

FIRST MIXED HE/C ION BEAMS IN A CLINICAL FACILITY: TWO YEARS FROM CONCEPT TO FIRST ION IMAGING EXPERIMENTS

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Abstract

Patient irradiation with mixed ${}^4\text{He}^{2+}$ and ${}^{12}\text{C}^{6+}$ ion beams is a promising proposal for online monitoring in carbon ion therapy. Over the past years, major developments have enabled the generation of such beams at MedAustron, where they are now used in accelerator, detector, and medical physics research projects.

This contribution summarizes the key innovations that made this achievement possible. Among these are a new double multiturn injection scheme for merging helium and carbon ion beams in the synchrotron, concepts for simultaneous slow extraction of both ion species, and dedicated diagnostic tools for mixed beam characterization in the accelerator and experimental room. Together, these advances pave the way for continued progress in the field of mixed ion beam acceleration and application.

INTRODUCTION

In recent years, patient irradiation with mixed helium (${}^4\text{He}^{2+}$) and carbon ion (${}^{12}\text{C}^{6+}$) beams has been proposed as a new concept for online monitoring in carbon ion therapy [1, 2]. Given their similar mass-to-charge ratio, with a relative difference of $\frac{\Delta(m/q)}{(m/q)} = 6.5 \times 10^{-4}$, both ions can be simultaneously accelerated and delivered to the patient. Extracted at the same energy-per-mass $\frac{E}{m}$, ${}^4\text{He}^{2+}$ has an approximately three times larger range in matter than ${}^{12}\text{C}^{6+}$. This means that the carbon Bragg peak can be used to deliver the treatment dose to the tumor (blue in Fig. 1), while helium can be detected behind the patient to indicate, for example, anatomical changes or patient setup errors (orange in Fig. 1).

The development and application of mixed helium and carbon ion beams is still in an early research phase. In 2023, such beams were delivered for the first time to medical physics researchers at GSI using the SIS18 synchrotron [3, 4]. In the same year, a concept study was launched to explore how such beams could be delivered for research users at MedAustron, a synchrotron-based center for ion beam therapy and research in Austria. A key requirement from the project outset was to deliver such beams using the existing infrastructure, without requiring any hardware upgrades. The first milestone was reached in summer 2024 when the first mixed beam was extracted to the research irradiation room (IR1) at MedAustron [5], which is to the knowledge of the

authors the first mixed He/C beam delivery at a clinical synchrotron facility. Since summer 2025, we have been able to reliably deliver such beams with suitable beam properties for first research applications. First range probing experiments have been performed since late 2025 (Fig. 1).

This paper summarizes the accelerator developments undertaken to enable mixed-beam delivery at MedAustron.

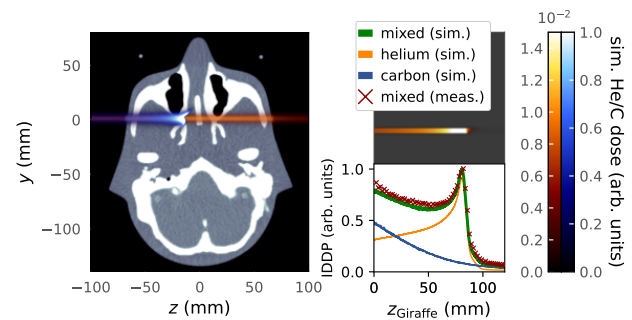


Figure 1: Preliminary results from first mixed beam irradiation experiments at MedAustron. Analysis and benchmarking with OpenGate [6] simulations are ongoing.

MIXED BEAM DELIVERY

Mixed Beam Generation

The starting point of the project was to identify a scheme for mixed-beam generation compatible with the existing infrastructure. The straightforward approach would be to extract the ion mixture directly from an ion source and transport it through the accelerator chain. This method was used for the mixed beam studies at GSI, using a mixture of ${}^4\text{He}^{1+}$ and ${}^{12}\text{C}^{4+}$ with $\frac{m}{q} \approx 4$ [3]. However, this is not possible with the existing infrastructure at MedAustron (or comparable clinical facilities), as no possible helium-carbon isotope combination simultaneously meets the requirements of the 14.5 GHz ECR ion source, the LINAC ($\frac{m}{q} < 3$) and the synchrotron [5, Sec. II.B].

