

How Low Can We Go?

Routine Reliability and Low Energy Limits for AMS with a Cs Sputter Source

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AMS – Why do we do it?

AMS is an ultra-sensitive method to detect trace amounts of long-lived radionuclides.

With both cosmogenic and anthropogenic sources, these nuclides can be used as a 'clock' for:

- Archeology/paleoclimate (^{14}C 5.7×10^3 yr)
- Earth sciences/geomorphology – ^{10}Be (1.38×10^6 yr), ^{26}Al (717×10^3 yr)
- Environmental/hydrology – ^{36}Cl (300×10^3 yr), ^{129}I (15.7×10^6 yr)
- Biomedicine – ^{14}C , ^{41}Ca (99×10^3 yr)
- Nuclear science/oceanography – actinides (Pu isotopes, U, etc.)

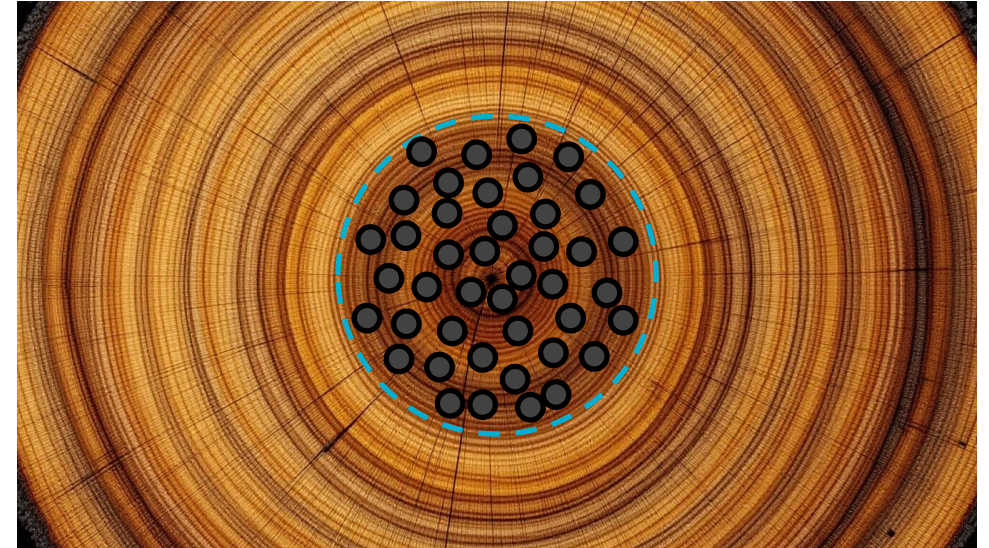


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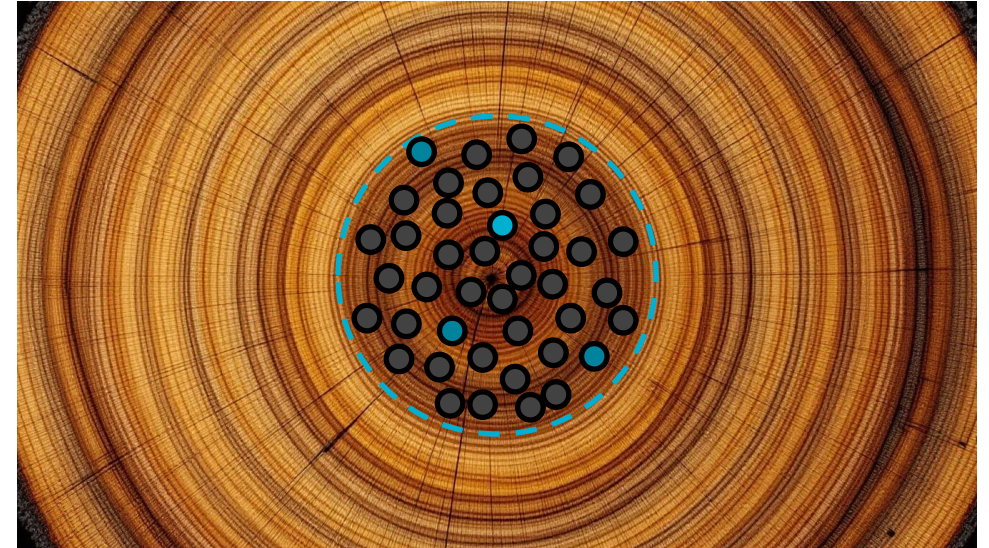


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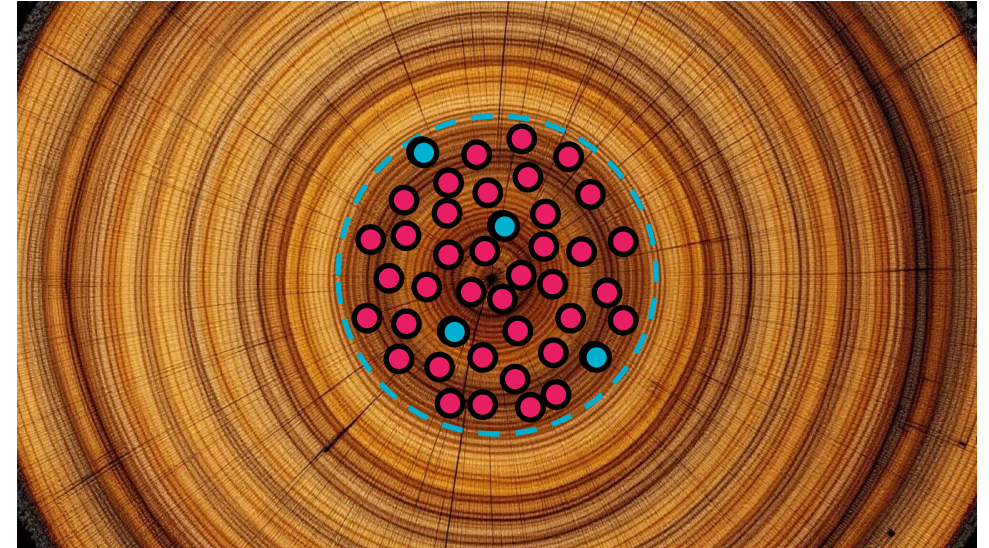
Decay counting
counts atoms
that decay over
time: grams of
sample, days of
counting

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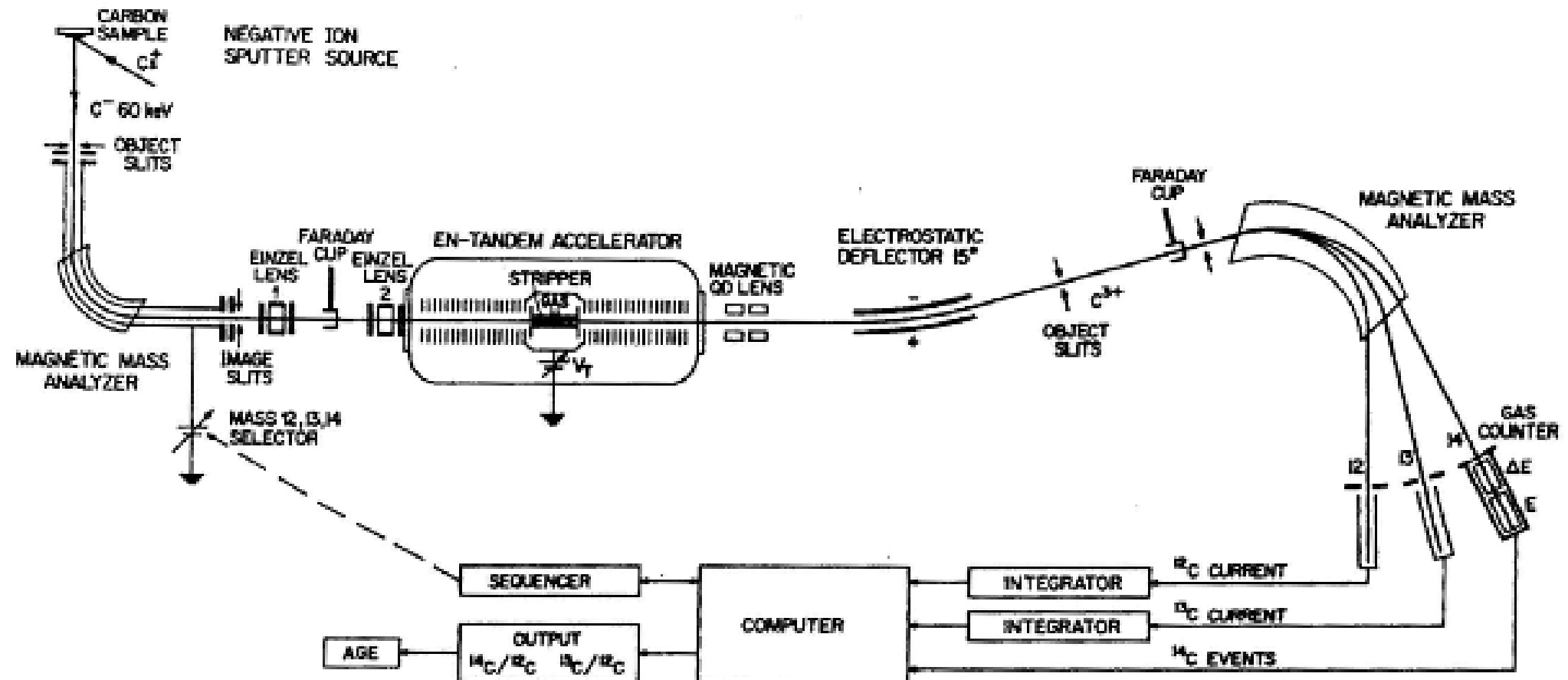
Decay counting
counts atoms
that decay over
time: grams of
sample, days of
counting

AMS utilizes direct
detection – potentially
every atom can be
extracted and detected:
mg of sample, minutes
of counting

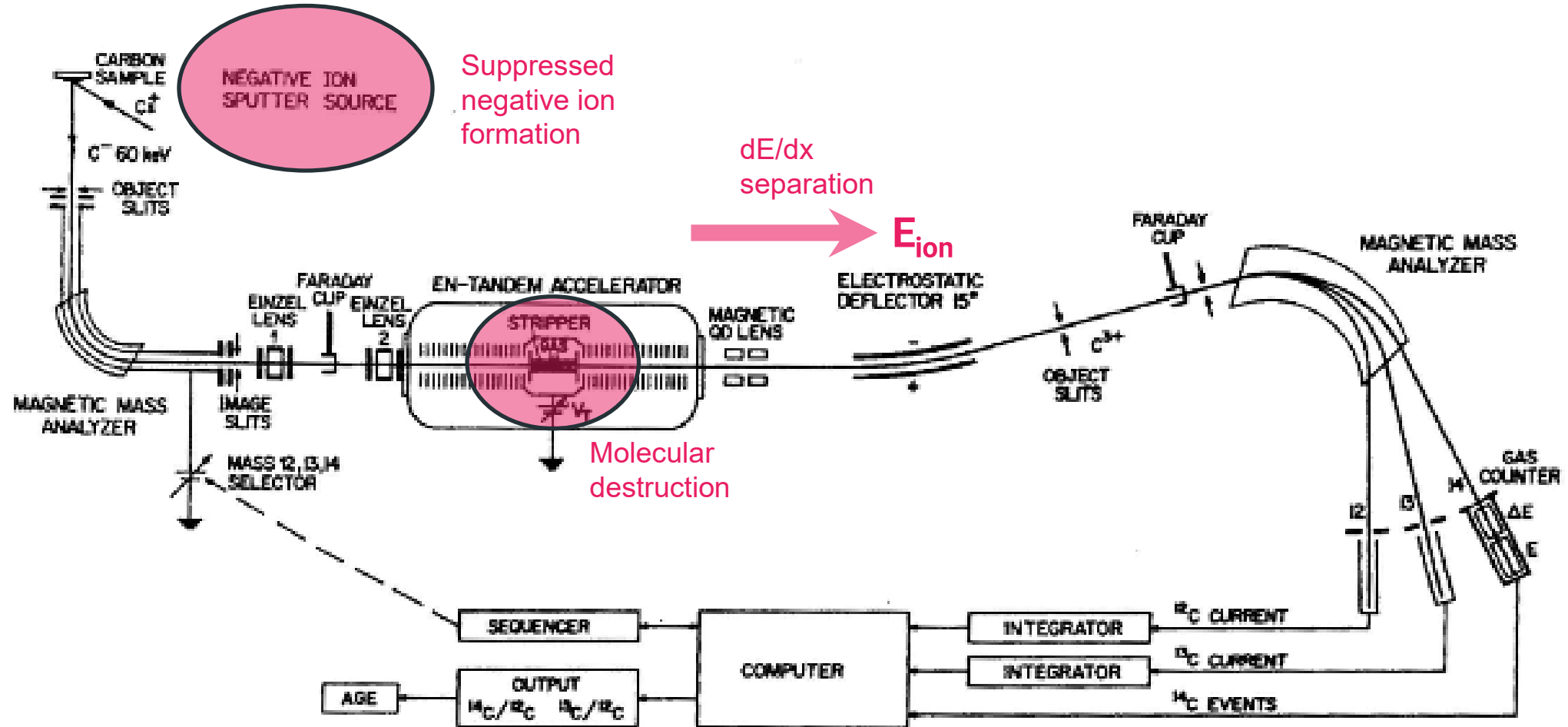
The main challenge of (A)MS?

The isobar

AMS – how do we do it?



AMS – how do we do it? (isobar suppression)



AMS – how do we do it?

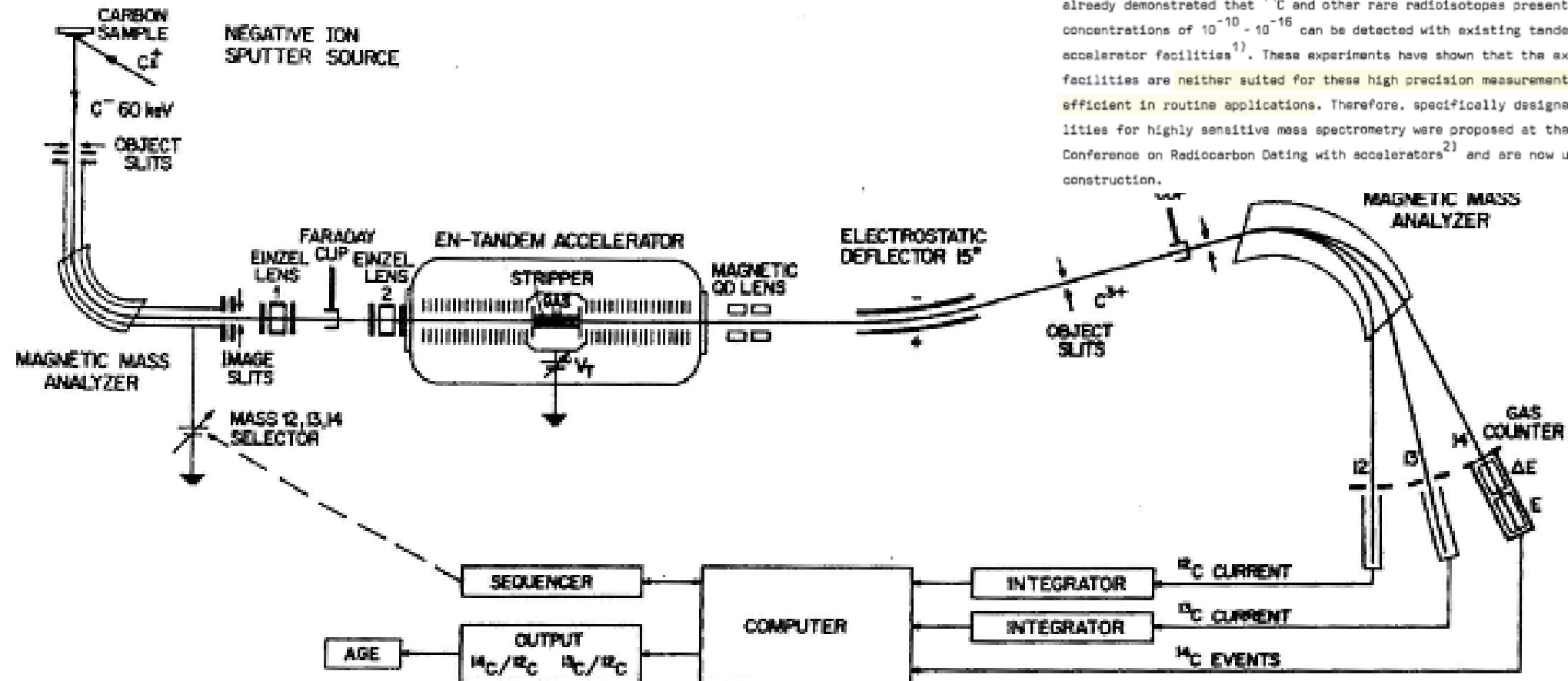
IMPROVEMENTS IN THE APPLICATION OF A TANDEM VAN-DE-GRAAFF ACCELERATOR FOR ULTRA-SENSITIVE MASS SPECTROMETRY

M. Suter, R. Balzer, G. Bonani, Ch. Stoller and W. Wölfli
Laboratorium für Kernphysik, Eidg. Technische Hochschule, 8093 Zürich, Switzerland

J. Beer, H. Deschler and S. Stauffer
Physikalisches Institut, Universität Bern, 3012 Bern, Switzerland

1. INTRODUCTION

In 1979, when this project was started, several other laboratories had already demonstrated that ^{14}C and other rare radioisotopes present in concentrations of 10^{-10} - 10^{-16} can be detected with existing tandem accelerator facilities¹⁾. These experiments have shown that the existing facilities are neither suited for these high precision measurements nor efficient in routine applications. Therefore, specifically designed facilities for highly sensitive mass spectrometry were proposed at the First Conference on Radiocarbon Dating with accelerators²⁾ and are now under construction.



AMS – how do we do it? (compact AMS)

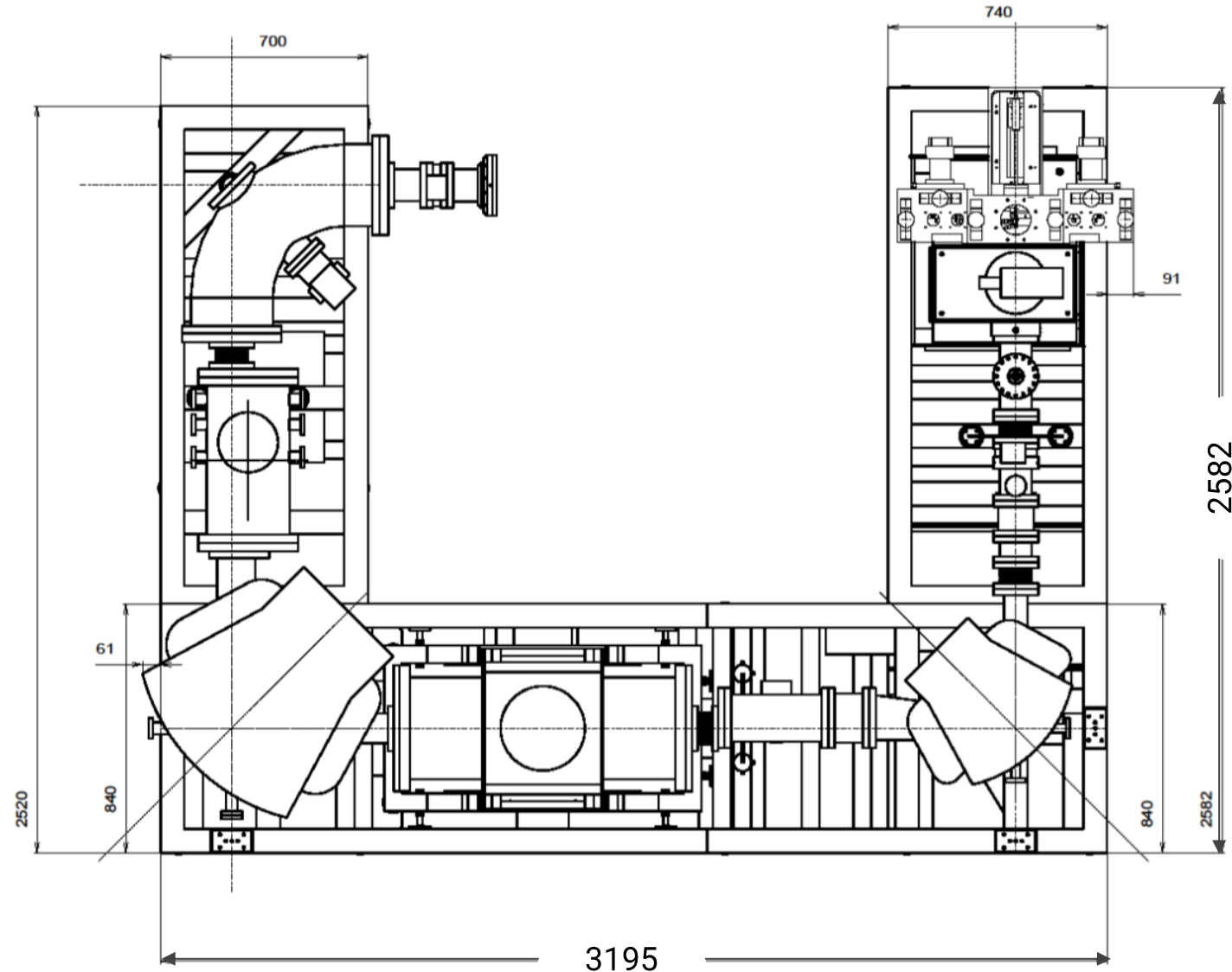
The working solution at ETH Zürich:
compact AMS.

