TECHNISCHE UNIVERSITÄT WIEN

Mixed Beams @ MedAustron: *Acceleration and Extraction*

5th Ion Imaging Workshop | Vienna, Austria | 21.-22.10.2024

Elisabeth Renner, Atominstitut, TU Wien
elisabeth.renner@tuwien.ac.at

Matthias Kausel, MedAustron / TU Wien

Claus Schmitzer, MedAustron

The financial support of the Austrian Ministry of Education, Science, and Research is gratefully acknowledged for providing beam time and research infrastructure at MedAustron.

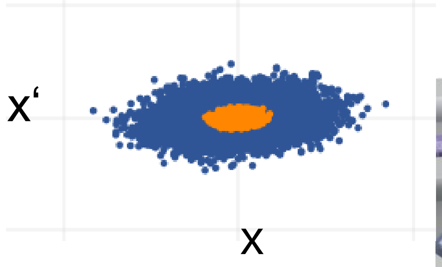
Background & Outline

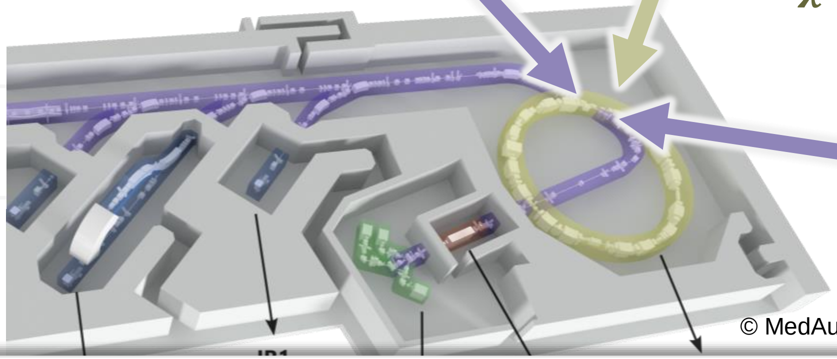
Following the double-injection, the **helium and carbon ions** in the **MedAustron synchrotron** exhibit *(see Matthias Kausel's talk)…*

… a **beam rigidity offset** in the **synchrotron** due to **the charge-to-mass ratio difference** *(even for the same $^{E}/_{m}$)*

$$\chi = \frac{q_{He}}{m_{He}} \Big/ \frac{q_C}{m_C} = 0.99935 \qquad \frac{d\,(B\rho)}{(B\,\rho)} \approx 6 \times 10^{-4}$$

… different horizontal beam distributions.





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… an E/m offset during injection into the synchrotron

(prior to RF capture, because of different q/m in the LINAC).

$$\frac{d\,(B\rho)}{(B\,\rho)} \approx 5 \times 10^{-3}$$

Outline

- Impact of E/m **difference** on **RF capture + mitigation measures**
- Impact of q/m **difference** on the **acceleration in the synchrotron**
- Impact of q/m **difference** and **transverse beam sizes** on the **extraction process**

Synchrotron RF Concepts Relevant for this Talk

RF field oscillation must **be in synchromism with arrival time** of the particles.

Synchronous particle

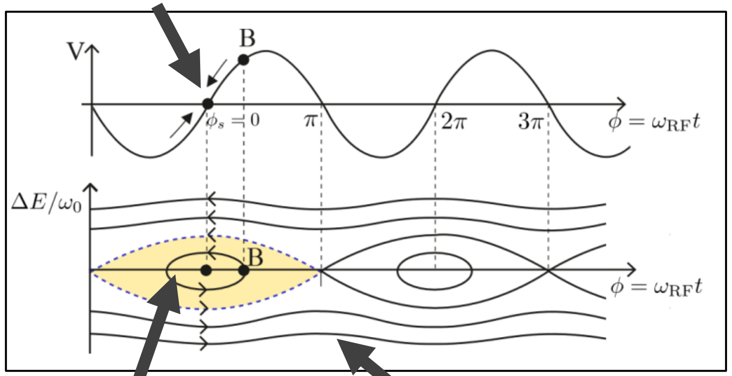
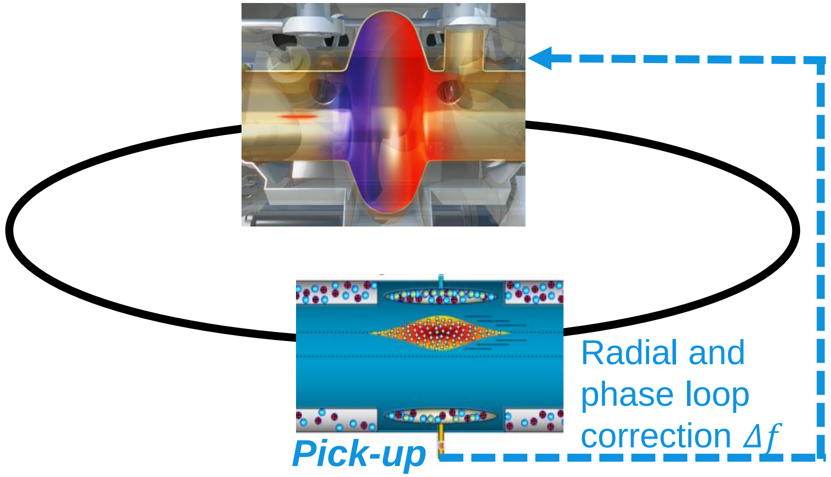


FIGURE CREDITS: V. FORTE PHD THESIS

Particles in **stable "bucket" oscillate around synchronous particle** (bunched beam).

Off-bucket particles will be **lost** during acceleration.

