ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB419

ACCELERATION AND MEASUREMENT OF ALPHA PARTICLES AND HYDROGEN MOLECULAR IONS WITH THE HZB CYCLOTRON

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Abstract

The HZB cyclotron has treated more than 4000 patients with eye tumors using protons. The accelerator can also provide heavier ions which could be suitable for ocular radiation therapy. Helium ions exhibit less lateral spread, increased relative biological effectiveness and a sharper Bragg-Peak compared to protons of the same range, while minimizing nuclear fragmentation and thus excessive dose downstream the irradiated volume compared to more heavy ions. When accelerating fully stripped helium ions (alpha particles), hydrogen molecular ions can also be accelerated to the same energy with a small tuning of the machine due to having almost the same mass-to-charge ratio, yielding a proton beam of double current after the beam exits the vacuum window towards the target.

The acceleration and characterization of these two ion species are described in this paper, suggesting the feasibility of a corresponding clinical cyclotron for ocular or even deep-seated tumors.

MOTIVATION

The cyclotron of Helmholtz-Zentrum Berlin (HZB) in Germany has been providing protons for the treatment of ocular tumors to more than 4000 patients since 1998, with a local tumor control of 96% and an eye-retention rate of 95% five years after the treatment [1]. In order to further improve its therapeutic effectiveness and safety, the emerging technique of FLASH irradiation is currently being researched [2]. Another upgrade scheme under consideration is the utilization of helium ions alongside with protons.

A fully-stripped helium ion (He^{2+} or α-particle) carries double the charge of a proton and needs approximately four times the kinetic energy to reach the same range in water [3]. As a result, He^{2+} yields a ~4 times higher linear energy transfer according to the Bethe formula, leading to a sharper Bragg-Peak and an increased relative biological effectiveness [4], while exhibiting only half of the lateral spread due to multiple scattering compared to protons [5]. At the same time, α-particles undergo minimal fragmentation contrary to heavier ions such as carbon [4], eliminating excessive dose tails from projectiles at the end of the Bragg peak and sparing thus healthy tissues downstream the irradiated volume. The latter is especially important for the non-conformal (single-direction) irradiation of eyes, which requires a millimeter-narrow distal fall-off of the dose to protect critical structures such as the optical nerve and macula.

Once these promising features can be demonstrated, the established ocular radiotherapy could be supplemented by He^{2+} beams. From the accelerator point of view however, a two times stronger magnetic field would be needed compared to the proton beams, making a transition between the two species not very suitable for routine clinical operation. This obstacle can be overcome by substituting protons with hydrogen molecular ions ($H_2{}^+$), which have practically the same charge-to-mass ratio as α-particles (1:2), and can be easily stripped to give two single protons. In this case, a cyclotron can accelerate both ion species to the same range in the tissue, only by tuning the RF frequency so that the slight mass discrepancy is compensated for.

The above concept was tested at HZB in order to evaluate its feasibility and usefulness. This paper describes the corresponding machine configuration and radiation properties for both beams delivered at the the end of the common beamline.

MACHINE AND EXPERIMENTAL SETUP

Initially a 5 GHz Electron Cyclotron Resonance (ECR) ion source [6] with up to six different gas cylinders supplies particles to a 6 MeV Van-de-Graaff generator, which provides the pre-acceleration required for the injection into the cyclotron. The HZB k = 132 isochronous separated-sector cyclotron offers a maximum magnetic field of 1.57 T and a variable RF frequency between 10–20 MHz. A series of adjustable collimating slits and apertures along the machine controls the beam current and Faraday Cups are used to measure it. A 90° spectrometer dipole is used to measure the final energy of the particles. The vacuum pressure along the beam path remains below 2×10^{-6} mbar.

Approximately 3 m downstream the cyclotron's exit, an actuator is used to insert thin foils into the beamline, which act as electron strippers. In order to investigate if the 75 µm-thin Kapton vacuum window at the end of the beamline (12.63 m downstream) is sufficient to fully dissociate $H_2{}^+$, the same material in different thickness levels is used for the stripping foils.

