Slow Extraction of Mixed He-2+ and C-6+ Beams for Online Range Verification

5th Slow Extraction Workshop 2024

Wiener Neustadt / MedAustron – 12.-14.02.2024

TECHNISCHE UNIVERSITÄT WIEN

MedAustron

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Outline

- Motivation for mixed $^{4}He^{2+}$ and $^{12}C^{6+}$ beams
- Feasibility study for delivering mixed beams at MedAustron
- Considerations for slow extraction of the mixed beam
- Outlook & conclusion

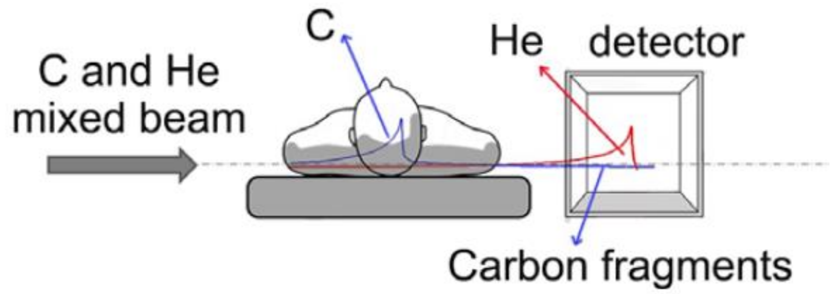
Mixed Beams for Online Range Verification

- **$^{4}He^{2+}$ and $^{12}C^{6+}$** exhibit very **similar charge-to-mass ratio.**
  - Simultaneous acceleration & delivery to irradiation room could be possible.
  - Extraction at (almost) same energy per nucleon

	q/m (e/u)
$^{12}C^{6+}$	0.5001
$^{4}He^{2+}$	0.4998

$$\Delta\left(\frac{q}{m}\right)\Big/\frac{q_C}{m_C} \approx -0.065\ \%$$

- **Helium** has around **3 times the range of carbon** at the same energy per nucleon.
  - Possibility for **online range verification, ion CT, …**
  - If extracting an intensity ratio of He:C=1:10, $^{4}He^{2+}$ accounts for only $\sim$ 1% of the dose delivered to the patient [1].
  - Note: Helium Bragg peak needs to traverse patient, only possible for larger tumor depths.
  - Described & proposed in refs. [1-3].
  - *First experimental results at GSI in 2023 – See David Ondreka's talk!*



Schematic mixed beam irradiation, Mazzucconi et. al **[1]**

[1] D. Mazzucconi et.al (2018), https://doi.org/10.1002/mp.13219
[2] L Volz et al (2020), Phys. Med. Biol. 65 055002
[3] Graeff et al (2018), https://doi.org/10.1016/j.ejmp.2018.06.099

Feasibility Study: Mixed Beams @ MedAustron?

Background: MedAustron delivers $^{12}C^{6+}$ and p+ for clinical treatment, $^{4}He^{2+}$ is currently being commissioned for non-clinical research.

Objective: Assess the feasibility of delivering a **mixed beam for nonclinical research (IR1).**

- PhD student started in 2023
- Collaboration between **MedAustron**, **TU Wien** & **HEPHY**

Infrastructure at MedAustron:

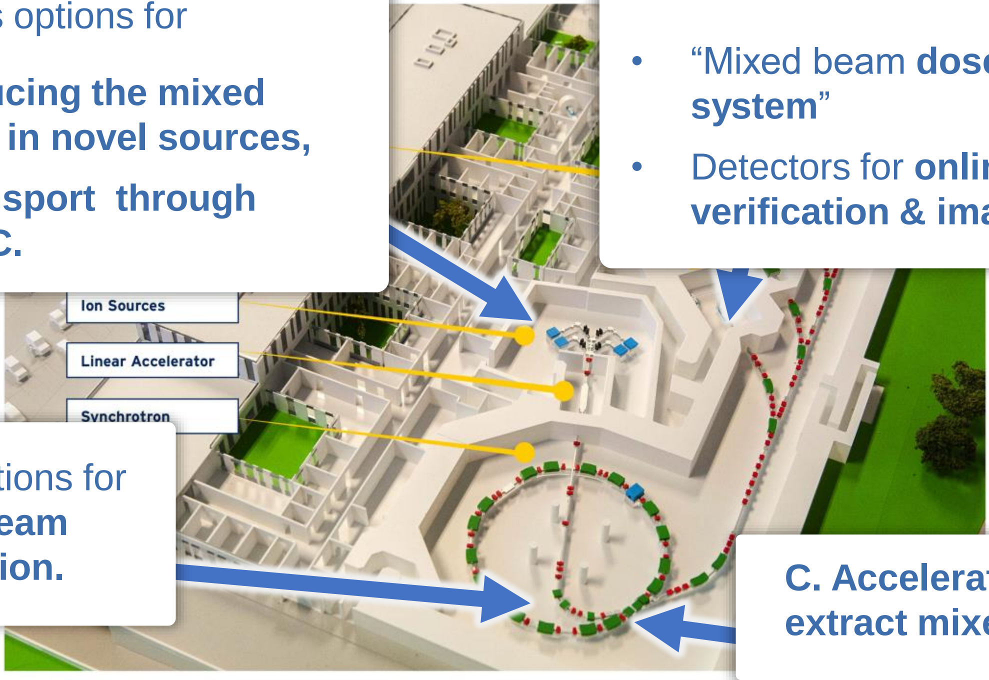
- Separate ion sources producing $^{4}He^{2+}$ (q/m≈0.5) and $^{12}C^{4+}$ (q/m≈1/3)
- Transport with different q/m through the LINAC, stripping after the LINAC
- (Nearly) same q/m≈0.5 in the synchrotron

A. Assess options for

- **producing the mixed beam in novel sources,**
- **+ transport through LINAC.**

D. Mixed beam detection:

- “Mixed beam **dose delivery system**”
- Detectors for **online range verification & imaging in IR1**



B. Assess options for **mixing the beam during injection.**

C. Accelerate and extract mixed beam

Matthias Kausel, Valentin Kirchweger

Scenarios for Mixed Beam Generation

A. Generation in a single ion source is currently not possible at MedAustron.

- Would require novel source and depending on the source LINAC upgrades (LINAC can only accelerate $\frac{q}{m} \geq \frac{1}{3}$).

