Recent Progress on Heavy-Ion Acceleration: Towards the Fission-Fusion Nuclear Reaction Scheme

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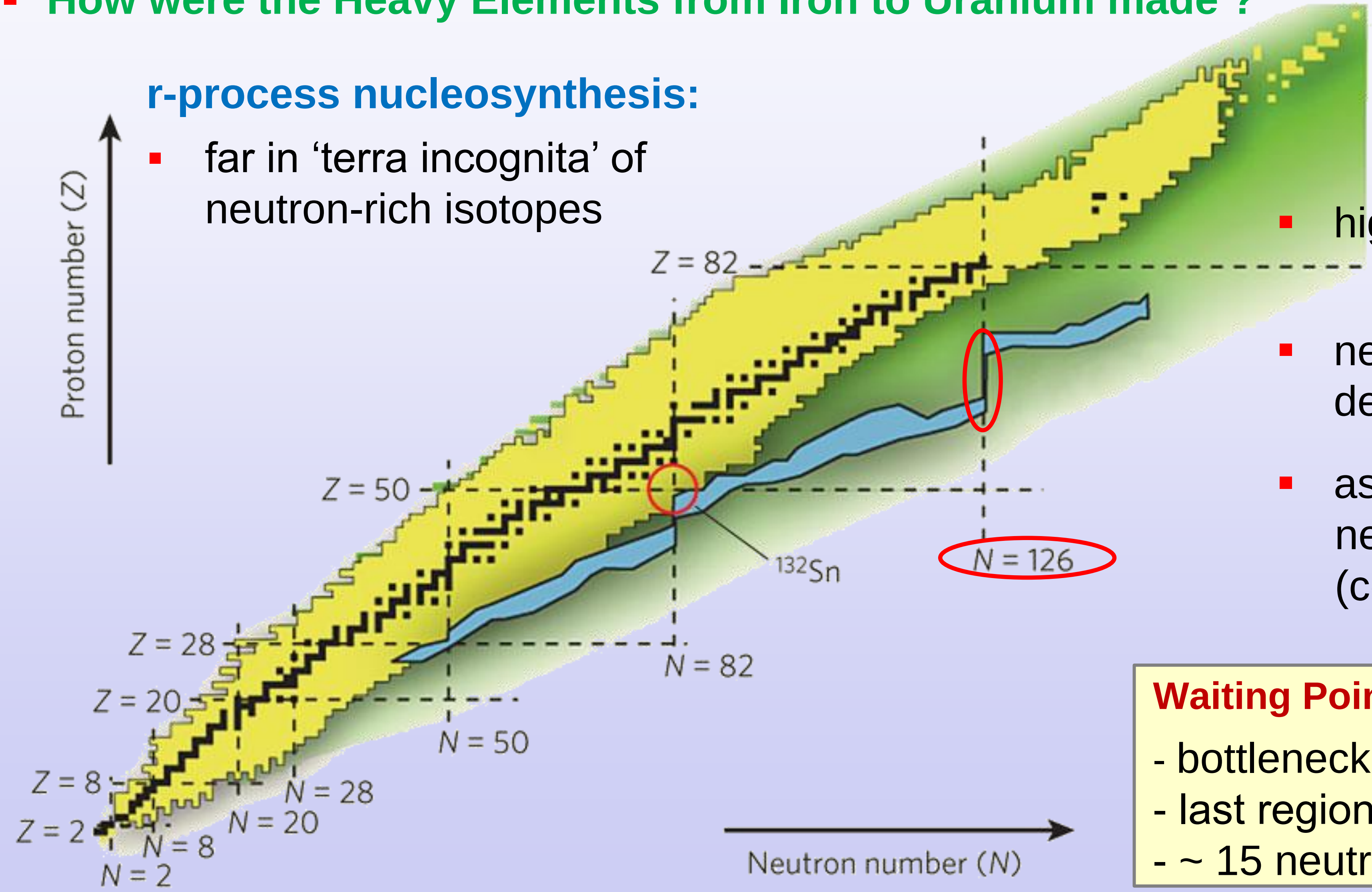
Motivation: Cosmic Nucleosynthesis

- **How were the Heavy Elements from Iron to Uranium made ?**

r-process nucleosynthesis:

- far in 'terra incognita' of neutron-rich isotopes

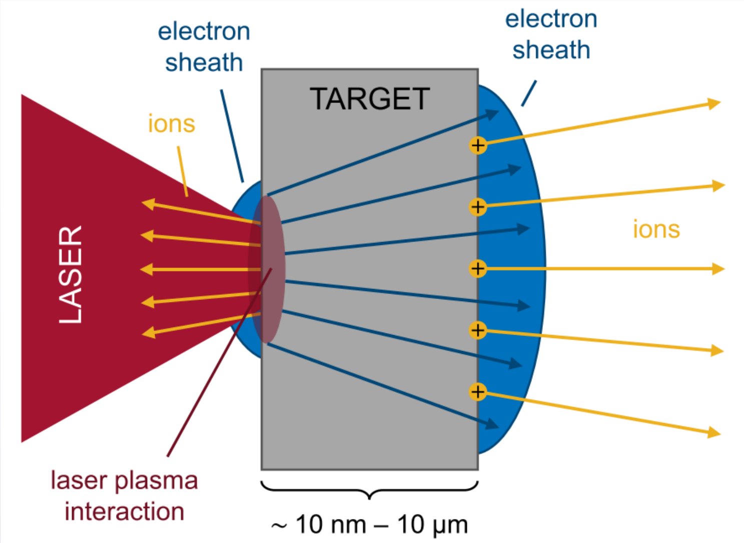


- high neutron density required: $n_n \geq 10^{28}$ cm^{-3}
- neutron capture much faster than β decay $\tau_{(n,\gamma)} \ll \tau_\beta$
- astrophysical site: neutron star mergers, supernovae (ccSN II)

Waiting Point N=126: (n,γ) ≈ (γ,n)

- bottleneck for nucleosynthesis of actinides
- last region of r process 'close' to stability
- ~ 15 neutrons from last known isotope

Laser accelerated ions: Complementary to conventional accelerators

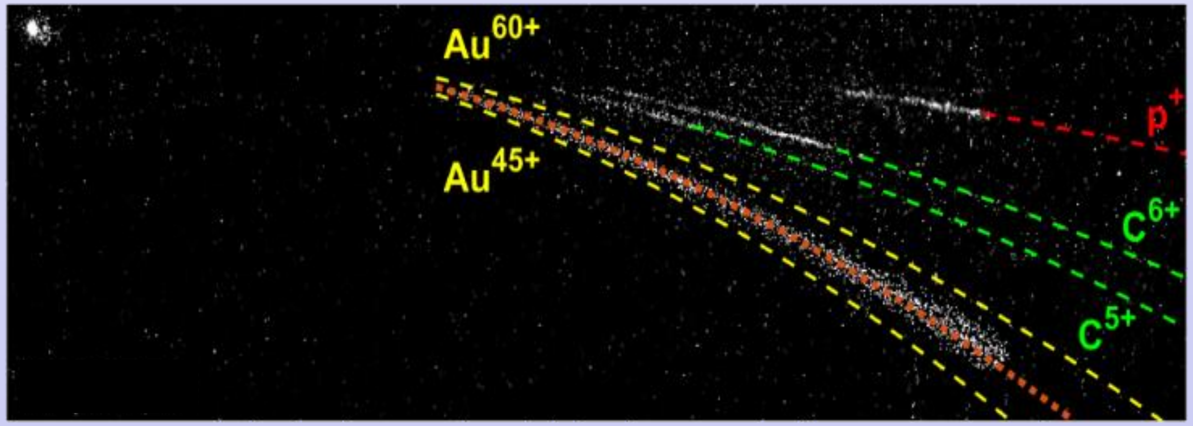


- laser-plasma interaction of intense and short laser pulses with thin foils accelerates ions
- most studied: Target Normal Sheath Acceleration (TNSA)
- acceleration gradients: GV/m - TV/m

- **properties of laser-driven ion bunches:**

  - continuous (exponential) energy spectrum
  - several species and charge states
  - very short bunch duration (~fs-ps)
  - ultra-high particle density (ultimate limit with RPA: ~ solid-state like)

