Three-year review of mixed-beam delivery in synchrotrons

October 9, 2026 | TU Wien | Vienna, Austria

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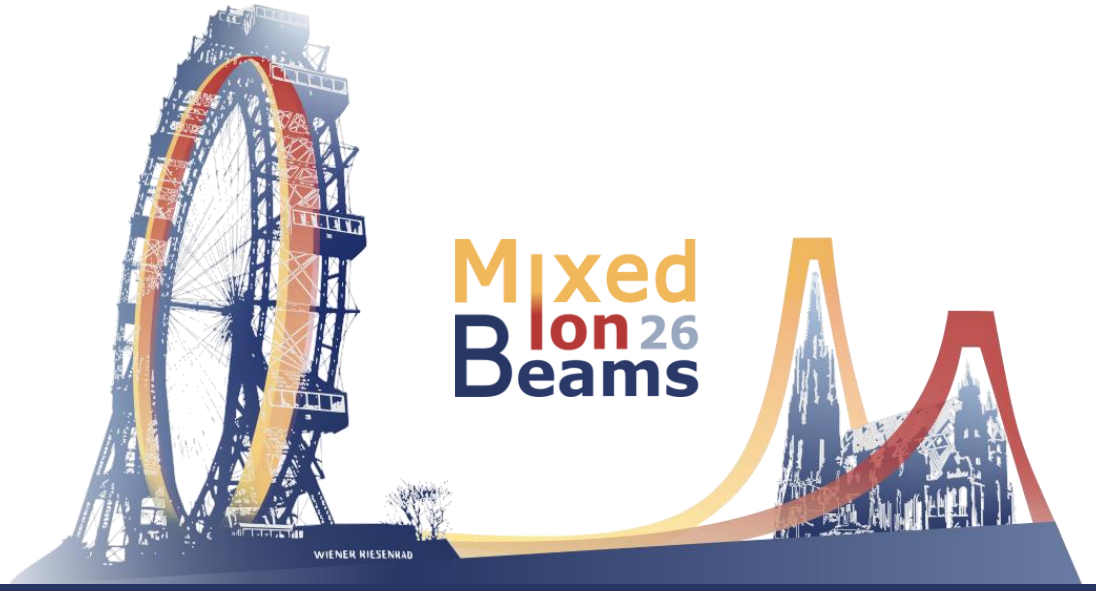
*Referring to & citing work from **many others** (see slides)!*



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Introduction

- **Previous studies** of multiple ion species in synchrotrons mainly concerned ...
  → ... unintended beam contamination
  → ... secondary particles produced in collimators.

- Studies on **deliberate & controlled** mixed-ion beam delivery **intensified only recently**:
  → *similar m/q: ~2023*
  → *distinct m/q: ~2025*

- **Initial motivation**: mixed He-C beams for **online range monitoring in carbon-ion therapy**
  → Mixed He-C beams have since been **delivered at MedAustron and GSI**
  → Research applications in accelerator physics, detector development and medical physics.

- **Growing interest** in other ion combinations and from **other user communities.**

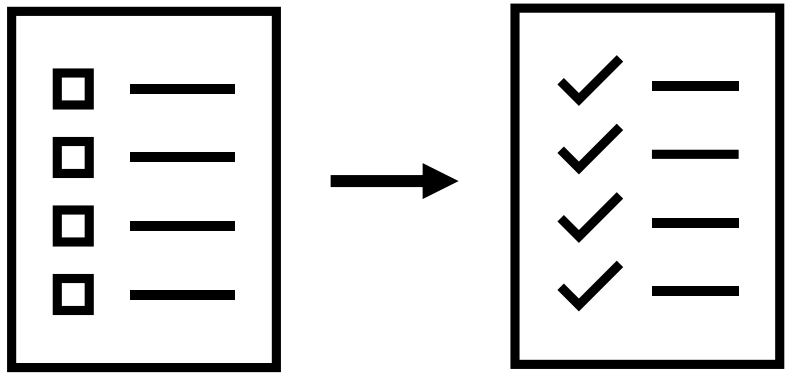
Collection of cited papers

- Feel free to browse through it during coffee breaks and approach us or the authors for discussions ☺



Collection of questions

- Throughout the presentations, we will highlight selected open questions for the different topics.
- List is also displayed in coffee area (take a copy!)
- **Feel free to add additional questions!**
- Our aim is, to discuss as many of these questions as possible during this workshop, the round-table and panel discussions!



Example for previous studies I

[1] N. Angert et al., “Accelerating and separating mixed beams of ions with similar charge to mass ratio in the CERN PS complex” EPAC 1988, pp. 1367

[2] S. Hancock et al., “Transition revisited” CERN/PS/90-53 (OP), 1990

Removal of O^{8+} contamination in S^{18+} beam during transition crossing in the CERN PS [1,2]

- Late 1980s
- Was not possible to deliver S^{12+} beam from 14.5 GHz ECRIS without O^{6+} contaminations (stripped afterwards)
- Ion mixtures was “cleaned” from O contamination when crossing transition in the PS

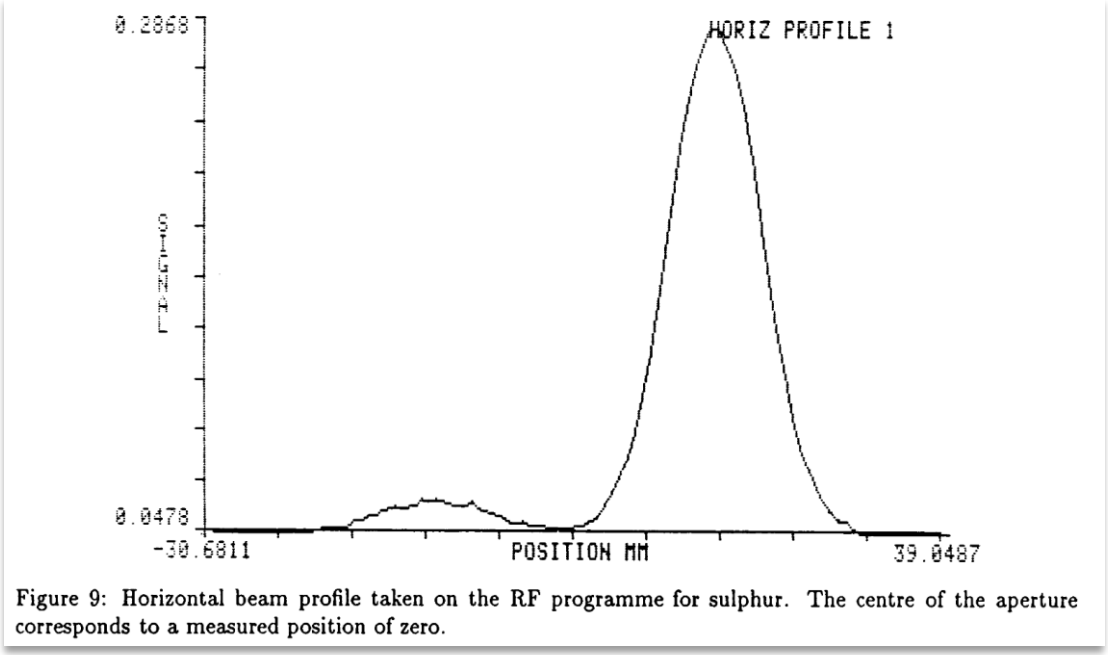


Figure 9: Horizontal beam profile taken on the RF programme for sulphur. The centre of the aperture corresponds to a measured position of zero.

