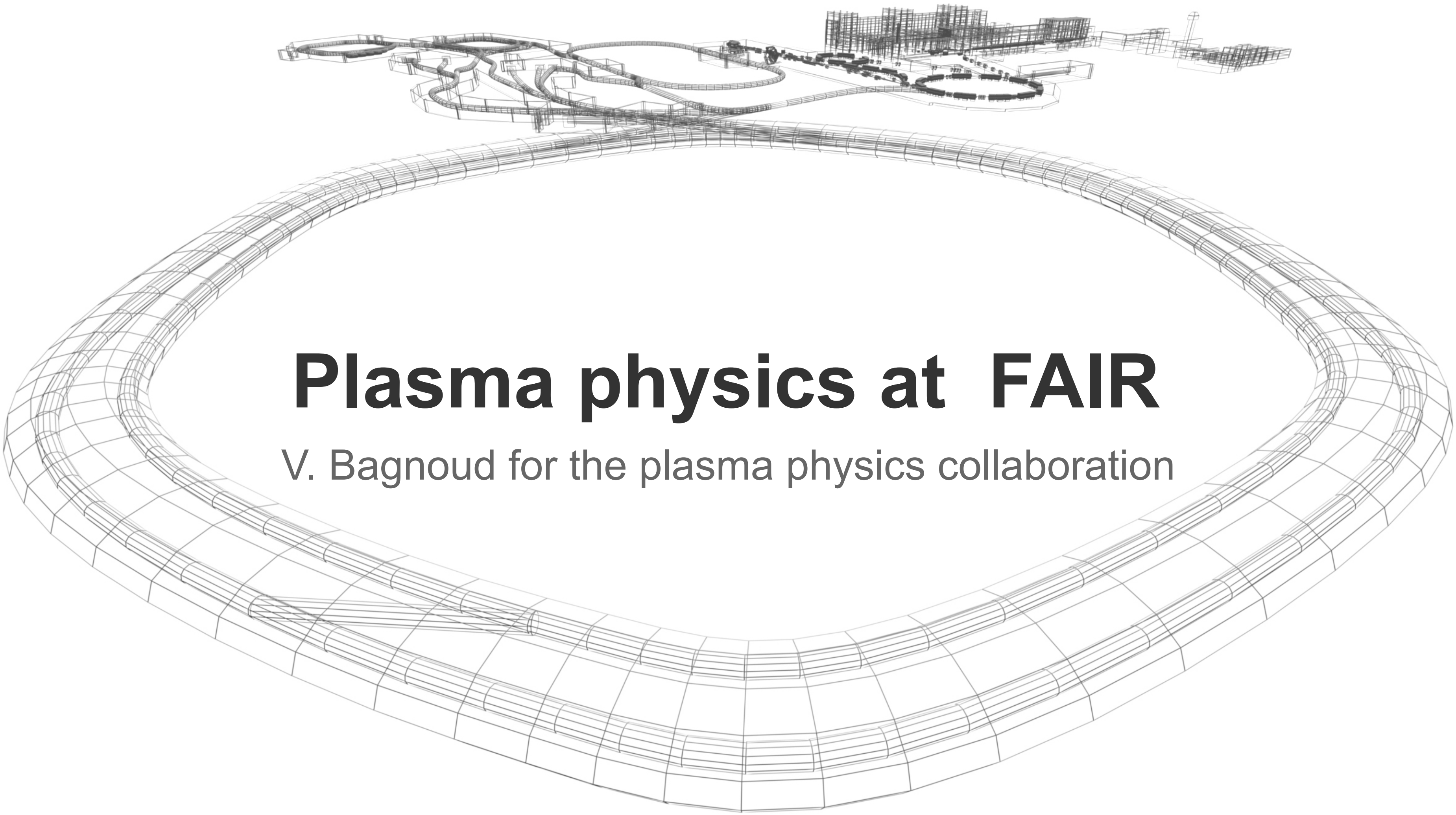
GSI Helmholtzzentrum für Schwerionenforschung GmbH

Plasma physics at FAIR

V. Bagnoud for the plasma physics collaboration

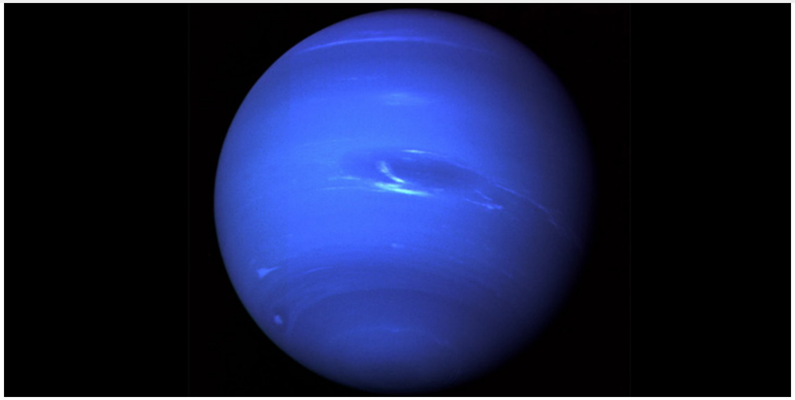


FAIR is a very attractive driver for plasma physics

- Plasma physics is pertinent to some outstanding planetary science questions but also it is a field that can be studied at FAIR on its own.
- Compared to other drivers, FAIR offers many unique advantages: quasi-equilibrium and mesoscopic scales.
- FAIR-generated plasma require power diagnostics.
  - pump-probe setups are standard in plasma physics
  - laser-generated sources of particles (ions, electrons) used to generate tertiary sources (neutrons, X-rays) offer the most promising solution for direct measurement of plasma parameters

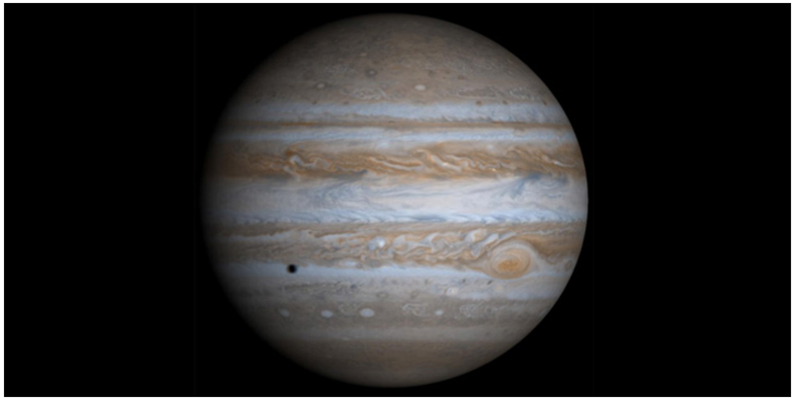
Current questions in planetary science are relevant to plasma physics

