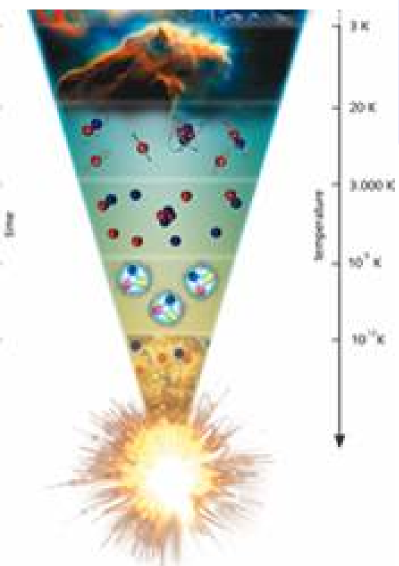
Heavy Ions at GSI: An overview of research activities at GSI

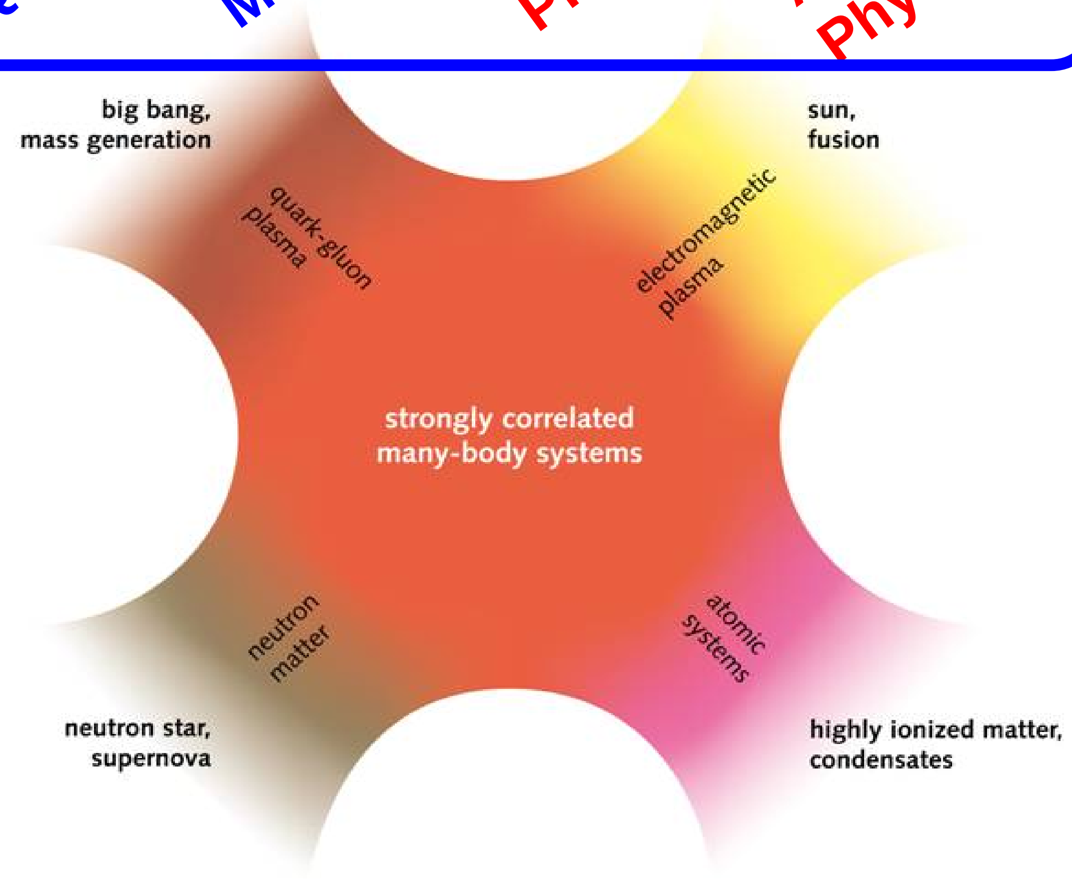
Th. Kühl, GSI Darmstadt

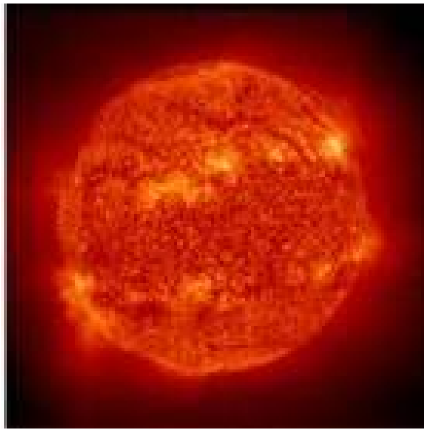
Helmholtz Alliance: EMMI

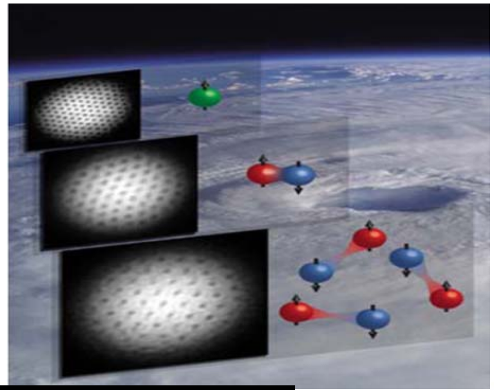
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

QGP | Neutron Matter | EM Plasma | Atomic Physics









12 Partners and 23 Associated Partners worldwide

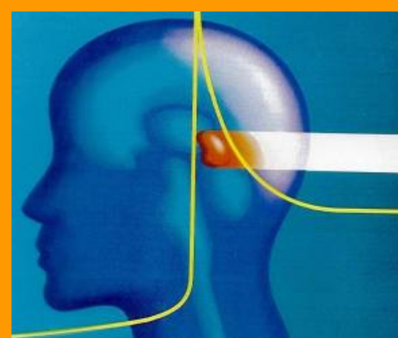
The Ion Part of PNI

Research Focus: Matter under Extreme Conditions

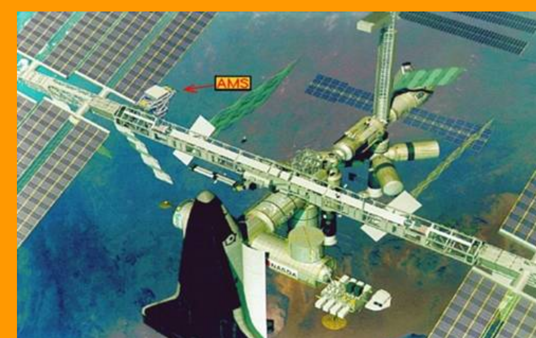
Highest Charge States	***Extreme Static Fields***
Relativistic Energies	***Extreme Dynamical Fields and Ultrashort Pulses***
High Intensities	***Very High Energy Densities and Pressures***
High Charge at Low Velocity	***Large Energy Deposition***

Contributions to Solving Grand Challenges

Energy



Health



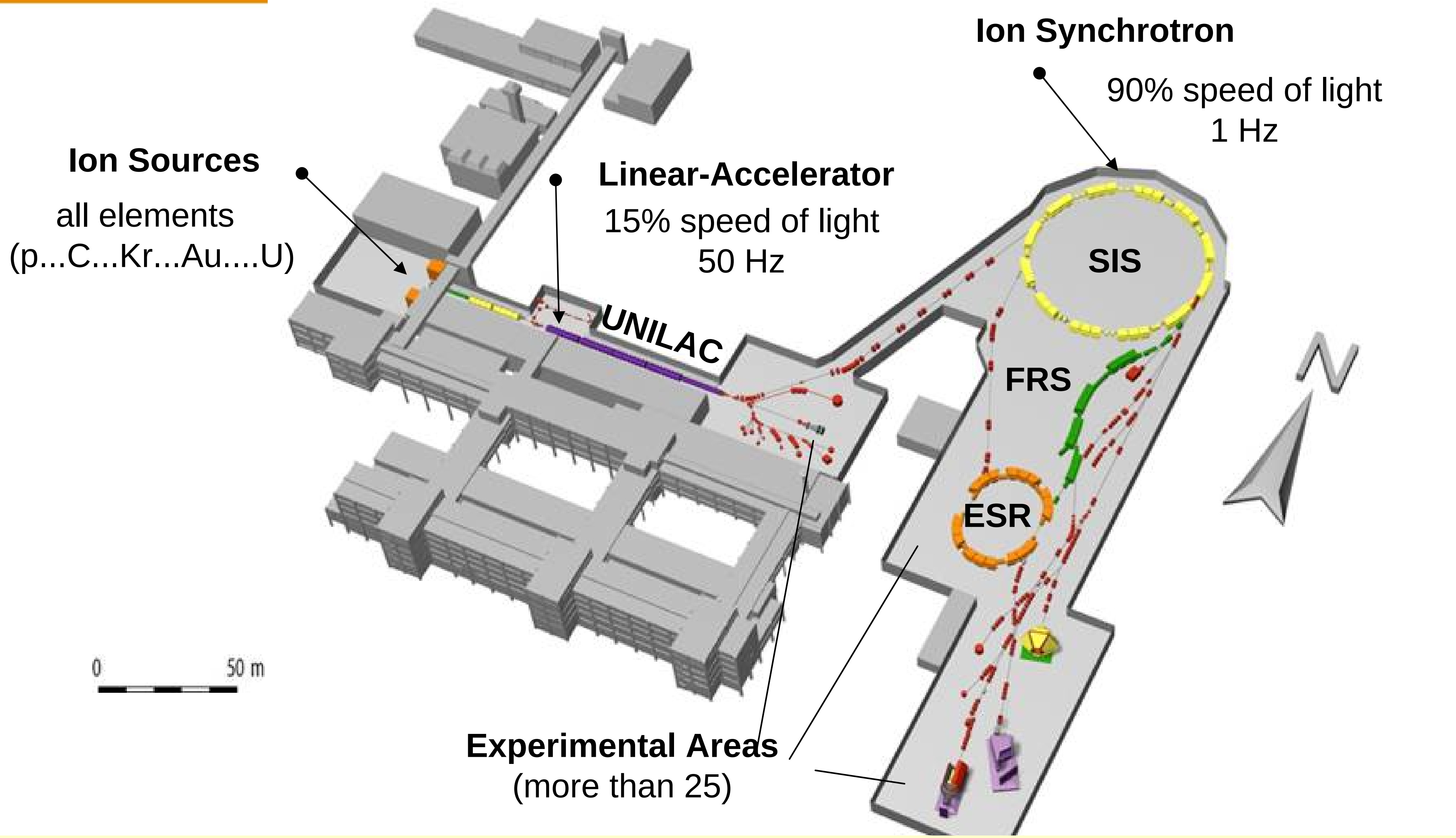
Aeronautics, Space

fusion energy research
... behaviour of compound materials

cancer therapy
... response of cells to irradiation by heavy ions

aerospace engineering
... active and passive radiation shielding of cosmic radiation

Ion Beam Accelerator Facility



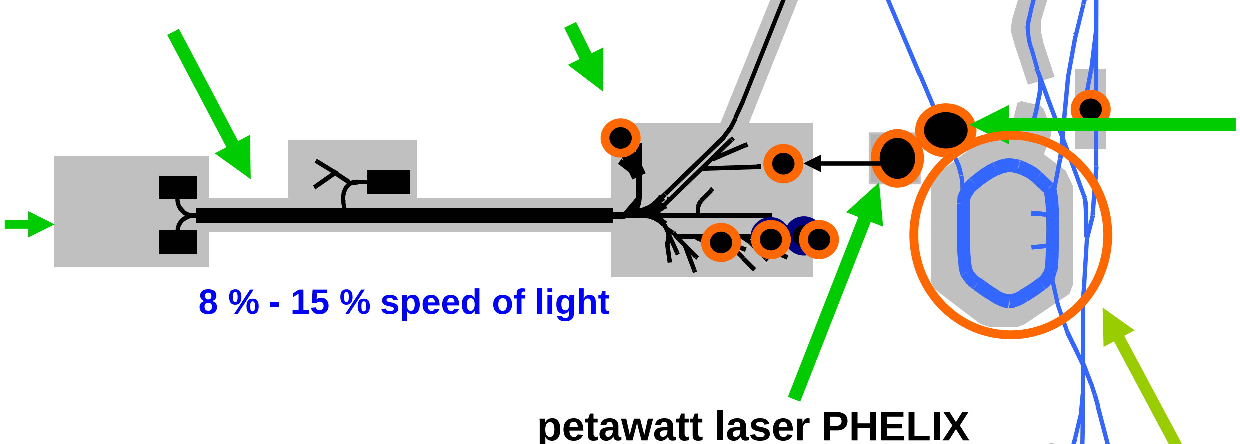
Parallel operation of 2 to three ion sources: up to 5 experiments

The GSI Accelerator Facility for Heavy Ions

linear accelerator UNILAC

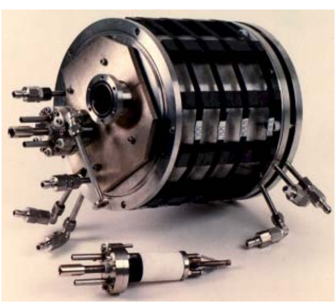
M-branch UNILAC

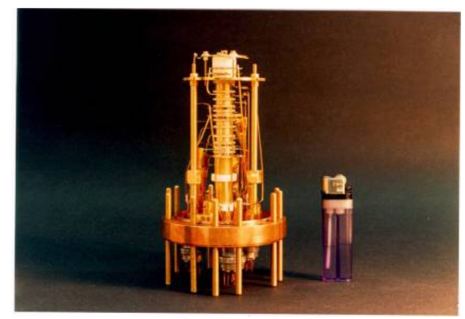
up to 90 % speed of light



heavy-ion synchrotron SIS

ion sources





ion trap facility HITRAP

petawatt laser PHELIX

storage ring ESR

Accelerated ions: H^+,..., U^{92+}

Research with Heavy Ions at GSI

HELMHOLTZ ASSOCIATION GSI

Atomic Physics

QED in non-perturbative regime
Correlated many-body dynamics for atoms and ions
Precision determination of fundamental constants
Influence of atomic structure on nuclear decay properties

Plasma Physics

Materials Science

Experiment Facilities for Atomic Physics

X3/X4

E_{max} 11.4 MeV/u

Test facility

SHIP-TRAP

E_{max} =11.4 MeV/u

- mass measurements of exotic nuclei
- laser spectroscopy

Cave A

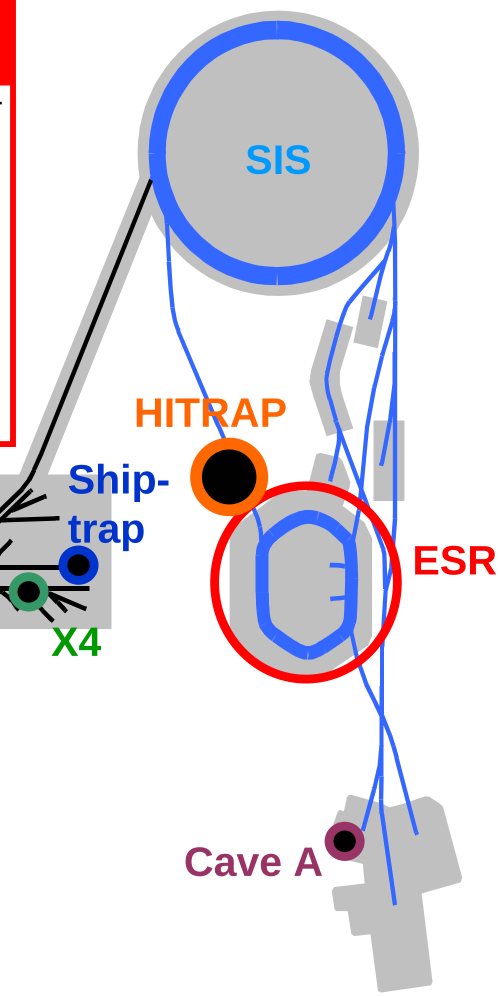
4 - 500 MeV/u; all ions up to U^{92+}

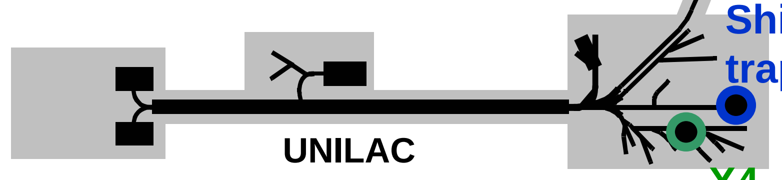
- ion channeling
- lifetimes of atomic states

ESR

4 - 500 MeV/u; all ions up to U^{92+}

Structure and collision studies with cooled heavy ions





HITRAP (under commissioning)

Trap facility for heavy ions

with A/Q < 3; up to U^{92+}

E=5 keV*Q to rest

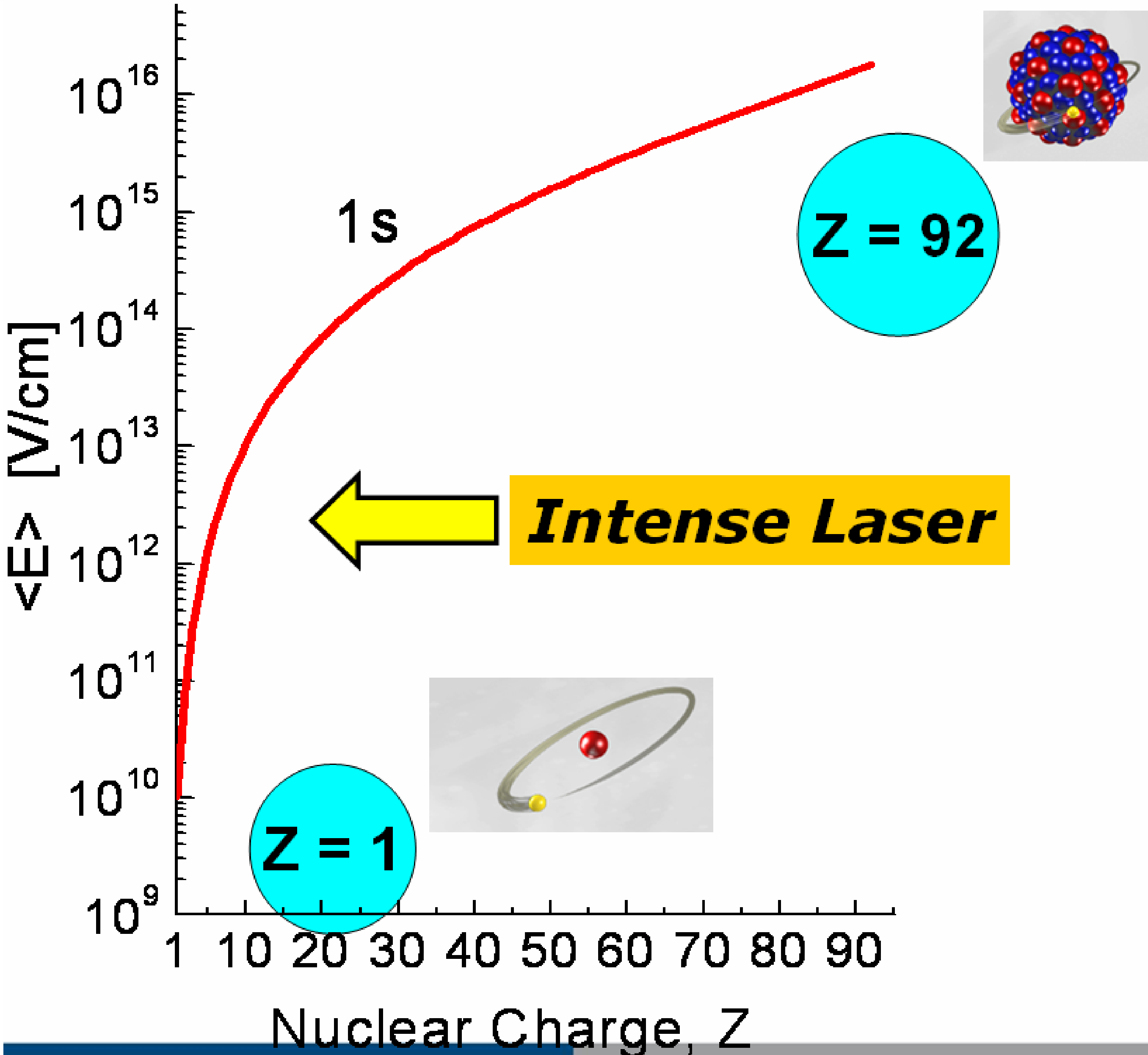
Penning trap experiments, ...