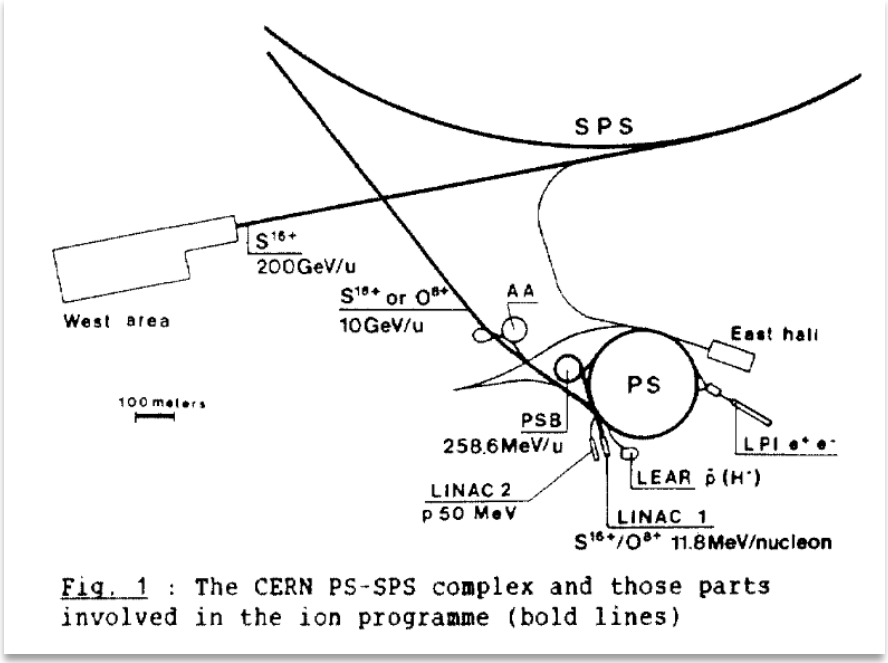


Fig. 1 : The CERN PS-SPS complex and those parts involved in the ion programme (bold lines)

Example for previous studies II

Proposal to measure **mass difference between proton and anti-protons** based on dispersive orbit offsets (S. van der Meer, 1978)

3. Examples

Simultaneous acceleration of p and $\bar{p}$ is foreseen for the p-$\bar{p}$ project, both in the PS and in the SPS. As an example, for $\Delta m/m = 10^{-5}$ and $\gamma-\gamma_T = 0.1$, we would have $\Delta R/R = 0.83$ mm for the PS or $\Delta R/R = 4.6$ mm for the SPS. Such differences in mean orbit position would be easily detectable with a transverse pick-up followed by a narrow-band amplifier tuned to the r.f. frequency. The position of the pick-up relative to the cavities should be such that p and $\bar{p}$ bunches will pass at different times. The intensity need not be high so that no danger of longitudinal instability should exist.

The value of γ_T depends slightly on radius in practice. This effect should be taken into account if a mass difference were found. If ΔR is unobservable, the effect of varying γ_T is negligible in the estimation of the upper limit for $\Delta m/m$.

Later discarded, as subsequent analyses indicated that for that specific use case alternative methods could achieve higher accuracy [4, Chp. 13].

[3] S. van der Meer, Measuring the p − p mass difference by the transition energy method , Technical Report No. CERN-PS-AA-78-17 (CERN, Geneva, 1978).

[4] Bryant and K. Johnsen, “The Principles of Circular Accelerators and Storage Rings”, 1993

Mixed He-C beams for range monitoring

- ***Since <2018:*** **Initial proposals and concept studies**
  - CNAO [5], GSI [6], DKFZ [7,8]
  - No mixed beam experimentally available back then
- ***Since 2023:*** **ERC project PROMISE at GSI** [9-13].
  - *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:*** **Mixed-beam project at TU Wien & MedAustron** [14-17]
  - *Techniques for mixed-ion beam delivery in medical synchrotron facilities*

    ⟶ *Summer 2024:* first mixed beam in a clinical synchrotron facility, enabled by new double multiturn injection [13]

    ⟶ *Since late 2025:* first mixed beam imaging experiments, in collaboration with **MUW, MBI, GSI, CNAO**

Selected examples (non-exhaustive):

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

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

[7] L. Volz et al., Phys Med Biol 65/2, 2020

[8] J. Hardt et al, Phys Med Biol 69/5, 2024

[9] C. Graeff et al. PROMISE Project, GSI

[10] M. Galonska et al., GSI, IPAC'24

[11] D. Ondreka et al., GSI, IPAC'24

[12] L. Volz, R. Hetzel et al, https://arxiv.org/pdf/2603.12975

[13] A. Pastushenko et al., GSI, IPAC'26, THP4093

[14] M. Kausel, PRAB 28, 111001 (2025)

[15] E. Renner PRAB 29, 093802 (2026)

[16] E. Renner, IPAC'26, TUO8T01 and THP4091

[17] M. Kausel, IPAC'26, TUP8004

Different infrastructure required **different techniques** in the two facilities

Two (currently demonstrated) **options for mixed He-C beam generation**

(A) Direct generation in a single ion source

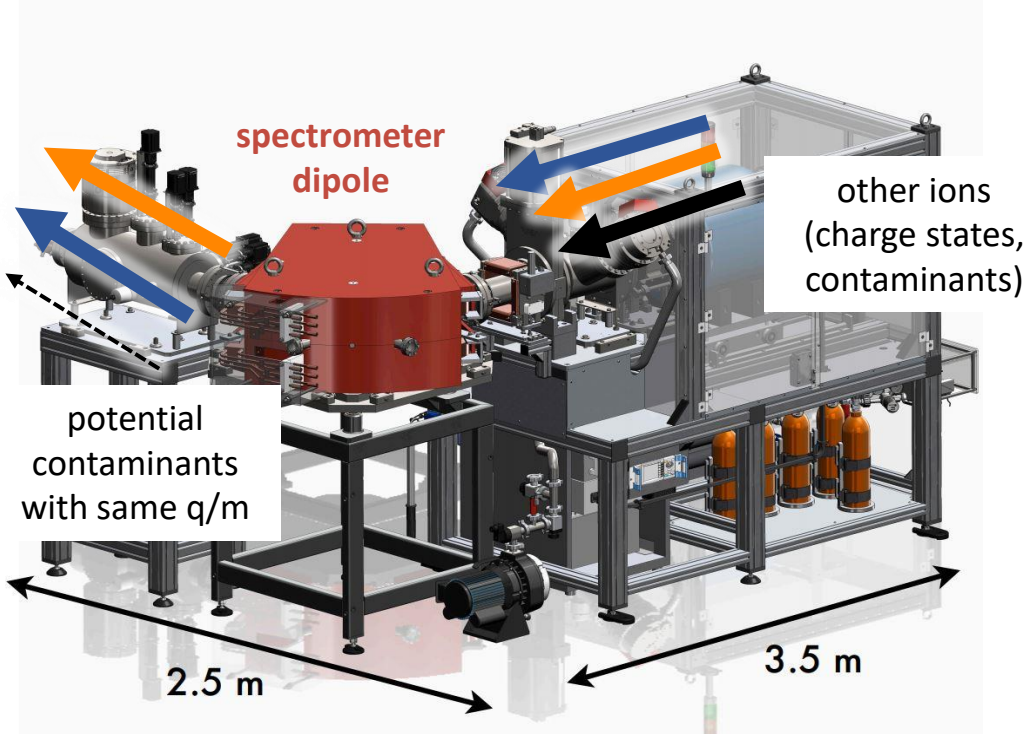
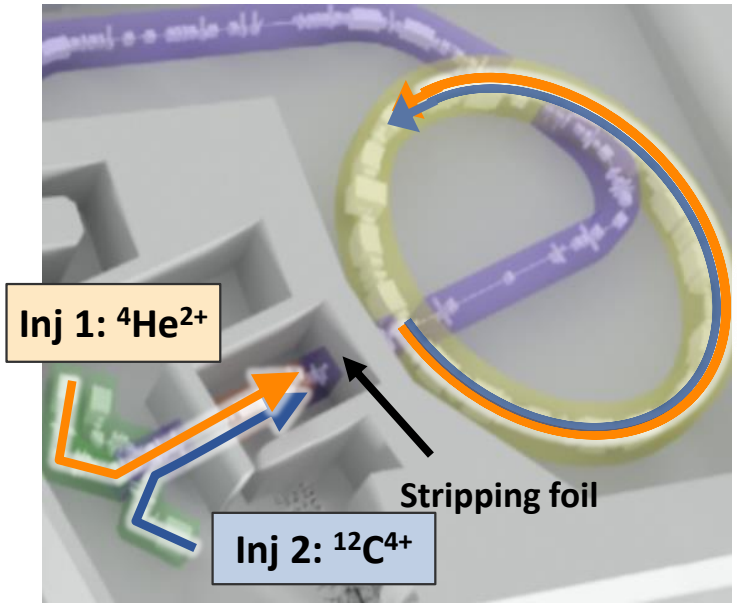


