

Mixed Ion Beam Applications in Plasma Physics and beyond

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Outline

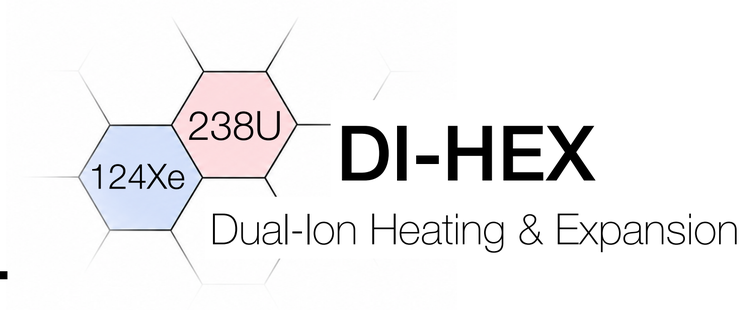
Part I

$^{4}He^{1+}$ & $^{12}C^{4+}$ Imaging & Treatment

PRIOR
Proton Microscope for FAIR

Part II

$^{124}Xe^{38+}$ & $^{238}U^{73+}$ WDM experiment



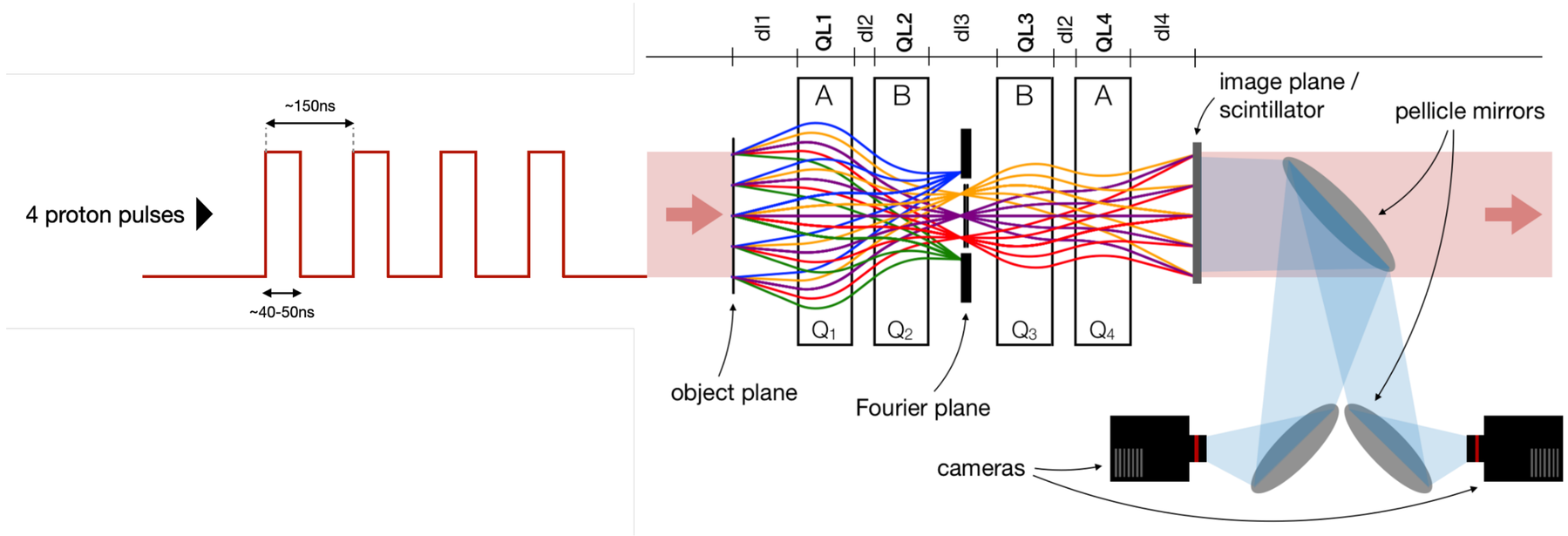
Part I

Multi-Ion Species Imaging & Treatment



Mouse Tomography, 4 GeV p+, GSI 2022

Lens-based charged particle radiography



Lens-Based Charged Particle Radiography

- µm spatial resolution performance with a cm-size FOV
- Image contrast proportional to object scattering (areal density)
- Fast imaging possible (ns exposure times)

!

