The FAIR phase-0 program at GSI/HHT (2021-2025)

Paul Neumayer, GSI

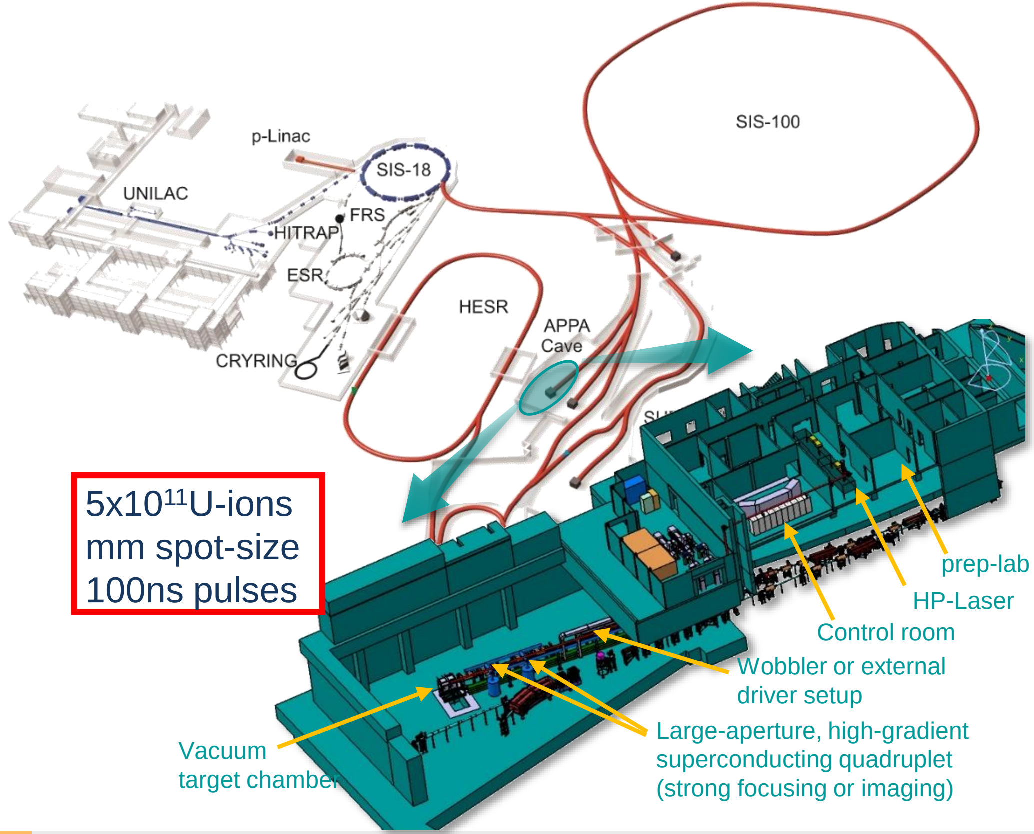
Workshop on High Energy Density Physics Opportunities at FAIR
ETSIAE, UPM, Madrid, Spain
November 18, 2022

Summary

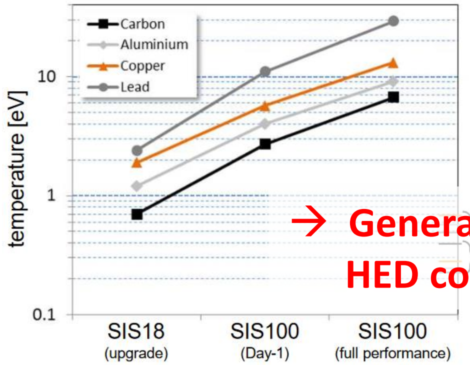
Within FAIR Phase-0 the HED@FAIR collaboration has exciting opportunities for HED-science experiments

- Experiments with intense ion pulses at the HHT-cave
  - Heavy-ion heating for generation of extreme matter states
  - New laser beamline from PHELIX enables x-ray probing schemes
  - IPD-measurements on HI-driven samples planned as day-1 experiment
  - PRIOR: a unique high-energy proton microscope for dynamic experiments
- Intense laser-matter experiments at PHELIX
  - Development of high-flux sources (x-ray, protons, neutrons, gamma) for applications (x-ray backlighting, neutron-imaging, nuclear reactions)

FAIR will offer exciting new possibilities for research in high-energy density matter science



5×10^{11}U-ions
mm spot-size
100ns pulses

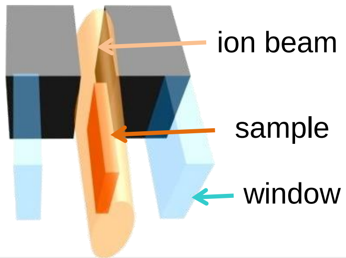


→ **Generation of HED conditions!**

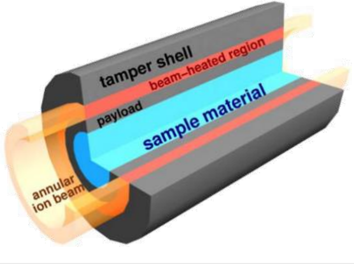
Ion beam driven plasmas:

- large mm-size samples
- homogenous energy deposition
- equilibrium conditions

Heating + expansion



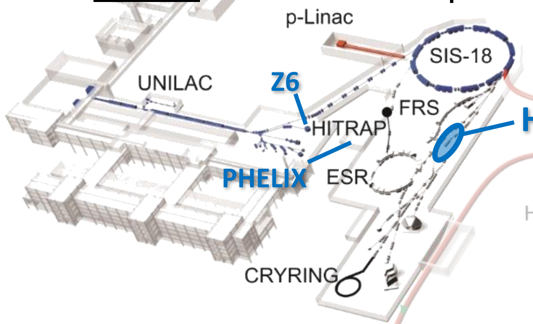
Isentropic compression



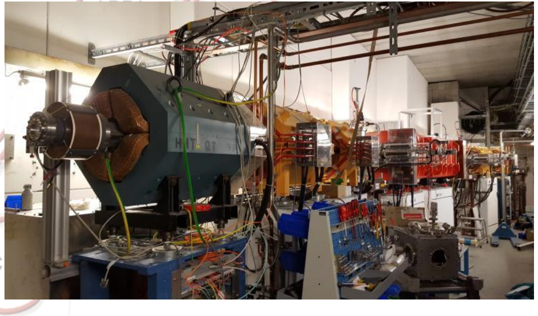
Early experiments in FAIR Phase-0 at HHT

FAIR „Phase-0“:

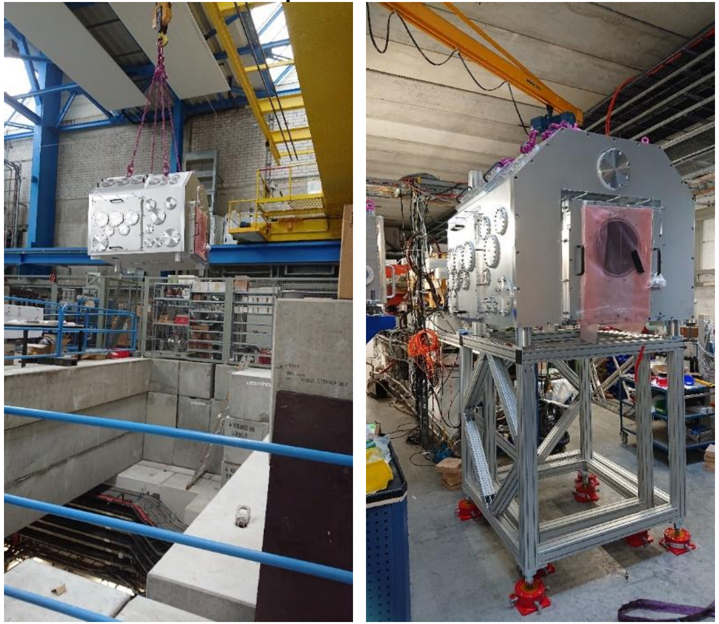
Research activitites related to or relevant for FAIR, before start of FAIR operation in 2025.



Focusing quadrupoles @HHT



APPA target chamber installation in the HHT experimental area

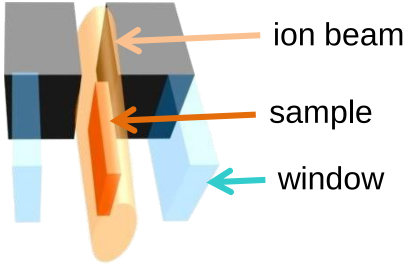


HIHEX: *Heavy Ion Heating and EXpansion*

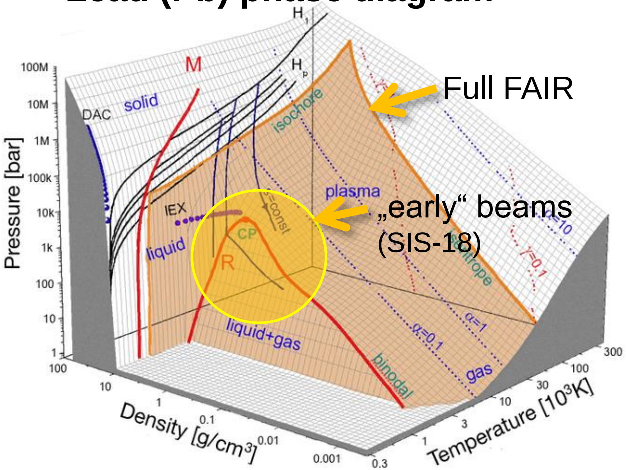
- For most metals in the periodic system the locations of the critical points are still unknown!
- Theoretical estimates of the critical point location differ by up to 100–200% in T and P

HIHEX:

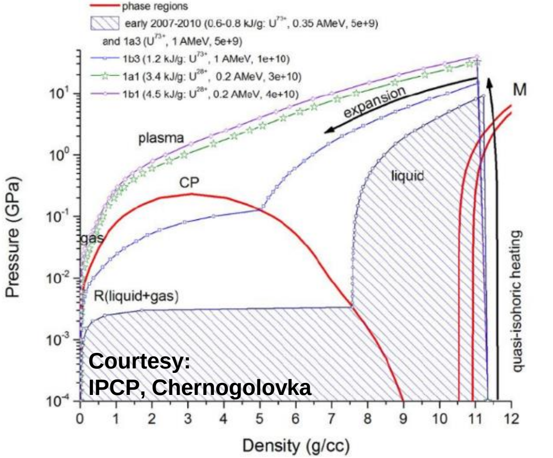
- Heating by heavy ion pulses
- Subsequent expansion



Lead (Pb) phase diagram



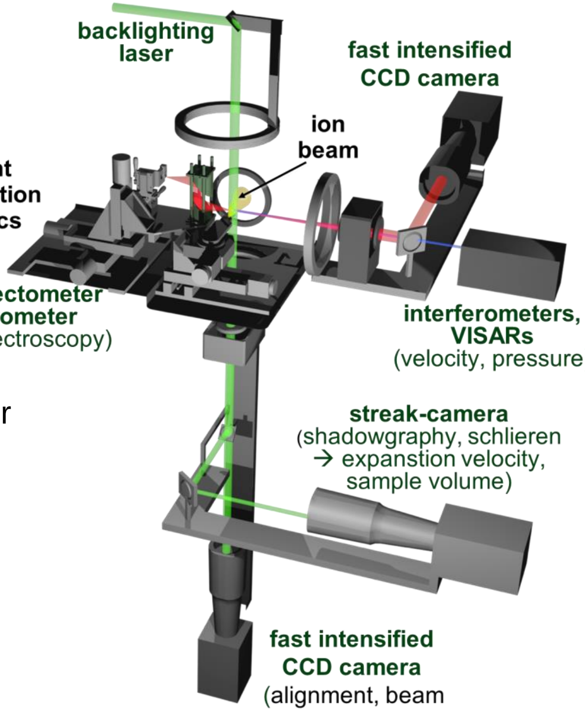
Simulations of parameter evolution



Courtesy:
IPCP, Chernogolovka

“Early” HIHEX can access region around critical points of various materials

Proof-of-principle HIHEX-experiments at GSI



backlighting laser

fast intensified CCD camera

ion beam

light collection optics

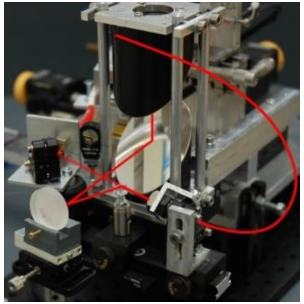
pyrometer, reflectometer streak-spectrometer
(temperature, spectroscopy)

interferometers, VISARs
(velocity, pressure)

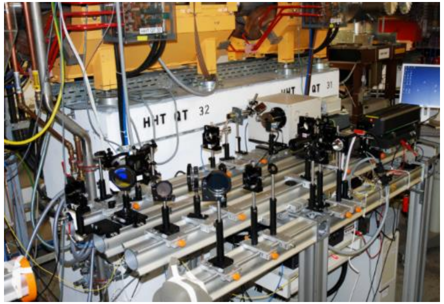
streak-camera
(shadowgraphy, schlieren
→ expanstion velocity,
sample volume)

fast intensified CCD camera
(alignment, beam diagnostics, self-emission)

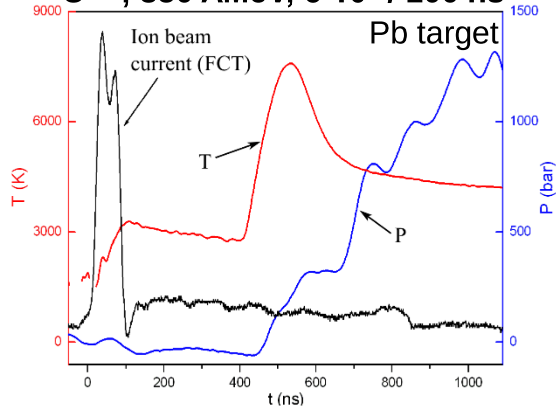
fast pyrometer/reflectometer



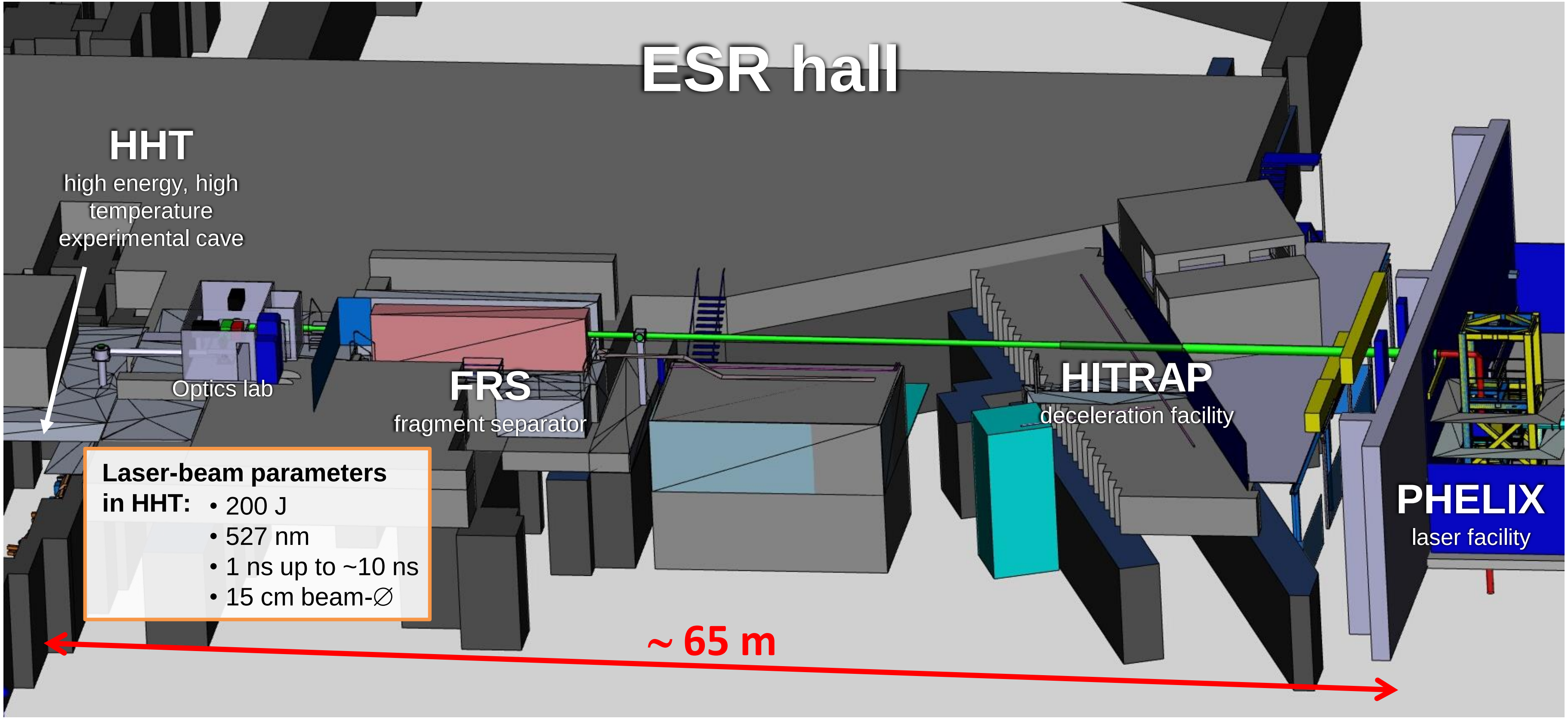
laser interferometer



U^{73+}, 350 AMeV, $3\cdot10^9$ / 100 ns

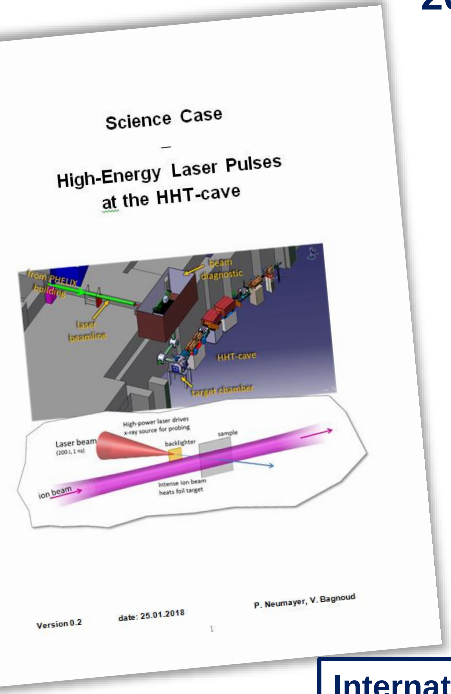


HHT-beamline: transport of high-energy laser pulses from PHELIX to the HHT-cave



Laser-beam parameters in HHT:
- 200 J
- 527 nm
- 1 ns up to ~10 ns
- 15 cm beam-∅

New capabilities enabled by high-energy laser pulses at the HHT-cave



Science Case

–

High-Energy Laser Pulses at the HHT-cave

Version 0.2

date: 25.01.2018

P. Neumayer, V. Bagnoud

1

200J/ns laser pulses, focused to 10^{12}-10^{15}W/cm^2 can drive:

- Intense He-α line-radiation sources (<10keV) from mid-Z plasmas, few keV quasi-continuous radiation from high-Z plasmas

⇒ **Diagnostic capabilities enabled by laser-driven x-rays:**

- Radiography
  - low-Z targets: (isentropic) expansion/compression, ablation/fracture/spallation/explosion
  - high-Z targets: expansion into low-Z tamper
- X-ray diffraction
  - lattice constant + strength, structural phase transitions (e.g. diamond-graphite), melting
- X-ray scattering
  - liquid structure (ion-ion distance, coupling strength, ion temperature, compressibility)
- Absorption spectroscopy
  - XANES (electron temperature), VUV-opacity (e.g. Bi, Pb), continuum lowering