We therefore implemented an alternative scheme in which helium and carbon ions are generated in separate ion sources, as in standard operation, and mixed during a sequential multiturn injection into the synchrotron [5, 7] (Fig. 2). In the first step, helium is injected. The injector is subsequently reconfigured for carbon injection from the second ion source. When ramping the injection bump in preparation for the carbon multiturn injection (hereafter referred to as *bump 2* for brevity), most of the previously injected helium beam is

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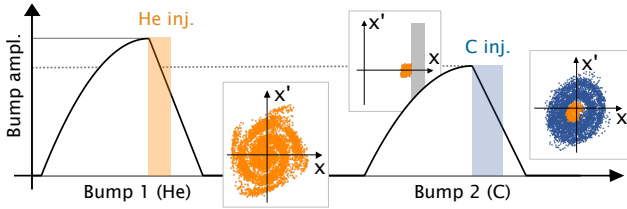


Figure 2: Schematic of the mixed beam generation by means of a double multiturn injection. Adapted from [5].

lost at the injection septum. However, by ramping bump 2 only to a reduced amplitude, a small fraction of helium ions can be maintained. By adjusting the bump 2 amplitude, the helium fraction $r = \frac{N_{\text{He}}}{N_{\text{He}} + N_{\text{C}}}$ can be tuned between 0 and 1 [8, 9]. A direct result of the sequential multiturn injection is the distinct horizontal phase space distributions of the two ion species, a helium core surrounded by a carbon annulus, which is observed in both Xsuite [10] simulations and measurements [5, 8]. It should be noted that, due to the different $\frac{m}{q}$ of the two ion species in the LINAC (${}^4\text{He}^{2+}$ and ${}^{12}\text{C}^{4+}$ upstream of the stripping foil) and regulation limitations, the helium beam is injected with a slight offset in $\frac{E}{m}$ compared to the carbon ion beams [5, Sec. V.B-C]. To ensure efficient capture of both ion species despite this energy offset, the helium ions need to be slightly decelerated prior to carbon injection while keeping the B-field constant [7]. After this deceleration, the helium frequency spectrum largely overlaps with that of carbon, enabling efficient simultaneous capture.

Overall, sequential injection provides a valuable and flexible approach for mixed-beam research using existing infrastructure. An additional advantage of this scheme is that the resulting beams are not prone to oxygen contamination, in contrast to mixed-beam generation in a single ion source [3, 11]. There are, however, several operational challenges to address [5]. For example, in the current setup, reconfiguring the injector between helium and carbon injection requires approximately 2 s. Further studies are needed to determine to which extent this dead time can be reduced, and if the consequent cycle length would be compatible with requirements from clinical implementation.

Mixed-species Beam Dynamics in Synchrotrons

Once both ion species are injected, they are simultaneously captured and accelerated. While the RF acceleration process itself is operationally straightforward, the small $\frac{m}{q}$ difference between the two species introduces distinct beam dynamics effects: Helium ions, with larger $\frac{m}{q}$, move on an orbit with slightly longer path length. However, when the RF system is turned on, both species are forced to the same revolution frequency, despite differences in the closed-orbit length. At the MedAustron synchrotron, which operates below transition, this implies that helium ions are accelerated to a marginally higher $\beta\gamma$ than carbon ions. The resulting offset, $\frac{\Delta(\beta\gamma)}{\beta\gamma}$, depends on the proximity to the transition energy [9, 12, 13]. In the MedAustron synchrotron, the combined effect of the intrinsic $\frac{m}{q}$ offset and the RF-

induced energy offset yields a total effective rigidity offset of $\frac{\Delta(B\rho)}{(B\rho)} \approx 0.95 \times 10^{-3}$ to 1.35×10^{-3} for clinical extraction energies of $E_{\text{kin}} = 120 \text{ MeV/u}$ to 400 MeV/u [9].