- **Are there diamond layers in Uranus and Neptune? – Ross *et al.*, Nature 292 435 (1981)**



- **Does high density metallic state of water contribute to sustaining magnetic field in Uranus and Neptune? (Stevenson *et al.*, Rep. Prog. Phys. 46, 555, 1983)**

- **What is equation of state of H across range of conditions for Jupiter, how does it separate from He? (Nepelman *et al.,* Astrophys. J 683 1217, 2008)**



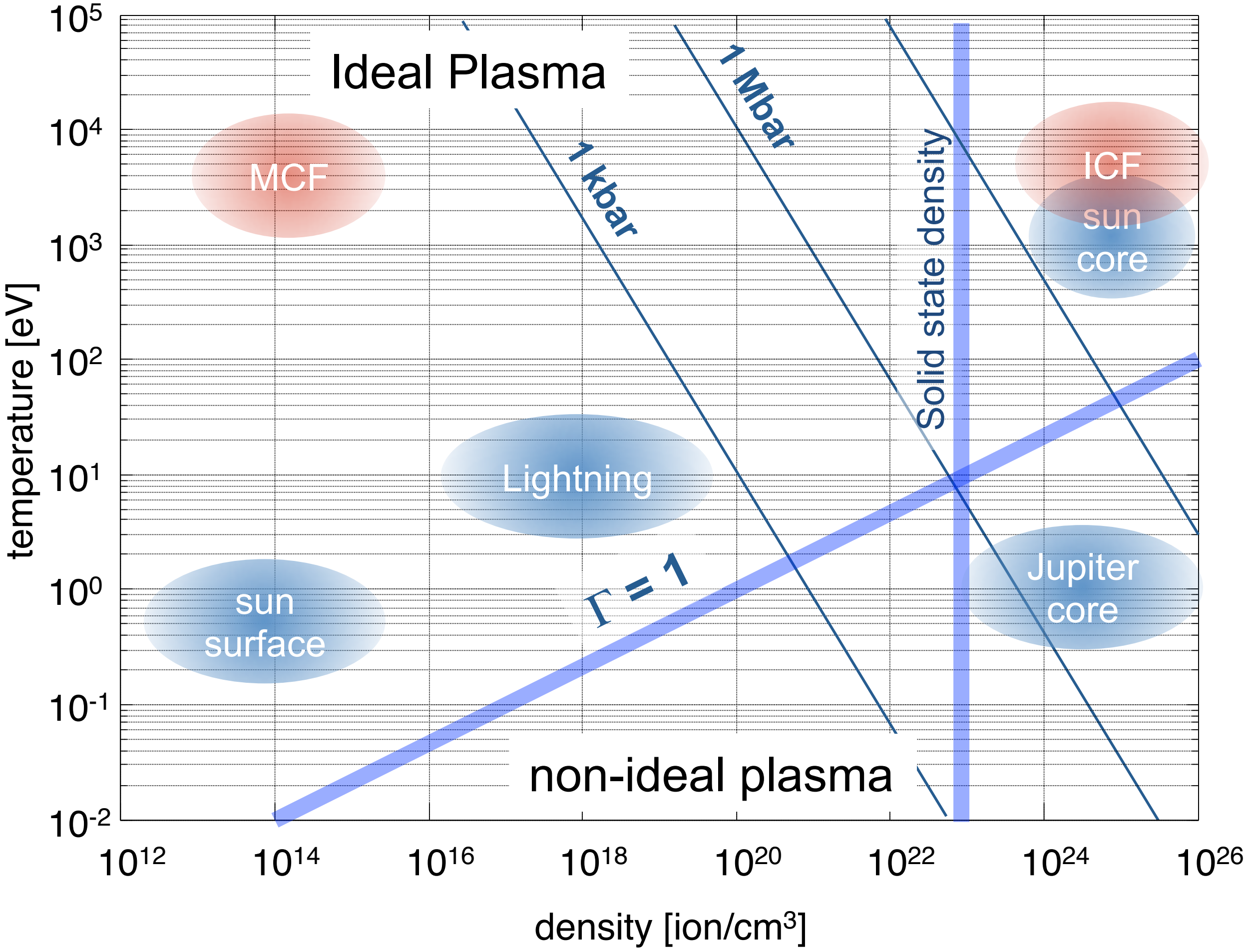
- **What is exact melting curve for Fe? (Anzellini *et al.*, Science 340, 2013)**

Dense plasmas are strongly correlated many particle quantum systems

- A great challenge for theory:
  - Strong coupling: $E_{pot} > kB_T$
  - Collisions (conductivity, heat transport)
  - Partial ionization
  - Continuum lowering

- Exotic states, complex properties:
  - Equation of state, melting + phase transitions, transport properties, metallization,...
  - Transport properties (heat, radiation), equilibration,...., non-equilibrium states
  - Interaction of ions and photons with plasma
  - Atomic & nuclear physics in dense plasmas

