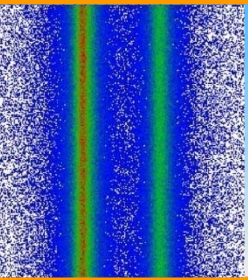
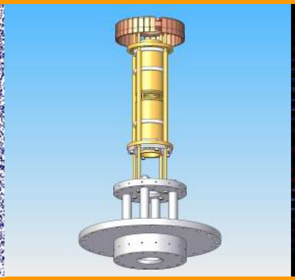
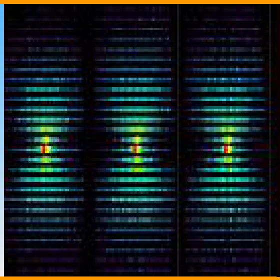
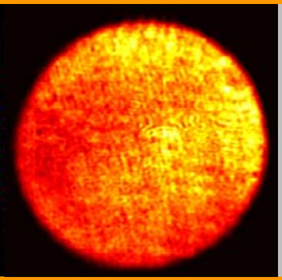
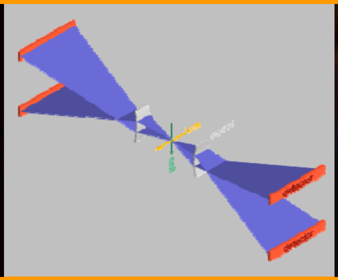


Plasma Physics @ GSI

Thomas Stöhlker
GSI-Darmstadt and Helmholtz Institute Jena

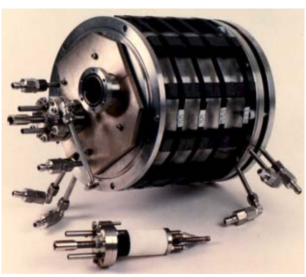
Facilities for Heavy Ions at GSI

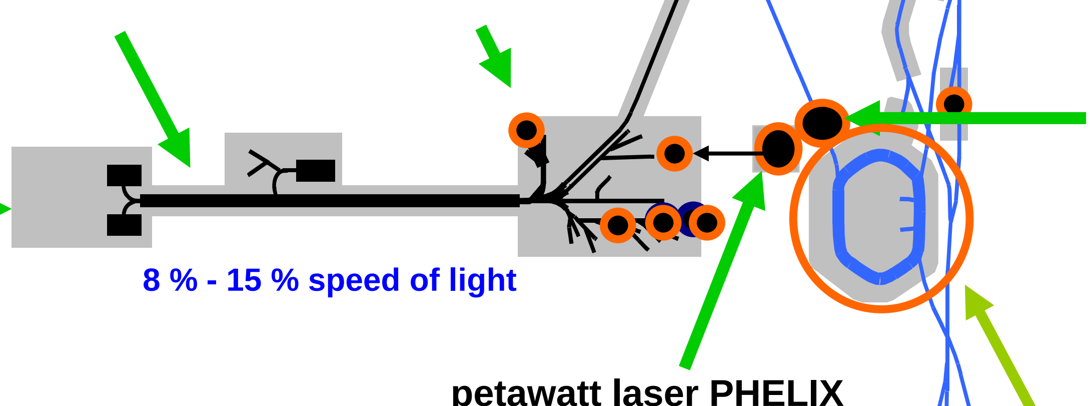
HELMHOLTZ ASSOCIATION

linear accelerator UNILAC

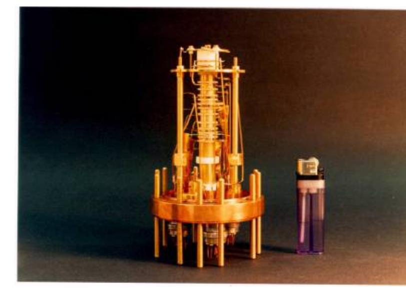
M-branch UNILAC

ion sources





heavy-ion synchrotron SIS



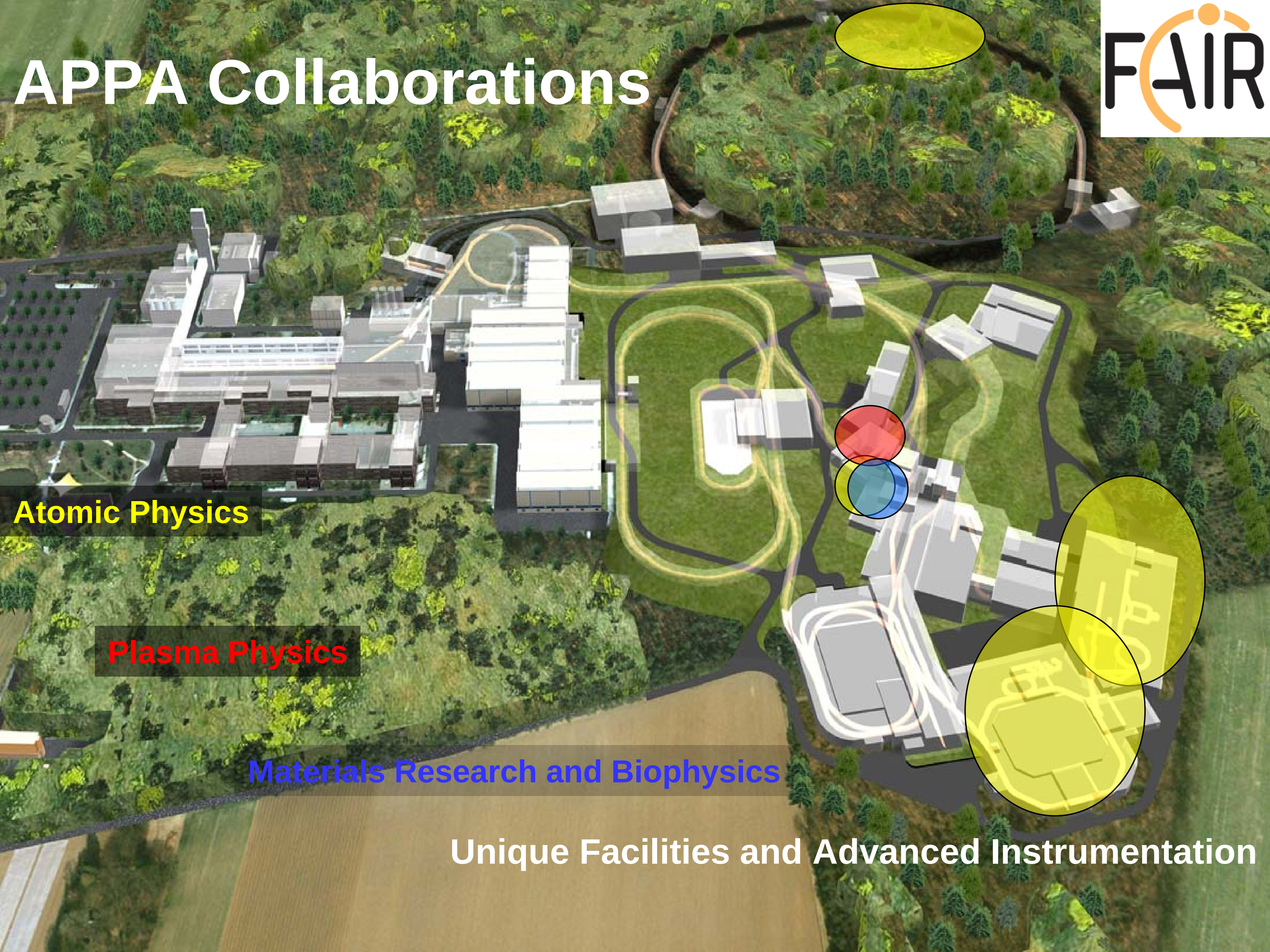
ion trap facility HITRAP

petawatt laser PHELIX

storage ring ESR

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

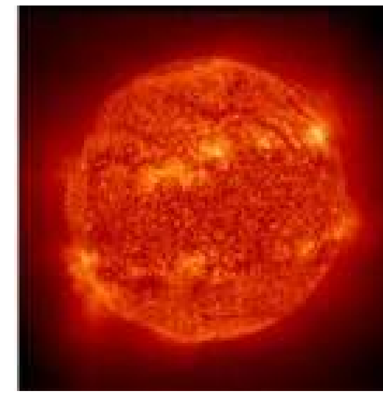
APPA Collaborations



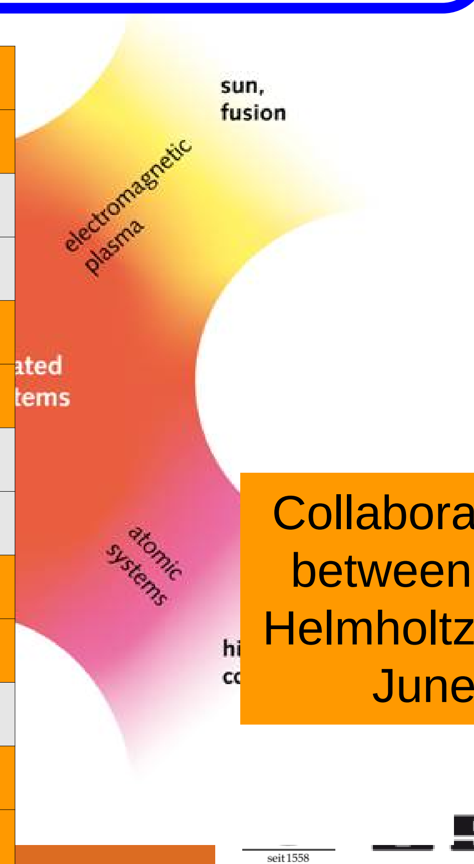
Helmholtz Alliance: EMMI

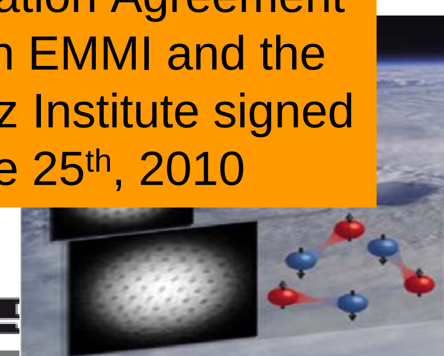
Extremes of Density and Temperature: Cosmic Matter in the Laboratory

QGP | Neutron Matter | EM Plasma | Atomic Physics



GSI
FZ Jülich (P. Gibbon et al.)
FIAS
JINA
LBNL (W. Leemans et al.)
MPIK, Heidelberg (C. Keitel, J. Ullrich et al.)
Tokyo Univ. / RIKEN
TU Darmstadt
Univ. Frankfurt (J. Maruhn et al.)
Univ. Heidelberg
Univ. Münster
Univ. VI, Paris (P. Indelicato, F. Rosmej, D. Vernhet)
Ass. Partners e.g. R. Schuch (Univ. Stockholm)





Collaboration Agreement between EMMI and the Helmholtz Institute signed June 25th, 2010

Interdisciplinary Aspects

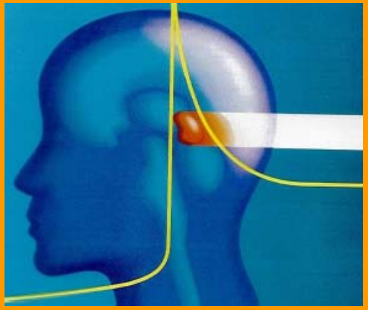
HELMHOLTZ ASSOCIATION

Research Focus: Matter under Extreme Conditions

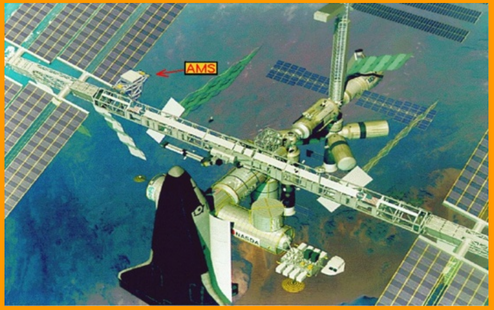
Highest Charge States	*Extreme Static Fields*
Relativistic Energies	*Extreme Dynamical Fields and Ultrashort Pulses*
High Intensities	*Very High Energy Densities and Pressures*
High Charge at Low Velocity	*Large Energy Deposition*

Contributions to

Energy



Health



Aeronautics, Space

fusion energy research

... behaviour of compound materials

cancer therapy

... response of cells to irradiation by heavy ions

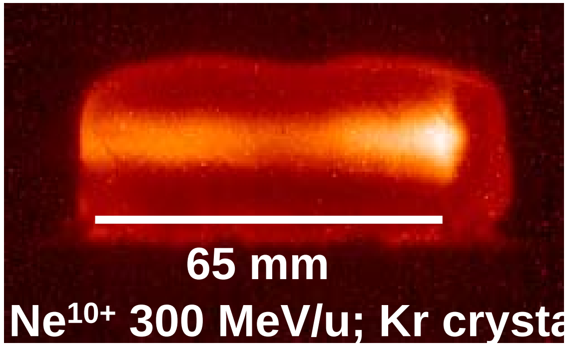
aerospace engineering

... active and passive radiation shielding of cosmic radiation

Creation and Study of Warm Dense Matter (WDM) and of Matter at High Energy Density (HED)

Novel XUV photon sources of highest brilliance and the ions beams at GSI provide complementary tools to study warm dense matter

intense, energetic beams of heavy ion (GSI)



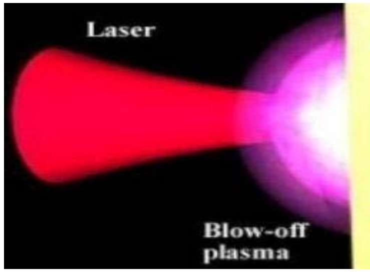
large volume of sample (mm³)
long time scales (50 ns)
fairly uniform physical conditions
any target material

specific energy: ~ kJ/g

temperature: up to 1 eV

pressure: multi-kbar range

photon pulses (XUV) of highest brilliance (FLASH)



small volume of sample (100 μm^3)
ultra-short time scales (100 fs)
high gradients
low-Z target material

HI-Jena and Helmholtz

Helmholtz Institute Jena

PHOTONS

Intense fields of real photons

&

HEAVY IONS

Intense fields of virtual photons

Helmholtz Center Dresden/Rossendorf

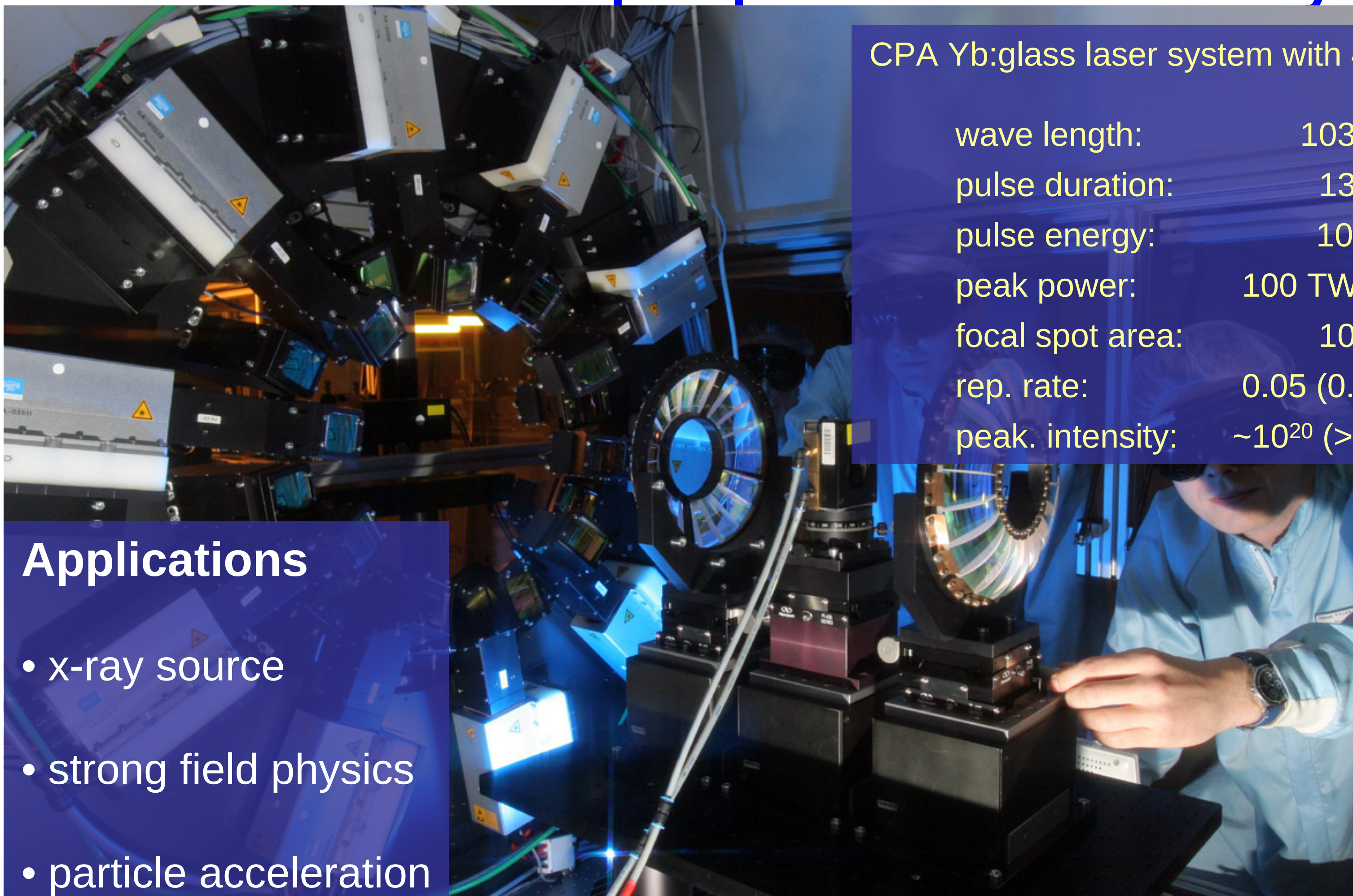
In-House Research
Atoms, Molecules, and Plasmas

