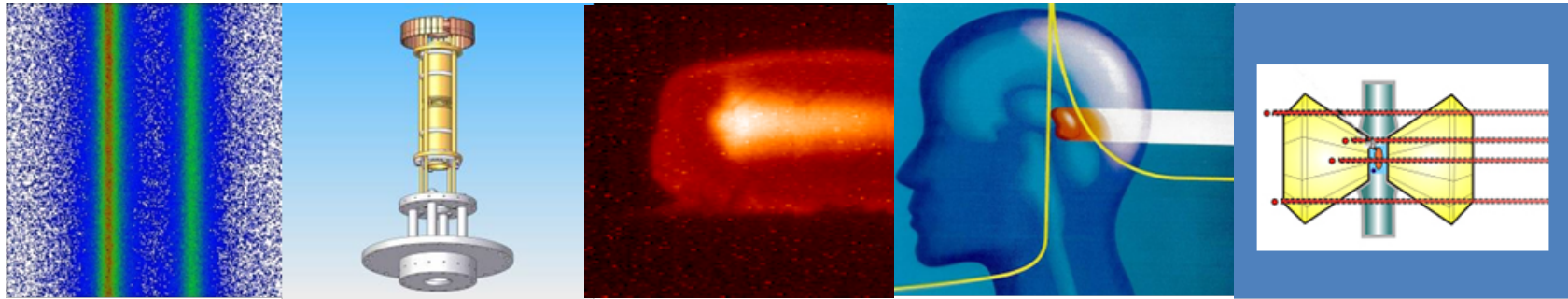


## *From Basic Science to Applications*



# FAIR

Thomas Stöhlker on behalf of the APPA-Collaborations  
*Helmholtz Institute Jena and Friedrich Schiller University, Jena*

# Atomic Physics, Plasma Physics, Bio Physics and Applied Sciences

**Research Focus: Matter under Extreme Conditions**

- **Highest Charge States**
- **Relativistic Energies**
- **High Intensities**
- **High Charge at Low Velocity**
- **Low-Energy Anti-Protons**

***Extreme Static Fields***

***Extreme Dynamical Fields and  
Ultrashort Pulses***

***Very High Energy Densities and  
Pressures***

***Large Energy Deposition***

***Antimatter Research***

# The APPA Collaborations at FAIR

## SPARC

SP: R. Schuch

- 302 scientists
- 83 institutions
- 26 countries

## APPA

- > 500 scientists
- > 90 institutions
- > 30 countries

## FLAIR

SP: K. Blaum

- 144 scientists
- 49 institutions
- 15 countries

## HEDgeHOB

SP: D. Varentsov

- 175 scientists
- 43 institutions
- 14 countries

## BIOMAT

SP: M. Durante  
C. Trautmann

- 110 scientists
- 28 institutions
- 12 countries

## WDM

SP: F. Rosmej

- 71 scientists
- 24 institutions
- 8 countries

# APPA Facilities at FAIR (Status 2009)

## Consequences of the MSV for APPA

No storage rings and traps at FAIR for experiments ☹️

No low-energy pbar ☹️

No proton radiography beam line ☹️

All APPA collaborations squeezed into a “Zero Budget” Cave ☹️

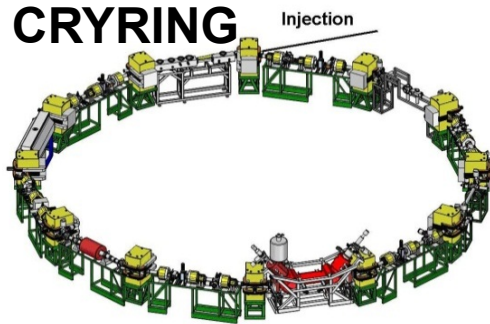
→ In 2009, most of the APPA work packets had to be redefined (in particular for Atomic Physics) ☹️



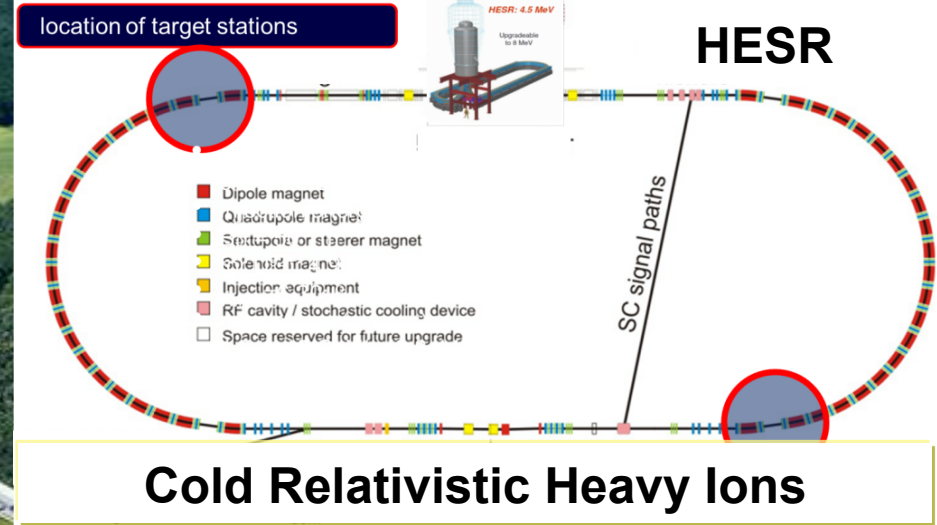
# MSV for APPA (Status 2012): The Facilities



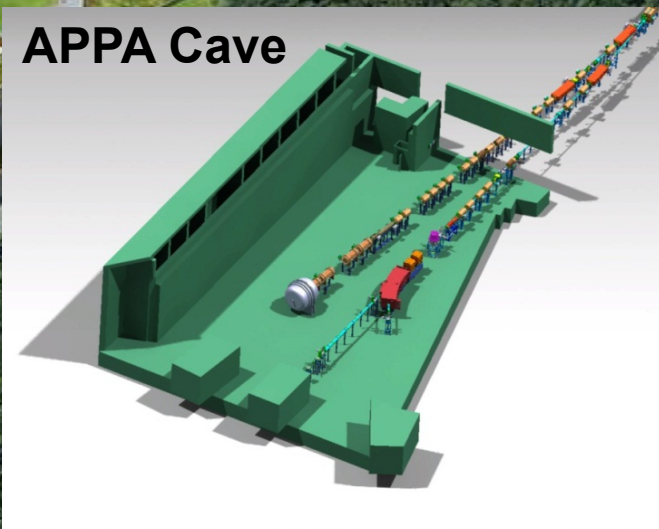
## CRYRING



**Cold Low-Energy Heavy Ions and Anti-Protons**



## APPA Cave



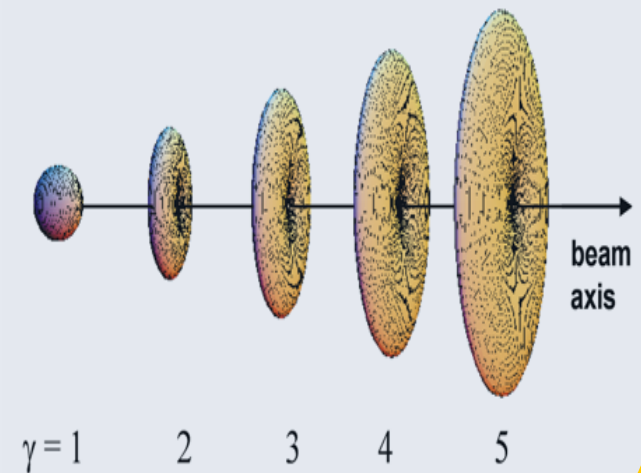
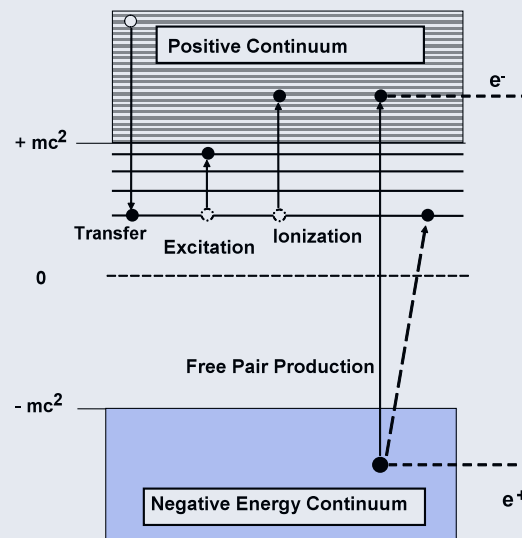
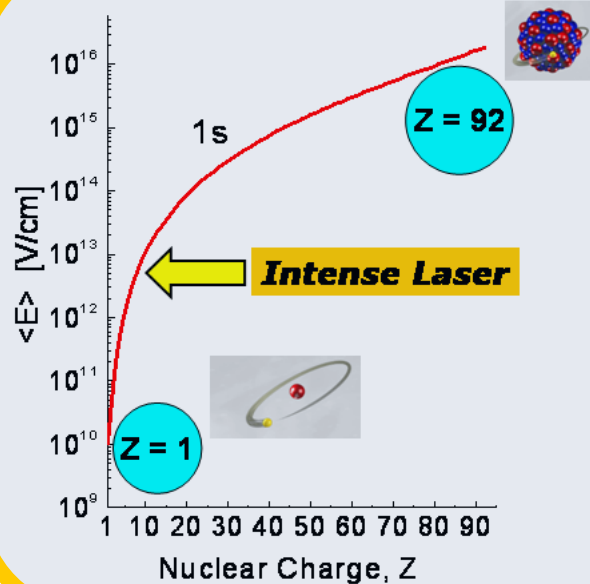
**Unique physics opportunities !!!** 😊

