SELF-EXTRACTION IN A COMPACT HIGH-INTENSITY H^+ CYCLOTRON AT IBA

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Abstract

At IBA a compact 14 MeV H^+ cyclotron is under construction. A special feature of this cyclotron is that there is no electrical deflector installed, i.e. the beam is self-extracted. This is achieved by a special shaping of the magnetic field, which shows a very steep fall-off near the outer radius of the pole and at the same time a strong first harmonic component in the extraction region. The steep fall-off is obtained with a small quasi-elliptical pole gap and the machining of a groove in one of the poles. The strong first harmonic is obtained with permanent magnet field bumps placed in two opposite valleys. Results of Tosca simulations, field mapping and tracking are presented.

1 INTRODUCTION

In 1995 IBA proposed a new method to extract positive ions from a cyclotron without the use of an electrostatic deflector[1]. The method is based on a very fast transition of the average magnetic field near the pole radius from the internal isochronous region to the region where the field index is smaller than -1 and the bending strength of the field is too low to keep the beam in the machine. Self-extraction of particles was already experimentally observed on the IBA 230 MeV proton-therapy cyclotron, where there was some beam intensity present in the extracted beam line even when the deflector was removed from the machine. Encouraged by these experiences and their agreement with computer simulations of the self-extraction principle, IBA started in 1998 the construction of a high intensity self-extraction cyclotron. For this prototype, an energy of 14 MeV was selected for the following reasons: i) 14 MeV is a preferred energy for the production of the commercially important radioisotope ^{103}Pd, ii) the proposed extraction method requires a large turn separation at extraction which is easier to achieve at lower energies, iii) its small investment presents a small financial risk.

2 REALIZATION

The new design is illustrated in Fig. 1 and in Fig. 3. There are several unconventional features:

i) the hill gap has a quasi-elliptical shape, decreasing from 36 mm in the center to 15 mm at extraction. This allows to create an average magnetic field which remains isochronous even very close to the pole radius.;

ii) the sector that guides the extracted beam and (for symmetry reasons) also the opposite sector have an extended radius;

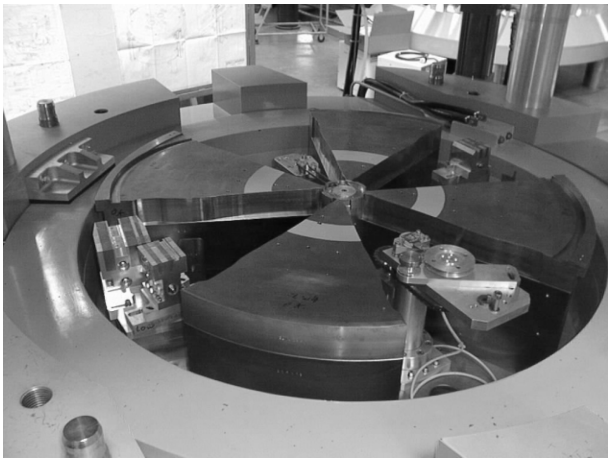

Figure 1: The self-extraction cyclotron.

iii) in this extended pole a groove is machined along the extracted orbit creating a sharp dip in the magnetic field and the desired region where the field index is smaller than -1 as is illustrated in Fig. 2. The groove is deep and narrow at the entrance of the sector, giving a strong separation gradient between the last internal turn and the extracted beam. It is shallow and wide at the exit of the sector. In this way a too large magnetic sextupole and an unnecessarily large increase of emittance is avoided. The plateau has a small gap at the entrance and a big gap at the exit. Fig. 4 shows a Tosca simulation of such an optimized extraction path;

iv) the presence of two opposed Sm-Co harmonic kickers located at an azimuth of $\pm 90^\circ$ with respect to the entrance of the groove. The last internal orbit is moved by these kickers from the limit of the isochronous region into the

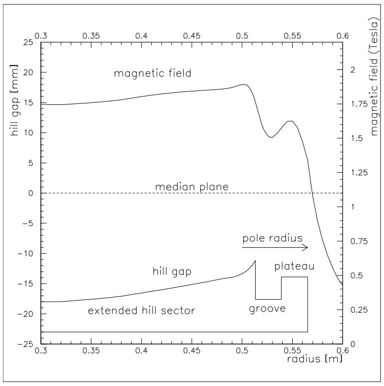

Figure 2: Radial magnetic field profile in the groove.

