Sequential Synchrotron Injection Schemes for Mixed Ion Beam Generation

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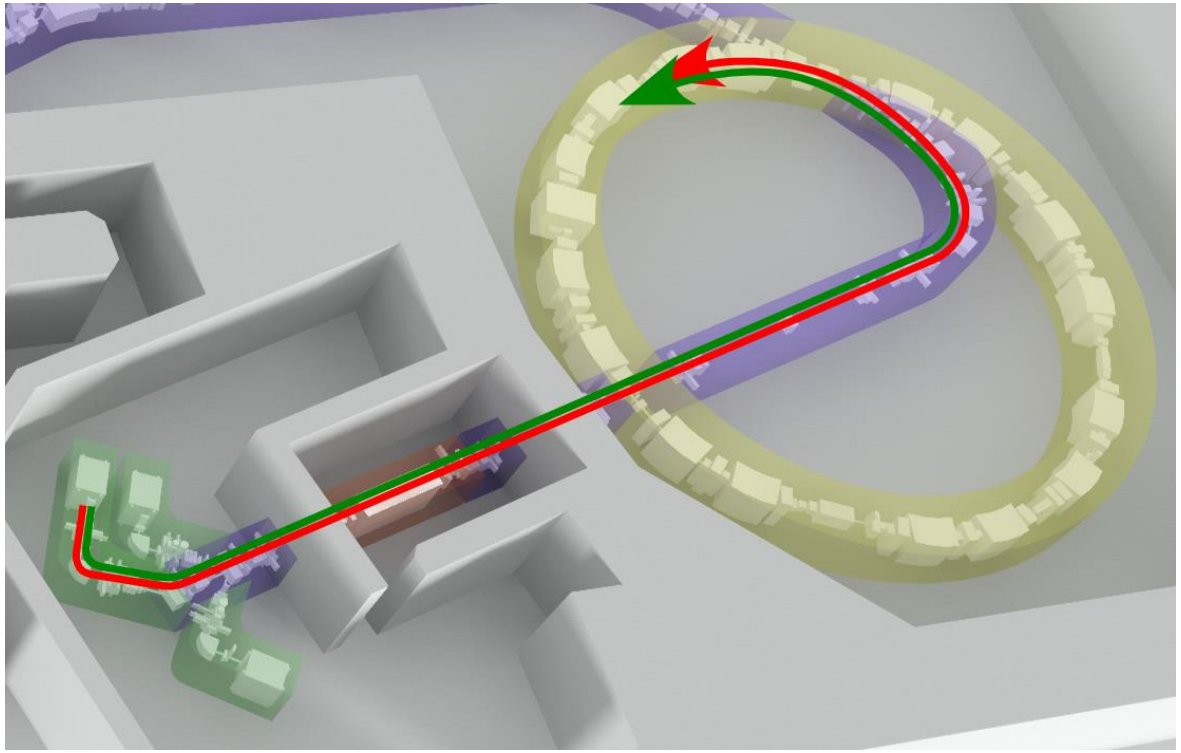


Outline

- Limitations of Generating Mixed Beams in Ion Sources & Sequential Injection Schemes
- Double Multiturn Injection Scheme
  - Implementation, Challenges and Measured Beam Properties at MedAustron
  - Experimental Trials at GSI
- Impact of the Double Multiturn Injection on the Machine Occupation

D *Discussion Input:* *Throughout the presentation potential questions to discuss in the coffee breaks / round table sessions are raised.*
Feel free to discuss them with me or among one another!

Limitations of Generating Mixed Ion Beams in an Ion Source



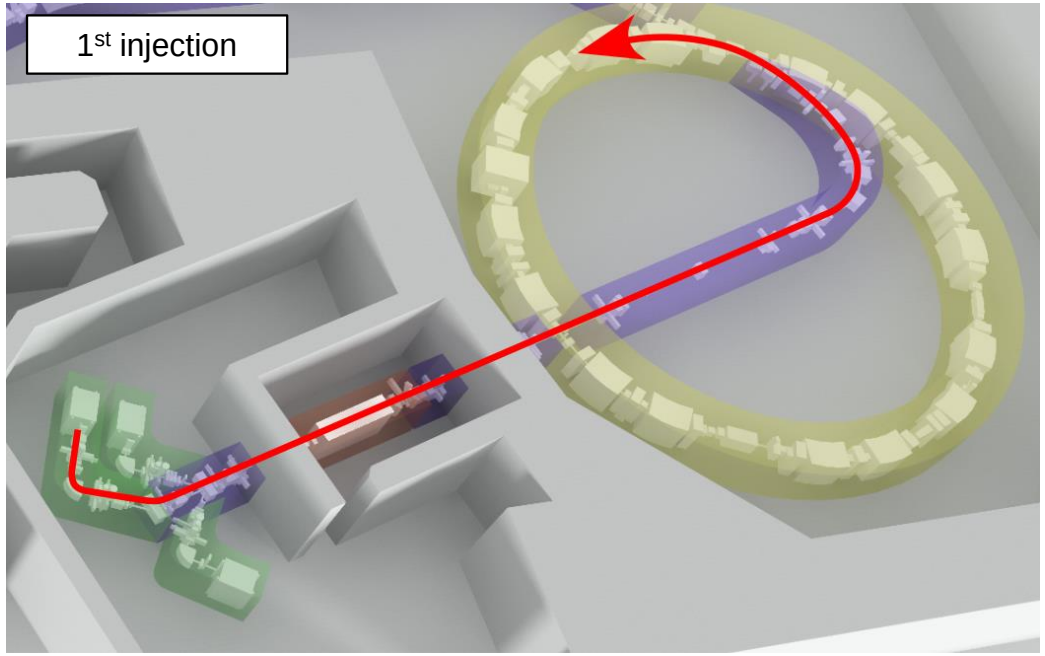
Injection from one ion source not possible if:

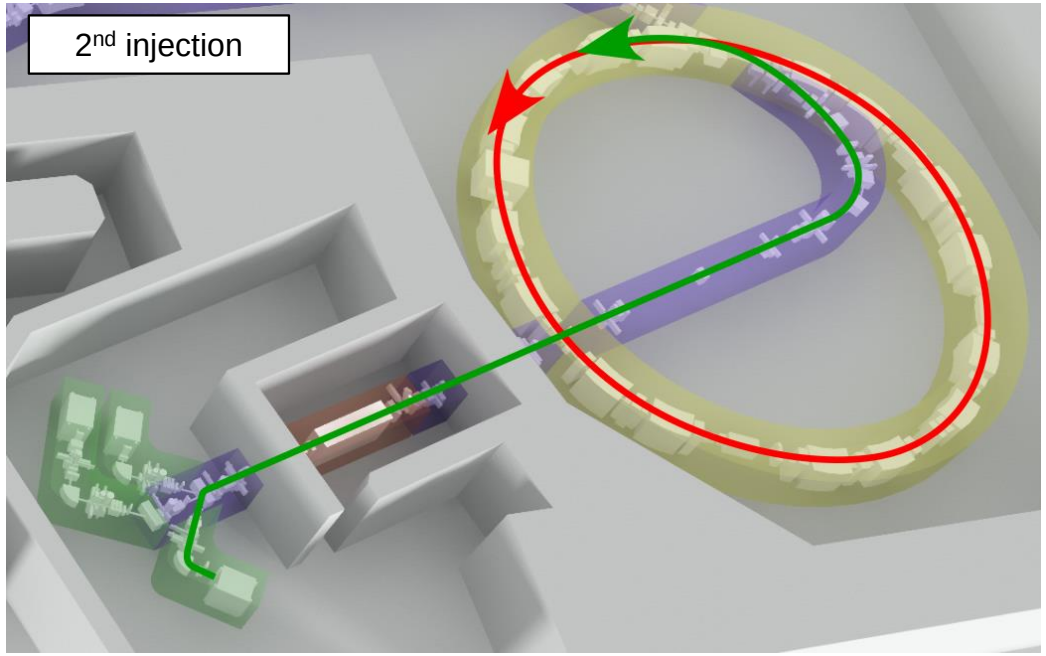
- ions do not feature (almost-)identical q/m.
- injector hardware (magnets, cavities) cannot accommodate the selected q/m
- ion sources cannot produce the ion mix in sufficient intensity and at the desired beam composition
- contamination with an unwanted ion species cannot be avoided

