BEAM OPTICS CONSIDERATIONS FOR ISOTOPE PRODUCTION AT THE PSI CYCLOTRON FACILITY

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Abstract

The isotope production beam line starts at the electrostatic beam splitter, which peels off a beam of a few tens of µA from a main beam of high intensity up to 2.4 mA. The beam optics has to ensure that the beam on target will be in right size. Due to the parasitic nature of the beam line, the beam optics also has to get along with the tuning of the main beam, especially in the sections upstream of the beam splitter. Aiming at a reliable and efficient isotope production, the beam optics is monitored for each irradiation session. The operational experience together with further development is presented.

BEAM LINE

The isotope production beam line starts at the electrostatic beam splitter EXT and ends at the target station as illustrated in Figure 1, where the important beam optics elements, namely the bending magnets, the steering magnets and the quadrupoles, are marked blue, orange and red, respectively. The length of the beam line is approximately 22 m.

The splitter EXT peels off a beam of a few tens of µA from the main beam coming from the 72 MeV Injector II cyclotron. The intensity of the peeled beam is regulated through adjusting the position of the splitter with respect to the main beam by a control loop [1].

The beam for the isotope production is deflected around 0.6° by the electrostatic field, whereas the main beam passes through a field-free region. A separation more than 40 mm may be created at the entrance of the septum magnet AYA, about 4 m downstream of the splitter EXT. The magnet AYA bends the peeled beam 17.5° further away from the main beam.

The beam energy may be reduced from 72 MeV to 40 MeV by inserting the graphite degrader DYD into the beam line. The degrader DYD locates in front of the quadrupole QYA6.

The beam position is controlled by the beam centering program through adjusting the strength of steering magnets according to the actual beam positions measured by the beam position monitors named as MYS*N* in Figure 1. Here *N* is an integer number with odd and even representing horizontal and vertical position, respectively. The measured beam positions are stored automatically into the database.

The beam profiles are measured by the beam profile monitors named MYP*N* in Figure 1. Here *N* is also an integer number with odd and even representing horizontal and vertical profile, respectively. The profile scan may be carried out with a single monitor or a group of preselected monitors. The profile measurement and the database registration are performed not automatically, but on demand.

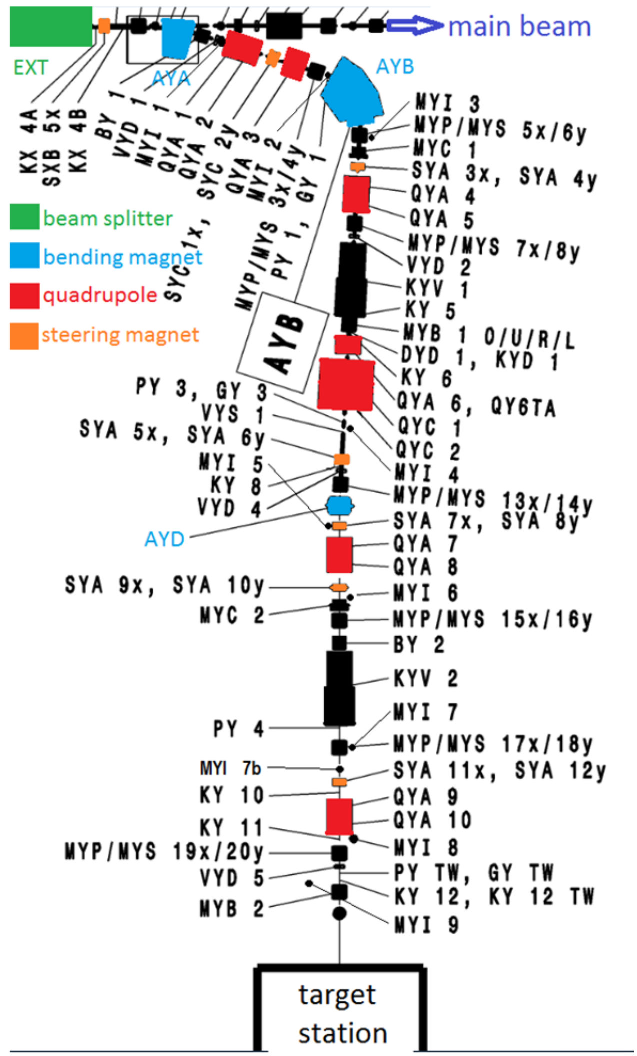

Figure 1: Isotope production beam line.

BEAM OPTICS

The beam line has to guide the beam of desired size onto the target. The challenge to the beam optics comes firstly from the fact that the required beam size differs significantly from one isotope production to another. For example, the diameter of $^{44}CaCO_3$(graphite) target for ^{44}Sc production is around 6 mm which requires a beam of 2σ less than 5 mm, while $^{64}Ni(Au)$ target for ^{64}Cu production requires a beam of 2σ greater than 7 mm. The difficulty arises also from the fact that the beam size on target cannot be measured in situ in real-time. The profile monitor next to the target is one meter away. The other difficulty arises from the parasitic nature of the beam line. As a

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matter of fact, the emittance of the peeled-off beam might be significantly reduced when the main beam intensity is dropped, for instance when the intensity of the main beam has to be reduced from 2.2 mA to 1.7 mA in case that the neutron target is not in operation. In extreme case, the main beam of a few tens of μA has to be guided directly onto the isotope target. In Table 1 the measured emittance of a 50 μA beam is listed along with the intensity of the main beam. In spite of all these difficulties, the beam size can still be well controlled to meet the requirement. The setup procedure is described as following.