F.H.Lindner, PhD thesis, LMU Munich, 2021

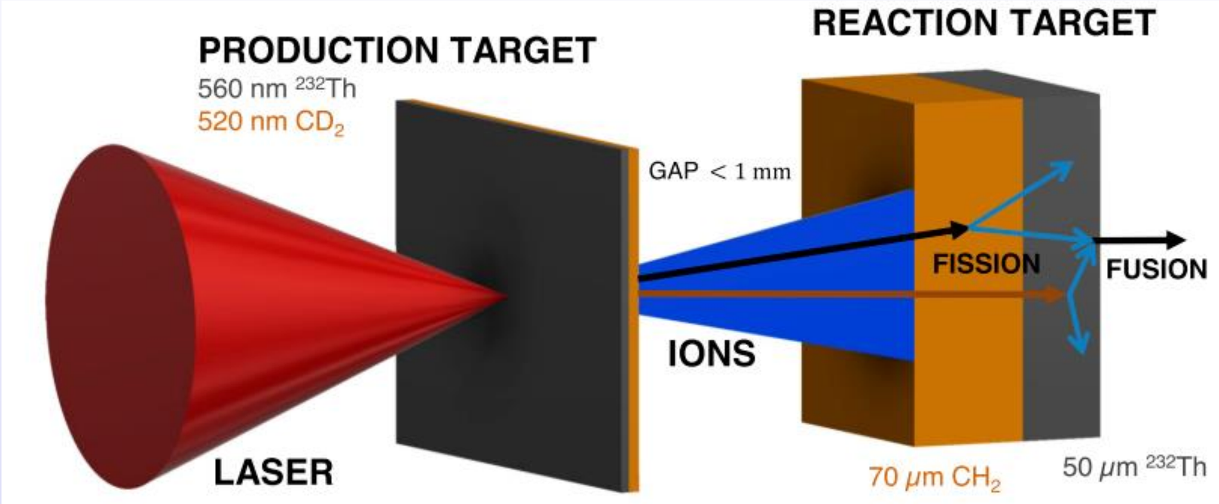


Fission-fusion reaction scheme

1. Production of laser-accelerated heavy (fissile) ions

2. Fission of projectile- and target-like heavy ions

3. Fusion of neutron-rich light fission fragments

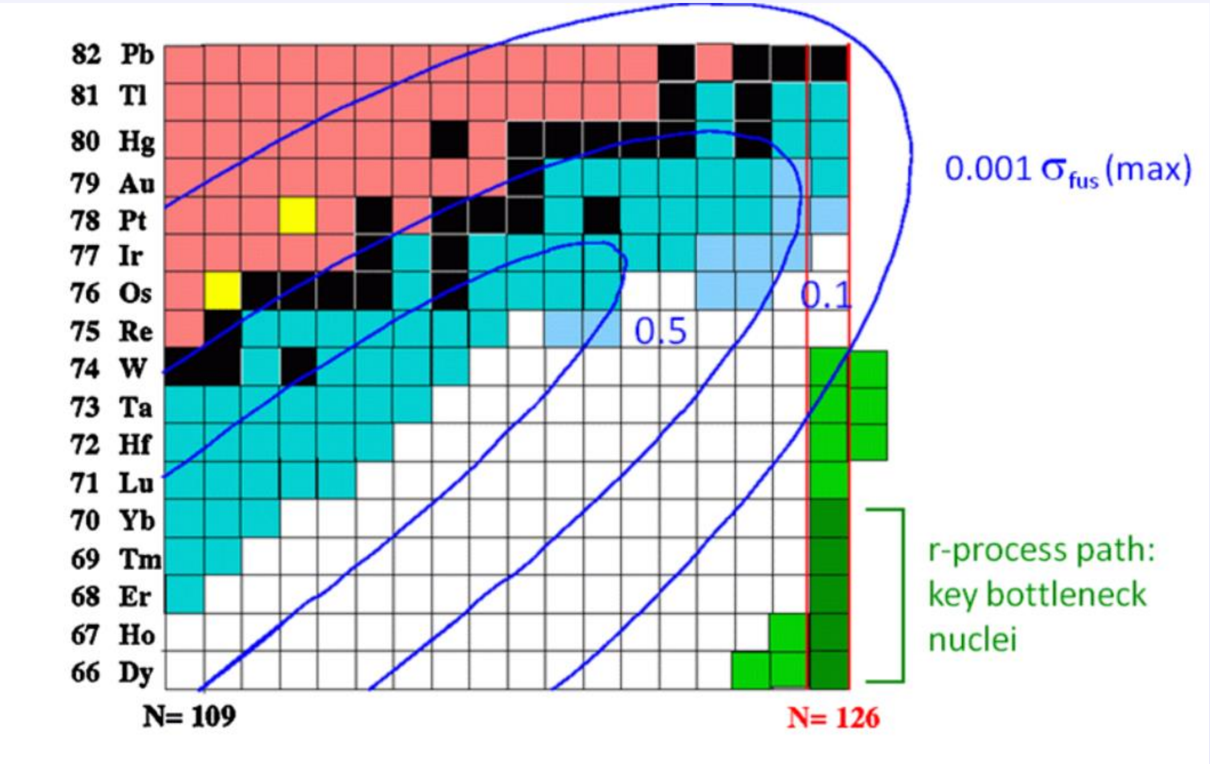


D. Habs, PT et al., Appl. Phys. B 103, 471-484 (2011)
F.H.Lindner, Nucl. Instrum. Meth. B 302, 354-357 (2017)

Requirements:

- ions accelerated with very high density, enabling this reaction scheme
- kinetic energy of fissile species needs to exceed fission barrier at ca. 7 MeV/u
- collective effects in stopping power ?

r-process Nucleosynthesis near N=126



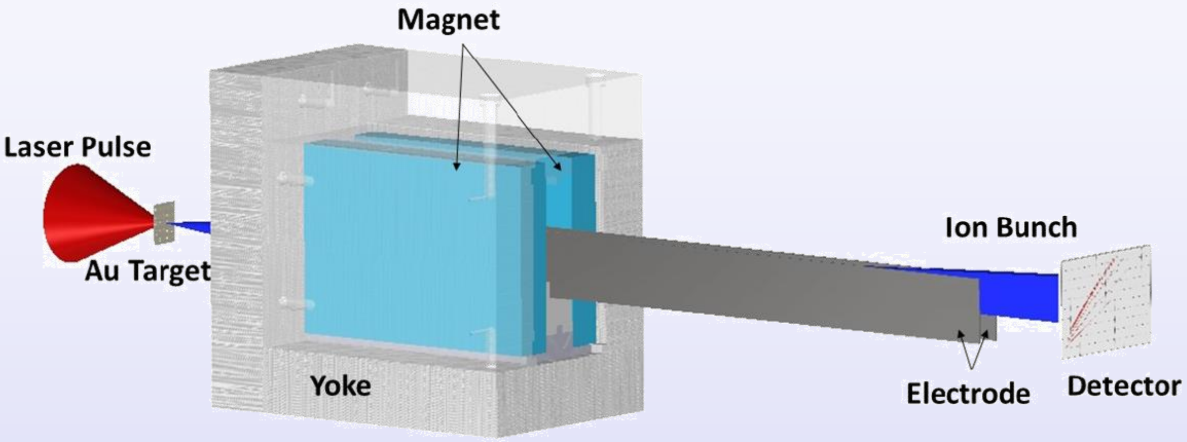
D. Habs, PT et al., Appl. Phys. B 103, 471-484 (2011)

- fusion of 2 neutron-rich fission fragments leads into very neutron-rich mass region of A≈190-200, N≈126

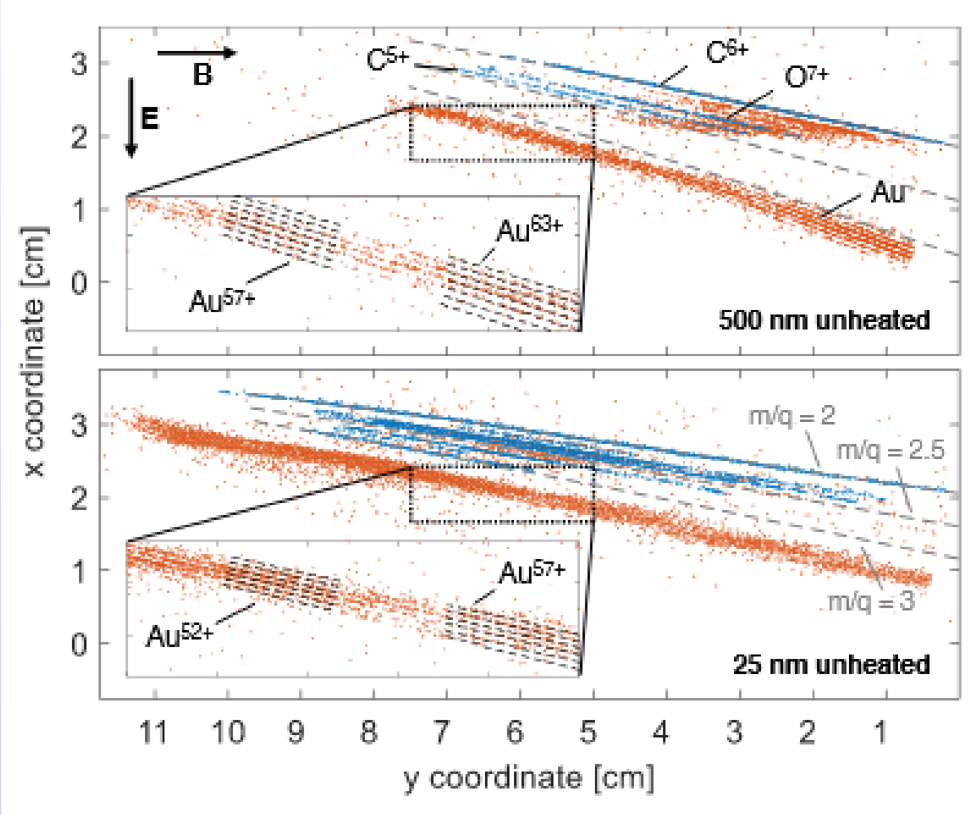
- ca. 15 neutrons from last known isotope

  → extremely difficult to access (if at all) by conventional acceleration and nuclear reaction schemes

Heavy ion acceleration & detection



- individual charge-state resolution obtained
- heavy-ion signal detected inside light-ion region
  → may arise from in-target fission fragments



- Thomson Parabola Spectrometer (TPS) designed for high resolution of heavy ions
- permanent magnet with B=0.85 T
- variable electric field up to E≈30 kV/cm
- successfully applied during beamtime at PHELIX (GSI)

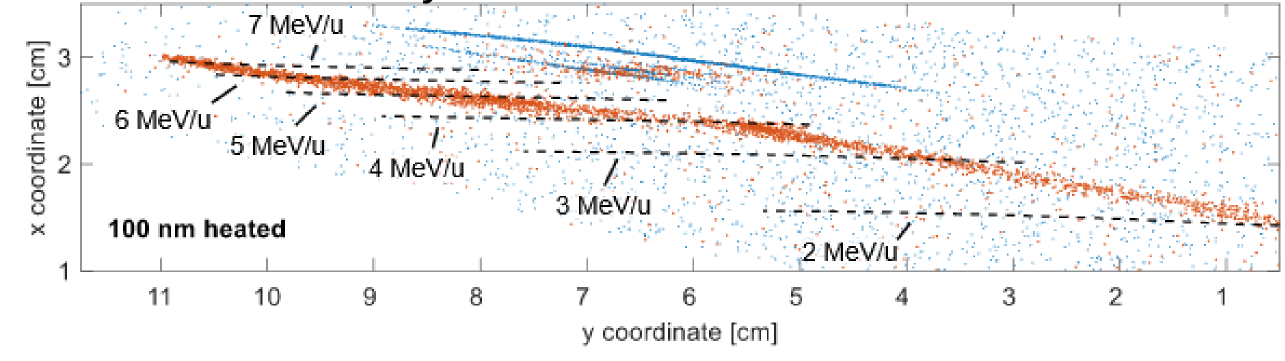
F.H. Lindner et al., Sci. Rep. 12, 4784 (2022)

