Overview of the Plasma and Atomic Physics Activities at GSI

Thomas Stöhlker

May 14th 2009; Moscow

Helmholtz Alliance: EMMI

HELMHOLTZ | ASSOCIATION

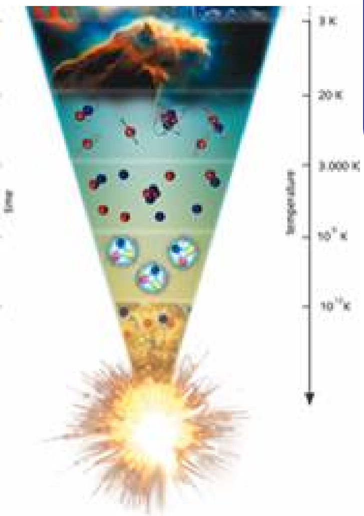
Extremes of Density and Temperature: Cosmic Matter in the Laboratory (started April 2008)

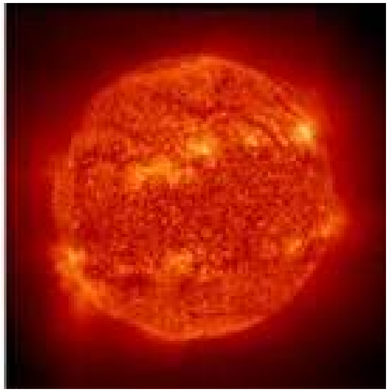
QGP

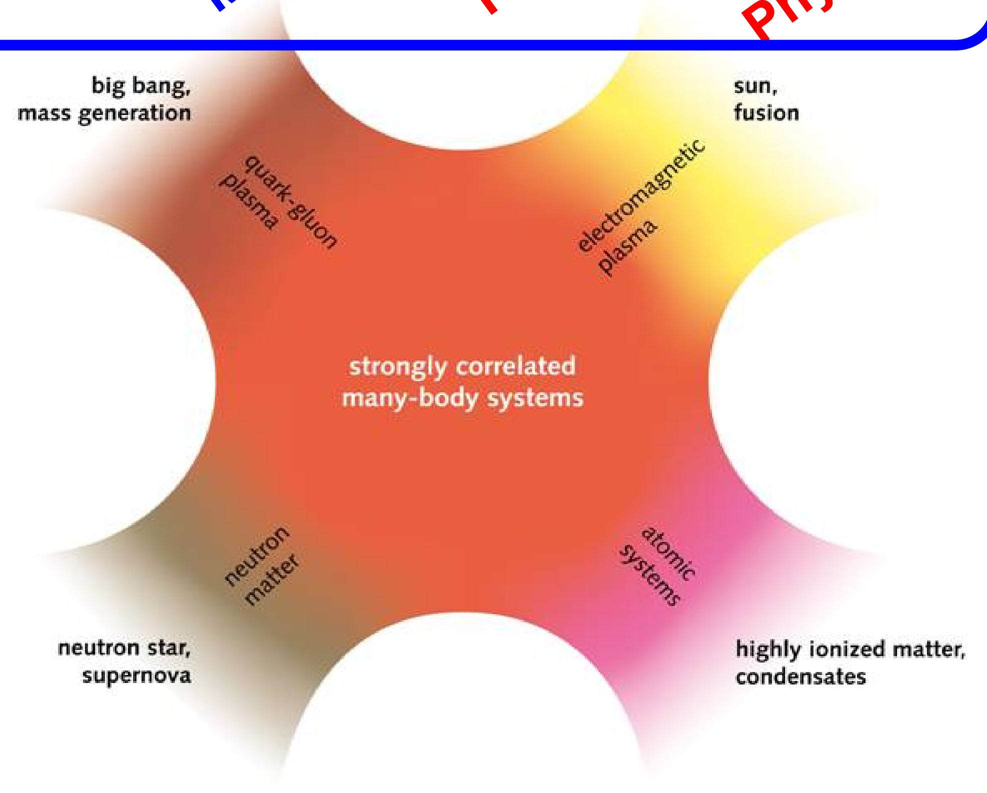
Neutron Matter

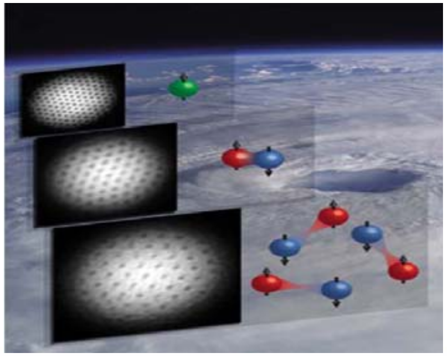
EM Plasma

Atomic Physics







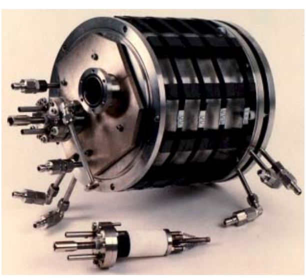


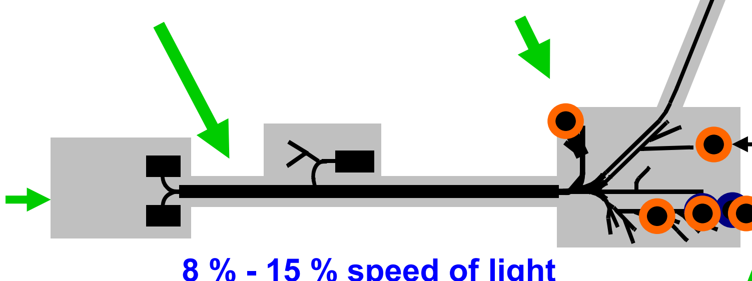
The GSI Accelerator Facility for Heavy Ions

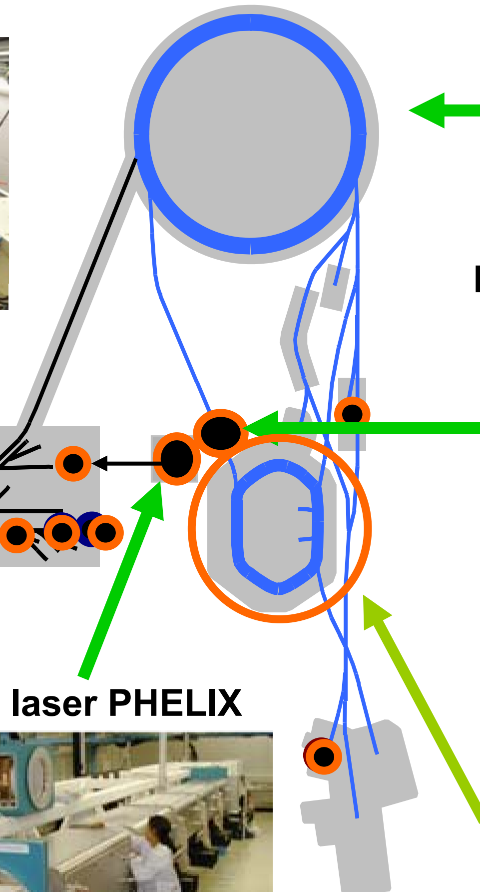
linear accelerator UNILAC

M-branch UNILAC

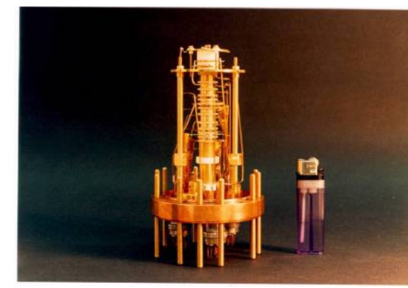
ion sources







heavy-ion synchrotron SIS



ion trap facility HITRAP

petawatt laser PHELIX

storage ring ESR

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

Research with Heavy Ions at GSI

HELMHOLTZ ASSOCIATION

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

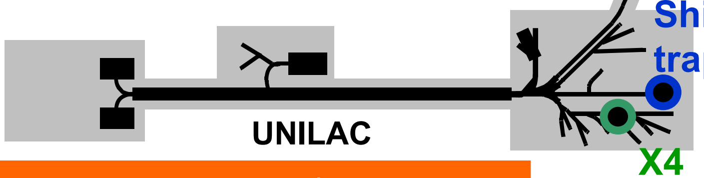
4 - 500 MeV/u; all ions up to U^{92+}

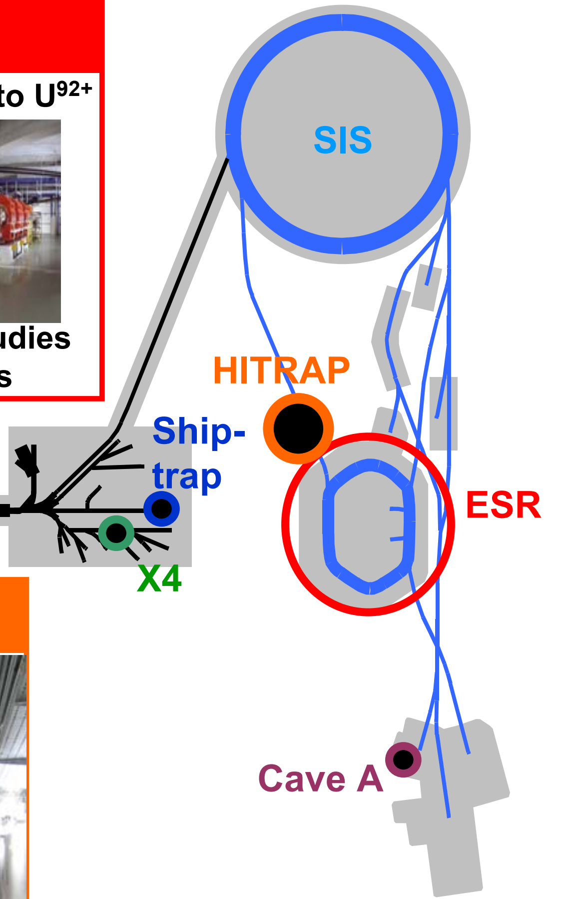
- ion channeling
- lifetimes of atomic states

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, ...

