

Slow Extraction of Mixed Ion Beams

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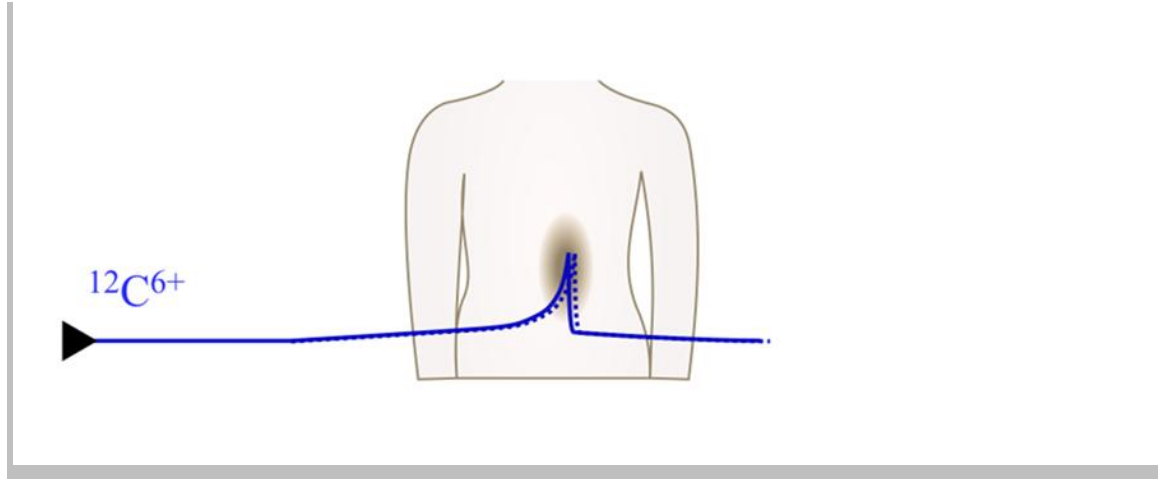
[3] MedAustron

[4] CNAO

Mixed Ion Beams for Concurrent Therapy and Monitoring

Ion beam therapy vs. conventional radiotherapy

- + Improved dose conformity (Bragg peak) & higher biological effectiveness
- More sensitive to uncertainties
- ▶ **Accurate treatment planning & monitoring crucial***



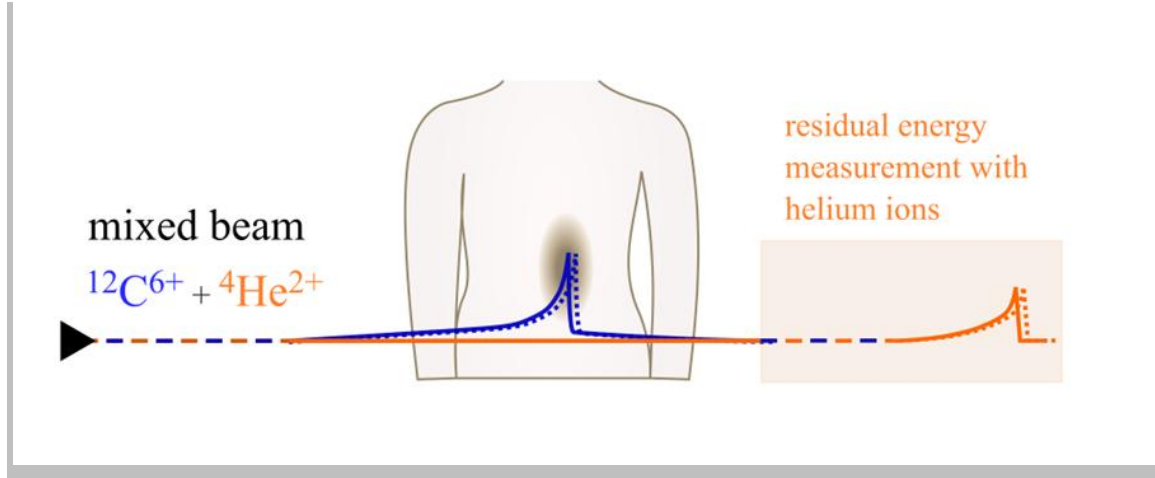
* Various proposals for **monitoring in addition to routine regular treatment plan verification**

CTs: e.g. prompt gamma, nuclear fragmentation imaging, pRad,...

Mixed Ion Beams for Concurrent Therapy and Monitoring

Ion beam therapy vs. conventional radiotherapy

- + Improved dose conformity (Bragg peak) & higher biological effectiveness
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* Various proposals for **monitoring in addition to routine regular treatment plan verification**
CTs: e.g. prompt gamma, nuclear fragmentation imaging, pRad,...

Proposal: Add small $^4\text{He}^{2+}$ contribution to therapeutic $^{12}\text{C}^{6+}$ beam for monitoring [1,2]

- similar charge-to-mass ratio (≈ 0.5)

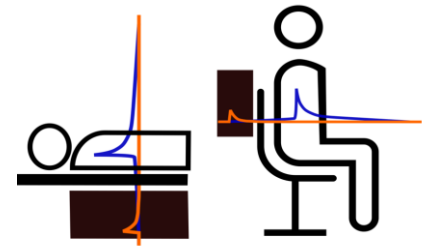
$$\frac{\Delta(q/m)}{q/m} = -0.065\%$$

- Extracted with similar E/m → **range of $^4\text{He}^{2+}$ approx. 3x larger than of $^{12}\text{C}^{6+}$**
- Preliminarily aim: **approx. 10% helium ions throughout the spill:**
 - He still distinguishable from C fragments
 - acceptable dose contribution from He ($\sim 1\%$)

[1] D. Mazzucconi et al., CNAO, Med. Phys. 45 (11), 2018

[2] C. Graeff et al., GSI, Physica Medica 52, 2018

Towards Mixed Beam Radiography Systems



Particle-integrating approach

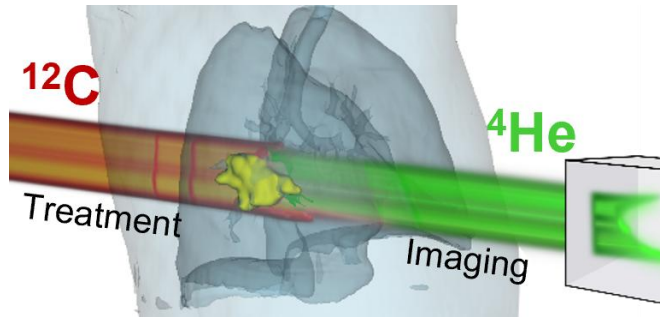


Figure: ERC PROMISE project, C. Graeff [7]

- Obtain WET map (e.g. per energy layer)
- E.g. range telescope, scintillator, ...

Single-particle tracking

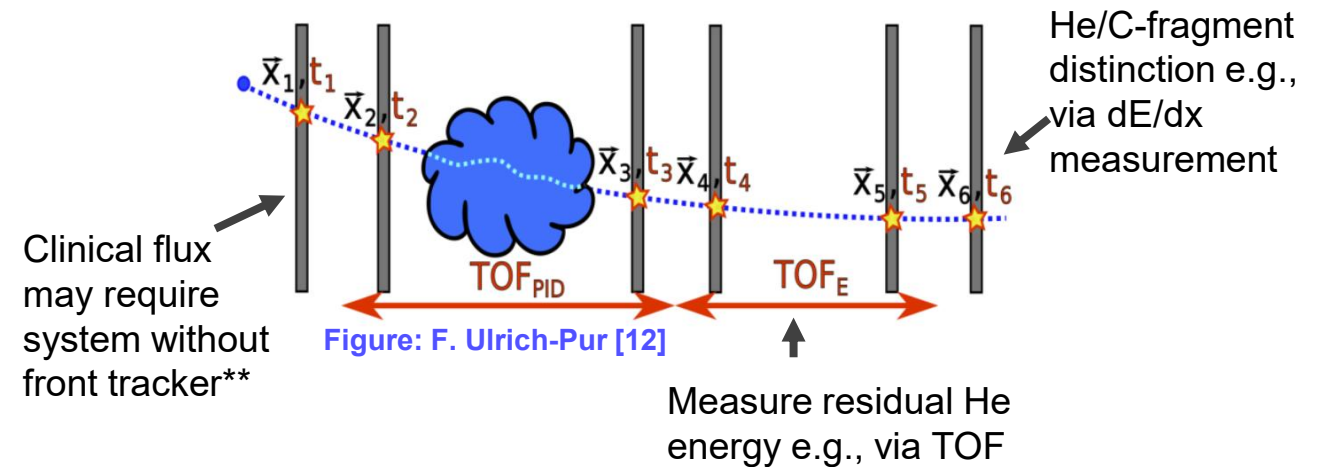


Figure: F. Ulrich-Pur [12]

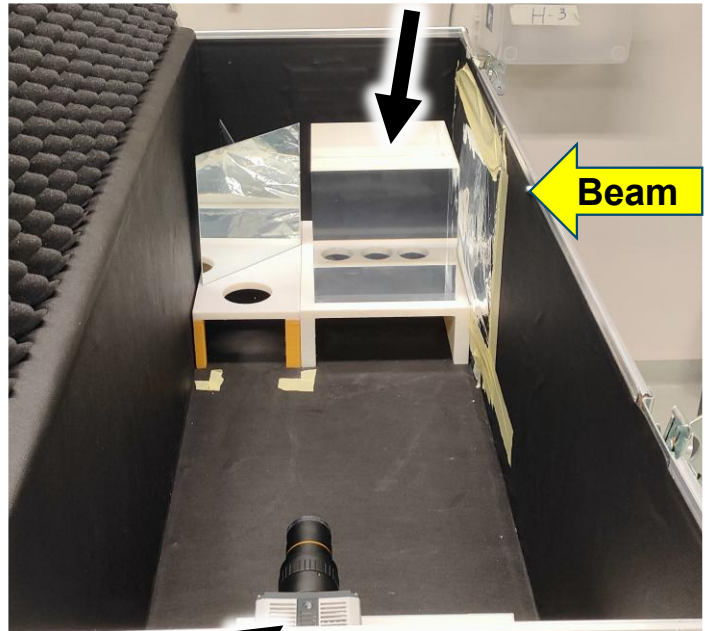
Needs to detect as **wide a range as possible of residual He energies**, while enabling **distinction of He from C fragments**

* alternative: range shifter between nozzle and patient and/or patient and detector to increase dynamic range

** would require sophisticated 4D-clustering to deal with increased hit multiplicity

Example: Scintillator Based Monitor I

Cubic plastic (BC408) scintillator, 20x20x20 cm



CMOS
camera

[1] D. Mazzucconi et al., CNAO,
Med. Phys. 45 (11), 2018

Slide courtesy of M. Pullia & Simone
Savazzi (CNAO)

Experiments at GSI in May 2025: **scan of a dual beam through a sphere**

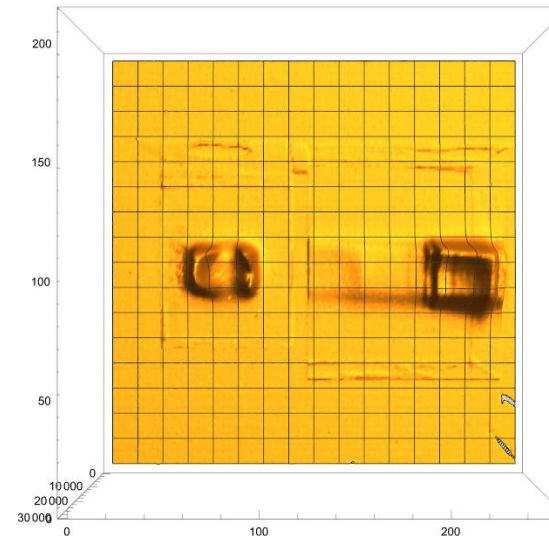
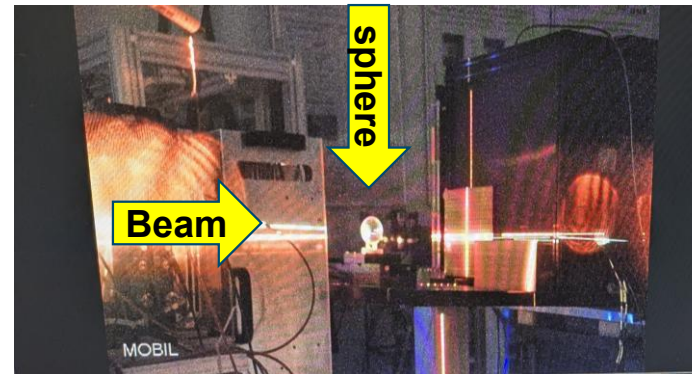
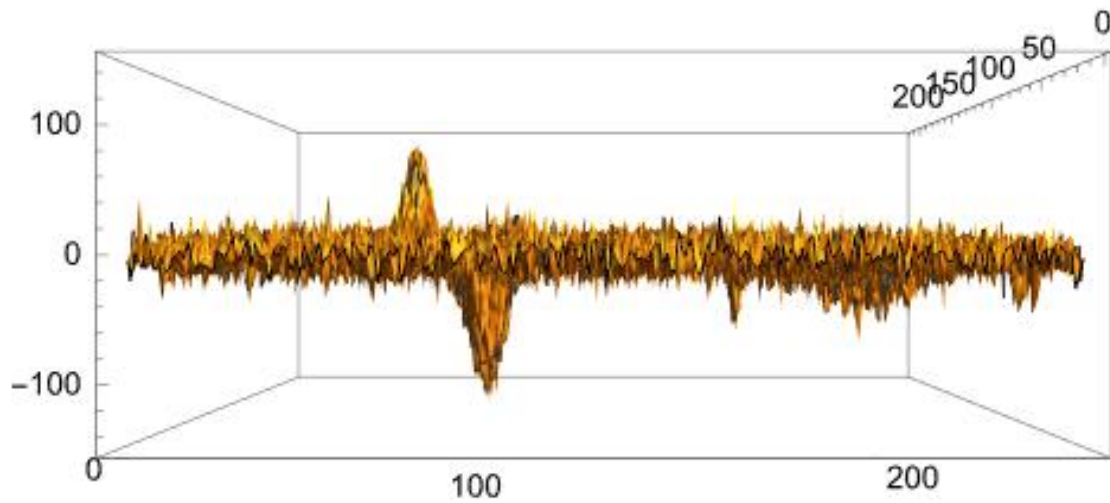


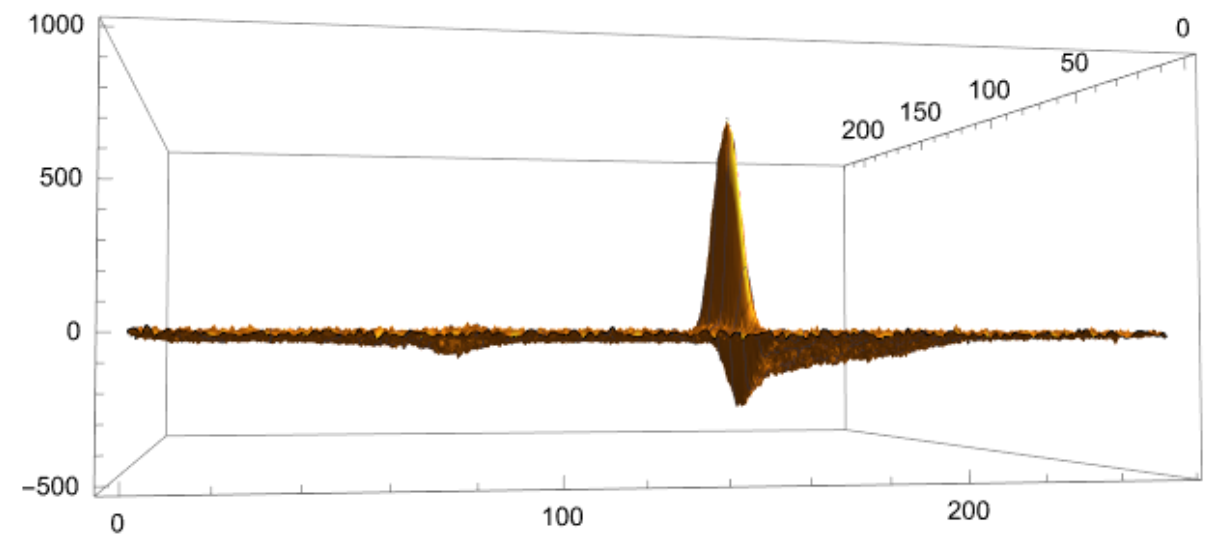
Figure and video: C+He#21 with sphere, no range shifter.

