First experimental demonstration of generating mixed carbon and helium beams using a sequential injection scheme

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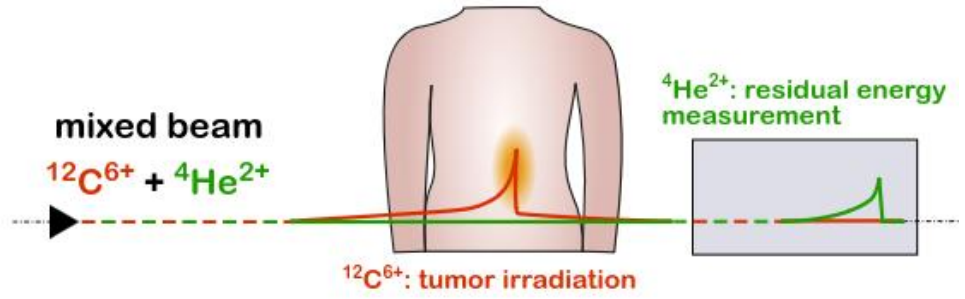
Idea and motivation

Within simultaneously accelerated mixed beam the helium ions have around **3 times higher penetration depth** compared to the carbon ions.

10% helium causes only small increase in dose

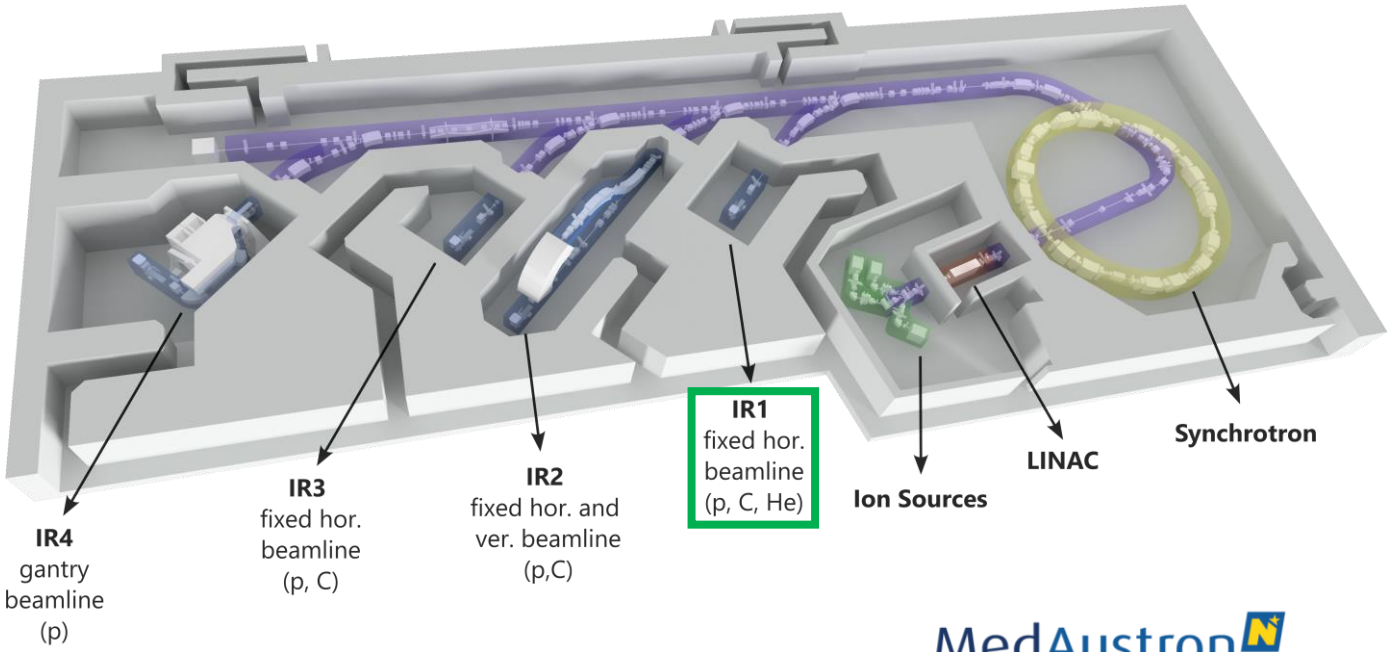
➔ in future: potentially online range verification possible



*The **objective** is to …*

- *generate*
- *accelerate*
- *slowly extract*

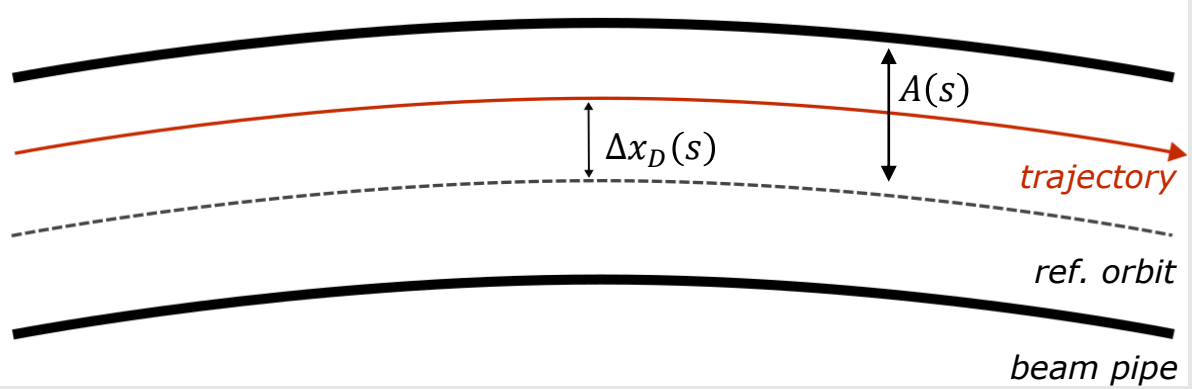
… a mixed helium and carbon beam into IR1 at MedAustron



Mixed beams in synchrotrons

Requirements

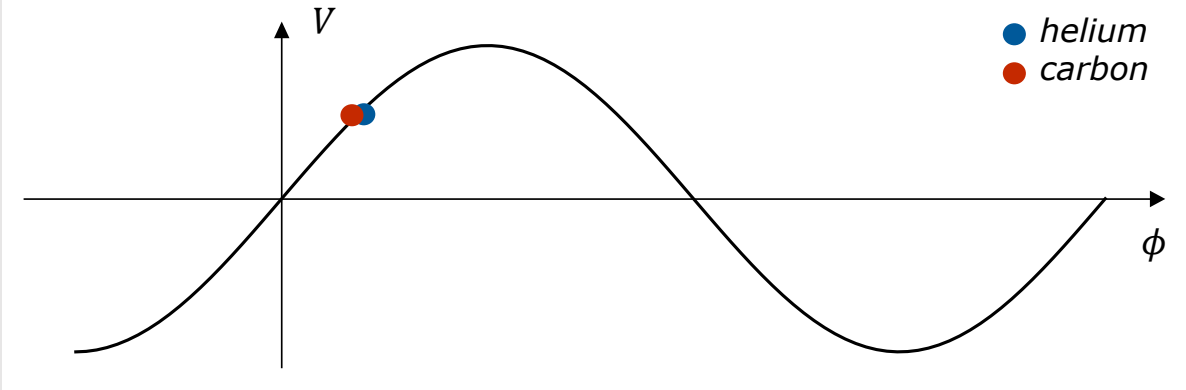
magnetic rigidity



$$\Delta x_D(s) = D(s) \cdot \frac{d(B\rho)}{B\rho} < A(s)$$

$$\rightarrow \frac{d(B\rho)}{B\rho} \ll 1$$

revolution frequency



with RF system on

$$\frac{df_{\text{rev}}}{f_{\text{rev}}} \ll 1 \rightarrow \frac{d(\beta\gamma)}{\beta\gamma} \ll 1$$

$$B\rho = \frac{p}{q} = \frac{m}{q}\beta\gamma c \rightarrow \frac{d\left({}^{m}/_{q}\right)}{{}^{m}/_{q}} \ll 1$$

Ion combinations

Mixed helium and carbon beams

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

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

Source ✔
LINAC ✔
Synchrotron ✘

disp. offset in synchrotron[1]