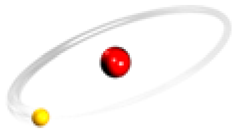
- Laser spectroscopy
- g-factor of bound electrons

Collision experiments, ...

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

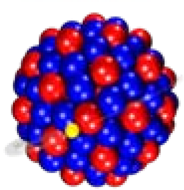
Atomic Physics: Quantum Electrodynamics in the Extreme Field Limit

hydrogen

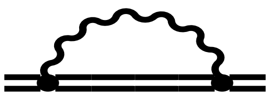


Z=1
E_b = 13.6 eV
$Z \cdot \alpha \ll 1$

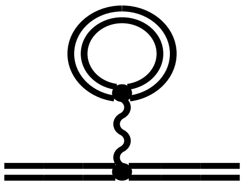
uranium ion

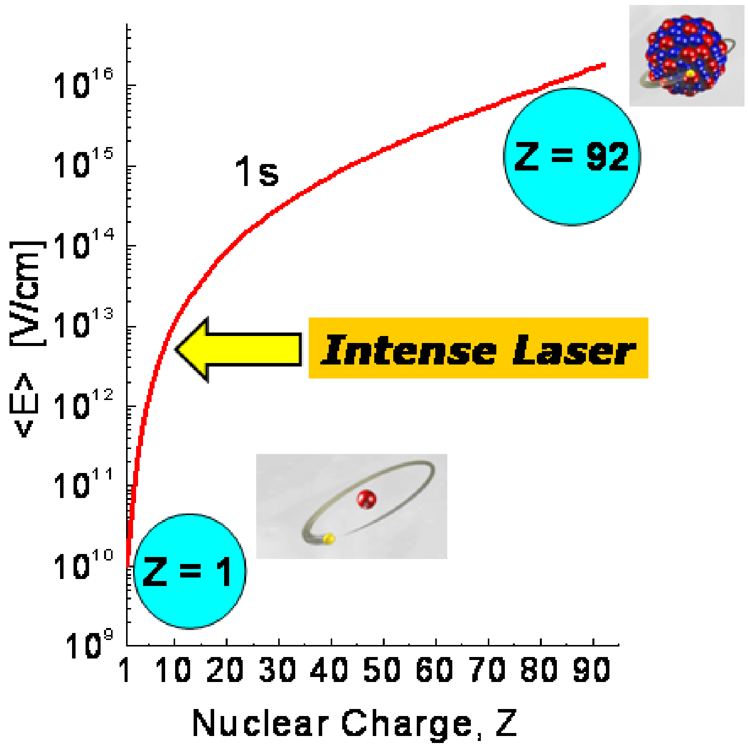


Z=92
E_b = 132 keV
$Z \cdot \alpha \approx 1$



Strong Field QED

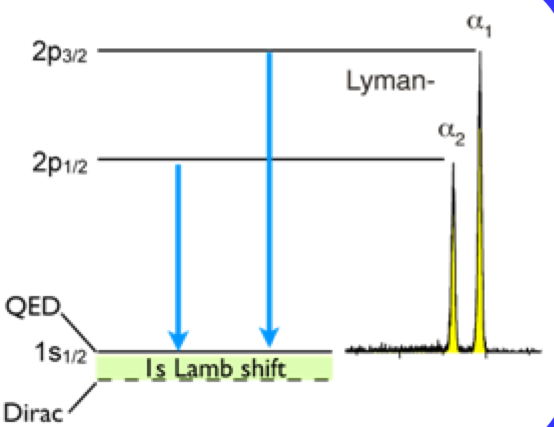


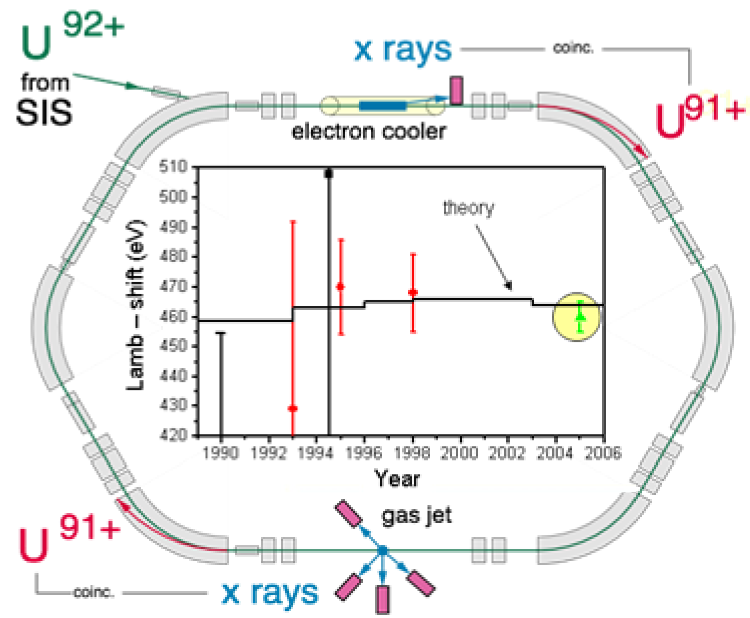


- **1s-Lamb Shift**
- **g-factor**
- hyperfine structure
- towards super-critical fields
- border line to nuclear physics

QED in the Extreme Field Limit: Experiments at the the Heavy-Ion Storage Ring ESR

High Precision X-Ray Spectroscopy: 1s Lamb-Shift





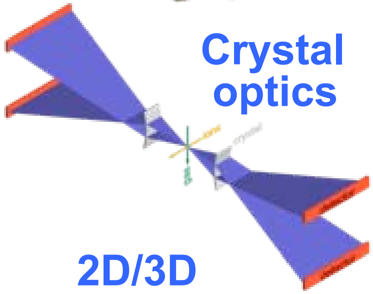
Experiment
459.8 eV ± 4.6 eV

A. Gumberidze, PRL 94, 223001 (2005)

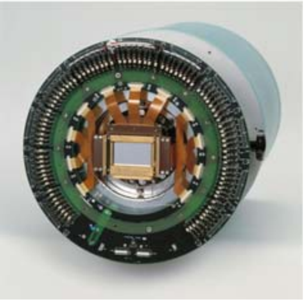
Research Highlights
Nature **435**, 858-859 (16 **June 2005**)

FOCAL

Crystal optics



2D/3D detectors



Challenge:
Further accuracy gain by a factor 5 to 10
(detector and spectrometer development is required)

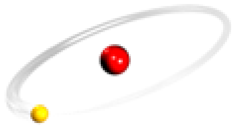
Caen · Cracow · Greenbelt · Grenoble · Grenoble · Heidelberg · Jena · Jülich · Kielce · Madison · Mainz · Paris

Atomic Physics Research with Cooled Heavy Ions at GSI

HELMHOLTZ ASSOCIATION

Quantum electrodynamical effects in extreme electromagnetic fields

hydrogen



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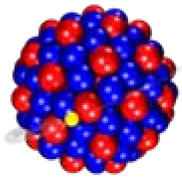
uranium ion



