FLAT C/HE SPILLS FOR ONLINE RANGE MONITORING IN PARTICLE THERAPY [*]

A. Pastushenko[†], C. Graeff, B. Gålnander, R. Hetzel, D. Ondreka, J. Stadlmann, L. Volz,
GSI Helmholtz Centre for Heavy Ion Research, Darmstadt, Germany
E. Renner, TU Wien, Vienna, Austria

Abstract

The use of mixed ion beams is a developing approach aimed at improving current carbon-ion therapy by enabling online monitoring of dose deposition. In such a configuration, the main dose is still delivered by carbon ions, while lighter ions traverse the patient with negligible dose contribution and can be used for imaging. The main challenges of this approach include the need to simultaneously accelerate both ion species and to slowly extract them with a stable species ratio, a prerequisite for potential clinical application. At GSI, a mixed beam of $^{12}C^{3+}$ and $^{4}He^{+}$ ions was provided in May 2025 for biophysics experiments. The very small mass-to-charge difference of 0.065 ‰ between these ion species enables simultaneous acceleration in the SIS18 heavy-ion synchrotron. To slowly extract them with transverse RF-knockout, chromaticity in the ring was adjusted, and the spill optimization system was used. These measures enabled a nearly rectangular spill with a constant helium/carbon ratio within the spill, confirmed by ionization-chamber measurements in the medical cave. This contribution presents the experimental results and discusses their implications for mixed-beam operation.

INTRODUCTION

Particle therapy with ions, particularly carbon ions, offers significant advantages over other treatment methods in terms of dose localization. A maximum stopping power is reached near the end of the ion path, forming the so-called Bragg peak, which enables highly localized dose deposition. However, this also poses a challenge, since range uncertainties may cause the Bragg peak to fall outside the targeted tumor area. It is one of the major challenges in ion therapy [1]. One proposed solution is the addition of a small fraction of helium ions to a primary carbon beam [2]. In this approach, the helium ions traverse the patient and enable range monitoring, while the carbon ions deliver the therapeutic dose. Such a scheme was successfully tested at the SIS18 synchrotron at GSI in 2023 [3]. Parallel investigations of the mixed helium/carbon beams are also being carried out at other facilities, in particular at MedAustron [4, 5].

Table 1: SIS18 Synchrotron Parameters at Extraction Relevant to the May 2025 Mixed-beam run.

Parameter at the extraction	Value
Kinetic energy, E_k	225 and 260 MeV u^{-1}
Working point, Q_x/Q_y	4.33/3.28
Natural chromaticity, ξ_x^N/ξ_y^N	-6.5/4.1
Norm. horizontal emittance, ϵ_x	≈16 µm
Slow extraction scheme	RF-KO
Spill length	2 s

The simultaneous acceleration of carbon and helium ions is possible because the charge states can be chosen such that both ion species have nearly identical mass-to-charge ratios. For the studies presented here, $^{12}C^{3+}$ and $^{4}He^{+}$ were used. The relative difference in mass-to-charge ratio is only 0.065 ‰, making the two species nearly indistinguishable from the machine point of view. At the same time, the 2023 measurements showed that the slow extraction of the mixed beam is highly sensitive even to this small difference in mass-to-charge ratio. The goal of the experiment in 2025 was to fine-tune the slow extraction in order to achieve a stable helium-to-carbon ratio within the spill. This paper summarizes the mixed beam measurements performed at SIS18 in May 2025.

MACHINE AND EXPERIMENT DESCRIPTION

The carbon–helium mixture is produced in the ECR ion source using methane, with helium as a support gas [6]. The injector was tuned to $A/q = 4$, resulting in the extraction of $^{12}C^{3+}$ and $^{4}He^{+}$. This also leads to a small oxygen contamination from $^{16}O^{4+}$. The mixture is accelerated in the UNILAC linear accelerator to the energy of 11.5 MeV u^{-1} and injected into SIS18 over multiple turns. The mixed beam is then accelerated to the desired kinetic energy and slowly extracted towards GSI's medical research room (Cave M). A transverse RF-KO extraction scheme was used to provide a spill length of 2 s. In May 2025, the tests in Cave M were performed at two energies: 225 and 260 MeV u^{-1}. Other extraction parameters relevant to the May 2025 mixed-beam run are listed in Table 1.