- Laser spectroscopy
- g-factor of bound electrons

Collision experiments, ...

- Collisions at very low velocities
- Surface studies, hollow-atoms

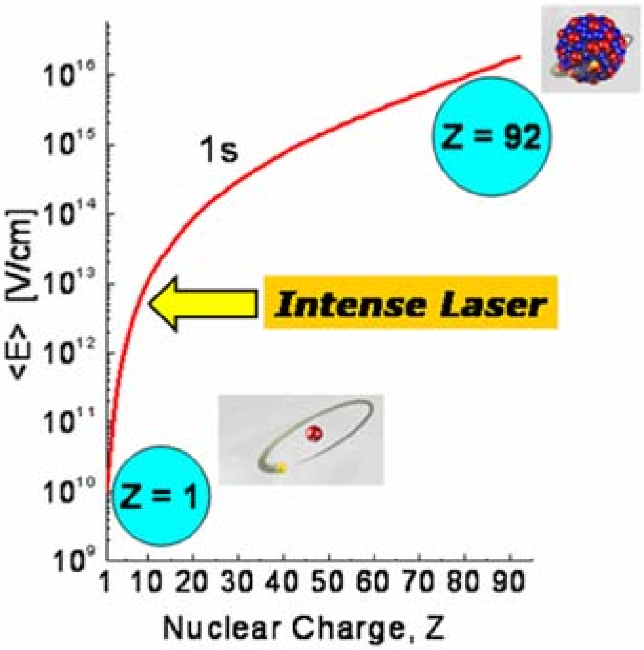
Atomic Physics in Extremly Strong Coulomb Fields



H-like Uranium
E_K = -132 • 10^3 eV
<E>= 1.8 • 10^{16} V/cm

Hydrogen
E_K = -13.6 eV
<E>= 1 • 10^{10} V/cm

Atomic Physics in Extremly Strong Coulomb Fields



$$\Delta E = \alpha/\pi \, (\alpha Z)^4 \, F(\alpha Z) \, m_e c^2$$

theory of bound-state QED still valid at high-Z ?

1s, 2s Lamb Shift

g-factor of bound electrons

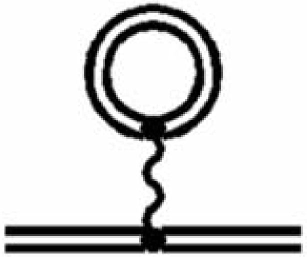
hyperfine structure

precision mass measurements

super-critical fields

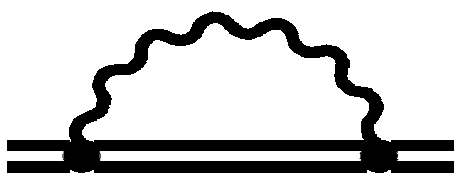
Self Energy

Vacuum Polarization

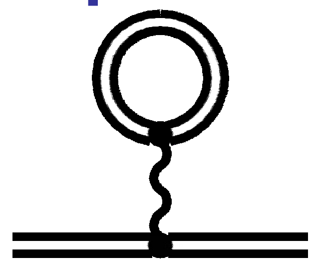


Bound-State QED: 1s Lamb Shift at High-Z

Self energy



Vacuum polarization



U^{91+}	SE	VP	NS
	355.0 eV	-88.6 eV	198.7 eV

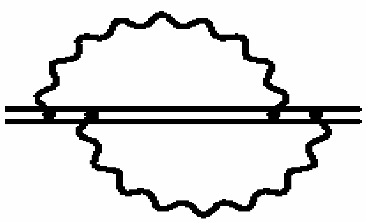
$$\Delta E = \alpha/\pi \, (\alpha Z)^4 \, F(\alpha Z) \, m_e c^2$$

Low Z-Regime: $\alpha Z \ll 1$

$F(\alpha Z)$: series expansion in αZ

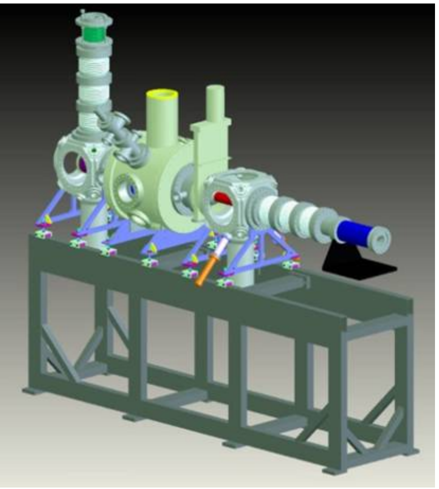
High Z-Regime: $\alpha Z \approx 1$

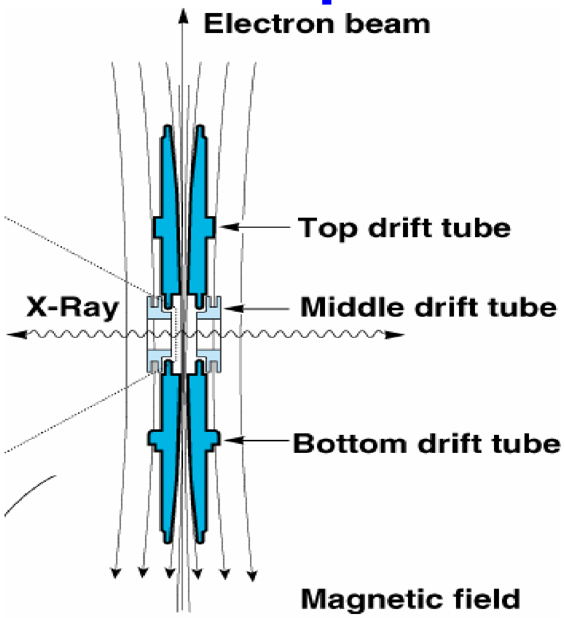
$F(\alpha Z)$: series expansion in αZ not appropriate

Goal:  **±1 eV**

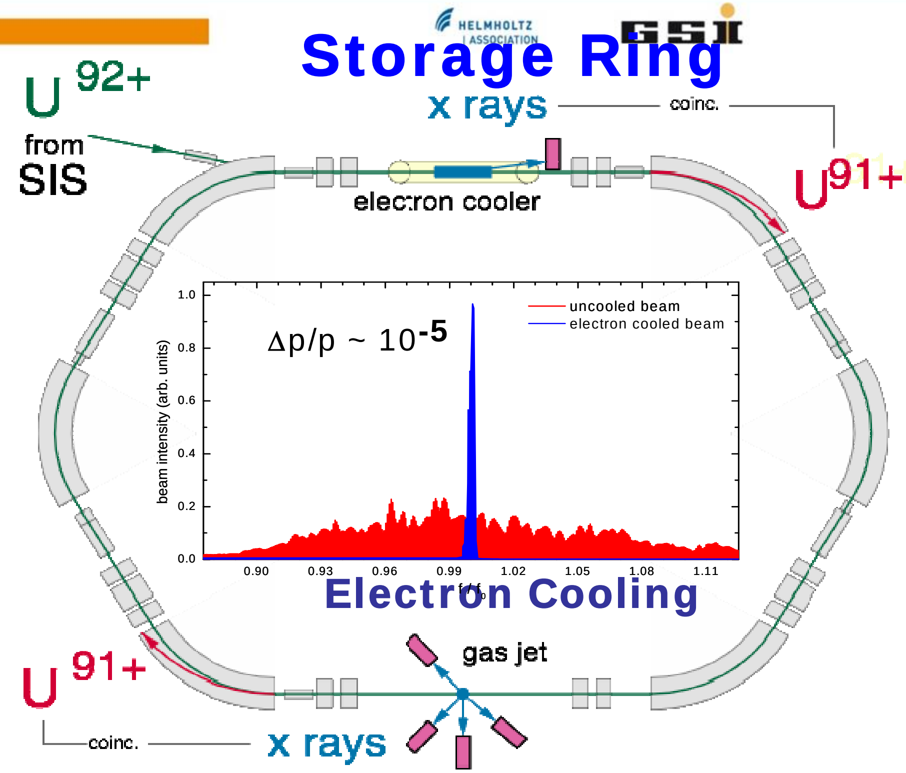
Production, Storage, and Cooling of HCI

Electron Beam Ion Trap





Storage Ring



Cooling in traps

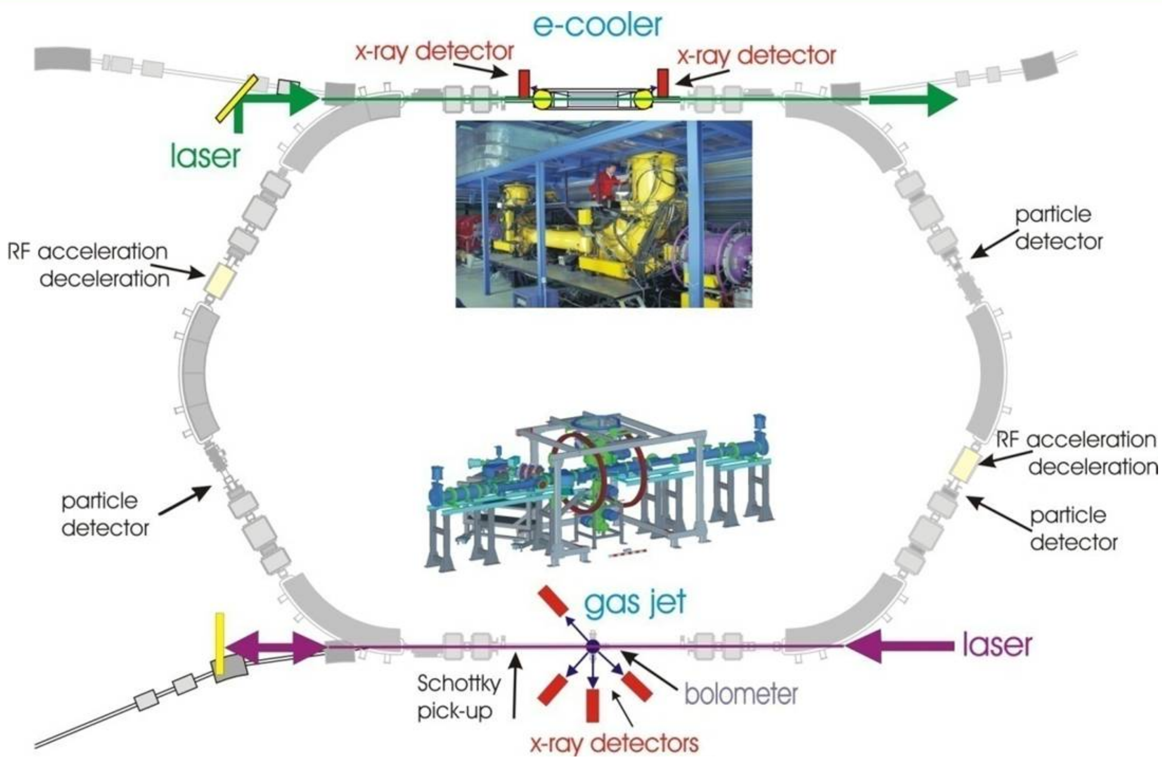
resistive cooling
evaporative cooling
laser cooling
electron cooling

Cooling in Storage Rings

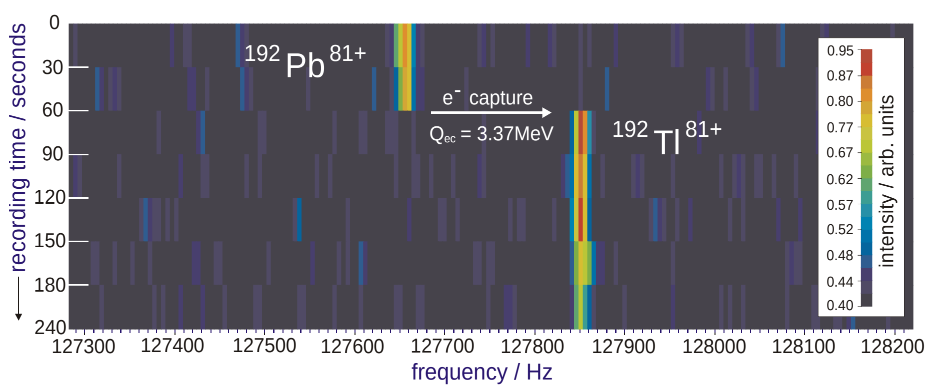
electron cooling
stochastic cooling
laser cooling

Storing and Cooling ist the key for precision

The Experiment Storage Ring ESR



Single-Ion Detection



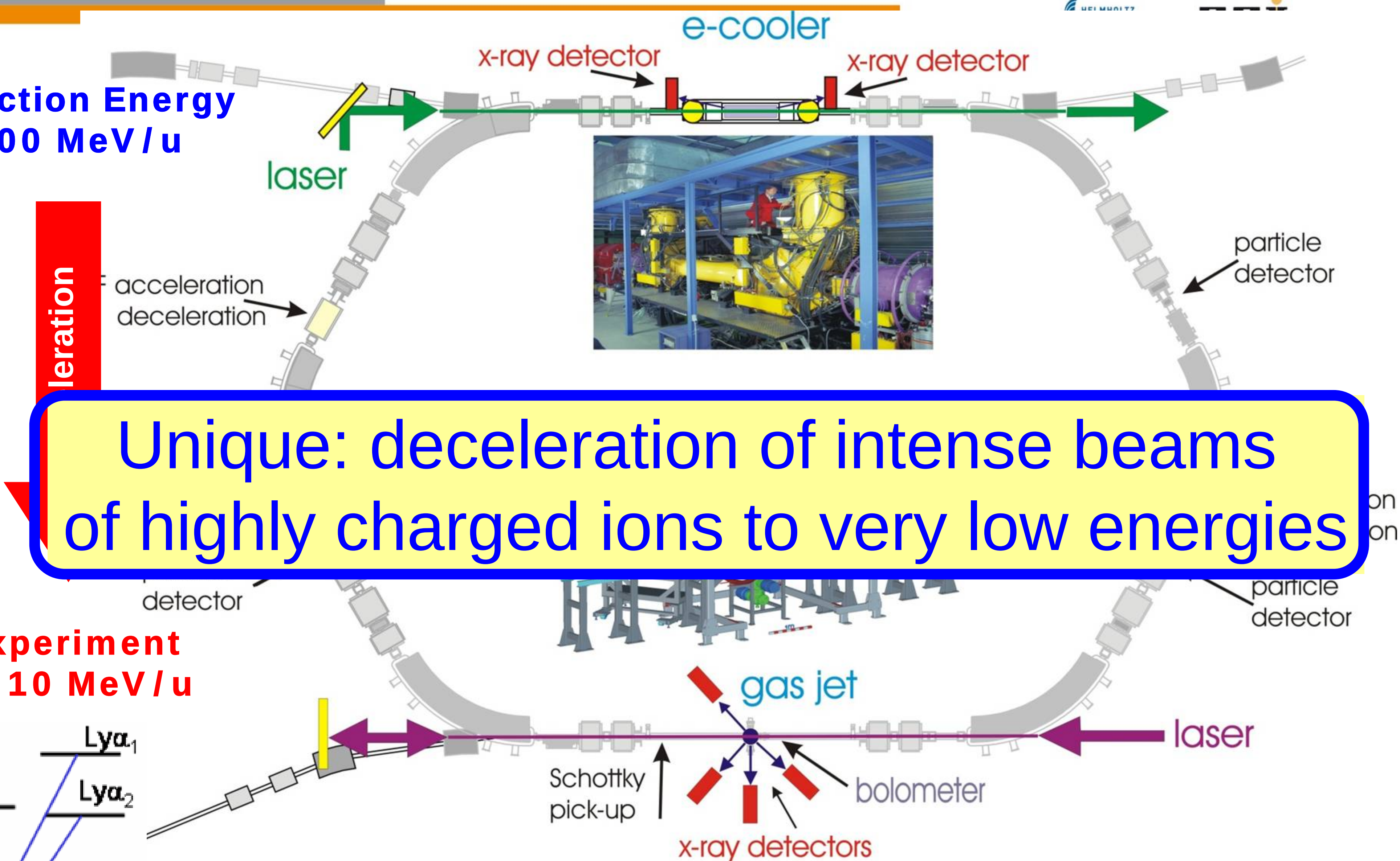
HELMHOLTZ ASSOCIATION GSI

Key features / instrumentation

- *Stochastic and electron cooling*
- *Relativistic ions (typically 400 MeV/u)*
- *Deceleration (down to 4 MeV/u)*
- *Schottky and TOF mass and lifetime spectroscopy (single ion sensitivity)*
- *Internal gas jet target*
- *Superfluid targets*
- *Position sensitive x-ray and particle detectors*
- *Crystal spectrometer*
- *Microcalorimeter detectors*
- *Collinear laser spectroscopy.*
- *Electron spectrometer*
- *Recoil ion spectrometer*