Example: Scintillator Based Monitor II

Figures: **difference between the *present image***, taken after the target has changed, and **the *reference image***.



3 mm sphere displacement



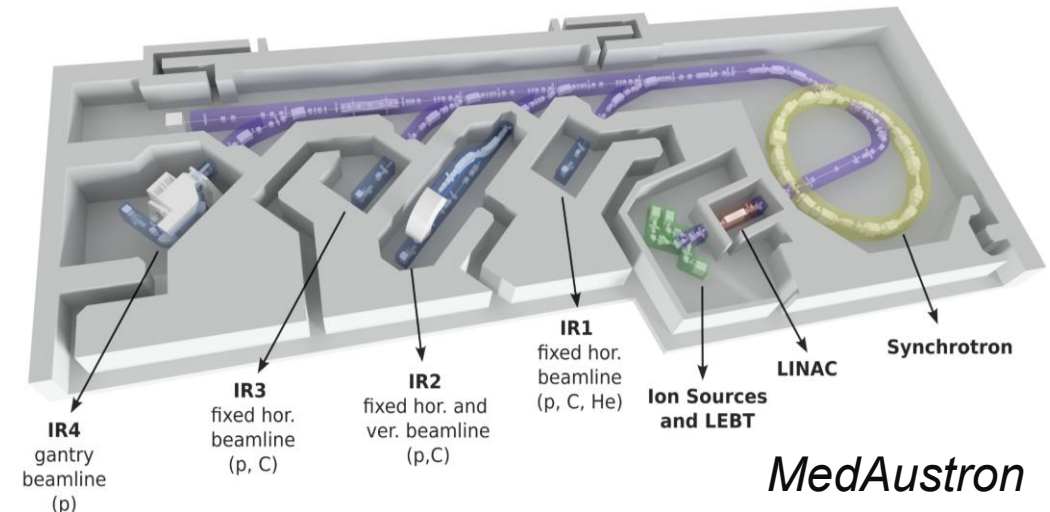
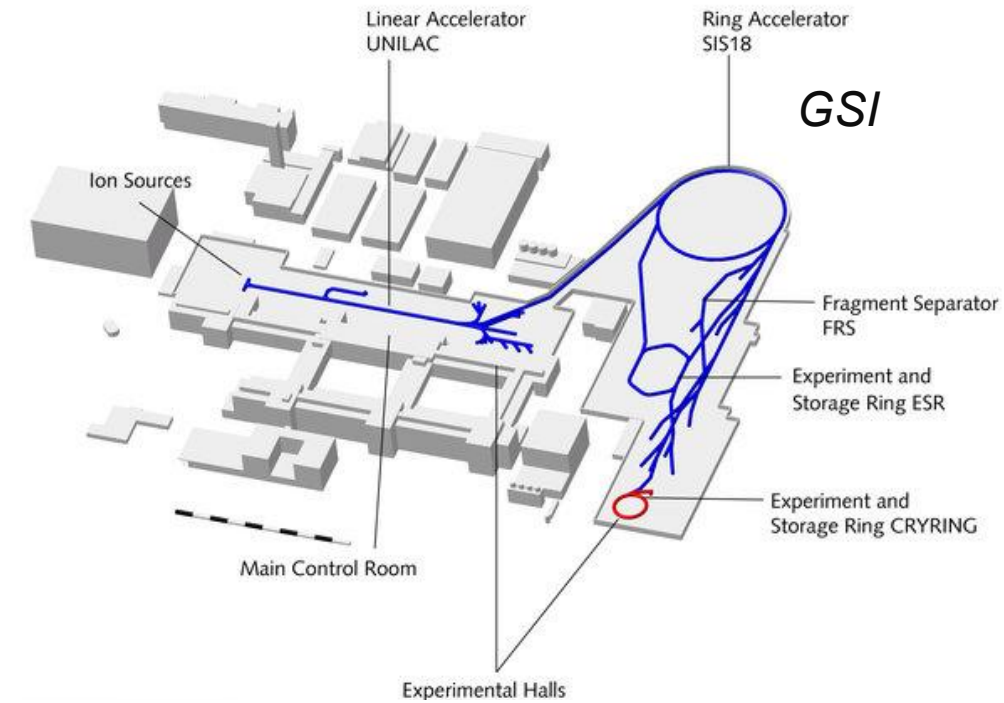
4 mm range variation

Slide courtesy of M. Pullia & Simone Savazzi (CNAO)

Experiments performed in 05/2025 at GSI (C. Graeff)

Outline

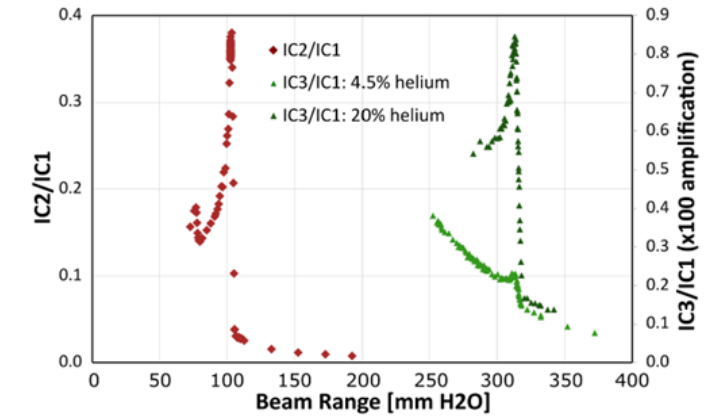
- I. Overview: ongoing mixed helium-carbon ion beam experiments
- II. Mixed beam slow extraction at GSI
- III. Mixed beam slow extraction at MedAustron
- IV. Conclusion and Outlook



Recent Activities

- *Since <2018*: Initial concept studies (**CNAO** [1], **GSI** [2], **DKFZ** [3,4])
 - No mixed beam experimentally available back then
 - *Detection & treatment planning* (simulations, sequential irradiation, ...)
- *Since 2023*: ERC project **PROMISE** at **GSI** (C. Graeff et al. [5-7]).
 - “Portal Range Monitoring in Mixed Ion Beam Surgery”
 - *Imaging & mixed beam delivery concepts, ...*
 - Nov. 2023: **First delivery of mixed $^{12}\text{C}^{3+}$ and $^4\text{He}^{1+}$ beam (single ion source)**
 - Very successful beam time in May 2025.
- *Since 2023*: Collaboration between **TU Wien & MedAustron** [8-10].
 - Focus: *Mixed ion beam delivery in medical synchrotron facilities*
 - Summer 2024: **First delivery of a mixed beam in a medical facility ($^{12}\text{C}^{6+}$ & $^4\text{He}^{2+}$, double injection)**

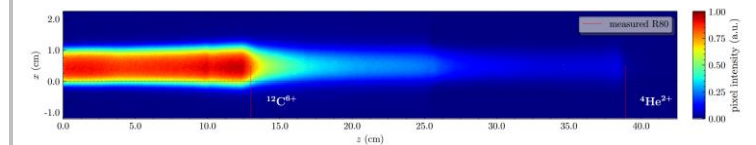
- [1] D. Mazzucconi et al., CNAO, Med. Phys. 45 (11), 2018
- [2] C. Graeff et al., GSI, Physica Medica 52, 2018
- [3] L. Volz et al., DKFZ, Phys Med Biol 65/2, 2020
- [4] J. Hardt, DKFZ, Phys Med Biol 69/5, 2024



[5] M. Galonska et al., GSI, IPAC'24

[6] D. Ondreka et al., GSI, IPAC'24

[7] C. Graeff et al. PROMISE Project, GSI



[8] E. Renner et al., IPAC '24

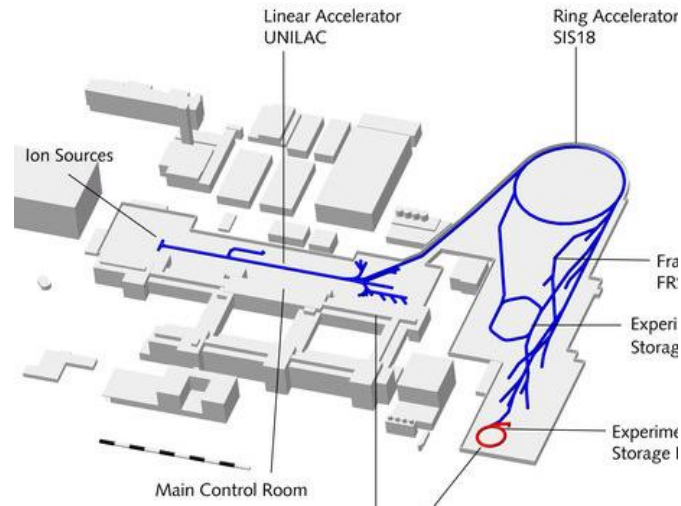
[9] M. Kausel, E. Renner et al. Submitted to PRAB, 2025

[10] M. Kausel, et al. IPAC '25

Mixed Ion Beams at GSI

■ Direct extraction of $^{12}\text{C}^{3+}$ & $^4\text{He}^{1+}$ mixture from single ion source [5]

- 14 GHz ECRIS
- Source gas: methane & helium
- $q/m = 1/4$
- Acceleration in **UNILAC** & **SIS18** → biophysics cave



■ $^4\text{He}^{1+}$ content tailored by stepwise addition of helium flow to ion source plasma

- Monitor He contribution using **optical emission spectroscopy**
- 2023 $^{16}\text{O}^{4+}$ **contamination** of less than 10%
- 2025 $^{16}\text{O}^{4+}$ contamination significantly reduced.

[5] Galonska et al. IPAC '24

[11] L. Volz et al, Ion Imaging '24

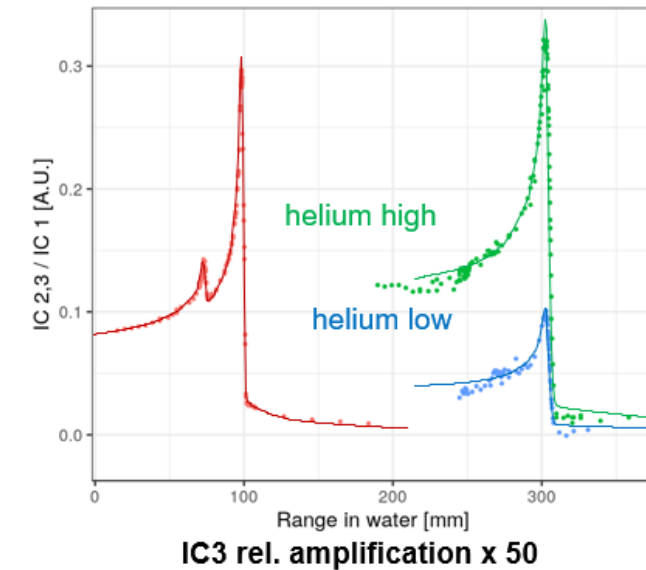


Figure: Mixed beam depth-dose curve measured in 2023 at GSI. Signal from IC3 and IC2 are carbon fragment tail corrected [11].

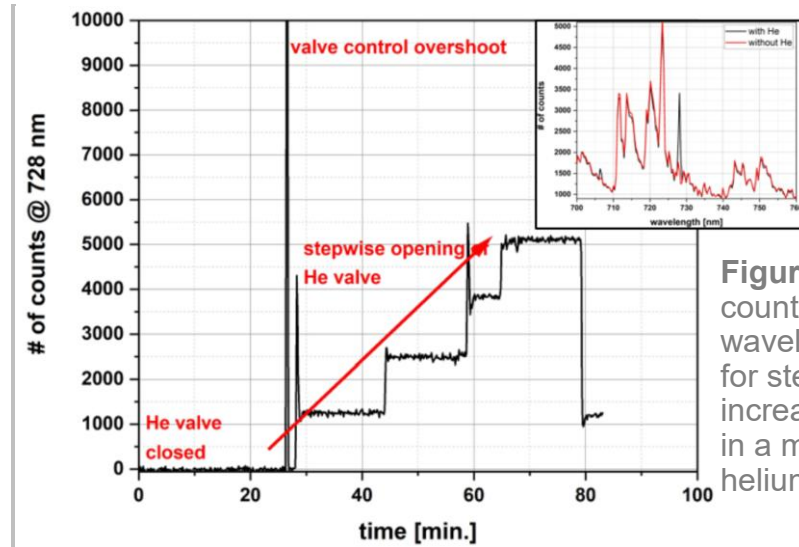


Figure: Number of counts at 728 nm wavelength (He I) for stepwise increase of He flow in a methane / helium plasma [5].

Mixed Ion Beams at MedAustron



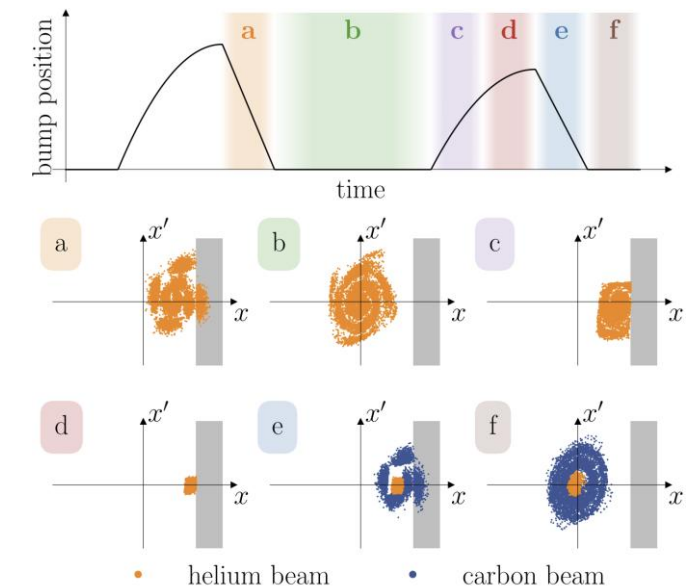
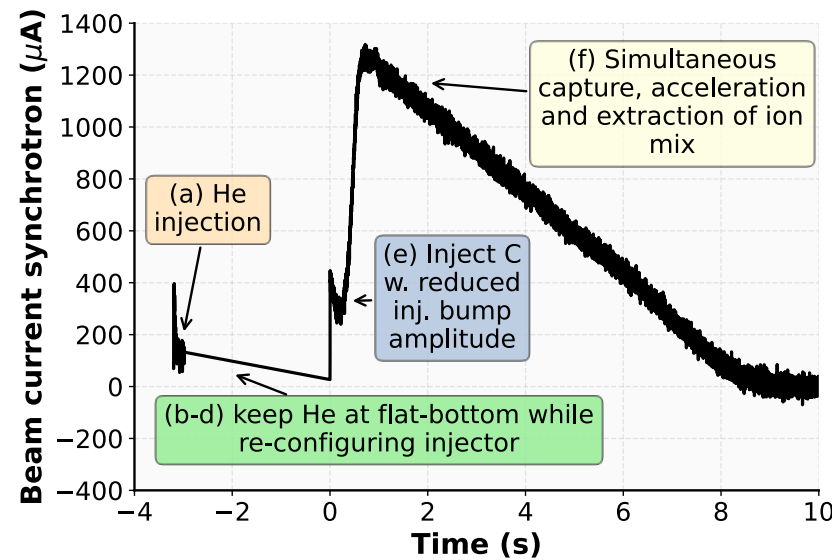
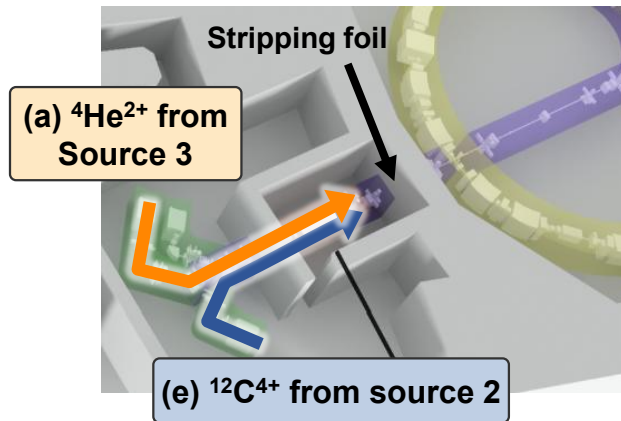
[9] M. Kausel et al.,
submitted to PRAB

Mixed beam from single ion source not deliverable in current medical synchrotron facilities.

