Measuring mixed-beam properties in the accelerator complex

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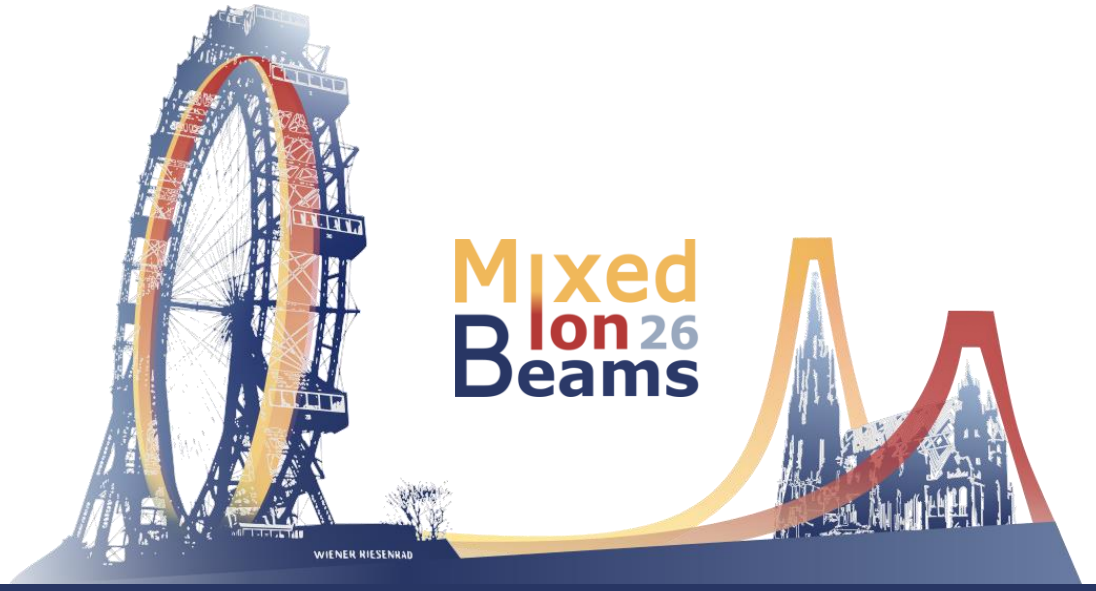
Based on input from discussions with many people over the years: Hermann **Fuchs,** Piera **Galeazzo,** Nadia **Gambino**, Katrin **Holzfeind,** Matthias **Kausel**, David **Ondreka,** Marco **Pullia,** Claus **Schmitzer**, Markus **Wolf**...



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MedAustron
MEDIZINISCHE UNIVERSITÄT WIEN
MBI Marietta-Blau-Institut für Teilchenphysik
GSI

What do we need?

Methods to **characterize the mixed beam properties within the acceleratore** for efficient commissioning, operation, monitoring during experiments, interlock systems, ...

Problem: Conventional beam diagnostics measures overall charge distribution
→ **He and C indistinguishable**



Rubens and Brueghel, "Sight" (1617)

Solution: Use our **other** senses!



Rubens and Brueghel, "Hearing" (1617)

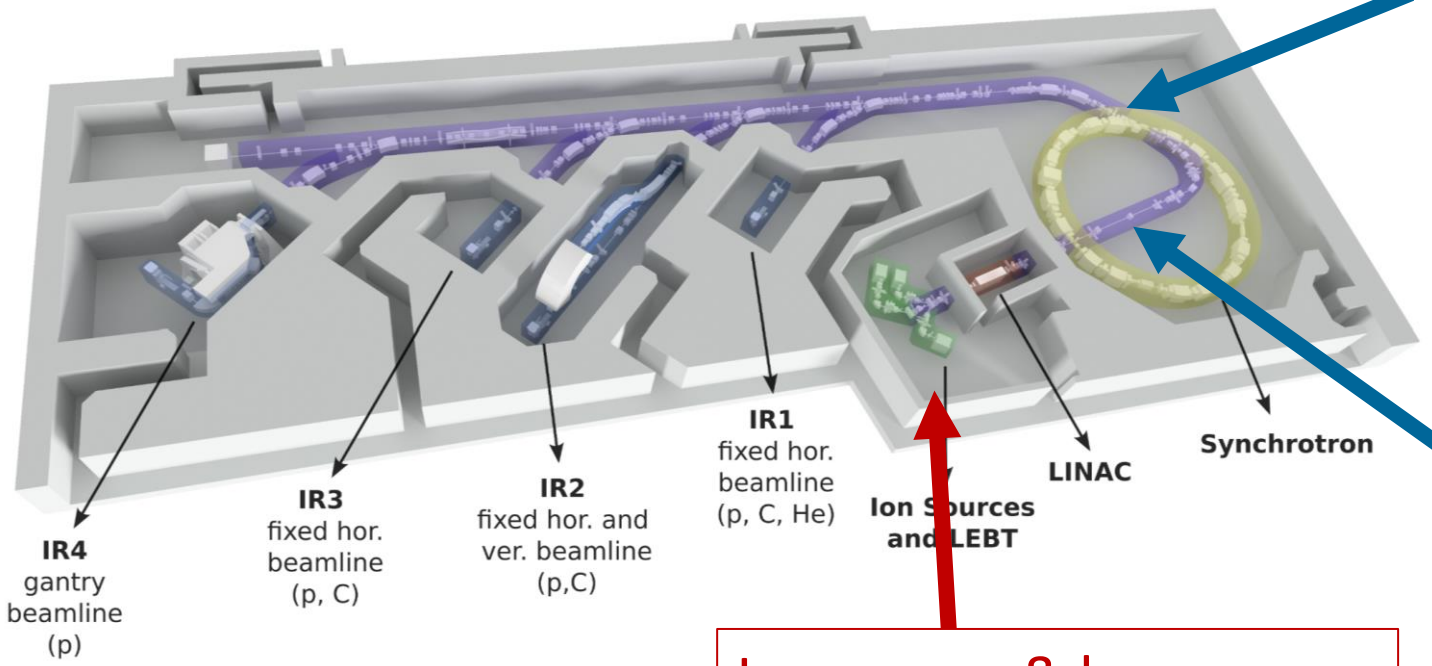


Rubens and Brueghel, "Smell" (1617)

Objective (A): **New diagnostic methods** to measure mixed-beam characteristics using **existing instrumentation**

Objective (B): **Propose new beam instrumentation** for mixed-beam characterizations

Different energy regimes require different methods



Synchrotron and high-energy beam transport **(a few hundred MeV/u)**

Medium-energy beam transport **(a few MeV/u)**

Ion source & low-energy beam transport **(keV/u)**

Ion source: Optical Emission Spectroscopy (C4+, He1+)

Noninvasive, indirect

Employed during GSI mixed-beam times

- Noninvasive analysis of source plasma
- Characteristic bound-bound emission lines arising from atomic transitions
- For $^{12}C^{3+}$ and $^{4}He^{1+}$: lines in **visible range**
- Intensity ratio of characteristic emission lines → relative abundance of He vs C

See talk by L. Celona and M. Galonska

Similar setup now also installed at MedAustron

See poster by P. Galeazzo, N. Gambino et al.