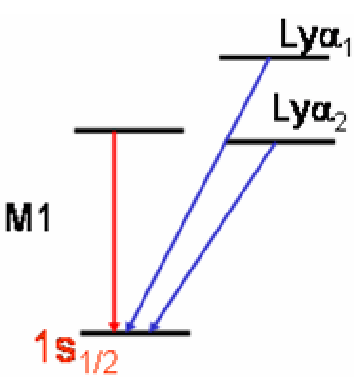
X-Ray Spectroscopy at the ESR

Injection Energy 400 MeV/u



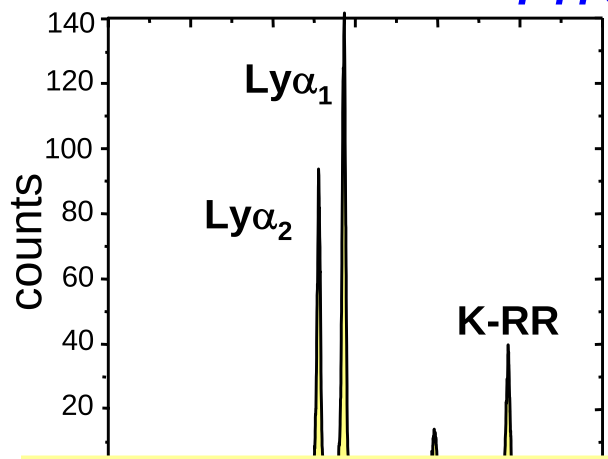
Unique: deceleration of intense beams of highly charged ions to very low energies

Experiment @ 10 MeV/u



Test of Quantum Electrodynamics (1s-LS)

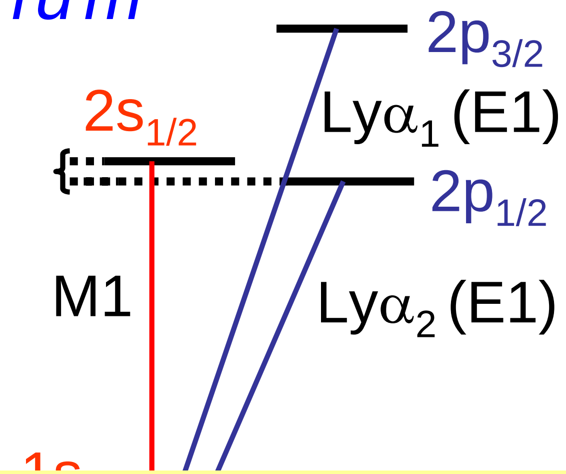
The 1s-LS in H-like Uranium



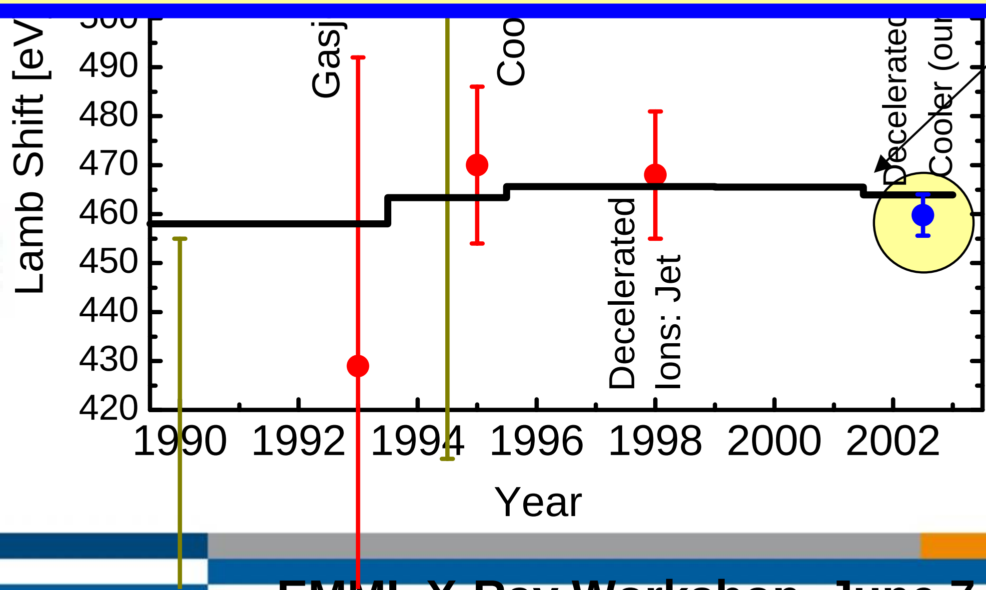
1s-Lamb Shift

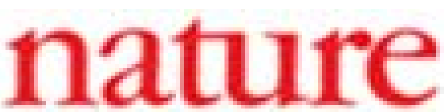
Experiment: 459.8 eV ± 4.6 eV

Theory: 463.95 eV



Most accurate test of bound-state QED for simple one-electron ions at high-Z



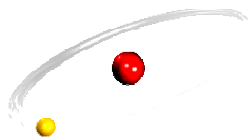


Research Highlights
Nature **435**, 858-859
(16 **June 2005**)

A. Gumberidze
PRL 94, 223001
(2005)

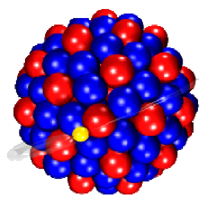
Quantum Electrodynamical Effects in Extreme Electromagnetic Fields

hydrogen

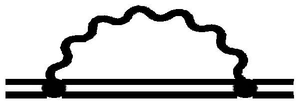


Z=1
E_b = 13.6 eV
$Z \cdot \alpha \ll 1$

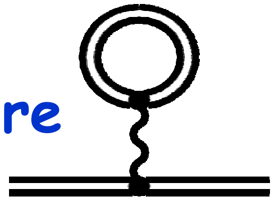
uranium ion



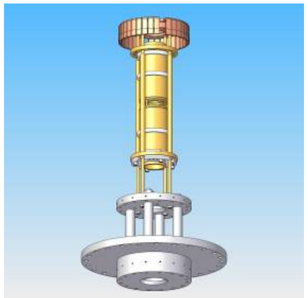
Z=92
E_b = 132 keV
$Z \cdot \alpha \approx 1$

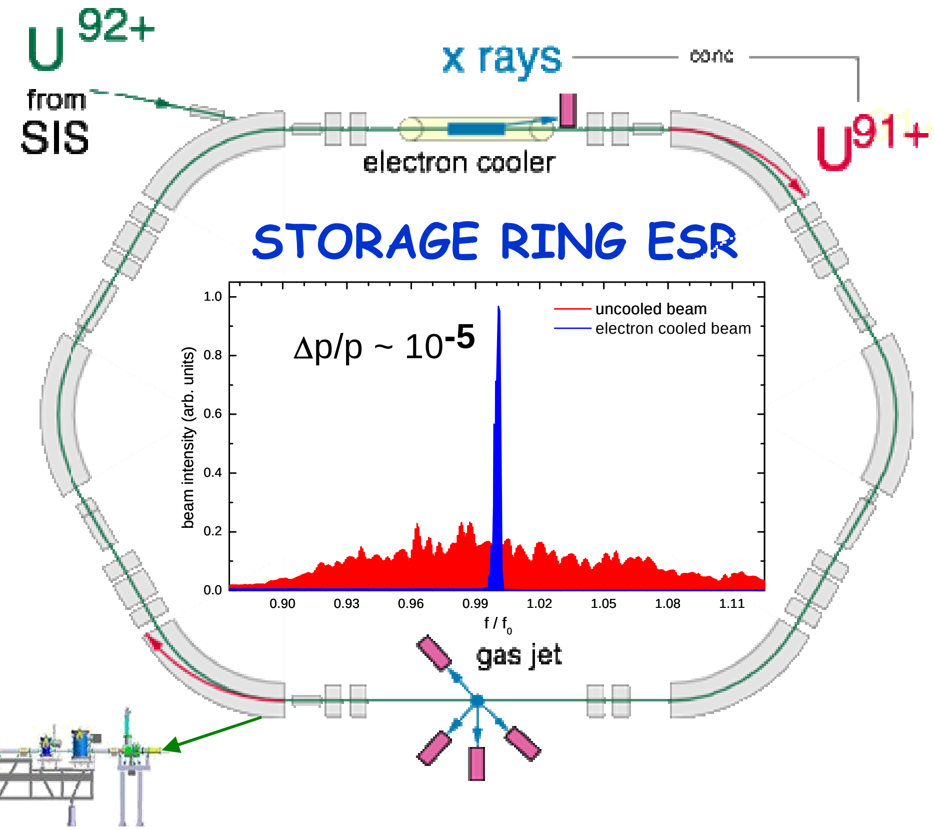


Lamb Shift
Hyperfine Structure
g-Factor

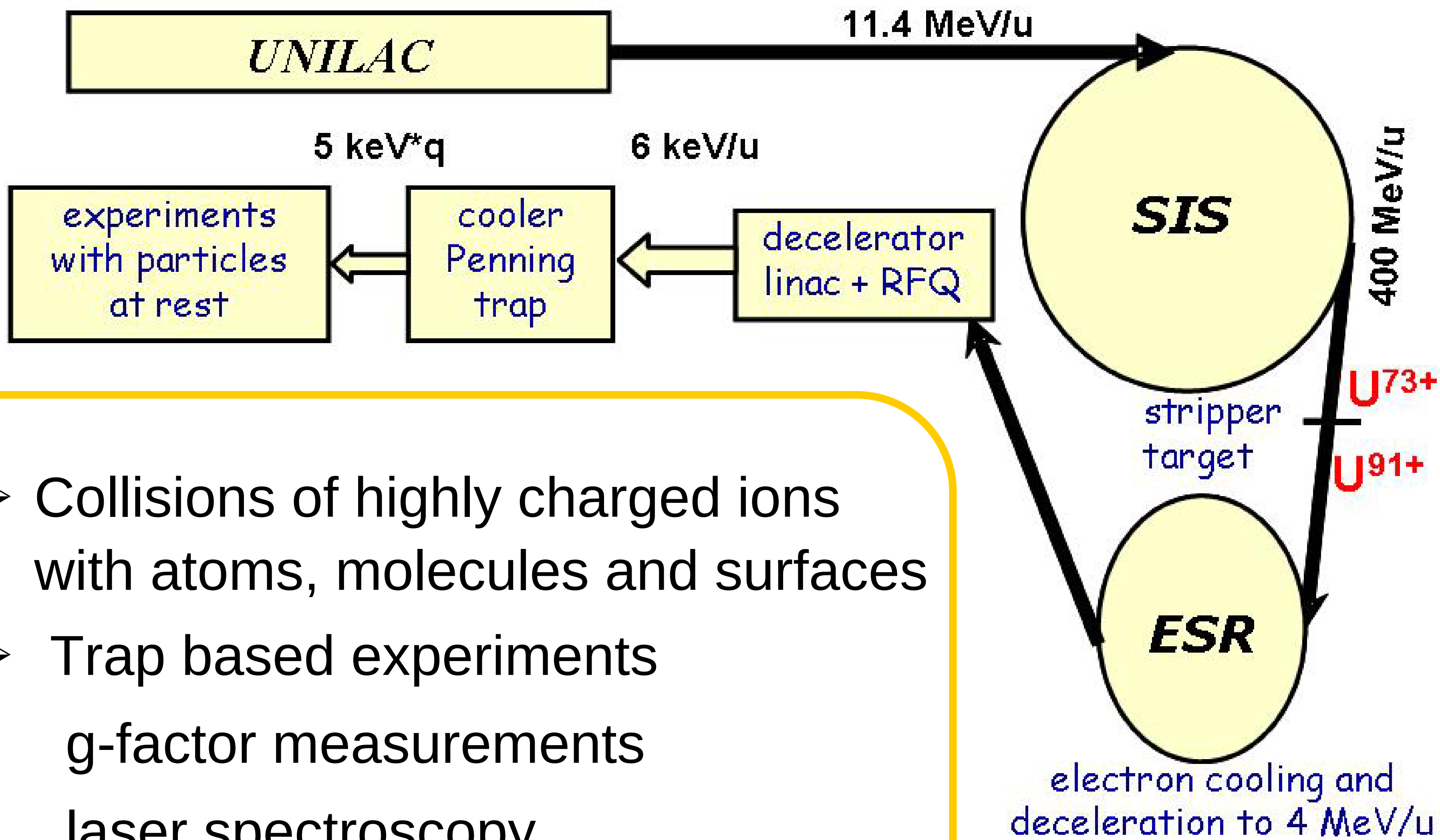


HITRAP





HITRAP – Trap facility for heavy highly charged ions



- Collisions of highly charged ions with atoms, molecules and surfaces
- Trap based experiments

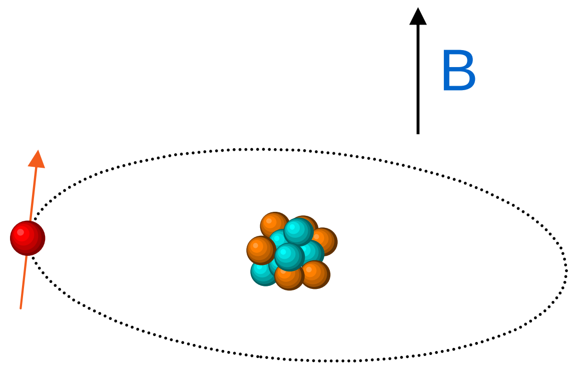
  g-factor measurements

  laser spectroscopy

  mass measurements

g-Factor of the Bound Electron

H-like ions stored in precision traps



Larmor precession frequency of the bound electron:

$$\omega_L^e = \frac{geB}{2m_e}$$

ion cyclotron frequency:

$$\omega_c^i = \frac{qB}{M_i}$$

$$g = 2\left(\frac{q}{e}\right)\left(\frac{m_e}{M_i}\right)\left(\frac{\omega_L^e}{\omega_c^i}\right)$$

g-factor

external input parameter

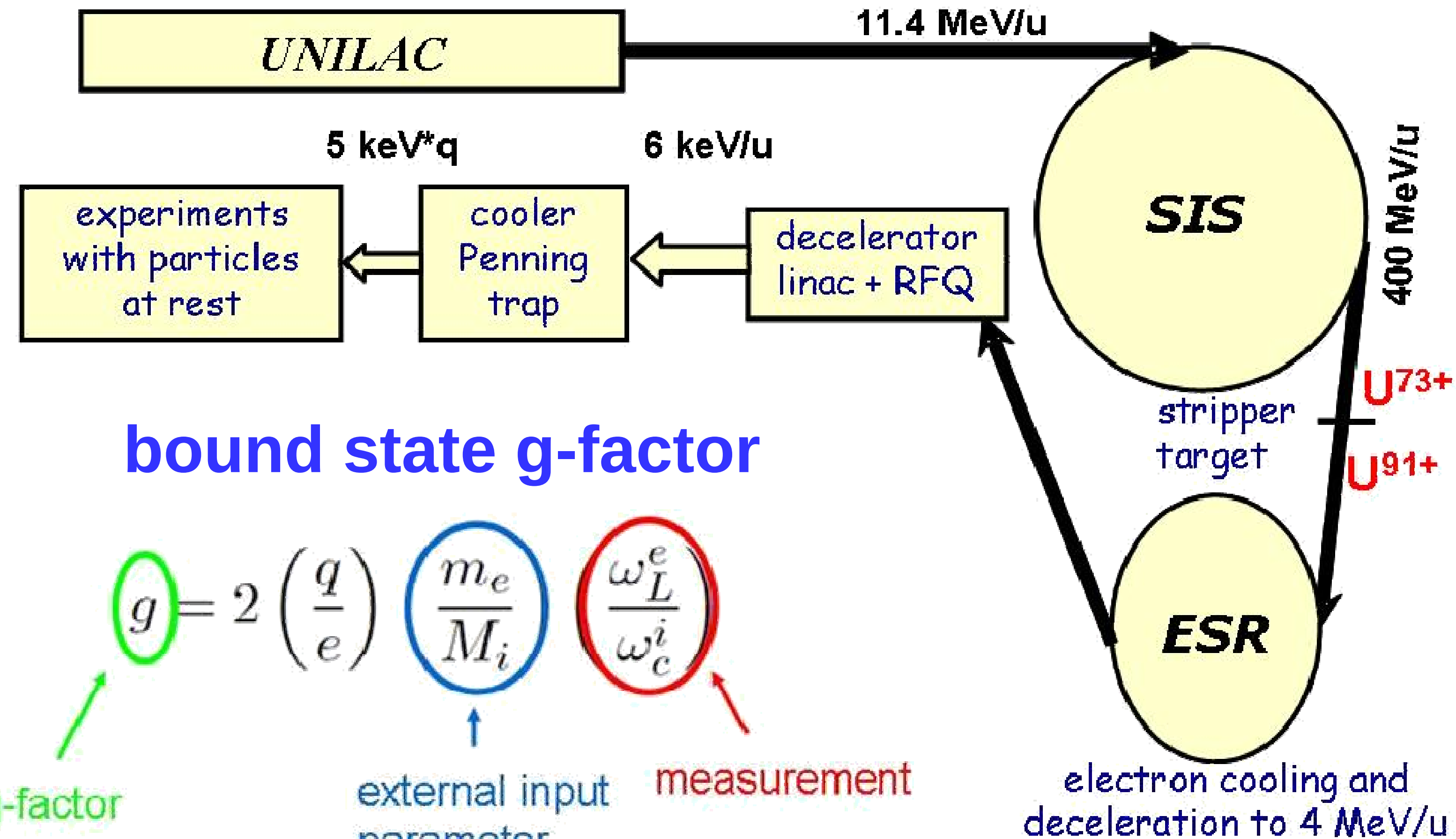
measurement

Recent highlight:
g-factor measurements on H-like carbon $^{12}C^{5+}$ and oxygen $^{16}O^{7+}$ with resolution better than 10^{-9}. Most accurate determination of the electron mass.

