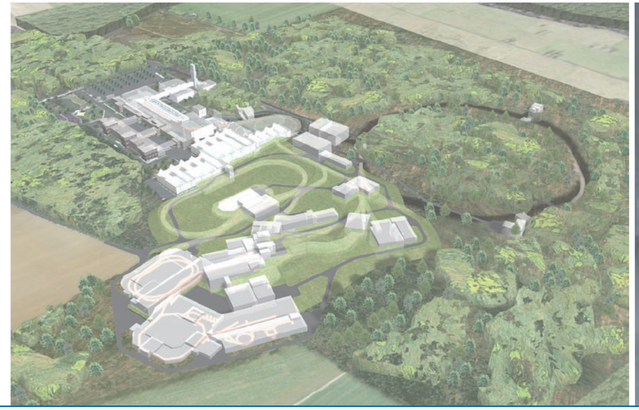
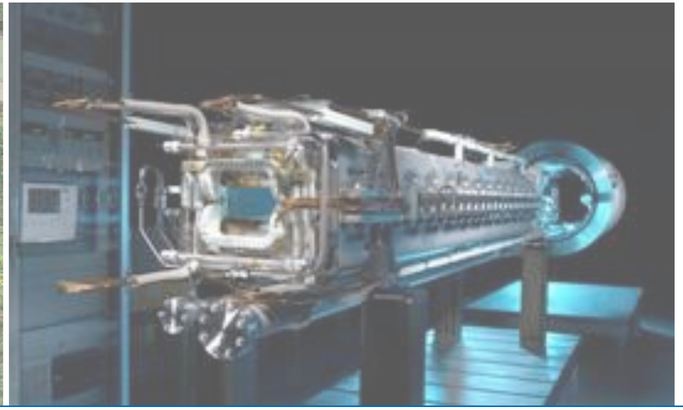




HED@FAIR Status Report

12th Meeting of the RRB

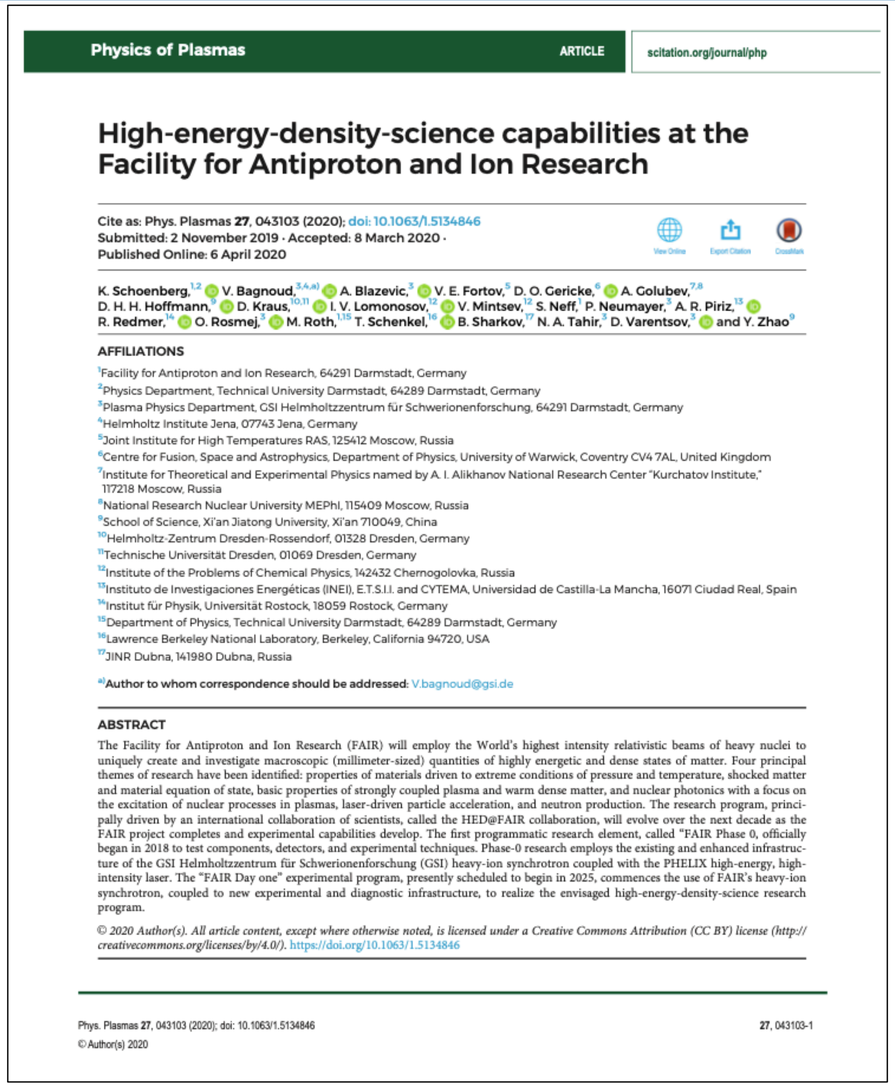
June 5th, 2023

Kurt Schoenberg
Spokesperson HED@FAIR

The HED @ FAIR collaboration developed an internationally competitive research roadmap in 2020

- **The roadmap, published in the Physics of Plasmas, comprised four principal focus areas for HED research at FAIR.**
  - **Properties of materials driven to extreme conditions of pressure and temperature relevant to planetary science**
  - **Dynamic compression science**
  - **Strongly coupled plasma physics**
  - **Nuclear photonics**

FAIR, as envisaged in 2020, provided internationally competitive research opportunities for each focus area



Physics of Plasmas ARTICLE scitation.org/journal/php

High-energy-density-science capabilities at the Facility for Antiproton and Ion Research

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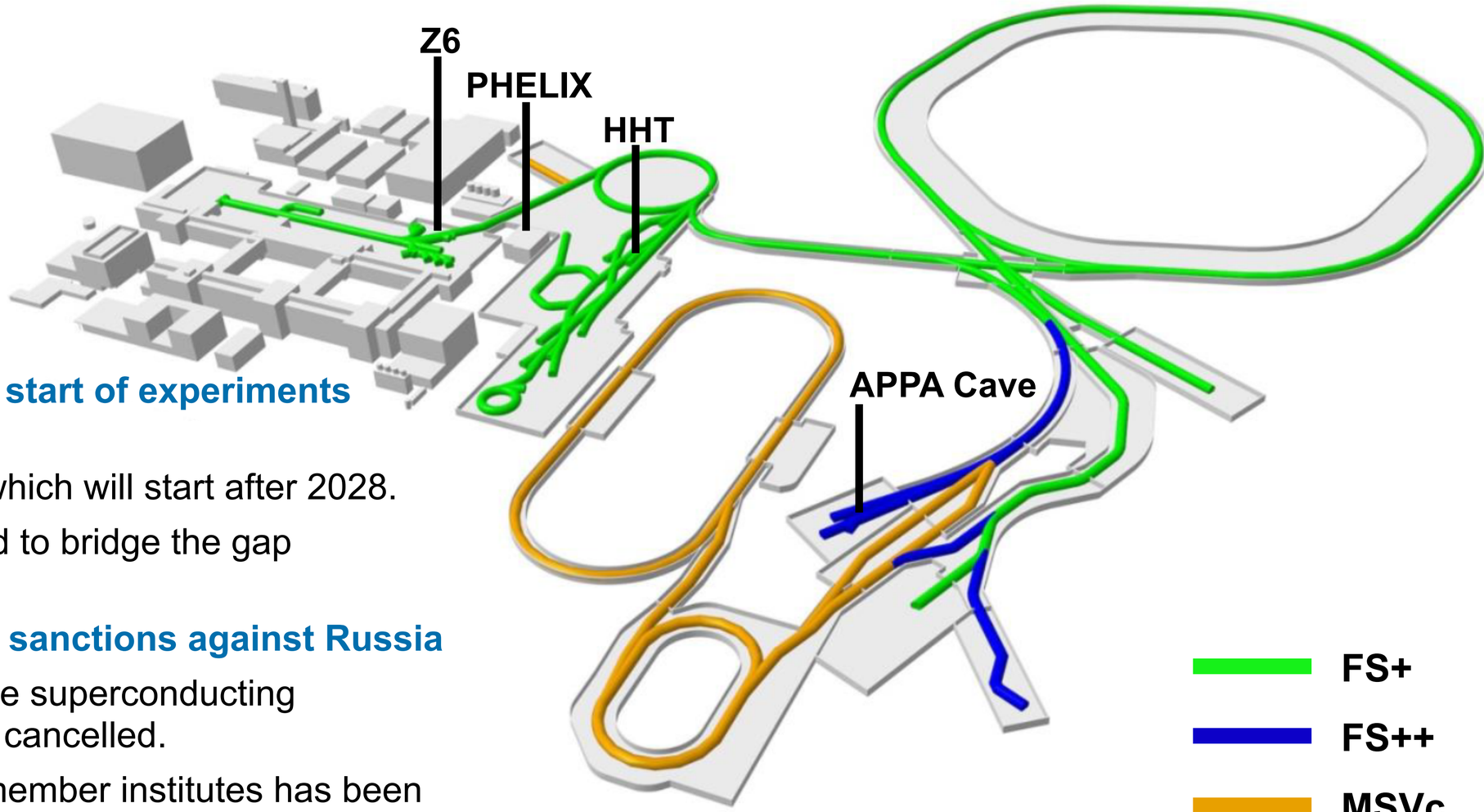
ABSTRACT

