

First mixed He/C ion beams at a clinical facility: Two years from concept to first ion imaging experiment

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Dale Prokopovich, Claus Schmitzer (*MedAustron*), Hermann Fuchs (*Medical University of Vienna*)



TECHNISCHE
UNIVERSITÄT
WIEN



MedAustron^{N*}



MEDIZINISCHE
UNIVERSITÄT WIEN

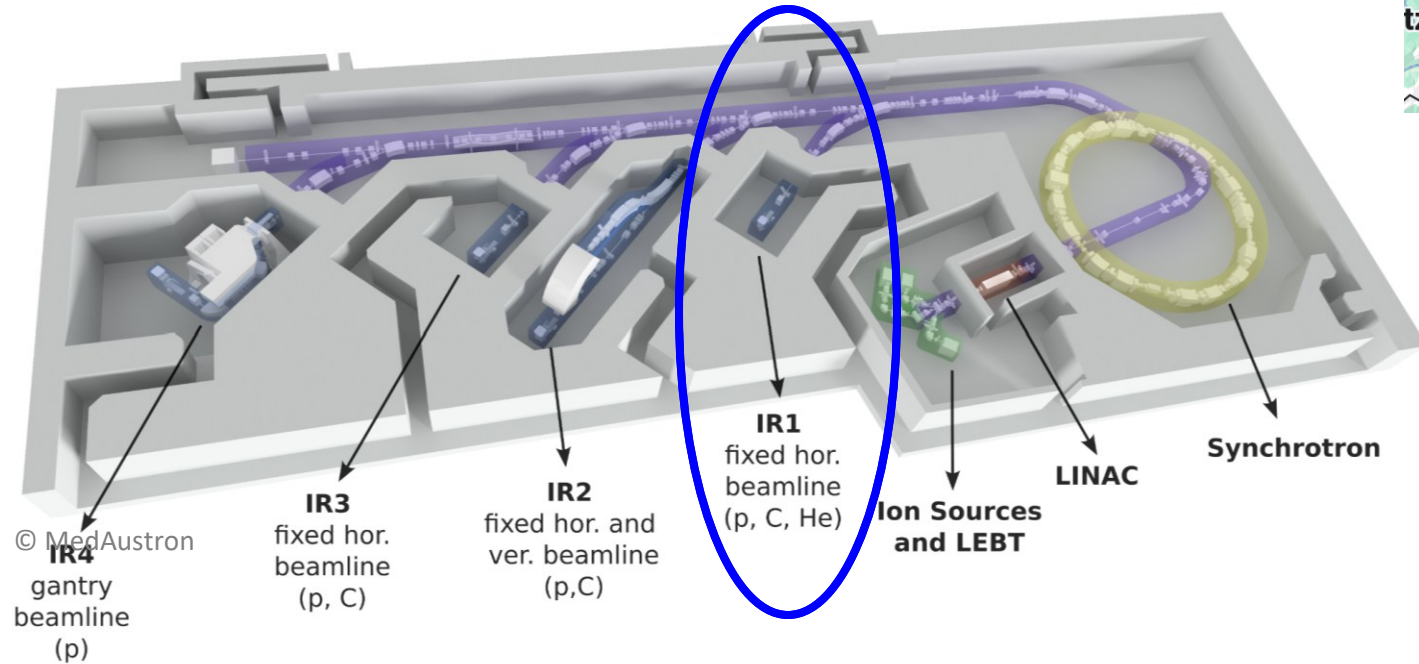
MBI

Marietta-Blau-
Institut für
Teilchenphysik

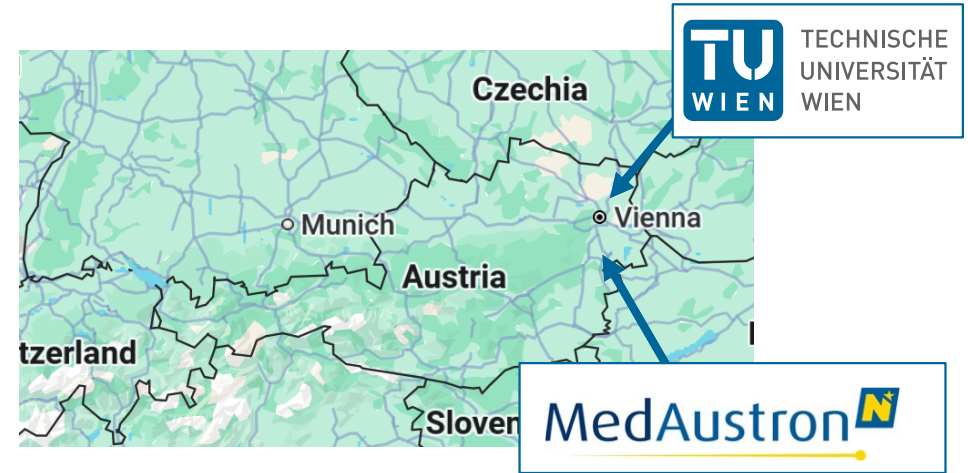
First successful delivery of mixed He/C ion beams for research at MedAustron

MedAustron

Center for ion beam therapy and research in Wiener Neustadt, Austria



Irradiation room for research users (IR1)



	E_{kin} (MeV/u)*
p+	60 – 250; 800
$^{12}\text{C}^{6+}$	120 – 400
$^4\text{He}^{2+}$	40 – 400

*Clinical and research, *research*

Ion beam therapy (IBT)

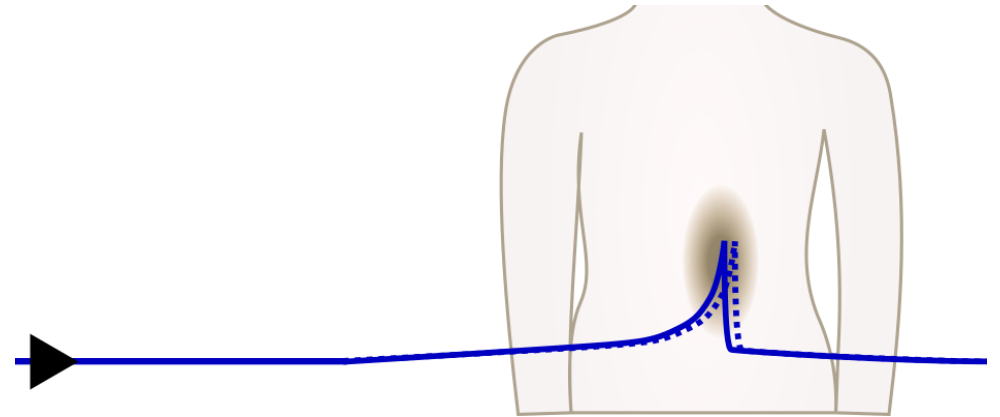
IBT compared to conventional radiotherapy

- + Highly localized dose deposition (Bragg peak)
- + Increased biological effectiveness
- **More sensitive to uncertainties**
(*anatomical changes, CT calibration, ...*)

Accurate treatment planning & monitoring crucial

Several proposals to enhance accuracy via simultaneous treatment & monitoring

- *Prompt- γ imaging, nuclear fragmentation imaging, MR-guided particle therapy, ...* **& mixed beam irradiation.**



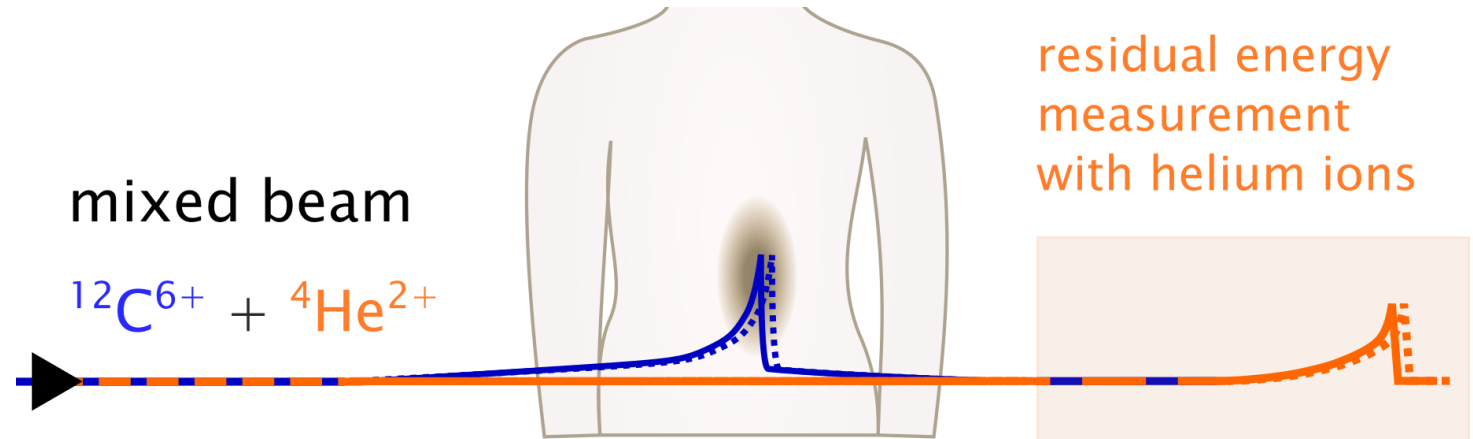
Mixed ion beams for online range verification