RF cavity



RF feedback loops

- take pick-up measurements (bunch phase, horizontal offset) as input

to **apply frequency correction Δf** to the RF system, regulating

- beam energy (horizontal offset; radial loop)
- bunch phase (arrival time; phase loop)

"RF capture"

= switching the RF system on to capture part of the unbunched beam within the RF bucket.

1. Inject beam with RF system turned off.

2. Start RF capture with fixed f_{RF}.

3. Activate RF feedback loops.

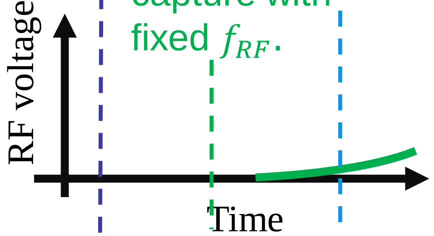


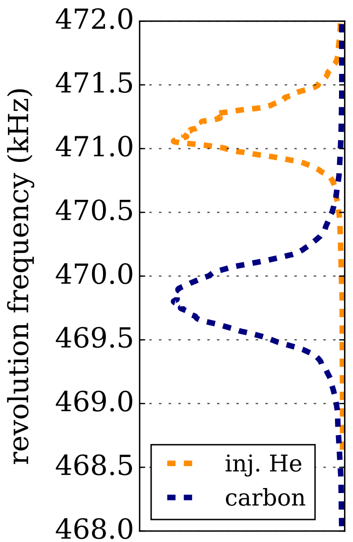
FIGURE CREDITS: : HTTPS://ARXIV.ORG/PDF/2005.14081.PDF (PICK-UP); CERN (CAVITY ANIMATION)

Mixed beam acceleration: initial challenges …

We generally aim to **maintain machine settings (**magnetic fields, RF setup) **similar as for clinical C beams**.

- **But: capturing** the ion mix **with a fixed frequency that is optimized for $^{12}C^{6+}$ …**
- **…** is **"messy"** due to the **injection energy offset** (low capture efficiency of $^{4}He^{2+}$, $^{4}He^{2+}$ disturbs RF feedback loops, …).

Measured **revolution frequency distribution.**



Simulation of the longitudinal phase space towards the end of the **capture process.**

▶ *Capture with fixed frequency optimized for carbon*

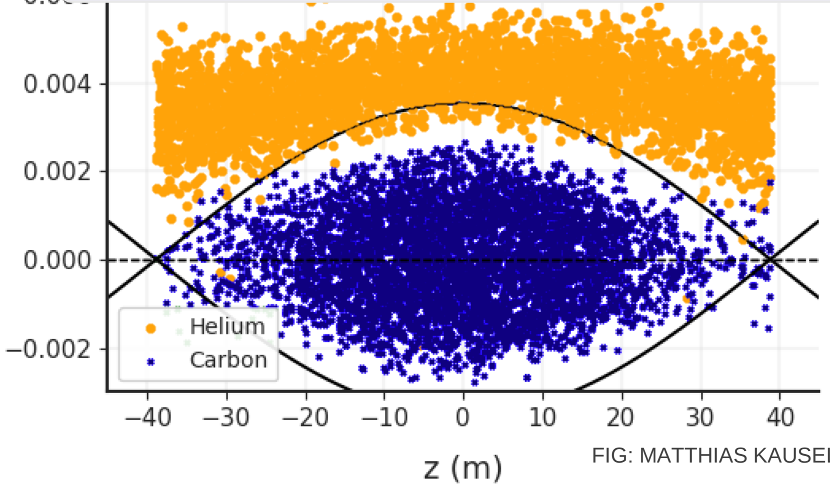
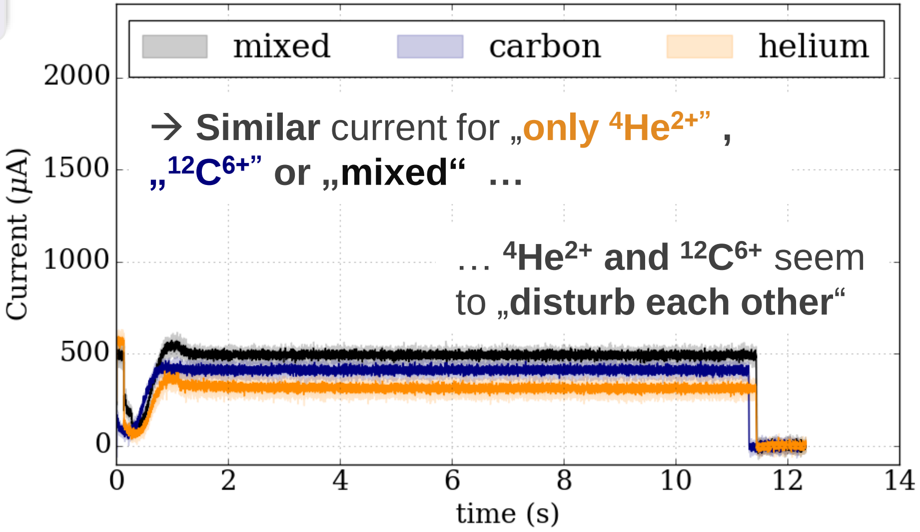


FIG: MATTHIAS KAUSEL

Beam current measured in the **synchrotron.**



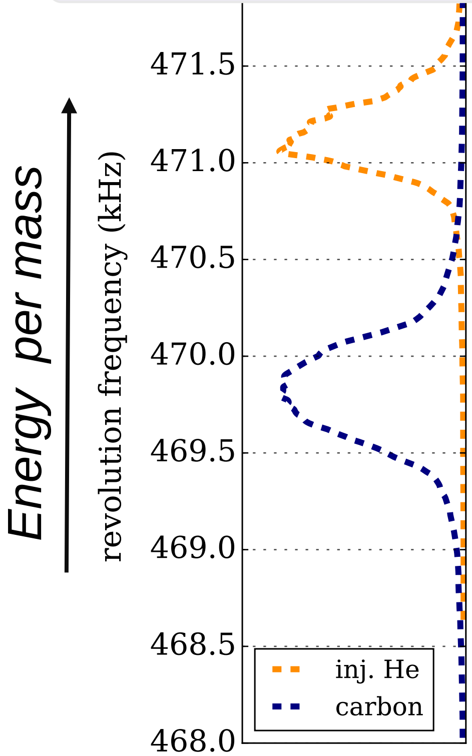
262 MeV; capture w/o prior He-deceleration