Atomic Physics: The Physics of Strong Electromagnetic Fields

Plasma Physics: Creation and Study of Warm and Hot Dense Matter

High-Power Laser System in Jena

POLARIS – an all-diode pumped PW-class laser system



CPA Yb:glass laser system with 4 (5) amplifiers

wave length:	1030 nm
pulse duration:	130 fs
pulse energy:	10 (100) J
peak power:	100 TW (1 PW)
focal spot area:	10 mm^2
rep. rate:	0.05 (0.01) Hz
peak. intensity:	$\sim 10^{20}$ ($>10^{22}$) W/cm^2

Applications

- x-ray source
- strong field physics
- particle acceleration

seit 1558

HELMHOLTZ ASSOCIATION

The Helmholtz Institute Jena

• acts as a competence centre for innovative high-power lasers and light sources

• serves as an interface for future advancements of conventional and laser based acceleration of electrons and ions

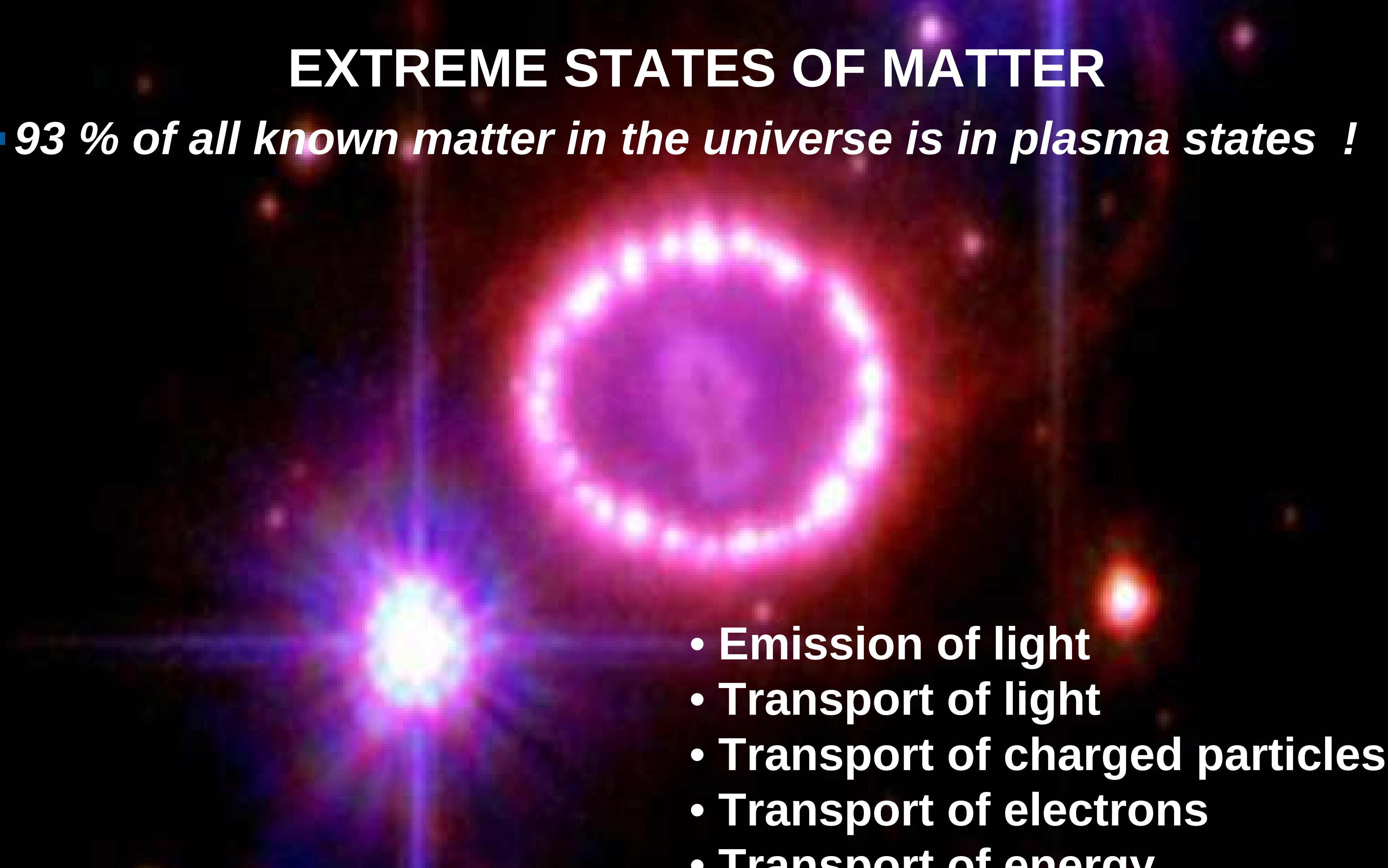
• develops and advance innovative ideas in measurement techniques and diagnosis applicable to investigating the interaction between light and matter

• experiments in the fields of the physics of extremely strong electromagnetic fields and of warm, dense matter

• foster basic and advanced education at the graduate and post-graduate level in the field of high-power laser and accelerator physics.

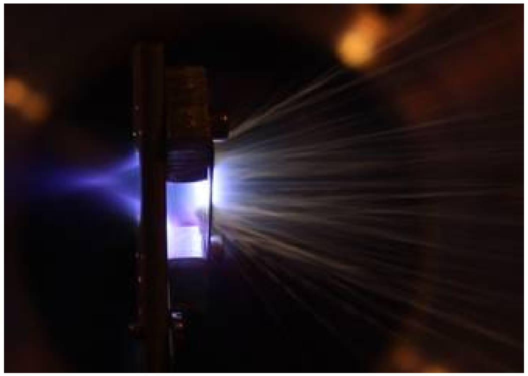
EXTREME STATES OF MATTER

93 % of all known matter in the universe is in plasma states !



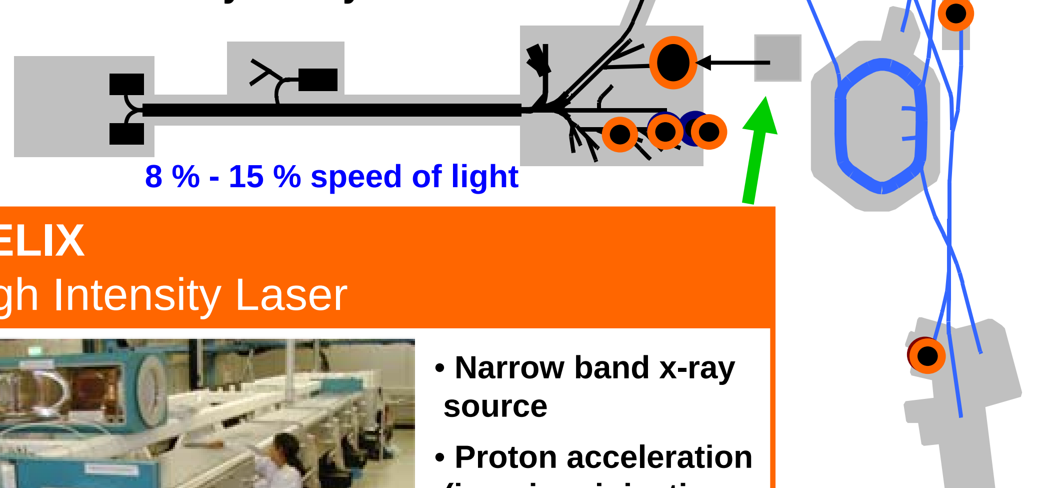
- **Emission of light**
- **Transport of light**
- **Transport of charged particles**
- **Transport of electrons**
- **Transport of energy**
- **Nuclear Processes?**

High Intensity / High Energy Laser at GSI
The PW Class Laser Facility PHELIX



laser heated plasma target

heavy-ion synchrotron SIS



PHELIX

High Energy / High Intensity Laser

Laser bay: 0.5 PW, 250 J @ 500 fs

Z6: 0.3 – 1 kJ @ 1 – 15 ns

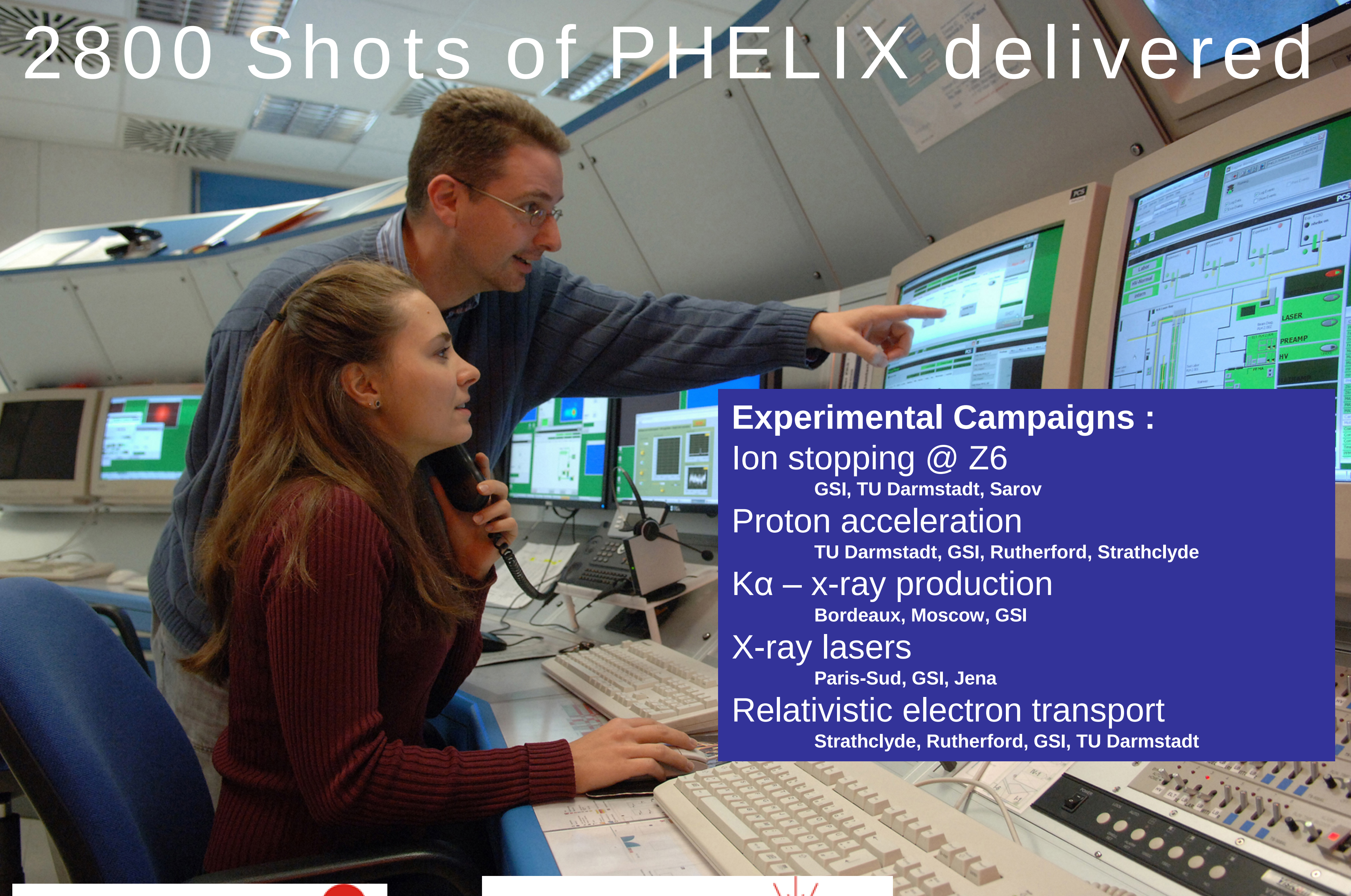
50 J @ 0.5 – 2 ps (100 TW)

2011: 150 J -- 2 w @ 1 – 15 ns

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

seit 1558

2800 Shots of PHELIX delivered



Experimental Campaigns :

Ion stopping @ Z6
GSI, TU Darmstadt, Sarov

Proton acceleration
TU Darmstadt, GSI, Rutherford, Strathclyde

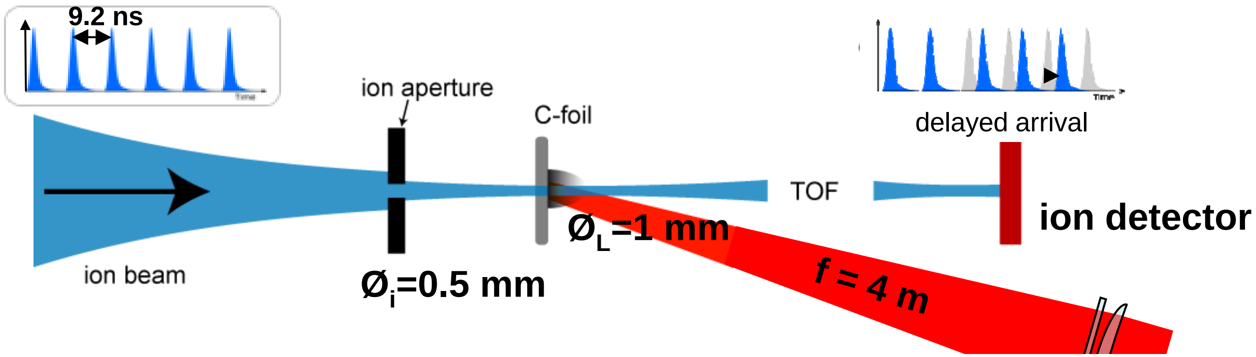
Kα – x-ray production
Bordeaux, Moscow, GSI