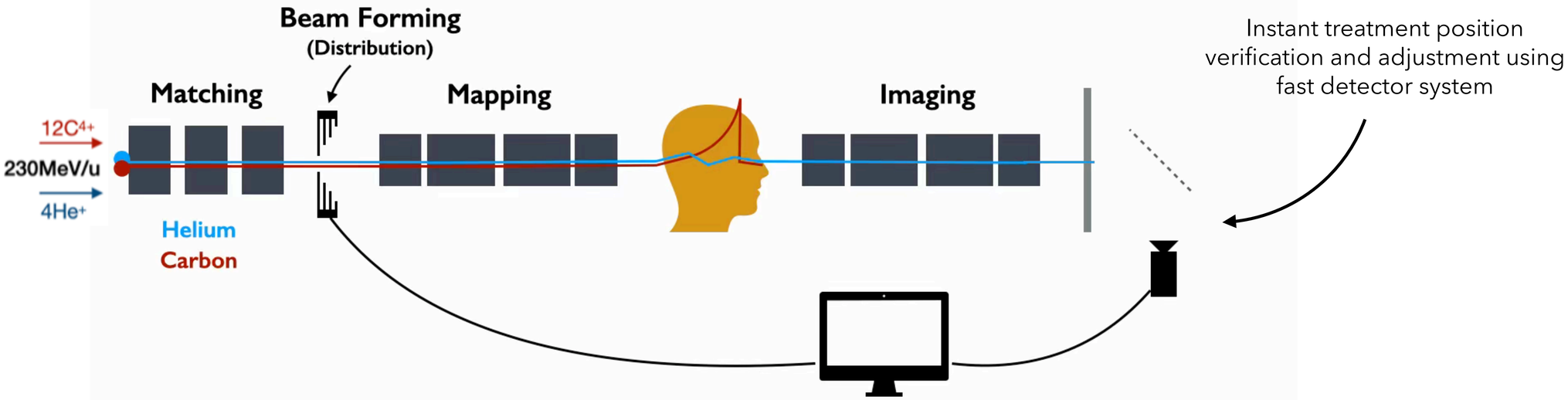
Not compatible with current PBS approach

Present status of imaging for particle therapy

Disadvantages of X-Ray CT

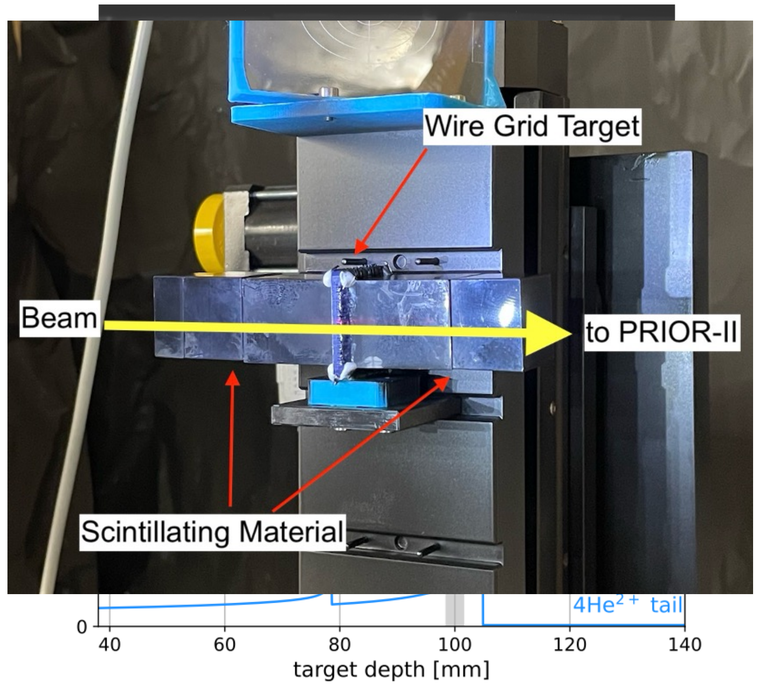
- Density reconstruction error (HLUT → WEPL) **- solved with dual-energy CT**
- Positioning error (different coordinate systems & patient movement)
- No in-situ & live position verification possible