The Facility for Antiproton and Ion Research (FAIR) will employ the World's highest intensity relativistic beams of heavy nuclei to uniquely create and investigate macroscopic (millimeter-sized) quantities of highly energetic and dense states of matter. Four principal themes of research have been identified: properties of materials driven to extreme conditions of pressure and temperature, shocked matter and material equation of state, basic properties of strongly coupled plasma and warm dense matter, and nuclear photonics with a focus on the excitation of nuclear processes in plasmas, laser-driven particle acceleration, and neutron production. The research program, principally driven by an international collaboration of scientists, called the HED@FAIR collaboration, will evolve over the next decade as the FAIR project completes and experimental capabilities develop. The first programmatic research element, called "FAIR Phase 0, officially began in 2018 to test components, detectors, and experimental techniques. Phase-0 research employs the existing and enhanced infrastructure of the GSI Helmholtzzentrum für Schwerionenforschung (GSI) heavy-ion synchrotron coupled with the PHELIX high-energy, high-intensity laser. The "FAIR Day one" experimental program, presently scheduled to begin in 2025, commences the use of FAIR's heavy-ion synchrotron, coupled to new experimental and diagnostic infrastructure, to realize the envisaged high-energy-density-science research program.

Phys. Plasmas **27**, 043103 (2020)

The plans of HED@FAIR have been significantly impacted by recent events



The new staging of FAIR delays the start of experiments in the APPA cave by several years

- The APPA cave is part of FS++ which will start after 2028.
- Phase-0 experiments are needed to bridge the gap until the start of FAIR.

HED@FAIR is severely impacted by sanctions against Russia

- The Collaboration Contract for the superconducting final focusing magnets has been cancelled.
- The collaboration with Russian member institutes has been suspended.

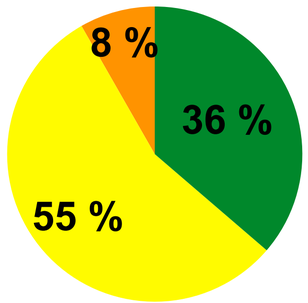
HED@FAIR is currently updating its plans and working on mitigation strategies to remain scientifically competitive.

Funding table for HED@FAIR

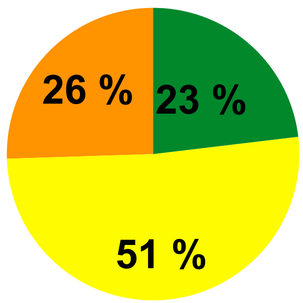
Work packages (PSP codes)	System	Estimate (k€, 2005)	Secured (k€, 2005)	EoI (k€, 2005)	TbA (k€, 2005)
1.3.2.1.2, 1.3.2.1.5, 1.3.2.2.2.1, 1.3.2.3.1, 1.3.2.3.2, 1.3.2.4.1, 1.3.2.6, 1.3.2.7.1	**Day-1 setup** HIHEX and PRIOR start setup	8,623	3,130	4,780 *	713
1.3.2.1.4, 1.3.2.2.2, 1.3.2.2.3, 1.3.2.3.4, 1.3.2.4.2, 1.3.2.5, 1.3.2.7.2	**Upgrade to MSV** HIHEX, PRIOR and LAPLAS with full performance	4,922	0	2,180	2,742
	Total cost of MSV	**13,545**	**3,130**	**6,960**	**3,455**

* The EoI include a FAIR EoI (4395 k€) for the replacement of the superconducting magnets.

Day-1 setup
8.6 M€



Full MSV
13.6 M€



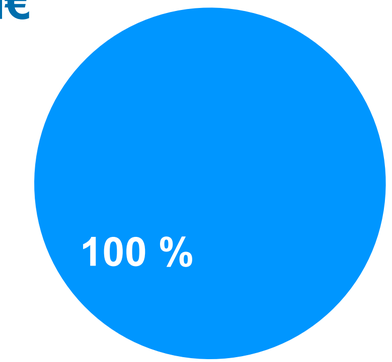
Secured
EoI
TbA

EoI: Expression of Interest
TbA: To be Assigned

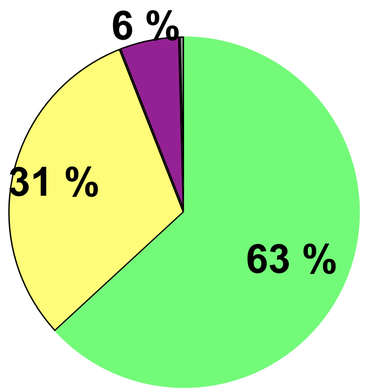
Funding by country for HED@FAIR

Funding by Country (k€, 2005 prices)	Germany		FAIR		Russia		China		Romania	
	Secured	EoI	Secured	EoI	Secured	EoI	Secured	EoI	Secured	EoI
Day-1 setup (8,623 k€)	3,130	-	-	4,395	-	-	-	385	-	-
Upgrade to MSV (4,922 k€)	-	-	-	-	-	2,150	-	-	-	30
Grand total for MSV (11,950 k€)	3,130	0	0	4,395	0	2,150	0	385	0	30

Secured
3.1 M€



EoI
7 M€



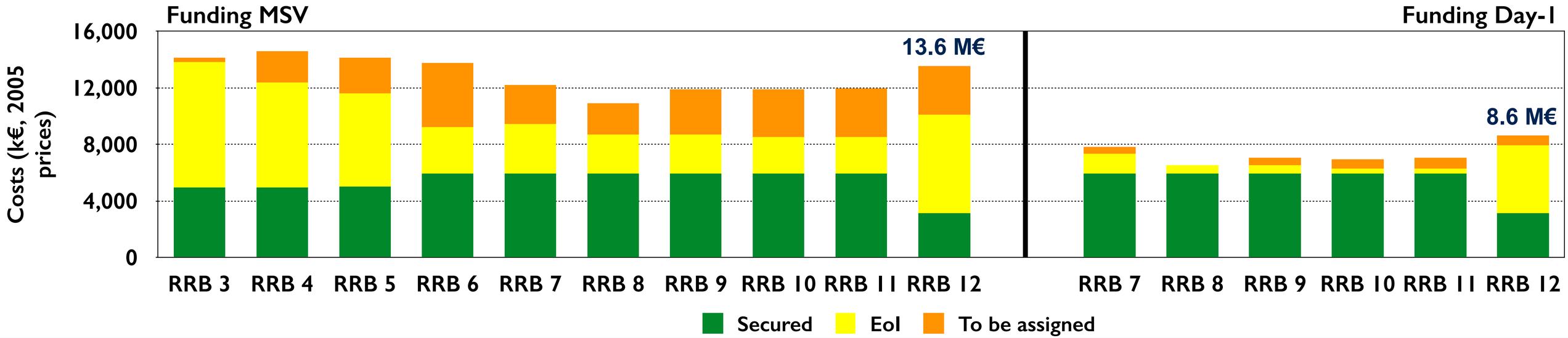
EoI: Expression of Interest
TbA: To be Assigned

Evolution of funding for HED@FAIR

The costs of the Day-1 setup are 8.6 M€, of which 36% are covered by secured funding. The costs for the replacements of the superconducting magnets (4.4 M€, 51% of total costs) are covered by an EoI from FAIR.