Bound State QED and Fundamental Constants: The New HITRAP Facility at the ESR

- **medium-Z**
  fine-structure constant α

- **high-Z**
  test of bound-state QED



bound state g-factor

$$g = 2\left(\frac{q}{e}\right)\frac{m_e}{M_i}\frac{\omega_L^e}{\omega_c^i}$$

g-factor — external input parameter — measurement

Challenge for POFII: First precision experiments at HITRAP

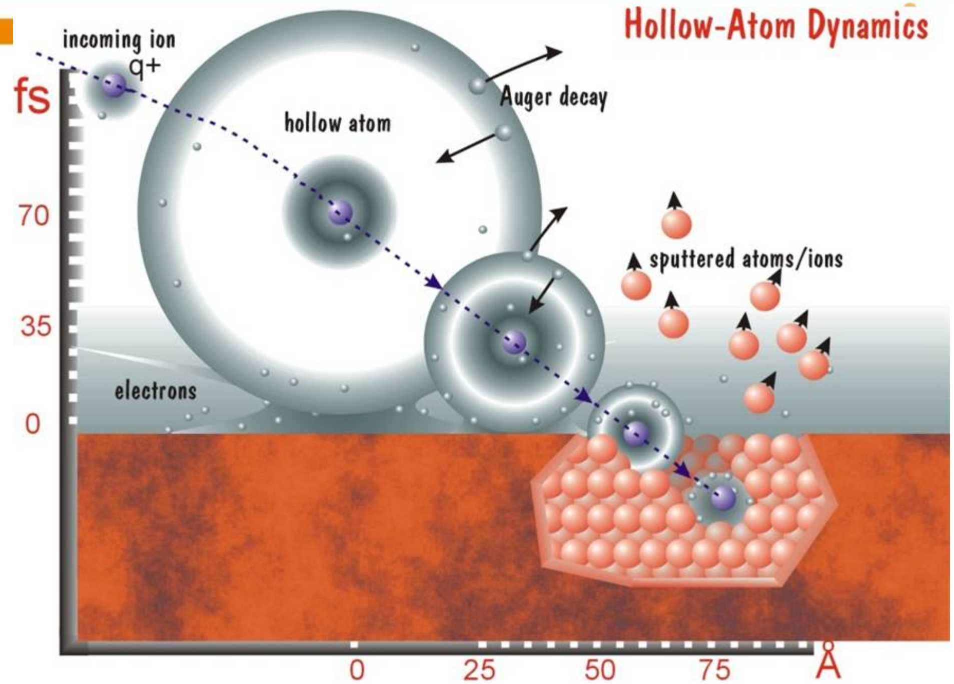
PHD work of Klaas Brantjes

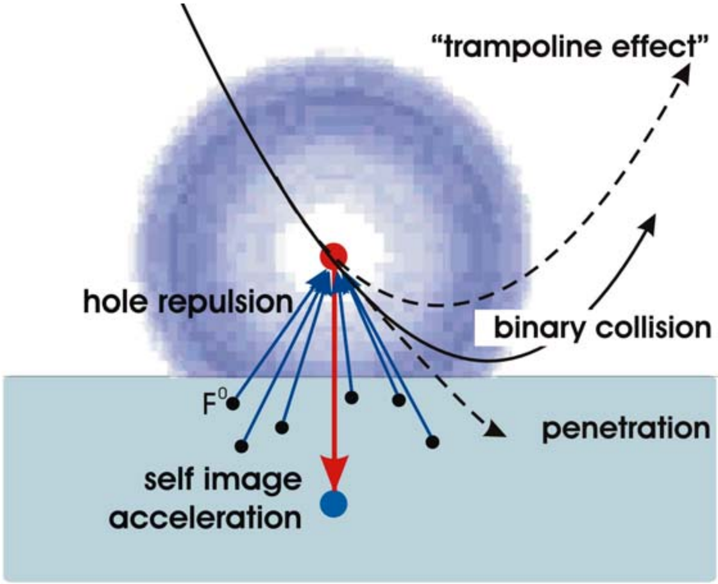
V. M. Shabaev et al., Phys. Rev. Lett. 96 253002-1-4 (2006)
J. L. Verdu et al., Phys. Rev. Lett. 92 093002-1-4 (2004)

Ion-surface interaction

questions to be addressed:

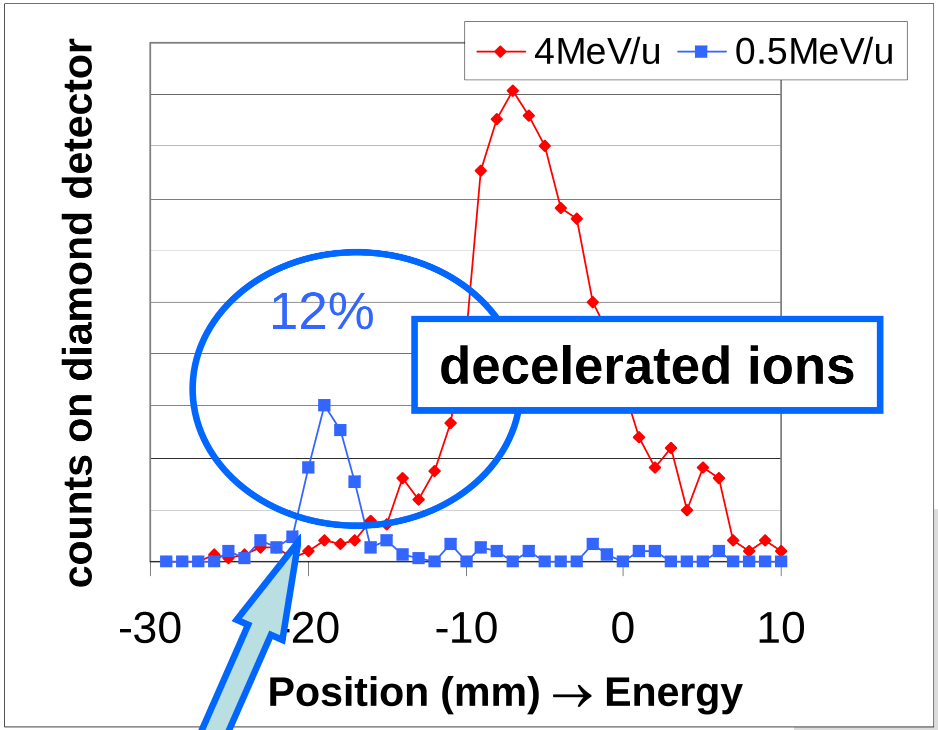
- hollow atom spectroscopy
- high-spin states via electron capture from magnetised surfaces
- electron dynamics at surfaces and thin films
- trampoline effect existent above a critical charge state?
- surface lithography by means of HCI impact?





Exp. H2, groups:
R. Hoekstra, KVI Groningen
A. Warczak, Krakow
J. Burgdörfer, Vienna

HITRAP – IH Structure
deceleration from 4 to 0.5 MeV/u

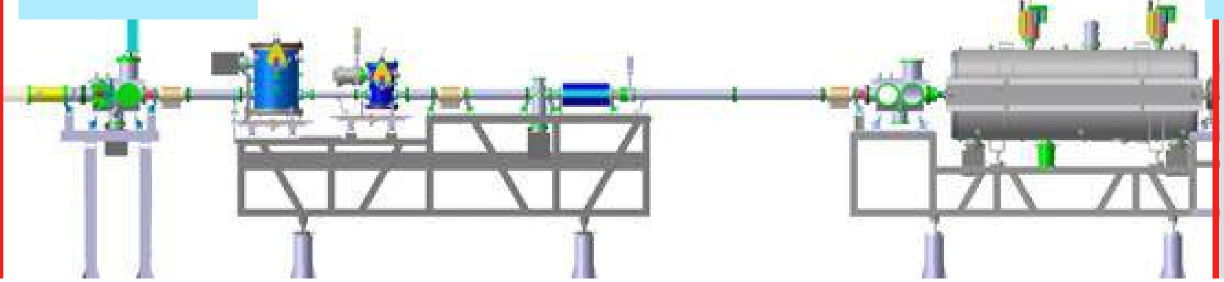


about 12% decelerated – Aim: ~60%

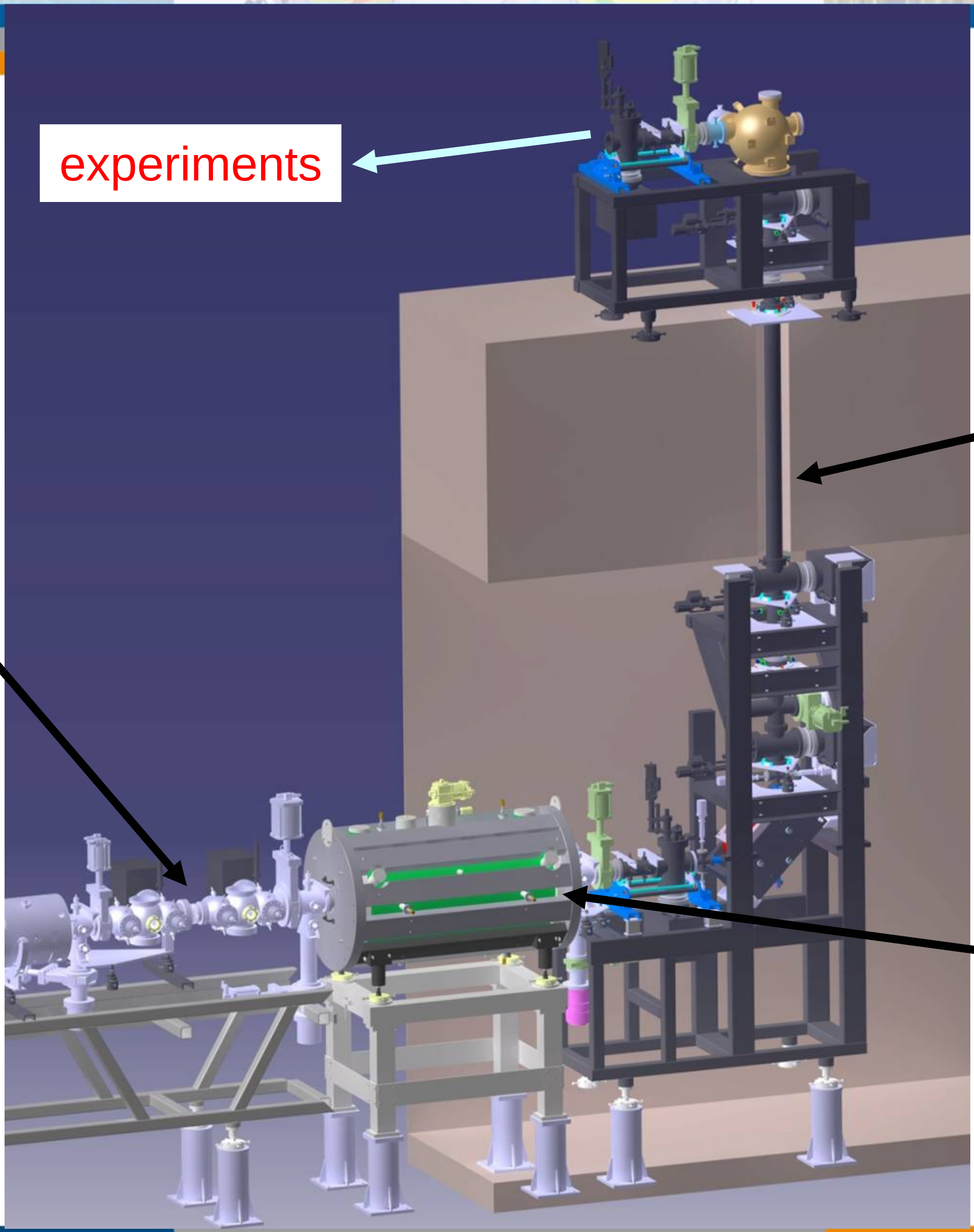
4 MeV/u

0.5 MeV/u

6 keV/u



HITRAP low beam energy section



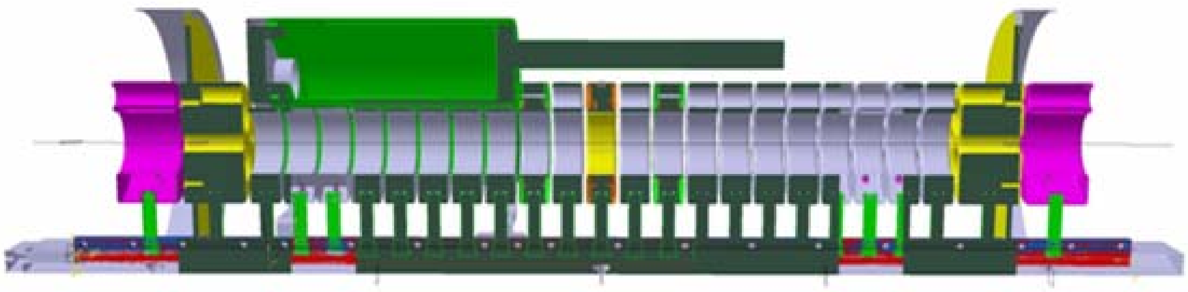
vertical beamline
($<10^{-10}$ mbar)

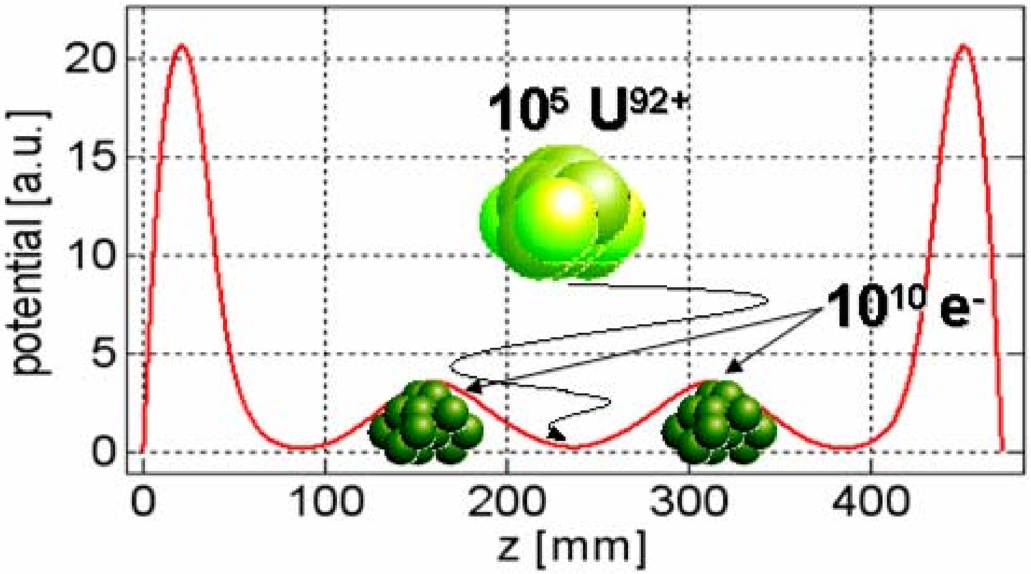
LEBT
(two differential
pumping stages)

Cooler trap
($<10^{-13}$ mbar)

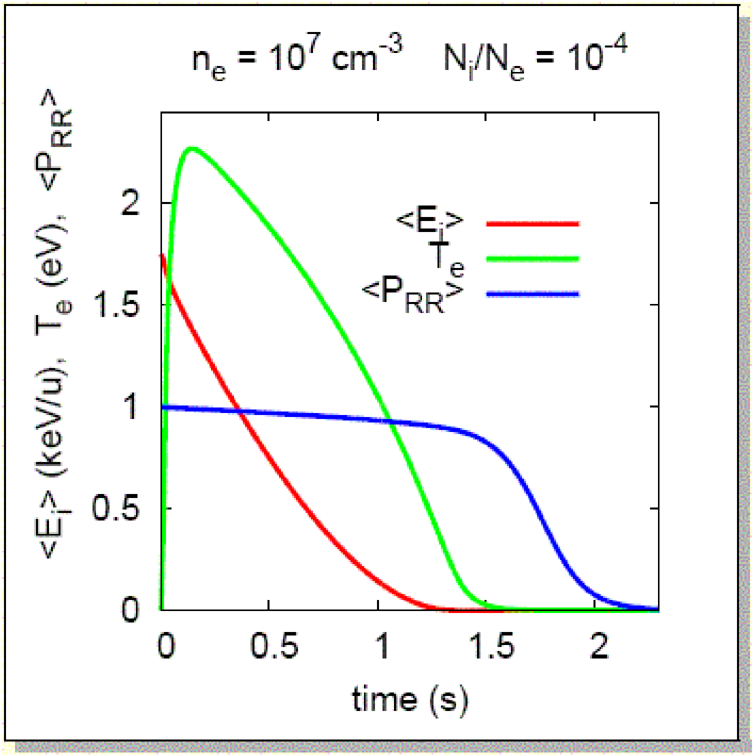
RFQ
(10^{-8} mbar)

The HITRAP cooler trap





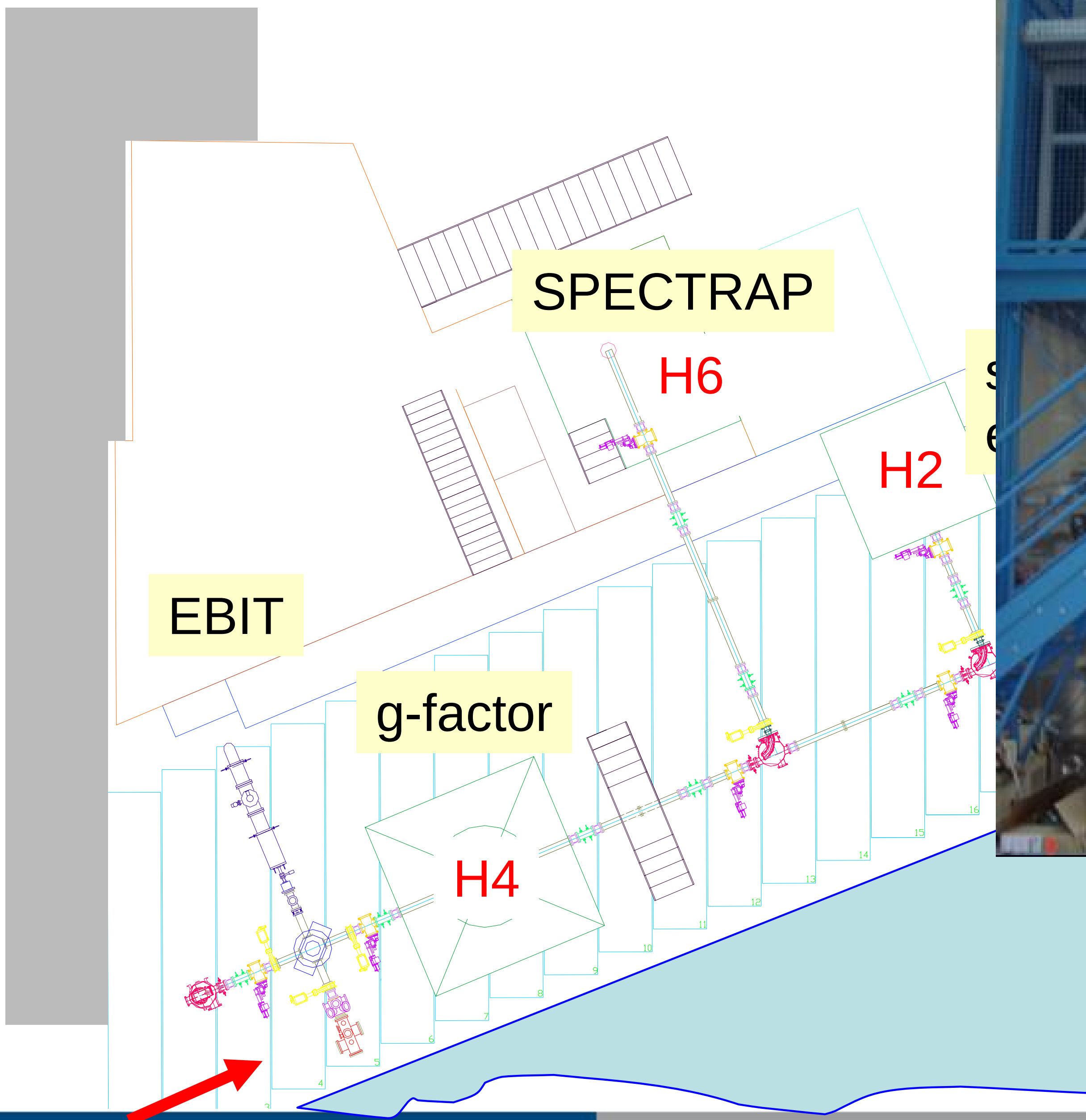
- potential shaping => nested traps for 10^5 ions, 10^{10} e^-
- e- cooling to 10 eV
- resistive cooling to 4 K
- vacuum better than 10^{-13} mbar