# Atomic & Fundamental Physics

*sparc*  
Stored Particles Atomic Physics Research Collaboration

FLAIR  
Facility for Low-energy Antiproton and Ion Research

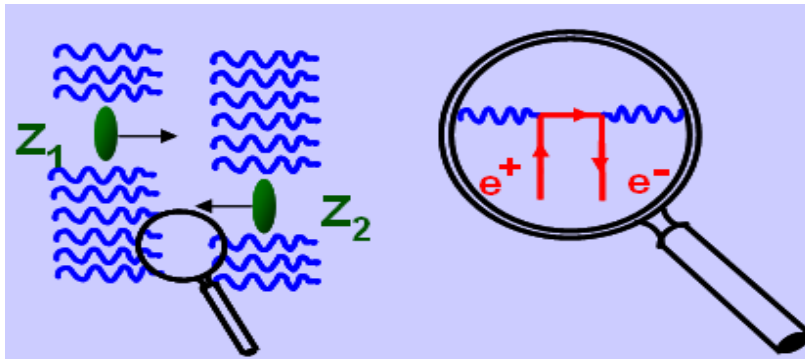
**QED in the non-perturbative regime**  
**Correlated multi-body dynamics for atoms and ions**  
**Precision determination of fundamental constants**  
**Influence of atomic structure on nuclear decay properties**  
**Fundamental physics and antimatter**



"Heisenbergs dream"  
shot out the nucleus,  
let electrons explode !

1

## World-wide unique for strong interaction with vacuum



- Multiple Pair Production
- Recombination with the Vacuum

$t \leq 0.1 \text{ as}$

Explore correlated electron dynamics

- sub-attosecond time-scale
- not accessible by other means

# Experimental Conditions at the HESR

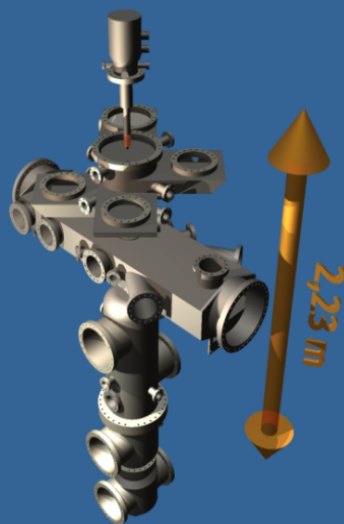
## location of target stations



**Worldwide premiere:  
Precision experiments using  
cooled relativistic ion beams**

- species: p, pbar, HCl, RIB
- circumference 574 m
- injection energy 740 MeV
- $B_p = 50 \text{ Tm}$
- for  $U^{92+}$ : 4.937 GeV/u
- $\gamma_{MAX}=6.30$ ;  $\beta_{MAX}=0.987$
- momentum (energy) range (0.8-14.4 GeV/c) / e-cool

- Stochastic cooling & electron cooling
- electron-, gasjet-, fiber-targets (!)
- Particle detectors
- Ion stacking
- Luminosity (number of stored ions)
- Beam diameter/charge separation
- Acceleration and deceleration
- Coupling of laser to the ion beam line
- Building / Space for setups



the  
SR



# Precision Experiments at High Energies (HESR)

## pair-production phenomena

- non-perturbation regime ( $\alpha Z_1 \approx \alpha Z_2 \approx 1$ )
- multiple pairs
- negative continuum dielectronic recombination

## radiative processes

- recombination (polarization phenomena etc.)
- photon-photon angular correlation

## target ionization

- correlated electron motion – exploring the ultrafast, extremely strong transient fields of relativistic ions

## electron impact phenomena

- electron impact excitation and ionization

## bound state QED and nuclear parameters

- laser excitation in Li-like ions ( $\Delta n = 0$ )

## laser Interaction at high $\gamma$

- test of special relativity
- laser cooling
- laser assisted pair creation

## fundamental physics

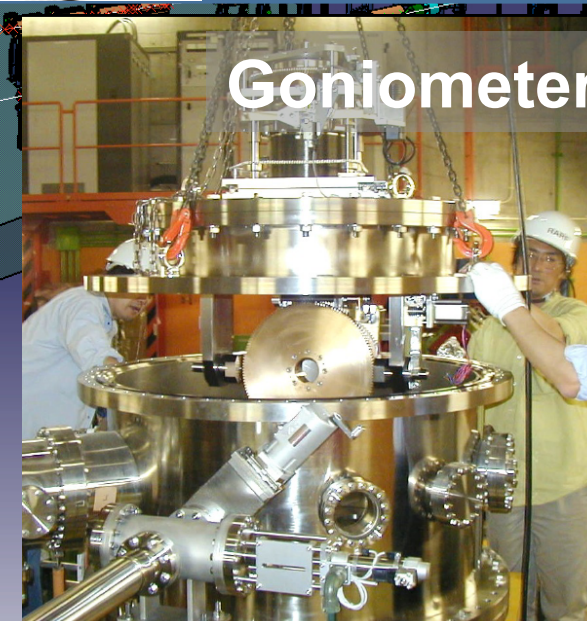
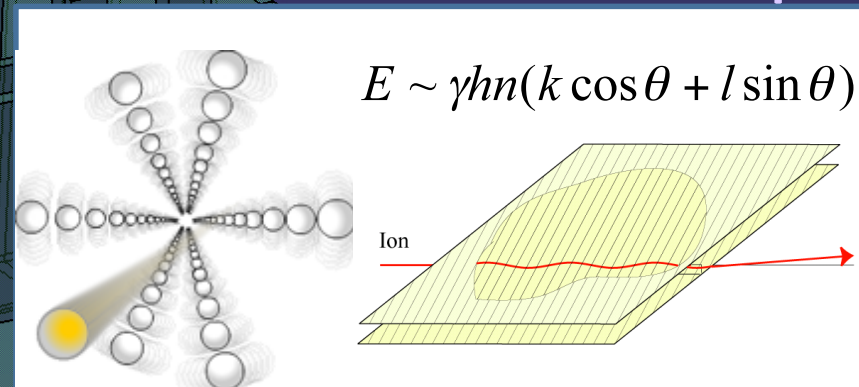
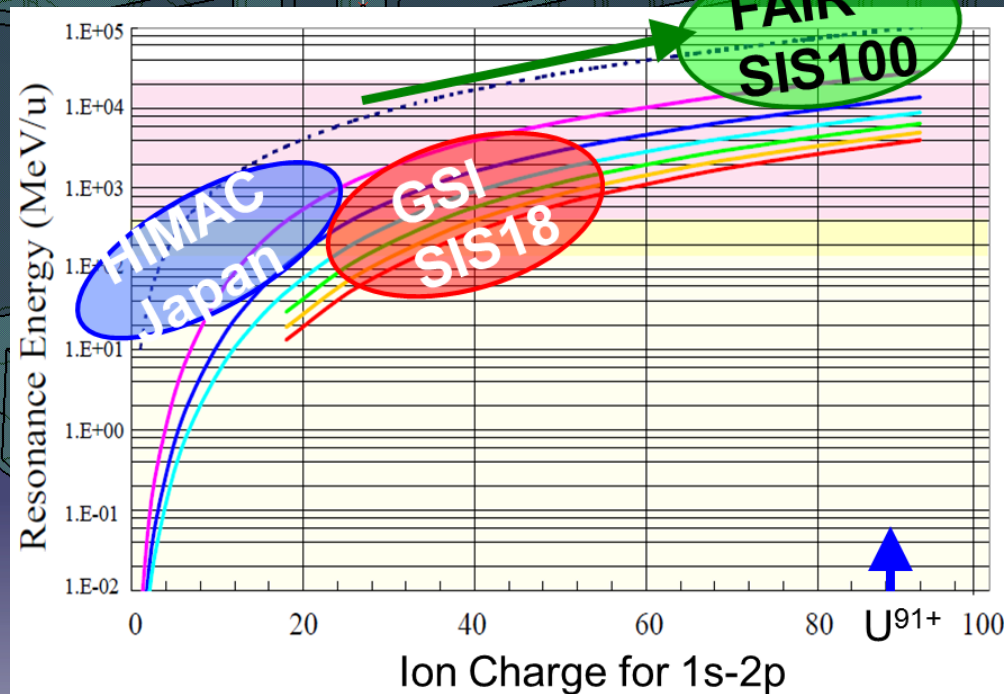
- PNC effects in high-Z ions