Figure: Supernanogan ECRIS (Pantechnik)

(B) "Mix" He & C via sequential injection into the synchrotron



Not currently feasible in typical clinical synchrotron facilities

Possible (in experimental research setup)

Mixed beam generation in a single ion source @ GSI

- **14.5 GHz ECRIS to deliver mixed $^{12}C^{3+}$ and $^{4}He^{1+}$ beams**
  - November 2023 & May 2025
  - A/q =4
  - Methane and helium as source gas
  - Further acceleration in UNILAC and SIS18

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

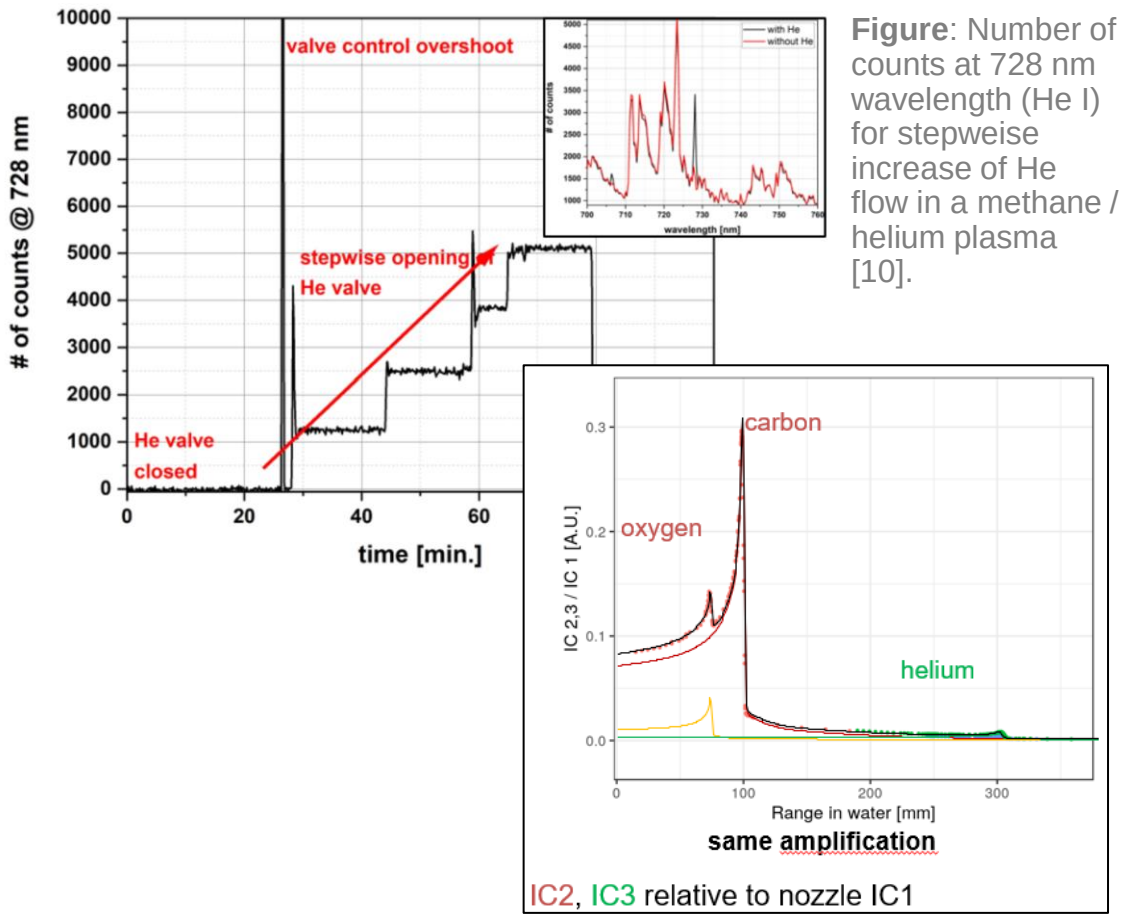
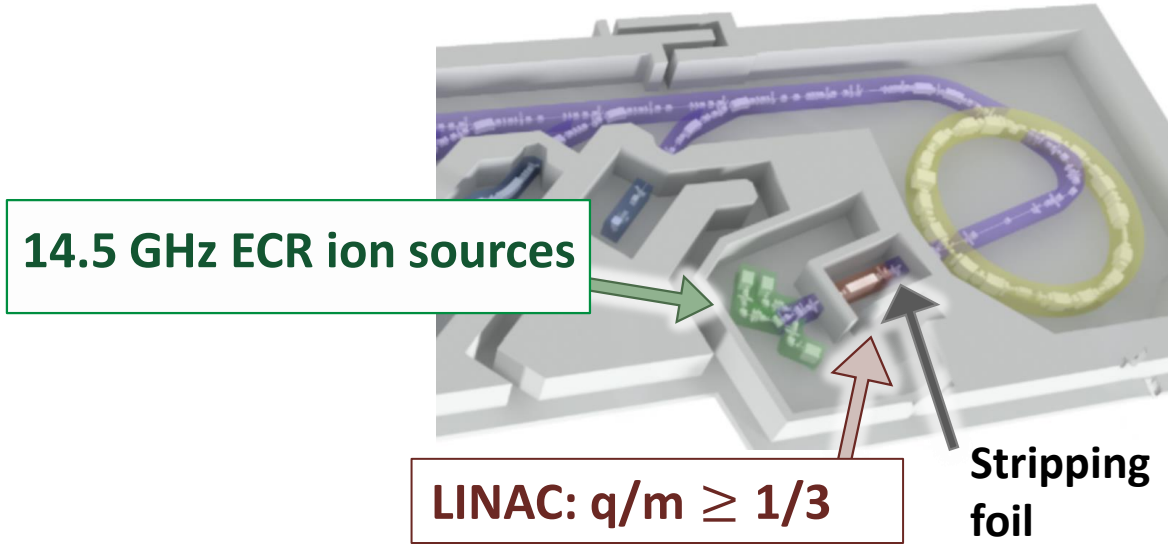


Figure: Number of counts at 728 nm wavelength (He I) for stepwise increase of He flow in a methane / helium plasma [10].