Idea: Add small ${}^4\text{He}^{2+}$ contribution (e.g. $\approx 10\%$) to therapeutic ${}^{12}\text{C}^{6+}$ beam [1,2]

- Similar mass-to-charge ratio

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

→ simultaneous delivery possible



- Range of ${}^4\text{He}^{2+}$ approx. 3x larger than of ${}^{12}\text{C}^{6+}$

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

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

New and developing field

- < 2018: First proposals (GSI, CNAO) [e.g. 1,2]
- 2023: First mixed He/C beam extraction from a synchrotron at GSI [3]

2023: Project start at TU Wien & MedAustron

2024: First mixed beam at MedAustron

First in clinical synchrotron facility [4]

Since 2025: First respective medical physics experiments at MedAustron

Objective: Deliver mixed beams to research users at MedAustron using existing infrastructure (*no clinical setup*)

- WP1: Mixed beam generation
- WP2: Mixed beam acceleration
- WP3: Mixed beam slow extraction
- WP4: Mixed beam diagnostics

This talk

[1] D. Mazzucconi *et al.*, Med. Phys. 45 (11), 2018 [3] M. Galonska *et al.*, IPAC'24, WEAN1

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

[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)

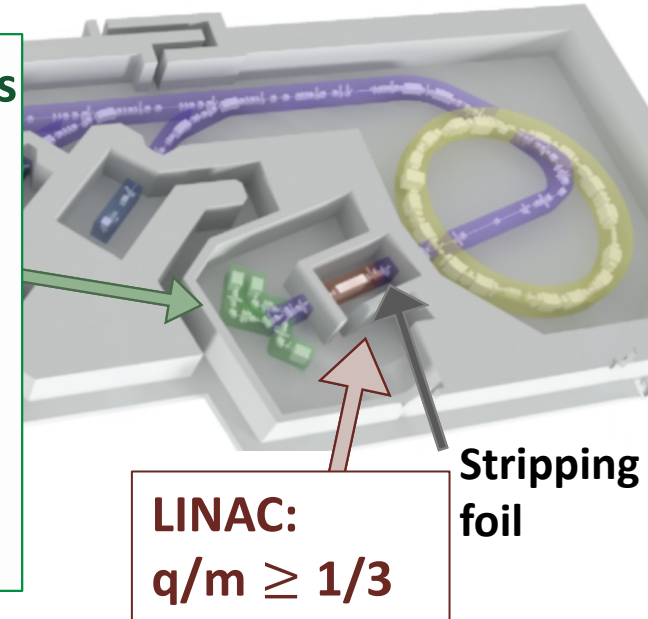
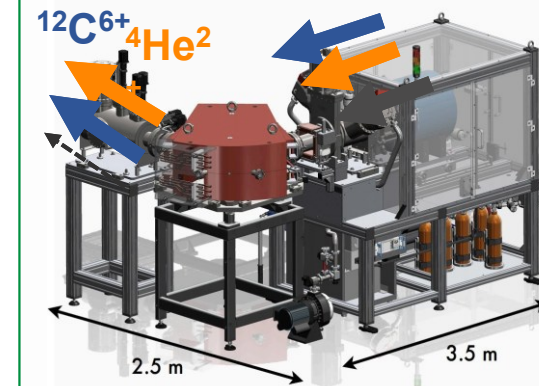
WP 1: Mixed beam generation

Generation of mixed He/C beams in single ion source?

- Employed for mixed beam delivery at GSI [3]

- With existing infrastructure **not possible at MedAustron** [4] or comparable clinical synchrotron facilities

14.5 GHz ECR ion sources

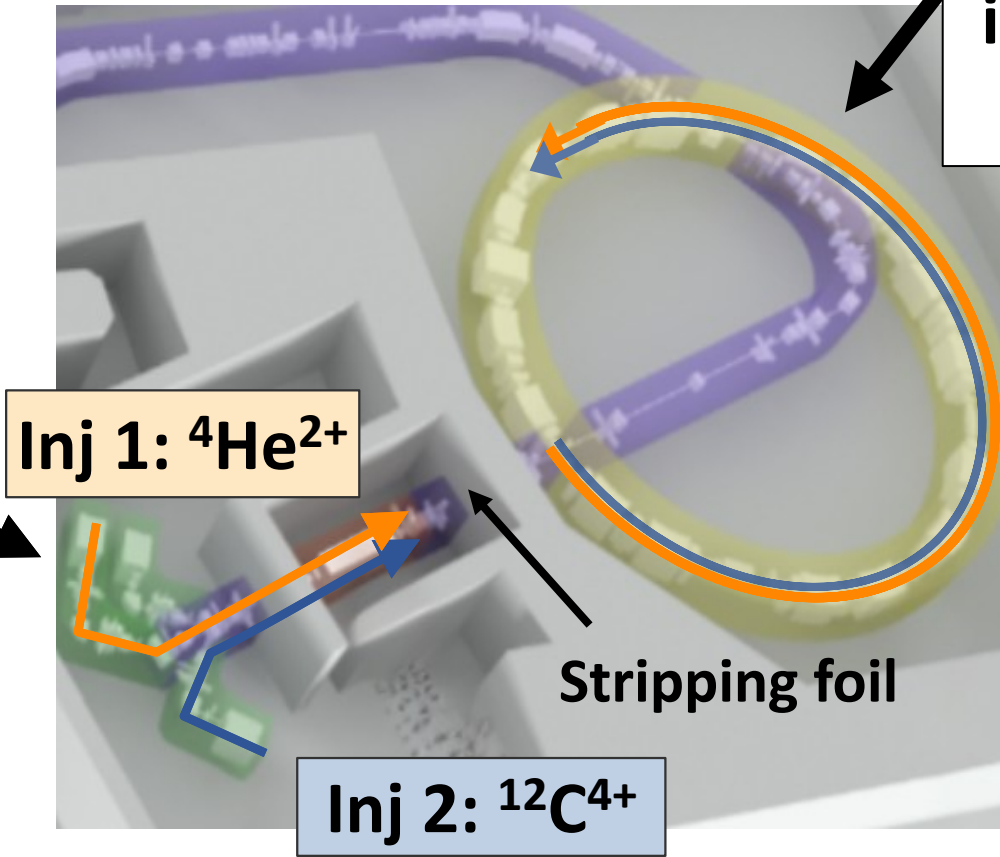


Ion pair	q/m LINAC	q/m Synch.	$\Delta(q/m)/(q/m)$	Source	Linac	Synch.	
${}^4\text{He}^+ / {}^{12}\text{C}^{3+}$	1/4	1/2	$\approx -6.5 \cdot 10^{-4}$	✓	✗	✓	LINAC requires $q/m \geq 1/3$
${}^4\text{He}^{2+} / {}^{12}\text{C}^{6+}$	1/2	1/2	$\approx -6.5 \cdot 10^{-4}$	✗	✓	✓	14.5 GHz ECRIS: insufficient ${}^{12}\text{C}^{6+}$ yield
${}^3\text{He}^+ / {}^{12}\text{C}^{4+}$	1/3	1/3	$\approx -5.3 \cdot 10^{-3}$	✓	✓	✗	Synch.: limited E for $\frac{q}{m} = \frac{1}{3}$, large $\frac{\Delta(B\rho)}{B\rho}$

[3] M. Galonska *et al.*, IPAC'24, WEAN1 [4] M. Kausel *et al.*, PRAB 28, 111001 (2025)

Mix ion species via new double multiturn injection (DMTI) into synchrotron [4,5]