Concept: lens-based MIB Imaging & Treatment

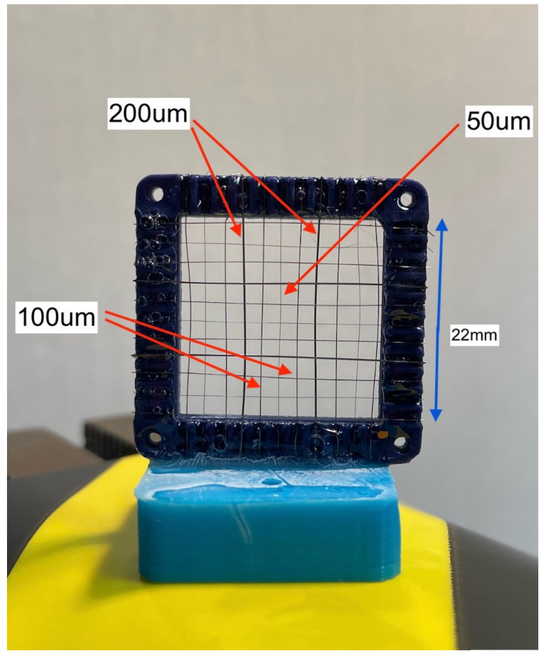


Beam Time 2023 „Proof-of-Concept“

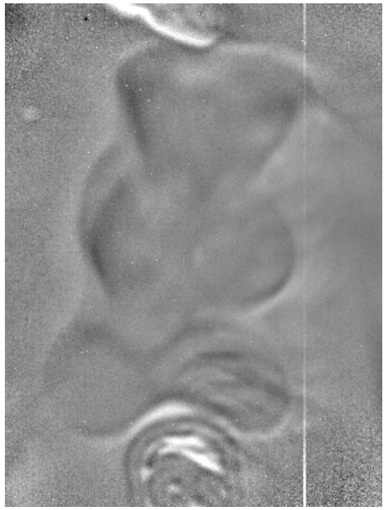
MIB Proposal P-24-00241
Ranked A / 12 Parasitic Shifts
Scheduled early 2027 / now postponed



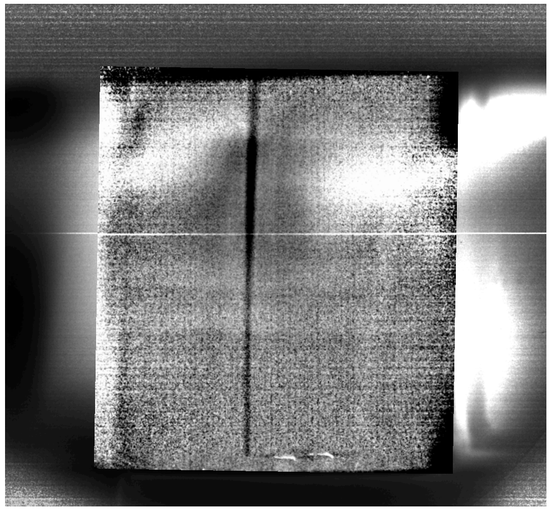
- Bragg peaks of $12C^{6+}$ and $16O^{8+}$ contamination clearly visible



Wire Grid target in 150mm scintillator
(190,5mm H_2O equivalent)
Focus @ 153.7 MeV/u (Helium)



Gummy Bear in a cube of gelatine
(60mm edge length)
Focus @ 198.8 MeV/u (Helium)



PMMA step wedge (0.5mm) in PVC
(125mm H_2O equivalent)
Focus @ ~160 MeV/u (Helium)

