Slow Extraction of Mixed Ion Beams

Slow Extraction Workshop 2025 | Stony Brook, Long Island | 06-10-2025

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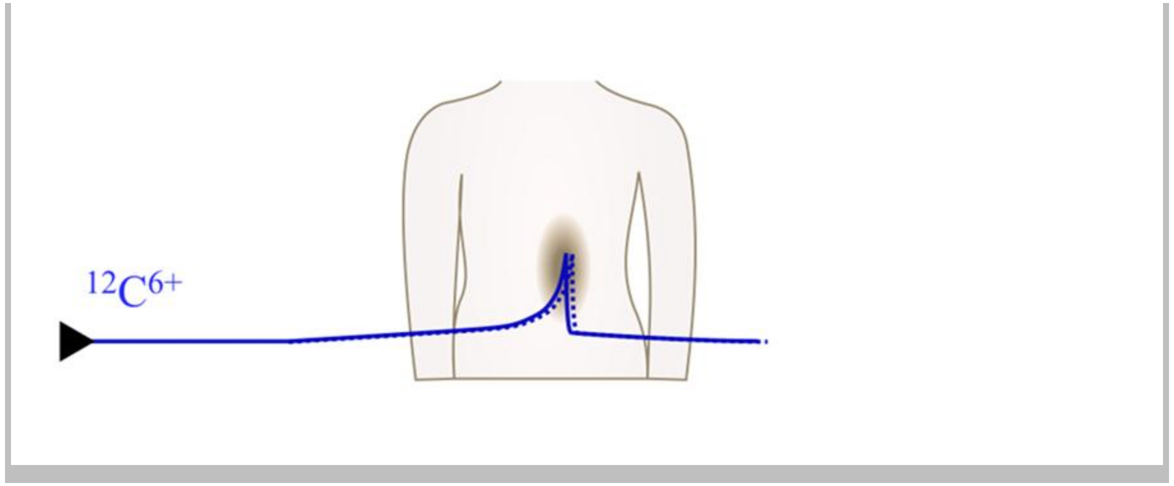
[3] MedAustron
[4] CNAO

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

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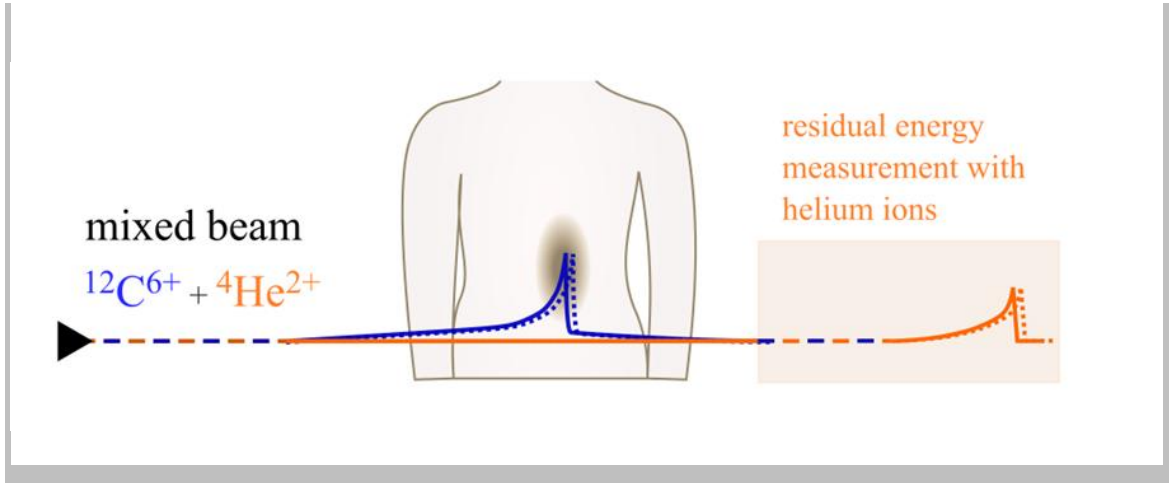


* Various proposals for **monitoring in addition to routine regular treatment plan verification CTs**: e.g. prompt gamma, nuclear fragmentation imaging, pRad,...

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

- similar charge-to-mass ratio (≈0.5)

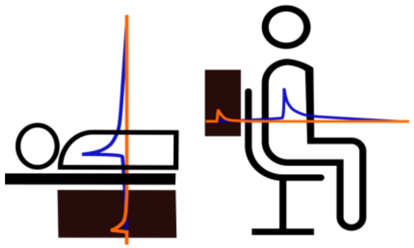
$$\frac{\Delta(q/m)}{q/m} = -0.065\%$$

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

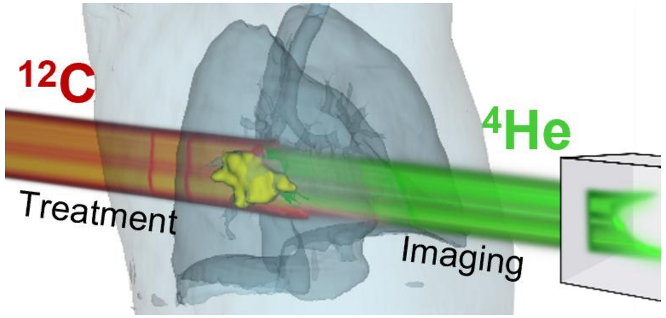
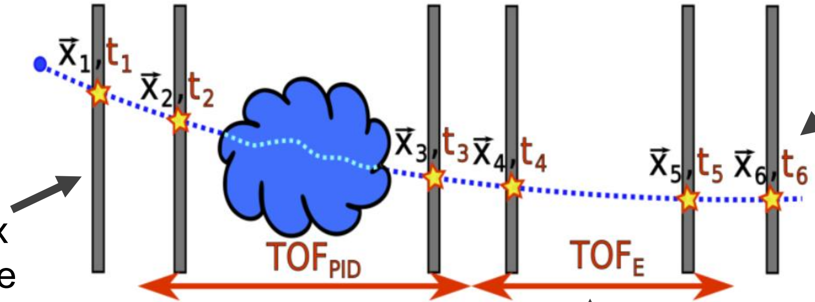


Figure: ERC PROMISE project, C. Graeff [7]

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

Single-particle tracking



He/C-fragment distinction e.g., via dE/dx measurement

Clinical flux may require system without front tracker**

Figure: F. Ulrich-Pur [12]

Measure residual He energy e.g., via TOF

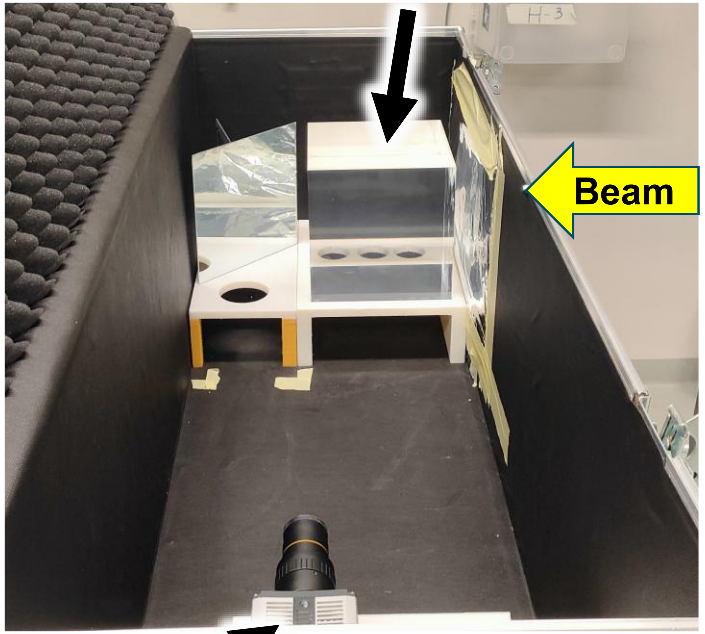
Needs to detect as **wide a range as possible of residual He energies**, while enabling **distinction of He from C fragments**

* alternative: range shifter between 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

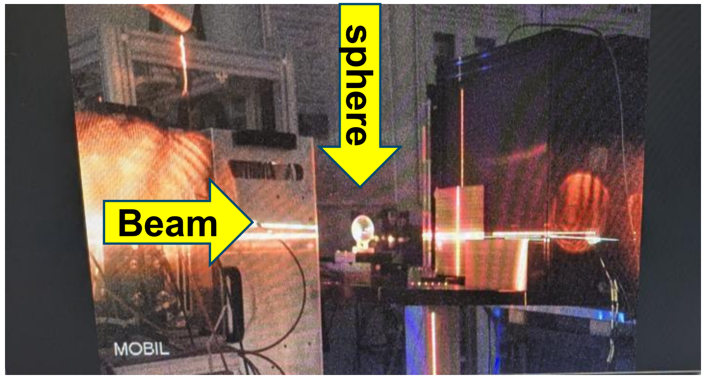


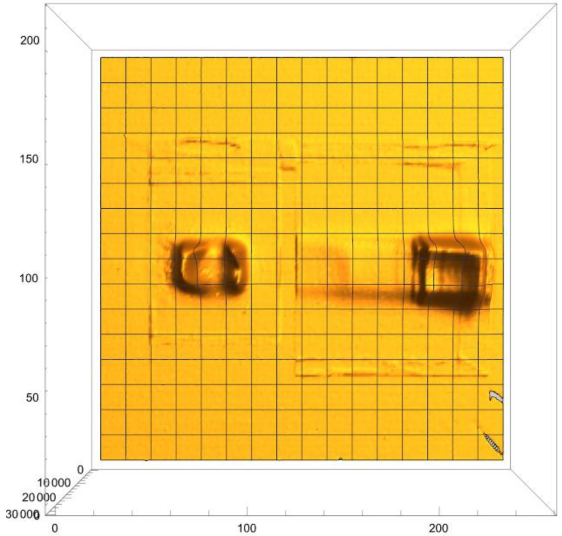
CMOS camera

[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**





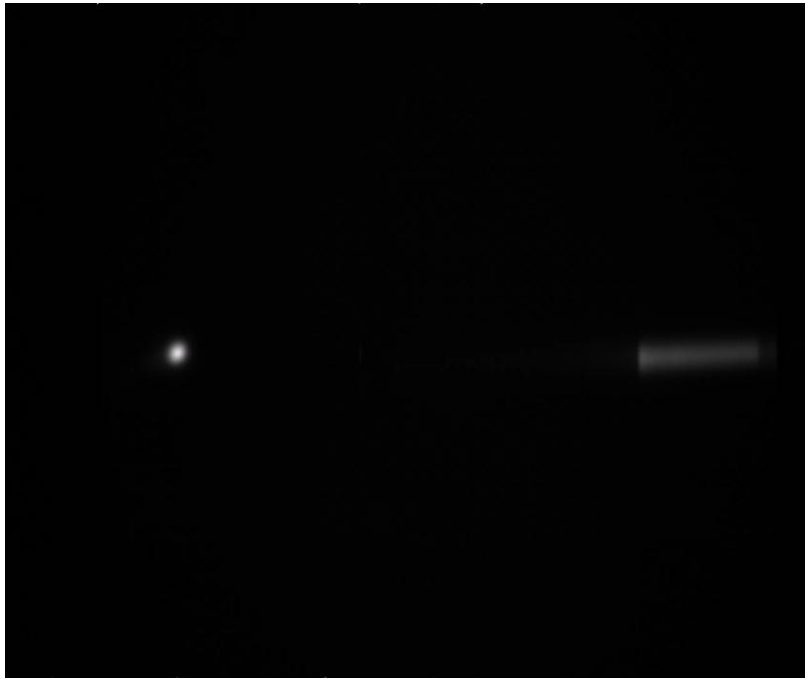
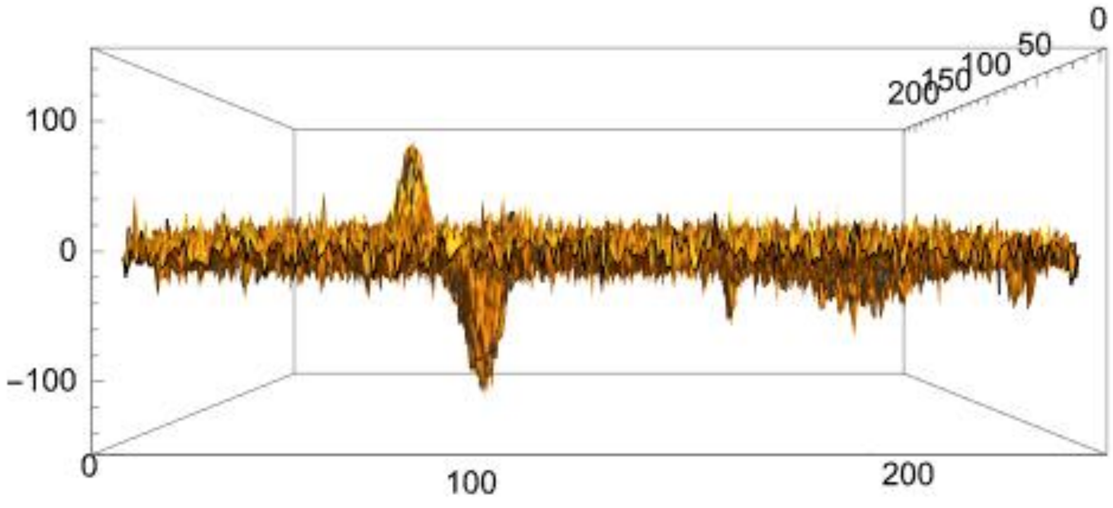


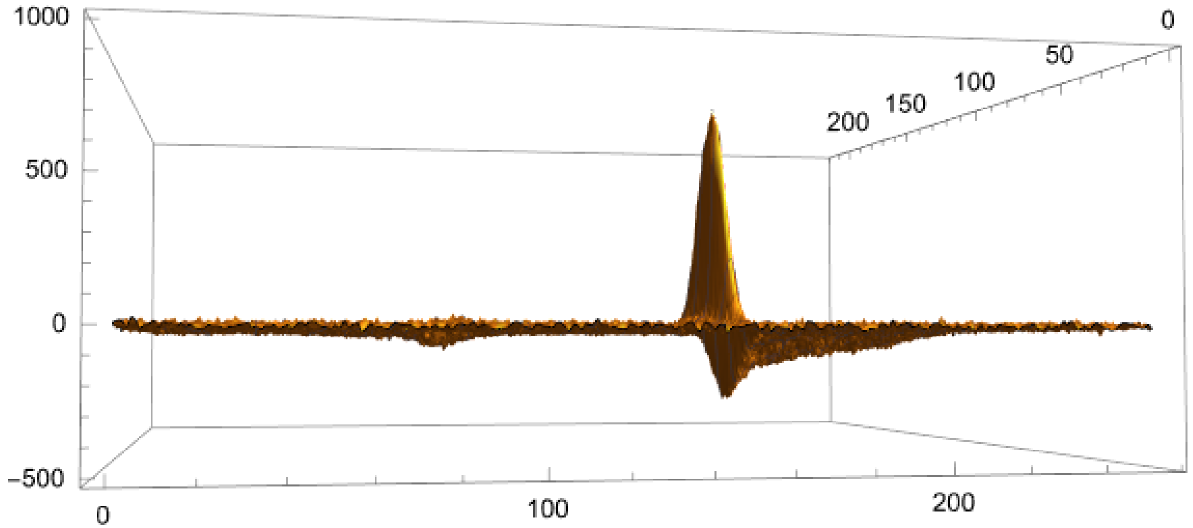
Figure and video: C+He#21 with sphere, no range shifter.