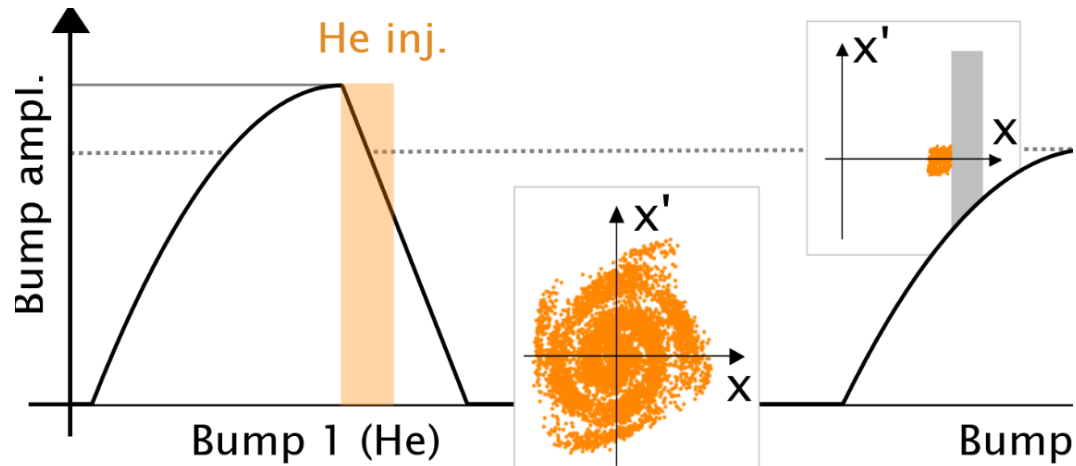
Keep generating He & C ions in separate ion sources



[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)
[5] M. Kausel *et al.*, IPAC'25, TUPB099

Mix beam via double multiturn injection into synchrotron

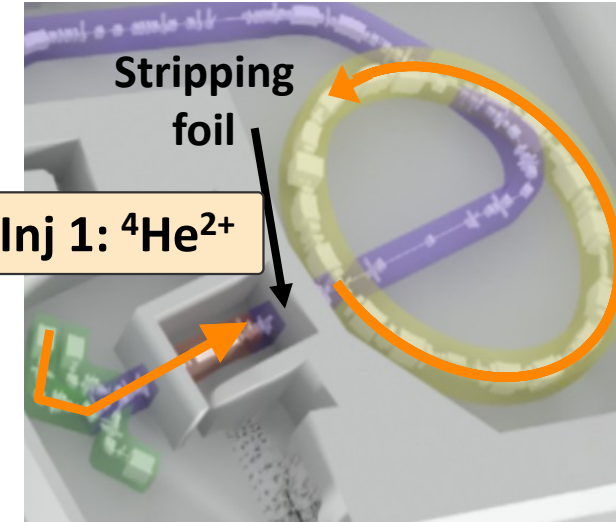
1. Helium multiturn injection (MTI)



3. Ramp orbit bump again to prepare for carbon MTI

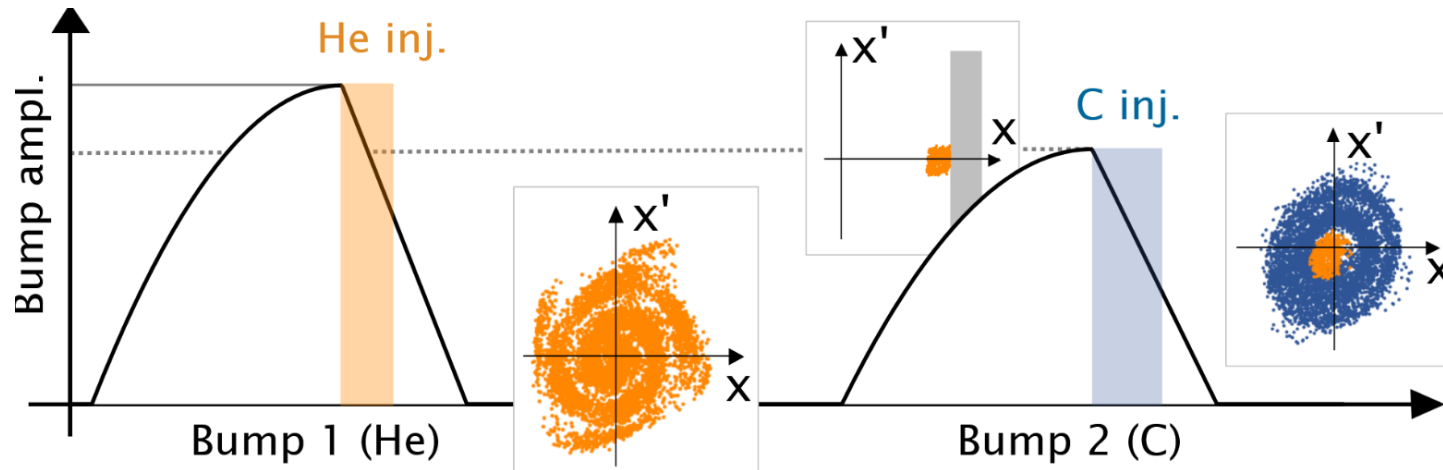
2. Keep He at flat-bottom while re-configuring injector

Reduced amplitude to maintain small He core

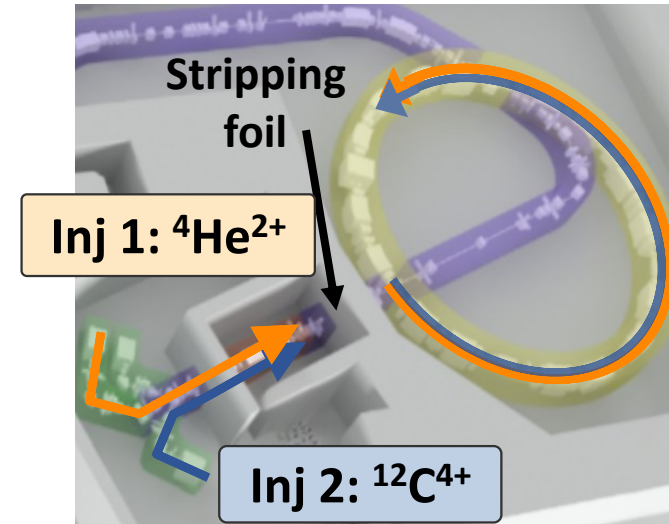


[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)
[5] M. Kausel *et al.*, IPAC'25, TUPB099

Mix beam via double multiturn injection into synchrotron



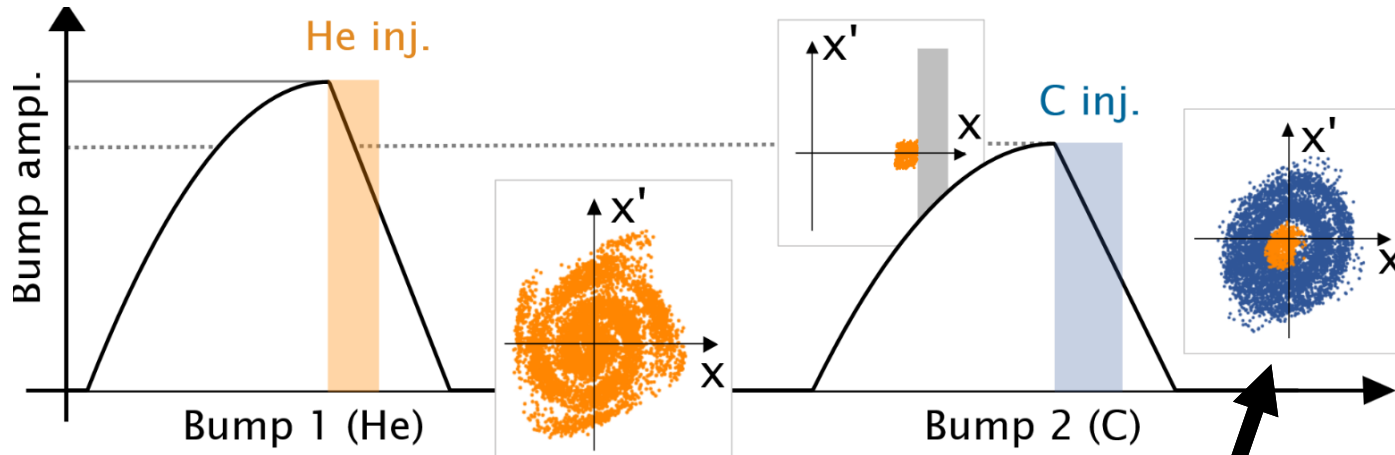
4. Multiturn injection of carbon on top of He



[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)