Table 1: Horizontal and Vertical Beam Emittance, ε_x, ε_y

Main Beam Intensity mA	ε_x **π·mm·mrad**	ε_y **π·mm·mrad**
2.4	1.18±0.06	4.6±0.3
2.25	1.12±0.05	4.0±0.5
2.05	1.07±0.05	3.8±0.4
1.85	1.02±0.05	3.6±0.5
1.65	1.02±0.04	3.3±0.4
0.05	0.86±0.06	0.64±0.04

An irradiation is often started with setting up the beam line according to a setup recently recorded during the production of the same isotope and under identical conditions. Over the years a comprehensive database has been established for the production of a variety of isotopes and under different conditions. Soon after the irradiation is started, the beam profiles are scanned, and the beam envelope is calculated with the program TRANSPORT [2]. Figure 2 shows the beam envelopes measured during ^{44}Sc and ^{64}Cu irradiations, depicted by the black and orange curves, respectively. The lower and upper halves represent the horizontal and vertical directions, while the ┬ and ┴ symbols represent the 2σ beam sizes from beam profile measurement. On the figure the blue and red blocks symbolize the position, dimension and aperture of the dipole and quadrupole, respectively, while the aperture is scaled by a factor of 0.25.

From the envelope fit, the beam size on target can be indirectly derived. The beam size on target is repeatedly measured during an irradiation session. For example, ten envelope-fits are performed in a ^{44}Sc irradiation session in 90 minute, which gives typically a 2σ beam radius on target around 4.5±0.1 mm. The fluctuation of the beam size on target is thus around 2%. Figure 3 shows ten beam profiles in horizontal and vertical direction measured with the monitors one meter in front of the target, namely MYP19 and MYP20, which indicates that not only the beam size but also the beam position are stable.

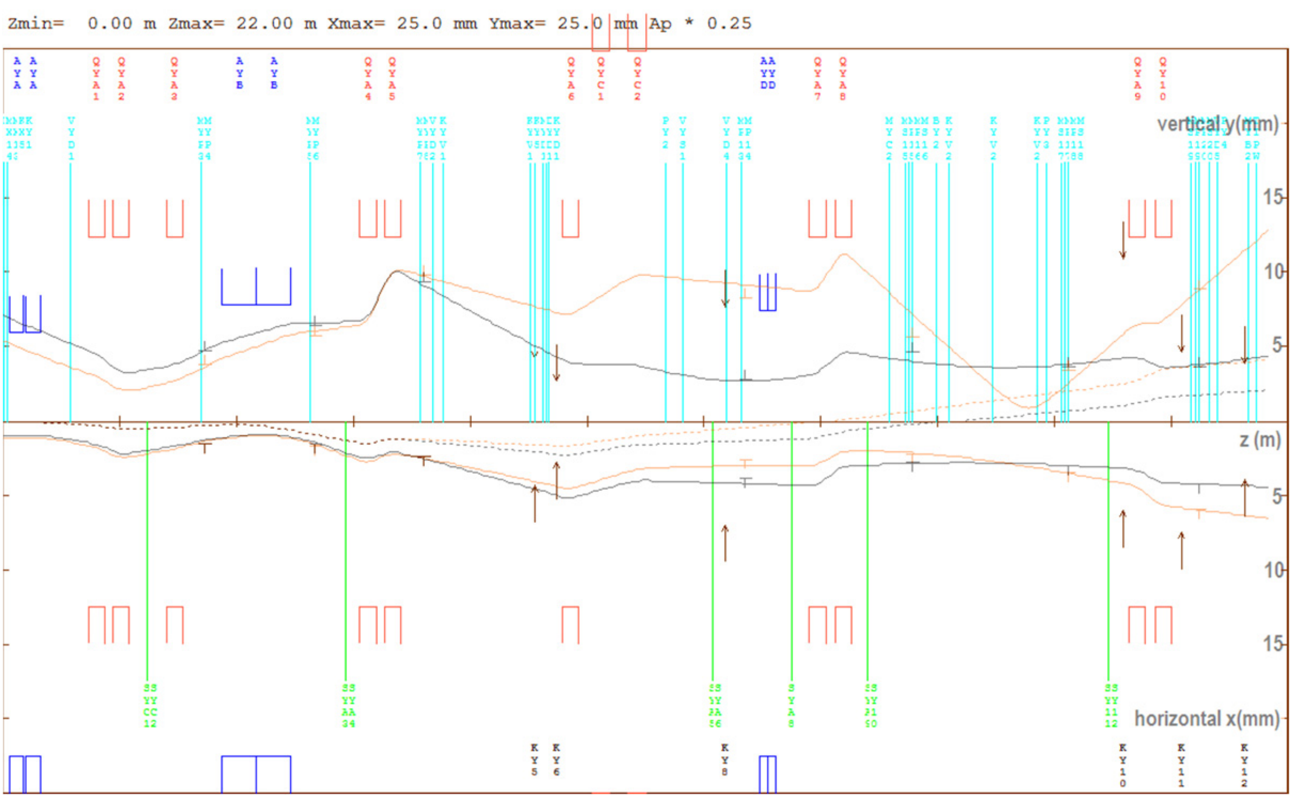

Figure 2: Beam envelopes for ^{44}Sc and ^{64}Cu productions in black and orange.