Questions

space charge and frequency shifts
cooling times
survival probability

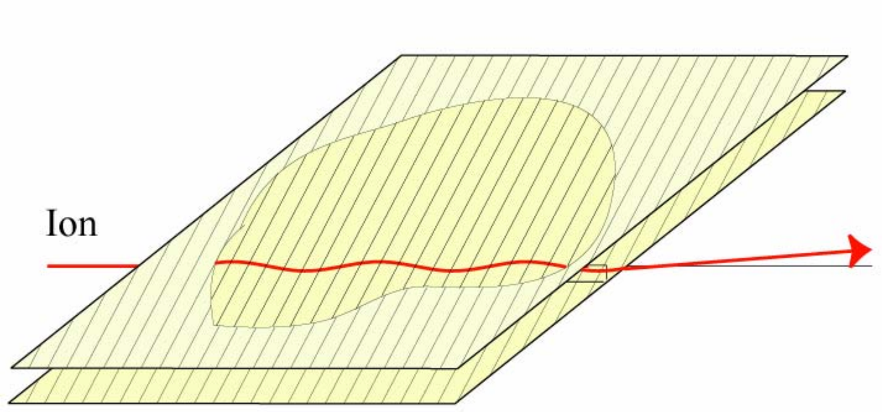
HITRAP experiment area



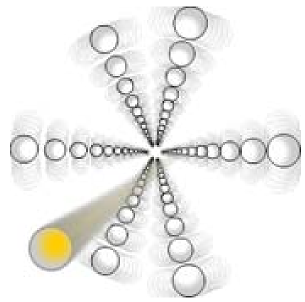
Resonant Coherent Excitation Experiment on Highly Charged Uranium

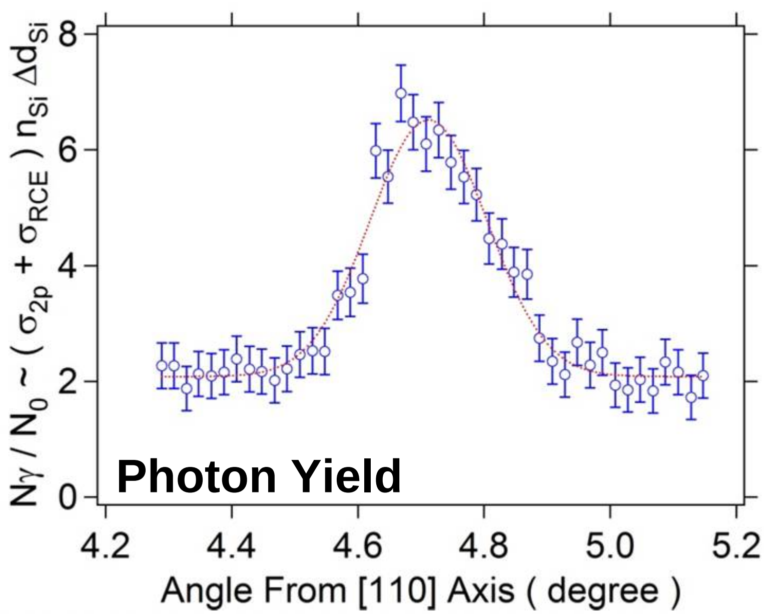
high precision spectroscopy of $\mathbf{1s^2 2s_{1/2}}$-$\mathbf{1s^2 2p_{3/2}}$ transitions of Li-like U at 193 MeV/u.

SIS - CaveA



CHANNELING





Resolution: $\Delta E/E \approx 10^{-3}$

determined by:

- momentum spread of SIS beam 6-7 • 10^{-4}
- beam divergence

Next experiment will employ ESR
→ two orders of magnitude better resolution expected

International Collaboration:

- Japan (Riken, Tokyo Univ.)
- Germany (GSI)
- France (Lyon)

Research with Heavy Ions at GSI

Atomic Physics

QED in the non-perturbative regime
Correlated multi-body dynamics for atoms and ions
Precision determination of fundamental constants
Influence of the atomic structure on nuclear decay properties

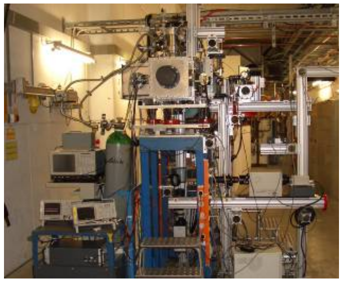
Plasma Physics

Interaction of ions and photons with plasmas
Equation of state, phase transitions, transport phenomena
Matter under high pressure
Intense Laser (PHELIX): plasma production, particle acceleration

Materials Science

Experiment Facilities for Plasma Physics

HHT



U-ions:
0.2 - 1 GeV/u

Ions/pulse:
up to $2*10^{10}$

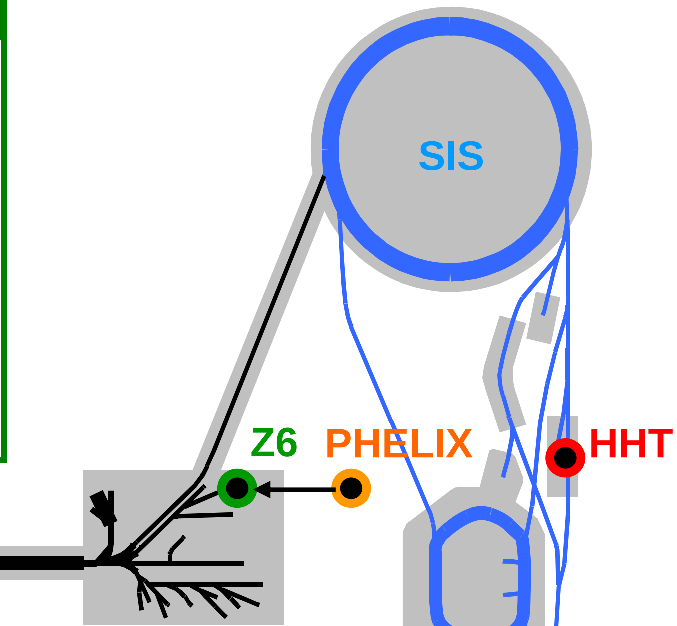
- High energy density physics
- EOS, phase transitions
- Transport properties
- Warm Dense Matter
- High pressure matter (giant planets)

Z6

Ion energy:
3 - 13 MeV/u

Intensity:
~1 pmA

- Heavy ion interaction with plasma
- Charge states of projectile ions in ionized and cold matter
- Fusion related studies



PHELIX

High Energy / High Intensity Laser

Laser bay: 0.5 PW, 250 J @ 500 fs

2008: 0.2 PW, 100 J @ 500 fs

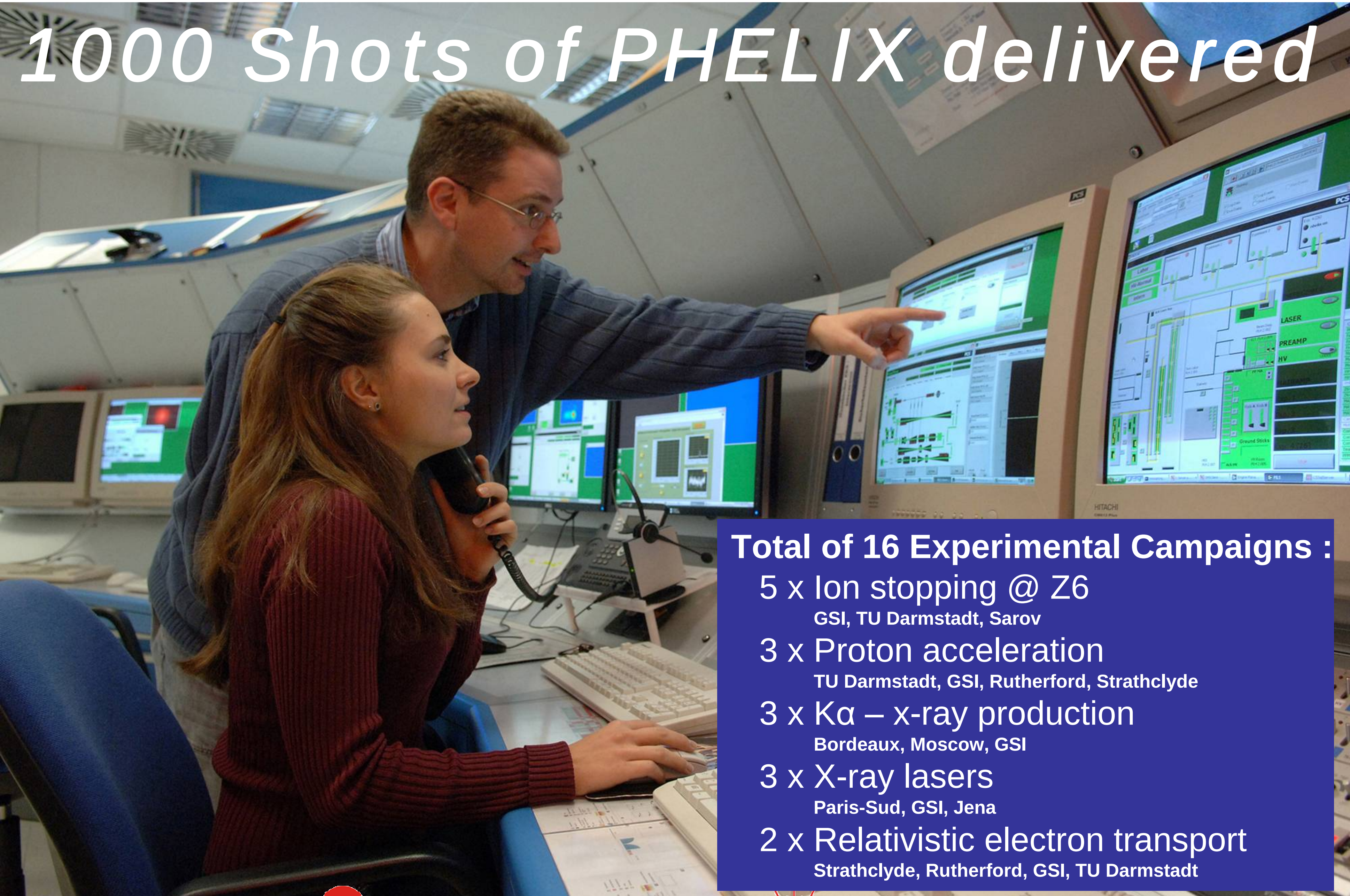
Z6: 0.3 – 1 kJ @ 1 – 15 ns

50 J @ 0.5 – 2 ps (100 TW)

2008: 300 J @ ~ns

- Narrow band x-ray source
- Proton acceleration (imaging, injection in accelerator)
- High field effects in highly charged ions

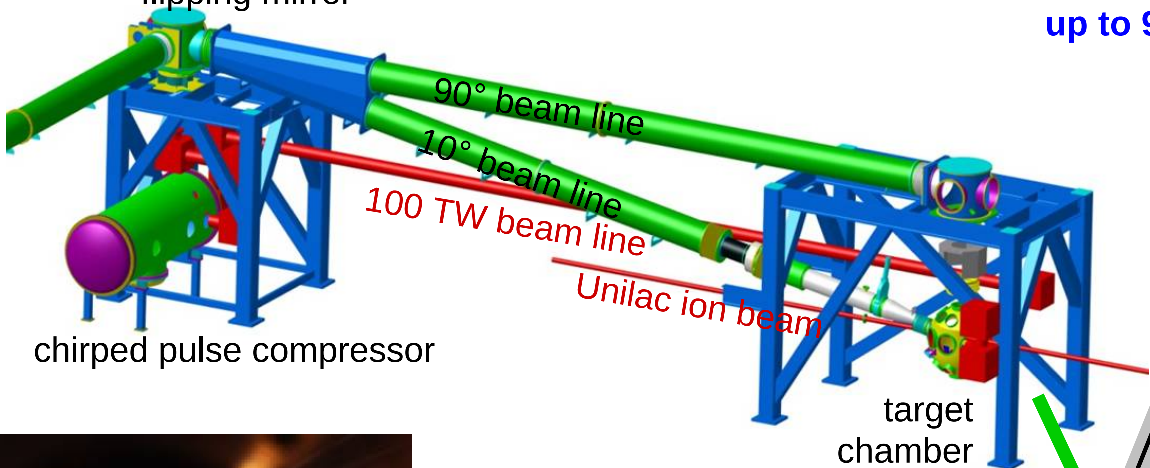
1000 Shots of PHELIX delivered

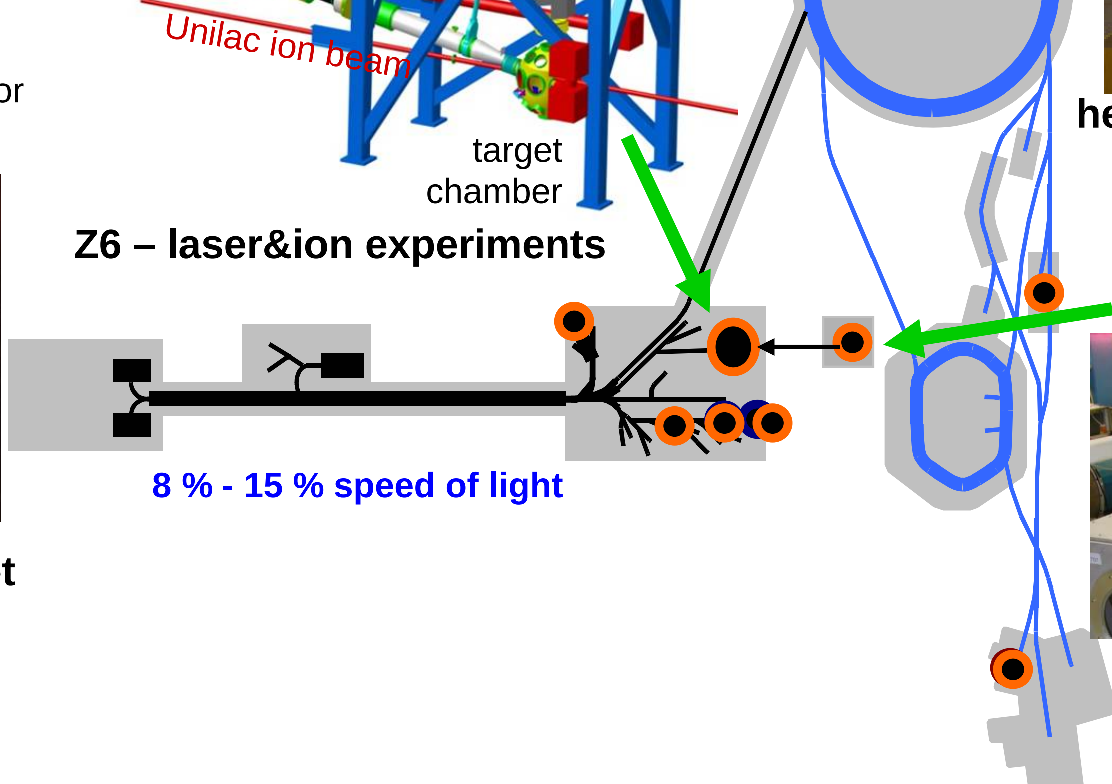


Total of 16 Experimental Campaigns :

- 5 x Ion stopping @ Z6
  GSI, TU Darmstadt, Sarov
- 3 x Proton acceleration
  TU Darmstadt, GSI, Rutherford, Strathclyde
- 3 x Kα – x-ray production
  Bordeaux, Moscow, GSI
- 3 x X-ray lasers
  Paris-Sud, GSI, Jena
- 2 x Relativistic electron transport
  Strathclyde, Rutherford, GSI, TU Darmstadt

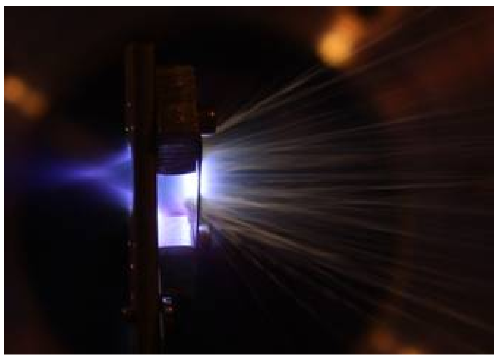
Z6 – a unique facility offering ion and laser beams for combined experiments





heavy-ion synchrotron SIS

petawatt laser PHELIX



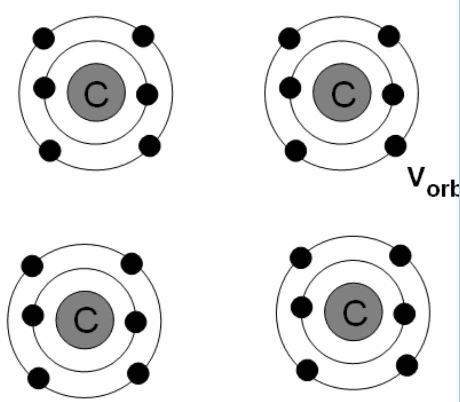
laser heated plasma target

10° beam line: directly laser driven plasma → energy loss in ideal plasma

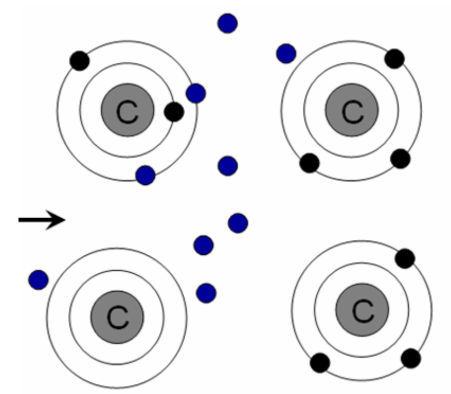
90° beam line: Hohlraum radiation driven plasma → energy loss in non-ideal plasma