- ${}^4\text{He}^{1+} + {}^{12}\text{C}^{3+} \rightarrow$ cannot be accelerated in **LINAC** (requires $q/m \leq 1/3$)
- ${}^4\text{He}^{2+} + {}^{12}\text{C}^{6+} \rightarrow$ insufficient ${}^{12}\text{C}^{6+}$ yield with 14 GHz **ECRIS**
- ${}^3\text{He}^{1+} + {}^{12}\text{C}^{4+} \rightarrow$ limited energy range + large $\Delta B_p/B_p$ in **synchrotron**

Alternative: mixing via sequential multi-turn injection of ${}^4\text{He}^{2+}$ and ${}^{12}\text{C}^{6+}$ into synchrotron

Aim: provide beam for research*



*In the current configuration, mixed beam setup not suitable for clinical use.

Tailor He:C ratio: adapt 2nd inj. bump amplitude

First mixed beam in summer '24

Implication of Charge-to-Mass Ratio During RF Acceleration

$\Delta(q/m)$ causes acceleration to slightly different E/m (depending on extraction and transition energy)

$$\chi = \frac{q_{\text{He}}/m_{\text{He}}}{q_{\text{C}}/m_{\text{C}}} = 0.99935$$

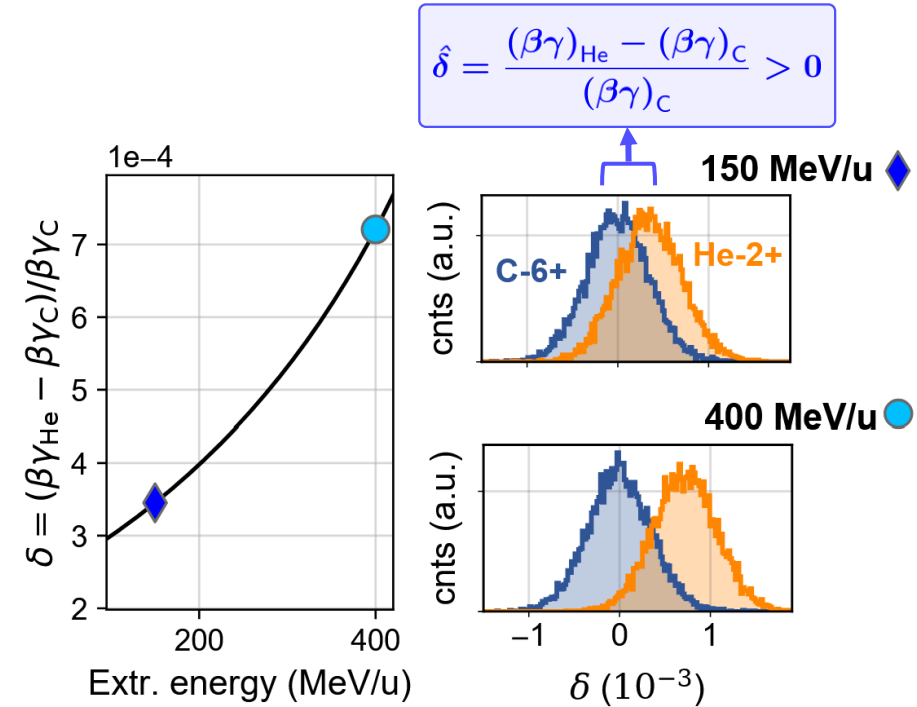
$$\Rightarrow \frac{\Delta C}{C} = \alpha_c \frac{\Delta B\rho}{B\rho} > 0$$



with long. RF field: $\frac{\Delta f}{f} = 0 = \frac{\Delta \beta}{\beta} - \frac{\Delta C}{C}$

$\Rightarrow \Delta \beta$ depends on extraction (γ_{C}) and transition energy (γ_{tr}):

$$\frac{\beta_{\text{He}} - \beta_{\text{C}}}{\beta_{\text{C}}} = \frac{1}{\gamma_{\text{tr}}^2 - \gamma_{\text{C}}^2} \cdot \left(\frac{1}{\chi} - 1 \right)$$



Example: Relative momentum per mass offset (δ) between the two ion species in a PIMMS-like synchrotron ($\gamma_{\text{tr}} \approx 2$, $\delta_{\text{rms}} \approx 0.35 \cdot 10^{-3}$)

[8] E. Renner, IPAC '24

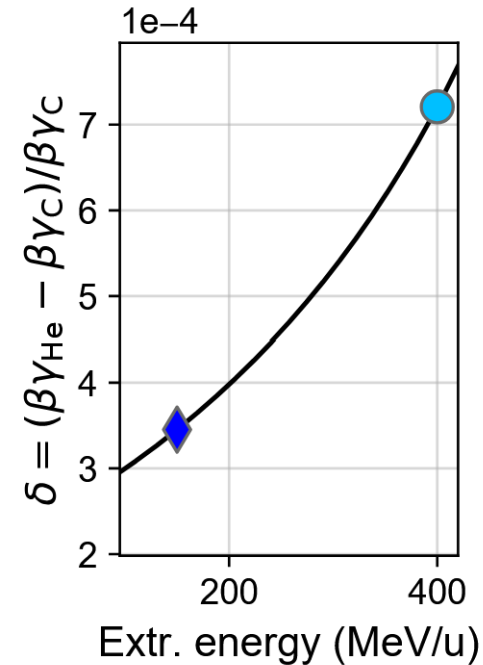
Take Away: Mixed Beams & RF Acceleration

Both contributions **add up to total rigidity offset** (depending on extraction and transition energy)

....

$$\frac{d(B\rho)}{B\rho} = \frac{1}{\beta^2} \frac{d\left(\frac{E}{m}\right)}{\frac{E}{m}} + \frac{1}{\chi} - 1$$

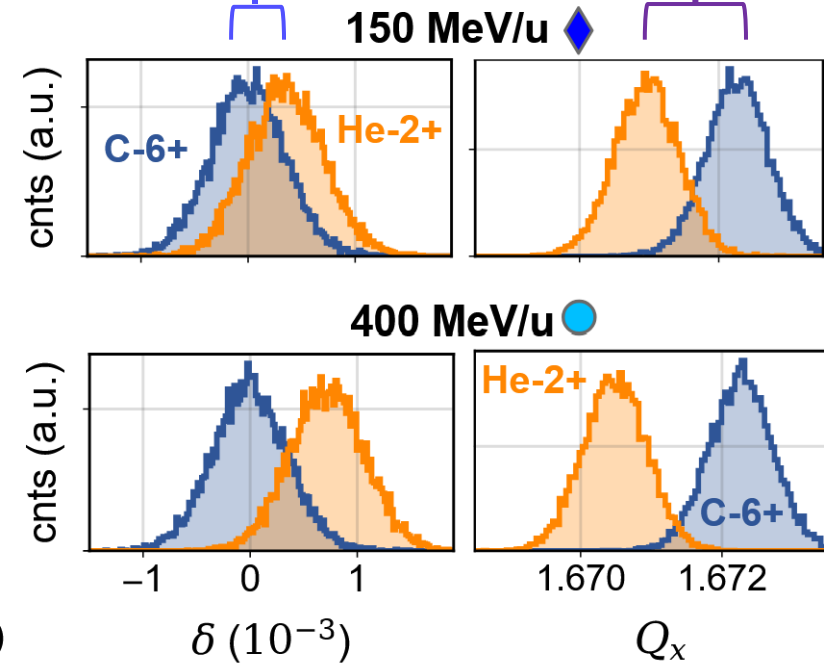
... & hence **affect closed orbit and tune.**



$$\delta = \frac{(\beta\gamma)_{\text{He}} - (\beta\gamma)_{\text{C}}}{(\beta\gamma)_{\text{C}}} > 0$$

$$\delta_{\text{eff}} = \frac{1 + \hat{\delta}}{\chi} - 1$$

$$\Delta Q = Q' \cdot \delta_{\text{eff}}$$



Example: Relative momentum per mass offset (δ) and horiz. tune (Q_x) separation between 4He2+ and 12C6+ in a PIMMS-like synchrotron ($\gamma_{\text{tr}} \approx 2$, here $Q'_x = -1.3$ and $\delta_{\text{rms}} \approx 0.35 \cdot 10^{-3}$).

[8] E. Renner, IPAC '24

Slow Extraction Requirements in a Nutshell



Helium and carbon feature

- **different rigidity distributions** (depending on extraction and transition energy),
- in case of sequential injection also **different horizontal phase space distributions**.



Goal: Ideally extract mixed beam with **(roughly) constant He:C ratio** throughout the spill.

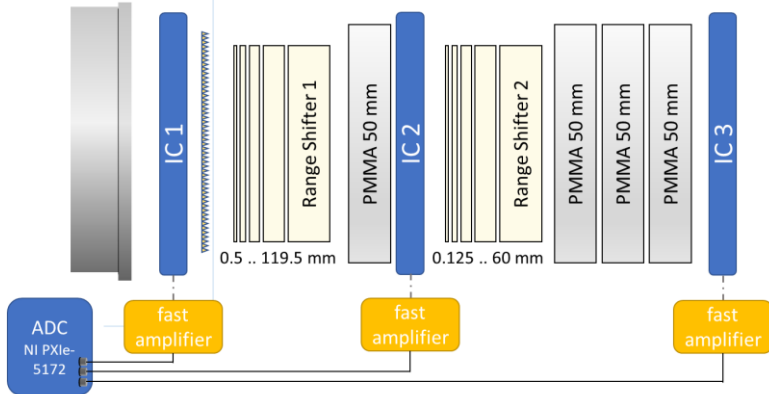
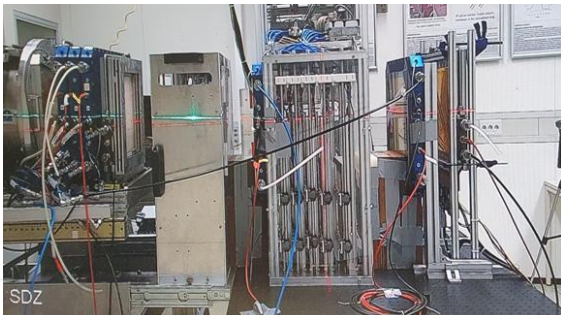


Long term goal: custom tailoring of He:C ratio throughout the spill.

Selected Tools for Mixed Beam and Spill Characterization I

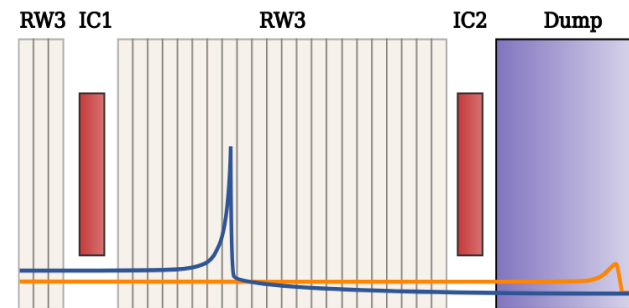
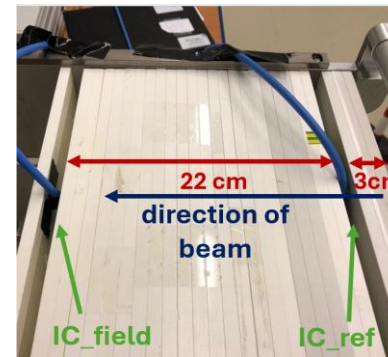
(A) **Time-resolved** characterization of the extracted **He:C ratio** (e.g., using ionization chambers at different depths)

Set-up at GSI (Biophysics cave)

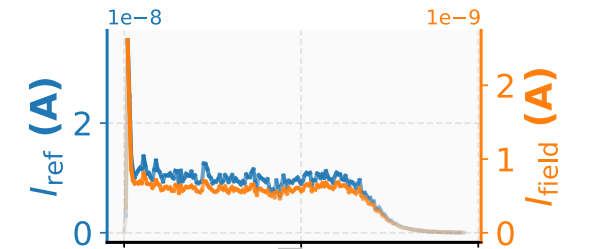


Courtesy of C. Graeff, L. Volz et al. [5, 11]

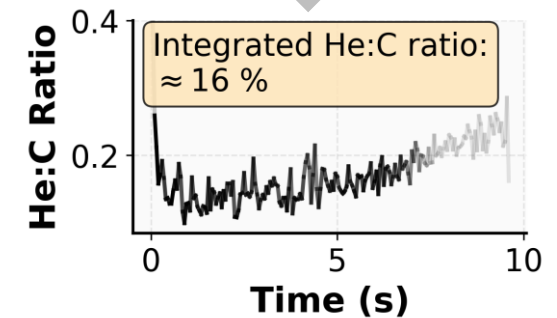
Set-up at MedAustron



M. Kausel, C. Becker, et al. IPAC'25 [10]

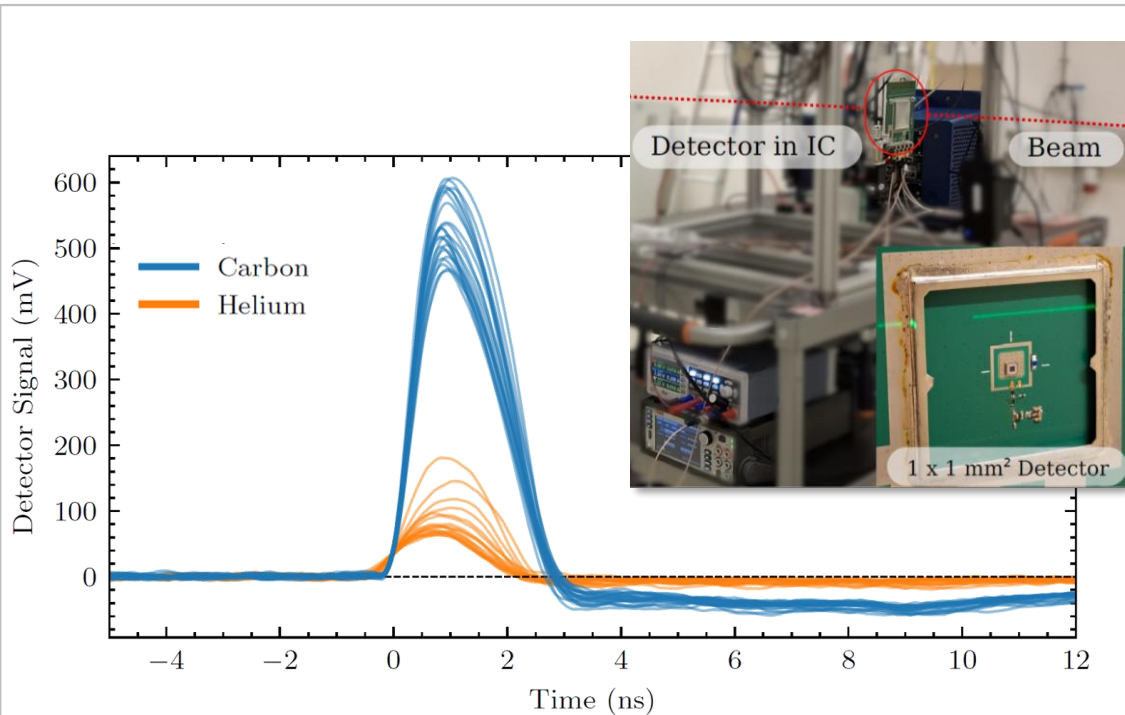


He:C ratio obtained from $I_{\text{field}} / I_{\text{ref}}$ (corrected for C fragments).



