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HIGH INTENSITY CYCLOTRONS FOR PRODUCTION OF MEDICAL RADIOISOTOPES

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Abstract

At the previous cyclotron conference an overview of the cyclotrons for radioisotopes production was shown. Here, we will focus on the development of IBA's accelerators in the recent three years. Notably the Cyclone® 70, the Cyclone® 30XP and the Cyclone® KIUBE have made progress. The expertise gained with the development of these machines has led IBA to develop a completely new cyclotron for 30 MeV protons, the Cyclone® IKON. As its first construction is ongoing, details on the design of this accelerator will be presented.

ONGOING COMMISSIONINGS

Two major projects are ongoing for the older generation cyclotrons: a Cyclone® 70 at IBS in Korea, and a Cyclone® 30XP at the INM in Germany [1].

Cyclone® 70

In 2019 a contract was signed between IBA and IBS for the installation of a 70 MeV cyclotron with beam lines leading to two separate target vaults [2]. After a design phase fitting the system in the already existing building, the installation was performed in 2021.

For this installation, IBA developed a beam profile monitor using a wire scanner. In Fig. 1, results from the tuning at 70 MeV are shown with the donut-shape requested by the customer. As of November 2022, only 12 months after the start of the rigging, the commissioning was finished with a beam of 715 µA on target.

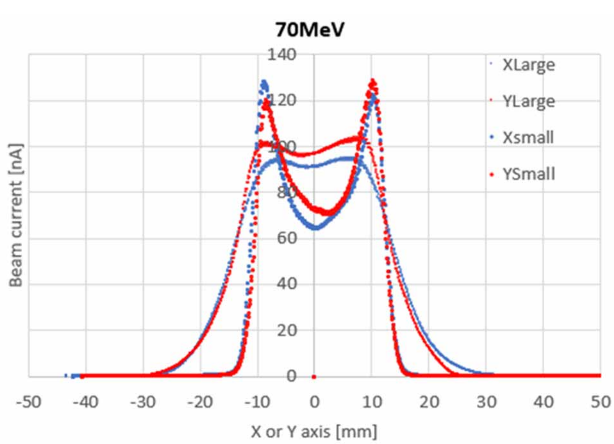

Figure 1: Beam current measured along the X and Y axis, using either a large or a small beam spot, with wobbler.

Cyclone® 30XP

The Cyclone® 30XP is a multi-particle cyclotron that IBA is to install at the Forschungszentrum Jülich in Germany. The installation had been on hold for several years, but recently the commissioning could finally start.

Table 1: Properties of the Multi-particle Cyclone® 30XP

Particle	Energy	Beam Intensity	Extraction Method
Proton	15 ~ 30 MeV	300 eµA	Stripping
Deuteron	8 ~ 15 MeV	50 eµA	Stripping
Alpha	30 MeV	50 eµA	Electrostatic deflection

In Table 1, an overview is given of the different particle beams that can be extracted. For the proton and deuteron beams, stripping extraction is used. The latest results of the commissioning, only recently obtained, confirm that also the third particle type can be extracted: a stable alpha beam of 20 eµA has been measured on target, with an efficiency of the deflector of 75%. Higher beam intensities are expected soon.

CYCLONE® IKON

With the expertise gained on IBA's Cyclone® KIUBE [3, 4], the new Cyclone® IKON was designed, see Fig. 2. Compared to the previous 30 MeV cyclotron, it is more compact, more efficient and delivers better performance.

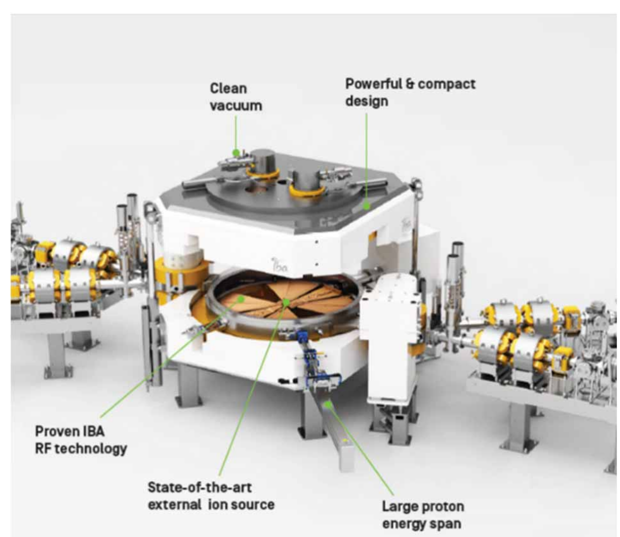

Figure 2: Image of the Cyclone® IKON with dual extraction, switching magnets and the start of four beam lines. A third target can be mounted on each switching magnet.