HESR

# Precision Experiments at High Energies (APPA Cave)

## Ion channeling at relativistic energies



Y. Yamazaki et al.

FAIR SIS100: excitation of 1s-2p in  $U^{91+}$  possible for first time

- **Spectroscopy for tests of QED**

- High-precision x-ray spectroscopy
  - 1s-Lamb-Shift
  - Two-Electron-QED
- Recoil ion momentum spectroscopy
  - Highly-excited states
- Laser spectroscopy
- Recombination spectroscopy with high resolution

- **Atomic collisions**

- Sub-femtosecond correlated dynamics
- Unexplored regime: strong perturbation  $Q/v$

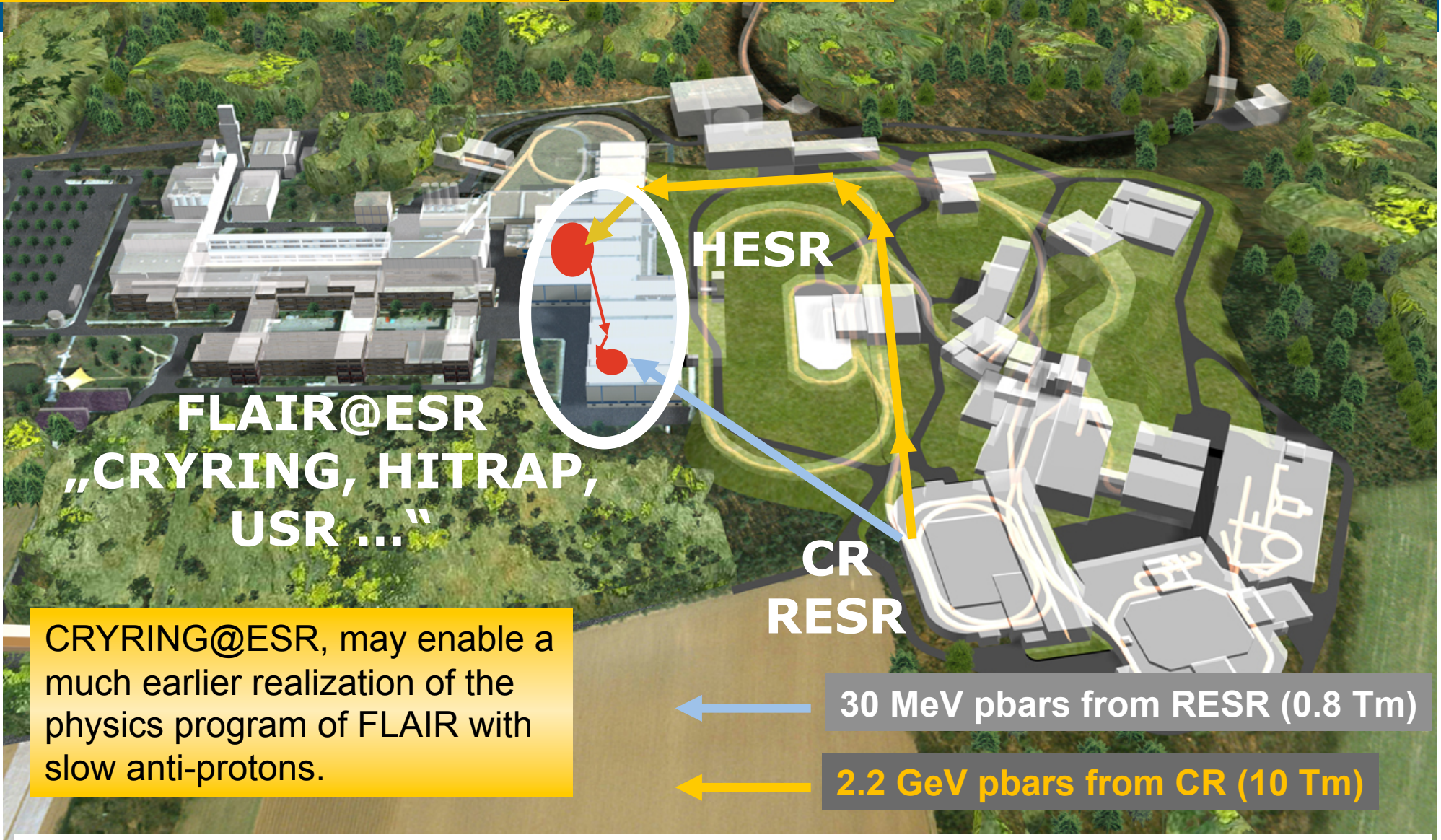
- **Nuclear Physics at low-energies**

- exotic nuclear decay modes
- astrophysical reactions

## ***Features@Cryring***

- Low-energy and electron cooled beams
- Electron cooling with adiabatic expansion
- High-luminosity for in-ring experiments
- Very fast deceleration 7 T/s
- Internal jet and electron target
- Slow extraction

# Modularized Start Version of FAIR and beyond

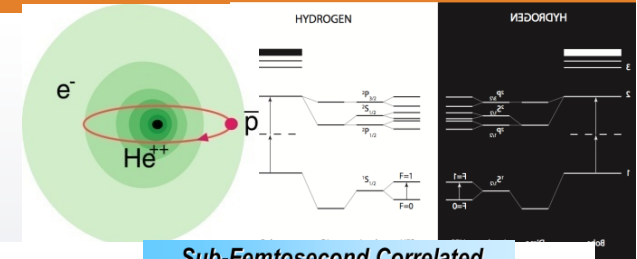


CRYRING@ESR, may enable a much earlier realization of the physics program of FLAIR with slow anti-protons.



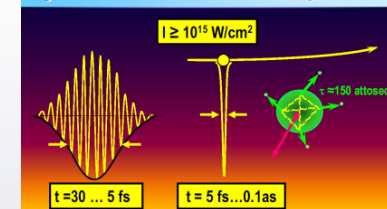
# Experiments with Low-E Pbars

- **Spectroscopy for tests of CPT and QED**
  - Antiprotonic atoms (pbar-He, pbar-p), antihydrogen

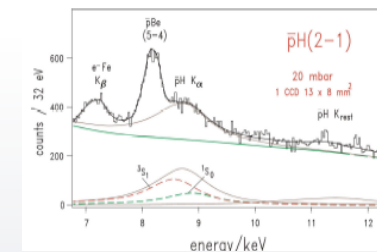


- **Atomic collisions**
  - Sub-femtosecond correlated dynamics: ionization, energy loss, antimatter-matter collisions

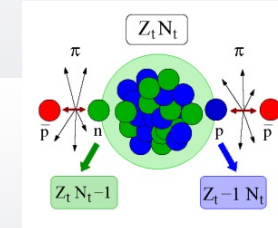
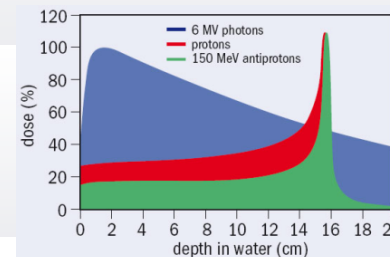
*Sub-Femtosecond Correlated Dynamics Probed with Antiprotons*