Selected Tools for Mixed Beam and Spill Characterization II

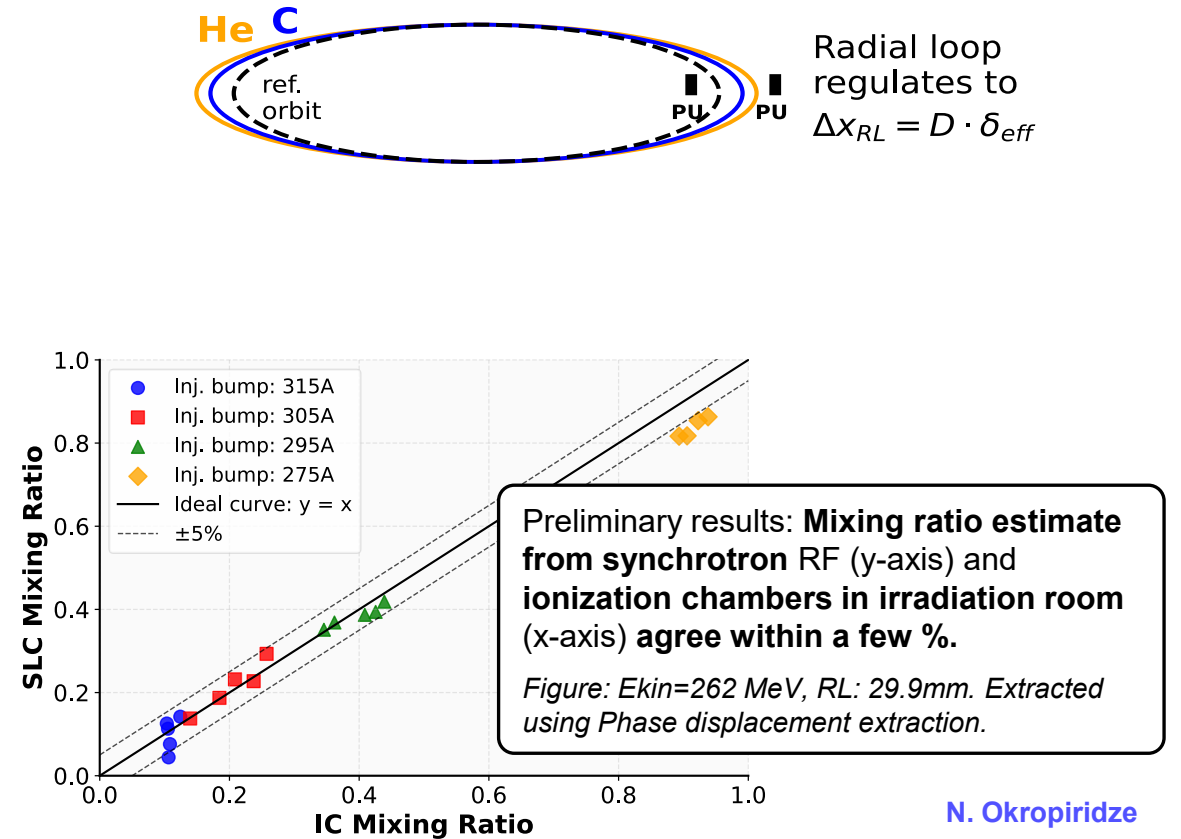
(B) Alternative: **Single particle distinction via dE/dx** , e.g., with 50 μm Si sensor.



HEPHY A. Gsponer, M. Kausel

Not routinely employed
in current studies

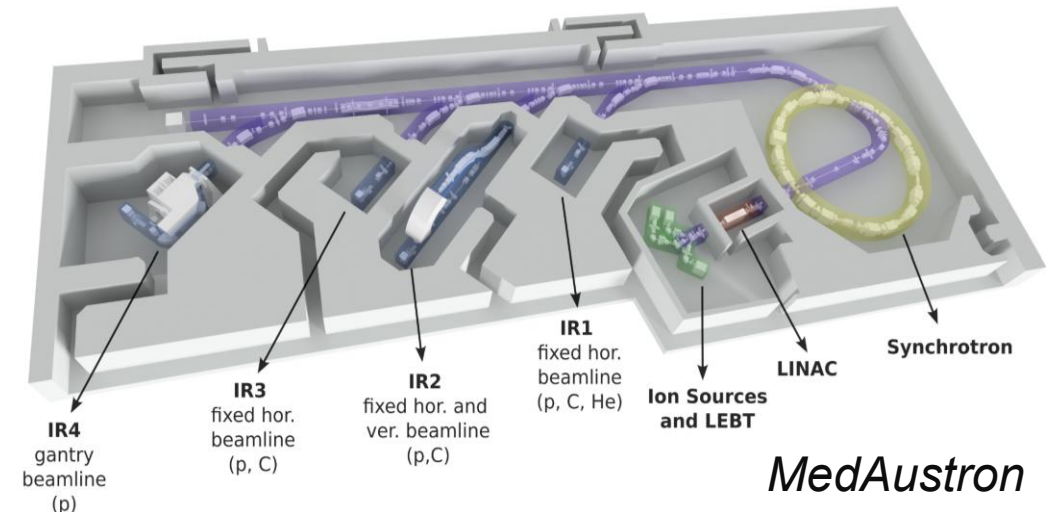
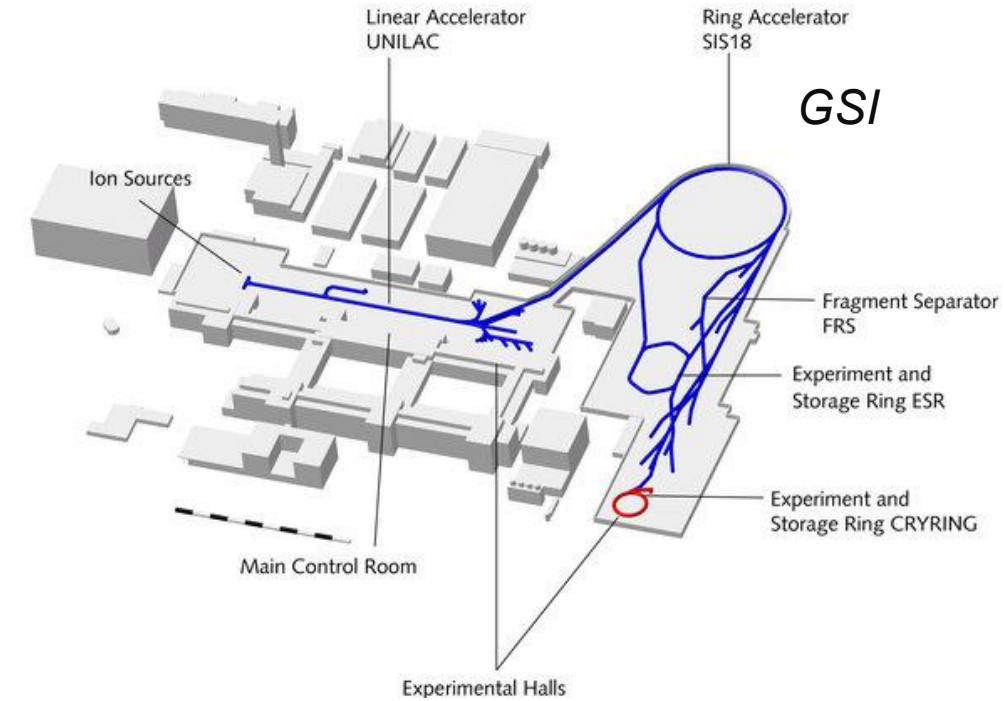
(C) **Non-invasive mixing ratio quantification** based on RF regulation loop corrections.



N. Okropiridze

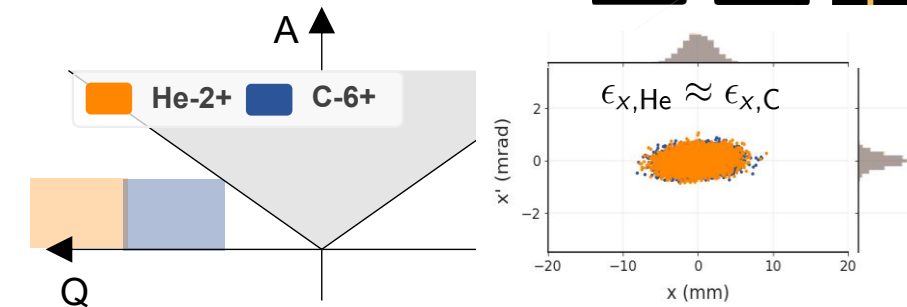
Outline

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Mixed Beam Slow Extraction at GSI: Overview

- Single ion source: He and C with similar initial horiz. emittances
- **Beam time in 2023: tune sweep and RFKO**
 - Successful, but further studies needed.
 - $\Delta x = 1\text{-}2\text{mm}$ between He and C at isocenter $\rightarrow$ most likely due to D_x (see appendix)
- **In May 2025: main on achieving stable He-to-C ratio across spill.**
 - **RFKO**, utilize **spill feedback for rectangular spill**.
 - Check chromaticity and dispersion in transfer line (see appendix)



Schematic illustration. Proportions not to scale

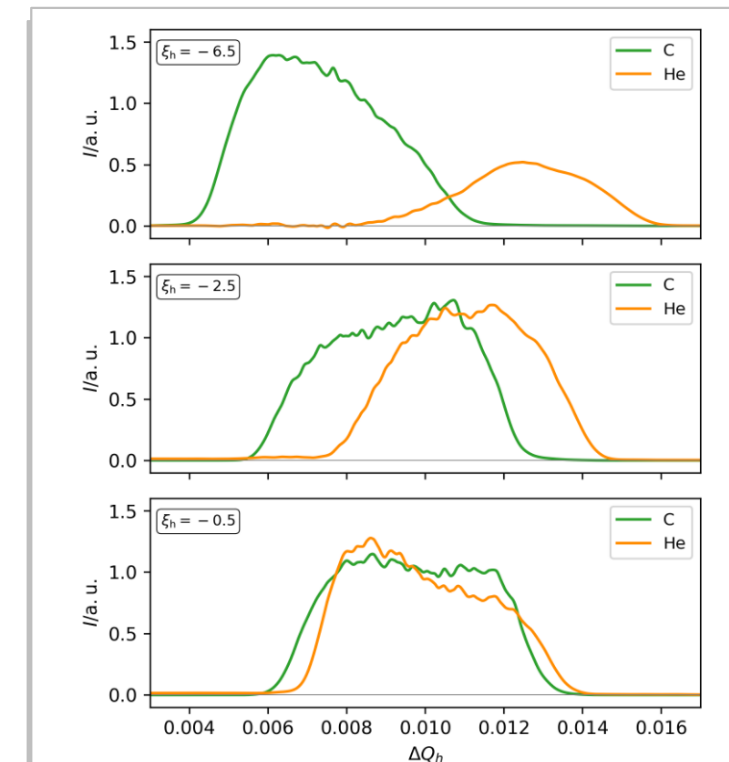


Figure: tune sweep extr. with **different chromaticities** (2023)

D. Ondreka et al. IPAC'24 [6]



Poster - A. Pastushenko: Flat C/He spills for online range monitoring in particle therapy

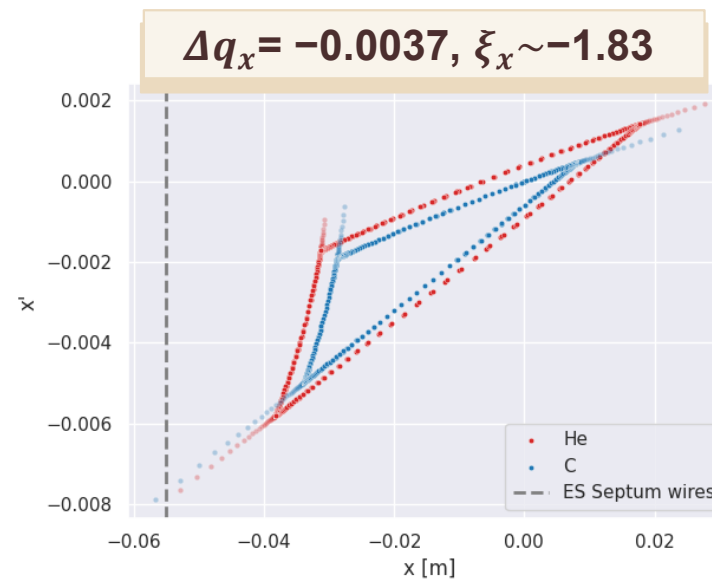
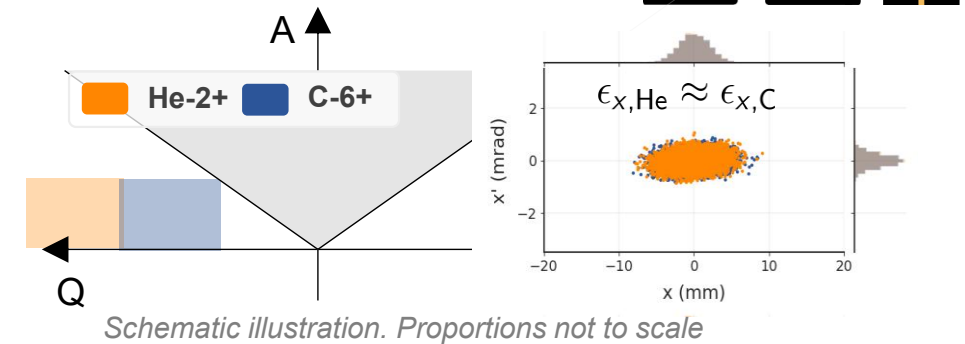
Slide courtesy of A. Pastushenko

Mixed Beam Slow Extraction at GSI: Settings

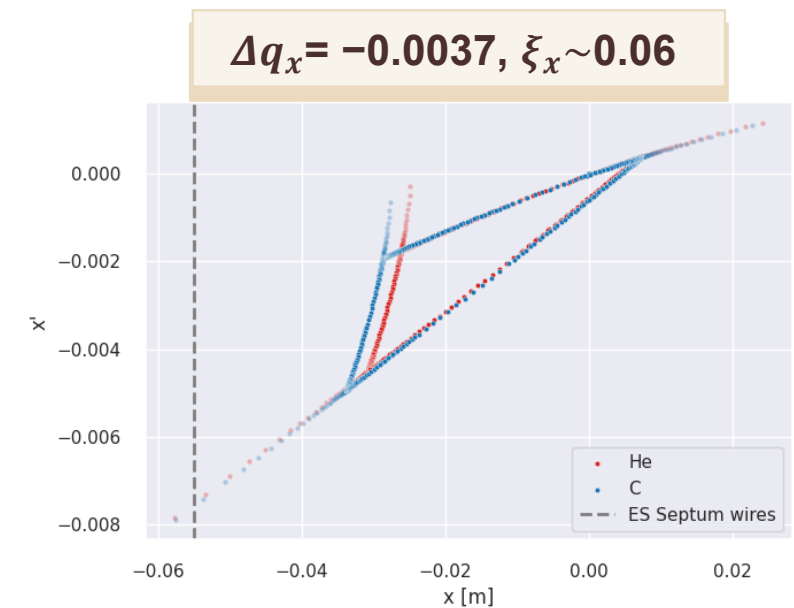
SIS 18 mixed beam slow extraction configuration 05/2025

- Extr. from below resonance (here: $\Delta q_x = -0.0037$)
- At natural chromaticity ($\xi_x \sim -6.7$): tune difference betw. He and C is $q_x^{He} - q_x^C \sim -0.0042 \rightarrow$ similar to Δq_x

→ To set up the condition for the **simultaneous extraction of C and He** one has to **adjust the chromaticity**.