The analysis of the extracted beam was performed using the setup installed in Cave M. A schematic representation of the apparatus is shown in Fig. 1. It comprises three ionization chambers (IC), namely IC1, IC2, and IC3 [7]. IC1 is located at the nozzle, while IC2 and IC3 are positioned, by means of range shifters, at the carbon and helium Bragg peaks, respectively. The signal from each ionization chamber is sampled at 50 kHz and can be monitored online for

---

[*] This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 101124273. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

[†] a.pastushenko@gsi.de

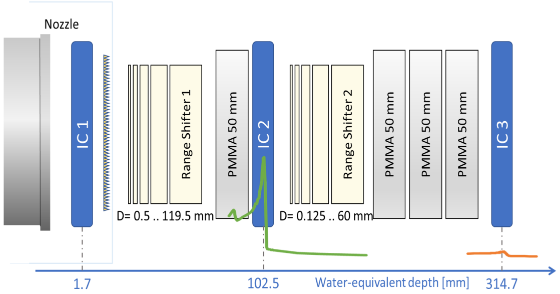

Figure 1: Schematic representation of the experimental setup in Cave M.

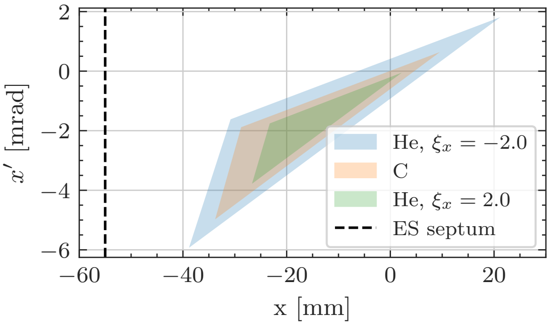

Figure 2: Phase space and a simulated stable area at the entrance of the Electrostatic (ES) septum for carbon and helium. The tune distance to the 3rd-integer resonance was set to −0.0037.

beam diagnostics. The signal recorded by IC2 is dominated by carbon, and the contribution from other species can be neglected. By contrast, the signal in IC3 contains contributions from helium as well as from light fragments produced by nuclear interactions of carbon with matter. To extract the pure helium signal, a calibration obtained from the 2023 measurements is used.

Phase Space at the Extraction

The rigidity mismatch between carbon and helium causes helium to behave in the ring similarly to off-momentum carbon. As a result, helium is particularly sensitive to chromatic effects in the ring. This was already observed in 2023, when the spill shape was found to correlate with chromaticity for tune-sweep extraction [3]. In that study, the carbon and helium components could be separated in time at natural chromaticity, while they overlapped for $\xi_x = -0.5$. This occurs because the tune distance to the resonance for helium changes with chromaticity. This effect can be visualized by simulating the stable area in the phase space near the 3rd-integer resonance, see Fig. 2. Chromaticity has little effect on carbon, apart from nonlinear effects such as amplitude-dependent tune shift. For helium, however, the stable area shrinks as chromaticity increases. Given the diffusive nature of the RF-KO extraction, in which particles are extracted by being driven towards the unstable region, chromaticity plays a key role in determining how rapidly helium is extracted.

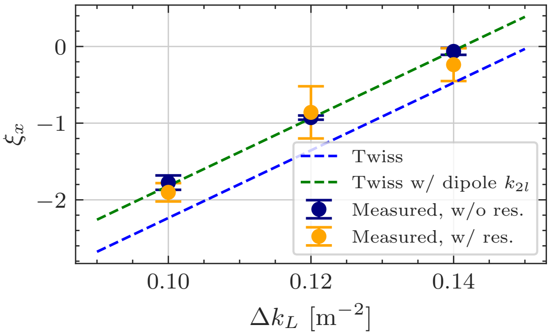

Figure 3: Chromaticity measurements at SIS18 in May 2025.

MEASUREMENTS

During the preparation of the mixed beam for the tests in Cave M, several studies were performed with the aim of achieving a stable helium-to-carbon ratio in the extracted beam. First, chromaticity measurements were carried out to verify the machine settings and to refine the SIS18 model used in the simulations. The helium-to-carbon ratio in the extracted beam was then adjusted by tuning the chromaticity.