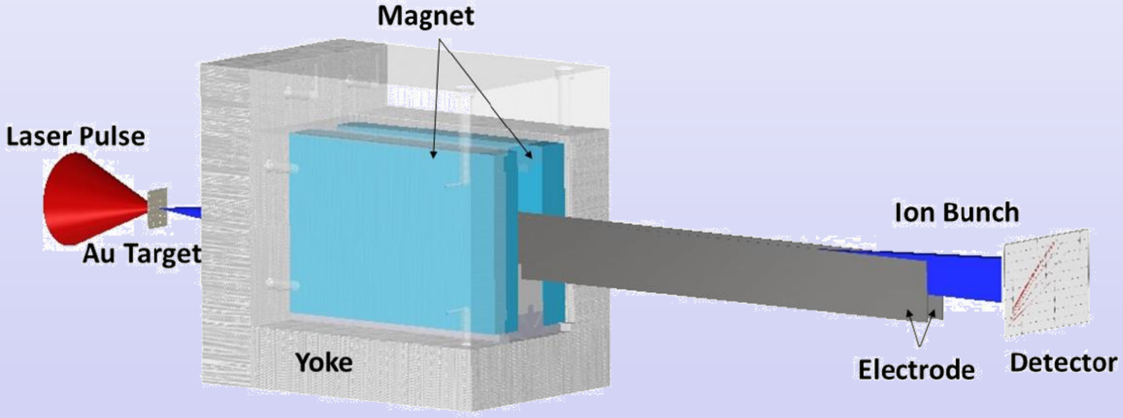
Heavy ion acceleration & detection

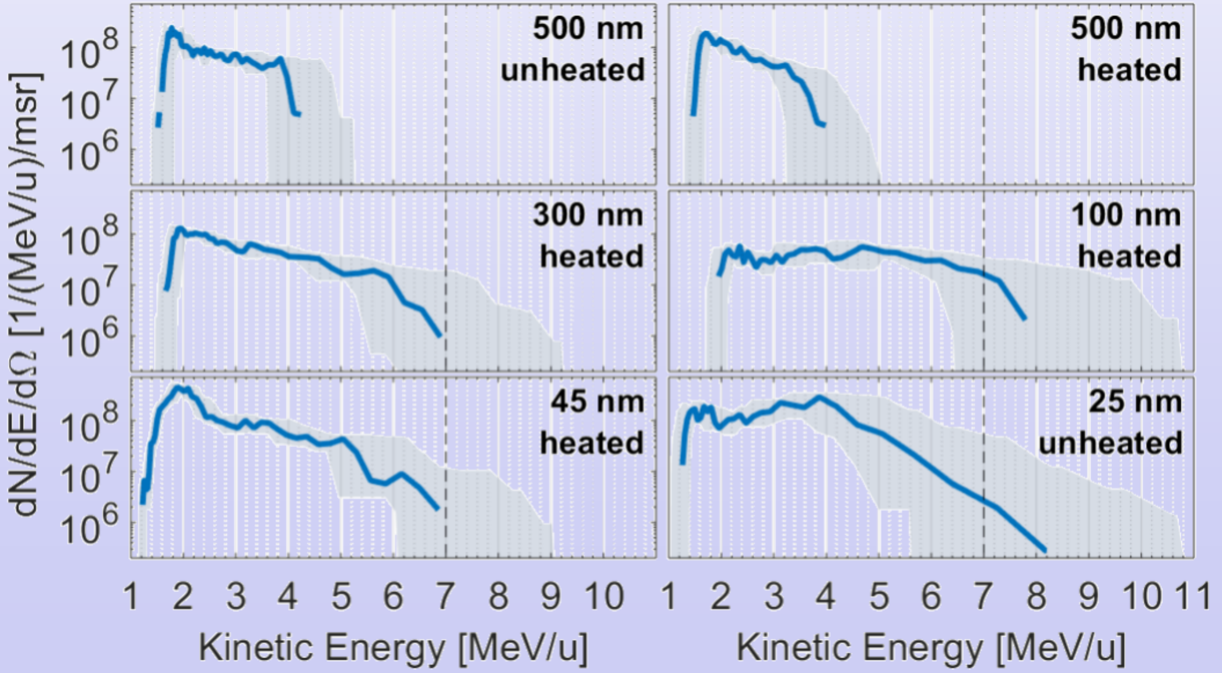
- energies above 7 MeV/u reached

  (sufficient for fission barrier in fissile species)

CR39 track analysis:







F.H. Lindner et al., Sci. Rep. 12, 4784 (2022)

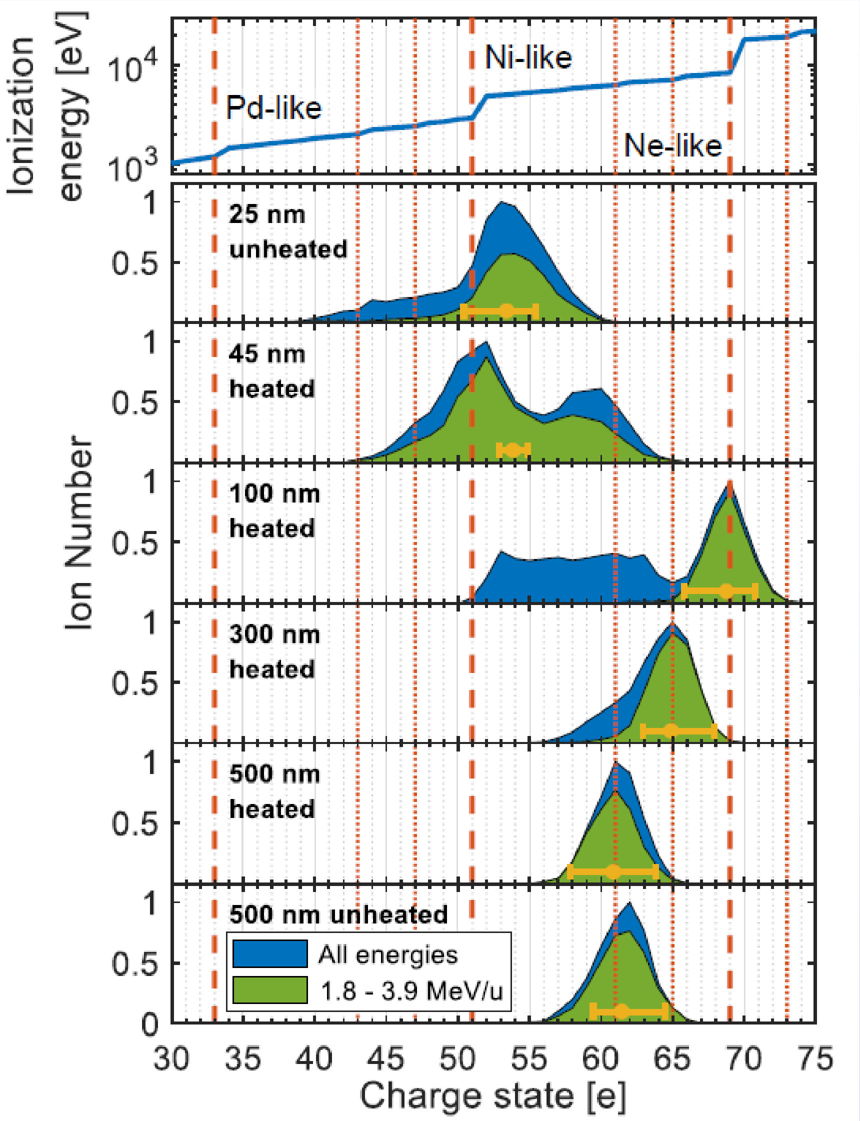
Individual gold charge-state resolution

- charge-state distributions each display clear maximum
  green: number of Au ions integrated from 1.8 – 3.9 MeV/u
- considerably higher charge states observed than expected from field ionization models:

  → laser peak intensity: ADK formula [1] predicts (field-) ionization of Au up to 51^+

  → highest charge state measured: 74^{+2}_{-3} (in agreement with q=72+ from Hollinger et al. Nat. Phot. 14, 607 (2020))
- remarkable dependence on target thickness

[1] M. V. **A**mmosov, N. B. **D**elone, and V. P. **K**rainov
Tunnel ionization of complex atoms and of atomic ions in an alternating electromagnetic field.
Soviet Physics - JETP, 64(6):1191–1194, 1986



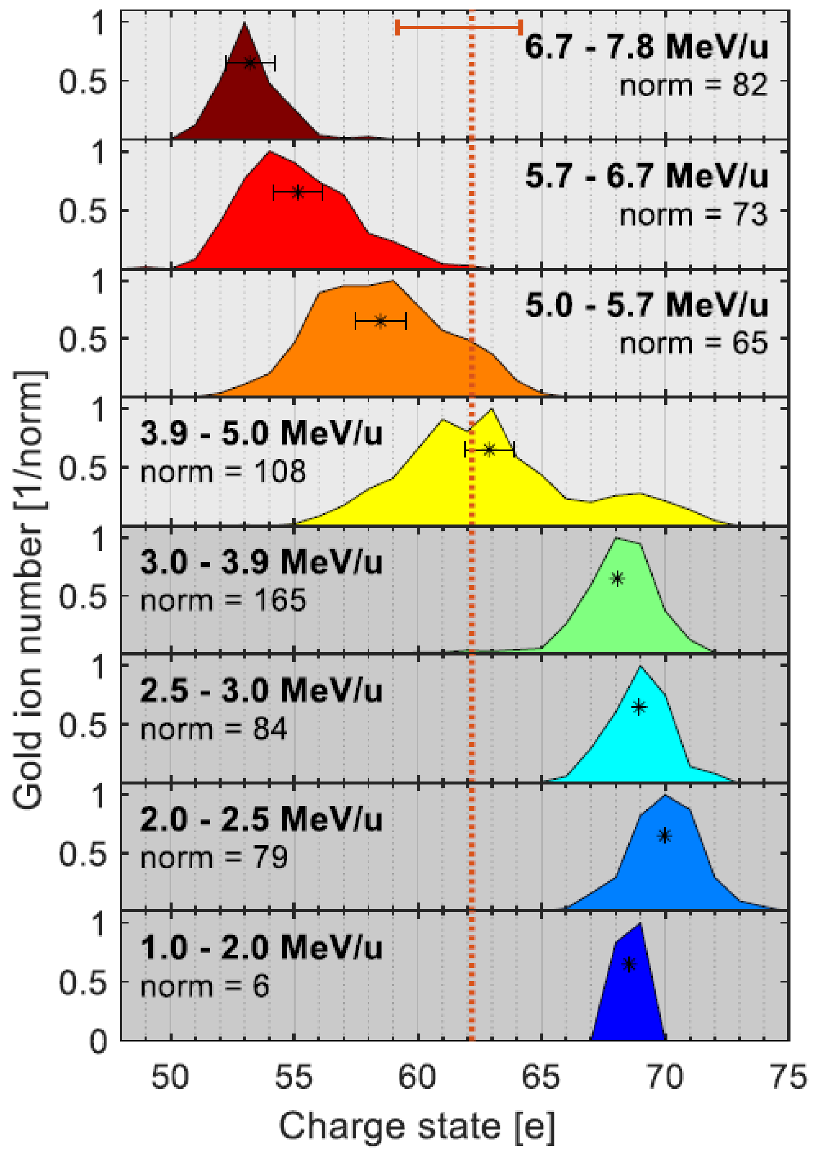
F.H. Lindner et al., Sci. Rep. 12, 4784 (2022)

Gold ion charge-state distributions

- energy dependent gold ion charge-state distributions: single shot on a **heated, 100 nm thick gold foil**
- ion numbers normalized to respective maximum
- Au ion charge states decrease with increasing kinetic energy
- in agreement with simulations that showed lower charge states being accelerated to higher energies.

➡ faster particles leave target earlier as slower ones, which remain longer in high-field region

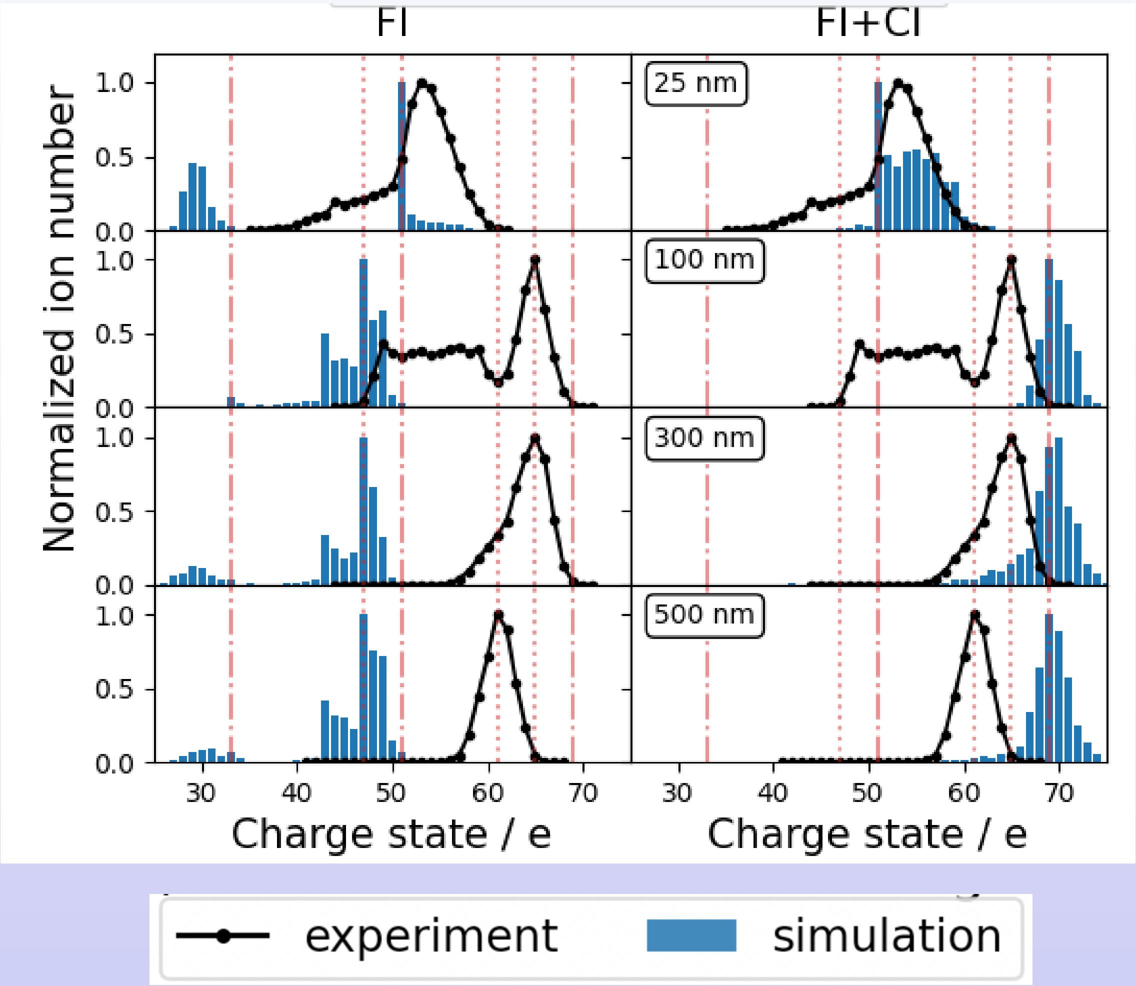
→ higher kinetic energy particles keep lower charge state