Use of He as stripper gas allows
lower energies → better transmission

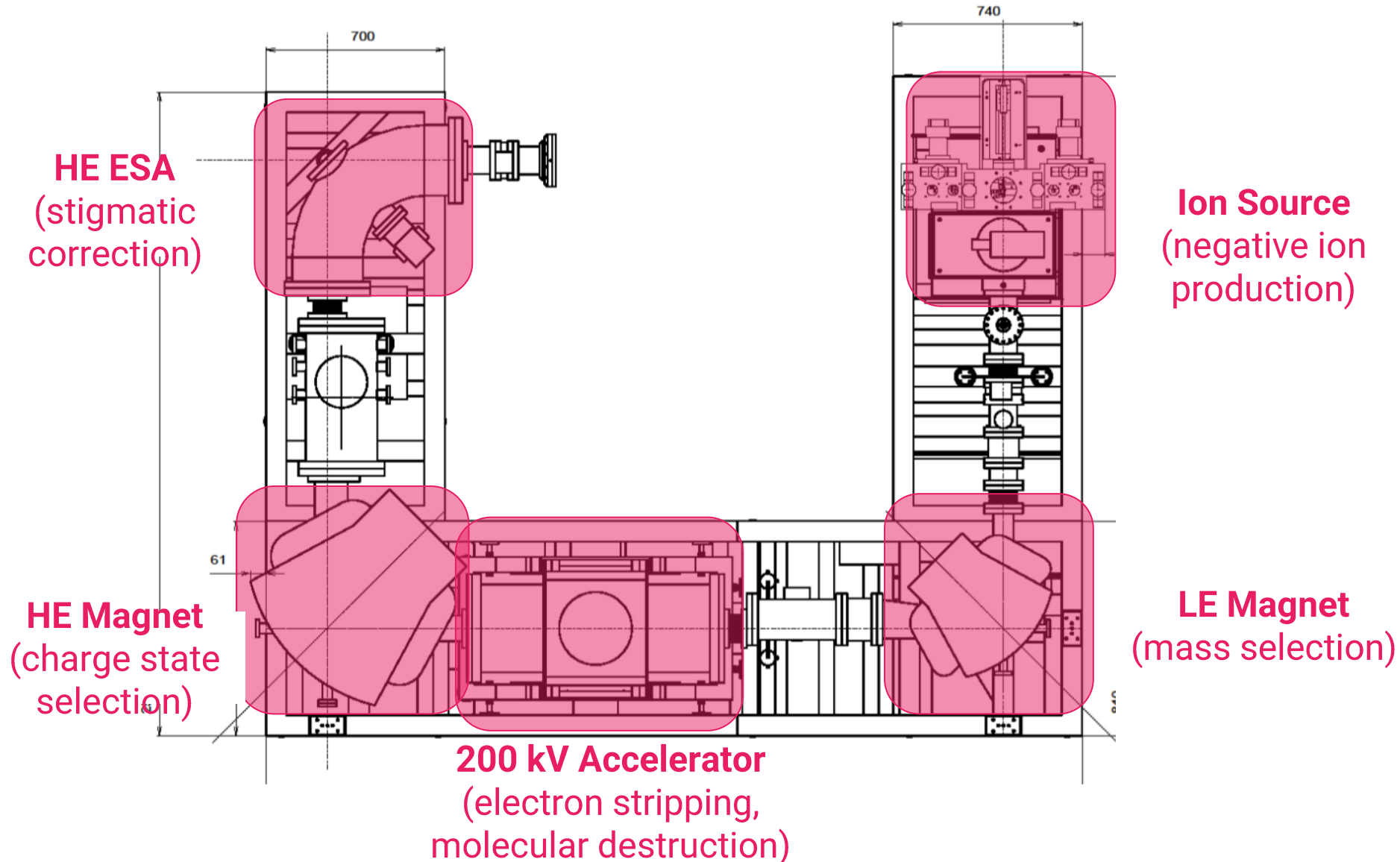
200kV MICADAS (46%) ($^{12}\text{C}^{1+}$ – 50%)
50kV LEA (50%) ($^{12}\text{C}^{1+}$ – 60%)



AMS – how do we do it? (compact AMS)



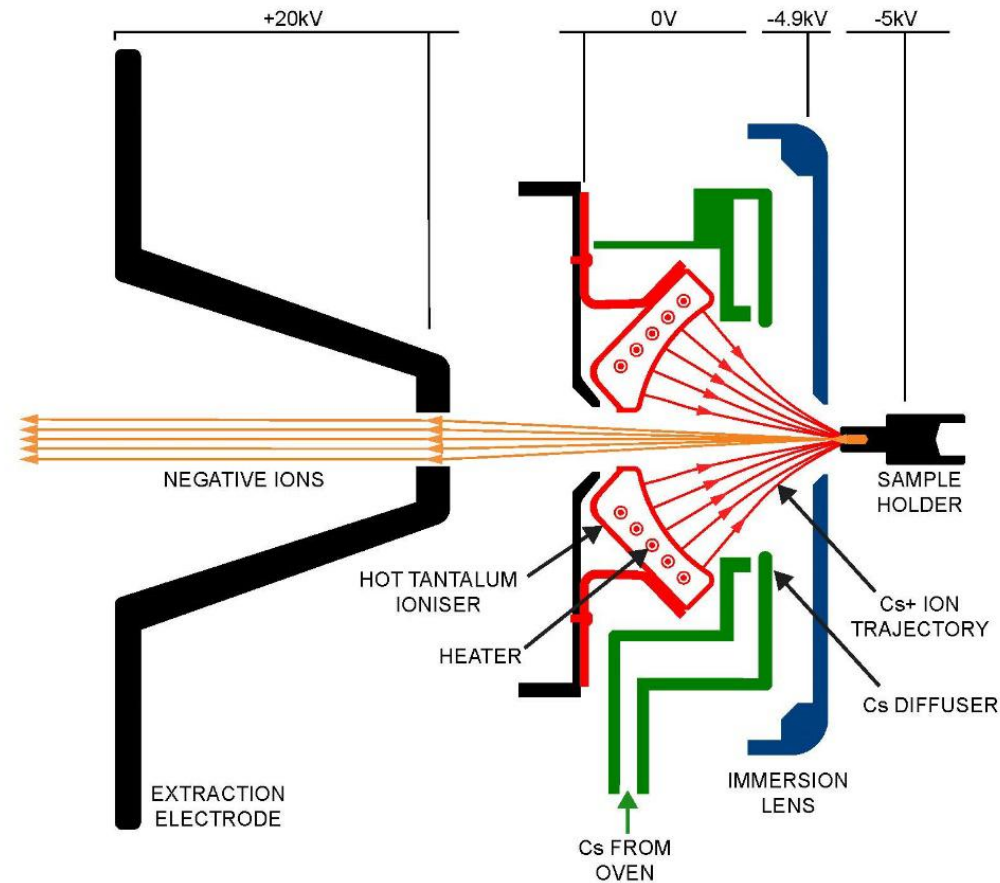
AMS – how do we do it? (compact AMS)



What do we need from the source?

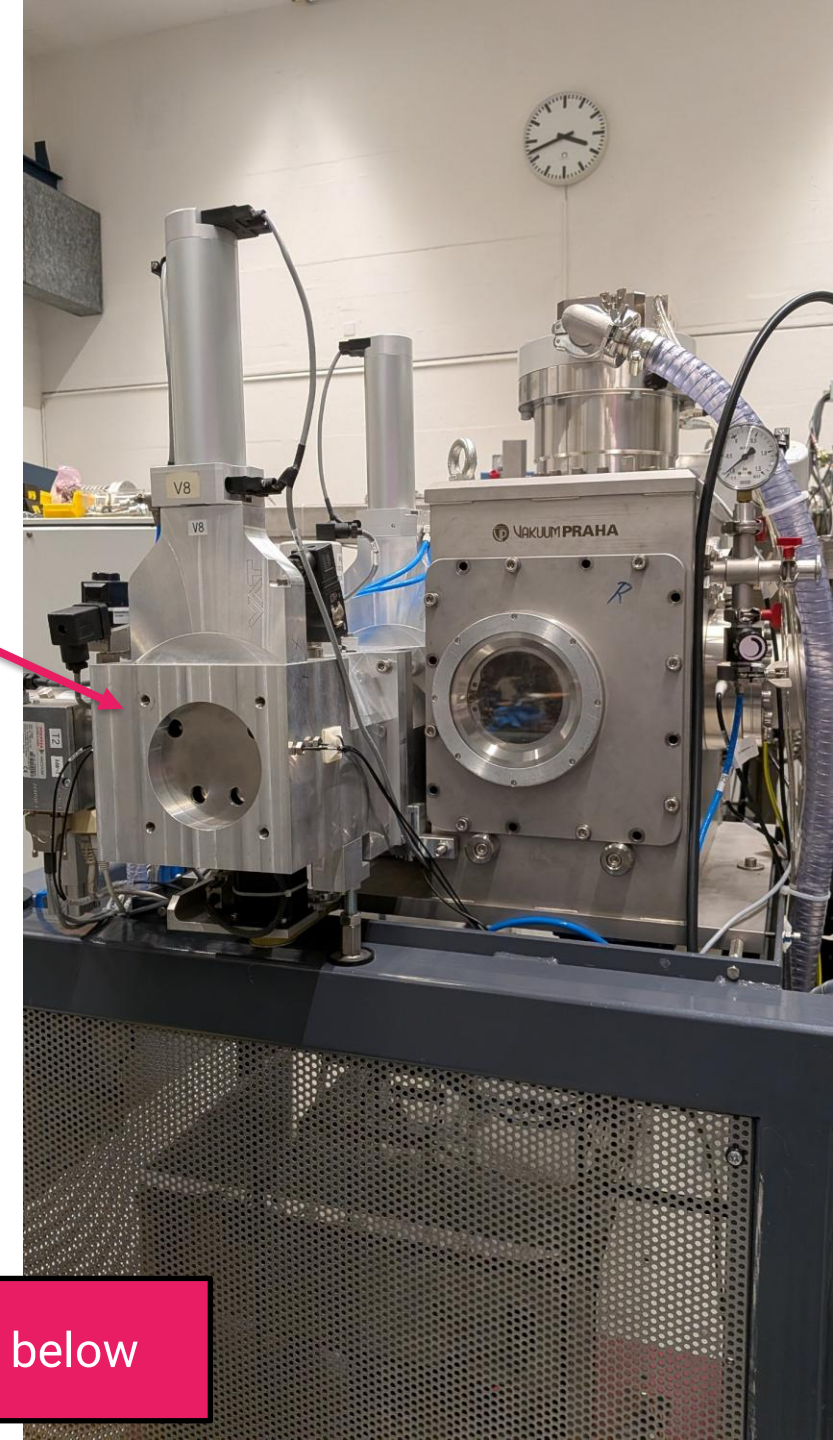
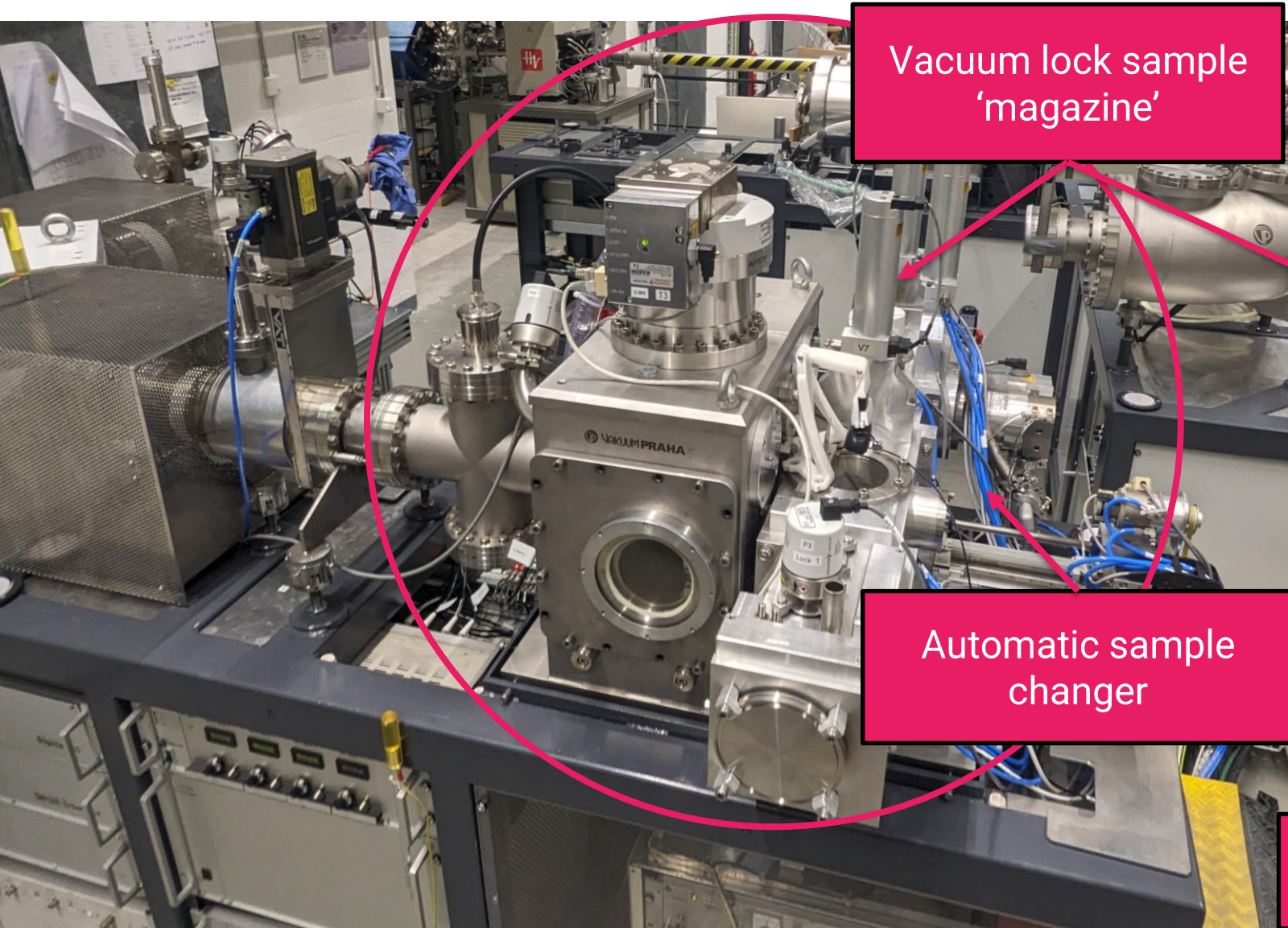
- Good efficiency – both sputtering efficiency and extraction, so that we can use the smallest amount of sample possible and that measurements do not take too long
 - **1 mg of carbon**
- Good stability – so that optimum tuning parameters further downstream do not drift too far during the measurement
- Ideally also: low maintenance!

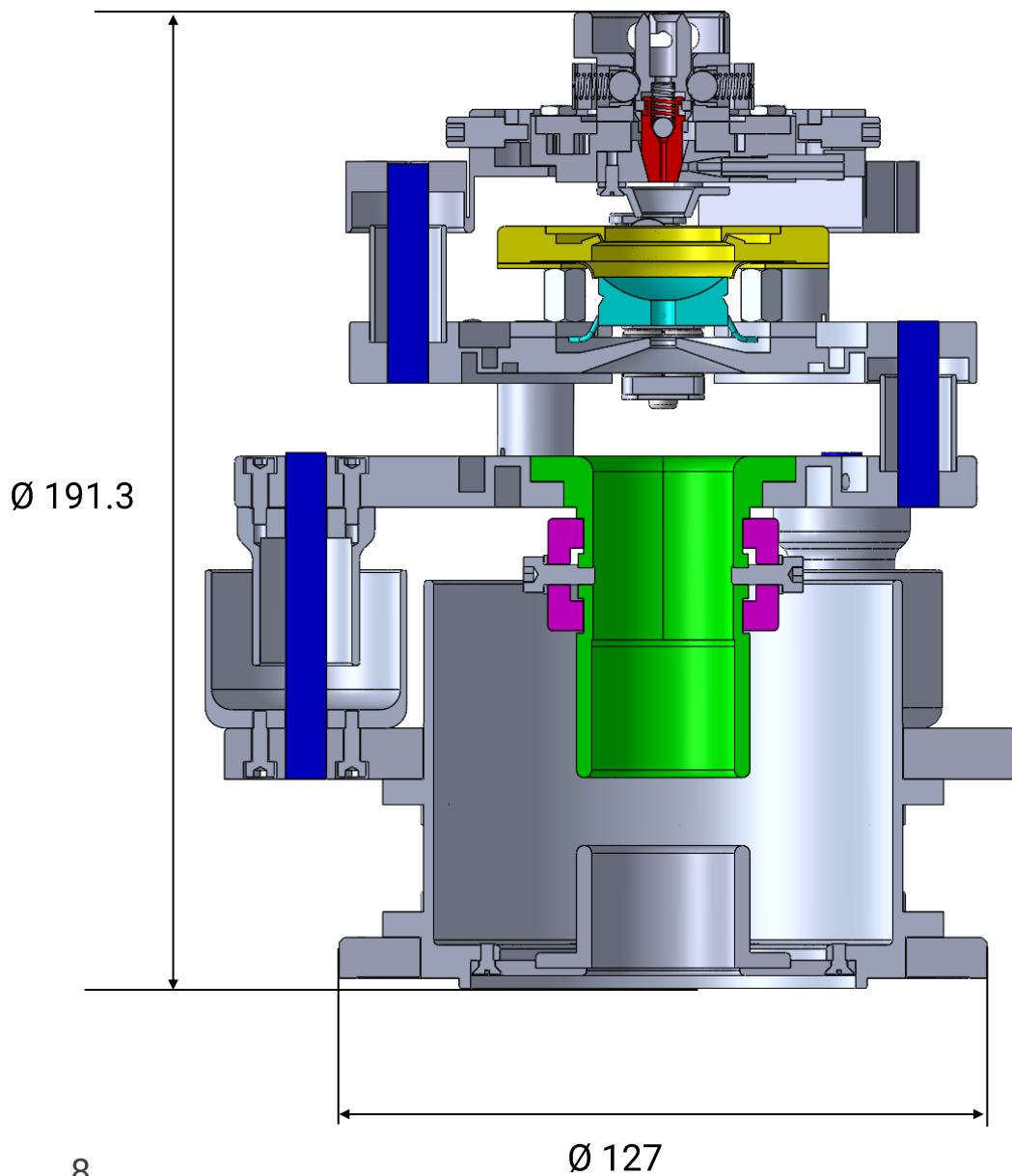
What is a Cs sputter source?