$\Delta x_{D,\max} \approx 45\ \text{mm}$

aperture

$A_{D,\max} = 60\ \text{mm}$

[1] calculated for $(\beta\gamma)_{\text{He}} = (\beta\gamma)_{\text{C}}$

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

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

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Synchrotron ✔

LINAC can only accelerate $\frac{q}{m} > \frac{1}{3}$

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

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

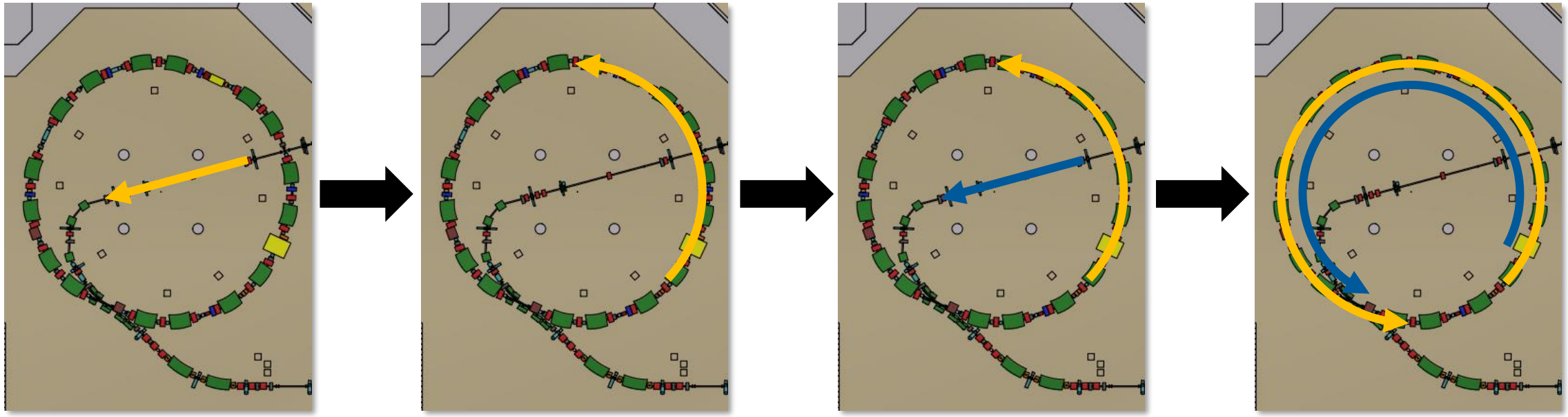
Source ✘
LINAC ✔
Synchrotron ✔

$^{12}C^{6+}$ yield from ion sources around *100 times lower* than for the clinically used $^{12}C^{4+}$

Sequential injection

An alternative approach

Sequential injection of $^{4}He^{2+}$ and $^{12}C^{6+}$ into the synchrotron!