F.H. Lindner et al., Sci. Rep. 12, 4784 (2022)

Modelling the charge-state distribution

- field ionization (FI) predicts highest charge state at 51$^+$ (Ni-like)
- observed highest charge state is ~74$^+$
- conducted simulations with EPOCH-PIC code and new collisional ionization (CI) branch
- CI brings simulation output closer to experimental distribution (ion-electron CI included, not ion-ion)
- deviation for thicker targets still under investigation



M. Afshari et al., Sci. Rep. 12, 1-8 (2022)

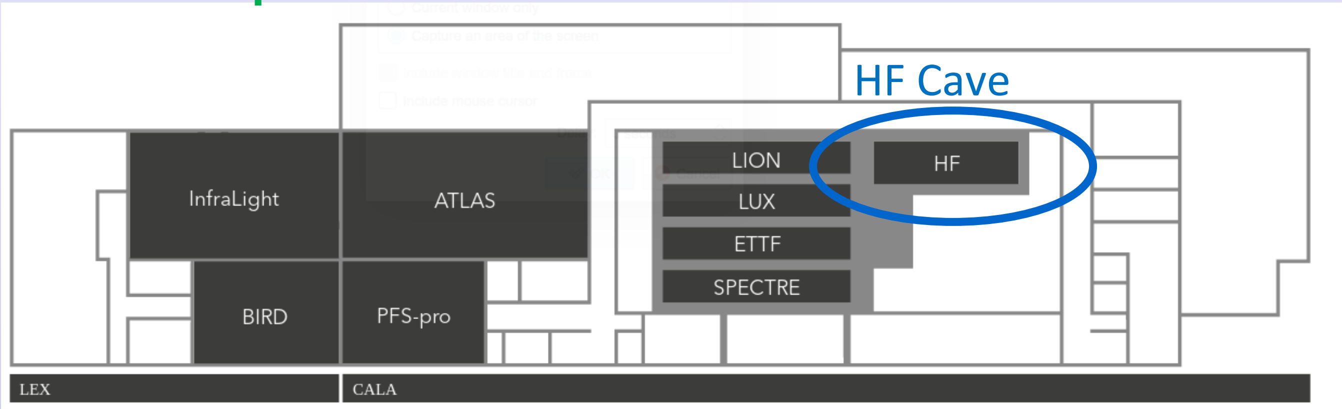
High Fields (HF) Beamline @ CALA

high-energy part of ATLAS 3000

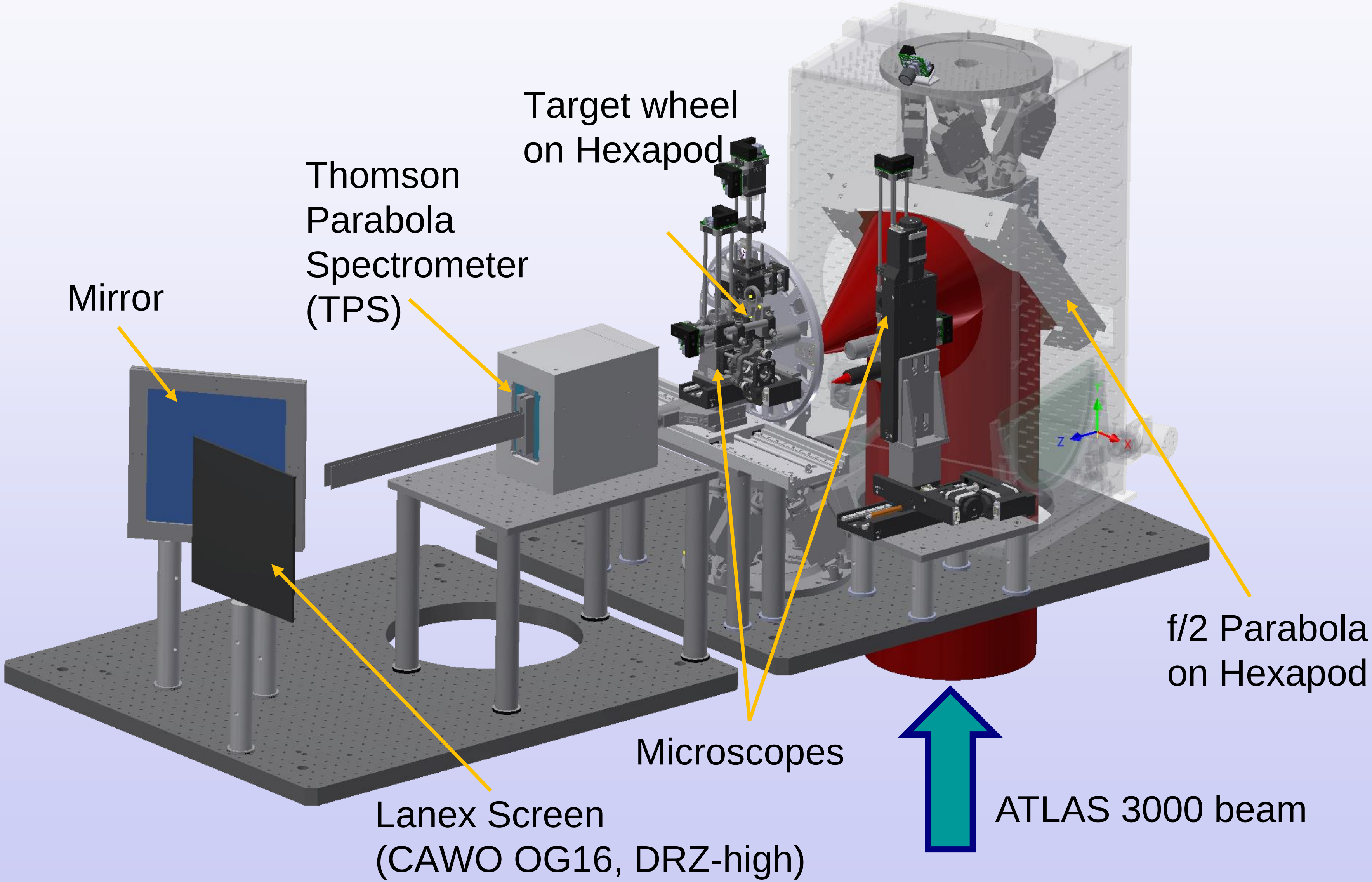
ATLAS 3000

- CPA based Ti:Sa laser system
- $\tau_L = 20$ fs (28 fs)
- f_L = 1 Hz
- E_L = 60 J

CALA floorplan:

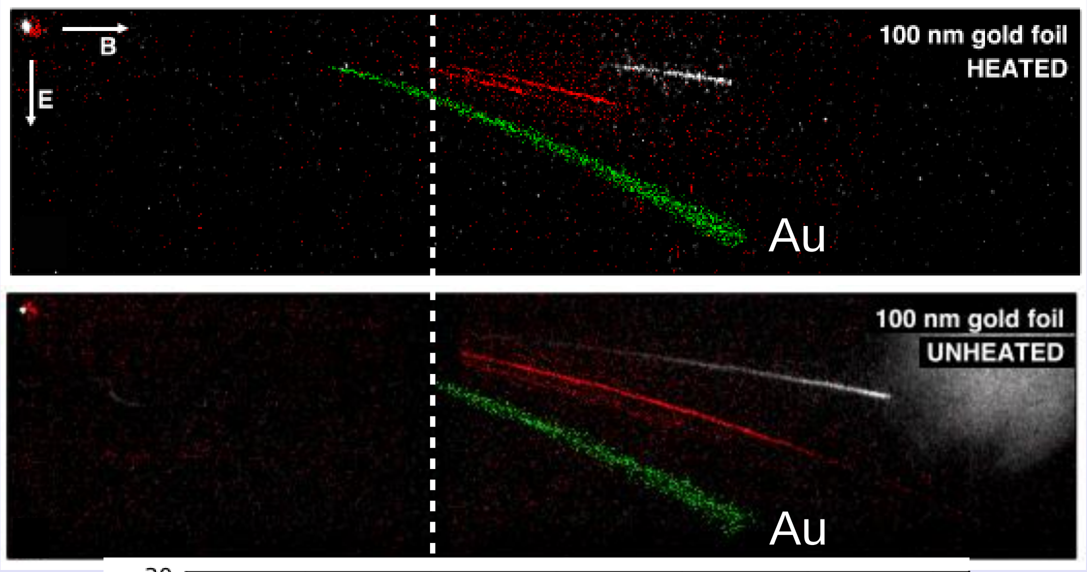


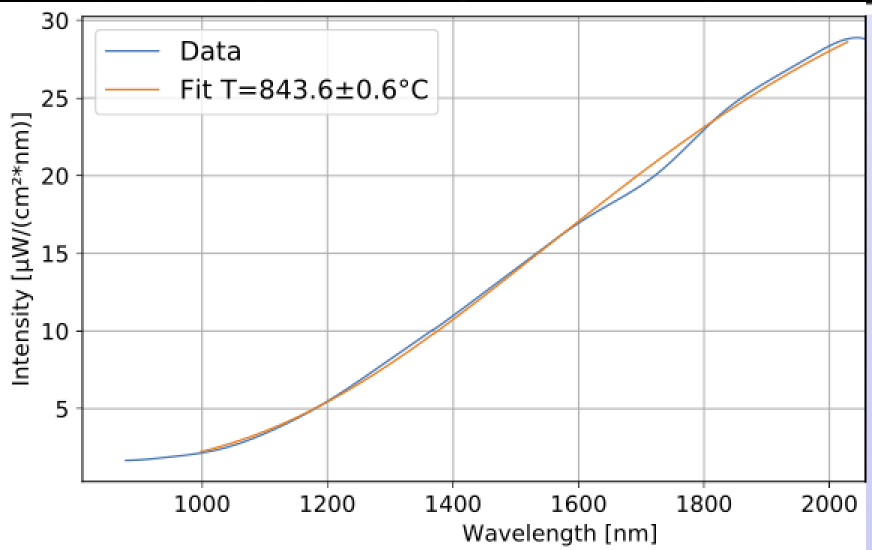
Setup for Au acceleration at CALA

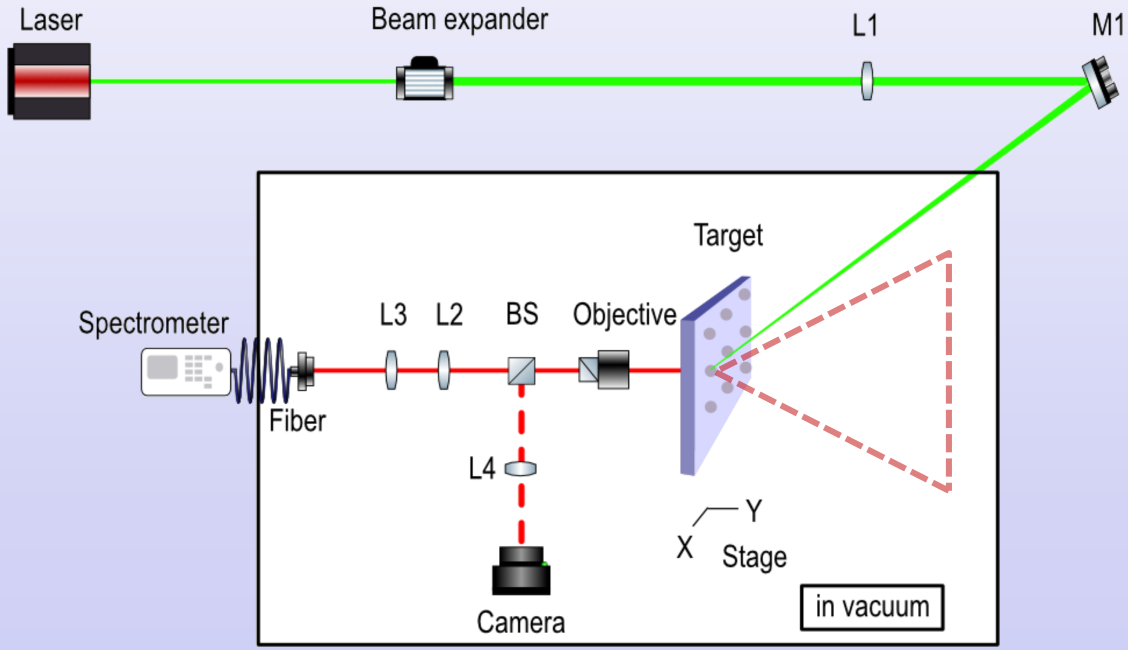


Target heating for enhanced Au acceleration

- heat target to reduce contamination layer
- enables more efficient acceleration of Au ions
- additional spectrometer to retrieve target temperature

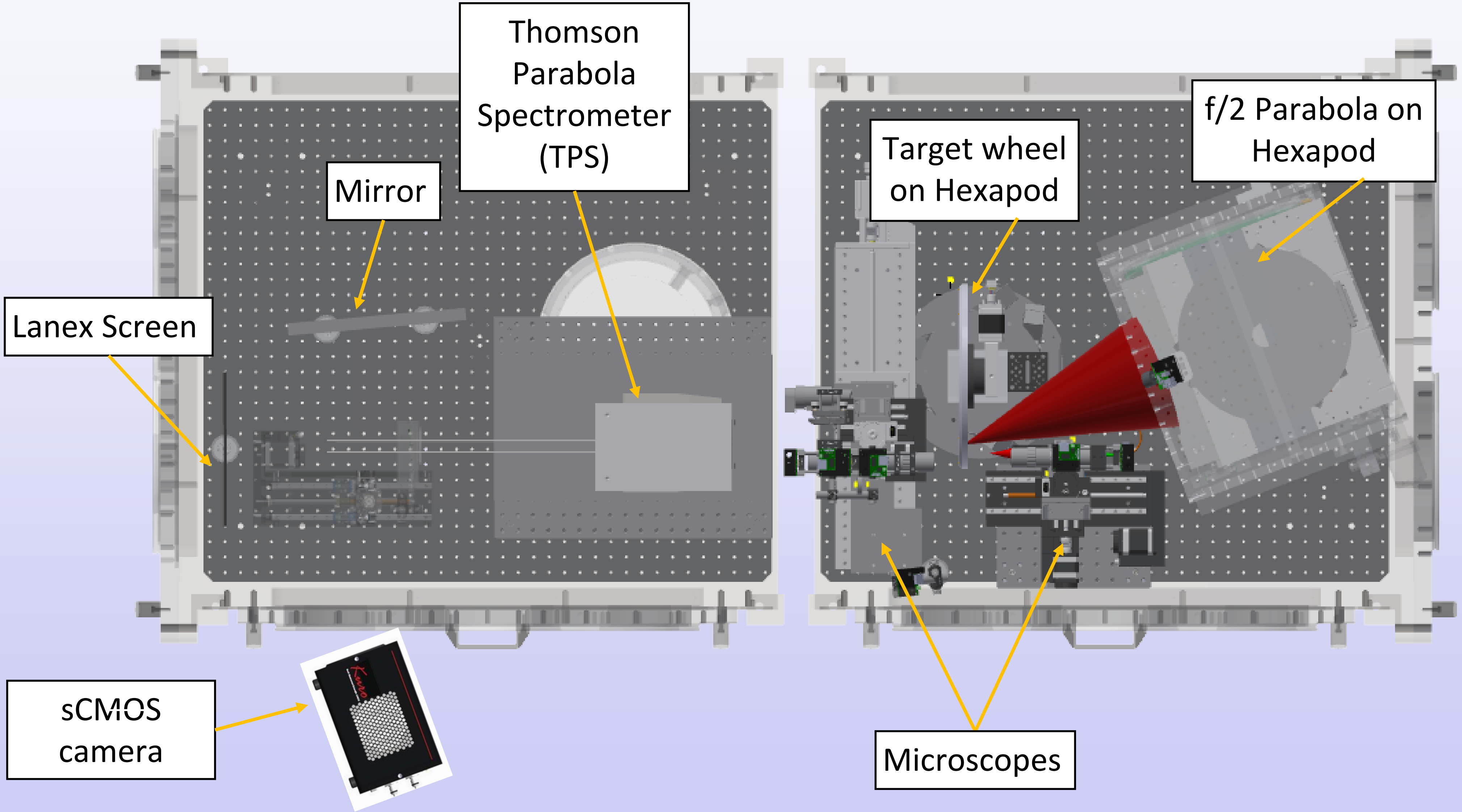




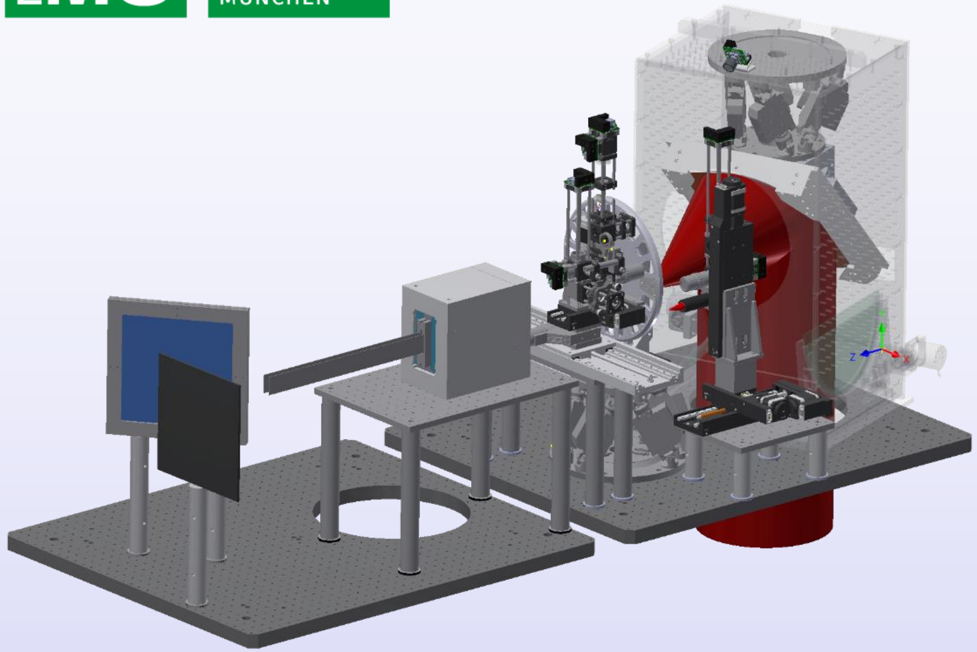


M. Weiser, MSc thesis, 2021
V. Kratzer, MSc thesis in prep., 2024

Au acceleration @ CALA

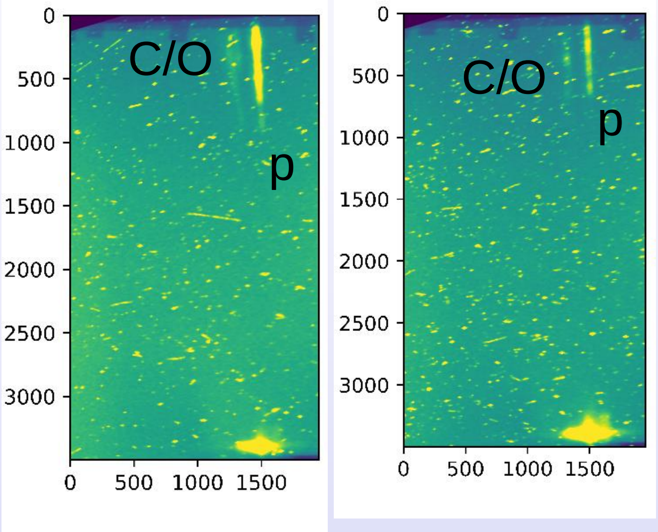


Au acceleration @ CALA



DRZ-high Lanex screen (1.5 mm pinhole)

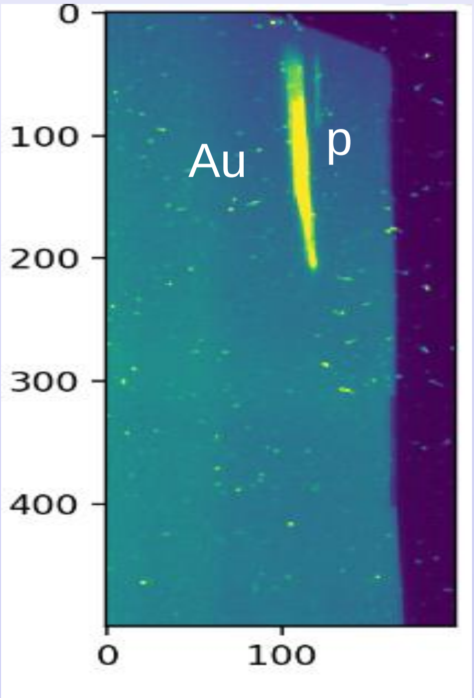
300 nm FormVar



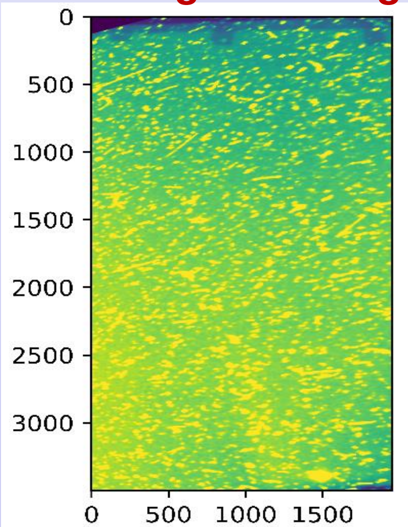
- **protons@HF:**
  typ. E_{max}~21-24 MeV