After exiting the vacuum chamber, the particles travel in the air for 33 cm, then meet a square collimating aperture of $1.2 \times 1.2\,cm^2$ and finally reach their target 7 cm downstream. The beam characterization at that location is done with a 12-bit CCD camera, which captures the transverse profile with a resolution of 1280 × 1024 pixels, and a compact

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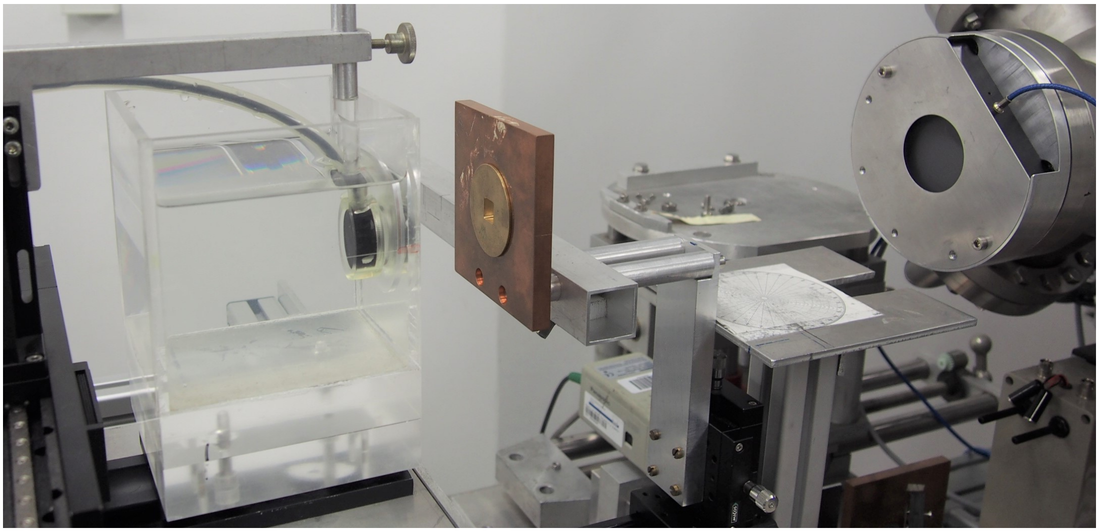

Figure 1: Photo of the common irradiation nozzle. The ions travel from right (vacuum beamline exit port) to left (dose detector in water phantom) in air, while passing through a square brass collimator. The water phantom can by replaced be a CCD camera.

water phantom, which measures the depth dose profile with a 0.1 mm longitudinal step using an Advanced Markus® parallel-plate ionization chamber (PTW-Freiburg, Germany). A photo of this nozzle, which is common for both beams, is shown in Fig. 1.

CYCLOTRON TUNING, STRIPPING AND SCATTERING

The cyclotron was tuned to accelerate H_2^+ to an energy of 45 MeV (22.33 MeV/u) for this study, requiring an RF frequency of 17.1975 MHz. When inserting a 50 µm-thin Kapton foil at the stripping location, the measured beam current was doubled few centimeters downstream, confirming the hypothesis that even a thinner vacuum window at the exit port is able to remove the electron of the molecule, which is bound by an energy of a few eV. The resulting proton beam has then a foil-induced scattering angle of 2.45 mrad rms, as calculated by the LOOKUP code [7].

For a fair comparison of the radiation field between the two ion species, we need to induce the same scattering to He^{2+} as well. Therefore, a 130 µm-thick Kapton foil is inserted for the α-beam, even though stripping is not relevant there. The RF frequency had to be increased by 124.6 kHz in this case to reach the kinetic energy of 90 MeV (22.49 MeV/u), which corresponds to the same range in water (5.3 mm). For an optimal transmission through the cyclotron, the current of the main magnet had to be reduced by 0.5 A (<0.4‰). The overall machine adjustment between the two ions is done within half an hour.

DEPTH-DOSE PROFILES

A comparison between the measured Bragg peaks in water is demonstrated in Fig. 2, where both curves are normalized to the same peak dose. The measurement starts at a depth of 2.6 mm, which is the water equivalent thickness of the front wall of the water phantom and the detector's protective cover.