B. Investigate sequential injection into the synchrotron as (temporary) alternative production scheme:

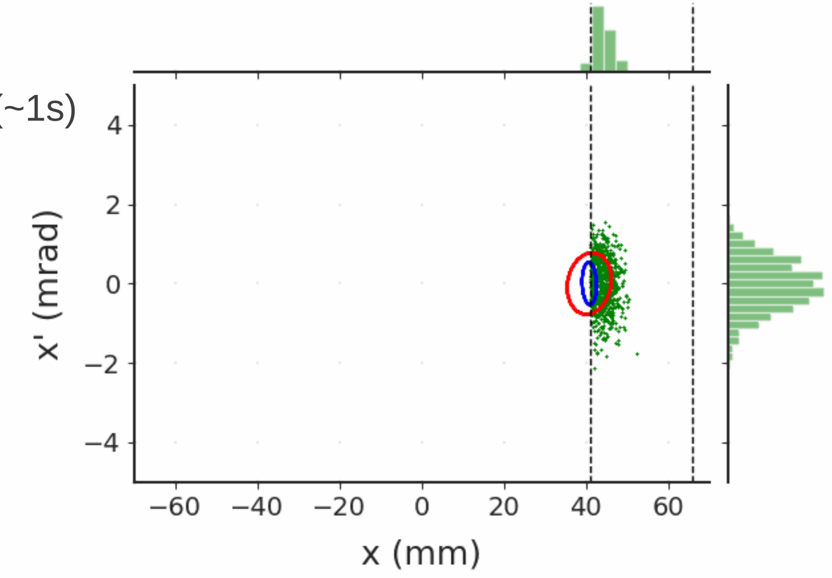
"Double multi-turn injection"

I. **1^{st} injector cycle: Inject $^{4}He^{2+}$** into synchrotron + maintain beam at flat bottom (~1s)

II. **2^{nd} injector cycle: Inject $^{12}C^{6+}$** on **top of $^{4}He^{2+}$** :

- Adapt injection bump to sustain small He core

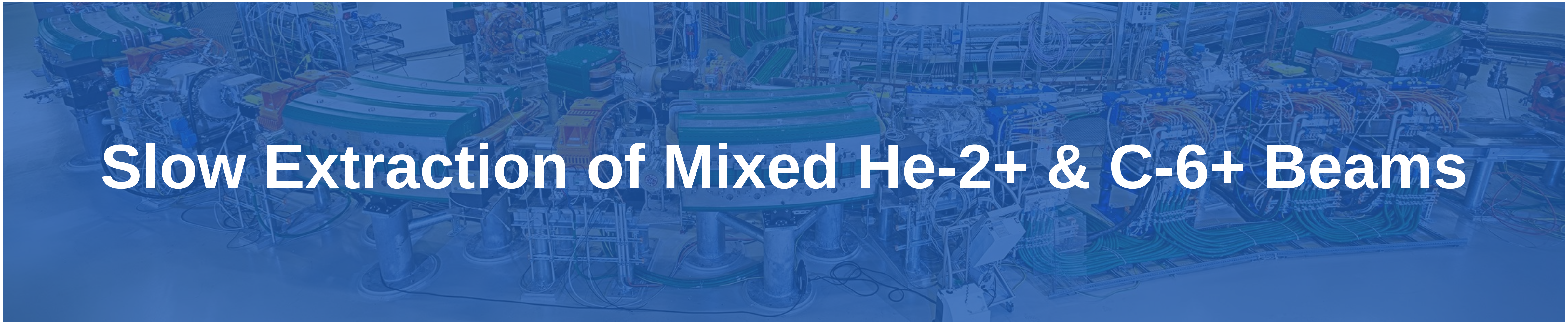
III. Capture, acceleration + extraction of ion mix



Status:

- Managed to operate injector in proposed way & inject He and C sequentially*.
- So far, no show-stoppers from the control system identified.
- Next steps: optimize injection bump, harmonize injection energy, capture, acceleration, …

** Note: So far, tests focused on demonstrating technological feasibility. He-2+ was still lost when injecting C-6+, injection has not yet been optimized.*



Slow Extraction of Mixed He-2+ & C-6+ Beams

Objective & Simulation Set-Up

Objective: **Proof-of-principle simulations** of the **slow extraction of the mixed He^{2+}/C^{6+} beam** to identify challenges & propose mitigation:

- Results serve as input for mixed beam generation and detection studies.

▶ **Preliminary aim:** deliver **constant and/or known intra-spill particle fluence ratio** of the two species:

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

- **Preliminary target** is ~ **He:C = 1:10** → $\xi(t) \approx 0.1$
- Is ***ion distinction possible in a dose delivery system?***
  - *Yes:* Possibility to adapt ξ and/or scanning during the spill ?
  - *No:* Can we guarantee a constant species ratio?