[5] M. Kausel *et al.*, IPAC'25, TUPB099

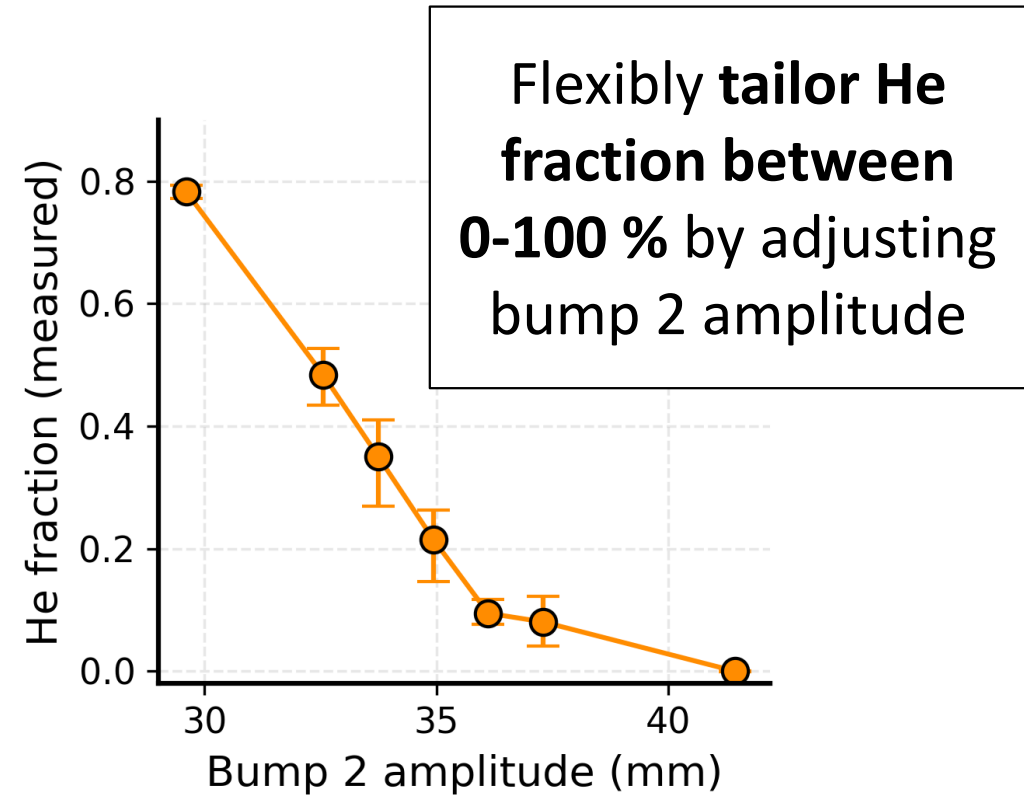
Mix beam via double multiturn injection into synchrotron



Distinct horizontal phase space distributions

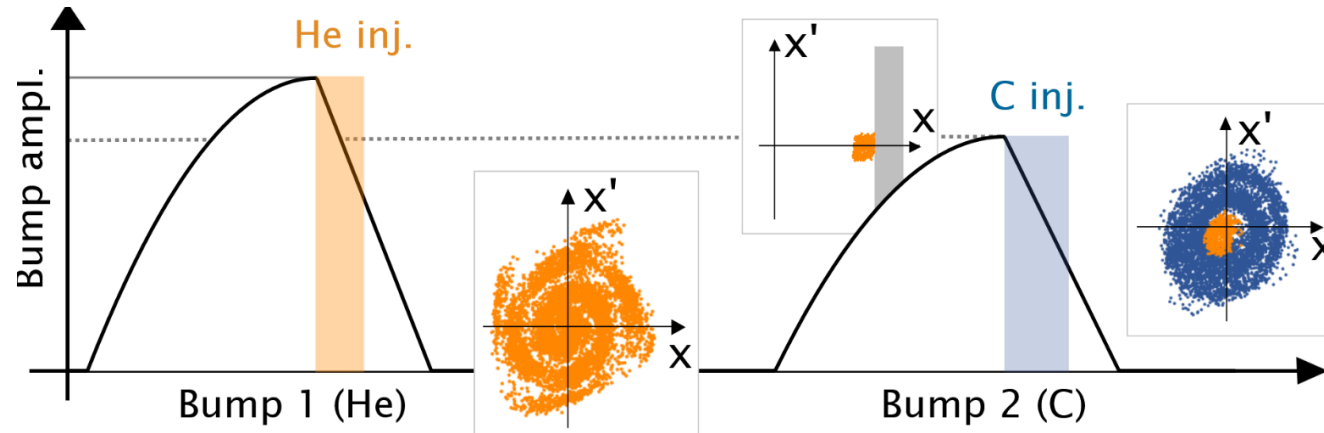
- Helium core
- Carbon annulus

Measured profile of a pure carbon beam with DMTI settings



[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)
 [5] M. Kausel *et al.*, IPAC'25, TUPB099

Mix beam via double multiturn injection into synchrotron



Implementation not straight forward

More information:

[4] M. Kausel *et al.*, PRAB 28, 111001 (2025)

[5] M. Kausel *et al.*, IPAC'25, TUPB099



M. Kausel
(MedAustron):
TUP8004 (Tuesday)

2025: DMTI at GSI for first acceleration of mixed beams with unequal m/q in a synchrotron (Fe, Bi)



D. Ondreka (GSI): THV4001
(Thursday, invited poster)

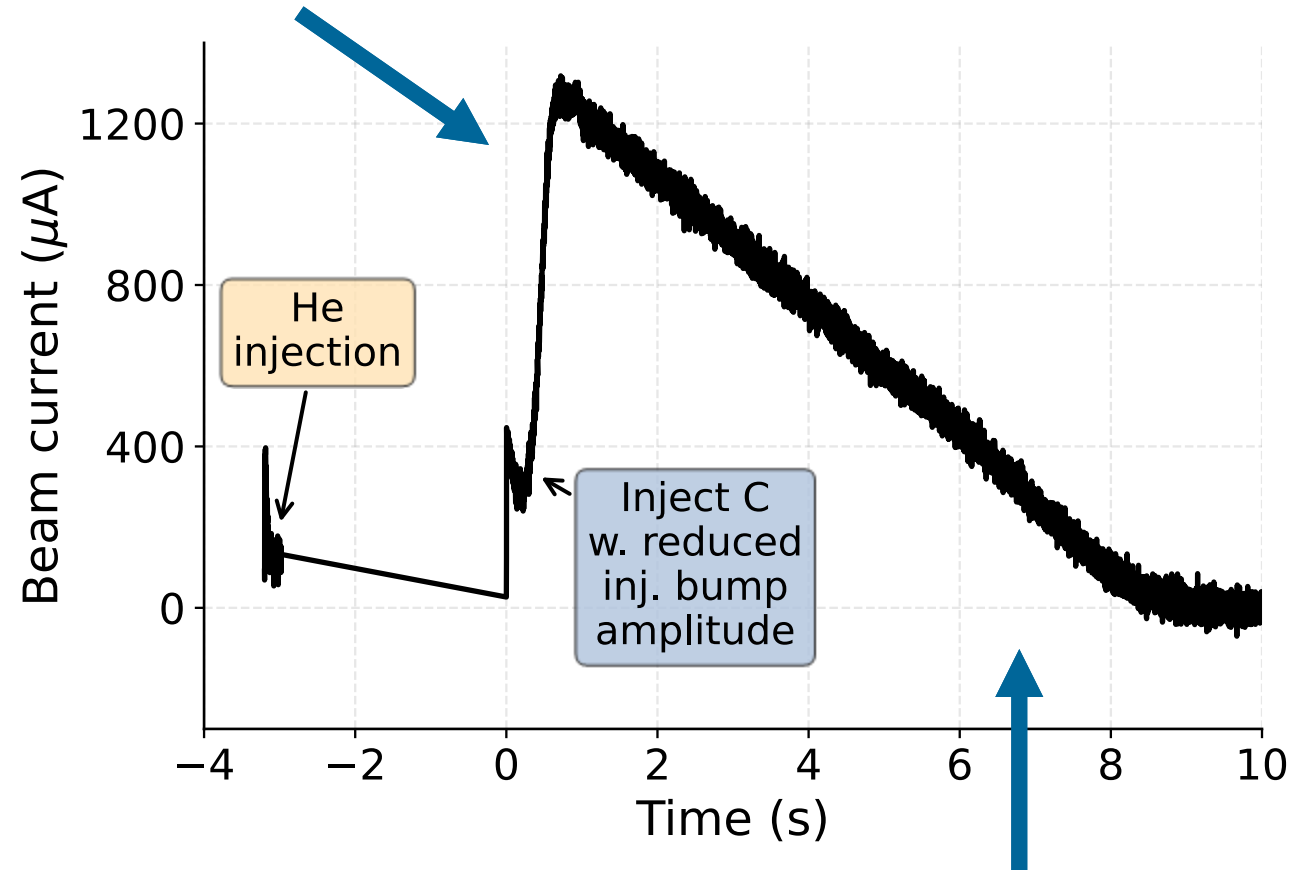
WP 2: Mixed beam capture & acceleration (120-400 MeV/u)

- Acceleration operationally no challenge
- But: Small offset in m/q between He and C**

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

affects particle motion

→ needed to be understood to prepare slow extraction studies.