Simulations: Xsuite

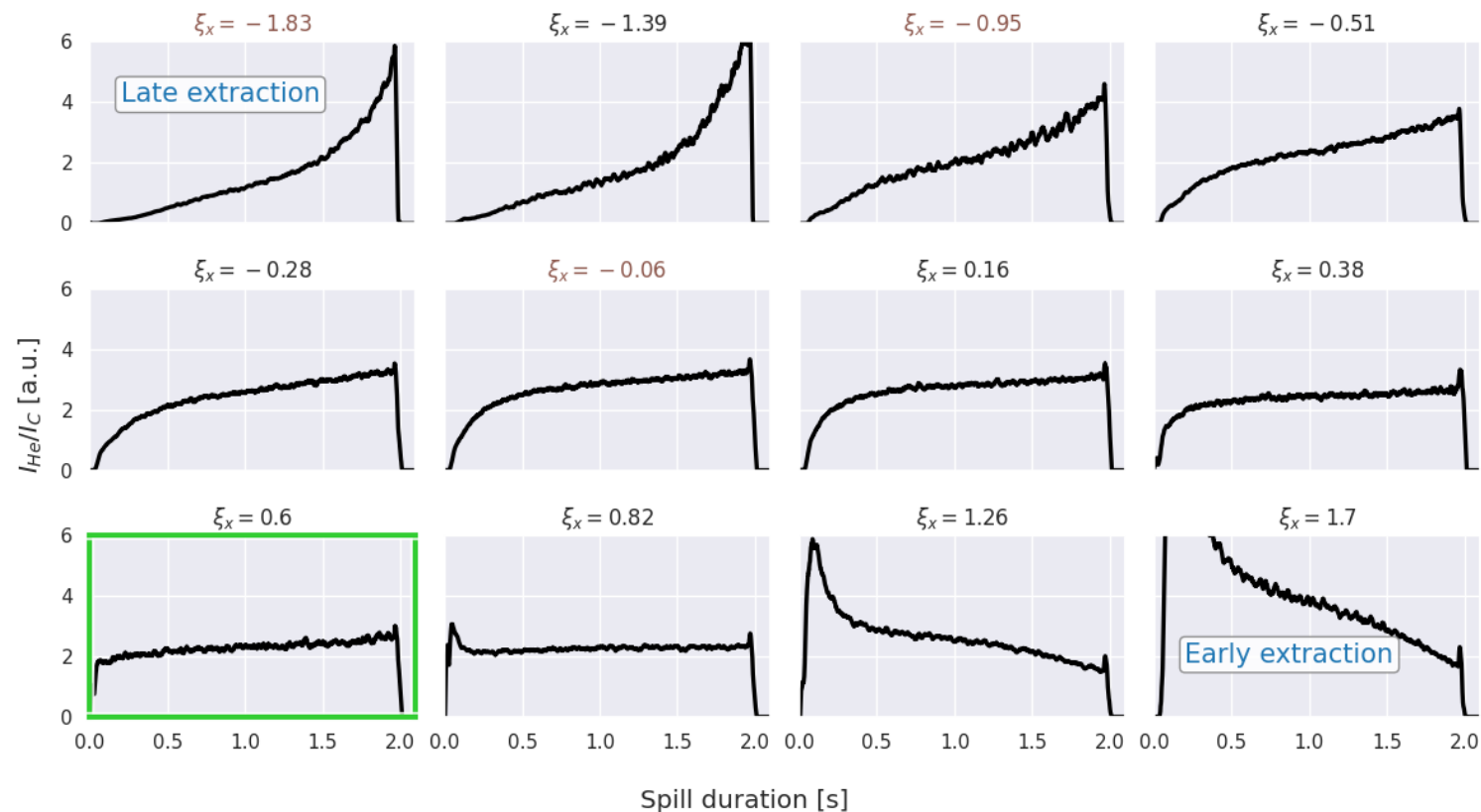


Slide courtesy of A. Pastushenko

Mixed Beam Slow Extraction at GSI: Chromaticity Scan

Estimate impact of **horizontal chromaticity** on the extracted **He:C ratio** throughout spill:

- Scan the range of $\xi_x = [-2.0, 2.0]$
- **RFKO signal**: BPSK; center tune 4.(3) – 0.0037 and BW 0.01
- Get **He:C ratio** from normalized ionization chamber currents IC2/IC1 and IC3/IC1
 - Late extraction of He for $\xi_x < 0.6$
 - Early extraction of He for $\xi_x > 0.6$
 - For positive chromaticity we had to move away from resonance to avoid He extraction without RF-KO
- $\xi_x \sim 0.6$ was set for the operation

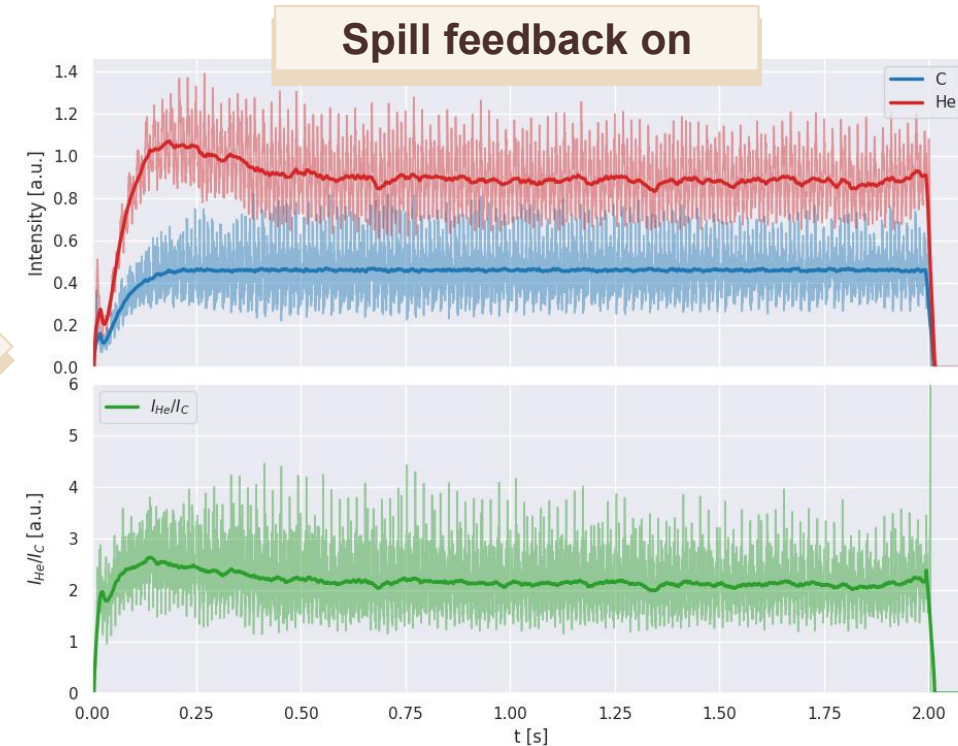
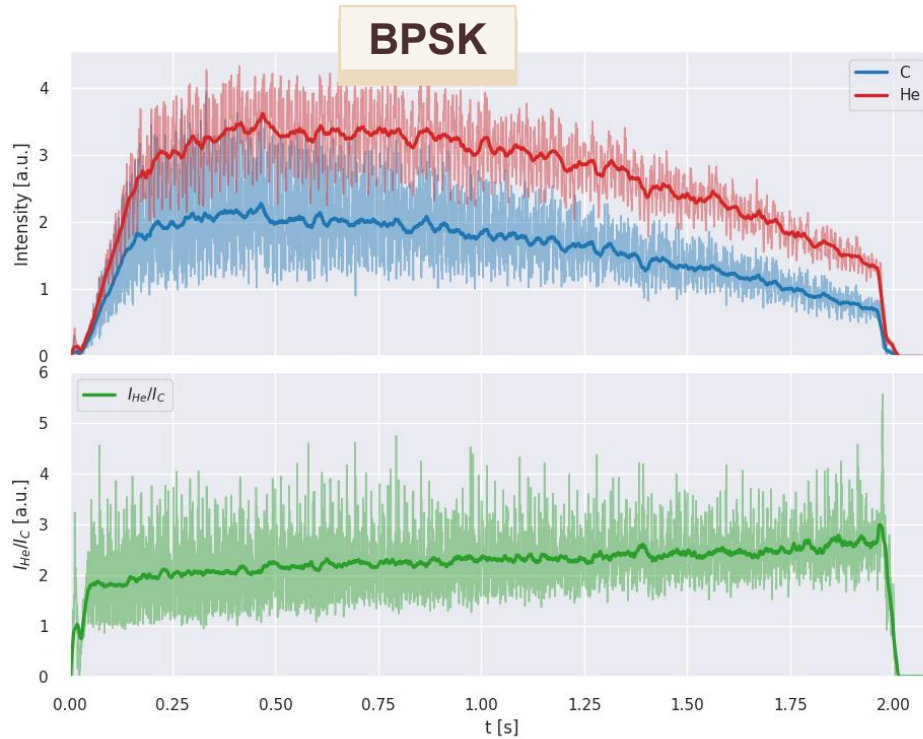


**labels in brown – chromaticity was measured*

Slide courtesy of A. Pastushenko

Mixed Beam Slow Extraction at GSI: Spill Optimization

Spill for the chromaticity of $\xi_x \sim 0.6$, with and without spill optimization system



Average of ~20 cycles

 **Talk - P. Niedermayer:**
Spill feedback and optimisation system for RFKO and tune scan extraction

Slide courtesy of A. Pastushenko

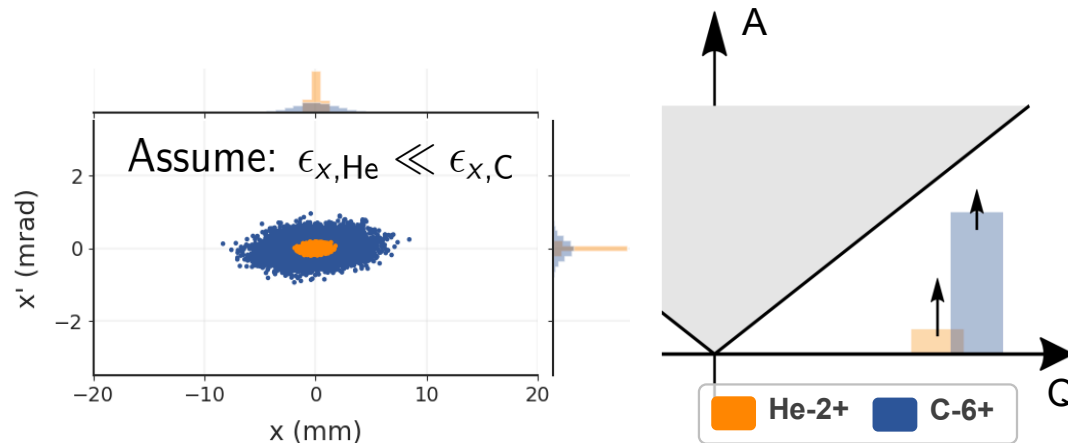
Mixed Beam Slow Extraction at MedAustron: Overview

■ First mixed beam extracted in summer 2024

- Betatron core (clinically used for extraction) currently not operational in double cycle setup for mixed beams
- Until 01/2025: Preliminarily extract using **Phase Displacement Extraction**, without focus on spill characteristics.

■ Since winter 2025: baseline RFKO

- Investigate effects due to **differences in initial horizontal He & C (x, x') and dpp distributions** (*double injection*)
 - Application of **different RFKO signals & combinations**, both for bunched and coasting beams



 **Employ experimental RFKO setup as described in:**

Talk (Wednesday) - F. Plassard

Status of RF knock-out extraction development at MedAustron

Talk (Tuesday) - K. Holzfeind

Investigations into multi energy extraction at MedAustron

Poster - F. Plassard

MedAustron Facility Overview

Poster - C. Schmitzer

Ultra High Dose Rate Beam Monitoring with Radiation-Hard SiC-Based Detectors



Putting the glasses on: Where are He and C located?

Example: Slow RFKO frequency sweep through coasting beam stack (from higher frequencies towards resonance).

$$Q_x = 1.672$$

(off momentum)

$$Q'_x \approx -1.3$$

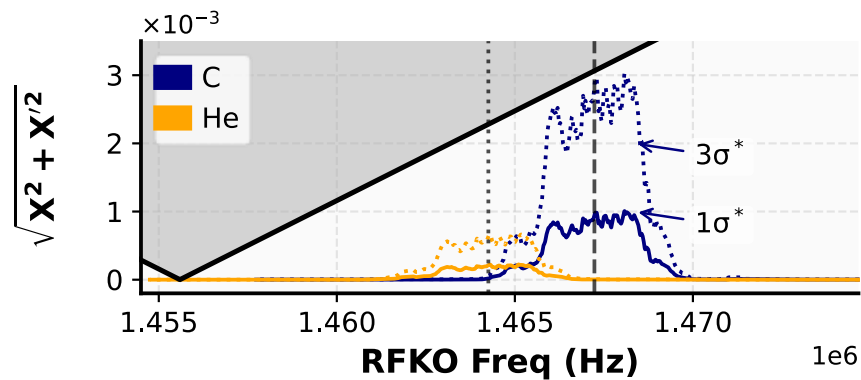
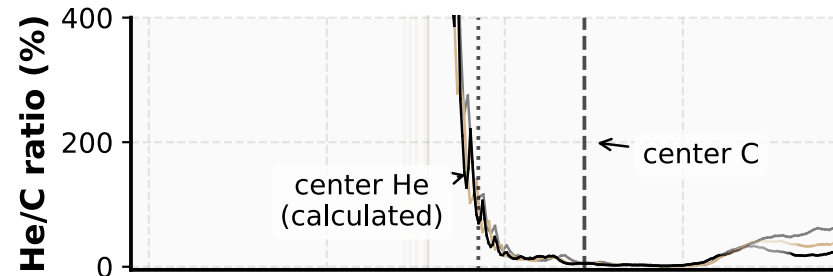
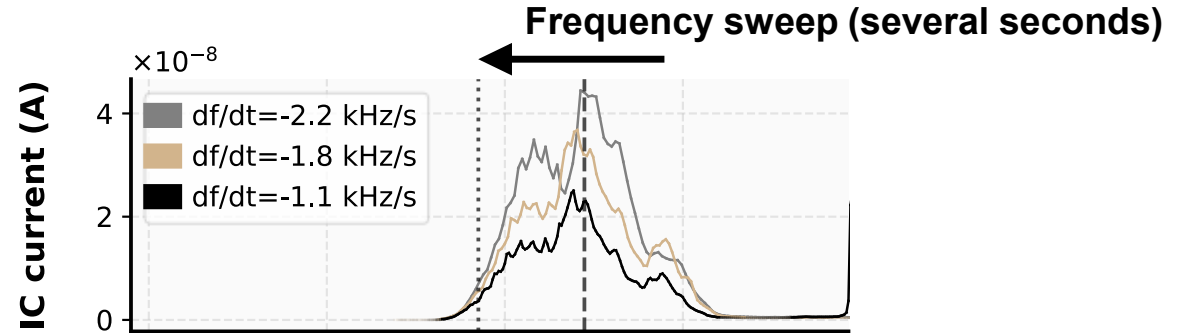
$$\frac{\epsilon_{x,He}}{\epsilon_{x,C}} \approx 0.05^*$$

$$E_{kin} = 200 \text{ MeV/u}$$

$$N_{He}/N_C \approx 10 - 15 \%$$



He and C with the expected offset in f_β



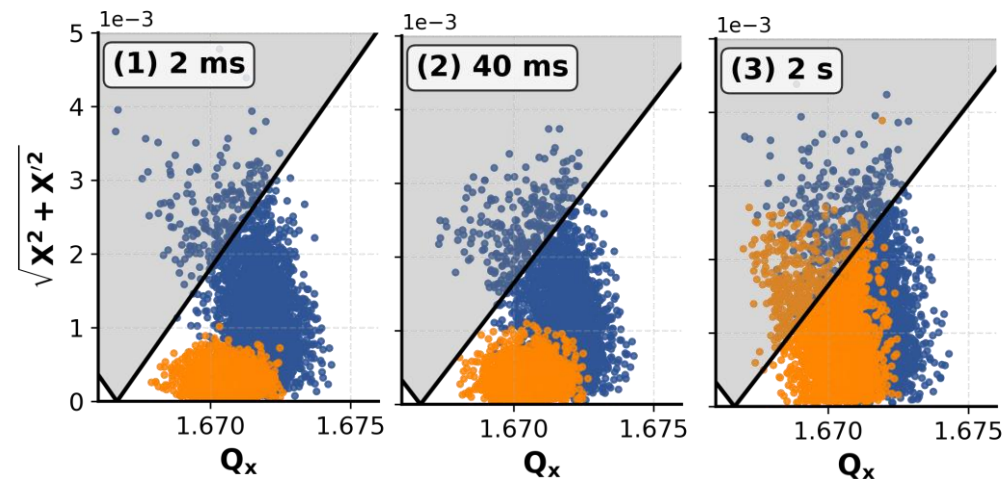
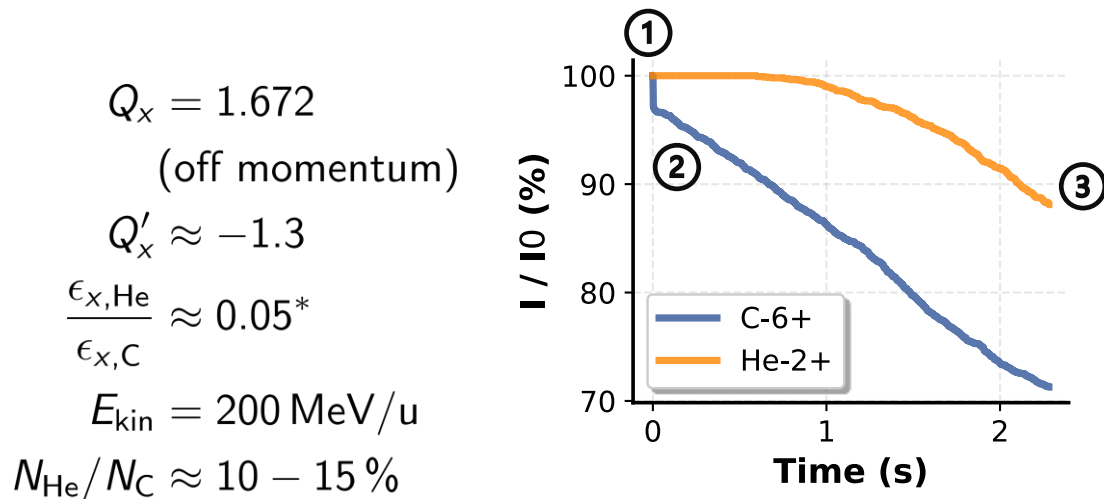
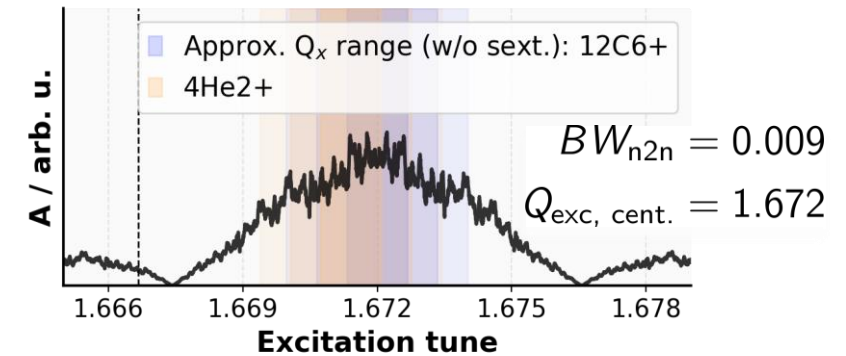
← *Schematic illustration (!)*
based several assumptions

See appendix

* Assumed value

Mixed Beam SX at MedAustron: Simulations

In this configuration, **Xsuite simulations** suggest that when applying a ... **broadband phase shift keying excitation** centered at C tunes, ... **He extraction begins with a delay** due to the initially smaller horizontal He emittance.



