NEW CYCLOTRON DEVELOPMENTS AT IBA

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Abstract

This paper describes some recent cyclotron developments done at IBA - Ion Beam Applications s.a. For radioisotope production, the self-extracting cyclotron now works very reliably at extracted beam currents above 1 mA, producing Pd103 for Brachytherapy devices. Based on a better understanding of the self-extraction process gained with this first machine, an improved design has been made, reducing the extraction losses to less than 10% and allowing extracted currents in excess of 2.5 mA. In the field of protontherapy, progress has been made in the fast and accurate control of the extracted beam current, allowing to slave the extracted beam to an external control signal up to 2.5 kHz, and this over a large dynamic range which is essential for high performance proton therapy using pencil beam scanning techniques. For the radiotherapy of cancer using Carbon beams, IBA has made the design of a fixed field, fixed frequency, elliptical gap, K = 1200 superconducting cyclotron, allowing to accelerate ions with Q/M = 0.5 to 300 MeV/U.

THE SELF-EXTRACTING CYCLOTRON

Current Status of the Prototype

The self-extracting cyclotron [1] is a high-intensity 14 MeV H^+ machine for isotope production. Figure 1 shows of photograph of the interior of this machine. There is no electrostatic deflector. Extraction is achieved with a special shaping of the magnetic field. There are two long poles and two short poles, both with an elliptical gap profile; this provides a steep fall off of the magnetic field at the pole radii. An extraction groove is machined in the iron of one of the longer poles. First harmonic coils create an orbit separation at the entrance of the extraction path and extract the beam. A high power low activation beam catcher is used to collect beam that is not properly extracted. The prototype machine is in use for production of Pd-103. Commercial use of the machine started in 2002 and since then the beam current on target could be gradually increased and now routine productions of up to 3 weeks of duration with 1 mA of beam current on target are normal. Beams of more than 1.5 mA have been extracted and transported. The extraction efficiency is 80% for low beam intensity and decreases to about 75% for production intensity (1 mA). This slight decrease is probably due to an increase of dee-voltage ripple induced by variations of the cavity beam loading resulting from ion source plasma noise. The machine is very easy to operate and also extremely stable and reliable. The main new development efforts have been on the target design. The target material consists of a thin Rhodium wire that is wound around an aluminum drum which is rotating around its axis and which is placed at angle of about 15 degrees with respect to the beam direction. Cooling of the Rhodium wire has been substantially improved by applying a convective flow of helium on the rotating drum. Figure 2 shows the target station that is placed in a separate vault at about 8 meters from the cyclotron.

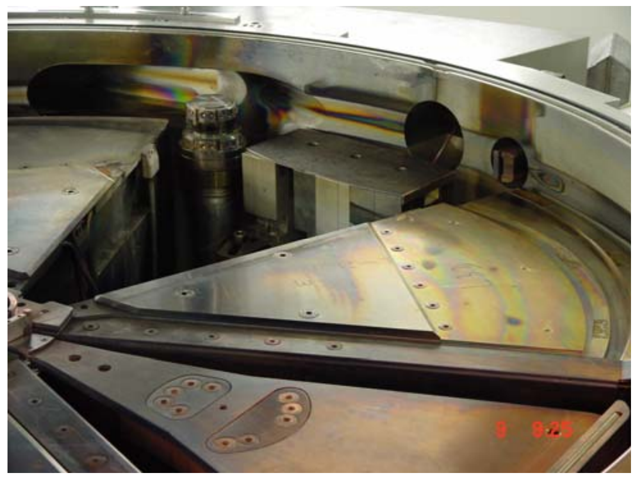

Figure 1: Median plane view and extraction path in the prototype self-extracting cyclotron, showing the groove in the pole, the gradient corrector and the beam separator. The harmonic coils are placed underneath the pole covers