100 TW beam line: ion acceleration by ultra intense lasers → injection into conventional accelerator structure

Z6: combined laser & ion beam experiments



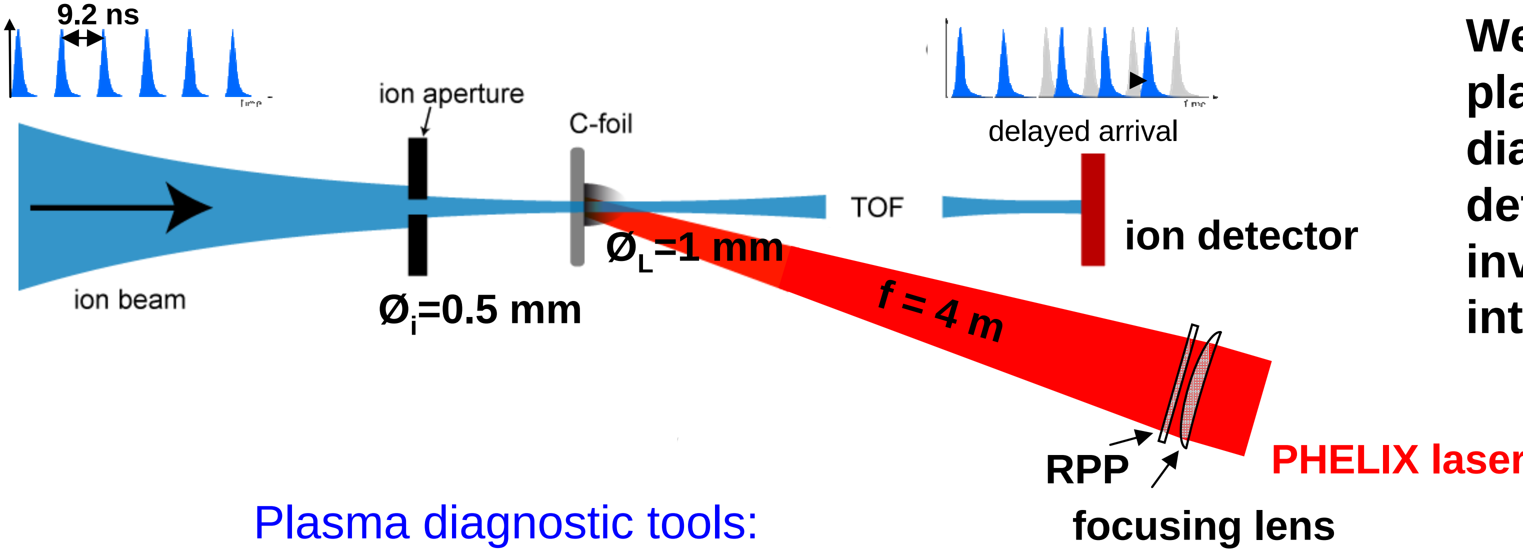
1. Ion stopping in ideal and non-ideal plasma
   - Increased energy transfer from the projectile to free plasma electrons compared to bound electrons in cold matter
2. Charge exchange with free plasma electrons
   - Increased projectile charge state due to suppression of the capture cross section in plasma (σ_{capt}(bound e^-) >> σ_{capt} (free e^-))
3. Ion acceleration by an intense laser beam
   - Injection of a laser accelerated proton beam into conventional ion accelerator structure



Experiments worldwide only feasible at GSI due to the combination of intense ion beams from UNILAC and a powerful laser beam from PHELIX

Interaction of ions with plasma targets generated by the PHELIX laser

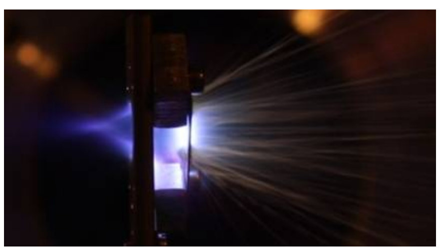
HELMHOLTZ ASSOCIATION GSI



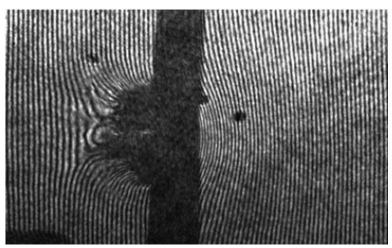
We have developed the plasma and ion beam diagnostics to precisely detect the physics involved in ion - plasma interaction!

T. Heßling

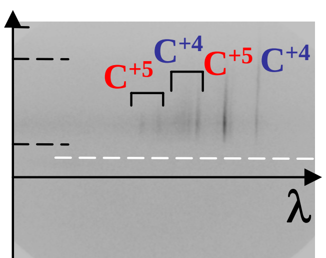
Plasma diagnostic tools:



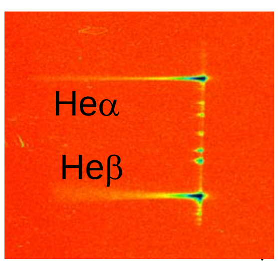
Expanding plasma heated by a laser



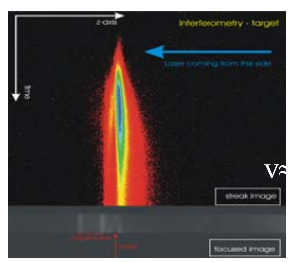
3ω laser interferometry



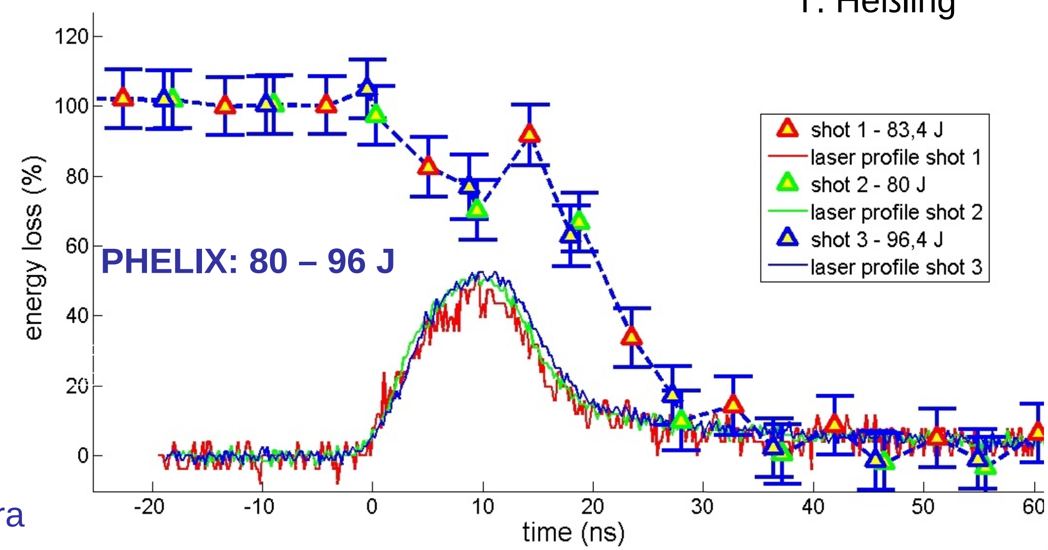
X-ray streak camera



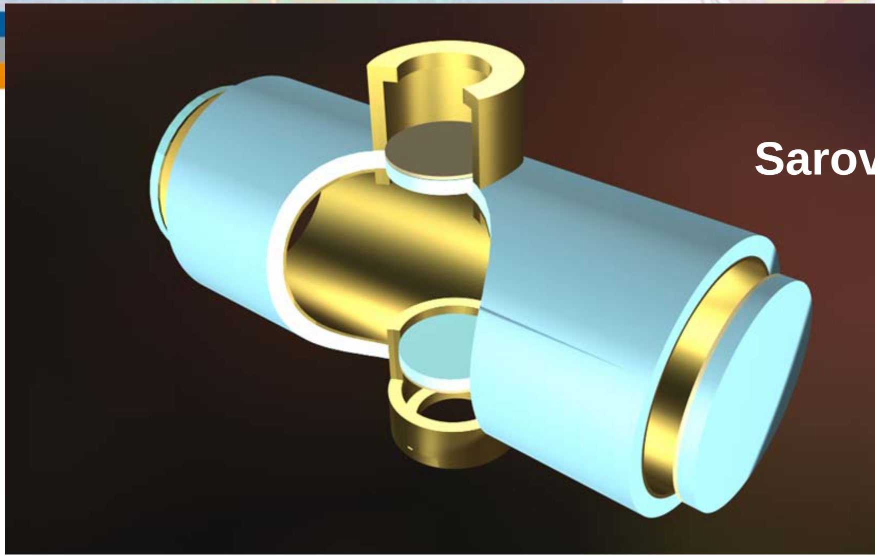
X-ray spectrometer with spatial resolution



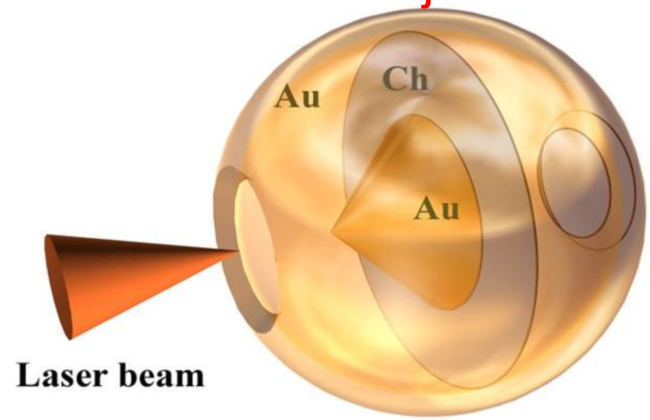
Visible streak camera



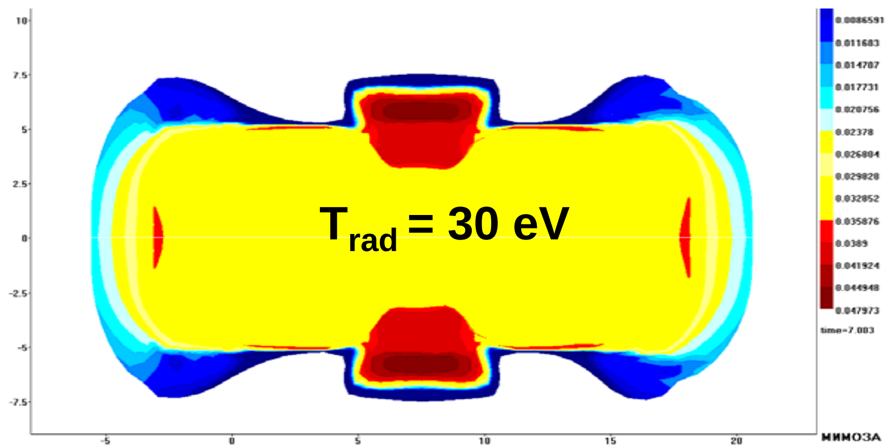
Hohlraum target design and experiments



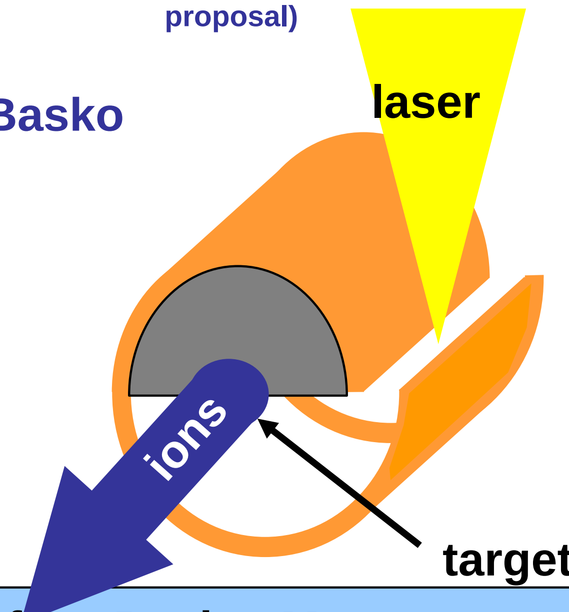
See O. Rosmej's following talk !



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



Basko

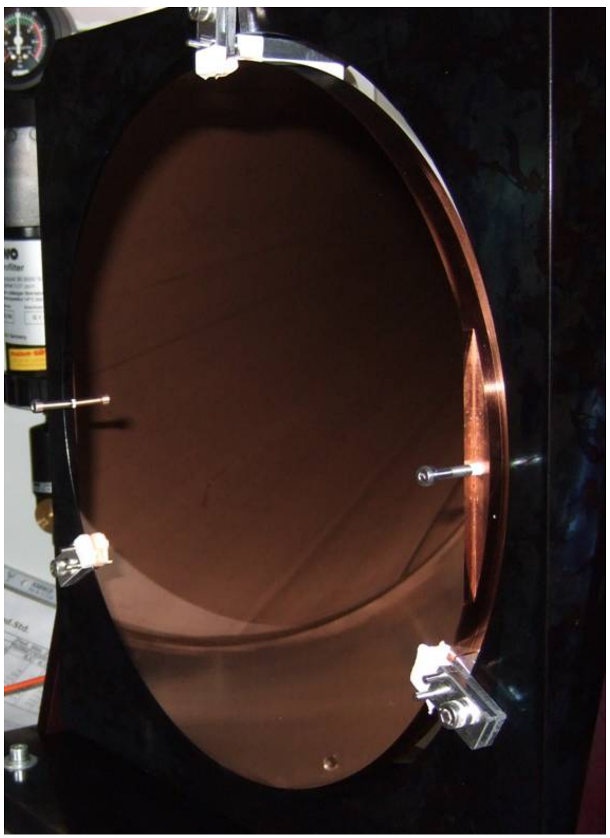


<u>Theoretical support</u>: Y.Belyakov et al., Sarov; Maruhn, Frankfurt; Basko, Moscow

Experiments with close to 0.5 Petawatt in the laser hall

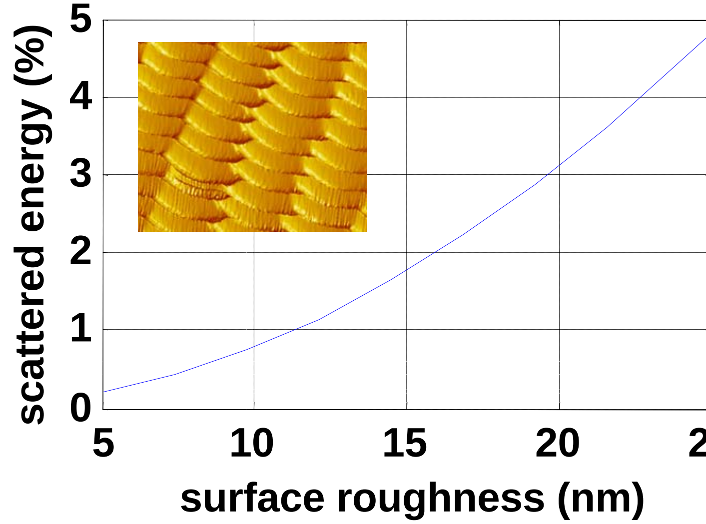
- The 90-degree massive metallic mirror is machined to ~1 micron accuracy (PV),
- The surface roughness and machining precision have to the balanced to get the best trade-off between scattering losses and wavefront error.

Mirror in its Holder



Back View

Estimation of scattered energy based on simulated surface roughness

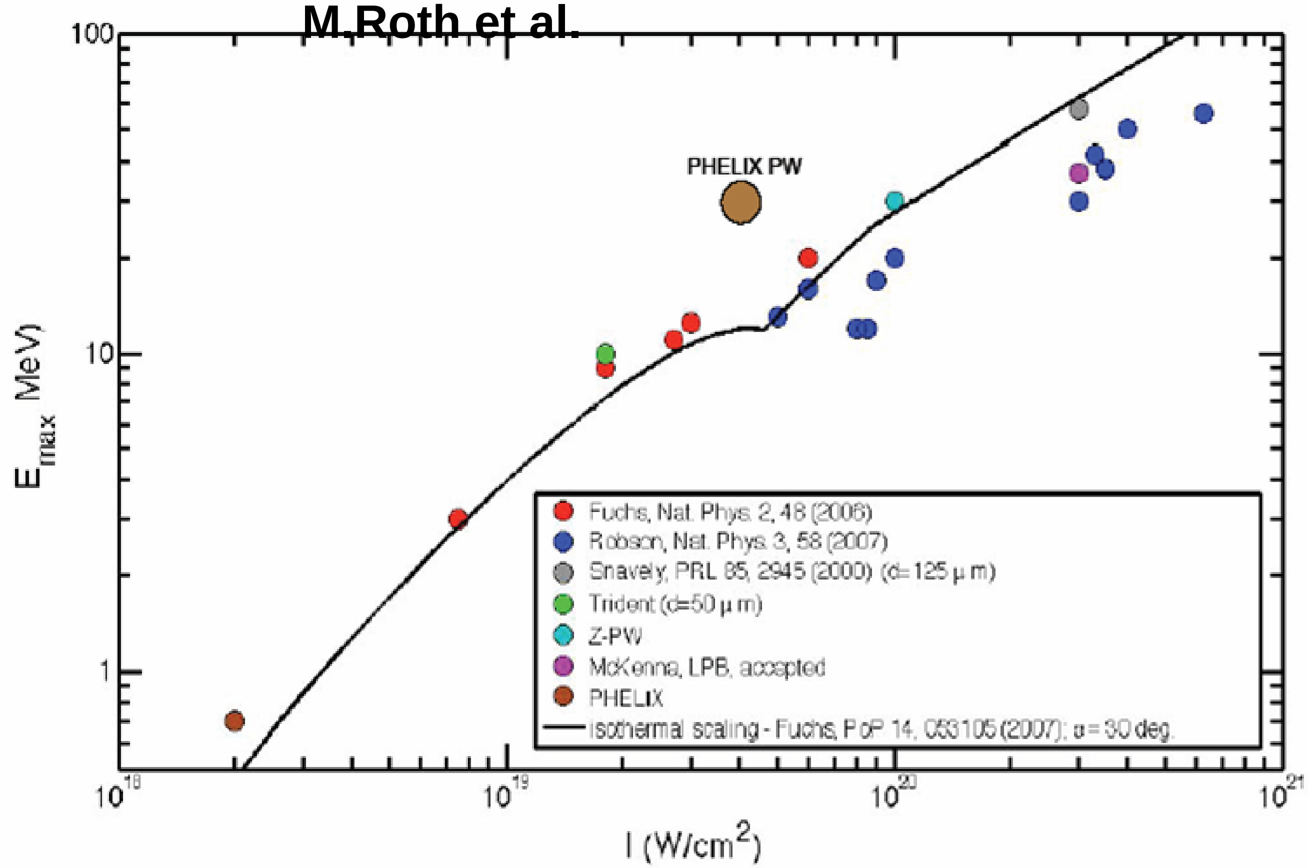


Currently proton acceleration is being evaluated

HELMHOLTZ ASSOCIATION GSI

- **Laser accelerated ions are of interest for diagnostic purposes, but also as a complementary path to the traditional accelerators**

M.Roth et al.



