NUKLEONIKA 2003;48(Supplement 2):S59–S67

PROCEEDINGS

The IBA self-extracting cyclotron project

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Abstract The self-extracting cyclotron is a high-intensity 14 MeV H^+ machine for isotope production. 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 a large orbit separation at the entrance of the extraction path and extract the beam. The machine is presently installed in the industrial isotope production site where the final commissioning and tests took place. Beams of more than 1.5 mA have been extracted and transported. Further development is ongoing in order to increase the current on target to at least 2 mA in the coming months. Commercial isotope production will start in the course of this year. The concept of the machine is explained and the layout of the machine and beam lines is presented. Results of orbit calculations and central region optimizations are given. Results of the measurement of extracted beam shapes and emittances are given. The progress and present status of the project are discussed.

Key words cyclotron • extraction • radioisotopes

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Received: 26 November 2002

Introduction

In 1995, IBA proposed a 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 cyclotron [3, 5, 6].

Basic magnetic design

The design as illustrated in Fig. 1, has 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: a region where the field index is smaller than –1,

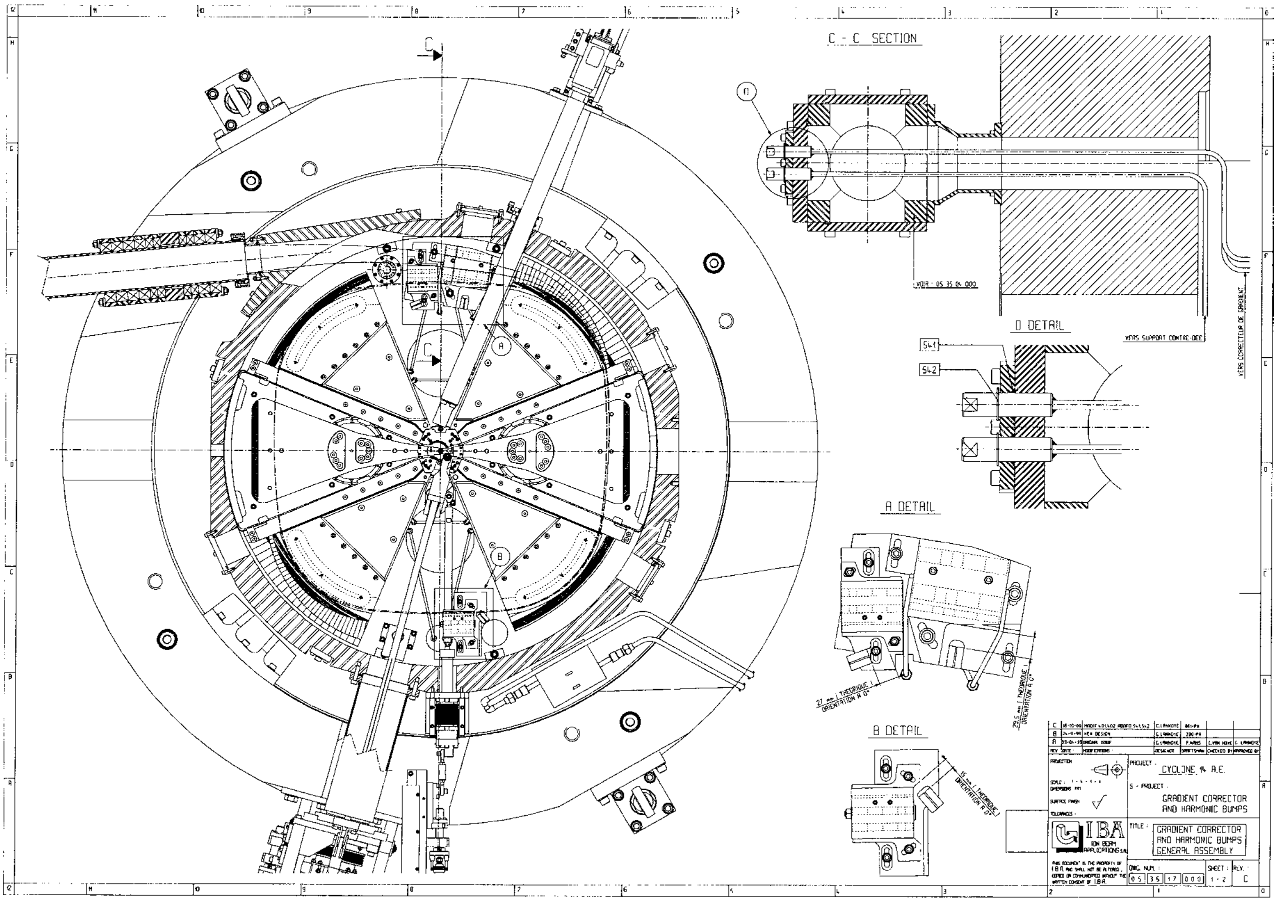

Fig. 1. Median plane drawing of the self-extracting cyclotron.