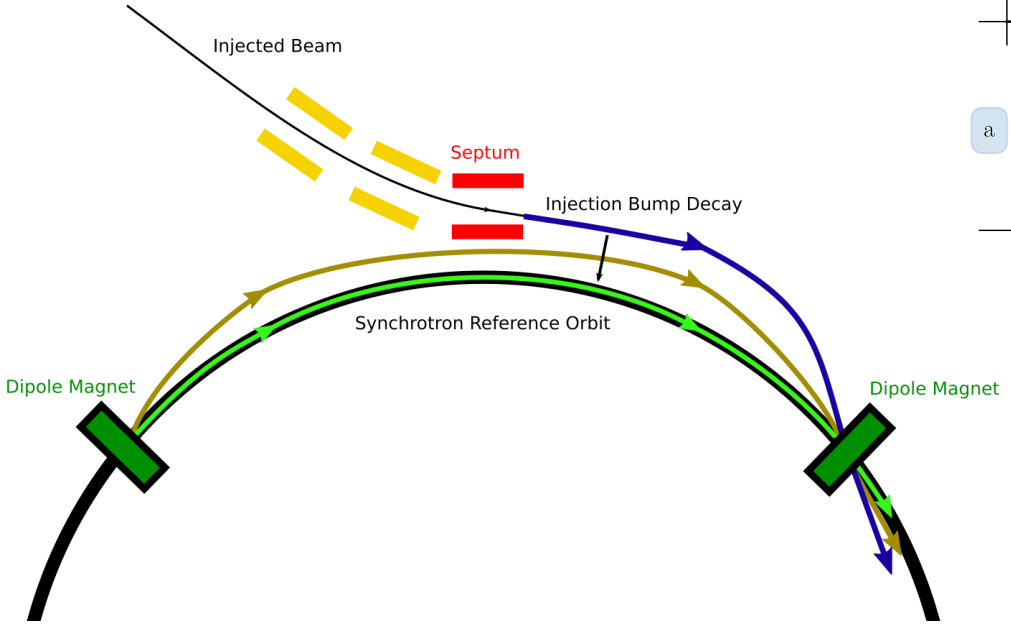


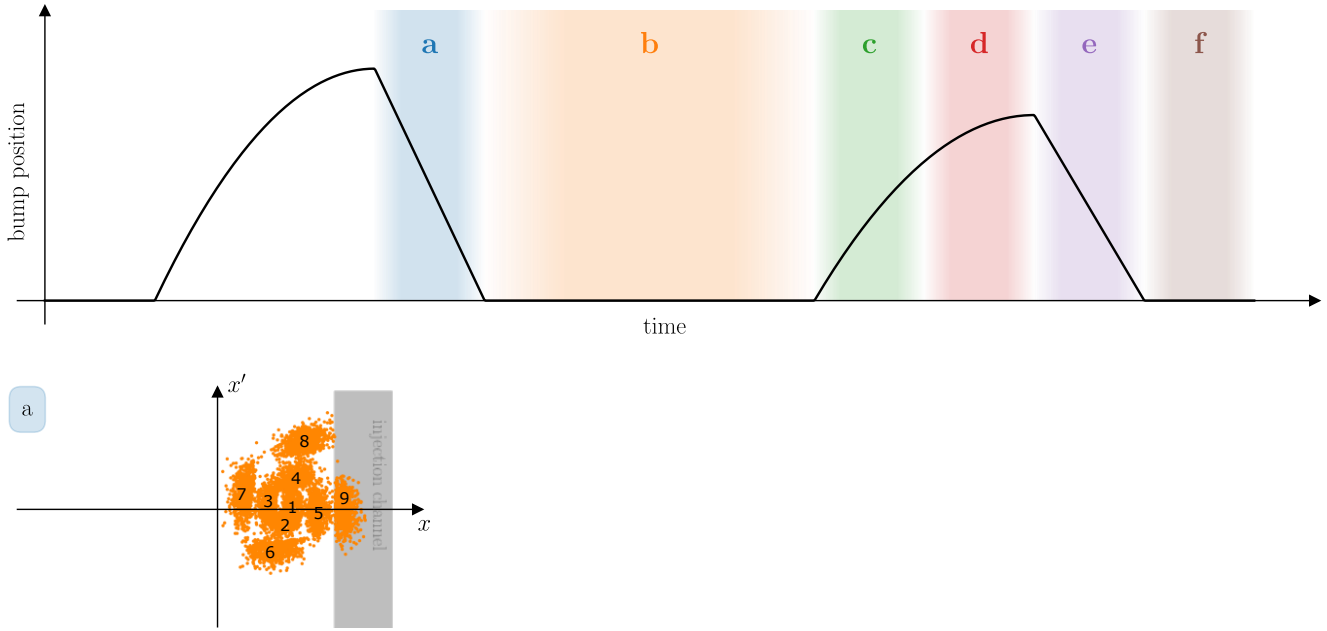
$^{4}He^{2+}$ $^{12}C^{6+}$

Double multi-turn injection

Two multi-turn injections

a) **nominal helium injection**



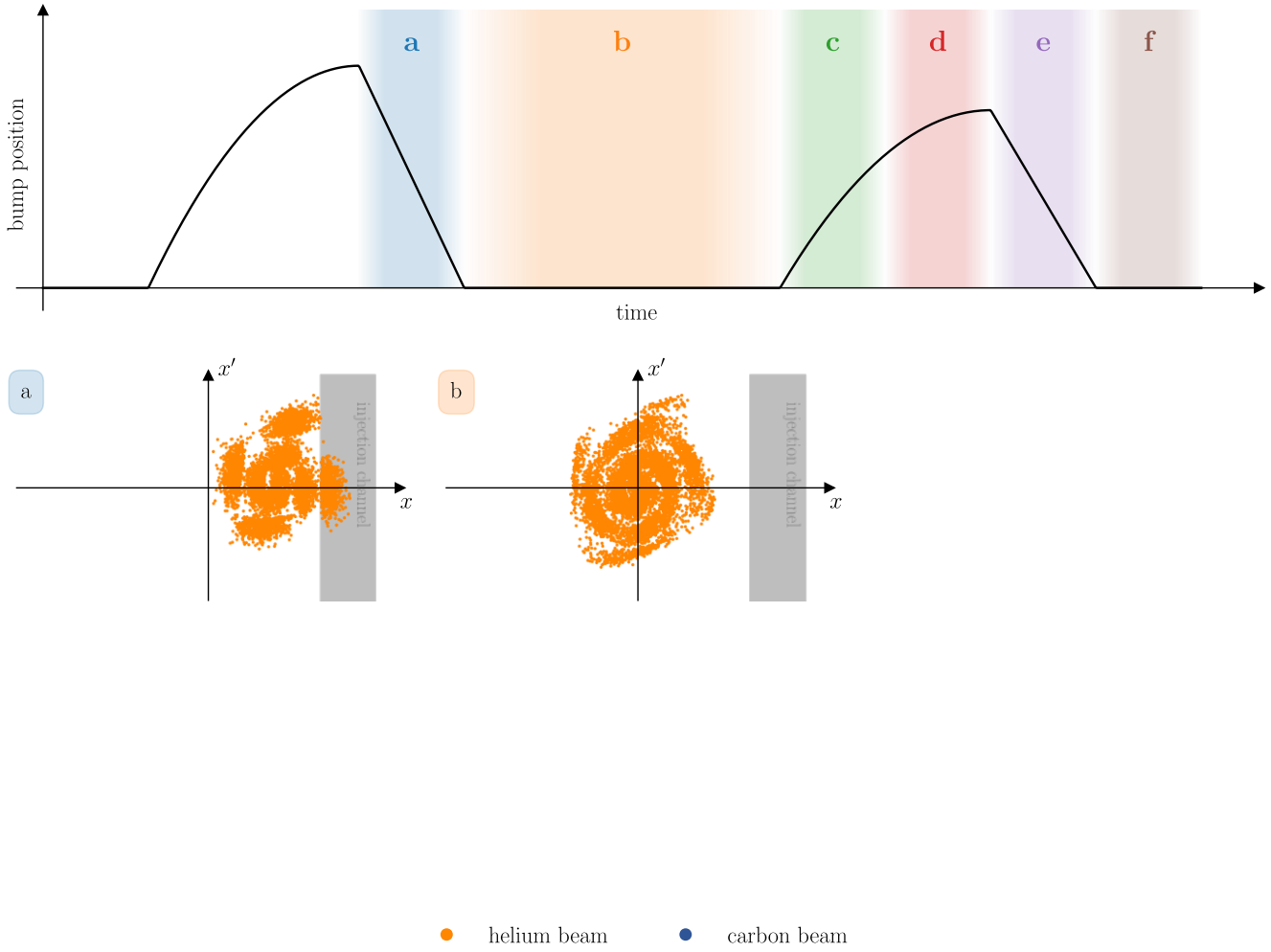


Double multi-turn injection

Two multi-turn injections

a) nominal helium injection

b) helium kept at flat bottom



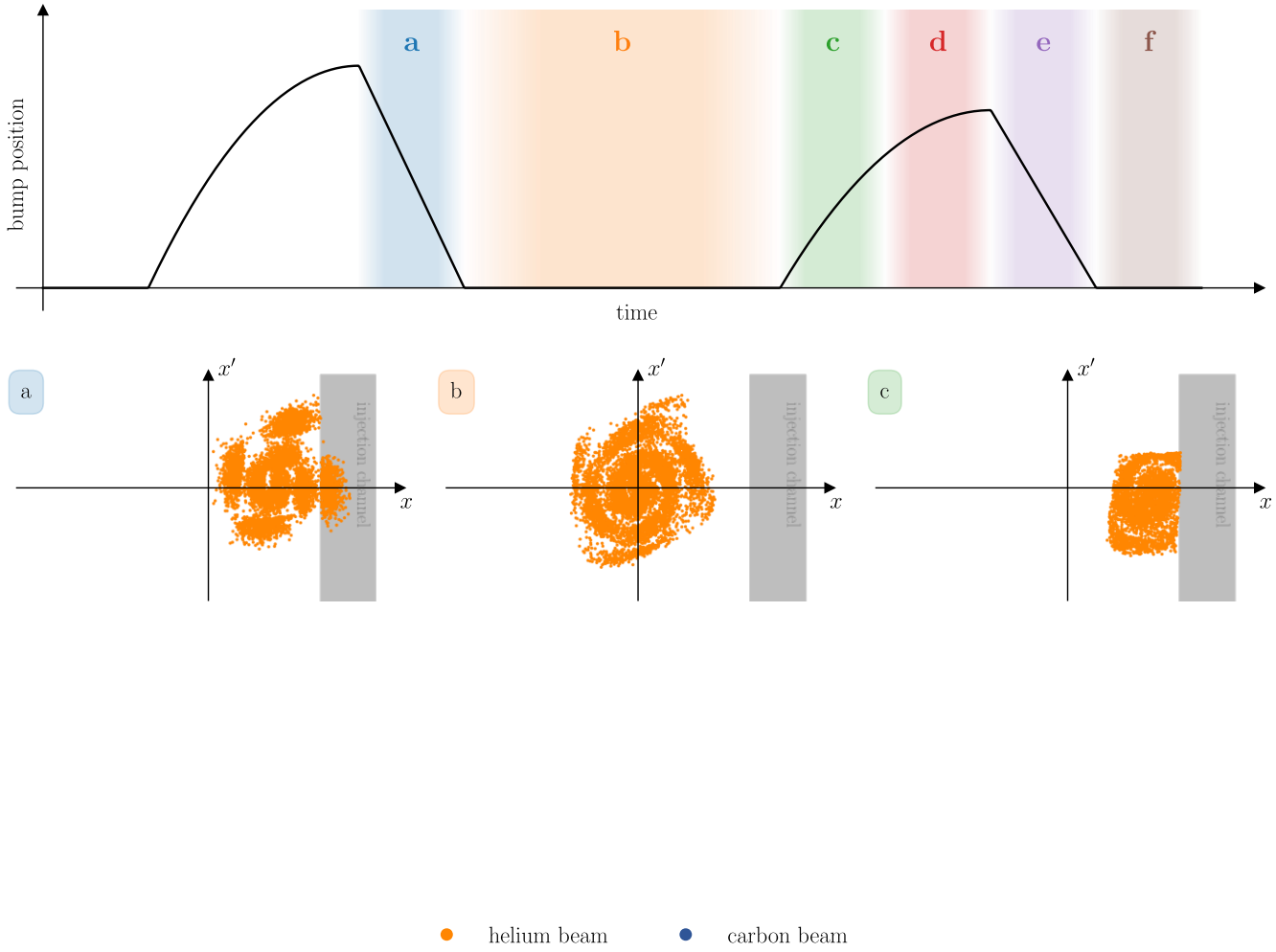
Double multi-turn injection

Two multi-turn injections