Chromaticity Measurements

In SIS18, there are six horizontal sextupoles located in the odd-numbered sections. They are used both to excite the 3rd-integer resonance and to correct the horizontal chromaticity. The latter is achieved by applying an equal offset to the integrated sextupole strength. During the experiment, the chromaticity was estimated by observing the tune variation as a function of beam energy offset. Continuous transverse noise was applied to the beam, and the tune was determined from the BPM spectrogram. Figure 3 shows the measured chromaticity and compares it with the Twiss model. The chromaticity measurements were performed both with and without resonance excitation. The results are consistent in both cases, although the BPM data are generally noisier with the resonance excited. A systematic offset of approximately 0.5 is observed with respect to the simulated model. This discrepancy may arise from various sources, such as allowed or forbidden field harmonics in the magnets, alignment errors, or strength errors. The observed offset can be reproduced by including the first allowed sextupolar harmonic in the dipoles. A fit yields a value of $k_{2L} \simeq 0.04\,\mathrm{m}^{-2}$ for each of the 24 dipoles and results in excellent agreement with the measurements. This calibration is used in the following to predict the actual chromaticity in the machine.

Spill Optimization

The beam was extracted using the RF knockout method with a random binary phase-shift keying (RBPSK) excitation signal. For a broadband excitation, the RBPSK was set to a center tune of 0.3285 with a bandwidth of 0.01. The amplitude modulation was defined by two exponents set for a typical increase towards the end of the spill. The mixed-beam spill was monitored online using the setup in Cave M. With IC2 and IC3 positioned at the corresponding Bragg

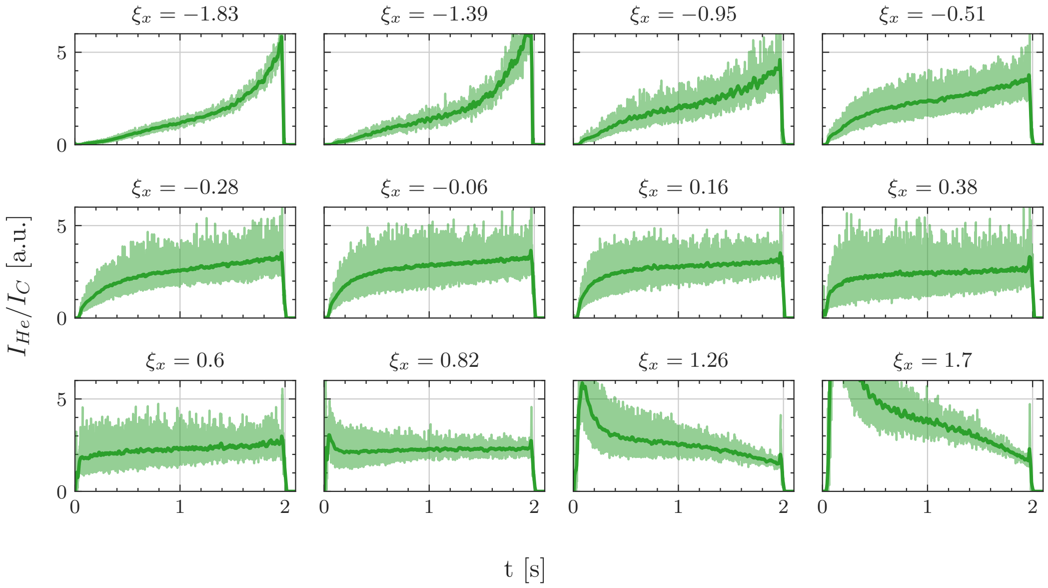

Figure 4: Reconstructed He-to-C ratio within the spill as a function of chromaticity at the extraction.

peaks, the carbon and helium spill components could be observed almost separately. During the experiment, the carbon fraction in the mixture was assessed directly with normalized signal IC2/IC1. For helium and for the helium-to-carbon ratio, the signals IC3/IC1 and IC3/IC2 were used, respectively. Unfortunately, no online correction of the IC3 signal for fragments' contributions was available during the experiment. A later offline analysis showed that this did not significantly affect the operational decision-making, although an automatic fragment correction of the IC3 signal would be beneficial for next runs.