Plasma are found in many flavors

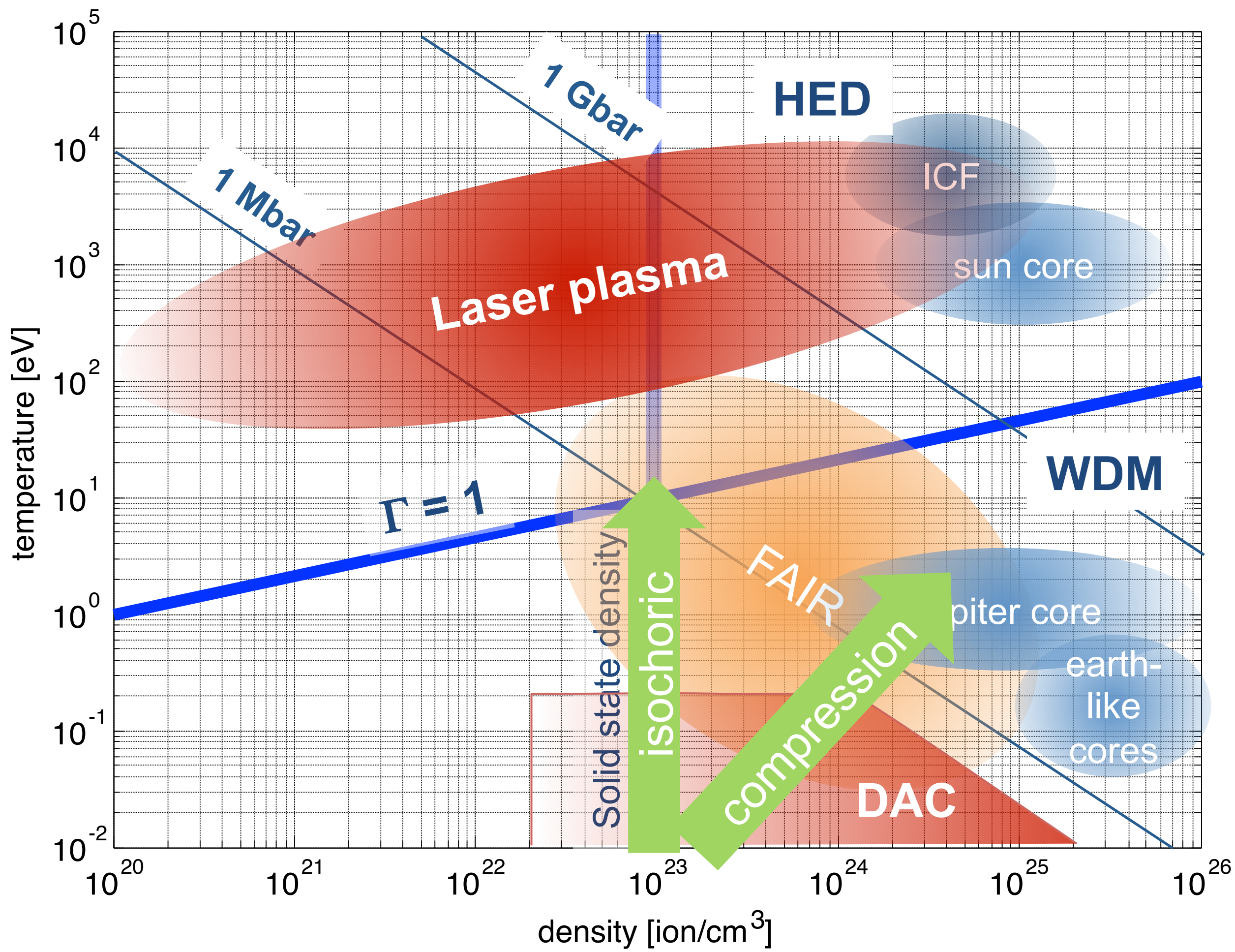


- **Plasma coupling parameter:**

$$\Gamma = E_{Coulomb} / k_B T$$

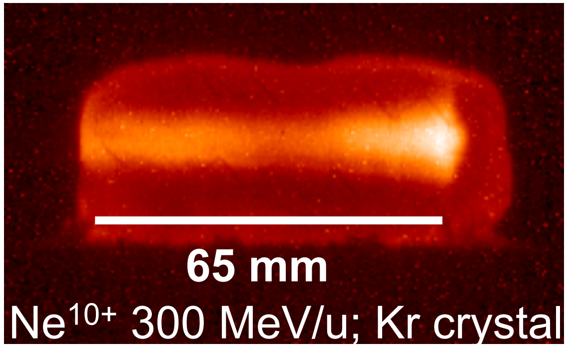
- **When Γ >1, plasma difficult to describe**

FAIR offers a unique alternative to other driver techniques



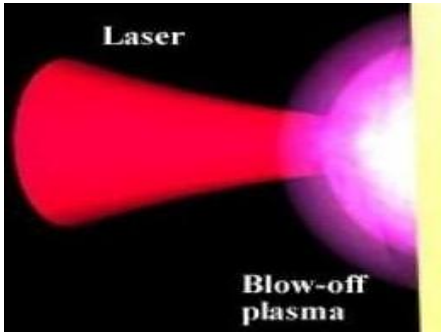
FAIR-driven plasma have also other advantages

Intense, energetic beams of heavy ions (GSI & FAIR)



large sample volume (mm^3)
uniform physical conditions
any target material
long time scales (50 ns)

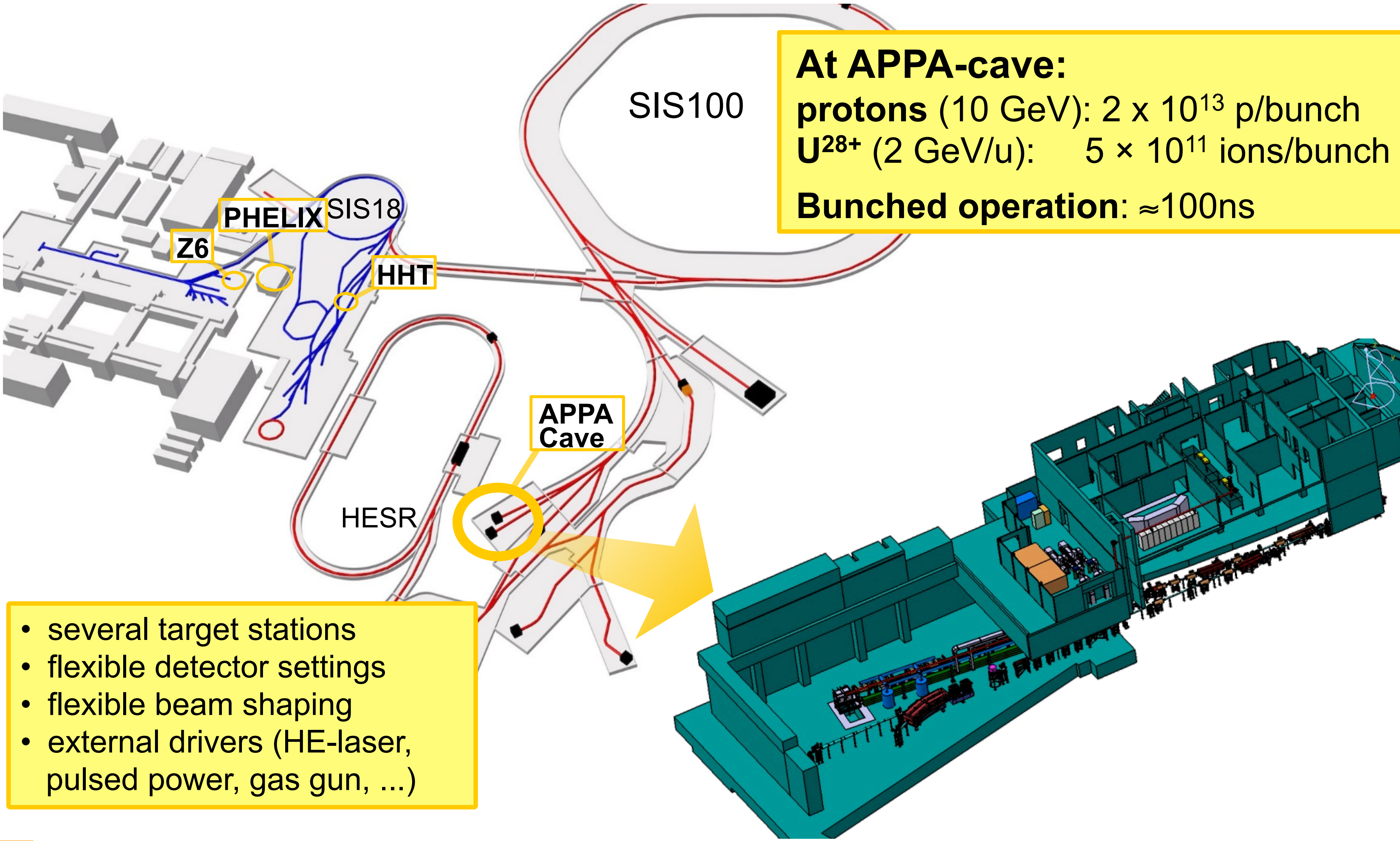
High-brilliance XUV photon sources (XFEL & DESY)