These effects must be considered for slow extraction in the presence of non-zero chromaticity (see section below), as well as for determining possible energy shifts of both ion species. In this context, two main flat-top energy shifts are expected, both of which are largely preserved during amplitude-driven radio frequency knock-out (RFKO) slow extraction. (1) The two ion species are expected to be extracted to the patient with the induced $\Delta(\beta\gamma)$ and hence $\Delta\left(\frac{E}{m}\right)$. At MedAustron, $\Delta\left(\frac{E}{m}\right)$ is expected to be between 0.1 and 0.5 MeV/u for the relevant energy range (experimental verification to be performed). While this is not expected to affect therapy, it should be considered when measuring the residual energy of helium ions for range verification.

(2) Another effect arises from the dispersive orbit offset between the two ion species in the synchrotron, which causes a composition-dependent shift of the overall center of charge. In facilities with RF loop regulation, the radial loop reacts with a composition-dependent frequency correction to maintain the reference orbit. Consequently, the flat-top $\frac{E}{m}$ of both beams is shifted depending on the ion composition. If extracted with RFKO, helium fractions of $r = 0.4$ would result in carbon Bragg peak range shifts of less than ≈ 0.02 to $\approx 0.2 \text{ mm}$ across the entire clinical energy range (values interpolated from ranges measured at MedAustron). This estimate shows that even for such large helium fractions, which are well above the expected operational range of $r = 0.1$ to 0.2 , the resulting energy shifts seem to remain within acceptable tolerances [9]. Nevertheless, more precise quantification and experimental validation of these effects are recommended.

Slow Extraction

A further key aspect of the project is the slow extraction of the mixed ion beam [14]. Ideally, the extracted helium fraction $r(t)$ should remain approximately constant throughout the entire spill. However, this is complicated by the above-described differences in horizontal phase space and beam rigidity distribution between the two ion species. As a baseline extraction method, we employ RFKO. We use an experimental RFKO setup [15] that allows us to tailor the applied RFKO signals for extracting the beam with $r(t) \approx \text{const.}$. So far, we have empirically identified an RFKO setup to achieve approximately constant mixing ratios, which is now used successfully to provide mixed beams to research users. However, the detailed response of the extracted He:C ratio to the employed RFKO signals is not yet fully understood. Future work will focus on resolving measurement-simulation discrepancies, finding a setup that can be re-tuned efficiently when changing helium fractions or extraction energy, studying He:C ripples, and designing RFKO signals for advanced He:C tailoring. Complementary studies are being performed at GSI [4, 16].

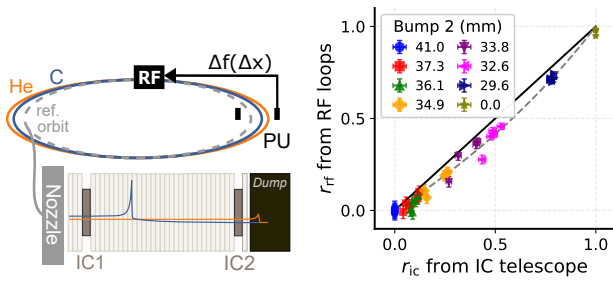


Figure 3: Left: Schematic of two complementary methods to determine the ion composition r of the mixed beam, the noninvasive RF-based measurement in the synchrotron and the post-extraction measurement with an ionization-chamber (IC) telescope. Right: Comparison of the two methods [9].

Mixed Beam Diagnostics

Different methods are employed to characterize the mixed beam both within the accelerator and IR1. While conventional beam instrumentation is used to characterize the combined charge distribution (e.g. total beam current, profiles, delivered dose [5]), it cannot distinguish helium from carbon ions. To address this gap, dedicated diagnostic systems were developed or adapted from projects of other MedAustron nonclinical research users.