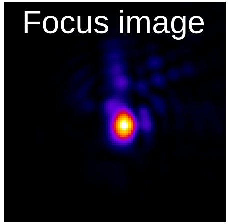
- few Mbar shocks into solids
  - Shock-induced ablation/spallation
  - Laser-accelerated flyer plates

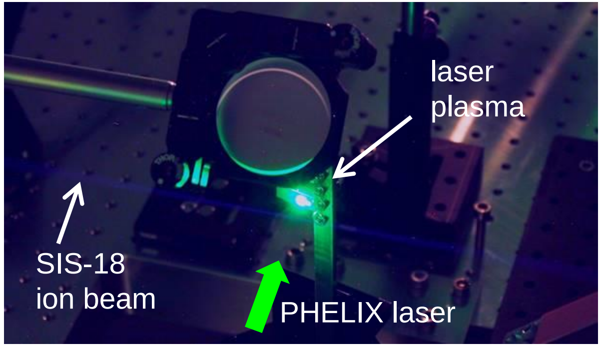
} → Proton microscopy with **PRIOR**

International panel discussion (HED@FAIR2017 workshop):
The unique combination of the intense heavy ion beams at HHT with a high-energy laser pulse significantly enhances the experimental possibilities and has a large scientific discovery potential

HHT-beamline: transport of high-energy laser pulses from PHELIX to the HHT-cave

- Beamline complete, vacuum system operational
- First light in HHT cave (May 2021)
- Simultaneous ion + laser pulses in new target chamber, synchronization <10ns
- up to 200J at 2ω (2ns pulse duration)
- focal spot-∅ 20 µm (~90% in 60µm)
- pointing fluctuations ±2x focal spot





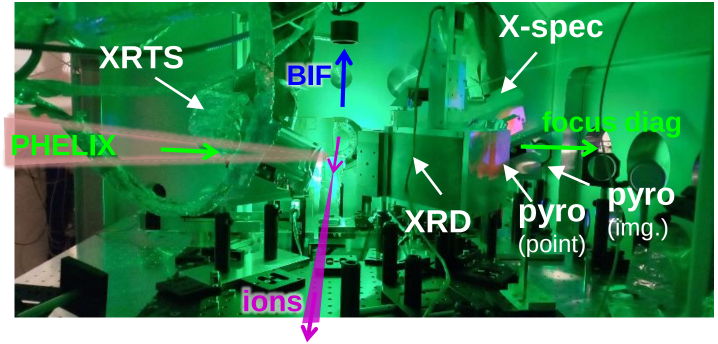
First combined laser-ion experiments at SIS18

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

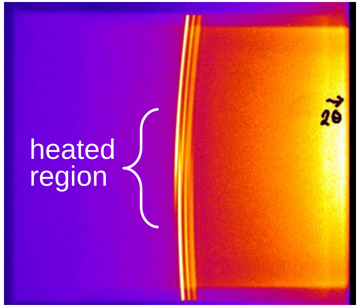
- APPA day-1 target chamber used in first experiment at HHT-cave
- High-energy laser beamline at full specs! (200J at 527nm)
- >4e9 Pb-ions/pulse, focusing down to 0.6x0.9mm (FWHM) !
- Variety of ion beam, optical + x-ray diagnostics fielded
- Demonstrated laser-driven x-ray probing of HI-heated targets

Strong participation by several university groups from within HED@FAIR

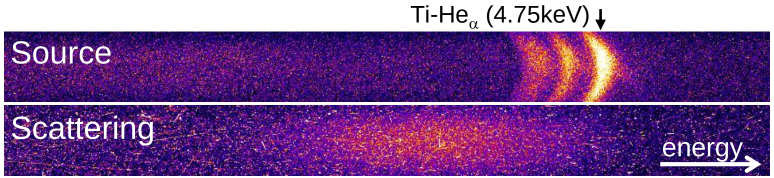
Setup in target chamber



X-Ray Diffraction
→ graphitization, melting



X-Ray Thomson Scattering → ionic vibrations (T_i)



→ X-ray probing reveals microscopic properties of HED samples

Ionization Potential Depression (IPD)

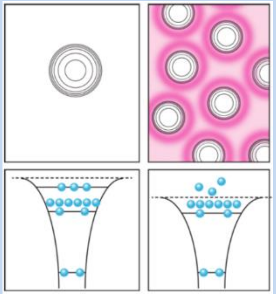
Ionization determines:

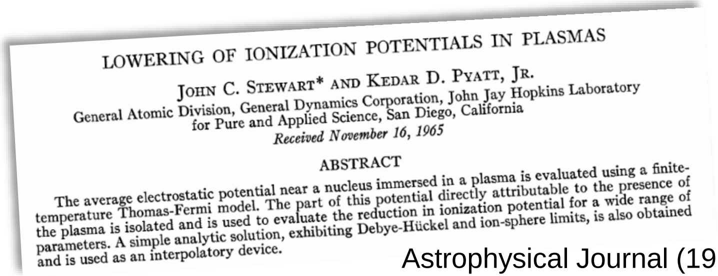
- Equation-of-State $P(\rho, \varepsilon)$
- Transport (radiation, electrical, heat)
- Microscopic structure
- ...

Important when modeling ICF,
planets and stars, plasma diagnostics

- In a plasma the field around an ion is perturbed by the neighboring charged particles (e+i).
- This leads to a shift of energy levels & reduction of the boundary between bound and unbound states (continuum)

  → Effective ionization energy is **reduced**
  (“IPD“, Ionization Potential Depression)





LOWERING OF IONIZATION POTENTIALS IN PLASMAS

JOHN C. STEWART* AND KEDAR D. PYATT, JR.
General Atomic Division, General Dynamics Corporation, John Jay Hopkins Laboratory
for Pure and Applied Science, San Diego, California
Received November 16, 1965

ABSTRACT

The average electrostatic potential near a nucleus immersed in a plasma is evaluated using a finite-temperature Thomas-Fermi model. The part of this potential directly attributable to the presence of the plasma is isolated and is used to evaluate the reduction in ionization potential for a wide range of parameters. A simple analytic solution, exhibiting Debye-Hückel and ion-sphere limits, is also obtained and is used as an interpolatory device.

Astrophysical Journal (1966)

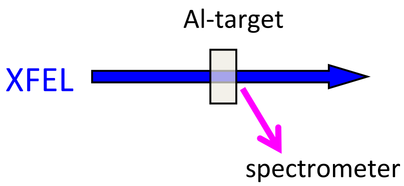
S&P-model: „smooth interpolation between IS and DH limits“

*weak coupling, non-degenerate electrons

Used in many modern codes:
CRETIN, FLYCHK, LASNEX-DCA, ...

Recent experiments test IPD models in dense plasmas

LCLS

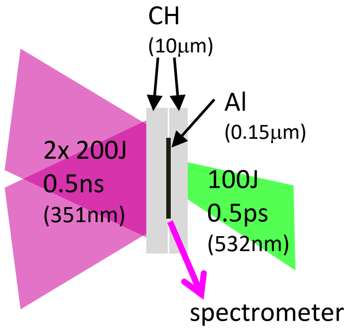


- Heating: X-FEL
- Probing: K-shell emission (from photo-ioniz.)

T=70...180eV
$\rho = \rho_0$ (isochoric)
highly transient, non-eq.

Ciricosta *et al.*, PRL (2012)

Orion

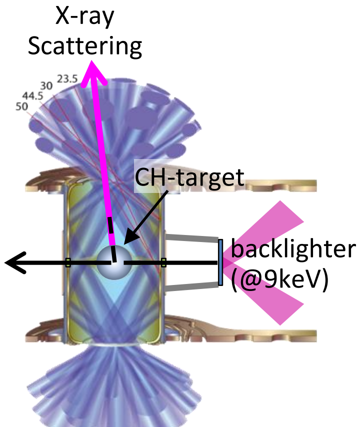


- Heating: ps (PW) laser
- Compression: ns-laser
- Probing: Resonance line emission (impact excitation)

T=500...700eV
$\rho = 0.5...4 x \rho_0$

Hoarty *et al.*, PRL (2013)

