

MEASURED PROPERTIES OF THE MIXED HELIUM AND CARBON ION BEAM AT MEDAUSTRON

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Abstract

The implementation of a sequential injection scheme for mixing helium and carbon ions from different ion sources at the MedAustron accelerator facility enabled the first successful delivery of a mixed helium and carbon ion beam in a synchrotron therapy facility. Precise knowledge of both the helium and the carbon properties is an essential input for designing treatment monitoring experiments, however, it is not trivial to distinguish the helium and carbon beam properties within the mixed beam.

This contribution discusses the acquired beam properties delivered to the first treatment monitoring research experiments at MedAustron since late 2025. Most notably, the measurements demonstrate that beam compositions with 0-100% helium content can be achieved. The mixed beam generation at MedAustron is still in an early stage, which is reflected in significant shot-to-shot fluctuations in the beam intensity and composition as well as differences in the transverse beam sizes of the extracted helium and carbon ions.

INTRODUCTION

A sequential injection scheme has been developed at the MedAustron ion therapy and research center to generate mixed helium (${}^4\text{He}^{2+}$) and carbon (${}^{12}\text{C}^{6+}$) ion beams for research on treatment monitoring [1–3]. The presence of both helium and carbon ions in the beam introduces additional degrees of freedom that need to be understood and controlled to guarantee the desired beam properties.

Although still in an early stage, mixed beams generated using the sequential injection scheme are already being employed in first treatment monitoring experiments conducted at MedAustron since late 2025. A detailed characterization of these beams is therefore required to provide input to the experimental programs. In this contribution, we present and discuss the results of ongoing characterization measurements, focusing on key beam parameters such as intensity, beam composition and extracted beam spot sizes. Further, we outline aspects related to the sequential injection scheme that offer potential for further optimization. Please note that the measurement procedures presented in this proceeding are still experimental and, as such, subject to systematic and statistical errors that have not yet been fully quantified. The presented data is only intended as input to the research users, to illustrate general trends, and highlight potential for optimization in the future.

MIXED BEAM GENERATION

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AT MEDAUSTRON

The generation of mixed helium and carbon ion beams via sequential injection at MedAustron [1, 2] consists of three stages: (i) multiturn injection of the helium ions from one ion source, (ii) deceleration of the stored helium beam to the carbon injection energy while the injector is reconfigured for carbon injection, and (iii) multiturn injection of carbon ions from a separate ion source using a lower injection bump amplitude. Following the sequential injection, the mixed beam is captured, accelerated, and extracted to the research irradiation room [4].

A key control parameter in this sequential injection scheme is the strength of the second (carbon) injection bump. By varying the carbon injection bump amplitude, helium contents from 0-100% can be achieved. The sequential injection produces a distinct horizontal phase space distribution [1] which directly correlates to the beam composition. In very simple terms, the situation can be understood as follows: For lower carbon orbit bump amplitudes, more helium survives in the core of the distribution, while predominantly carbon ions from the annulus are lost at the horizontal beam pipe apertures. Hence, we expect the helium content to increase and the carbon content to steadily decrease with lower injection kicker strengths. For details on the sequential injection scheme, please refer to references [1, 2].

BEAM COMPOSITION

One key characteristic of mixed beams is the beam composition, i.e. the number of helium and carbon ions in the beam (N_{He} , N_{C}). We quantified the beam composition using current measurements together with a novel RF-based quantification method in the synchrotron, as well as measurements with a range-separated ionization chamber array in the irradiation room. Both measurement procedures are described in reference [5]. Figure 1 shows the measured intensities for both ion species at flat-bottom (left), flat-top (middle), and after extraction in the irradiation room (right), each for various amplitudes of the carbon injection bump and hence different helium fractions. The underlying data corresponds to the 262.3 MeV/u measurement at a radial loop position of 27.5 mm reported in reference [5].

As expected, at flat-bottom after capture but before acceleration¹, lower orbit bump amplitudes lead to an increase in helium intensity and a corresponding decrease in carbon intensity. A comparison of the flat-bottom to the flat-top intensities indicates that the transmission to flat-top is reduced

¹ Note that uncaptured ions may slightly interfere with RF-based measurements at flat-bottom. This effect has not been investigated yet.