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.

The extraction of the beam is obtained by creating a turn-separation at the entrance of the groove. Two different ways have been investigated for this:

i) the use of harmonic extraction coils (precessional extraction) and
ii) the use of two Sm-Co harmonic kickers (brute force extraction).

Both methods give similar extraction efficiencies (more than 75% in both cases). However, with the permanent kickers, there was some vertical beam loss during the extraction of a few percent. This beam loss was smaller or even absent with the harmonic coils. Furthermore, the use of the coils allows for fine tuning which is not possible with the kickers. Therefore, the kickers have been removed from the machine. However, we think that for future new self-extracting cyclotrons, this brute force extraction concept could still be valuable.

A permanent magnet gradient corrector at the groove exit matches the beam phase space to the beam line. When passing the return yoke the beam is horizontally focused by a permanent magnet quadrupole. It is built up of layers of 2.0 cm and 3.0 cm thick allowing the total length of a quadrupole to be varied with 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. A special beam dump that is located at an azimuth where the power density of the beam is low catches this beam loss. This beam separator is optimized to minimize the activation (a 100 μm thick tantalum foil; most part of the beam is stopped in the cooling water) and maximize the allowable power dissipation (by maximizing the velocity of the cooling water at the surface). Figure 2 shows the long pole with the groove and also the placement of the

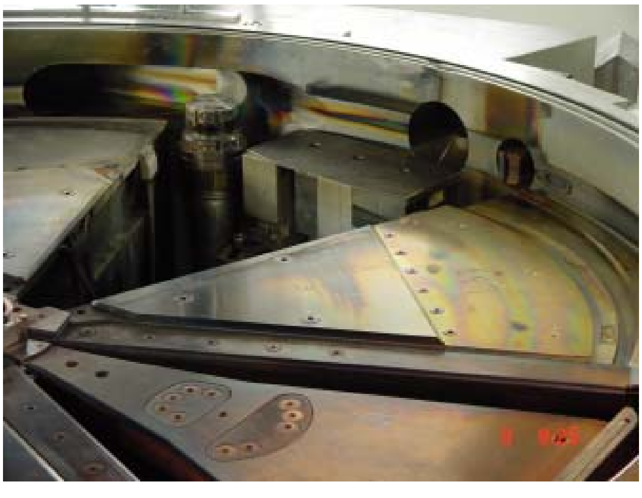

Fig. 2. The extraction path in the cyclotron, with the groove in the long pole, the gradient corrector, the beam separator and the vacuum exit port. The harmonic coils are placed underneath the aluminum outer pole covers.

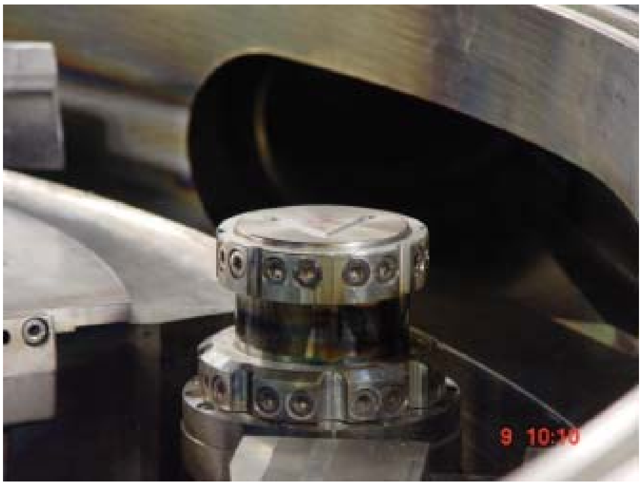

Fig. 3. The beam separator placed in the cyclotron.

gradient corrector and beam separator (catcher) in the machine. Figure 3 shows a close-up of the beam separator. A detailed account of the magnetic field calculation, mapping and shimming has been given in [4].

Harmonic coils

The harmonic coils create a coherent oscillation of the beam and an increased turn separation at the entrance of the extraction groove. The oscillation amplitude A as produced when a beam is smoothly accelerated through a first harmonic region with a Gaussian radial distribution has been calculated in Ref. [2]

$$A = \pi \sqrt{\frac{\pi}{2} r_0 C_1 \Delta n \exp\left(-\frac{\pi^2 \left(\nu_r - 1\right)^2 \Delta n^2}{2} \right)}. \tag{1}$$

Here, r_0 is the radial position of the center of the Gauss and C_1 its amplitude; ν_r is the radial betatron frequency at r_0 and Δn is the number of turns that the beam makes within the Gaussian profile (radial width of 2σ). There is an optimum width of the Gaussian curve, given by

$$\Delta n_{\text{opt}} = \frac{1}{\pi\left(\nu_r - 1\right)}. \tag{2}$$

This optimum number of turns corresponds exactly with a betatron phase advance of 180°. During these 180°, the kicks that the beam receives keep working in such a direction that the oscillation amplitude increases. Beyond this point, the oscillation becomes out of phase with the phase of the first harmonic and the amplitude which was built up before, is getting lost again.