(1) Initial losses during sextupole ramp: mainly C.

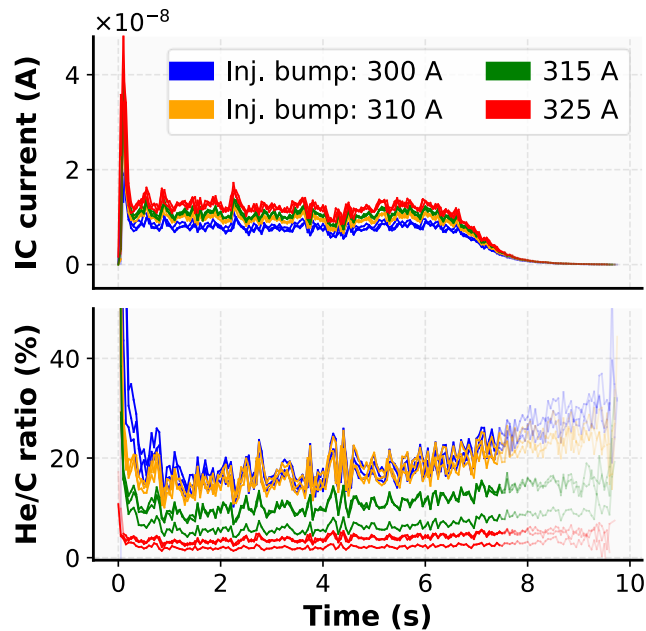
* **Disclaimer. Conceptual simulations:** initial (x, x') and $\delta p/p$ distributions for He and C, are based on assumptions.

Mixed Beam SX at MedAustron: Measurements

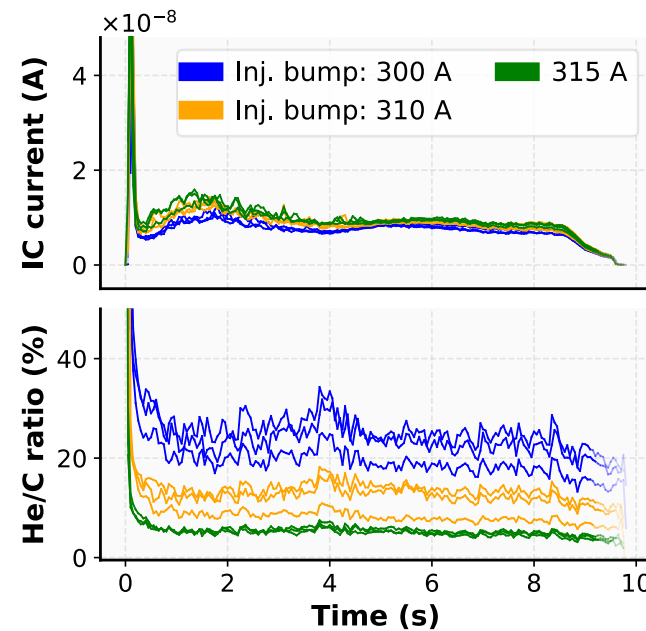
However, measurements show more constant He:C ratio throughout spill than expected.

Nice, but not fully understood ... Even when varying the 2nd injection bump and hence the (expected) $\epsilon_{x,He}/\epsilon_{x,C}$!

Coasting, BPSK

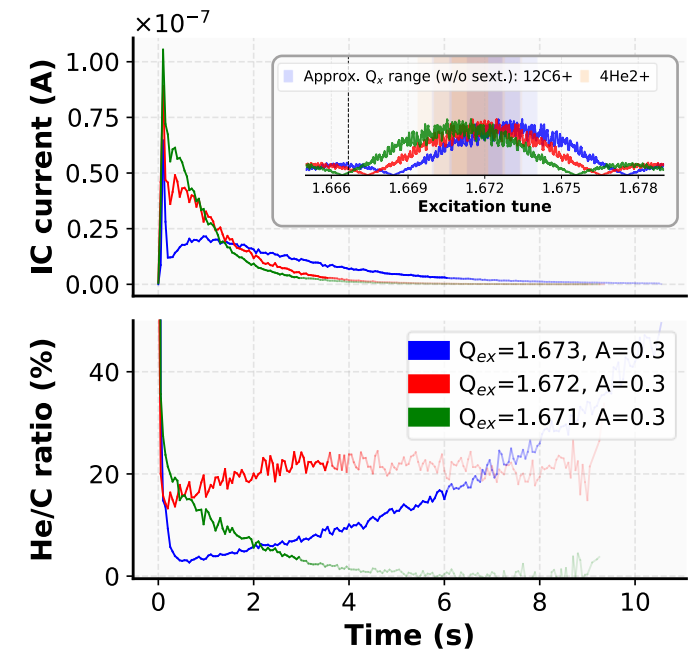


Bunched*



*presence of quadrupolar-mode synch. osc. during extr.

Lucky? Shift BPSK spectrum (coasting)



Follow-ups: sensitivity studies (RFKO signals, optics, extraction energies), **refine simulation model** (x, x' , dpp dist); assess **off-momentum losses** in transfer line, increase **resolution of measurements**,

Outlook: Mixed Beams with Different Charge-to-Mass Ratios

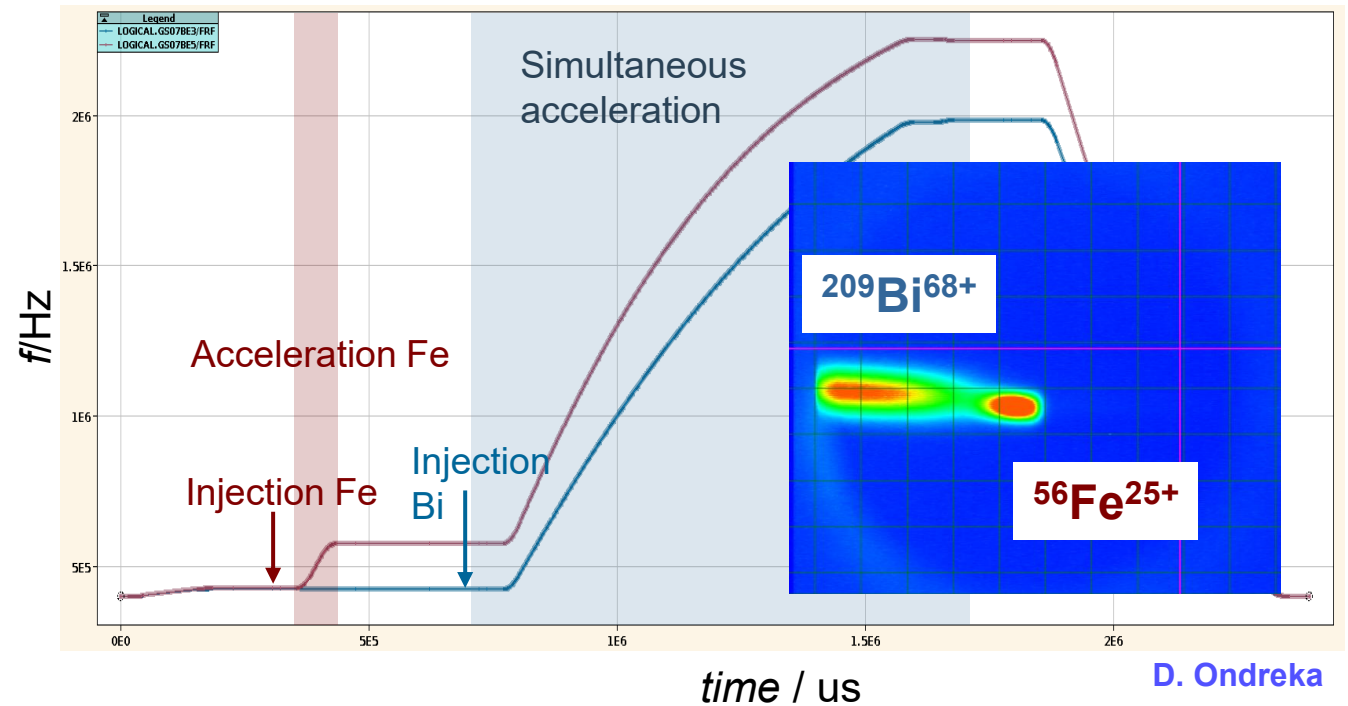
Multiple, independent RF frequencies allow simultaneous acceleration of ion species with different q/m

■ Milestone in May 2025 at GSI (SIS18)

- First successful acceleration and fast extraction of ion species with different q/m

■ Paves way for **new ion combinations** & respective range differences **for treatment monitoring**

- Simultaneous p+/C acceleration: feasibility tests at MedAustron in preparation



D. Ondreka

■ Opportunities for broader scientific communities. **Any potentially interested user groups?**

Conclusion & Outlook

■ Mixed helium and carbon beams are now available for experimental studies

- **GSI**: generated in single ion source → similar horizontal He and C emittances
- **MedAustron / TU Wien**: sequential multi-turn injection → different horizontal He & C emittances

■ Mixed beam slow extraction studies ongoing

- Managed to **extract constant He:C ratios**.
- Demonstrated sensitivity of He:C ratio to chromaticity and RFKO excitation signals.
- Follow-up experiments and Xsuite simulations ongoing
- **Long term goal: Flexibly tailor extracted He:C ratio across the spill** (multiple RFKO signals?)

■ Outlook: First simultaneous acceleration of ions with different q/m (Fe, Bi)

→ paves the way for new research applications

Our test set-ups are flexible – **any ideas welcome!**

Many thanks for your time!

Questions?

References

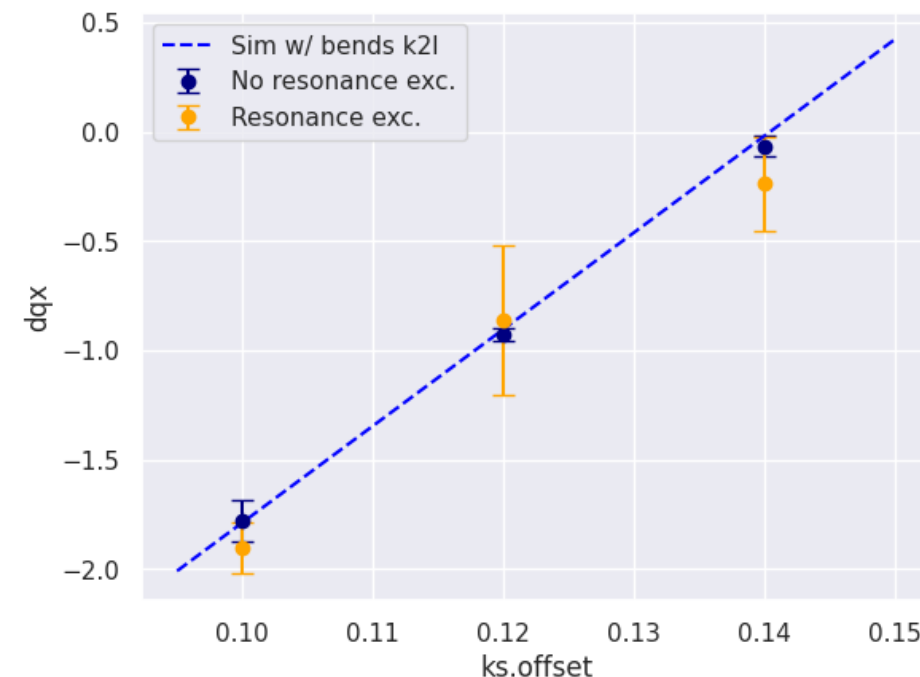
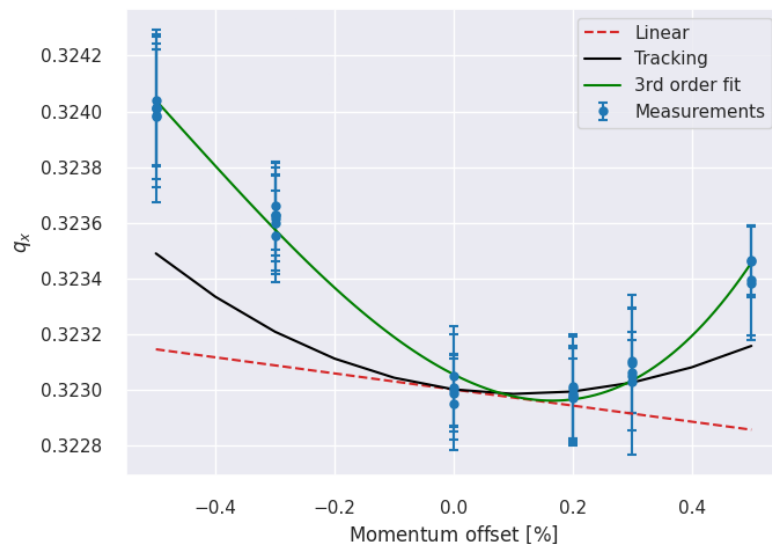
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- [2] C. Graeff et al. “Helium as a range probe in carbon ion therapy”, Physica Medica 52, 2018
- [3] L. Volz “Experimental exploration of a mixed helium/carbon beam for online treatment monitoring in carbon ion beam therapy” et al., Phys Med Biol 65/2, 2020
- [4] J. Hardt “The potential of mixed carbon–helium beams for online treatment verification: a simulation and treatment planning study”, Phys Med Biol 69/5, 2024
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- [6] D. Ondreka et al., “Slow extraction of a dual-isotope beam from SIS18”, IPAC’24
- [7] C. Graeff et al. *ERC PROMISE*, https://www.gsi.de/work/forschung/biophysik/erc_barb/promise
- [8] E. Renner et al., “Towards the slow extraction of mixed He-2+ and C-6+ beams for online range verification” IPAC’24
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- [10] M. Kausel et al., “Recent developments in delivering mixed helium and carbon ion beams for online treatment monitoring research at MedAustron”, IPAC ‘25
- [11] L Volz et al., “Portal imaging with mixed beams: Status and future Potential”, 5th Ion Imaging Workshop, 2024
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Spare Slides

GSI SIS 18 Machine Properties: Chromaticity

Chromaticity in the ring is set with a parameter (***ks.offset***). We checked if the relation agrees with the simulations.

- We measure on/off – momentum tunes. The beam is excited with a broad noise.
- **Agreement is reached** with $k_{2l} = 0.04 \text{ m}^{-2}$ component in the dipoles.
- Measurements were done with resonance sextupoles on and off.