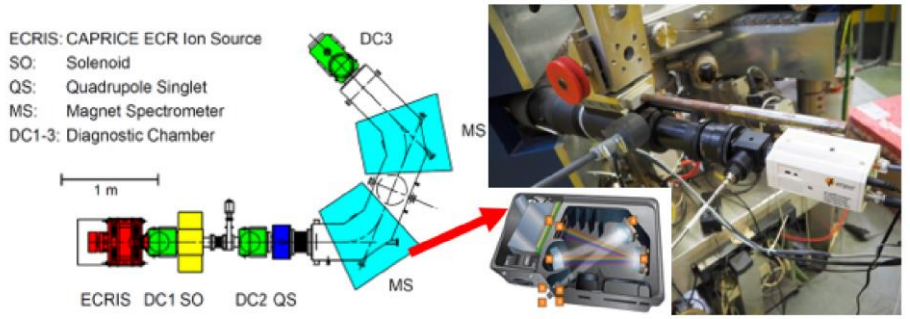


Figure 1: Scheme of the ion source and LEBT (left) including camera and optical spectrometer system (right).

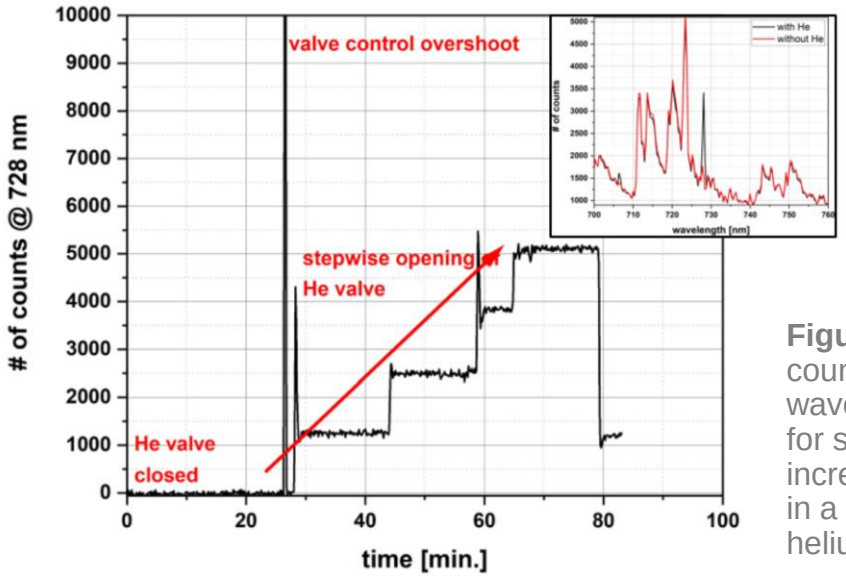


Figure: Number of counts at 728 nm wavelength (He I) for stepweise increase of He flow in a methane / helium plasma [5].

Ion source: Optical Emission Spectroscopy (C4+, He1+)

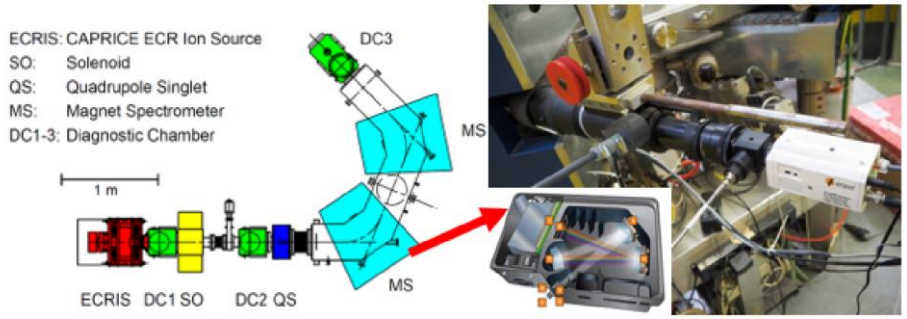
Noninvasive, indirect

Similar concept applicable for C6+ & He2+?

- Fully ionized → no bound-bound transitions.
- **Proposed alternatives:**
  - Radiative recombination lines (direct)
  - Transition lines from neighboring charge states (indirect), in combination with plasma model
- **Relevant lines in UV spectral range**

  → In-vacuum spectrometer

See poster by P. Galeazzo, N. Gambino et al.



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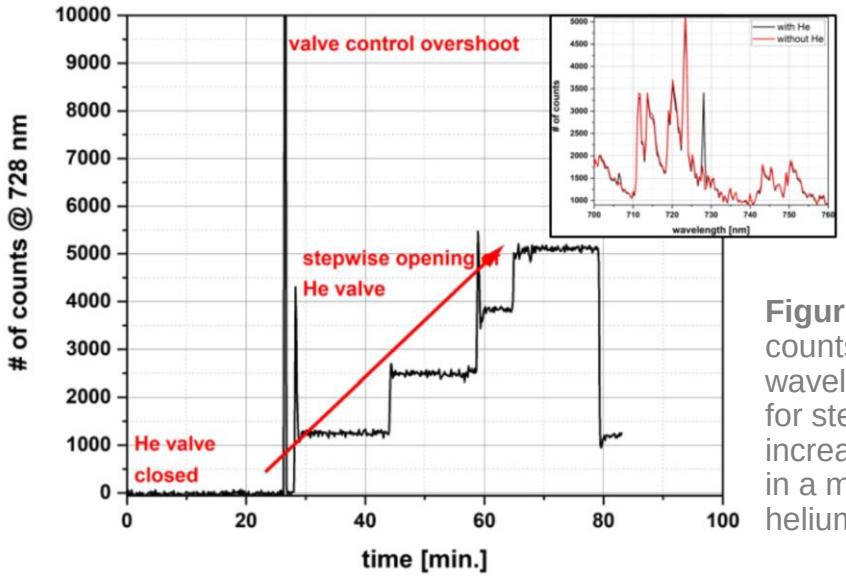


Figure: Number of counts at 728 nm wavelength (He I) for stepweise increase of He flow in a methane / helium plasma [5].