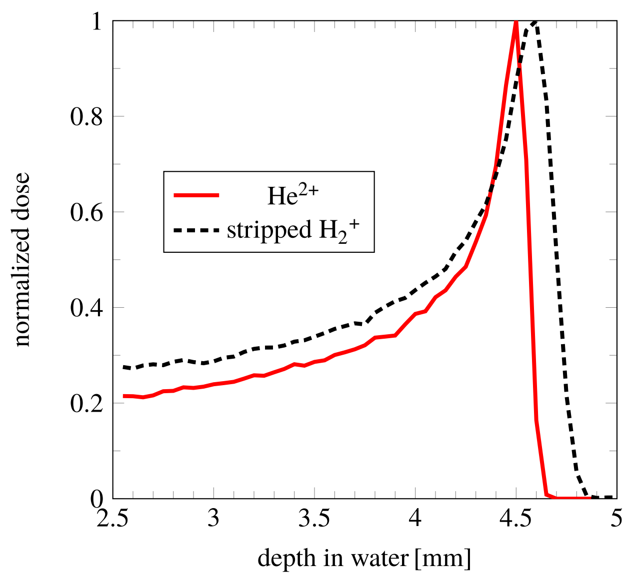

Figure 2: Measured depth-dose profiles in water, normalized to the same peak dose.

The α-beam exhibits a more concentrated dose deposition, with a sharper distal fall-off than the protons (0.1 mm vs. 0.2 mm between 90% and 10% of the peak dose) and a better peak-to-plateau ratio without any fragmentation tails at the end. The measured ranges differ by just 0.1 mm, which corresponds to the additional 80 µm in Kapton used for the scattering of He^{2+} (1 MeV added energy loss as calculated by the SRIM software [8]). The achieved range is suitable for in-vitro and in-vivo experiments, such as the irradiation of cell cultures and eyes of small animals.

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TRANSVERSE PROFILES

The radiation field from both accelerated ions at the target position is shown in Fig. 3, where the normalized vertical beam profiles are plotted.

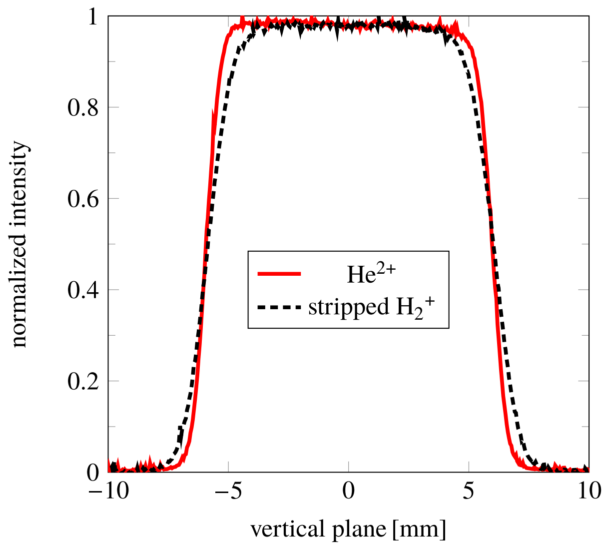

Figure 3: Vertical profile of the central cross-section of the delivered beams.

The quantities commonly used in medical physics to characterize the radiation profile are summarized in Table 1. The uniformity expresses the deviation from the average level in the flat-top region, the penumbra measures the lateral fall-off from 90% to 10%, and the symmetry indicates the difference between the two lateral edges. In short, the lower the value for every index, the better the radiation profile.

Table 1: Properties of the Radiation Profile from both Beams

Ion	Uniformity	Penumbra	Symmetry
stripped H_2^+	15 %	2.1 mm	2 %
He^{2+}	7 %	1.2 mm	2 %

A comparison between the two beams reveals the superior radiation field delivered by He^{2+} at the end of the common beamline in air.

CONCLUSIONS

Having demonstrated the advantageous radiation properties of α-particles, this study suggests the enhancement of the established proton radiotherapy of eye tumors with a "cocktail beam" of H_2^+ and He^{2+}. The HZB cyclotron has been able to accelerate both particle beams to the same range in water by slightly tuning the machine parameters within half an hour. The electron stripping of the molecular ion requires no additional foil other than the vacuum window at the exit port of the beam, doubling the intensity at the target location. Using the same irradiation nozzle, a similar radiation field can be delivered.

Taking into account that also ultra-high dose rates are available by the HZB cyclotron [9], biological experiments of high importance can be conducted to evaluate the FLASH effect for both ion species. The maximum achievable range suffices only for the irradiation of cell cultures and eyes of small animals, but can nevertheless serve as a demonstrator for a dedicated clinical cyclotron for ocular or even deep-seated tumors.

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