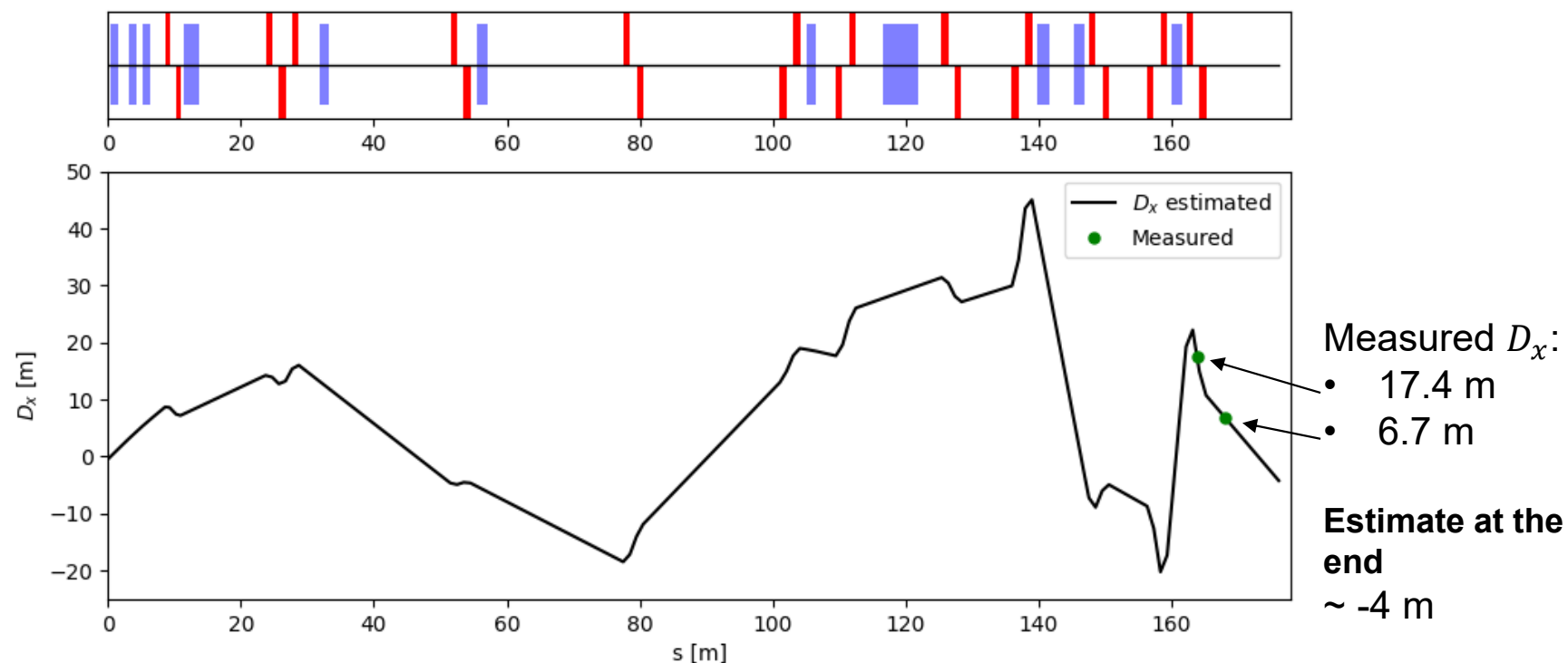


For one setting ($ks.offset = 0.14$, $\xi_x \sim -0.06$), (tune was measured for a bigger range of momentum offsets. **Nonlinear chromaticity** hints nonlinearities in magnets (k_{3l} in quads, ..)

GSI SIS 18 Machine Properties: Transfer Line Dispersion

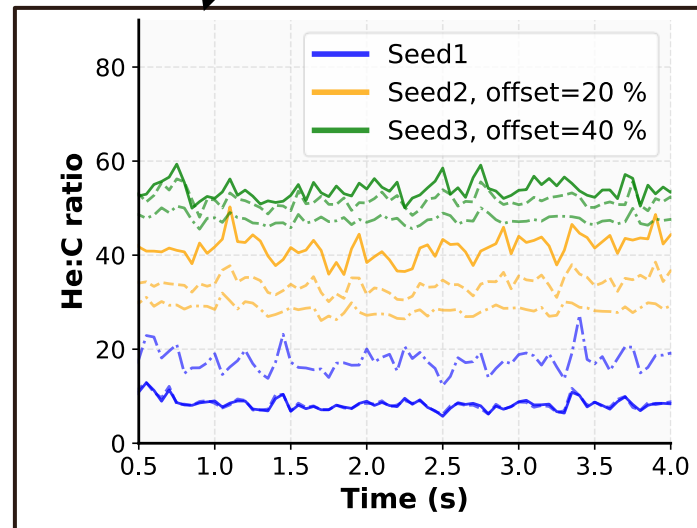
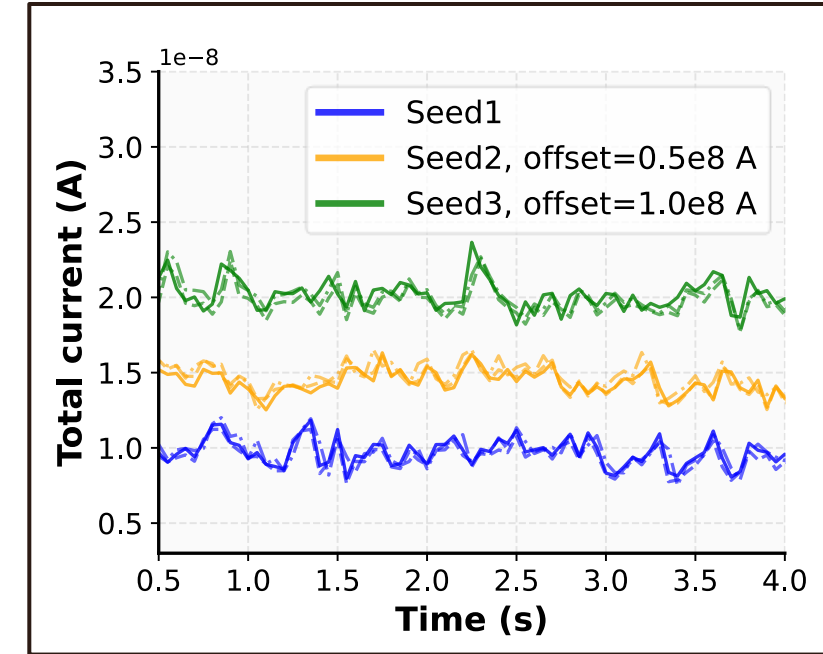
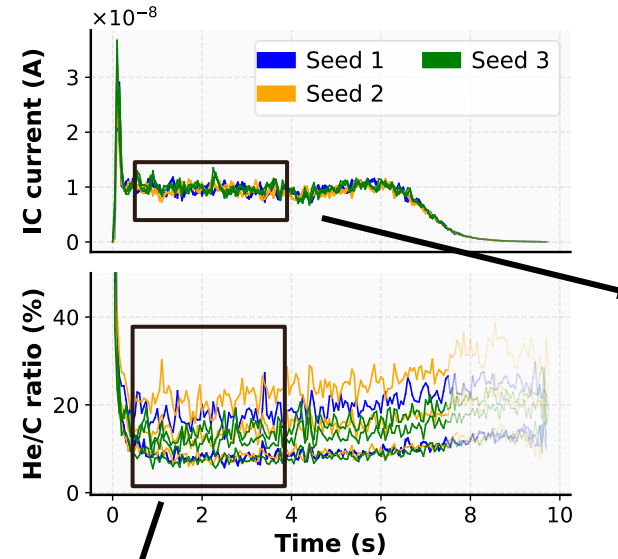
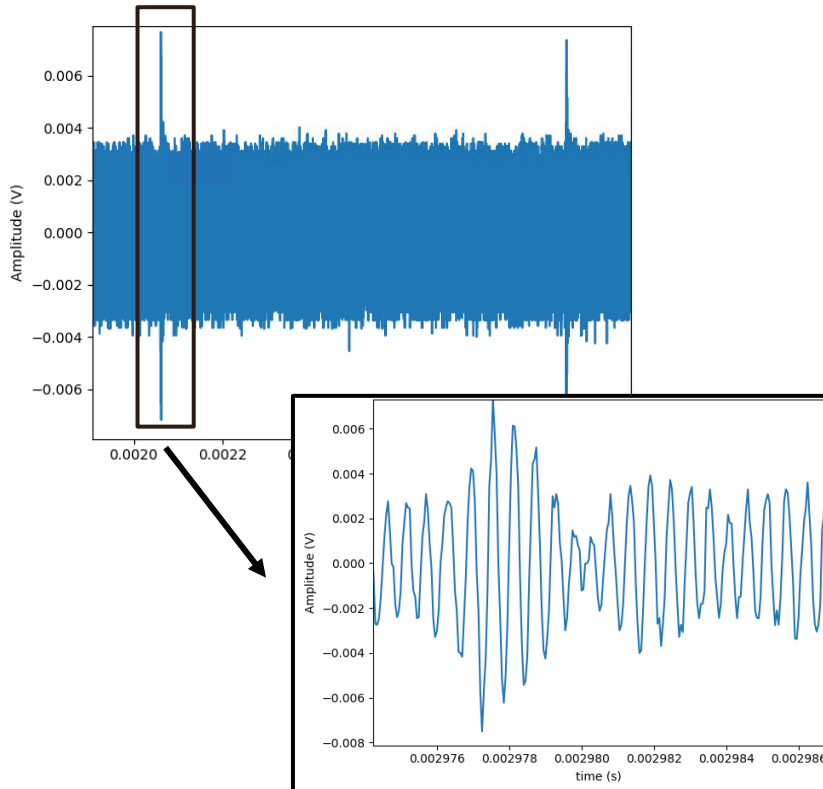
In 2023, horizontal positions of **He** and **C** at isocenter were 1 – 2 mm apart. Most likely explanation – **horizontal dispersion**.

- Due to the lack of time, measurements were done at 2 locations, upstream of the medical cave.
- Reconstructed dispersion shows large amplitudes along the transfer line. Need to be measured again (+) in other locations along the transfer line.



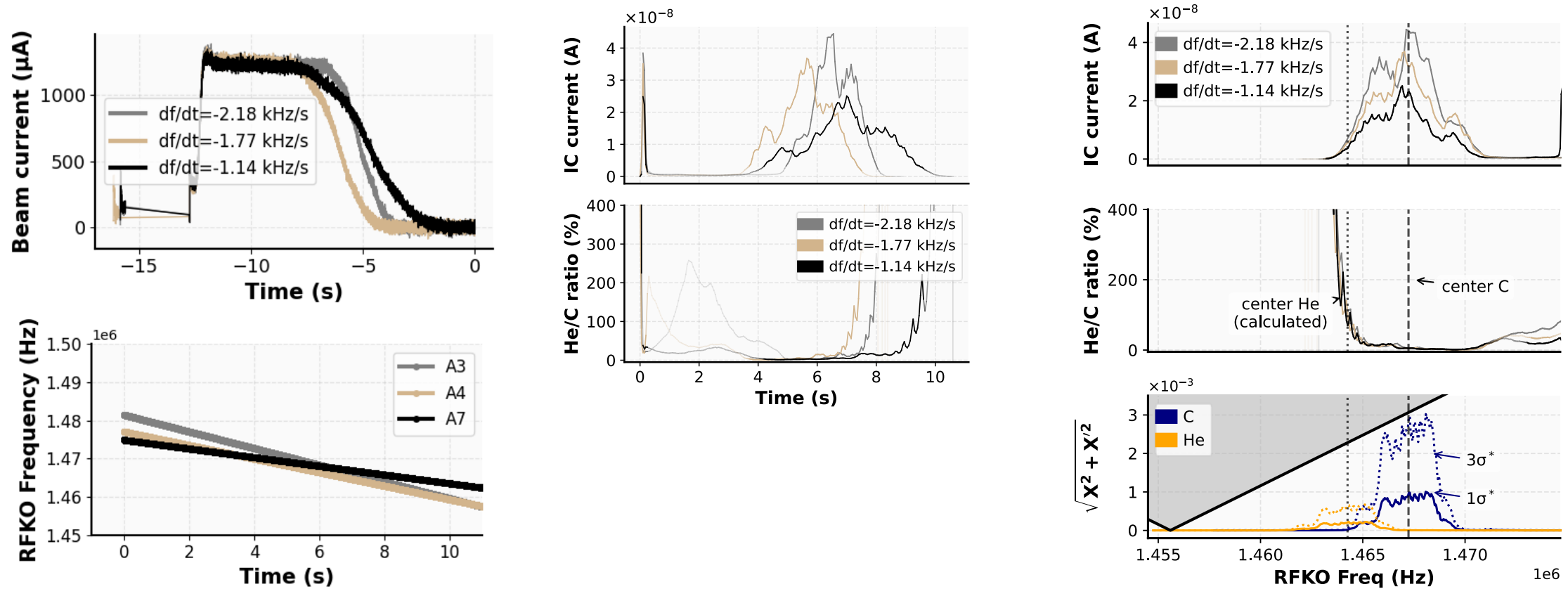
Supplementary Material for Mixed Beam SX at MedAustron

- Overshoot in BPSK signal
- With PSK seed reproducible ripple in intensity and He:C ratio.



Supplementary Material for Mixed Beam SX at MedAustron

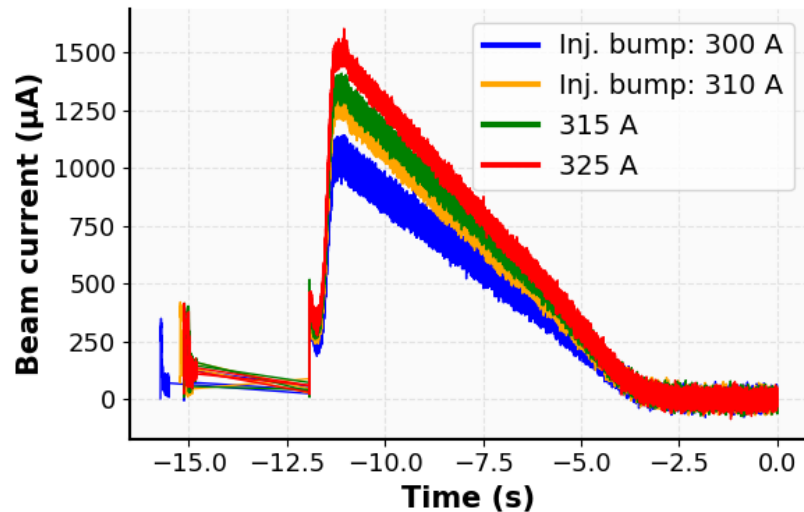
■ Slow RFKO frequency sweep through waiting beam stack



Supplementary Material for Mixed Beam SX at MedAustron

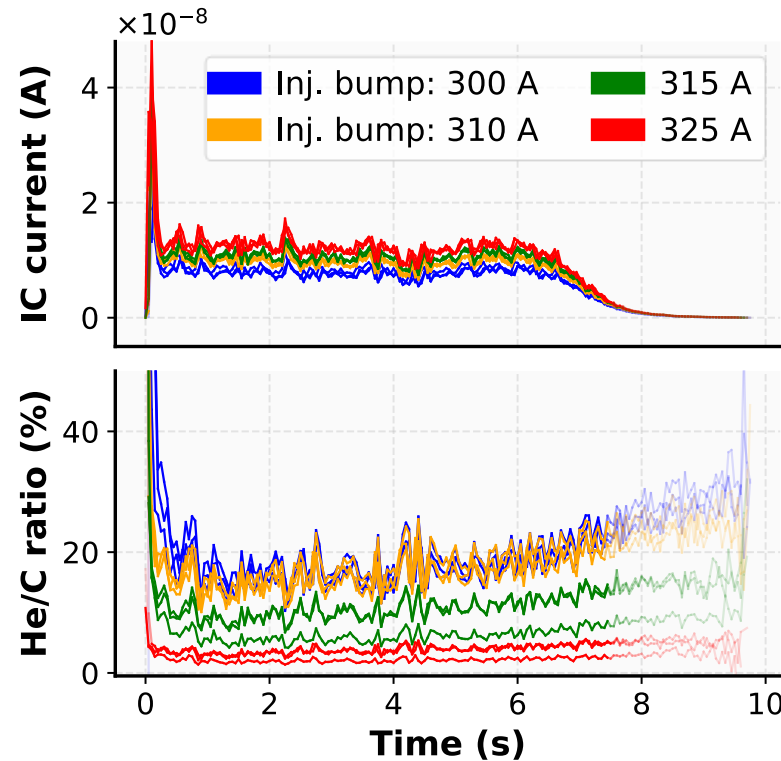
- 200 MeV/u
- Broadband PSK with amplitude modulation
- He:C ratio tailored by adapting the 2nd injection bump amplitude.