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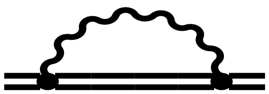
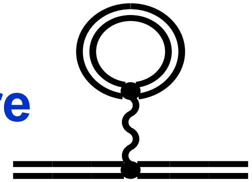
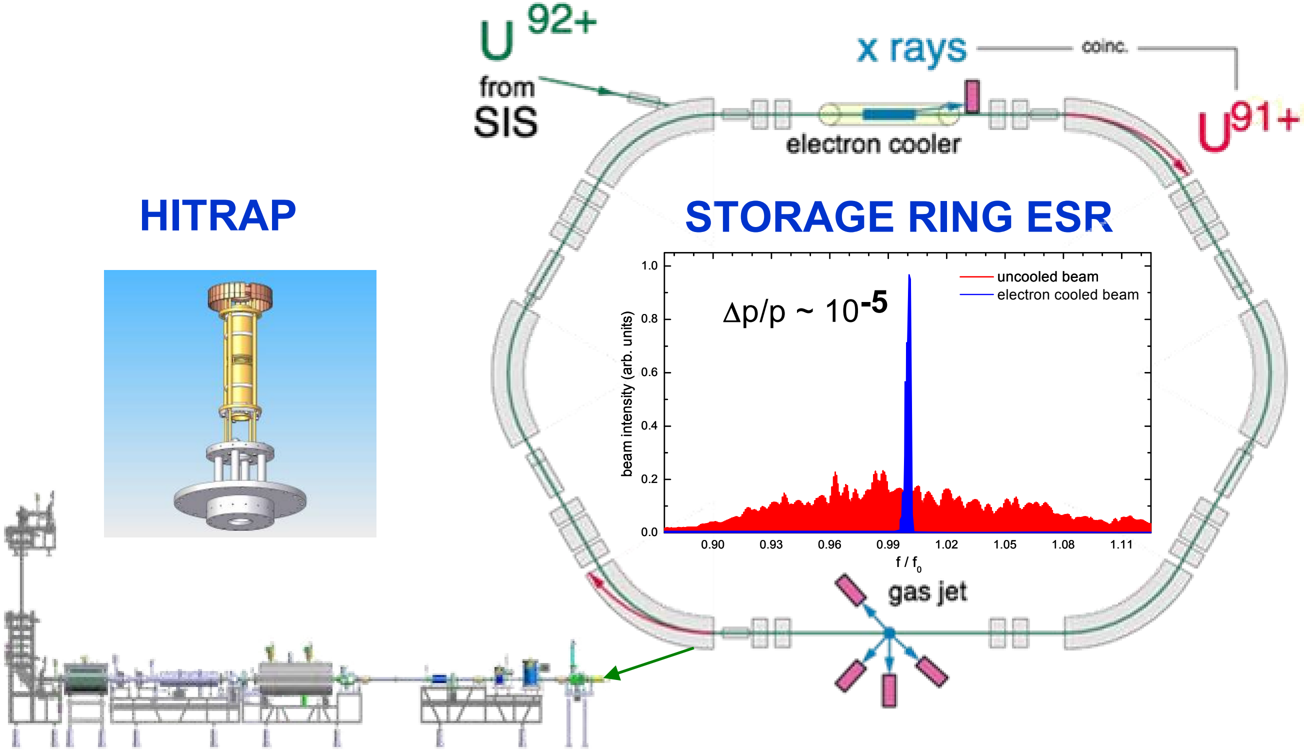


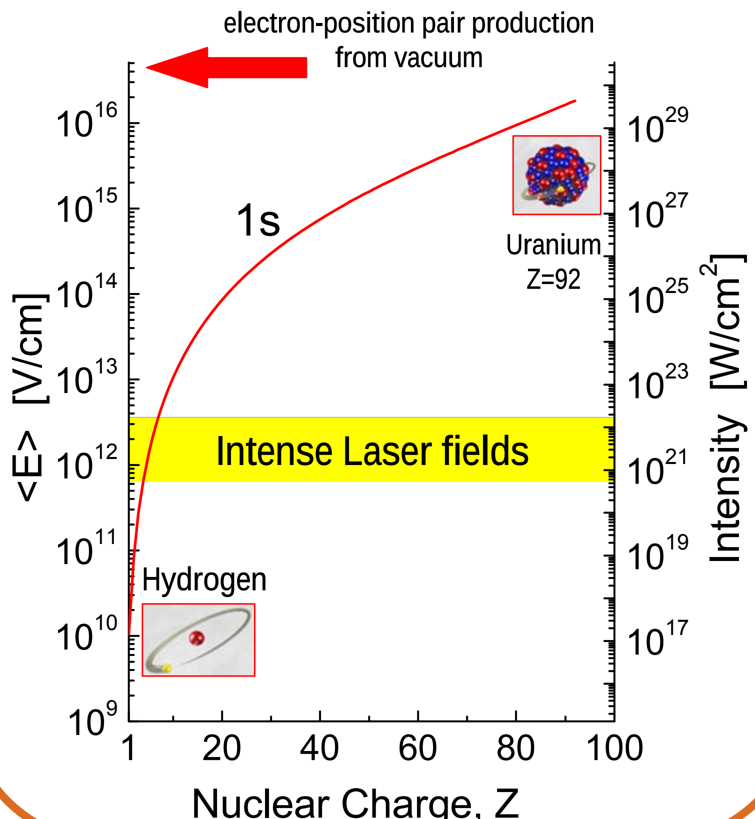
Lamb Shift
Hyperfine Structure
g-Factor



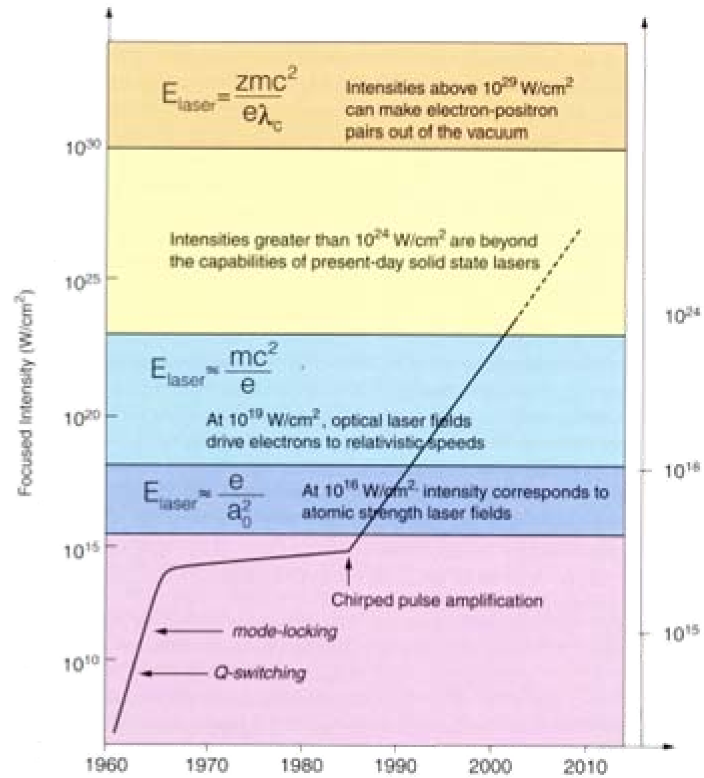


Strong Fields

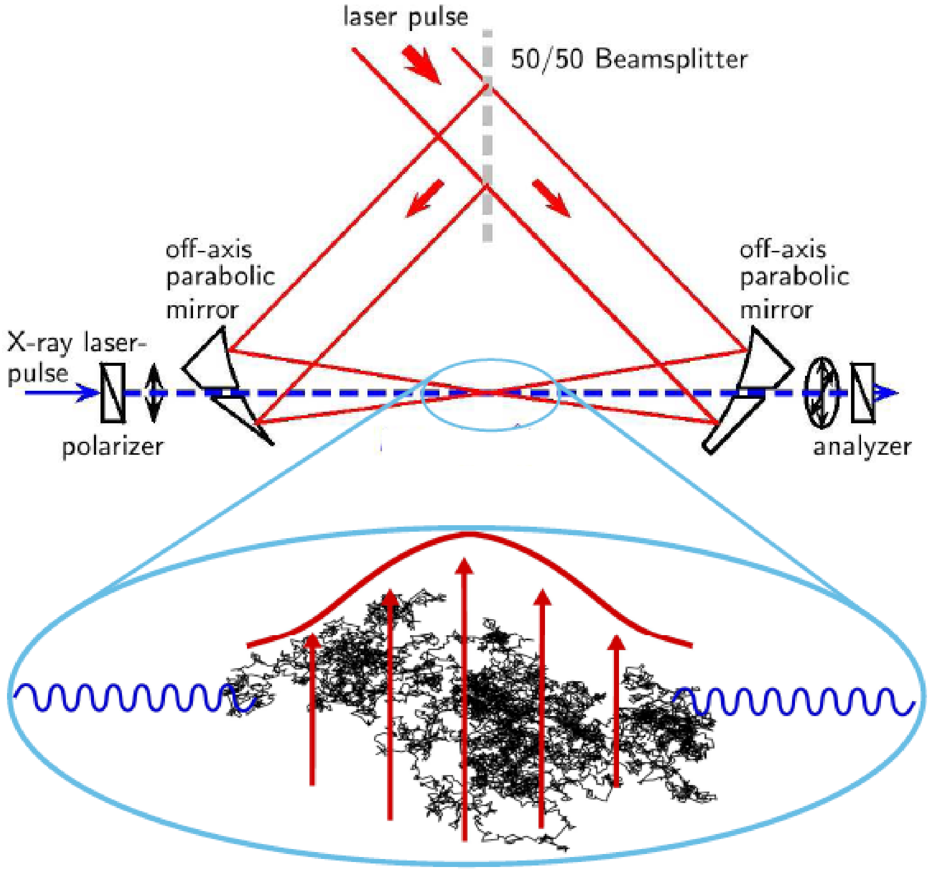
Ions: Huge Fields but of microscopic dimension



Laser: Large Fields but of macroscopic dimension



Probing the Vacuum Structure with Strong Fields



- **discovery potential of QED-induced nonlinearities**

- **e.g., ellipticity**

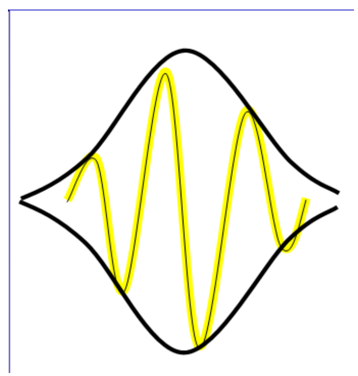
$$\Delta\phi_{QED} = \pi \frac{L}{\lambda} \Delta n_{QED} \sin 2\theta$$