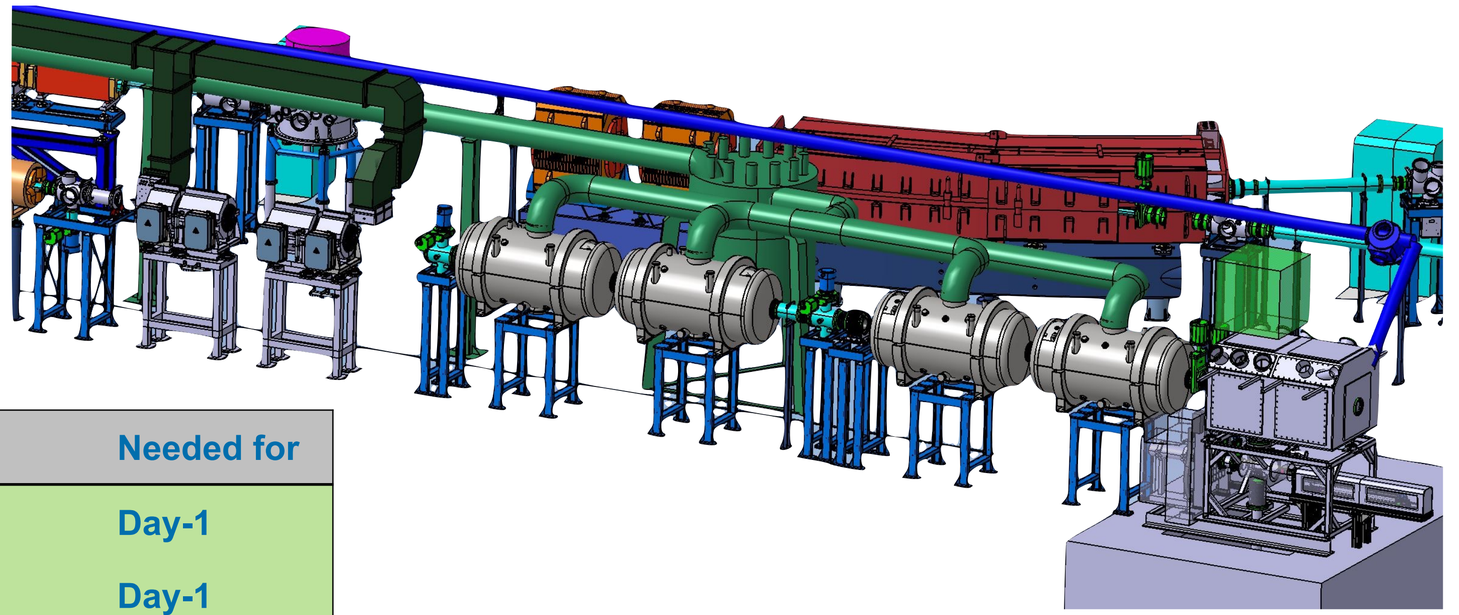
The cost of the full MSV setup is 13.6 M€, of which 23% are covered by secured funding.

The cost increase is due to the increased costs for purchasing replacements for the superconducting magnets.



HED@FAIR - Status of Technical Design Reports

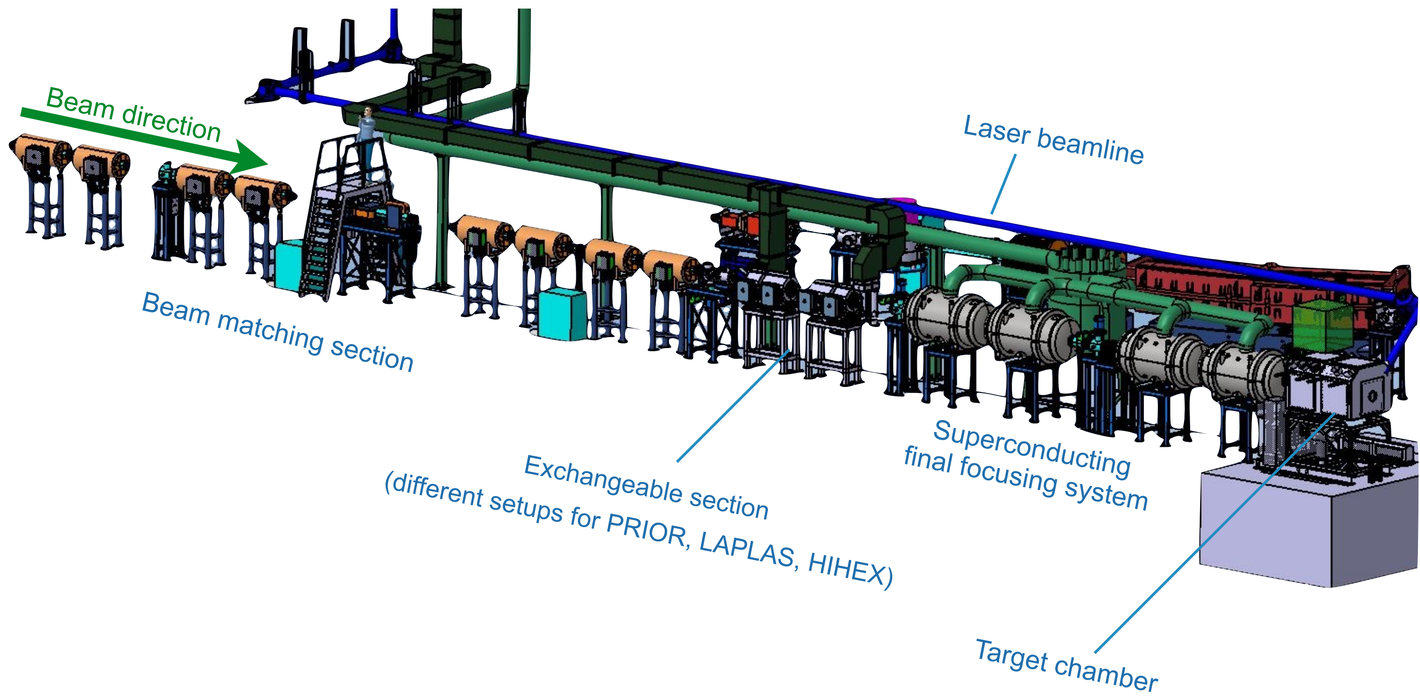
All Technical Design Reports needed for Day-1 experiments have been evaluated and approved



Technical Design Report	Status	Needed for
Superconducting final focusing system	Approved	Day-1
Detectors	Approved	Day-1
Diagnostic laser	Approved	Day-1
Data acquisition, triggering, controls	Approved	Day-1
Proton microscopy (PRIOR-II setup)	Approved	Day-1
RF beam rotator	Approved	Full MSV
Target chamber	Approved	Day-1
Cryogenic target fabrication	To be submitted	Full MSV

Current status of work packages for Day-1 setup

PSP	Work package	Status
1.3.2.1.2	Superconducting final focusing system	Magnets frozen/ power supplies & current leads under discussion
1.3.2.1.5	Proton microscope PRIOR-II	In use
1.3.2.2.1	Target chamber Day-1	In use
1.3.2.3	Detectors	In use/ under construction
1.3.2.4	Diagnostic laser	Project funding frozen
1.3.2.6	DAQ, controls	Project funding frozen
1.3.2.7	Infrastructure	Project funding frozen



The work package for the superconducting magnets for the final focusing system has been frozen

Four superconducting magnets (PSP 1.3.2.1.2.1)

- The contract with the IHEP in Protvino has been cancelled.
- Market inquiry yielded estimated costs between 4 M€ and 9 M€, existing design can be used. Estimated production time 4 years.
- **Since HED@FAIR is not part of FS+, no budget for replacements is currently available.**