Sequential Injection Schemes for Mixed Beam Generation

Sequential injection schemes provide additional flexibility

- ions can be generated in different ion sources
- independent beam manipulations in the injector
- independent beam manipulation for 1st ion species in the synchrotron





Sequential Multiturn Injection Scheme

Closely related scheme:
heavy ion accumulation with electron cooling (SIS18) [1]

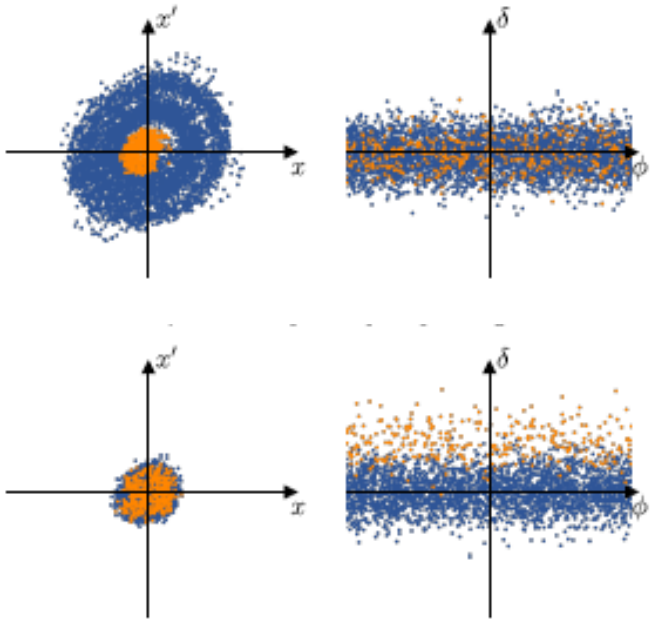
In this talk focus on **double multiturn injection scheme (DMTI)**

- two sequential transverse multiturn injections two from different ion sources
- employed at MedAustron ($^{4}He^{2+}/^{12}C^{6+}$) and GSI ($^{209}Bi^{68+}/^{56}Fe^{25+}$)

On a side note:
There are various other conceivable sequential injection schemes including

- different method of beam accumulation
  (e.g. sequential multiturn injection using momentum stacking at CERN LEIR)
- triple, quadruple, … injection schemes
- exotic injection schemes (e.g. inject He/C into separate RF buckets)

D *Can you think of other useful sequential injection schemes for mixed beam generation?*

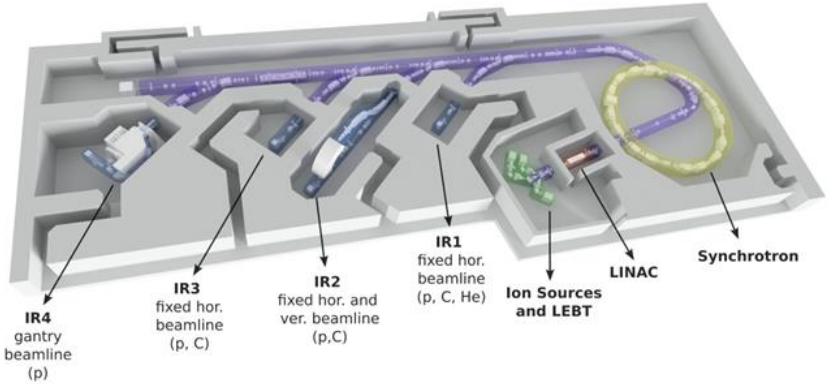


DMTI Implementation at MedAustron [4-6]



Wiener Neustadt, Austria. Approx. 1h south of Vienna (by public transport).





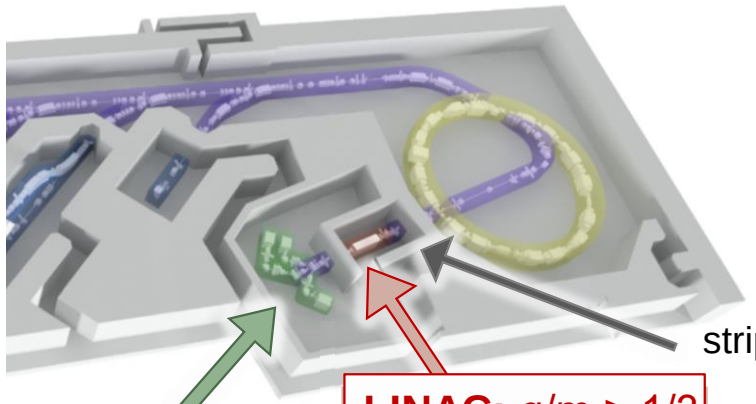




	E_{kin} (MeV/u)
p+	60 – 250; *800*
$^{12}C^{6+}$	120 – 400
$^{4}He^{2+}$	*40 – 400*

DMTI Implementation at MedAustron [4-6]

- Goal: generate, accelerate and deliver mixed He/C ion beams
- hardware limitations prohibit from injecting mixed He/C beam simultaneously from a single ion source
- sequential injection with …
  - different q/m in LEBT and LINAC, nearly-identical after LINAC
    $^{4}He^{2+}$, $^{12}C^{4+} \rightarrow {}^{12}C^{6+}$ after stripping foil