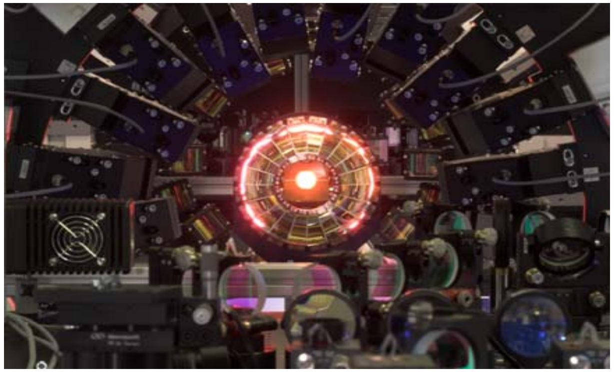
- **discovery potential of exotic particles**
  - axion-like particles
  - minicharged particles
  - hidden-sector photons

Complementarity: Extreme Light and Extreme Particle Beam Collisions

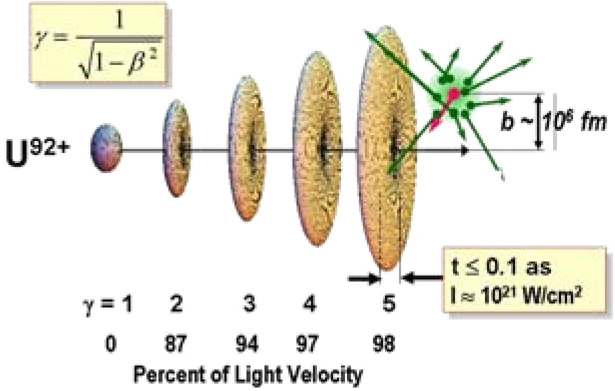
The fastest pulses

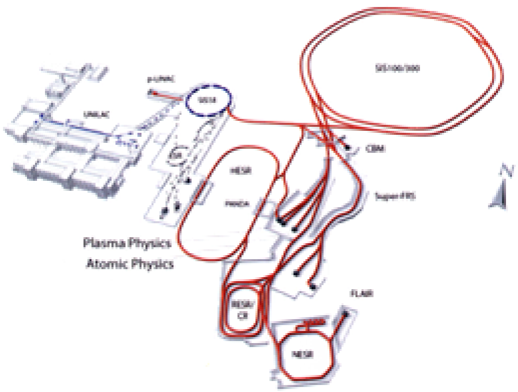
Laser: Femtosecond to Sub-Femtosecond





Ions: Sub Attosecond





Research with Heavy Ions at GSI

HELMHOLTZ ASSOCIATION

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

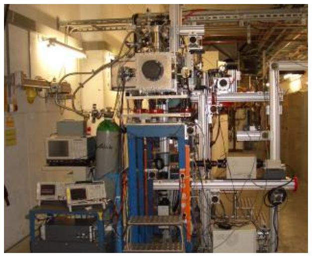
Interaction of ions and photons with plasmas
Equation of state, phase transitions, transport phenomena
Matter under high pressure
Intense Laser (PHELIX): plasma production, particle acceleration

Materials Science

Experiment Facilities for Plasma Physics

HELMHOLTZ ASSOCIATION

HHT



U-ions:
0.2 - 1 GeV/u

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

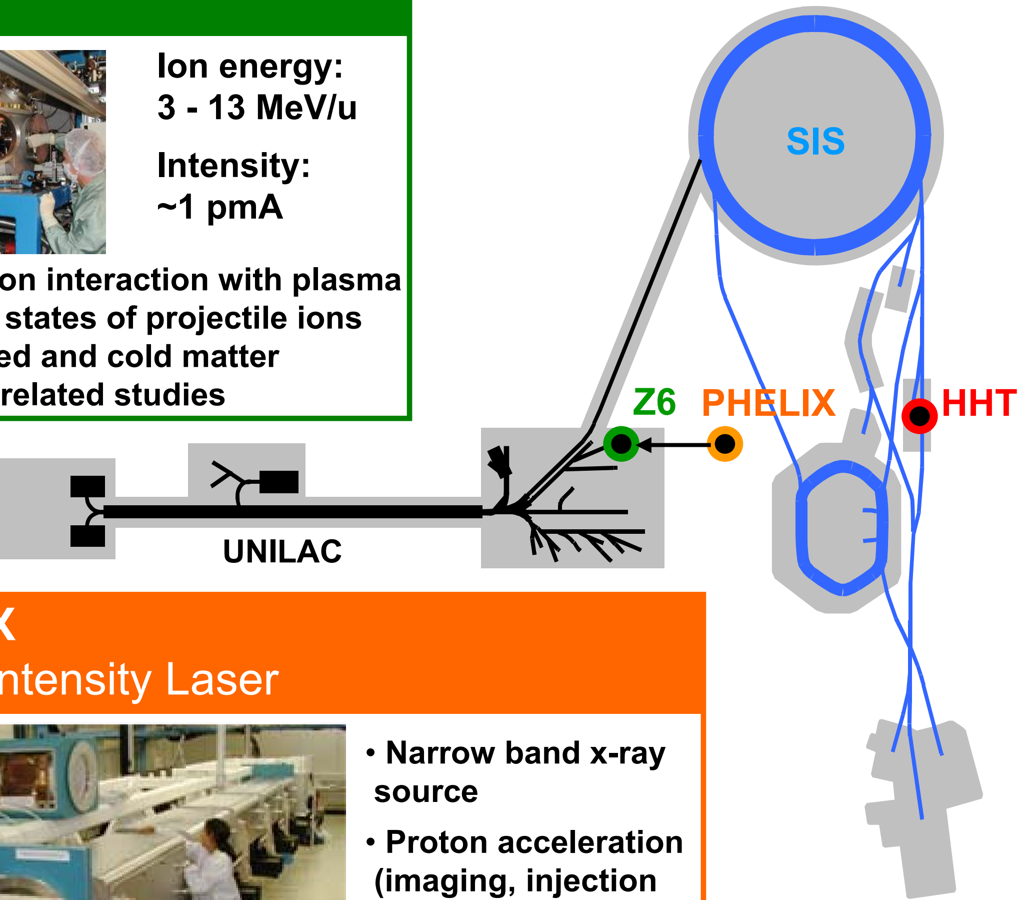
- High energy density physics
- EOS, phase transitions
- Transport properties
- Warm Dense Matter
- High pressure matter (giant planets)

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)

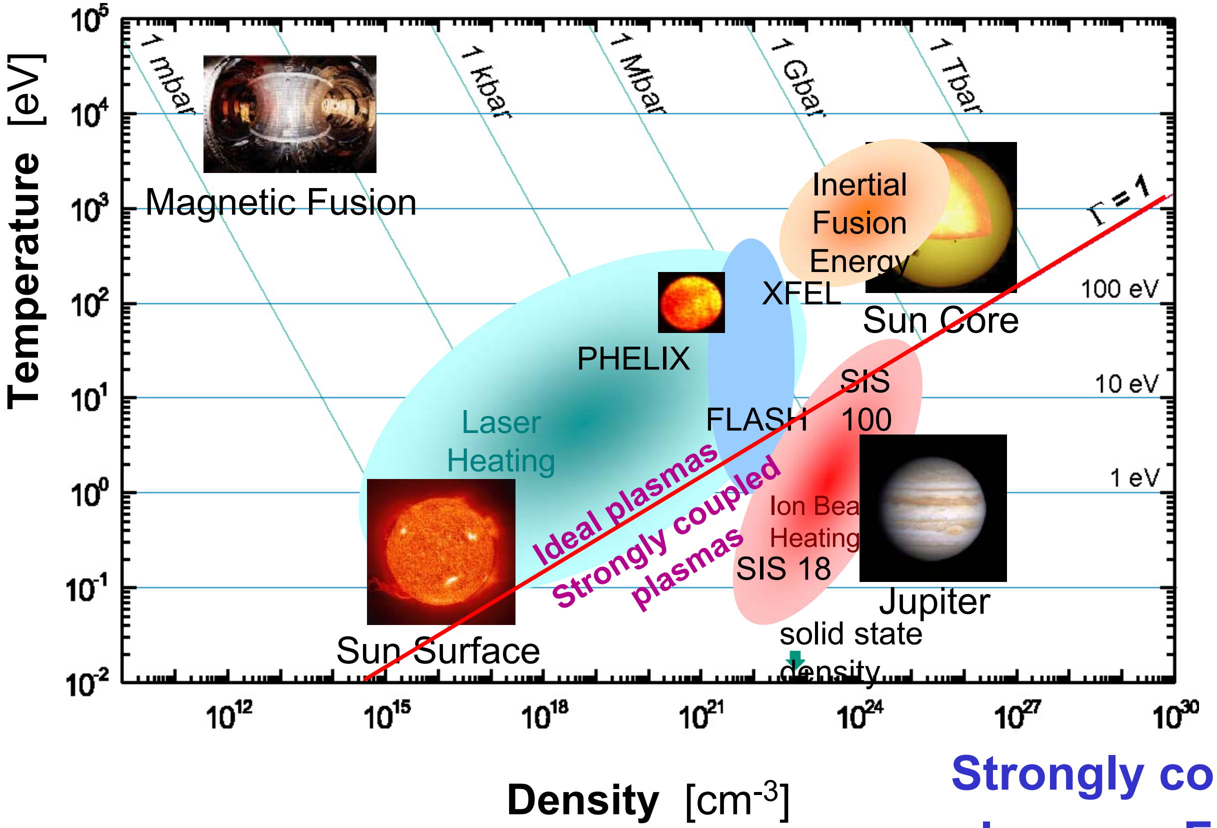
2008: 300 J @ ~ns

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

Plasma Physics with Intense Photon and Ion Beams

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

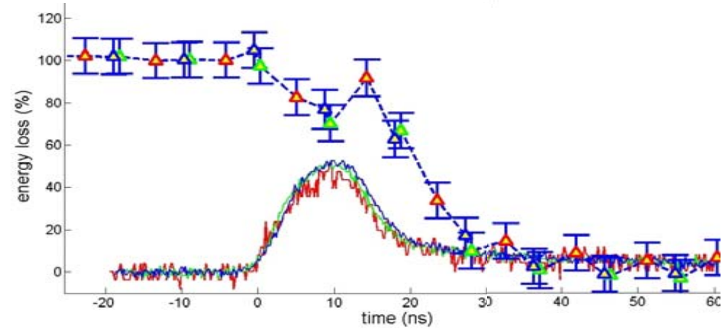
Measurements are required for guidance of theoretical models