Simulation performed using Xsuite [4]:

- Enables **6D-tracking of ions with non-nominal** q/m, also for bunched beams.
- *Results in this presentation obtained using custom version with fixed bugs concerning non-nominal q/m, as described in issue 446 [5].*

Many thanks to all Xsuite developers :)

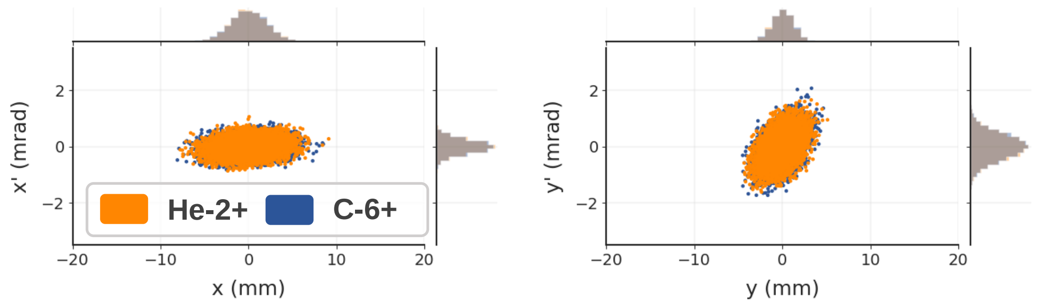
[4] https://github.com/xsuite/xsuite [5] https://github.com/xsuite/xsuite/issues/446

Transverse Distribution Prior to Extraction

The considered **options for generating the mixed-beam** result in **different initial horizontal emittances.**

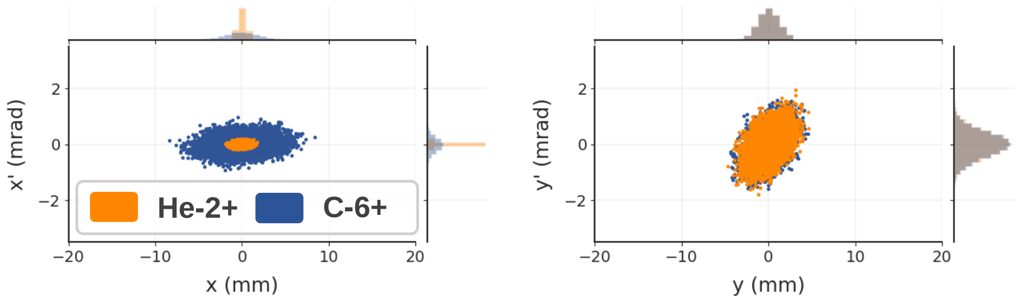
I) Mixed beam generation in ion source

Assume: $\epsilon_{x,\mathrm{He}} \approx \epsilon_{x,\mathrm{C}}$ $\epsilon_{y,\mathrm{He}} \approx \epsilon_{y,\mathrm{C}}$



II) Sequential injection + mixing at flat-bottom

Assume: $\epsilon_{x,\mathrm{He}} \ll \epsilon_{x,\mathrm{C}}$ $\epsilon_{y,\mathrm{He}} \approx \epsilon_{y,\mathrm{C}}$



Thus, for the current **proof-of-principle simulations**, we consider a **range of horizontal emittance ratios!**

Note: All simulations performed with 10k He-2+ and 10k C-6+ particles → Results will be subsequentially normalized to assumed initial intensity ratio of 1:10

Longitudinal Distribution Prior to Extraction I

$^4He^{2+}$ has **higher rigidity than** $^{12}C^{6+}$ (reference particle) due to the smaller q/m.

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

A particle with

- $\chi = \frac{q_{\mathrm{He}}}{m_{\mathrm{He}}} \Big/ \frac{q_{\mathrm{C}}}{m_{\mathrm{C}}} \neq 1$
- and a *relative momentum per mass offset* $\hat{\delta} = \frac{(\beta\gamma)_{\mathrm{He}} - (\beta\gamma)_{\mathrm{C}}}{(\beta\gamma)_{\mathrm{C}}} > 0$

… behaves in a magnetic field *like a particle with (see e.g. [7])*

- nominal charge-to-mass ratio, i.e. $\chi_{\mathrm{eff}} = 1$,
- and an **effective relative momentum per mass offset** $\delta_{\mathrm{eff}} = \frac{1+\hat{\delta}}{\chi} - 1.$

[7] P. Hermes (2016), PhD Thesis, CERN-THESIS-2016-230, https://cds.cern.ch/record/2241364/

Longitudinal Distribution Prior to Extraction II

Due to the rigidity offset, **$^4He^{2+}$** is accelerated to a **slightly higher momentum/mass than $^{12}C^{6+}$.**

- Synchronous $^4He^{2+}$ and $^{12}C^{6+}$ with same revolution frequency
- Rigidity + path length difference yields relative **velocity offset** (see e.g. [6])