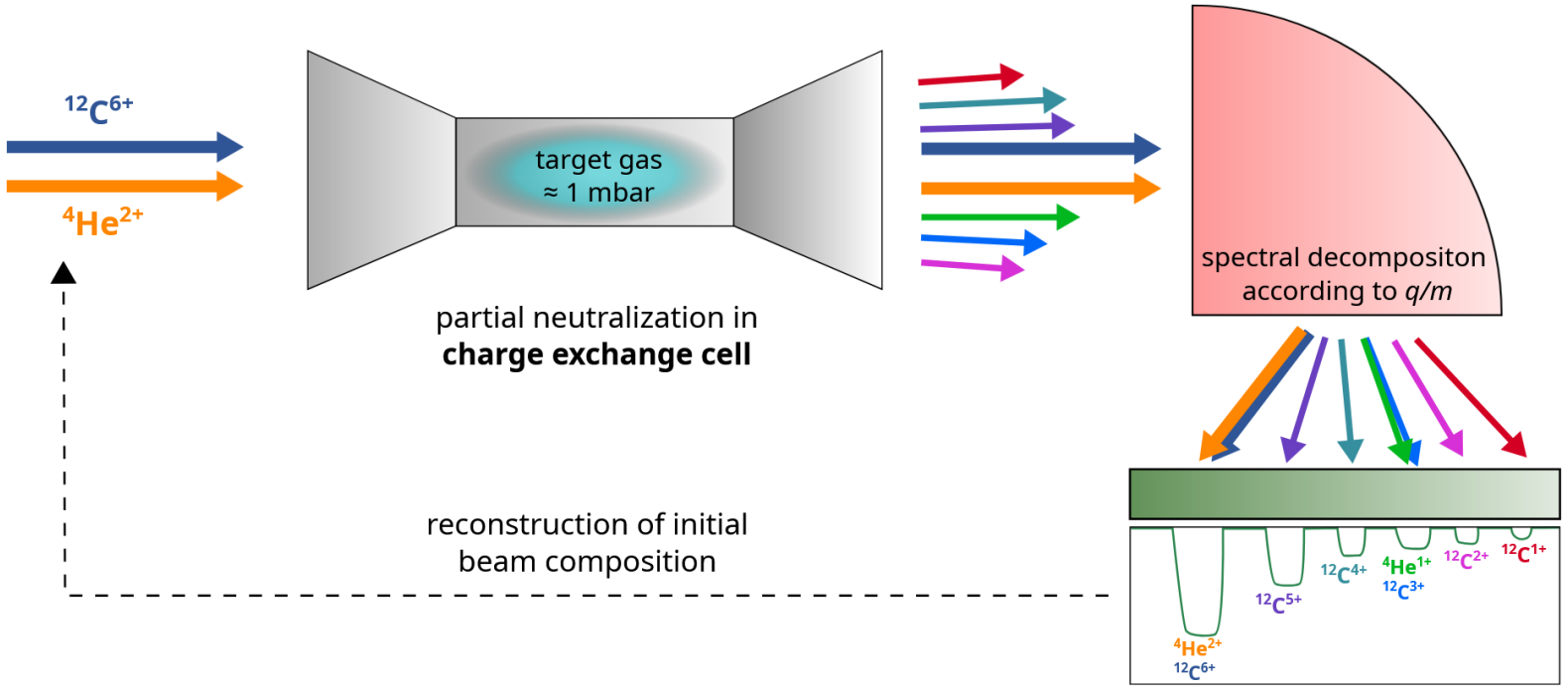
LEBT: Charge-Exchange Cell

Invasive, direct

See poster by M. Kausel et al.

Proposal to provide direct measurement of C6+ / He2+ ratio in the LEBT during mixed-beam source commissioning

- Beamline segment filled with e.g. alkali vapor (K, Na) or neutral gases (He, CO_2, N)
- Partial recombination of ions with electrons → different q/A.
- Quantify He/C ratio with subsequent spectral analysis
  - *Spectrometer/Wien filter, selective deceleration with constant E + ToF, ...*



M. Kausel et al, IPAC '25 (2025), TUPB100, 10.18429/JACoW-IPAC2025-TUPB100

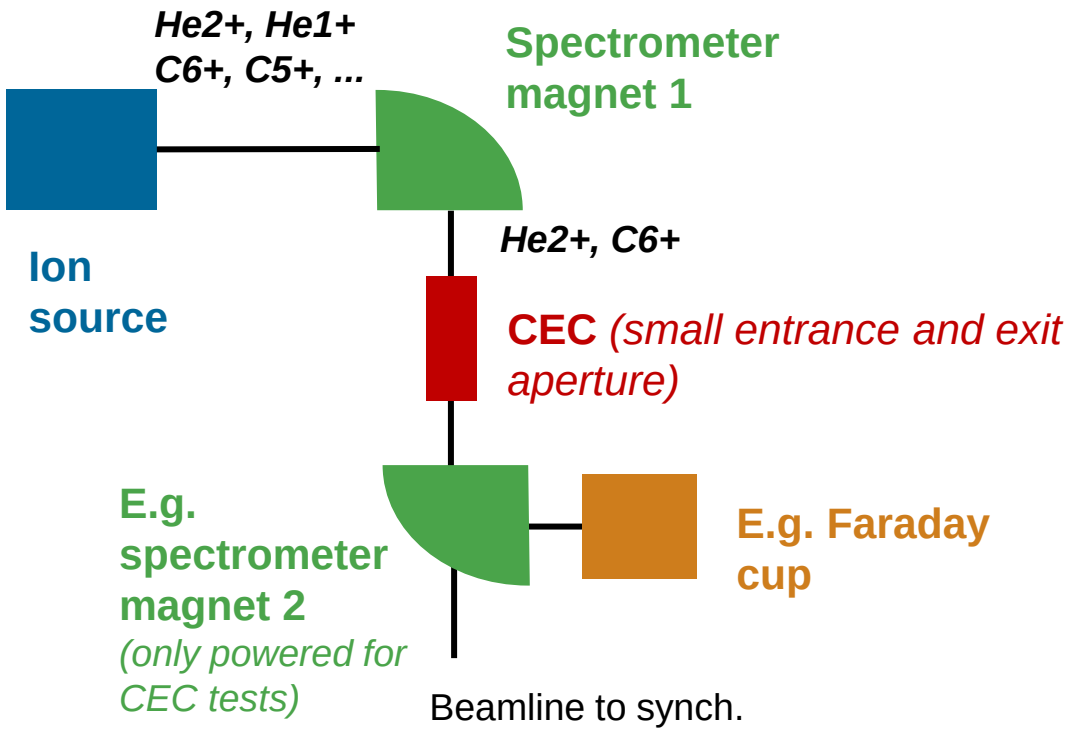
LEBT: Charge-Exchange Cell

Invasive, direct

See poster by M. Kausel et al.