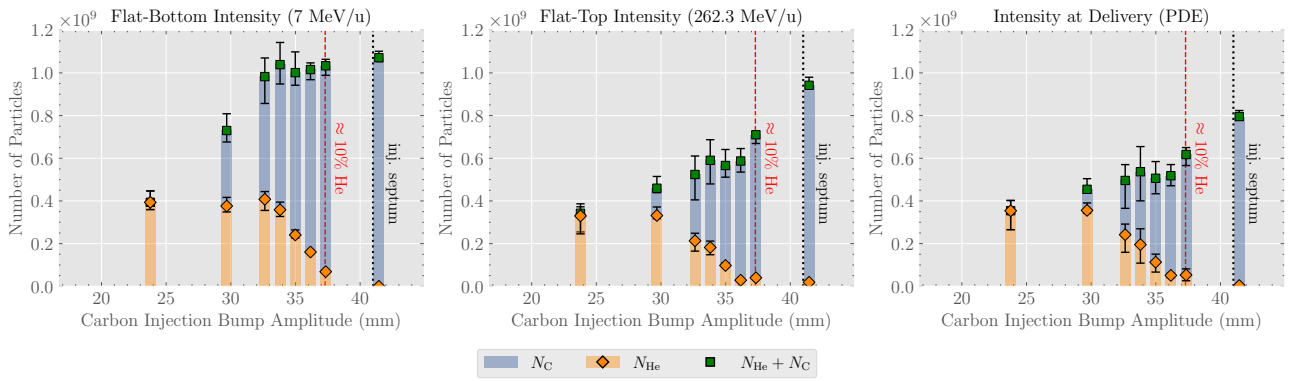


Figure 1: Helium and carbon ion intensities versus carbon injection bump amplitudes at flat-bottom (left), flat-top (center) and after delivery using phase displacement extraction (PDE, right). The markers indicate the mean intensities over multiple acquisitions. The error bars indicate the range of measured intensities (minimum to maximum).

due to the presence of both helium and carbon. These losses during the ramp are currently suspected to arise from two main effects. First, smaller injection bump amplitudes place carbon at larger actions, i.e. farther out in horizontal phase space, potentially increasing aperture losses during the start of the acceleration ramp when the momentum spread of the beam is increased [6]. Secondly, potential differences in the longitudinal distributions between the helium and carbon beam may perturb the active regulation of the radial and phase loop, resulting in overregulation and increased dispersive losses. Although significantly smaller than during the acceleration, additional losses occur during the slow extraction. Due to practical constraints, phase displacement extraction (PDE) was used during these measurements [5] instead of RF knock-out extraction [4], which is currently the baseline method for mixed-beam slow extraction. The latter is preferred as it provides better control of the beam composition over the full spill. The species-dependent extraction efficiency may vary between extraction methods and settings. Nevertheless, even if absolute values are likely to change for other injection and extraction configurations, these results demonstrate that changes in beam composition induced by different carbon injection bump amplitudes are generally reflected in the irradiation room.

Even in the presence of the described losses that still require optimization in the future, the results demonstrate that helium fractions between 0-100% can be realized. The proposed helium content of 10% [7, 8] for using the mixed beam as range probe in carbon radiotherapy is found at bump amplitudes around 36-37 mm. At this setting, an intensity of $7.5 \cdot 10^8$ carbon ions is achieved at flat-top. Given that the current clinical flat-top carbon intensity is around $5 \cdot 10^8$ ions, this would suffice for clinical carbon irradiation without prolonging treatment times.

Furthermore, the helium and carbon intensities exhibit significant shot-to-shot fluctuations up to $\pm 10\%$ for certain configurations. Since these are already present at flat-bottom, they are currently suspected to originate from fluctuations in injected intensity per species and injection jitter.