The oscillation as created by the coils must remain coherent upto extraction. There may be several causes by which the coherency is lost:

i) longitudinal space charge effects;
ii) ripple of the dee-voltage;
iii) a large RF phase width of the beam.

Fig. 4. The harmonic extraction coil.

It is, therefore, important to place the coils as close as possible to the extraction region. On the other hand, near extraction it becomes more and more difficult to meet the criteria of Eq. (2) because (ν_r – 1) is rather big (the coils cannot be placed on the resonance due to vertical gap limitation) and the turn pattern becomes more and more compact. In order to minimize the number of turns within the radial distribution of the coils, the shape of the coils follow precisely the shape of the equilibrium orbit. Because of the intrinsic 2-fold symmetry of the machine, the shape of the equilibrium orbits on the short and long sectors are not the same. For that reason there are two types of harmonic coils, one pair for the short sectors and one pair for the long sectors.

The harmonic coils have a radial extend of 50 mm, an azimuthal extend of 50 degrees (with respect to the center of the coil) and a height of 5.0 mm. There are 75 turns per coil and they are operated at a maximum current of 3 A per coil. They are placed at a radius of 46 cm which is about 10 turns before extraction. Figure 4 shows a photograph of the harmonic coil. Figure 5 shows the radial magnetic field profile for a few azimuth as obtained with an OPERA3D simulation. The full width at 1/*e* of the maximum is only 28 mm.

In order to verify the oscillation amplitude created by the coils, two orbits were calculated: the first with the harmonic coils off and the second with the harmonic coils on at full current. The oscillation amplitude was estimated by comparing the off-centering of the second orbit with

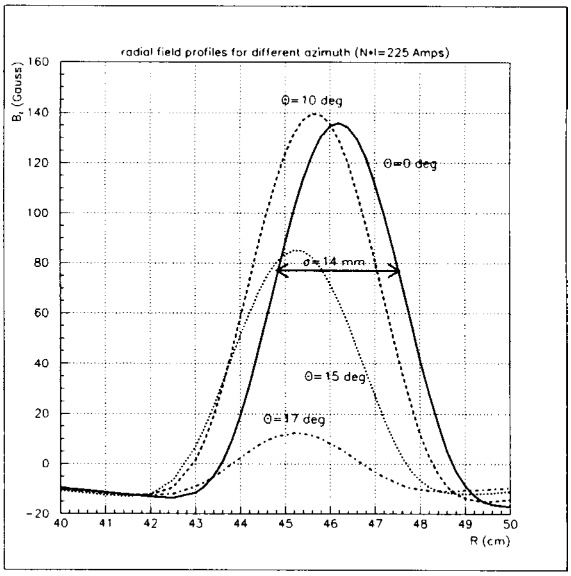

Fig. 5. Radial magnetic field profiles created by the harmonic coils at a few azimuth.

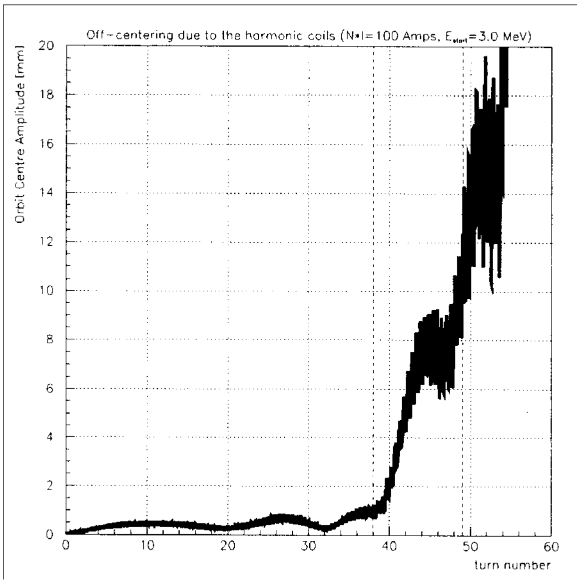

Fig. 6. Orbit simulation of the coherent oscillation amplitude produced by the harmonic coils.

respect to the first. The result is shown in Fig. 6. An oscillation amplitude of about 15 mm can be created.

