Injection and extraction for cyclotrons

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Abstract
The main design goals for beam injection are explained and special problems related to a central region with internal ion source are considered. The principle of a PIG source is addressed. The issue of vertical focusing in the cyclotron centre is briefly discussed. Several examples of numerical simulations are given. Different ways of (axial) injection are briefly outlined. A proposal for a magnetostatic axial inflector is given. Different solutions for beam extraction are treated. These include the internal target, extraction by stripping, resonant extraction using a deflector and self-extraction. The different ways of creating a turn-separation are explained. The purpose of different types of extraction devices such as harmonic coils, deflectors and gradient corrector channels are outlined. Several illustrations are given in the form of photographs and drawings.

1 Introduction
The topics of cyclotron injection and extraction have already been covered in earlier CAS proceedings in the framework of the general accelerator physics course [1] as well as in the framework of specialized courses [2–3]. An overview of issues related to the beam transport from the ion source into the cyclotron central region has been given by Belmont at the 23rd ECPM [4]. Since then, not so many substantial changes have occurred in the field especially if one only considers small cyclotrons that are used for applications. Exceptions maybe are the proposal of the axial magnetic inflector [5] on the side of cyclotron injection and the development of the self-extracting principle on the side of cyclotron extraction [6–7]. For this reason it was decided to choose an approach where the accent is less on completeness and rigor ness (because this has already been done) but more on explaining and illustrating the main principles that are used in small cyclotrons. Sometimes a more industrial viewpoint is taken. The use of complicated formulas is avoided as much as possible.

2 Part 1: Injection into cyclotrons
Injection is the process of particle beam transfer from the ion source where the particles are created into the centre of the cyclotron where the acceleration can start. When designing an injection system for a cyclotron, the following main design goals must be identified:

1. Horizontal centring of the beam with respect to the cyclotron centre
2. Matching of the beam phase space with respect to the cyclotron eigenellipse (acceptance)
3. Vertical centring of the beam with respect to the median plane
4. Longitudinal matching
5. Minimization of beam losses
The requirement of centring of the beam with respect to the cyclotron centre is equivalent to requiring that the beam is well positioned on the equilibrium orbit that corresponds with the energy of the injected particles. The underlying physical reasons for the first three requirements are the same. A beam that is not well centred or badly matched will execute coherent oscillations during acceleration. In the case of off-centring these are beam centre of mass oscillations. In the case of mismatch these are beam envelope oscillations. After many turns these coherent oscillations smear out and directly lead to increase of the circulating beam emittances (see Fig. 1). Consequently, beam sizes will be larger, the beam is more sensitive to harmful resonance, the extraction will be more difficult and the beam quality of the extracted beam will be lower.

The last two requirements directly relate to the efficiency of injection into the cyclotron. Longitudinal matching requires a buncher that compresses the longitudinal DC beam coming from the ion source into RF buckets. A buncher usually contains an electrode or small cavity that oscillates at the same RF frequency as the cyclotron dees. It works like a longitudinal lens that introduces a velocity modulation in the beam. After a sufficient drift this velocity modulation transfers into longitudinal density modulation. The goal is to obtain an RF bucket phase width smaller than the longitudinal cyclotron acceptance. For a compact cyclotron without flattop dees the longitudinal acceptance usually lies around 10 to 15%. With a simple buncher a gain of a factor 2 to 3 can easily be obtained. However, at increasing beam intensity the gain starts to drop, due to longitudinal space charge forces that counteract the longitudinal density modulation. The issue of beam loss minimization also occurs for example in the design of the electrodes of an axial inflector. Here, it must be assured that the beam centroid is well centred with respect to the electrodes. This is not a trivial task, due to the complicated 3D orbit shape in an inflector. It requires an iterative process of 3D electric field simulation and orbit tracking.

![x-P_x phase space](image)

**Fig. 1:** A mismatch between the cyclotron eigenellipse and the beam ellipse injected into the machine leads, after many turns, to an increase of the circulating emittance

It should be kept in mind that the design of the injection system often is constrained by requirements at one higher level of full cyclotron design. These can be constraints related to the magnetic structure such as the magnetic field level and shape in the cyclotron centre, the geometrical space that is available for the central region, the internal ion source or the inflector, constraints related to the accelerating structure such as the number of dees, the dee-voltage and the harmonic accelerating mode and constraints related to the injected particle(s) such as charge to mass ratio, the number of (internal) ion sources to be placed and the injection energy.