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

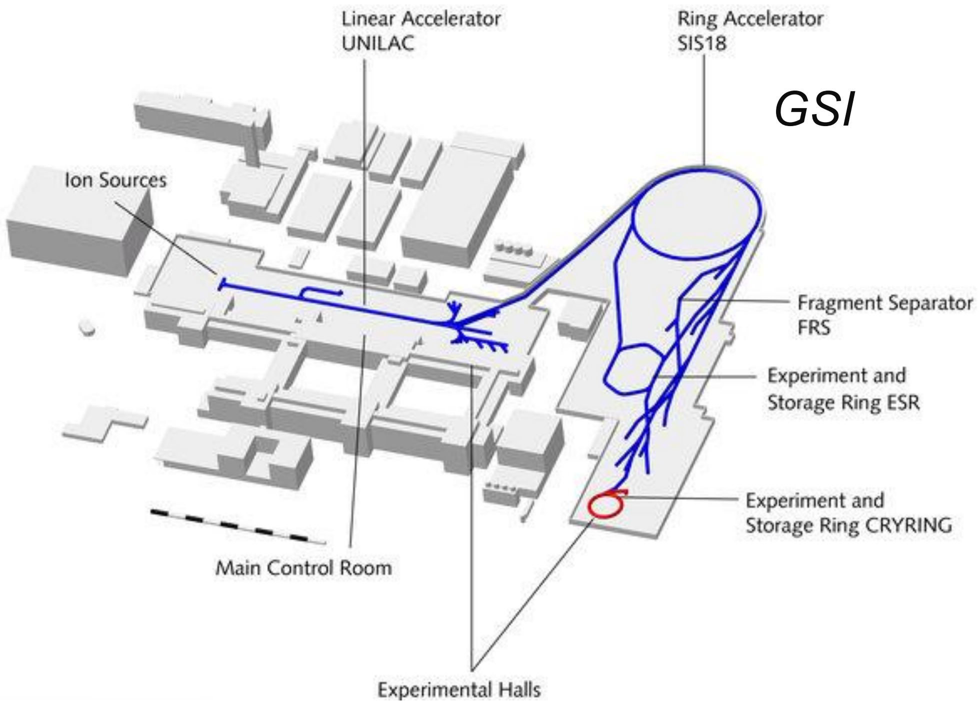
aka: how to deliver a mixed beam to get such nice videos?

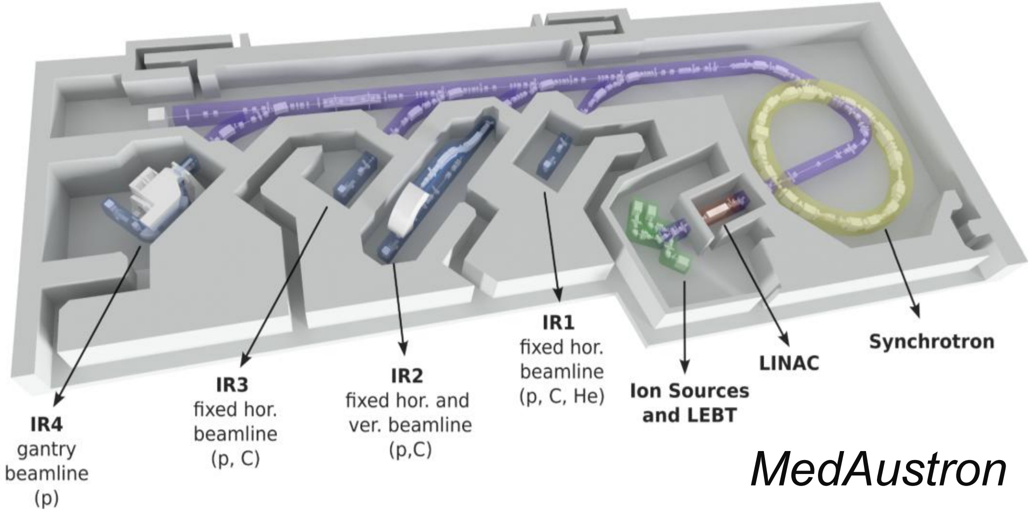
I. **Overview: ongoing mixed helium-carbon ion beam experiments**

II. Mixed beam slow extraction at GSI

III. Mixed beam slow extraction at MedAustron

IV. Conclusion and Outlook





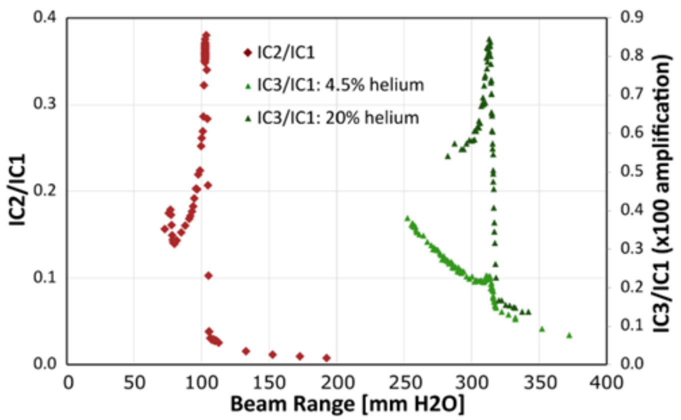
Recent Activities

- *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, ...)

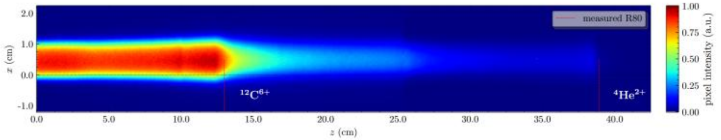
- *Since 2023:* ERC project **PROMISE** at **GSI** (C. Graeff et al. [5-7]).
  - “Portal Range Monitoring in Mixed Ion Beam Surgery”
  - *Imaging & mixed beam delivery concepts, ...*
  - Nov. 2023: **First delivery of mixed $^{12}C^{3+}$ and $^{4}He^{1+}$ beam (single ion source)**
  - Very successful 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 ($^{12}C^{6+}$ & $^{4}He^{2+}$, 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



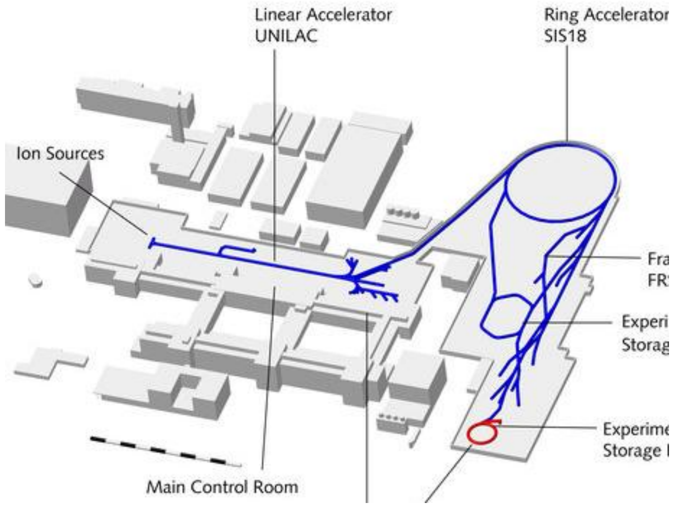
[5] M. Galonska et al., GSI, IPAC’24
[6] D. Ondreka et al., GSI, IPAC’24
[7] C. Graeff et al. PROMISE Project, GSI



[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 $^{12}C^{3+}$ & $^{4}He^{1+}$ mixture from single ion source [5]**
  - 14 GHz ECRIS
  - Source gas: methane & helium
  - $q/m = 1/4$
  - Acceleration in **UNILAC** & **SIS18** → biophysics cave



- **$^{4}He^{1+}$ content tailored** by stepwise **addition of helium flow** to ion source plasma
  - Monitor He contribution using **optical emission spectroscopy**
  - 2023 **$^{16}O^{4+}$ contamination** of less than 10%
  - 2025 $^{16}O^{4+}$ contamination significantly reduced.

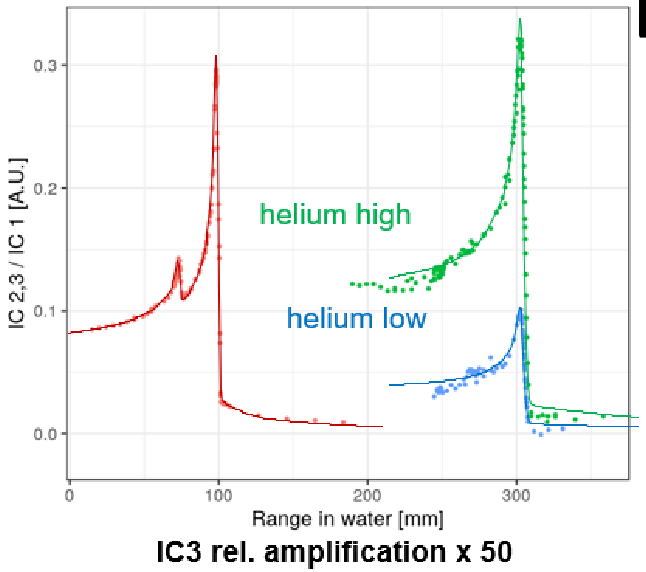


Figure: Mixed beam depth-dose curve measured in 2023 at GSI. Signal from IC3 and IC2 are carbon fragment tail corrected **[11].**

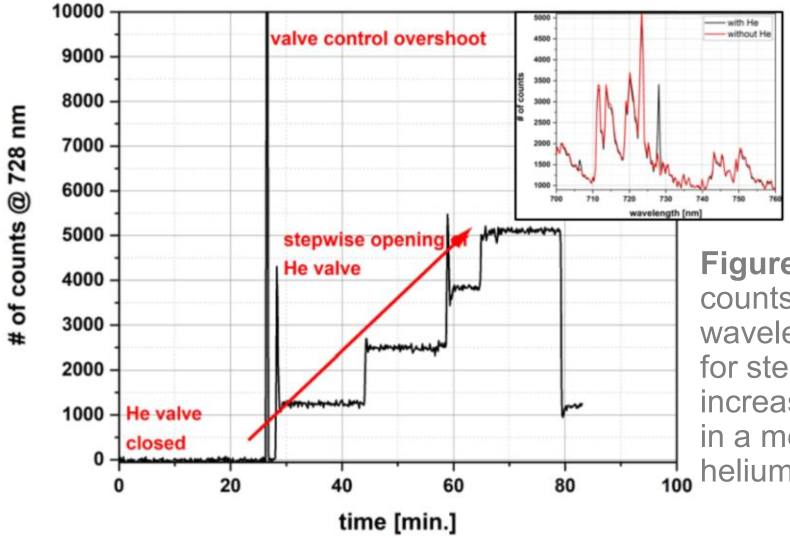


Figure: Number of counts at 728 nm wavelength (He I) for stepwise increase of He flow in a methane / helium plasma **[5].**

[5] Galonska et al. IPAC '24

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

Mixed Ion Beams at MedAustron

Poster - F. Plassard
MedAustron Facility Overview

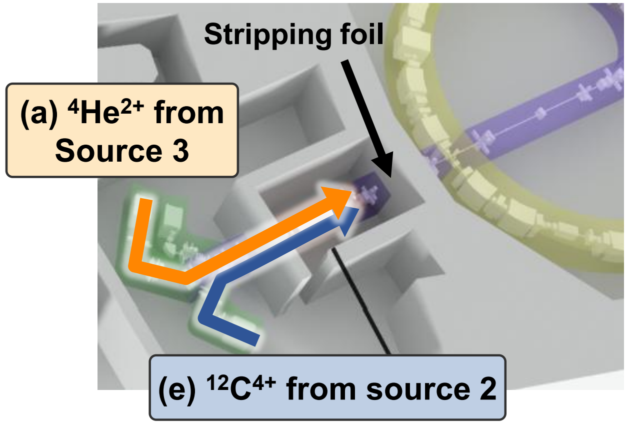
Mixed beam from single ion source not deliverable in current medical synchrotron facilities.

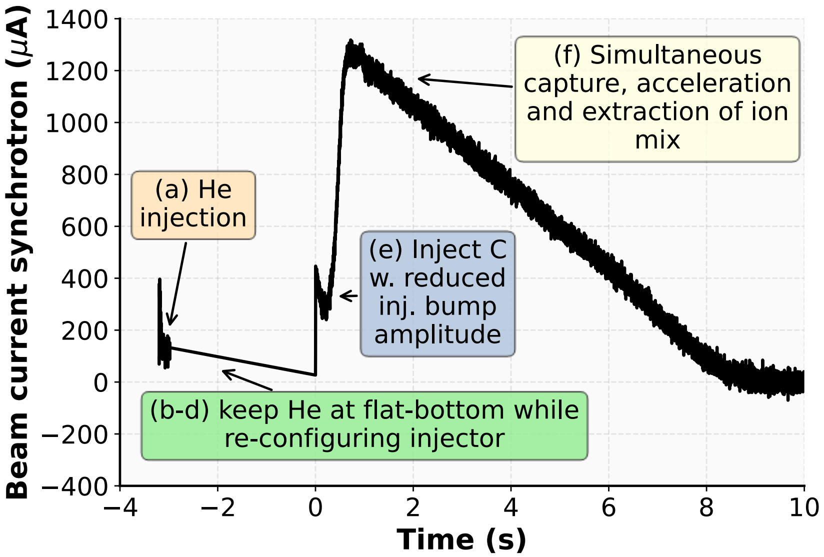
- **$^4He^{1+}$ + $^{12}C^{3+}$** → cannot be accelerated in **LINAC** (requires q/m ≤ ⅓)
- **$^4He^{2+}$ + $^{12}C^{6+}$** → insufficient $^{12}C^{6+}$ yield with 14 GHz **ECRIS**
- **$^3He^{1+}$ + $^{12}C^{4+}$** → limited energy range + large ΔBρ/Bρ in **synchrotron**

