THE SELF-EXTRACTING CYCLOTRON

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Abstract

At IBA a compact 14 MeV H+ cyclotron has been constructed. A special feature of this cyclotron is that there is no electrical deflector installed, i.e. the beam is self-extracted. The goal is to obtain high beam currents with good extraction efficiency without the need of single turn extraction. This is achieved with two ingredients: i) a special shaping of the magnetic field, showing a very steep fall-off near the outer radius of the pole and ii) the creation of a large turn-separation on the last turn. The pole gap has a quasi-elliptical shape, allowing for the steep fall-off of the magnetic field by the machining of a groove in one of the poles at a radius where the gap is small. The large turn separation is obtained by either the use of harmonic coils or by permanent magnet field bumps placed in two opposite valleys. Both methods have been tested and give good results with an extraction efficiency of 80 %. The concept and layout of the machine is explained. The status of the project is outlined. First results of beam tests are presented. The cyclotron is intended for medical isotope production at multi-mAbeam intensity.

1 INTRODUCTION

Many radioisotopes used in nuclear medicine are produced by cyclotrons. Amongthem are the more classical radioisotopes such as Thallium-201, Gallium-67, Indium-111 and Iodine-123 as used for diagnostic purposes and also the isotopes used for cancer treatment such as Paladium-103.

Commercial cyclotrons used for the production of radioisotopes have steadily improved through the years. The first cyclotrons were ”classical” positive ion machines where the beam is either extracted by an electrostatic deflector (ESD) at a current of about 100 μA or an internal target is used with several hundred μA deposited on it. The Cyclotron Corporation (TCC) produced more than 30 of these kind of machines. A major step was made with the introduction of the negative ion technology and the extraction by stripping as realized in the CP42 from TCC. The ESD limit on beam power was broken and extracted current exceeding 200 μA at 40 MeV were available. A next major step was made with the introduction of the CYCLONE 30 from IBA. This machine incorporates two major improvements: i) the use of an external multicusp ion source for the production of the H^-, thereby strongly improving the vacuum in the machine and avoiding the related significant beam loss due to rest gas stripping as observed in the CP42 and ii) the introduction of the deep valley principle that significantly improves the power efficiency of the accelerator.

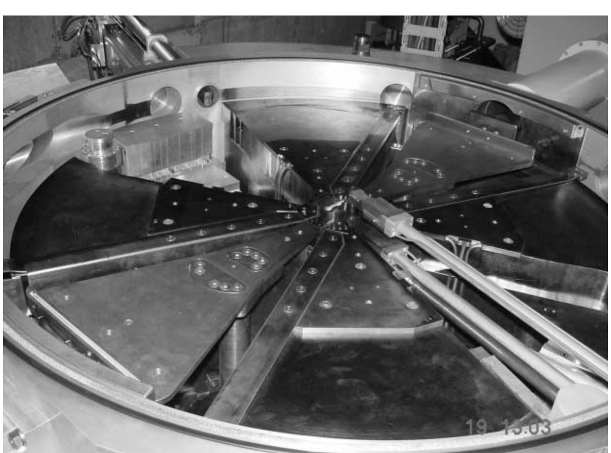

Figure 1: The self-extracting cyclotron

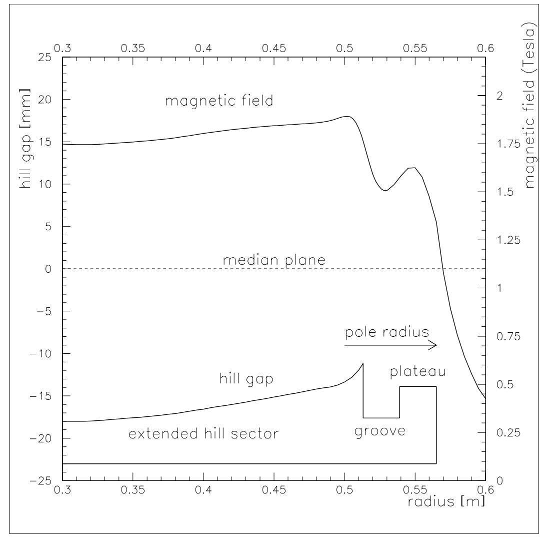

Figure 2: Magnetic field profile in the middle of the extended hill showing the field-dip produced by the groove