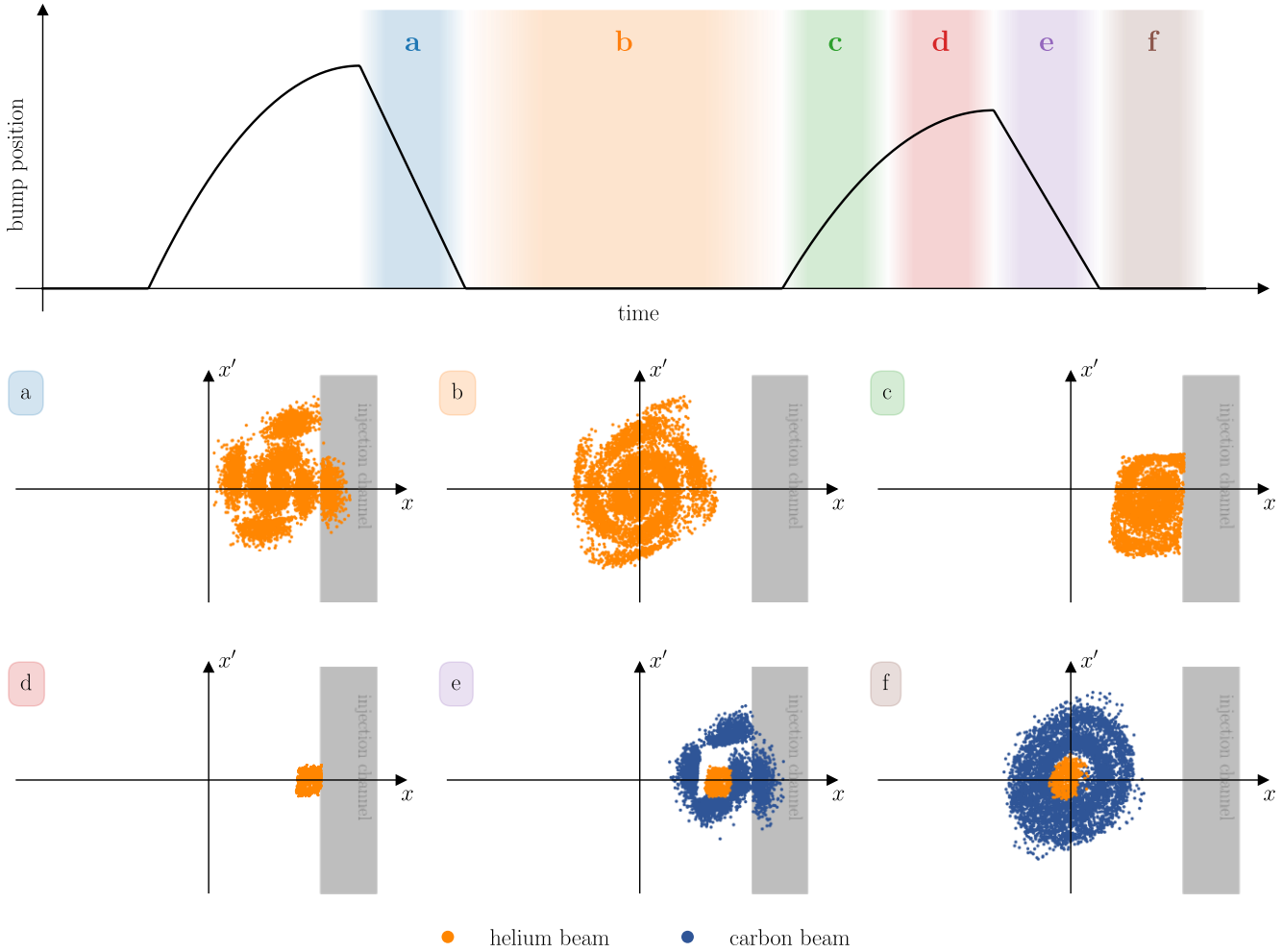
14.5 GHz ECR ion sources: different source branches (***$^{4}He^{2+}$*** , ***$^{12}C^{4+}$***)

Ion pair	q/m LINAC	q/m 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 $q/m \geq 1/3$
$^{4}He^{2+}$ / $^{12}C^{6+}$	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 $\frac{q}{m} = \frac{1}{3}$, large $\frac{\Delta(B\rho)}{B\rho}$

DMTI Implementation at MedAustron

Schematic Overview

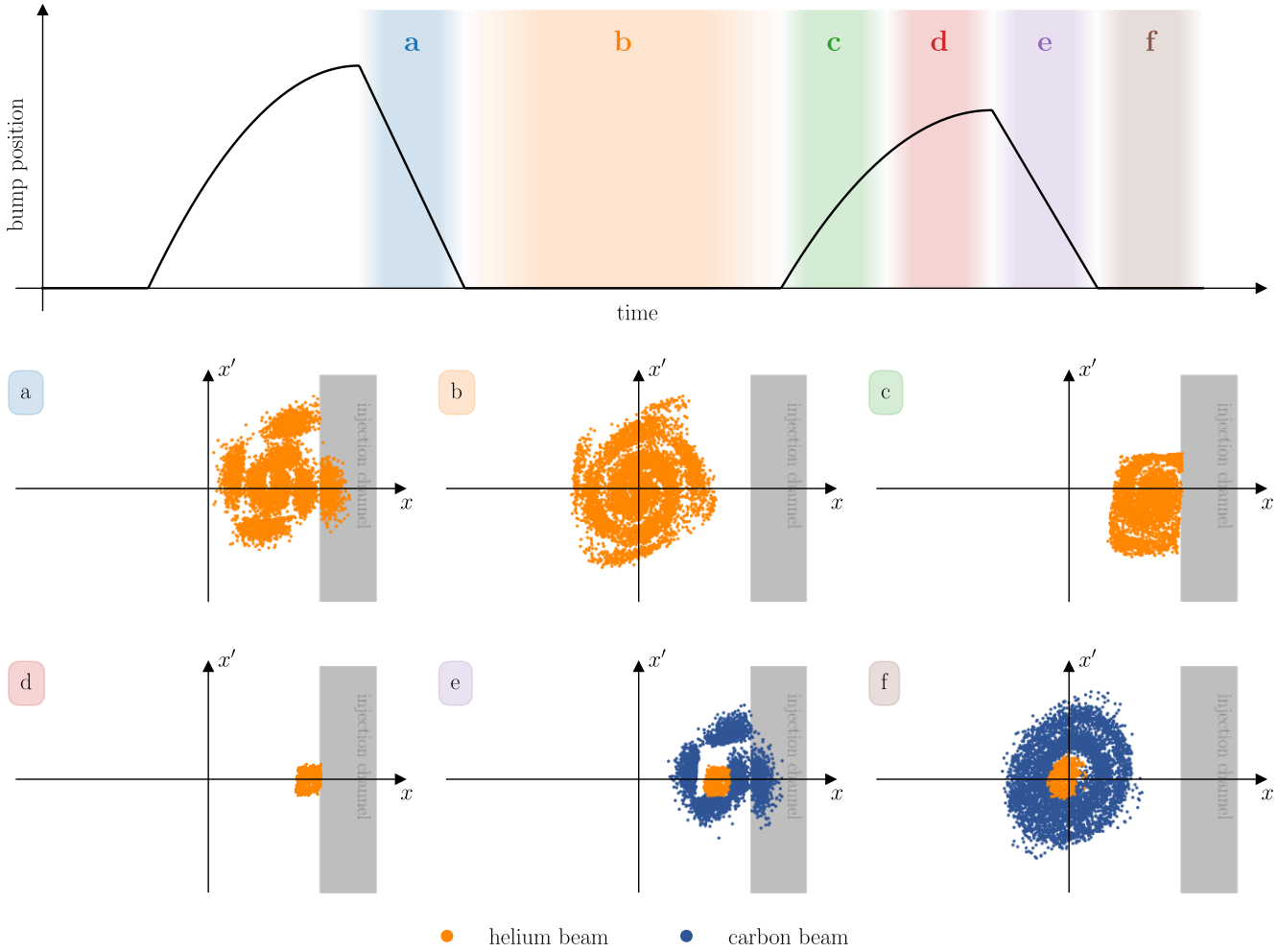
a) nominal helium injection
b) helium kept at flat bottom
c) second orbit bump rises to lower amplitude, most of helium is scraped
d) only the helium is core left
e) carbon injection from lower orbit bump amplitude
f) simultaneous acceleration