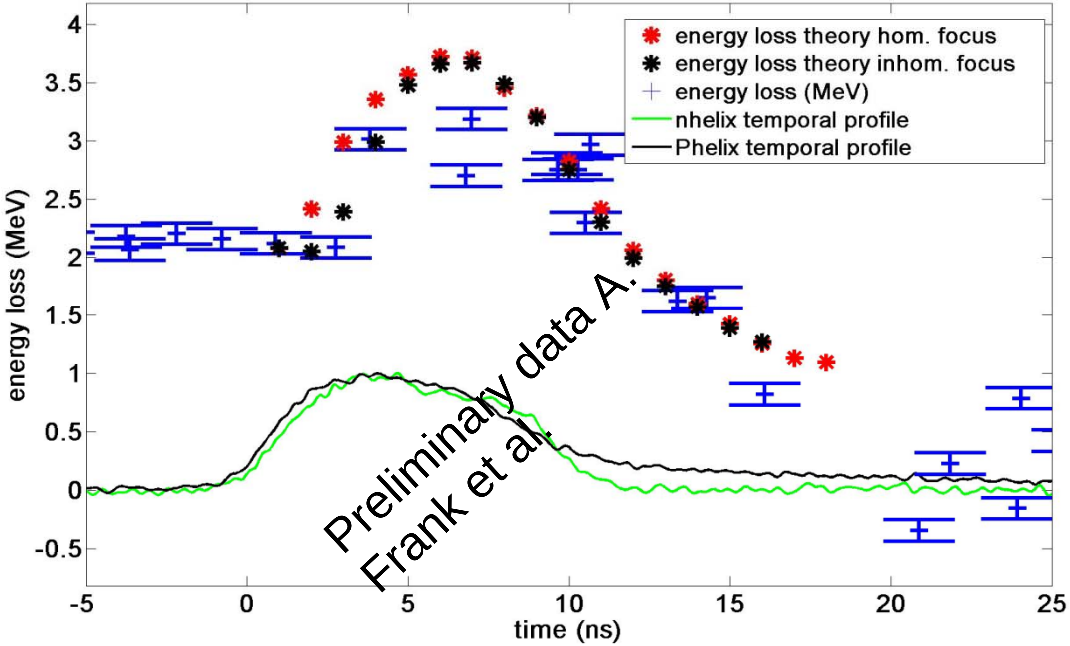
X-ray lasers
Paris-Sud, GSI, Jena

Relativistic electron transport
Strathclyde, Rutherford, GSI, TU Darmstadt

GSI PHELIX Laserlab Europe

Ion Interaction with Laser Generated Plasma Targets





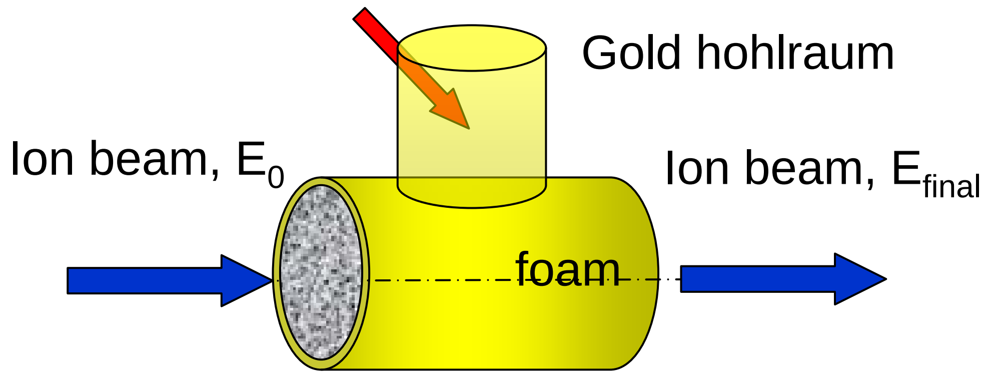
Experimental work by A. Frank et al. TUDa

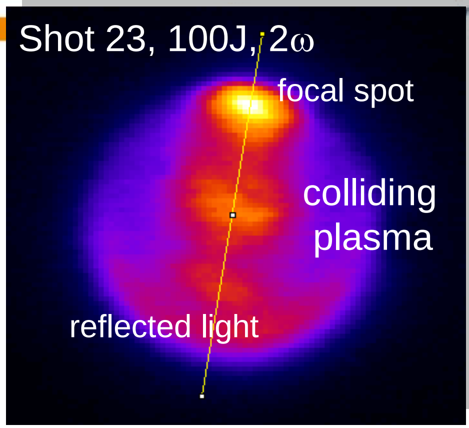
We have implemented a 2ω option in order to reduce target instabilities

A. Blazevic

Laser heated homogeneous high density plasma for heavy ion – plasma interaction experiments

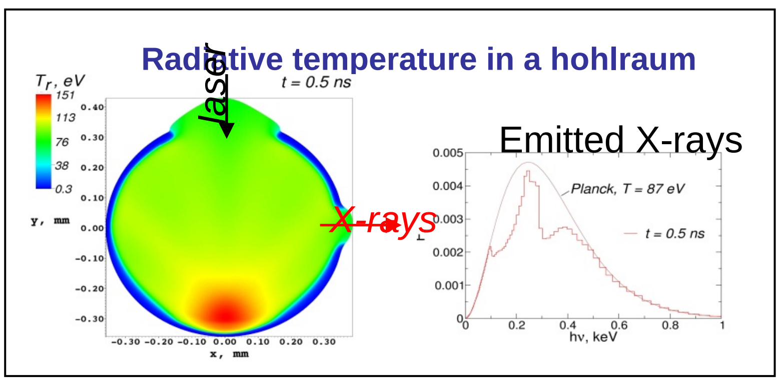
PHELIX Laser: 2ω, 1ns, 100-150 J, 10^{14} W/cm^2

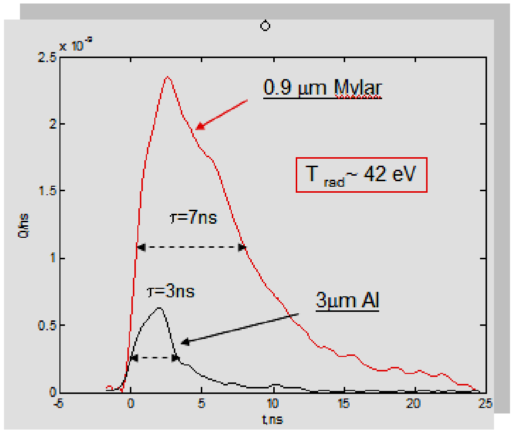




X-ray image of the laser interaction with hohlraum wall

Up to 40% of the laser energy is converted into soft (<0.5 keV) X-rays ***O.Rosmej et al.***



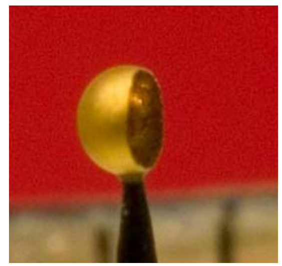


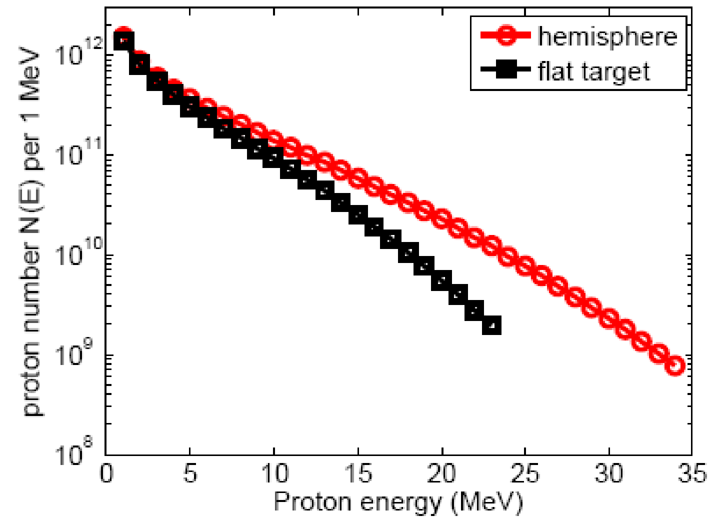
Measured X-ray pulse, duration up to 7 ns

Good agreement with theory, e.g. RALEF-2D !

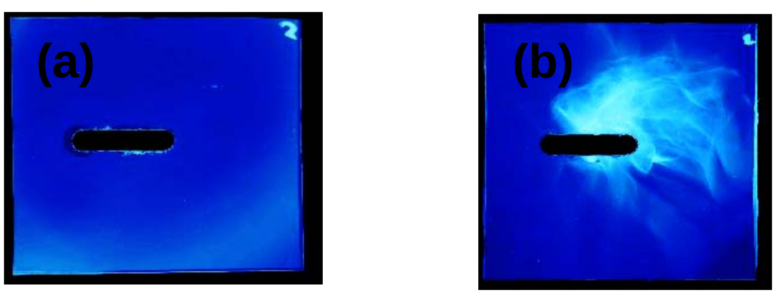
Significant results were obtained in particle acceleration

- An enhancement of the proton energy when hemispherical targets are used was shown
  - Targets developed by TU Darmstadt were shot at PHELIX yielding an increase in proton energy compared to flat foils

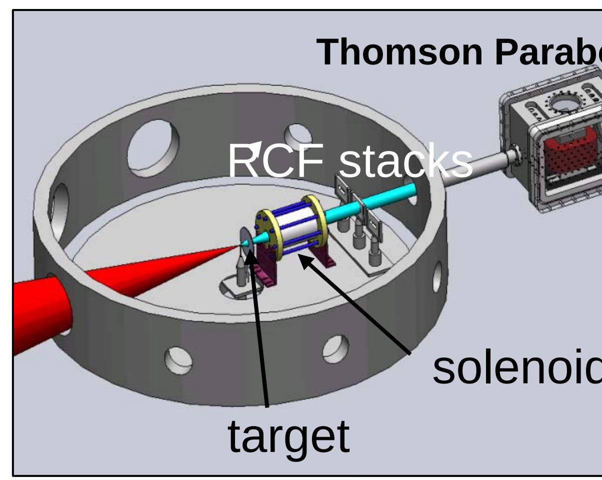




- GSI has started a program to couple laser-accelerated ions into conventional structures



Radio-chromic films recording the proton beam at 2.3 MeV when the solenoid is energized (b) and not (a)



Parametric amplification in the XUV/soft x-ray spectral range has been demonstrated

HELMHOLTZ ASSOCIATION GSI

nature physics ARTICLES

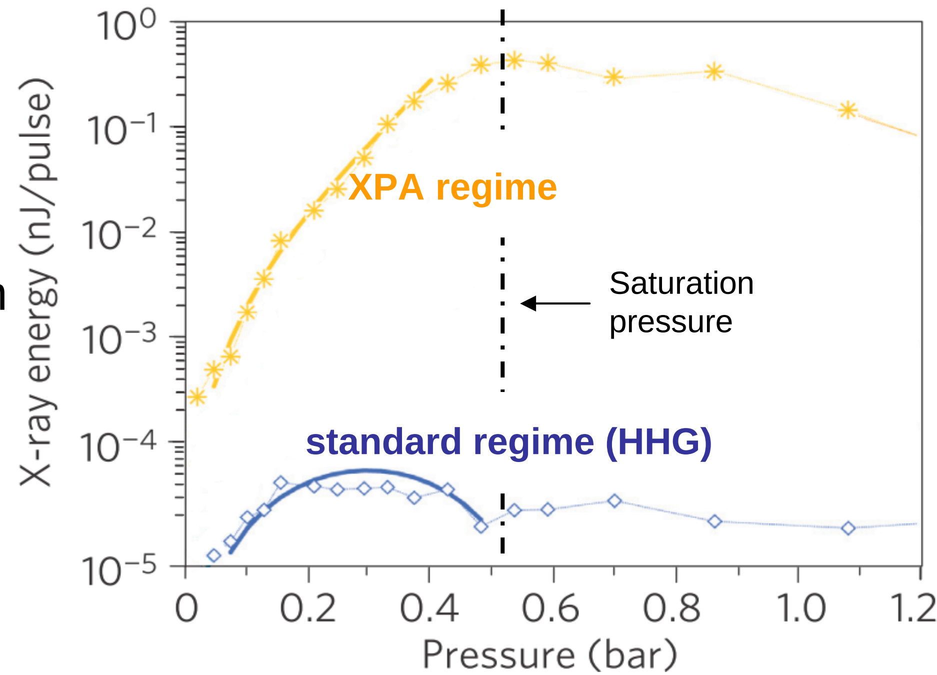
PUBLISHED ONLINE: 18 APRIL 2010 | DOI: 10.1038/NPHYS1638

Laser-driven amplification of soft X-rays by parametric stimulated emission in neutral gases

J. Seres[1,2], E. Seres[1], D. Hochhaus[3,4,5], B. Ecker[3,4], D. Zimmer[3,4,6], V. Bagnoud[3], T. Kuehl[3,4] and C. Spielmann[1,2]*

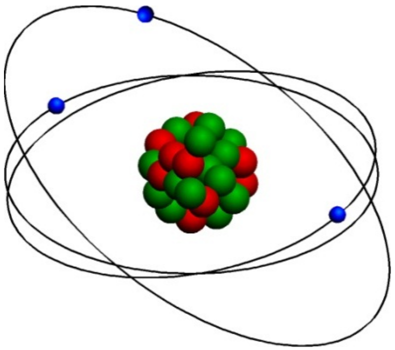
[1]Institute of Optics and Quantum Electronics, Friedrich-Schiller-University Jena, Max-Wien-Platz 1, 07743 Jena, Germany, [2]Department of Physics I. University of Würzburg, Am Hubland, 97074 Würzburg, Germany, [3]GSI Helmholtz Centre for Heavy Ion Research GmbH, Planckstrasse 1, 64291 Darmstadt, Germany, [4]Department of Physics, Johannes-Gutenberg-University Mainz, Staudingerweg 7, 55128 Mainz, Germany, [5]EMMI Extreme Matter Institute, Planckstrasse 1, 64291 Darmstadt, Germany, [6]LASERIX-CLUPS, LPGP UMR 8578, Université Paris-Sud 11, Bat 210, 91405 Orsay, France.
*e-mail: christian.spielmann@uni-jena.de.

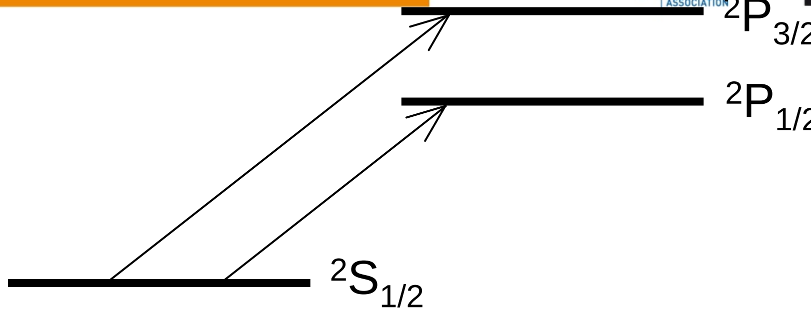
- We discovered an amplification mechanism based on parametric amplification :
  X-ray Parametric Amplification (XPA)
- We experimentally observed amplification factors **up to 8 x 10³** at 260 eV photon energy
- Our theoretical model describes for the first time the conditions for parametric amplification in the XUV and gives excellent agreement to experimental observations

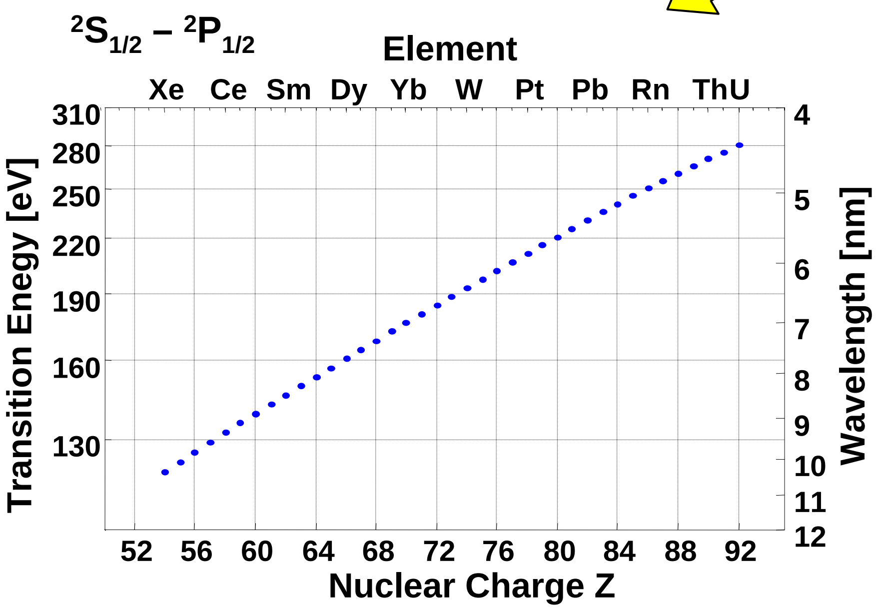


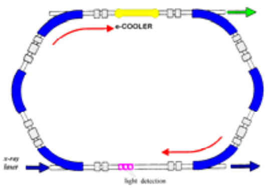
Experimental signature of a parametric process (exponential gain) in the XUV