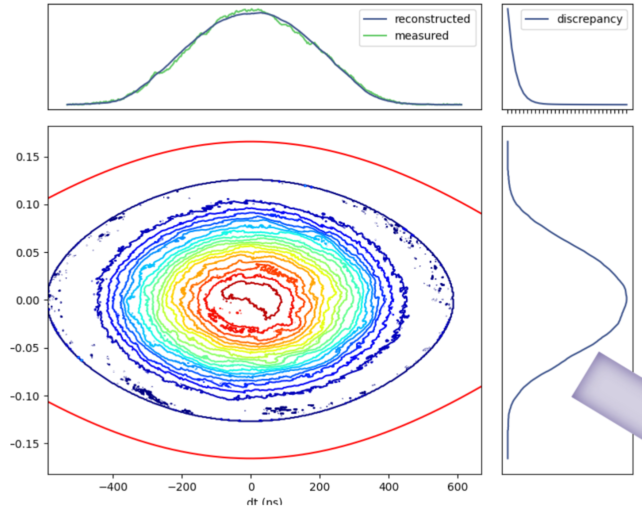
M. Kausel; IPAC'24; https://doi.org/10.18429/JACoW-IPAC2024-THPR42

Mitigation: Decelerate Helium in 1st cycle …

… prior to injecting carbon + subsequent mixed beam capture in 2nd cycle.

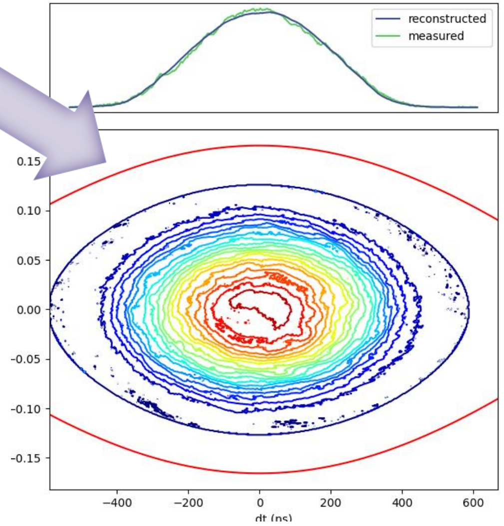
❶ **Inject $^{4}He^{2+}$** in 1st cycle (with energy offset).



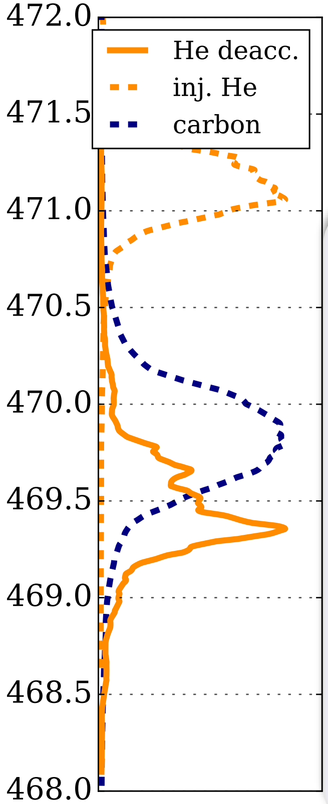


❷ **Capture $^{4}He^{2+}$** in the 1st cycle with RF **frequency adapted to** revolution frequency of $^{4}He^{2+}$.

❸ **Decelerate $^{4}He^{2+}$** in the 1st cycle **to match $^{12}C^{6+}$ frequency.**



MEASUREMENTS OF LONG. PHASE SPACE DISTRIBUTION: KATRIN HOLZFEIND



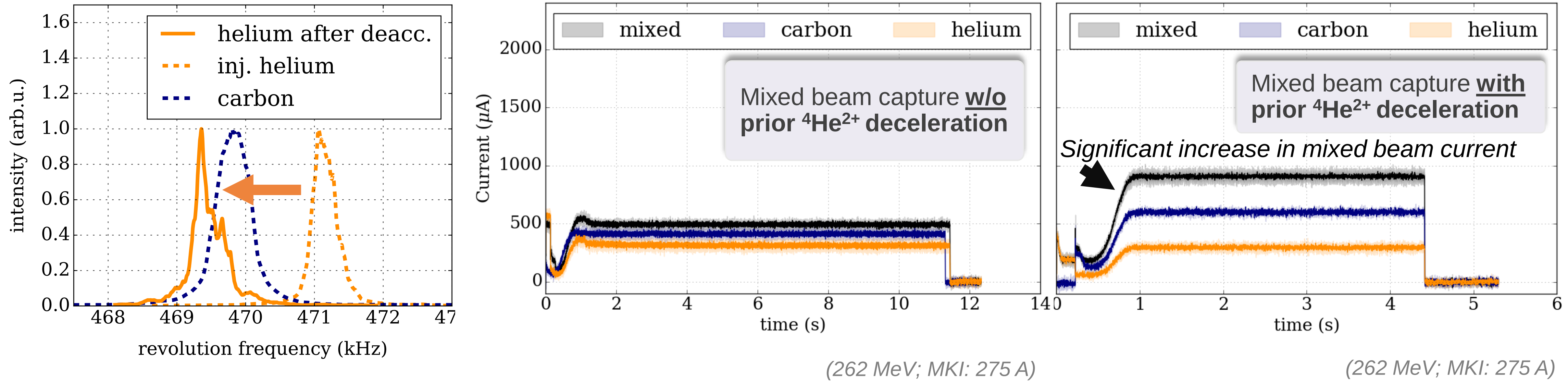
❹ **2nd cycle:**

- Turn RF system off;
- **Inject $^{12}C^{6+}$** (2nd cycle);
- **Capture both** ion species **together** with **RF frequency optimized for $^{12}C^{6+}$** .