4U-PI - Medical imaging with laser generated protons

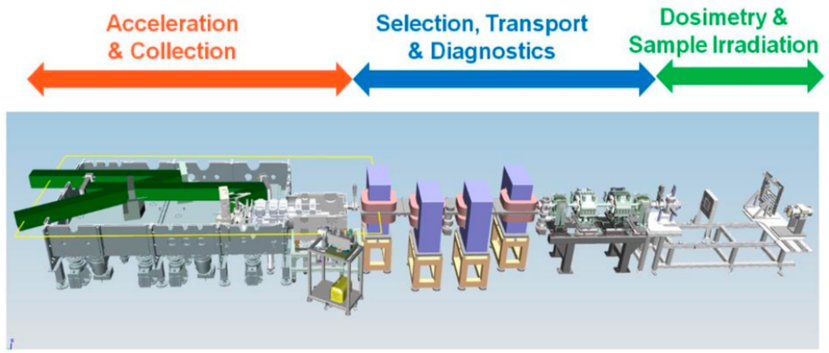


Funded by
the European Union

L3-HALPS Laser
- 13J @ 0.2 Hz burst mode

L4-ATON Laser
- 1.5kJ @ 0.1 Hz

ELIMAIA-ELIMED laser-plasma ion accelerator
- energy range (p+): 3 – 60 MeV / 10ns pulses
- energy selection chicane (±25% down to ±1%)



Design & construction of a PMQ-based imaging lens prototype for small animal imaging.

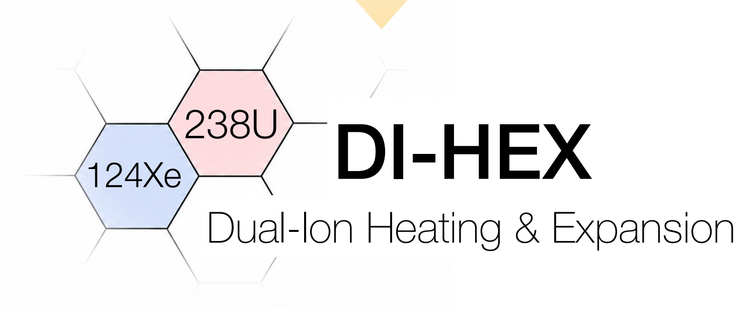
Part II

HI-HEX

Heavy-Ion Heating & Expansion

In-Flight Imaging of Heavy Ion Driven Plasma Targets, I.Hofmann et. al., *GSI Rep., GSI-2001-4* (**2001**) 29.

Simulations of Two-Beam Irradiation of Cylindrical Targets at the Upgraded SIS-18, N. A. Tahir et. al., *GSI Rep., GSI-2002-1* (**2002**) 132.

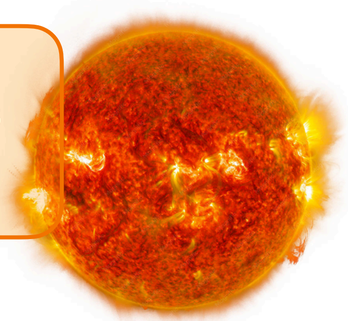


DI-HEX

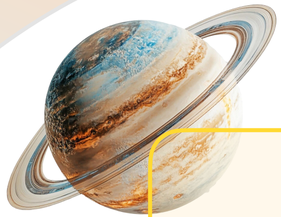
Dual-Ion Heating & Expansion

General Motivation

Plasma Physics
hot, diffuse



Energy/Temperature



WDM
Warm Dense Matter

- T ~ 0.1eV - 100eV
- Only accessible through DFT-MD simulations
- No analytical models available



Condensed Matter Physics
solid, cold

Coulomb Energy

Thermal Energy

$$\Gamma(n_{ion}, n_e, T) = \frac{\left(\frac{n_e}{n_{ion}}\right)^2 \frac{e^2}{4\pi\epsilon_0}}{\left(\frac{3}{4\pi n_{ion}}\right)^{1/3} k_B T}$$