Lithium-like Ions: Strong Field Physics

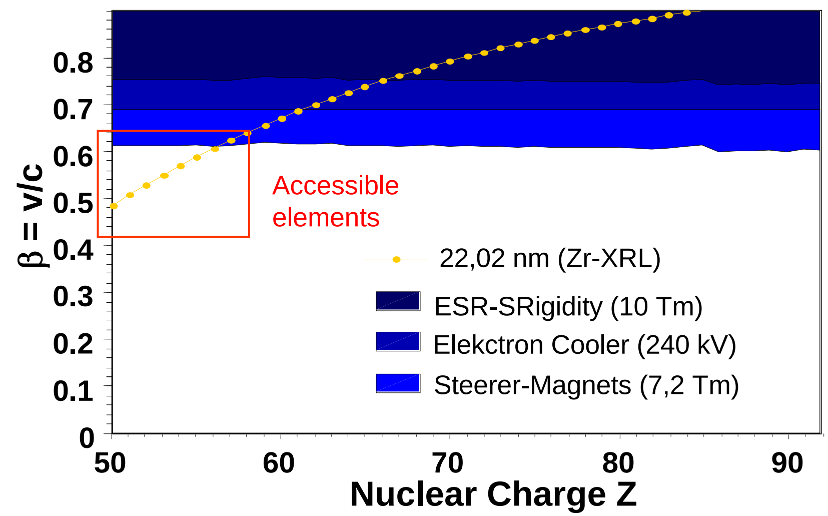




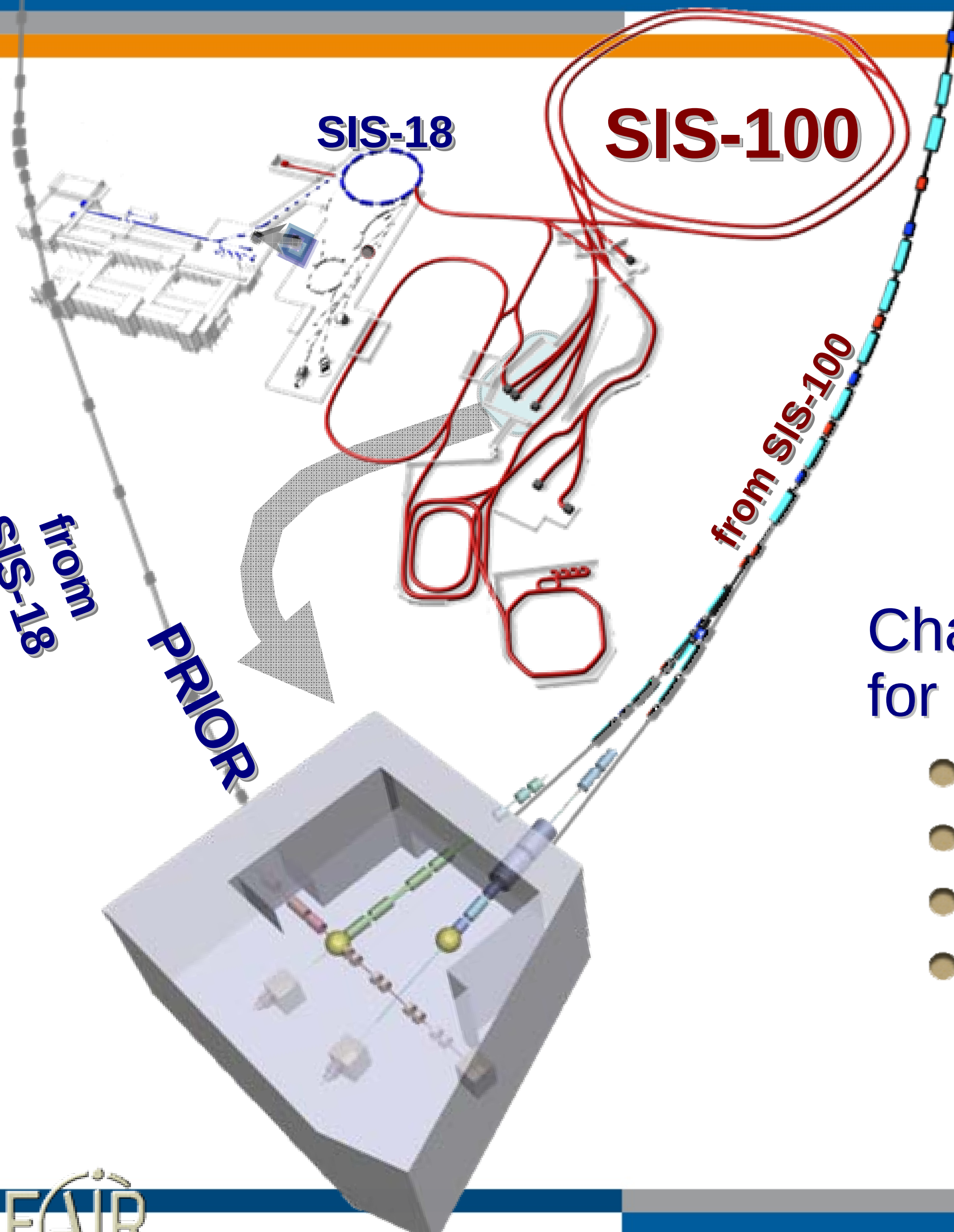




$$\lambda = \lambda' \sqrt{\frac{1-\beta}{1+\beta}}$$



PRIOR – Proton Radiography at FAIR



At FAIR: a dedicated beam line from SIS-18 for radiography

4.5 GeV, $5 \cdot 10^{12}$ protons

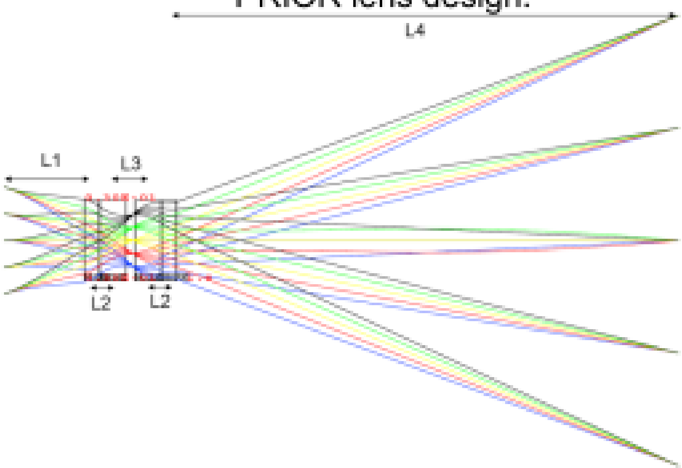
Challenging requirements for HEDP experiments:

- up to ~20 g/cm^2
- <10 µm spatial resolution
- 10 ns temporal resolution (multi-frame)
- sub-percent density resolution

PRIOR Goals

4.5 GeV Proton Microscopy

Proton trajectories through the baseline PRIOR lens design.



Lens and detector design goals (in accordance with FAIR pRad specifications):

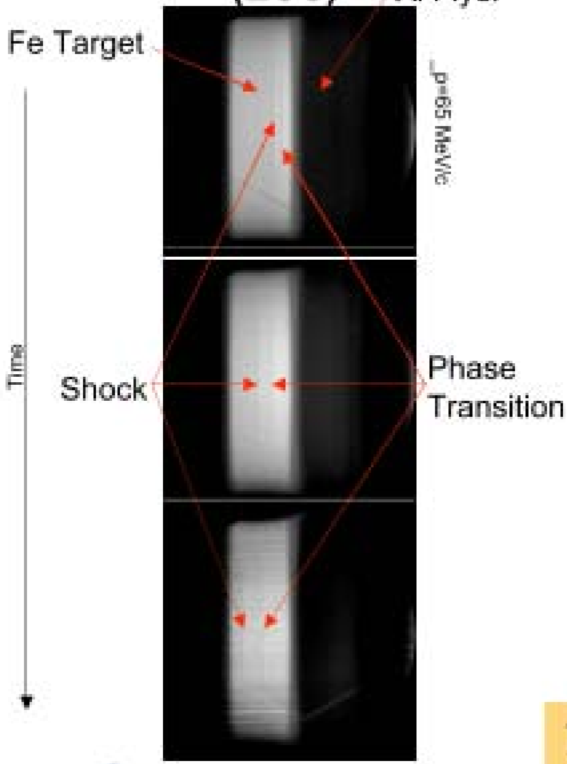
- less than 10 μm spatial resolution;
- sub-percent density resolution;
- target areal density up to 5 – 50 g/cm^2, high-Z targets;
- temporal resolution <10 ns (for FAIR), <100 ns (for GSI);
- field of view: 20 mm;

Dynamic experiment design goals:

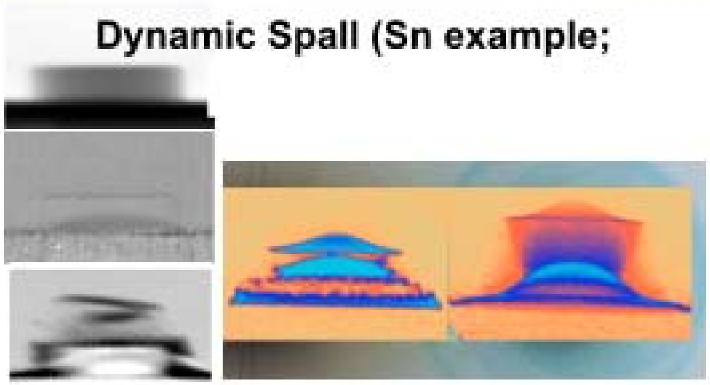
- Multiple drivers in combination with high resolution proton microscopy will provide a unique facility for the study of material properties at extreme temperatures and pressures.

Dynamic Materials:
What can we do today at LANSCE in dynamic materials?

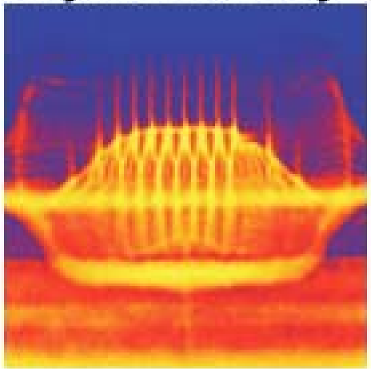
Internal Phase Transition (EOS)



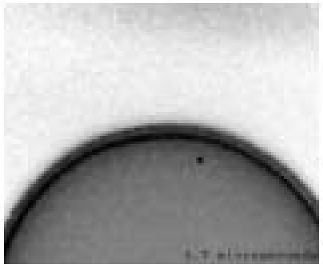
Dynamic Spall (Sn example;



Hydro Instability



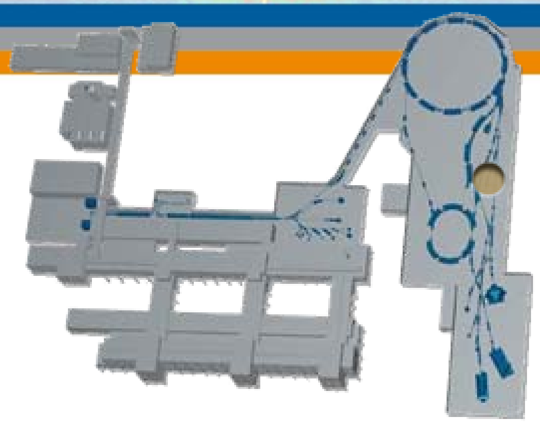
Dynamic Material Failure

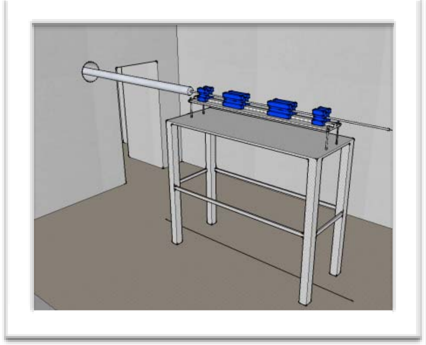


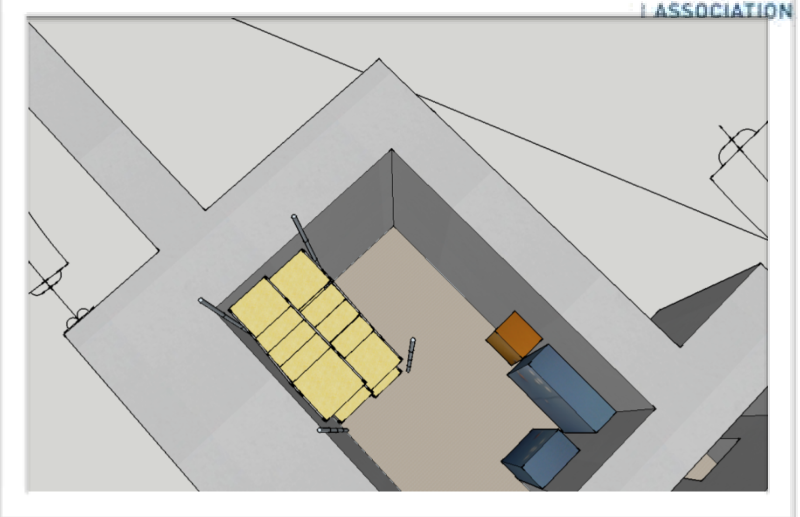
Initial material characterization

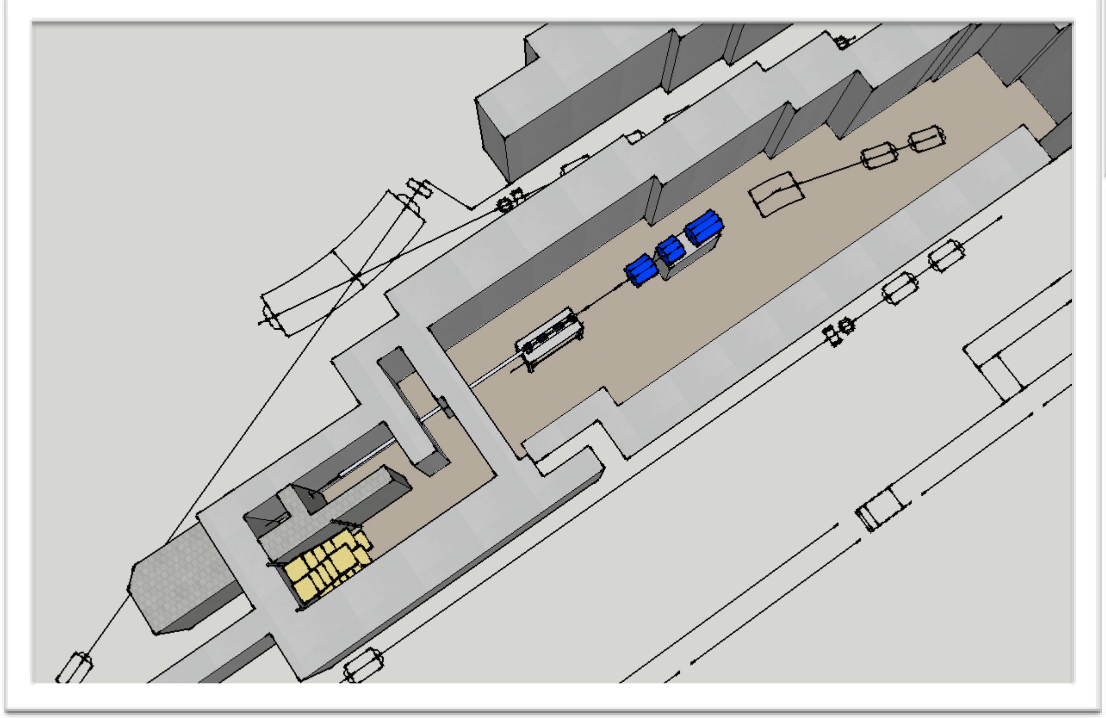
These studies provide excellent data at continuum scale, but don't address causes at microstructure scale; much more is needed to develop a predictive capability!