Helium deceleration: Proof-of-principle

First proof-of-principle attempts for $^{4}He^{2+}$ **deceleration** look **promising.**

- Frequency ramp not yet optimized.

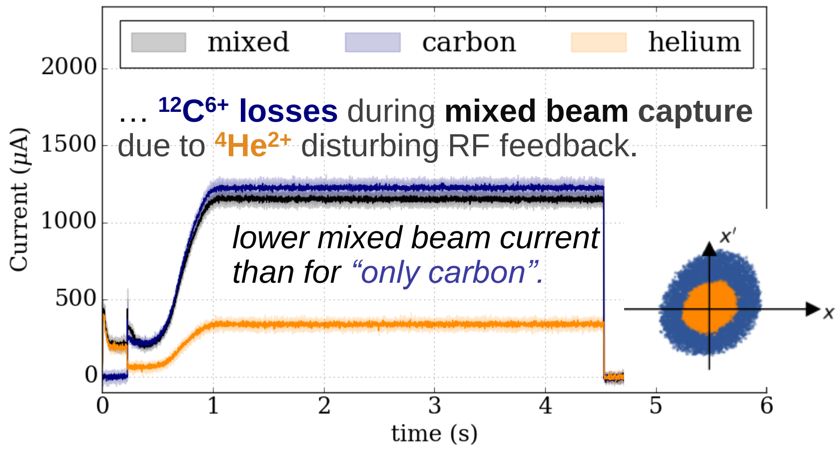


Note: **Complex combination of different loss mechanisms!**

→ It is ***not*** straight-forward to conclude from “only-helium” or “only-carbon” current on He:C ratio in the mixed beam!

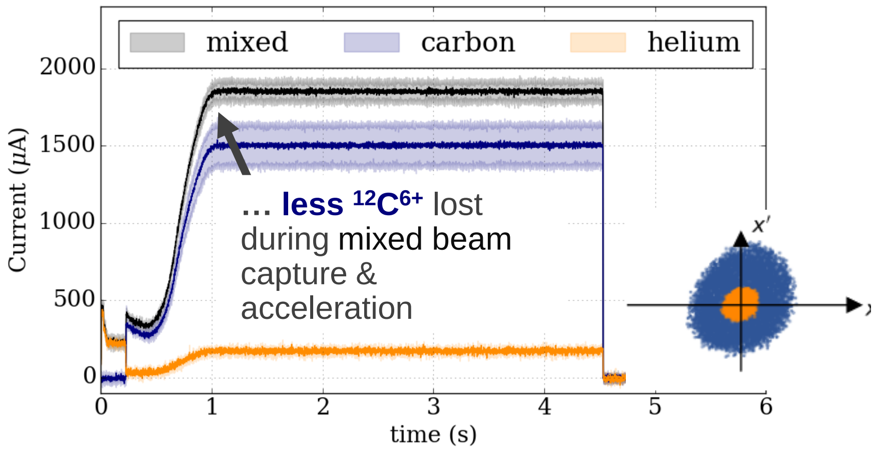
Convoluted loss mechanisms during mixed beam capture

Lower carbon inj. bump amplitude → maintain **more** $^{4}He^{2+}$ during $^{12}C^{6+}$ injection (before capture)…



(He deceleration, 402 MeV; MKI: 275 A)

Increase carbon inj. bump amplitude → maintain **less** $^{4}He^{2+}$ during $^{12}C^{6+}$ injection:



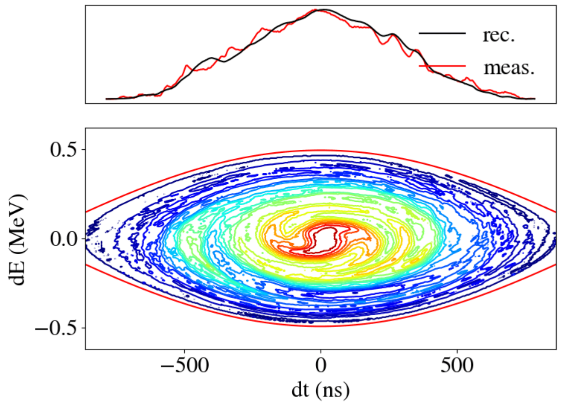
(He deceleration, 402 MeV; MKI: 300 A)