NIF

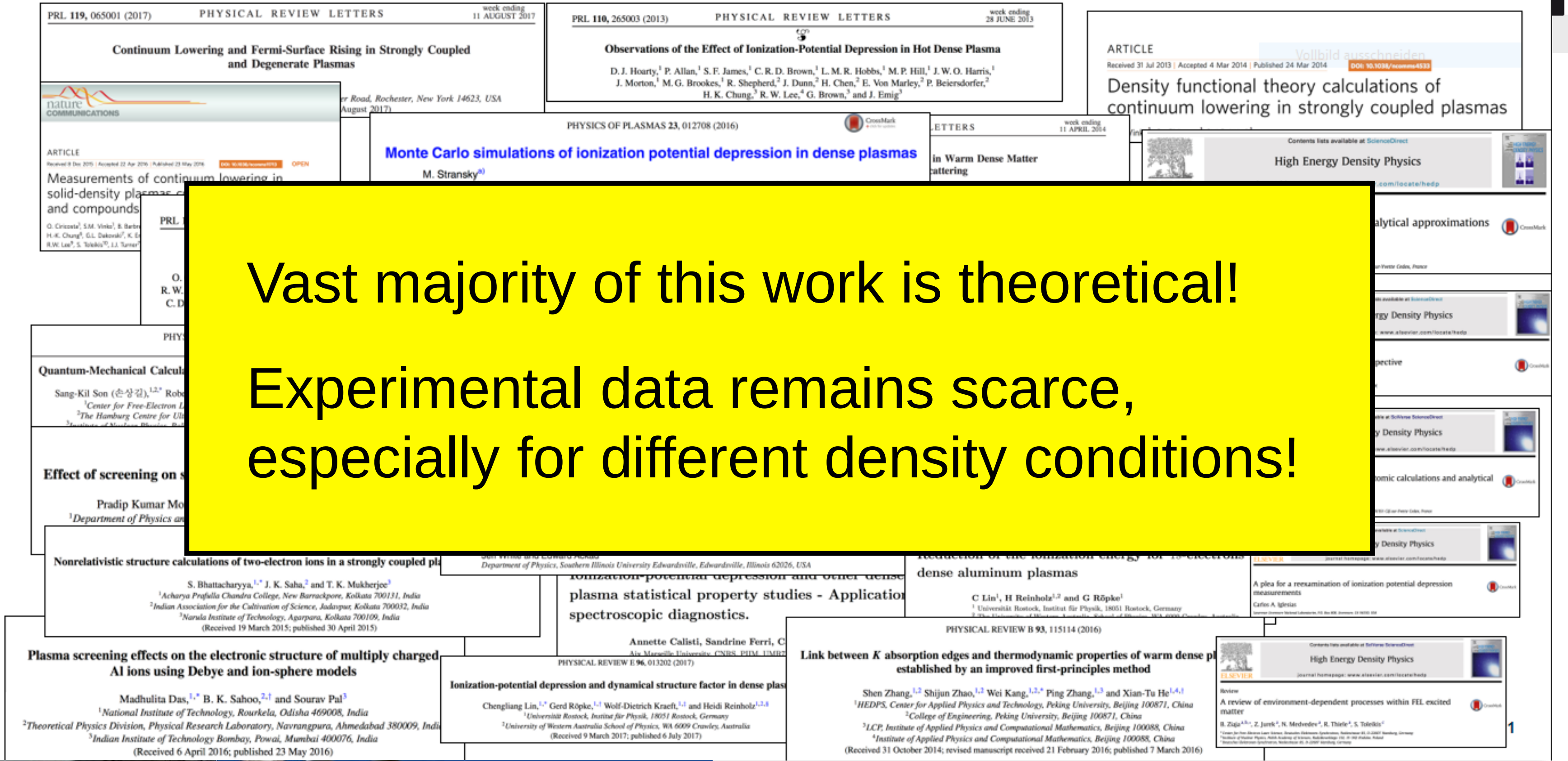


- Heating + compression: Hohlraum drive
- Probing: X-ray scattering

$T \approx 110$eV
$\rho \approx 7x\rho_0$

Kraus *et al.*, PRE (2016)

Disagreements in modelling/experiment have spurred renewed interest



PRL 119, 065001 (2017) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2017

Continuum Lowering and Fermi-Surface Rising in Strongly Coupled and Degenerate Plasmas

PRL 110, 265003 (2013) PHYSICAL REVIEW LETTERS week ending 28 JUNE 2013

Observations of the Effect of Ionization-Potential Depression in Hot Dense Plasma

D. J. Hoarty,[1] P. Allan,[1] S. F. James,[1] C. R. D. Brown,[1] L. M. R. Hobbs,[1] M. P. Hill,[1] J. W. O. Harris,[1] J. Morton,[1] M. G. Brookes,[1] R. Shepherd,[2] J. Dunn,[2] H. Chen,[2] E. Von Marley,[2] P. Beiersdorfer,[2] H. K. Chung,[3] R. W. Lee,[4] G. Brown,[2] and J. Emig[2]

ARTICLE

Received 31 Jul 2013 | Accepted 4 Mar 2014 | Published 24 Mar 2014

Density functional theory calculations of continuum lowering in strongly coupled plasmas

nature COMMUNICATIONS

ARTICLE

Measurements of continuum lowering in solid-density plasmas … and compounds

PHYSICS OF PLASMAS 23, 012708 (2016)

Monte Carlo simulations of ionization potential depression in dense plasmas

M. Stransky[a)]

High Energy Density Physics

Quantum-Mechanical Calcul…

Sang-Kil Son (손상길),[1,2,*] Rob…

Effect of screening on …

Pradip Kumar Mo…

Nonrelativistic structure calculations of two-electron ions in a strongly coupled pl…

S. Bhattacharyya,[1,*] J. K. Saha,[2] and T. K. Mukherjee[3]

(Received 19 March 2015; published 30 April 2015)

Plasma screening effects on the electronic structure of multiply charged Al ions using Debye and ion-sphere models

Madhulita Das,[1,*] B. K. Sahoo,[2,†] and Sourav Pal[3]

(Received 6 April 2016; published 23 May 2016)

plasma statistical property studies - Applicatio… spectroscopic diagnostics.

Annette Calisti, Sandrine Ferri, C…

dense aluminum plasmas

C Lin[1], H Reinholz[1,2] and G Röpke[1]

PHYSICAL REVIEW E 96, 013202 (2017)

Ionization-potential depression and dynamical structure factor in dense plas…

Chengliang Lin,[1,*] Gerd Röpke,[1,†] Wolf-Dietrich Kraeft,[1,‡] and Heidi Reinholz[1,2,§]

(Received 9 March 2017; published 6 July 2017)

PHYSICAL REVIEW B 93, 115114 (2016)

Link between K absorption edges and thermodynamic properties of warm dense pl… established by an improved first-principles method

Shen Zhang,[1,2] Shijun Zhao,[1,2] Wei Kang,[1,2,*] Ping Zhang,[1,3] and Xian-Tu He[1,4,†]

(Received 31 October 2014; revised manuscript received 21 February 2016; published 7 March 2016)

A plea for a reexamination of ionization potential depression measurements

A review of environment-dependent processes within FEL excited matter

Vast majority of this work is theoretical!

Experimental data remains scarce, especially for different density conditions!

Slide courtesy of S. Vinko, U Oxford

Recent experiments test IPD models in dense plasmas

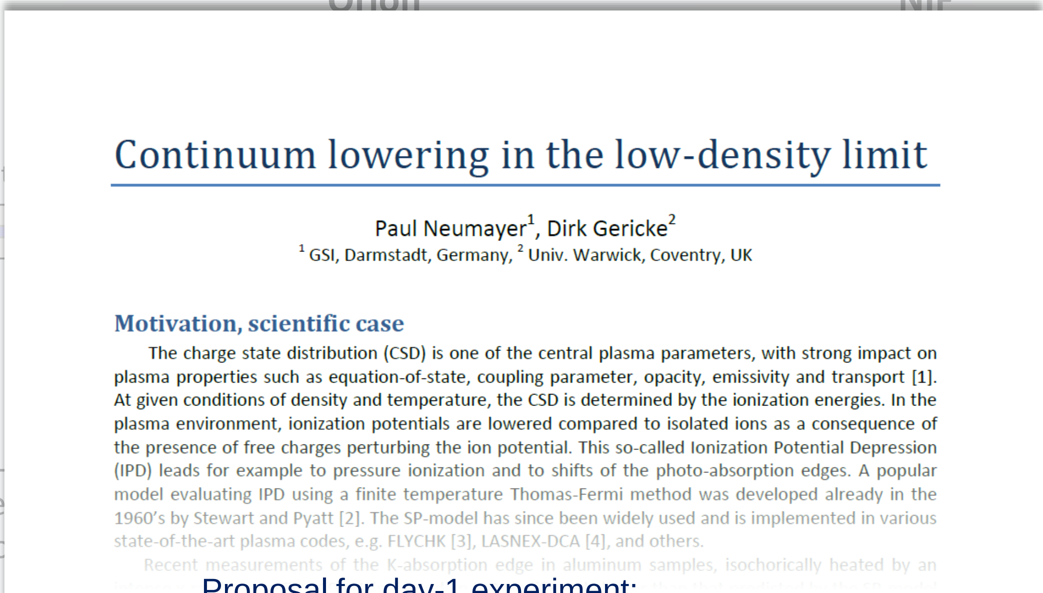
LCLS

- Heating: X-FEL
- Probing: K-she
  (from photo-io

T=70...180eV
$\rho=\rho_0$ (isochor
highly transie

Ciricosta *et al.*, PR

Orion



Continuum lowering in the low-density limit

Paul Neumayer[1], Dirk Gericke[2]
[1] GSI, Darmstadt, Germany, [2] Univ. Warwick, Coventry, UK

Motivation, scientific case

The charge state distribution (CSD) is one of the central plasma parameters, with strong impact on plasma properties such as equation-of-state, coupling parameter, opacity, emissivity and transport [1]. At given conditions of density and temperature, the CSD is determined by the ionization energies. In the plasma environment, ionization potentials are lowered compared to isolated ions as a consequence of the presence of free charges perturbing the ion potential. This so-called Ionization Potential Depression (IPD) leads for example to pressure ionization and to shifts of the photo-absorption edges. A popular model evaluating IPD using a finite temperature Thomas-Fermi method was developed already in the 1960's by Stewart and Pyatt [2]. The SP-model has since been widely used and is implemented in various state-of-the-art plasma codes, e.g. FLYCHK [3], LASNEX-DCA [4], and others.