a) nominal helium injection

b) helium kept at flat bottom

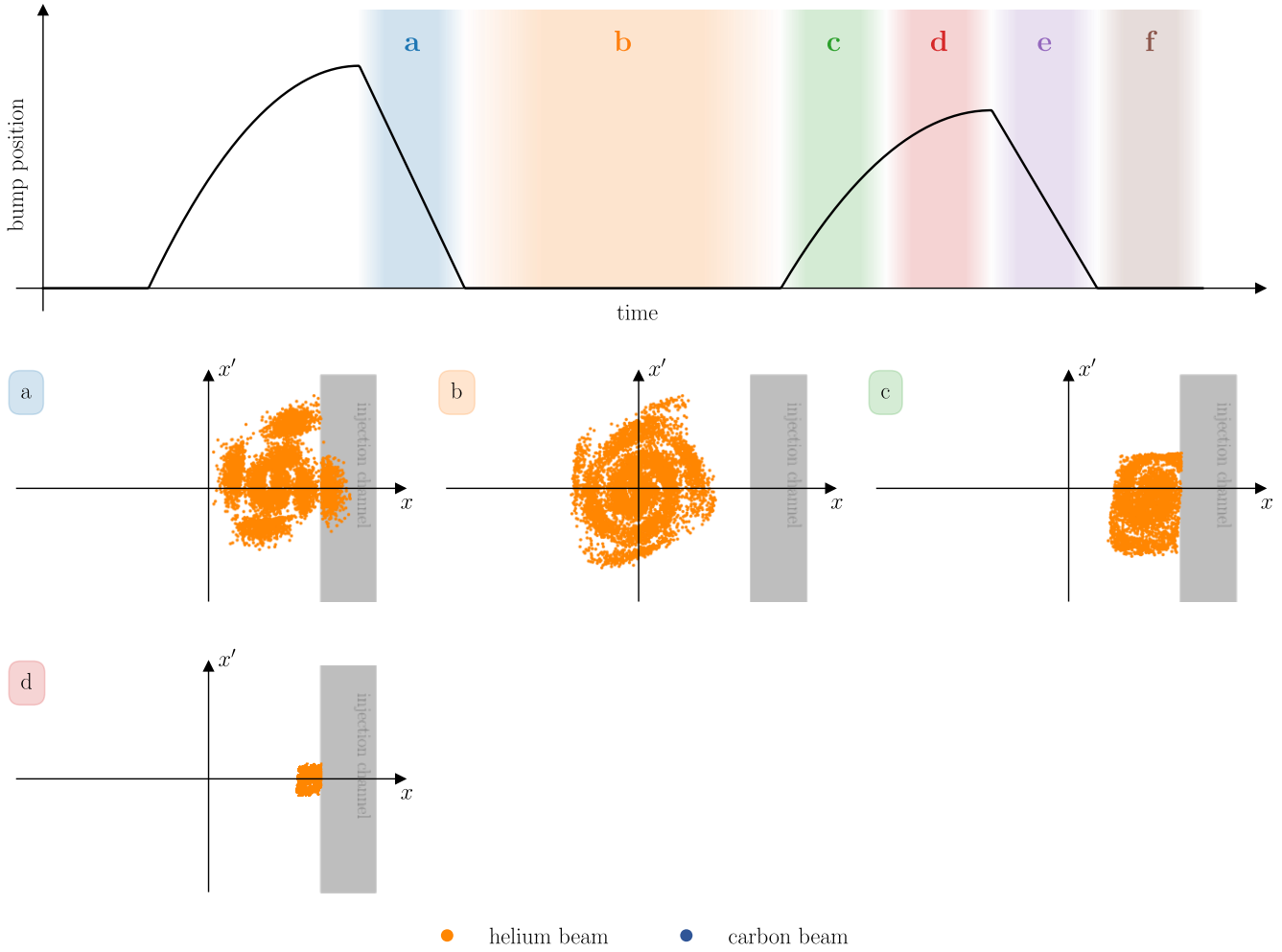
c) second orbit bump rises to lower amplitude, most of helium is scraped



Double multi-turn injection

Two multi-turn injections

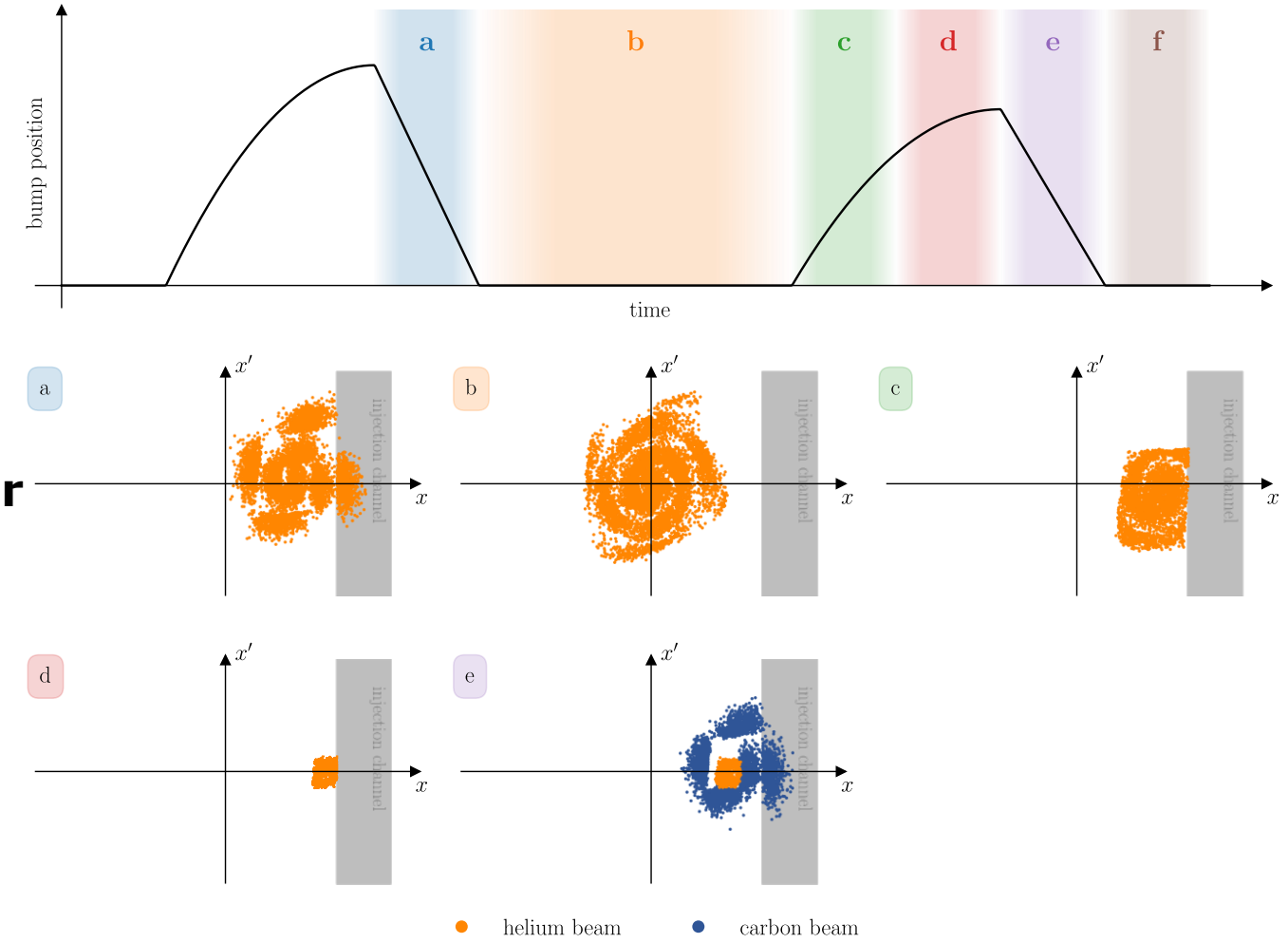
a) nominal helium injection
b) helium kept at flat bottom
c) second orbit bump rises to lower amplitude, most of helium is scraped
d) only the helium is core left