Take away

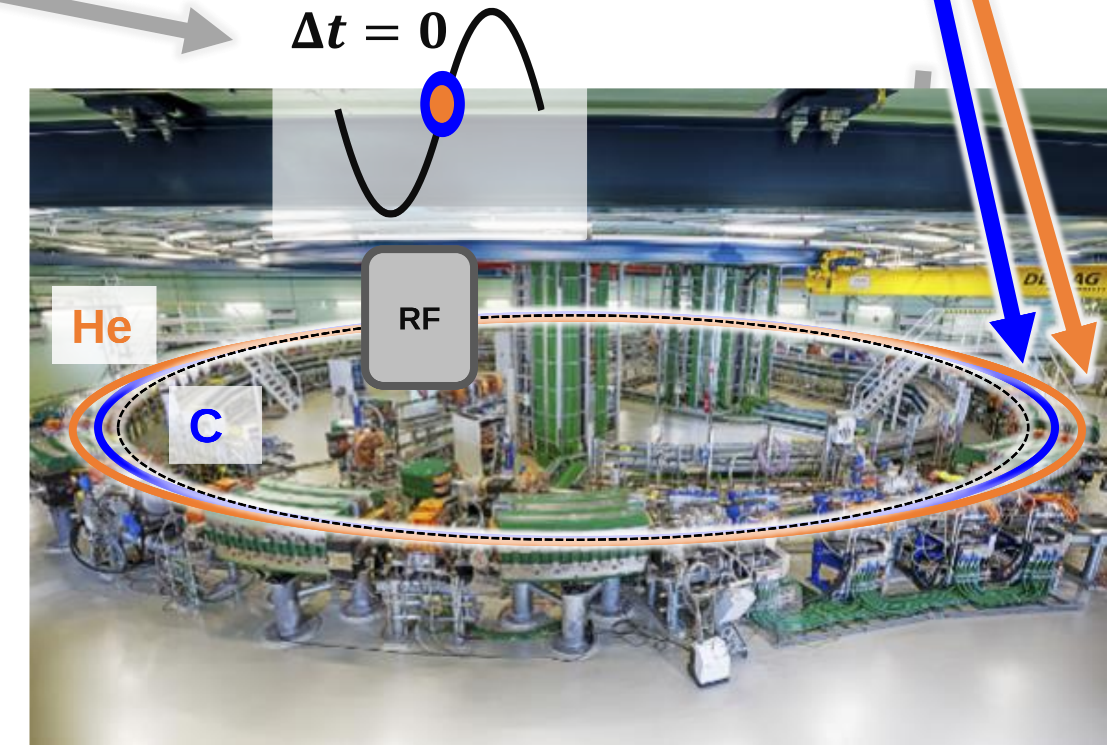
Interconnected loss processes during the **sequential injection and capture** process make it **complex to control** and know the final He/C ratio

- **Decelerating** $^{4}He^{2+}$ before mixed beam capture **promising,** but **excess** $^{4}He^{2+}$ with **large energy offsets** can still **disturb** $^{12}C^{6+}$ **distribution** and **cause** $^{12}C^{6+}$ **losses.**
- Detailed meas. and simulation studies are needed to enhance control over tailoring helium content.

Impact of charge-to-mass offsets on acceleration



After capture, **synchronous** $^{4}He^{2+}$ and $^{12}C^{6+}$ **particle** must arrive at the RF cavity at the correct phase, and hence feature the same revolution frequency;



… despite moving on orbits with different path lengths due to the (small) rigidity difference;

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

$$\frac{d\,(B\rho)}{(B\,\rho)} \approx 6 \times 10^{-4}$$

… **$^{4}He^{2+}$ will be accelerated** to slightly **higher velocities** (and hence E/m) than **$^{12}C^{6+}$.**

E. Renner, IPAC'24; https://doi.org/10.18429/JACoW-IPAC2024-THPR43
E. Renner, Slow Extr. '24; https://indico.gsi.de/event/18184/contributions/76328/

Acceleration to Slightly Different Energy per Mass

- This velocity difference **increases the *effective beam rigidity offset*** even further:

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

Contribution from q/m difference
$\chi = \frac{q_{He}}{m_{He}} / \frac{q_C}{m_C} = 0.99935$

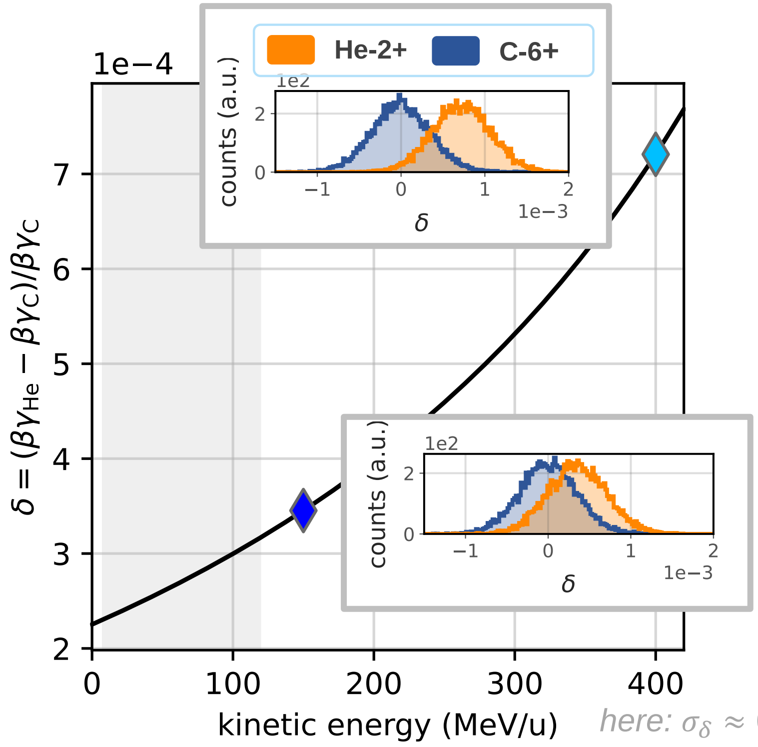
Contribution from velocity increase $\hat{\delta}$…

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

$$\rightarrow \hat{\delta} = \frac{(\beta\gamma)_{\mathrm{He}} - (\beta\gamma)_{\mathrm{C}}}{(\beta\gamma)_{\mathrm{C}}} > 0,$$