In this study, chromaticity was scanned over the range of ±2. For each setting, IC data were recorded over 15–20 cycles for later analysis. For overcompensated or positive chromaticity, the tune distance was readjusted in order to avoid premature helium extraction without RF-KO. Figure 4 shows the correlation between the helium-to-carbon ratio in the extracted beam and the chromaticity. The data shown already include the fragment correction. For smoothing, the signals were averaged over multiple cycles and filtered using a Savitzky–Golay filter. As expected, helium tends to be extracted later for negative chromaticity and earlier for positive chromaticity. The optimal chromaticity selected during the operation was $\xi_x = 0.6$. The analysis confirms that this value lies within the optimal chromaticity range for which the helium-to-carbon ration remains approximately constant, see Fig. 4. In contrast to the simulations, the optimum was found not at fully compensated but at slightly overcompensated chromaticity. This difference is not yet fully understood, but it may originate from differences in the phase-space occupancy of carbon and helium, or from nonlinear effects.

After the chromaticity had been set, the spill feedback system (SOS) [8] was switched on. In this mode, the signal provided by SOS was used instead of RBPSK. This helped to reduce the intensity fluctuations in the extracted beam and to achieve a nearly rectangular carbon spill. Figure 5 shows the carbon and helium intensities over the spill with SOS enabled. In this case, with the carbon spill being nearly rectangular, the helium-to-carbon ratio also remained stable.

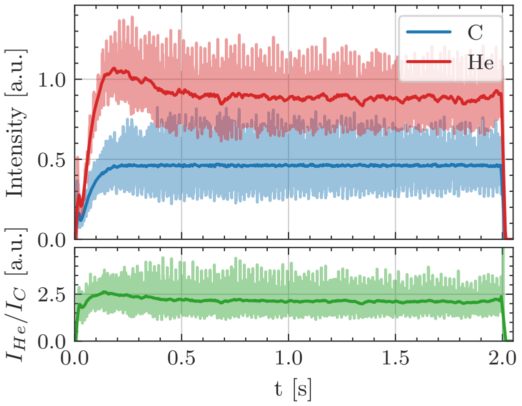

Figure 5: Carbon and helium extracted intensities (top) and the helium-to-carbon ratio (bottom) after the SOS was switched on. The data represents an average over 20 cycles.

CONCLUSION

A mixed carbon–helium beam was routinely provided for experiments in Cave M over several days in May 2025. The beam was slowly extracted from SIS18 using RF-KO, and the helium-to-carbon ratio within the spill was optimized by tuning the chromaticity. A reasonably stable helium-to-carbon ratio was achieved for slightly overcompensated chromaticity, with the operational optimum found at $\xi_x \approx 0.6$. After switching on the spill feedback system (SOS), a nearly rectangular carbon spill and a stable helium component were obtained. These results demonstrate that stable slow extraction from a synchrotron of the mixed carbon–helium beam is feasible and provide an important basis for future mixed-beam studies in ion therapy.

REFERENCES

[1] C. Graeff, L Volz, M. Durante. “Emerging technologies for cancer therapy using accelerated particles”, *Prog. Part. Nucl. Phys.*, vol. 131, p. 104046, July 2023. doi:10.1016/j.ppnp.2023.104046

[2] L. Volz *et al.*. “Experimental exploration of a mixed helium/carbon beam for online treatment monitoring in carbon ion beam therapy”. *Phys. Med. Biol.*, vol. 65, no. 5, p. 055002, Feb. 2020. doi:10.1088/1361-6560/ab6e52

[3] D. Ondreka, L. Bozyk, C. Graeff, P. Spiller, J. Stadlmann, and L. Volz, “Slow extraction of a dual-isotope beam from SIS18”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 1698–1701. doi:10.18429/JACoW-IPAC2024-TUPS29

[4] E. Renner *et al.*, “Progress on mixed He/C beam slow extraction at MedAustron”, presented at the 17th International Particle Accelerator Conf. (IPAC’26), Deauville, France, May 2026, paper THP4091, this conference.

[5] 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

[6] M. Galonska *et al.*, “First dual isotope beam production for simultaneous heavy ion radiotherapy and radiography”, in *Proc. IPAC’24*, Nashville, TN, USA, May 2024, pp. 1893–1896. doi:10.18429/JACoW-IPAC2024-WEAN1

[7] L. Volz *et al.*, “Mixed Ion Beams Enable Simultaneous Treatment and Real-Time Imaging in Carbon Ion Therapy”, arXiv:2603.12975 [physics.med-ph], 2026. doi:10.48550/arXiv.2603.12975

[8] P. Niedermayer *et al.*, “Highlights of Spill Optimization System Usage at GSI and Progress of Controls Integration”, presented at the 17th International Particle Accelerator Conf. (IPAC’26), Deauville, France, May 2026, paper WEP6111, this conference.