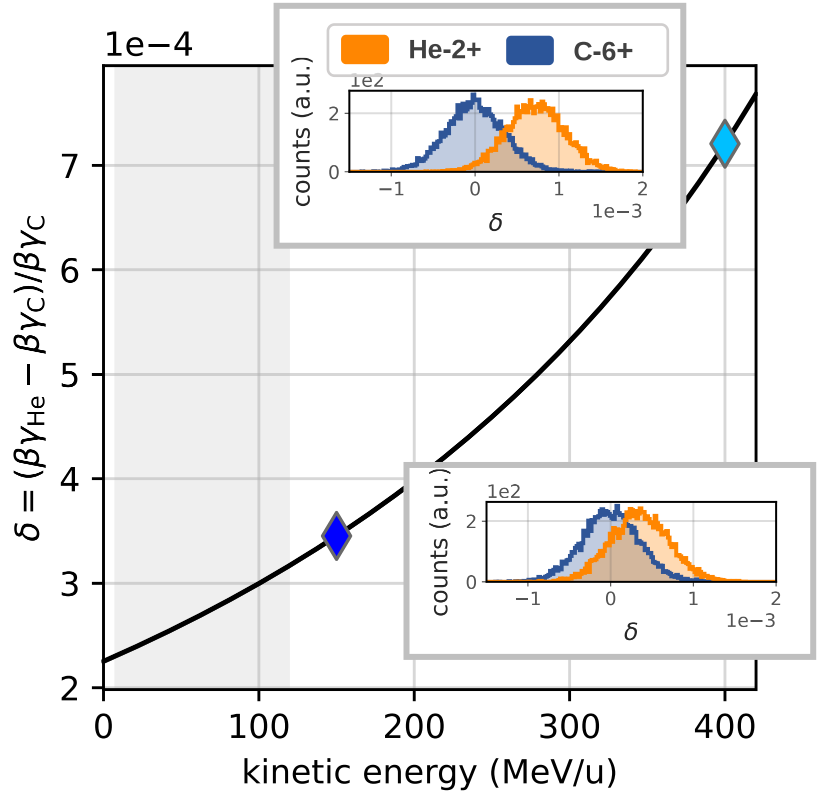
$$\frac{\beta_{\mathrm{He}} - \beta_{\mathrm{C}}}{\beta_{\mathrm{C}}} = \frac{1}{\gamma_{\mathrm{tr}}^2 - \gamma_{\mathrm{C}}^2} \cdot \left(\frac{1}{\chi} - 1\right)$$

and hence **relative momentum per mass offset**

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

which **depend on the difference between extr. and transition energy**

- *Crucial for small medical machines, e.g. @ MedAustron* $\gamma_{TR} \approx 2, \gamma_C \approx 1.1 - 1.4$



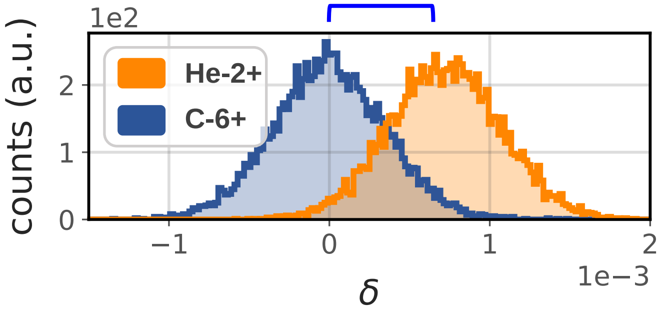
here: $\sigma_\delta \approx 0.35 \cdot 10^{-3}$

[6] P. Bryant (1993), The Principles of Circular Accelerators and Storage Rings, Chapter 7.7.6

Tune Distribution Prior to Extraction I

Momentum per mass distribution

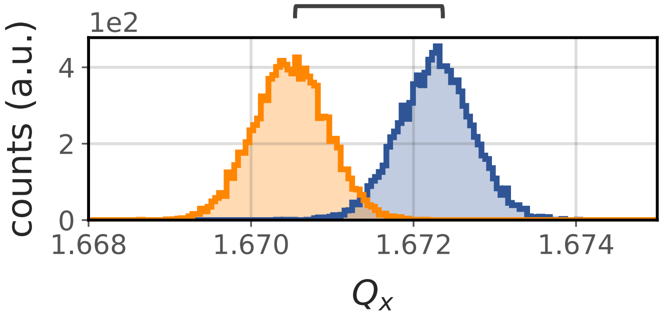
$$\hat{\delta} = \frac{(\beta\gamma)_{\mathrm{He}} - (\beta\gamma)_{\mathrm{C}}}{(\beta\gamma)_{\mathrm{C}}} > 0$$



Tune distribution

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

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



here: $\delta_{RMS} \approx 0.35 \cdot 10^{-3}$, $Q' \approx -1.3$

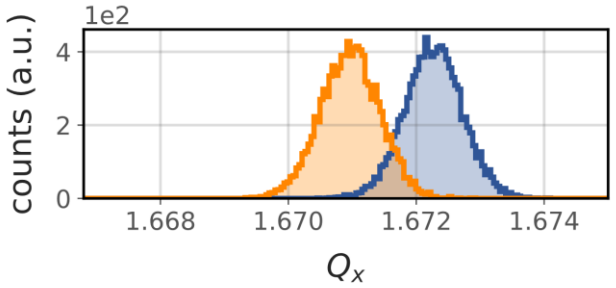
[7] P. Hermes (2016), PhD Thesis, CERN-THESIS-2016-230, https://cds.cern.ch/record/2241364/

Tune Distribution Prior to Extraction II

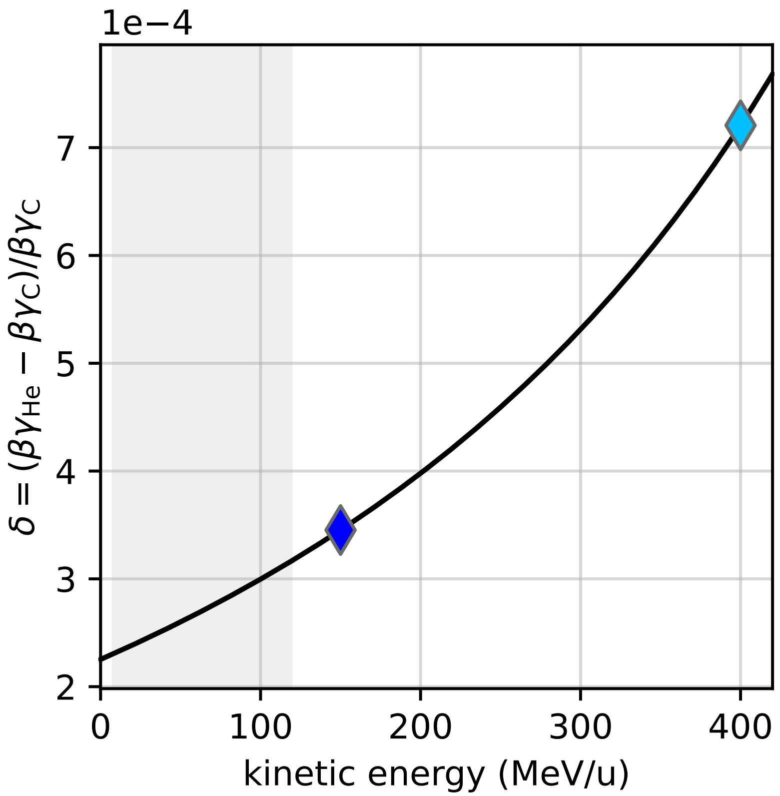
Consequently, the tune separation between $^{4}He^{2+}$ and $^{12}C^{6+}$ **depends on the extraction energy** ($Q' \neq 0$).