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

- **Advantages of FAIR-generated plasma:**
  - **large samples**
  - **local thermodynamical equilibrium**
  - **uniform samples**

The APPA Cave

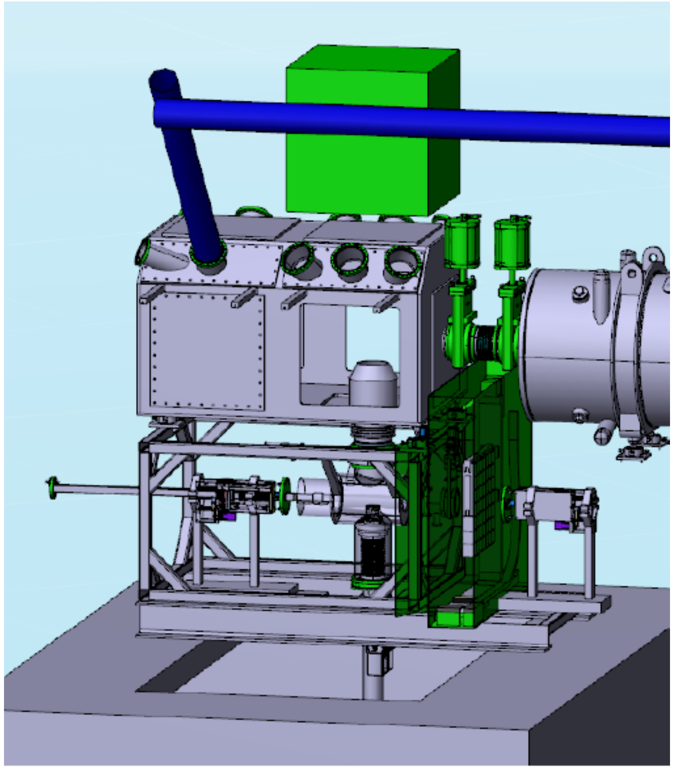


At APPA-cave:
protons (10 GeV): 2 x 10^{13} p/bunch
U^{28+} (2 GeV/u): 5 × 10^{11} ions/bunch
Bunched operation: ≈100ns

- several target stations
- flexible detector settings
- flexible beam shaping
- external drivers (HE-laser, pulsed power, gas gun, ...)

Specificities of the FAIR experiments

- Complicated experiment conditions
  - Large amount of debris per shots and repetition rates require robust diagnostics
  - large activation (in-target ion stopping) limit the repetition rate
  - Fully remote target positioning and exchange
- Enhanced diagnostic setups
  - Backlighting is necessary (not in the starting phase)
  - High-energy backlighter mandatory because of the large volumes
  - "safety" distance between optics and target



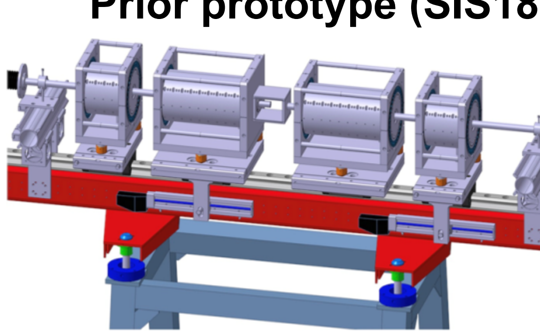
Target station in the APPA Cave

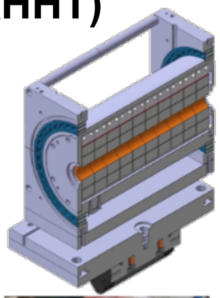
A high-energy laser is the most versatile and efficient diagnostic driver

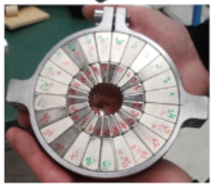
FAIR as a proton microscope

- **Proton-beams from FAIR will enable unprecedented capabilities**
  - **High-magnification: 10 μm spatial resolution**
  - **High field-of-view: several cm**
  - **Intense proton pulses → high density contrast even for short (10ns) exposure**

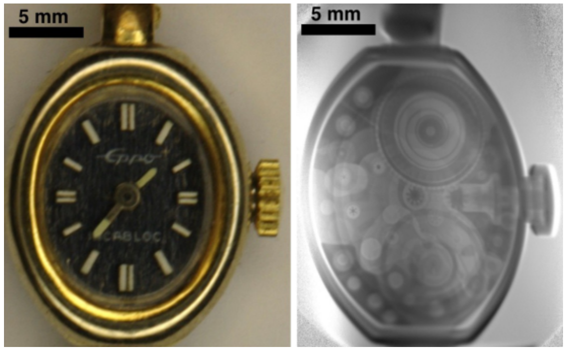
Recent successful demonstration of Prior prototype (SIS18@HHT)