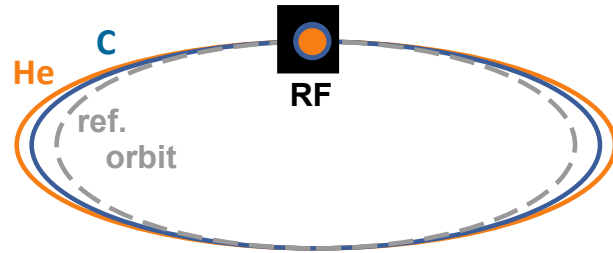
WP 3: Mixed beam slow extraction

Mixed beam acceleration in synchrotrons

He larger $m/q \rightarrow$ more rigid \rightarrow longer path

$$B\rho = \frac{m\gamma\beta c}{q}$$

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



Take away: Both contributions add up
 \rightarrow total magnetic rigidity offset

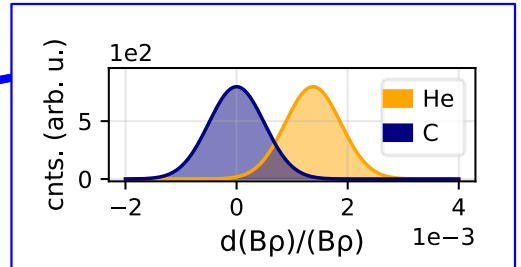
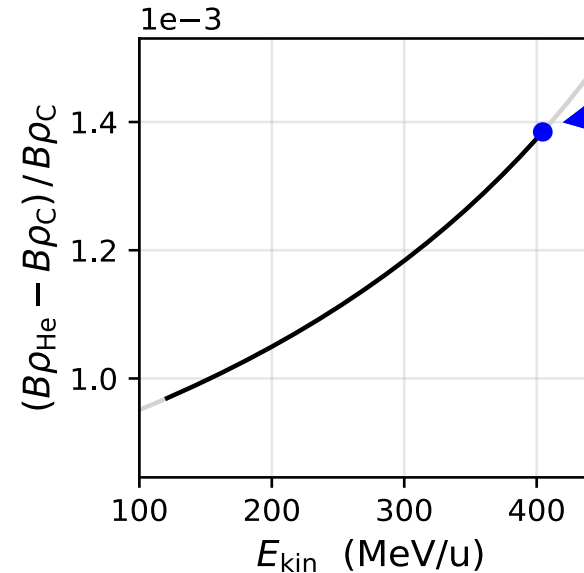
$$\frac{d(B\rho)}{B\rho} = \hat{\delta} + \frac{q_C/m_C}{q_{He}/m_{He}} - 1 \quad (\text{linearized})$$

With RF on: $f_{He} = f_C = f_{RF}$

\rightarrow He accelerated to higher velocities

Resulting $\frac{p}{m} = \beta\gamma$ offset depends on proximity to transition energy γ_{tr} :

$$\hat{\delta} = \frac{\Delta(p/m)}{p/m} = \frac{\gamma^2}{\gamma_{tr}^2 - \gamma^2} \cdot \left(\frac{q_C/m_C}{q_{He}/m_{He}} - 1 \right)$$



Rigidity offset at MedAustron ($\gamma_{tr} \approx 2$) for different extraction energies:

0.095 % -1.35 %

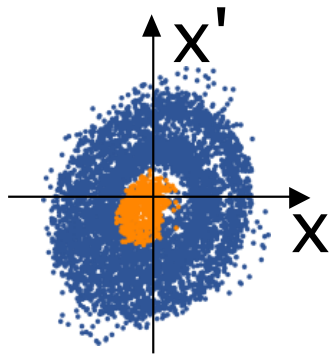
More details: [6] E. Renner *et al.*, submitted to PRAB (2026), <https://arxiv.org/abs/2603.01088>

Mixed beam slow extraction

Target: Maintain approx. constant He:C ratio while delivering the beam to the patient over 1-10s

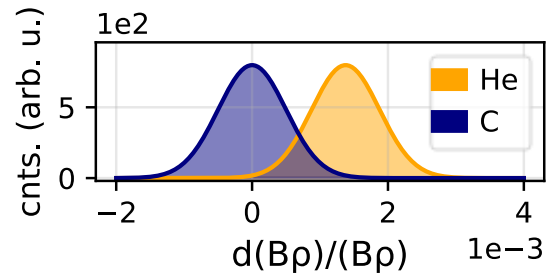
But: Differences in beam distributions

Distinct **horiz.**
phase space
distributions ...



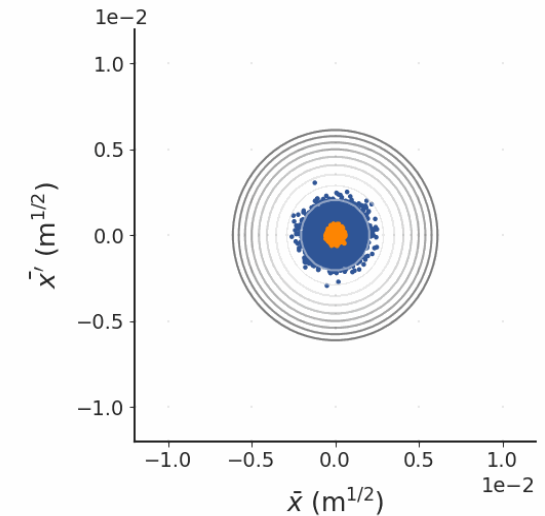
&

(Energy-dependent)
offsets in **beam rigidity**



For $Q' \neq 0 \rightarrow$ **tune offset**

Species-specific dynamics
during slow extraction



Mixed beam slow extraction: Status



E. Renner (TU Wien): [THP4091](#) (Thursday)

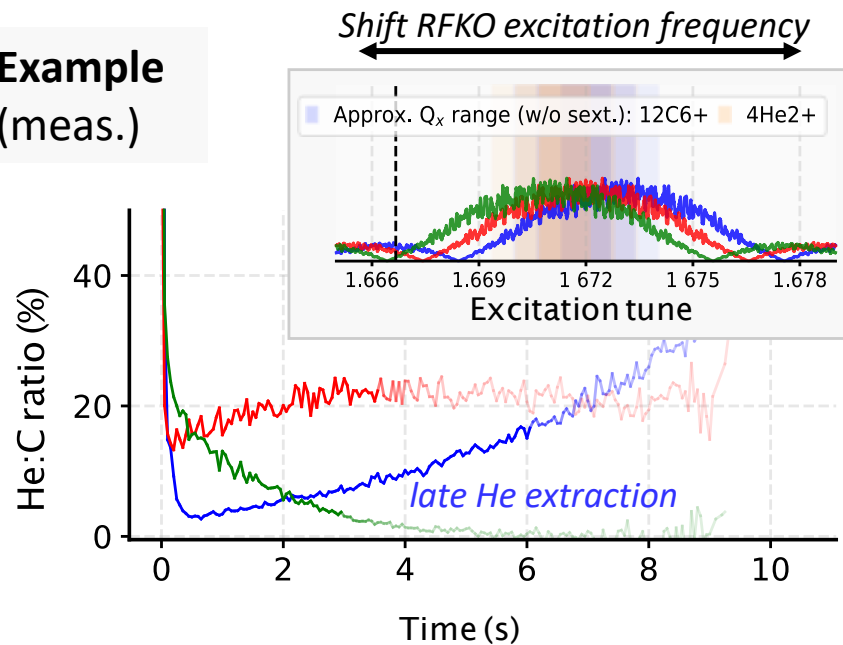
A. Pastushenko (GSI): [THP4093](#) (Thursday)