K. Fifield, *The Methodology and Physics of Accelerator Mass Spectrometry* (2025)

ETH source design





Target/cathode
(on potential)

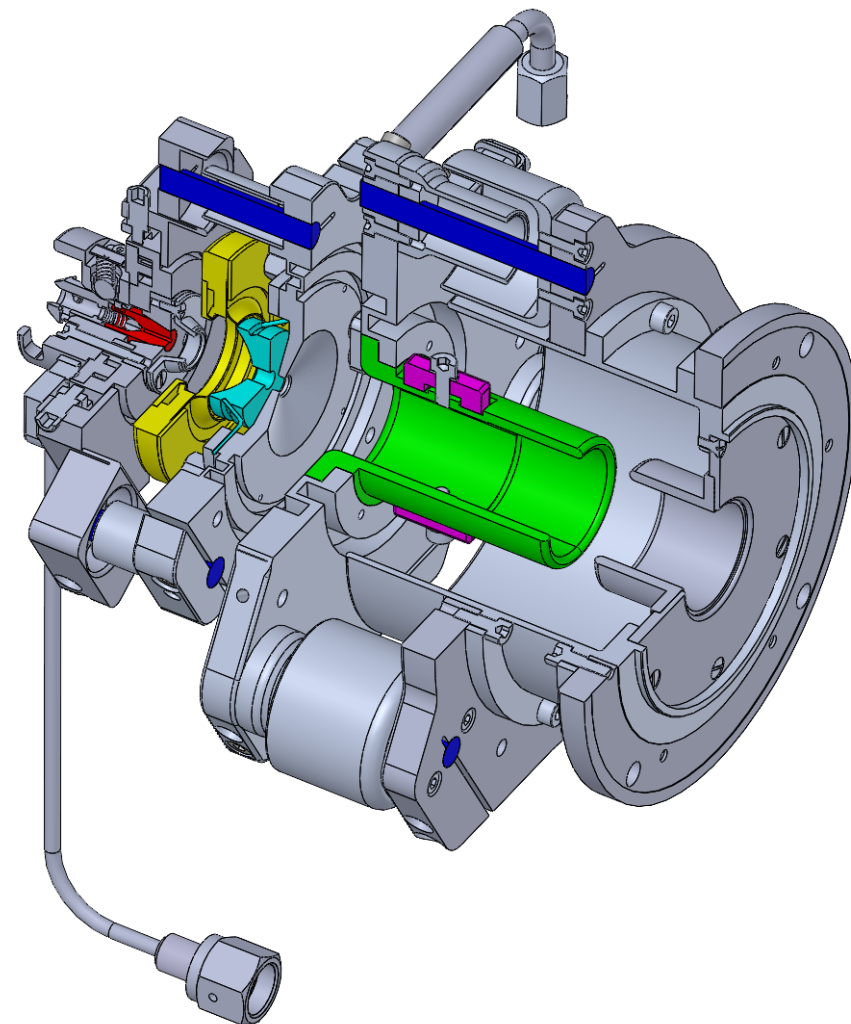
Cs nozzle

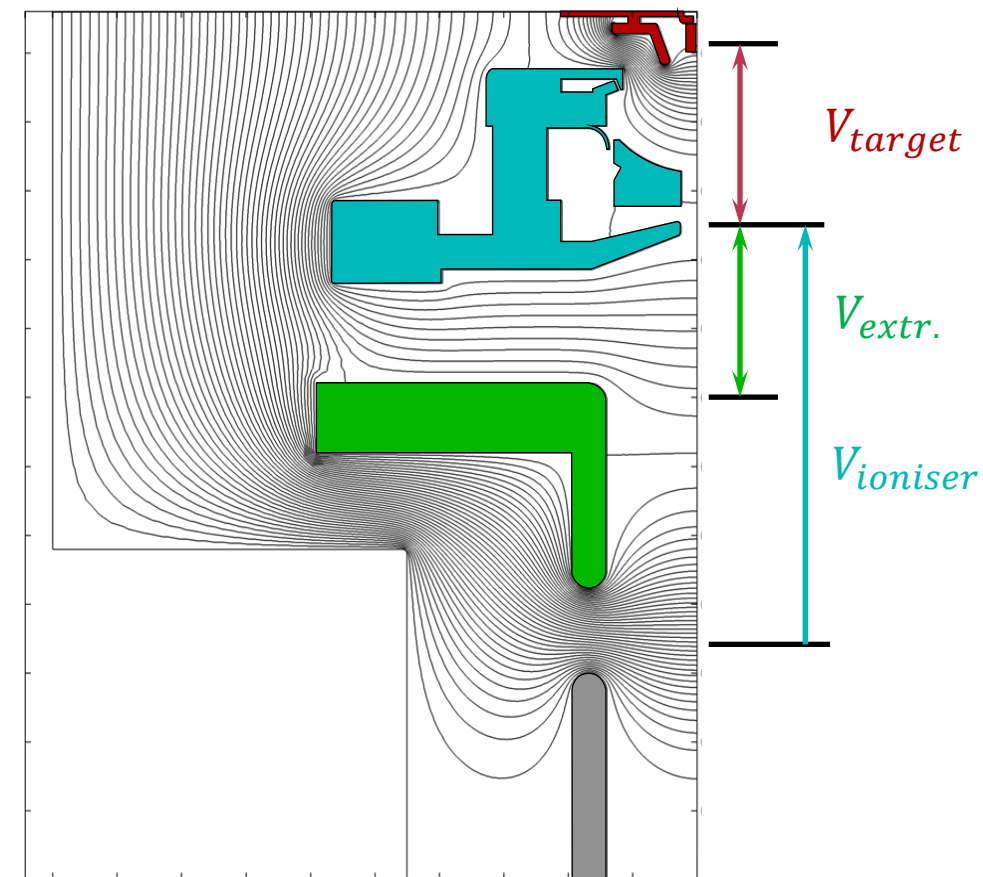
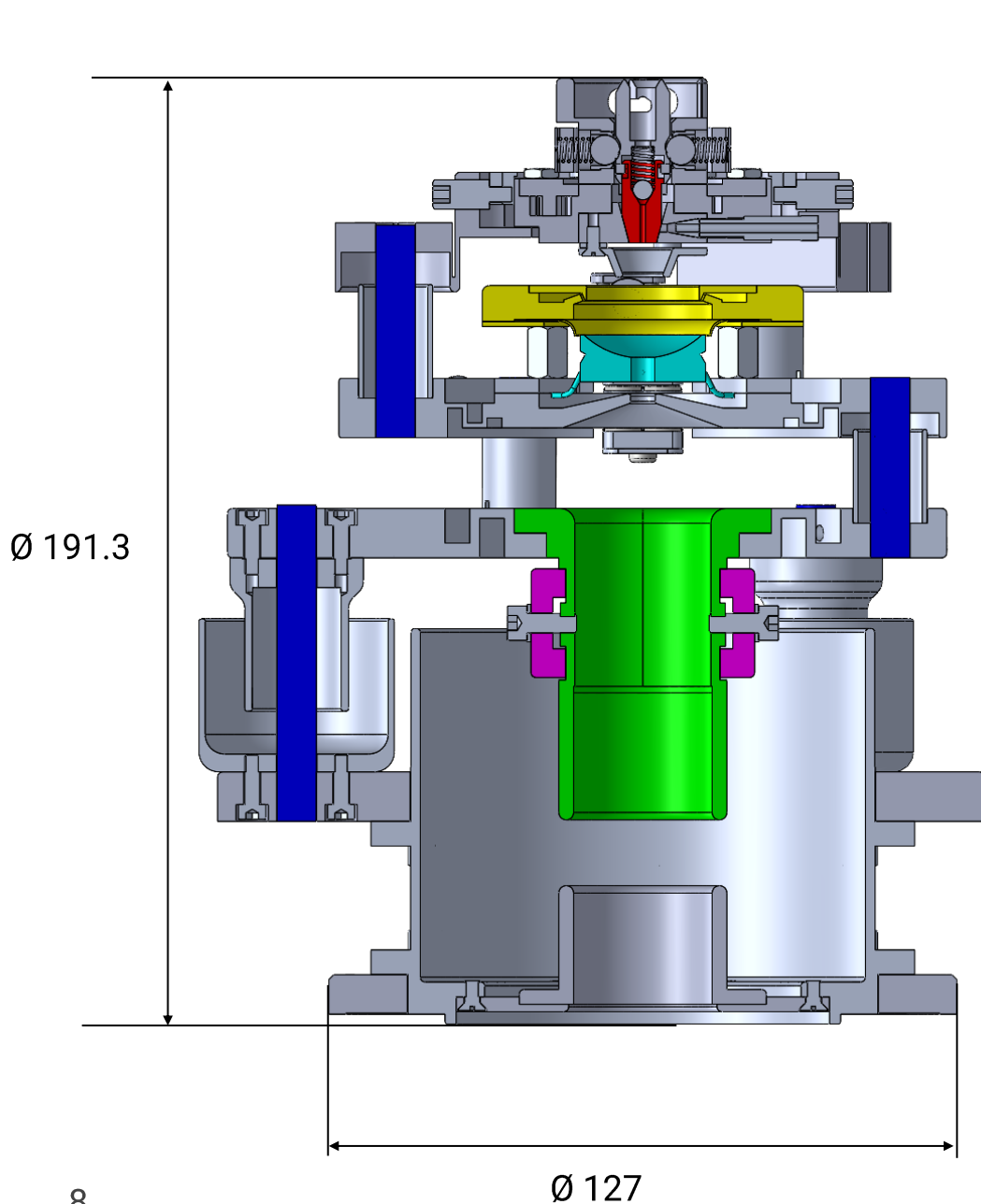
Ioniser

Permanent
magnets

Extractor lens

Isolating ceramics
(Macor)





$$E_{ion}^{-1} = V_{target} + V_{ioniser}$$

Ioniser platform (Cu wire for heating ioniser, generally operated at 15 A, 6V $\rightarrow$ 90 W)

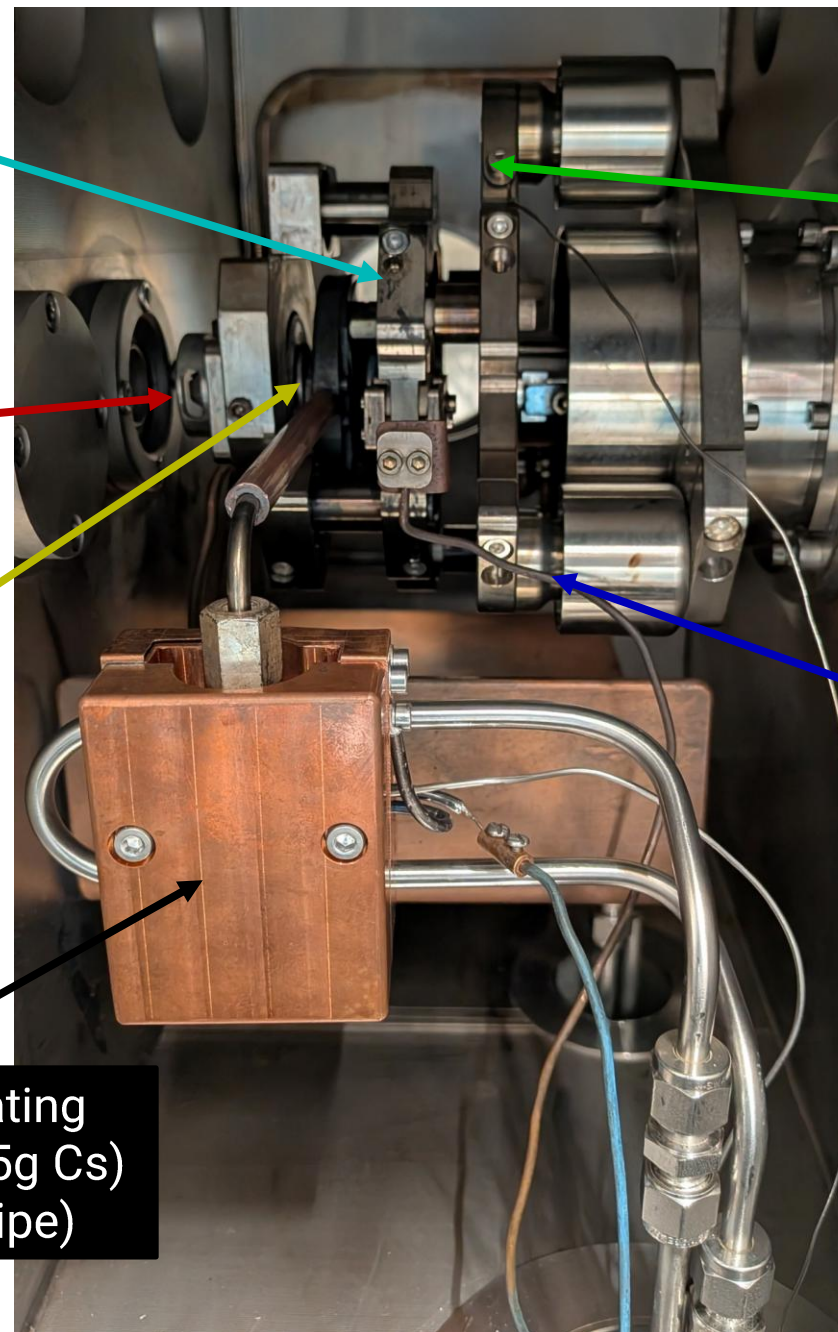
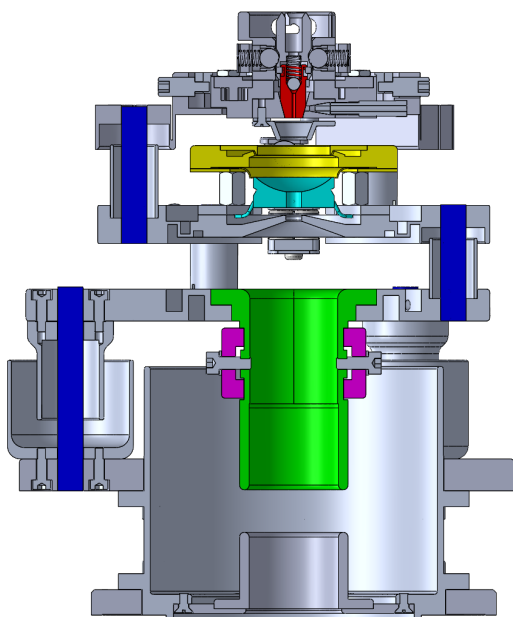
Target/cathode
(-6 kV)

Cs nozzle

Extraction potential
(up to 10 kV)

Ceramic spacers
between each voltage platform,
with shields to protect from
excessive carbon
build up

Cu block for Cs heating
-Cs reservoir inside (5g Cs)
- air-cooled (1/4" pipe)



ETH source parameters and performance

'Typical' operation:

Ioniser = -36 kV

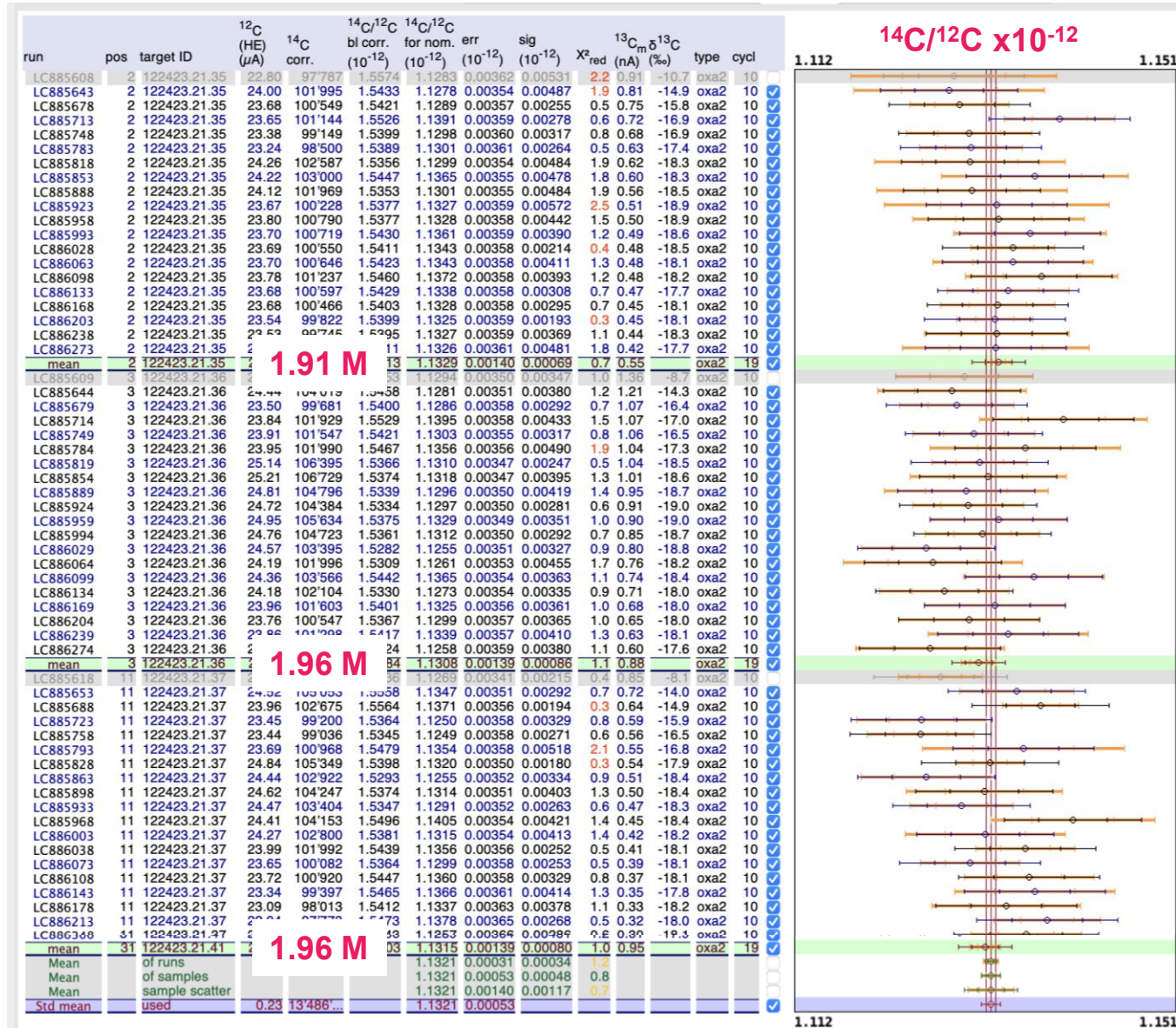
Target = -5.5 kV

Extractor = 5.6 kV

Corresponds to ~10s keV injection energy

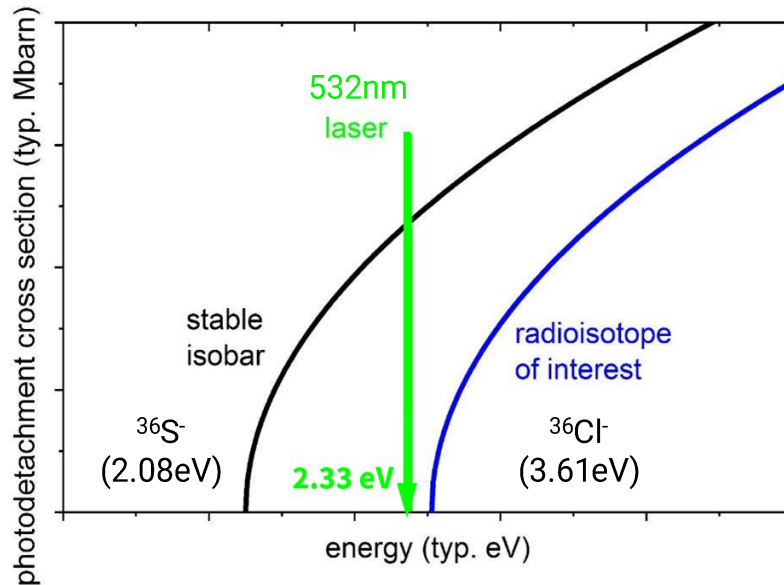
"If the machine is running 24/7 (30uA ^{12}C at the high energy end), then the source needs to be cleaned every 45-60 days"

ETH source parameters and performance



Why push to even lower energy?

(It's isobar suppression again)



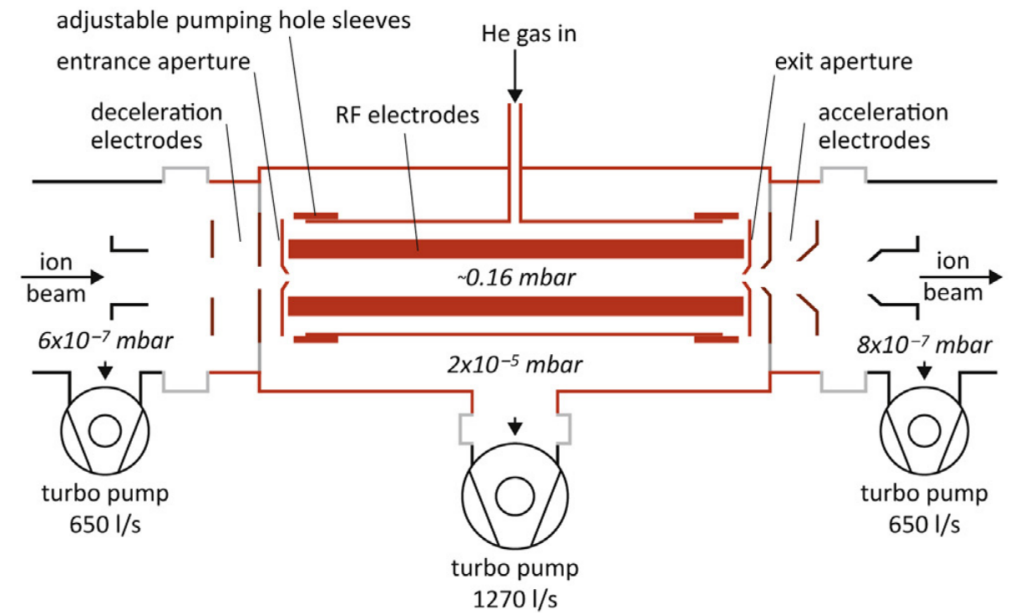
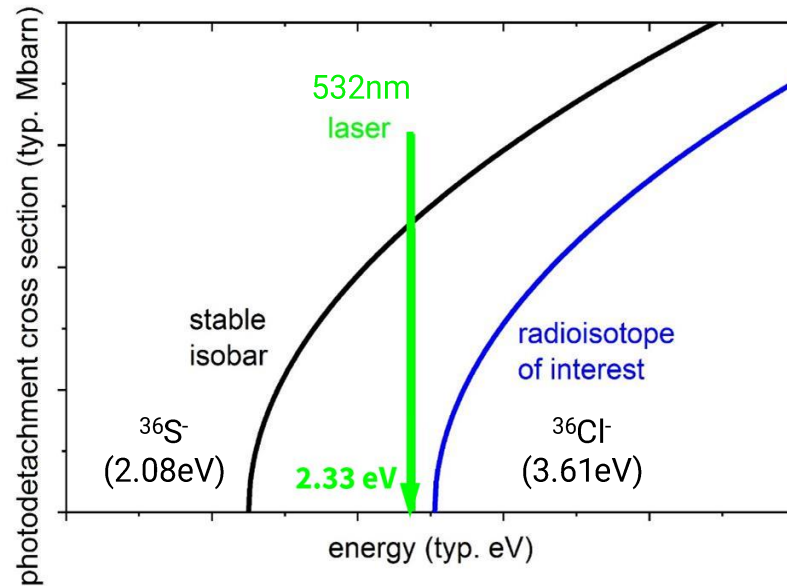
$$N_{\text{surviving}} = N_0 \cdot e^{(-\sigma\phi t)}$$