Two fundamentally different injection approaches can be distinguished depending on the position of the ion source. An internal ion source is placed in the centre of the cyclotron where it
constitutes an integrated part of the RF accelerating structure. This may be a trivial case, but it is the one that is mostly implemented for compact industrial cyclotrons. The alternative is the use of an external ion source where some kind of injection line with magnets for beam guiding and focusing is needed, together with some kind of inflector to kick the beam onto the equilibrium orbit.

2.1 Cyclotrons with an internal ion source

The use of an internal ion source is the simplest and certainly also the least expensive solution for injection into a cyclotron. Besides the elimination of the injection line, a main advantage lies in the compactness of the design. It opens the possibility to place simultaneously two ion sources in the machine. In many small PET cyclotrons an H-minus as well as a D-minus source is placed in order to be able to accelerate and extract protons as well as deuterons. These two particles are sufficient to produce all four well known PET isotopes $^{11}$C, $^{13}$N, $^{15}$O and $^{18}$F. On the other hand an internal ion source brings about several limitations: i) often only low to moderate beam intensities can be obtained, ii) only simple ion species such as for example H-plus, H-minus, D-minus, He-3 or He-4 can be obtained, iii) injected beam manipulation such as matching or bunching is not possible, iv) careful central region design is required in order to obtain good beam centring and vertical focusing, v) there is a direct gas-leak into the cyclotron which may be especially limiting for the acceleration of negative ions because of vacuum stripping vi) high beam quality is more difficult to obtain and vii) source maintenance requires venting and opening the cyclotron.

![Fig. 2: Schematic drawing of a cold cathode PIG ion source (left), photograph showing two chimneys, two cathodes and a puller (right). The chimney on the right shows an eroded slit.](image)

2.1.1 The PIG ion source

Often a cold-cathode PIG (Penning Ionization Gauge [19]) ion source is used as internal source. The PIG source contains two cathodes that are placed at each end of a cylindrical anode (See Fig. 2). The cathodes are at negative potential relative to the anode (the chimney). They emit electrons that are needed for ionization of the hydrogen gas and the creation of the plasma. The cyclotron magnetic field is along the axis of the anode. This field is essential for the functioning of the source as it enhances confinement of the electrons in the plasma and therefore the level of ionization of the gas. The electrons oscillate up and down as they are reflected between the two cathodes and spiralize around the vertical magnetic field. In order to initiate the arc current, the cathode voltage initially must be raised to a few kilovolts. Once a plasma exists, the cathodes are self-heated by ionic bombardment and the arc voltage will decrease with increasing arc current. Usually an operating voltage of a few...
hundred volts is obtained. This is enough to ionize the gas atoms. The ions to be accelerated are extracted from the source via a small aperture called the slit. This extraction is obtained by the electric field that exists in between the chimney and the so-called puller. This puller is at the same electric potential as the RF accelerating structure as it is mechanically connected to the dees (See Fig. 3).

Figure 2 on the right shows a photograph of chimneys and cathodes used in compact IBA cyclotrons. The chimneys are made of a copper-tungsten alloy, because of good thermal properties and good machining properties. The cathodes are fabricated from tantalum also because of the good thermal properties and the low work function for electron emission.

Fig. 3: The central region of the IBA C18/9 cyclotron. One of the two ion sources has been removed in order to show the puller. The figure also shows the four hill sectors. The removable circular disk underneath the central region is the central plug; it is used to fine-tune the magnetic field bump in the centre.