- **Antiprotons as hadronic probes**
  - X-rays of light antiprotonic atoms: low-energy QCD
  - X-rays of neutron-rich nuclei: nuclear structure (halo)
  - Antineutron interaction

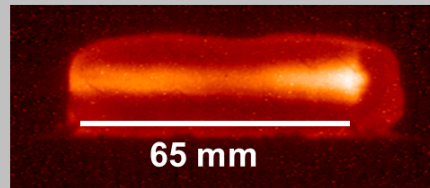


- **Medical applications: tumor therapy**



**FLAIR collaboration uses low-E antiprotons at CERN-AD to test decelerator schemes and to perform initial experiments of the FLAIR physics program**

# Plasma Physics at FAIR



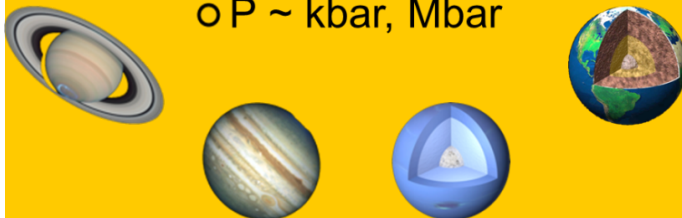
Ne<sup>10+</sup> 300 MeV/u; Kr crystal

WDM

**Interaction of ions and photons with plasmas**  
**Equation of state, phase transitions, transport phenomena**  
**Matter under high pressure**  
**Coupling of intense light with matter**

## Warm Dense Matter

- o  $T \sim 0.2 - 10 \text{ eV}$
- o  $\rho \sim \text{solid density}$
- o  $P \sim \text{kbar, Mbar}$



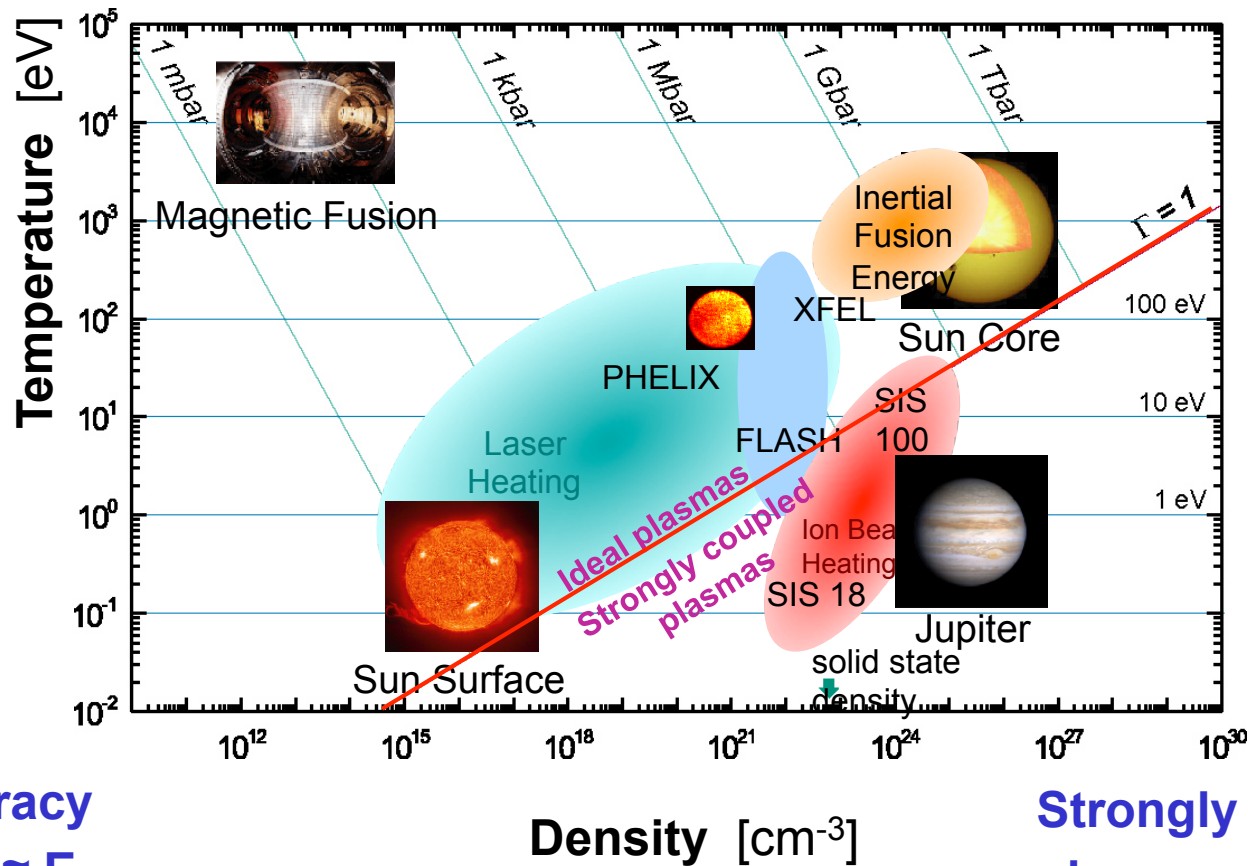
- o large volume of sample ( $\text{mm}^3$ )
- o fairly uniform physical conditions
- o high entropy @ high densities
- o high rep. rate and reproducibility
- o any target material

**Compared to GSI, FAIR will provide a specific intensity and energy deposition increase by a factor of 100 !**

# Plasma Physics with Intense Ion Beams

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

Measurements are required for guidance of theoretical models



Degeneracy

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

Strongly coupled

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

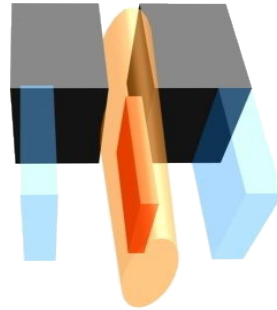
# HEdgeHOB experiments



## HIHEX

Heavy Ion Heating and Expansion

$U^{28+}$ , 2 GeV,  $5 \cdot 10^{11}$ , SC  
FFS



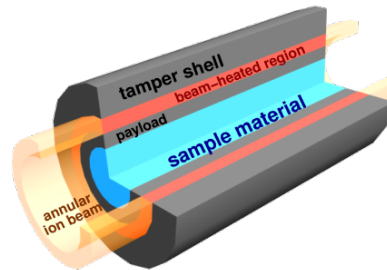
uniform quasi-isochoric heating of a large-volume dense target and isentropic expansion

numerous high-entropy HED states:  
EOS and transport properties of non-ideal plasmas / WDM for various materials

## LAPLAS

Laboratory Planetary Sciences

$U^{28+}$ , 1 GeV,  $5 \cdot 10^{11}$ ,  
Wobbler



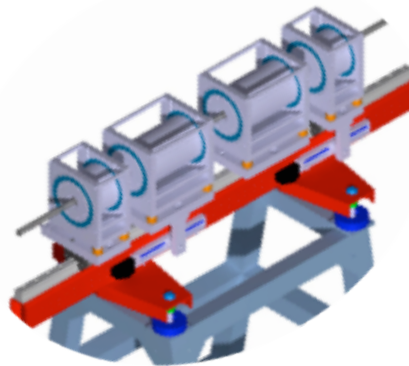
ring-shaped beam implodes a heavy tamper shell, low-entropy shell compression of hydrogen

Mbar pressures @ moderate temperatures:  
hydrogen metallization, interior of Jupiter, Saturn or Earth