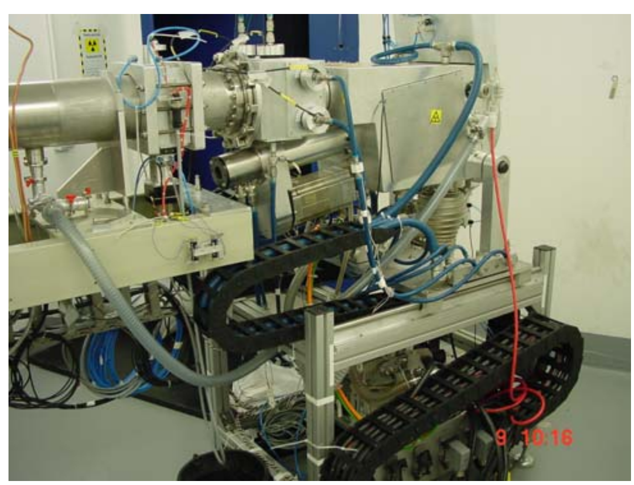

Figure 2: The Pd-103 target station is irradiated by the self-extracted beam of the SEC prototype

Development of an Improved Magnetic Design

Although the prototype SEC is operating reliably in an industrial environment, the extraction efficiency of 75% and the corresponding beam loss on the beam separator limits the maximum beam current. It was only after building and operating the prototype that we came to understand better the physics and full optimisation scheme of self-extraction. Therefore, the following improved concepts have been developed:

- Instead of milling a groove parallel to the beam trajectory into a circular pole, we decided to make the pole edge parallel to the beam trajectory. The pole surface is therefore machined on a NC milling machine instead of on a NC lathe. By this, a sharper field transition from the isochronous region to the extraction path is achieved.
- Since the groove is inducing a strong sextupole in the extracted beam optics, it has been changed by a kind of plateau. As can be seen from Figure 3, this results in a sharp drop of the field in the extraction path with about 3 kG, but there is no subsequent field rise (sextupole) as is found in the prototype.
- The vertical pole gap near extraction has been optimised such that the radial tune function ν_R shows a slow transition from 1.1 down to about 0.6 in the last ten turns before extraction. This is illustrated in Figure 4. The low value of ν_R results in a large turn separation via the mechanism of precessional extraction. This behaviour of ν_R obtained with a field bump between 450 mm and 520 mm as illustrated in Figure 3. Of course such a shaping of the radial tune influences the isochronism of the field but the induced RF phase motion is still limited and fully acceptable as is shown in Figure 5.

Extensive use of the OPERA3D finite element code of Vector Fields was made in order to include those features and optimise the magnet. Figure 6 shows the modelling of the extraction sector. As can be seen, iron is removed from underneath the pole tip, in order to be able to properly adjust the magnetic flux flow towards the extraction path.

At the same time extensive orbit tracking simulations were performed in order to find the extraction efficiency and the extracted beam quality. The IBA Advanced Orbit Code (AOC) was used to simulate fully accelerated beams (each containing multiple-thousands of particles) from the ion source up to the exit of the cyclotron. These simulations took into account precise OPERA3D electrical field maps from the central region but also from the full dee-structure as well as the precise isochronised OPERA3D magnetic field maps. During these calculations the three freely available magnetic field parameters (two harmonic coil settings and the main coil)