CAWO Lanex screen
(1.5 mm pinhole)

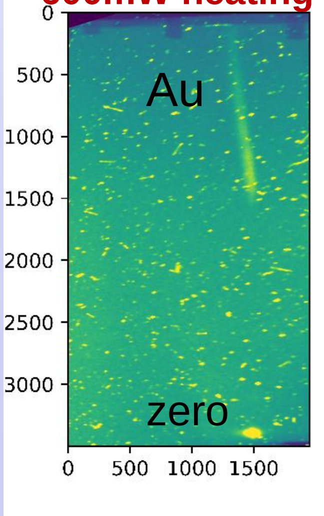
400 nm Au ; 650mW



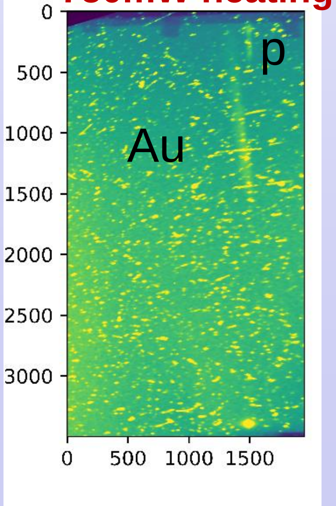
no target heating



300 nm Au; 600mW heating



400 nm Au; 750mW heating

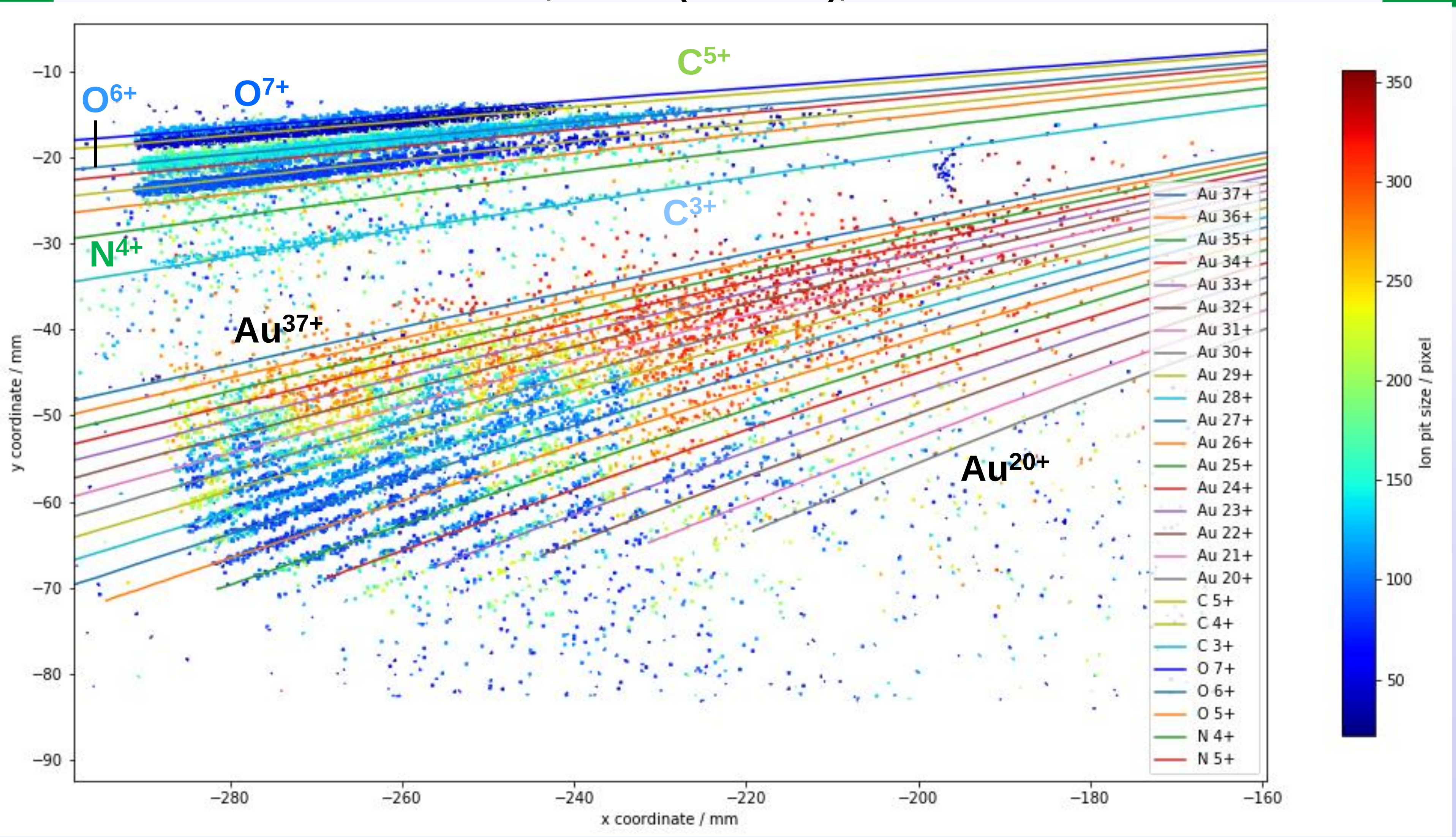


- **Online diagnostics:**
  Lanex screen + camera
- **DRZ-high LANEX:**
  + higher brilliance
  - high (X-ray) background

Au acceleration @ CALA

400 nm Au, heated (1000 mW), 10.5 J

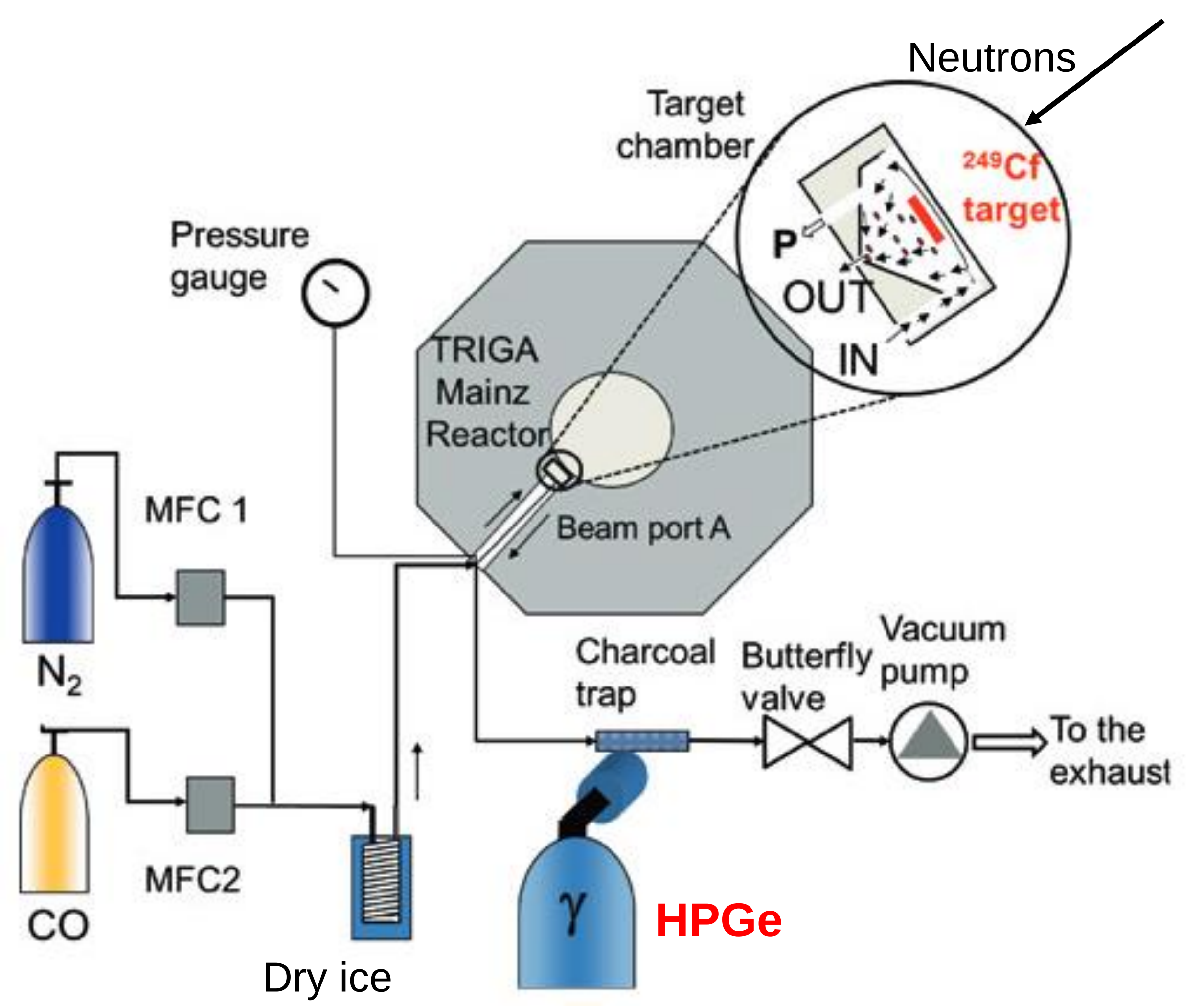
CR39:



- individual charge states resolved: q~ 20-37 (PHELIX: q= 50-72)

Fission Stage of "Fission-Fusion"

- **start with laser-driven p-induced fission**
- **challenges:**
  - strong EMP at laser-target interaction
  - radiation protection
- **method:**
  - use established method from radiochemistry and neutron sources (research reactors):
  - neutrons produce fission fragments in Cf-249
  - **transport fission fragments from target via gas flow to shielded γ spectroscopy (HPGe) detector**
  - charcoal trap delays fragment flow