σ : detachment cross section

ϕ : photon flux

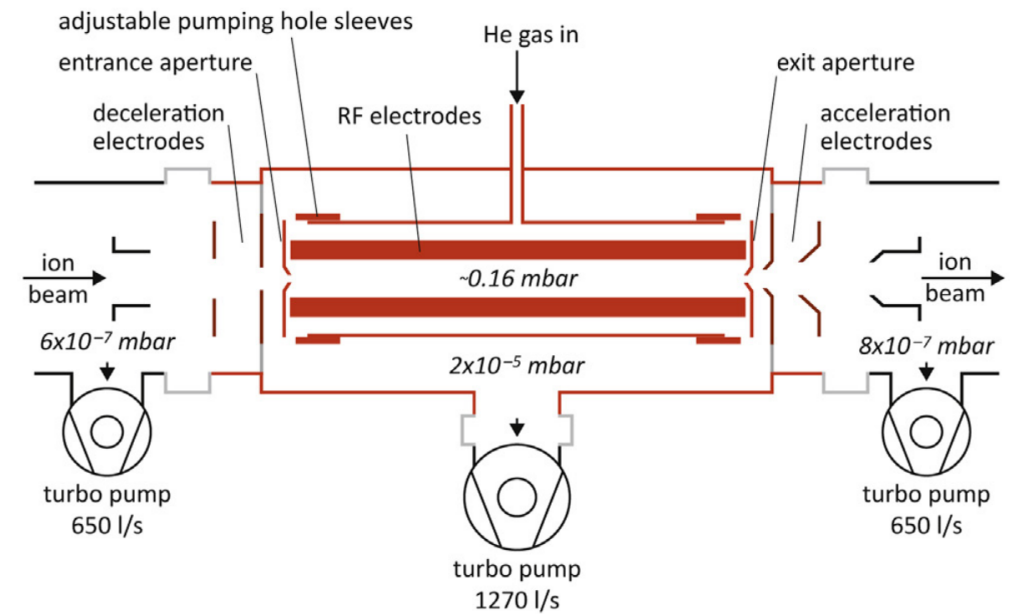
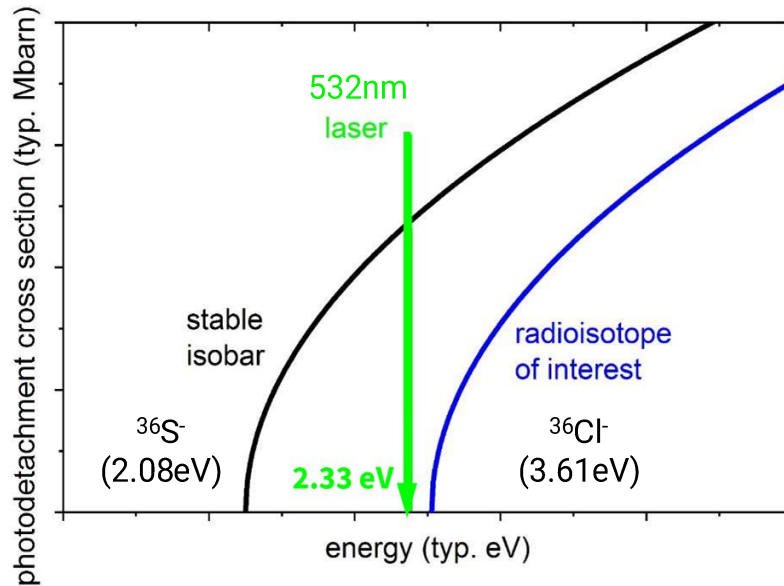
t : interaction time

Why push to even lower energy?



M. Martischini et al, IJMS 415, 9-17 (2017)

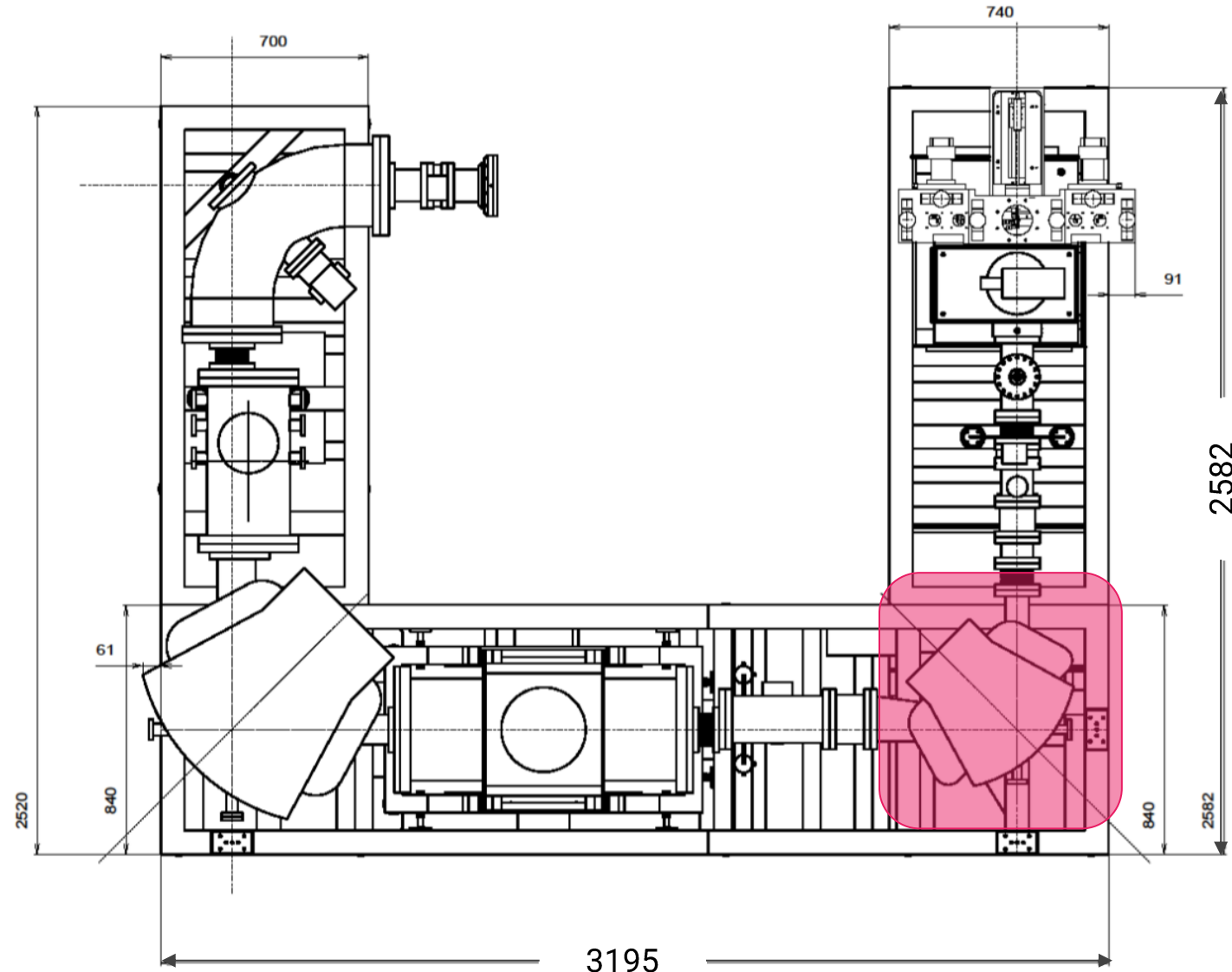
Why push to even lower energy?



M. Martischini et al, IJMS 415, 9-17 (2017)

Reason 1: ease of RFQ construction

Why push to even lower energy?



For a maximum field
of 0.695 T at LE
magnet:

$^{36}\text{Cl}^- = 40 \text{ keV}$

$^{41}\text{CaH}^- = 32 \text{ keV}$

$^{41}\text{CaF}_3^- = 14 \text{ keV (!!!)}$

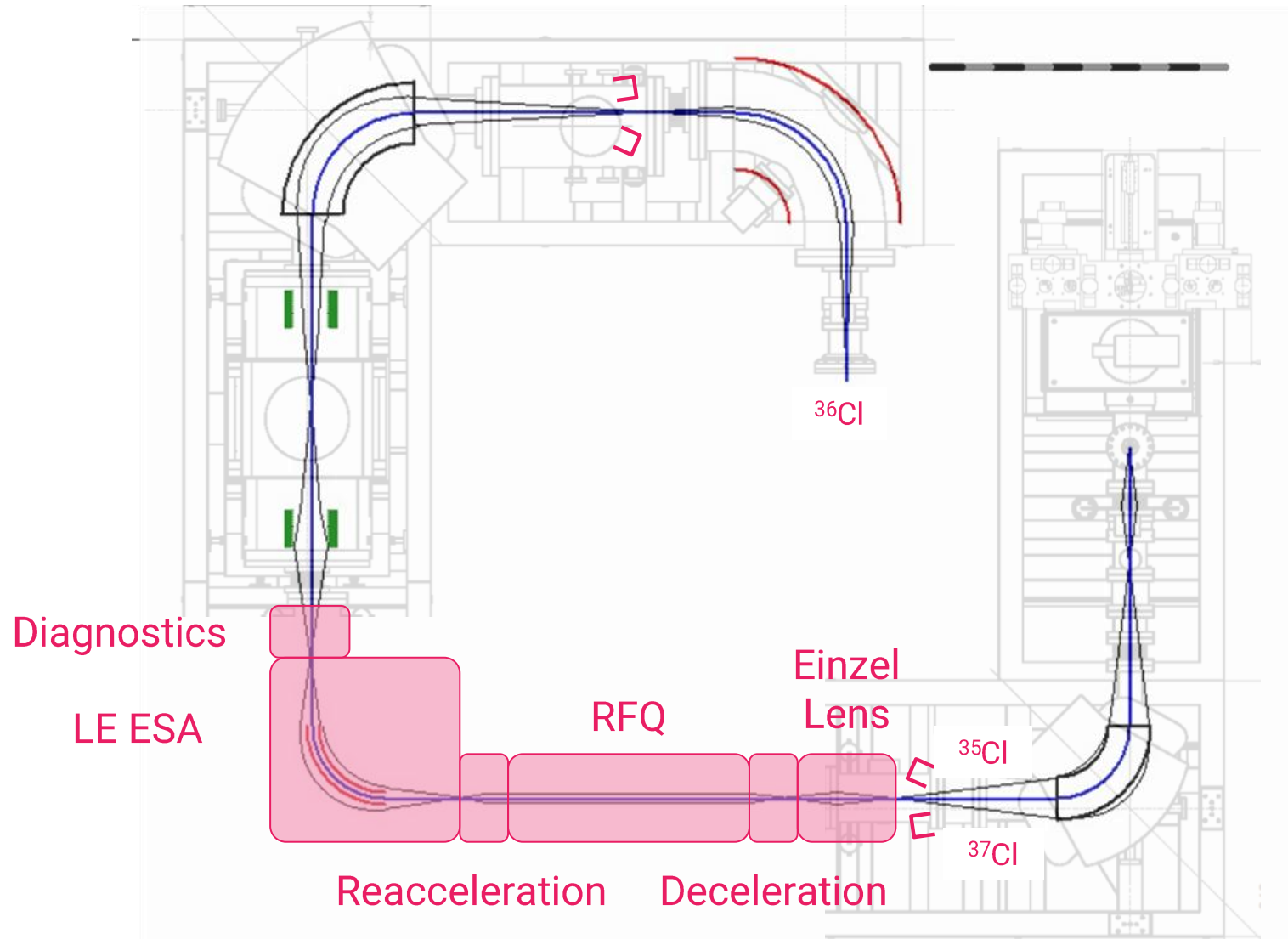
**Reason 2: existing LE magnet
limit**

Why push to even lower energy?

Reason 1: ease of RFQ construction

Reason 2: existing LE magnet limit

Reason 3: utilize the benefits of compact AMS for more isotopes



What parameters can we optimise?

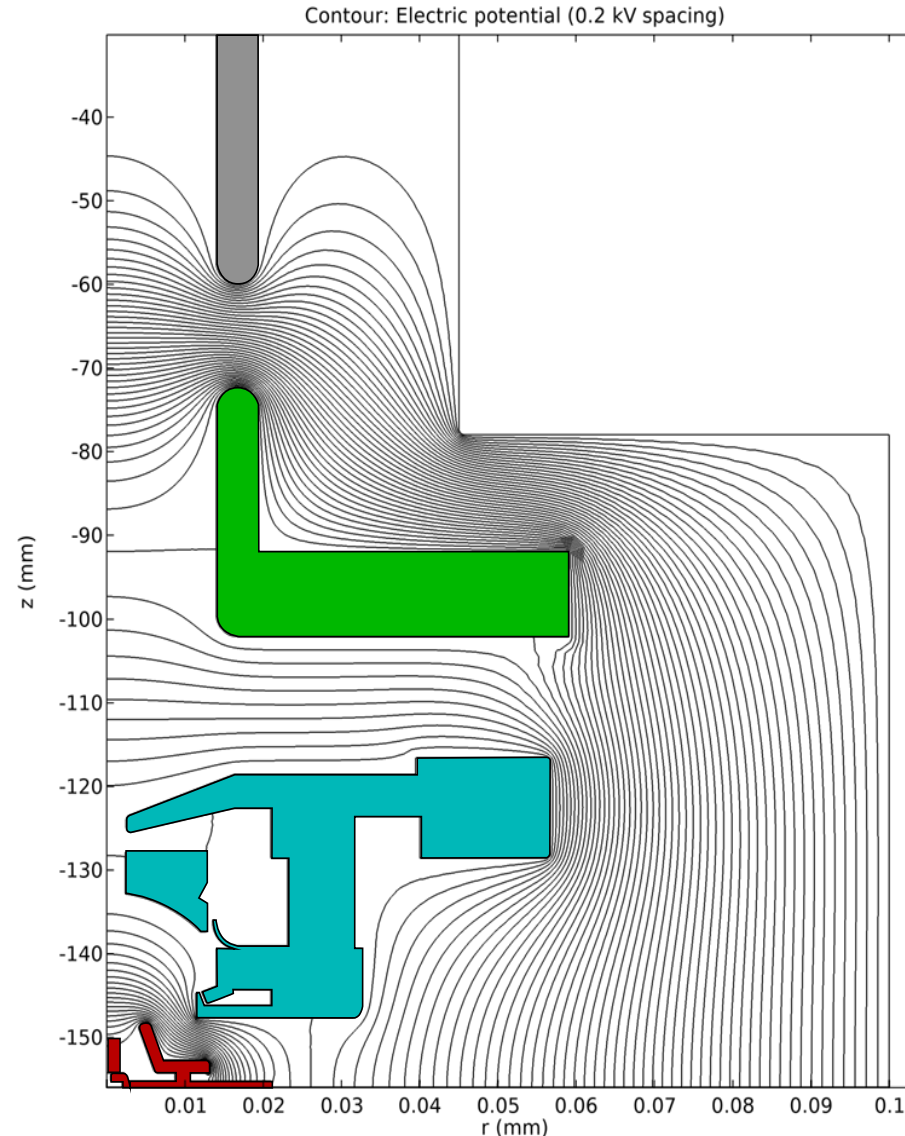
For the same total energy, we can independently control:

- Target/sputter potential and ioniser potential
- Ioniser-sample distance
- Cs temperature
- Plus more (!)

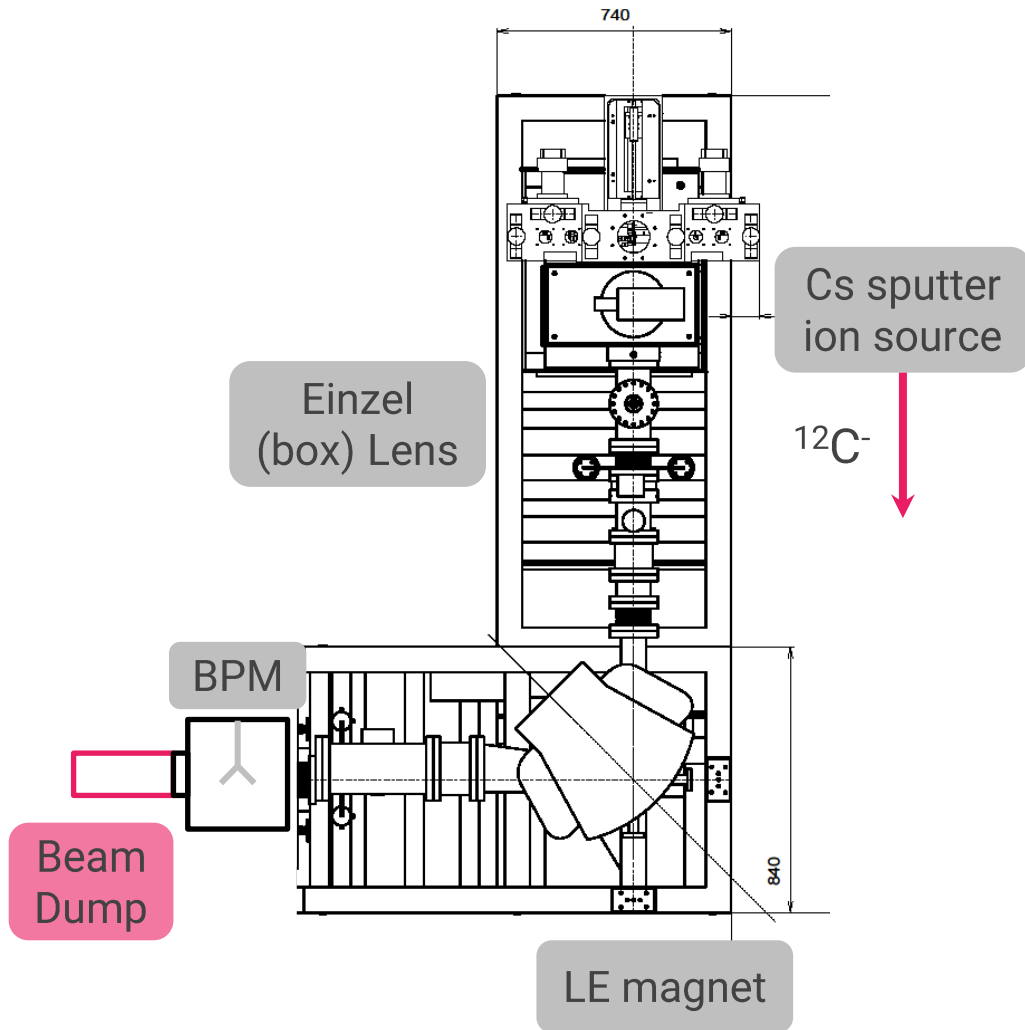
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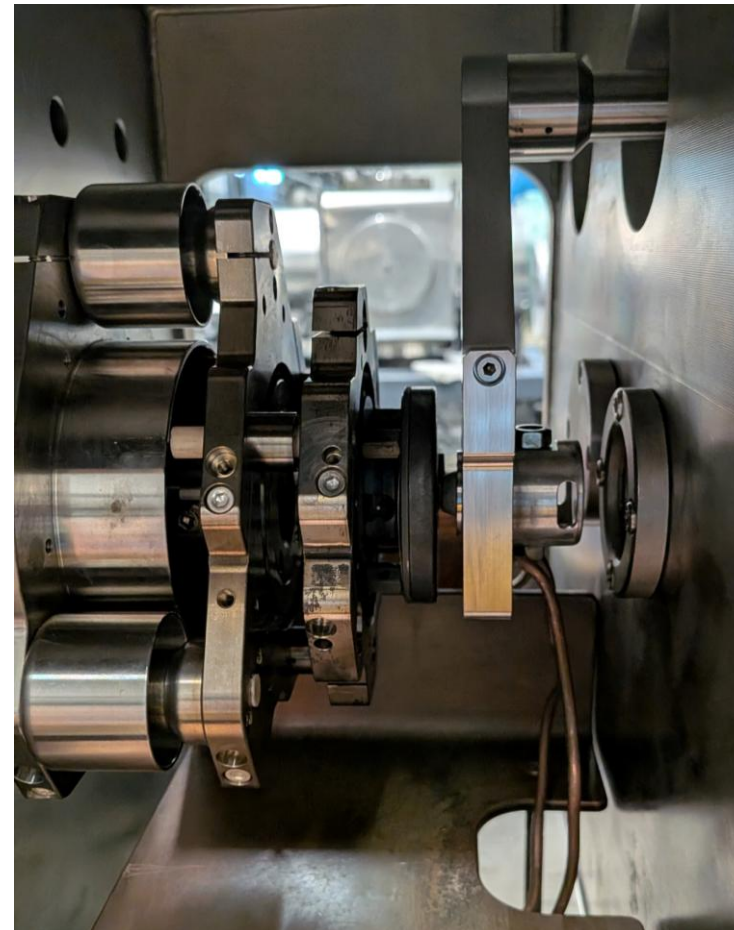
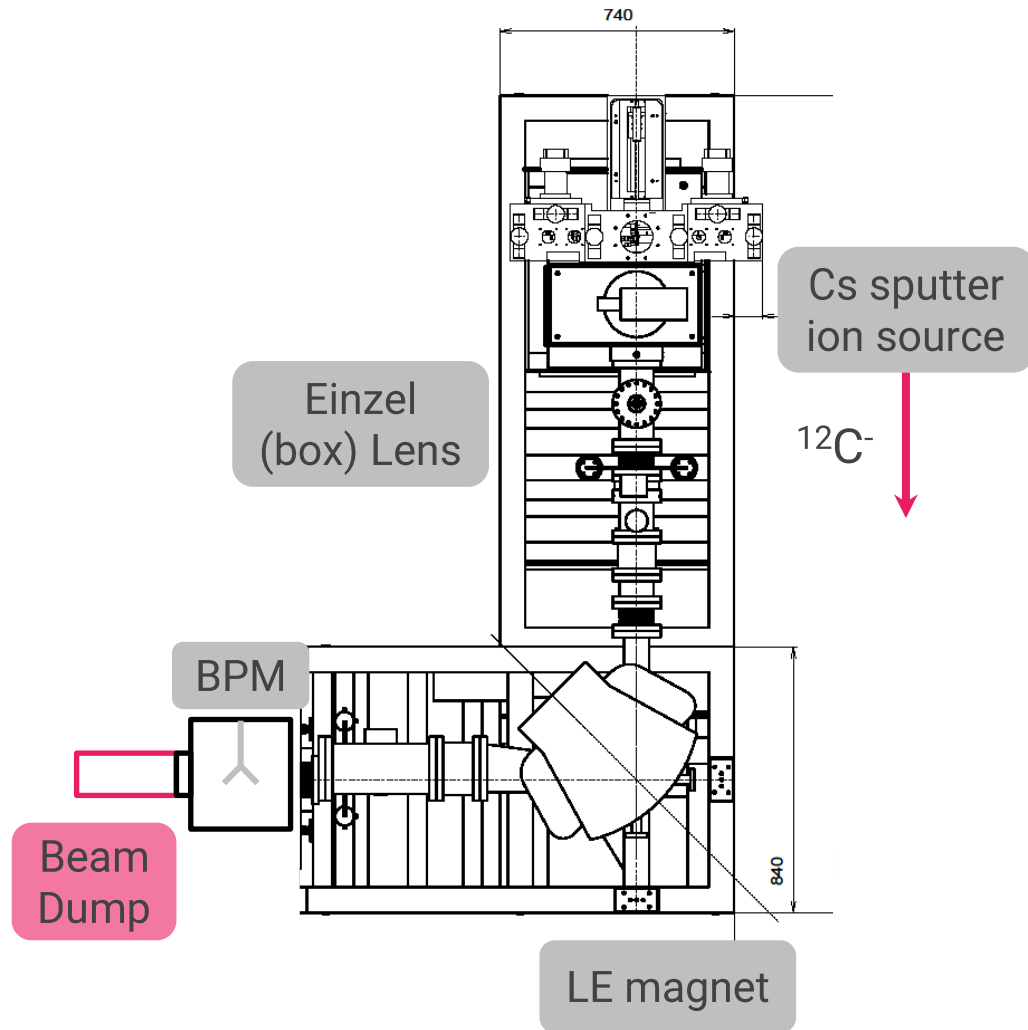
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How were these measurements made?