Experiments by:

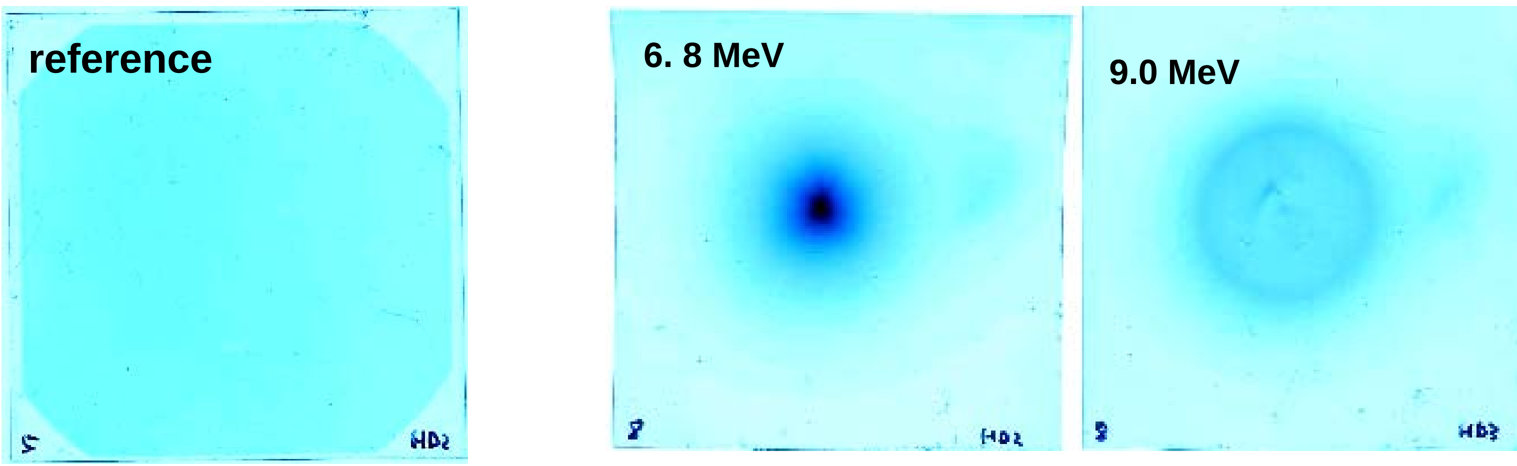
M. Roth et al.

D. Neely et al.

P. McKenna et al.

Focusing of Laser Accelrated Protons

Stack located 405 mm from the target



Converging proton beams

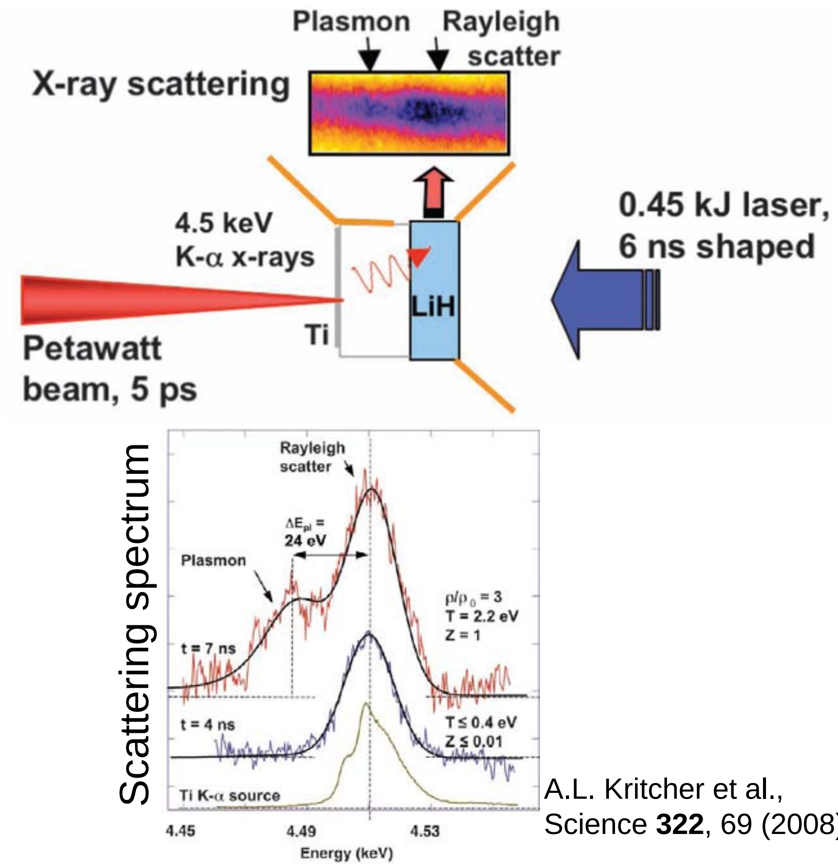
Progress in particle acceleration (Courtesy of K. Harres)

Up to 14 MeV protons were collimated using a coil developed at FZD

A program to combine laser acceleration with standard accelerator components is started

Laser-generated K-alpha sources have a large application potential in High Energy Density Science experiments

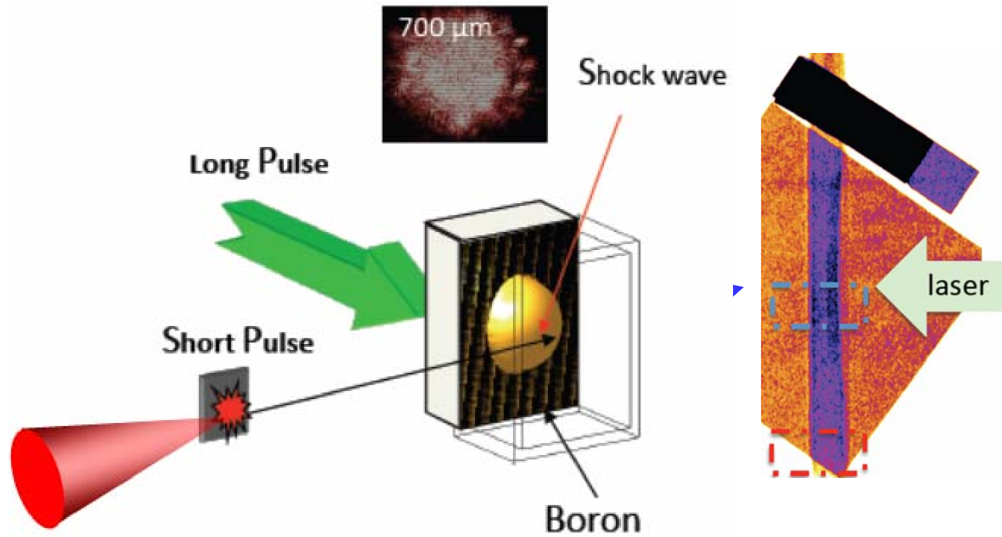
Spectrally resolved X-ray Thomson scattering

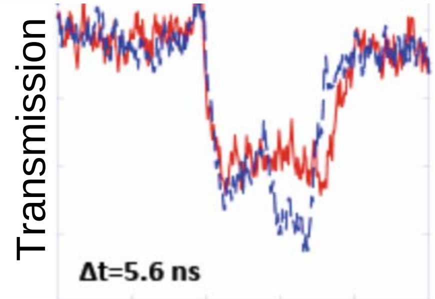


A.L. Kritcher et al., Science **322**, 69 (2008)

- Spectral quality (satellite-free)
- Temporal resolution (~10ps)

High-resolution X-ray radiography





S. LePape et al., APS-DPP (2009)

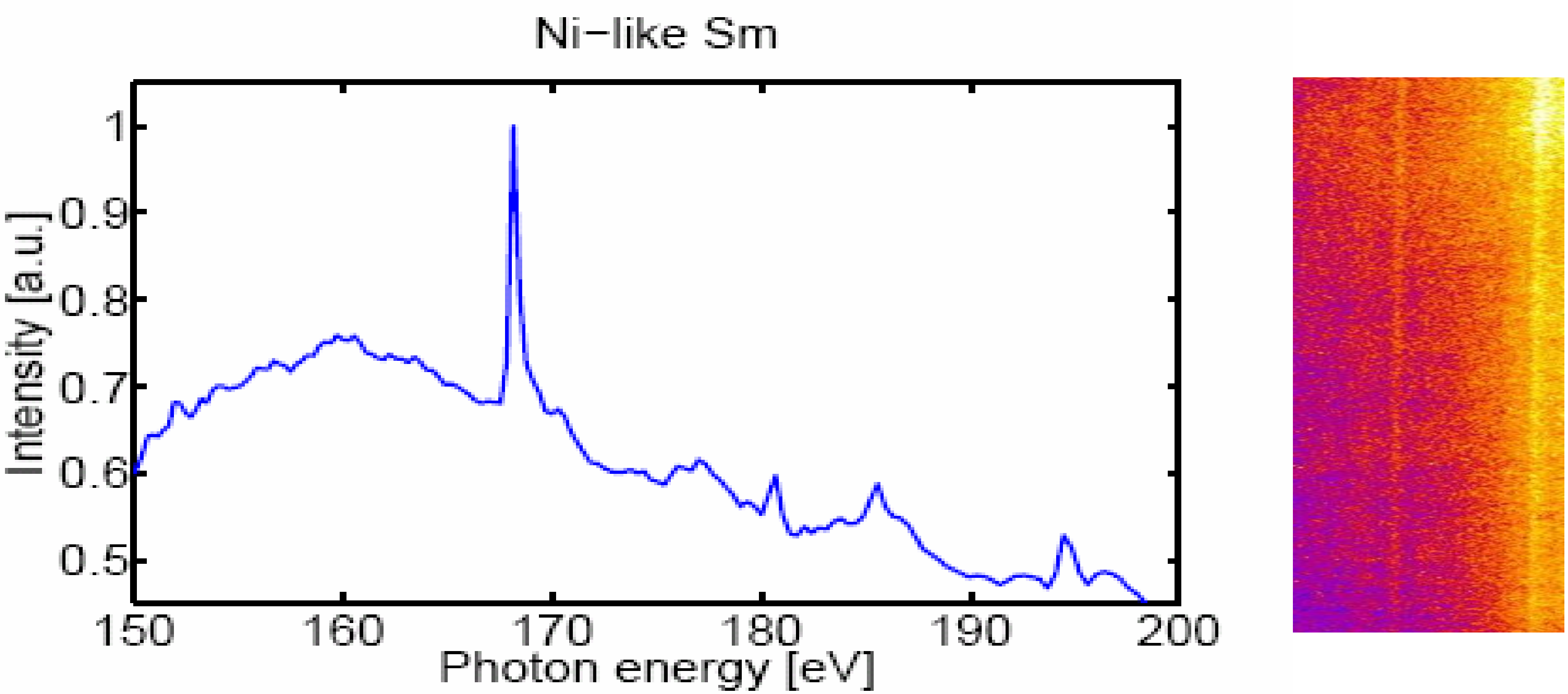
- Small source size (<10µm)
- Temporal resolution (~10ps)
- Z-scaling

Experiments:

Ch. Labaune, P. McKenna, P. Neumayer, O. Rosmej, et al

X-Ray Lasers

- **We are using PHELIX to pump X-ray laser with Ni-like Samarium and recently Ni-like Dysprosium (photon energy > 200 eV)**
  - **We have developed an innovative two pulse scheme* to create transient collisionaly excited (TCE) plasma X-ray laser (DGRIP)**



D. Ros et al.

XPA

Amplification of soft x-rays in the regime of 40 eV and about 260 eV with a small signal gain of up to 8 x 10³ was observed using the PHELIX front-end. The parametric amplification of high-order harmonics as a seed is explained by a simple model of energy transfer into the x-ray field.

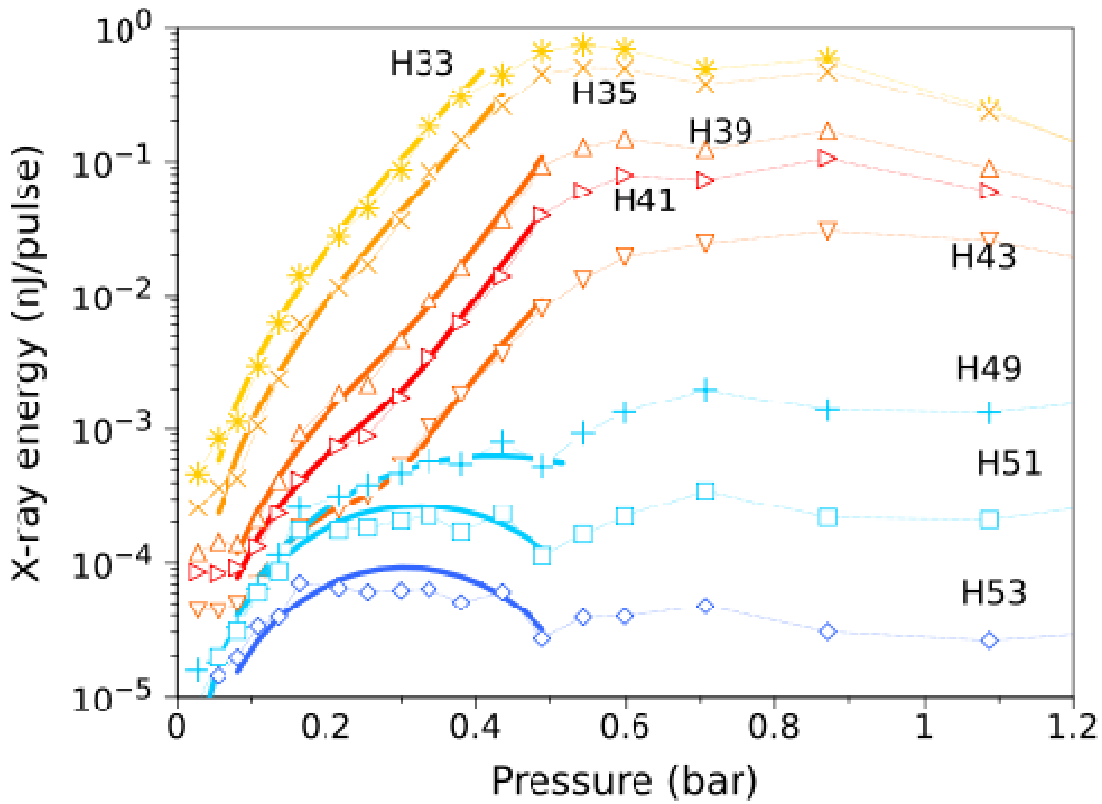
$$I_{\mathrm{XPA}} = I_0 \frac{e^{gL} - 2e^{gL/2}\cos(\Delta k L) + 1}{(\Delta k L)^2 + (gL/2)^2}$$

$$g_{k,\max} \approx \sigma_{eq} n_0 - \alpha_k$$

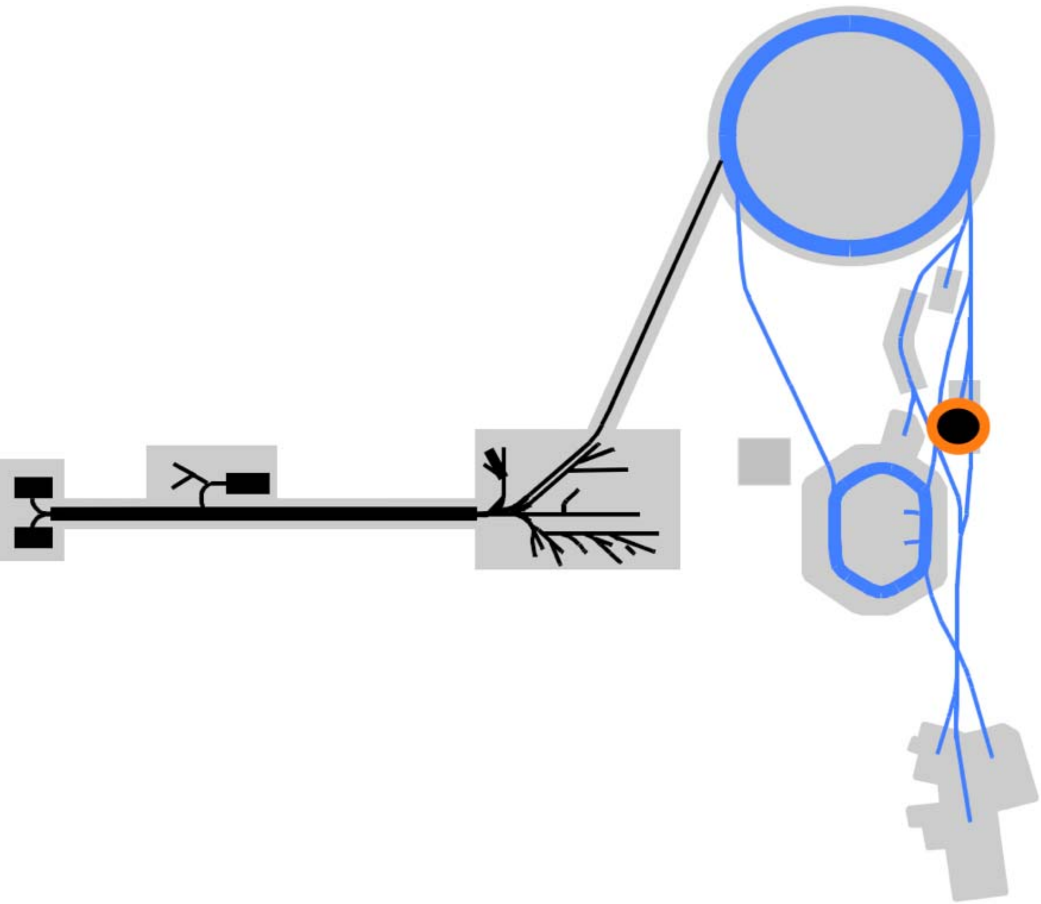
Potential for a new powerful x-ray source !