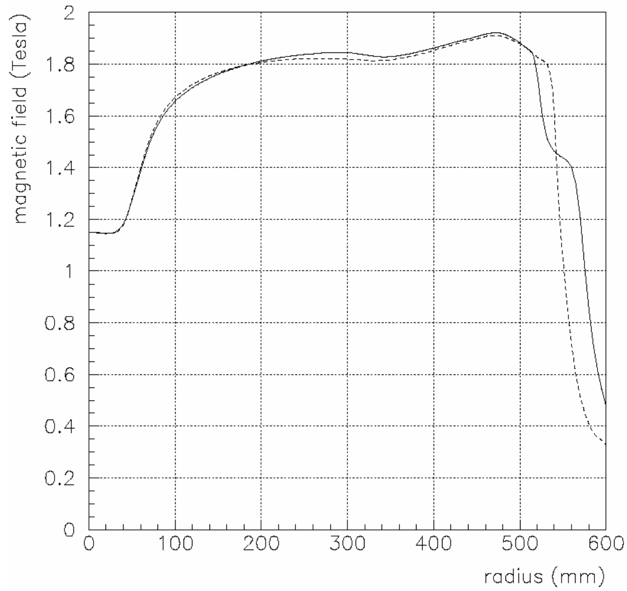

Figure 3: Magnetic field on the middle of the extraction-sector. The field bump in between 450 mm and 520 mm creates the required fall of the ν_R function near extraction. The extraction path in between 520 mm and 560 mm is created by machining of the plateau in the pole. The dotted line gives the filed on the other three sectors, which have an extended radius

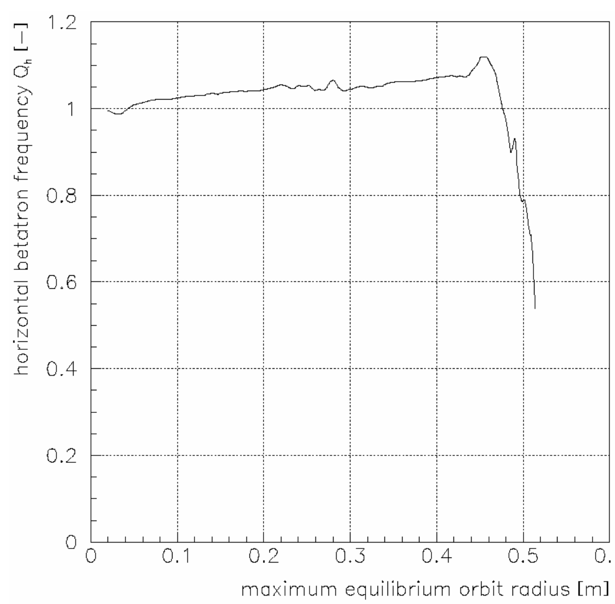

Figure 4: Shaping of the radial tune function near extraction as needed for increasing the turn separation

were optimised in order to find the maximum extraction efficiency. These computations were done on a cluster of 11 personal computers in order to gain calculation speed.

With these simulations an extraction efficiency of at least 90% is predicted for the improved design and an extracted beam emittance of about 100 π mm-mrad. These values must be compared to 75% and 300 π mm-mrad respectively for the prototype. We have good confidence in these figures, because the same simulations were carried out for the prototype and here, good agreement with the experimental values were found.

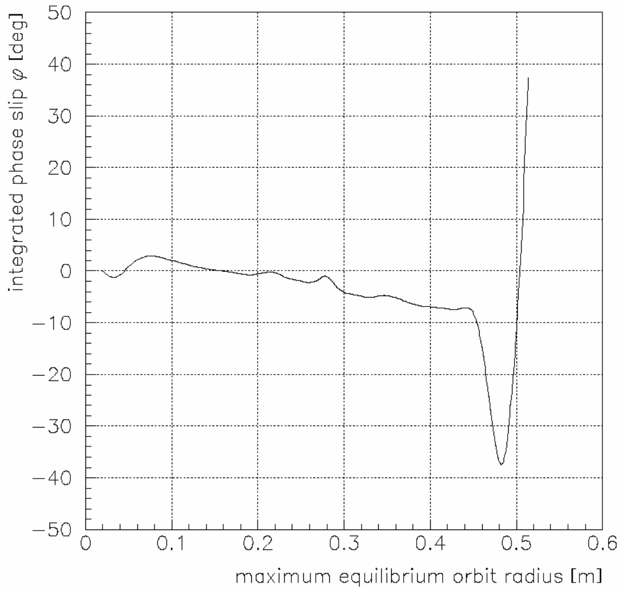

Figure 5: RF phase slip for the new SEC magnetic design. The phase motion near extraction relates to the corresponding shape of radial tune as shown in Figure 2