$\mathbf{E_{kin} = 150\ MeV/u}$

- $\hat{\delta} \quad = 0.35\mathrm{e}{-3}$
- $\delta_{\mathrm{eff}} = 0.996\mathrm{e}{-3}$

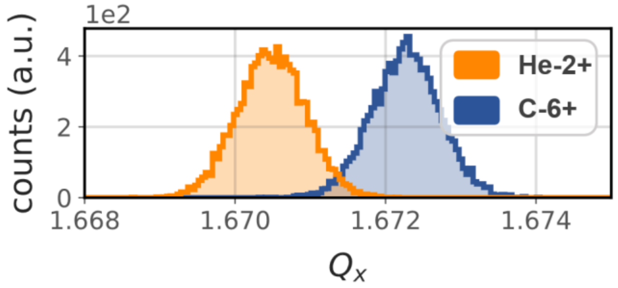


here: $\delta_{RMS} \approx 0.35 \cdot 10^{-3}$, $Q' \approx -1.3$



$\mathbf{E_{kin} = 400\ MeV/u}$

- $\hat{\delta} \quad = 0.72\mathrm{e}{-3}$
- $\delta_{\mathrm{eff}} = 1.37\mathrm{e}{-3}$



here: $\delta_{RMS} \approx 0.35 \cdot 10^{-3}$, $Q' \approx -1.3$

Proposed Extraction Strategy

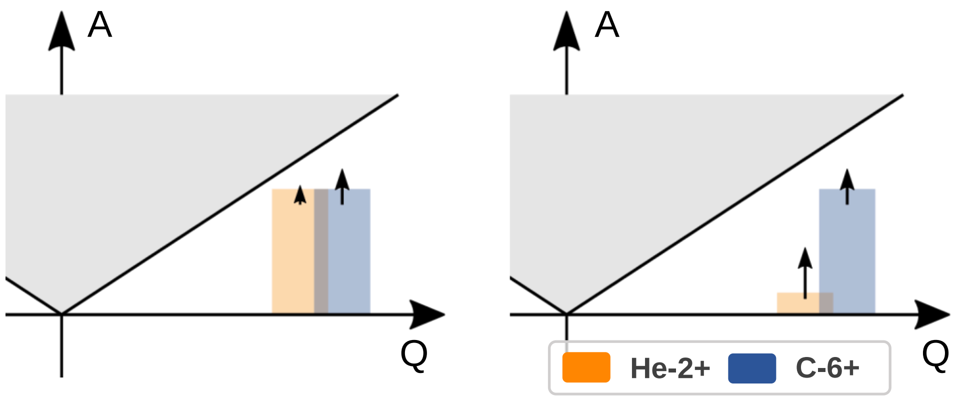
Summary/Requirements: Aim to **simultaneously extract (**with **similar particle fluence) two ion species,** which can feature

- **energy-dependent tune separation ($Q' \neq 0$)**
- and potentially **different horizontal phase space distributions**.

Baseline: Extraction based on amplitude selection (RFKO)

▶ **Multiple knobs** for **controlling intra-spill ion fluence ratio ξ** depending on emittance ratios, extraction energy, **…**

- *E.g., Q, Q'_x (tune separation), sextupole strength (ratio of stable areas), RFKO excitation signals / combinations, … .*



▶ **Next slides: first, illustrative examples ...**

- For now, **coasting beams** preliminarily based on **machine settings within the parameter range described in [8]** → *to be adapted*
- *Today: RFKO excitation (no variation of Q', $k2L$, …)*

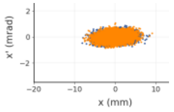
Parameter	Unit	Value
Q_x, Q_y	-	1.672, 1.79
Q'_x, $Q_{y'}$	-	-1.3, -2.6
α_C	-	0.257
σ_δ	-	0.35e-3
$\epsilon_{\text{n, rms},x/y}$	mm mrad	0.5 / 0.5

See talk by F. Kühteubl in the afternoon!