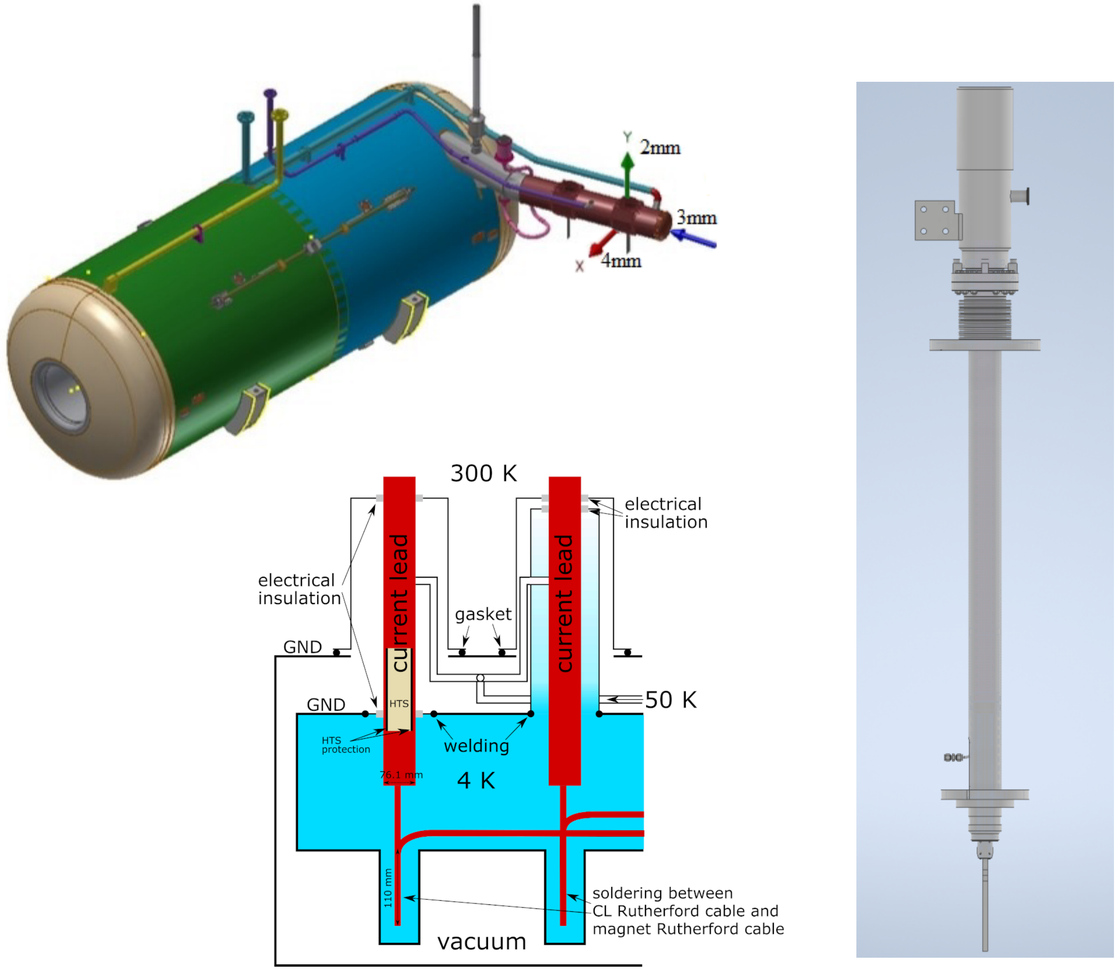
Current leads (PSP 2.8.2.13.1) (German accelerator in-kind contribution)

- FDR has been completed by contractor (Mark & Wedell)
- On hold

Power supplies (PSP 1.3.2.1.2.2) (German in-kind contribution)

- FDR has been completed by contractor (OCEM).
- On hold

Termination or continuation of contracts for current leads and power supplies under discussion.
Decision by management expected soon.



Design of the superconducting magnet and current leads

Phase 0 experiments behind SIS-18 are using the PRIOR-II setup and the Day-1 target chamber

Coupled laser beam - ion beam experiments (target chamber)

Ion beam parameters

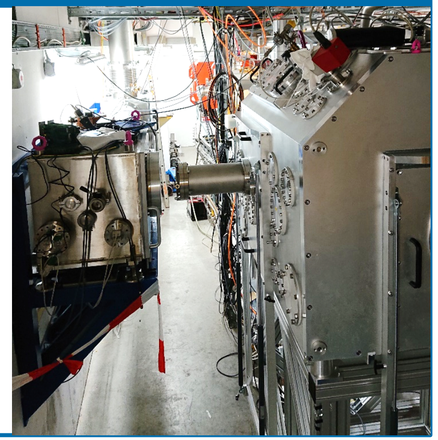
350 MeV/u U^{73+}

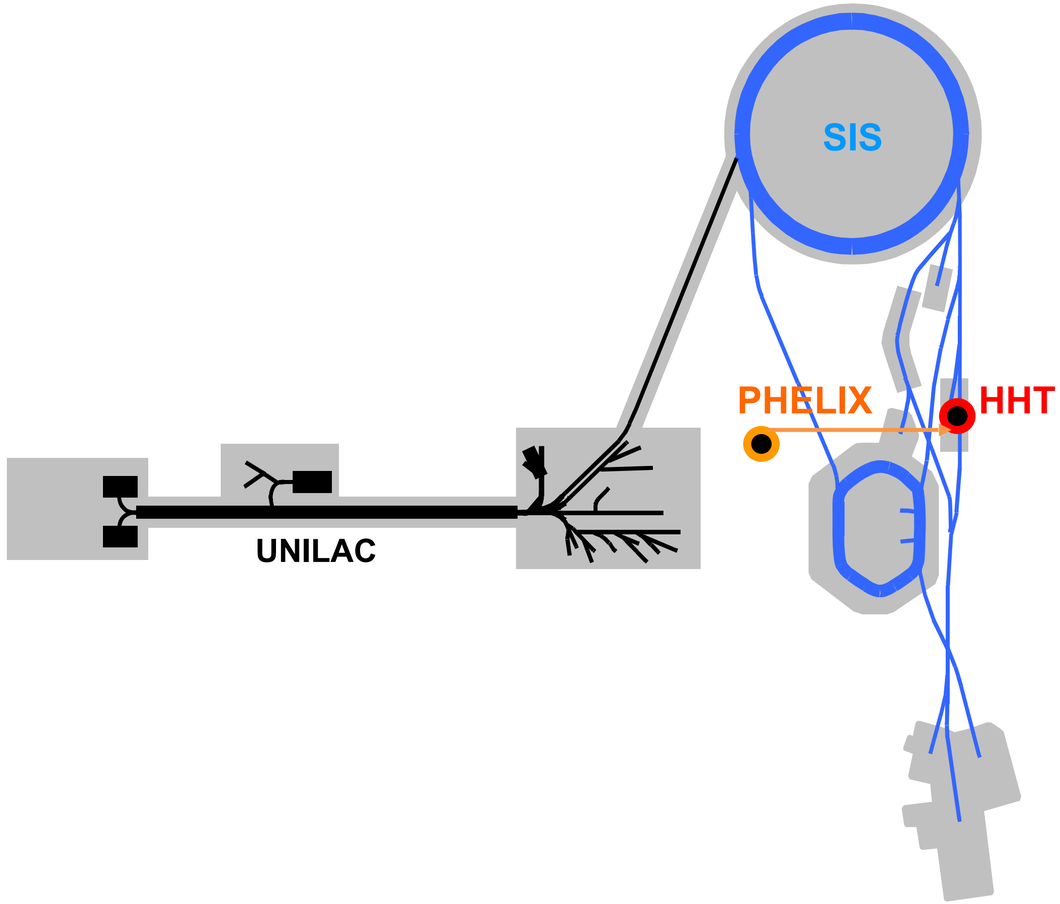
$4 \cdot 10^9$ ions/bunch

Laser beam parameters (PHELIX long pulse)