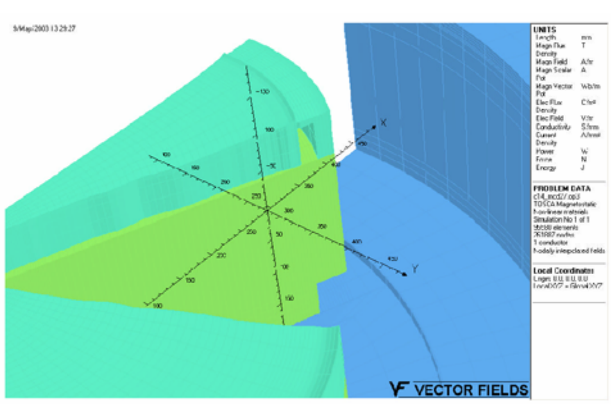

Figure 6: The OPERA3D software was used extensively for modelling the SEC II. Iron is removed underneath the pole tip on the extraction sector in order to adjust the magnetic flux towards the extraction path

PROTON THERAPY SYSTEMS

Overview

During the last 10 years, IBA took a leadership position on the proton therapy market (see Table 1).

NPTC - Northeast Proton Therapy Center at MGH in Boston MA, USA was the first IBA proton therapy project. The C230 cyclotron was developed with the Japanese company SHI - Sumitomo Heavy Industries. Treatment of patient started on November 8th, 2001. The cumulative up-time of 95 percent confirms the reliability of IBA equipment.

The collaboration between IBA and SHI was very successful. The second SHI and IBA proton therapy system was constructed by SHI in NCC – National Cancer Center in Kashiwa. The first treatment of patients has been done even before NPTC.

Today (October 2004), IBA field engineers perform initial beam tests and validation of other equipment in Wanjie Tumor Hospital in Zibo, China. We expect that the first treatment of a patient in the fixed beam room will take place before the end of this year. At the same time at IBA, we test C230 cyclotron destined for Florida Proton Therapy Institute at University of Florida in Jacksonville FL, USA.

Table 1: Sales of proton therapy systems

Year	**Customer**	**Provider**
1995	MGH, Boston MA, USA	**IBA**
1996	NCC, Kashiwa, Japan	SHI/**IBA**
1996-99	Tsukuba University	Hitachi
	Wakasa Wan Energy Research Center	Hitachi
	Shizuoka Prefecture	Mitsubishi
2001	PSI – Villigen, Switzerland	Accel
	Wanjie Tumor Hospital – Zibo, China	**IBA**
	Chang An PMC – Beijing, China	**IBA**
2002	Rinecker PTC – Munchen, Germany	Accel
	Korean NCC - Seoul	**IBA**
	IUCF (MPRI), Bloomington IN, USA	**IBA**
	M.D. Anderson CC, Houston TX, USA	Hitachi
2004	University of Florida, Jacksonville FL, USA	**IBA**

Fast beam current adjustment

The high dynamic beam adjustment is necessary for Pencil Beam Scanning (PBS) and to compensate the spread of Bragg peak tilt due to imperfect machining of range modulator wheel.

The current adjustment is done by an electronic unit that controls the ion source arc power supply. Input signals are coming from treatment rooms and from an ionization chamber located at the cyclotron exit which measures the beam current.

The feedback system in this case is complex due to delay caused by the beam acceleration. The arc current to beam current ratio is non-linear and also may drift over long time periods. The beam is noisy at higher frequencies. Disturbances as deflector or RF system discharge can cause the beam to disappear for some short instant. In such moment, the adjustment system should not increase the arc current.

To improve the adjustment we added feed-front predictive system. Before each irradiation the proton therapy system performs 10 sweeps and records values of the arc current and the extracted beam current. In this way we obtain the look-up table that can be used later. The error signal between extracted current and the given function uses the look-up table to adjust settings of the ion source arc power supply.