In 1995 IBA proposed a new method to extract positive ions from a cyclotron without the use of an electrostatic deflector[1]. It relies 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 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-extracting

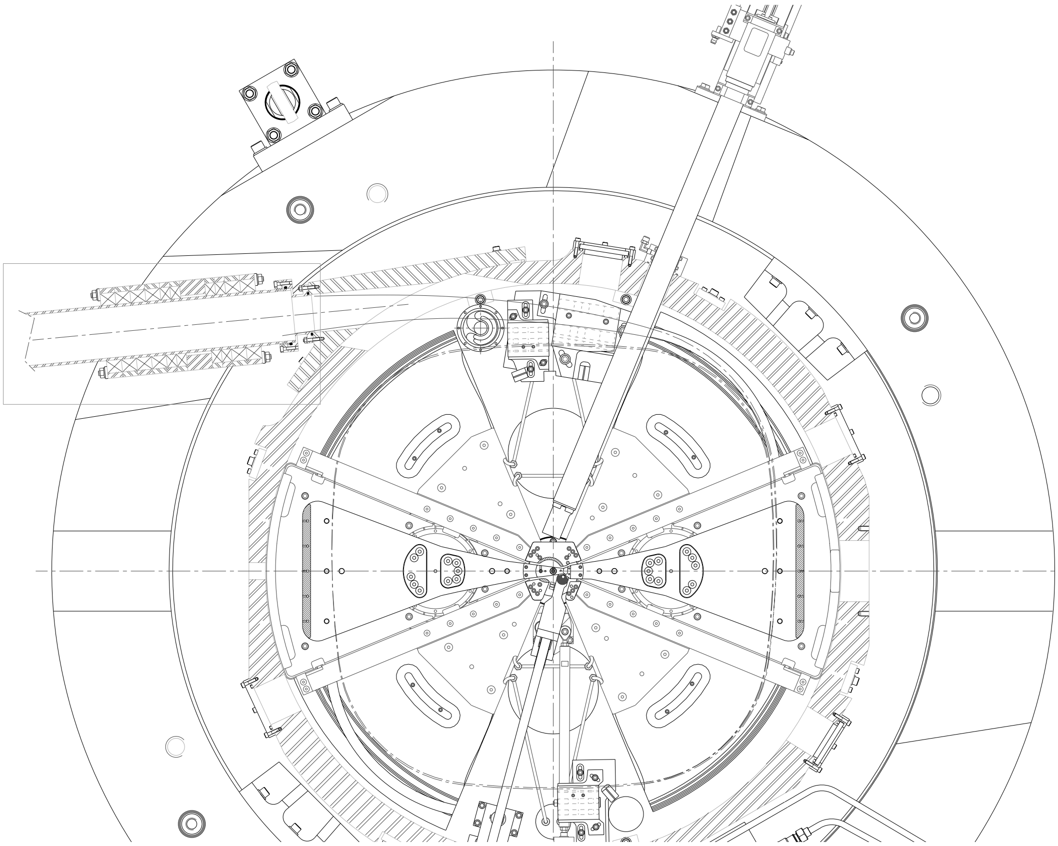

Figure 3: Median plane view of the self-extracting cyclotron

cyclotron[2, 3]. In a parallel paper[4], results of the magnetic field calculations and shimming are given 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 CONCEPT AND REALIZATION

The new design is illustrated in figures 1 and 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 radial edge;

ii) the hill–sector that guides the extracted beam and, for symmetry, also the opposite hill–sector have an extended radius;

iii) in this extended hill–sector a groove is machined along the extracted orbit, creating a sharp dip in the magnetic field (see figure 2): a region where the field index is smaller than -1, as requested. The groove is deep and narrow at the entrance of the sector, giving a strong separation gradient (septum action) 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 (figure 2) has a small gap at the entrance and a big gap at the exit. Figure 4 shows a TOSCA simulation of the magnetic field shape in the extraction path; here the entrance of the groove is located at the corner 2 and the exit at corner 4.