Recent measurements of the K-absorption edge in aluminum samples, isochorically heated by an

Proposal for day-1 experiment:

Measure Ionization Potential Depression in strongly-coupled Al-plasma

- Heating + expansion by heavy ion pulse
  → create large, homogenous, well-defined sample of strongly-coupled plasma
- Probing: X-ray absorption spectroscopy

NIF

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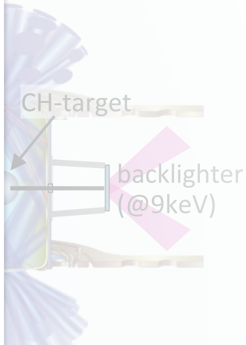


+ compression:
m drive
X-ray scattering

V

l., PRE (2016)

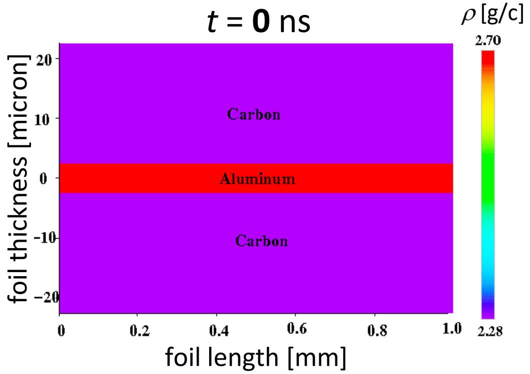
Hydrodynamic simulations show heavy-ion heating and quasi-1D expansion

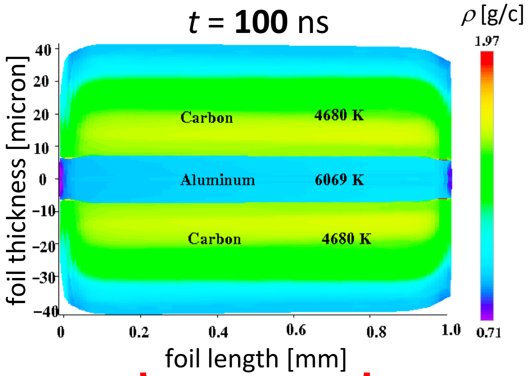
Ion beam parameters:

- 5e10 U-ions
- 1.25 mm FWHM focal spot
- 100 ns pulse duration

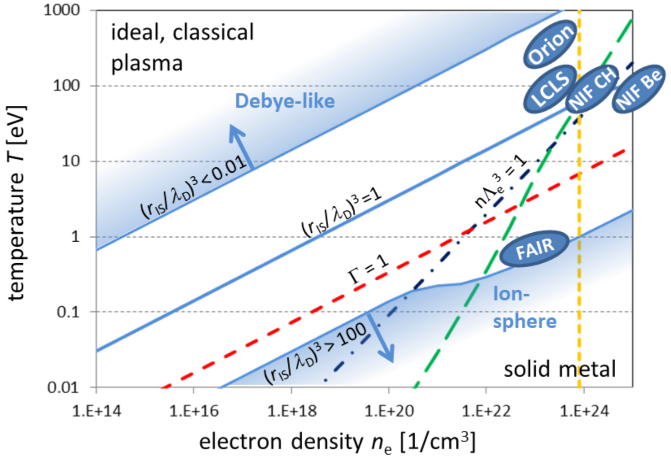
Target:

- Al-foil (5 μm)
- C-tamper (2x20 μm)





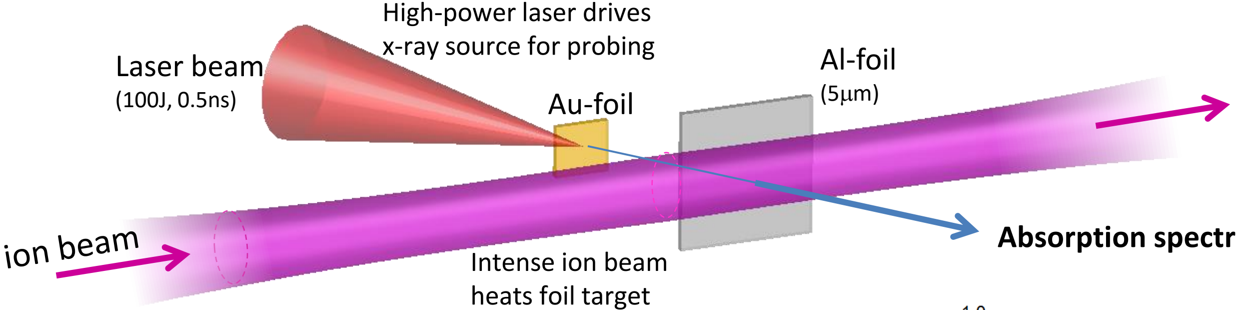
homogenous over >0.5mm !



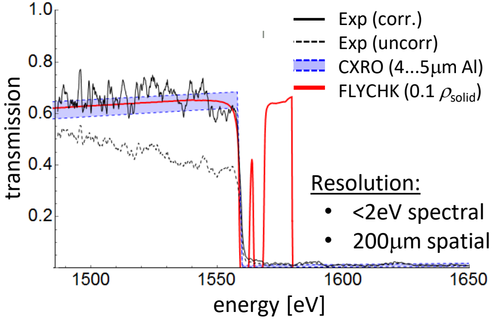
Heavy-ion heating will yield:

- large, homogenous, near-LTE samples
- strongly-coupled, highly degenerate state (i.e. WDM)

Probing by x-ray absorption spectroscopy



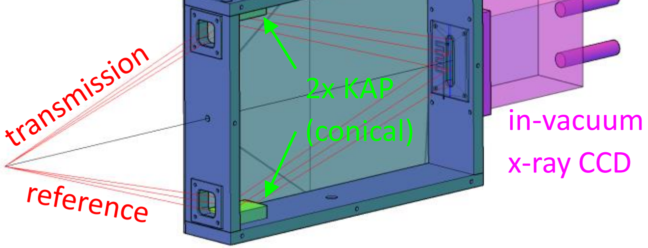
Absorption spectra



- K-edge shift
- M-shell rebinding
- also: XANES/EXAFS

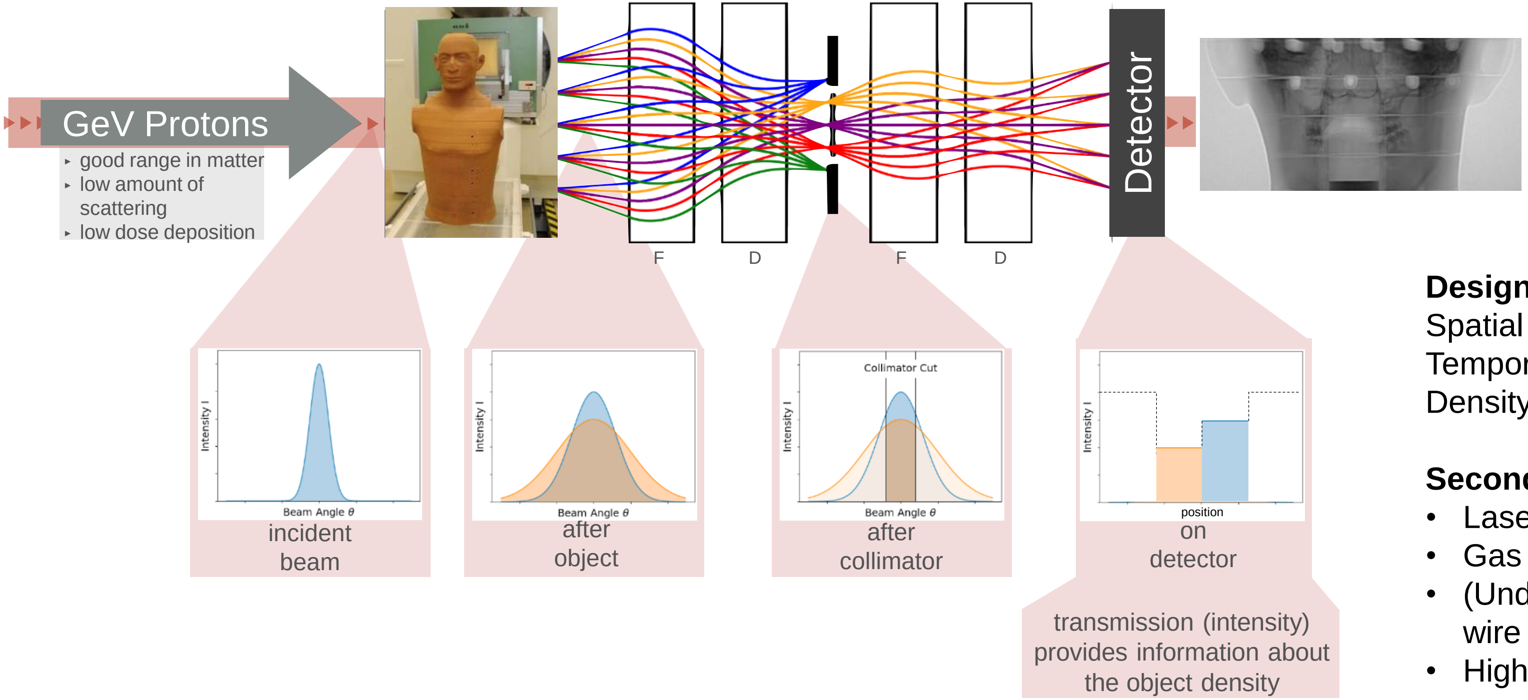
Spectrometer development

- High-resolution dual-channel x-ray spectrometer (C. Spielmann, Univ. Jena)
- Gated x-ray imager (R. Cheng, IMP/Lanzhou)



→ **Experiment will access transition from metal to dense atomic gas**

Proton Microscopy at FAIR (PRIOR): imaging dense samples generated with secondary drivers



GeV Protons

- good range in matter
- low amount of scattering
- low dose deposition

incident beam

after object

after collimator

on detector

transmission (intensity) provides information about the object density

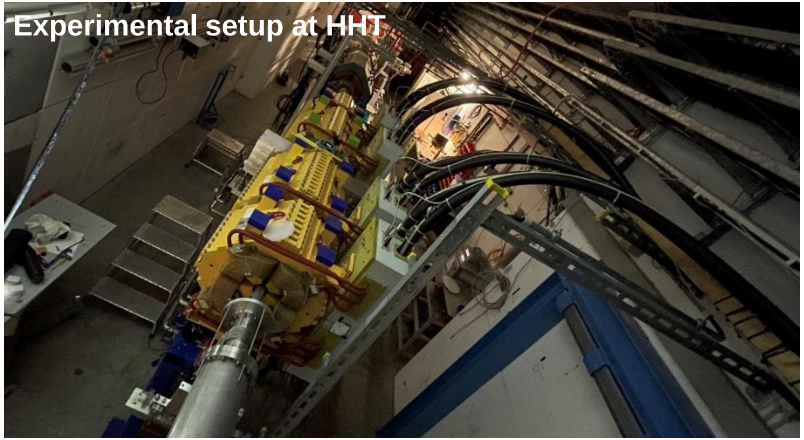
Design goal:
Spatial resolution 10 µm
Temporal resolution 10 ns
Density resolution 1%