Double multi-turn injection

Two multi-turn injections

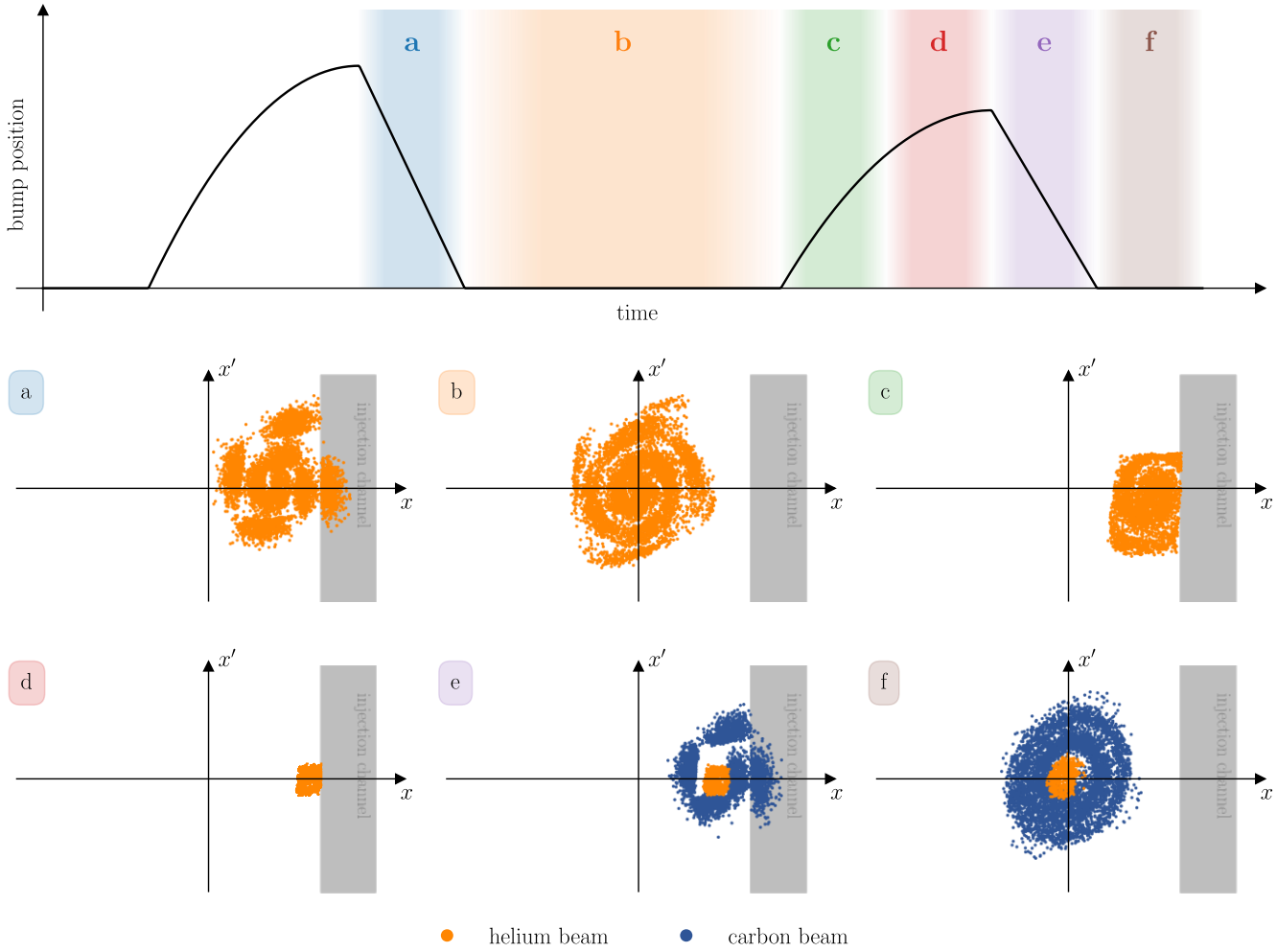
a) nominal helium injection
b) helium kept at flat bottom
c) second orbit bump rises to lower amplitude, most of helium is scraped
d) only the helium is core left
e) carbon injection from lower orbit bump amplitude



Double multi-turn injection

Two multi-turn injections

a) nominal helium injection
b) helium kept at flat bottom
c) second orbit bump rises to lower amplitude, most of helium is scraped
d) only the helium is core left
e) carbon injection from lower orbit bump amplitude
f) mixed beam generated via double multiturn injection



Implementation at MedAustron
Technical implications: Double cycle

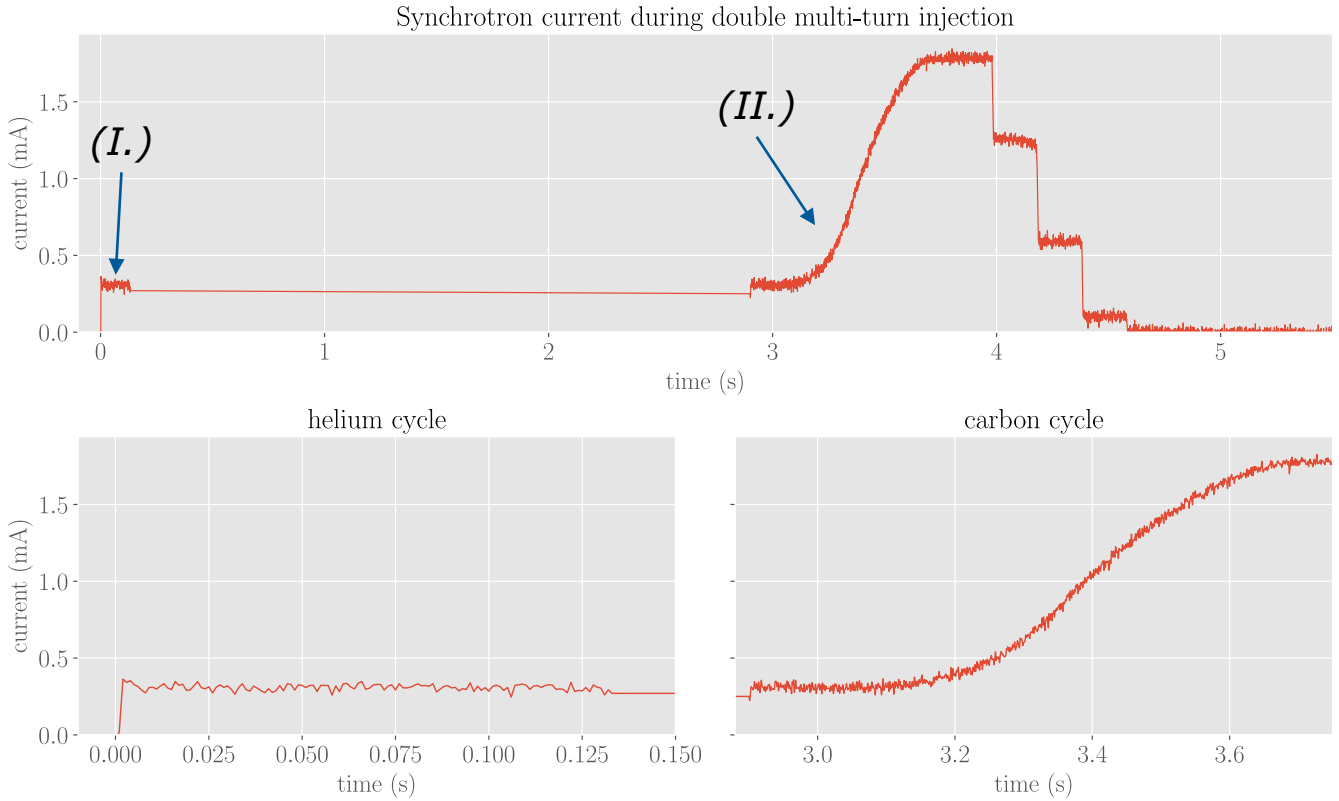
- **Double cycle** necessary …
  - components expect to receive timing events in certain order
    e.g. two injection cannot be triggered if acceleration and extraction are not triggered in between

(I.) *<u>first (helium) cycle</u>*

- helium injection
- no capture and acceleration
- dummy triggers to keep components happy

(II.) *<u>second (carbon) cycle</u>*

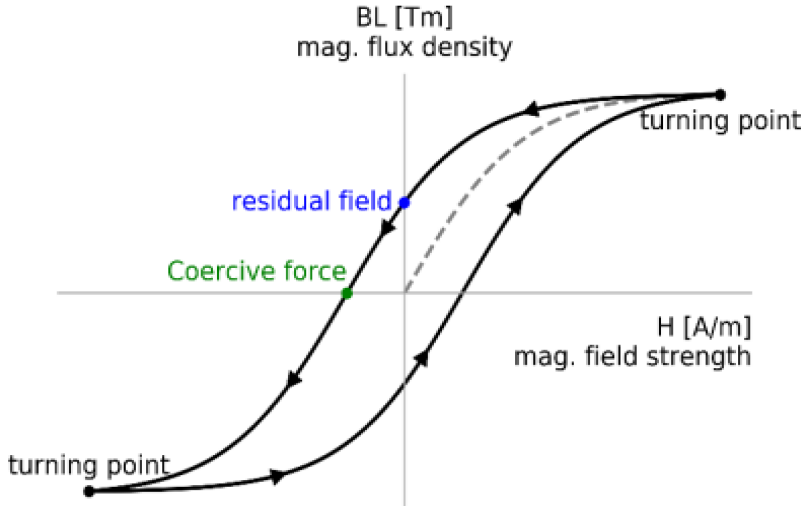
- carbon injection
- decreased injection bump amplitude
- synchrotron ramp and extraction