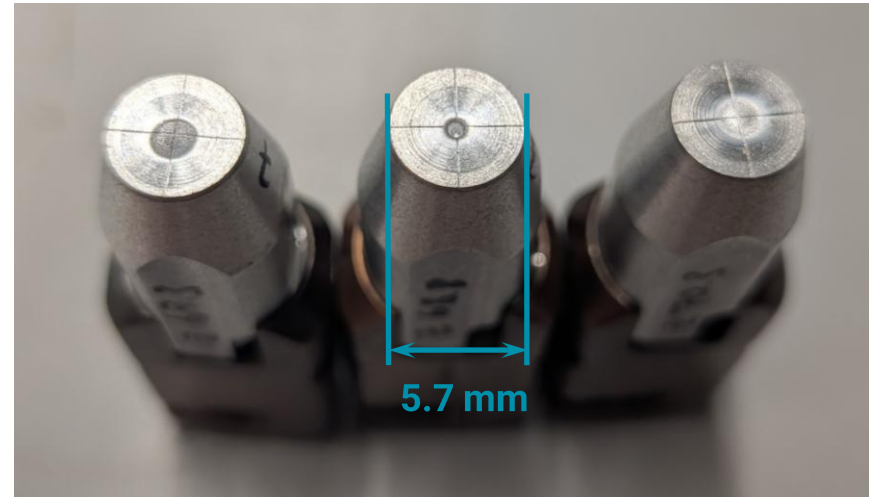


How were these measurements made?



First examination: target potential and distance

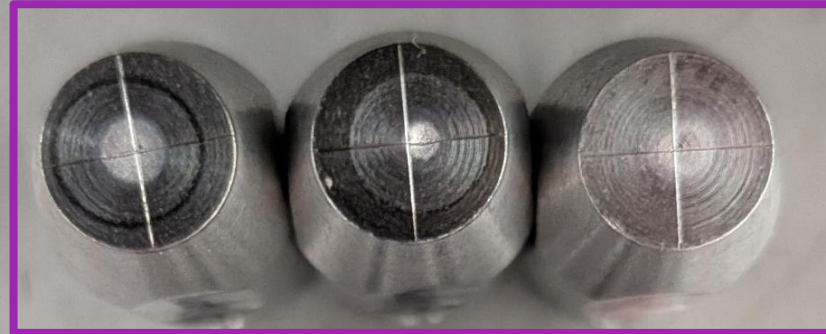
- Examined using aluminium 'dummy' targets
- Optimum sputter spot (size, 'sharpness') found for fixed target potentials



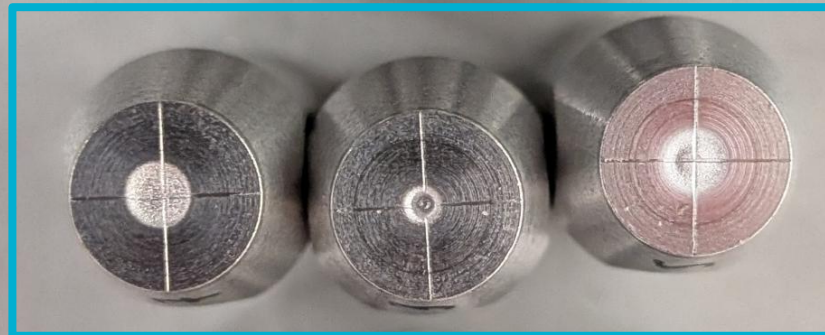
Target potential 4 kV
Ioniser potential 22 kV
Total energy 26 keV



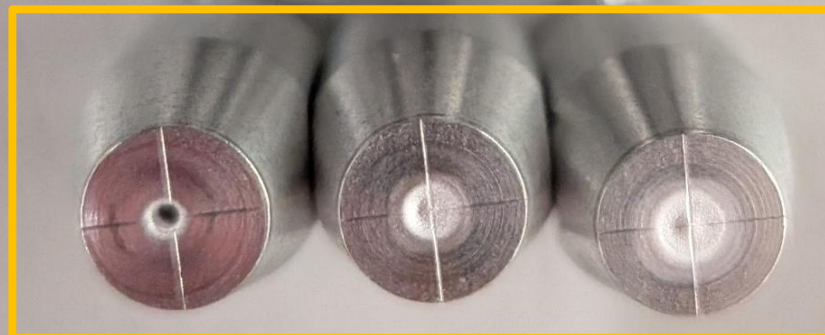
2kV sputter energy

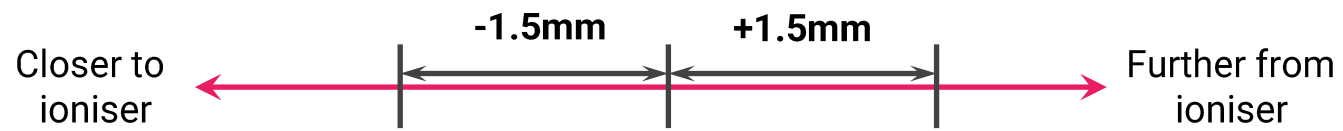


4kV sputter energy

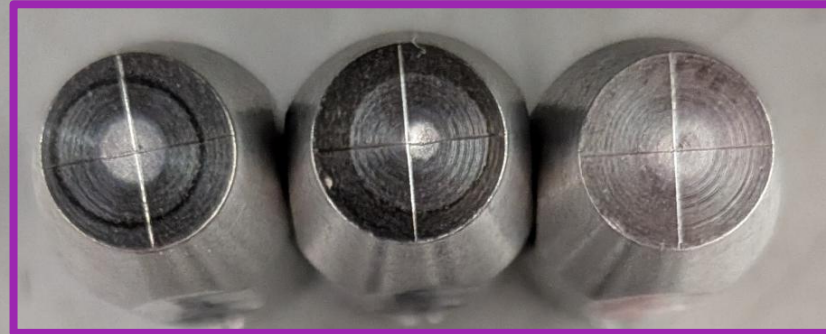


6kV sputter energy

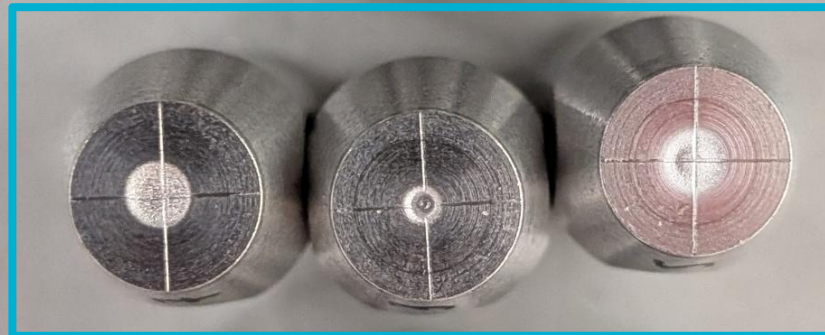




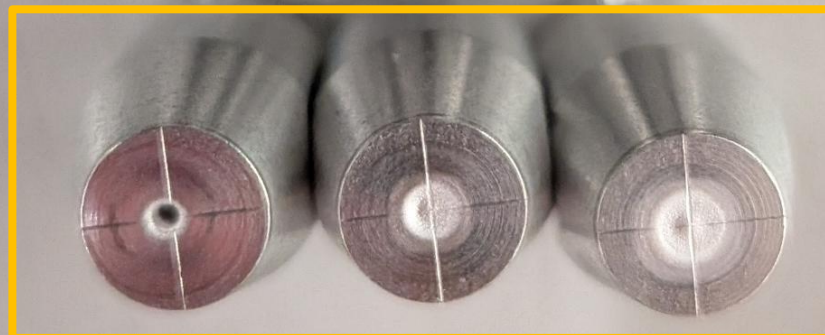
2kV sputter energy



4kV sputter energy



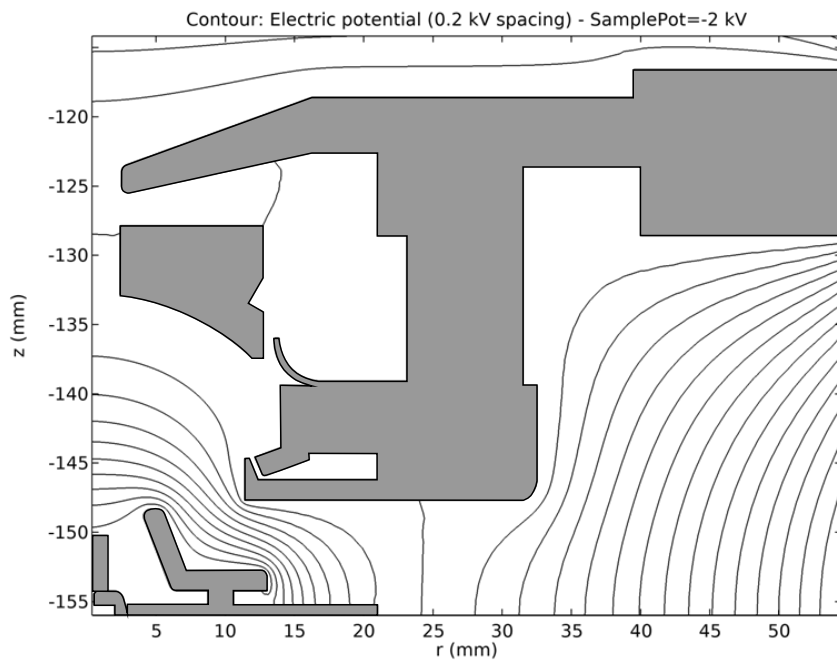
6kV sputter energy



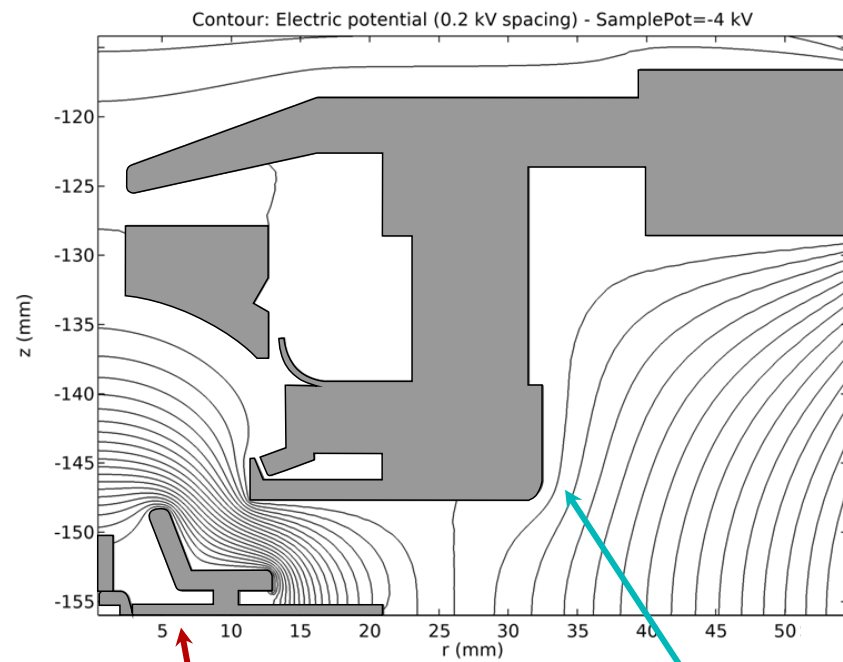
As sputter energy increases, the 'ideal' sputter spot is created when the sample is closer to the ioniser

Why?