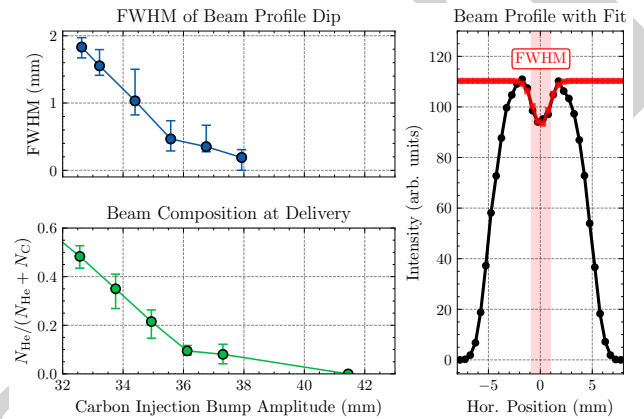


Figure 2: Measurements of the dip in the horizontal profiles of the hollow carbon ion beam. The dip's FWHM is inferred by fitting a Gaussian distribution (right). Both FWHM and beam composition increase for lower carbon injection amplitudes. The markers indicate the mean over multiple acquisitions. The error bars indicate the range of measured values (minimum to maximum).

PHASE SPACE AND BEAM SPOT SIZES

The phase space distributions in the synchrotron and beam spot sizes are key inputs for slow extraction studies [4] as well as experimentalists using the mixed beam.

Horizontal Phase Space Distribution

The distinct horizontal phase space distribution, with helium in the core and carbon in an annular region, was probed using beam profile measurements in the synchrotron [9]. As these measurements are not easily compatible with the double-cycle setup required for the sequential injection scheme, we performed these settings with a pure carbon beam, in a single-cycle setup, but with settings as employed in mixed-beam operation. The hollow carbon distribution appears as a local minimum (dip) in the horizontal beam profile, the width of which provides a measure of the helium core distribution after the sequential injection. As this measurement requires a high signal-to-noise ratio on the synchrotron current monitor, attempts to measure the beam

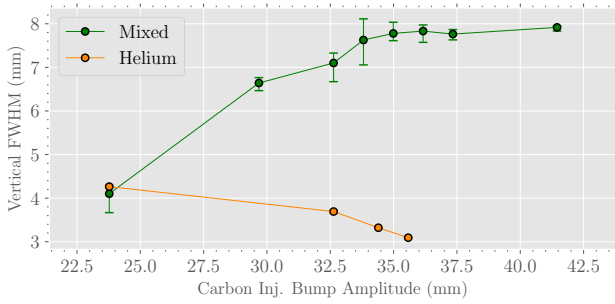


Figure 3: Vertical beam FWHM versus carbon injection amplitudes after phase displacement extraction into the irradiation room. The markers indicate the mean over multiple acquisitions. The error bars indicate the range of measured FWHM (minimum to maximum).

profiles at flat-bottom were not conclusive. To maximize signal quality, the measurement was therefore performed at flat-top at the maximum energy of 402.8 MeV/u. While this significantly improves the signal, both the gap width and the overall beam size are reduced compared to flat-bottom due to adiabatic damping.

Figure 2 (top left) shows the evolution of the acquired central dip full-width at half maximum (FWHM) for various carbon injection bump amplitudes. As expected, the FWHM decreases with increasing injection bump amplitude until it becomes smaller than the measurement sensitivity at around 39 mm. A comparison with the beam composition at delivery in the irradiation room in Fig. 2 (bottom left) confirms that larger dip widths correspond to higher helium content in the beam, which is also consistent with the expectations.

Although the helium and carbon ions are separated in horizontal phase space, the horizontal beam spot FWHM after PDE extraction to the irradiation room was around 8 mm for both species, independent of the carbon injection amplitude. This is because slow extraction decouples the horizontal phase space distribution in the synchrotron from the one after extraction. The impact of the distinct phase space distributions in the synchrotron on the time-structure of the extracted helium-to-carbon ratio is under investigation [4].

Vertical Phase Space Distribution

While the sequential multiturn injection is performed in the horizontal plane and thus primarily causes a distinction in horizontal phase space distribution between the two species, a change in vertical beam size was not initially expected. Nonetheless, when investigating the vertical beam spot size in the irradiation room after PDE extraction, we saw significant differences. Figure 3 shows that the FWHM of the vertical helium beam profile in the irradiation room depends on the carbon injection bump amplitude. When there is only helium in the mixed ion beam, which according to Fig. 1 happens at around 24 mm carbon injection bump amplitude, the vertical FWHM is around 4 mm, whereas if there is only carbon in the beam at around 41 mm, the vertical FWHM is approximately 8 mm, possibly due to differences injection steering and optics.