The extraction of the beam is obtained by creating a

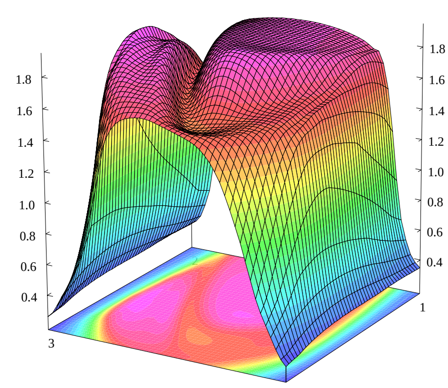

Figure 4: TOSCA histogram of the groove and plateau magnetic field shape

turn–separation at the entrance of the groove. Two different ways have been investigated for this:

a) the installation of two Sm-Co harmonic kickers at angles of $\pm 90°$ 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 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).

b) the use of two pairs of harmonic coils placed at a radius of 21.0 cm.

It is not trivial to produce a substantial beam displacement with harmonic coils: their radial position and their shape should be optimized for this purpose. The total betatron phase advance of the beam, when passing the first harmonic region should not be bigger than about $180\,°$. This leads to an optimum radial width of the first harmonic field profile (expressed in the number of turns made within two sigma of its gaussian profile) given by[5]

$$\Delta n_{opt} = \frac{1}{\pi(\nu_r - 1)} \tag{1}$$

The efficiency of the harmonic coils is increased by giving them a banana-like shape as shown in figure 3. The coils were optimized with TOSCA in order to produce a 200 Gauss field bump (at 3 Amps) with a narrow radial width (FWHM=32 mm). These properties have been confirmed by field mapping as shown in figure 6. An estimated orbit displacement of 10 mm can be produced with this.

After exiting 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. The kickers have a gap of 25 mm and a length along the beam direction of 80 mm. For the gradient corrector, these values are 40 mm and 60 mm respectively. Both systems can be positioned with two degrees of freedom in the machine. They were modelled with TOSCA in order to optimize the kicking gradient and the focusing gradient respectively. Excellent agreement was found between these calculations and the results of field measurements[4].

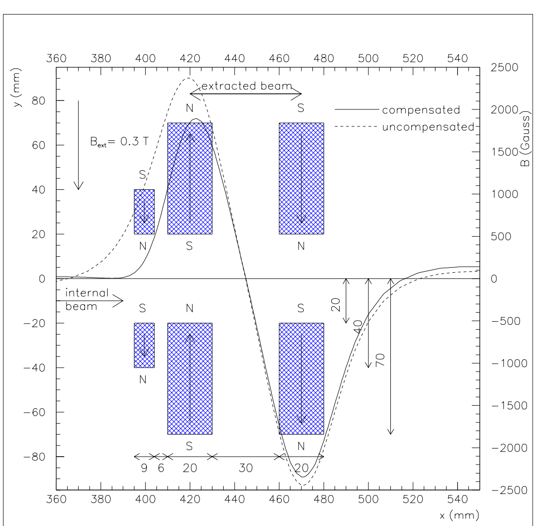

Figure 5: Field of the gradient corrector. The same layout but other dimensions are used for the kickers