Up to 200 J @ 527 nm, 1 ns - 10 ns

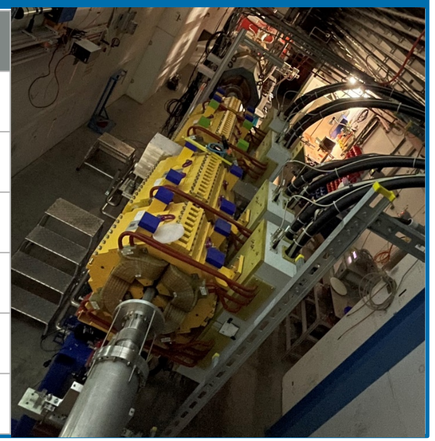
~50 µm focal spot, good stability



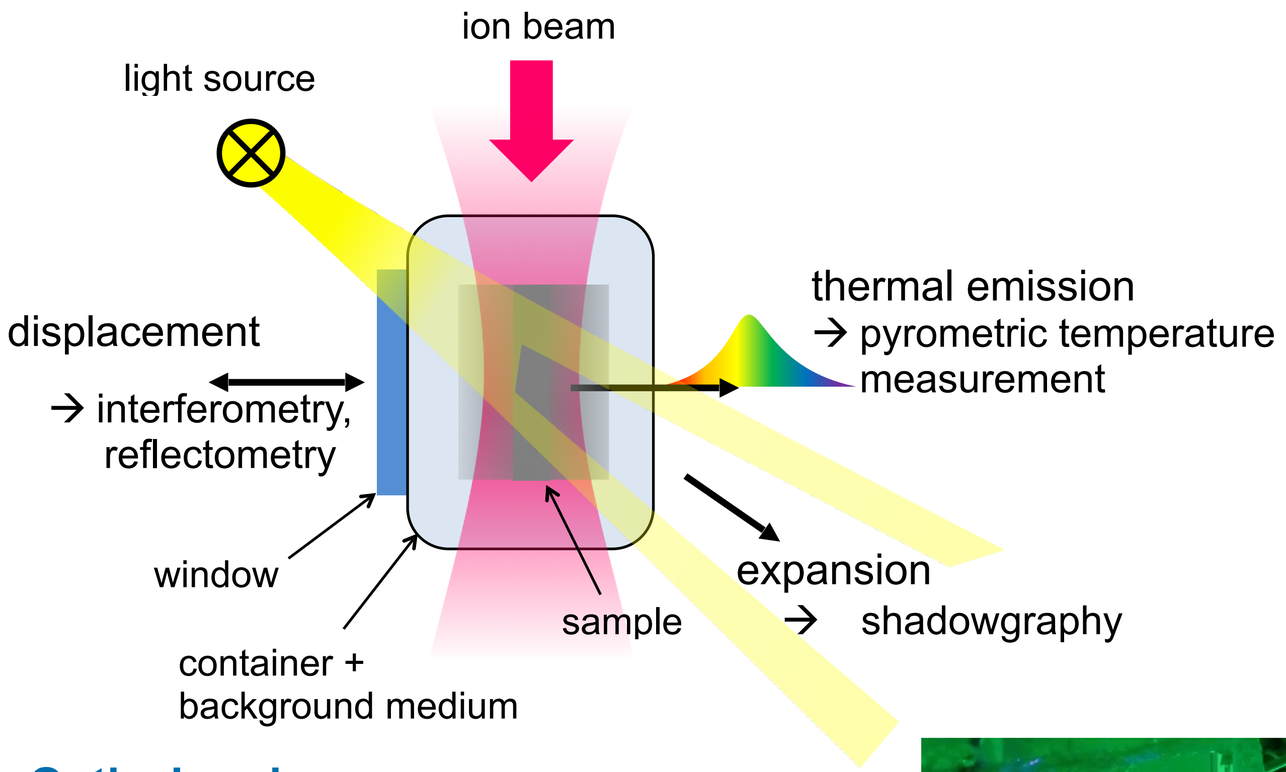


Proton microscopy (PRIOR-II)

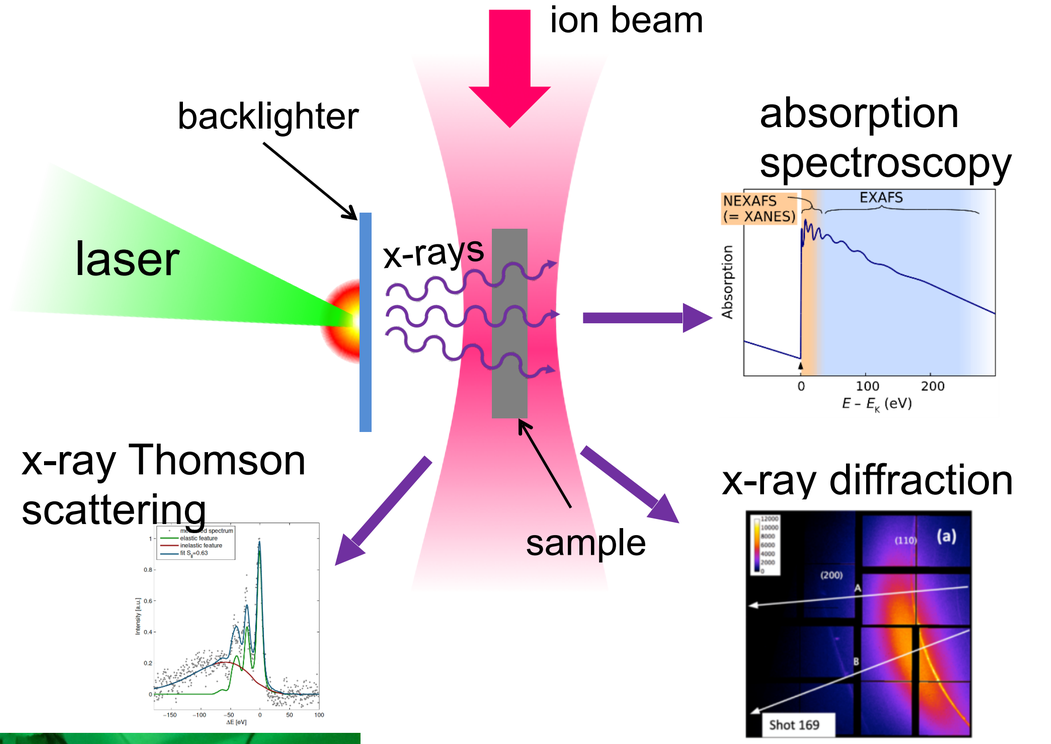
Design Parameters	PRIOR-II • GSI	
Reference energy (MeV)	4000	
Magnification	3.49	
Collimator acceptance (mrad)	2.0	5.0
Field of view(mm)	30 x 57	30 x 54
Chromatic RMS resolution (µm)	1.9 x 3.6	4.7 x 8.9
Off-Axis RMS resolution (µm)	2.1 x 4.0	5.3 x 10.1



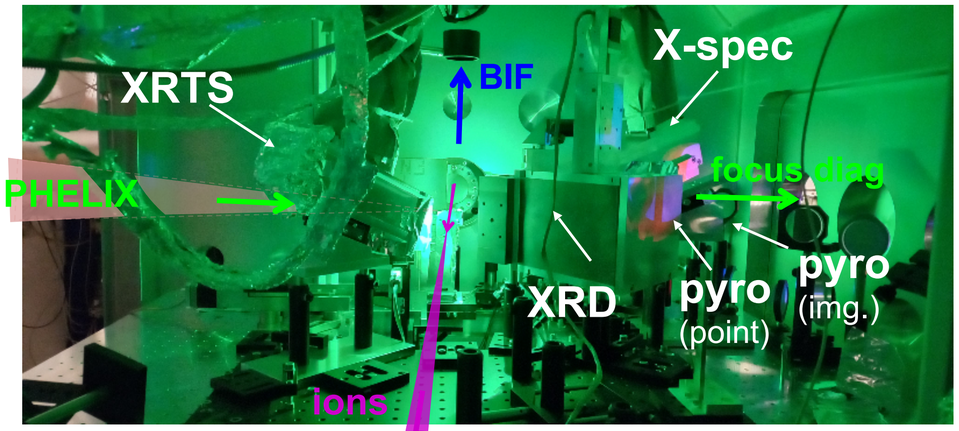
Many detectors are already used in Phase-0 in coupled laser-ion beam experiments at HHT



Optical probes
→ macroscopic observables (p,T,V)



X-rays
→ microscopic structure



Diagnostic setup from beam time in 2022

XRTS: *X-ray Thomson scattering*
BIF: *Beam induced fluorescence*
X-spec: *X-ray spectrometer*
XRD: *X-ray diffraction*
pyro: *Pyrometry*

Detector development by German university groups is funded by BMBF Verbundforschung.

Funding for the diagnostic laser has been frozen, but work on laser technology is continuing

Project funding for the construction of the diagnostic laser (PSP 1.3.2.4) has been frozen

- Funding for the construction of the laser has been frozen.
- Work on the construction of the laser has been stopped.
- R&D work continues.
- TU Darmstadt & FSU Jena will apply for funding to upgrade PHELIX to temporally-incoherent pulses. This would also benefit experiments at HHT.

GSI and FAIR are part of the THRILL consortium

- The goal of the European THRILL project is to advance technology in the field of high energy, high repetition rate lasers and to train researchers.
- Funding for GSI and FAIR amounts to 3.3 M€.
- The deliverables include a design study for a high-energy laser at FAIR.