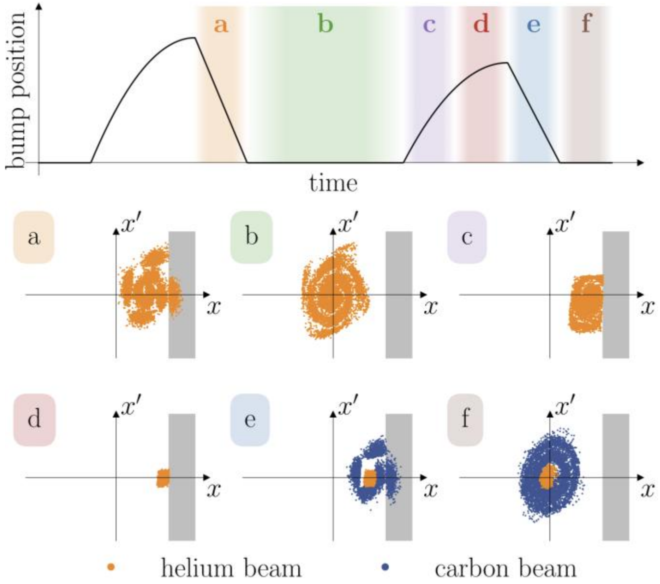
[9] M. Kausel et al., submitted to PRAB

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

Δ(q/m) causes acceleration to slightly different E/m *(depending on extraction and transition energy)*

$$\chi = \frac{q_{He}/m_{He}}{q_C/m_C} = 0.99935$$

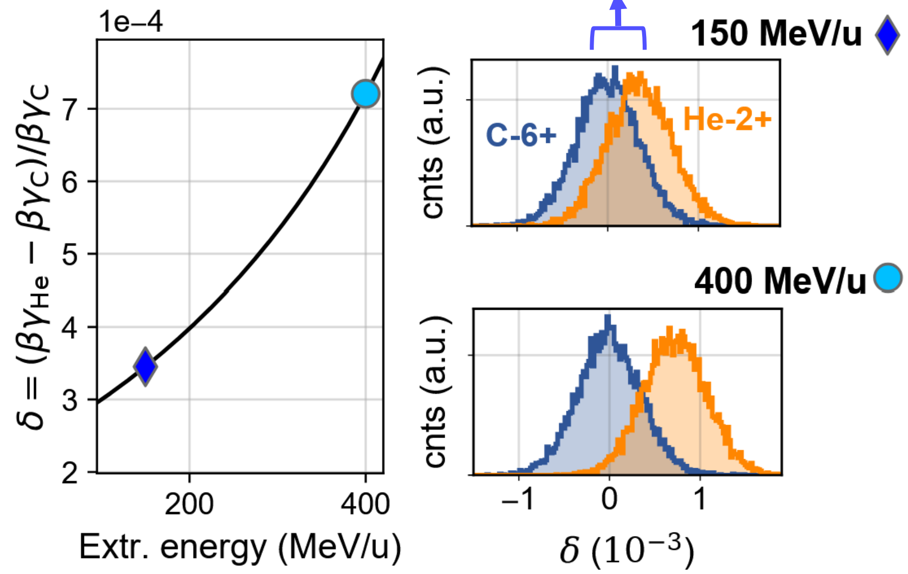
$$\Rightarrow \frac{\Delta C}{C} = \alpha_c \frac{\Delta B\rho}{B\rho} > 0$$

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}):

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

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



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

[8] E. Renner, IPAC '24

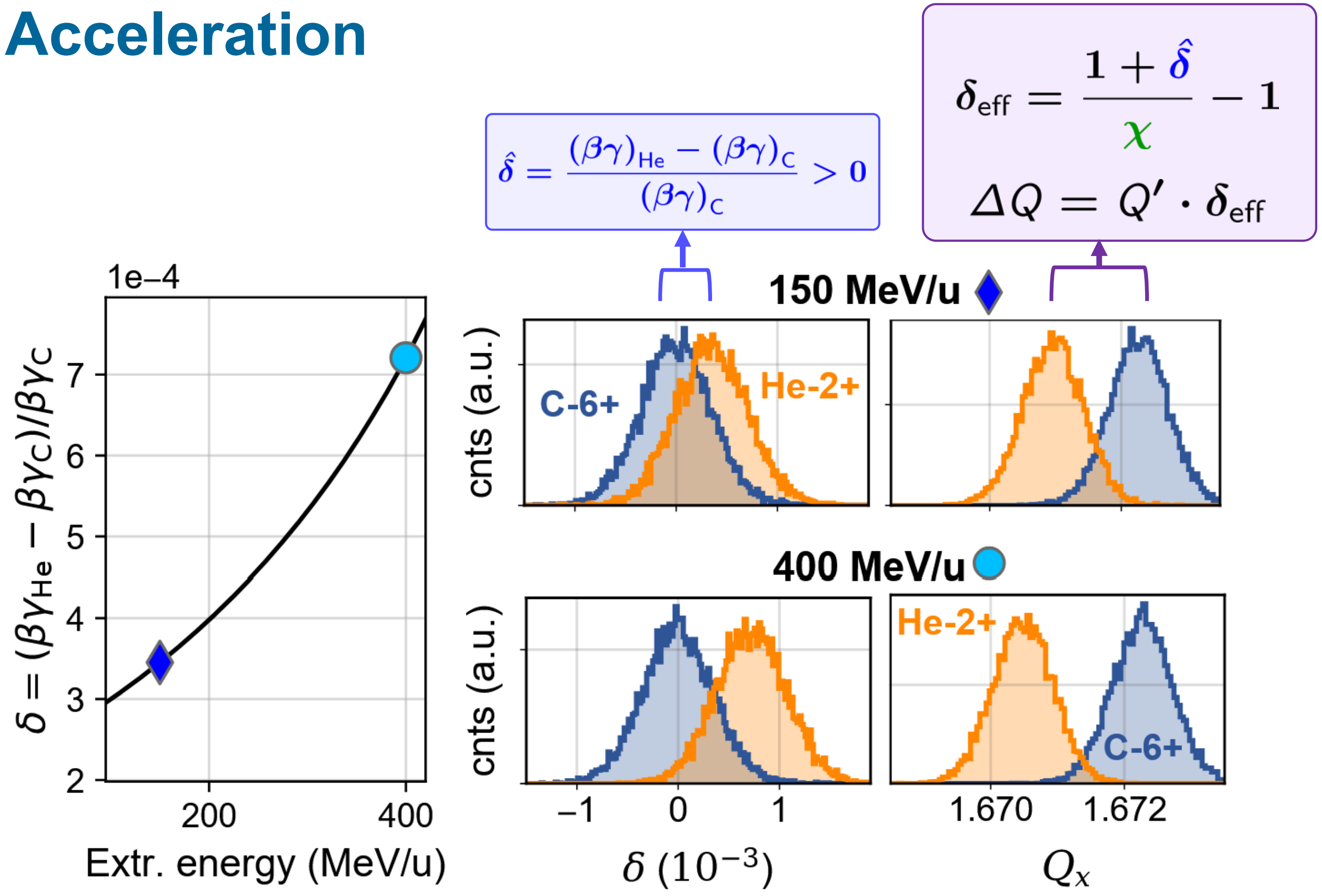
Take Away: Mixed Beams & RF Acceleration

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.**



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

[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.**

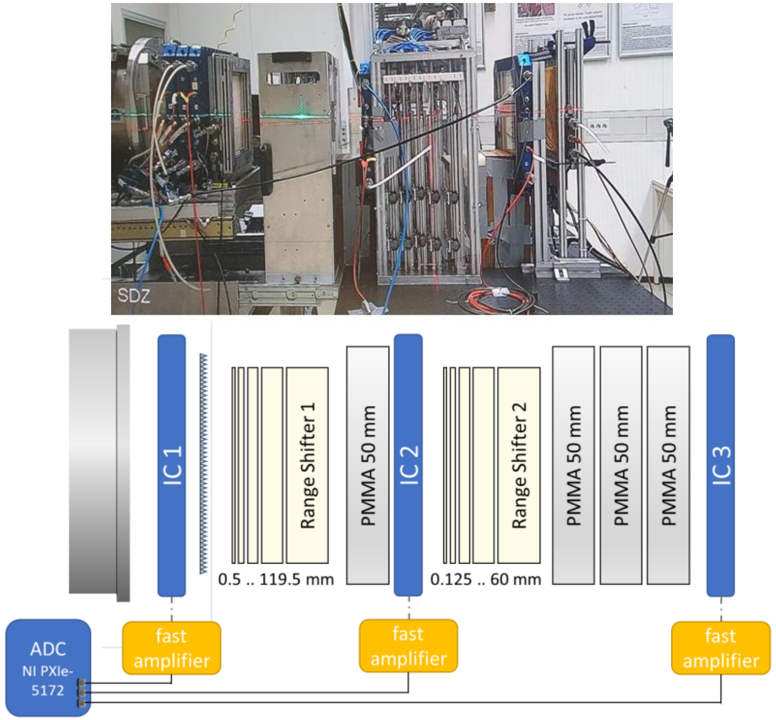
- **Goal**: Ideally extract mixed beam with **(roughly) constant He:C ratio** throughout the spill.

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

Selected Tools for Mixed Beam and Spill Characterization I

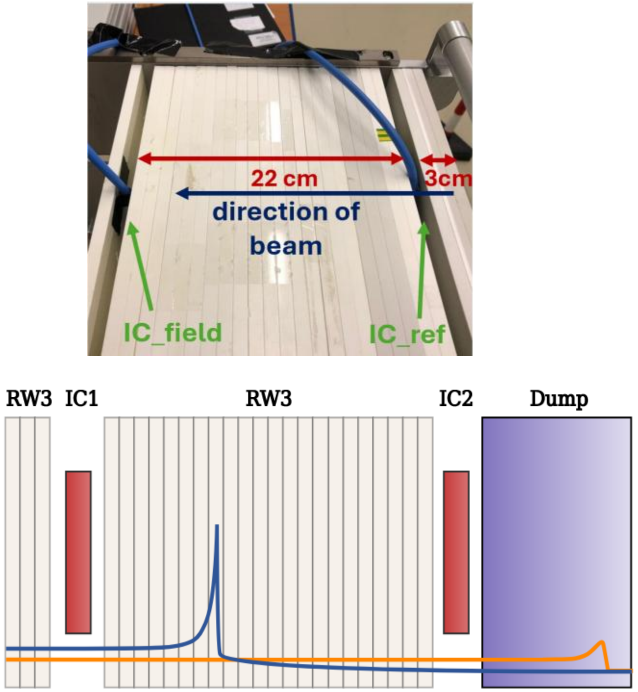
(A) Time-resolved characterization of the extracted **He:C ratio** (e.g., using ionization chambers at different depths)

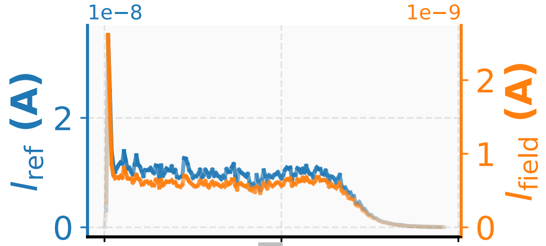
Set-up at GSI (Biophysics cave)



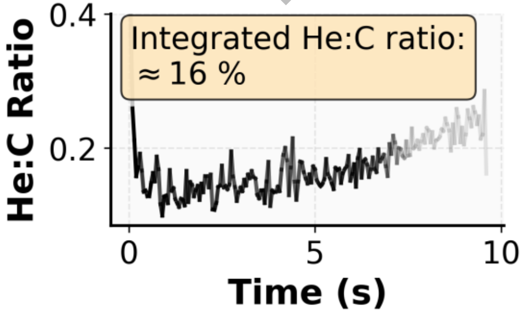
Courtesy of C. Graeff, L. Volz et al. [5, 11]

Set-up at MedAustron





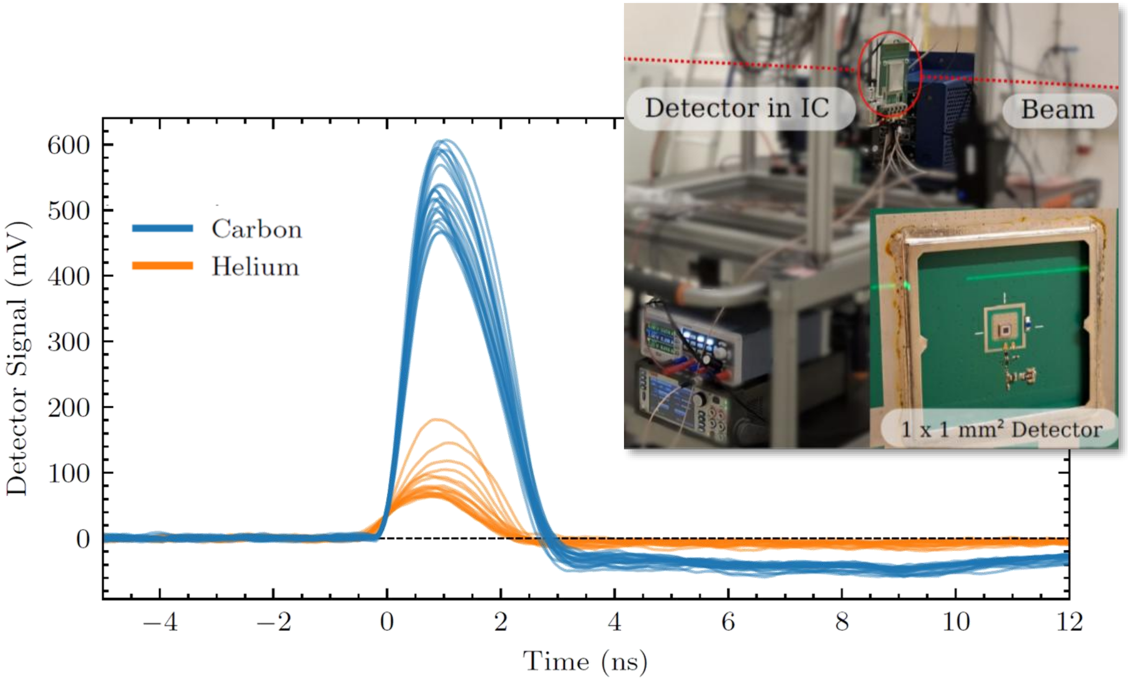
He:C ratio obtained from I_{field} / I_{ref} (corrected for C fragments).



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

Selected Tools for Mixed Beam and Spill Characterization II

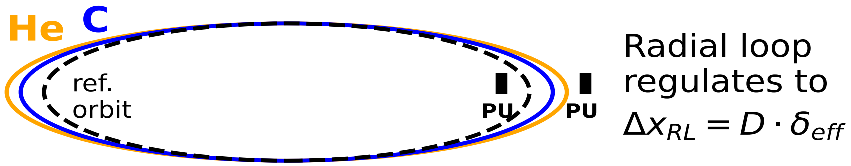
(B) Alternative: **Single particle distinction via dE/dx**, e.g., with 50 µm Si sensor.