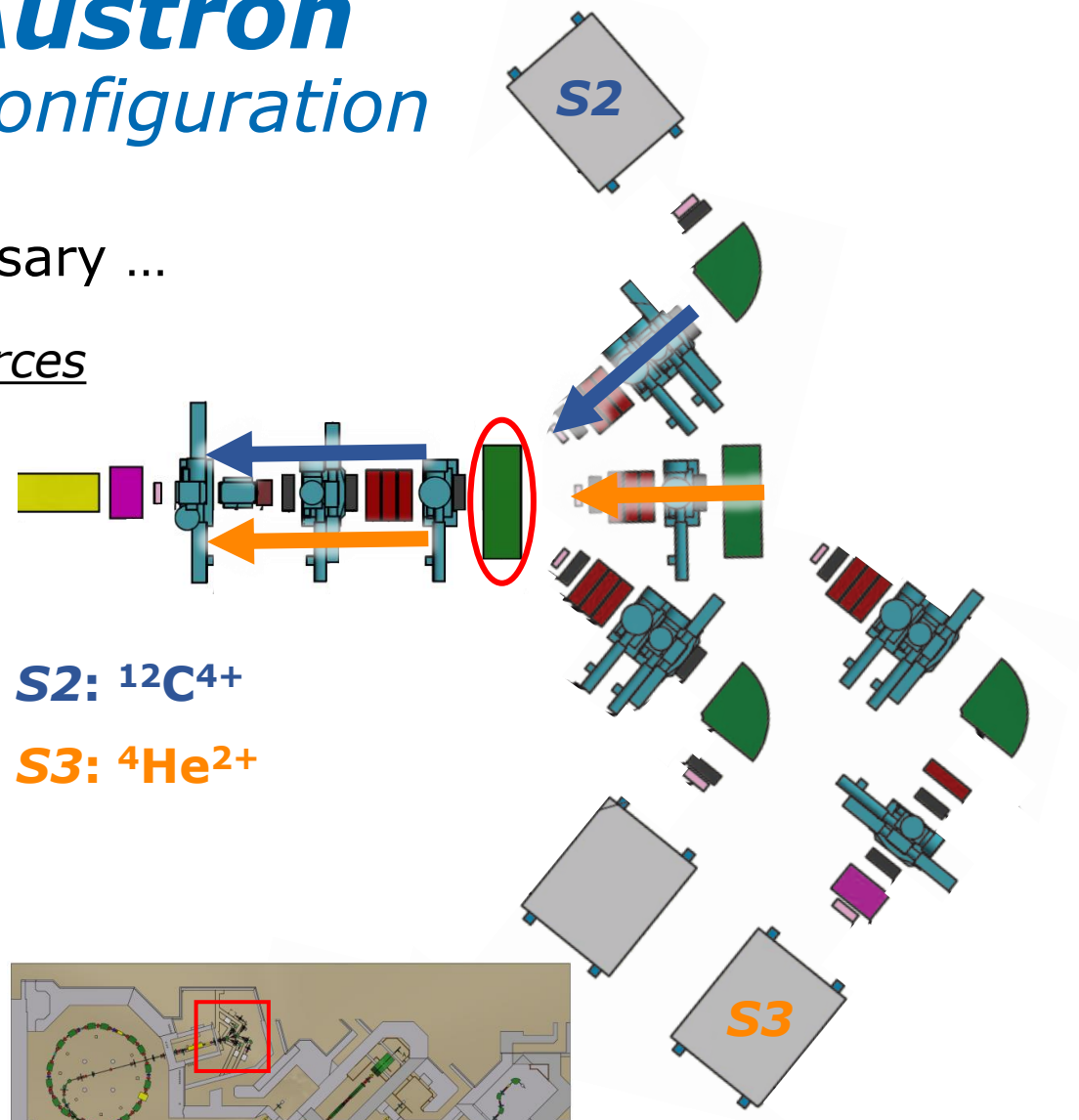


Implementation at MedAustron

Technical implications: Injector reconfiguration

- Before carbon injection **reconfiguration** necessary …
  - $^{12}C^{4+}$ and $^{4}He^{2+}$ extracted from *different ion sources* with selection via a ***switching magnet***
    - *Note:* $^{12}C^{4+} \rightarrow {}^{12}C^{6+}$ *at stripping foil after LINAC*
  - different charge-to-mass ratio
    - *magnet washing after each double cycle*





S2: $^{12}C^{4+}$

S3: $^{4}He^{2+}$

Implementation at MedAustron

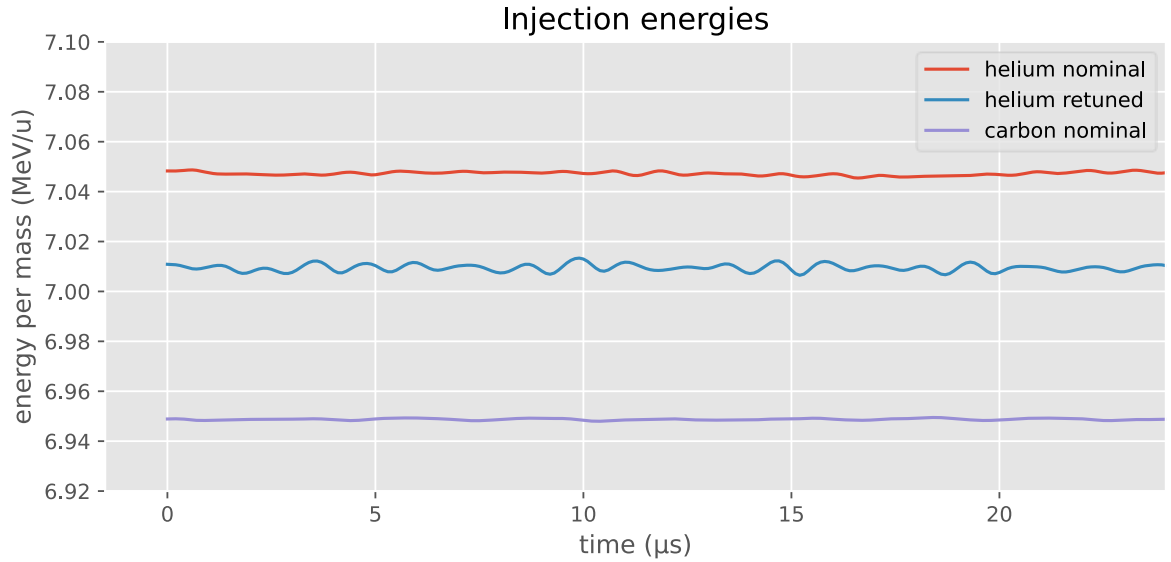
Technical implication: Injection energy offset