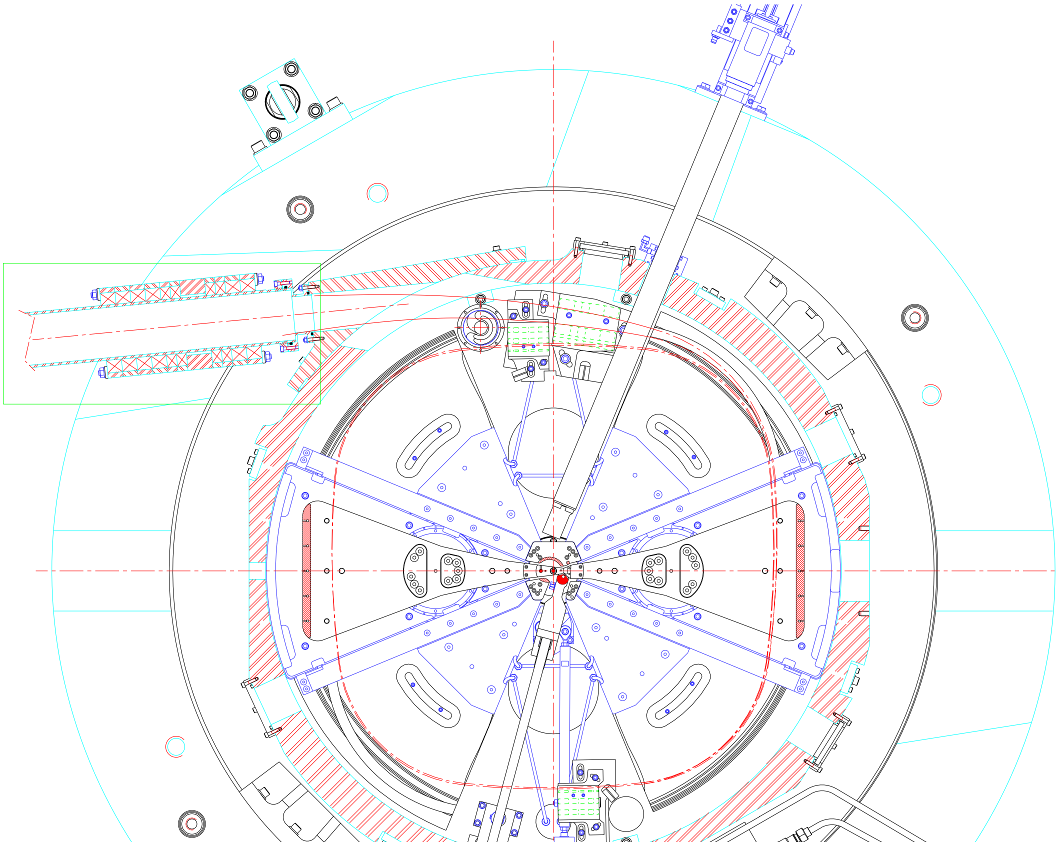

Figure 3: Median plane view of the self-extraction cyclotron.

field dip at the entrance of the groove. The magnetic layout is illustrated in Fig. 5. One pair of large permanent magnets is used to create a field bump. The second opposite pair is used to roughly cancel the strong perturbation of the first pair on the internal orbits. This compensation is fine-tuned with a third pair of small permanent magnets allowing for a field shape with a small tail (< 20 Gauss) and a sharp rising gradient (> 1 kG/cm).

The extraction of the beam can be fine-tuned with two pairs of first harmonic centering coils that are placed at a radius of 21.0 cm. The geometry of these coils has been optimized in order to produce a 200 Gauss field bump with a narrow radial width (FWHM=32 mm).

After exiting from the groove the beam is still slightly diverging and therefore a Sm-Co gradient corrector is placed immediately after this exit. The magnetic layout of this element is the same as that of the kickers but the dimensions are different. However, in this case the linear field curve in between the two larger pairs of permanent magnets is used. When passing the return yoke the beam is again refocused by a doublet of permanent magnet quadrupoles. The external beam will contain a sextupole magnet in order to further correct the beam emittance if required.

The extraction principle allows for multi-turn extraction. Of course, some particles will fall in between the inner limit of the extracted beam and the outer limit of the internal beam. This beam loss is catched by a special beam dump that is located at this azimuth where the power density of the beam is low. The beam dump is optimized to minimize the activation and maximize the allowable power dissipation.

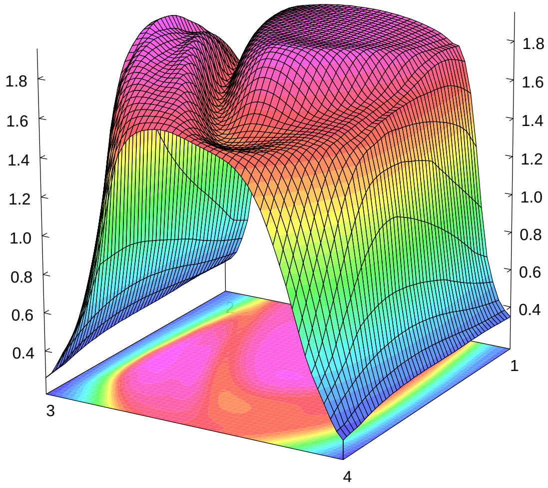

Figure 4: Tosca histogram of the groove and plateau magnetic field shape.