2kV sputter energy



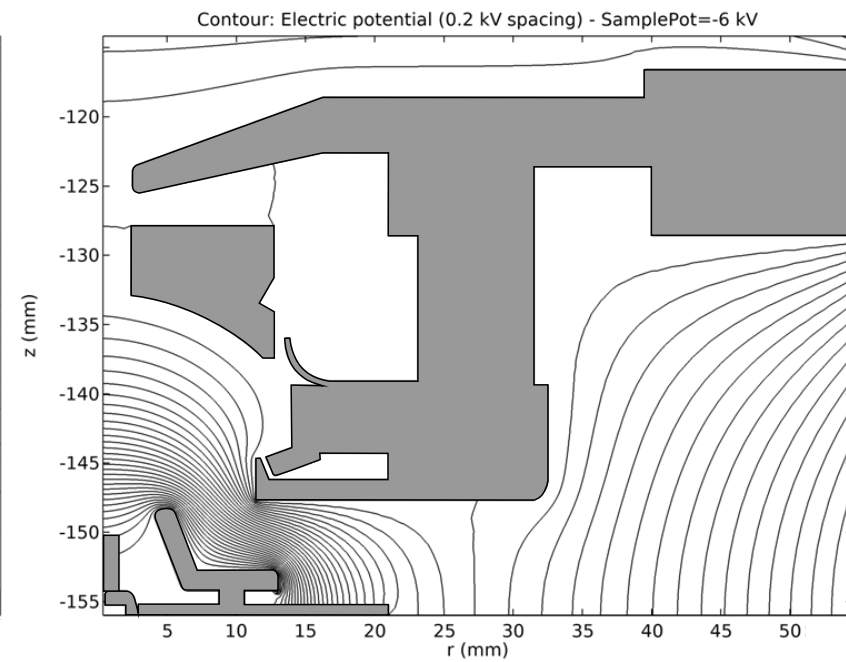
4kV sputter energy



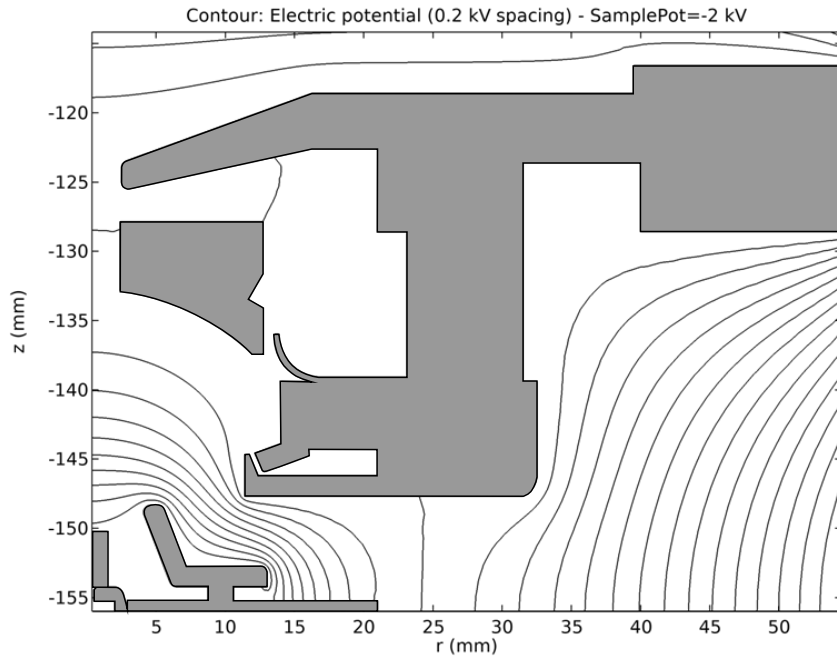
Sample + immersion
lens

Ioniser + Cs nozzle

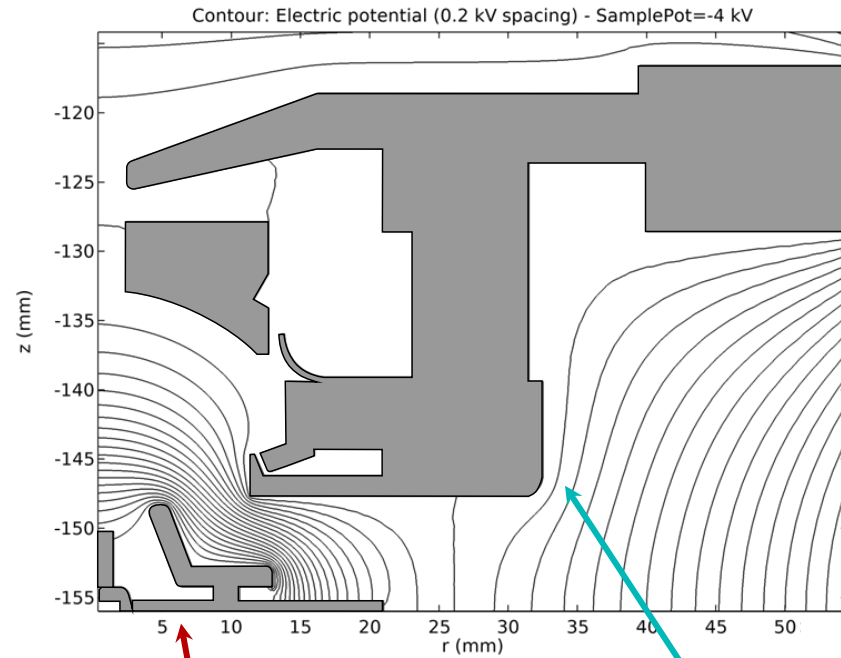
6kV sputter energy



2kV sputter energy



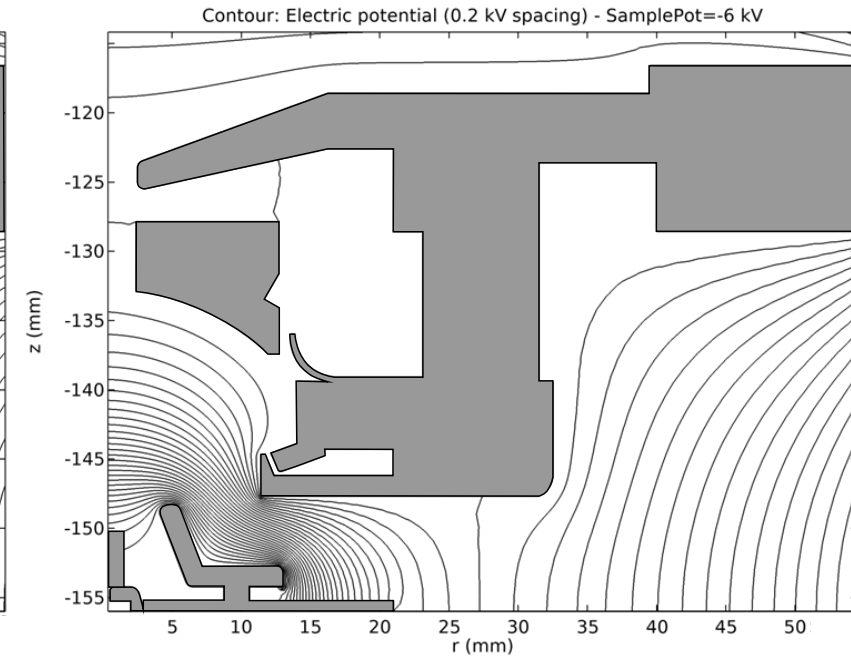
4kV sputter energy



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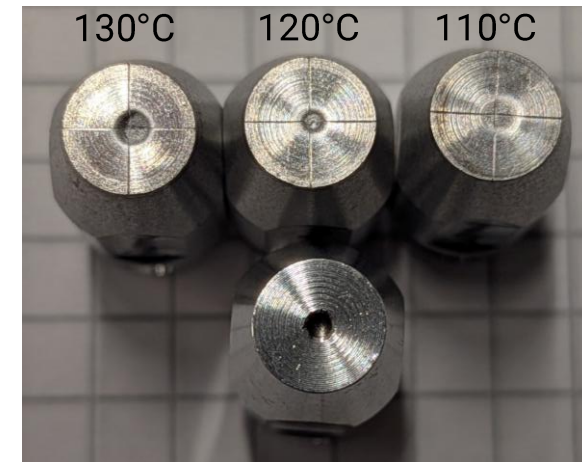
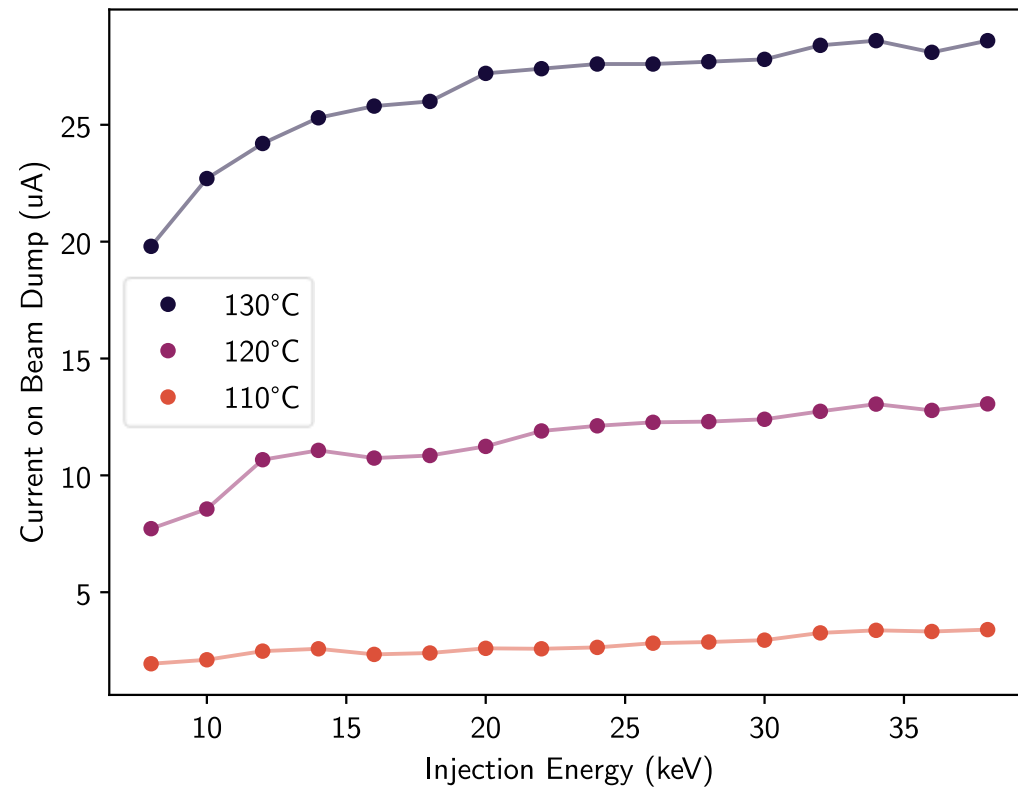
Ioniser + Cs nozzle

6kV sputter energy

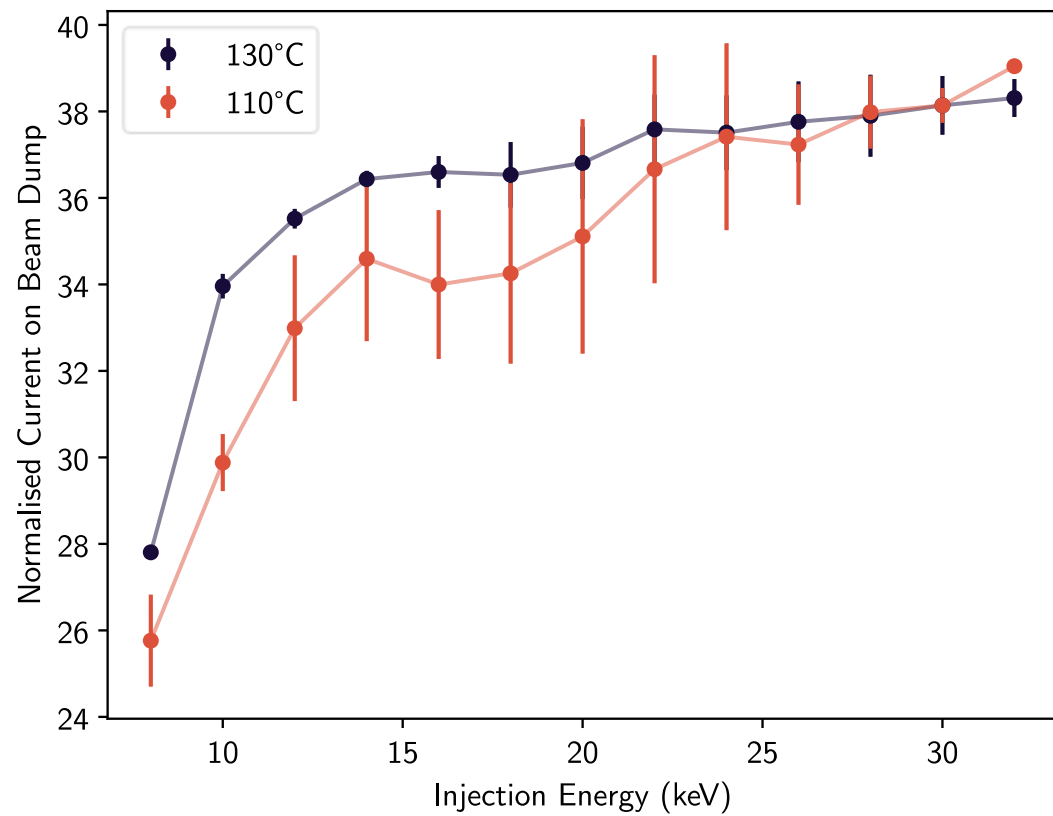


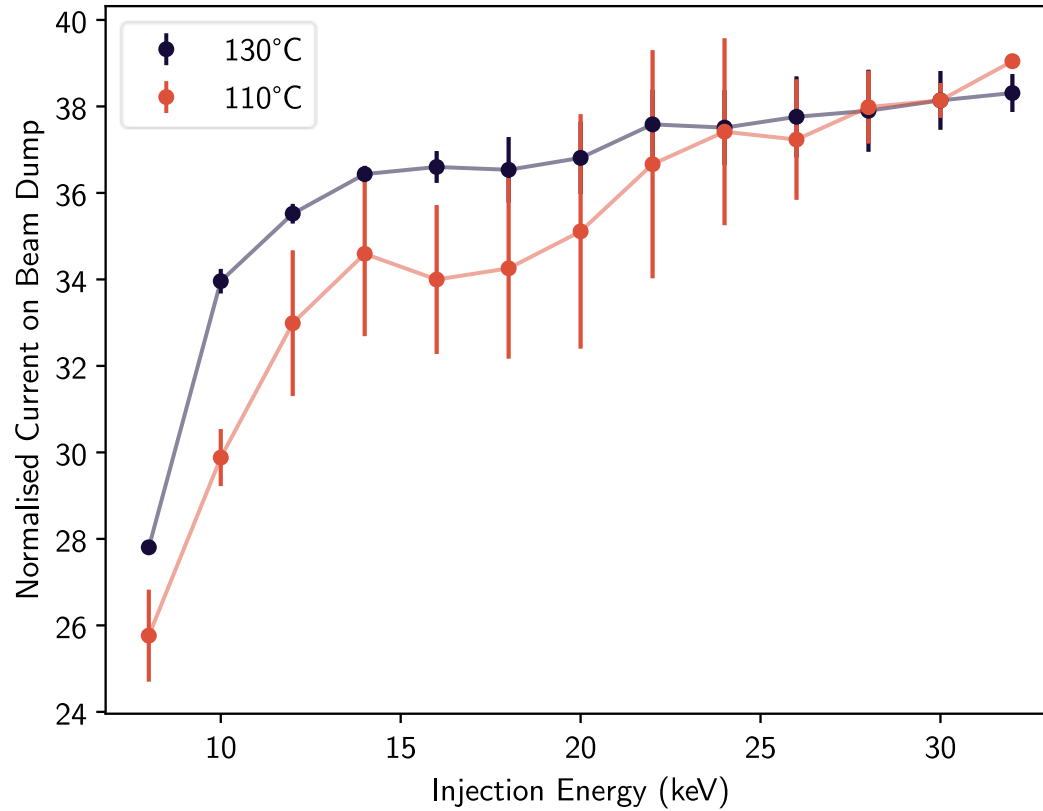
As sputter energy increases, gradient between ioniser and sample is stronger, bringing Cs⁺ to a focus in a shorter distance → sample needs to be moved closer

Second examination: temperature and ionizer potential

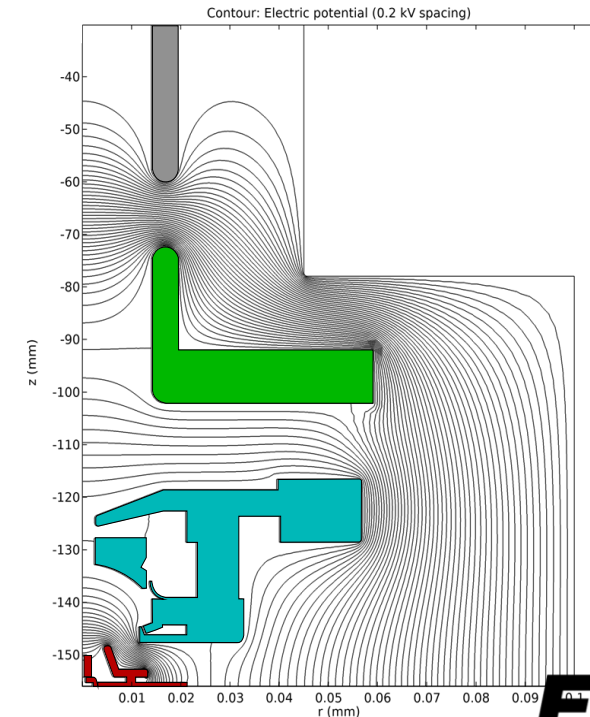


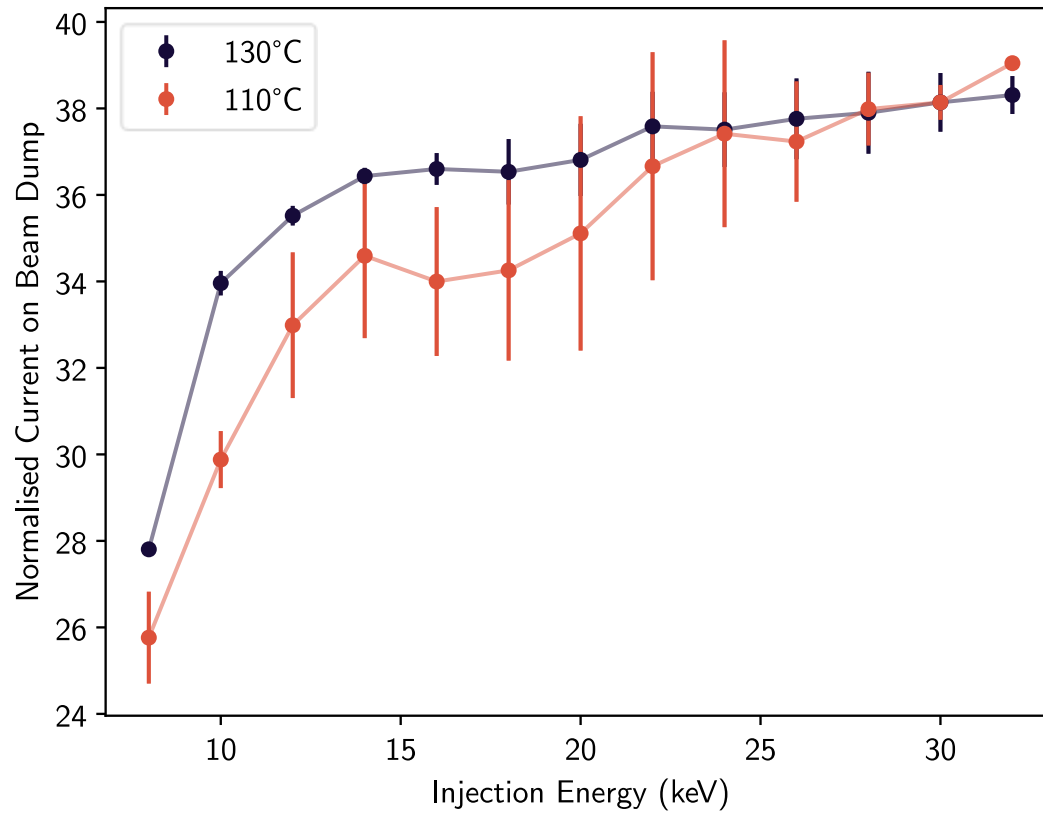
More Cs temperature gives a greater Cs^+ density, which 'shields' the target, hence needing a greater sputter energy to overcome it



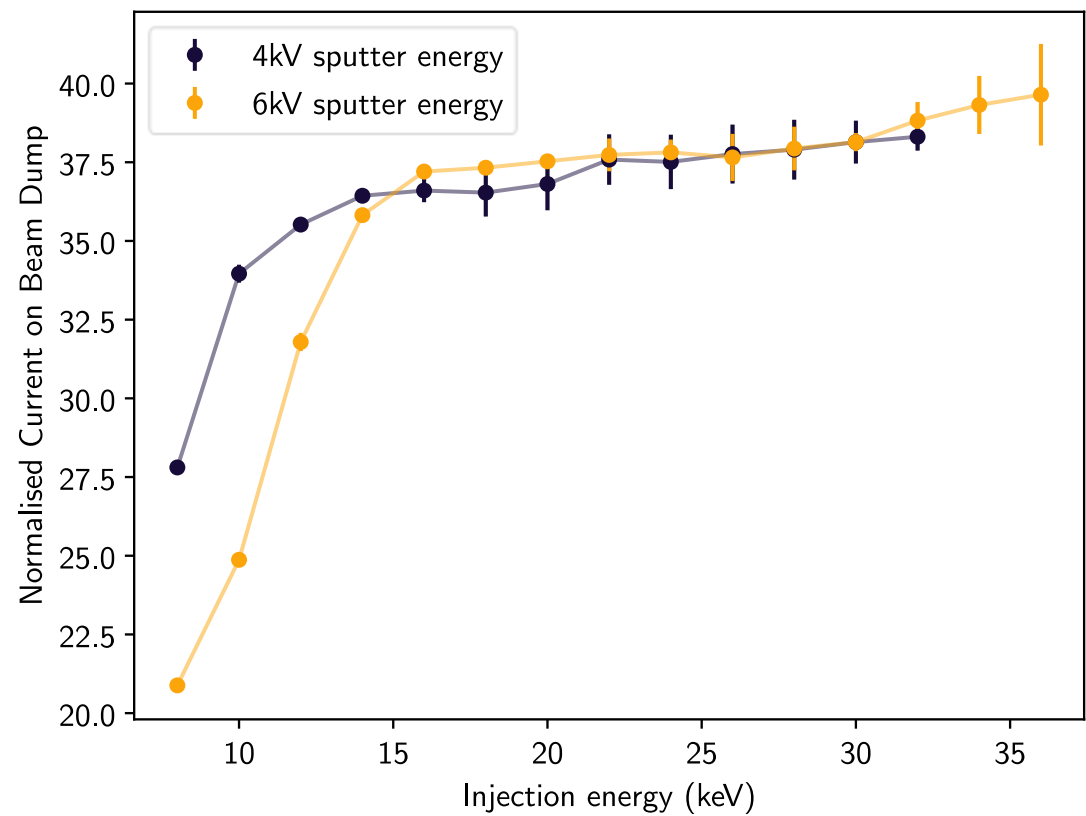


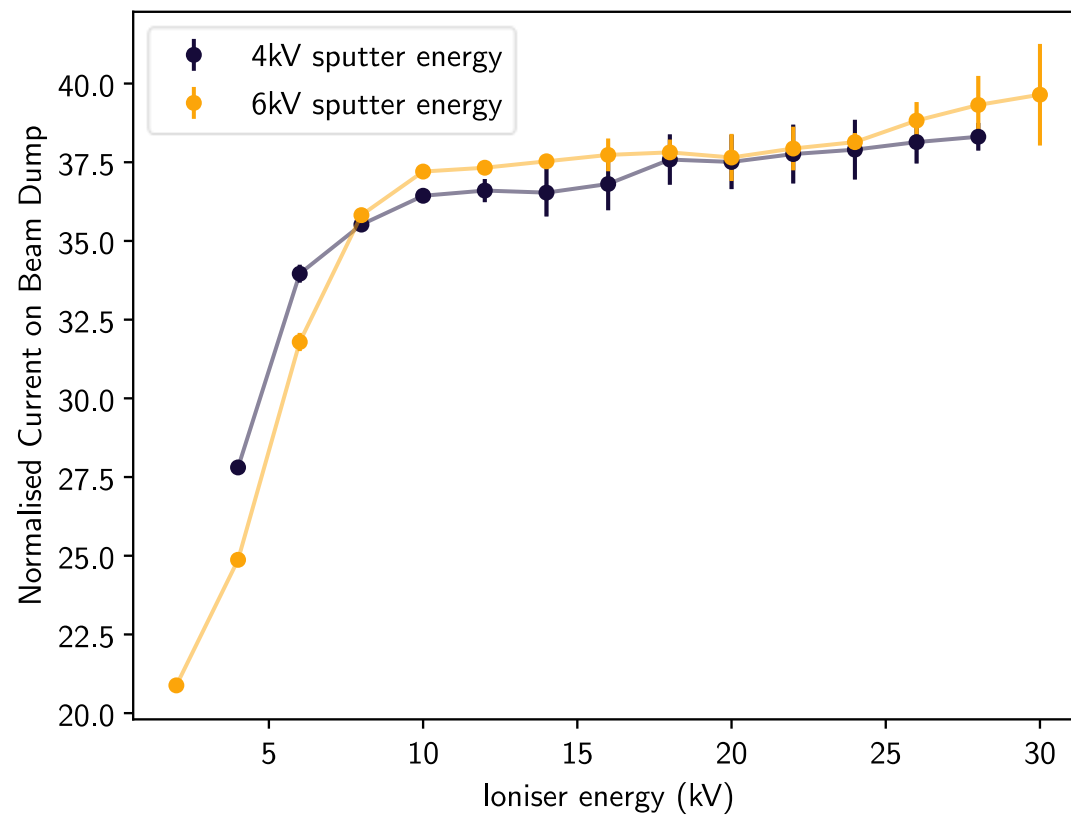
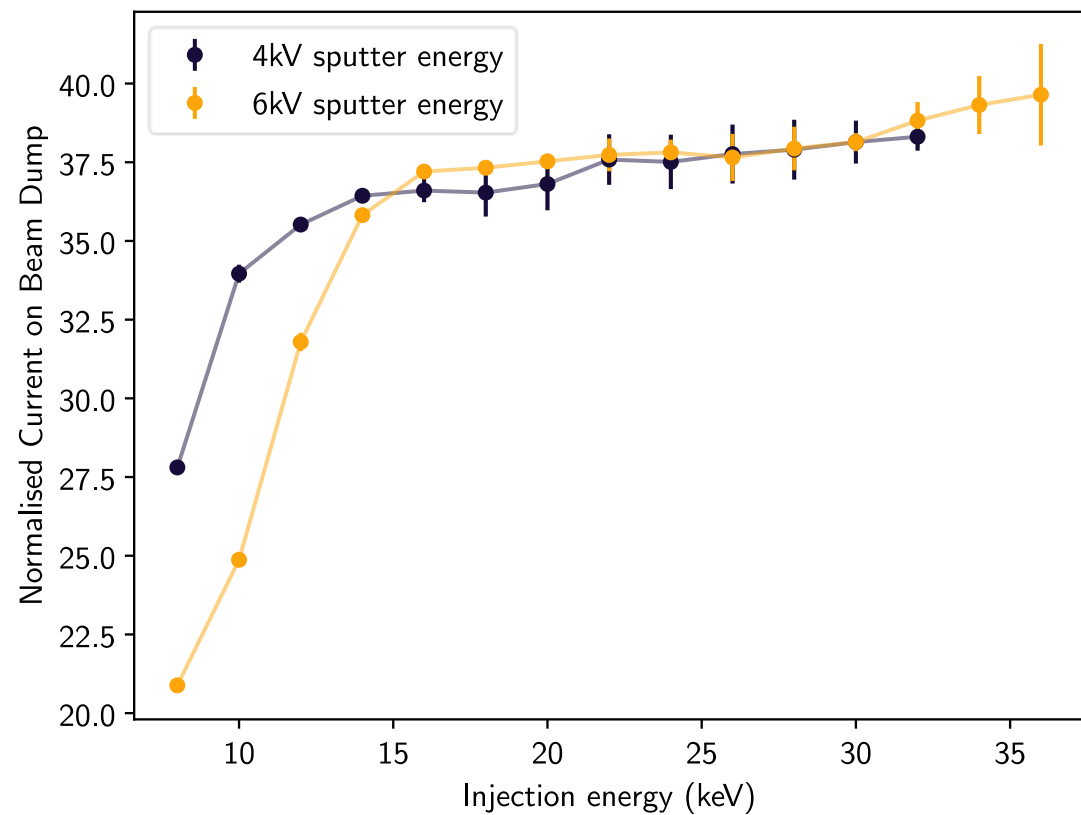
- Seem to be *extractor limited* at the low energies
 - That is, the lens formed between the extractor and the ioniser is not appropriate to extract all of the beam formed at these energies