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

PHELIX shows promising first results

- Interaction of swift heavy ions with laser-produced plasma



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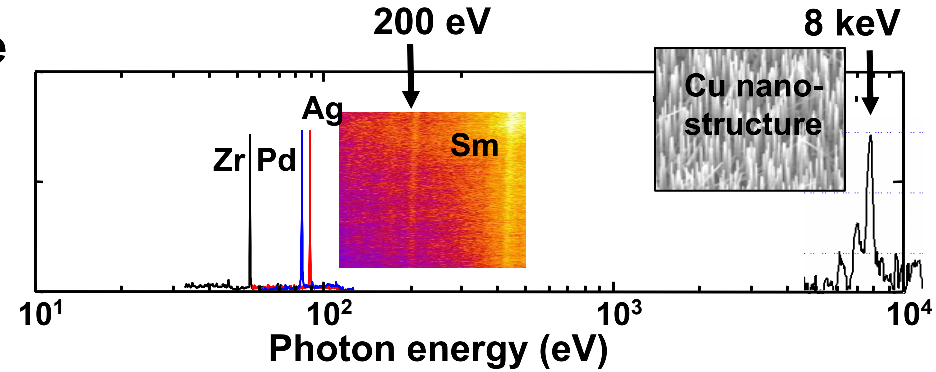
- X-ray lasers for spectroscopy of stable and radioactive highly-charged ions at ESR/NESR
- Narrowband intense x-ray sources for backlighting and Thomson scattering



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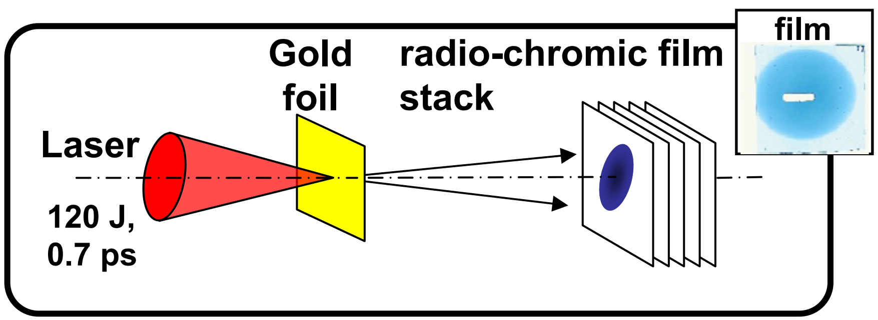
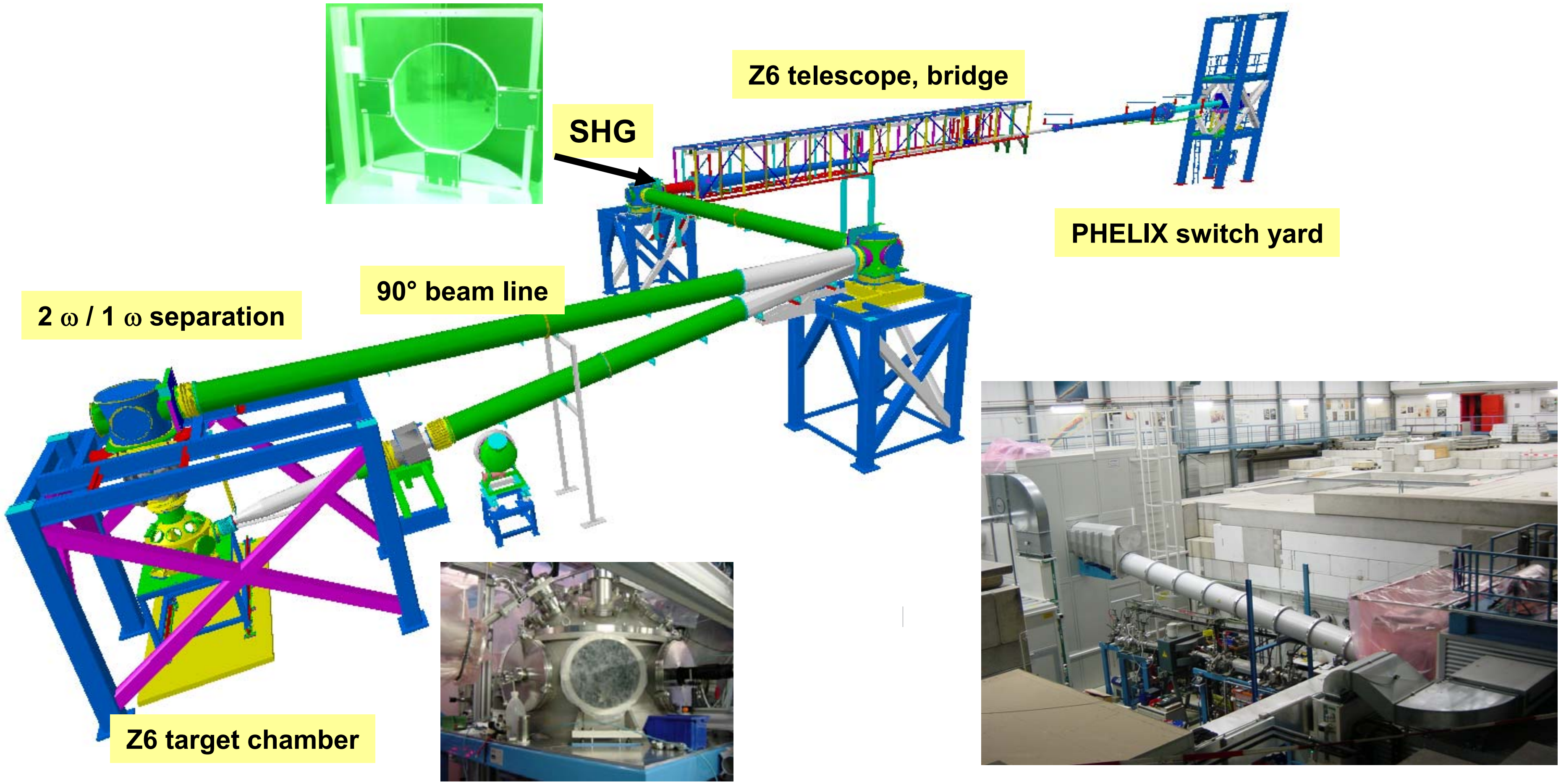
- Proton acceleration for backlighting
- Coupling of laser-accelerated particles into conventional accelerator structures



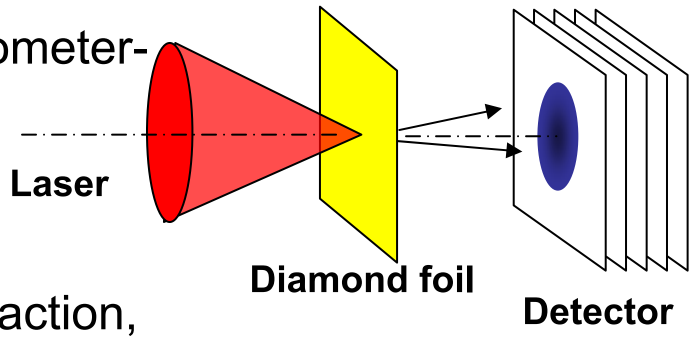
Second Harmonic Generation (SHG) extension project at Z6

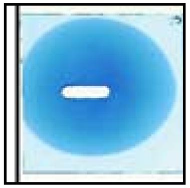


SHG extension of PHELIX laser at GSI will enable efficient generation of Hohlraum radiation for homogeneous target heating at the Z6 experimental area