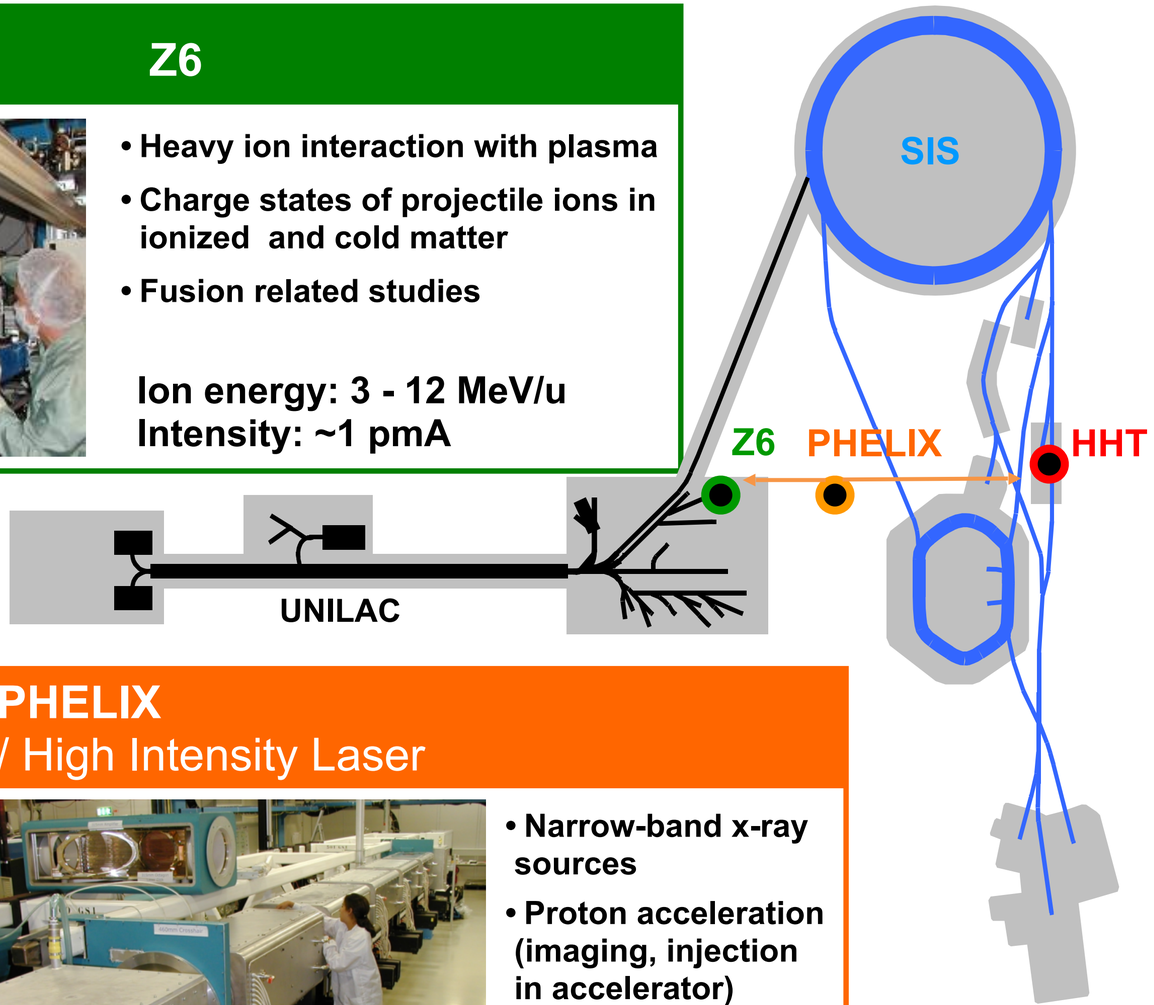
www.thrill-project.eu

Experiments in Phase-0 will be essential to bridge the gap until the start of FAIR experiments

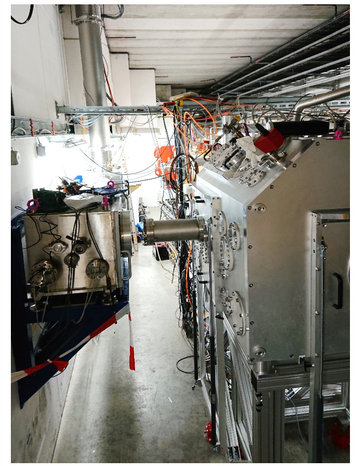
Z6

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

Ion energy: 3 - 12 MeV/u
Intensity: ~1 pmA



HHT



Ion energy:
350 MeV/U U^{73+}

Intensity:
$4 \cdot 10^9$ ions/bunch

- Proton microscopy
- Heavy ion heating
- FAIR-related developments

PHELIX
High Energy / High Intensity Laser

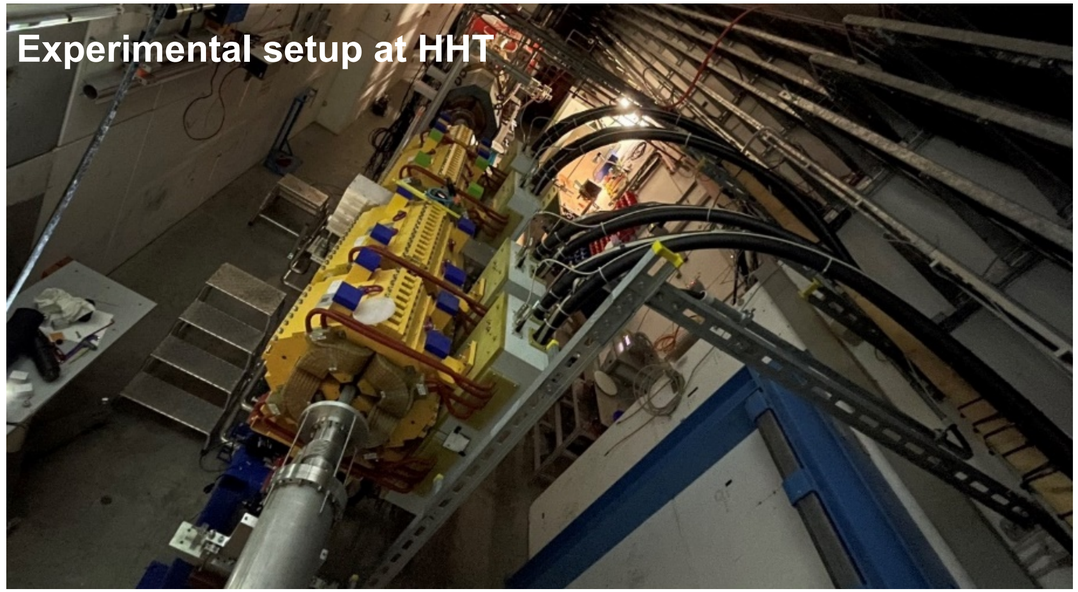
Laser bay: 0.5 PW, 200 J @ 400 fs

Z6: 200 J @ 1 – 10 ns, 2ω
30 J @ 0.3 – 2 ps (100 TW)

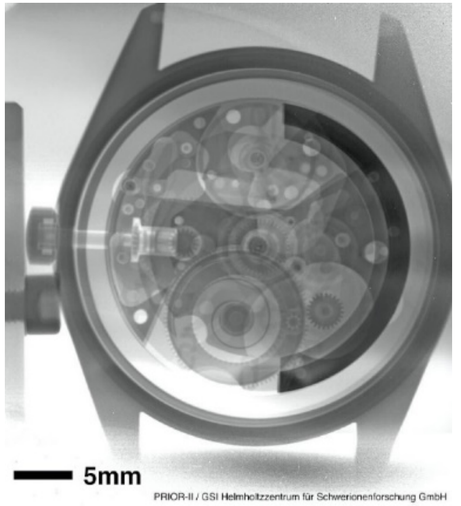
HHT: 200 J @ 1 – 10 ns, 2ω

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

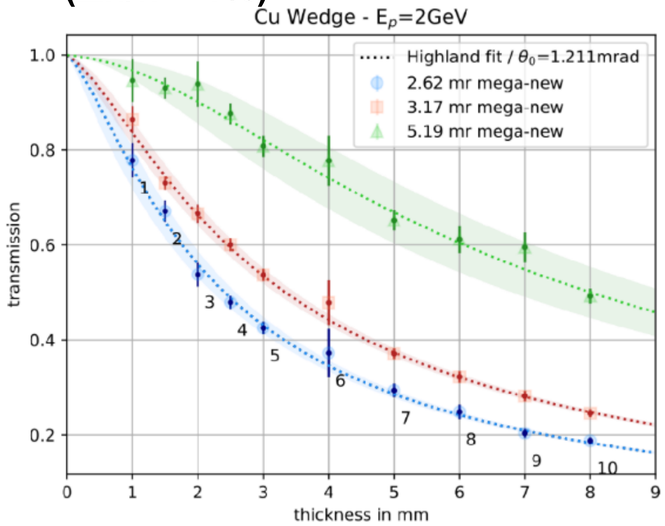
A first proof-of-principle experiment to study liquid-liquid phase transitions has been carried out with PRIOR-II



Static imaging (watch)