[8] F. Kuehteubl, IPAC23, doi:10.18429/JACoW-IPAC2023-TUPM091

Test Case 1: He & C with Similar Horizontal Emittances

- **Emittance ratio:** $\epsilon_{X,He} \approx \epsilon_{X,C}$

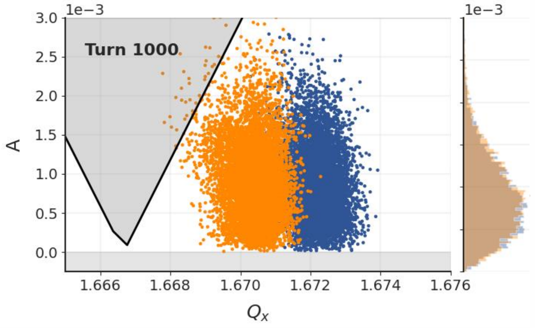


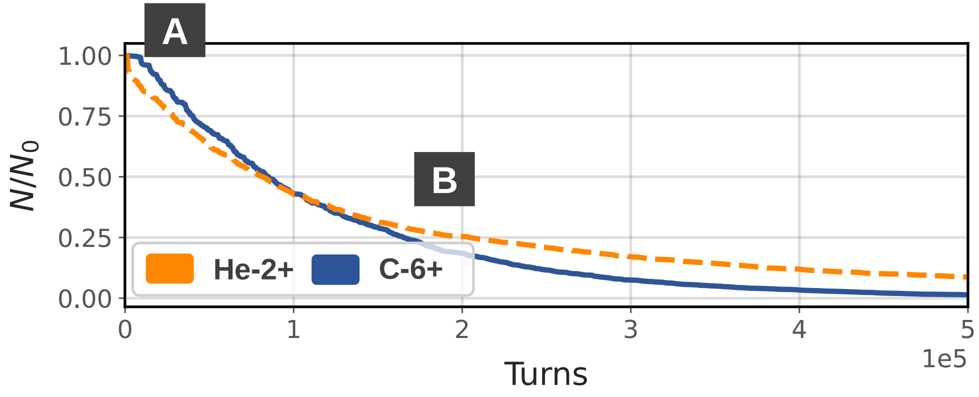
- **Extraction energy:** 400 MeV/u
- **Intensity ratio in the synchrotron**: He:C=1:10
- **Excitation**: single, constant BPSK signal with $\mathrm{BW_{N2N}} = 10\mathrm{kHz}$

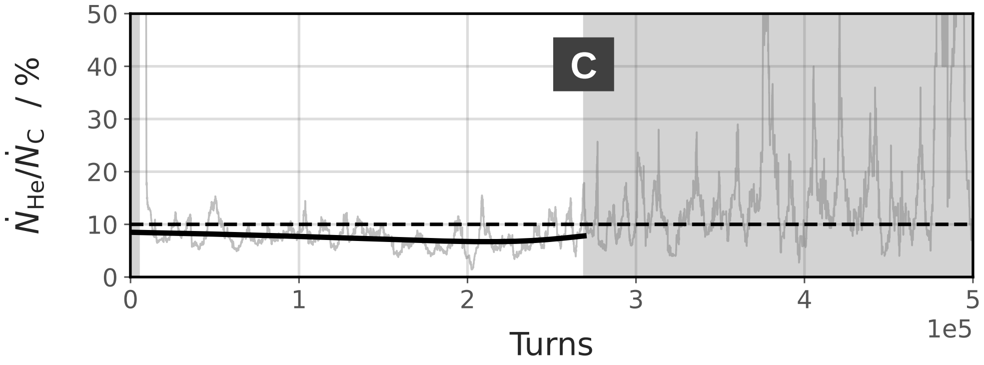
Note: Example to show dependency, non-optimized excitation for C-extraction

A. Initial helium peak during sextupole ramp

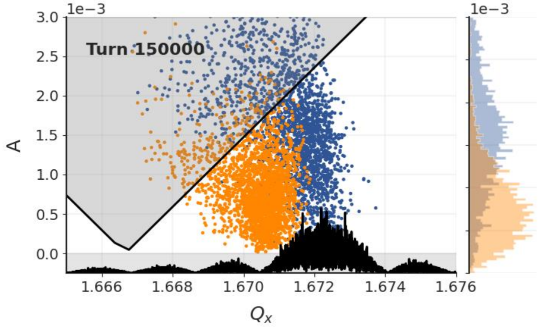
→ *Flexibility to close chopper*

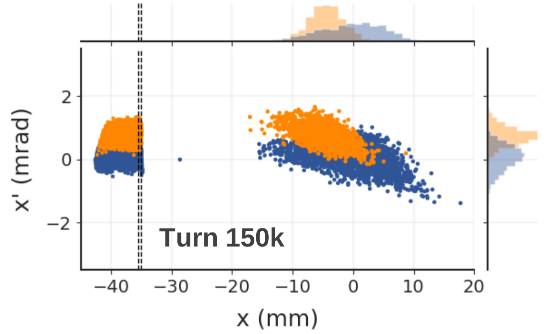






B. Extract with $\xi(t) = \dot{N}_{He}:\dot{N}_C$ depending on applied signal.





C. Flexibility to abort extraction once majority of C is extracted.

Here arb. threshold = 90% of C extracted.