RF knockout (RFKO) slow extraction

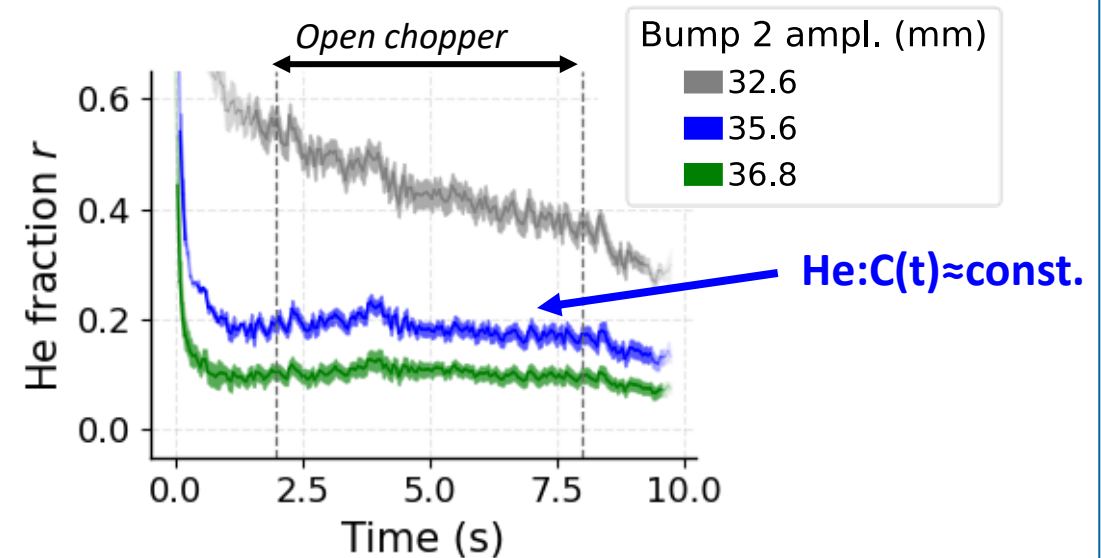
Knobs for tailoring time evolution of extracted He/C ratio:

- RFKO signals (for $Q' \neq 0$), chromaticity, ...

Example (meas.)



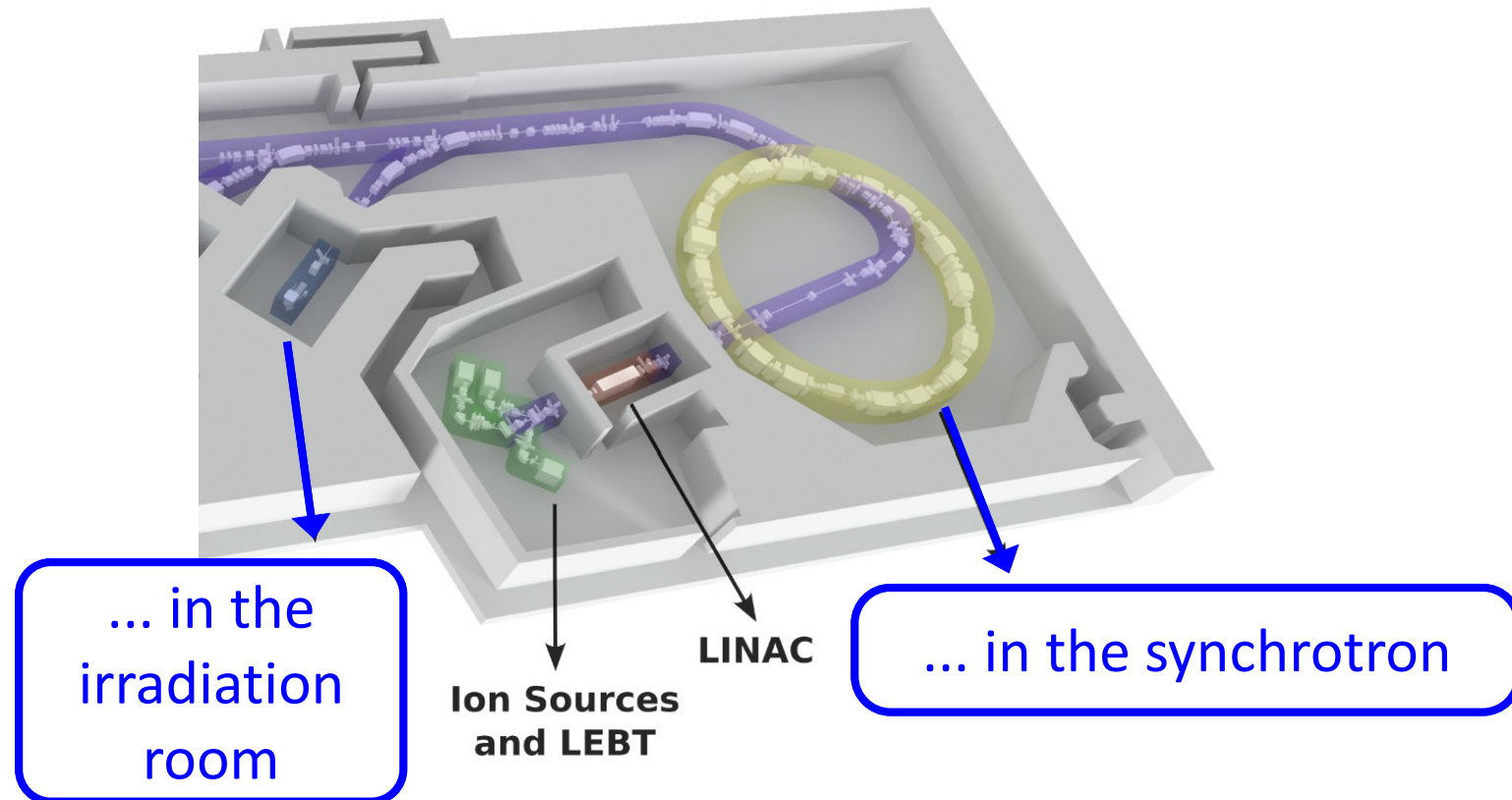
Preliminary setup for first experiments empirically established



Several open topics \rightarrow continue **Xsuite simulations** and **experiments** to enhance understanding & control

WP 4: Mixed beam diagnostics

Develop diagnostic tools, that allow to distinguish He from C ions ...

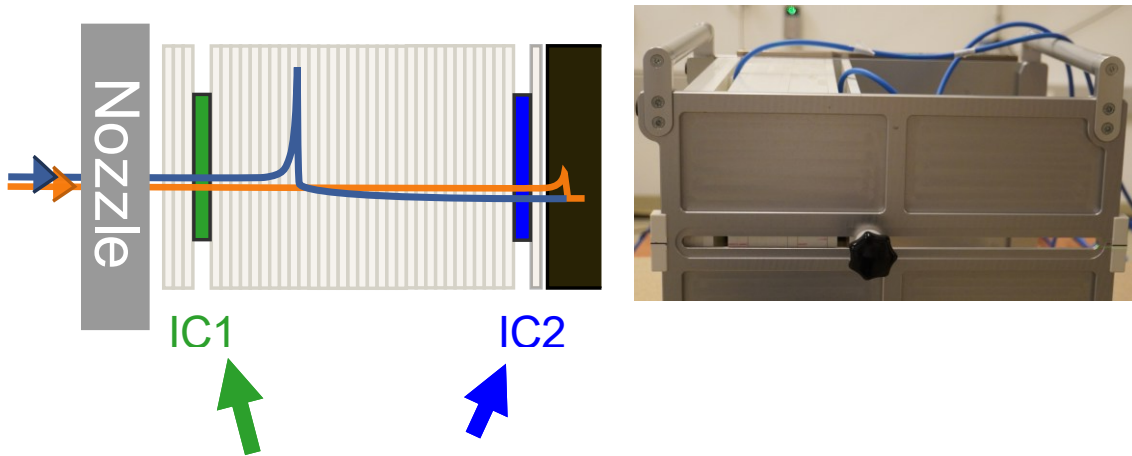


Mixed beam diagnostics developments

Irradiation room:

E.g. measure time evolution of extr. He:C ratio

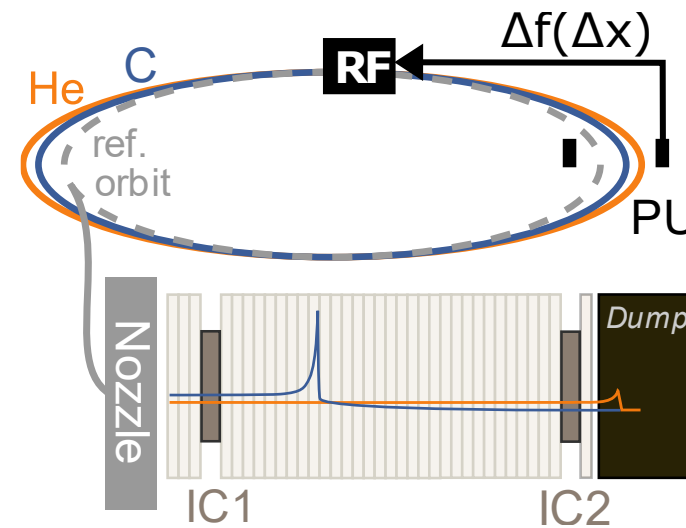
Two-stage ionization chamber (IC) telescope [6]