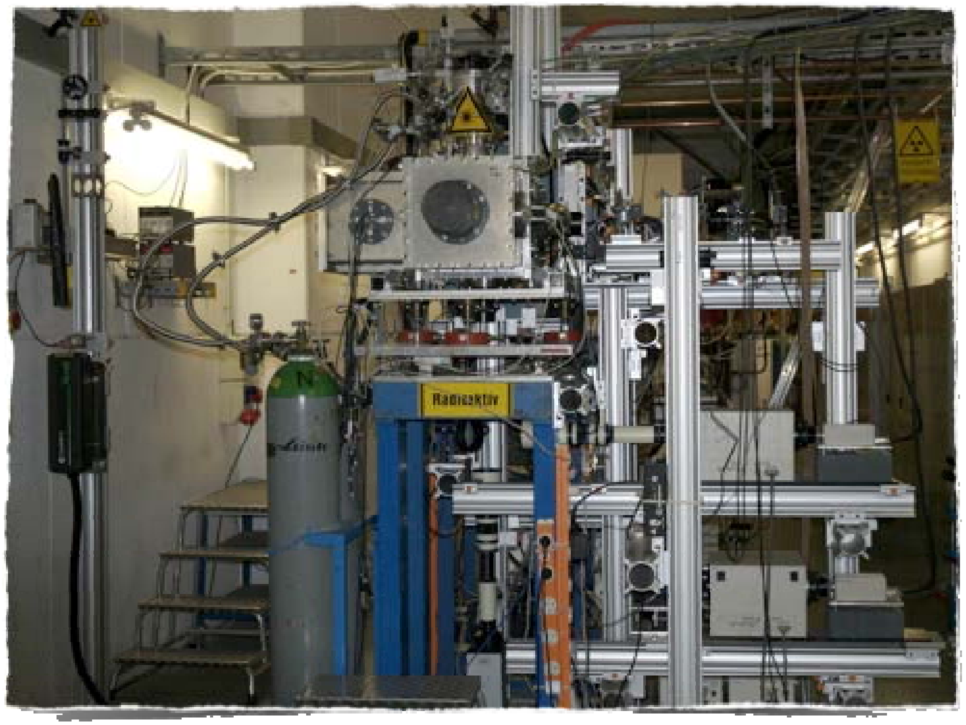
Nature Physics 4/2010

In collaboration with Ch. Spielman and J. Seres, Uni Jena



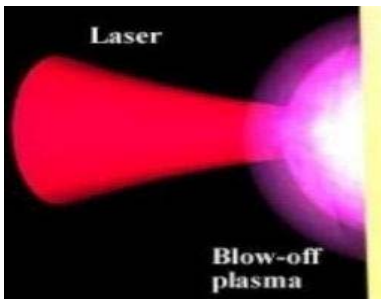
Plasma physics experimental area HHT





FLASH and the ions beams at GSI provide complementary tools to study warm dense matter

photon pulses (XUV) of highest brilliance (FLASH)



small volume of sample (100 μm³)

ultra-short time scales (100 fs)

high gradients

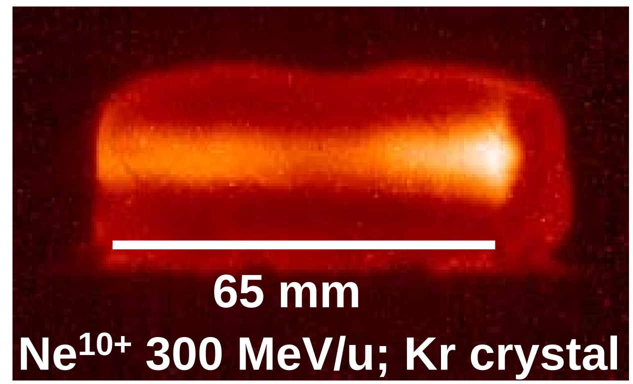
low-Z target material

specific energy: ~ kJ/g

temperature: up to 1 eV

pressure: multi-kbar range

intense, energetic beams of heavy ion (GSI)



large volume of sample (mm³)

long time scales (50 ns)

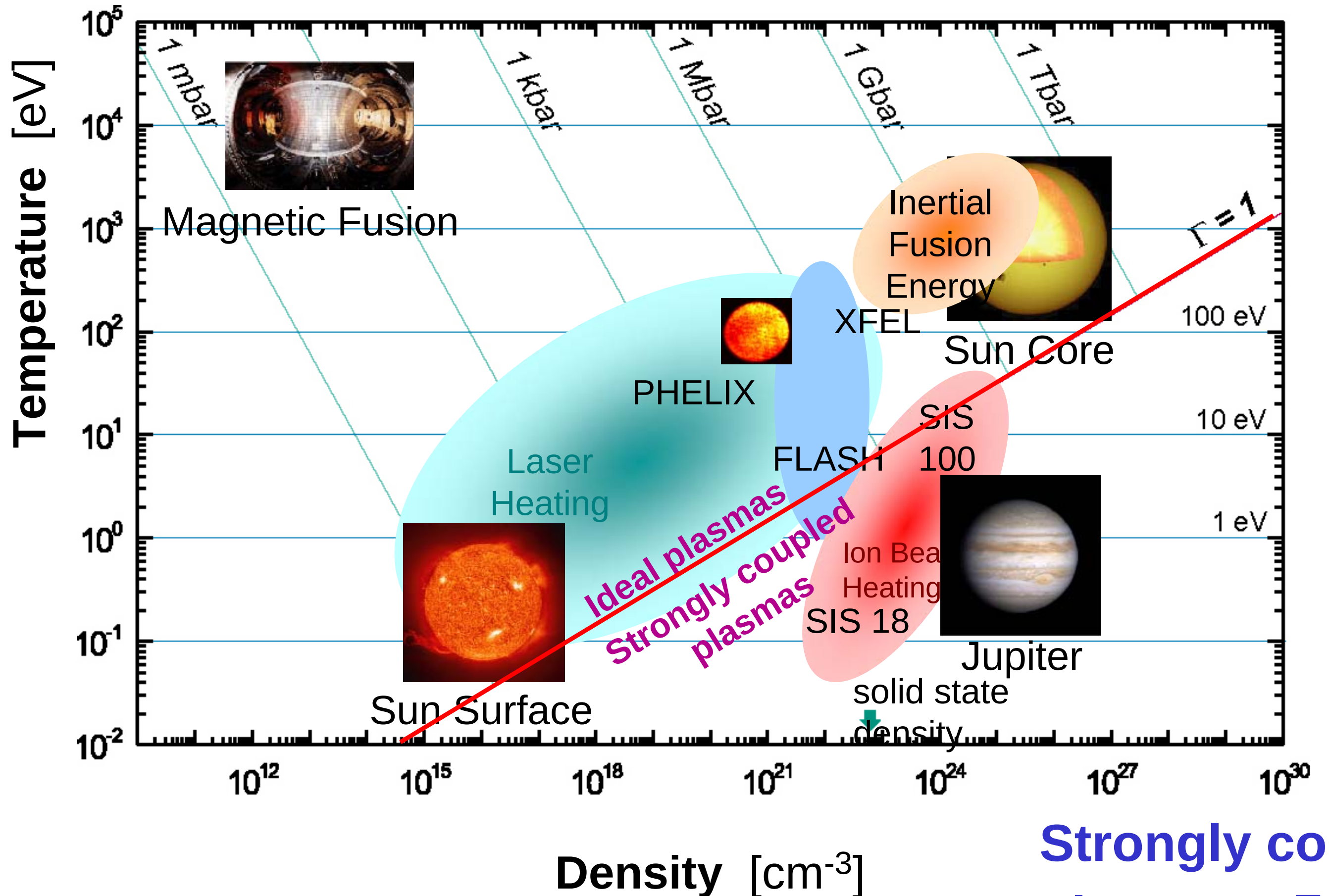
fairly uniform physical conditions

any target material

Plasma Physics with Intense Photon and Ion Beams

Relevant for astrophysics, planetary science, inertial confinement fusion research, material science under extreme conditions

Measurements are required for guidance of theoretical models



Strongly coupled plasmas, $\Gamma = E_C / E_{KIN} > 1$

Research with Heavy Ions at GSI

HELMHOLTZ ASSOCIATION GSI

Atomic Physics

QED in non-perturbative regime
Correlated multi-body dynamics for atoms and ions
Precision determination of fundamental constants
Influence of atomic structure on nuclear decay properties

Plasma Physics

Interaction of ions and photons with plasmas
Equation of state, phase transitions, transport phenomena
Matter under high pressure
Intense Laser (PHELIX): plasma production, particle acceleration

Materials Science

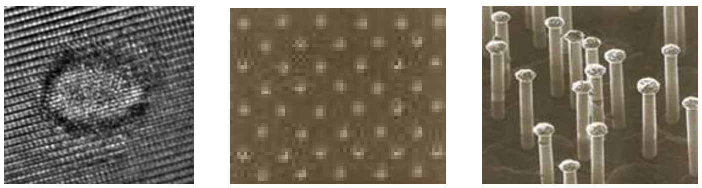
Material modifications
Writing with single ions
Ion-track nanotechnology
High-pressure irradiations

Experiment Facilities for Materials Research

UNILAC

X0 & Microprobe

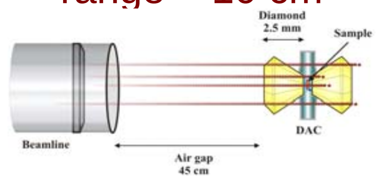
E=11.4 MeV/u, range ~100 µm



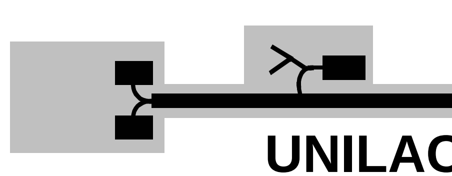
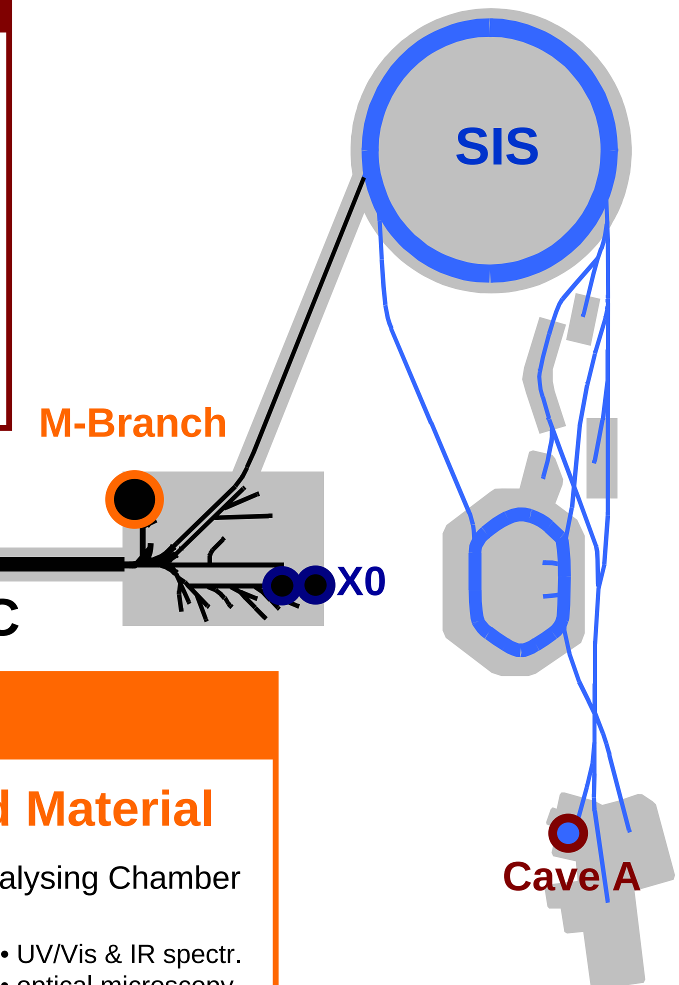
- **Material modifications**
- **Writing with single ions**
- **Ion-track nanotechnology**
  (nanopores & nanowires)

SIS Cave A

E=1-2 GeV/u
range > 10 cm



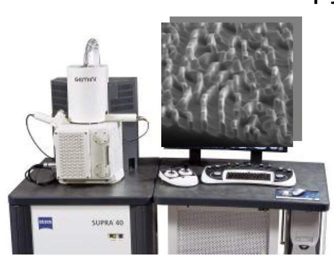
High pressure irradiations

M-Branch

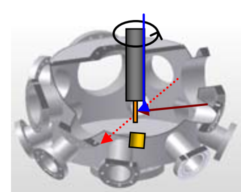
In-situ and On-line Analysis of Irradiated Material

M1: Electr. Microscopy



M2: X-Ray Diffraction

M3: Multi-Analysing Chamber



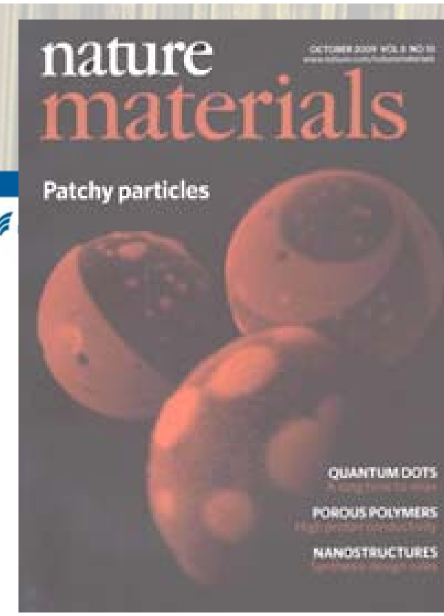
- UV/Vis & IR spectr.
- optical microscopy
- mass spectroscopy
- curvature test
- cryo sample stage

nature materials
LETTERS
PUBLISHED ONLINE: 6 SEPTEMBER 2009 | DOI: 10.1038/NMAT2528

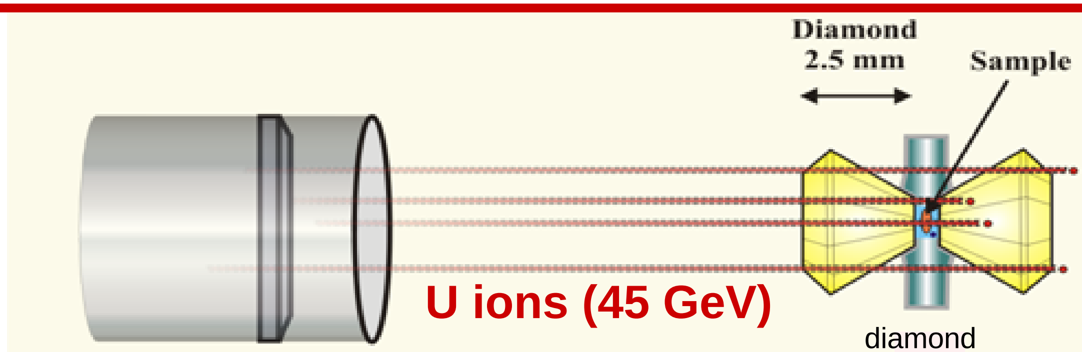
Nanoscale manipulation of the properties of solids at high pressure with relativistic heavy ions

Maik Lang[1], Fuxiang Zhang[1], Jiaming Zhang[1], Jianwei Wang[1], Beatrice Schuster[2], Christina Trautmann[2], Reinhard Neumann[2], Udo Becker[1] and Rodney C. Ewing[1]*

[1] University of Michigan, [2] GSI Helmholtzzentrum



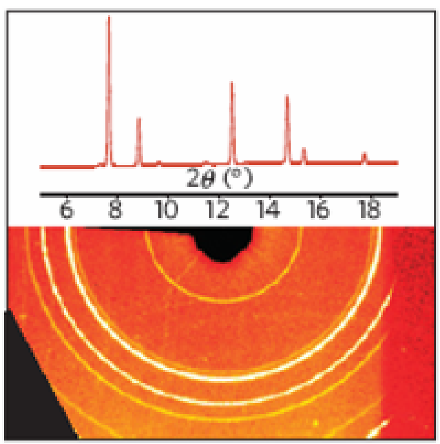
SIS



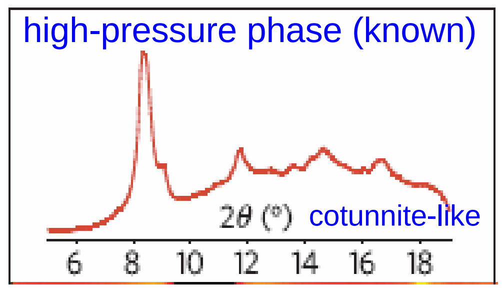
Sample:

$Gd_2Zr_2O_7$ pyrochlore at 200 kbar

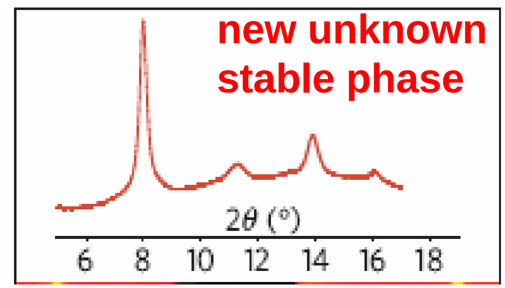
1 bar, before irradiation



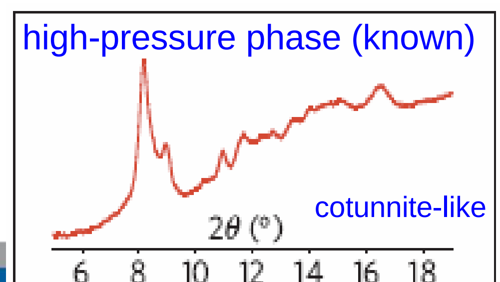
ions + pressure (202 kbar)



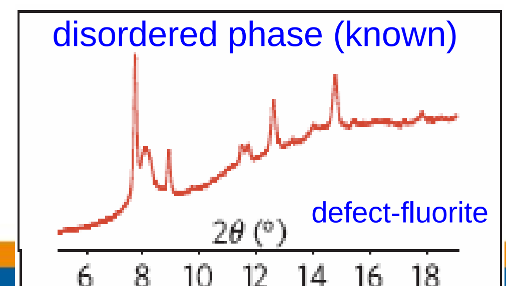
relax to 1 bar



only pressure (215 kbar)



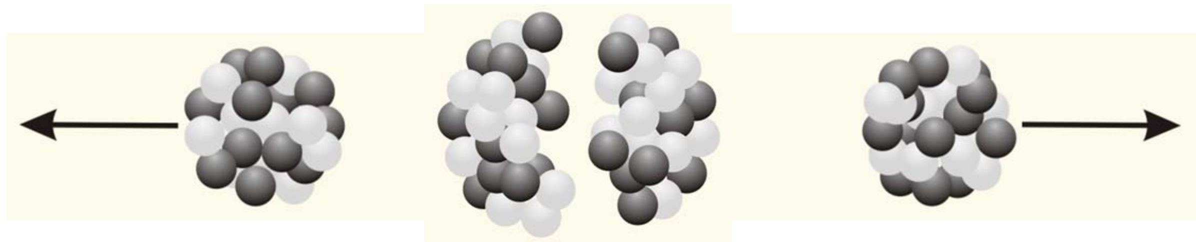
relax to 1 bar



Motivation in Geosciences

spontaneous fission → fission fragments

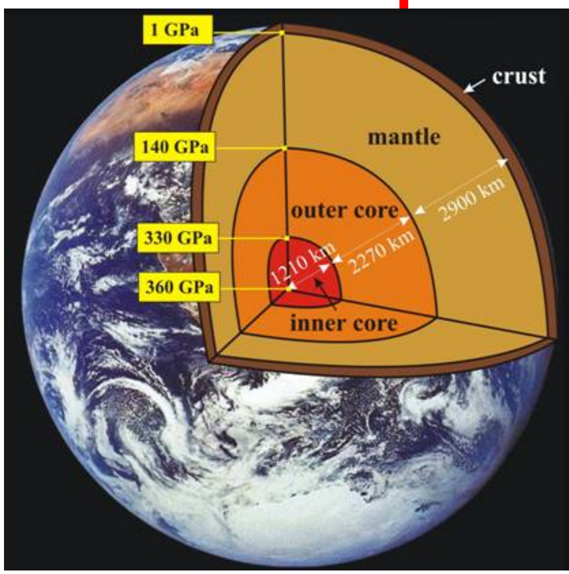
^{238}U



daughter nucleus 1

200 MeV

daughter nucleus 2



Earth's interior:

25 °C/km - 50 MPa/km

fission tracks in minerals → dating

★ track formation ↔ temperature ☑

★ track formation ↔ pressure ?

temp. & pressure ?

Future Developments and Perspectives

Atomic and Plasma Physics

matter under extreme conditions

Summary

Atomic Physics: The ESR and HITRAP are worldwide unique facilities for probing our understanding of matter in the extreme electromagnetic field regime.

Plasma Physics: Ion beams can produce well defined homogeneous samples of dense plasma relevant for fundamental studies such as testing models of planetary and stellar structure.

Materials Research: The GSI ion beams are particularly suitable for radiation hardness tests and application-oriented nanotechnology.

FAIR **Opportunities and Challenges:** ***Unique Facilities and Instrumentation for Heavy Ion and Anti-Proton Research***