Gradient corrector

The beam which exits from the cyclotron is horizontally as well as vertically diverging. A magnetic gradient corrector is placed in the valley behind the groove in order to adapt the beam phase space to the external beam line. A side effect of it is an increase of extraction efficiency with at least 5%. The gradient corrector is made of Sm_2Co_{17} permanent magnets. The external magnetic field in the valley is low (less than 3500 Gauss) and, therefore, shielding of the magnets was not required. Due to this, disturbing fringe fields can be kept small. The magnetic layout is shown in Fig. 7 with dimensions in millimeters. The polarities are indicated by the labels ‘N’ and ‘S’ and the field directions by arrows. There is an open gap everywhere (no return yoke) and thus no interception of the continuous extracted beam distribution. The magnetic field as given in Fig. 7 was calculated with the Vector Field software. The quadrupole field shape is obtained with two opposed dipoles separated 50 mm from each other. A gradient of 2000 Gauss/cm is obtained with a vertical aperture of 40 mm. The additional small dipole on the inner side serves to reduce the fringe field at the internal beam in the cyclotron. Its effect is illustrated in Fig. 7 by the difference in solid line (corrected) and dashed line (not corrected): the stray field is reduced to values smaller than 20 Gauss. The gradient corrector is made of slices 15 mm and 30 mm thick which are stacked in order to obtain the required length. Figure 8 shows the gradient corrector in the cyclotron.

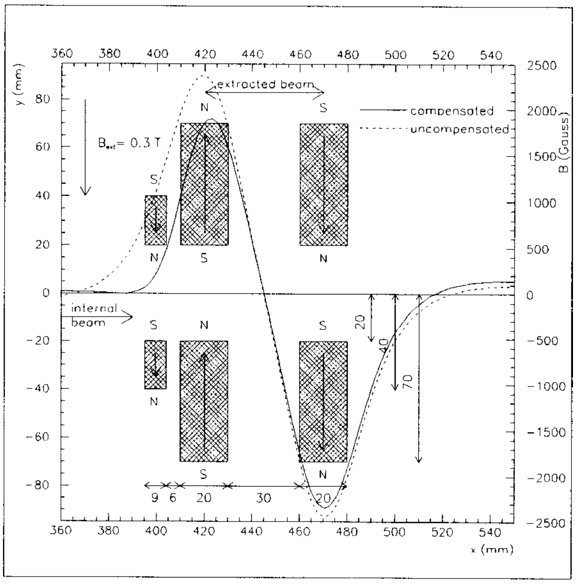

Fig. 7. Magnetic field profile of the gradient corrector.

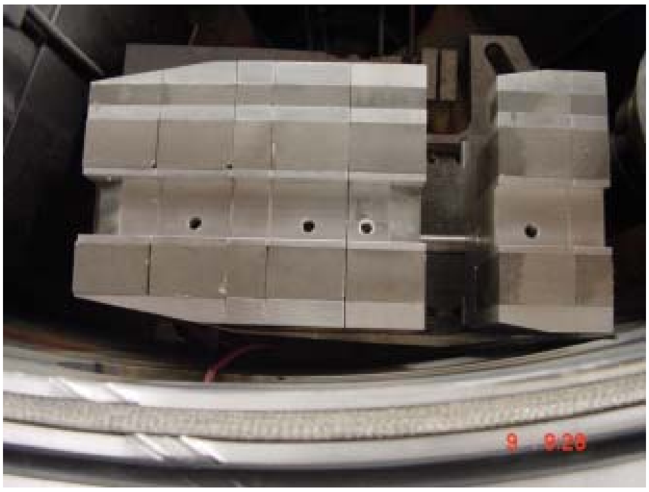

Fig. 8. The gradient corrector placed in a valley; it consists of a horizontally focusing part (13.5 cm long) and a vertically focusing part (4.5 cm long).

OPERA3D model of the central region and dees

The electric fields of the accelerating structure were calculated with the OPERA3D finite element software of VF (Vector Fields). This package offers a few advantages as compared to the more commonly used codes:

i) a separate module is available to create and modify the geometry;
ii) the mesh size can be locally adapted to the details of the geometry;
iii) a separate module is available to analyze, debug and visualize the results;
iv) electric field output maps can easily be adapted to the requirements for orbit integration.

A separate C-program was written that generates the input model for the OPERA3D package. This allows for parametrizing the geometry of the central region and the dee-structure and thus for fast modifications and optimizations. Essential features which were parameterized are for example:

i) the ion source (position, orientation and dimensions);
ii) ion source slit dimensions;
iii) the puller geometry;
iv) the position and orientation of the first six gap crossings;
v) the geometry of the dees and dummy dees;

vi) the vertical structure of the dees, dummy dees and central region.

A special feature of the model is that not only the central region but the complete dee-structure is calculated. This opens the possibility to integrate the orbits in one pass from the ion source upto extraction. This has been realized in the advanced orbit code as described in the next section.

Advanced orbit code

The design of the self-extracting cyclotron requires a relative complex optimization of beam properties such as extraction efficiency, extraction optics and beam transmission in the machine and also the integration of sub-sytems (central region, vertical collimator plates and extraction elements such as groove, beam separator, gradient corrector) of which the designs may be mutually dependent. A new advanced orbit code was written in order to realize this optimization. This code is a generalization and extension of already existing orbit codes at IBA.

The following issues were studied with the code:
i) optimization of the extraction efficiency using the harmonic coils;
ii) beam losses in the machine (high beam intensity in a small vertical gap);
iii) relation between central region design or beam collimation and extraction efficiency;
iv) size and positioning of the beam separator;
v) optimization of the extraction optics.