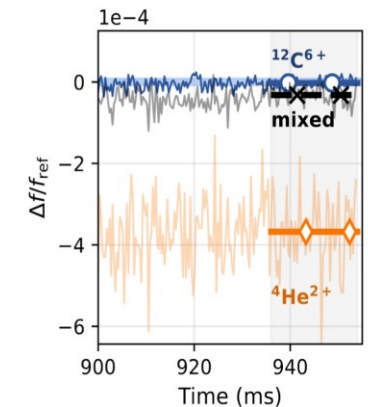
Retrieve He:C ratio from currents in **ICs before/after** carbon Bragg peak

New method to noninvasively measure helium fraction in the synchrotron [6]

Rigidity offset \rightarrow composition-dependent dispersive orbit shift

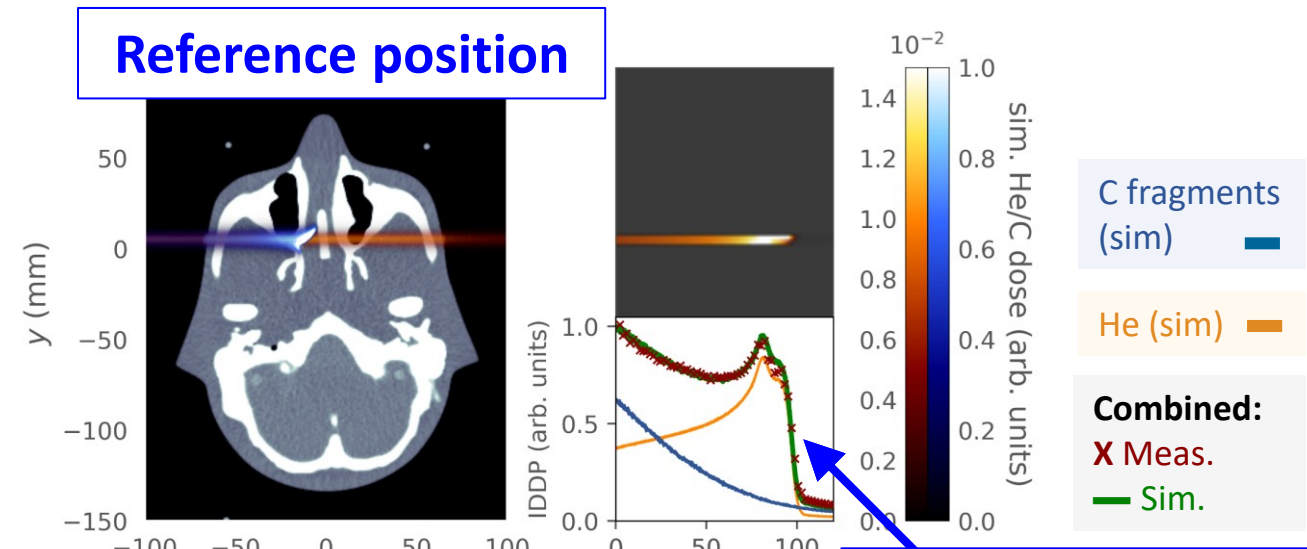
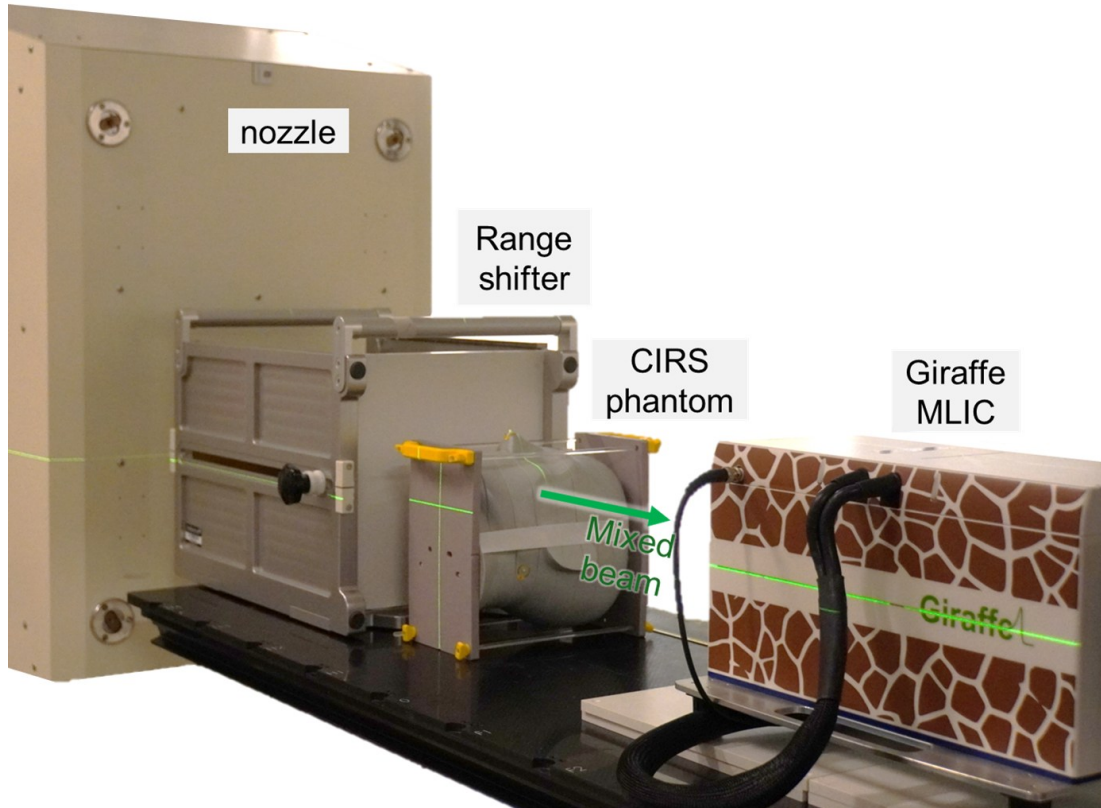


Reconstruct He:C ratio from radial loop frequency correction

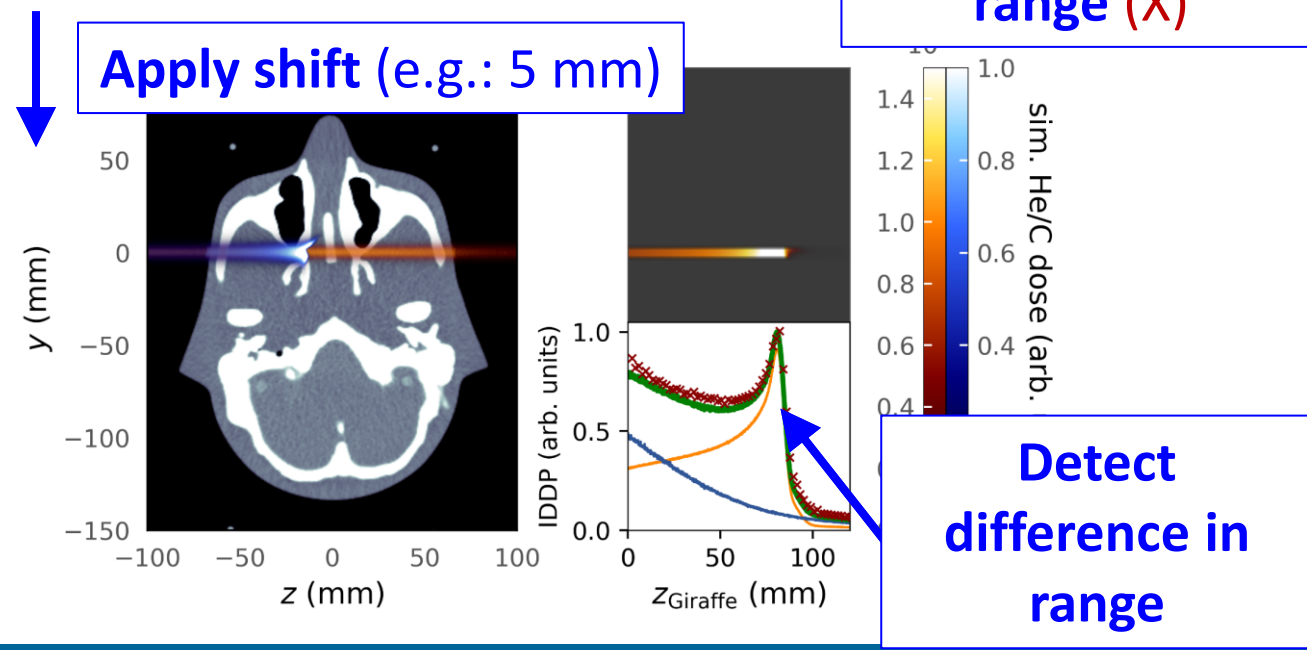


First medical physics experiments

Example: Irradiation of head phantom



Measure Helium range (X)