Fielding at GSI – a minor reconstruction of the HHT cave





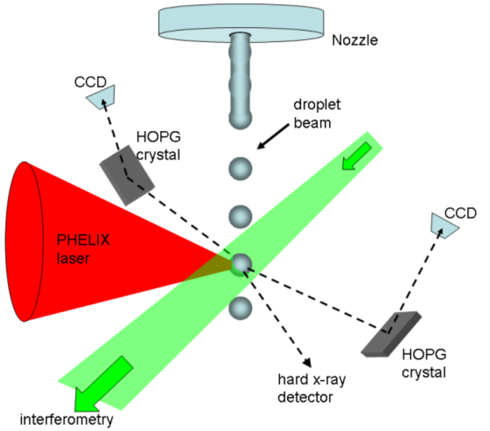




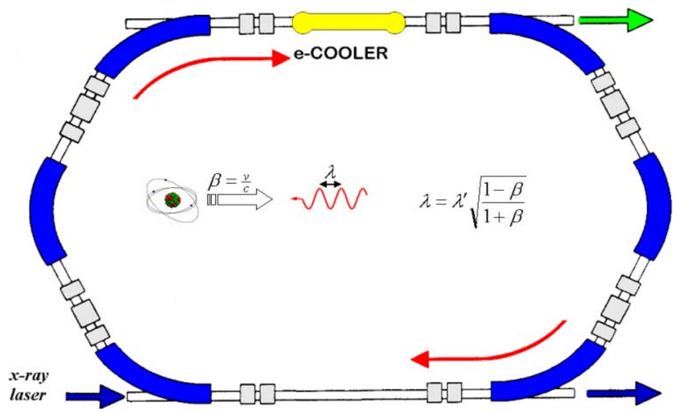
- a compact system but long drift is needed for the microscope

D. Varentsov

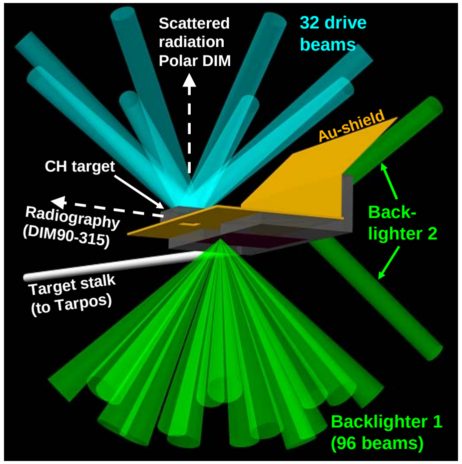
Future Perspectives



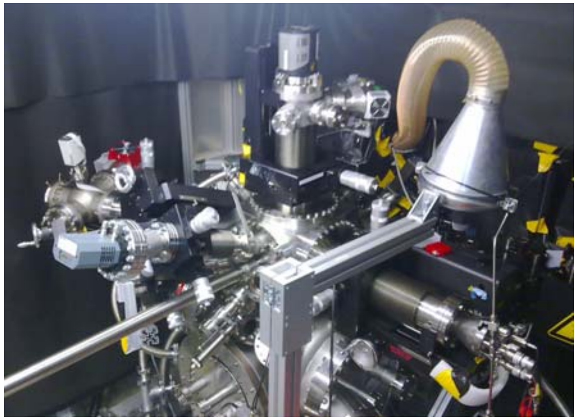
Droplet target at GSI (Grisenti)



X-Ray Laser at ESR/Nuclear Excitation

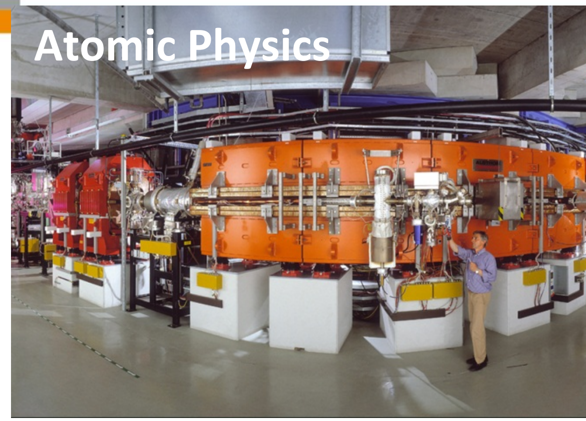


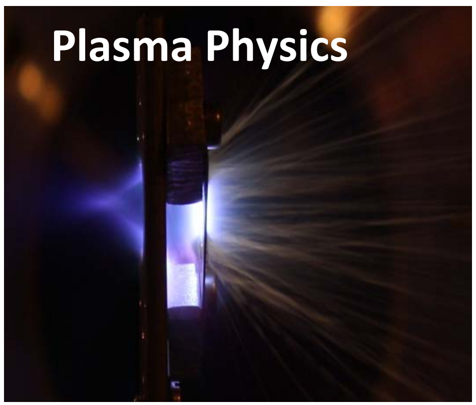
Accepted proposal at NIF (P. Neumayer)

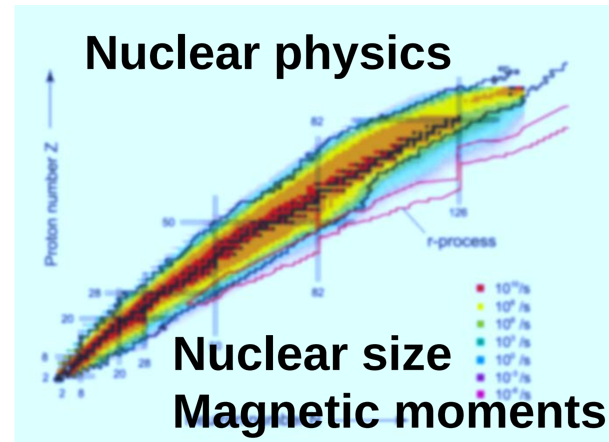


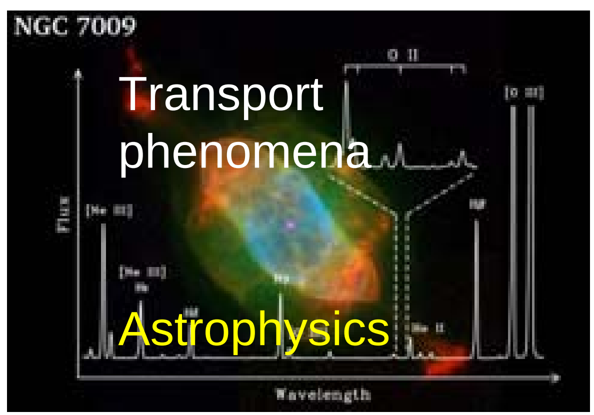
Experiments at FLASH

Interactions within EMMI

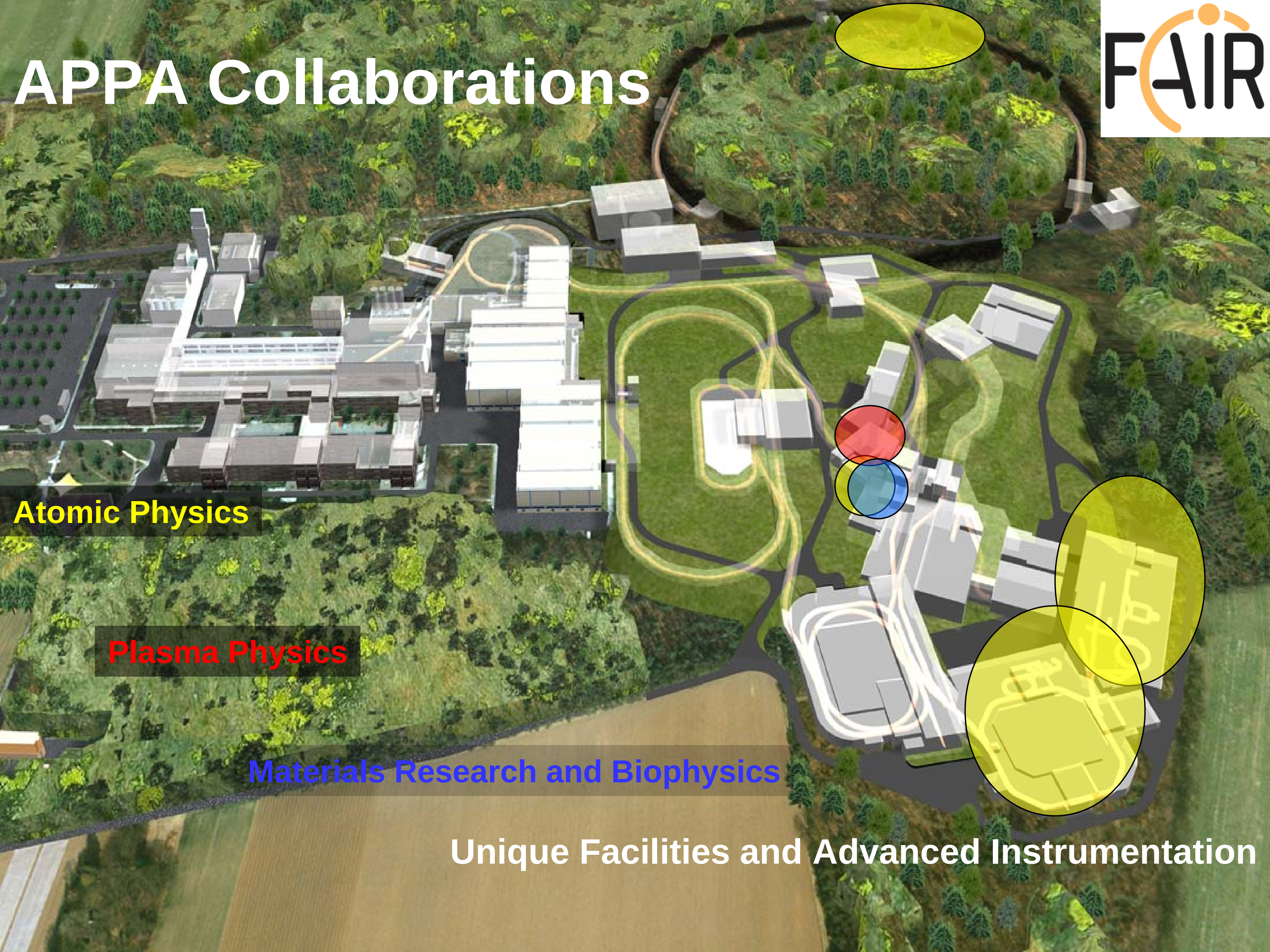








APPA Collaborations



New route in HEDP/ WDM research

- **Equation-of-state of High Energy Density matter**
  basic thermodynamic properties of matter in unexplored regions of the phase diagram (two-phase regions, critical points, non-ideal plasmas)
- **Phase transitions and exotic states of matter**
  metal-to-insulator or plasma phase transition, hydrogen metallization problem, etc.
- **Transport and radiation properties of HED matter**
  electrical and thermal conductivity, opacity, etc.
- **Stopping properties of non-ideal plasma**
  anomalous temperature and density dependence of heavy ion stopping and charge-exchange cross sections

Additional diagnostic tools are an option: high energy protons and high energy high power laser

The APPA Collaborations

HELMHOLTZ ASSOCIATION

BIOMAT

- 110 scientists
- 28 institutions
- 12 countries

SPARC

- 284 scientists
- 83 institutions
- 26 countries

FLAIR

- 144 scientists
- 49 institutions
- 15 countries

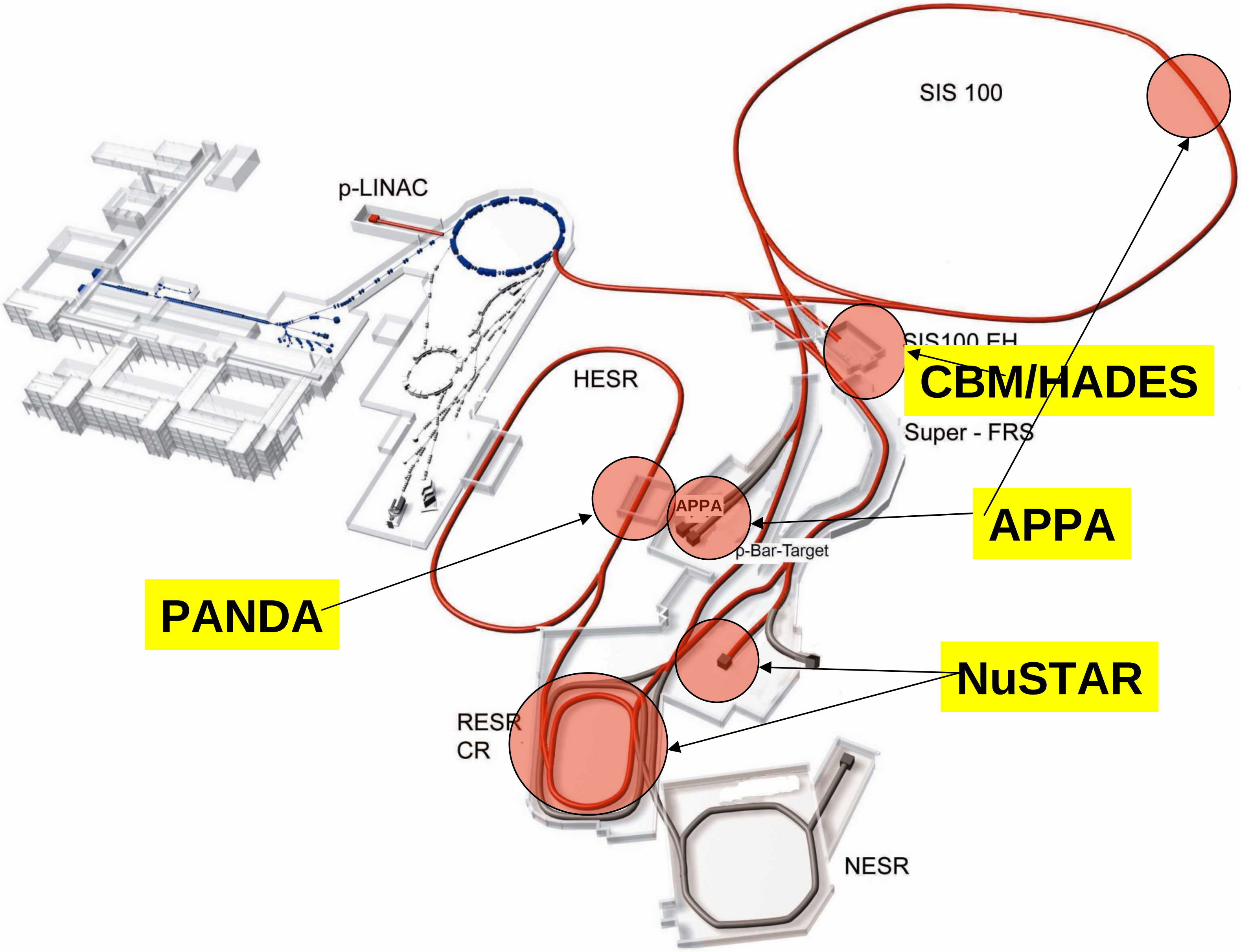
HEDgeHOB

- 175 scientists
- 45 institutions
- 16 countries

WDM

- 71 scientists
- 24 institutions
- 8 countries

Science with the Modularized Start Version



Development of Project Staging

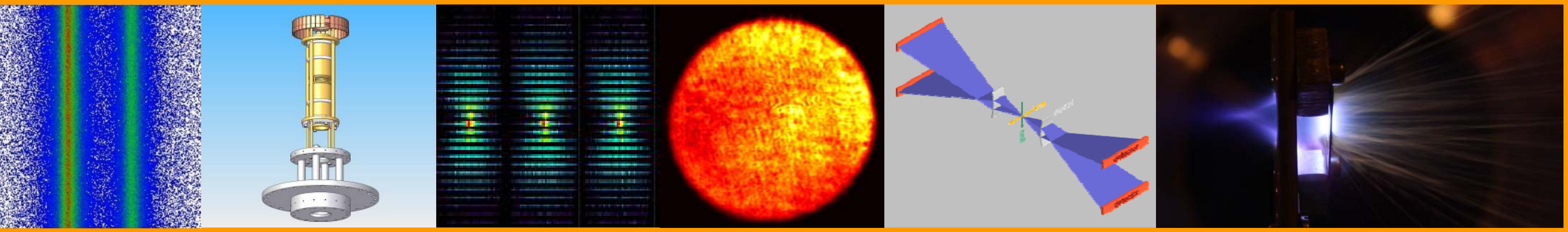
2003	**Recommendation by Wissenschaftsrat – FAIR Realisation in three stages**						
2005	**Entire Facility Baseline Technical Report**						
2007	**Phase A**						**Phase B** SIS300
2009	**Module 0** SIS100	**Module 1** experimental areas for CBM/HADES and APPA	**Module 2** Super-FRS fixed target area NuSTAR	**Module 3** pbar facility, incl. CR for PANDA, options for NuSTAR	**Module 4** LEB for NuSTAR, NESR for NuSTAR and APPA, FLAIR for APPA	**Module 5** RESR nominal intensity for PANDA & parallel operation with NuSTAR and APPA	**Phase B** SIS300
	The Modularized Start Version						