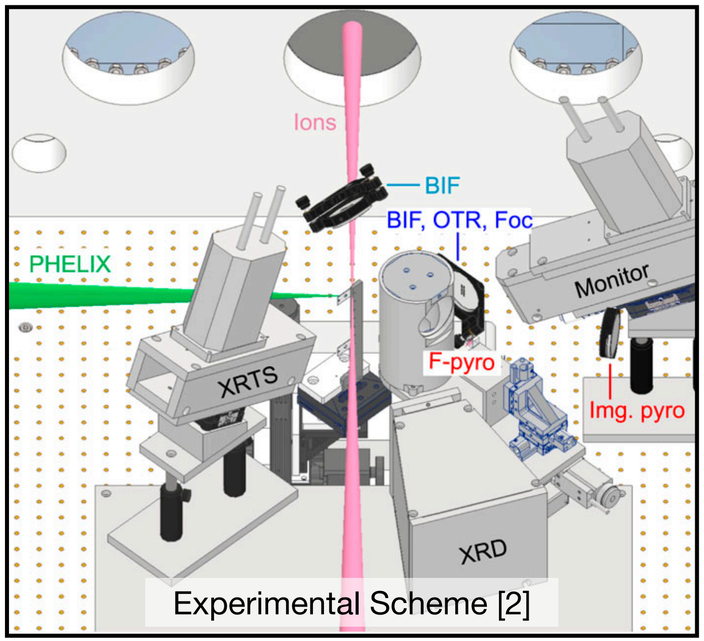
$\Gamma \ll 1$ **weakly coupled**
classical plasma treatment

$\Gamma \gg 1$ **strongly coupled**
cold-solid treatment

Currently Available Diagnostics

PHELIX-HHT Beamline

Motivation: use the PHELIX Petawatt Laser as additional WDM Diagnostic [1]



Experimental Scheme [2]

XRTS (X-Ray Thomson Spectrometry)

Temperature measurement through a per-material DFT-MD calibration

XRD (X-Ray Diffraction Spectrometry)

Structural/lattice information

F-pyro (Fiberoptical Pyrometry)

Surface Temperature Measurement

!

$$Z_{free} = \frac{n_{electron}}{n_{ion}}$$ not accessible from either channel alone!

Single laser flash experiment (2ns). Good reproducibility required!

[1] Major Zs. et al. High-energy laser facility PHELIX at GSI: latest advances and extended capabilities *High Power Laser Science and Engineering,* **2024**; doi: 10.1017/hpl.2024.17

[2] P. Hesselbach et. al., Platform for laser-driven X-ray diagnostics of heavy-ion heated extreme states of matter *Matter Radiat. Extremes,* **2025**; doi: 10.1063/5.0233548