In IR1, we require systems to characterize the spatial and temporal evolution of the extracted helium fraction r over the entire spill. The primary system we use is a two-stage ionization chamber (IC) telescope, shown in Fig. 3 [9]. $r(t)$ is reconstructed by comparing the currents measured in the two range-separated ionization chambers IC1 and IC2, with input from calibration measurements and Monte Carlo simulations. While this system is very useful and accessible for quick mixed-beam quality assurance and general slow extraction studies, the current configuration does not provide spatial resolution, and the time resolution is limited to 50 ms by the employed electrometer.

In addition, we have used silicon Low Gain Avalanche Diode (LGAD) sensors in IR1 to demonstrate their ability to characterize the extracted mixed beam [5]. Their excellent timing (< 100 ps) and spatial (< 100 μm) resolution enable detection of individual ions at high particle rates and discrimination based on their different linear energy transfer (LET) in the LGAD. While proof of principle has been demonstrated, these detectors remain in experimental use. Further investigations on fragment identification and particle-rate limitations of the currently employed data-acquisition (DAQ) system [17] are ongoing. The detectors and DAQ system were originally developed for time-of-flight ion computed tomography (TOF-iCT) [17], highlighting strong synergies between the two applications.

All systems described above are invasive and require beam extraction to IR1. For commissioning tasks and online monitoring during experiments, however, a noninvasive measurement of the helium fraction r directly in the synchrotron is highly desirable. We therefore developed a method that exploits the small rigidity difference and consequent dispersive offset between helium and carbon ions to noninva-

sively quantify the helium fraction in the synchrotron [9]. This approach determines the helium fraction either from composition-dependent frequency corrections applied by the radial loop or, when using feed-forward RF frequency control, from measured dispersive offsets. We demonstrated the viability of this technique experimentally (Fig. 3, right panel). The RF-based mixing ratio estimates r_{RF} were in good agreement with independent IC-based ion composition estimates of the extracted beam in IR1, r_{IC} . The method is now used at MedAustron for mixed beam commissioning and diagnostics during user experiments [9]. Furthermore, it provides a potential foundation for developing a mixing ratio interlock system.

Finally, first concept studies were performed for using a gas-filled charge-exchange cell to characterize the ion composition of a \mathcal{O} (keV/u) mixed beam extracted from an ion source [18]. Initial results are encouraging, though further studies are needed to assess the viability of this approach.

FIRST IMAGING EXPERIMENTS

Since late 2025, these developments at MedAustron have allowed us to reproducibly deliver mixed beams at various energies, mixing ratios, and fluxes for initial medical physics experiments. We irradiated, for example, an anthropomorphic head phantom by SunNuclear/CIRS (ATOM Male) with different intentional alignment offsets (Fig. 1). These offsets were successfully resolved based on the distally measured helium signal, using both the commercial Giraffe multi-layer ionization chamber (IBA Dosimetry) and a TOF-iCT based on silicon LGADs [17]. As an alternative detection approach, research groups at GSI and CNAO employ scintillator-based detectors for similar studies [2, 11].

SUMMARY AND OUTLOOK

Over the last three years, several accelerator developments have allowed us to regularly deliver mixed ion beams for research applications at MedAustron. The availability of such beams at a clinical facility with dedicated research infrastructure provides unique opportunities for advancing research on mixed-beam-based online range monitoring, while remaining closely connected to clinical experience.

The mixed beams are generated via a sequential multiturn injection scheme into the synchrotron, which allows the helium fraction to be tuned between 0 and 100 % by adjusting the injection parameters. The small mass-to-charge ratio difference between the two species influences the slow extraction dynamics, but can also be exploited for diagnostic purposes. Ongoing and future accelerator studies aim to further improve the efficiency, reproducibility, and tunability of the mixed-beam delivery.

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