M. Galonska, et al. IPAC'24 [10] L. Volz et al., 5th Ion Imaging Workshop '24

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

Not possible with existing infrastructure at MedAustron [4] or comparable clinical synchrotron facilities (see table).



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

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

Mixed-beam generation from single ion source: selected questions I

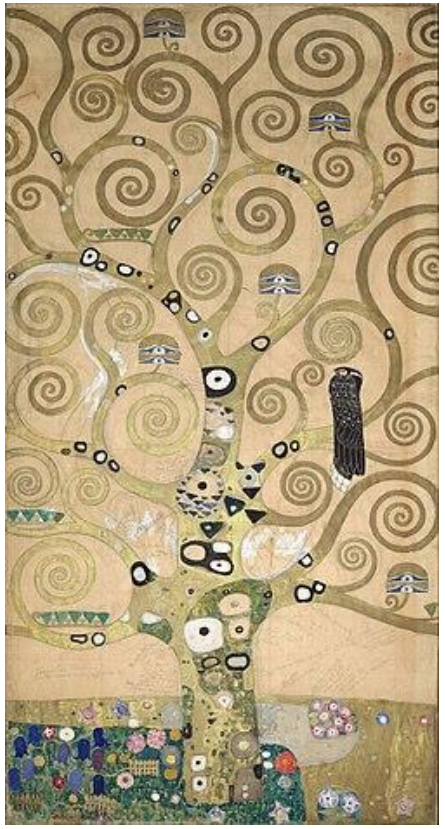
Delivery & diagnostics

- How precisely can we **control the mixing ratio** and how fast can we adjust?
- How can we monitor or **measure the mixing ratio** of the generated beam (direct vs indirect)?
- Can we assume that ion species are extracted with similar **emittances**?

Deliverable ion combinations

- Can we deliver a **C^{3+}/He^{1+} beam** with acceptably low **O^{4+} contamination** using a 14.5 GHz ECRIS?
- Can we use an **18 GHz ECRIS** (e.g. AISHA at CNAO) to deliver **C^{6+}/He^{2+} beams** (with acceptably low O^{8+} contamination) with clinically useable intensities?
- Which **other ion sources** would be suitable candidates?

Talks: ***"Mixed-beam generation in ion sources"***
L. Celona (INFN) and M. Galonska (GSI)



"**L'Arbre de Vie**" **Gustav Klimt** (Museum of Applied Arts, Vienna, Austria). Draft for wall frieze in the Palais Stoclet in Brussels [https://en.wikipedia.org/wiki/The_Tree_of_Life,_Stoclet_Frieze]

Mixed-beam generation from single ion source: selected questions II

LINACs

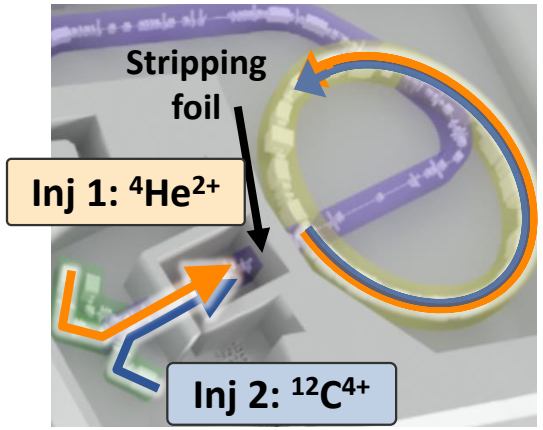
- Could the **LINACs** at HIT, CNAO, … be upgraded to accelerate **ions with A/q=4**?
- Could a **LINAC for acceleration of ions with A/q=4** be built at a cost comparable to present LINACs for therapy facilities?

Talks: “***LINACs in medical synchrotron facilities***” B. Schlitt (GSI)



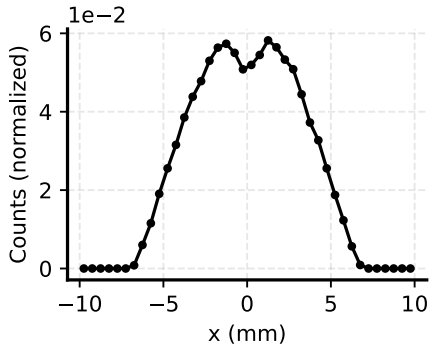
“L'Arbre de Vie” Gustav Klimt (Museum of Applied Arts, Vienna, Austria). Draft for wall frieze in the Palais Stoclet in Brussels [https://en.wikipedia.org/wiki/The_Tree_of_Life,_Stoclet_Frieze]

Alternative: Generate mixed He/C beam via **double multiturn injection** into synchrotron

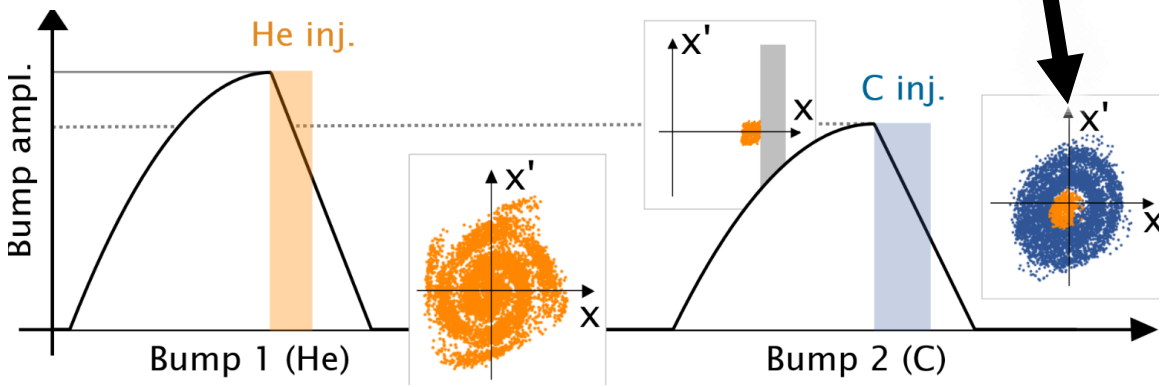


Distinct horizontal phase space distributions

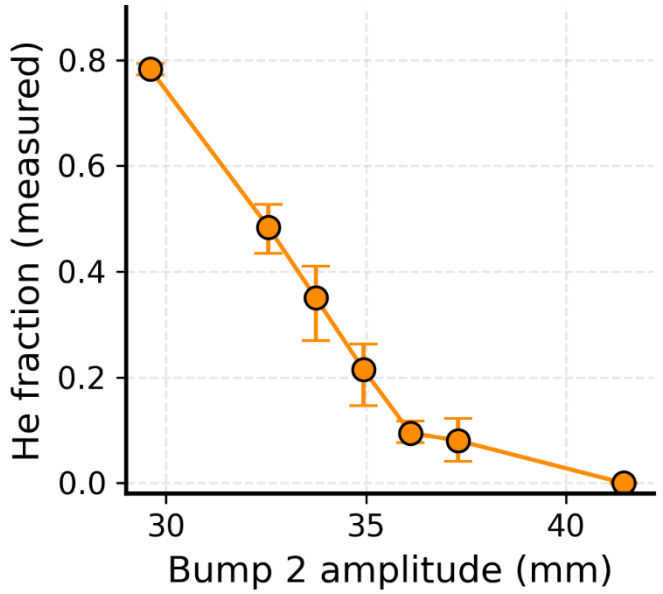
- Helium core
- Carbon annulus



Measured profile of a pure carbon beam with DMTI settings



Flexibly **tailor He fraction between 0-100 %** by adjusting bump 2 amplitude



e.g. [14] M. Kausel *et al.*, PRAB 28, 111001 (2025),[17] M. Kausel *et al.*, IPAC'26, TUP8004

Mixed-beam generation via sequential injection: Selected questions

- How can we **minimize fluctuations** in the mixing ratio?
  [What level of fluctuations would actually be acceptable?]
- To which level can we **minimize the cycle-time overhead** required for pulsing the injector twice?
- Do we need to or how can we **optimize the distinct phase space distributions** of the ion mixture?
- What are the advantages and disadvantages of different horizontal phase space distributions (shared vs. nested) for slow extraction, especially a flat He:C ratio?