CARBON-PROTON, 300 MEV/U, Q/M=1/2 SUPER-CONDUCTING CYCLOTRON FOR HADRON THERAPY

This cyclotron is based on the design of the current PT (proton therapy) C230 cyclotron. It can accelerate ions with Q/M = ½, such as $^{12}C^{6+}$, $^{10}B^{5+}$, $^{6}Li^{3+}$, $^{4}He^{2+}$ and H_2^+ at an energy of 300 MeV/u.

The acceleration of Q/M = 1/2 ions at 300 MeV/u requires a larger extraction radius of 1.48 m and a larger average magnetic field of 3.7 Tesla at extraction. At extraction radius, the hill field is 4.5 T and the valley field is 2.45 T. The spiral angle increases from zero in the center to 66° at extraction radius. The RF frequency is 86 MHz, on the fourth harmonic mode. The RF cavity is almost exactly a scaled up version of the cavity of the 235 MeV proton cyclotron. The azimuthal length of dee is 35 degrees and nominal dee voltage is 200 kV. Dee voltage varies with radius to maximize kinetic energy gain per turn in the extraction region. The outside diameter is only 5.88 meter, in contrast with 4.7 m for the current 230 MeV proton cyclotron. The magnet height is 3.2 m and the mass of the steel is about 656 Tons. An artist view of the cyclotron is presented on Figure 7.

The super-conducting coils have a relatively modest current density. The super-conducting wire, based on Nb-Ti filaments has a large copper to superconductor ratio, resulting in a cryo-stable design. The coil operates at 4.2 K in a helium bath. Like in the latest super-conducting cyclotrons, the helium evaporated in the super-conducting coils in re-liquefied by a set of five cryo-generators located in a re-liquefaction reservoir adjacent to the coils

Two or three external ions sources are mounted on a switching magnet on top of the cyclotron. The C^{6+} are produced by a high performance ECR source provided by Pantechnik (Caen, France). The alphas are also produced by a small ECR source, while the H_2^+ are produced by a multicusp ion source. In order to allow a quick change between ion species, all three ion sources are kept in operation. The selection of the beam is made by the switching magnet also placed on top of the axial injection line. All species have a Q/M ratio of 1/2 and all ion sources are at the same potential, so that only a small retuning of the frequency is needed to switch from H_2^+ to alphas or to C^{6+}. We expect that the time to switch species can be not more than two minutes, the same as the time needed to retune the beam transport line between different treatment rooms. The beam is injected in the cyclotron by a quite classical axial injection line with a pseudo-cylindrical spiral inflector.

The extraction uses an electrostatic deflector and gradient corrector quite similar to the deflector used in the PT cyclotron. In addition, extraction by stripping of the H_2^+ could be considered to get protons of kinetic energy lower than 300 MeV/u.

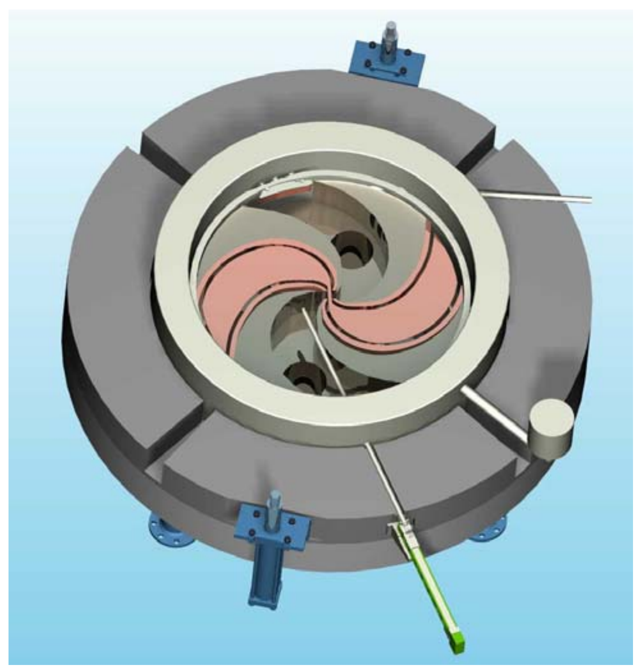

Figure 7. Artist view of the median plane in Carbon-proton, 300 MeV/u, super-conducting cyclotron.