Some important new features of this orbit code are the following:
i) calculation and storage of a complete beam (multiple-particle code);
ii) adaptive step-size and error control for speed optimization;
iii) electric field representation in multiple 3D meshes located only there where needed;
iv) calculation from the source to extraction (medium energy machines) using realistic electric field maps;
v) free choice of interpolation order (electric as well as magnetic);
vi) detection of particle loss on the electrodes;
vii) fast table lookup in electric and magnetic field arrays (hunting technique);
viii) integration of 3D motion in polar coordinates;
ix) post-processing of a calculated beam.

The code is written in C-language. Under linux on a common personal computer (Dell Optiplex) it takes about 35 min to calculate a complete beam (1500 particles) from the source to the extraction (75 turns). Particles are stored in a binary file which can be re-read. This offers the possibility to re-process the orbits (for cases where electric and magnetic fields remain unchanged). Examples of post-processing options are:
i) output of individual particles;
ii) simulation of a radial probe scan;
iii) TRANSPORT-like analyses of subsets of the beam defined by initial RF phase bins including beam centroid and beam sigma matrix calculations;
iv) filtering of the beam by adding, removing or modifying beam collimators such as phase-selecting slits in the center, vertical collimators and beam separator.

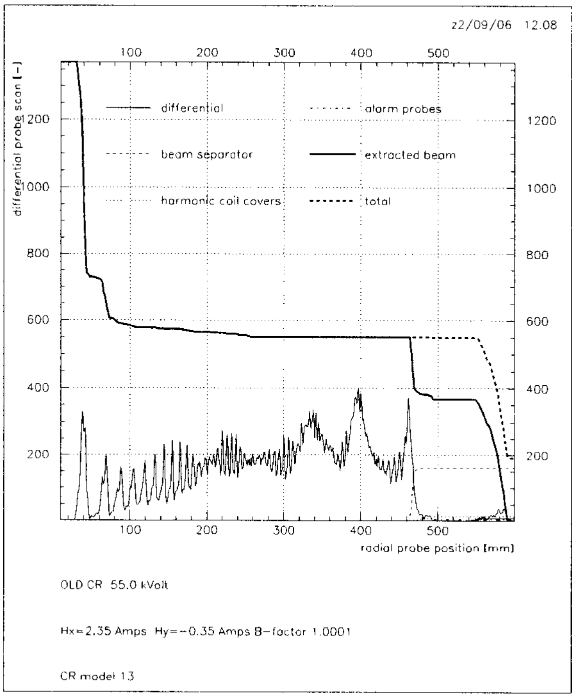

Fig. 9. Simulation of a radial probe scan with the advanced orbit code.

As an example, Fig. 9 shows a radial probe scan as calculated with the orbit code. This scan is on a constant azimuth, just in between the beam separator and the exit port in the vacuum chamber. The Figure shows the turn pattern and also the total beam transmission in the machine from the source to the extraction. It also clearly illustrates the extraction mechanism with the beam coming up on the beam separator and then being extracted. Also included are the vertical losses on the harmonic coil covers and on the alarm probes (security probes located in the cyclotron at a place where normally there is no beam except if there is an unwanted drift in the main field).

Figure 10 shows an example of the extracted beam as calculated with the orbit code. The calculation was done

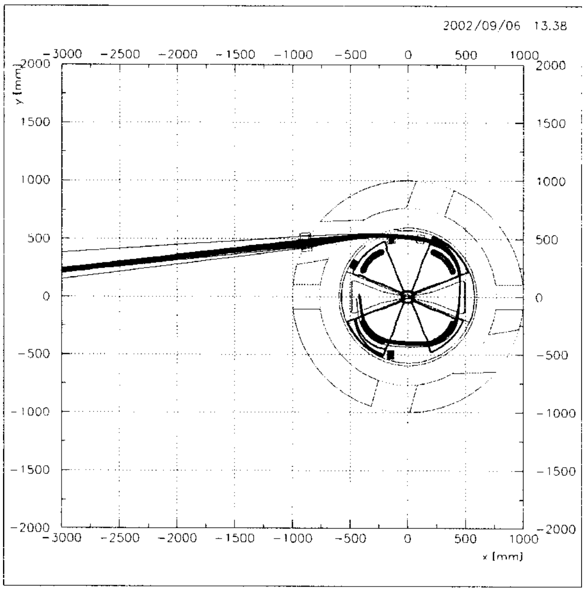

Fig. 10. Simulation of the extracted beam.