Test Case 1: Sensitivity to PSK Side Lobes

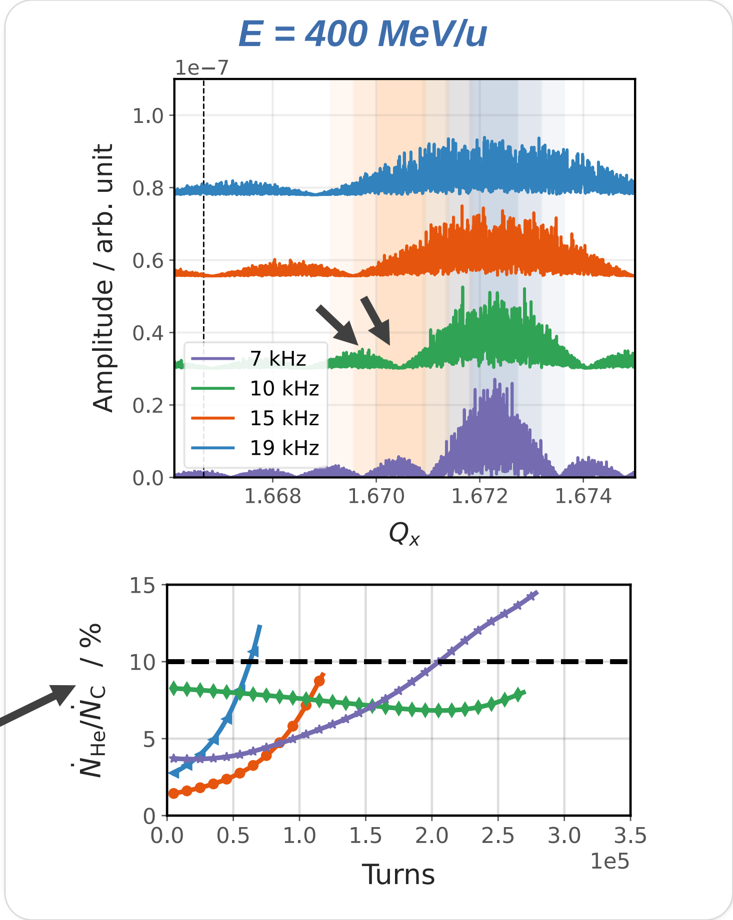
Re. B) First tests to assess **impact of applied RFKO signal on $\dot{N}_{He}:\dot{N}_{C}(t)$** by changing BW of BPSK signal

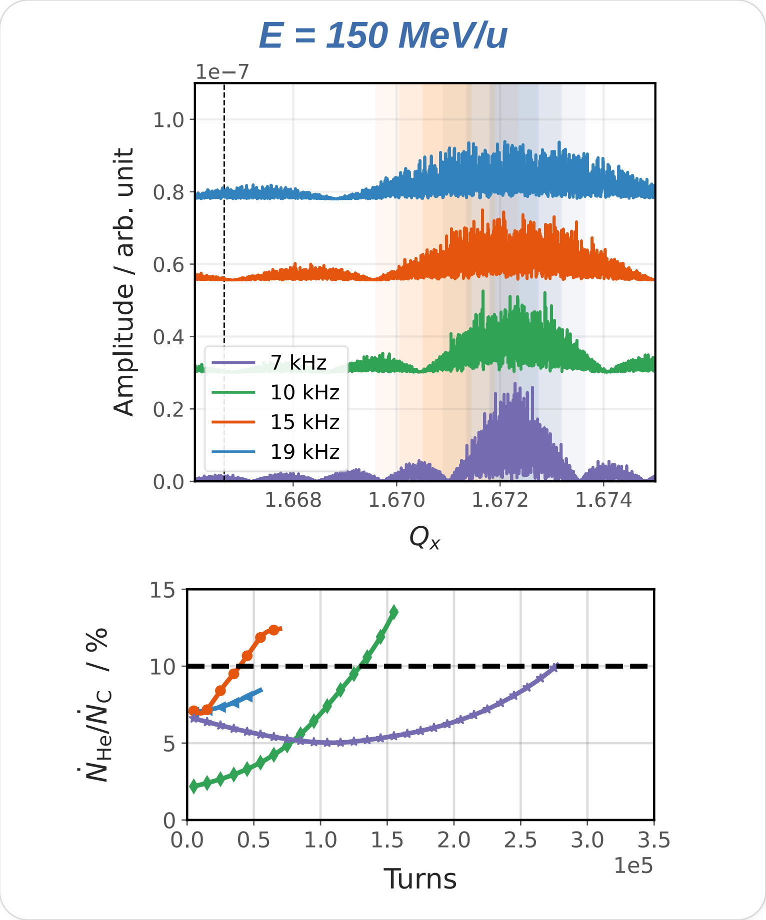
Demonstrates sensitivity of

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

to frequencies of nulls and maxima of the side lobes.

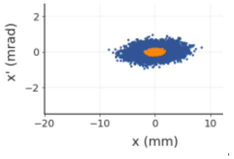
Next: combine more targeted multiple (amplitude modulated) signals, adapt Q' etc. to stabilize $\xi(t) \approx const.$, …





Test Case 2: "Pre-Heating" of Helium Core

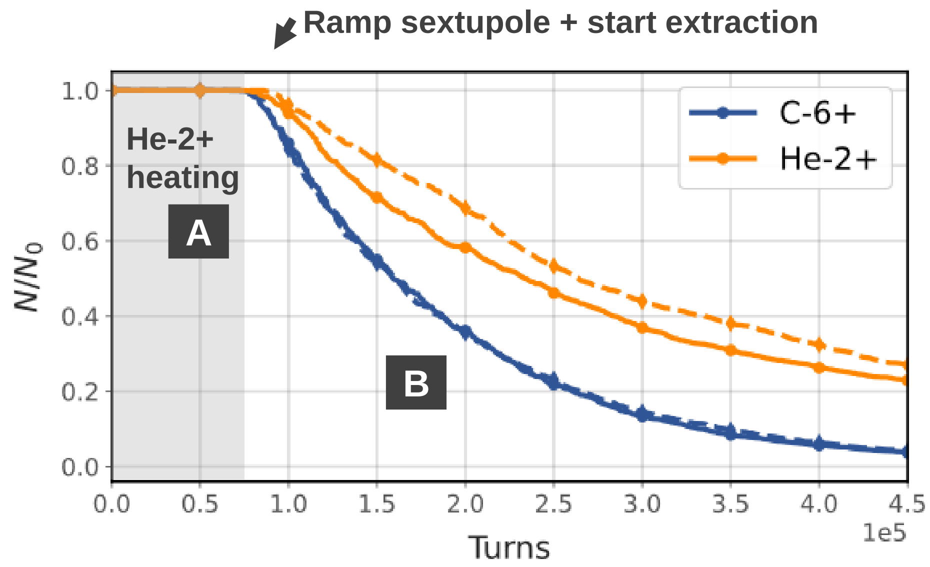
- **Emittance ratio:** $\epsilon_{X,He} \approx 0.05\ \epsilon_{X,C}$