Proton Acceleration

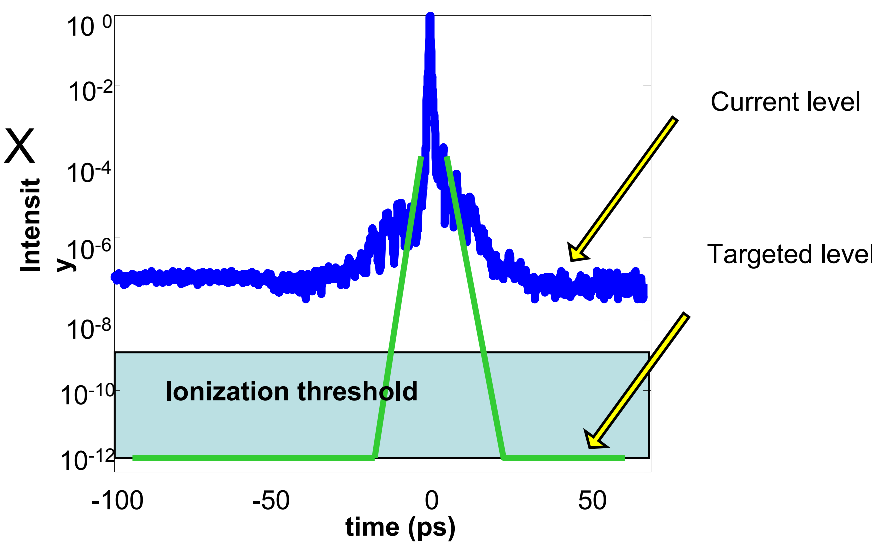
- Motivation:
  - acceleration of particles from nanometer-thick diamond foils



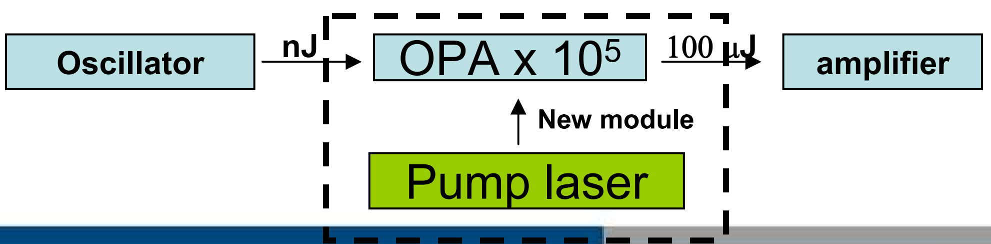


10 MeV proton beam at PHELIX

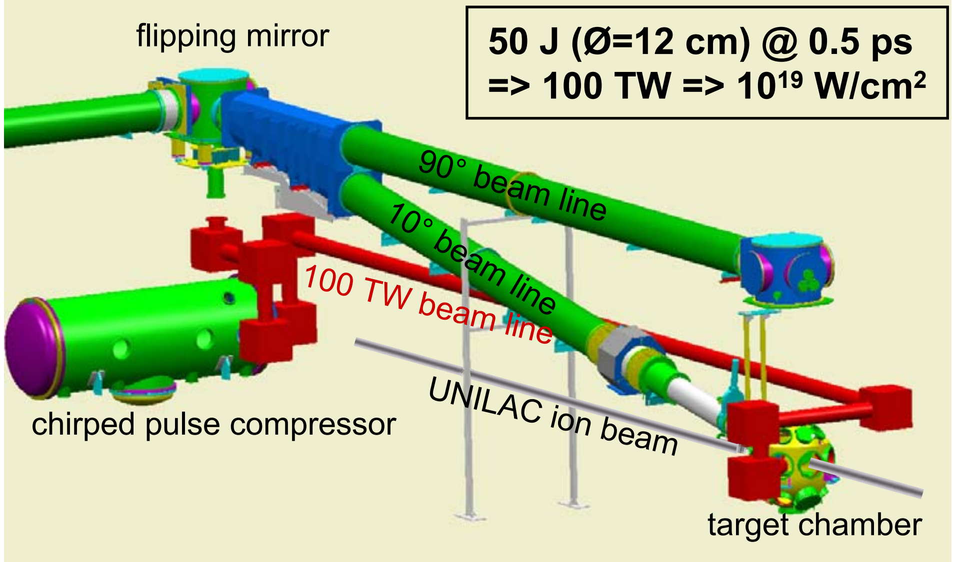
- Challenge:
  - target destruction, before the interaction, by the intensity background at laser intensities of 10^{21} Wcm^{-2}
  - noise reduction of 10^5 compared to the current laser background level at PHELIX



- Proposed solution
  - Noise-free parametric amplification



Commissioning of the 100 TW PHELIX beam line to Z6



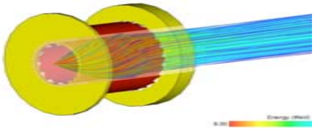
Phase 1: finishing of compressor and beam line to target chamber at Z6

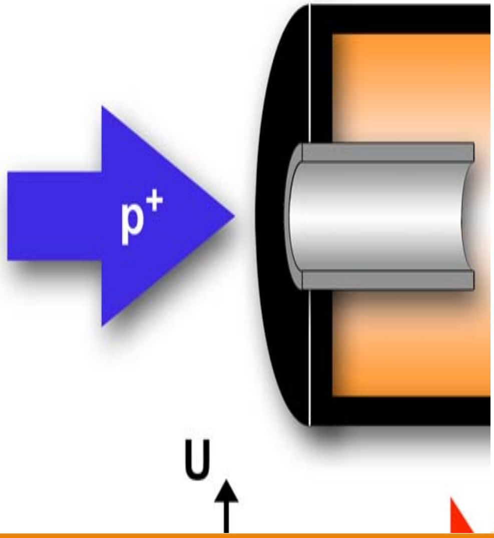
done:
- technical design
- compression grids
- most optics and mounts
- vacuum components

to do:
- vacuum beam line (red)
- compression grid mounts
- short pulse diagnostics

Phase 2: Injection of a laser accelerated ion pulse (10^{10} protons @ 10 MeV) into a conventional accelerator structure at an existing beam line at Z6.

- generation of laser accelerated ion pulse
- collimation of the pulse with a pulsed solenoid
- de-neutralization of the proton pulse
- compression of the proton pulse in a 108 MHz bunching unit (existing technology at GSI)
- diagnostic of the ion bunch



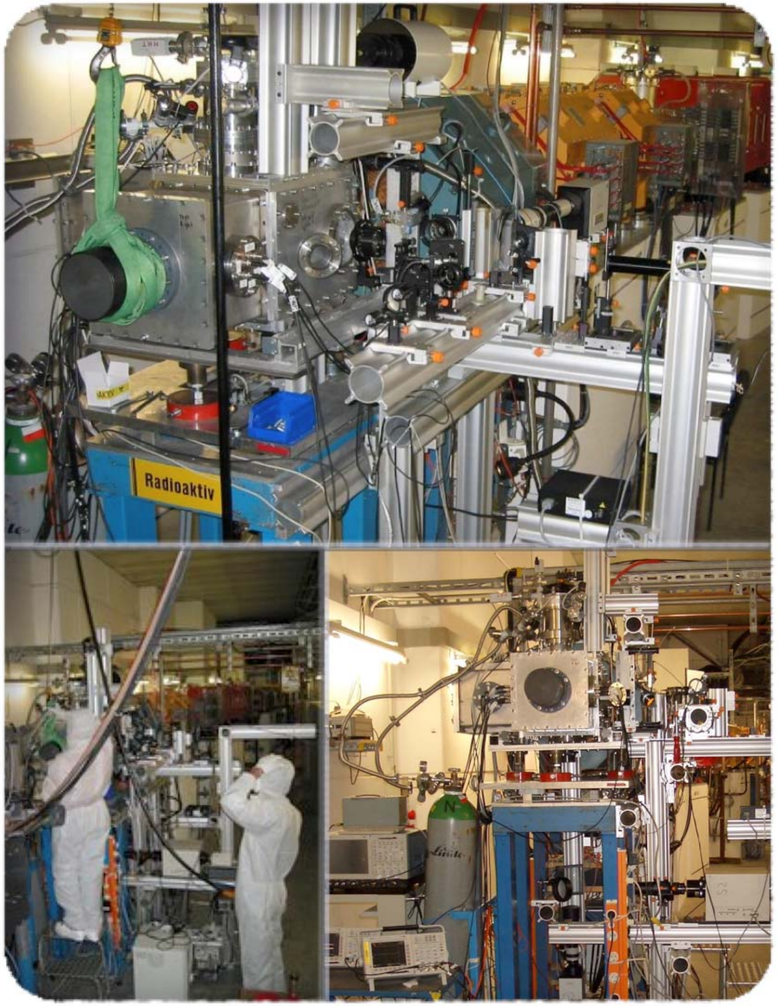


HHT: experimental area for WDM / HEDP experiments with intense heavy ion beams

HELMHOLTZ GEMEINSCHAFT GSI

HHT: High energy, High Temperature

- strong Final Focus System
- ions up to uranium, 50 – 1000 AMeV
- pulse duration 100 – 1400 ns
- focal spot size 0.15 – 2.5 mm
- diagnostics for intense, short ion pulses



Beams for WDM experiments:

- $^{238}U^{73+}$, 350 AMeV, e-cooled
- $2 - 4 \cdot 10^9$ ions in 70 – 300 ns bunch
- ≤ 300 μm (FWHM) spot at the target

Solid density (metallic) targets:

- specific energy from few kJ/g to 50 kJ/g
- temperature from ~1 eV to 10 eV
- pressure from multi-kbar to sub-Mbar
- mm^3-size WDM samples

Experiments at HHT

	SIS-18 present	SIS-18 upgrade	
Ion species	from protons to uranium		
Ion energy	up to 1 AGeV uranium; 4.5 GeV protons		
Beam intensity	$4 \cdot 10^{9}$ (U^{73+})	$2 \cdot 10^{10}$ (U^{73+})	$1 \cdot 10^{11}$ (U^{28+})
Bunch length (FWHM)	100 ns	70 ns	
Focal spot (FWHM)	0.1 mm – 1 mm		2.5 mm