## PRIOR

Proton Microscope for FAIR

p, 5–10 GeV,  $2 \cdot 10^{12}$ , PRIOR



worldwide unique high-energy proton microscopy setup with SIS-100 proton beam

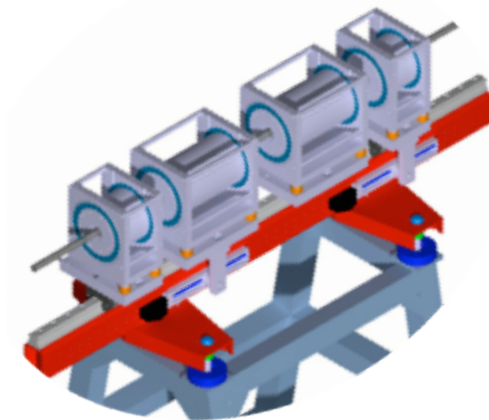
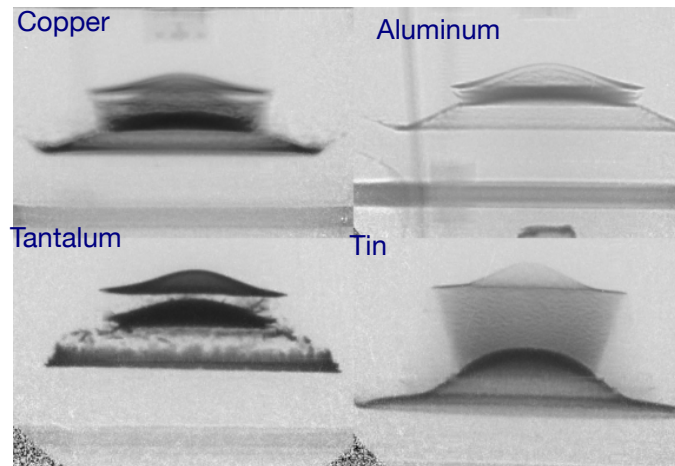
dynamic HEDP experiments and PaNTERA, jointly with BIOMAT collaboration:  
unparalleled density distribution measurements and Proton Therapy and Radiography (PaNTERA) project



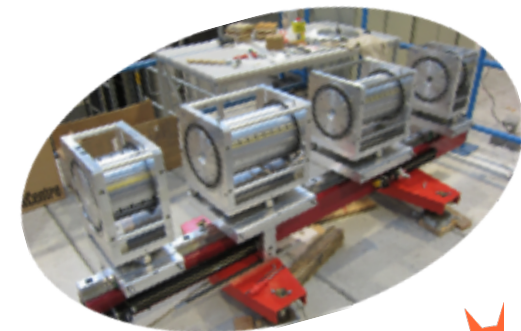
# PRIOR – Proton Microscope for FAIR

## Pump-Probe: Ion and Proton beams

- the worldwide unique high energy proton microscopy facility PRIOR (10  $\mu\text{m}$  / 10 ns resolution, sub-percent density reconstruction) will be integrated into the HEDgeHOB beam line
- using high-energy (5 – 10 GeV), high intensity ( $5 \cdot 10^{12}$ ) SIS-100 proton beams



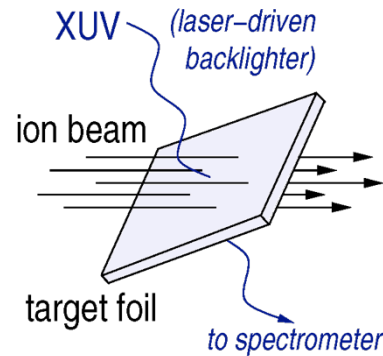
- joint multidisciplinary research of HEDgeHOB and BIOMAT during FAIR MSV:
  - materials at extreme dynamic environments generated by external drivers (plasma physics and materials research)
  - PaNTERA (Proton therapy and radiography) project (biophysics)
- PRIOR setup beam time commissioning at GSI: 2013/2014



# WDM: Investigation of Atomic and Thermophysical Properties in Dense Plasma Environments

## Opacity measurements at constant temperature

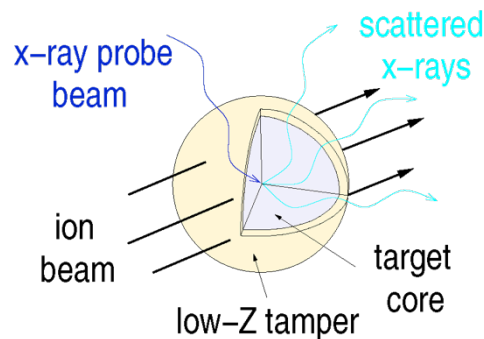
Isothermal expansion of thin foil targets



- **Opacities are very sensitive to electronic levels and population** (test of atomic physics in dense environments)
- **Benchmark for theoretical approaches** (existing models strongly diverging)

## Optical diagnostics at constant volume

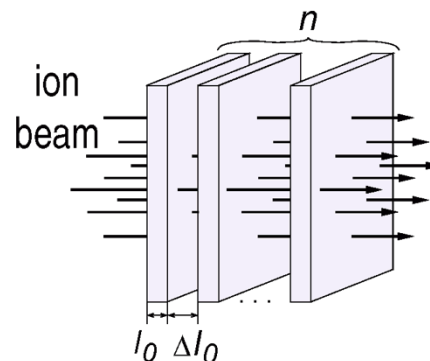
Dynamic confinement of low-Z targets



- **Investigation of WDM with emphasis on Optical properties** (atomic physics in dense environments)
- **Laser as key diagnostics tool** (XANES, X-ray scattering)

## EOS measurements at constant pressure

Quasi-static heating of stacked foil targets



- **Thermophysical properties along the two-phase boundary**
- **Quasistatic heating ensures homogeneous pressure, density and temperature**

# Helmholtz Beamline project (2016- 2019)

High intensity, high-energy lasers in the context of FAIR  
Pump-Probe: Ion and Laser beams

## Scope:

- Building a kilojoule high-repetition-rate laser

## Use:

- Advanced diagnostics for HED targets at the APPA cave (backlighting with X-rays, ions, neutrons, electrons)
- Relativistic laser-ion interactions in the nearby HESR hall



**Helmholtz-  
Beamline**

Initiative of the Helmholtz Center HZDR in close collaboration with HI-Jena. Already part of the Helmholtz roadmap for new research infrastructures.

## Biophysics



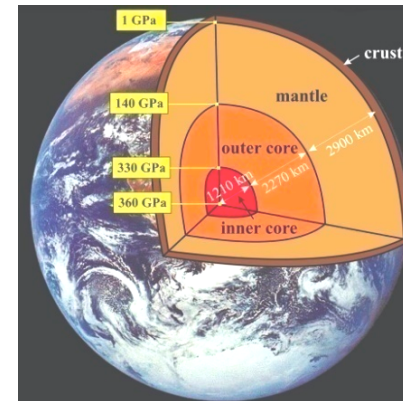
**Cosmic radiation: the main hindrance toward manned space exploration**

**Widely unknown biological effects of heavy ions**

**NASA and ESA started a large experimental campaign in space radiation biophysics**

**Particle Therapy**

## Materials Research



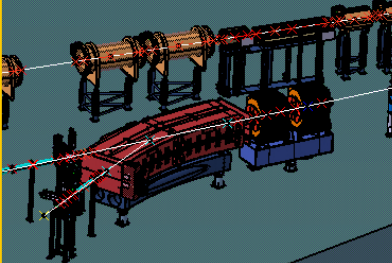
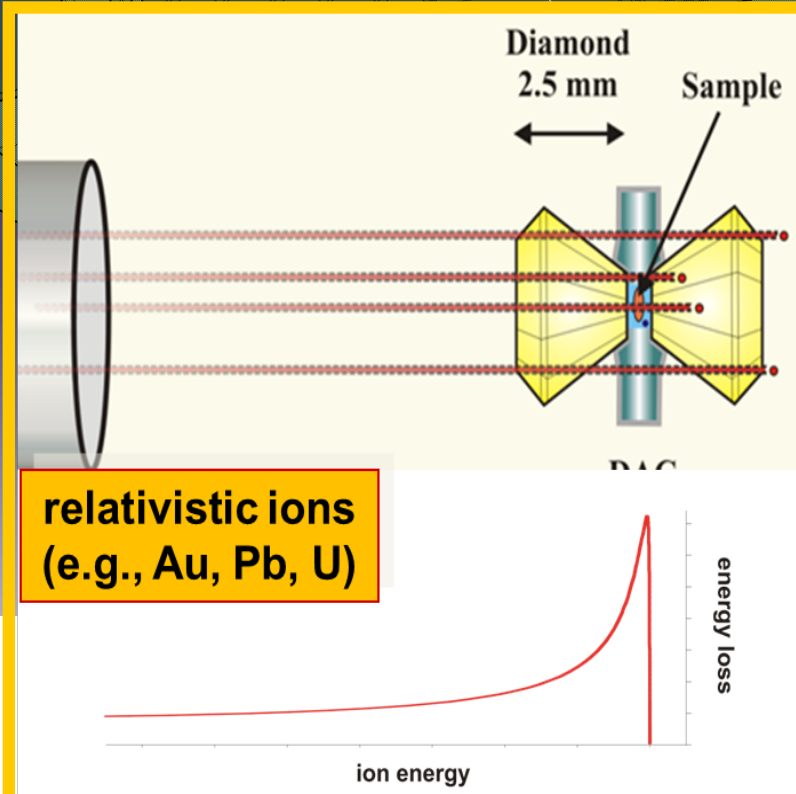
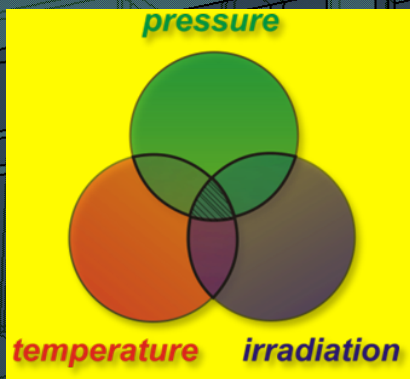
**Exposure of matter to relativistic ions and high pressure: phase transitions in mineralogy and geophysics**