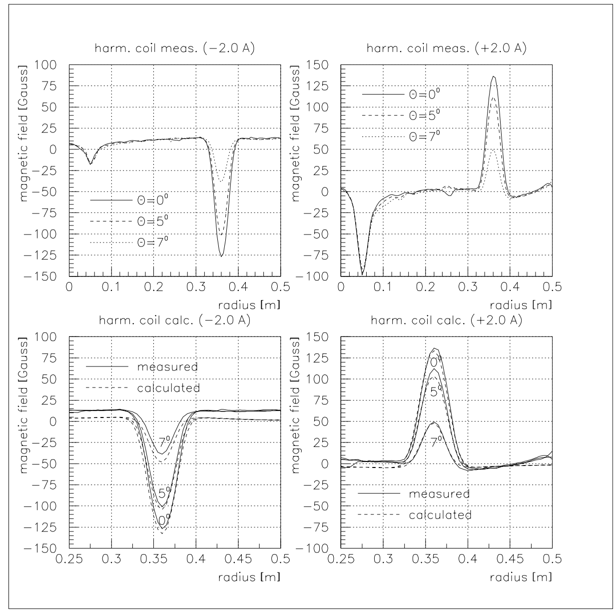

Figure 6: Comparisson of measurements and calculations of the harmonic coils

When passing the return yoke the beam is again refocused by a doublet of permanent magnet quadrupoles. These are built up of layers of 2.0 cm and 3.0 cm thick. In this way the total length of a quadrupole can be varied with

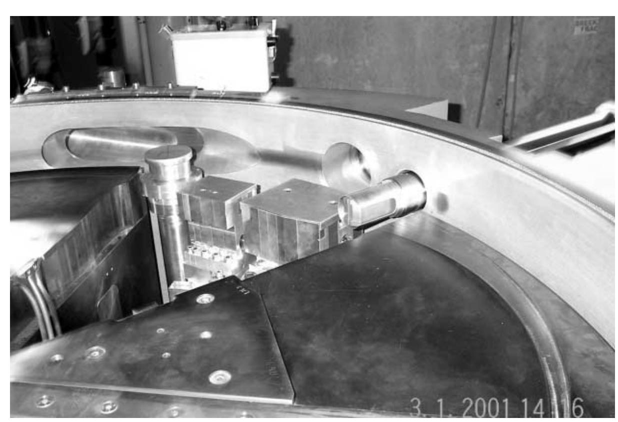

Figure 7: View of evolved shape of the groove, the radial probe, the gradient corrector, the harmonic kicker, the beam separator and the exit port in the vacuum chamber. The harmoic coils are placed under the pole covers.

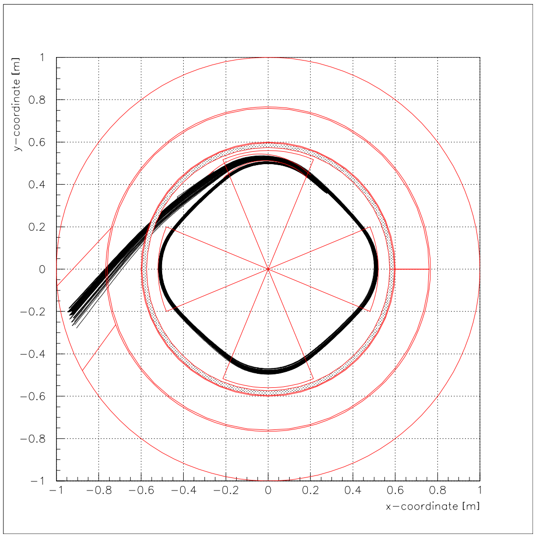

Figure 8: Simulation of the extracted beam

a step of 1.0 cm.

The extraction principle allows for multi-turn extraction. Of course, some particles 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 an azimuth where the power density of the beam is low. This beam separator is optimized to minimize the activation (aluminium construction and stopping most part of the beam in the cooling water) and maximize the allowable power dissipation (by maximizing the velocity of the cooling water at the surface). Figure 7 shows the placement of the gradient corrector, harmonic kicker and beam separator (catcher) in the machine.

Extensive calculations have been carried out in order to verify the different concepts. As an example, figure 8 shows the simulation of the extracted beam in the measured magnetic field.