Special Thanks

All colleagues of the Plasma Physics Division at GSI

&

The colleagues from TU-Darmstadt



Atomic and Plasma Physics, and Applied Sciences APPA@FAIR

From Basic Science to Applications

Thomas Stöhlker

GSI-Darmstadt and Helmholtz Institute Jena

APPA Collaborations
(PNI relevant FAIR collaborations)

Atomic Physics
SPARC: 285 members from 26 countries
FLAIR: 144 members from 15 countries

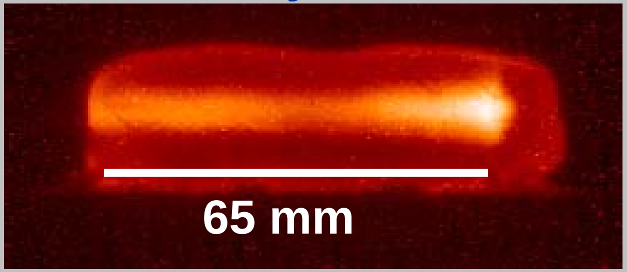
Plasma Physics
HEDgeHOB: 175 members from 16 countries
WDM: 71 members from 8 countries

Materials Research and Biophysics
BIOMAT: 110 members from 12 countries

Unique Facilities and Advanced Instrumentation

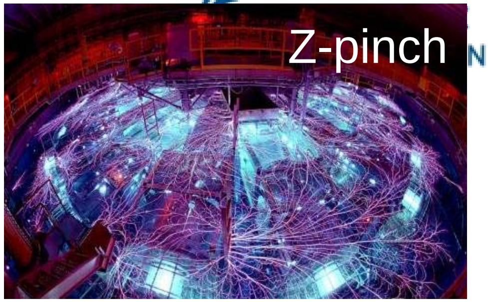
The uniqueness of heavy ion beams compared to other techniques (Laser, Z-pinch)

intense, energetic beams of heavy ions



Ne^{10+} 300 MeV/u; Kr crystal

- large volume of sample (mm^3)
- fairly uniform physical conditions
- thermodynamic equilibrium
- any material



Compared to GSI, FAIR will provide an intensity and energy density increase by a factor of 100.

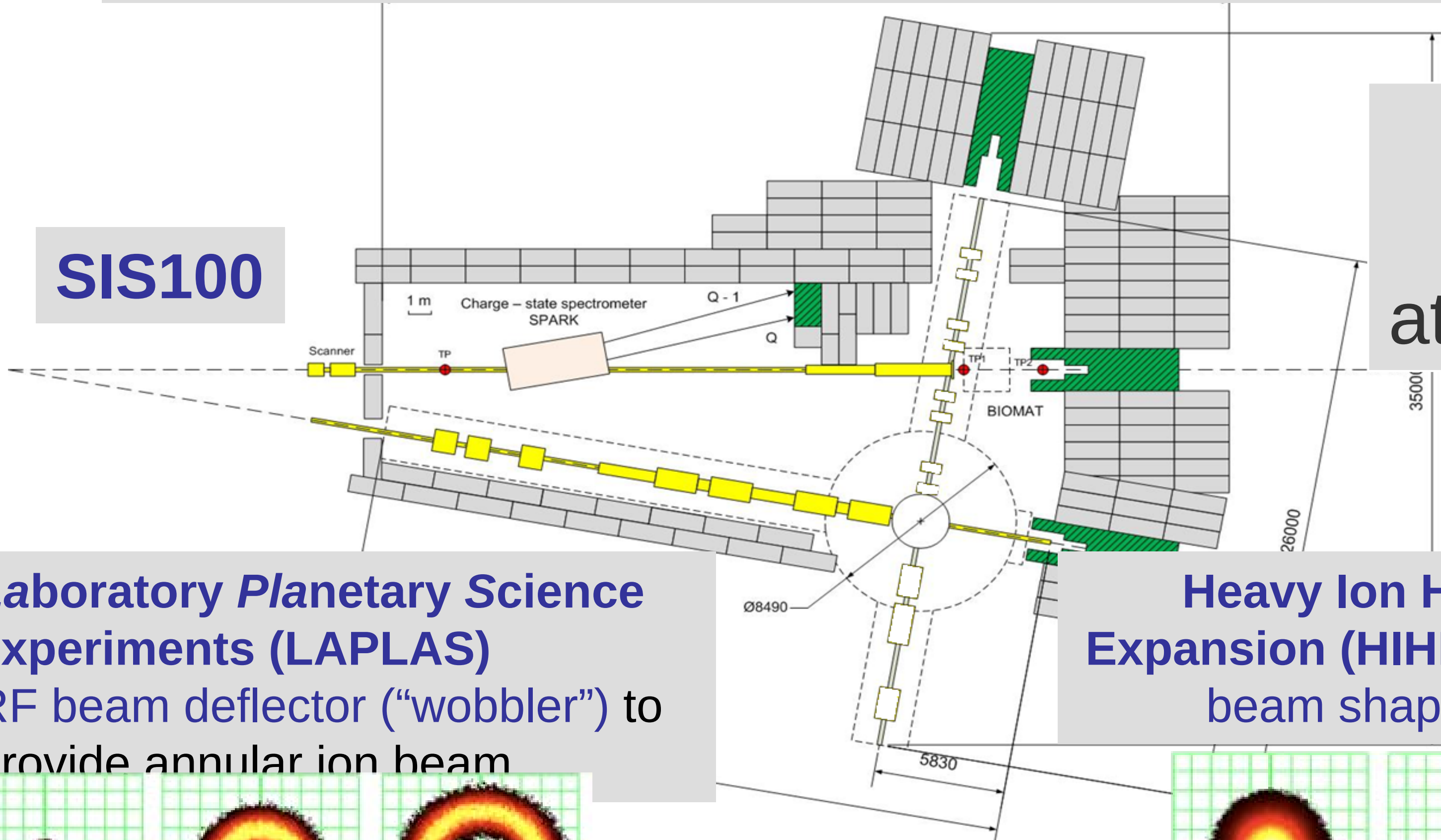
WDM-parameters: **T:** up to 10 eV **ρ:** ~ solid **P:** up **to 1** Mbar

Plasma Physics beam line at SIS-100

SIS-100: One beam line with replaceable elements:

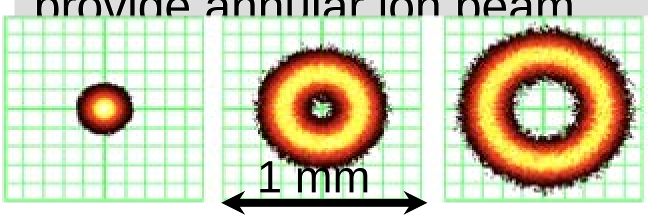
SIS100

APPA cave at SIS100

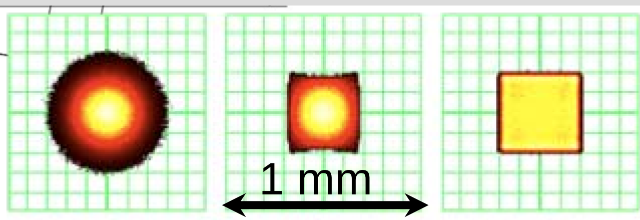


***La*boratory *Pla*netary *S*cience experiments (LAPLAS)**
RF beam deflector ("wobbler") to provide annular ion beam

Heavy Ion Heating and Expansion (HIHEX) experiments
beam shaping system



Transverse distributions of beam intensity at focal plane for LAPLAS



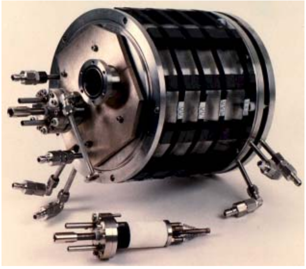
Transverse distributions of beam intensity at focal plane for HIHEX

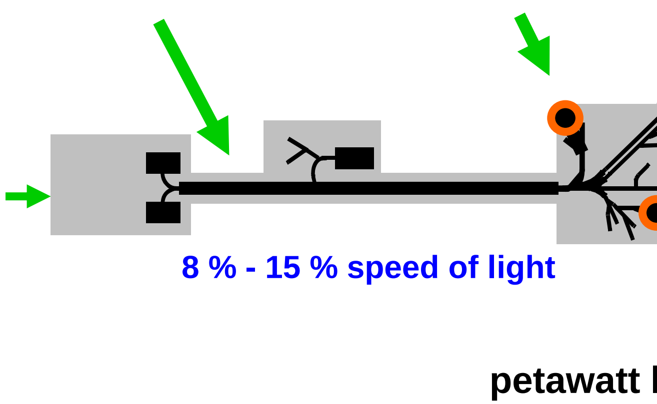
The GSI Accelerator Facility for Heavy Ions

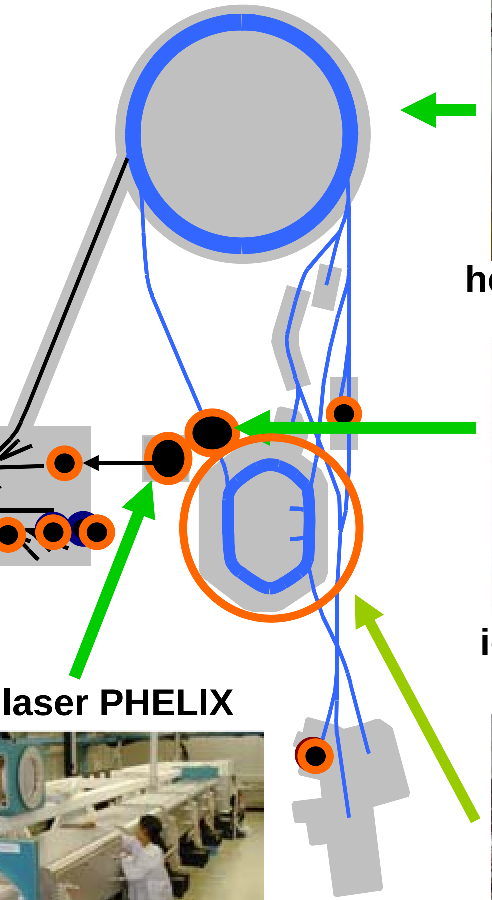
linear accelerator UNILAC

M-branch UNILAC

ion sources

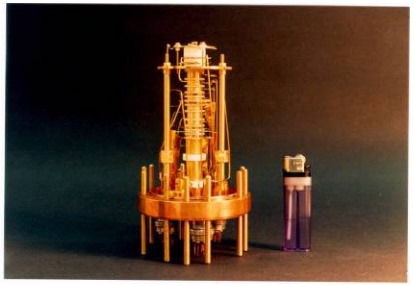






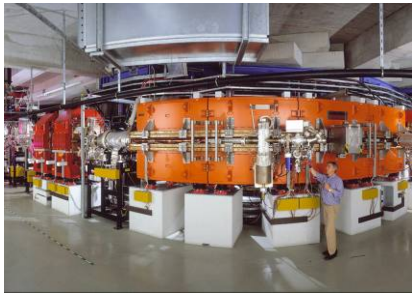
heavy-ion synchrotron SIS

ion trap facility HITRAP



petawatt laser PHELIX

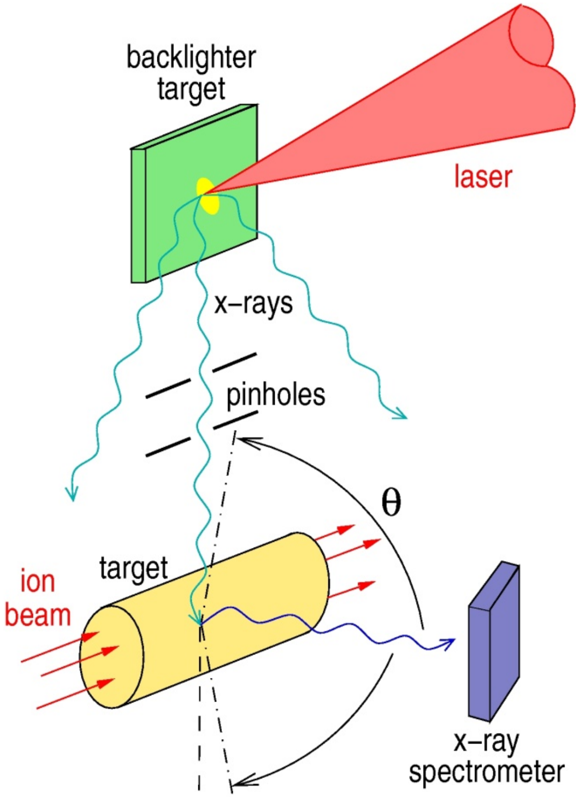
storage ring ESR



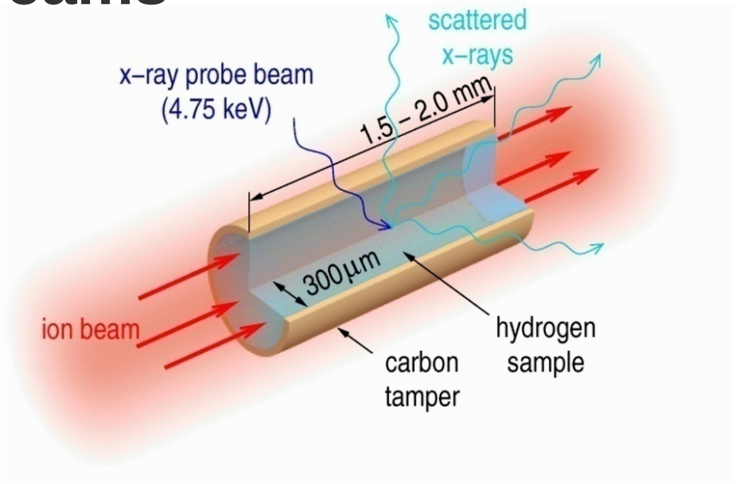
Accelerated ions: H^{+},..., U^{92+}

WDM collaboration – Atomic physics in dense environments

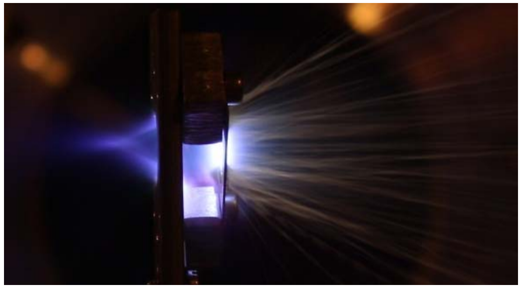
WDM produced by Intense Heavy Ion Beams and probed by Intense Laser Beams



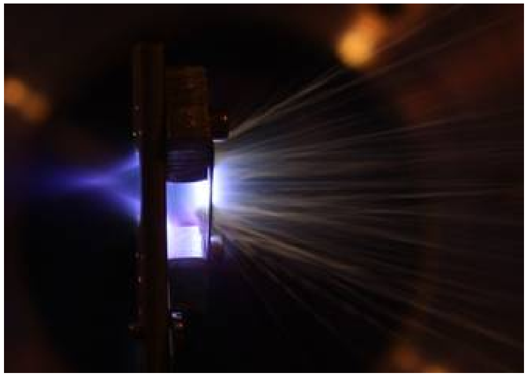
Unique combination of intense heavy ion beam driven experiments + PHELIX driven diagnostics