Secondary drivers:

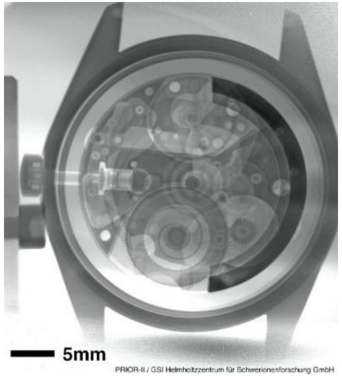
- Laser shocks
- Gas gun
- (Under-water) electric wire explosions
- High-explosives
- …

D. Varentsov et al.,
Rev. Scient. Instrum. 87, 023303 (2016)

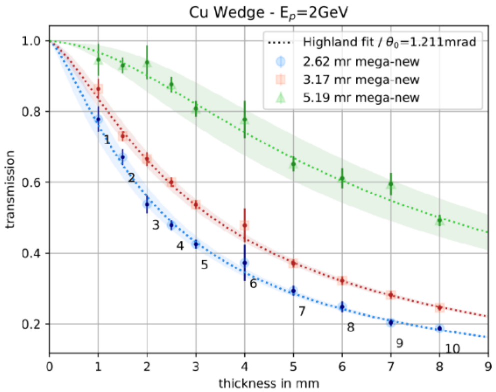
The proton microscope PRIOR has been successfully commissioned in Phase 0 experiments in 2021 & 2022


Experimental setup at HHT

Static imaging (watch)

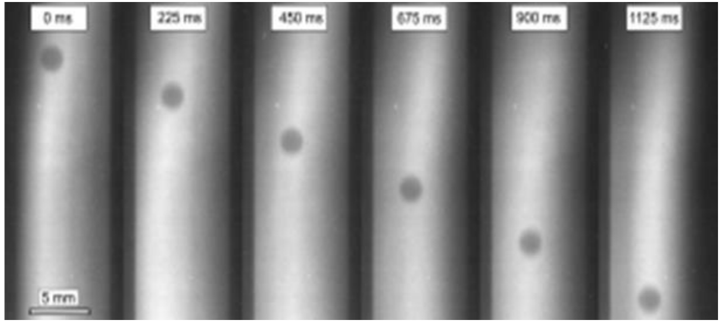


Excellent density resolution



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

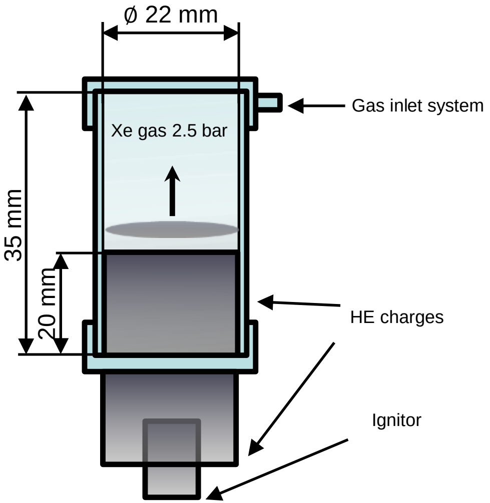
High pressure heated Titanium-vessel →



← Steel ball „falling“ in liquid Sulfur

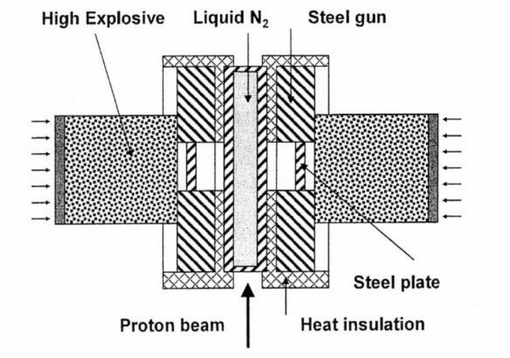
Compact HE generators can be used to create shocked samples to be studied with PRIOR

Example 1: Shock-Compressed Non-Ideal Plasmas of Rare Gases

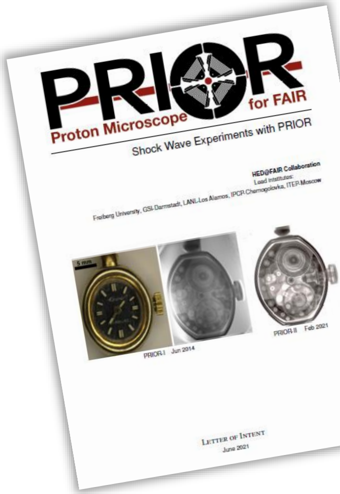


M_{HE} ~ 30 g
p ~ 10 kbar
T ~ 3 eV

Example 2: Phase Transitions in Molecular Liquids at High Pressures



M_{HE} ~ 60 g
p ~ 600 kbar
u_S ~ 3 km/s



PRIOR for FAIR
Proton Microscope
Shock Wave Experiments with PRIOR

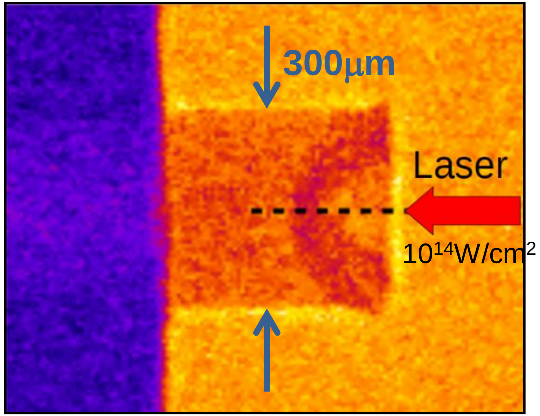
HED@FAIR Collaboration
Lead institutes:
Freiberg University, GSI-Darmstadt, LANL-Los Alamos, IPCP-Chernogolovka, ITEP-Moscow

Letter of Intent
June 2021

- PRIOR will offer unique possibilities to diagnose explosively-driven shock wave experiments
- A letter-of-intent for explosively driven experiments has been submitted to FAIR for evaluation
- Once the science case is approved by FAIR, preparations (technical, applying for needed permits) will start

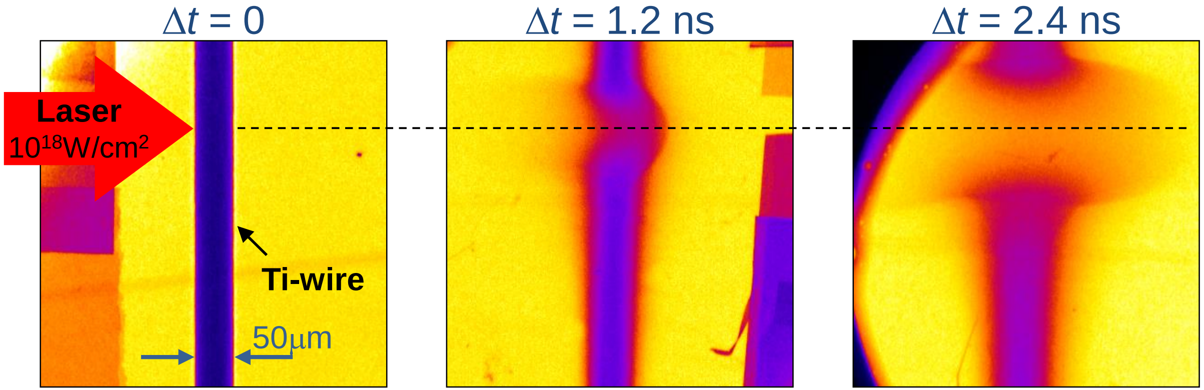
PHELIX: Laser-driven x-ray sources for high-resolution x-ray radiography

Spherical shock propagation in polystyrol-cylinder



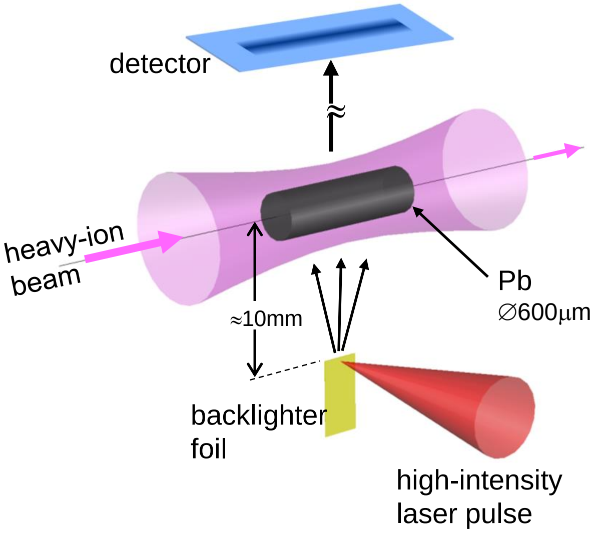
L. Antonelli et al., EPL **125**, 3 (2019)