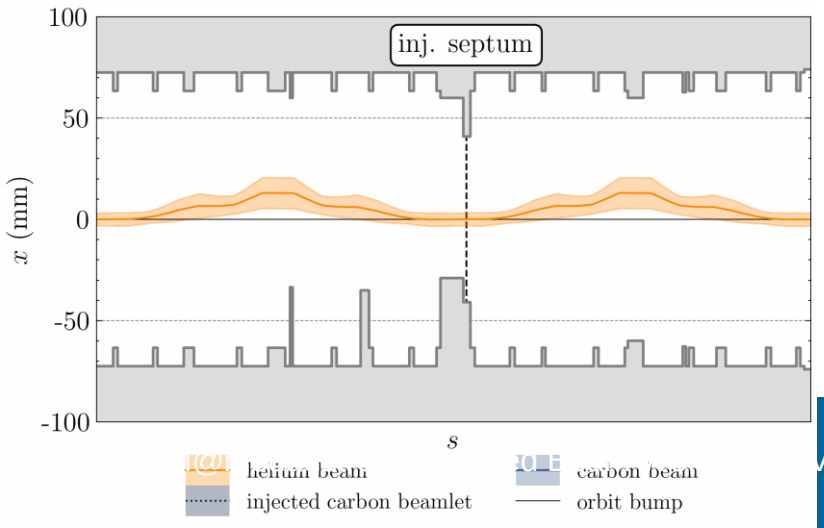


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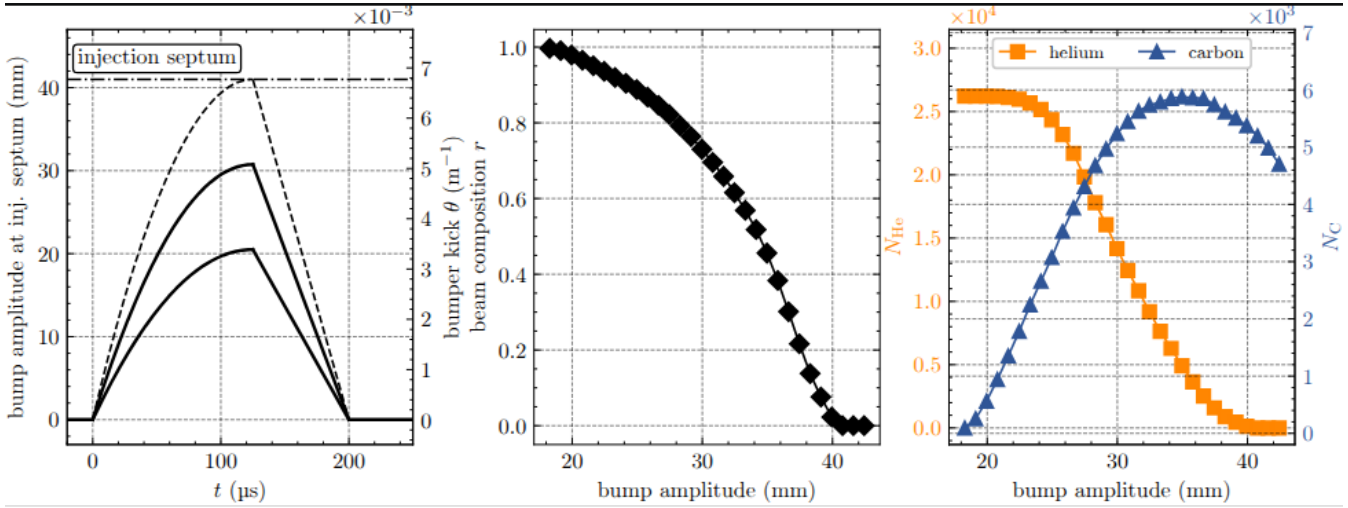




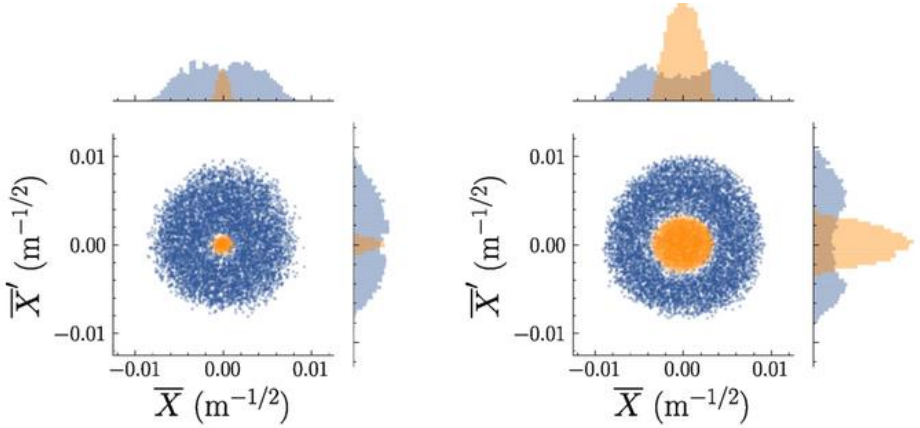
DMTI Implementation at MedAustron

Control over Beam Composition

- Control over the beam composition $r = \frac{N_1}{N_1+N_2}$ by adapting the second orbit bump amplitude



Sequential He/C multiturn injection simulated in Xsuite for different second orbit bump amplitudes



Simulated phase spaces for $r = 10\%$ and $r = 50\%$ [4]

- Beam composition can be adapted on a spill-to-spill basis, including the full suppression of helium ions $r = 0$

D *Is the flexibility to adapt the beam composition on a spill-to-spill basis a major advantage for the application of helium as range probe?*
Is there a major advantage to being able to "turn-off" helium on demand?
Consider that He range might not be sufficient to penetrate the patient for all treatment spots!

Challenges: DMTI Implementation at MedAustron

Injection Energy Offset & Helium Deceleration

Different q/m in LINAC ($^{4}He^{2+}$,$^{12}C^{4+}$) → slight offset in inj. energy $\Delta\frac{E}{m} = 0.1\,\frac{\mathrm{MeV}}{\mathrm{u}}$

Mitigation in two steps:

1. tuning of LINAC cavity settings (IH-tank, debuncher)
   - achieved energy offset $\Delta\frac{E}{m} = 0.06\,\frac{\mathrm{MeV}}{\mathrm{u}}$
   - injection possible but still unfavorable momentum offset

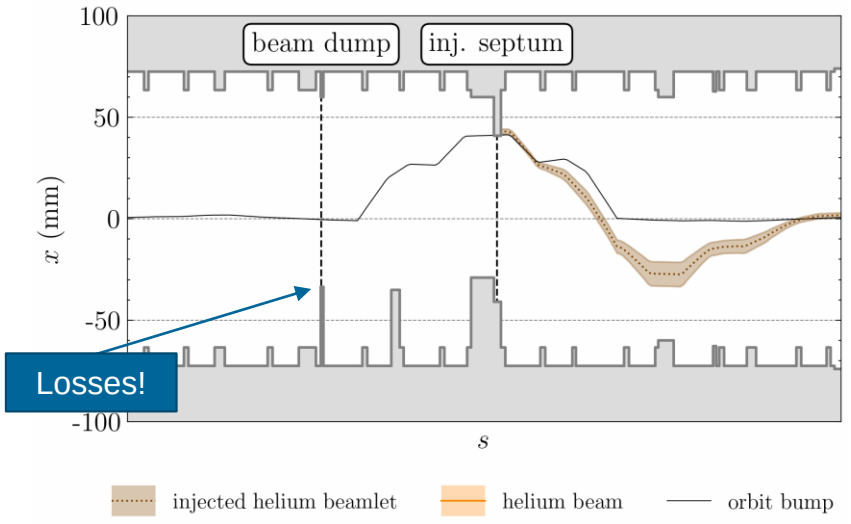
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Challenges: DMTI Implementation at MedAustron

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2. deceleration using radial position regulation until $f_{\mathrm{He}} = f_{\mathrm{C}}$