Technical considerations

- Ideally positioned **in between two analyzing elements** (spectrometer, Wien filter, ...)
- CEC requires **small entrance and exit aperture** to confine gas to CEC
  - Ideally <10mm
  - Minimize strain on vacuum system
  - If in main beam lines → located around beam waist or movable valves?
- Preliminary assessments: **~50-70 cm length!**



M. Kausel et al, IPAC '25 (2025), TUPB100, 10.18429/JACoW-IPAC2025-TUPB100

LEBT: Charge-Exchange Cell

Invasive, direct

See poster by M. Kausel et al.

Preliminary feasibility tests in 2025

- Performed at Helmholtz-Zentrum Dresden-Rossendorf
  - R. Rockenbauer & M. Kausel (MedAustron, TU Wien) with R. Heller (HZDR)
- No real mixed beam available → tests with pure He^{1+}, C^{3+} beams
- Results helpful towards demonstrating working principle, but still many gaps

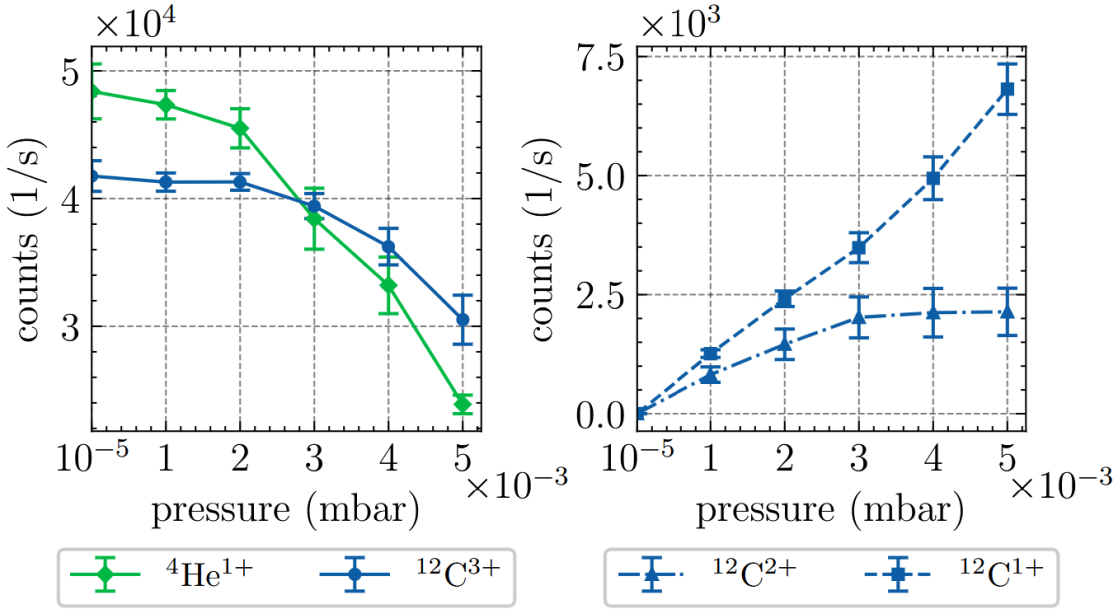
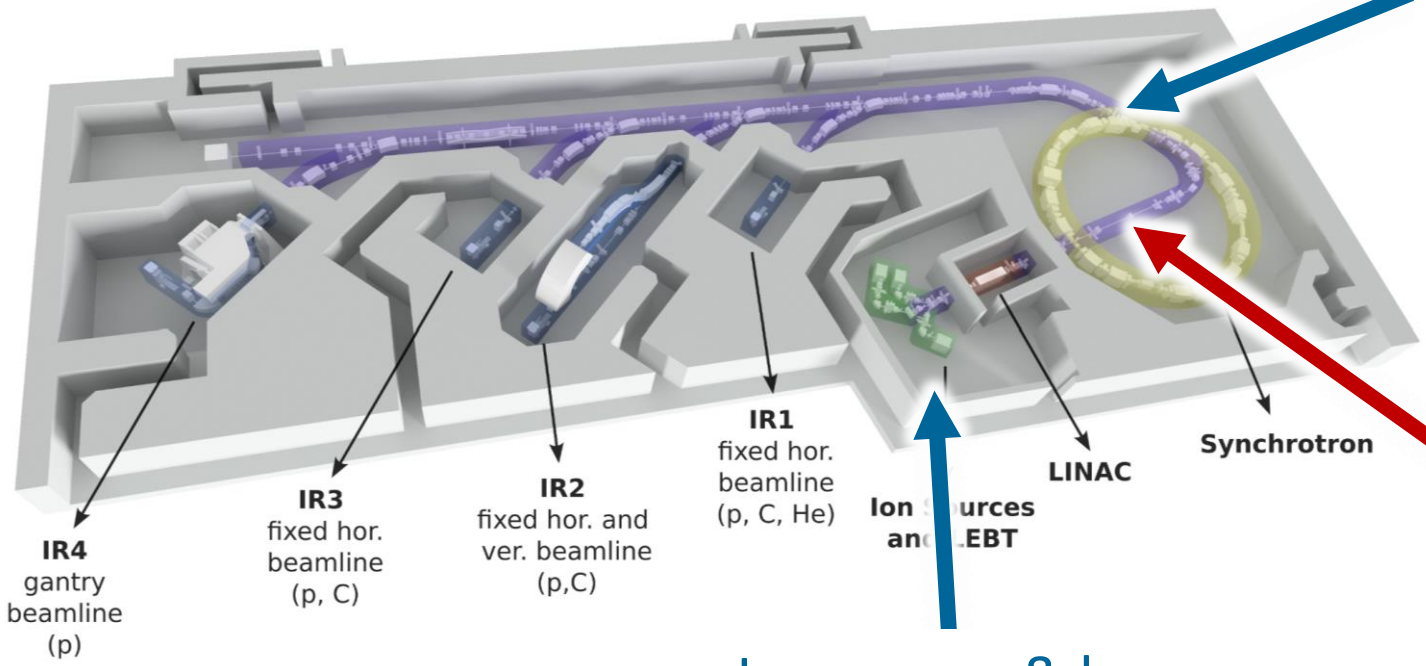


Figure 2: Counts of primary (left) and secondary (right) ion species at the channeltron after passage through the charge exchange cell and the electrostatic analyzer for different cell pressures.