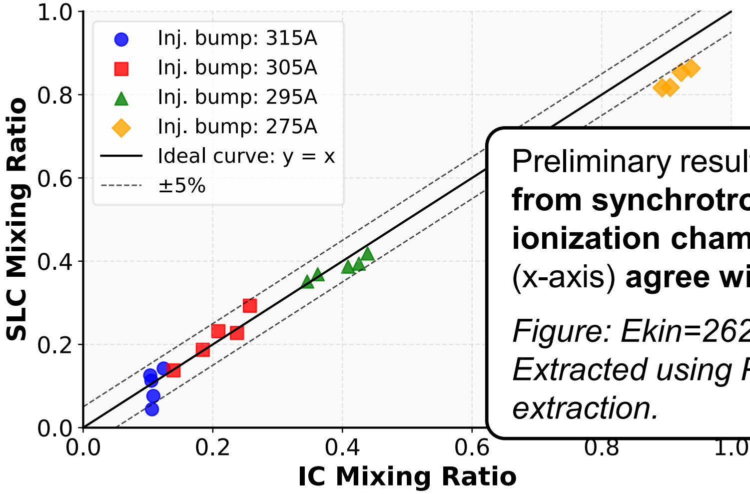
HEPHY **A. Gsponer, M. Kausel**

Not routinely employed in current studies

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



$$\left\langle \frac{df}{f} \right\rangle = \left(\frac{\gamma_{tr}^2}{\gamma^2} - 1 \right) \left\langle \frac{dR}{R} \right\rangle - \frac{n_{He} \cdot q_{He}}{n_{q,tot}} \frac{1}{\gamma^2} \left(\frac{1}{\chi} - 1 \right)$$



Preliminary results: **Mixing ratio estimate from synchrotron** RF (y-axis) and **ionization chambers in irradiation room** (x-axis) **agree within a few %.**

Figure: Ekin=262 MeV, RL: 29.9mm. Extracted using Phase displacement extraction.

N. Okropiridze

Outline

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II. Mixed beam slow extraction at GSI

III. Mixed beam slow extraction at MedAustron

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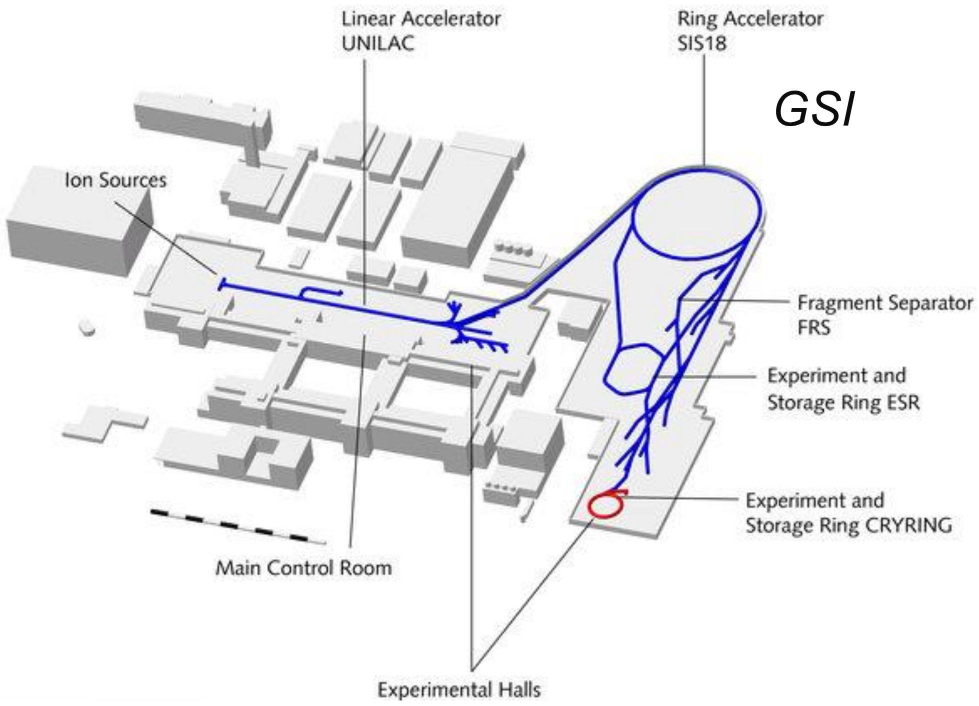
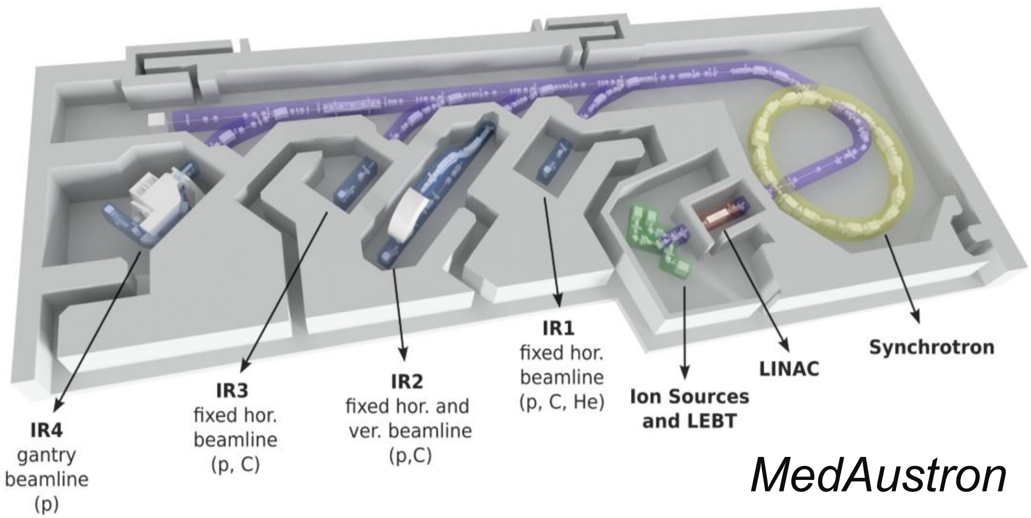
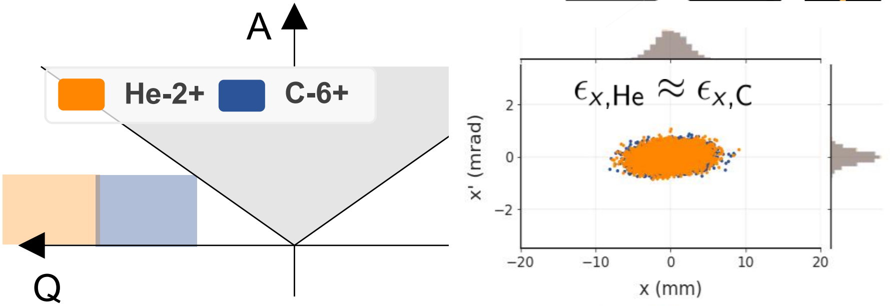




Mixed Beam Slow Extraction at GSI: Overview

- **Single ion source: He and C with similar initial horiz. emittances**



Schematic illustration. Proportions not to scale

- **Beam time in 2023: tune sweep and RFKO**
  - Successful, but further studies needed.
  - Δx=1-2mm between He and C at isocenter → 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)*

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

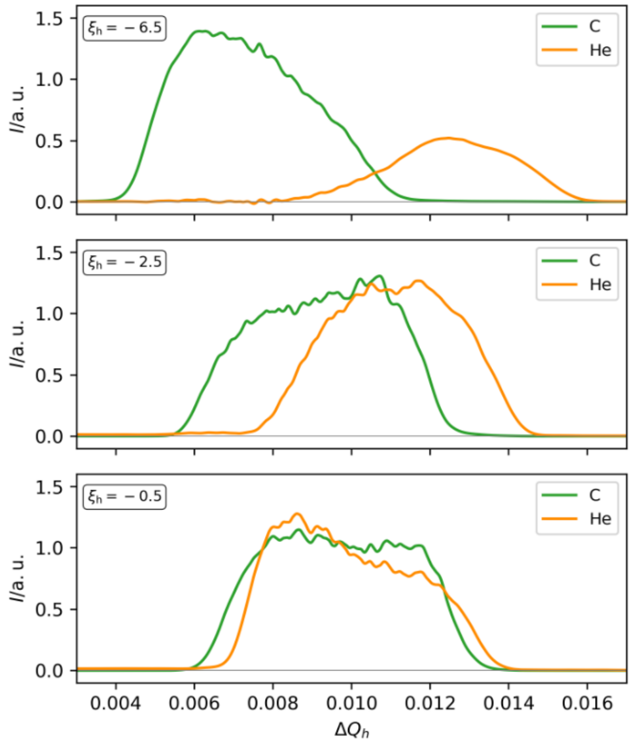
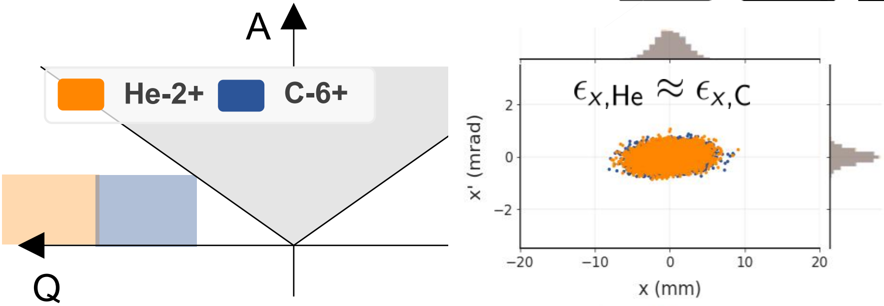


Figure: tune sweep extr. with **different chromaticities** (2023)

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

Slide courtesy of A. Pastushenko

Mixed Beam Slow Extraction at GSI: Settings

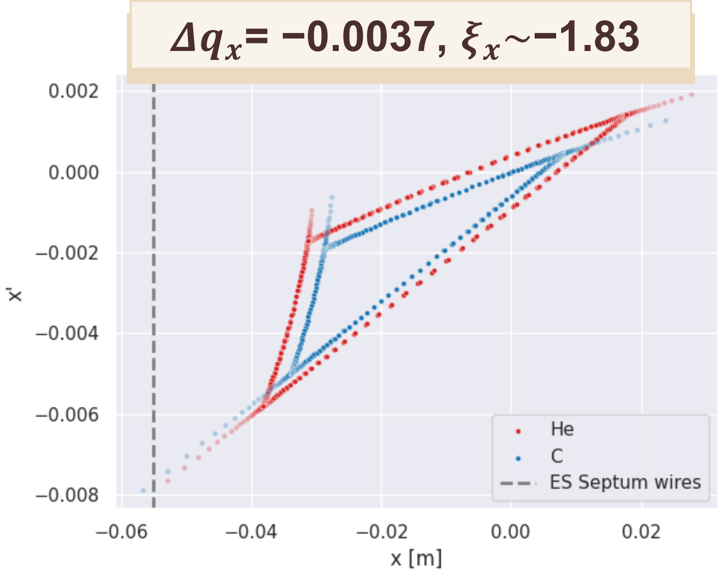


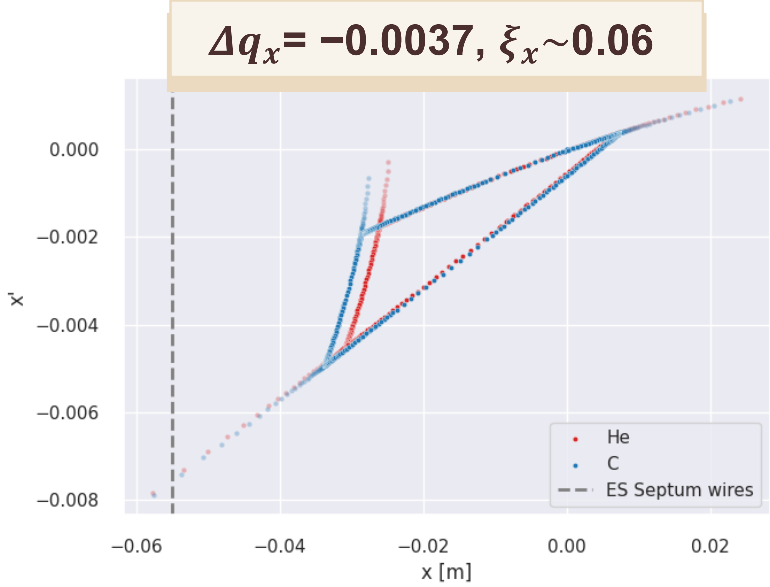
Schematic illustration. Proportions not to scale

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 $q_x^{He} - q_x^{C} \sim -0.0042$ → similar to Δq_x

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





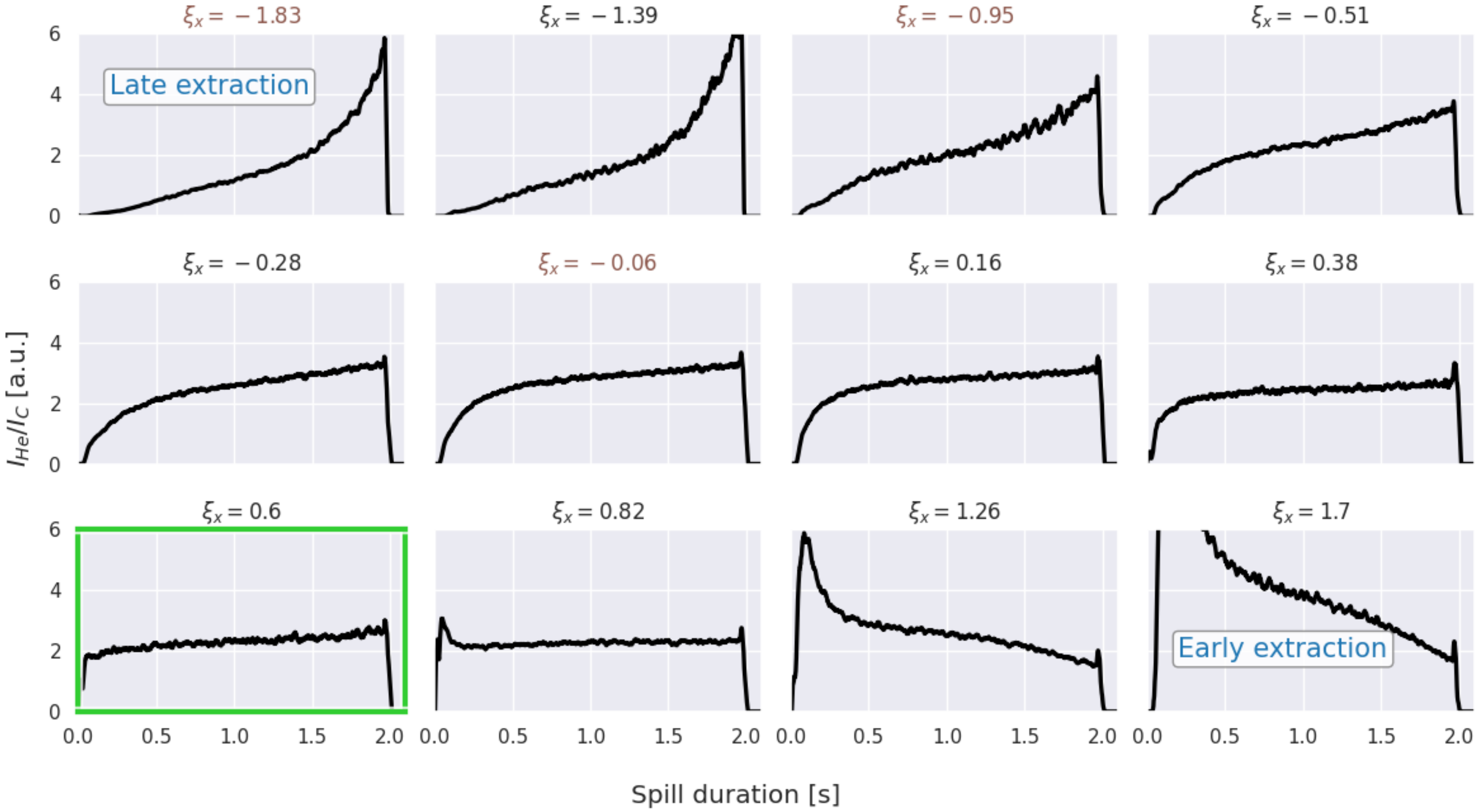
Simulations: Xsuite

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 ξ_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**