Beam current measurement in the synchrotron

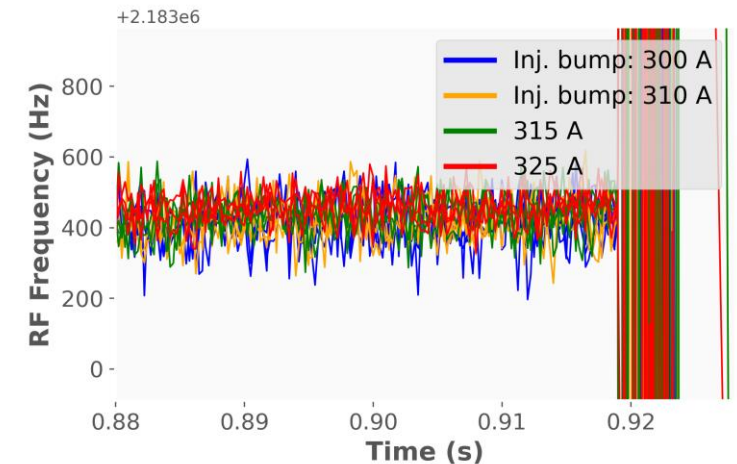
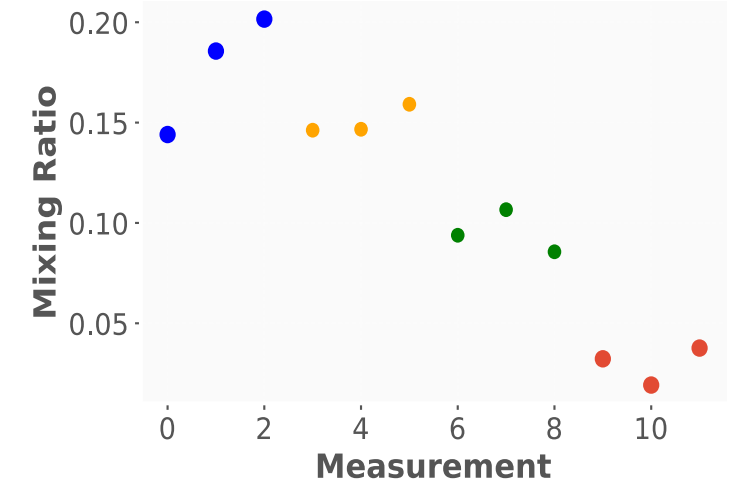


Current measurement: only 1 measurement per setting

Extraction He:C ratio throughout the spill

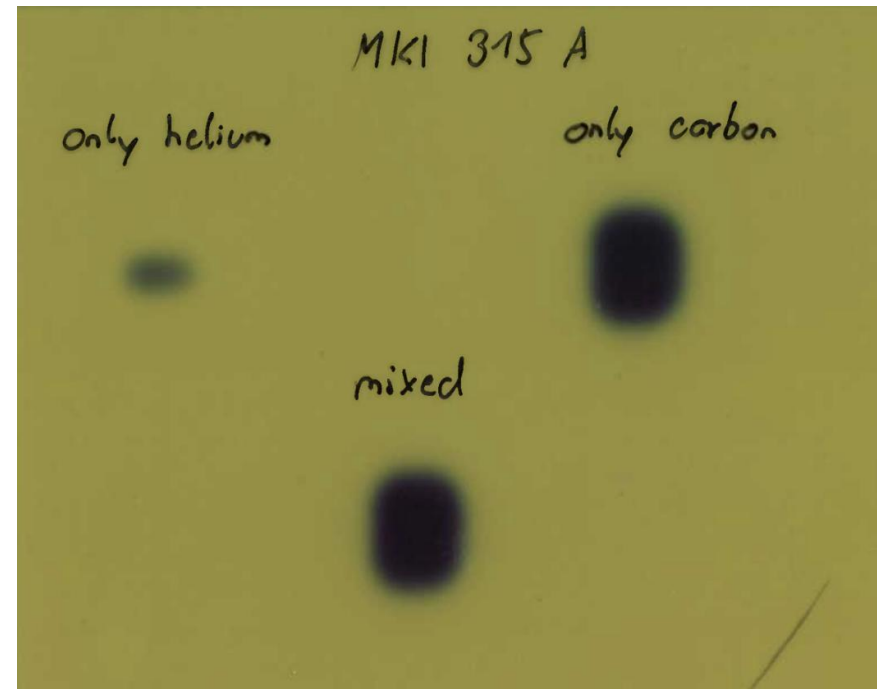
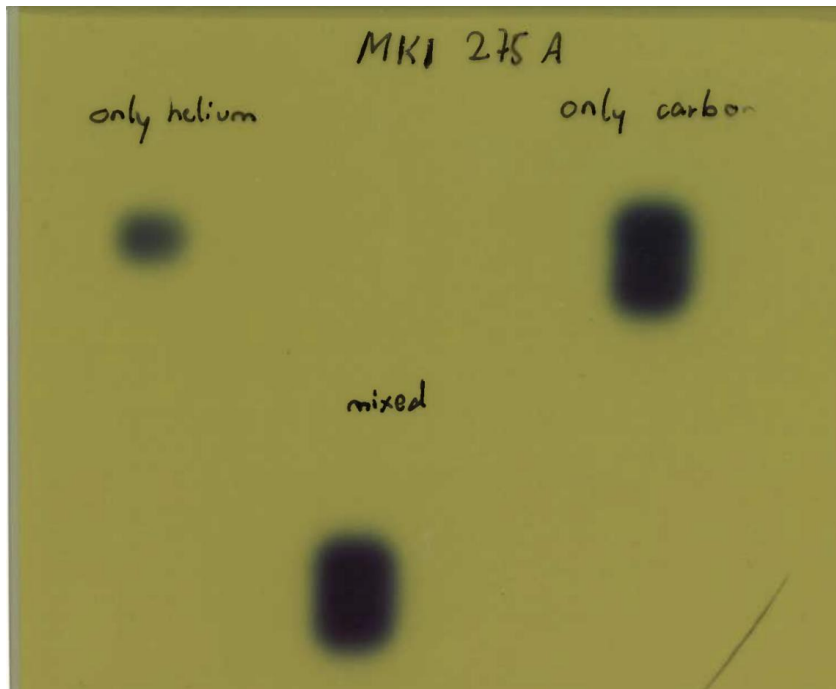


Mixing ratio estimate based on synchrotron RF frequency



Supplementary Material for Mixed Beam SX at MedAustron

- In this double-cycle configuration, the vertical beam size of He appears to be smaller than that of C.

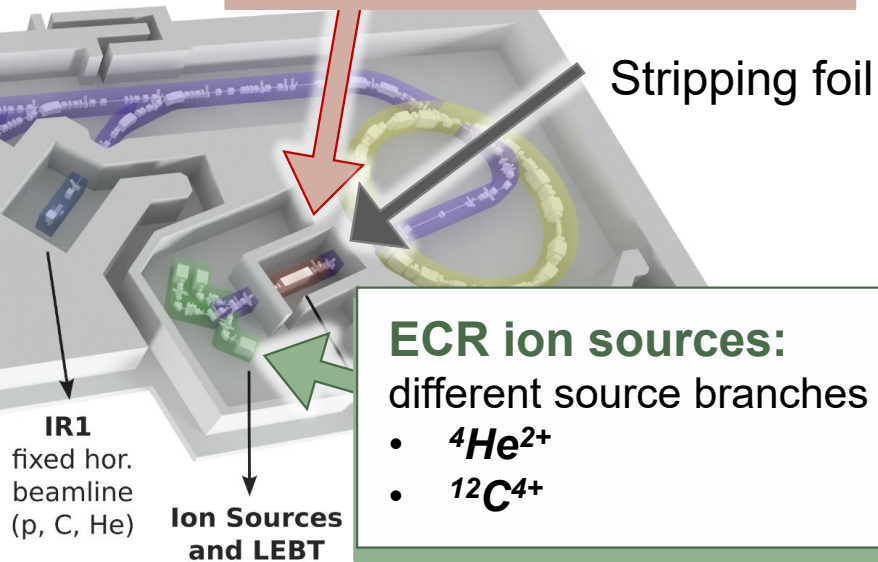


Single Ion Source in Clinical Facilities?

$$\frac{d(B\rho)}{B\rho} = \frac{1}{\beta^2} \frac{d\left(\frac{E}{m}\right)}{\frac{E}{m}} + \frac{1}{\chi} - 1$$

LINAC: $q/m > 1/3$

standard at e.g. MedAustron, CNAO, HIT



ECR ion sources:
different source branches

- ${}^4\text{He}^{2+}$
- ${}^{12}\text{C}^{4+}$

${}^4\text{He}^{1+}$ and ${}^{12}\text{C}^{3+}$

$$\frac{q}{m} \approx \frac{1}{4} \quad \frac{d(q/m)}{q/m} \approx -6.5 \cdot 10^{-4}$$

Source ✓ **LINAC** ✗ Synchrotron ✓

${}^4\text{He}^{2+}$ and ${}^{12}\text{C}^{6+}$

$$\frac{q}{m} \approx \frac{1}{2} \quad \frac{d(q/m)}{q/m} \approx -6.5 \cdot 10^{-4}$$

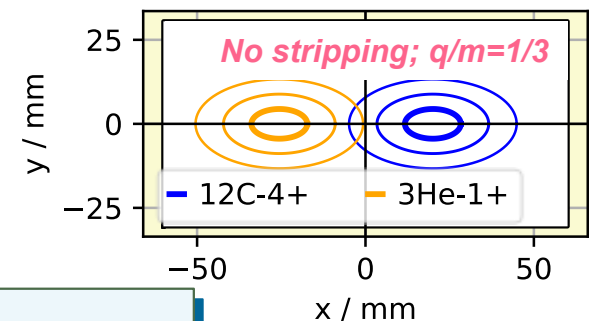
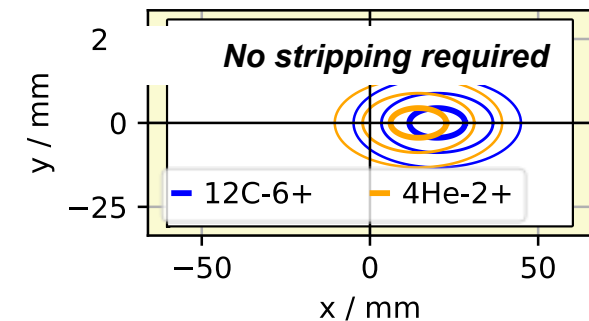
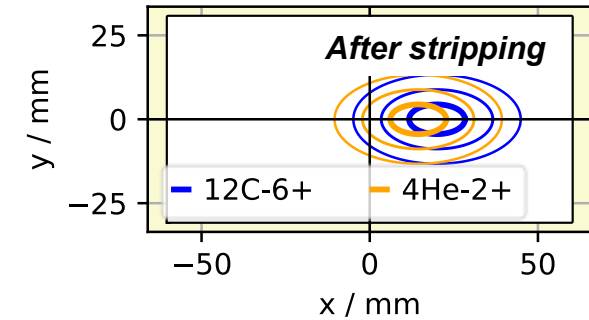
Source ✗ **LINAC** ✓ Synchrotron ✓

${}^3\text{He}^{1+}$ and ${}^{12}\text{C}^{4+}$

$$\frac{q}{m} \approx \frac{1}{3} \quad \frac{d(q/m)}{q/m} \approx -5.3 \cdot 10^{-3}$$

Source ✓ **LINAC** ✓ **Synchrotron** ✗

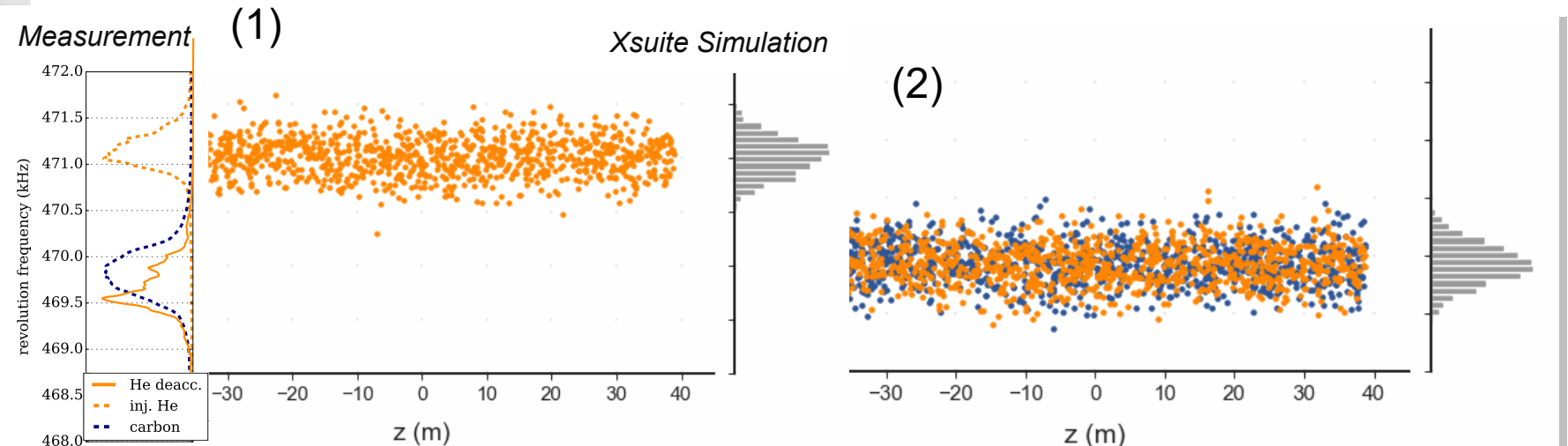
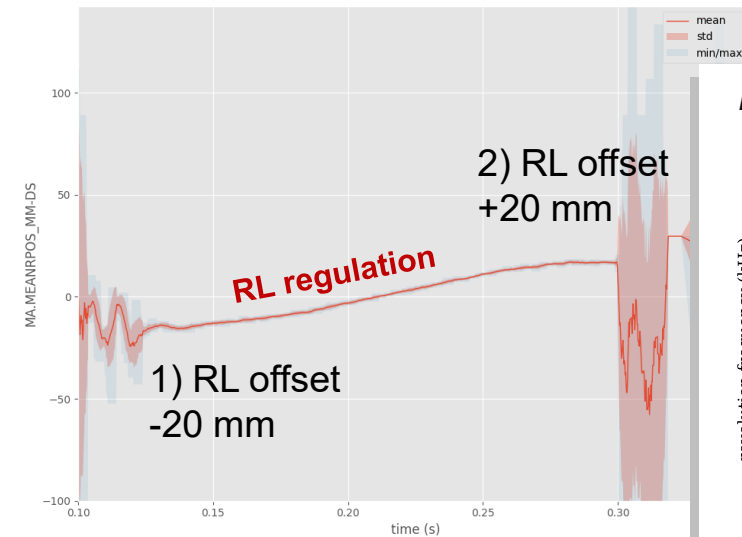
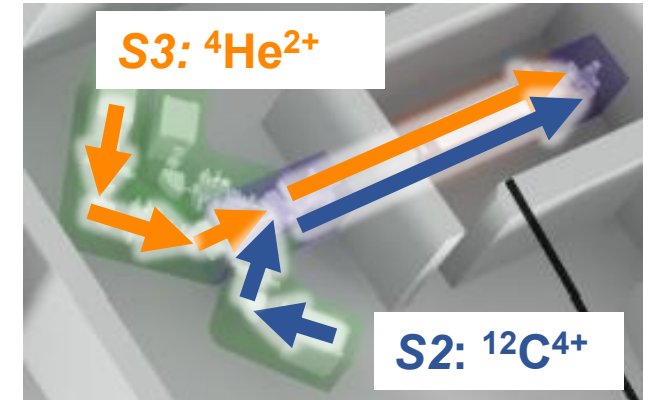
($E_{\text{kin,max}} \approx 200 \text{ MeV/u} < 400 \text{ MeV/u}$)



Mixed beam generation **within single ion source currently not possible** in state-of-the-art **medical synchrotron facilities.**

Double Multi-Turn Injection: Technical Challenges @ MedAustron

- Different injection energies due to $\Delta q/m$ in LINAC
 - Mitigation measures (decelerate helium):
 1. **Injector:** debuncher cavity (*allows to inject He into the synchrotron*) and
 2. **Synchrotron:** deceleration prior to carbon inj. (using radial loop regulation; facilitates simultaneous capture)



(1) Capture + decelerate helium prior to carbon injection. (2) Inj.. C; capture und acc. He+C