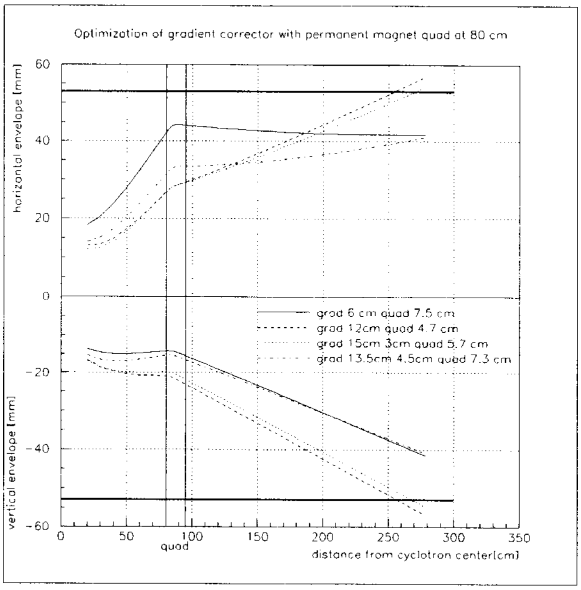

Fig. 11. Optimization of the extraction optics. The solid lines represent the beam pipe. Horizontal distance is measured with respect to the valley symmetry plane.

up to a few meters from the cyclotron in order to well establish the beam direction and to properly adapt to the external beam line. Many of such beams were calculated for various harmonic coil settings, in order to optimize the extraction efficiency.

Figure 11 illustrates the optimization of the extraction optics that was carried out with the advanced orbit code. The extraction optics consists of the gradient corrector and a permanent magnet quadrupole that is placed in the exit port of the return yoke. The optimization was carried out as follows: first, the harmonic coils were optimized for maximum extraction efficiency (in this stage, the beam was started at the ion source and the gradient corrector was kept constant). The extracted particles of this optimized beam were then re-started, but just one turn before extraction. Now, various configurations of the gradient corrector were calculated, with the same starting beam. The post-processing options of the program were used in order to calculate rms beam envelopes of the extracted beam. The optimum gradient corrector configuration consists of horizontal focusing part (13.5 cm long) and a vertical focusing part (4.5 cm long) separated by a drift (3.0 cm long). This configuration gives minimum beam sizes up to the first active doublet in the beam line.

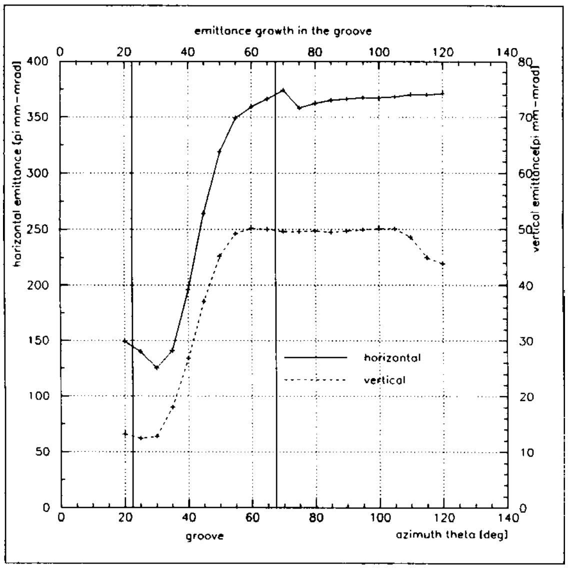

Fig. 12. A calculation of the emittance growth when the beam passes the groove.

Figure 12 illustrates the effect of the extraction groove on the beam. Here the rms analysis options of the code were used to obtain the emittances from the stored particle orbits. As can be seen, the horizontal emittance increases with a factor of 2.5 and the vertical emittance with a factor of 4. This is due to the non-linear magnetic field shape in the groove.

Beam line layout

In July 2001, the cyclotron was moved from the IBA premises to its final site for industrial isotope production. Figure 13 shows the layout of the irradiation area and the beam line. There are two target vaults which can be selected with a 30 degree switching magnet. The diameter of the beam pipes is 110 mm. The total length of a beam line from the cyclotron to the target is about 9 m. The main optical elements in the cyclotron vault are a permanent magnet quadrupole located in the exit port of the cyclotron return yoke, an active doublet at about 2.5 m from the cyclotron and the switching magnet. Each irradiation vault contains an active doublet and a scanning magnet that scans the beam over the target. There is an XY-steering magnet in each of the vaults. Furthermore, in each of the three vaults there is an interceptive beam stop for current measurement (Faraday cup) and a non-interceptive current measurement (Bergoz). At about 1 m from the cyclotron there is a pair of horizontal and a pair of vertical drum collimators, that cut away the halo of the beam. Just before the target there are two BPM's for measurement of the horizontal and vertical beam profile at high beam intensity. These BPM's are made of water-cooled hollow copper tubes that make a half-circle oscillation through the beam. One of the irradiation areas is equipped with a paladium-production target that consist of a rhodium wire which is wound around a cylindrical drum of about 20 cm diameter and 30 cm long. The drum is placed at an angle of about 9 degrees with respect to the beam and rotates at a frequency of 15 Hz. At the same time the beam is scanned vertically at a frequency of about 500 Hz.