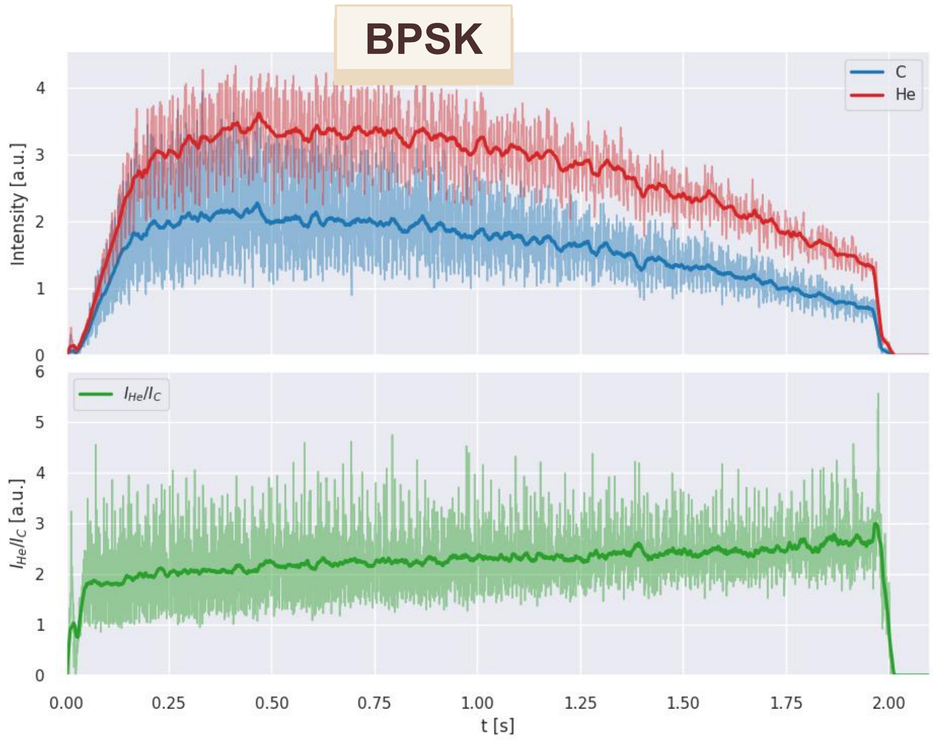


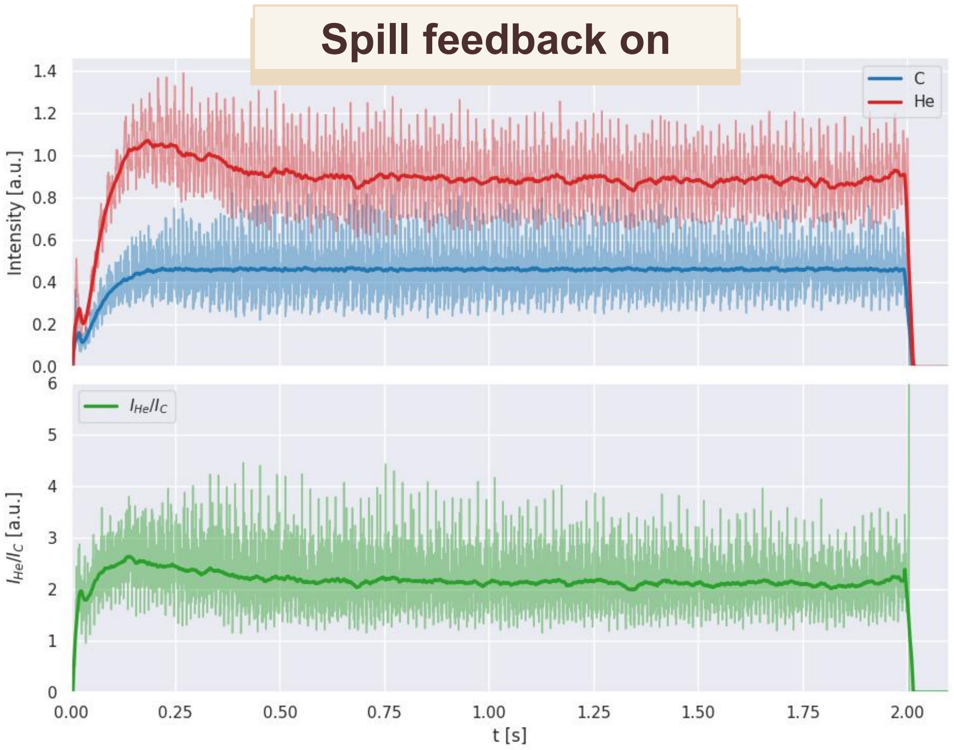
**labels in brown – chromaticity was measured*

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

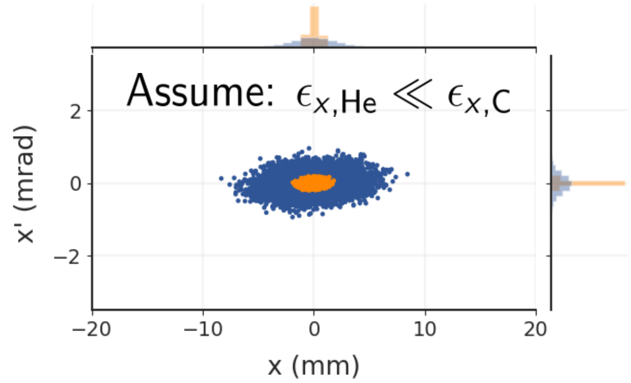
Talk - P. Niedermayer:
Spill feedback and optimisation system for RFKO and tune scan extraction

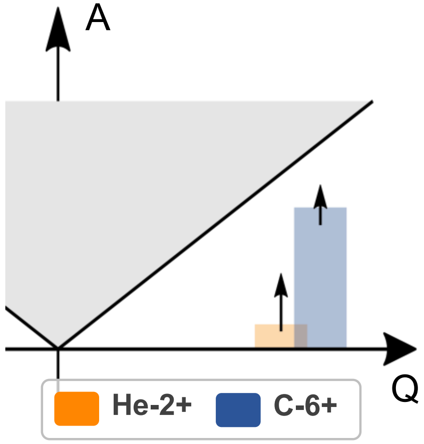
Slide courtesy of A. Pastushenko

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

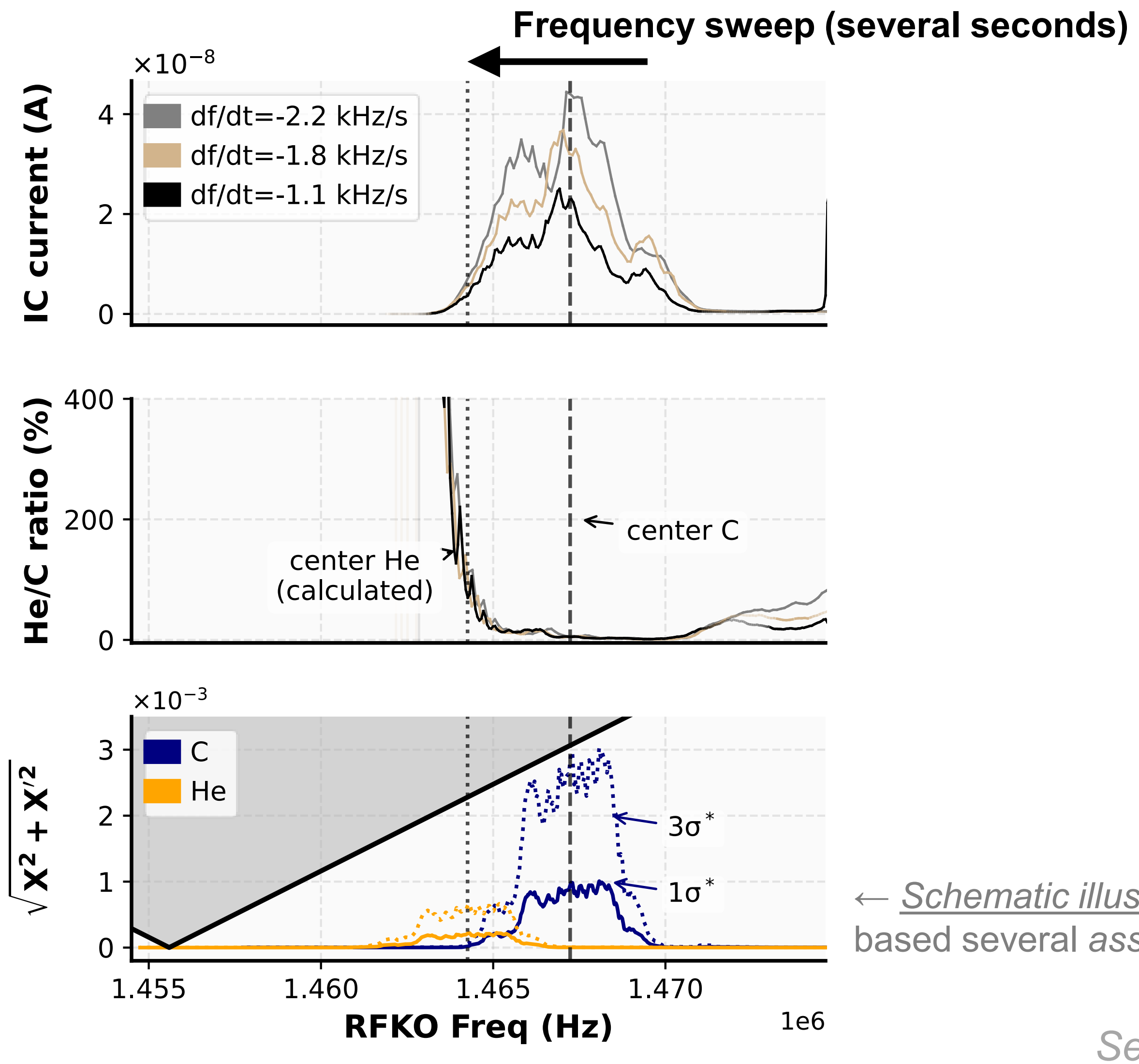
Poster – C. Schmitzer
Ultra High Dose Rate Beam Monitoring with Radiation-Hard SiC-Based Detectors

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

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

$$
\begin{aligned}
Q_x &= 1.672 \\
&\quad \text{(off momentum)} \\
Q'_x &\approx -1.3 \\
\frac{\epsilon_{x,\mathrm{He}}}{\epsilon_{x,\mathrm{C}}} &\approx 0.05^* \\
E_{\mathrm{kin}} &= 200\,\mathrm{MeV/u} \\
N_{\mathrm{He}}/N_{\mathrm{C}} &\approx 10 - 15\,\%
\end{aligned}
$$

☑ **He and C with the expected offset in f_β**



← *Schematic illustration (!)* based several *assumptions*

See appendix

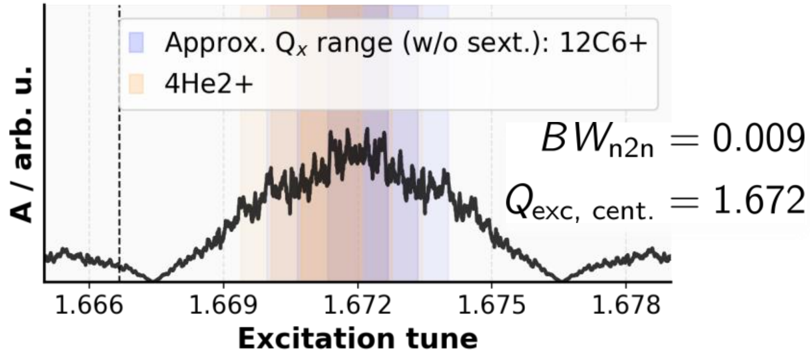
* *Assumed value*

Mixed Beam SX at MedAustron: Simulations

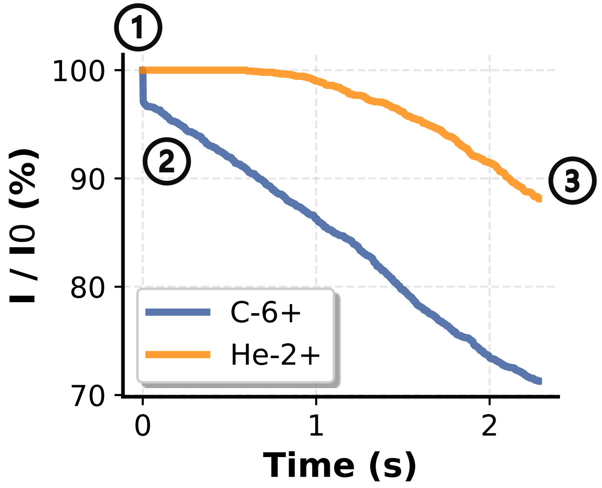
In this configuration, **Xsuite simulations** suggest that when applying a

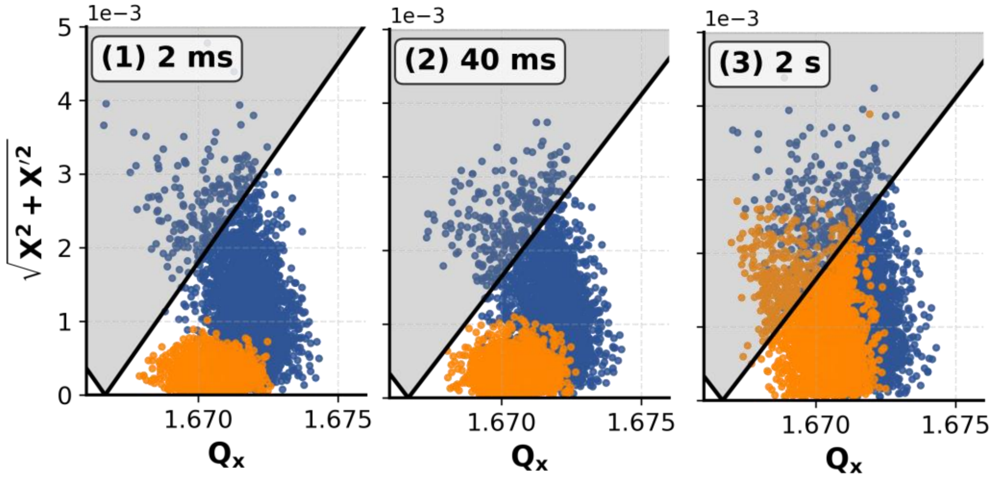
... **broadband phase shift keying excitation** centered at C tunes,

... **He extraction begins with a delay** due to the initially smaller horizontal He emittance.



$$Q_x = 1.672$$
(off momentum)
$$Q'_x \approx -1.3$$
$$\frac{\epsilon_{x,He}}{\epsilon_{x,C}} \approx 0.05^*$$
$$E_{kin} = 200\,\mathrm{MeV/u}$$
$$N_{He}/N_C \approx 10 - 15\,\%$$





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

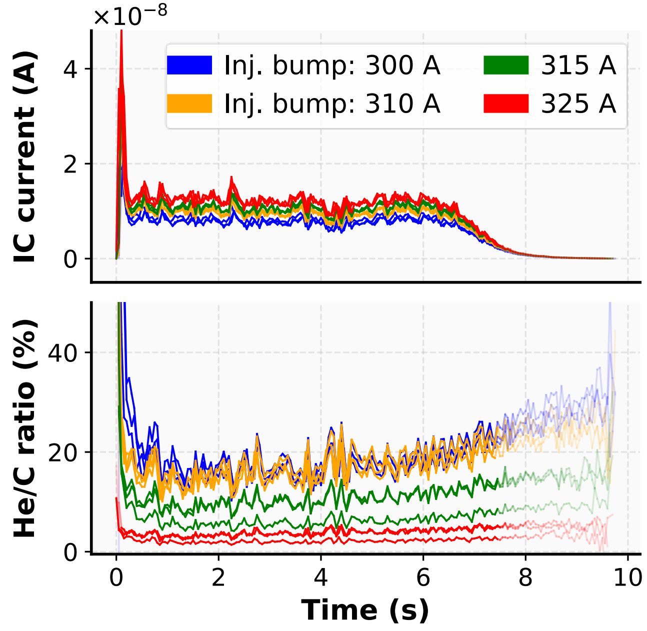
*** *Disclaimer*: Conceptual simulations:** initial (x, x') and δp/p distributions for He and C, are based on assumptions.