3 SOME RESULTS OF BEAM TESTS

First beam was extracted from the cyclotron in december 2000. Figure 9 shows the beam-induced illumination of an aluminium-oxide disc placed on the exit port of the cyclotron. Since then, parameters have been optimized and an extraction efficiency of 80% has been obtained for the first configuration where the harmonic kickers are used, as well as for the second configuration where only harmonic coils are used. We prefer the second configuration because it is simpler and also seems to give a better extracted beam quality.

Figure 10 shows a radial track of the differential probe with the following signals: the differential and integral currents on the probe, the current on the beam separator, the extracted current (measured on a flange placed on the exit window of the vacuum chamber) and the total of these four signals. The differential shows the large turn separation between the last internal orbit and the extracted orbit at the exit of the groove. The most inner part of this extracted beam hits the beam separator with a uniform distribution. The rest is extracted. The total current decreases between the ion source and a radius of 300 mm due to vertical losses (the vertical gap in the center is only 6 mm) but then becomes more or less constant. The inner losses are not very important, because they do not activate the machine.The losses beyond r=30 cm are less than 2%. About 18% of the beam hits the beam seperator and the rest is extracted.

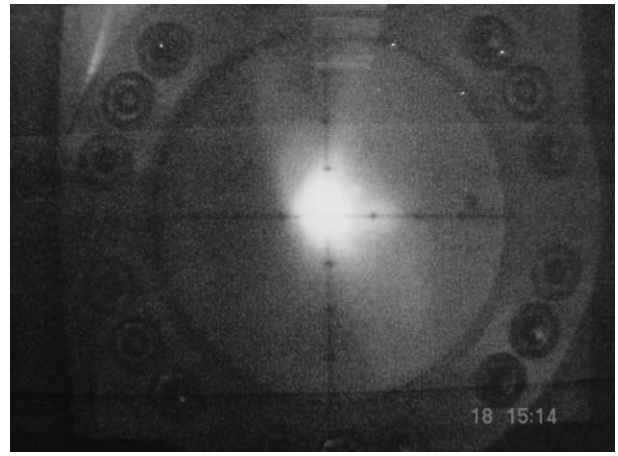

Figure 9: The extracted beam observed on the exit port of the cyclotron vacuum chamber

Different ion source vs puller geometries were tested in order to optimize the current extracted from the source. Figure 11 shows the beam current on a pop-up probe placed on the 2nd turn (300 keV) as a function of the arc. A beam current of 13 mA has been extracted. In order to find the position of the beam in the central region, thin paper foils were placed at several positions and then burned by the beam. The result of this is shown in figure 12 Here the