110 MEV, H^- AND H^+ HIGH CURRENT CYCLOTRON FOR TRADE

This cyclotron was design for the ENEA in Italy (prof. Carlo Rubbia). The proton beam of this cyclotron was foreseen to drive-in sub critical mode a low power (2 MW thermal power) TRIGA reactor of the ENEA located in

Casaccia (Italy). TRADE stands for TRiga Accelerator Driven Experiment. The TRADE experiment is funded by the EC, but the needed cyclotron will be purchased by the ENEA.

For this cyclotron, the requirements were: a beam of extracted protons (H^+) having kinetic energy of 110 MeV, the beam current of 2 mA. A beam will be extracted also as H^- to be injected by stripping in a booster synchrotron.

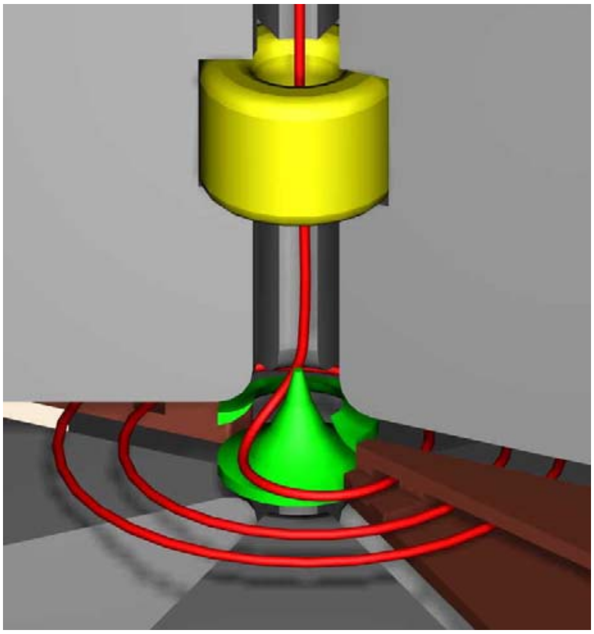

Figure 8. View of a magnetostatic inflector with symmetry of revolution in the end of axial injection line.

IBA proposed an H^- negative ion cyclotron, where the beam could be extracted either by self-extraction or by stripping. The original aspect of this design is that the sectors are not circular, but the outside border of the sectors follows the trajectory of the beam. To reach 2 mA, and to overcome space charge limits in the axial injection, the bias of the source is increased to 60 kV. To avoid problems of arcing in the inflector, the concept of a magnetostatic inflector with symmetry of revolution was developed. The Figure 8 presents this concept.

In the self-extraction mode, the beam separator was replaced by stripper foil, in such a way that the beam not properly extracted by self-extraction was extracted by stripping. In this way a true 100% extraction efficiency is always achieved.

CONCLUSIONS

- Since 1986, IBA is a key player in the development of not only cyclotrons but also several other types of industrial accelerators.
- The IBA self-extracting cyclotron now has become a reality as an industrial high current machine for isotope production.
- During the last 15 years IBA has accumulated a large amount of experience in the field of proton therapy and was able to obtain the CE-clearance (Europe) and FDA-approval (USA) for its equipment
- With the proposed new concepts for hadron therapy and the Trade-experiment, IBA wants to continue its efforts towards future developments in the field of cyclotrons

REFERENCES

[1] W. Kleeven, S. Lucas et.al., “The IBA self-extracting cyclotron project ” , Proceedings of the XXXIII European Cyclotron Progress Meeting, ECPM2002, NUKLEONIKA 48, supplement 2 (2003)59-67.