HHT offers intense ion beams for different research fields:

- plasma physics
  from EoS of ion-beam generated WDM to high-energy proton radiography
- atomic physics
  ion-beam pumped excimer lasers, gas spectroscopy with heavy-ion excitation
- nuclear and particle physics
  high-load production targets and beam dumps; diamond detector R&D
- accelerator technology
  diagnostics for powerful ion beams, beam-induced dynamic vacuum problem
- aerospace technology
  radiation hardness test and anti-meteoroid protection of spacecraft elements

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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

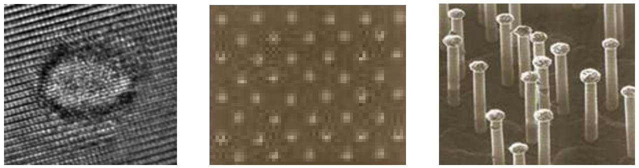
Material modifications
Writing with single ions
Ion-track nanotechnology
High-pressure irradiations

Experiment Facilities for Materials Research

UNILAC

X0 & Microprobe

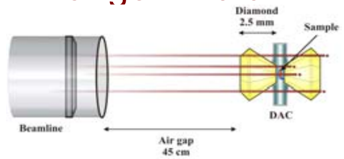
E=11.4 MeV/u, range ~100 µm



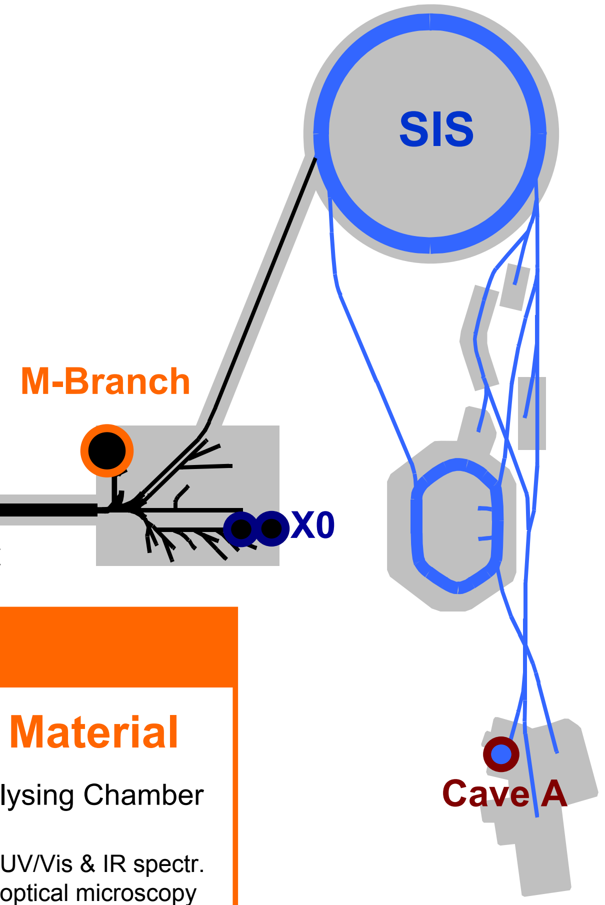
- **Material modifications**
- **Writing with single ions**
- **Ion-track nanotechnology**
  (nanopores & nanowires)

SIS Cave A

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



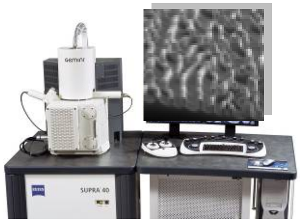
High pressure irradiations



M-Branch

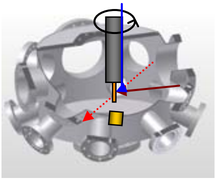
In-situ and On-line Analysis of Irradiated Material

M1: Electr. Microscopy



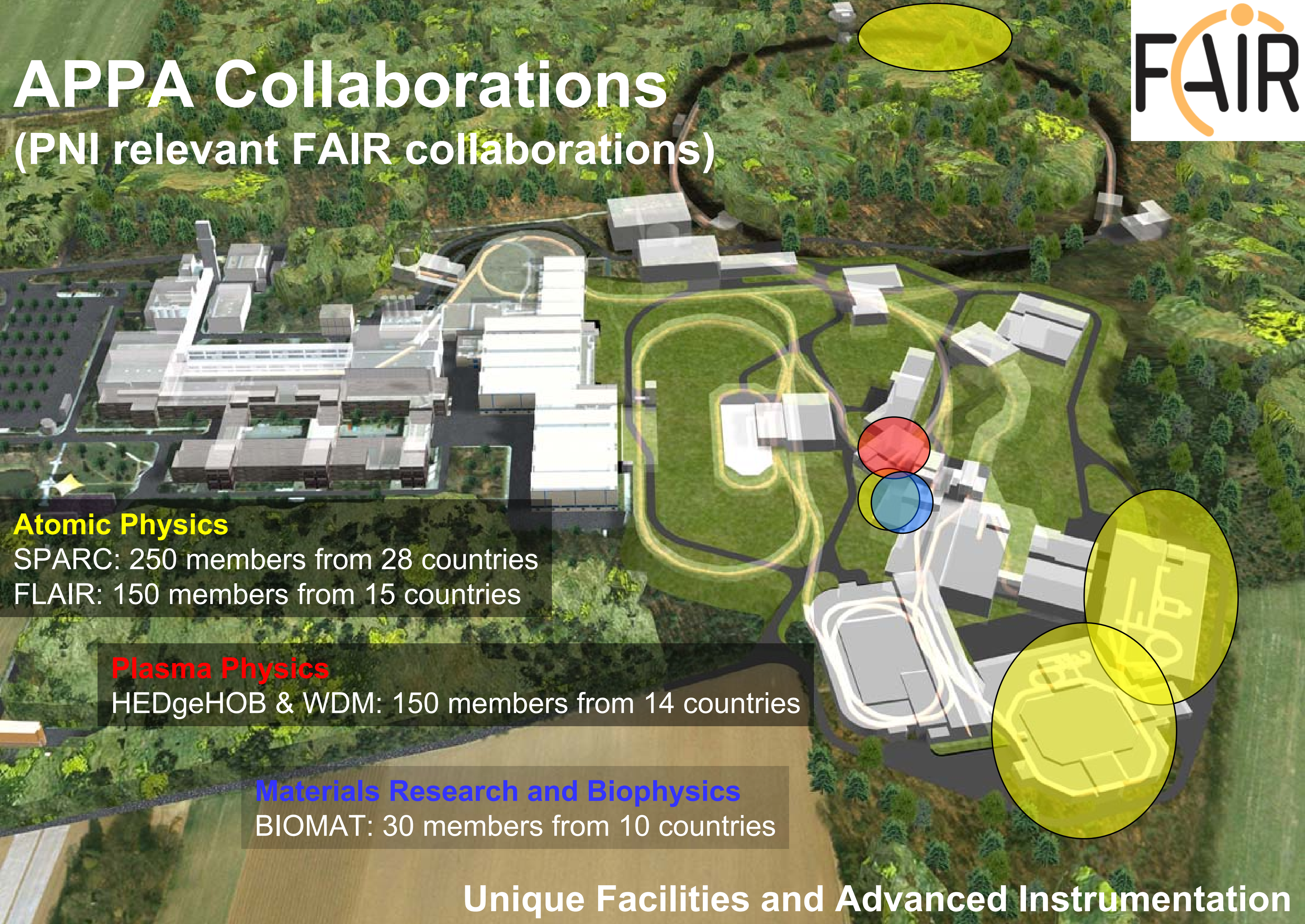
M2: X-Ray Diffraction

M3: Multi-Analysing Chamber



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

APPA Collaborations
(PNI relevant FAIR collaborations)