High Power Laser PHELIX

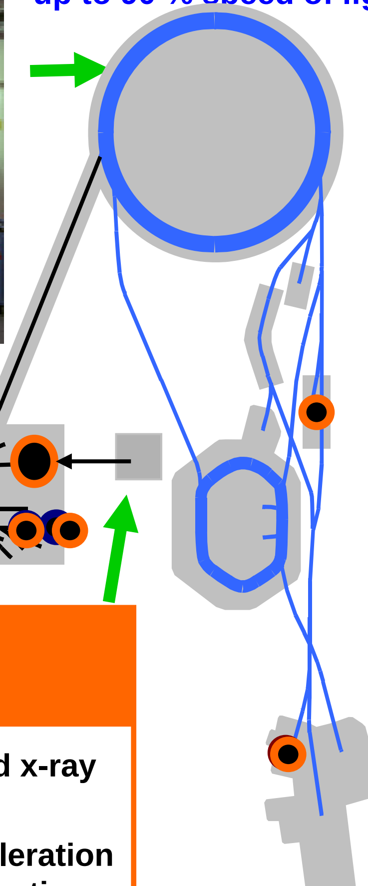


High Intensity / High Energy Laser at GSI
The PW Class Laser Facility PHELIX



laser heated plasma target

heavy-ion synchrotron SIS



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

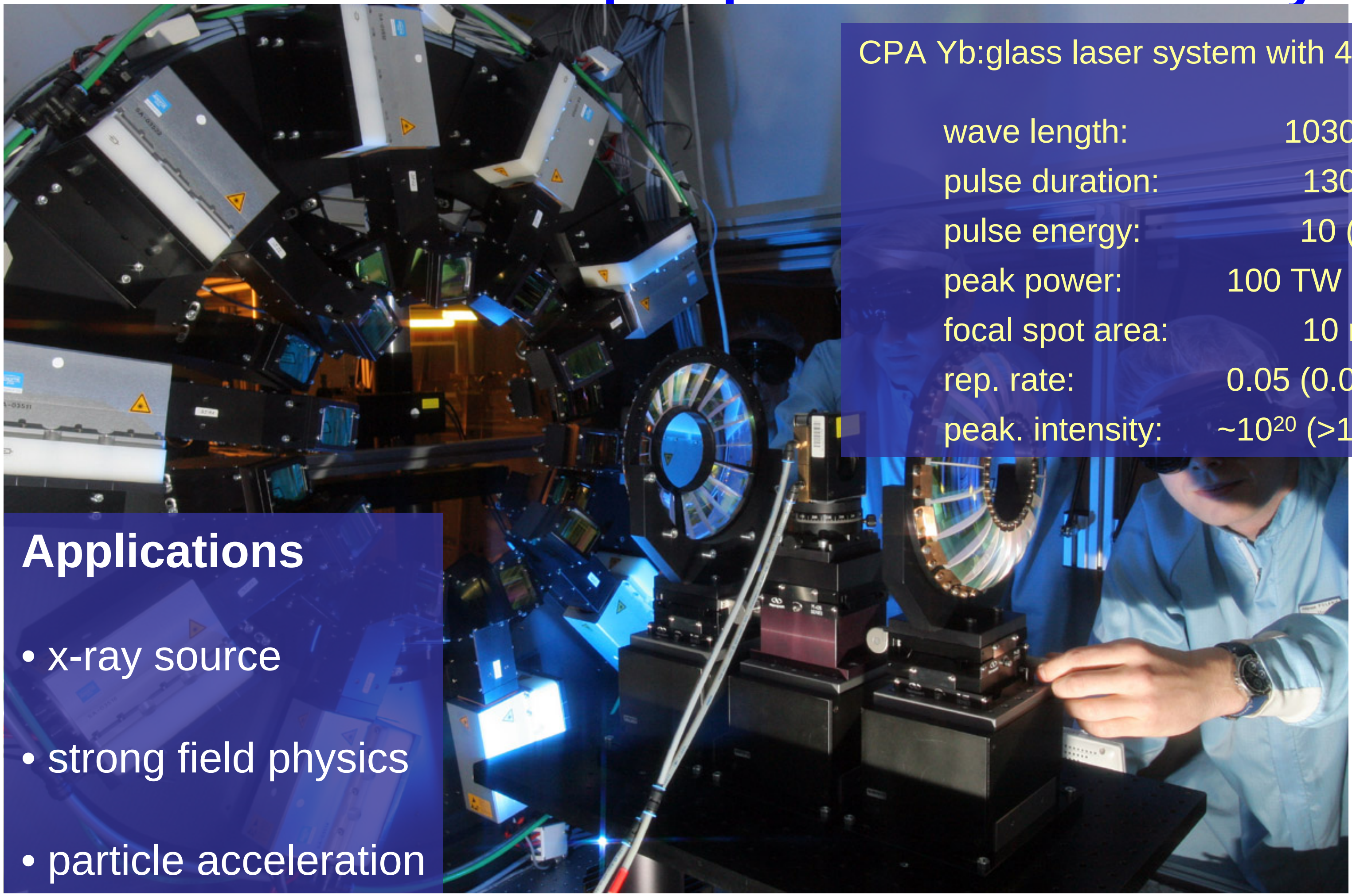
50 J @ 0.5 – 2 ps (100 TW)

2008: 300 J @ ~ns

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

High-Power Laser System in Jena

POLARIS – an all-diode pumped PW-class laser system



CPA Yb:glass laser system with 4 (5) amplifiers

wave length:	1030 nm
pulse duration:	130 fs
pulse energy:	10 (100) J
peak power:	100 TW (1 PW)
focal spot area:	10 mm^2
rep. rate:	0.05 (0.01) Hz
peak. intensity:	~10^{20} (>10^{22}) W/cm^2

Applications

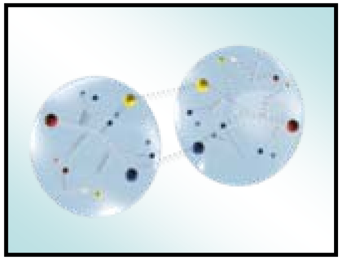
- x-ray source
- strong field physics
- particle acceleration

HIC for FAIR

Helmholtz International Center

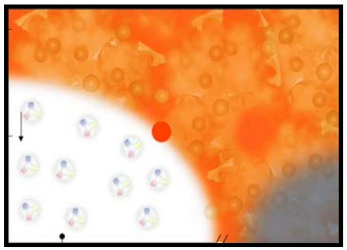
The first three years, the next three years and beyond

Helmholtz International Center



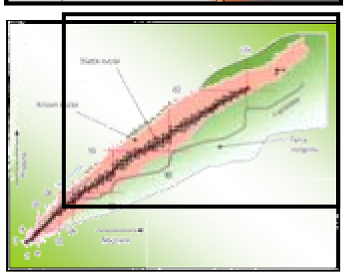
Hadron Structure and Dynamics:
COSY, SIS, FAIR
+ Theory

PANDA



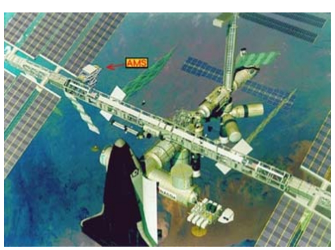
Nuclear and Quark Matter:
SIS, CERN, RHIC,
NICA, FAIR
+ Theory

CBM



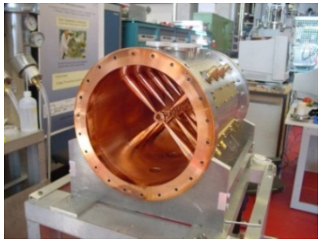
Exotic Nuclei and
Nuclear Astrophysics:
UNILAC, SIS, FAIR
+ Theory

NUSTAR



From Fundamentals to
Applications:
UNILAC, PHELIX, ESR,
SIS, FAIR
+ Theory

APPA



FAIR high-tech foundations:
Accelerator Development
High Performance Computing

HED-experiments at SIS-100

Up to **200 times** the beam power and **100 times** higher energy density in the target will be available at FAIR

Ion beam	SIS-18(U^{73+})	SIS-100 (U^{28+})	
Energy/ion	400 MeV/u	up to 1GeV/u	
Number of ions	4.10^{9} ions	5.10^{11} ions	x100
Full energy	0.06 kJ	6-15 kJ	
Beam duration	130 ns	50 ns	
Beam power	0.5 GW	0.1-0.3 TW	x 200-600

Research Program at GSI Directed Towards FAIR
Example: Atomic Physics

Strong Field QED / Fundamental Constants

• Precision x-ray Spectroscopy on Cooled Heavy Ions: **1S Lamb Shift**

• Laser Spectroscopy of the **Hyperfine Structure of High-Z ions** Confined in Storage Rings and Traps

• Trapped Single H-like Ions: **The Bound State g-Factor**

• Towards **Super-Critical Fields**

• Towards **Parity Violation in High-Z Ions**

At the Borderline to Nuclear Physics

• **Atomic Structure and Nuclear Decay Modes**

Novel Instrumentation and Installations for Atomic Physics

new internal target (micro-cluster target), new target chamber (impact parameter), micro-calorimeter detectors, diamond detectors, electron spectrometer, transverse electron target

HED-experiments at SIS-100

Up to **200 times** the beam power and **100 times** higher energy density in the target will be available at FAIR

Ion beam	SIS-18(U^{73+})	SIS-100 (U^{28+})	
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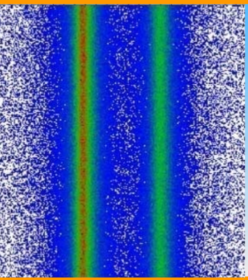
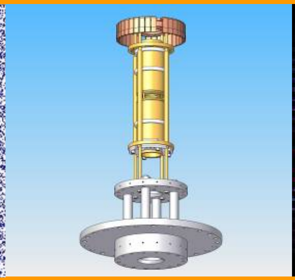
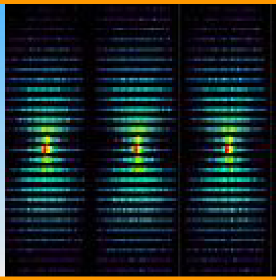
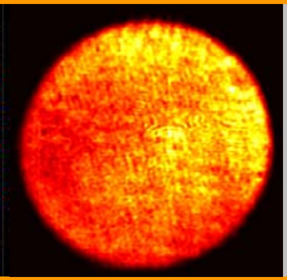
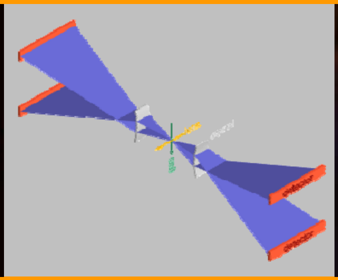
Beam power	0.5 GW	0.1-0.3 TW	x 200-600

Lead Target

Specific energy	1 kJ/g	100 kJ/g	X 100
Specific power	5 GW/g	1 TW/g	X 200
WDM temperature	~ 1 eV	10-20 eV	

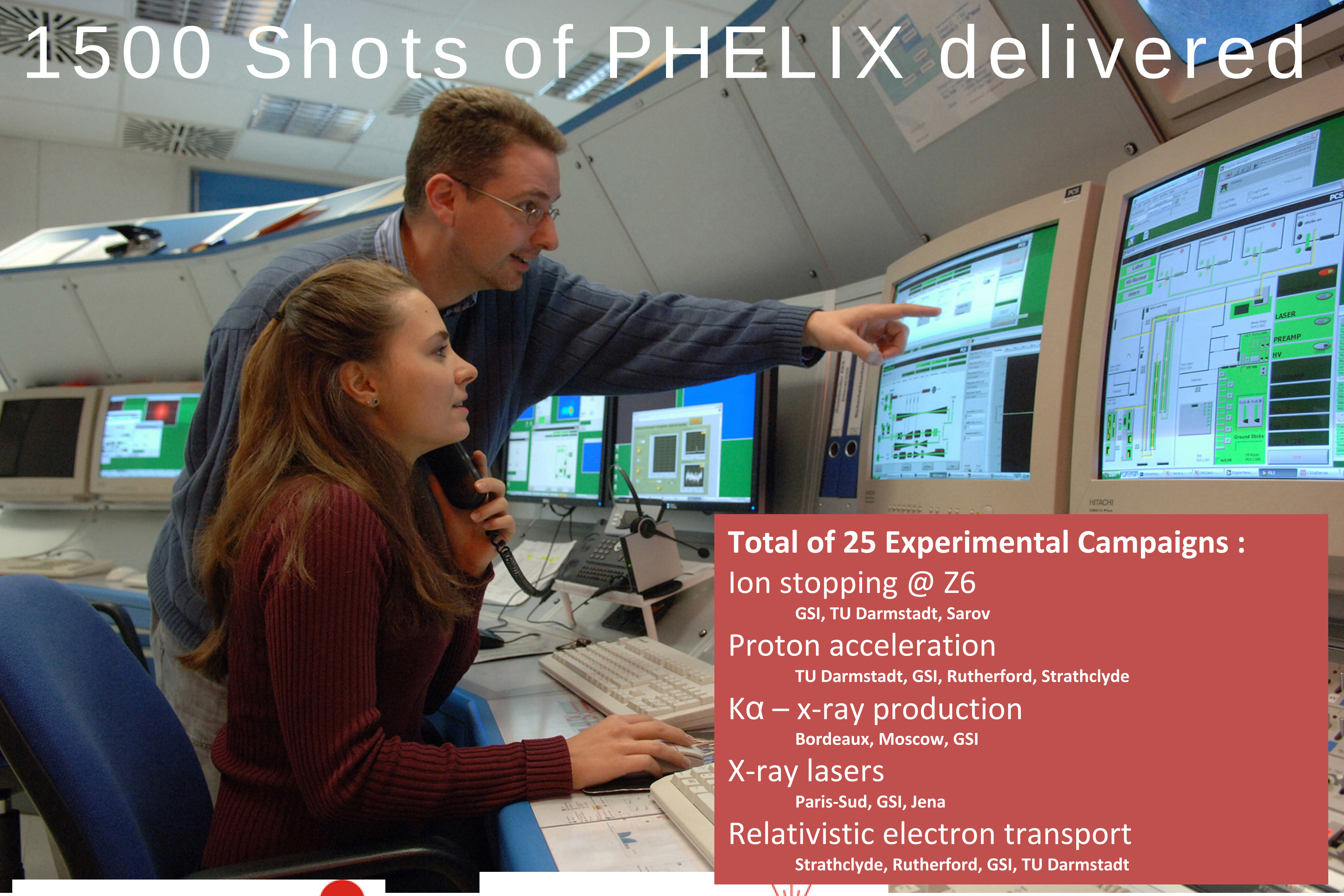

Atomic and Plasma Physics, and Applied Sciences APPA@FAIR

From Basic Science to Applications

Thomas Stöhlker

GSI-Darmstadt and Helmholtz Institute Jena

1500 Shots of PHELIX delivered



Total of 25 Experimental Campaigns :

Ion stopping @ Z6
GSI, TU Darmstadt, Sarov

Proton acceleration
TU Darmstadt, GSI, Rutherford, Strathclyde

Kα – x-ray production
Bordeaux, Moscow, GSI

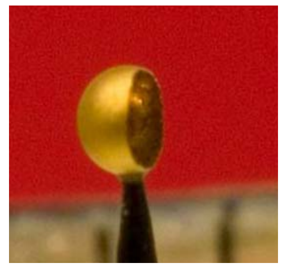
X-ray lasers
Paris-Sud, GSI, Jena

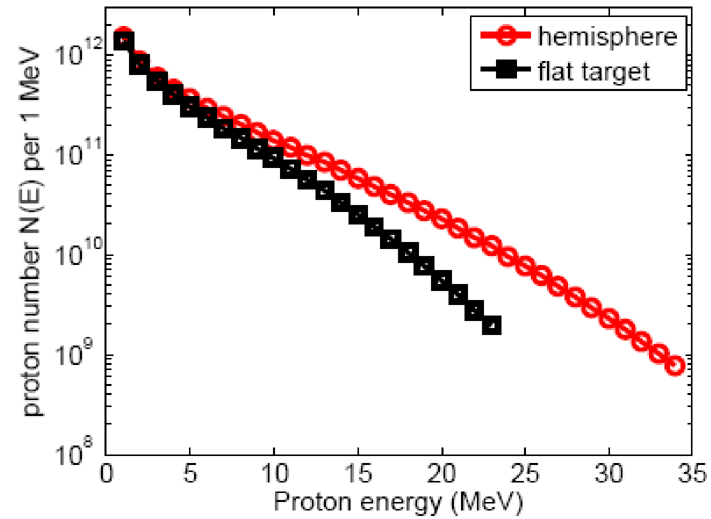
Relativistic electron transport
Strathclyde, Rutherford, GSI, TU Darmstadt