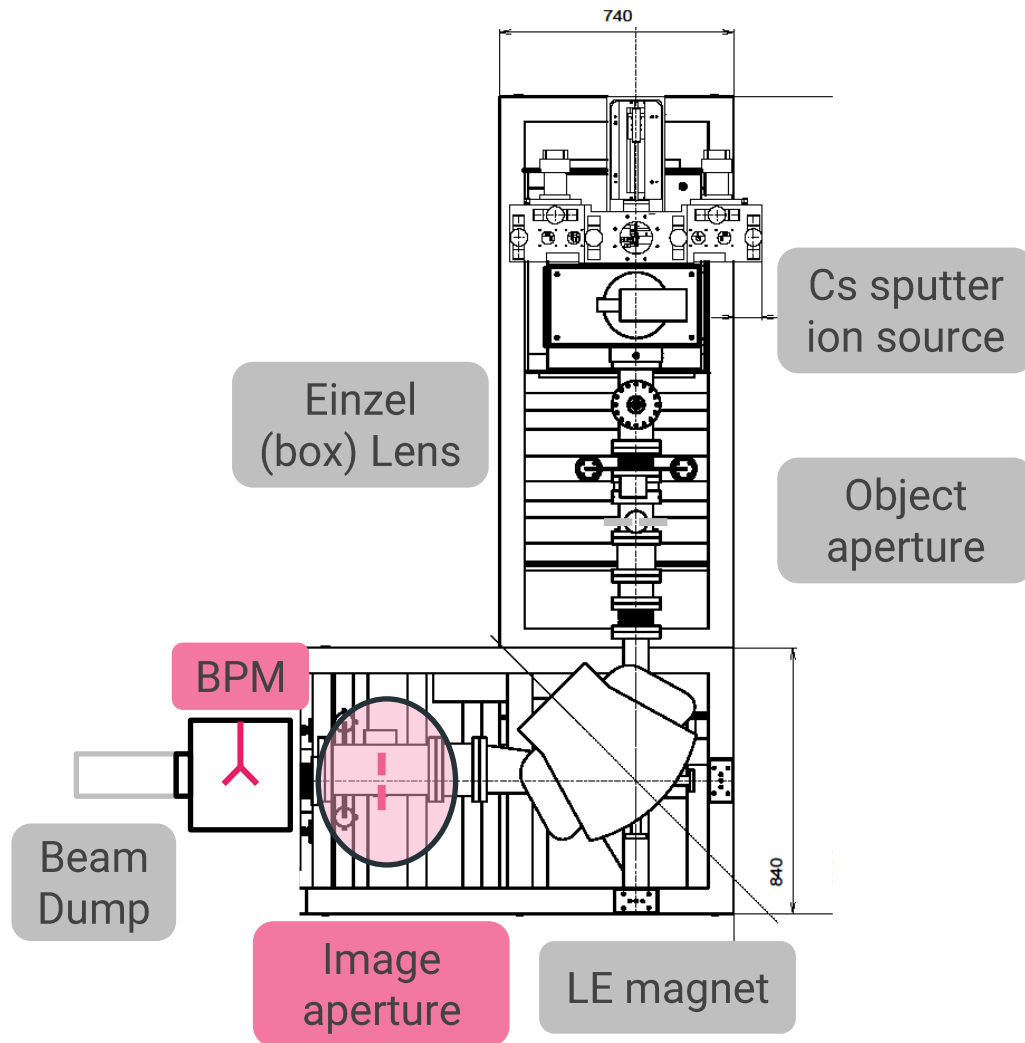


- Seem to be *extractor limited* at the low energies
 - That is, the lens formed between the extractor and the ioniser is not appropriate to extract all of the beam formed at these energies
- The other possibility is that the phase space is so large, that the beam is hitting the magnet chamber

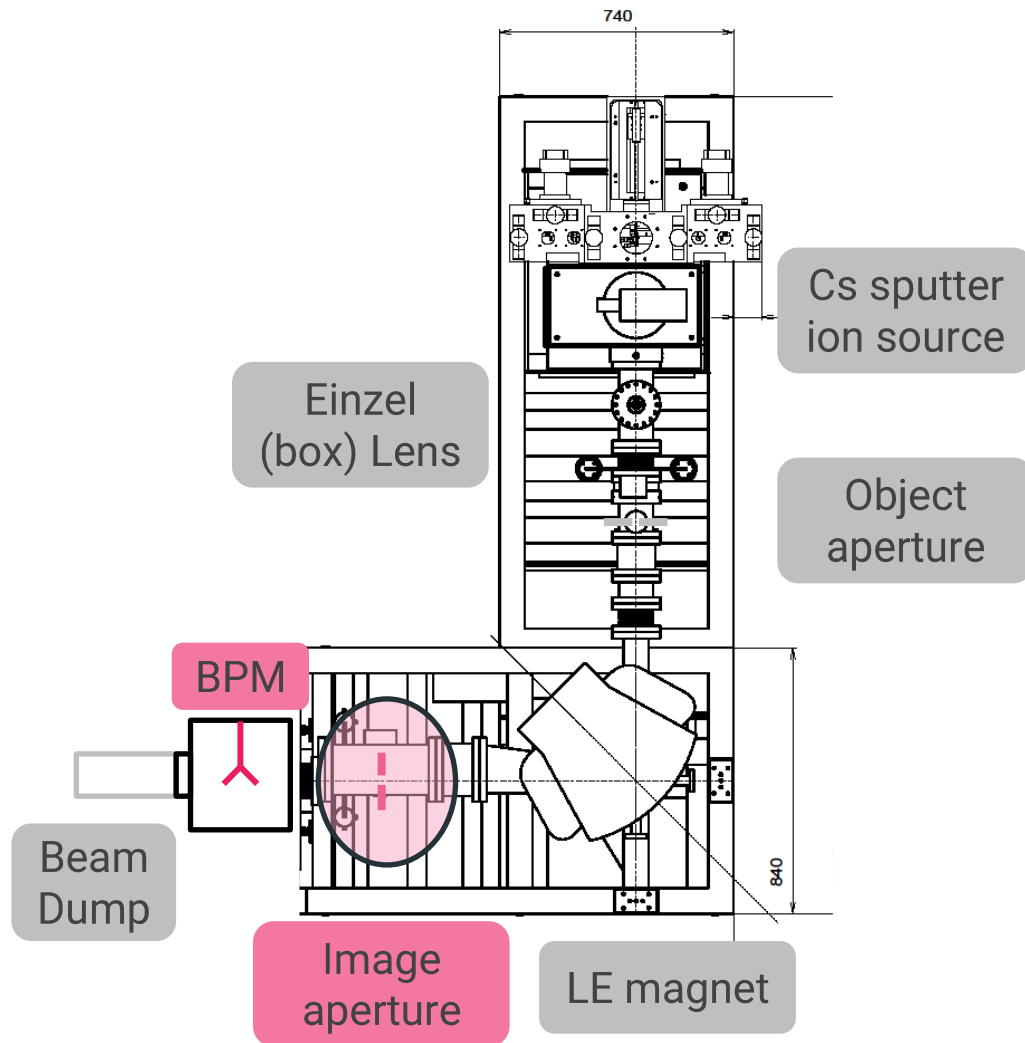




What about the phase space?



What about the phase space?



$$r = \sqrt{FWHM_x^2 + FWHM_y^2}$$

$$r' = \frac{r - a}{d}$$

$$\epsilon = r \times r' \times 1000 \text{ [mm mrad]}$$

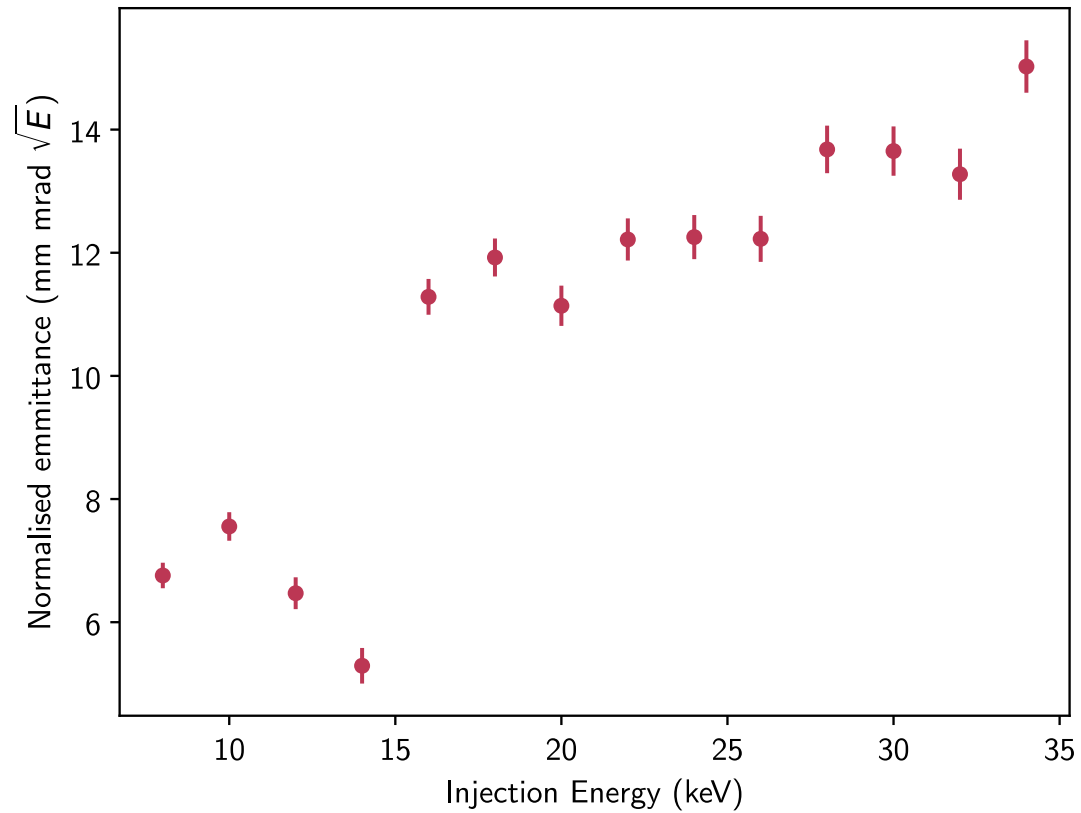
$$\epsilon_{norm} = \epsilon \sqrt{E}$$

a = aperture diameter = 3 mm

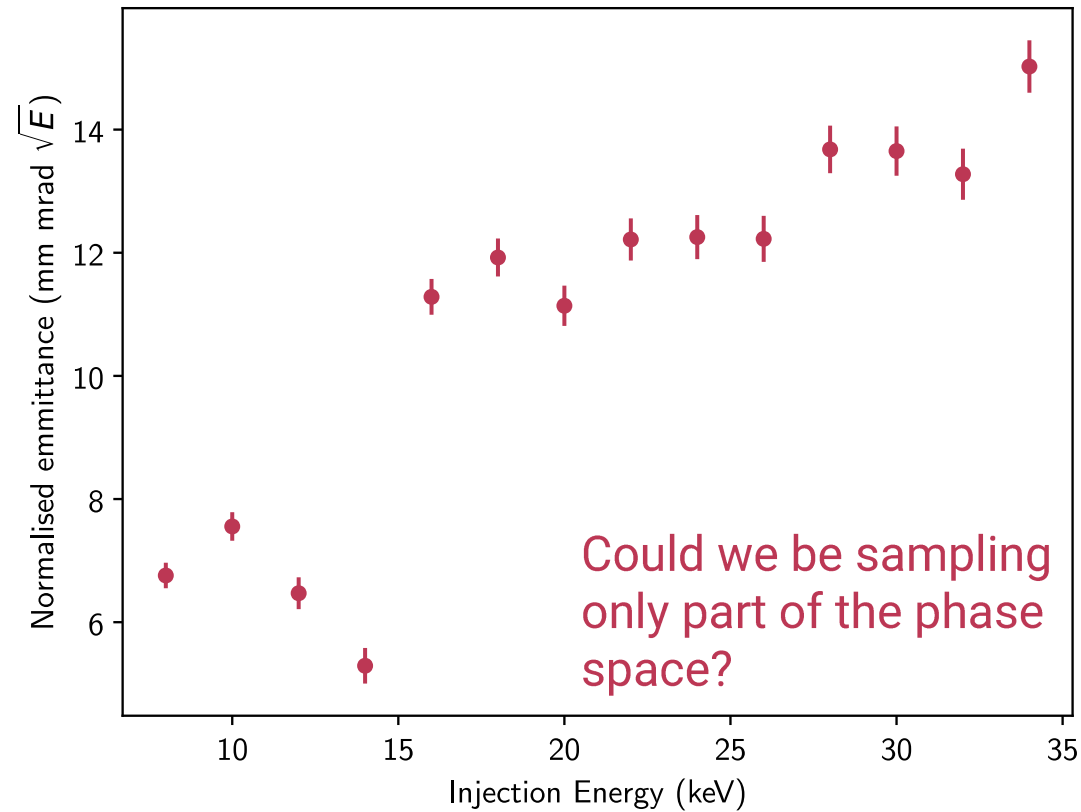
d = drift length = 247 mm

* Calculations assume image aperture is size-defining

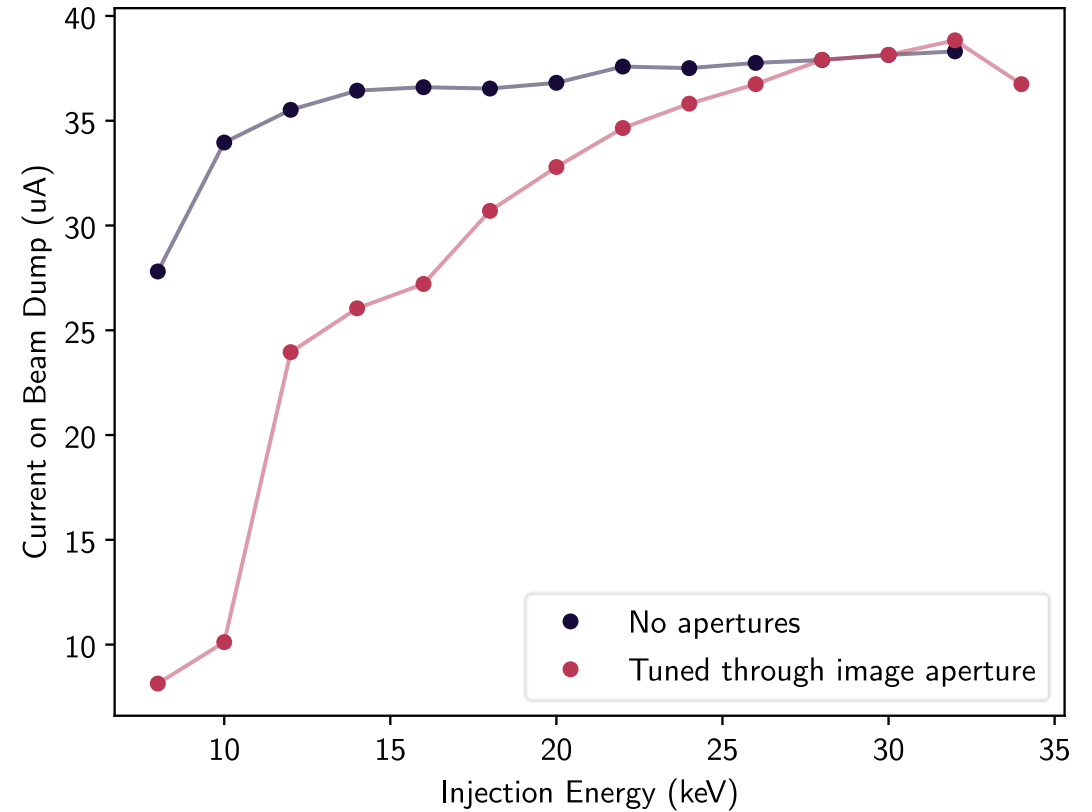
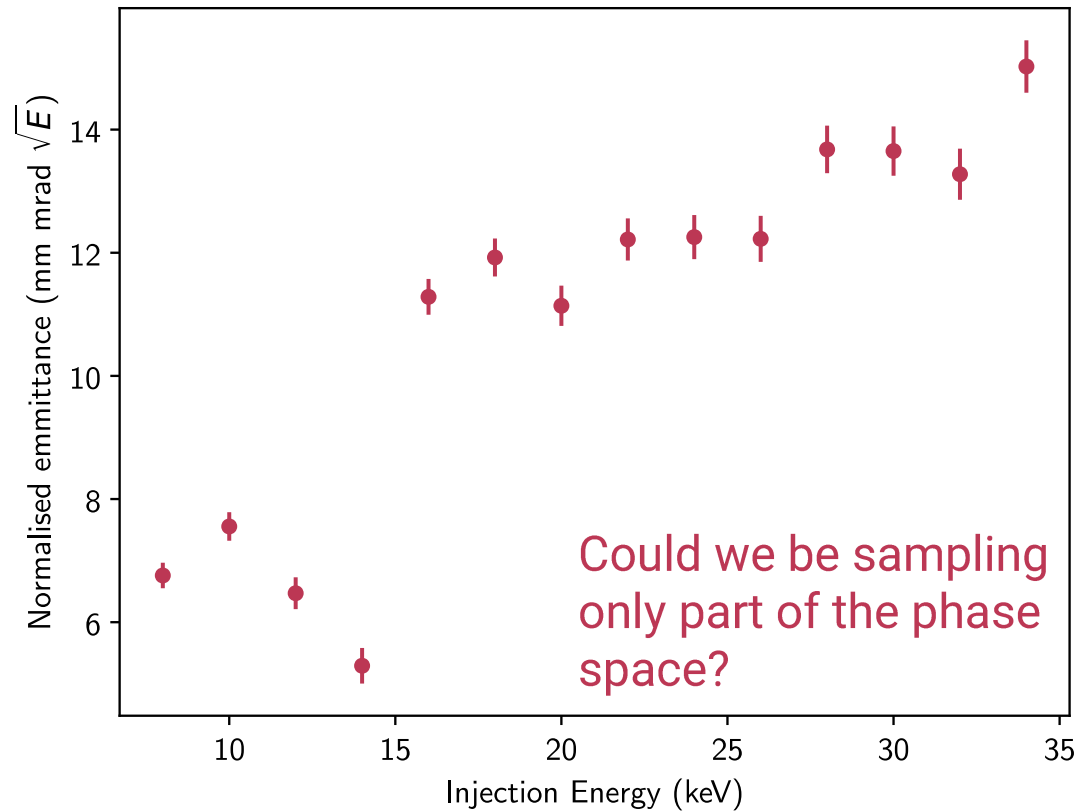
What about the phase space?



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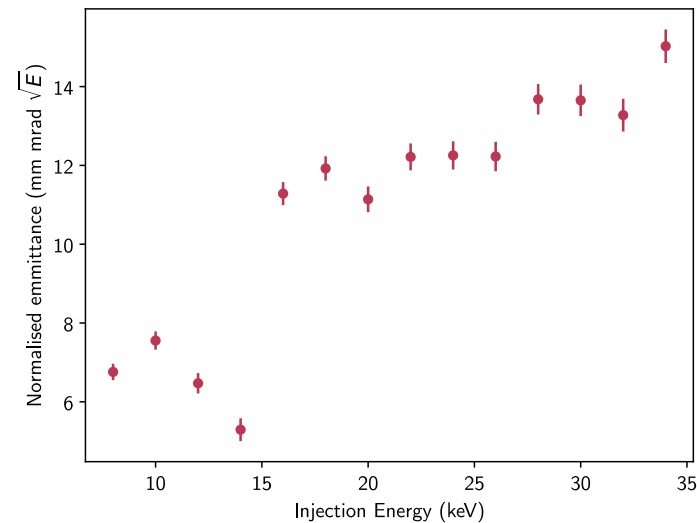
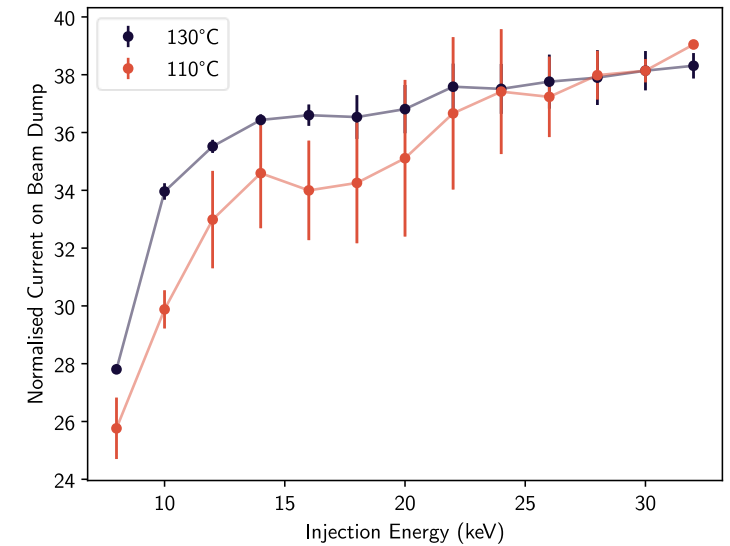


What about the phase space?