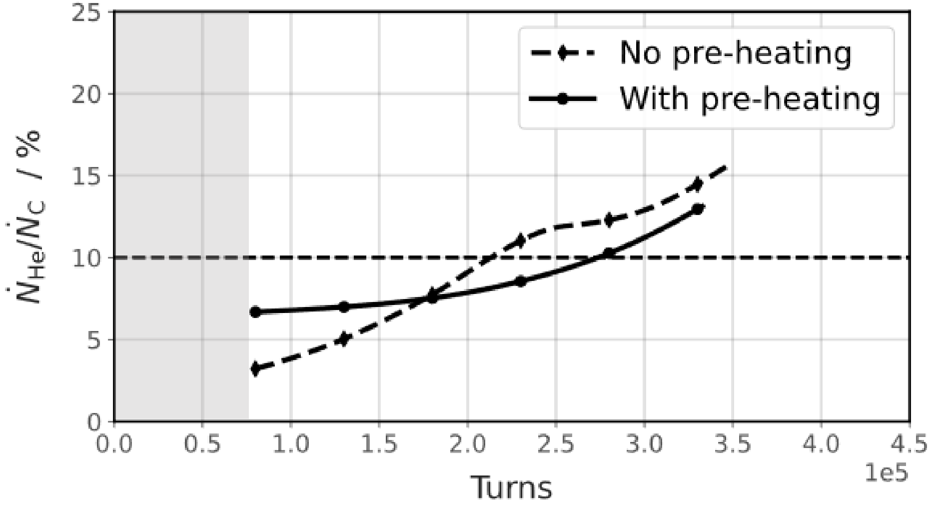


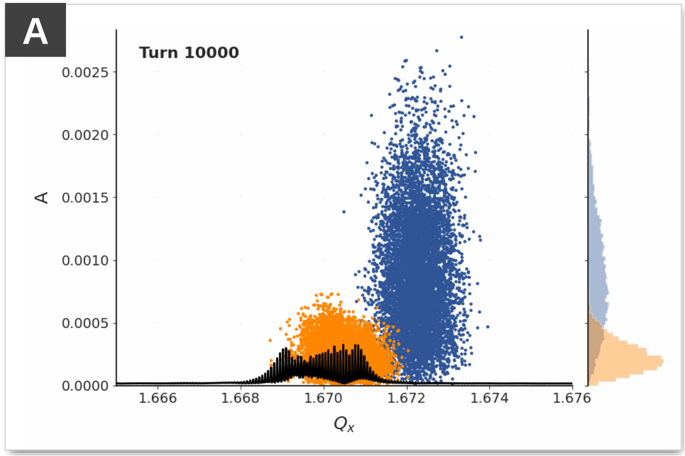
- **Extraction energy:** 400 MeV/u
- **Intensity ratio in the synchrotron**: He:C=1:10
- **Excitation**: single, constant BPSK signal with $\mathrm{BW_{N2N}} = 10\mathrm{kHz}$

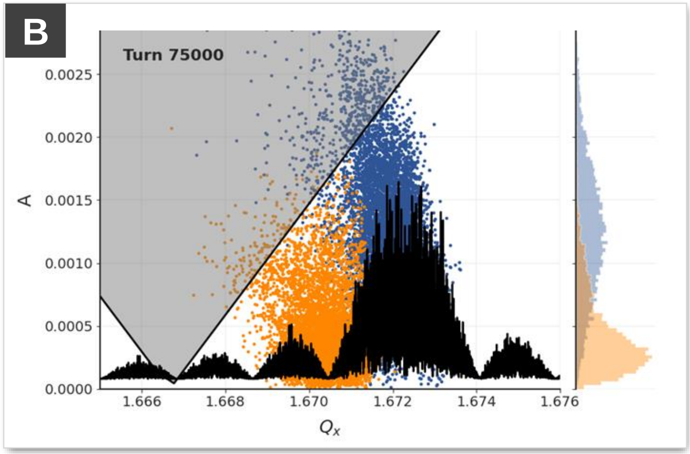
For $\epsilon_{X,He} \ll \epsilon_{X,C}$, selectively increase $^{4}He^{2+}$ emittance prior to extraction:

- Apply RFKO excitation only (mainly) in frequency range of $^{4}He^{2+}$.
- Here: first example using frequency modulation
- *Demonstrates beneficial effect, to be optimized!*









Conclusion & Next Steps

Take aways:

- ✓ **Study the feasibility** of delivering a **mixed beam for nonclinical research** (TU Wien, MedAustron, HEPHY).
- ✓ **Proof-of-principle simulations using Xsuite for** slow extraction of ion mix currently being performed.
- ✓ Due to the beam rigidity offsets between He-2+ and C-6+, **RFKO selected as baseline extraction mechanism.**
- ✓ Evaluating **robustness of extraction to differences in momentum/mass** between He-2+ and C-6+ (depending on extr. & transition energy) & impact of different **horizontal emittance ratios.**
- ? *Desired input: what is the acceptable range for the intra-spill ion fluence ratio?*

Only the beginning of the journey - next steps:

- Study different scenarios to **further develop extraction set-up**, …
  - **RFKO signal composition,**
  - **machine settings** (chromaticity, tune, momentum spread),
  - **momentum acceptance** of extraction line,
  - **ripples, bunched beams**, …

Thank you for your attention!