Talk: ***"Sequential Synchrotron Injection Schemes for Mixed Ion Beam Generation"***
(M. Kausel, MedAustron / TU Wien)



Pointe de la Jonction Rhone-Arve (Geneva)
[https://www.geneve.ch/pointe-junction]

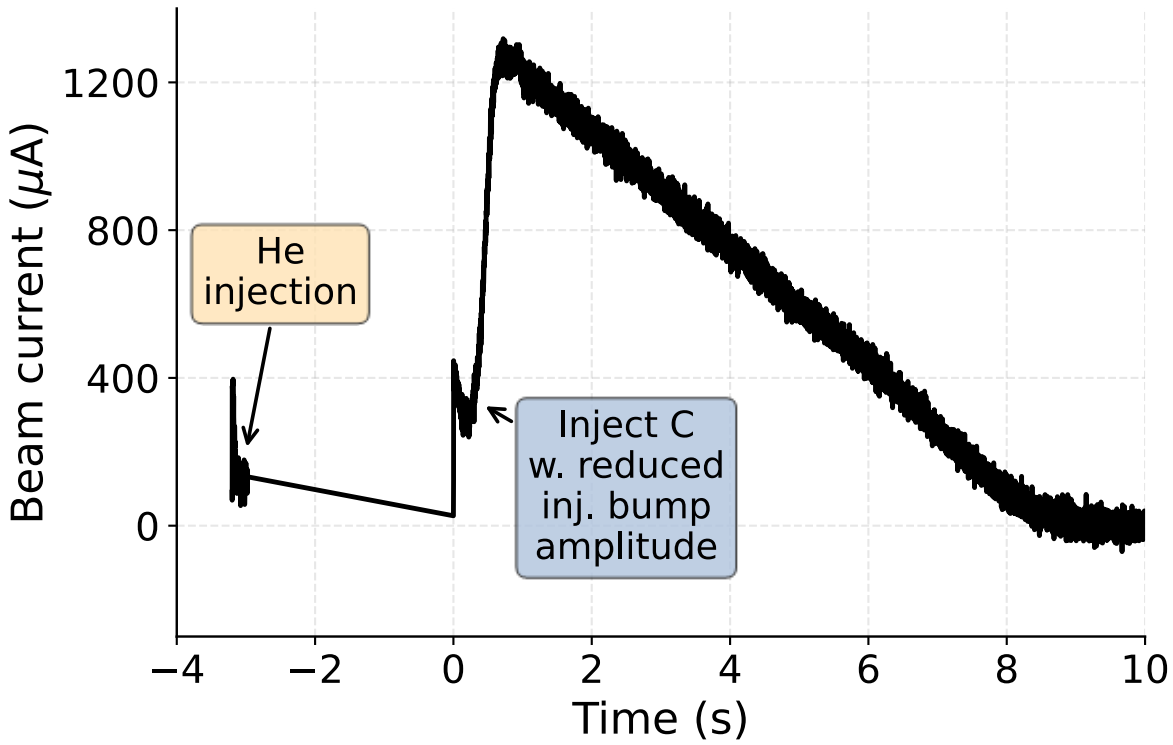
Mixed-beam acceleration in synchrotrons (same q/A)

- 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

⟶ needs to be understood, e.g. to prepare slow extraction studies.

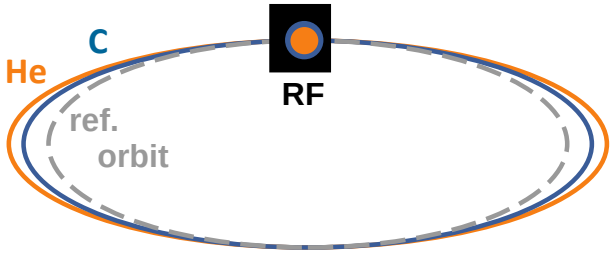


Mixed-beams in synchrotrons (similar q/m)

He larger m/q → more rigid → longer path

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

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



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

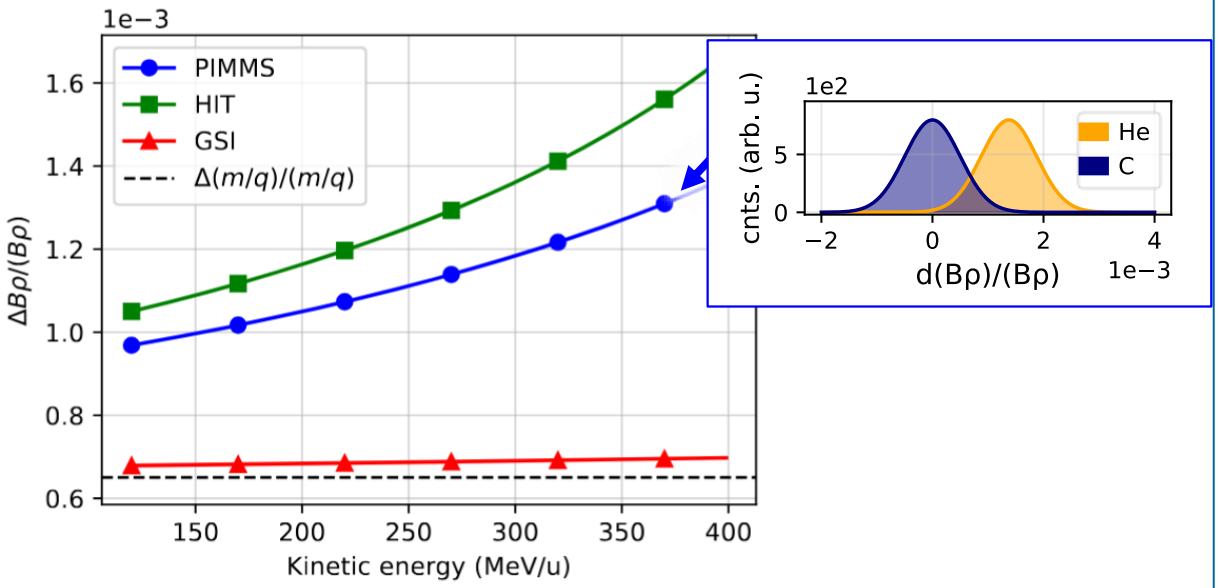
→ He accelerated to higher velocities

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

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

Take away: **Both contributions add up to total rigidity offset** → *depends on facility & energy!*

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



[15] E. Renner PRAB 29, 093802 (2026)

Mixed-beam acceleration: Selected questions

- How do the longitudinal and transverse particle **distributions evolve in detail during acceleration**?
- E.g. so far, no collective effects or interaction with resonances during acceleration included!