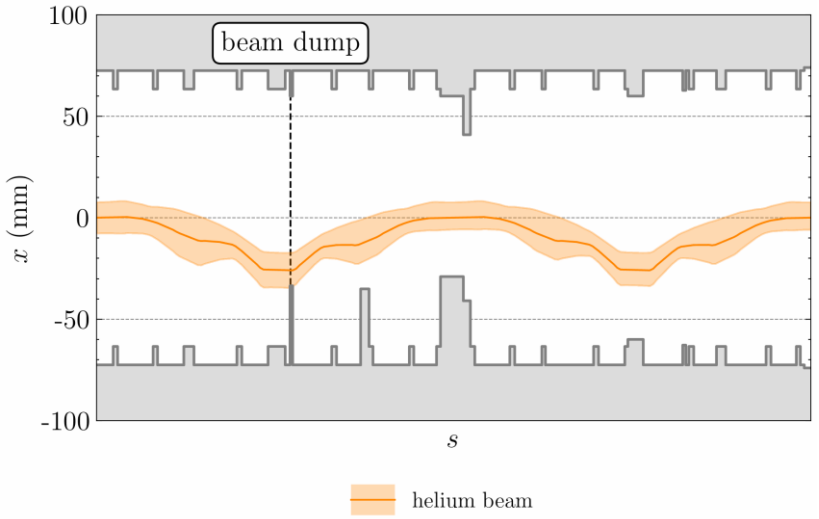
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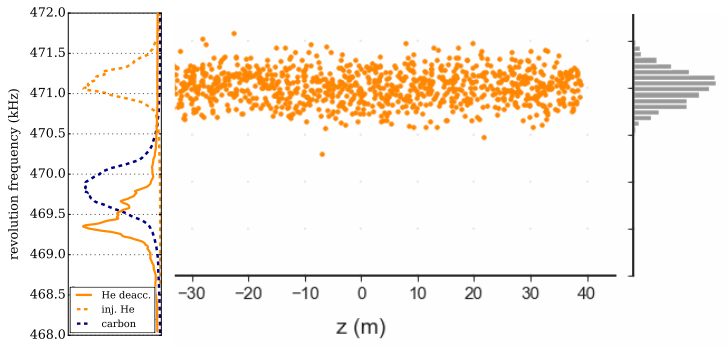
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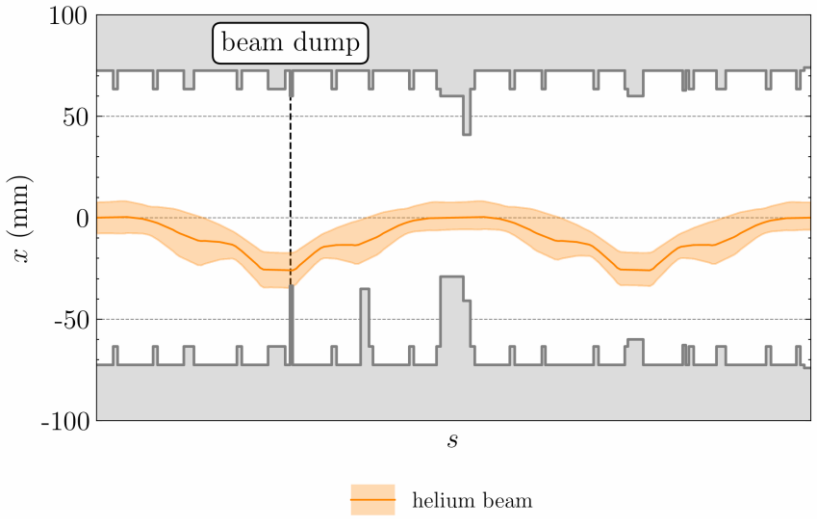
Challenges: DMTI Implementation at MedAustron

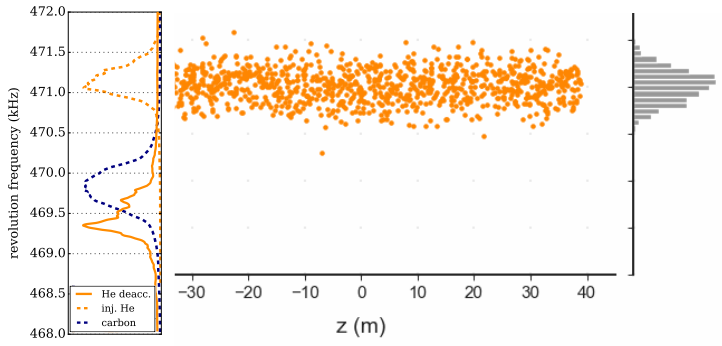
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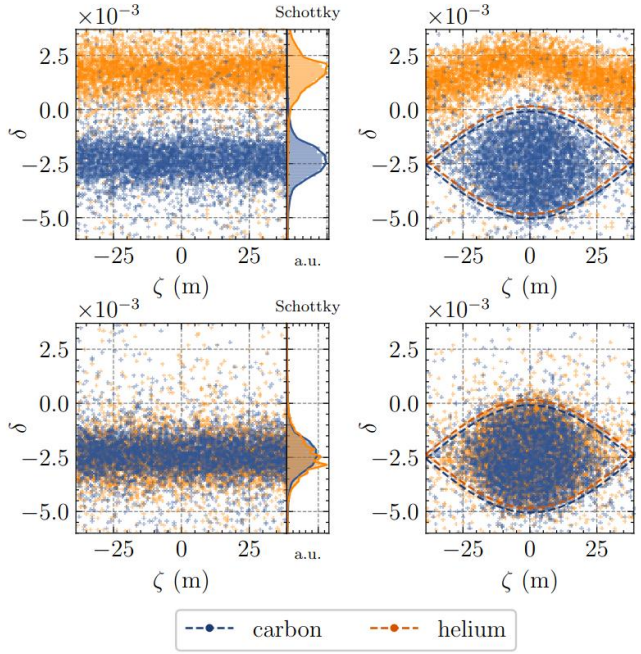
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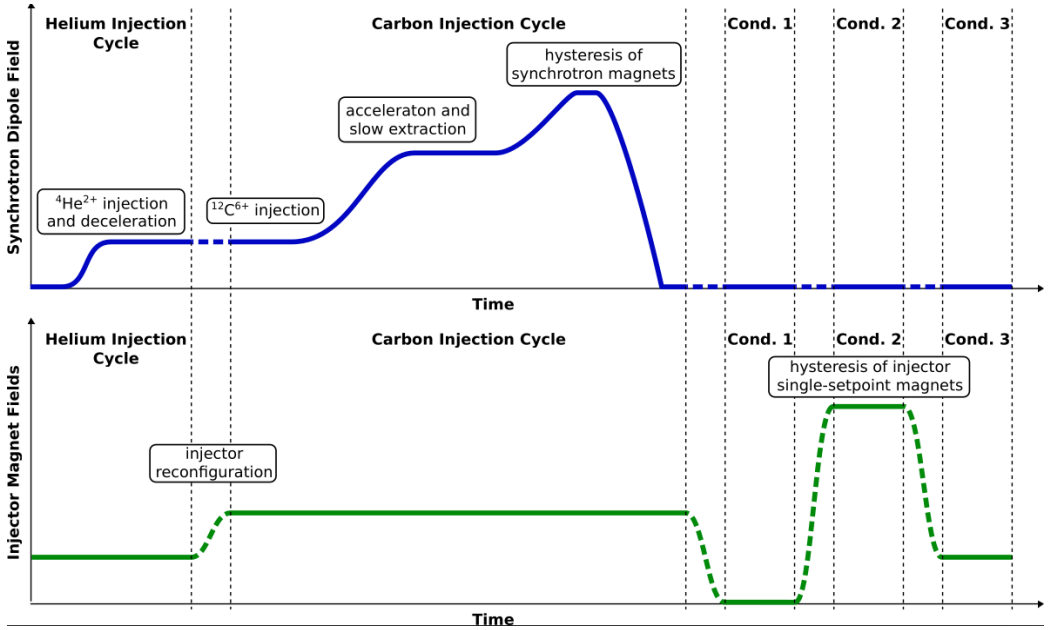
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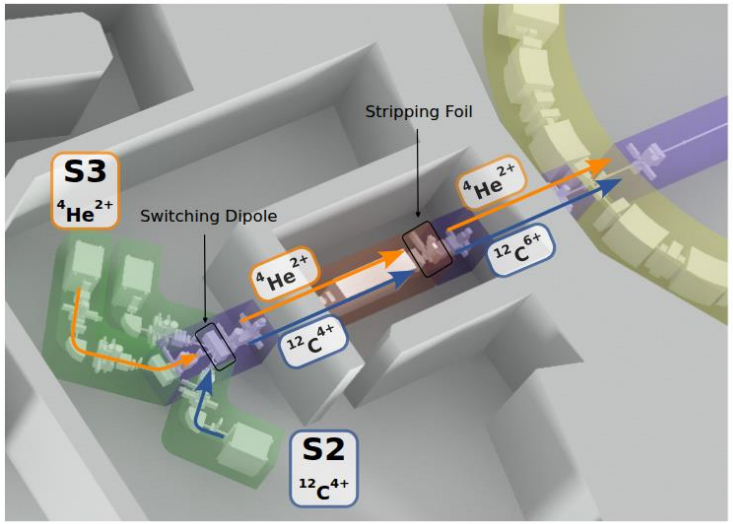
Cycle Prolongation