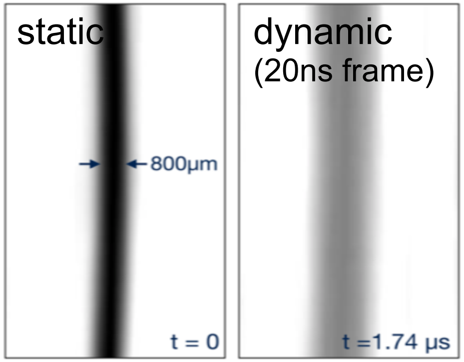




High resolution static images with 30μm spatial resolution



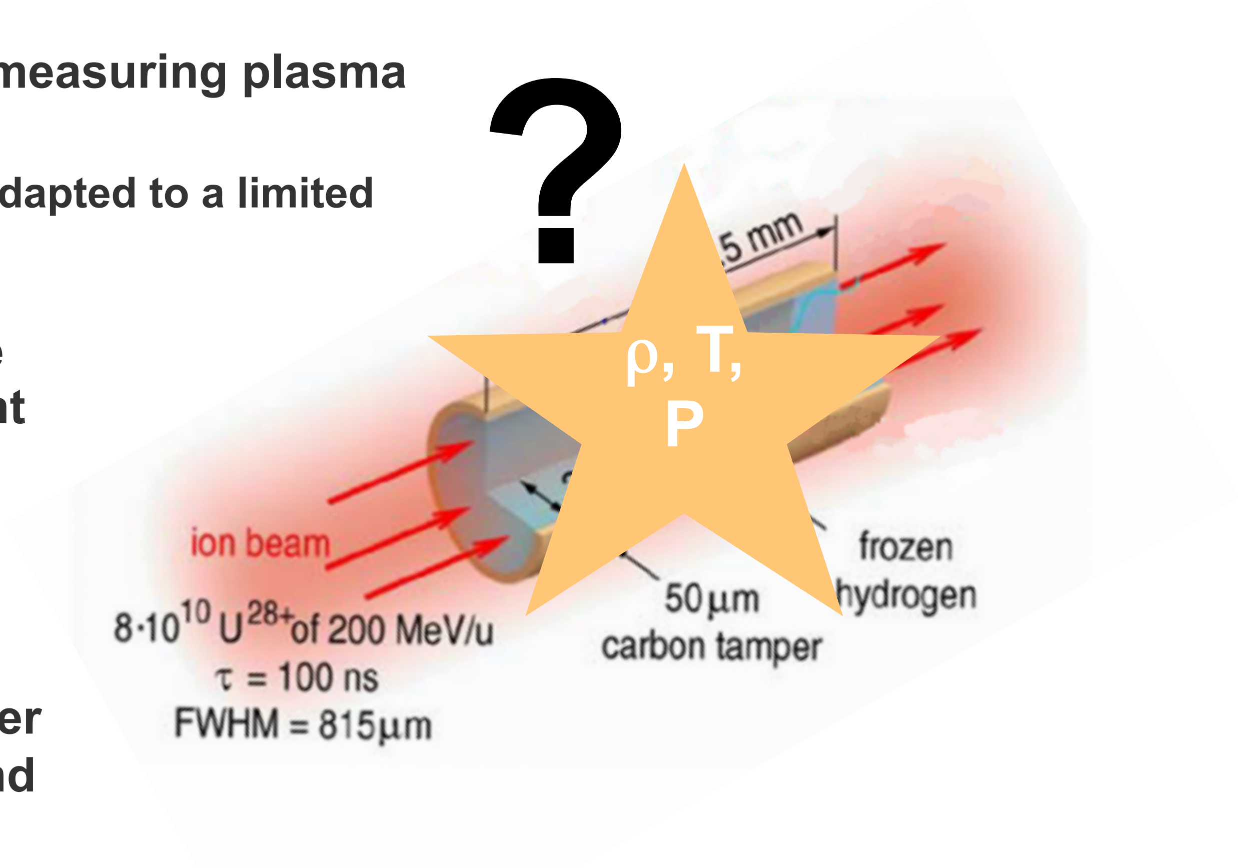
Framing mode for dynamical events (Underwater electrical wire explosion)



PRIOR should be used with external drivers (pump-probe)

Pump probe experiments

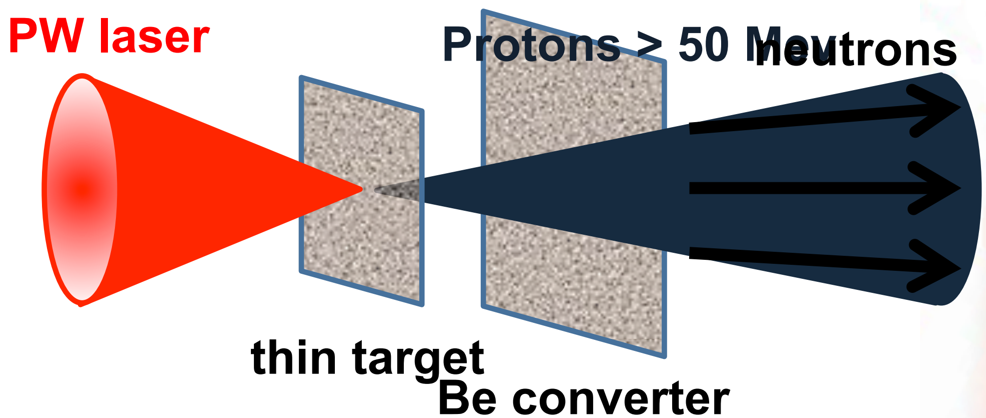
- Plasma physics relies on measuring plasma parameters
  - surface diagnostics are adapted to a limited numbers of configuration
- Pyrometry allows surface temperature measurement that are:
  - time-resolved
  - spatially resolved
- VISAR measurements offer information on shocks and indirectly on pressures
  - quasi one-dimensional geometry required