Emittance measurements

The VaryQuad method has been used to determine the horizontal and vertical beam emittances. The beam profile is measured at a fixed position but for several different optical settings of the beam line in between a reference point and the Beam Profile Monitor (BPM). The beam optics between these two points must be well known. With a minimum of 3 different profiles, three independent variables describing the phase space (for example the 3 second moments of the phase space or the 3 Twiss parameters) can be determined. If more than 3 profiles are available,

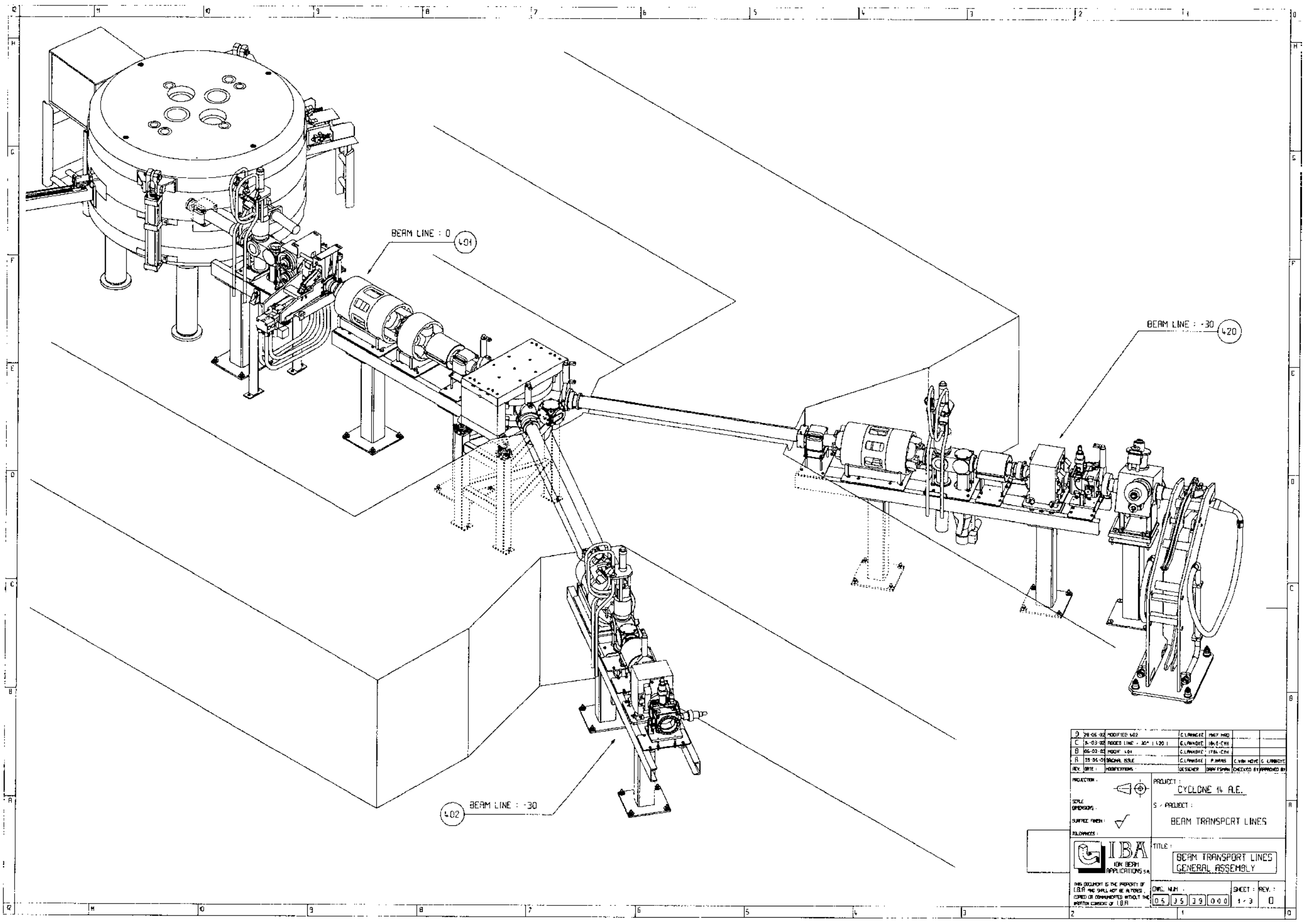

Fig. 13. Beam line layout of the isotope production facility showing the self-extracting cyclotron and two irradiation areas.

then these parameters can be fitted. This will increase the accuracy. The method gives the best result, when the waist of the beam is moved through the BPM position, by varying a focusing quadrupole upstream of the BPM.

As BPM an oscillating wire scanner was used. It was placed directly behind the 30 degree switching magnet in the cyclotron vault. The first doublet in the cyclotron vault was used to vary the beam profile at the BPM. The switching magnet was turned off. The optical properties of the quadrupoles (effective length and gradient) are well known from a rotating coil measurement. Figure 14 shows a typical horizontal beam profile.