**Ion-matter interaction at FAIR energies: energy-deposition and short-time processes at relativistic projectile velocities**

**Radiation hardness of materials: requirements for accelerator and spacecraft-components**

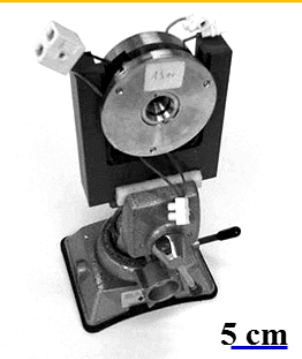
# Target station for irradiation under high pressure

**BIO\*MAT**  
Materials research

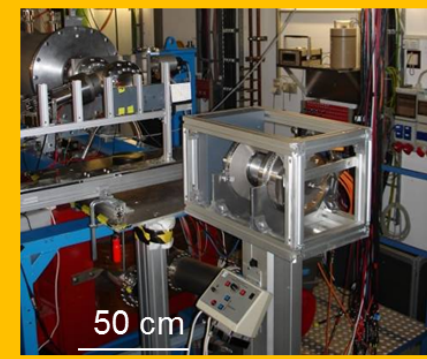


## FAIR

- larger sample volumes ( $\text{mm}^3$ )
- higher beam intensities
- temperature



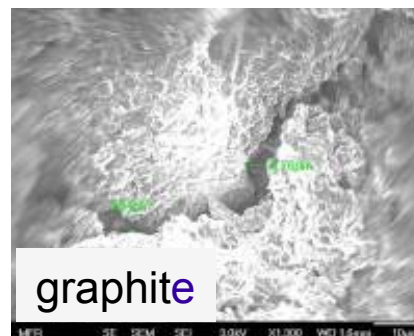
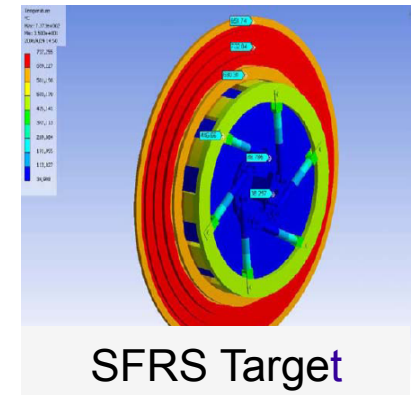
Merrill-Bassett type diamond anvil cell



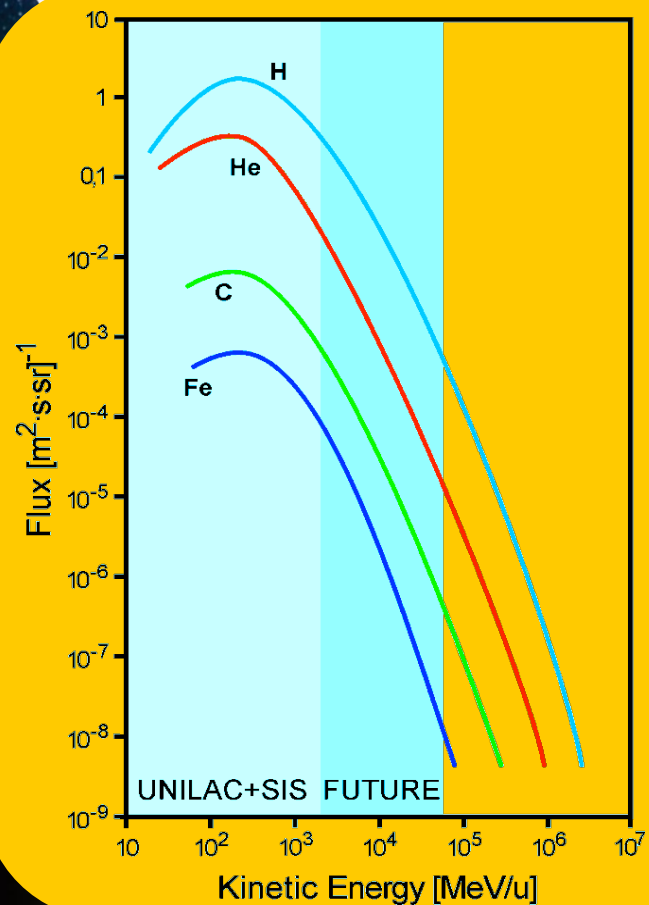
Paris-Edinburgh cell

## Radiation hardness of materials

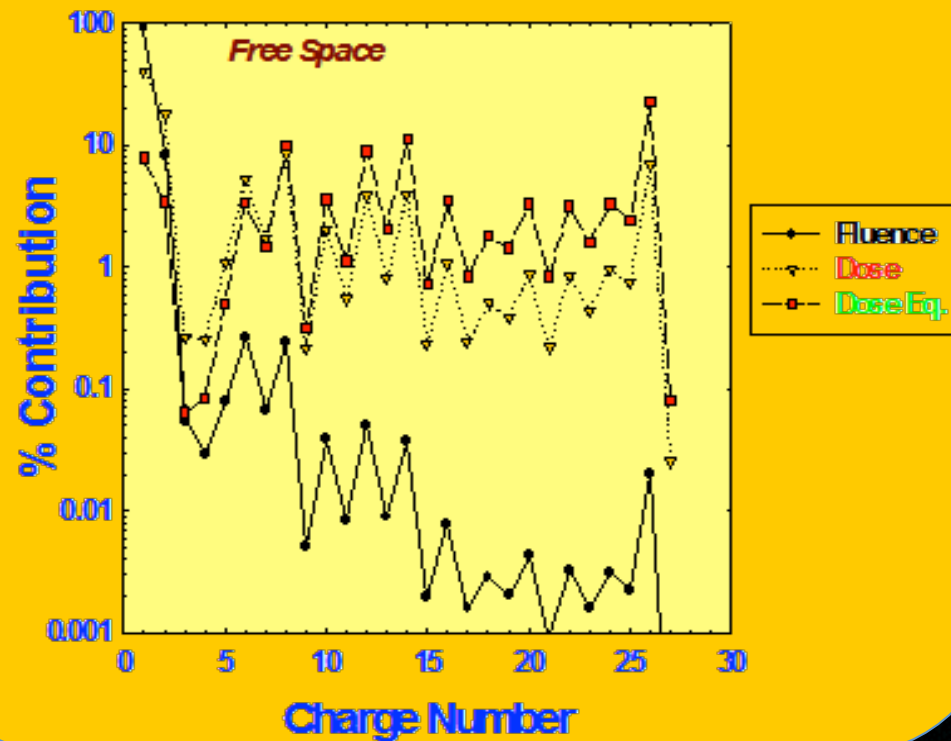
- mechanical and electrical degradation
- stripper foils
- target wheel for SFRS, beam dumps, collimator