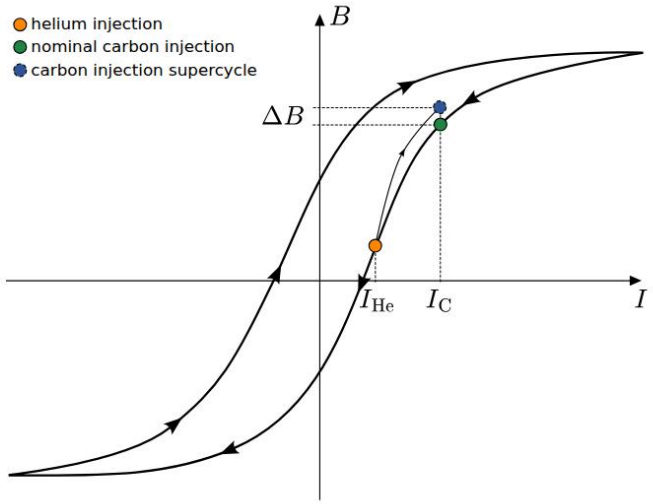
Currently 5 machine cycles are required for per mixed beam spill, this implies …

- only <u>one injection per machine cycle</u> (2 cycles)
- different q/m before stripping foil in LEBT and LINAC → requires <u>magnet conditioning</u> (3 cycles)

~20 s idle time between deliveries!







D

Does the control system of your facility provide more flexibility to request multiple injections with different setpoints in the same machine cycle?

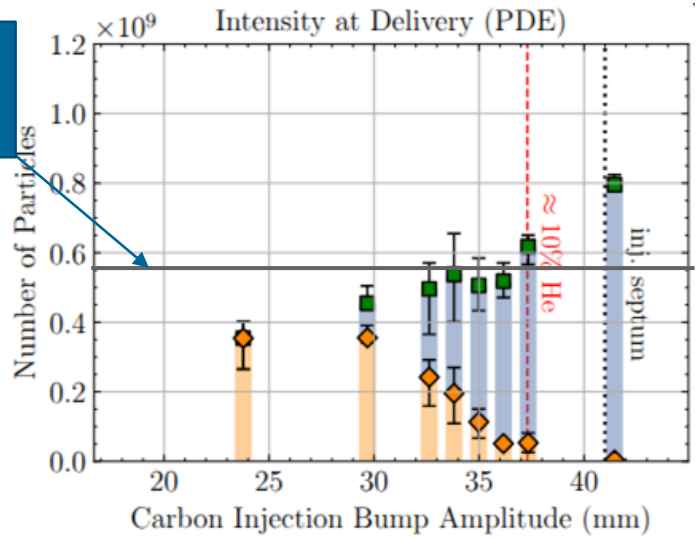
Beam Properties: DMTI Implementation at MedAustron

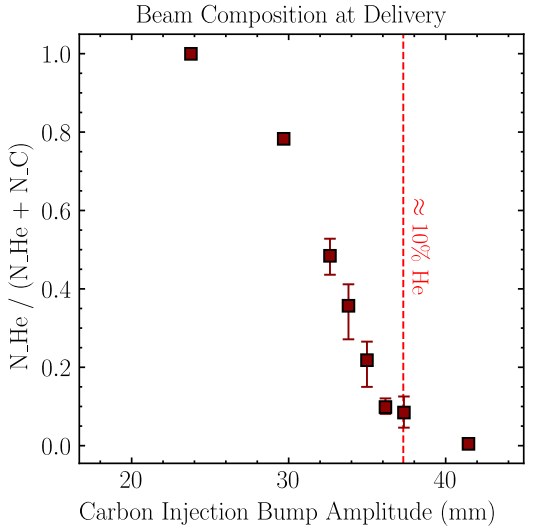
Beam Composition

Beam composition can be controlled using the second injection bump amplitude

- For 10% helium content there is enough intensity for clinical treatment (see figure)
- Beam composition is subject to significant fluctuations (in the current setup up to $\pm 10\%$)

Clinical carbon intensity at MedAustron





D *How much fluctuation is acceptable for application as range probe?*
How do these fluctuations compare to fluctuations from single ion source operation?
Which are the main drivers for these fluctuations (source stability pulsed and CW mode, injection trajectory or optics jitter) and how can we mitigate them?

Beam Properties: DMTI Implementation at MedAustron

Delivered Beam Size

Discrepancies in beam size could be the result of e.g. …

A. different trajectories of helium and carbon ions when accelerating using a single-harmonic RF
   also applicable for generation in a single ion source

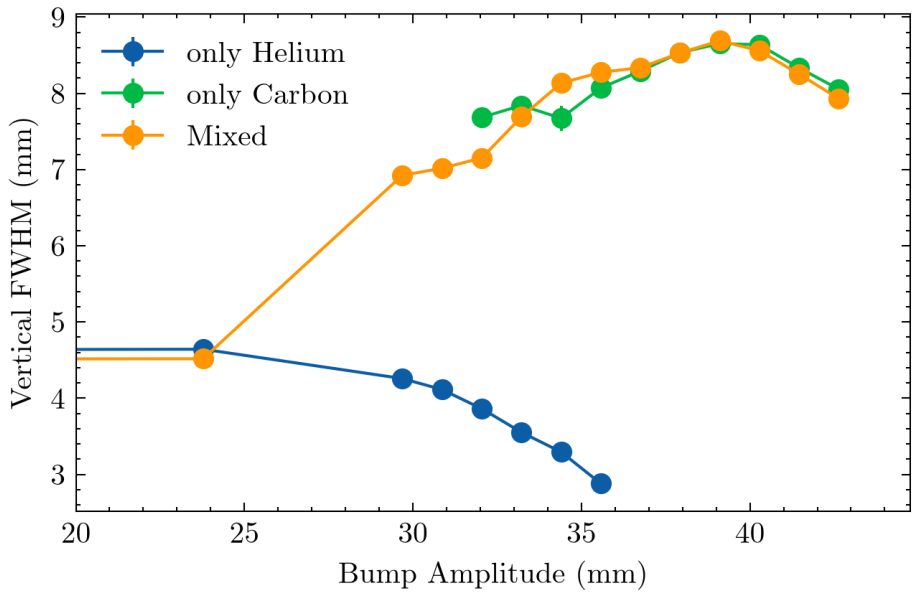
B. different injection steering/optics for the two injections
   inherent to sequential injection, could be optimized