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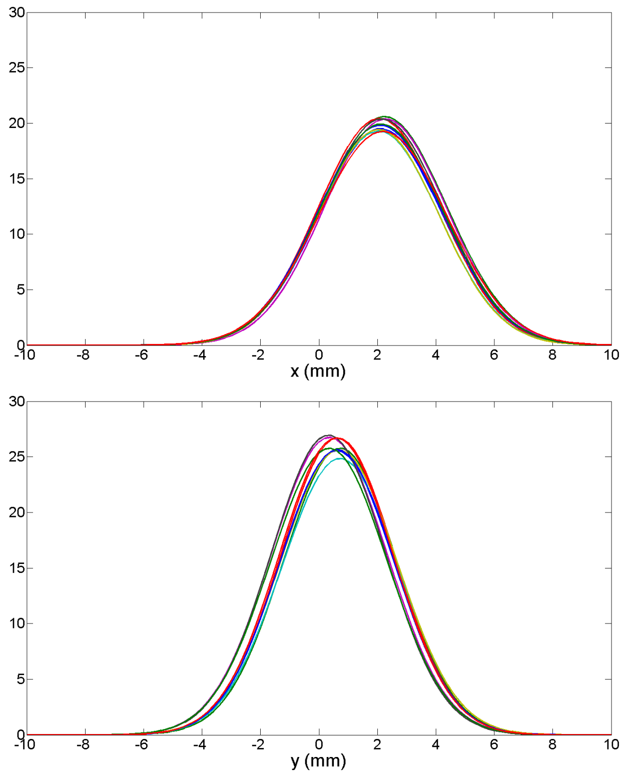

Figure 3: Ten beam profiles measured in one session. Top: horizontal; Bottom: vertical.

Provided that the target could be sufficiently cooled, the efficiency of the isotope production could be optimized by matching the beam with the target. In practice, a divergent beam is guided onto the target and the beam diameter is larger than the effective diameter of the target. For example, the 2σ beam diameter is around 9 mm, while $^{44}CaCO_3$(graphite) powder is pressed to form a thin disc 6mm in diameter. The irradiation might not be highly efficient, but can still deliver high yield. Nevertheless the target, especially the $^{44}CaCO_3$(graphite) target, may occasionally be overheated. The exact cause of target overheating can be identified only on rare occasion. There are several uncertainties, for example, the peeled-off beam might be different after tuning the main beam, or the target might be prepared in a different way, or the cooling water might be running extraordinarily. Anyway, in case that the target is overheated and that the yield is much lower than expected, the beam size has to be increased for the next irradiation by adjusting the strengths of certain quadrupoles. The adjustment is often started with a test target to avoid wasting the expensive target material. The quadrupole setting may be optimized step by step until the yield is back to high level. The setting is then stored in database for future application.

Theoretically it is possible to increase the beam size to such an extent that the target can be freed from overheating. However, the irradiation would then be inefficient and the yield would be too low for the following radiopharmacy applications. At present the yield from a reduced beam size is more than tripled so that the risk of occasional target overheating can still be tolerated.

FUTHER DEVELOPMENT

The Injector II cyclotron can deliver a beam up to 2.7 mA, while the proton facilities are licenced for the operation with a beam up to 2.4 mA. Furthermore, the Injector II cyclotron is back in operation one month before the official end of annual shutdown. Therefore it is possible to deliver a beam over 2 mA exclusively for the isotope production for four weeks every year, which is an attractive option.

On the existing isotope beam line, the so-called direct shot is actually a routine practice. A beam of 50 µA from Injector II cyclotron is deflected without splitting by the beam splitter and guided on to the target for the isotope production, in case that the 590 MeV Ring cyclotron is out of operation. However, the beam current seldom exceeds 50 µA in the past, and the limiting factors are the cooling and the shielding of the target. As the modification to the target station is rather difficult and expensive, the beam optics, specifically the maximizing of the beam-on-target size has been explored at first. Preliminary experiments have been performed applying a direct shot of 70 µA beam. The beam-on-target size can be increased up to a 2σ diameter of 30 mm. Nevertheless, the beam optics has to be significantly modified and certain quadrupoles have to be pushed near to their limits.

For the existing target station, the optimization of the cooling scheme has been high on the agenda. A more ambitious project aiming at the full use of the high power proton beam, including a new target station and a beam line connecting the Injector II and the target station, has been under discussion. The bunker for the decommissioned Injector I cyclotron could be used for the target station, while the beam line connecting Injector I and the 590 MeV Ring cyclotron could be partially reused [3].

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