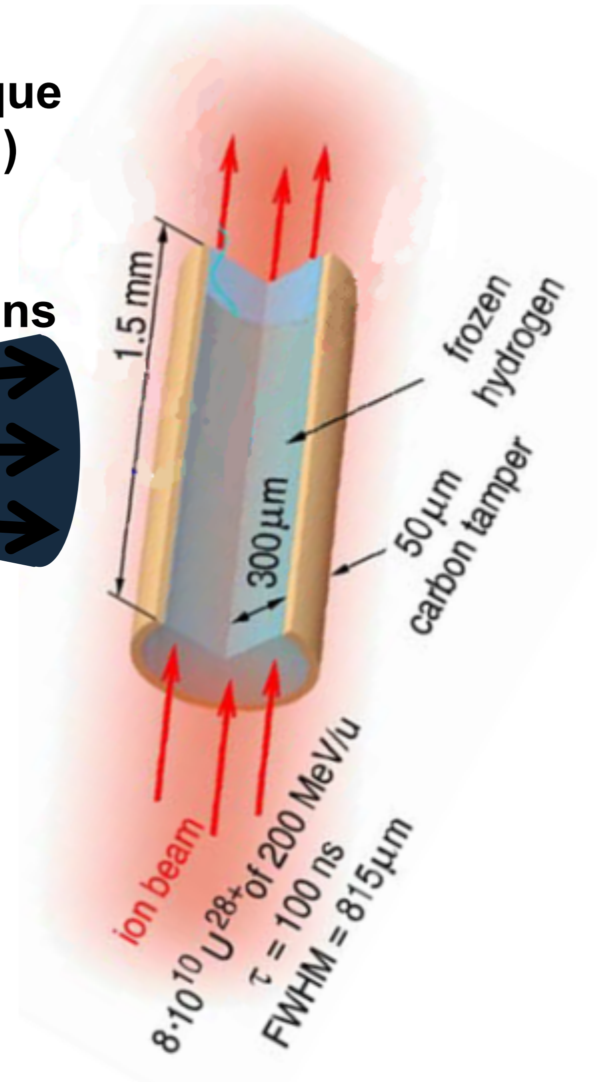


Volumetric measurements are mandatory with FAIR targets

Diagnostics based on laser-accelerated particles

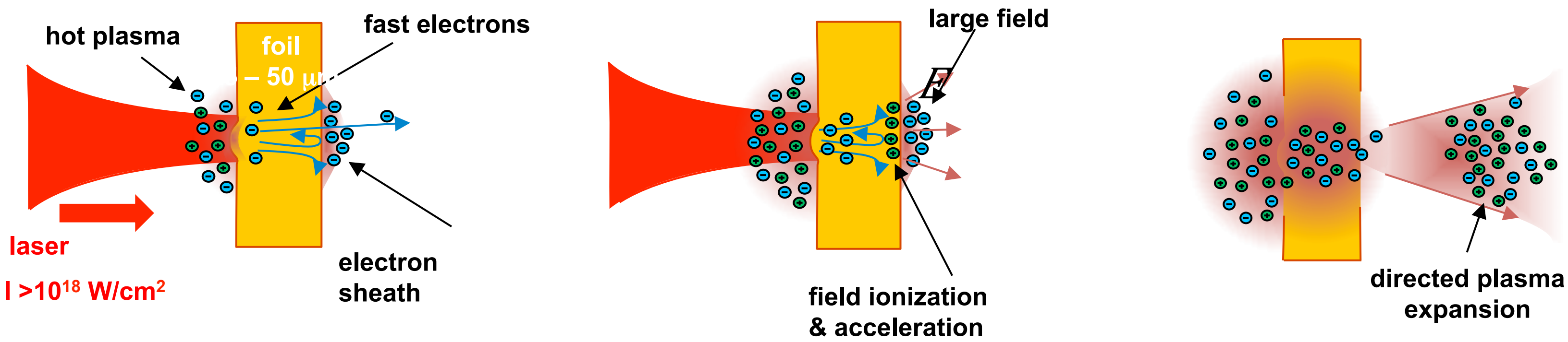
- **Proton imaging can be applied exploiting the unique properties of such beams (sub ns resolution etc...)**





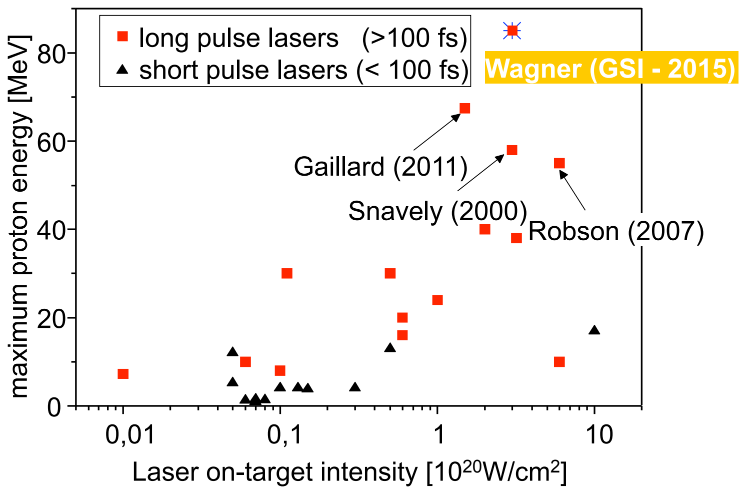
- **Advanced schemes are even more promising**
  - **laser driven neutron sources**
  - **proton beam transport**

Laser-driven proton and neutron sources as diagnostics



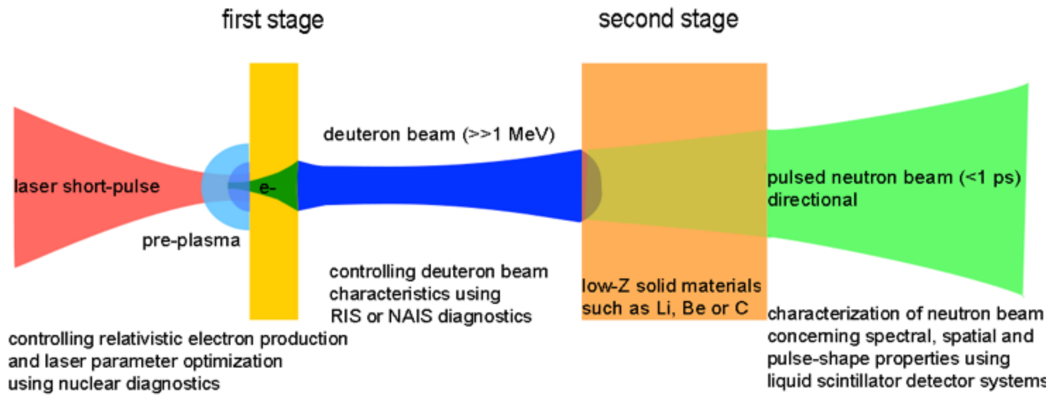
- **GSI belongs to the leading laboratories when it comes to laser-driven particle acceleration. Highlights are:**
  - **record-high proton energies and numbers obtained at PHELIX[1]**
  - **host-lab for the LIGHT[2] (Laser Ion Generation Handling and Transport) experiment**

Proton source performance (cut-off energy) at various facilities



1 - F. Wagner et al. PRL **116**, 205002 (2016)
2 - S. Budold et al. Scientific reports **5** (2015)

A direct application of proton/deuteron sources[1] is the temperature measurement of WDM states



- **Laser–driven deuterons produce large neutron numbers when a moderator is employed**
- **Laser-driven neutrons are produced in sufficient numbers**
- **first conclusive proof-of-principle experiments on neutron resonance spectroscopy**

Shock Temperature Measurement Using Neutron Resonance Spectroscopy

V. W. Yuan, J. David Bowman, D. J. Funk, G. L. Morgan, R. L. Rabie, C. E. Ragan, J. P. Quintana, and H. L. Stacy
Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA
(Received 3 September 2004; published 30 March 2005)