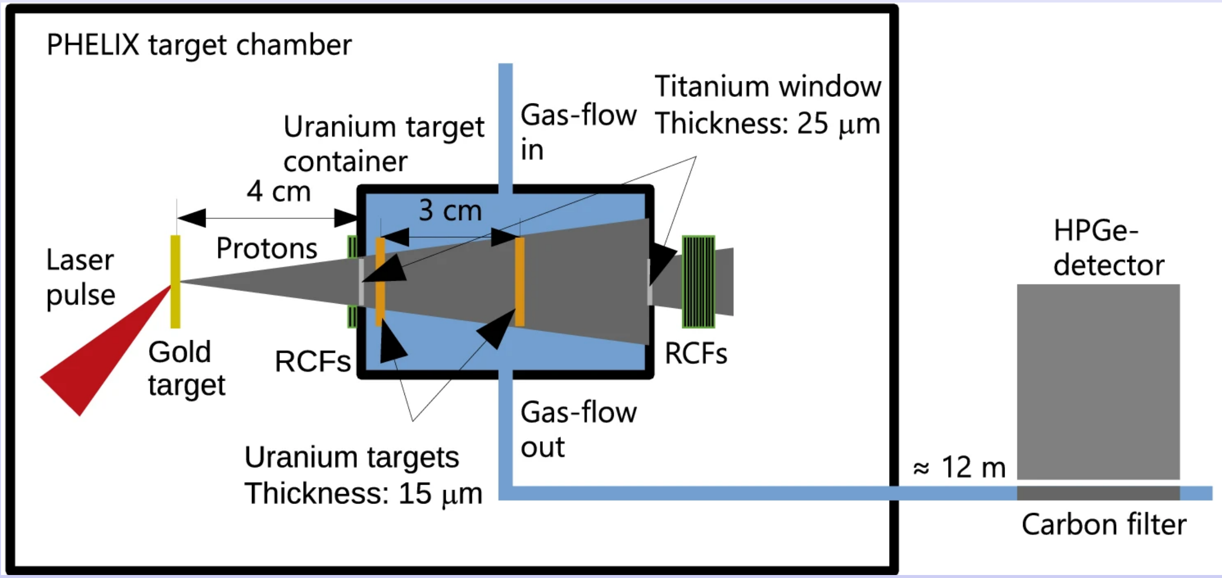


J. Even et al., Radiochim. Acta 2014; 102(12): 1093–1110

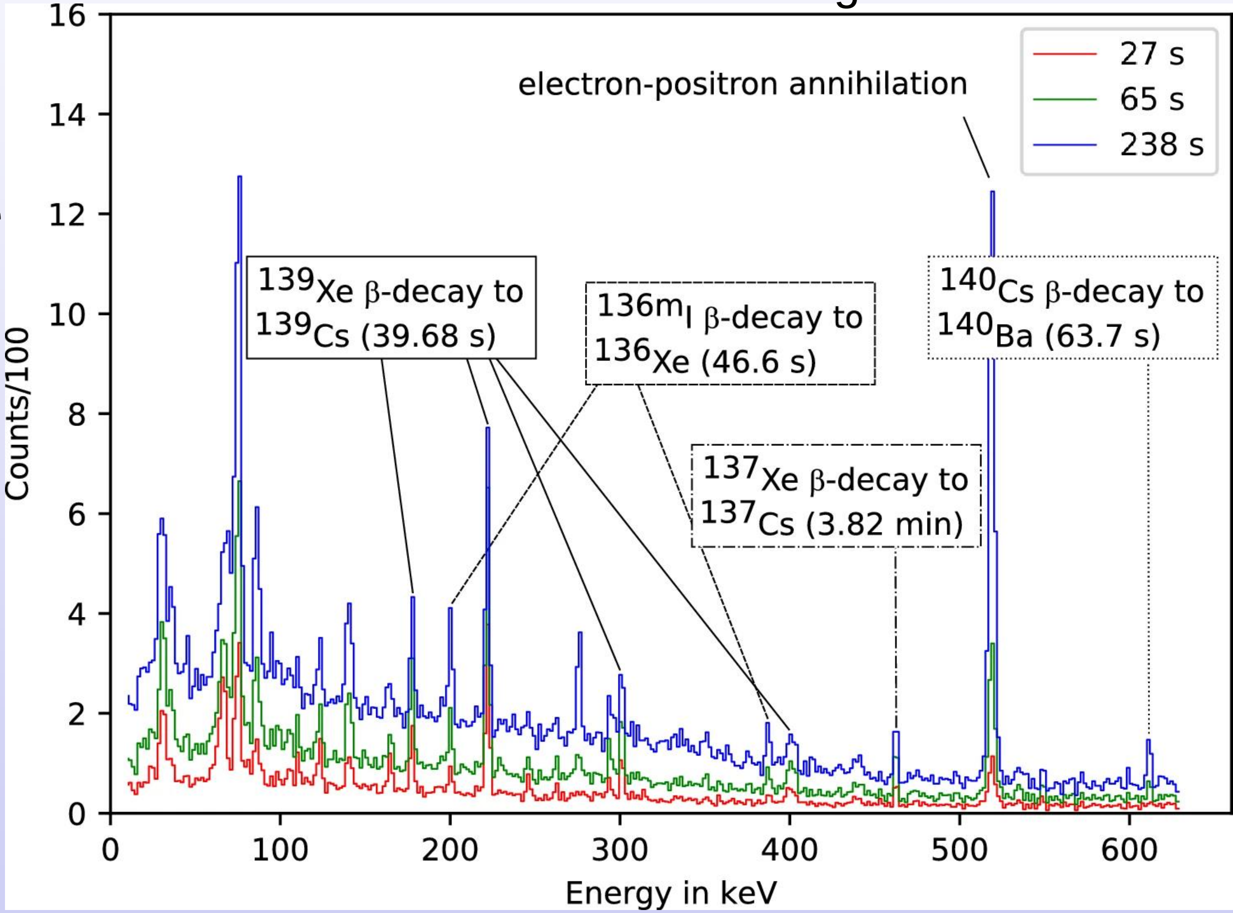
Fission Stage of "Fission-Fusion"

- **experimental realization using laser acceleration:**

- laser accelerated protons induce fission in secondary target (later also heavy-ion induced fission)
- PHELIX laser (GSI): 200 J, 500 fs, 10^{11} protons/pulse
- pressure: 1 bar; gas: He/Ar 1:1
- transport time: 18 s, flow rate: 0.5 l/min