# Relativistic Energies: Galactic Cosmic Radiation (GCR)

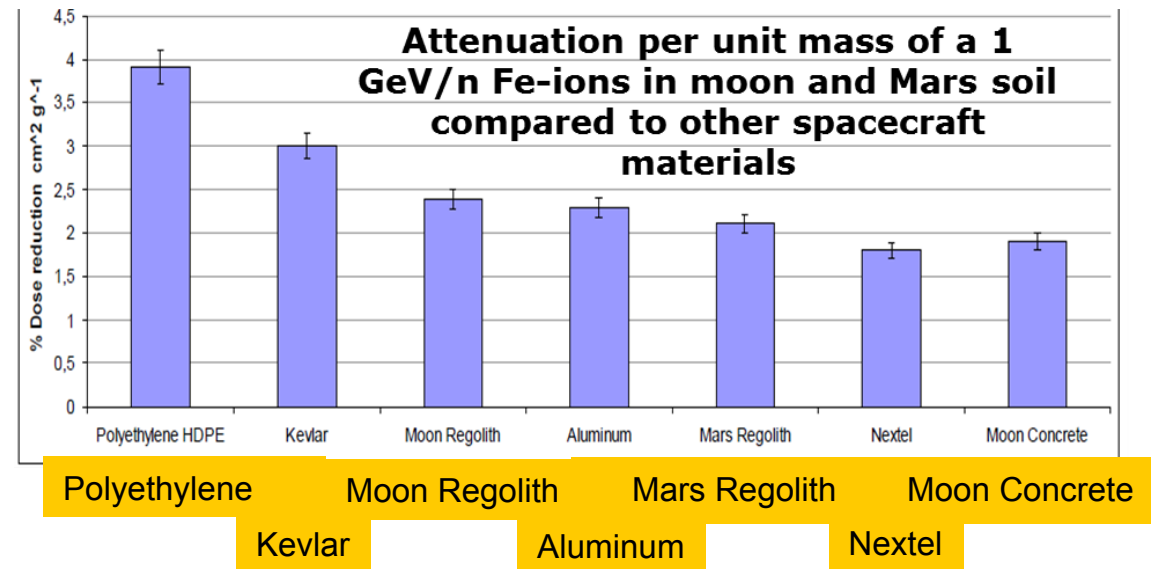


## GCR Charge Contributions



# Biophysics

- **Cosmic radiation** → main hindrance toward manned space exploration: moon (2015), Mars (2030), and beyond
- High uncertainty on **biological effects of heavy ions**
- No effective counter measures
- NASA started experimental campaign in **space radiation biophysics**
- ESA approved in 2008 a similar program (IBER) in the framework of Aurora, based at GSI/FAIR
- Example: shielding properties of the moon and Mars regolith

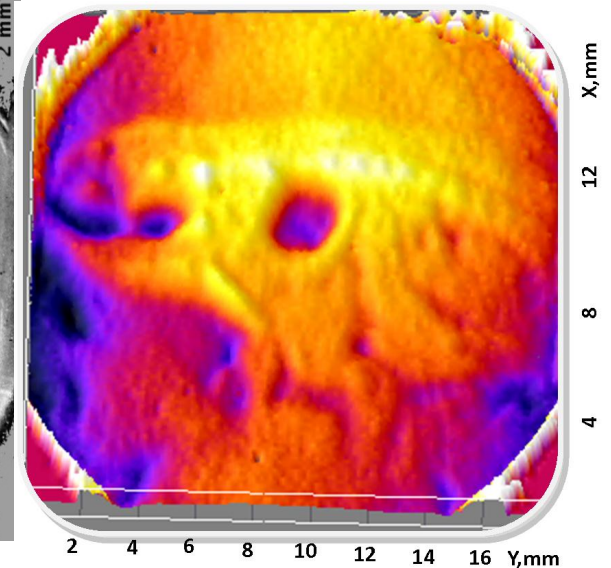
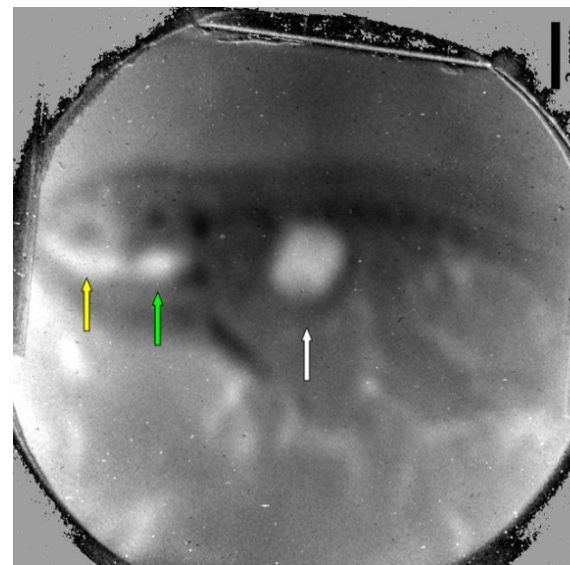
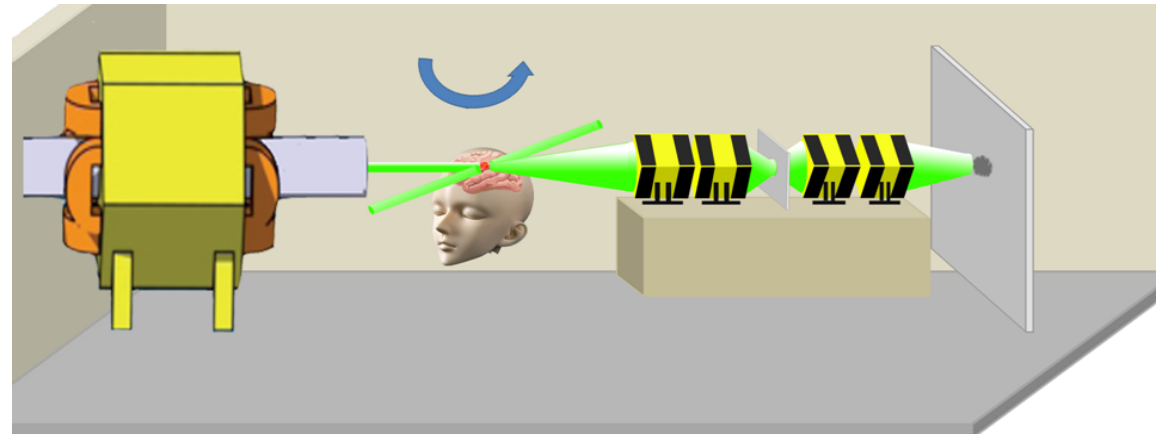


*Nextel is a semi-rigid material widely used in satellites and spacecrafts for its extraordinary shielding properties against micrometeorites.*



# Particle Therapy at FAIR

- New project (PANTERA) within APPA to exploit the PRIOR setup for therapy
- Relativistic protons (4.5 GeV) for image-guided, high-resolution, realtime, stereotactic radiosurgery (proton theranostics), (PRIOR setup)
- First image of a biological target (a zebrafish) with proton microscopy at ITEP (800 MeV protons)
- Investigating also to use high-energy antiprotons for theranostics (together with FLAIR)



# TDRs and Reports of the SPARC & FLAIR Collaborations

## LSR: Technical Design Report



## CRYRING@ESR: A study group report

CRYRING@ESR:  
A study group report

Michael Crotzky<sup>1</sup>, Norbert Angerer<sup>2</sup>, Ralf Heil<sup>3</sup>, Ralf Becker<sup>4</sup>, Matti Bevilacqua<sup>5</sup>, Udo Hoff<sup>6</sup>, Walter Beck<sup>7</sup>, Angela Weisinger-Davies<sup>8</sup>, Erikas Danneberg<sup>9</sup>, Oksana Dolnikova<sup>10</sup>, Wolfgang Enders<sup>11</sup>, Mats Engström<sup>12</sup>, Arhan Franke<sup>13</sup>, Bernhard Franke<sup>14</sup>, Georg Gruber<sup>15</sup>, Peter Hübner<sup>16</sup>, Andrea Kähler<sup>17</sup>, Oliver Kauer<sup>18</sup>, Carl Michael Kierdorf<sup>19</sup>, Yuri A. Litvinov<sup>20</sup>, Carmen Mähl<sup>21</sup>, Bernhard Müller<sup>22</sup>, Ina Pecher<sup>23</sup>, Roman Radon<sup>24</sup>, Hans Rauscher<sup>25</sup>, Hans-Joachim Spenner<sup>26</sup>, Dag Stenlund<sup>27</sup>, Gertina Stenlund<sup>28</sup>, Marcus Schneider<sup>29</sup>, Ansgar Simonow<sup>30</sup>, Jan Strohriegl<sup>31</sup>, Oskar Stoppacher<sup>32</sup>, Markus Stock<sup>33</sup>, Thomas Wehrli<sup>34</sup>, Wolfgang Witsorin<sup>35</sup>, and Hans Vetter<sup>36</sup>