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Table 2: Parameters of the New 30 MeV Cyclotron Design Compared with its Predecessor

Parameters	**Cyclone® 30P**	**Cyclone® IKON**
Pole gap	30 mm	30 mm
Valley depth	550 mm	159 mm
Cyclotron height	1550 mm	920 mm
Diameter (width)	2700 mm	2145 mm
Ampere-turns	42.7×10^3 A	35.9×10^3 A
Iron mass	43 T	23 T
Coil mass	1440 kg	1125 kg
RF frequency	62 MHz	75 MHz
Energy	15 ~ 30 MeV	13 ~ 30 MeV
Extr. current	0.5 ~ 1.2 mA	1.2 mA

In Table 2, the parameters of the old and new accelerator are listed. As can be seen, its height has significantly been reduced, mainly by lowering the valley depth. Consuming less Ampere-turns, the machine can extract a larger span of energies, with 1.2 mA of 30 down to 13 MeV.

The injection line, seen in Fig. 3, is similar to that of the injection line designed for a previous upgrade of the Cyclone® 30HC [1]. One difference is that the Glaser has its own yoke, as it is now outside of the cyclotron's yoke. A D-pace DC Volume-Cusp source is used, designed for 15 mA of H^- beam at 30 keV [5].

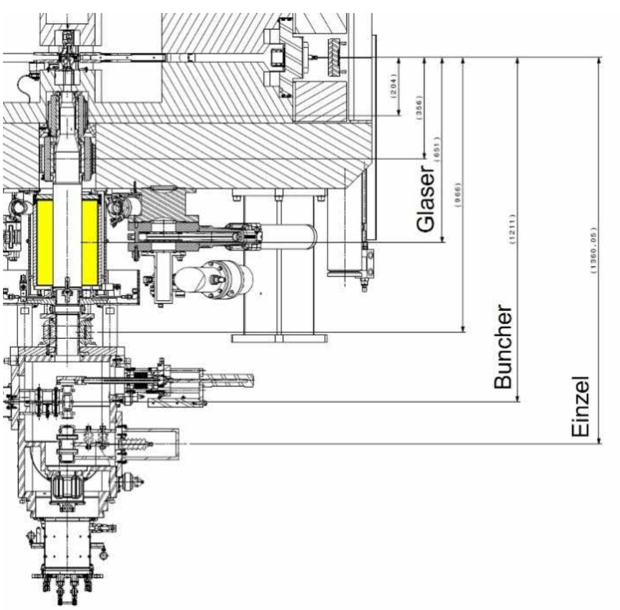

Figure 3: Injection line of the Cyclone® IKON.

Magnetic field optimizations were computed in Simulia OPERA [6], whereas beam tracking was performed with AOC [7]. Using these tools, an inflector has been designed and the dee tips were optimized for good orbit centring, phase acceptance and electric focusing, see Fig. 4, for an injected beam of 40 keV.

As its baby brother, the Cyclone® KIUBE, the Cyclone® IKON comes with pole inserts in the centre of the poles, that can be removed during the magnetic mapping process and easily milled to obtain an isochronous magnetic field [8]. In Fig. 5 the inserts can be seen, mounted in the poles.

Figure 4: View of the inflector and dee tips.

Figure 5: View of the inserts mounted in the poles, assembled with the dees.

The position of the switching magnets has been optimized to minimize the cut-out in the return yoke, while taking into account the properties of the beam as extracted from 13 to 30 MeV, as seen in Fig. 6. The result is a clocking of the external squared yoke by 20° compared to the symmetry axes of the poles.

According to the calculated beam transport from the switching magnet through the beamlines (with one permanent magnet focussing element, plus two quadrupole doublets), a minimal transmission of 94% at 13 MeV is expected, and 99% at 30 MeV.