Bridget Riley (UK, op art painter) [from https://www.wikiart.org/de/bridget-riley]

No dedicated talk, but partially included in

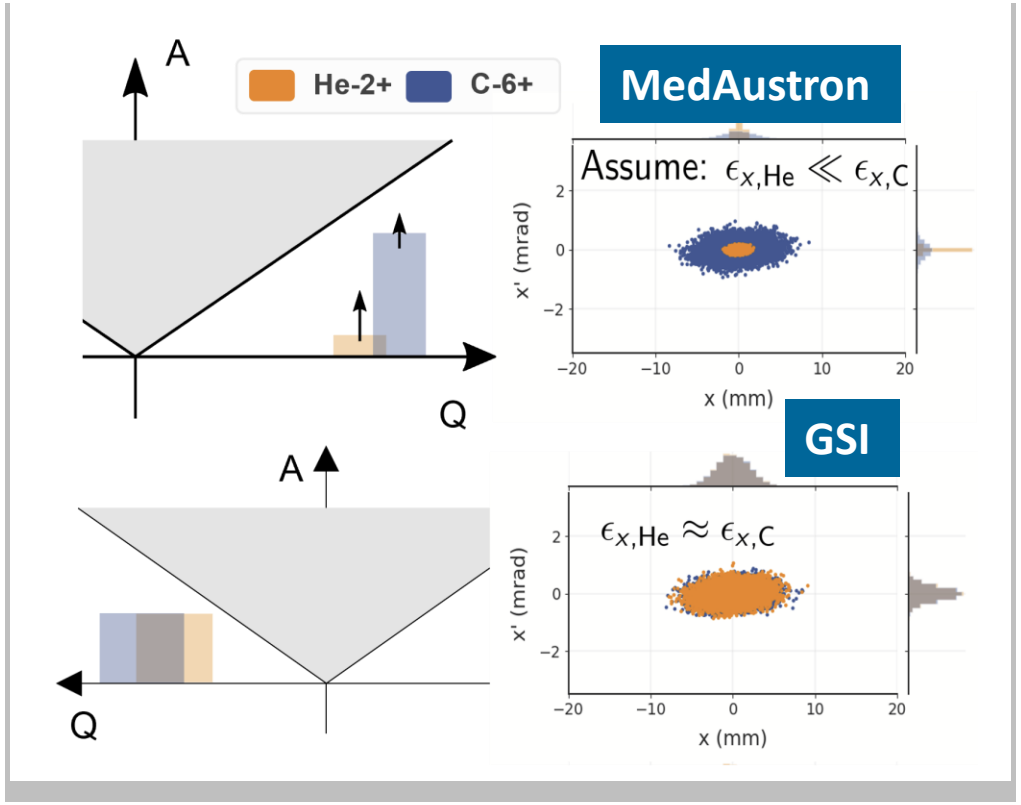
- ***"Slow extraction of mixed ion beams"*** (A. Pastushenko, GSI)
- ***"Measuring mixed-beam properties in the accelerator complex"*** (E. Renner, TU Wien)

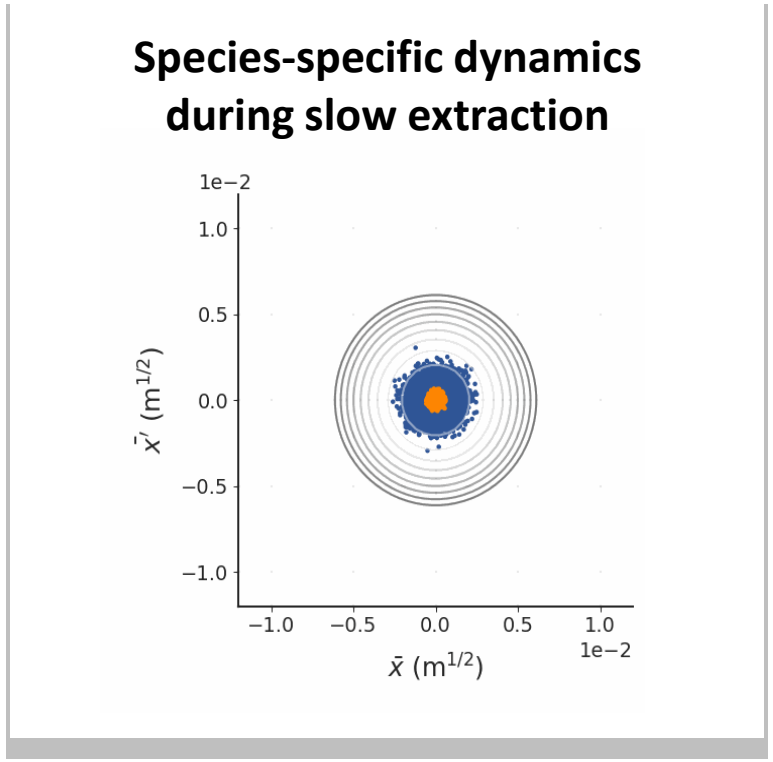
Linearized calculations in "**Noninvasive ion fraction quantification of dual-species beams in synchrotrons**" (E. Renner et al. PRAB 29, 093802, 2026)

Mixed beam slow extraction

Target: Maintain **approx. constant He:C ratio** while delivering the beam to the patient over 1-10s, **despite differences in beam distributions**.

Challenge: species-dependent distributions and beam rigidities





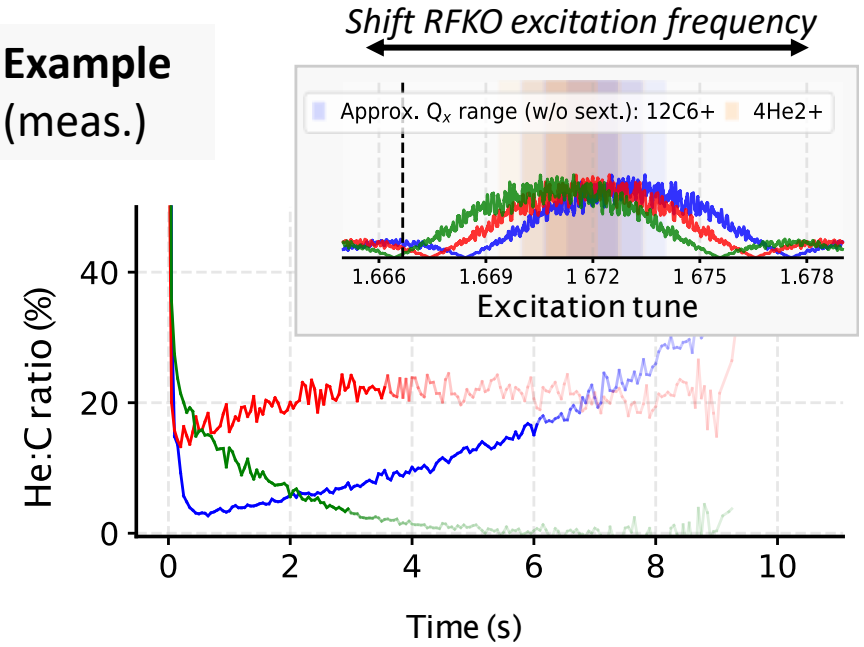
Mixed beam slow extraction

RF knockout (RFKO) slow extraction

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

- RFKO signals (for Q'≠0),
- chromaticity, ...