Mixed Beam SX at MedAustron: Measurements

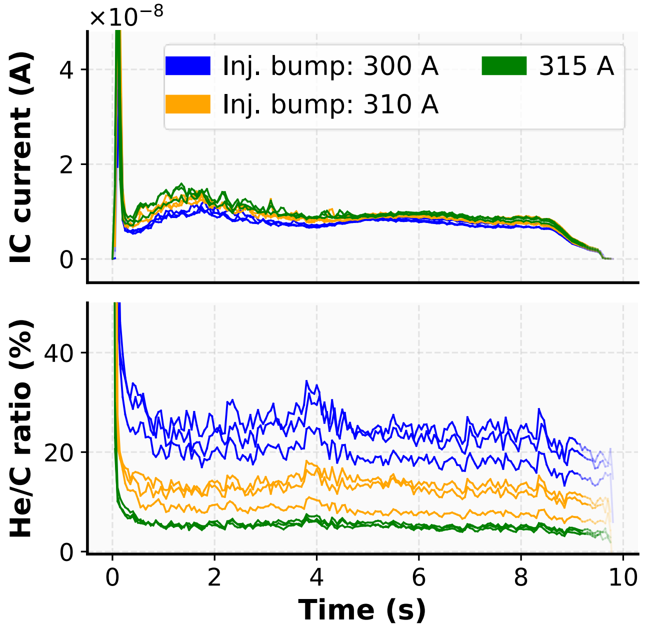
However, **measurements** show **more constant He:C ratio throughout spill than expected**.

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

Coasting, BPSK

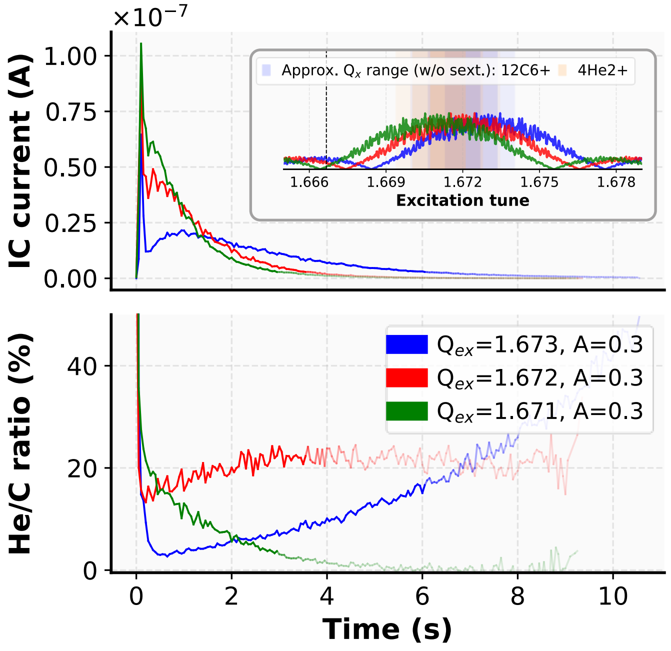


Bunched*



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

Lucky? **Shift BPSK spectrum (coasting)**

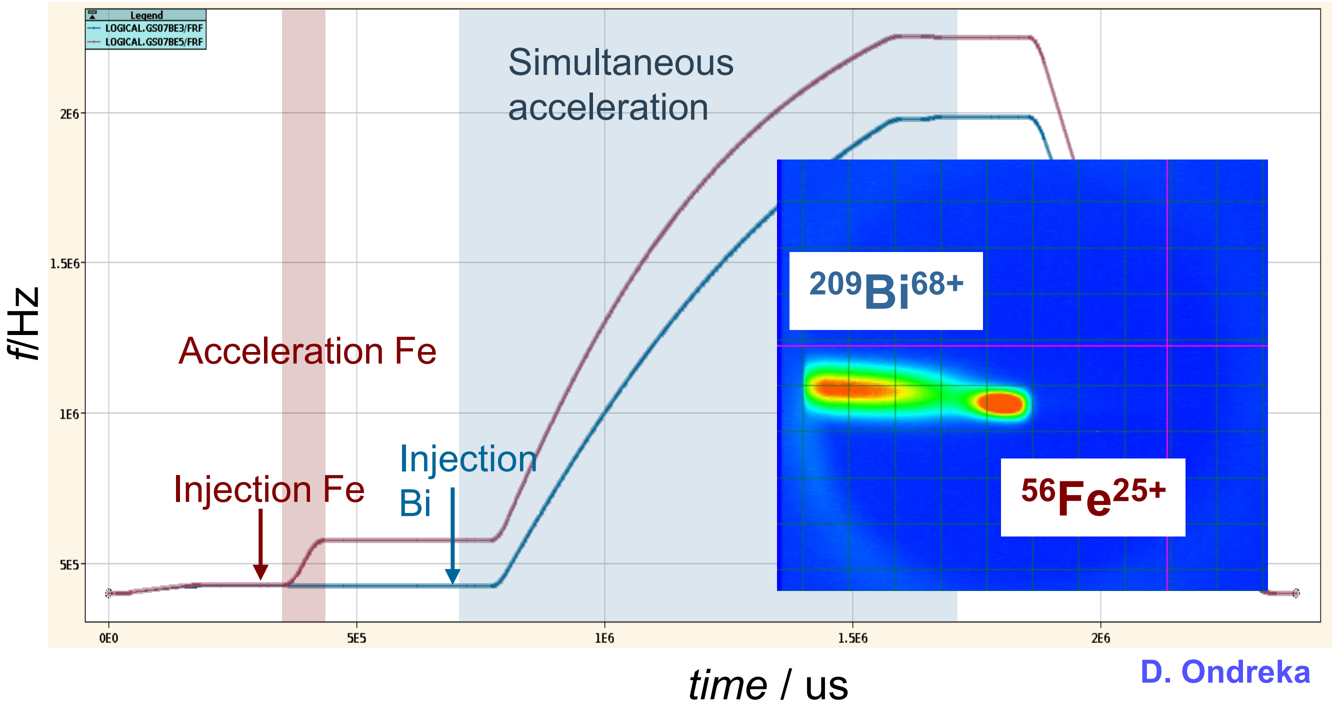


Follow-ups: sensitivity studies (RFKO signals, optics, extraction energies), **refine simulation model** (x,x', dpp dist); assess **off-momentum losses in transfer line,** increase **resolution of measurements**, ...

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?)

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

- **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

[1] D. Mazzucconi, M. Pullia et al., "*Mixed particle beam for simultaneous treatment and online range verification in carbon ion therapy: Proof-of-concept study"* Med. Phys. 45 (11), 2018

[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

[5] M. Galonska et al., "*First dual isotope beam production for simultaneous heavy ion radiotherapy and radiography"*, IPAC'24

[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

[9] M. Kausel et al. "*A double multi-turn injection scheme for generating mixed helium and carbon ion beams at medical synchrotron facilities*" submitted to PRAB, https://arxiv.org/abs/2501.12797, 2025

[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

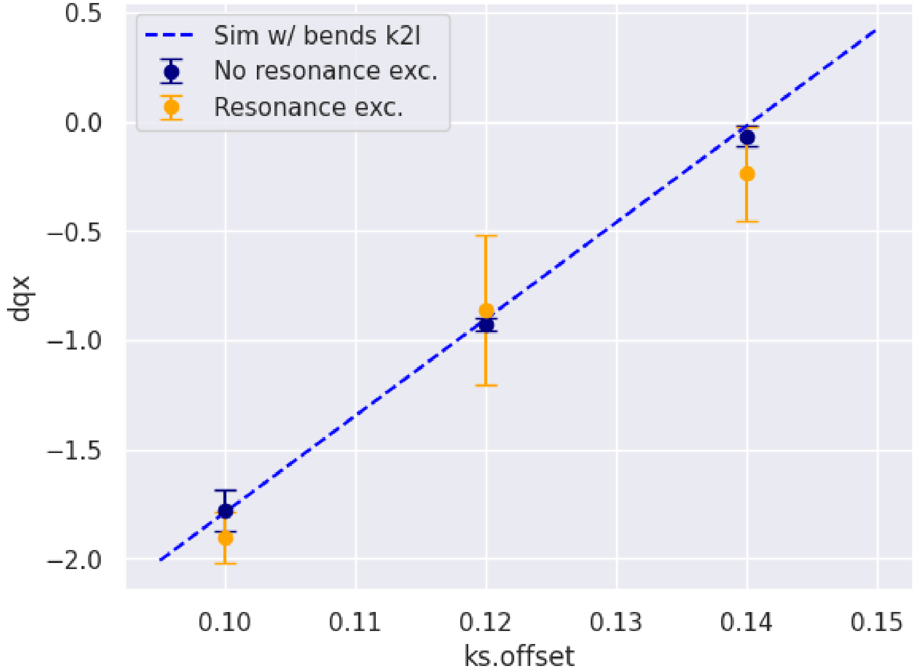
[12] F. Ulrich-Pur "*First experimental time-of-flight-based proton radiography using low gain avalanche diodes*" Phys Med Biol 69 (2024)

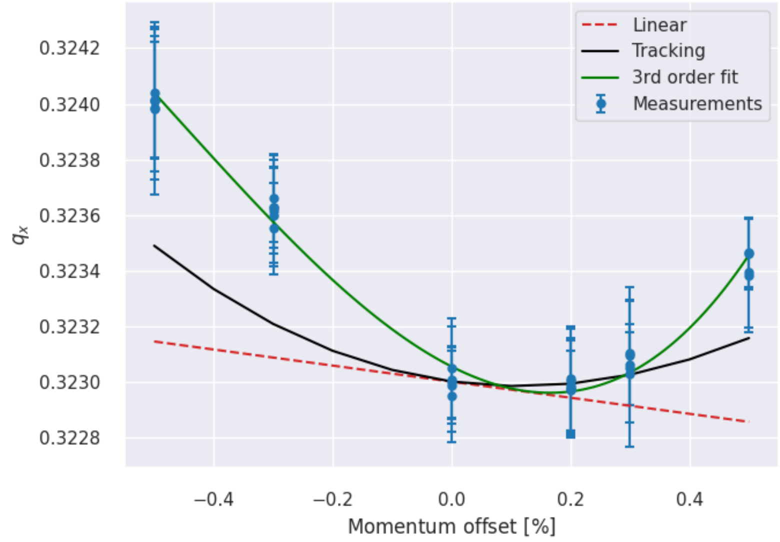
Spare Slides

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 $k_{2l} = 0.04$ m^{-2} component in the dipoles.
- Measurements were done with resonance sextupoles on and off.



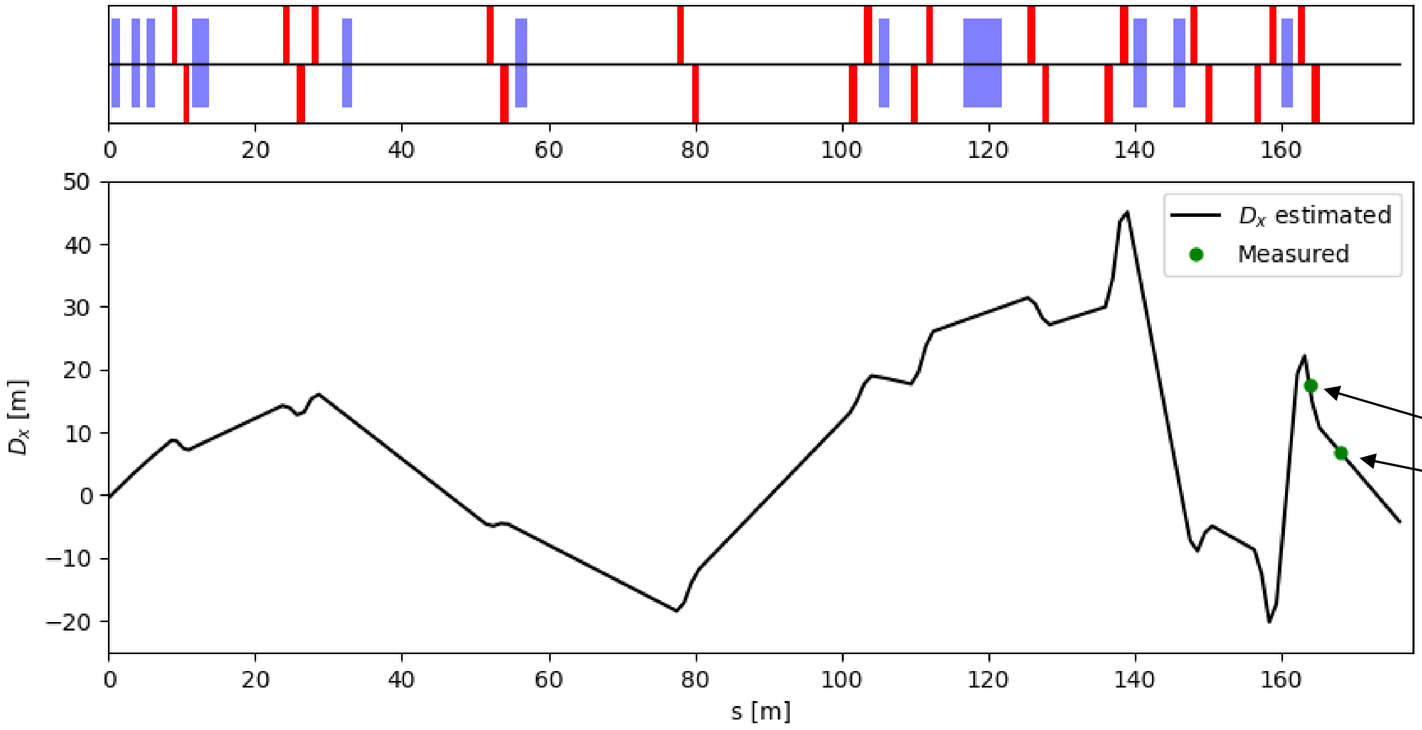


For one setting (*ks.offset = 0.14*, $\xi_x \sim -0.06$,(tune was measured for a bigger range of momentum offsets. **Nonlinear chromaticity** hints nonlinearities in magnets (k_{3l} in quads, ..)