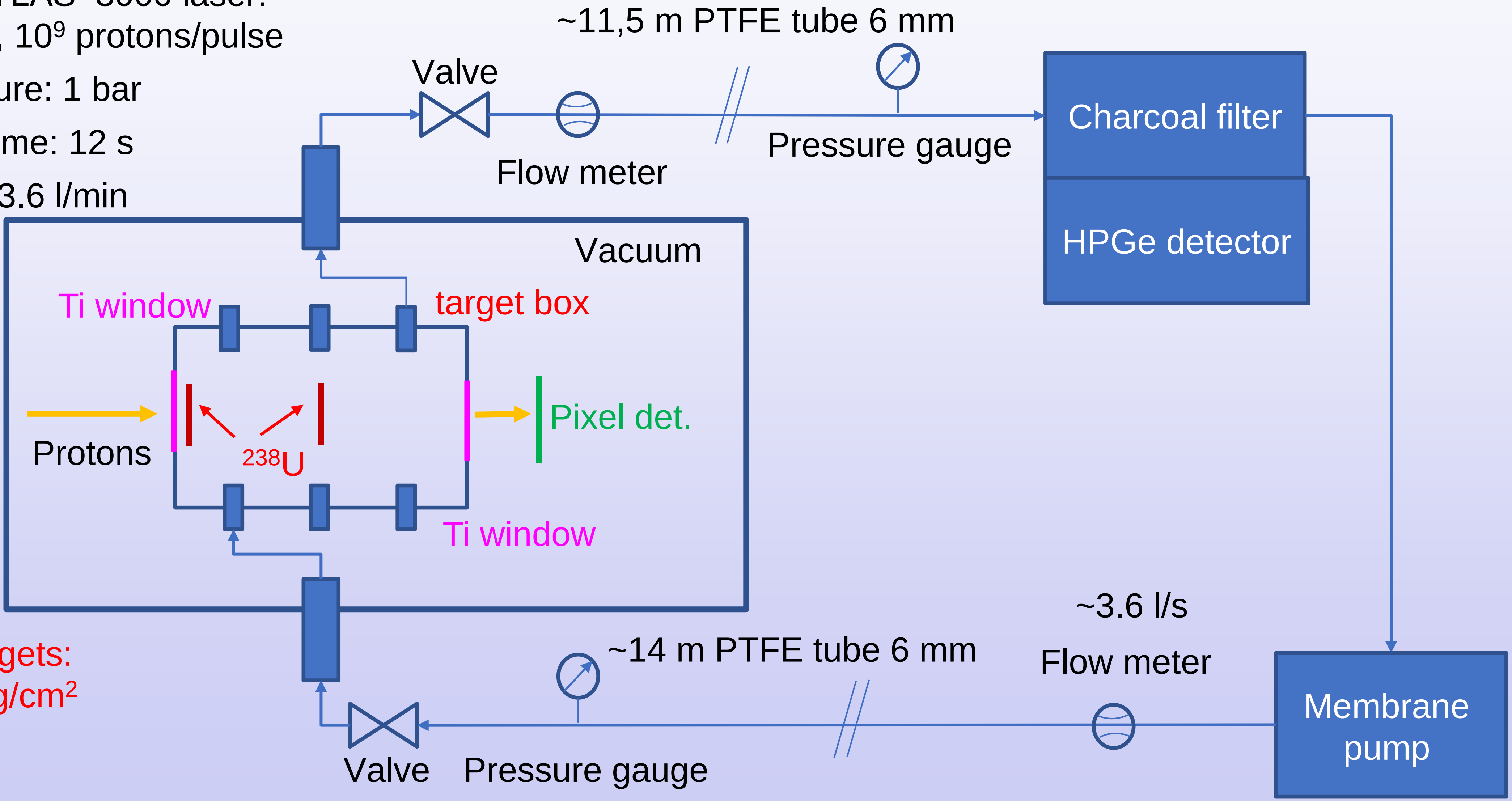
detection of volatile fission fragments



P. Boller et al., Sci. Rep. (2020), 1-9, 10(1)

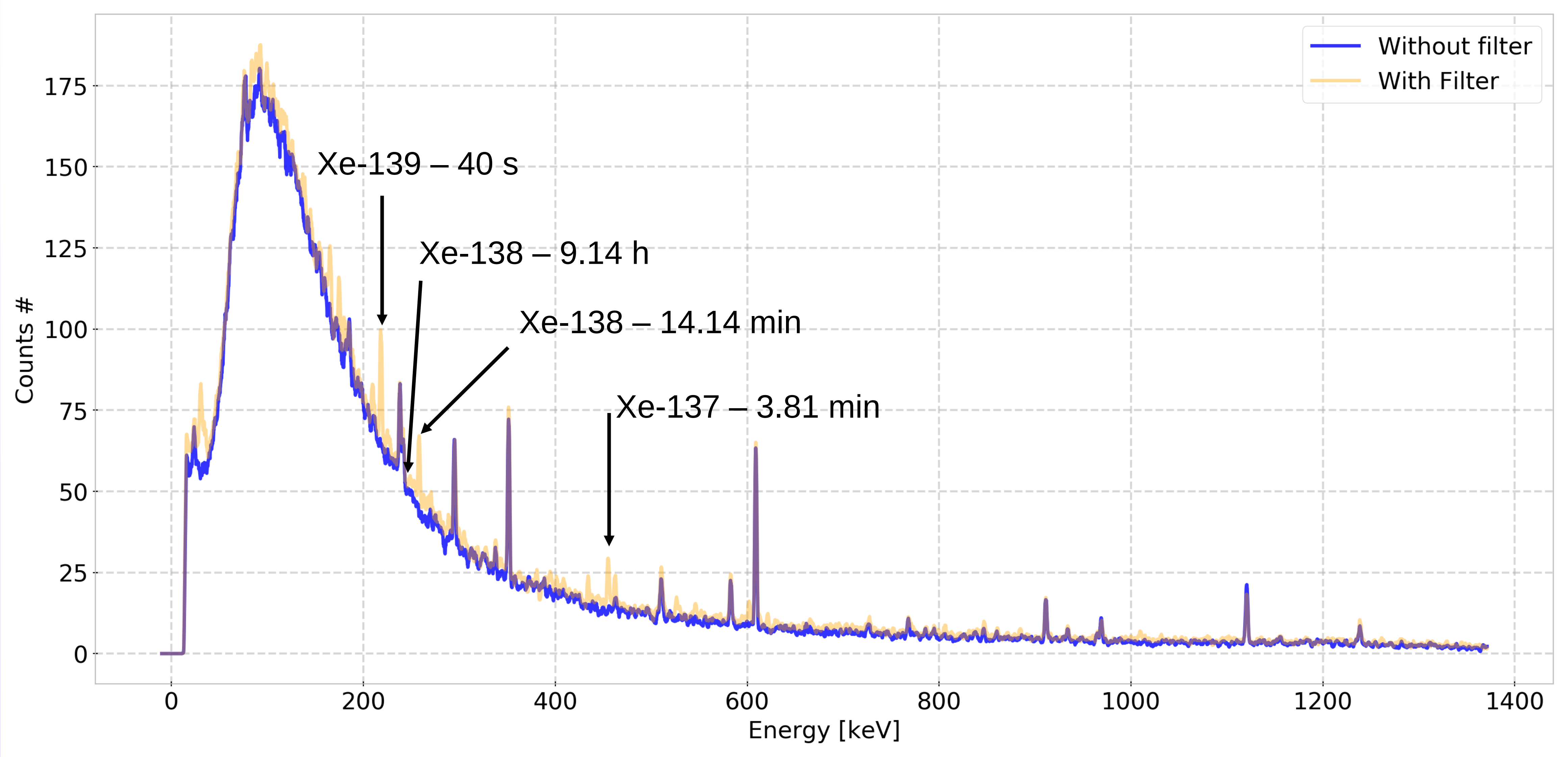
Fission Fragment Transport @ CALA

- CALA – ATLAS 3000 laser: 60 J, 27 fs, 10^9 protons/pulse
- (air) pressure: 1 bar
- transport time: 12 s
- flow rate : 3.6 l/min



2x3 ^{238}U targets: each 1.3 mg/cm^2

Offline Test: ^{252}Cf



Fission Stage of "Fission-Fusion"

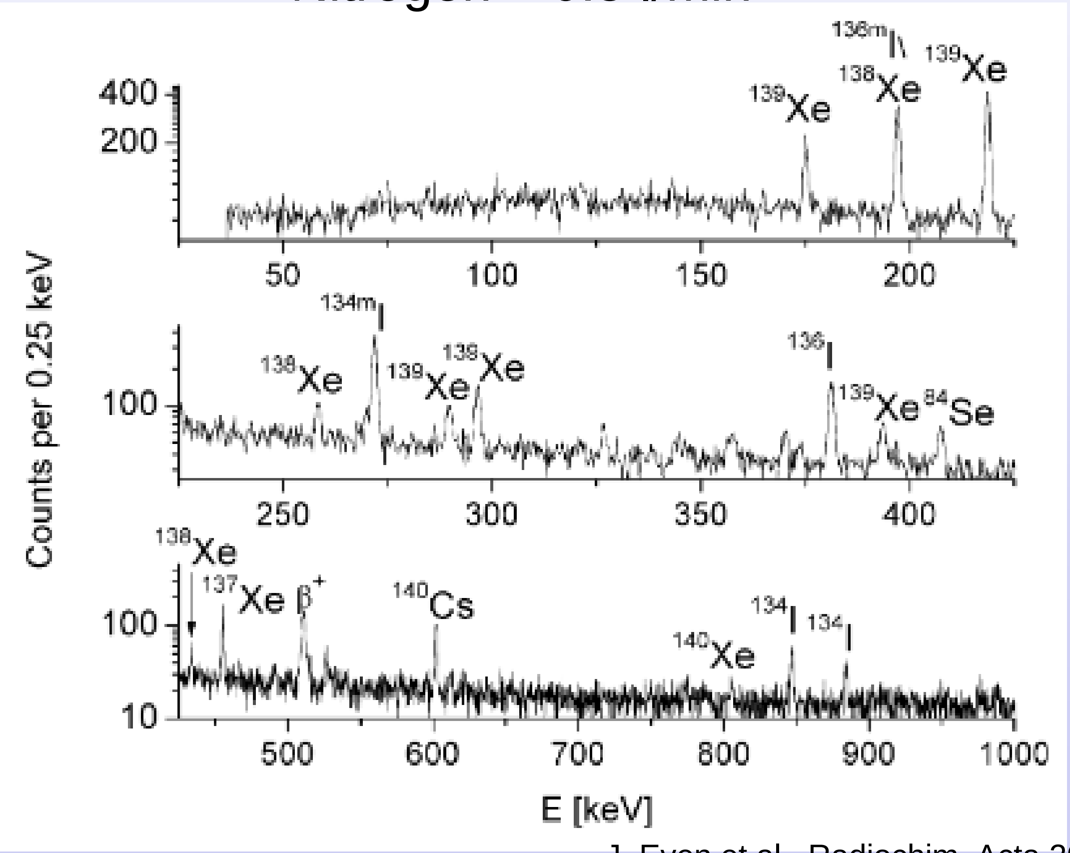
- sensitivity optimization:

  cooling of charcoal filter
  increase gas flow & reduce transport time

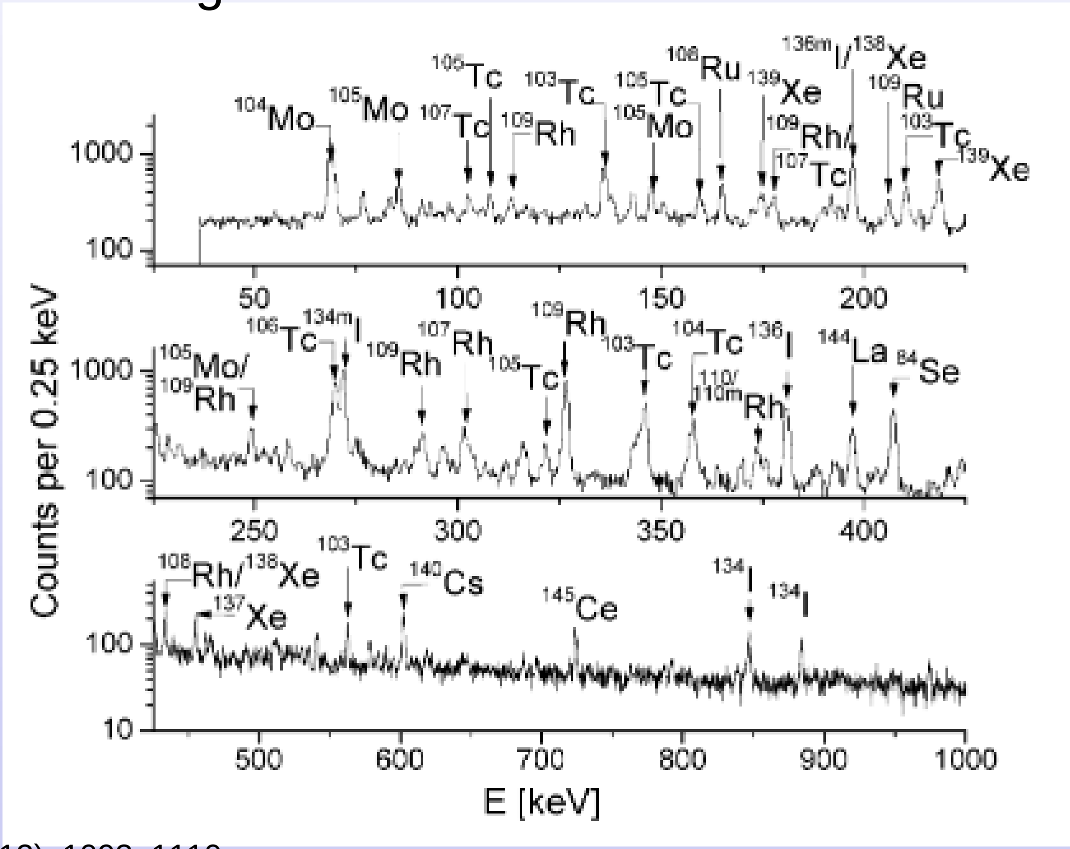
- transport of non-volatile species:

  adhesion to aerosols or
  conversion to volatile species by **CO admixture**

Nitrogen – 0.5 l/min



Nitrogen – 0.15 l/min + CO 0.35 l/min



J. Even et al., Radiochim. Acta 2014; 102(12): 1093–1110

Conclusion and Next Steps

- **towards “Fission-Fusion”:**
  - detection of laser-accelerated gold ions achieved with energies exceeding 7 MeV/u
  - ion bunch density estimate: $10^{13}\,\frac{1}{cm^3}$ at 1 mm from target
    $10^{16}\,\frac{1}{cm^3}$ at 0.1 mm from target
    (already 3-6 orders of magnitude higher than at LHC collision point)
  - individual charge-states resolved, challenging ionization models
    → impact of collisional ionization revealed for PHELIX pulses (500 fs), unclear situation for CALA pulses (lower q observed for 28 fs pulses)
  - setup for laser-driven, p-induced ^{238}U fission in commissioning

- **ongoing/next steps:**
  - further optimizing online detection of gold ion acceleration at CALA (28 fs, 60 J)
  - investigating potential collective effects of ion bunch density on stopping range
  - online characterization of laser-driven p-induced fission

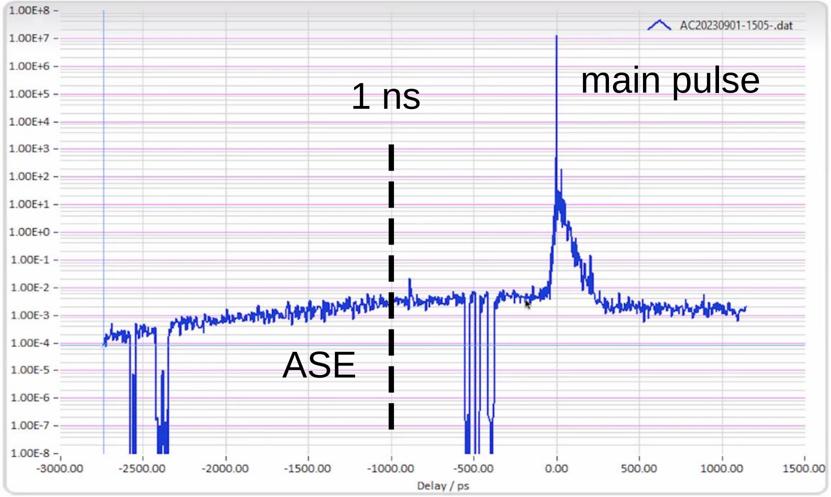
Open Questions & Challenges

Temporal Laser Contrast

focused intensity: 10^{21} – 10^{22} W/cm^2 (> 10^{23} W/cm^2 envisaged)
target ionization : beyond ≈ 10^{10} W/cm^2

→ (temporal) contrast needed: > 10^{12} - 10^{13}

PHELIX: ~ 10^{12} for 0.5-20 ps pulses,
ELI-NP: 10^{13} @ -100 ps (goal)
CALA (no plasma mirror): ~ 10^{10}



Rep-rated targetry

liquid film targets
cryogenic hydrogen jet targets
metal/plastic foil target wheel
mass-limited targets: microspheres in Paul trap
droplets

Reprate-capable ion diagnostics (EMP resistant)

CMOS pixel detectors (e.g. RadEye): ok for protons,
ions: radiation damage
CMOS+scintillators: limited light yield
LANEX scintillating screens + CCD camera: limited sensitivity, resolution

Thanks to .....

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Thank you for your attention !