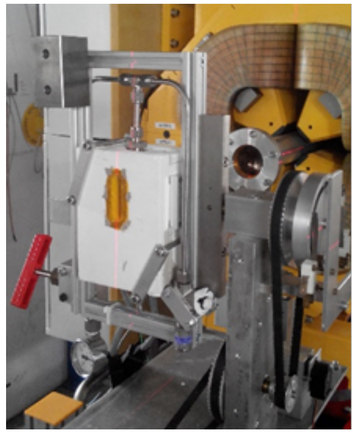


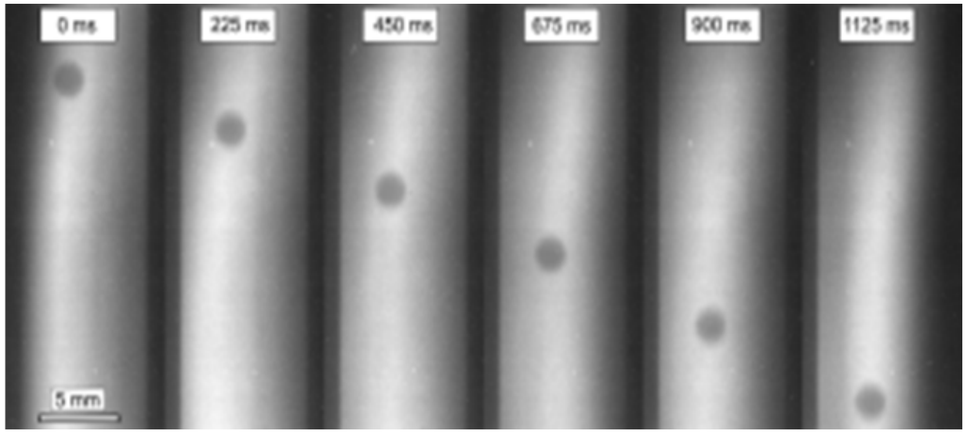
Excellent density resolution (Δn/n < 1%)



Experiment: "Understanding liquid-liquid phase transformations by temperature-dependent viscosity measurements at high pressures using high energy proton microscopy"

High pressure heated Titanium-vessel →





← Steel ball „falling" in liquid Sulfur

First combined laser-ion experiments at SIS-18

May 2022: First beam time combining intense heavy-ion beams with high-energy laser pulses

- APPA day-1 target chamber used in first experiment at HHT-cave
- High-energy laser beamline at full specs! (200J at 527nm)
- >4·10^9 Pb-ions/pulse, focusing down to 0.6x0.9mm (FWHM) !
- Variety of ion beam, optical + x-ray diagnostics fielded
- Demonstrated laser-driven x-ray probing of HI-heated targets

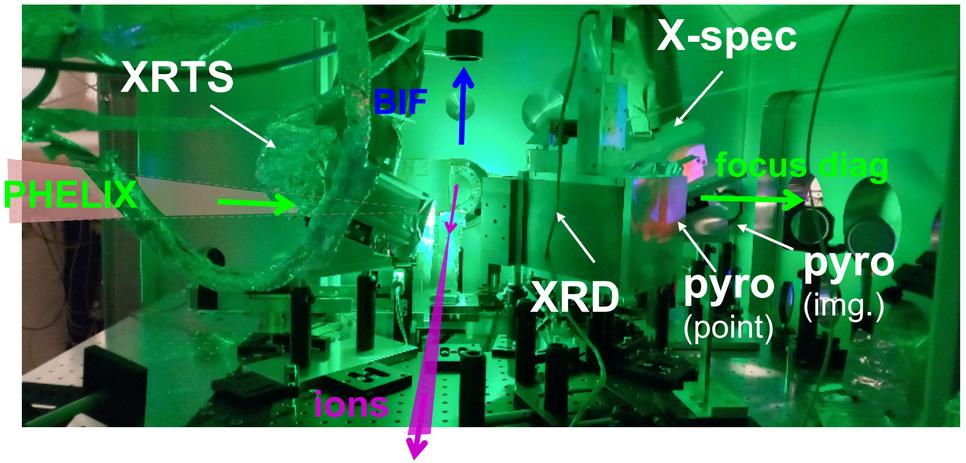
Strong participation by several university groups from within HED@FAIR

GOETHE UNIVERSITÄT FRANKFURT AM MAIN

Queen's University

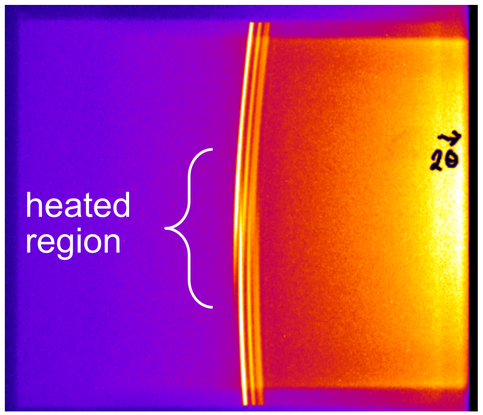
Universität Rostock Traditio et Innovatio

Setup in target chamber

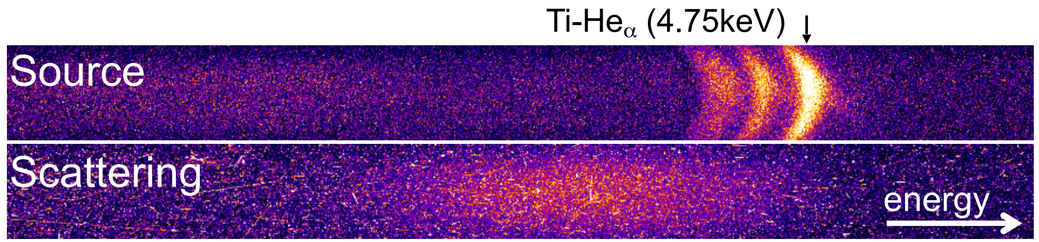


X-Ray Diffraction

→ graphitization, melting



X-Ray Thomson Scattering → ionic vibrations (T_i)



→ X-ray probing reveals microscopic properties of HED samples

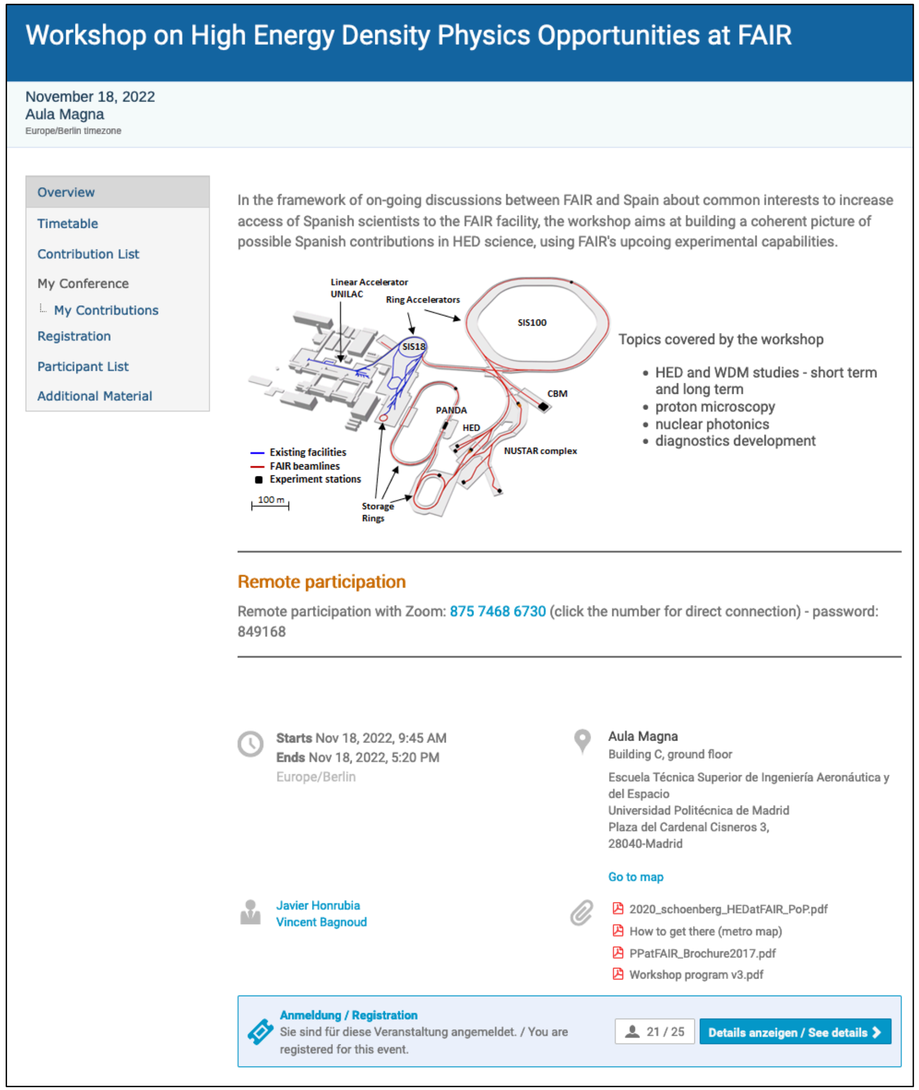
Discussions are underway with other partners to compensate for the loss of contributions from Russian member institutes

Discussions with Spanish researchers about participation in FAIR

- Kick-off meeting with representatives from 10 research groups in Madrid in November 2022
- A potential supplier for superconducting magnets (Elytt Energy) took also part in the meeting.
- Several research topics of common interest have been identified, a white paper is in preparation.