Hydro-evolution of „isochorically heated“ wires

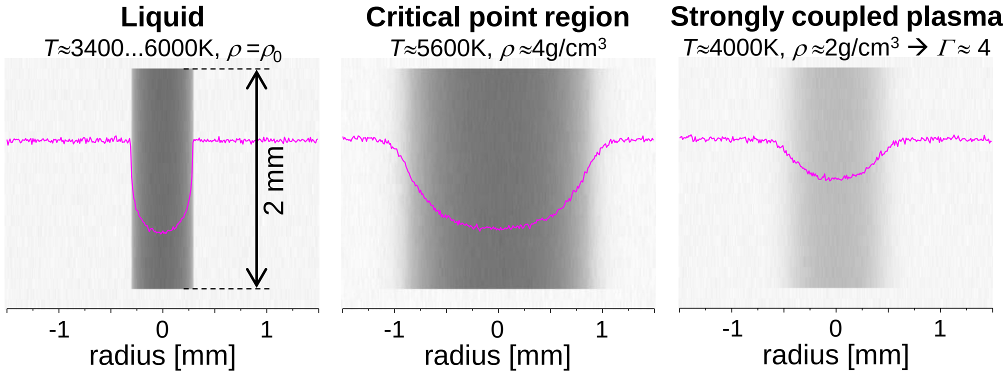

$\Delta t = 0$ $\Delta t = 1.2$ ns $\Delta t = 2.4$ ns

Laser-driven x-ray radiography as density diagnostic in HIHEX experiments

HIHEX + laser-driven radiography



Simulated radiographs


Liquid

$T\approx3400\ldots6000\mathrm{K}$, $\rho=\rho_0$

Critical point region

$T\approx5600\mathrm{K}$, $\rho\approx4\mathrm{g/cm^3}$

Strongly coupled plasma

$T\approx4000\mathrm{K}$, $\rho\approx2\mathrm{g/cm^3} \rightarrow \Gamma\approx4$

Demonstration at PHELIX

Laser parameters:

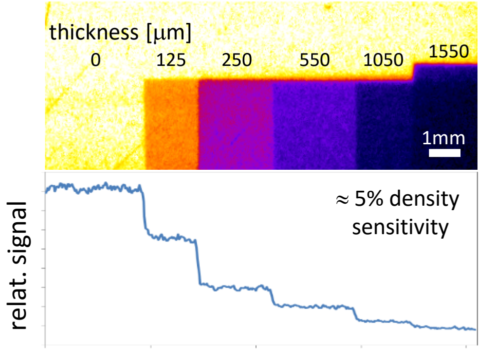
E_L=120 J

τ_p = 0.6 ps

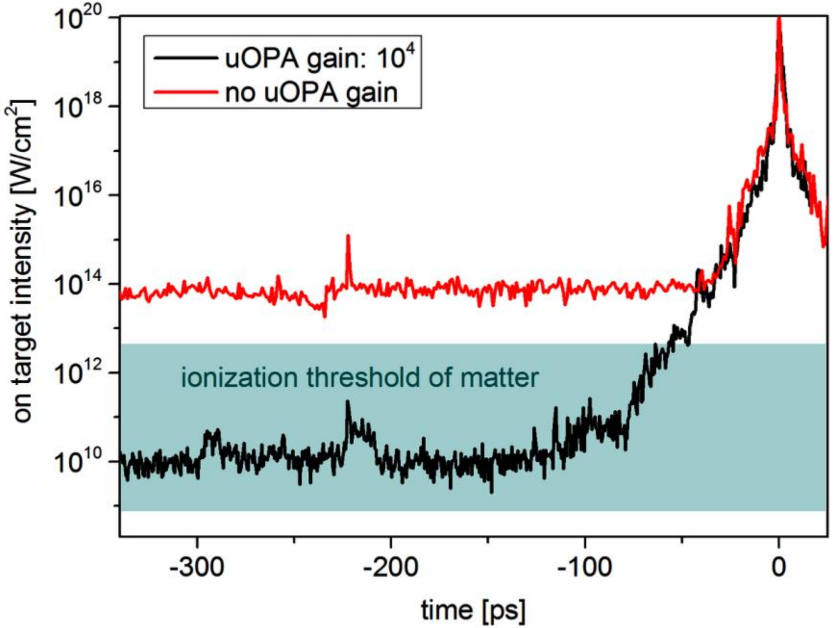
Target:

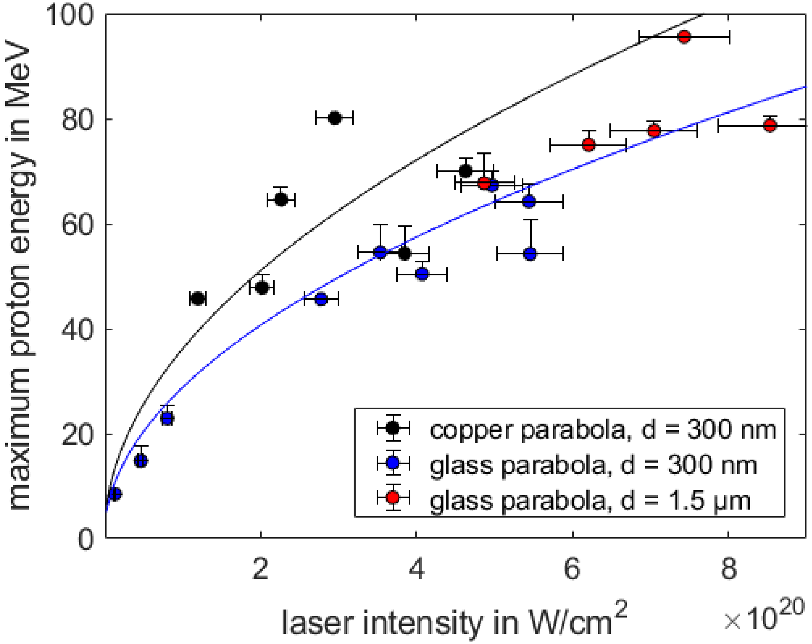
Au-foil

(5.3µm)



Performance of PHELIX

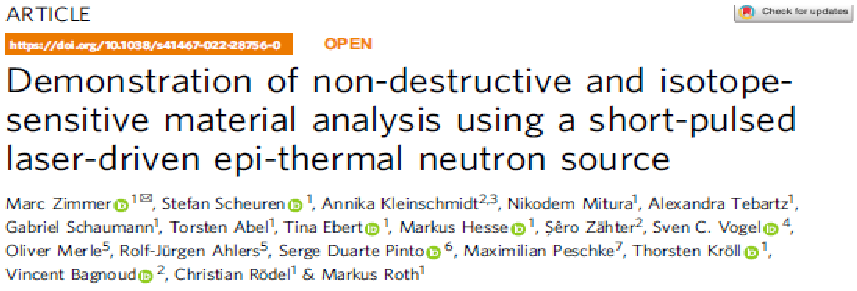




- Using ultrafast optical parametric amplifier (uOPA) temporal contrast of 10^6 to $\mathbf{10^{11}}$ can be applied

- Improvement of beam transport, implementation of a deformable mirror and focussing by a glass parabola; max. proton energy increased from 80 MeV to **93 MeV**

Demonstration of laser-driven neutron resonance spectroscopy (NRS) with PHELIX



ARTICLE

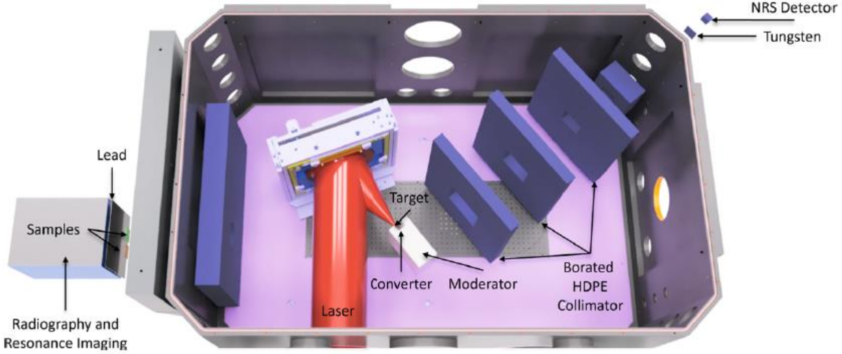
Check for updates

https://doi.org/10.1038/s41467-022-28756-0

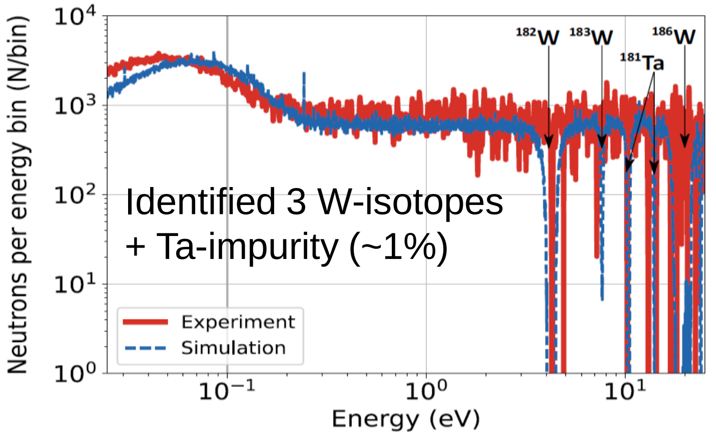
OPEN

Demonstration of non-destructive and isotope-sensitive material analysis using a short-pulsed laser-driven epi-thermal neutron source

Marc Zimmer[1✉], Stefan Scheuren[1], Annika Kleinschmidt[2,3], Nikodem Mitura[1], Alexandra Tebartz[1], Gabriel Schaumann[1], Torsten Abel[1], Tina Ebert[1], Markus Hesse[1], Şêro Zähter[2], Sven C. Vogel[4], Oliver Merle[5], Rolf-Jürgen Ahlers[5], Serge Duarte Pinto[6], Maximilian Peschke[7], Thorsten Kröll[1], Vincent Bagnoud[2], Christian Rödel[1] & Markus Roth[1]