… depends on difference between

- extraction energy (clinic: $\gamma_C \approx 1.1 - 1.4$)
- and transition energy γ_{TR} (= machine parameter; generally higher for larger synchrotrons)
  - MedAustron: $\gamma_{TR} \approx 2$
  - → γ_c *closer to* γ_{tr} in small synchrotrons



here: $\sigma_\delta \approx 0.35 \cdot 10^{-3}$

Take away

Once captured, the q/m difference between $^{4}He^{2+}$ and $^{12}C^{6+}$ of $O(10^{-4})$ **results in acceleration to slightly different E/m.**

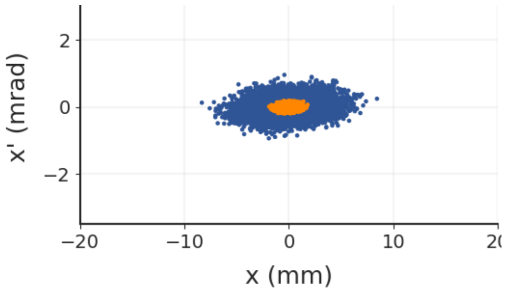
- Offset is **specific to the synchrotron lattice** and **the extraction energy.**
- For a PIMMS-like synchrotron: **order of magnitude of the rms. energy spread of the beam** (see figure).

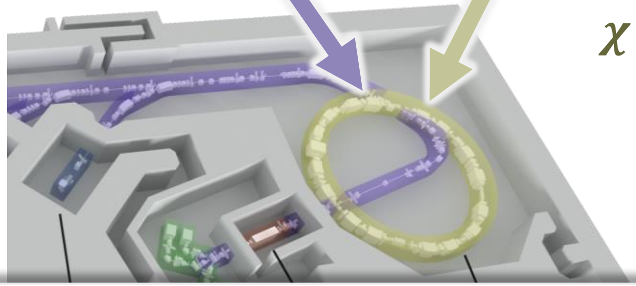
E. Renner, IPAC'24; https://doi.org/10.18429/JACoW-IPAC2024-THPR43
E. Renner, Slow Extr. '24; https://indico.gsi.de/event/18184/contributions/76328/

Mixed Beam Slow Extraction

Slow extraction of the mixed beam is affected by…

… different horizontal beam distributions;





… the slight beam rigidity offset in the synchrotron.

$$\chi = \frac{q_{He}}{m_{He}} \Big/ \frac{q_C}{m_C} = 0.99935 \qquad \frac{d\,(B\rho)}{(B\,\rho)} \approx 6 \times 10^{-4}$$

Outline

- Impact of E/m **difference** on <u>RF capture</u> **+ mitigation measures**
- Impact of q/m **difference** on the <u>**acceleration**</u> **in the synchrotron**
- Impact of q/m **difference** and **transverse beam sizes** on the <u>**extraction process**</u>

Slow Extraction of Mixed Beams at MedAustron I

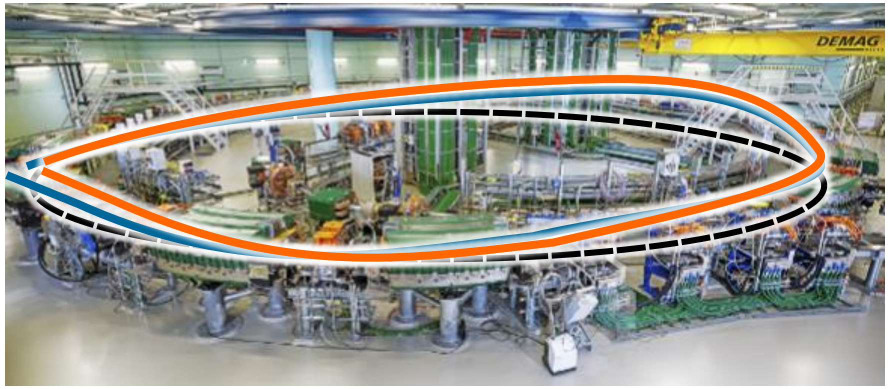


FIGURE CREDITS: MEDAUSTRON (MODIFIED)

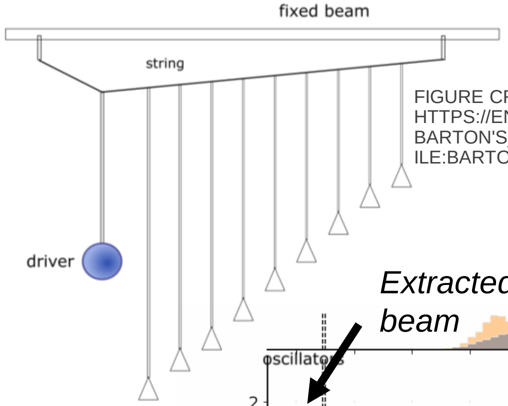
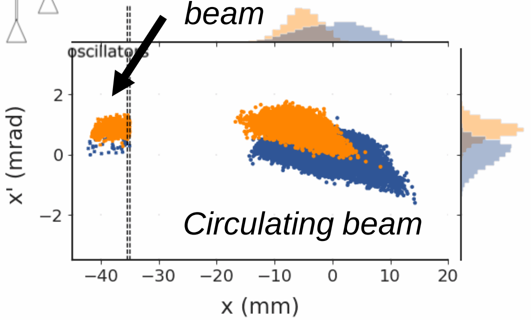
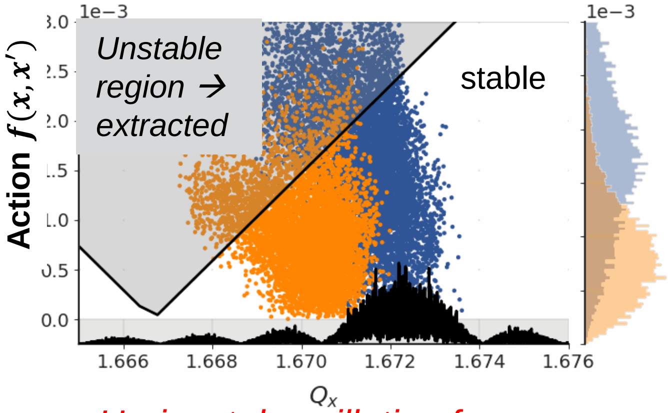