M. Kausel et al, IPAC '25 (2025), TUPB100, 10.18429/JACoW-IPAC2025-TUPB100

Different energy regimes require different methods



Synchrotron and high-energy beam transport **(a few hundred MeV/u)**

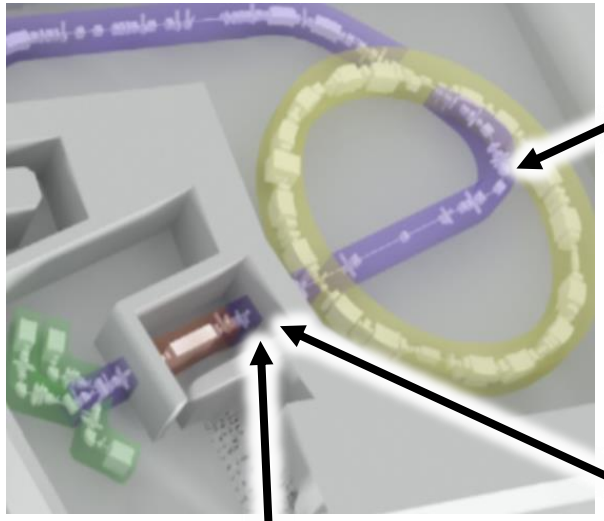
Medium-energy beam transport **(a few MeV/u)**

Ion source & low-energy beam transport **(keV/u)**

MEBT: Species-Dependent Energy Straggling in Stripping Foil

Invasive, direct

Very preliminary thought experiment:



Profile monitor in dispersive MEBT section, assume *(PIMMS 2 report)*

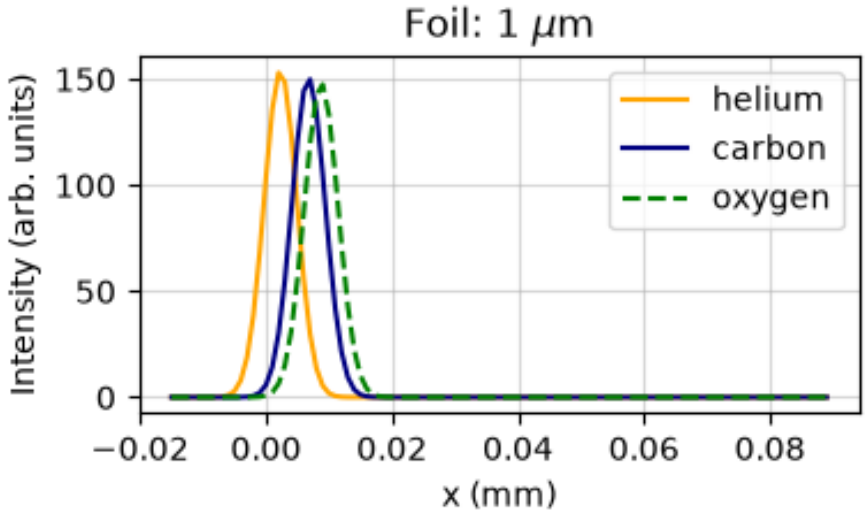
- $D_x = -3m$
- $\beta_x = 2.5\ m$
- $\epsilon_x = 2\ 10^{-7}\ m\ rad$
- Screen with 1mm resolution

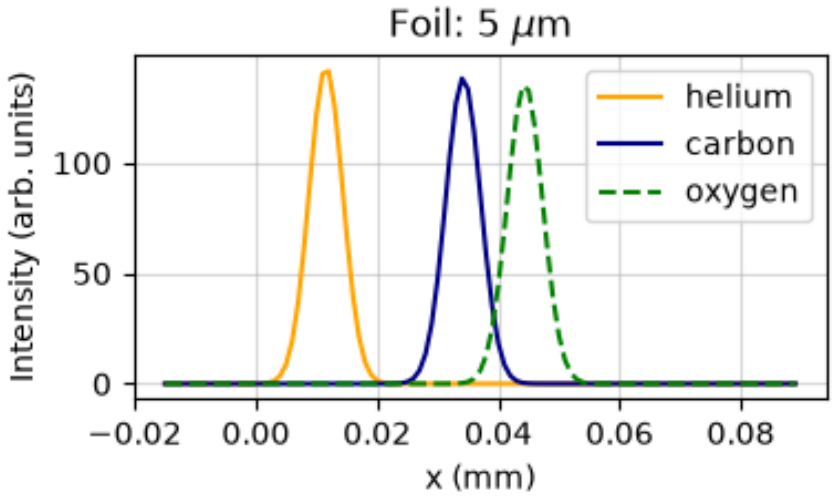
Stripping foil:

- Standard: 0.5um, carbon
- Thought experiment: explore different thicknesses
- **Causes shift and spread in** $\boldsymbol{\delta = \frac{\Delta\beta\gamma}{\beta\gamma}}$

Assume same $\boldsymbol{\frac{E}{m}}$ **after LINAC**

- $\frac{E}{m} = 7$MeV/u
- $\delta = \frac{\Delta\beta\gamma}{\beta\gamma} = 5\ 10^{-4}$





MEBT: Species-Dependent Energy Loss in Stripping Foil

Invasive, direct

- Employed at **CERN in 1980s** to quantify **oxygen-sulfur ratio** after the LINAC
- There, **flexibility in beam line** to optimize resolution
  - spectrometer,
  - focusing at the foil to minimize scattering
  - ...

ACCELERATING AND SEPARATING MIXED BEAMS OF IONS WITH SIMILAR CHARGE TO MASS RATIO IN THE CERN PS COMPLEX

N. Angert
GSI, D-6100 - Darmstadt 11
E. Brouzet, R. Garoby, S. Hancock, H. Haseroth, C. Hill, K. Schindl, P. Têtu
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Analysis of the S^{12+}/O^{6+} ratio out of Linac

A (destructive) system downstream of the Linac enabled separation of the two species after the foil used for stripping S^{12+} to S^{16+} and O^{6+} to O^{8+}. The different energy losses per nucleon (proportional to Z^2/A, i.e. a factor 2) of the two types of ion when passing through a thin aluminium foil (3 µm) was used as the basis of the measurement. A spectrometer separated the two beams which could then be observed on a SEMgrid. Beam separation was optimised by varying the angle of the foil relative to the beam. The optics adopted minimised the effects of scattering in the foil (small beam dimensions) and imaged the beam on the SEMgrid using a quadrupole triplet such that the horizontal transfer matrix was of the form (a1 0 /a3 a4). The energy resolution of the spectrometer is 26 keV/u per SEMgrid strip. Fig. 2b shows the two separated beams. In estimating the relative percentages of the two ions, account should be taken of the S^{15+}, S^{14+}, O^{7+} and O^{6+} created during the passage through the thin foil as well as the different yields in the SEMgrid according to ion type. Typically, about 5% of S^{16+} beam content was measured.