C. losses during beam manipulation of 1st species before injection of 2nd species
   includes the generation of the second orbit bump

At MedAustron discrepancy in vertical beam size

Potential reasons (ongoing investigation):

- different trajectories during acceleration or slow extraction
- aperture losses at the rise of second orbit bump



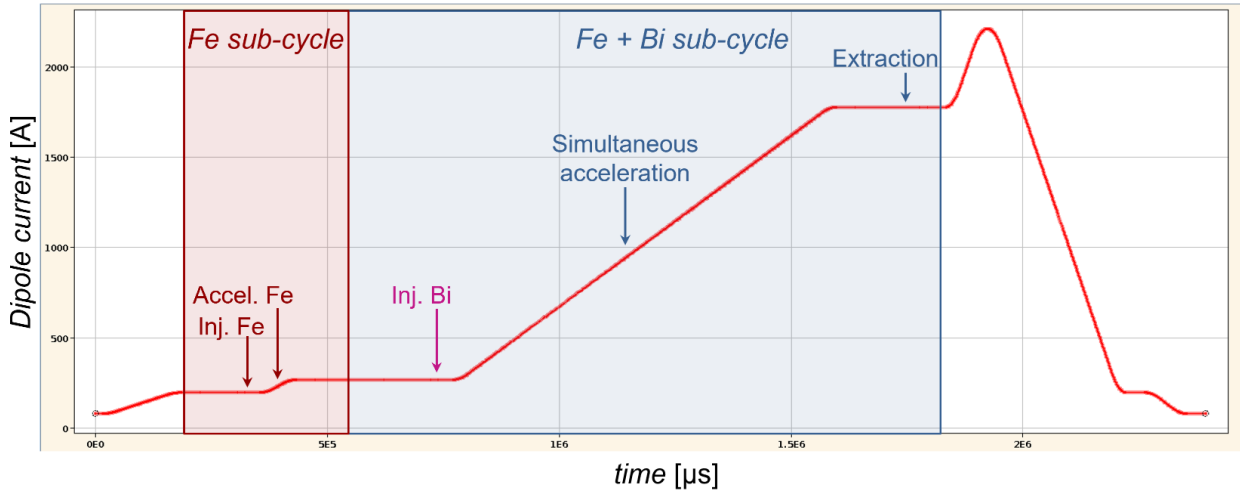
D

How would different beam sizes of the helium and carbon beam affect the mixed beam range probing approach?
Can you think of any other influences on the beam size that could generate different beam sizes for the helium and carbon beam?

Experimental Trials at GSI [7]

- Goal: generate, accelerate and deliver mixed $^{209}Bi^{68+}/^{56}Fe^{25+}$ ion beams with **different q/m**
- Injection **very similar** to sequential injection at MedAustron
  - Control system at GSI flexible enough to implement two injections with sub-cycles
  - Injector can deliver two ion species within 250 ms
    (limited by magnets in MEBT, UNILAC itself allows up to 50 Hz pulse-to-pulse switching for different species [8])
- Unfortunately little data available as only ~4h was dedicated to these trials up until now
- In the future also sequential injection of helium and carbon is envisioned to provide mixed beam without oxygen contamination

More Information:
Acceleration of mixed beams with unequal A/Q
D. Ondreka, 09.10. 09:05-09:30



Taken from Ondreka et al. IPAC26 [7]

Impact on Machine Occupation

(by the example of ion therapy treatment durations at MedAustron)

Prolonged cycle durations are acceptable in research applications but become problematic if they are employed in the clinical workflow!

The acceptable treatment prolongation depends on if …

- the mixed beam method provides substantial **additional information**
- the patient's **physical condition** allows for the scheduled treatment time
- the prolongation is acceptable from an **economic point of view**

Conclusion from informal discussions [9]:

- 10-20 % increase in treatment duration could be acceptable for most indications
- potentially not all spots need to be irradiated with the mixed beam

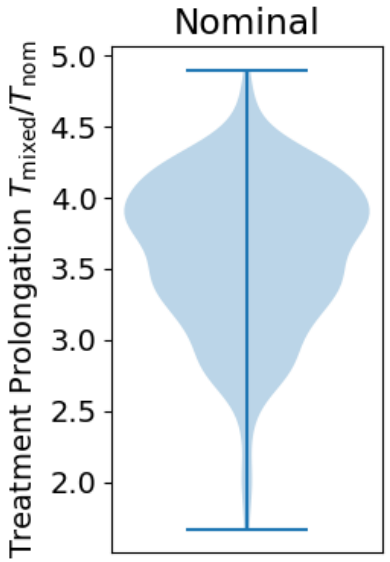
D *Do you agree with our estimation that 10-20% prolongation could be acceptable?*
Would you apply the mixed beam in each energy layer (spill)?

Impact on Machine Occupation

(by the example of ion therapy treatment durations at MedAustron)

As of now: At MedAustron ~20 s between two mixed beam deliveries

- treatment would be prolonged by a **factor of ~2-5**!
  minimum duration 6 min → 10 min
  maximum duration 45 min → 3 h 16 min



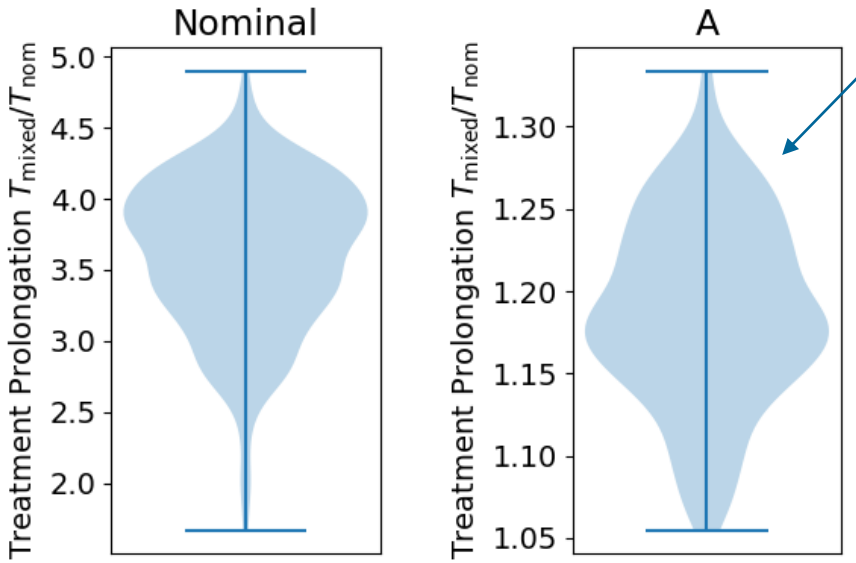
Impact on Machine Occupation

(by the example of ion therapy treatment durations at MedAustron)

Potential to reduce treatment prolongation

A. Control system upgrades *(least effort, no replacement/redesign)*

- two injections in one machine cycle
- set maximum ramp rates of LEBT/LINAC power converters
- helium deceleration simultaneously to injector reconfiguration
- hysteresis of LEBT magnets during acceleration and slow extraction



minimum required extraction time for conditioning distorts distribution of treatment durations