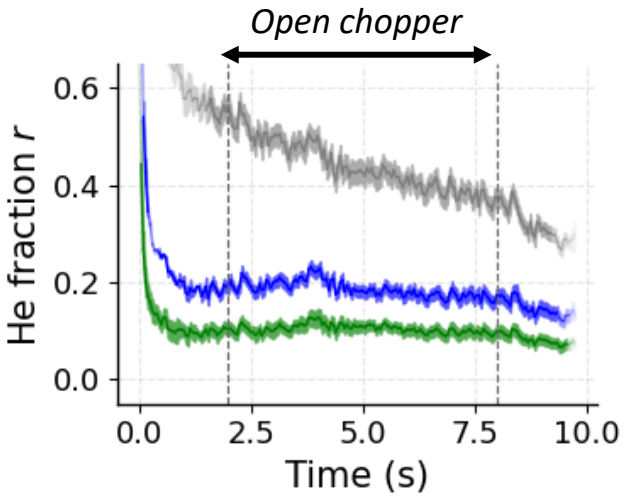
Example (meas.)



Both, at GSI and MedAustron, **preliminary mixed-beam SX setups for first experiments** established!

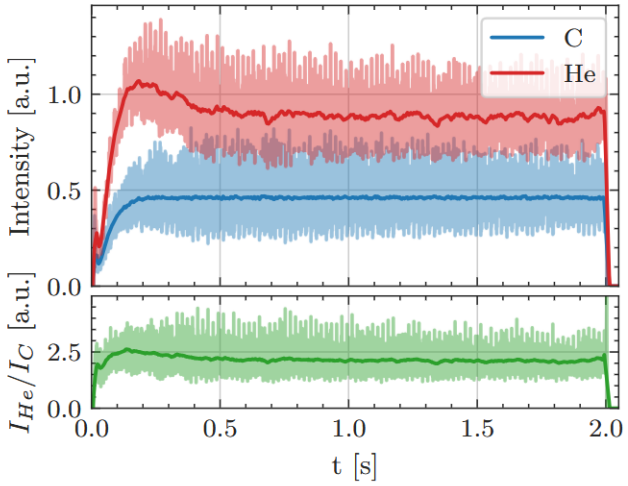
- He:C(t)≈const.
- He:C ratio empirically tuned
- Not all details understood yet

MedAustron



[16] E. Renner *et al.*, IPAC '26, THP4091

GSI



[13] A. Pastushenko *et al.*, IPAC '26, THP4093

Mixed-beam slow extraction: Selected questions

- What are potential causes for **measurement-simulation** inconsistencies?
- Given the energy-dependence of the beam rigidity offset, how can we **efficiently commission a "flat" He:C ratio** throughout the spill **for all extraction energies**?
- What is the acceptable level for **He:C intensity** and **beam size fluctuations** and how can we minimize them.
- Are there applications for selective extraction or **changing the mixing ratio during the spill**?



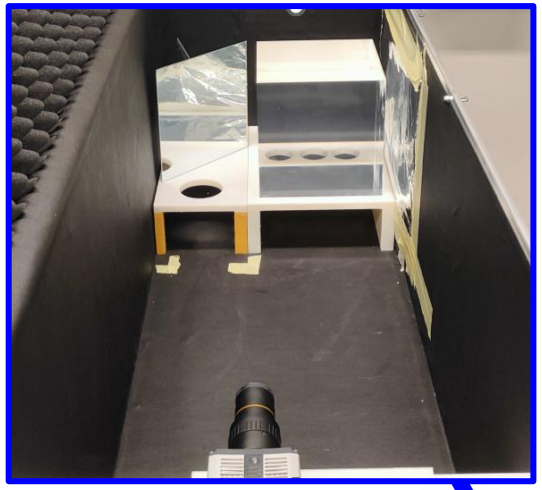
Giacomo Balla, 1912, Dynamism of a Dog on a Leash, (oil on canvas), Albright–Knox Art Gallery, New York [© Albright-Knox Art Gallery]

Talk: ***"Slow extraction of mixed ion beams"*** (A. Pastushenko, GSI)

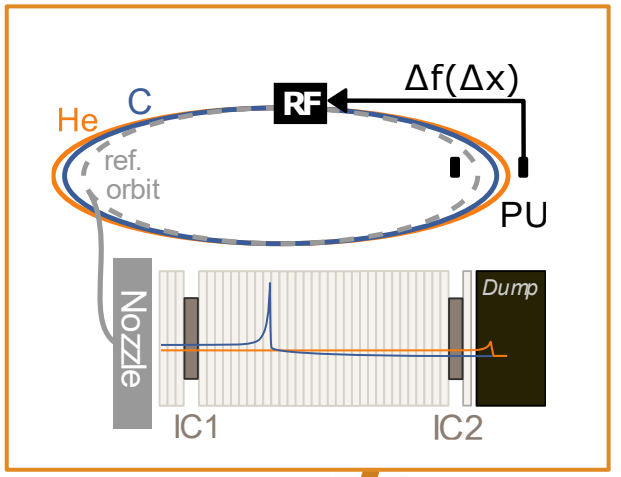
Mixed-beam diagnostics & imaging systems