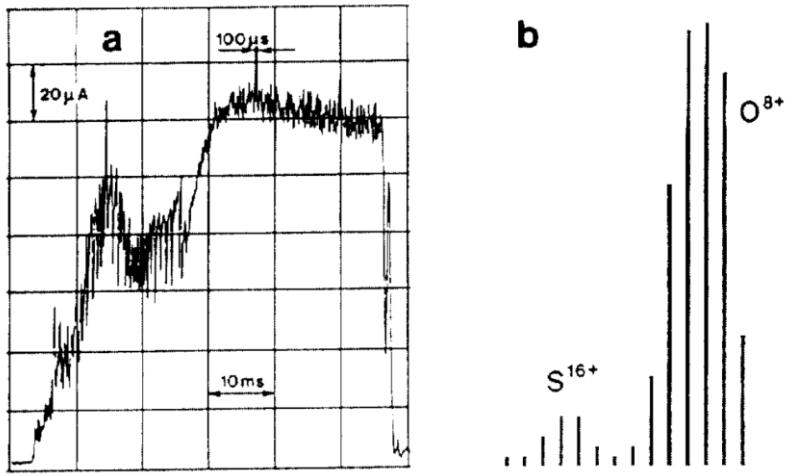
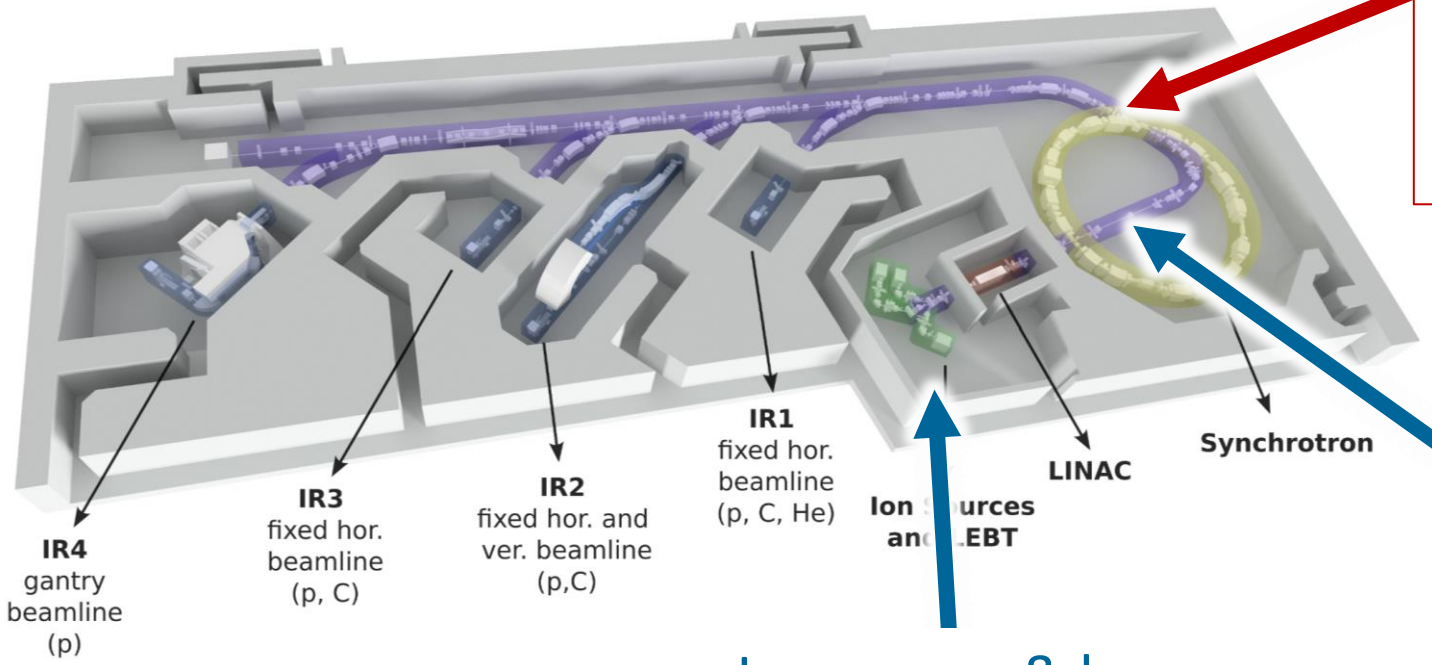


Fig. 2 : (a) S^{12+}/O^{6+} mixed beam current delivered by the E.C.R. source. (b) Monitoring the S^{16+}/O^{8+} ratio with a SEMgrid after the mixture's passage through a degrader and a spectrometer

Different energy regimes require different methods



Synchrotron and high-energy beam transport **(a few hundred MeV/u)**

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Ion source & low-energy beam transport **(keV/u)**

Synchrotron: Dispersive or RF Frequency Offset I

Noninvasive, direct

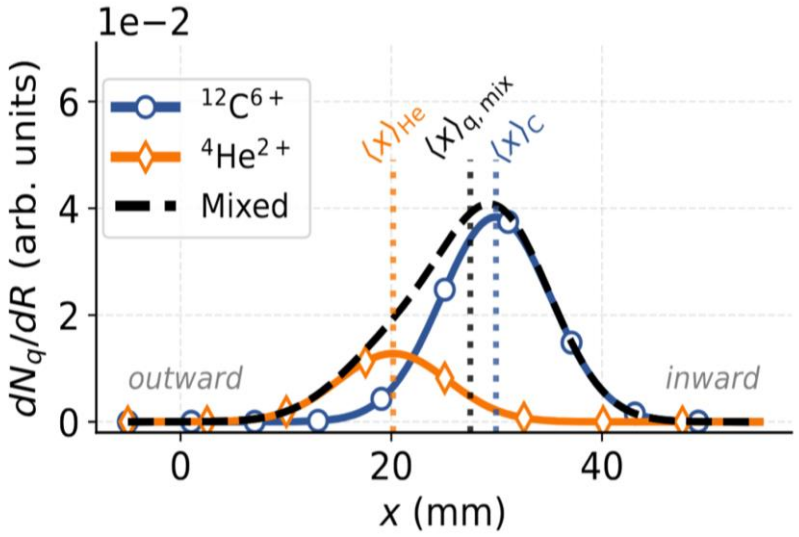
Rigidity offset $O(10^{-4} - 10^{-3})$ → He and C move on different orbits

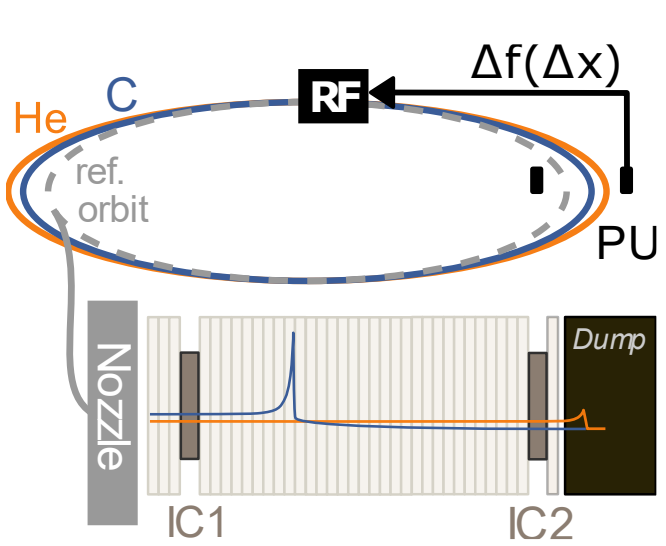
Feed-forward RF operation: composition-dependent dispersive orbit shift