FIGURE CREDITS: HTTPS://EN.WIKIPEDIA.ORG/WIKI/BARTON'S_PENDULUMS#/MEDIA/FILE:BARTON'S_PENDULUMS.SVG



$$\Delta Q = Q' \cdot \delta_{\mathrm{eff}} \qquad \delta_{\mathrm{eff}} = \frac{1+\hat{\delta}}{\chi} - 1.$$



Horizontal oscillation fequency
(∝ effective rigidity offset)

Particles perform **transverse oscillations around reference orbit.**

Oscillation frequency mainly given by

- quadrupole settings,
- with a **small frequency spread** proportional to effective rigidity spread of the beam.

3rd order resonant extr:

- Extract particles over millions of turns …
- … by slowly bringing the entire beam stack into resonance.

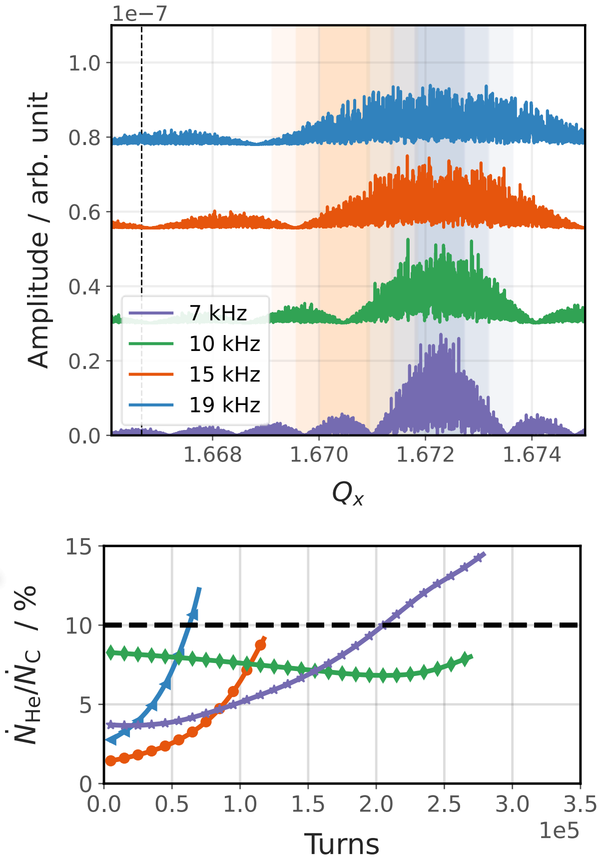
Specific for mixed beams:

- *Different frequency range* for **He** and **C.**
- Difference depends on extraction energy and is usually pronounced in synchrotrons with small circumference (lower γ_{TR}).

Slow Extraction of Mixed Beams at MedAustron II

- **Frequency difference** / overlap between He and C **needs to be considered during the extraction process, …**
  - … particularly, when aiming at extracting the beam with a **constant particle ratio throughout the spill.**

$$\xi := \left.\frac{dN_{\mathrm{He}}/dt}{dN_{\mathrm{C}}/dt}\right|_t \approx \mathrm{const.}$$



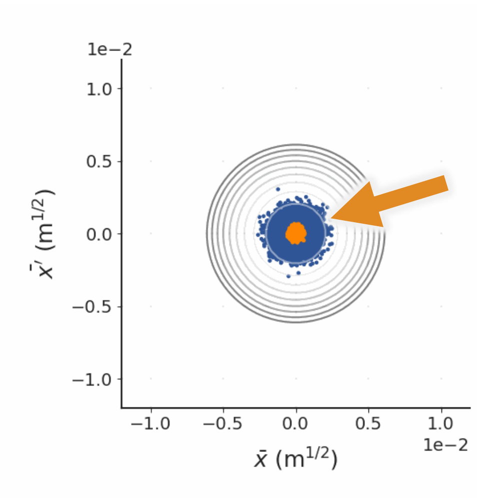
  - Different knobs available for tailoring this ratio, but small differences may have large impact.

"Feature, not a bug": frequency offset may also provide some **flexibility for tailoring the fluence ratio …**

E. Renner, IPAC'24; https://doi.org/10.18429/JACoW-IPAC2024-THPR43
E. Renner, Slow Extr. '24; https://indico.gsi.de/event/18184/contributions/76328/

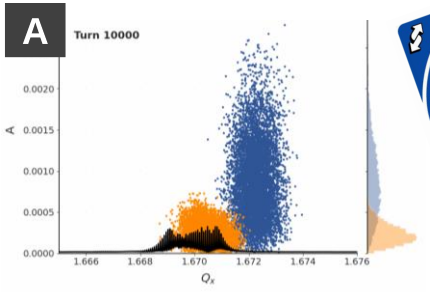
Slow Extraction of Mixed Beams at MedAustron III

Specific challenge for mixed beam generated during **sequential injection** (i.e. at MedAustron)