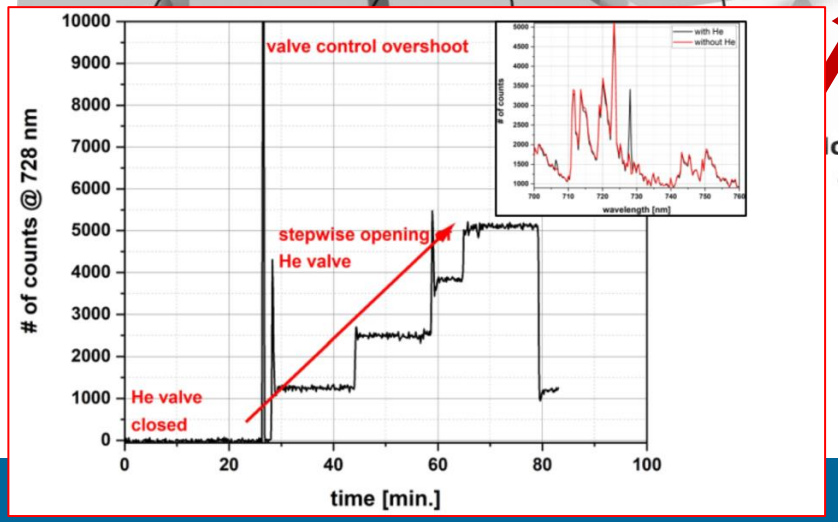
Develop systems

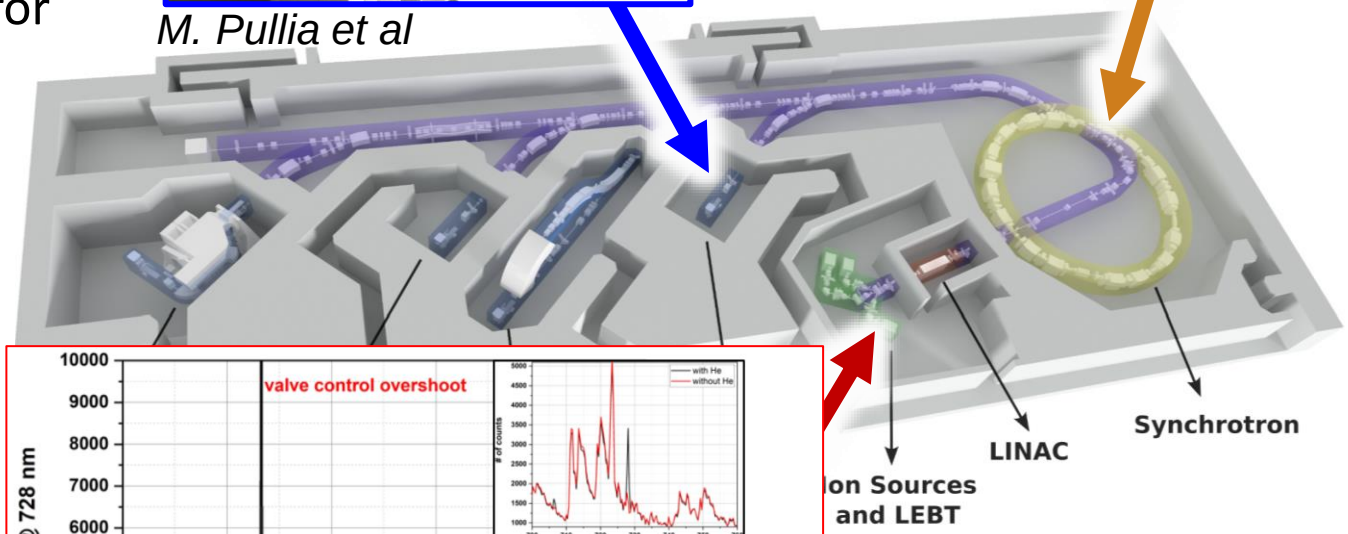
- to **characterize the mixed-beam** properties within **accelerator** & in the **irradiation room** for
  - efficient commissioning and operation,
  - monitoring during experiments,
  - interlock systems, ...
- for **range-probing** during patient treatment



M. Pullia et al







M. Galonska et al

Mixed-beam diagnostics & imaging systems: selected questions

- New concepts to improve or enable **mixed-species diagnostics** in the **accelerator complex** (at all energy stages) and **irradiation room**?
- Considering the detection capabilities of the different imaging systems, what is the **minimum required He fraction**?

Talks:

- ***"Measuring mixed-beam properties in the accelerator complex "*** (E. Renner, TU Wien)
- ***"Diagnostics to characterize the extracted mixed beam "*** (F. Ulrich-Pur, MBI, TU Wien)
- ***"Mixed-beam range probing systems"*** (L. Volz, GSI)



Claude Monet. Trouée de soleil dans le brouillard (Sun Breaking Through the Fog)
Houses of Parliament, 1904. London, Sun Breaking Through the Fog, 1904 Musée d'Orsay, Paris

Dual-Frequency acceleration (unequal A/q): Selected questions

Multiple, independent RF frequencies allow simultaneous acceleration of ion species with different q/m

- **Milestone in May 2025 at GSI (SIS18)**
  - Double multi-turn injection
  - First successful acceleration and fast extraction of ion species with different q/m
  - Q_x-dependent losses observed when applying "alien" frequency → reproduced in simulations;
  - Follow-up experiments at MedAustron in preparation
- Paves way for **new ion combinations** & respective range differences **for treatment monitoring**
  - e.g. simultaneous p+/He^{2+} acceleration: tests could be feasible at MedAustron with prototype for LLRF system upgrade.

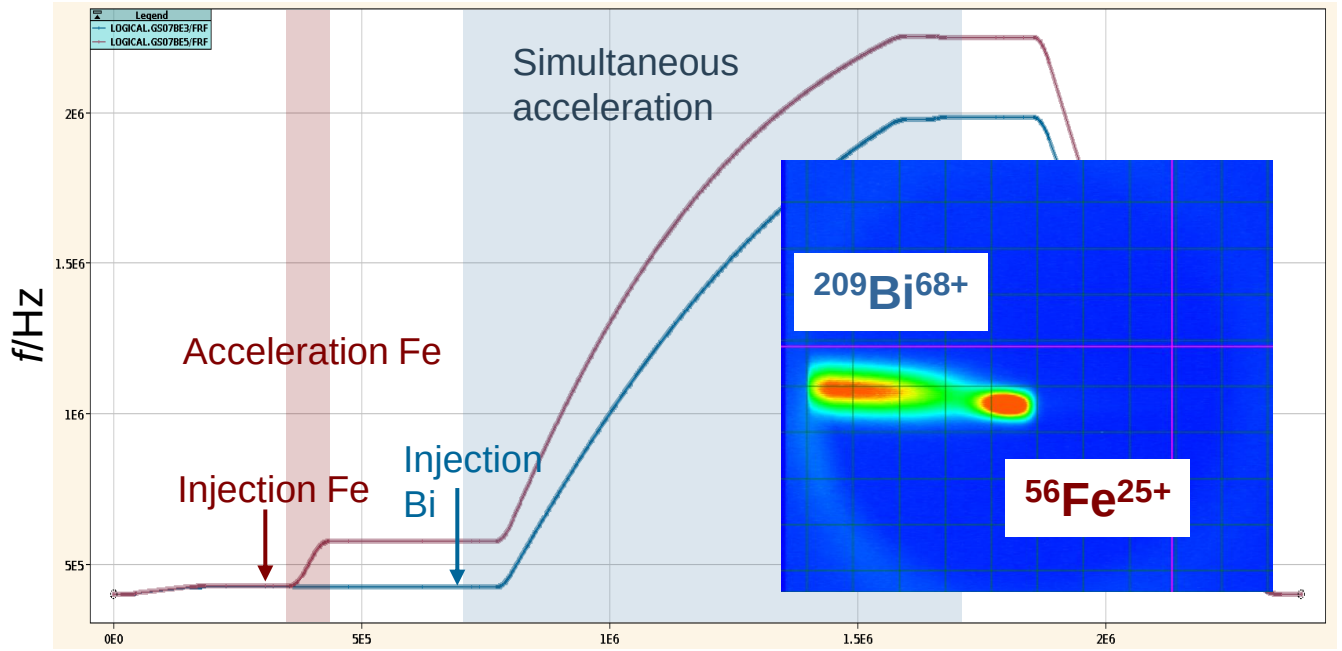


Figure courtesy of D. Ondreka (GSI)

- Opportunities for broader scientific communities (plasma physics).

Dual-Frequency acceleration (unequal A/q): Selected questions

- Concepts for the **fast extraction of the two ions**, time-separated but immediately after another.
- **Cavity regulation** when applying both frequencies to the same cavity: What **frequency separation** is required between the two frequencies (or between each frequency and the harmonics of the other), for existing and potential future systems?
- **Measuring beam parameters per ion species** (current/intensity, beam position) based on band-filtered signals, possibly also useable for feedback.



Giuseppe Arcimboldo, Summer,1563
(Vienna Museum of Art History)

Talks (concept and applications):

- "**Acceleration of mixed beams with unequal A/Q**" (D. Ondreka, GSI)
- "**Ion-pair candidates and design considerations for mixed-beam delivery in NIMMS**" (H. Huttunen, CERN)
- "**Mixed Ion Beam Applications in Plasma Physics and beyond**" (M. Schanz, GSI)

Terminology (my point of view ... up for discussion!)

Mixed beams

- Simultaneous delivery of two ion species
- Can be a subcategory of “cocktail beams” in some references.

Cocktail beams

- Accelerator setups that allow for fast switching between different ion species.
- Not necessarily simultaneous delivery
- Often used in LINAC- and cyclotron-based facilities.

→ **Talk**: “**Hearts ++**” (C. Cortes, CERN)

Mixed irradiation fields & LET painting

- Sequential irradiation of a device/sample or a patient using different ion species with different LETs (and energies)
- *I’d avoid using “mixed beams” for that.*

Any comments?



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