When operating with helium only (carbon dumped in the injector), the vertical beam size decreases with increasing carbon injection bump amplitudes, suggesting vertical aperture losses during the ramp and decay of the carbon injection bump. If both ions are injected, accelerated, and extracted, the beam size decreases with the carbon injection amplitude. This could have two reasons. Firstly, as for lower carbon injection bump amplitudes, there is more helium in the beam, the smaller helium beam size might influence the analysis of the FWHM. Secondly, for low carbon injection bump amplitudes the carbon ions are injected farther from the distorted closed orbit, leading to larger coherent betatron oscillations during the injection that can drive the injected beamlets close to vertical apertures (racetrack). Given the available data, it is not possible to conclusively state which effect is dominant. In the future, measurements with only carbon beam at different injection bump amplitudes could allow for further insights into the different vertical beam sizes.

Longitudinal Phase Space Distribution

The momentum distributions of the coasting helium and carbon ion beams after the sequential injection are determined by the momentum spreads of the injected distributions, as well as potential increases of momentum spread during the intermediate capture and small deceleration of the helium ions prior to carbon injection [2]. It is subject to current studies, whether these variations yield relevant differences in the longitudinal phase space distributions of mixed and carbon-only beams at flat-top. For this, we also employ longitudinal tomography [6]. However, at the time of writing, there is no conclusive evidence whether this method allows to identify potential differences in the mixed beam and only-carbon distributions.

CONCLUSION

The results presented in this proceeding demonstrate that the sequential injection process at MedAustron allows to deliver mixed helium and carbon ion beams with helium contents ranging from 0-100%. For a helium ratio of around 10%, as proposed for the application of helium as a range probe in carbon ion therapy, the delivered carbon intensities are comparable to clinical operation at MedAustron.

However, mixed beam operation at MedAustron is still in an early experimental stage. As such, the presented data also indicates several areas that still require optimization. Mitigating particle losses and fluctuations in the helium content, as well as matching the horizontal and vertical beam sizes at delivery, will need to be assessed in future investigations.

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REFERENCES

- [1] M. Kausel *et al.*, "Double multiturn injection scheme for generating mixed helium and carbon ion beams at medical synchrotron facilities", *Phys. Rev. Accel. Beams*, vol. 28, no. 11, p. 111001, Nov. 2025. doi:10.1103/t3b5-1xb6
- [2] M. Kausel, C. Schmitzer, K. Holzfeind, C. Becker, and E. Renner, "Recent developments in delivering mixed helium and carbon ion beams at MedAustron", in *Proc. IPAC'25*, Taipei, Taiwan, Jun. 2025, pp. 1147–1150, Jun. 2025. doi:10.18429/JACoW-IPAC2025-TUPB099
- [3] E. Renner *et al.*, "First mixed He/C ion beams at a clinical facility: two years from concept to first ion imaging experiments", presented at IPAC'26, Deauville, France, May 2026, paper TUO8T01, this conference.
- [4] E. Renner *et al.*, "Progress on mixed He/C beam slow extraction at MedAustron", presented at IPAC'26, Deauville, France, May 2026, paper THP4091, this conference.
- [5] E. Renner, M. Kausel, H. Fuchs, K. Holzfeind, and N. Okropiridze, "Noninvasive ion fraction quantification of dual-species beams in synchrotrons", *arXiv*, 2026. doi:10.48550/arXiv.2603.01088
- [6] K. Holzfeind *et al.*, "Longitudinal phase space measurements at MedAustron", in *Proc. IPAC'24*, Nashville, TN, USA, May 2024, pp. 1673–1676. doi:10.18429/JACoW-IPAC2024-TUPS17
- [7] C. Graeff *et al.*, "Helium as a range probe in carbon ion therapy", *Physica Med.: Eur. J. Med. Phys.*, vol. 52, p. 11, Aug. 2018. doi:10.1016/j.ejmp.2018.06.099
- [8] D. Mazzucconi *et al.*, "Mixed particle beam for simultaneous treatment and online range verification in carbon ion therapy: Proof-of-concept study", *Med. Phys.*, vol. 45, no. 11, pp. 5234–5243, Nov. 2018. doi:10.1002/mp.13219
- [9] L. Adler *et al.*, "Synchrotron Emittance Analysis Procedure at MedAustron", in *Proc. IBIC'18*, Shanghai, China, Sep. 2018, pp. 490–493. doi:10.18429/JACoW-IBIC2018-WEPC02