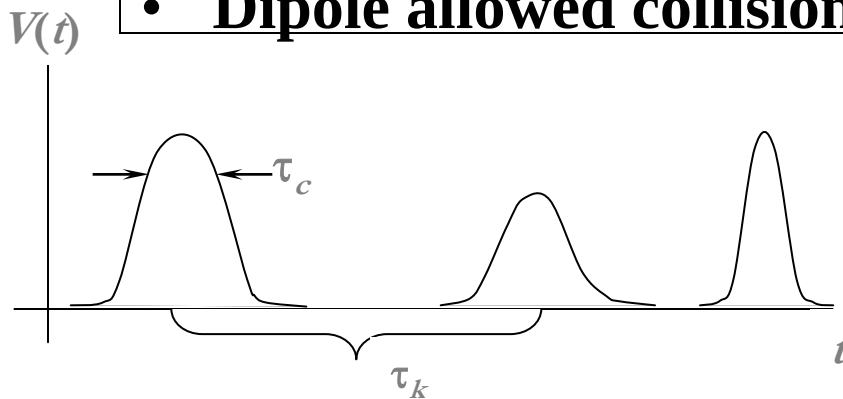
- Uniform energy deposition
- Change in atomic physics due to strongly coupled plasma environment



Atomic collisions in dense plasmas

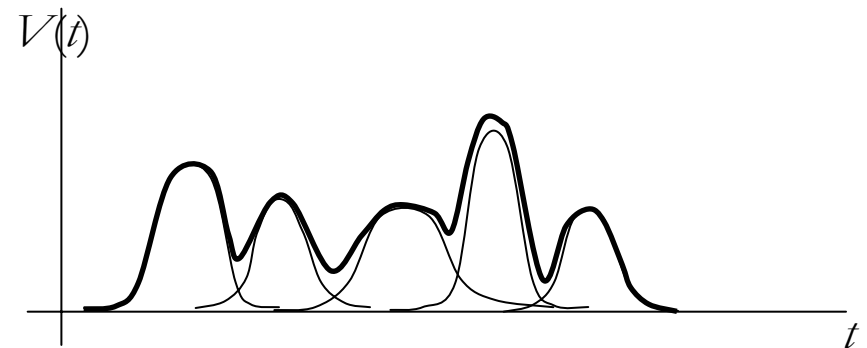
- Collision time $\tau_c \sim \rho_{\text{eff}}/v$
- Kinetic time $\tau_k \sim [Nv\pi\rho_{\text{eff}}^2]^{-1}$
- Dipole allowed collision transition

$$\tau_c / \tau_k \sim N \rho_{\text{eff}}^3$$



$N\rho_{\text{eff}}^3 \ll 1$ – separated collision

Born:
$$G \sim \frac{d_{if}^2}{v^2} \ln\left(\frac{\rho_D}{\rho_c}\right) = \frac{d_{if}^2}{v^2} \ln\left(\frac{v^2}{\omega_{pe} d_{if}}\right)$$



$N\rho_{\text{eff}}^3 > \sim 1$ – overlapping collision

$$\frac{\rho_c}{\rho_D} \sim \sqrt{10^5 N_e, a.u.} \geq 1$$

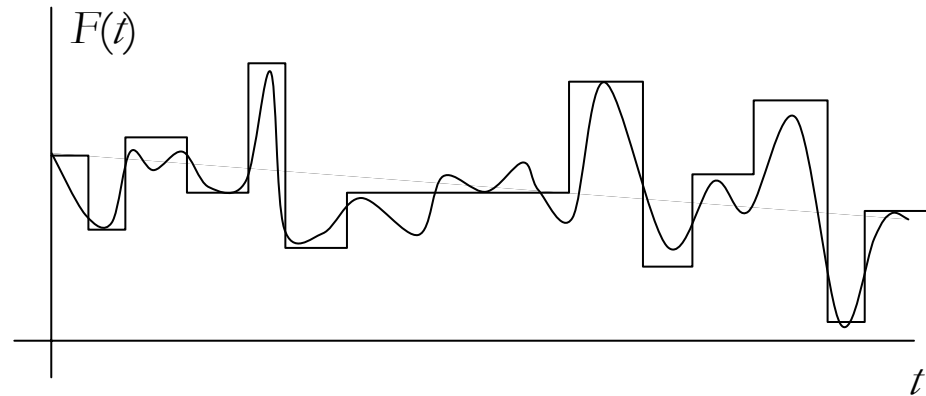
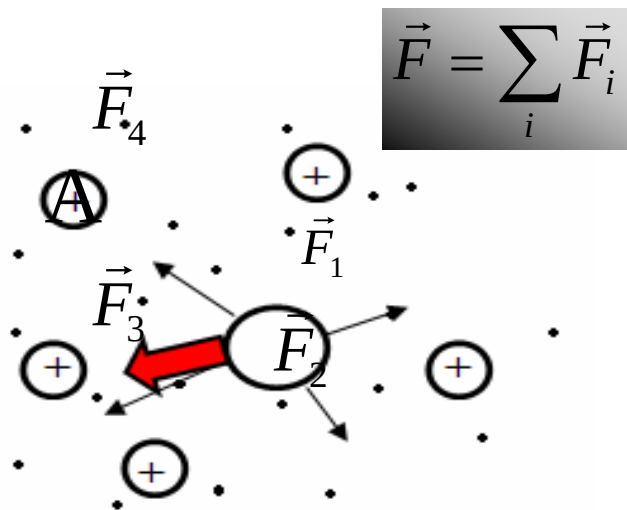
for $N_e \geq 10^{20} \text{ cm}^{-3}$



Conception of Plasma Microfield



- Long range dipole atom-plasma particles interaction



Plasma microfield dynamics and its approximation by Markoff process

$$i \frac{da}{dt} = \hat{V}(t) a$$

Stochastic Schrodinger equation



Atomic Physics in dense, strongly compressed matter

- strong inter-particle interaction
- experiment + theory
- self emission spectroscopy
- X-ray scattering

An Atom in Plasma Microfield

- What effects can be measured?

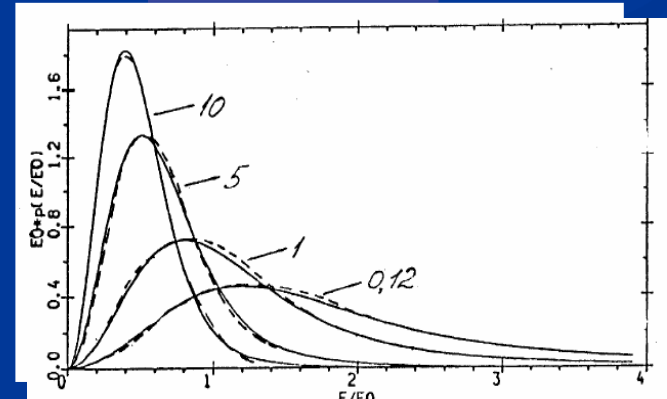
- Cut off of atomic energy levels

Critical field strength $F_c = \frac{Z^3}{16n_c^4} (a.u.)$

Hydrogen atom ($N_i \sim 10^{19} \text{ cm}^{-3}$): $n_c \approx 4 \div 5$

Statistical sum cut off: $n_{\text{max}} - ? \Rightarrow \sum_{n=1}^{n_{\text{max}}} g_n e^{-\frac{E_n}{T}}$

Effect of plasma coupling parameter Γ on microfield distribution



A transition to the continuum



RRC "Kurchatov Institute"