Research topics include:

- Warm dense matter studies
- Shock physics experiments with PRIOR
- Ion energy loss in warm dense matter
- R&D for diagnostics



Discussions are underway between GSI/FAIR and *Focused Energy* about exploring collaborations in HED science

GSI/FAIR and *Focused Energy* are exploring possible collaborations in high-energy-density laser-driven science

- Due to the new timeline, the completion of the APPA beam infrastructure will be significantly delayed.
- *Focused Energy*, a fusion-energy startup, is interested to use the APPA cave in the interim.
- The idea is to install a high-energy laser system in the vicinity of the APPA cave and to use the cave as a target area.
- This experimental campaign would be completed by the time FAIR operations in the APPA cave are scheduled to start.
- This collaboration would enable HED science in the APPA cave much earlier than in the current planning.

Current status

- As a consequence of the successful ignition shot at the Lawrence Livermore Laboratory last year, the German ministry of research has announced its interest to fund research into laser-driven fusion.
- First discussions between *Focused Energy* and the ministry have taken place. A decision on the funding of its research program is expected this year. Focused Energy is also seeking private investor funding.
- The FAIR management welcomes the project. *Focused Energy* is currently studying the technical feasibility of installing the laser system next to the APPA cave.

Summary

Effects of new prioritisation of the FAIR project on HED@FAIR

- Construction of the APPA cave will be frozen, once the final acceptance of the shell of the building is completed.
- The contract for the superconducting magnets has been cancelled and several work packages have been frozen.
- Construction of the superconducting magnets requires budget 4 years before the start of the experiments.
- Expected date for the start of HED experiments in the APPA cave has shifted to 2028-2030.
- The new timeline requires an overhaul of the research strategy.

Mitigation strategies

- Focus on Phase 0 activities at the existing facilities at GSI.
- Sufficient beam time in Phase 0 as well as third party funding (e.g. BMBF Verbundforschung) will be essential to keep the scientific community alive.
- We are in discussions with Spanish research groups to mitigate the effects of suspended collaboration with Russian institutes.
- A collaboration with *Focused Energy* is under discussion, which would offer new opportunities for HED@FAIR in the time until the start of FAIR operations in the APPA cave.

Thank you for your attention.

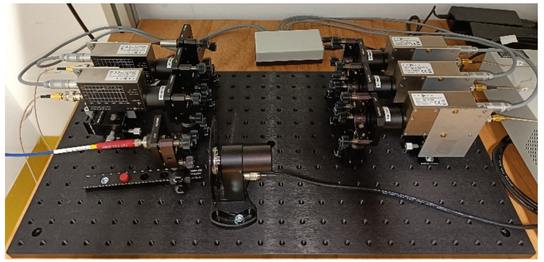
air view of the FAIR southern buildings
(NUSTAR & APPA Caves)

Backup slides

Research and R&D topics in Phase 0: Further development of HED diagnostics

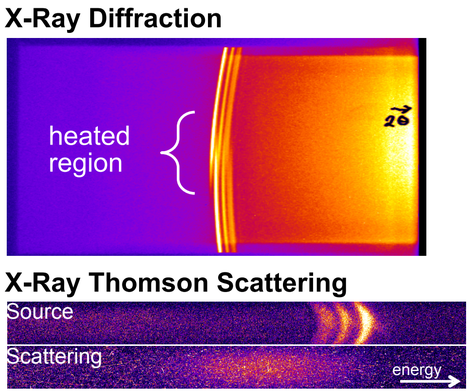
Understanding the temperature evolution during ion- and laser-beam heating with optical diagnostics

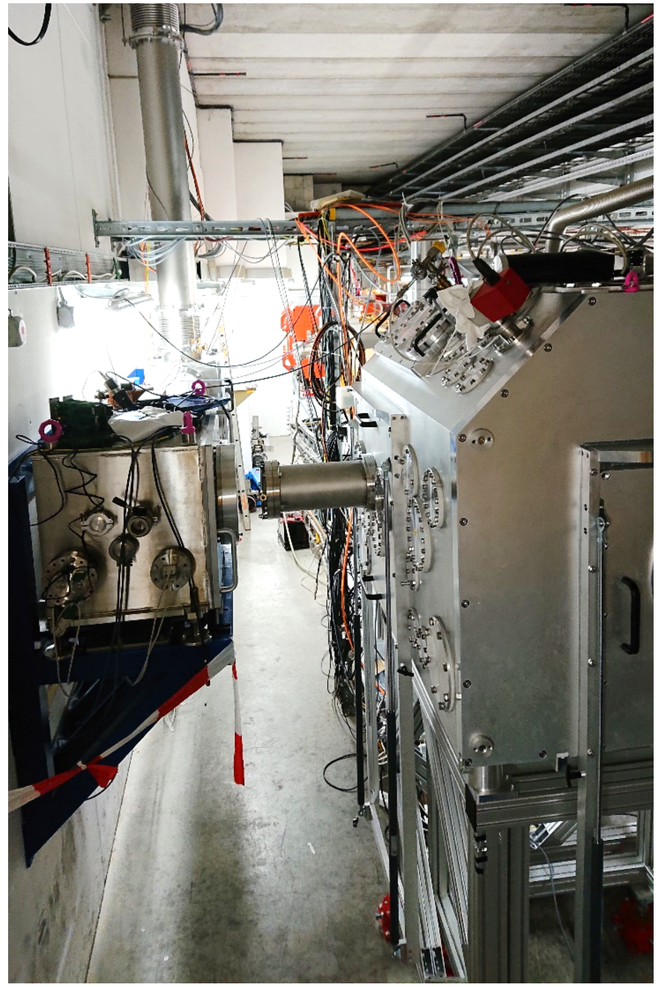
- Measuring the temperature accurately of ion heated target is a experimental challenge that requires redundancy to avoid systematic errors.
- A multi-channel pyrometer, developed in the current funding period should be further developed to support various approved HIHEX, LAPLAS and PRIOR experiments.



Further development of X-ray diagnostics

- FAIR experiments require the development high-performance laser-driven x-ray diagnostics.
- First proof-of-principle has been demonstrated, further beamtime has been granted.
- Further diagnostic development necessary (more efficient crystal spectrometers, large area x-ray detectors).
- Remote operation will be an important aspect.



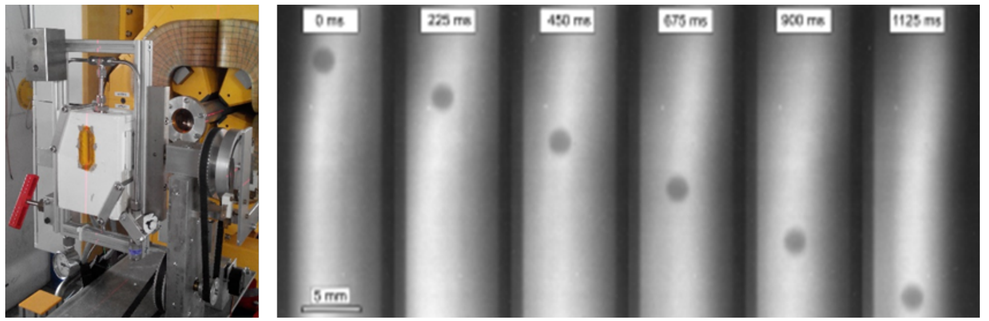


HIHEX target chamber installed at GSI/HHT

Research and R&D topics in Phase 0: Developing experimental capabilities for PRIOR-II

Properties of geophysically relevant melts

- First proof-of-principle experiment showed that PRIOR can measure fundamental properties of melts at high temperatures and pressures.
- Future experiments will build on this and study geophysically relevant conditions, e.g. in the atmosphere of Venus.



Left: High-pressure (90 bar) heatable vessel at the target plane of PRIOR-II at HHT.
Right: Single frames from a movie while measuring the viscosity of liquid sulfur at high pressure as a function of temperature. The position of a 2-mm-diameter ball inside a thick Ti high-pressure vessel is clearly detectable.

HE-driven shock wave experiments and related developments

- PRIOR is a unique instrument for shock physics.
- We are currently developing this new capability (small HE generators, confinement system, target diagnostics, detector setup) to be employed in various physics experiments with PRIOR.
- Experiments study conditions relevant for materials science, geoscience and planetary science.