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.



Measured D_x:

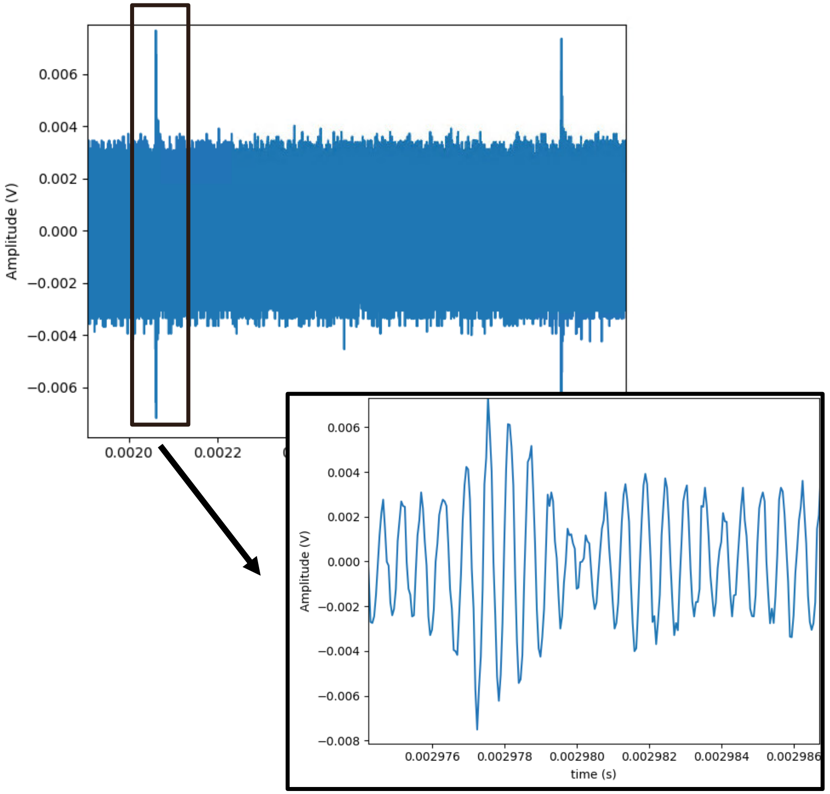
- 17.4 m
- 6.7 m

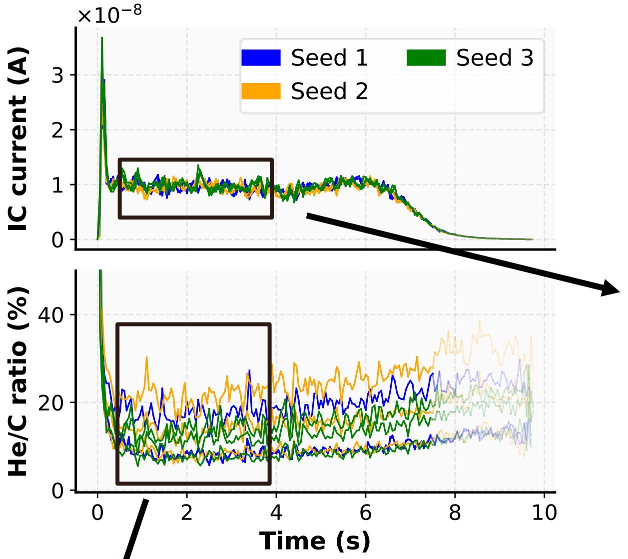
Estimate at the end

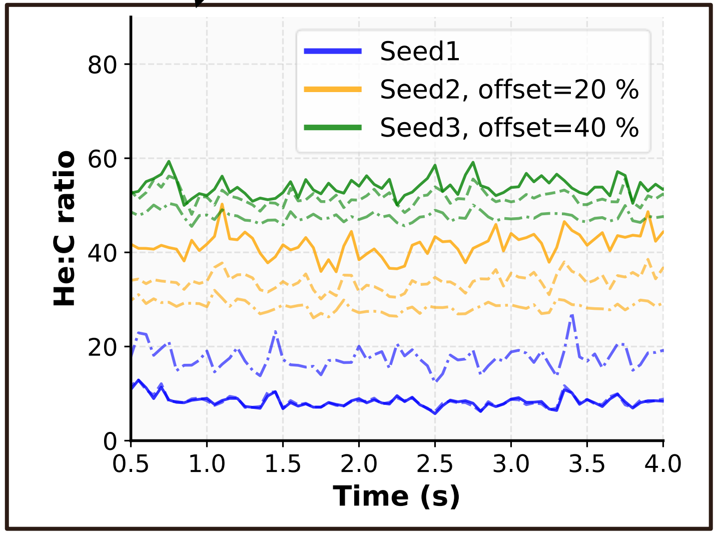
~ -4 m

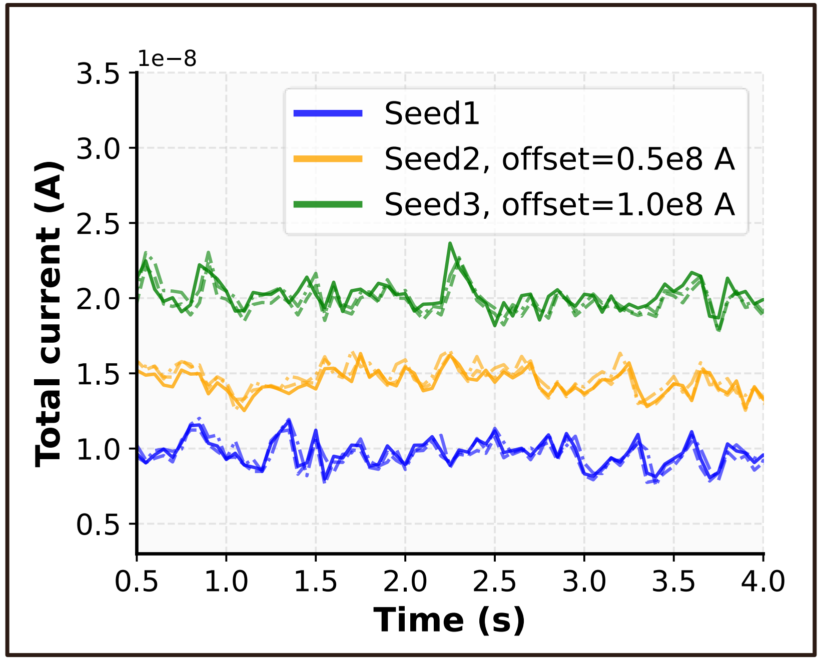
Supplementary Material for Mixed Beam SX at MedAustron

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



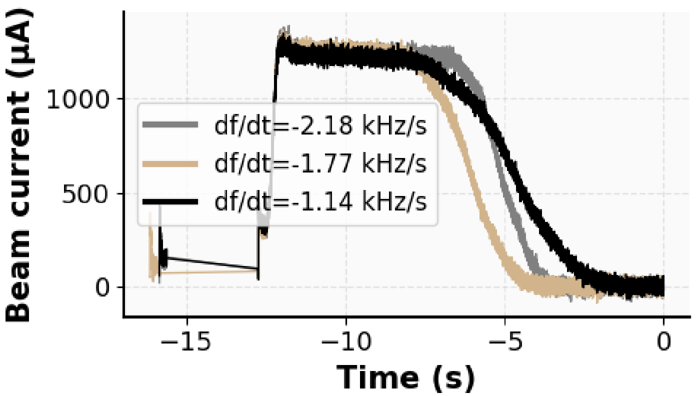


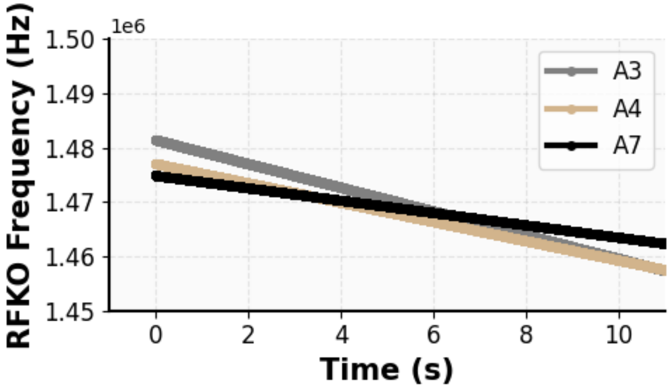


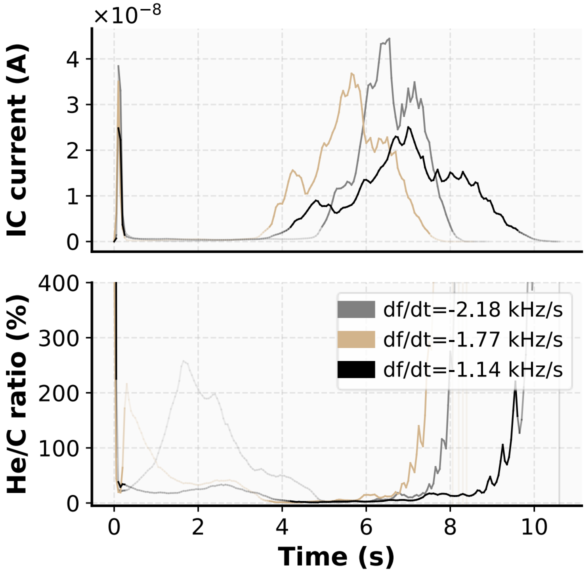


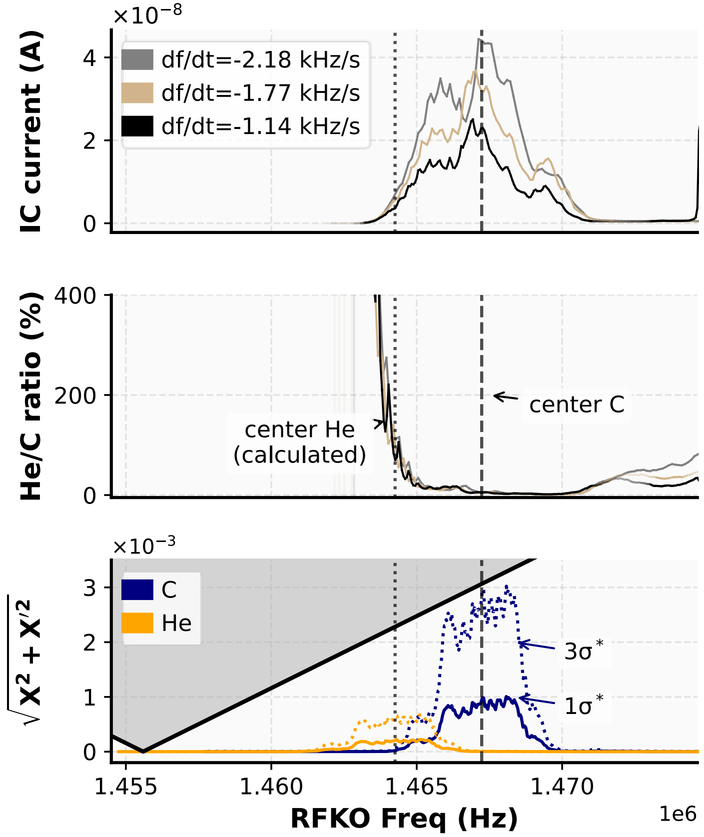
Supplementary Material for Mixed Beam SX at MedAustron

- Slow RFKO frequency sweep through waiting beam stack





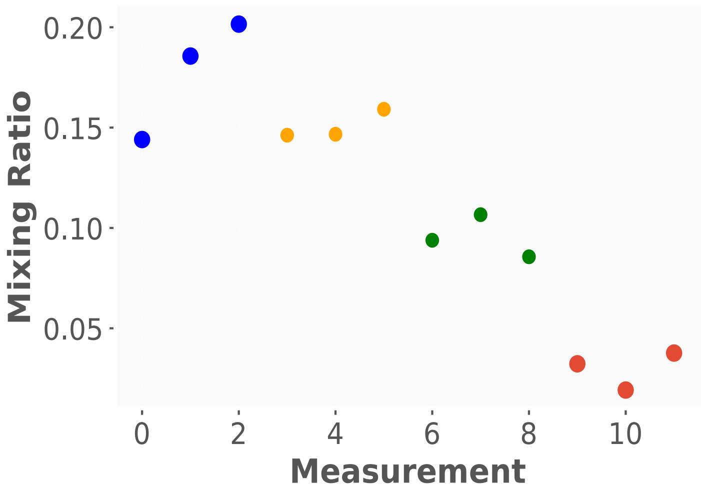


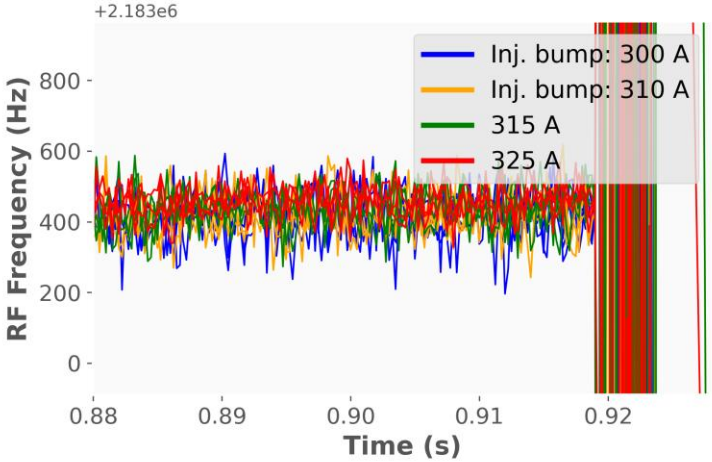


Supplementary Material for Mixed Beam SX at MedAustron

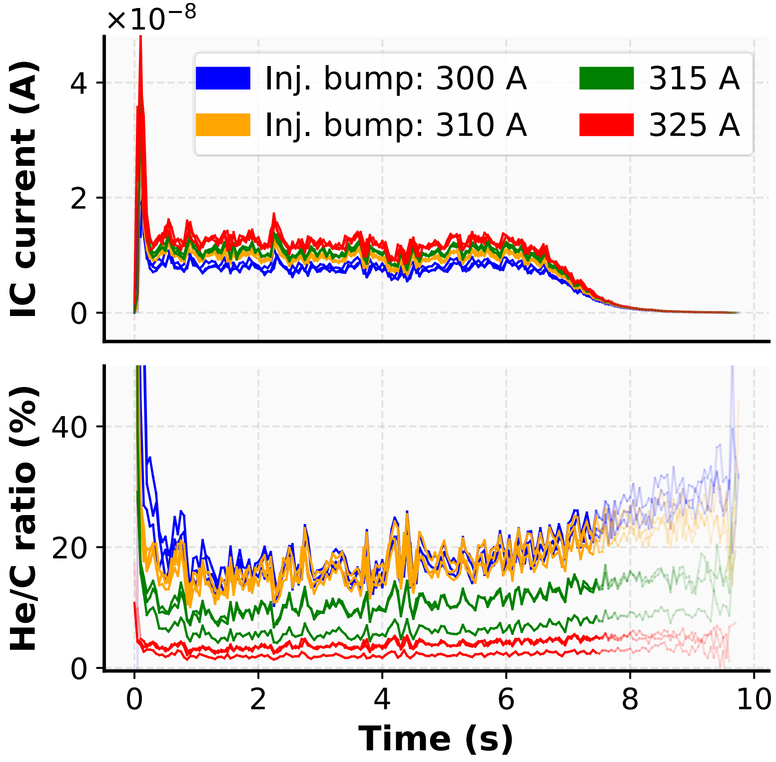
- 200 MeV/u
- Broadband PSK with amplitude modulation
- He:C ratio tailored by adapting the 2nd injection bump amplitude.