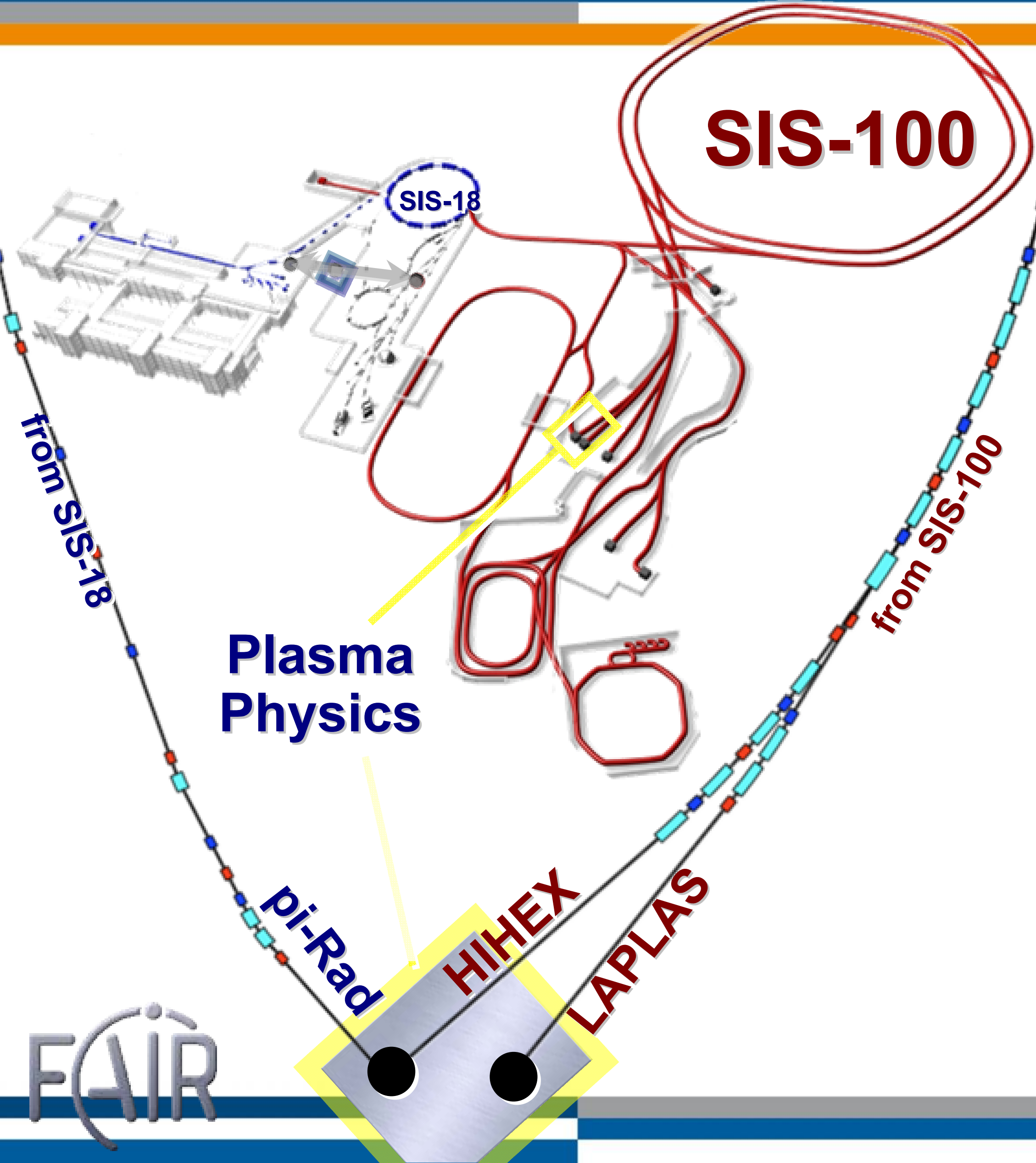
Atomic Physics
SPARC: 250 members from 28 countries
FLAIR: 150 members from 15 countries

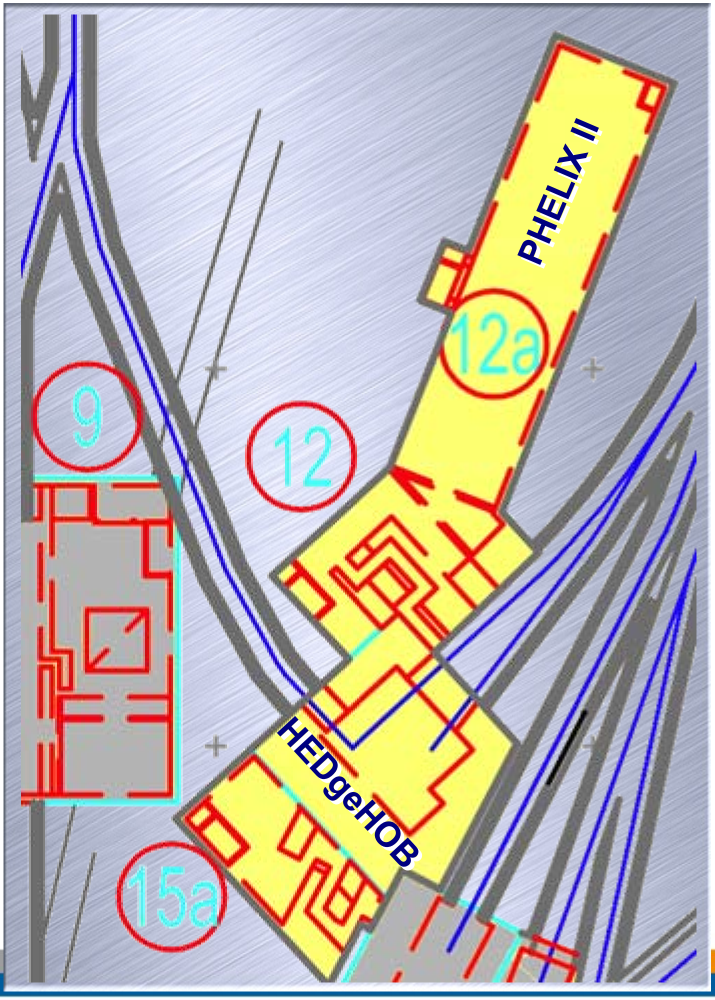
Plasma Physics
HEDgeHOB & WDM: 150 members from 14 countries

Materials Research and Biophysics
BIOMAT: 30 members from 10 countries

Unique Facilities and Advanced Instrumentation

Plasma Physics: WDM & HEDgeHOB beam lines, cave





The Physics of Highly Charged Ions

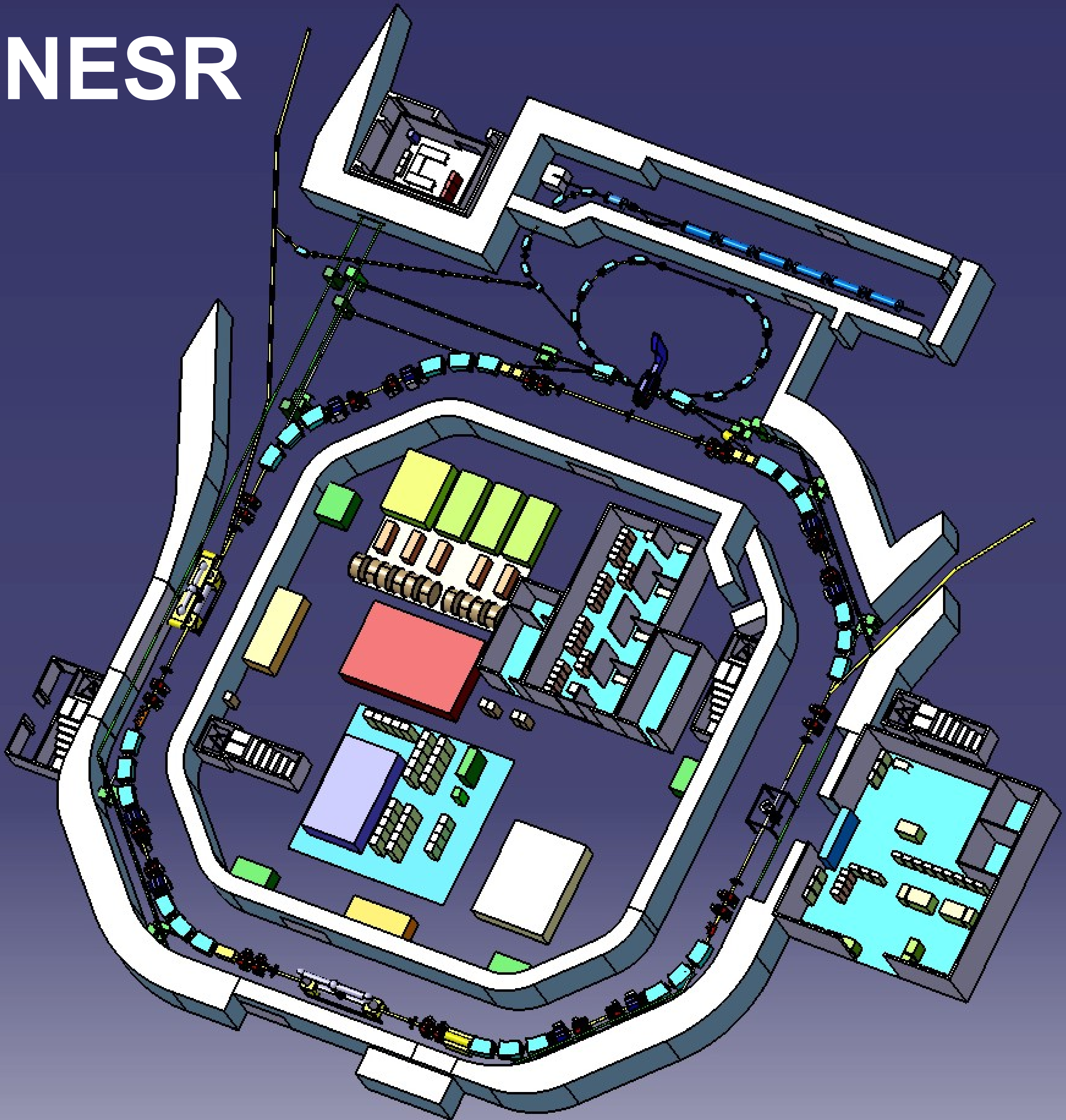
test of bound state QED in the critical field limit

correlated many-body effects on the atomic structure and dynamics

precision determination of fundamental constants

determination of nuclear properties

NESR



Summary

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

NEW: **the trap facility HITRAP at the storage ring ESR**

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.

New: **the high energy and high intensity laser PHELIX**

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

New: **new beam lines for materials science at M-Branch (UNILAC)**

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