Proof-of-Concept Experiment @ SIS-18

Isochoric heating of Al

constant volume

only increase of internal energy

200 MeV/u $^{238}U^{28+}$

1e10 Ions

4mm Focus

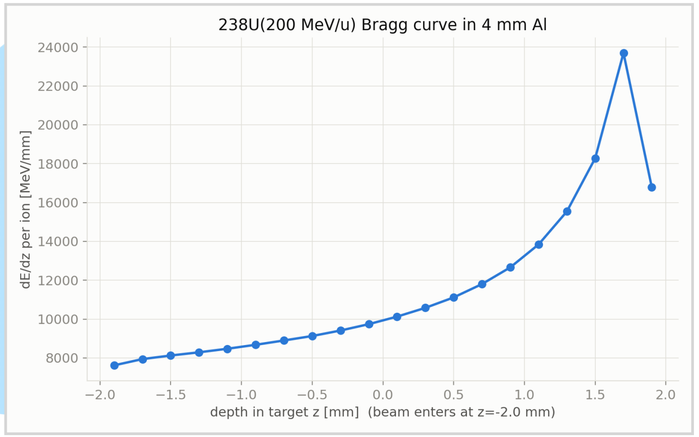
350 MeV/u $^{238}U^{73+}$

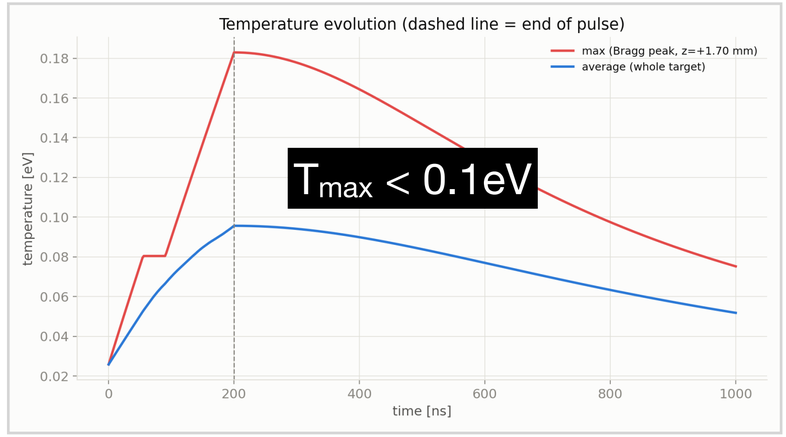
4e9 Ions

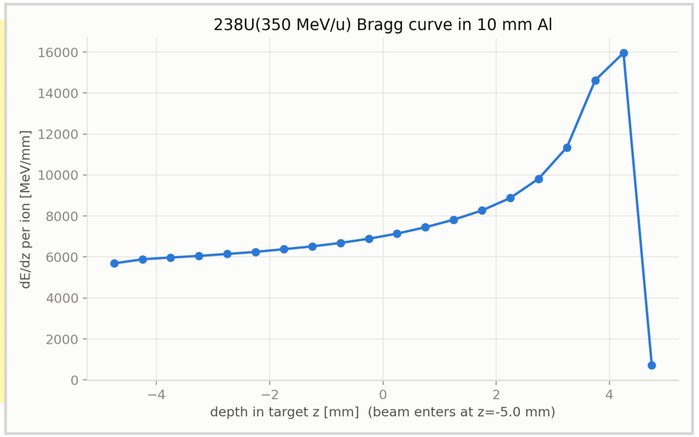
0.7mm Focus

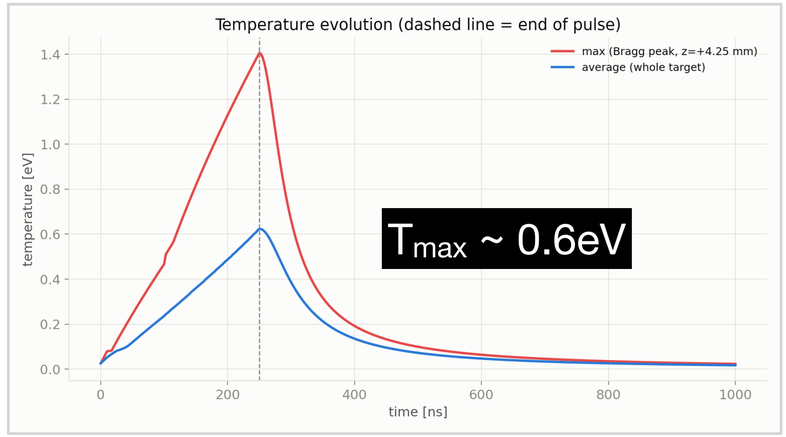
Problem:

$$E_{deposited} \propto \frac{n_{ion}}{r_{focus}^2}$$









Proof-of-Concept Experiment @ SIS-18

Incoming DI Beam

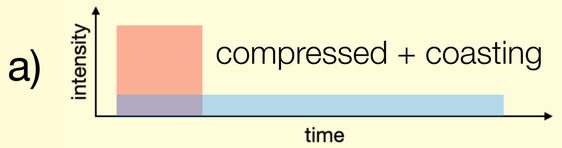
350 MeV/u

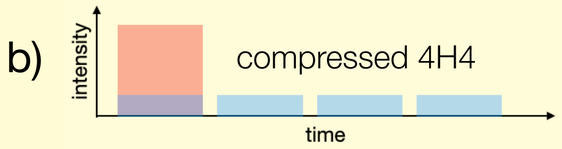
$^{238}U^{73+}$

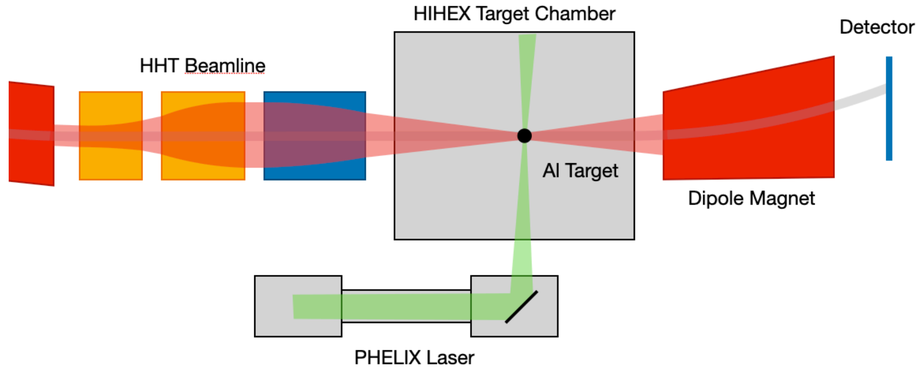
$^{124}Xe^{38+}$

A/Q ~ 3.26, T_{rev} ~ 1.13µs

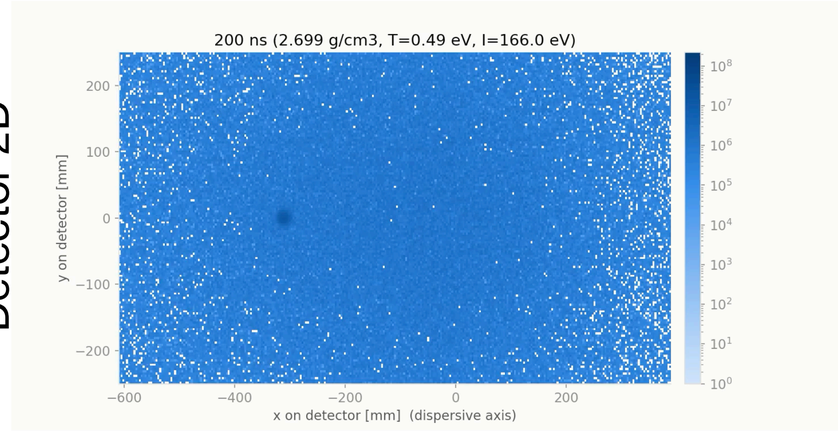
Timing structure



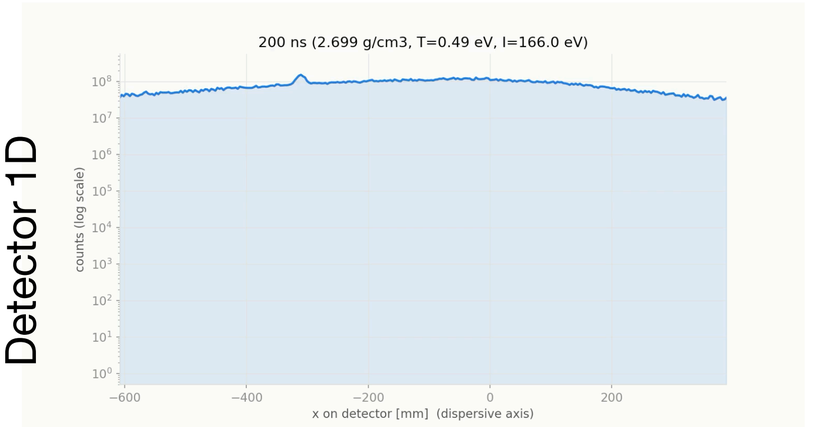




Detector 2D

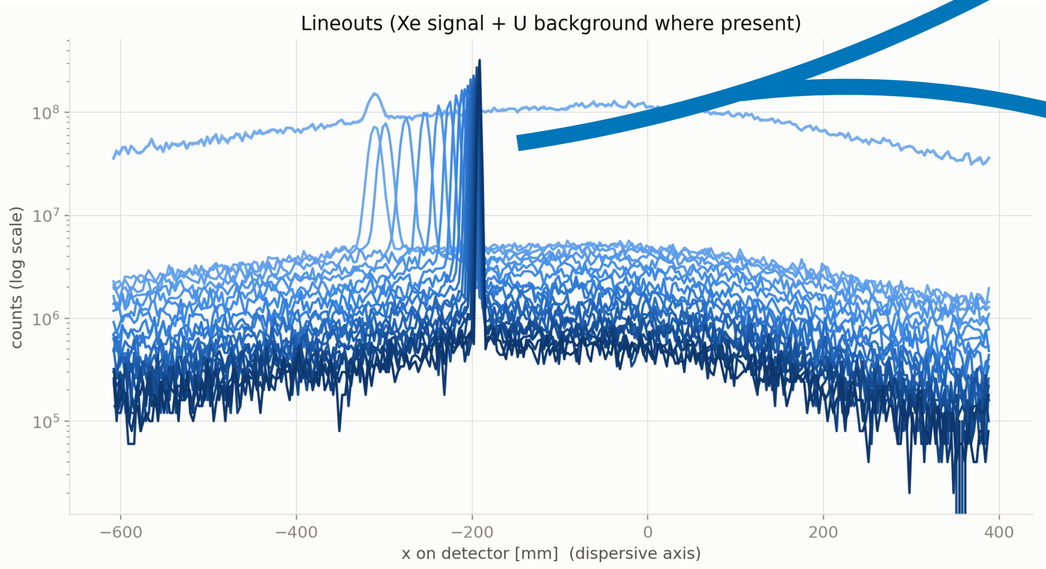


Detector 1D



Proof-of-Concept Experiment @ SIS-18

Detector 1D / 0 - 450 ns

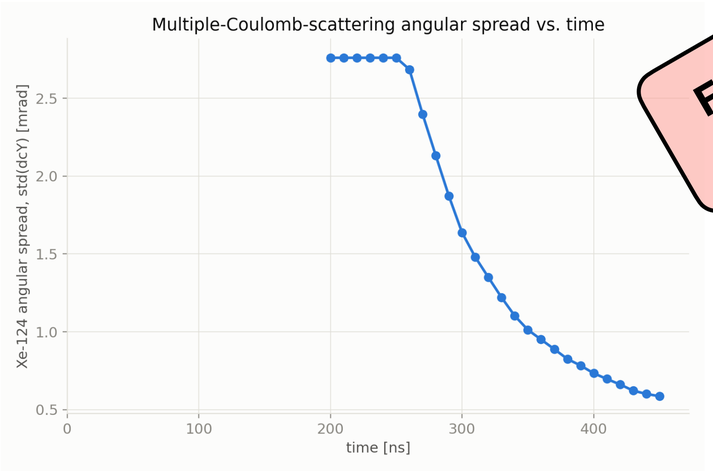


Peak Position

Equals energy loss / electronic stopping ($n_{electron}$)

Peak Width

Xe deflection by MCS off target nuclei (n_{ion})



Full target evolution available in a single experiment!

Summary

Part I

- Charged particle radiography is a fast and powerful imaging diagnostic with
  - µm spatial resolution performance,
  - areal density reconstruction capability
- In the distant future, dedicated imaging systems optimized specifically for medical purposes may provide benefits for full-field therapy approaches.

Part II

- MIBs can add a very powerful diagnostic capability to existing WDM experiments.
- At best, the current state of the GSI/FAIR facility allows for proof-of-concept experiments in five+ years, assuming the full restoration of the UNILAC.
  Scientifically interesting experiments require SIS-100 intensities and the new HEDgeHOB superconducting focusing system, which has not yet been funded as part of FS++.



Thank you for your attention!

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