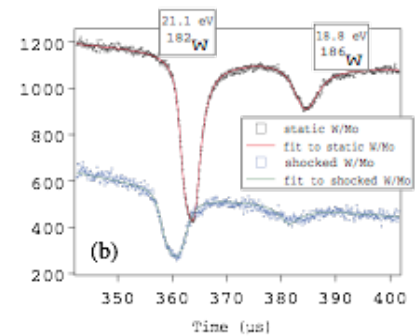


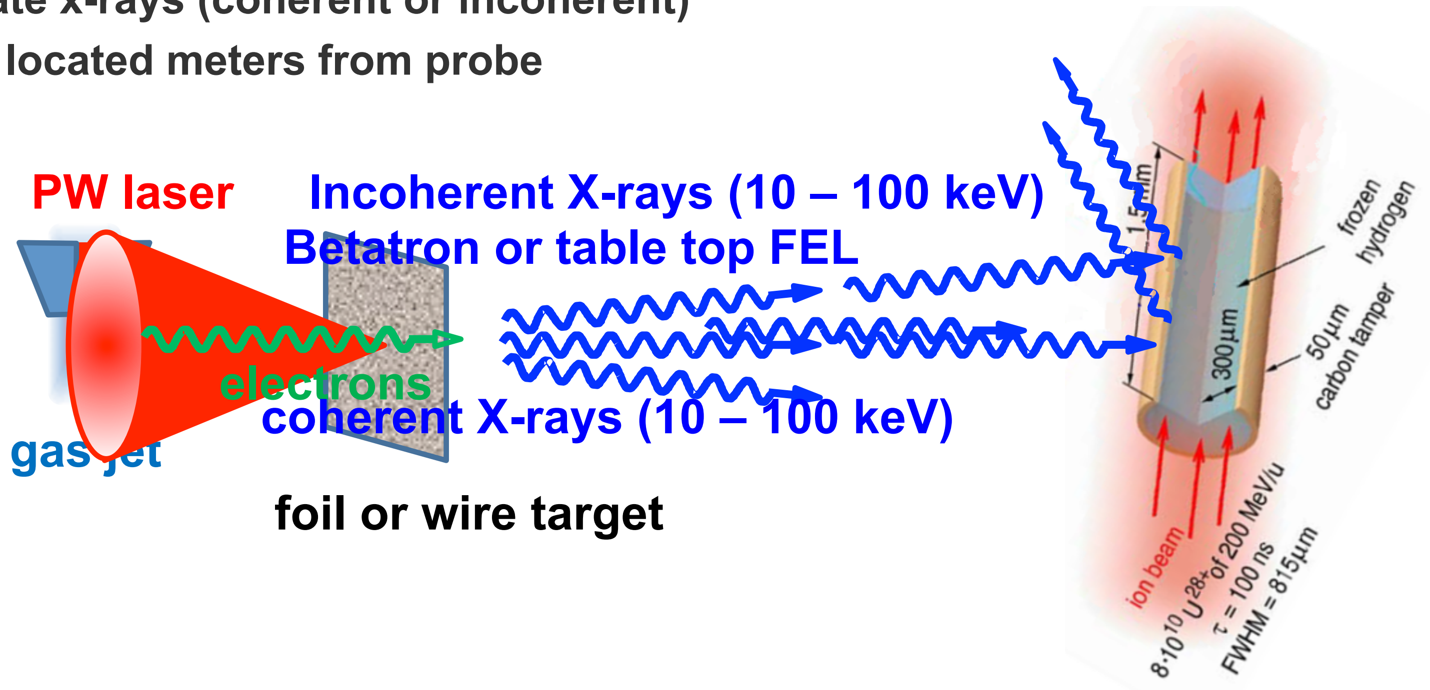
FIG. 2 (color). (a) Static (upper) and dynamic (lower) TOF spectra for shocked molybdenum. (b) Expanded view of data with fits (red and green curves) to the data. The horizontal scale for both (a) and (b) is time in microseconds.

Single shot neutron based temperature measurements of shocked material has been shown at LANSCE

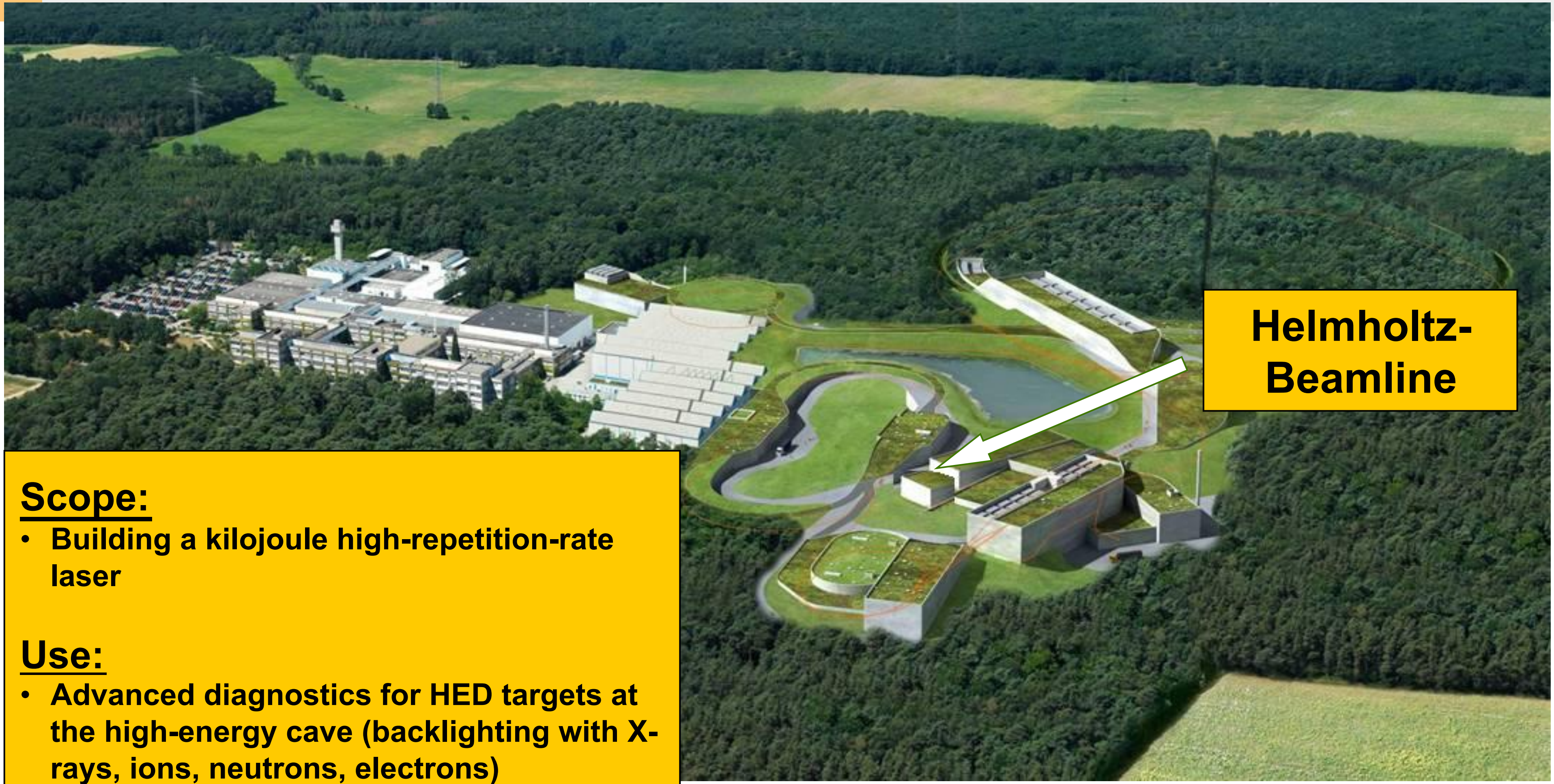
1 - M. Roth et al. PRL **110**, 044802 (2013)