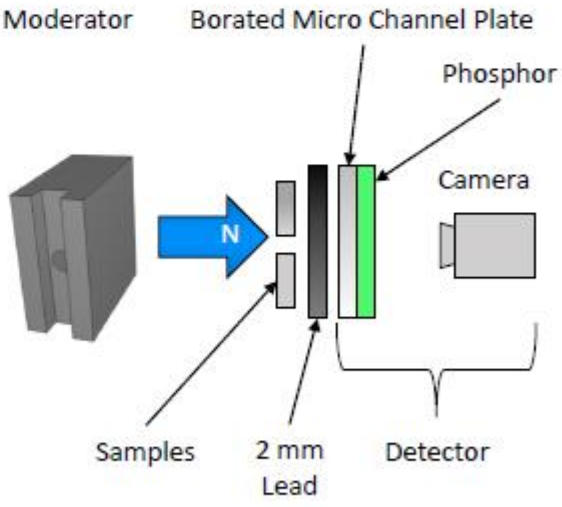


- PHELIX accelerates protons and deuterons to create intense neutron bursts in a converter (>10^{10} per shot)
- Neutrons are moderated for application in neutron resonance absorption spectroscopy (~4×10^7 n_{th}/sr/shot)

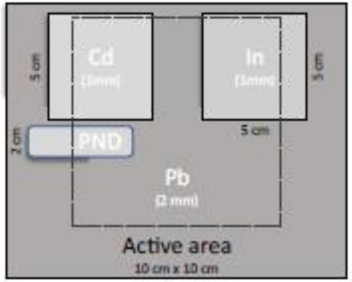


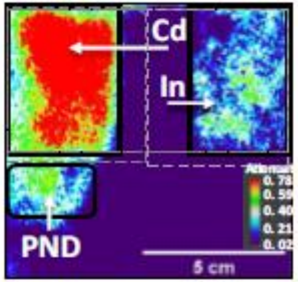
Identified 3 W-isotopes + Ta-impurity (~1%)

Laser-driven thermal neutron radiography

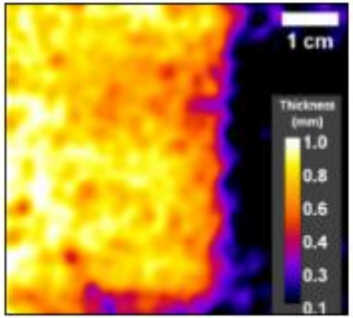


[Zimmer et al., Nat. Commun. (2022)]

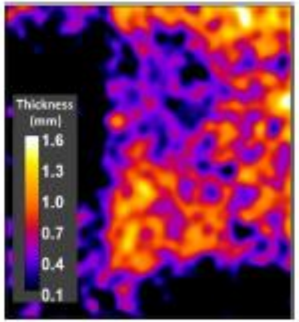




Reconstructed Cd thickness



Reconstructed In thickness

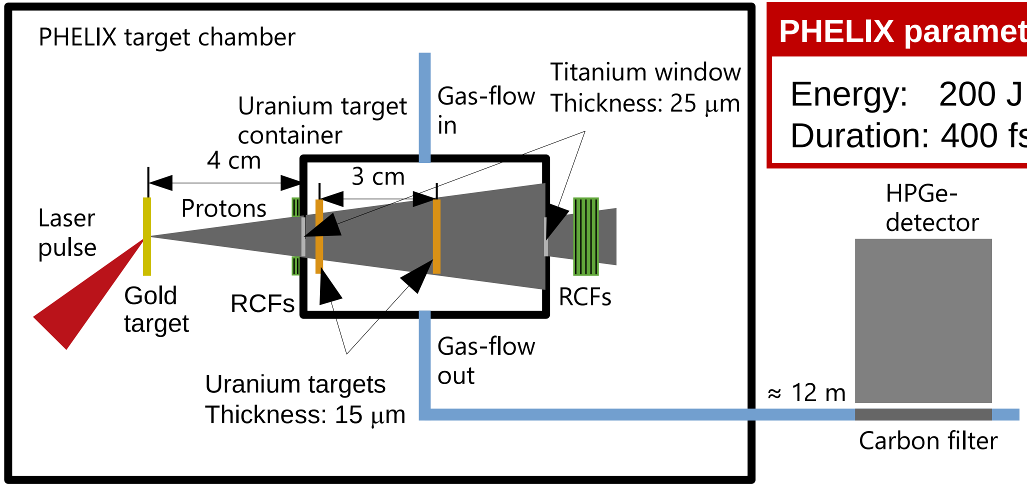


Single shot
Neutron
radiography

3 shots:
Determine
thickness
± 200 µm
and position
± 2 mm

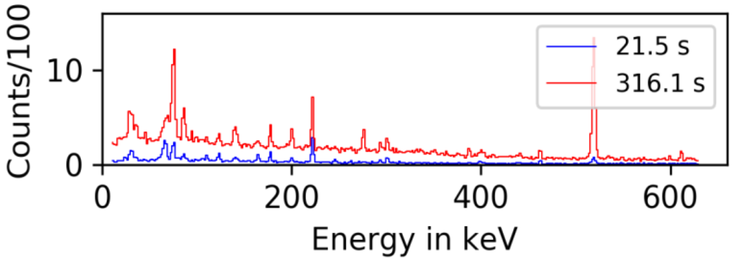
Fission of ^{nat}U with laser-driven protons at PHELIX

- PHELIX generates high proton fluxes (10^{12} p^+/pulse above 15 MeV ≈ 10^{22} p^+/sec.)
- Laser-induced nuclear physics
  - Fission in HED Environment
  - relevant for Nuclear Astrophysics
- Successful demonstration of a gas-transport-based detection method
- Identified short-lived nuclides: ^{134}I, ^{136}I, ^{137}Xe, ^{138}Xe, ^{139}Xe and ^{140}Cs (half-lives shorter than 40 s)



PHELIX parameters

Energy: 200 J
Duration: 400 fs



Gamma spectrum

time-resolved spectra facilitate nuclide identification

Lawrence Livermore National Laboratory

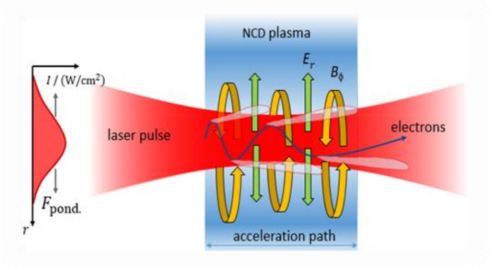
TECHNISCHE UNIVERSITÄT DARMSTADT

PHELIX

P. Boller et al., Scientific reports, **8**, 2020

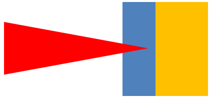
Strongly enhanced generation of directed MeV electrons in low-density polymer aerogels

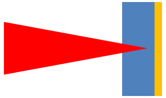
Direct laser acceleration in near-critical density plasma

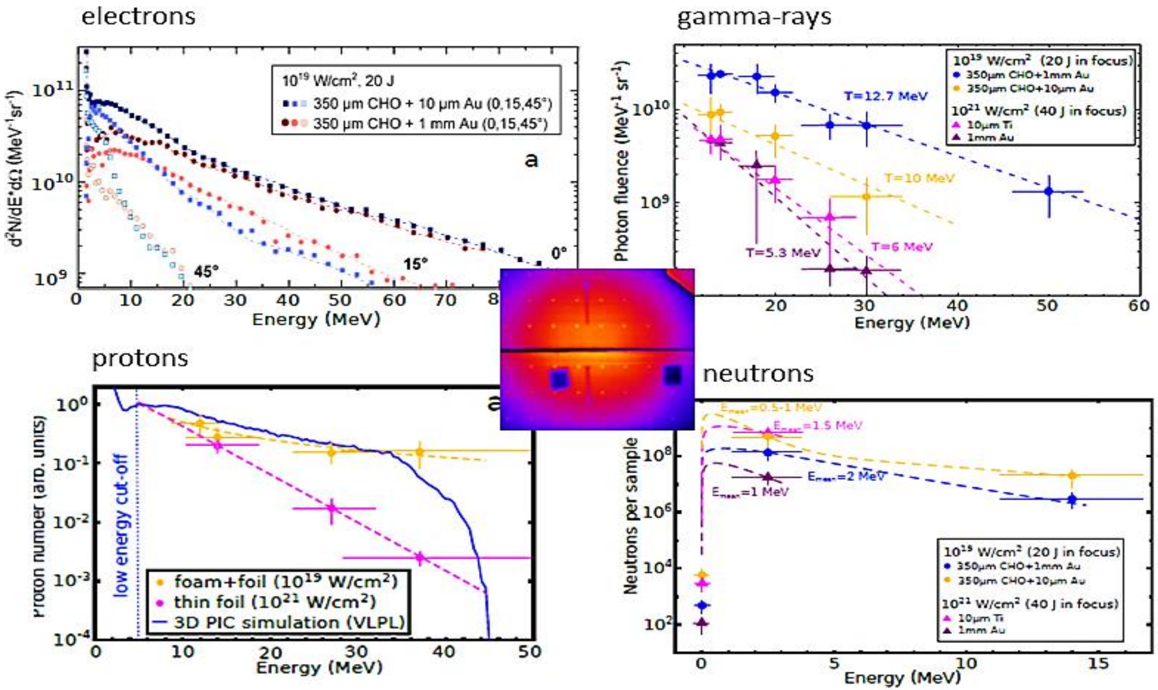


Intense sources of protons, gamma-rays and neutrons

foam + convertor	foam + thin foil
→ gammas	→ protons
→ positrons, neutrons	→ neutrons







M. M. Günther, O.N. Rosmej et al., Nat. Commun. 13, 170 (2022)

Summary

Within FAIR Phase-0 the HED@FAIR collaboration has exciting opportunities for HED-science experiments

- Experiments with intense ion pulses at the HHT-cave
  - Heavy-ion heating for generation of extreme matter states
  - New laser beamline from PHELIX enables x-ray probing schemes
  - IPD-measurements on HI-driven samples planned as day-1 experiment
  - PRIOR: a unique high-energy proton microscope for dynamic experiments
- Intense laser-matter experiments at PHELIX
  - Development of high-flux sources (x-ray, protons, neutrons, gamma) for applications (x-ray backlighting, neutron-imaging, nuclear reactions)

Thanks for your attention!