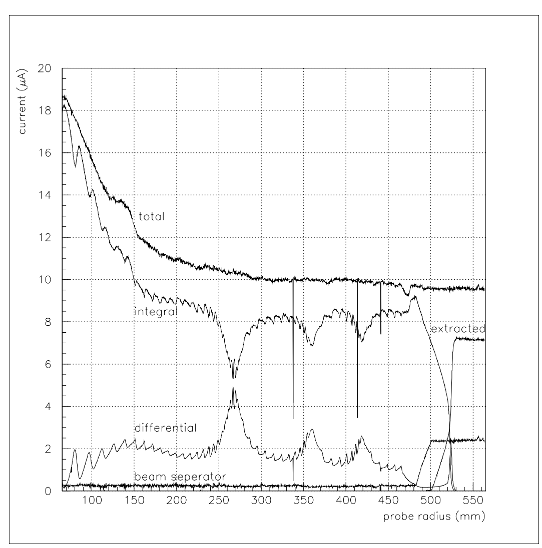

Figure 10: differential probe scan

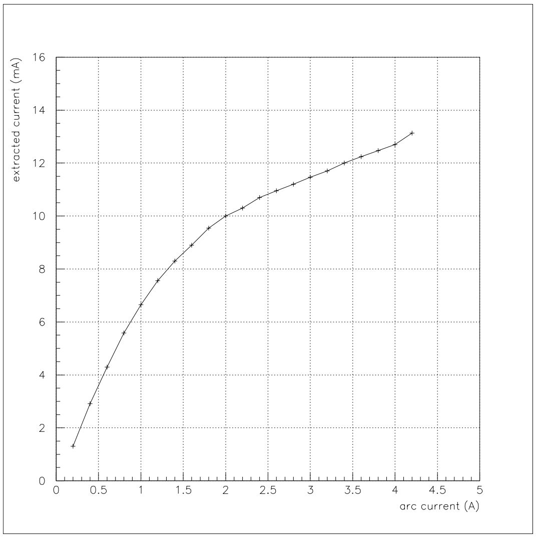

Figure 11: Source output current

width of the spot shown in the figure actually represents the height of the beam. At the azimuth of 270°, two beam spots are shown: the left spot was obtained after placing a phase slit on the first turn at an angle of 180° downstream of the ion source. This experiment was done in order to improve the resolution of the radial probe scans. During real use of the cyclotron, there will be no slits installed.

The beam has now been transported into a four meter long beam line that contains a horizontally focusing permanent magnet quadrupole, an xy–steering magnet, a Faraday cup, drum collimators, scanning wire bpm's, an electric quadrupole doublet and a sextupole magnet. After optimizing the length of the gradient corrector and the permanent magnet quad and good alignment of the beam line, almost 100% beam transmission is obtained. Figure 13 shows the vertical beam profile measured in this beam line. The FWHM is about 30 mm. An initial estimation of the beam emittances gives about 225 π mmmrad for the horizontal and 75 π mmmrad for the vertical.

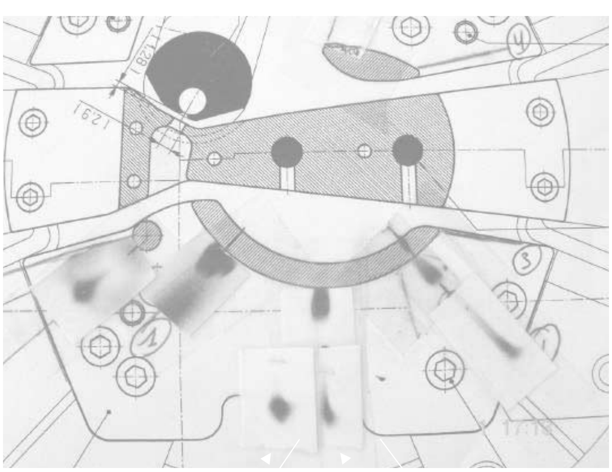

Figure 12: Beam spots in the central region

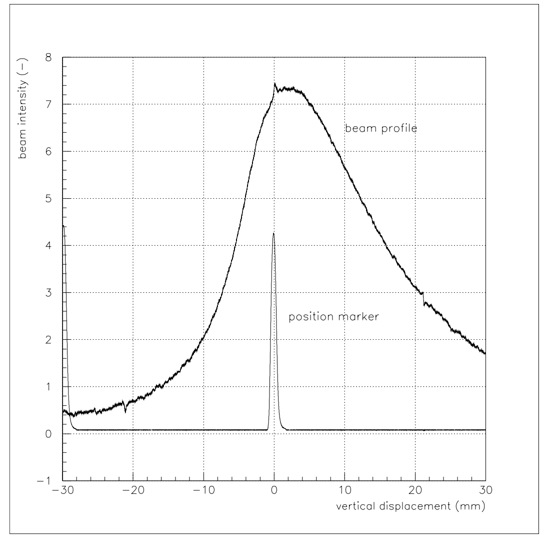

Figure 13: Vertical beam profile

4 CONCLUSION

The concept of a self-extracting cyclotron has been demonstrated. An extraction efficiency of 80 % is obtained for two independent realizations. The extracted beam can be transported to a production target in a relative simple beam line. So far, the beam tests were limited to low intensities (10 μA) in order to avoid activation, but intensities will be increased in the near future. Due to the multi-turn extraction scheme, where large RF phase width is accepted, the longitudinal beam density is relatively low as compared for example to the PSI injector, and therefore longitudinal space charge is not expected to be so important.

5 REFERENCES

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