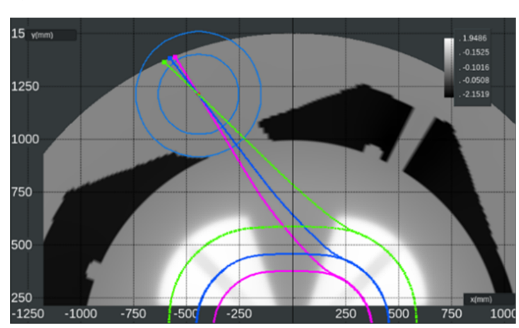

Figure 6: Return yoke has been rotated compared to the poles, to optimize the extraction.

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The magnetic field is shaped by machining the pole inserts according to field map results, all while taking into account external magnetic elements such as the hydraulic jacks, switching magnets, etc. The deformations of the magnet yoke due to atmospheric pressure and magnetic force are also considered. In Fig. 7, the integrated phase shift as a function of the radius is shown with less than ± 10° of excursion.

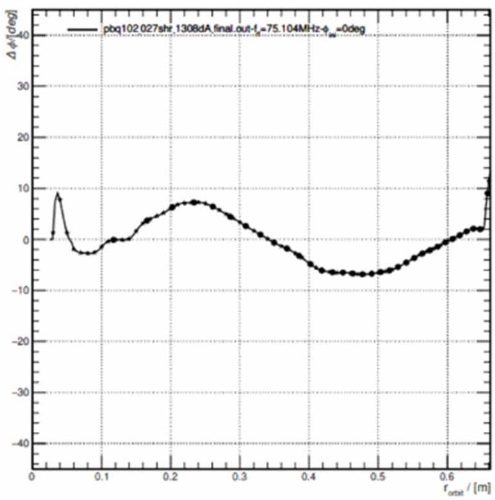

Figure 7: Integrated phase shift. Stars indicate the integer values of the average closed equilibrium orbit radii every 1 cm. Bullets correspond to integer values of the kinetic energy every 1 MeV.

In Fig. 8 the operation curve is shown. The resonance line that may deteriorate the beam emittance is the Walkinshaw resonance ($\nu_r - 2\nu_z = 0$). This resonance is crossed before an orbit radius of 25 cm, where large turn separation per MeV is found, see the bullets separation in Fig. 8. Fast crossing of the resonance condition is expected which will not deteriorate the beam emittance. Also, the crossing of the Walkinshaw resonance was avoided at energies close to extraction during the pole inserts correction.

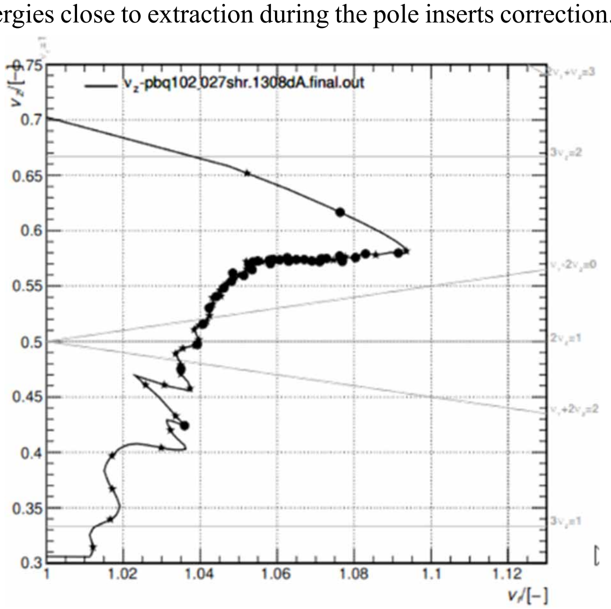

Figure 8: Operation point curve.

SPACE CHARGE CALCULATIONS

In AOC, there is the option to include the calculations of the space charge (SC) effects. For this, the particle-to-particle method is used for the calculation of the self-field of a bunch. It is assumed that the bunch is in free space, i.e. there are no electromagnetic boundary conditions, and the self-field acting on one particle is obtained as the sum of contributions of all other particles in the bunch. This slows down the calculation for large number of particles N, as computing time scales with N_2. However, for the injection and central region calculations, ~ 10000 particles can be enough, which keeps the needed CPU time reasonable.

The main advantage of the chosen method is that one can immediately include the SC option together with the existing 3D features of the E- and B-fields, simplifying tracking through regions such as that of a spiral inflector.