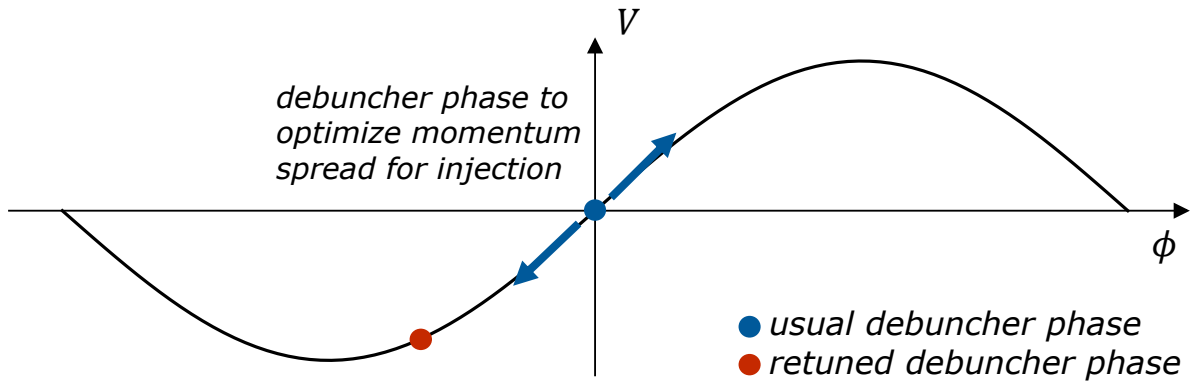
- **Injection energy offset** …
  - helium ions injected at ***7.05 MeV/u***
  - carbon ions injected at ***6.95 MeV/u***

$$\Delta\left({}^{E}/_{m}\right) \approx 0.1\,\mathrm{MeV/u} \rightarrow \Delta x_{D,\max} \approx 45\,\mathrm{mm}$$

- Retuning the **pre-accelerator cavities** …
  - reduction RF voltage on *LINAC cavity*
  - deceleration with the *debuncher cavity*

- **Helium ions at *7.01 MeV/u*** …
  - dispersive offset $\Delta x_{D,\max} \approx 20\,\mathrm{mm}$
  - higher momentum spread
    → *fluctuations in measured energy*





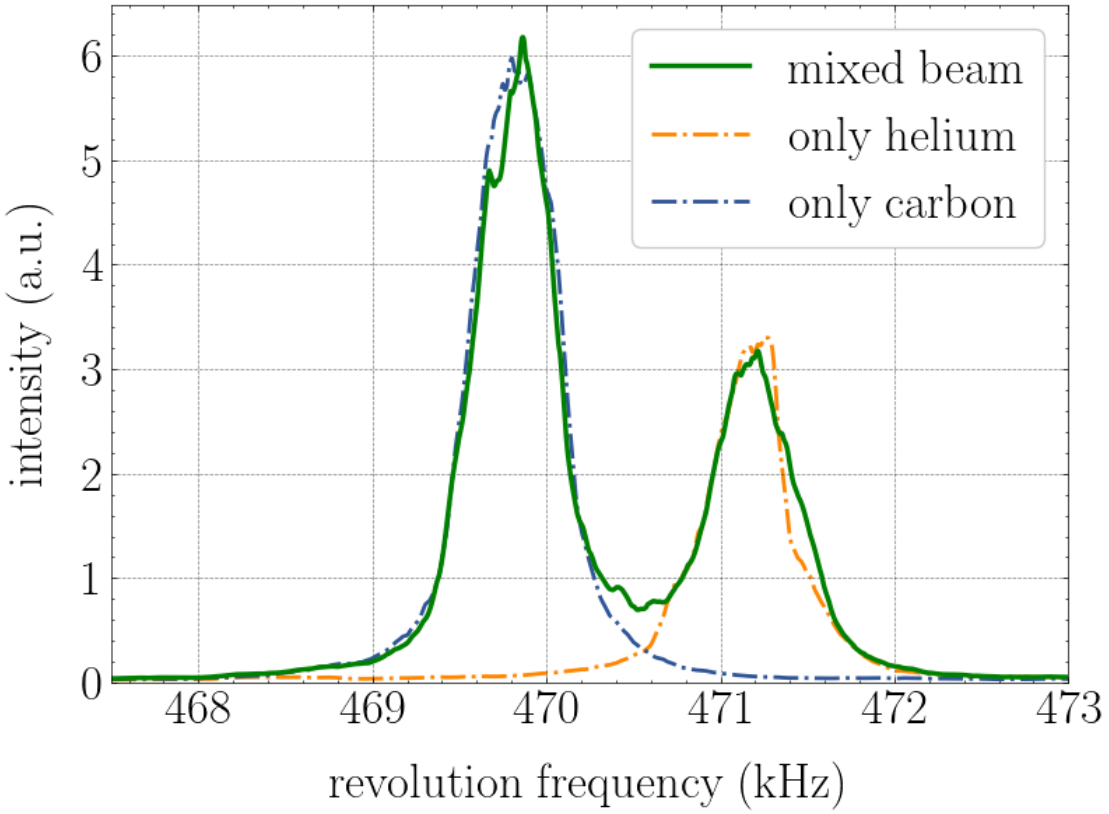
Successful double injection
Schottky spectrum

Schottky detector measurement
after double multi-turn injection

injection energy offset → different revolution frequency

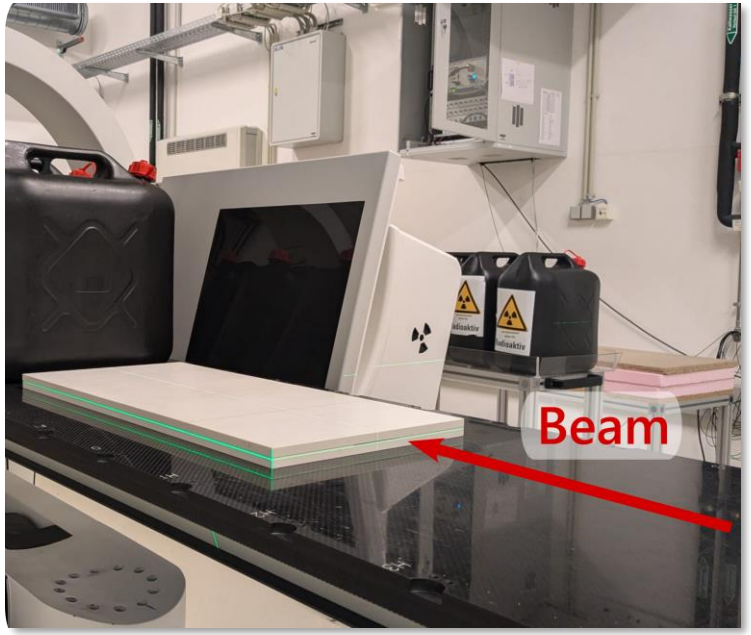
- sequential injection with *only helium*
  carbon dumped in injector
- sequential injection with *only carbon*
  helium dumped in injector
- sequential injection of *both ion types*

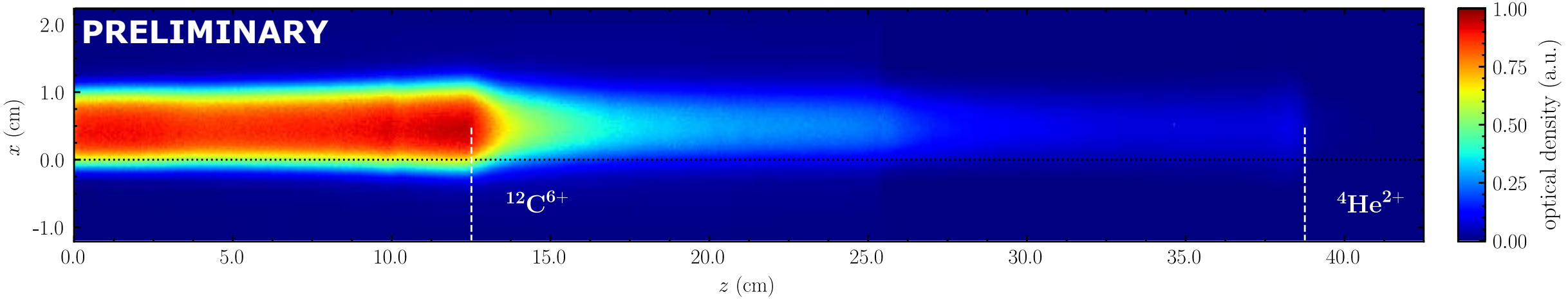
→ **identification possible!**



In-room measurements
Radiochromic films

- **Radiochromic film in isocenter** …
  - mixed beam at 262.3 MeV/u
  - phase-displacement extraction
  - 30 mixed beam spills
  - no time structure
  - no absolute intensity