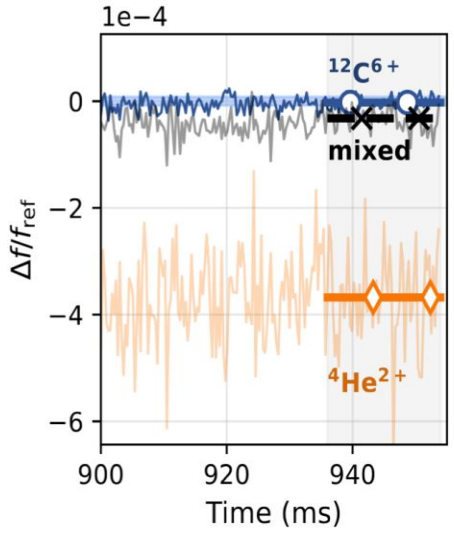
- $< x >_C = x_{ref}$
- Reconstruct $r = \frac{N_{He}}{N_{He}+N_C}$ from $< x >_{q,mix}$- x_{ref}

RF regulation with radial-loop: composition-dependent frequency shift

- $< x >_{mix} = x_{ref}$
- Reconstruct r from $\Delta f / f$







Synchrotron: Dispersive or RF Frequency Offset II

Noninvasive, direct

Noninvasive and can be measured every synchrotron cycle!

E. Renner et al, PRAB 29, 093802 (2026)

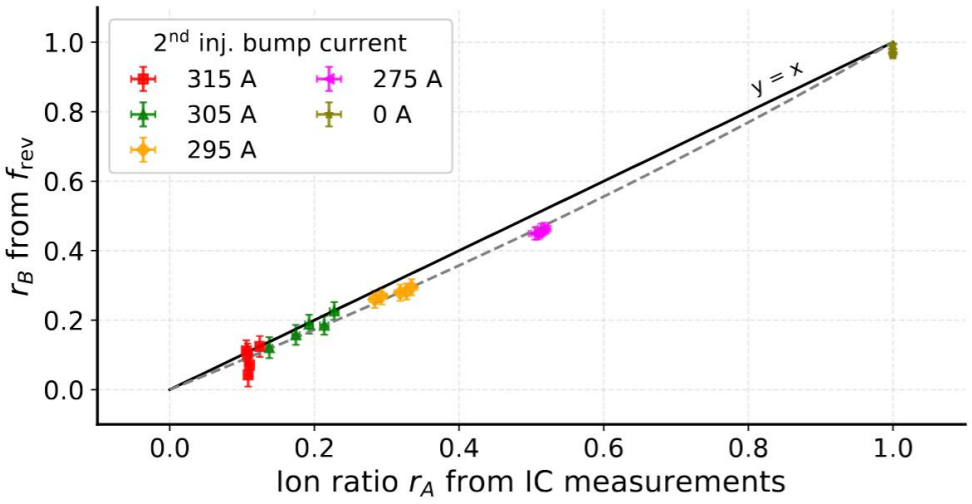
- Development of formalism
- Experimental demonstration at MedAustron
  - Phase displacement extraction → different extr. efficiancies
  - Validation of measurements in irradiation room
- Discussion of limitations

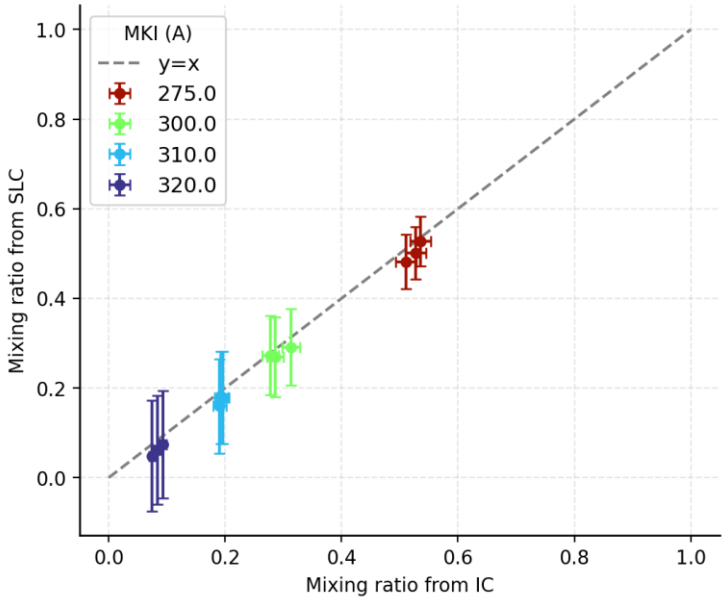
Since then

- Used for beam commissioning and monitoring during experiments
- Differences in extraction efficiency not observed for RFKO

Future

- Could it be used for a mixing-ratio interlock system? Biggest challenge: B-field fluctuations!





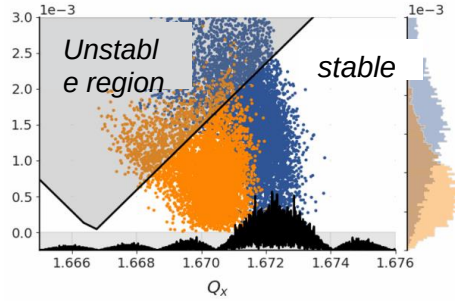
HEBT: Dispersive Offset

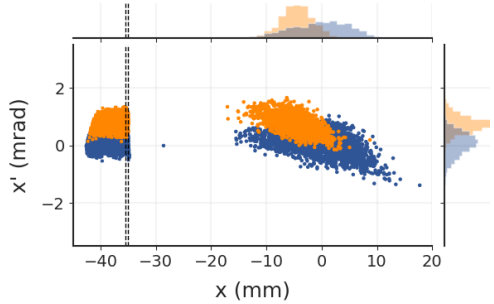
Invasive, direct

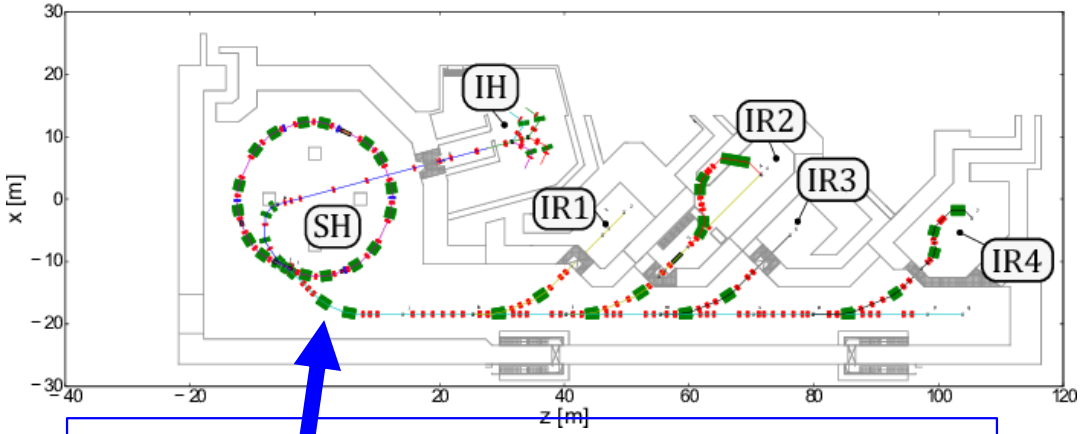
Background

- Rigidity offset between He & C at flat top:
  - MedAustron: ≈ 1 to 1.5‰ for $120 - 400$ MeV/u