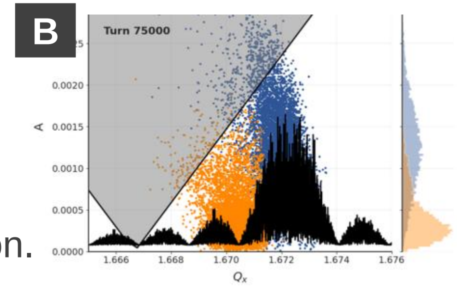


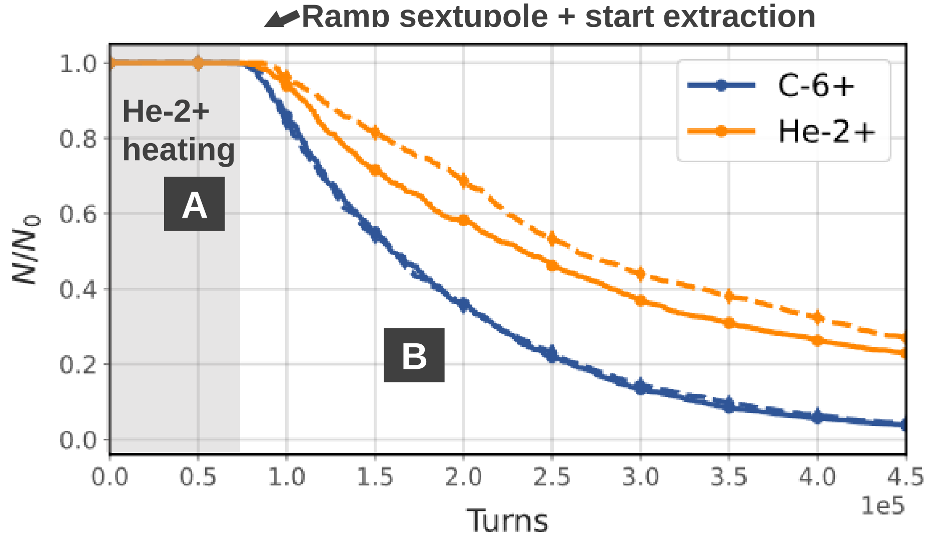
Helium requires additional excitation due to smaller initial horizontal emittance.

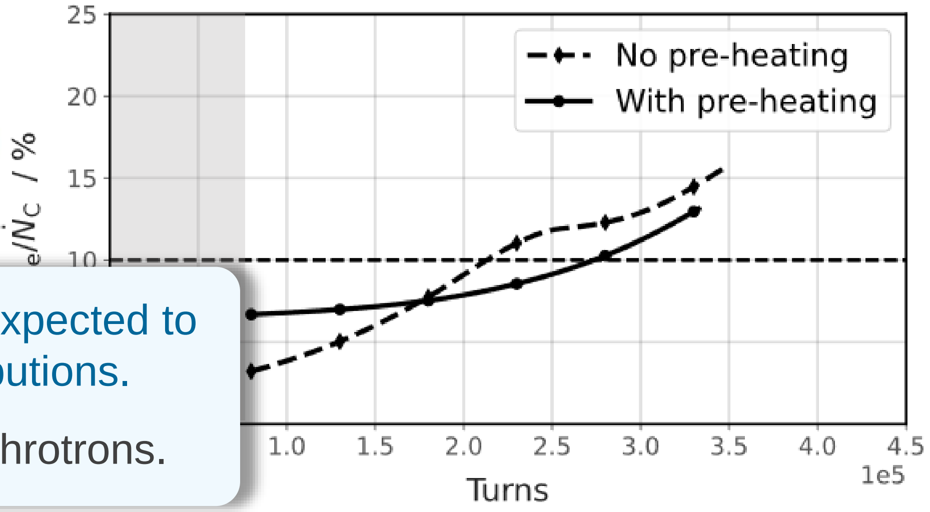
Proposal: profit of frequency offset to **“pre-heat” helium before extraction …**



… to harmonize ratio He:C during subsequent slow extraction.







Take away

Maintaining a constant He:C particle ratio throughout extraction is expected to be **challenging** due to differing horizontal, momentum, and tune distributions.

- Difference depends on extr. energy; more pronounced in small synchrotrons.

E. Renner, IPAC’24; https://doi.org/10.18429/JACoW-IPAC2024-THPR43
E. Renner, Slow Extr. ’24; https://indico.gsi.de/event/18184/contributions/76328/

Take Aways & Lessons learnt

- **Current challenge: interconnected loss processes** during the **sequential injection and capture** process make it **complex to control** and know the final He/C ratio.

  - ✓ So far, **main focus has been injection, capture and acceleration** of the ion mix.
  - ✓ Managed to maintain high carbon intensities (*towards* clinical int.), while helium contents could be varied coarsely.
  - ➞ Experimental **extraction studies will follow**; focus on tailoring the He/C ratio during extr.
  - No scanning foreseen in the near future.

- Once captured, the q/m difference between $^{4}He^{2+}$ and $^{12}C^{6+}$ causes the ions to be **accelerated to slightly different E/m.**

  - We could try to **use the combined rigidity offset to our advantage.**
  - Pre-excite He before extraction; non-invasive quantification of the He/C ratio prior to extraction,…

- Limited beam diagnostics and special cycle setup complicate machine development.

The financial support of the Austrian Ministry of Education, Science, and Research is gratefully acknowledged for providing beam time and research infrastructure at MedAustron.

Look into the future …

Reliably tailor and know **helium content** during injection/capture

Provide **helium in low flux** (independent of C content)

Experimental mixed beam **extraction** studies

Improve options for mixed beam **beam diagnostics** in the accelerator (intensity ratio, emittance,…)

Enable **scanning**

Survey: Wish List of Mixed Beam Properties

- Please share any **beam properties you think would be relevant or interesting** for mixed beam research or applications!
- Feel free to share **any ideas**, regardless of **whether they seem crazy or infeasible!**
- If you're interested in reviewing the data, please feel free to reach out. All shared data will be anonymized.

https://forms.office.com/e/sGgWHeETg6

Design studies for beam manipulation schemes enabled by facility upgrades or future facilities

Thank you for your time!