Transport Results Compared to AOC

In the Transport code, there is also the option to include space charge effects [9-11]. In Fig. 9, upper plot, the beam envelop can be seen as calculated by Transport for the Cyclone® IKON injection line, with and without space charge effects for a 15 mA beam. In the lower plot the same is given for the calculations with AOC.

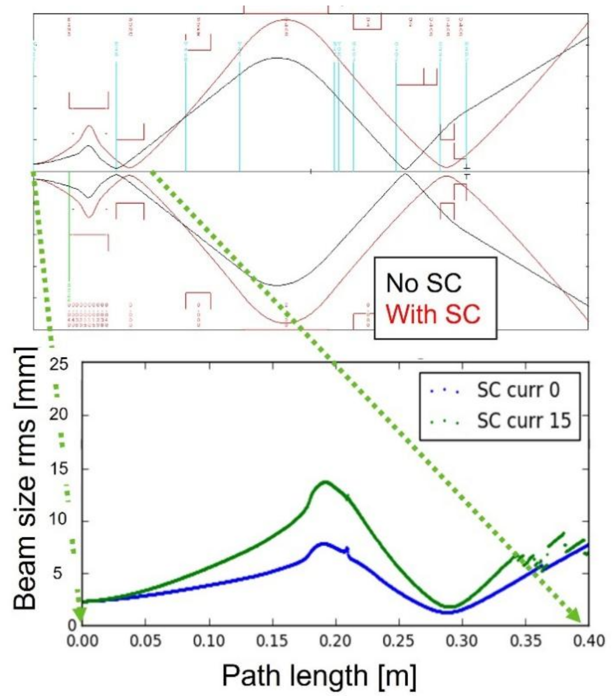

Figure 9: Beam envelope (2σ) calculations in Transport (up) and in AOC (down). In the upper plot the full injection line length is displayed, whereas in the lower plot only the first 40 cm is shown. The Einzel lens is located at ~ 20 cm and focuses the beam.

Including the SC effects, the transverse beam size increases in AOC by the same amount as in Transport. However, in Transport we notice a longitudinal shift of the waist of ~ 50 mm just after the Einzel lens, whereas it is not more than 5 mm in AOC, see also Table 3.

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Table 3: Distance from the source to the waist after the Einzel lens, calculated with transport and AOC, with and without the SC effects of a 15 mA beam.

Code	No SC	15 mA SC
Transport	300 mm	350 mm
AOC	285 mm	290 mm

The difference in results between the two programs comes from the fact that in Transport the beam is always assumed to be of a gaussian distribution. In AOC however, each particle is tracked individually and the dense distribution in the waist changes the transverse distribution: even though the beam starts gaussian at the source, the gaussian distribution is lost, as the halo is more populated.

Longitudinal Properties

In AOC, the particles extracted from the source come one by one. Thus, at the start of the calculations, there is only one particle, then two, etc. The first particle sees only particles behind it, and the last particle sees only others in front of it. Longitudinally, the SC effects thus create a debunching force, which is non-existent in a real DC beam.

To see this effect, we populate the beam in the simulation with 3 bunches, that is a uniform distribution of particles longitudinally, over a distance of 3× the βλ, which is equal to 37 mm. With the buncher set to its theoretical value of 563 V, to obtain the smallest bunches possible at the median plane, the distances between the bunches can be measured at the inflector: the results show that, with the SC effects of a 1 mA beam, the distance between bunches is ~ 36 mm, as expected from the βλ, but with the SC effects of a 5 mA beam the distance increases to 45 mm.

CONCLUSION

At IBA, the high intensity cyclotrons for the production of medical radioisotopes continue to evolve. The last two cyclotrons of the "previous" generation, the Cyclone® 70 and the Cyclone® 30XP, have been commissioned at the customer's sites. From the knowledge acquired with the Cyclone® KIUBE, a new 30 MeV proton cyclotron has been launched, the Cyclone® IKON. We presented the design of the new machine. It has been produced and isochronized in factory, and its installation is ongoing at the first customer's site.

With increasing requested beam intensities, as well as cyclotron compactness, the space charge effects in the beams become more and more relevant for the design and performances of high intensity cyclotrons. We have presented the start of a study on the space charge effects in the injection line of the Cyclone® IKON, using AOC. Benchmarking the results against those of Transport, some different results are observed. At the same time, a longitudinal defocussing effect is introduced in the particle-by-particle tracking in AOC, which is non-existent in a real DC bunch. Further studies will be needed to resolve this issue.

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