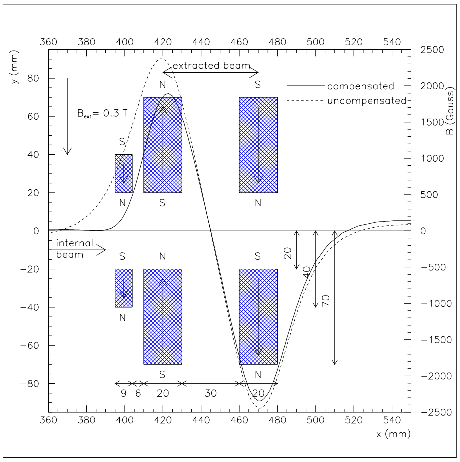

Figure 5: Magnetic field profile of the gradient corrector. The same layout but different dimensions are used for the kickers.

3 SIMULATIONS

The magnet was analyzed with the TOSCA computer code from Vector Fields. Several iterations were needed to find the optimum geometry of critical features such as i) the gap profile in the long poles and in the short poles (which are different), ii) the difference in length between these two types of poles, iii) the groove and the plateau iv) the pole edge angles needed to obtain isochronism and to minimize first and second harmonic field errors. This magnet optimization was only possible by using a fully parameterized generator of the Tosca input file (pre-processor), which is produced by a separate C-program. Full 360 degree models of the magnet were calculated with a total of about 300.000 nodes.

Closed orbit analyses were done with in house developed codes in order to find the isochronous errors and tune functions of Tosca generated field maps. After complete isochronization of a Tosca model, orbit tracking was used to find the properties of the extracted beam. As a measure for optimization, the horizontal phase space in the center of the machine which is accepted and extracted by the cyclotron is calculated. For this purpose, a very large emittance (1000π mm-mrad) is started at 1 MeV and tracked through the machine. An example is shown in Fig. 6. This is a tracking of 1500 particles which all have the same RF phase. In the phase space, islands with an area of more than 100π mm-mrad can be distinguished which are fully (100%) extracted. We then start a new emittance of about 100π mm-mrad which is centered on the largest island but now contains a real distribution of RF phases from for instance $-25°$ to $+25°$. This gives a good idea of the extraction efficiency which is estimated to be larger than 85%. Fig. 7 shows the cross section of the beam just before it leaves the vacuum chamber. The horiontal emittance of the extracted beam is estimated at 200π mm-mrad.

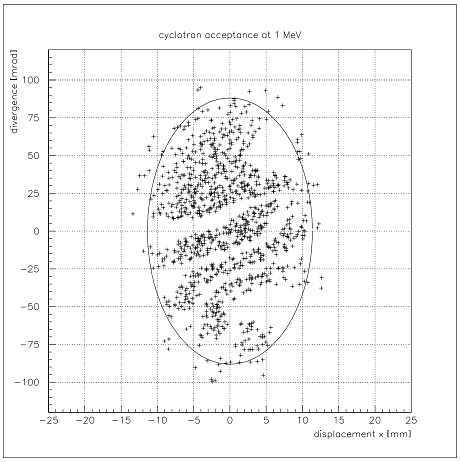

Figure 6: Cyclotron acceptance at 1 MeV

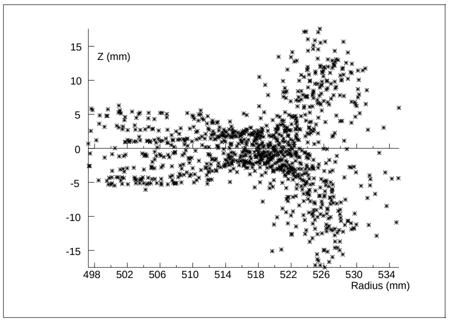

Figure 7: Cross section of the extracted beam.

4 MAPPING AND SHIMMING

The cyclotron is presently being mapped and shimmed. A computer controlled mapping system has been developed that allows for continuous positioning of a hall-probe in azimuthal as well as radial direction. The purpose of the shimming is to isochronize the machine, but also to remove the first and second harmonic field errors. Shimming is done by cutting the pole edges of the removable pole tips (vertical height about 8 cm). This procedure has already been succesfully completed for a first set of pole tips and is now being done for a second set which has an improved groove geometry. A software simulation has been developed which allows a fast convergence of the shimming process. This software is based on Tosca simulations of pole shimming and therefore effectively takes into account the re-distribution of magnetic flux that occurs when pole material is removed.

REFERENCES

[1] Y. Jongen, D. Vandeplassche, P. Cohilis ”High Intensity Cyclotrons for Radioisotope Production, or the Comeback of the Positive Ions’, Proc. 14th Int. Conf. on Cyclotrons and their Applications, Cape Town, South Africa, 1995, World Scientific Publisher, pp. 115-119.