What did we learn? - Conclusions

- Low energy operation seems to be extraction-optics limited
- Beam quality doesn't behave as expected – phase space vs magnet chamber?

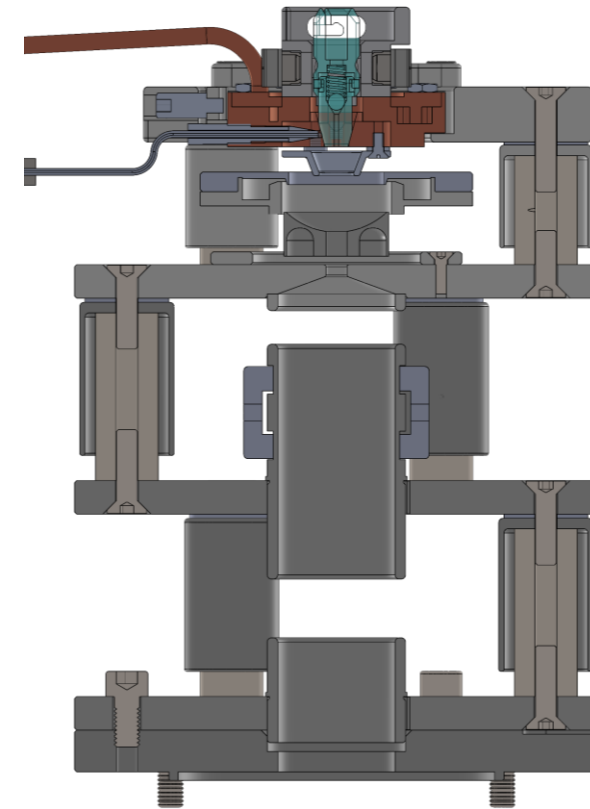


What next? – Future work

- **Diagnostics and measurement technique:**
 - Quad-scan emittance using box lens
 - Change aperture + BPM setup
- **Ion optics:**
 - Introduce negative extractor potential
- **Open physics question:**
 - Is the low-energy limitation dominated by re-neutralization or phase-space blow-up?

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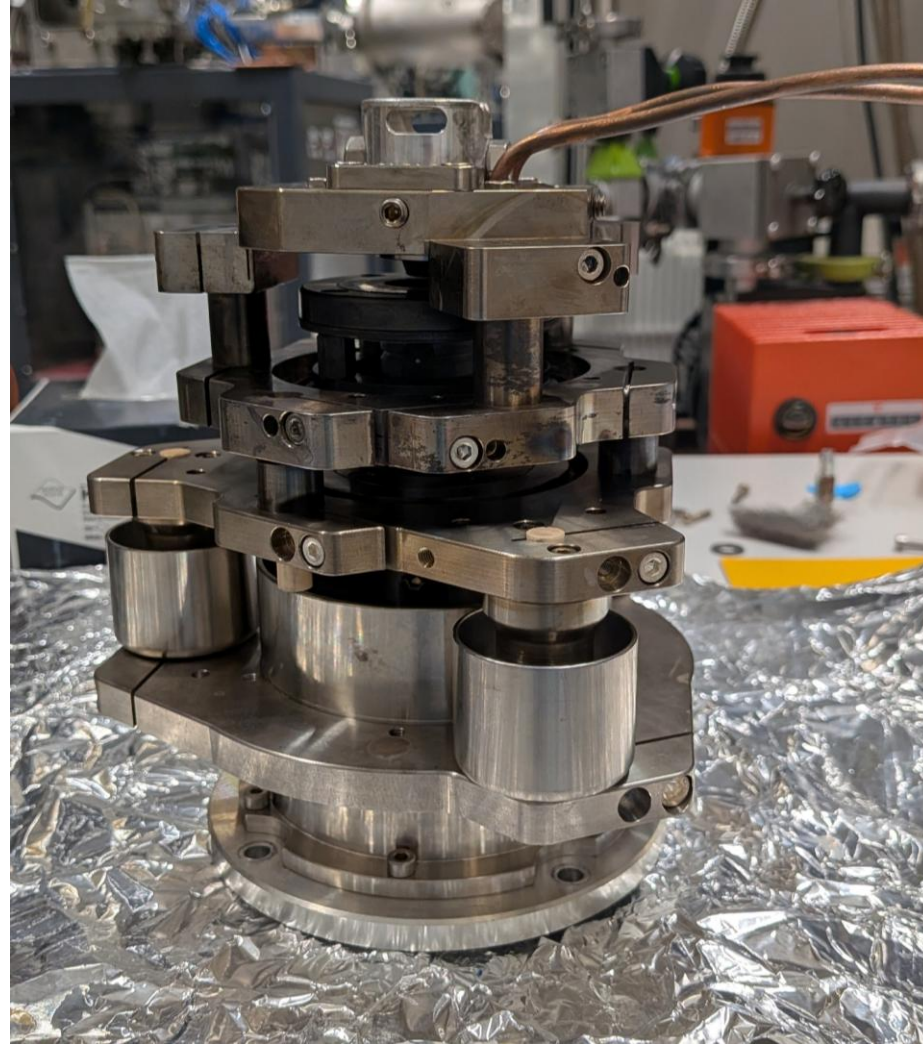
Acknowledgements

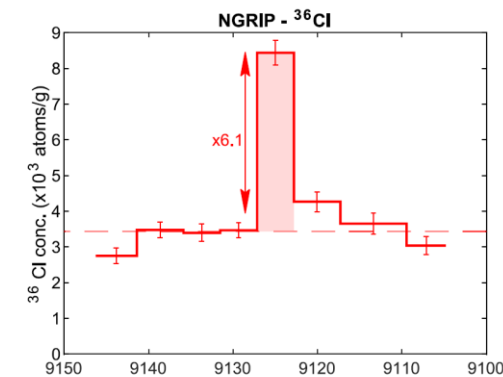
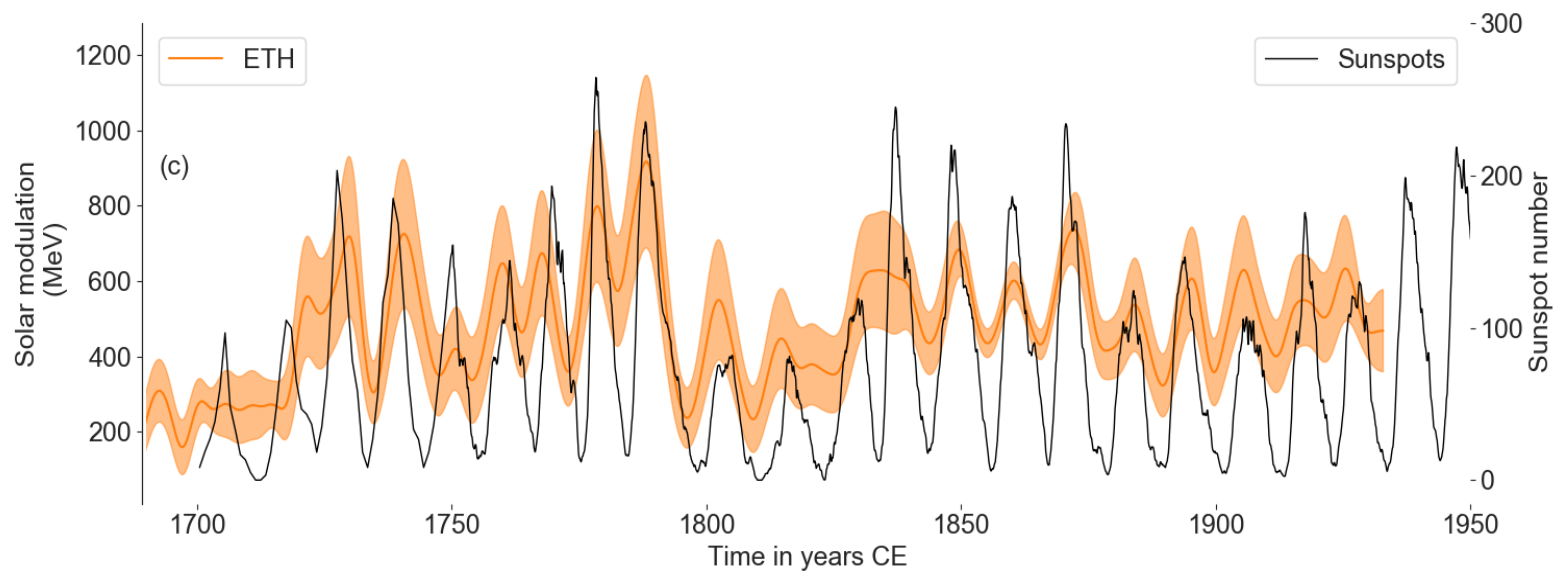
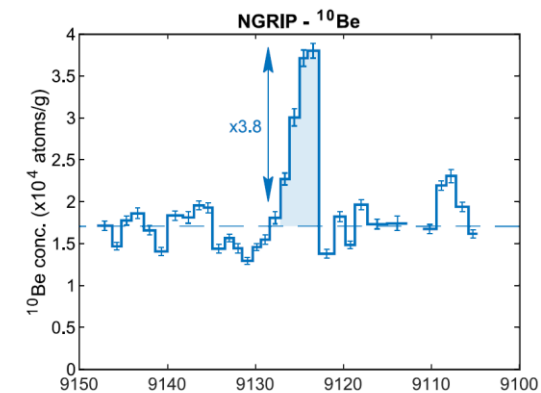
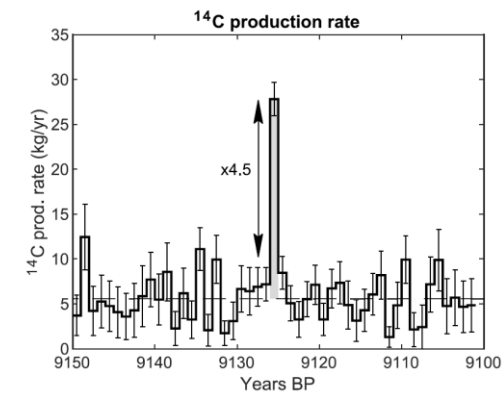
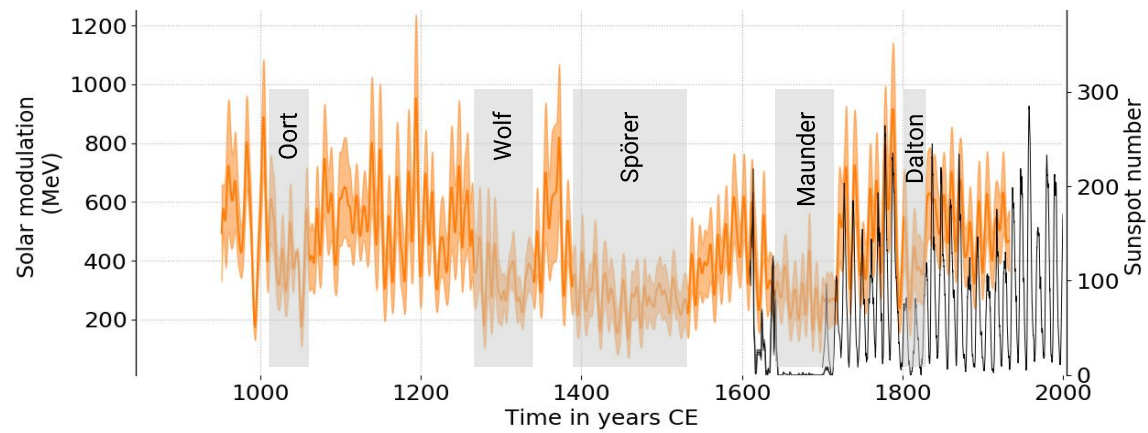
Laboratory of Ion Beam
Physics technical staff, and
the many semester students
and apprentices

Thank you for your attention!

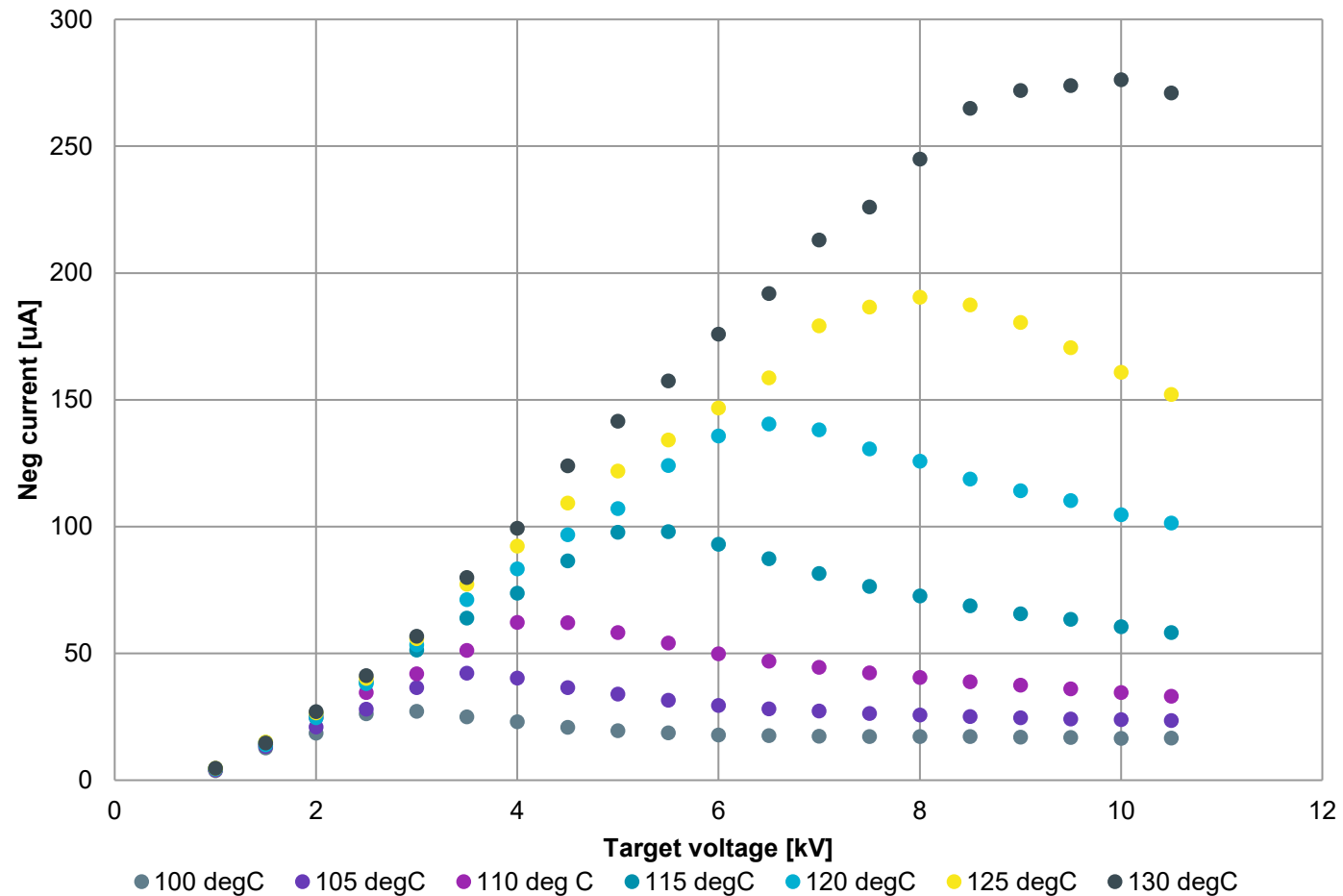


ETH Cs sputter source

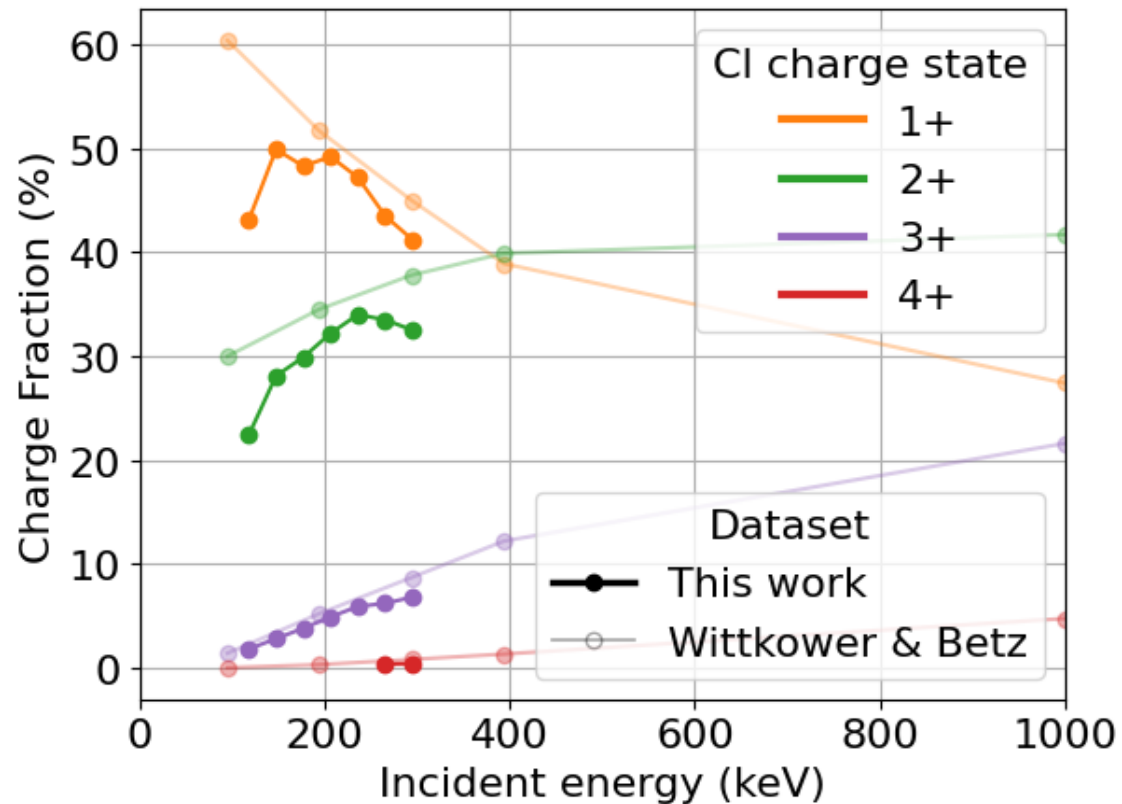




ETH source performance - temperature



Compact AMS - Cl charge states



Charge state yield for Cl^+ around 50% for compact accelerator energies (150-200 keV), while high energy tandem energies (46 MeV) requires use of a higher charge state 7+, which gives a much lower yield, around 15%

Measurements by L. Danini, semester project

Why push to even lower energy?

- RFQ + LPD: magnet limited for the higher masses (example for ^{36}Cl , ^{41}Ca), construction of RFQ, optimum ratio of accelerator to source potential (where we might want to operate - $\sim 100\text{kV}$ accelerator)

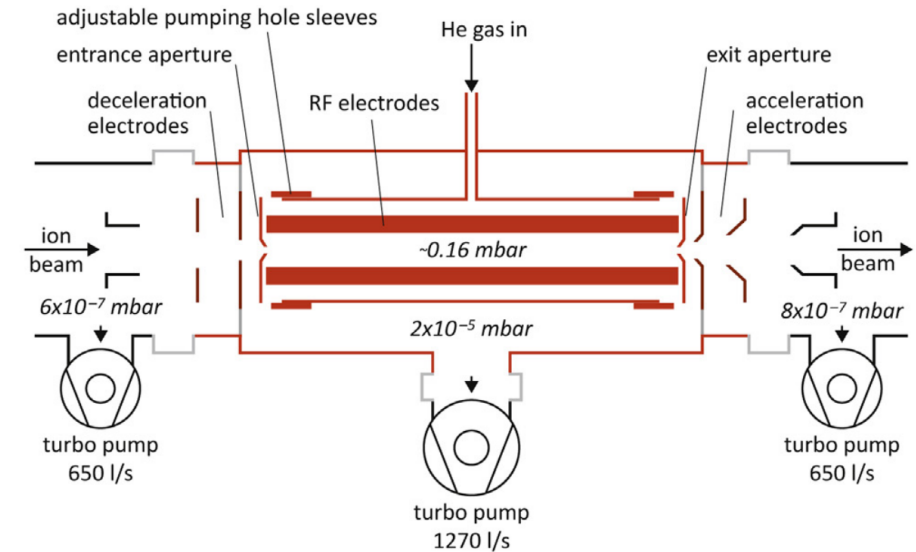
- 200kV MICADAS (46%) (CSY – 50%)

- 50kV LEA (50%) (CSY – 60%)

- Basically, better performance as you go down in energy (transmission wins in particular) but compromise on molecular destruction and angular spread/scatter

- Big advantage to move to low energy for Cl
- He advantage – anomaly in the $1+$ CSY due to lack of 'back reaction'/neutralisation reaction
- Ultimate question: how low can we operate the source while retaining a useful, transportable beam?

- i.e. small/reasonable phase space, good transmission



M. Martischini et al, IJMS 415, 9-17 (2017)

For a maximum field of 0.695 T at LE magnet

$^{36}\text{Cl}^- = 40\text{ keV}$

$^{41}\text{CaH}^- = 32\text{ keV}$

$^{41}\text{CaF3}^- = 14\text{ keV (!!!)}$