<sup>1</sup>CEIT, Karlsruhe Institute of Technology, 76344 Karlsruhe, Germany  
<sup>2</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>3</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>4</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>5</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
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<sup>17</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
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<sup>19</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>20</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>21</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>22</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
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<sup>24</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>25</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>26</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>27</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>28</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>29</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>30</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>31</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>32</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>33</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>34</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>35</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany  
<sup>36</sup>Physikalisches Institut, Universität Würzburg, 97082 Würzburg, Germany

## Infrastructure Proposal

### Infrastructure Proposal

Installation of CRYRING at GSI/FAIR for atomic and nuclear physics experiments

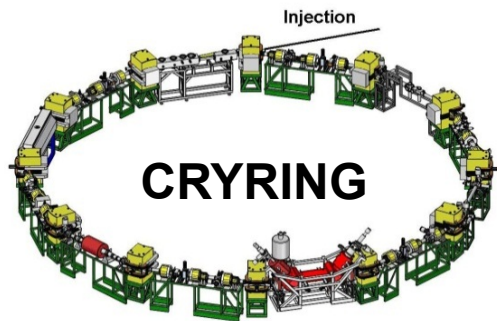
#### Executive summary

CRYRING is a Swedish storage ring for low-energy ions that has been financed by the Knut and Alice Wallenberg Foundation. It is proposed to couple CRYRING to an existing ring, ESR (Experimental Storage Ring), at the radioactive beam facility FRS (Fragment Separator) at the German GSI Helmholtzstrahlenzentrum. The infrastructure proposal is for the installation of CRYRING at GSI/FAIR, which currently under construction at the same site as ESR. This scenario provides access to a large number of stable and short-lived stored ion beams and a few limited samples. Such solutions are worldwide unique and offer excellent scientific opportunities for precision experiments in atomic, nuclear, and astrophysics extending the capabilities of an existing high-current injector.

#### Introduction

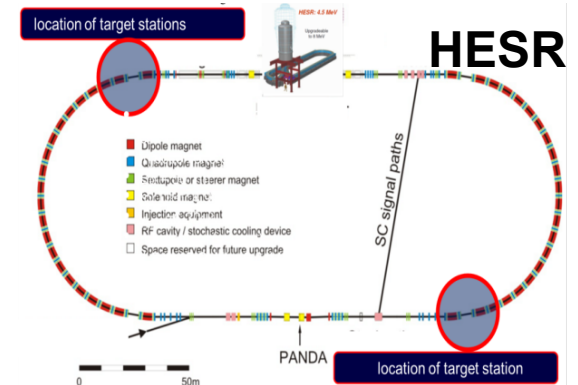
The main goal of this proposal is to merge the active beam facility FRS [1] of GSI/FAIR, ESR [2], and the Swedish storage ring YRING [3] into a combined facility. The Knut & Alice Wallenberg Foundation has funded, since 1985, the construction of CRYRING at Malmö Siegbahn Laboratory in Sweden. In following the general ideas and principles of ring rings are outlined below the advantages of operation of the current project are discussed in greater detail. The existing blocks of visible matter in the storage are atoms, consisting of negatively charged electrons, positively charged protons and neutral neutrons. The latter two form atomic nuclei. If electrons are present, the formation of

Atomic Masses 1993(1993) Appendix 1 (Infrastructure proposal) 1/10



## Physics book: CRYRING@ESR

## TDR: Internal target station



### FACILITY FOR ANTI-PROTON AND ION RESEARCH

#### Technical Design Report for Internal Target Station

for the SPARC Collaboration

N. Parada<sup>1</sup>, A. Kallini<sup>2</sup>, and B. E. Grunow<sup>3</sup>

<sup>1</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, Planckstr. 1, 42699 Darmstadt, Germany  
<sup>2</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, Planckstr. 1, 42699 Darmstadt, Germany  
<sup>3</sup> Karlsruhe Institute of Technology, 76344 Karlsruhe, Germany

SPARC Experiments at the HESR: A Feasibility Study

for the SPARC Collaboration

Thomas Ruch<sup>1</sup>, Ralf Heil<sup>2</sup>, Ralf Franke<sup>3</sup>, Yuri A. Litvinov<sup>4</sup>

<sup>1</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, 42699 Darmstadt, Germany  
<sup>2</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, 42699 Darmstadt, Germany  
<sup>3</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, 42699 Darmstadt, Germany  
<sup>4</sup> GSI Helmholtzstrahlenzentrum für Schwerionenforschung, 42699 Darmstadt, Germany

UPDATED on January 30, 2013

Abstract

The physics program of the SPARC collaboration at FAIR focuses on the study of collision phenomena in strong and weak interaction electromagnetic fields and on the fundamental interactions between electrons and heavy nuclei up to bare uranium. The current report documents the feasibility of the HESR storage ring operating with heavy ion beams with particular emphasis given to the requirements of the experimental program of the SPARC collaboration.

## SPARC experiments at HESR: A feasibility study

# HEDgeHOB TDRs in preparation

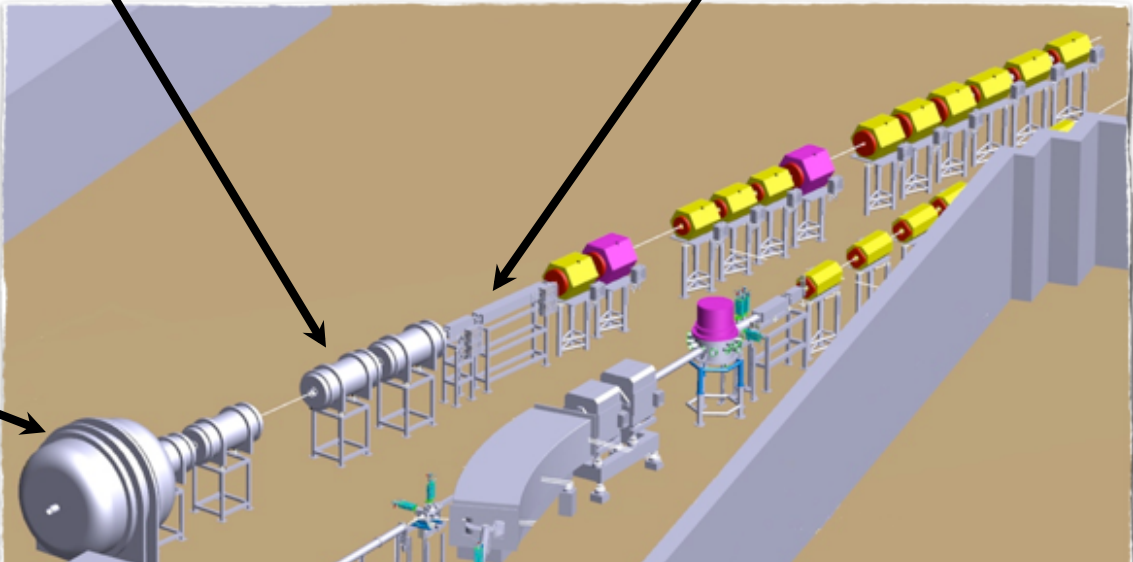
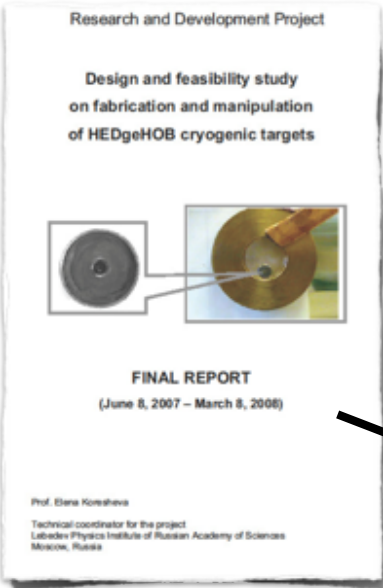


Super conducting quadrupoles for HIHEX FFS



RF beam rotator (wobbler) for LAPLAS

Cryogenic targets for LAPLAS



Many other TDRs are also in preparation by BIOMAT, FLAIR, and WDM !



# Worldwide Unique Research Opportunities ... & Challenges



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your  
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