Mixing ratio estimate based on synchrotron RF frequency

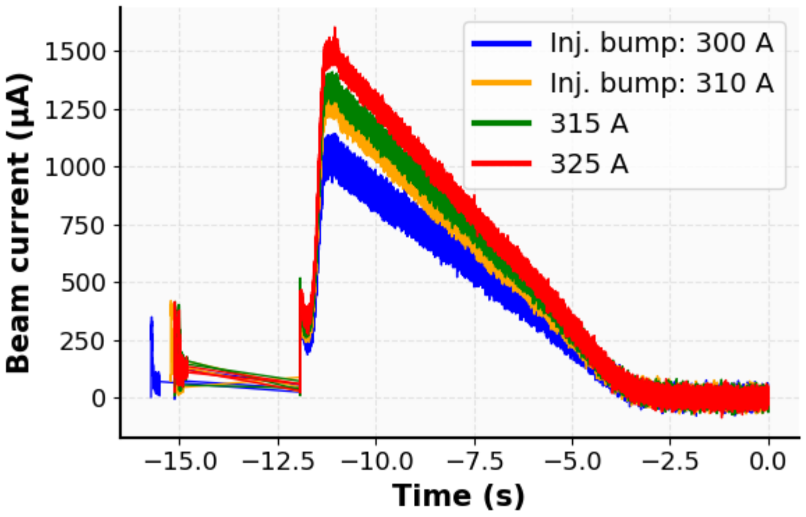




Extraction He:C ratio throughout the spill



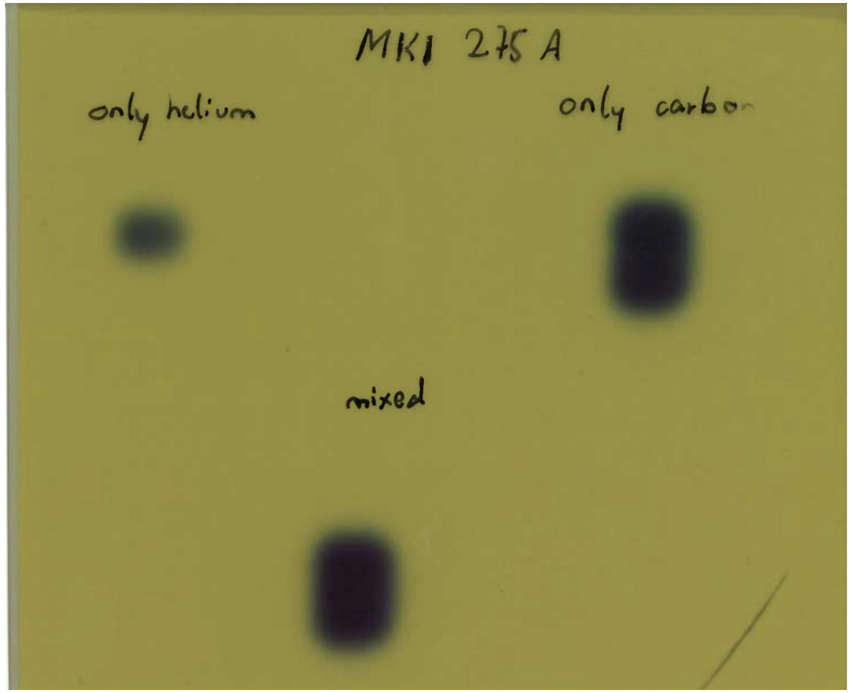
Beam current measurement in the synchrotron

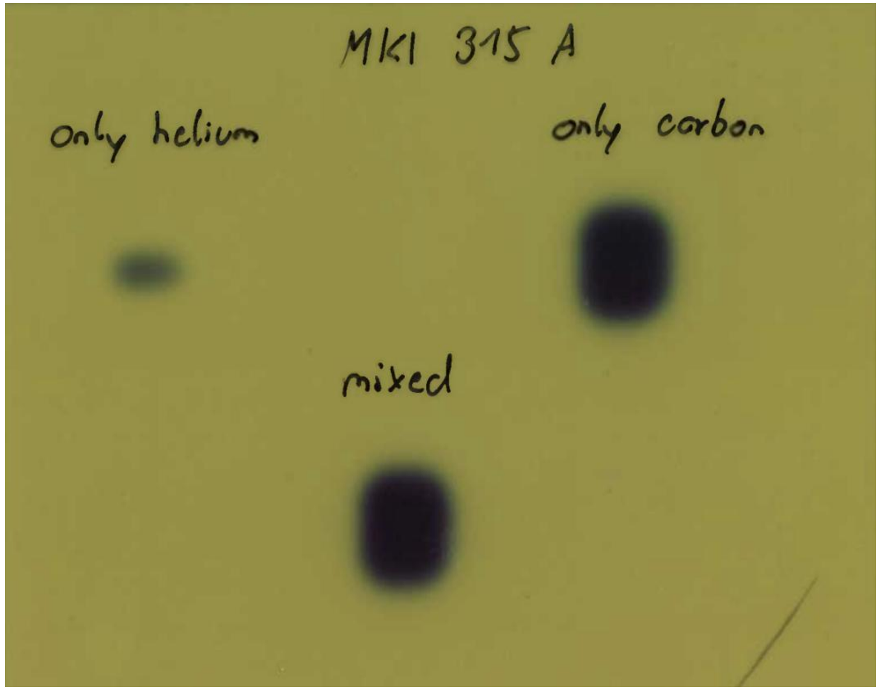


Current measurement: only 1 measurement per setting

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.

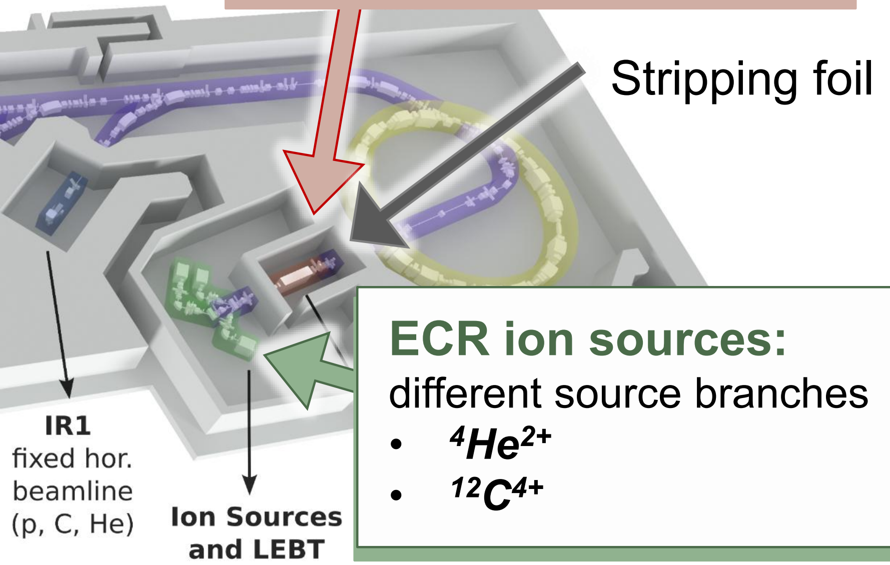




Single Ion Source in Clinical Facilities?

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

LINAC: q/m > 1/3
standard at e.g. MedAustron, CNAO, HIT



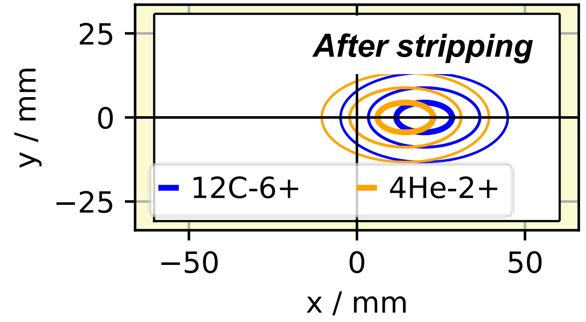
ECR ion sources:
different source branches

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

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

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

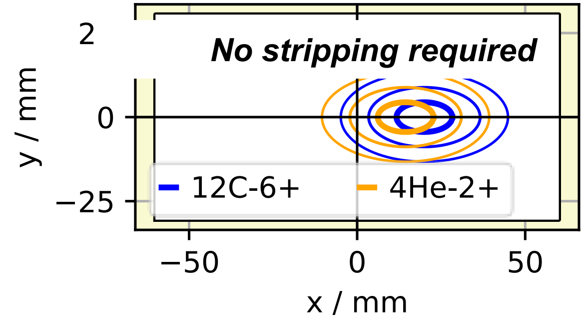
Source ✔ **LINAC ✘** Synchrotron ✔



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

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

Source ✘ LINAC ✔ Synchrotron ✔

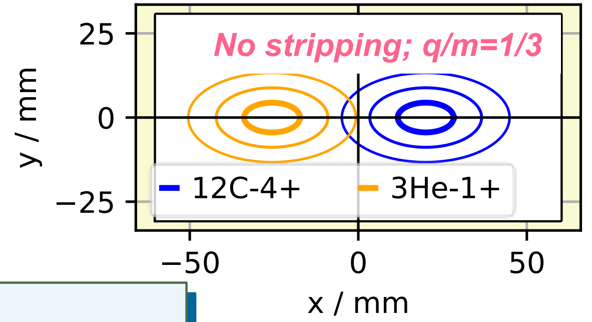


$^{3}He^{1+}$ and $^{12}C^{4+}$

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

Source ✔ LINAC ✔ **Synchrotron ✘**

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

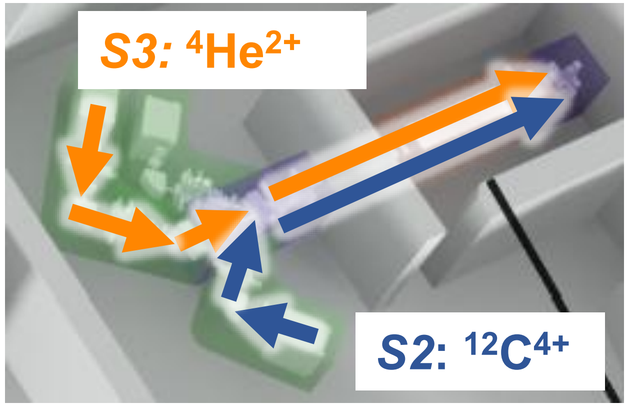


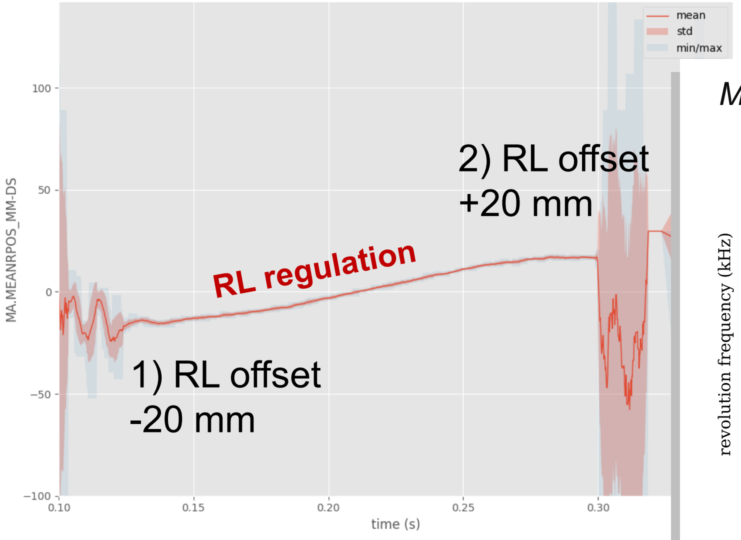
Take away

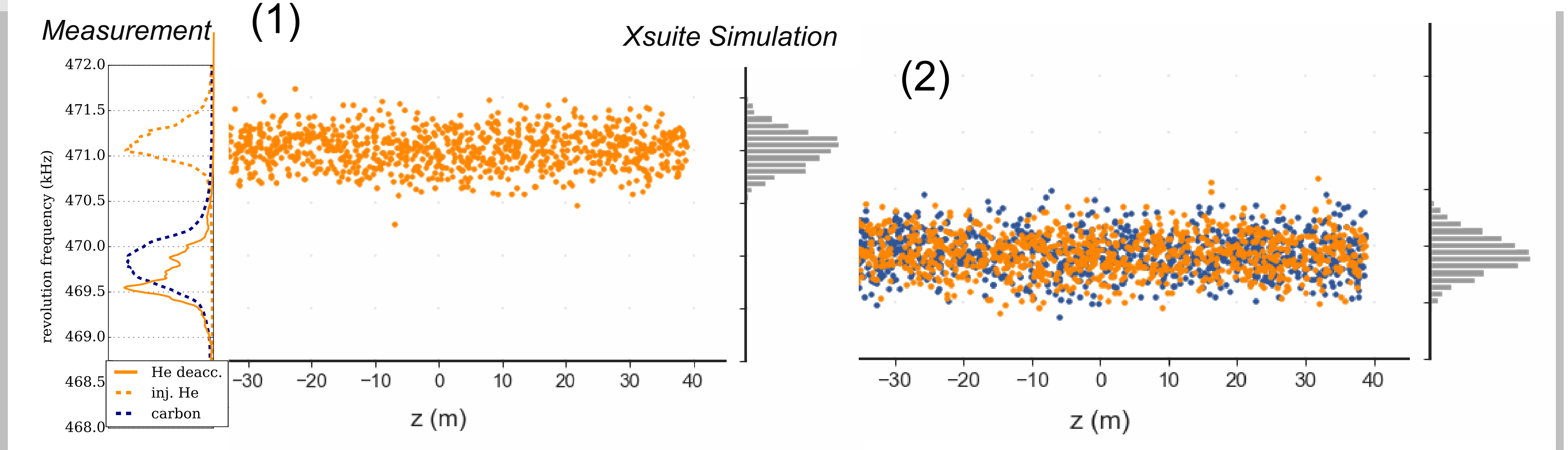
Mixed beam generation **within single ion source currently not possible** in state-of-the-art **medical synchrotron facilities**.

Double Multi-Turn Injection: Technical Challenges @ MedAustron

- **Different injection energies** due to Δq/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