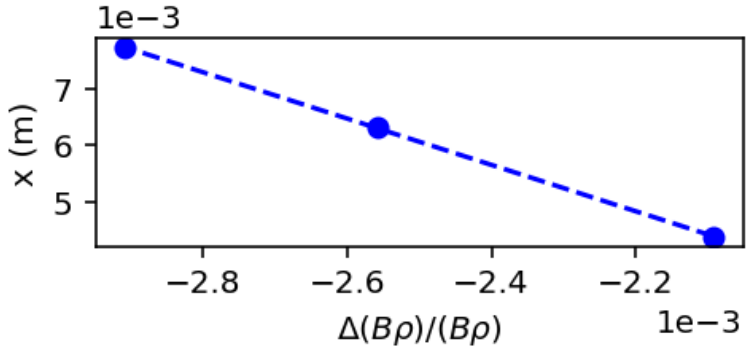
- SX settings define
  - extracted (x, x') distributions
  - initial conditions for D_x, $D_x{}'$ at the start of the HEBT







EX-01-000-SFX: D_x (m) = -4.12 ·Δ(Bρ)/(Bρ) + -0.0042



Preparation: **Dispersion measurement** in the MedAustron HEBT: a pure carbon-ion beam was set to different momentum-offsets in the synchrotron and afterwards extracted via RFKO. The CoG of the profile measurement at the scintillating fiber screen is used to fit D_x

Proposal: use a **profile monitor in the HEBT** to diagnose the extracted MB?

- **Located in a dispersive region**
- E.g. scintillating fiber monitor, Si-based monitor, ...

HEBT: Dispersive Offset

Invasive, direct

First feasibility tests

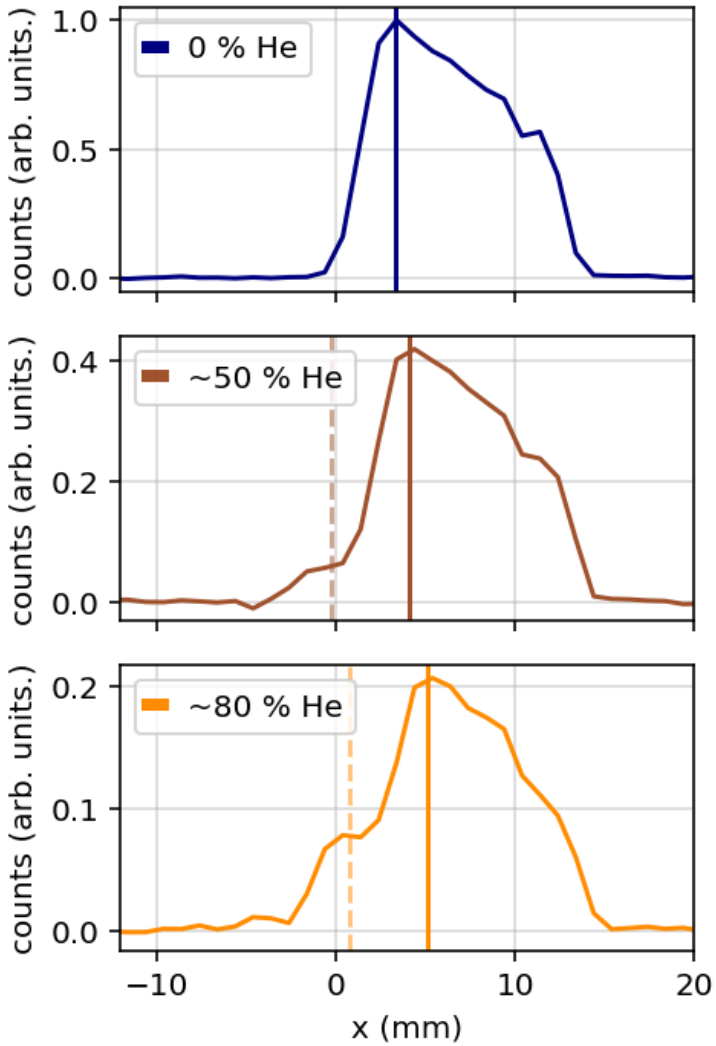
- Acquired beam profiles with different C-He mixing ratios
  - Resolution: 1mm
  - $D_x = -4.1\ m$
  - Mixed beams with 0, 50%, 80% He fraction

Preliminary results

- Clear He “bump” visible for large He fractions; details to be evaluated:
  - With RL, we expect both distributions to be shifted in $B\rho$, depending on mixing ratio → visible!
  - Distance between He-C bump seems larger than expected.
  - Where is center of gravity of He and C distribution?
  - C distribution is asymmetric. Scraping, losses during extraction?

Outlook:

- Explore meas. opportunities with Si-based FLASH-BPM
  - See F. Ulrich-Pur’s presentation



Conclusion

Method	Section	What	Noninvasive	Direct	Demonstrated
OES: C4+ / He1+	**Ion source**	Rel. ion abundance in plasma	✓	X	✓
OES: C6+ / He2+	**Ion source**	Rel. ion abundance in plasma	✓	X	X
Charge-exchange cell	**LEBT (keV/u)**	Mixing ratio	X	✓	X
Energy-loss in stripping foil + dispersive offsets	**MEBT (few MeV/u)**	Mixing ratio + species-dependent dispersive transverse profile	X	✓	~ *(for S18+ and O6+)*
LLRF measurements	**Synchrotron (few 100 MeV/u)**	Mixing ratio	✓	✓	✓ (via RL freq. correction) **X (via disp. offset in FF mode)**
Schottky spectrum	**Synchrotron, after inj, before capture**	Energy offset, species-specific momentum spread, mixing ratio before capture *(if separated enough!)*	✓	✓	✓
Profile monitor	**HEBT**		✓	✓	~ (only for large He fractions)

Discussion baseline ... to be reviewed and extended by you!