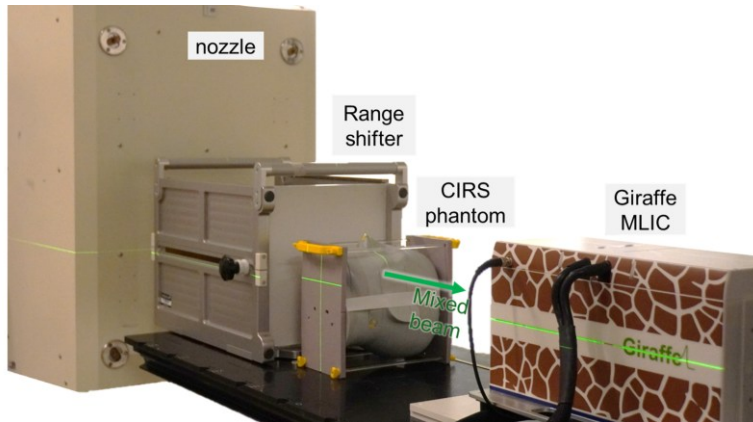


Detect difference in range

Yihan Jia (MedAustron), Matthias Kausel (MedAustron, TU Wien)

Application & development of different detection systems

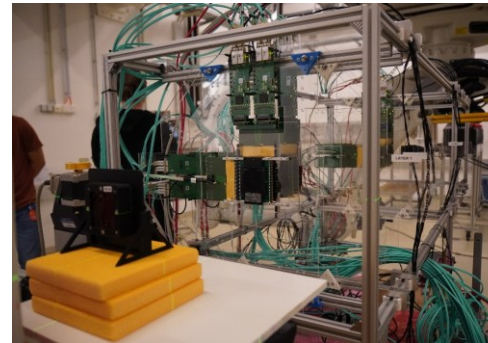
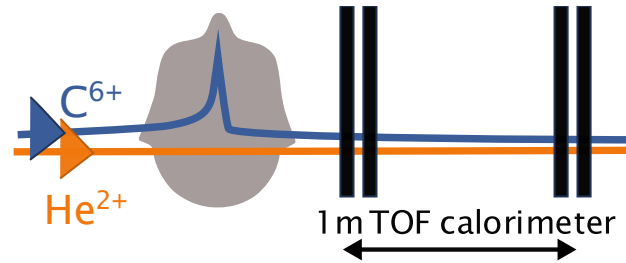
Giraffe Multilayer Ionization Chamber by IBA Dosimetry



Yihan Jia (MedAustron)

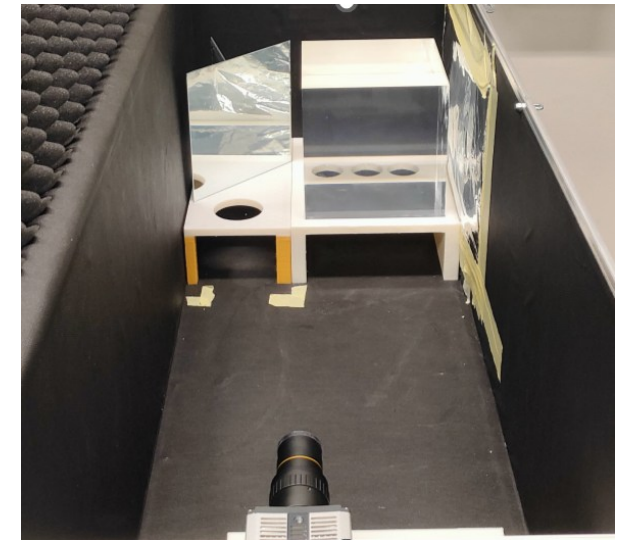
Time-of-flight (TOF) ion computed tomography system [7]

(TU Wien/MBI/GSI)



[7] Felix Ulrich-Pur *et al.*, Phys. Med. Biol. 69 075031, 2024

CNAO, GSI, UCL: Scintillation detectors [1,8]



[1] D. Mazzucconi *et al.*, Med. Phys. 45 (11), 2018
[8] L. Volz *et al.*, <https://arxiv.org/abs/2603.12975> (2026)

Fig.: Courtesy of M. Pullia (CNAO)

Summary and outlook

- **Mixed beam delivery R&D at TU Wien/MedAustron**
 - First mixed He/C beam in clinical synchrotron facility (*research setup*)
 - Regular delivery to medical physics experiments at MedAustron
- **Ongoing accelerator R&D**
 - Short-term: Improve research setup (*efficiency, reproducibility,...*)
 - Long-term: Methods for transitioning from research to clinical setup?
- **Importance of R&D close to clinical experience**
 - Mixed beam in clinical facility with dedicated research room = unique opportunity!
- **Growing interest of other user communities**



The poster features a stylized illustration of a synchrotron accelerator ring on the left and a particle beam path on the right. The text 'Mixed Ion Beams 26' is prominently displayed at the top right. Below the illustration, the text '1st Workshop on Mixed Ion Beam Delivery' is written in large, bold letters. A QR code is located on the left side of the lower half, and the dates 'October 8-9, 2026' and location 'TU Wien | Vienna | Austria' are on the right. At the bottom, logos for TU Wien, GSI, CNAO, and MedAustron are shown.

Mixed Ion Beams²⁶

1st Workshop on
Mixed Ion Beam Delivery

October 8-9, 2026
TU Wien | Vienna | Austria

<https://indico.global/event/17265/>

TU WIEN GSI CNAO MedAustron^N



Mixed Ion Beams 26

1st Workshop on
Mixed Ion Beam Delivery



October 8-9, 2026
TU Wien | Vienna | Austria

<https://indico.global/event/17265/>



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- **TU Wien**: C. Becker, D. Eichler, H. Handerkas, A. Hirtl, K. Holzfeind, F. Ulrich-Pur, N. Okropiridze, **E. Renner**
- **MedAustron**: L. Adler, A. Cherit, N. Gambino, L. Grevillot, G. Guidoboni, Y. Jia, **M. Kausel**, L. Kelleter, M. Pivi, F. Plassard, D. Prokopovich, V. Rizzoglio, C. Schmitzer, I. Strasik, O. Triebel, M. Wolf, ... OPS, MTA, MP departments
- **Medical University of Vienna**: H. Fuchs
- **Marietta Blau Institute**: T. Bergauer, A. Gsponer
- **CNAO**: M. Pullia, S. Savazzi
- **GSI**: A. Pastushenko, D. Ondreka

... and many others.

References

- [1] D. Mazzucconi *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] M. Galonska *et al.*, “First dual isotope beam production for simultaneous heavy ion radiotherapy and radiography”, in *Proc. IPAC’24*, Nashville, USA, 2024
- [4] M. Kausel *et al.* “A double multi-turn injection scheme for generating mixed helium and carbon ion beams at medical synchrotron facilities” *Phys. Rev. Accel. Beams*, vol. 28, no. 11, p. 111001, 2025
- [5] M. Kausel *et al.* “Recent developments in delivering mixed helium and carbon ion beams at MedAustron”, in *Proc. IPAC’25*, Taipei, Taiwan, 2025
- [6] E. Renner *et al.*, “Noninvasive ion fraction quantification of dual-species beams in synchrotrons”, submitted to PRAB (2026) arXiv:2603.01088 [physics.acc-ph]
- [7] F. Ulrich-Pur “First experimental time-of-flight-based proton radiography using low gain avalanche diodes” *Phys Med Biol* 69 (2024)
- [8] L Volz *et al.*, “Mixed Ion Beams Enable Simultaneous Treatment and Real-Time Imaging in Carbon Ion Therapy” arXiv:2603.12975v1 [physics.med-ph] (2026)