Impact on Machine Occupation

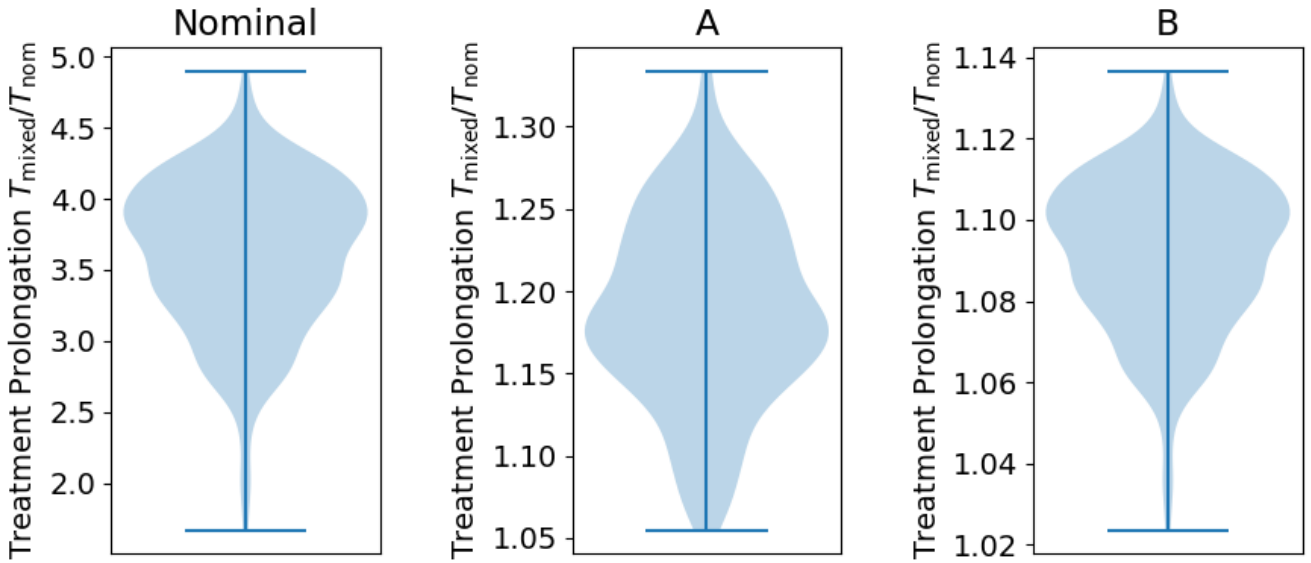
(by the example of ion therapy treatment durations at MedAustron)

Potential to reduce treatment prolongation

A. Control system upgrades *(least effort, no replacement/redesign)*

B. Avoid conditioning of injector magnets *(more effort, minor upgrades)*

- characterize and correct for hysteresis effects
  (field regulated magnets, adaptive magnet settings for consecutive injections)



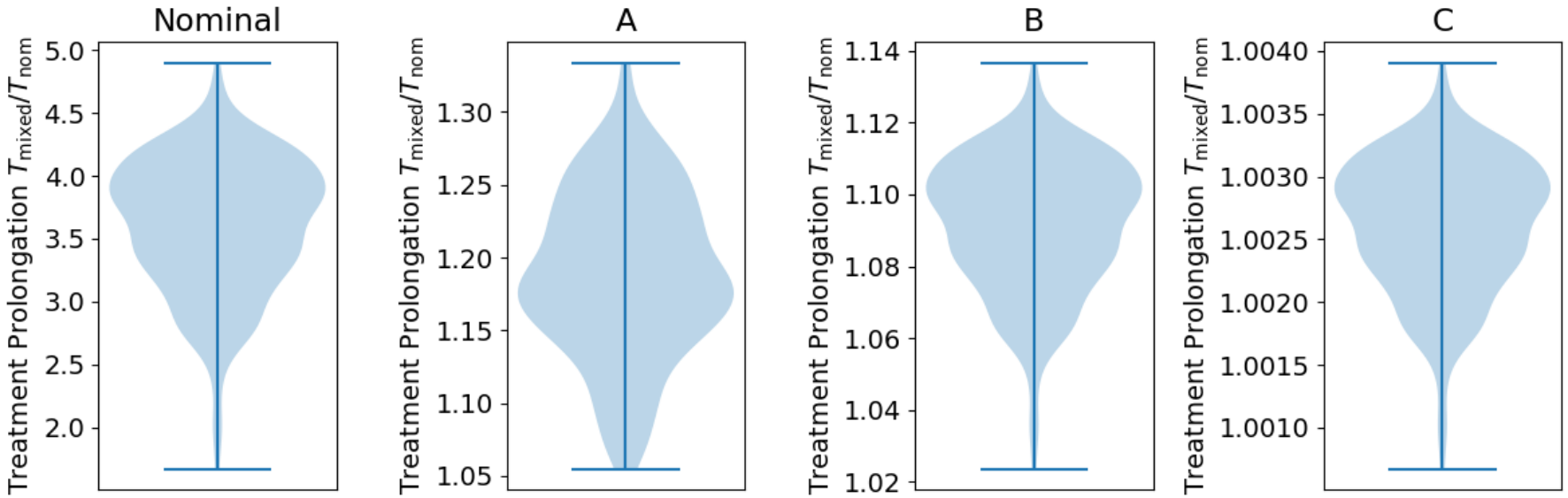
Impact on Machine Occupation

(by the example of ion therapy treatment durations at MedAustron)

Potential to reduce treatment prolongation

A. Control system upgrades *(least effort, no replacement/redesign)*
B. Avoid conditioning of injector magnets *(more effort, minor upgrades)*
C. Injector for 50 Hz switching time *(complete injector redesign/replacement)*
   - UNILAC-like injector designed for switching between ion species at 50 Hz
   - complete replacement of MedAustron injector or new facility

D *Which configurations (A-C) do you see feasible for*
1. an exisiting machine?
2. a newly designed machine?



Single Ion Source vs. Sequential Injection

	Single Ion Source	Sequential Injection
Possible **without major upgrades** in clinical synch. facilities	**No**	**Yes**
No cycle prolongation compared to pure carbon cycle	**Yes**	**No**
Selectively **turn on/off** He on a spill-to-spill basis (for each **energy layer)**	**No**	**Yes**
Robust against **contamination** with tertiary ion species	**No**	**Yes**
Robust against **shot-to-shot fluctuations** in the beam composition	**Probably Yes**	**No**
Advanced beam manipulation possibilities (e.g. longitudinal separation of helium and carbon)	**No**	**Yes**

Summary and Conclusion

- **Sequential injection schemes …**
  - allow to generate mixed ion beams otherwise not attainable from single ion sources
  - promises control over the beam composition on a spill-to-spill basis
- **Implementation at…**
  - MedAustron to generate mixed $^{4}He^{2+}/^{12}C^{6+}$ beams
  - GSI to generate mixed $^{209}Bi^{68+}/^{56}Fe^{25+}$ beams
- **Impact on machine occupation** (by the example of ion therapy treatment durations)
  - current implementation at MedAustron would increase treatment times up to x5
  - fully optimizing existing injector and adapting control system → up to 14% increase in treatment time
  - fast switching injector (50 ms as in UNILAC) → treatment times increased in the single ‰ range

Thank you for your attention!

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[1] Steck, M. et al. (1999) *“Electron Cooling Assisted Beam Accumulation in the Heavy Ion Synchrotron SIS by Repeated Multiturn Injection”*, Proceedings of the 1999 Particle Accelerator Conference, pp. 1704–1706. doi: 10.1109/PAC.1999.794228.

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[3] Aiba, M. (2018) *“Review of Top-up Injection Schemes for Electron Storage Rings”*, 9th International Particle Accelerator Conference. doi: 10.18429/JACoW-IPAC2018-WEXGBE1.

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[6] Kausel, M. et al. (2026) *“Measured Properties of the Mixed Helium and Carbon Ion Beam at MedAustron”*, Proceedings of the 17th International Particle Accelerator Conference, pp. 2245–2248. doi: 10.18429/JACoW-IPAC2026-TUP8004.

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