GSI PHELIX Laserlab Europe

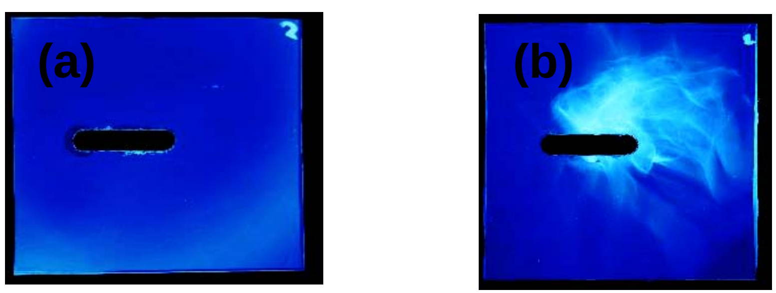
Significant results were obtained in particle acceleration

- **An enhancement of the proton energy when hemispherical targets are used was shown**
  - **Targets developed by TU Darmstadt were shot at PHELIX yielding an increase in proton energy compared to flat foils**

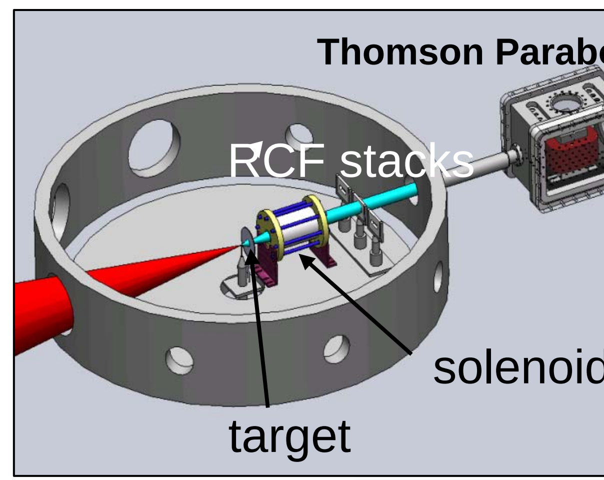




- **GSI has started a program to couple laser-accelerated ions into conventional structures**



Radio-chromic films recording the proton beam when the solenoid is energized (b) and not (a)



Plasma Physics @ GSI



The Plasma Physics Facilities @ GSI

Current Developments

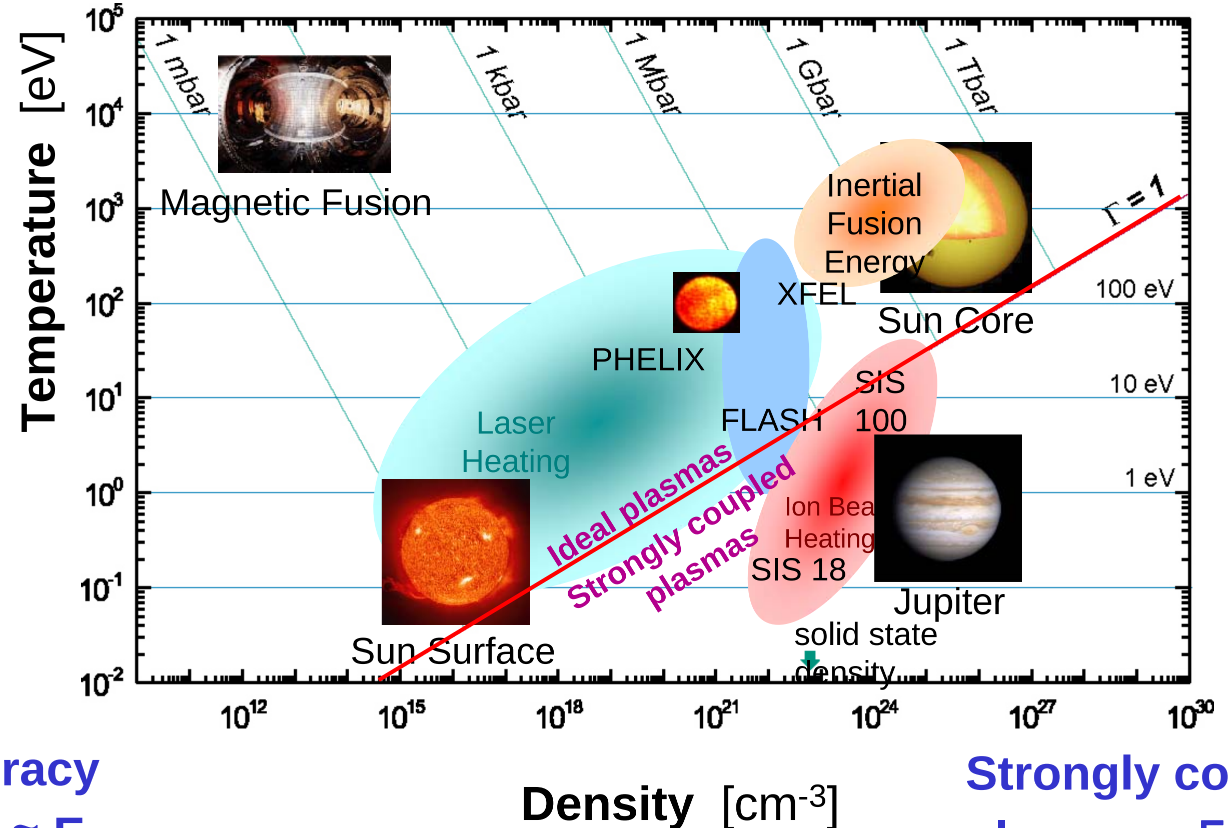
- EMMI, HIC4FAIR, HI-Jena, Helmholtz

FAIR

Plasma Physics with Intense Ion Beams

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

Measurements are required for guidance of theoretical models



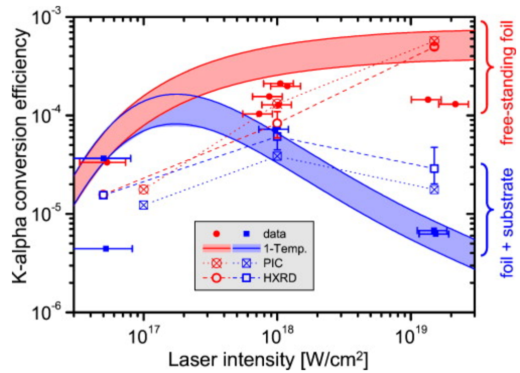
Degeneracy

$E_{KIN}=kT \approx E_{Fermi}$

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

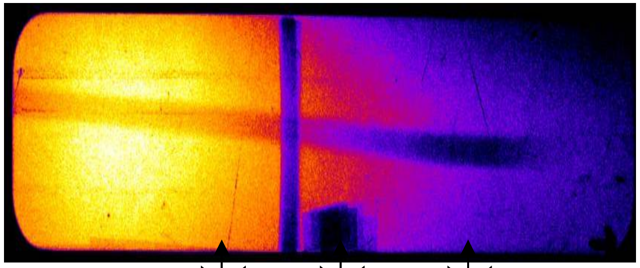
Electron Transport in a Solid Target

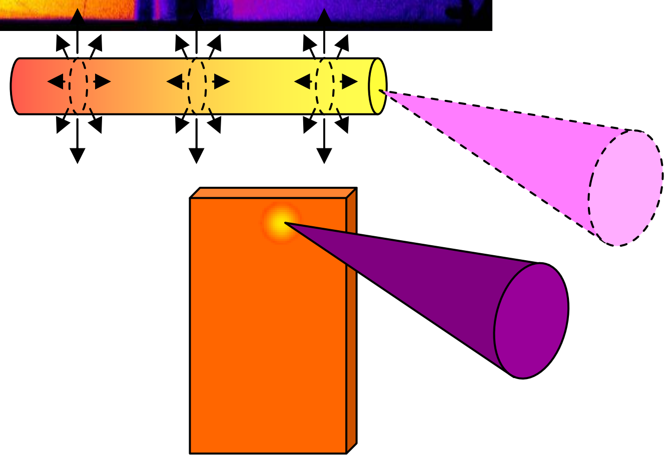
Code development “PEPC”
Scalable to300k cores of
IBM Blue Gene/P
A. Karmakar, M. Winkel,
L. Arnold, P. Gibbon



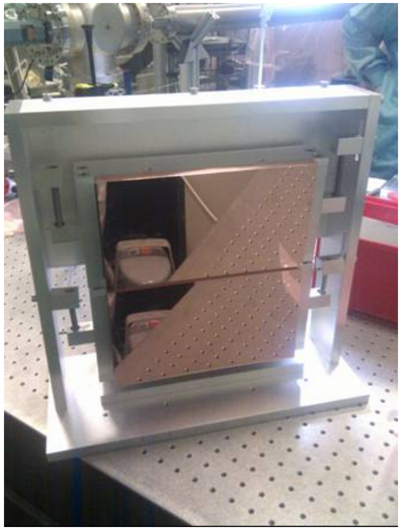
Role of refluxing electrons in the production of K-alpha radiation

Paul Neumayer et al.

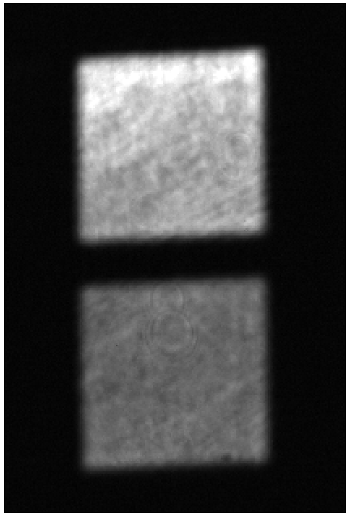




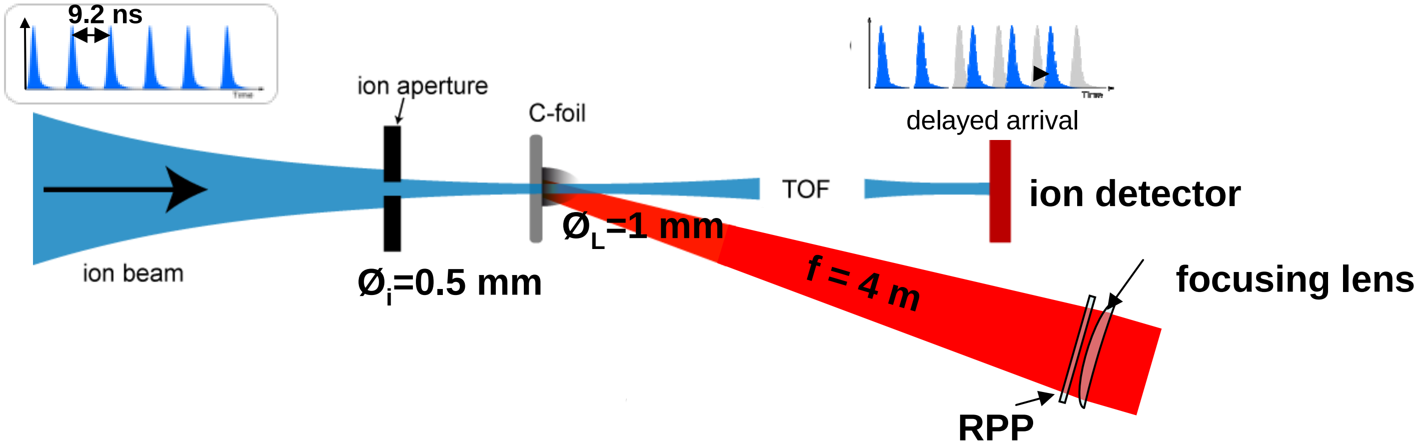
Picosecond resolution copper Ka diagnostic



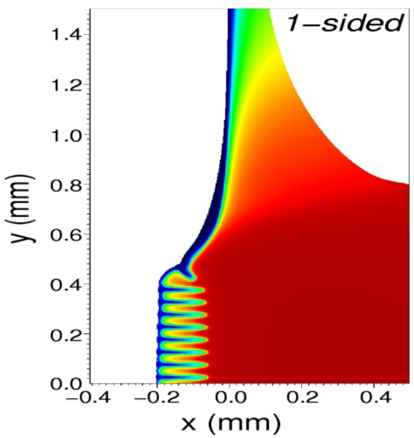
80 µm Ti wire,
Resolution: 20 µm
(longitudinal ~ 60 µm)



Ion Interaction with Laser Generated Plasma Targets



Code development RALEF-2D (***R**adiative* ***A**rbitrary* ***L**agrangian-**E**ulerian* ***F**luid dynamics*)
Hydrodynamics from WDM to radiation-dominated plasmas



Ionization of laser heated foils

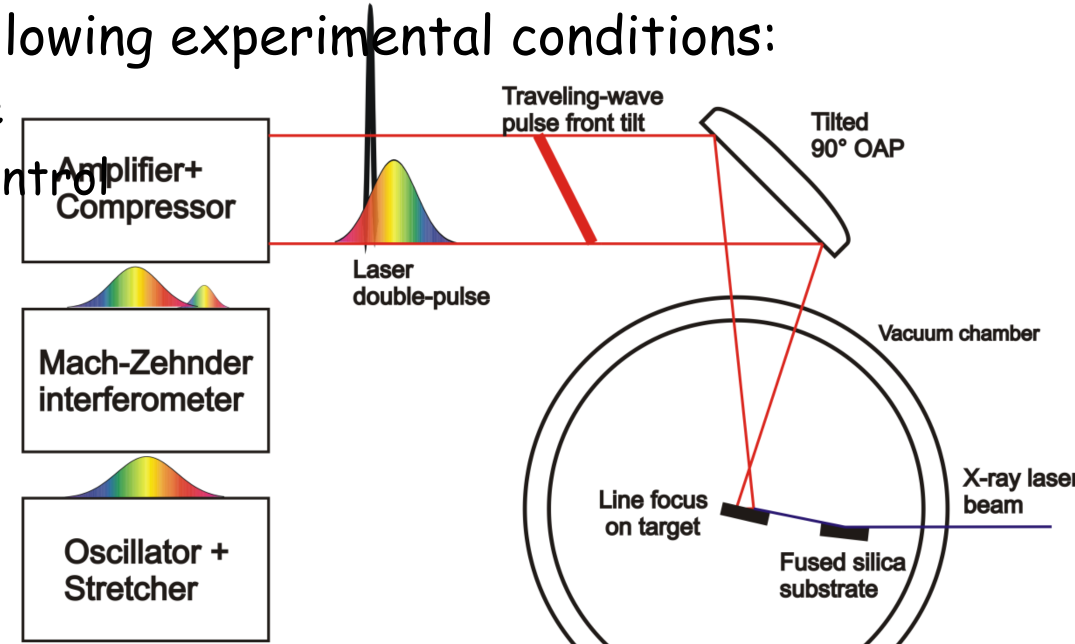
M. Basko, J. Maruhn, A. Tauschwitz

2ω option for Z6 was implemented in order to reduce target instabilities
New results by A. Frank et al. show expected improvement

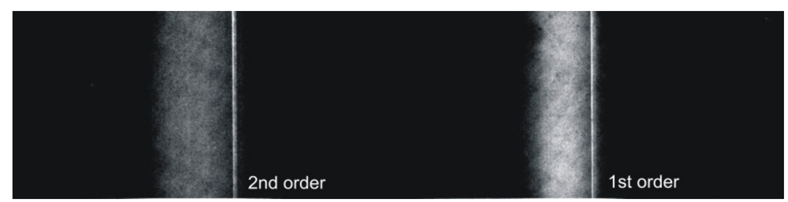
Theoretical Input From EMMI Decisive For Success !

GSI demonstrated an improved scheme for short-wavelength x-ray laser

- The setup answers the following experimental conditions:
  - High Energy Double Pulse
  - Exact Traveling-Wave Control



- **The results are:**
  - **A simplification of the setup**
  - **A decrease in the energy necessary to reach lasing threshold: 36 J for Ni-like samarium x-ray laser at 7.36 nm**



Signature of Ni-like samarium x-ray laser in the first and second order of a x-ray spectrometer

This brings short-wavelength x-ray laser within reach of high repetition rate systems

Th. Kühl