X-ray based diagnostics will play an important role

- Many diagnostic techniques employ bright x-ray sources:
  - baklighting with K-α or Bremsstrahlung radiation,
  - XANES, X-ray scattering
- Recent laser developments allow for a step-wise creation of powerful x-rays
  - generation of directed electrons beams
  - electrons radiate x-rays (coherent or incoherent)
  - source can be located meters from probe



The Helmholtz Beamline at FAIR



Scope:
- **Building a kilojoule high-repetition-rate laser**

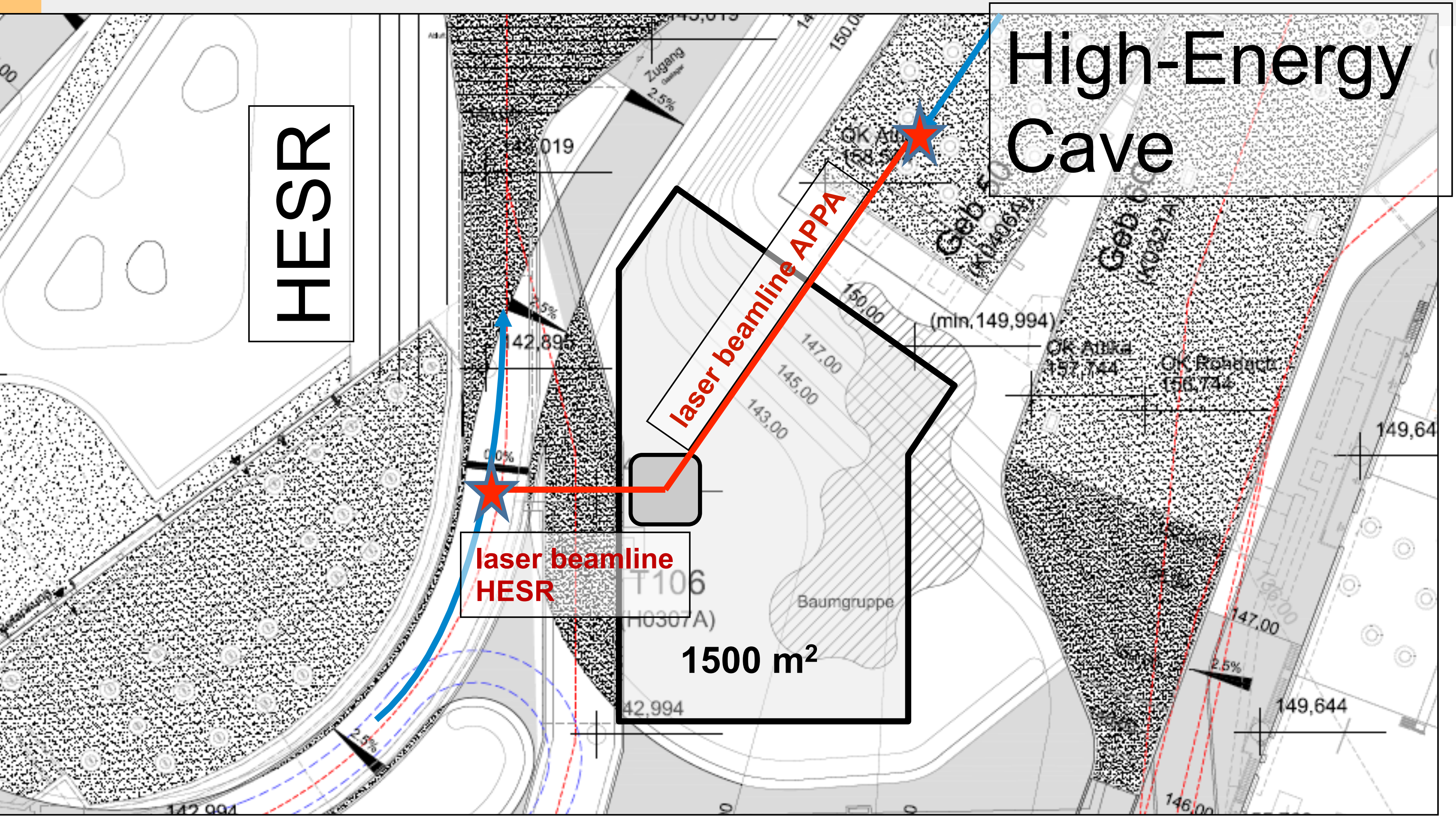
Use:
- **Advanced diagnostics for HED targets at the high-energy cave (backlighting with X-rays, ions, neutrons, electrons)**
- **Relativistic laser-ion interactions in the nearby HESR hall**

Technical requirements for a laser at FAIR

Laser parameters	value
Laser energy - short pulse	1 kJ
Laser Energy - long pulse (2ω)	10 kJ
Pulse duration	150 fs
Temporal contrast	10^{-14}
power	7 PW
Repetition rate	1 Hz
Proton energies	200 MeV

- An evolution of the existing architecture (PHELIX) in order to foster on existing expertise and minimize risks
- 2 Beam-lines with flexible characteristics (short and long pulses, high-temporal contrast)
- Moderate to high repetition rate (> 500 shots per day)

Site for the implementation of the Helmholtz Beamline at FAIR



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Thank You!