In Table 1, we give the measured horizontal and vertical phase space parameters at the exit of the vacuum chamber. The definitions in this Table correspond with the TRANSPORT definitions and the corresponding phase space would contain 86% of the beam if the phase space would have elliptical symmetry with a Gaussian distribution. Note that the results in Table 1 correspond with a situation where the horizontal and vertical drum collimators at the beginning of the beam line were fully open (80 mm). Another measurement of the horizontal emittance was made with the horizontal collimators opened up to 60 mm and the vertical collimators opened up to 40 mm. In this case a horizontal emittance of 170π mm·mrad was found.

The results obtained seemed to be self-consistent in view of the fact that the convergence of the phase space parameters with increasing number of profiles used for the fit looked reliable. Furthermore the measured value of the horizontal emittance (250π mm·mrad) corresponds reasonably with the value that was found by orbit calculations.

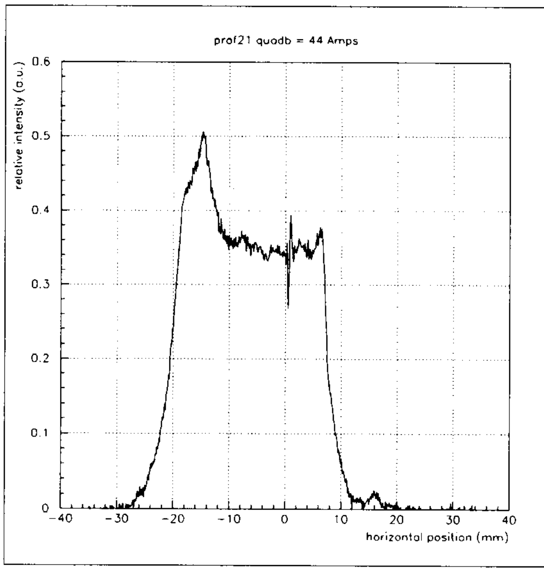

Fig. 14. A typical horizontal beam profile as measured with an oscillating wire BPM.

Table 1. Phase space parameters at the exit of the vacuum chamber. All quantities are rms defined. If the phase space would have elliptical symmetry with a Gaussian distribution, then the used definition would correspond with 86% of the beam.

		Horizontal	Vertical
Emittance	(π mm·rad)	250.1	40.3
Half beam size	(mm)	26.3	6.2
Max. divergence	(mrad)	59.3	9.79
Beam divergence	(mrad)	58.5	–7.29
Correlation		0.987	–0.745
Twiss α		–6.168	1.123
Twiss β	(mm/rad)	2.77	0.954
Twiss γ	(mrad/mm)	14.1	2.38
Converging/diverging		diverging	converging

Project progress and status

Table 2 gives a brief overview of the main milestones that have been achieved since the beginning of the project in March 1998. In the summer of 2001 the machine was transported from the IBA premises to the final isotope production site. High beam intensity tests performed since then have lead to several improvements of subsystems, such as the beam separator, the harmonic coils, the central region, the gradient corrector, the beam transport system and the control system. The system now is almost ready for commercial isotope production that will start by the end of 2002.

The main beam characteristics achieved up to now are listed in Table 3. The maximum beam current extracted up to now is about 2.0 mA. Future efforts will concentrate on increasing this current but also on improving the long term stability of the beam and availability of the system.

At the start of this project, there was quite some doubt concerning the probability of achieving the goals. Presently, there are important achievements in the field of hardware as well as software.

Concerning the hardware there is:

i) a prototype showing the proof of principle of self-extraction;
ii) a high intensity industrial isotope production facility based on this new principle;
iii) the development of innovative target technology, and
iv) new technology for handling of the unwanted beam loss (beam separator).

Concerning software and computations, there are:

i) advanced methods for cyclotron magnetic field calculations (parameterized);
ii) advanced methods of magnetic field shimming including harmonic field errors in a machine with intrinsic 2-fold symmetry and the presence of permanent magnet elements;
iii) advanced methods for complex 3D electric field calculations (parameterized);
iv) an advanced orbit code allowing for the simulation of the beam from ion source to extraction.

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 expected not to be so important. It seems that a sound basis has been made for further development of the self-extraction principle.

Table 2. Overview of progress since the beginning of the project.

Activity	Finishing date
Project start	March 1998
Basic magnetic design	January 1999
Detailed pole tip design	March 2000
Field mapping	August 2000
First extracted beam	December 2000
Beam transport in test beam line	April 2001
First beam on production site	September 2001
Removal of child deseases	August 2002
Start commercial production	end 2002

Table 3. Main beam properties currently achieved. Note that all percentages are relative to the internal beam current just before extraction.

Maximum extracted current	≈2.0 mA
Extraction efficiency	≥75%
Horizontal emittance	250π mm·rad
Vertical emittance	40π mm·rad
Beam losses	
Beam separator	≤24.0%
Cyclotron drum collimators	≤6.0%
Target collimators	≤6.0%
Unaccounted	≤4.0%
Current on target	≥60.0%

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