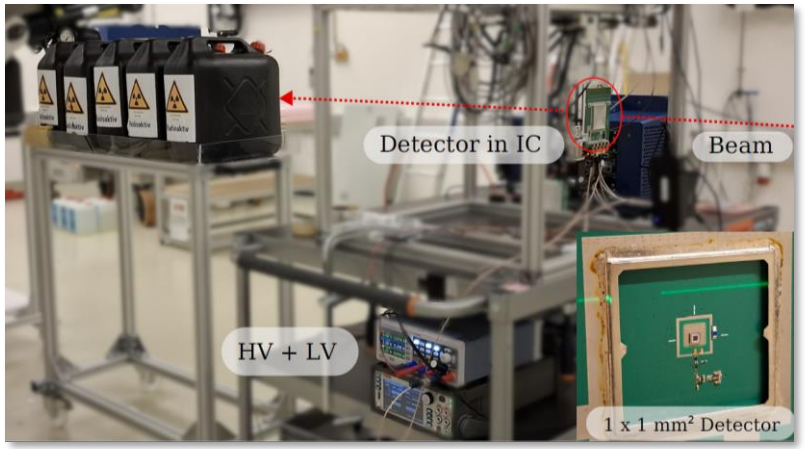


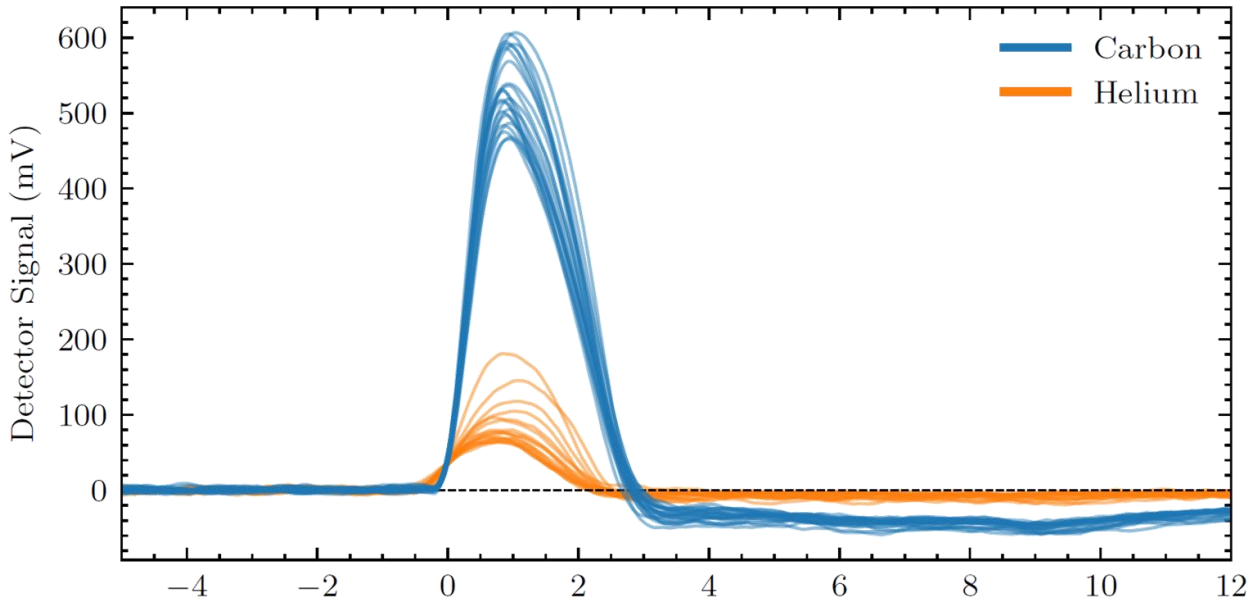


In-room measurements

Silicon low-gain avalanche detector (LGAD)

- **50 µm silicon LGAD in isocenter** …
  - mixed beam at 262.3 MeV/u
  - phase-displacement extraction
    - three sweeps at around 100 µs each
  - carbon and helium deposit different energy
    → *identification via detector signal amplitude*
  - detector signal measured with oscilloscope
  - pile-up is a problem
    - only few ms of acquisition time
    - pile-up events discarded in offline analysis





courtesy of Andreas Gsponer – ÖAW HEPHY

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  - **histogram of signal amplitudes**
    - sequential injection with *only helium*
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    - sequential injection with *only carbon*
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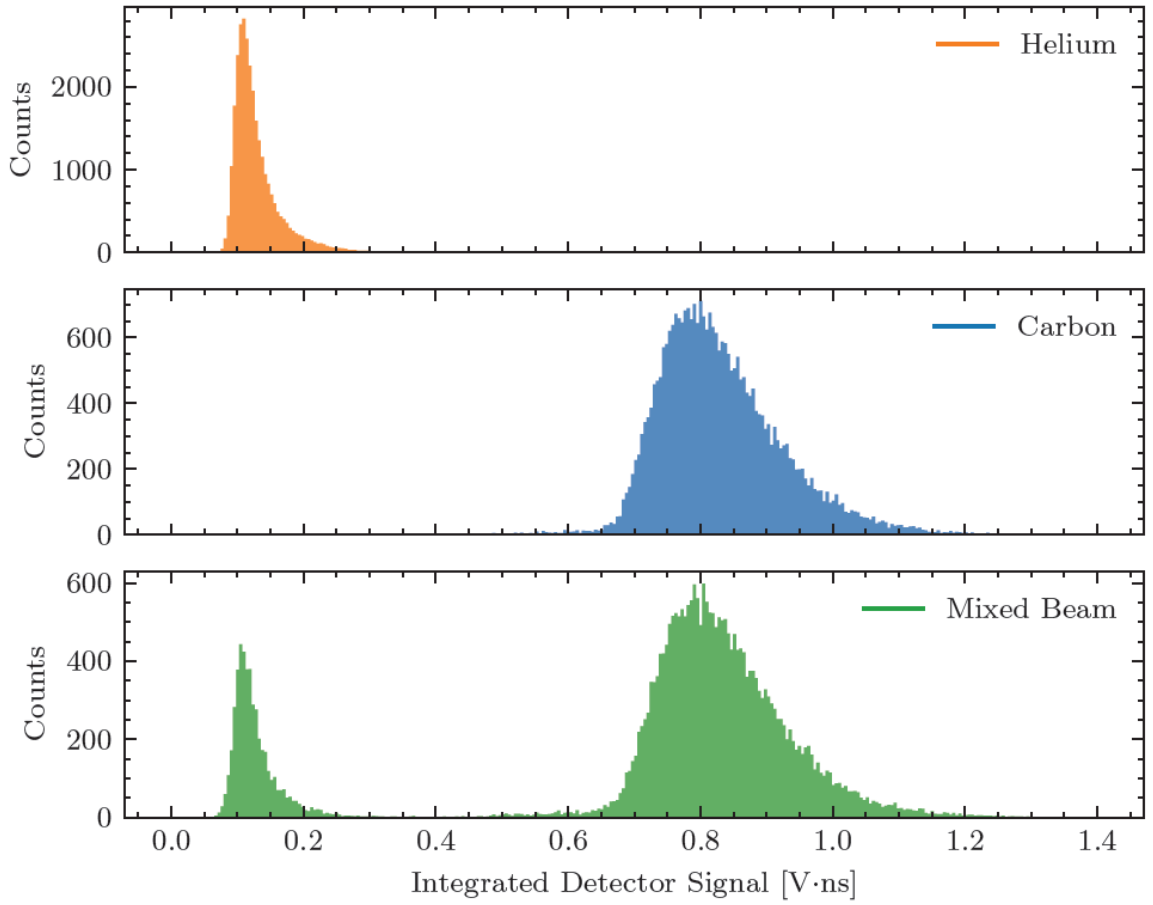
    - sequential injection of *both ion types*



courtesy of Andreas Gsponer – ÖAW HEPHY

Summary and Outlook

- First **mixed $^{4}He^{2+}$ and $^{12}C^{6+}$ beam** at MedAustron …
  - generated by *sequential injection* into the synchrotron
  - accelerated and extracted at *262.3 MeV/u*
  - detected via *radiochromic film* and *silicon LGAD* measurements
- Upcoming tasks are …
  - improving the overall *intensity* and *stability*
  - investigate *slow extraction mechanisms* to optimize time structure of delivered beam
  - *full time-resolved characterization* of the mixed beam

Thank you for your attention!

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