2.1.2 Some guidelines for central region design

The design of a central region with an internal ion source is a tedious task that requires precise numerical calculation and often many iterations before good beam centring, vertical focusing and longitudinal matching is obtained. Some general guidelines for such a design process can be given:

1. Start with a crude model and refine it step by step. Begin with a uniform magnetic field and assume hard edge uniform electric field in the gaps. Initially only consider orbits in the median plane. Try to find the approximate position of the ion source and the accelerating gaps that will centre the beam with respect to the cyclotron centre and centre the beam RF phase with respect to the accelerating wave (longitudinal matching). This may be done by drawing circular orbit arcs by hand, using analytical formulas [2] or even by using a pair of compasses (for drawing circular arcs between gaps) and a protractor (for estimating RF phase advance between gaps). Transit time effects should be taken into account, especially in the first gap [8]. The starting phase for particles leaving from the source should be roughly between −40° and −10° RF.

2. Once an initial gap layout has been found, the model should be further refined by using an orbit integration program. Here, the electric field map can still be generated artificially by assuming for each gap an electric field shape with a Gaussian profile that only depends on the coordinate that is normal to the gap and not on the coordinate that is parallel to the gap. Empirical relations may be used to find the width of the Gauss function in terms of the gap width and the vertical dee gap [9]. For the first gap between source and puller, a half-Gauss should be used. The advantage of this intermediate step is that the layout can be easily generated and modified. At this stage, the vertical motion can already be taken into account.
3. Create a full 3D model of the central region and solve the Laplace equation in order to calculate the 3D electric field distribution. Several 3D codes exist such as RELAX3D from Triumf [10] or the commercial code TOSCA from Vector Fields. The latter is a finite element code which allows the modelization of very fine details as part of a larger geometry without the need of very fine meshing everywhere (see Fig. 4). If possible, the model should be fully parametrized in order to allow for fast modifications and optimizations. With the availability of 3D computer codes, it is no longer needed to measure electric field distribution as has been done in the past by electrolytic tank measurements [11–12] or magnetic analogue model [9].

4. Track orbits in the calculated electric field and in the realistic magnetic field (obtained from field mapping or from 3D calculations). Fine-tune the geometry further for better centring (see Fig. 5), vertical focusing and longitudinal matching (RF phase centring, see Fig. 6).

5. Track a full beam (many particles) to find beam losses and maximize the beam transmission in the central region [7].

![Fig. 4: Example of a 3D finite element model of the IBA C18/9 central region. Fine meshing is used in regions with small geometrical details like the source-puller gap. The graded mesh size allows for modelization of the full dee-structure. Complete parametrization of the model is used for fast modifications and optimizations.](image)

### 2.1.3 Vertical focusing in the cyclotron centre

The azimuthal field variation (AVF) goes to zero in the centre of the cyclotron and therefore this resource for vertical focusing disappears. There are two remedies that are used to restore the vertical focusing:

1. Add a small magnetic field bump (a few hundred Gauss) in the centre. The negative radial gradient of this bump provides some vertical focusing. The bump may not be too large in order not to induce a too large RF phase slip. In the small IBA PET cyclotrons the bump is fine-tuned by modifying the thickness of the central plug (see Fig. 3).

2. Fully exploit the electrical focusing provided by the first few accelerating gaps.
Fig. 5: Illustration of an off-centred orbit due to imperfect central region design. The turn pattern density modulation results from the off-centred beam describing a coherent precessional oscillation with $\nu_r > 1$. Also a coupling into the longitudinal motion can be observed by plotting the particle position when $V_{\text{dee}} = 0$ (red dots).

Fig. 6: Calculated orbits in the IBA C18/9 central region. Note that parts of the D-minus chimney have been cut away in order to give sufficient clearance for the H-minus beam. Assessment of longitudinal matching is illustrated: the red dots and the green dots give the particle position when the dee-voltage is zero and maximum respectively. Ideally, the red dots should be on the dee centreline.

If an accelerating gap is well positioned with respect to the RF phase, it may provide some electrical focusing. Figure 7 illustrates the shape of the electric field lines in the accelerating gap between a dummy dee (at ground potential) and the dee. The particle is moving from left to right and is accelerated in the gap. As can be seen, in the first half of the gap the vertical forces point towards the median plane and this part of the gap is vertically focusing. In the second half of the gap the
vertical forces have changed sign and this part of the gap is vertically defocusing. If the dee-voltage would be DC, there would already be a net focusing effect of the gap for two reasons: a) a focusing and de-focusing lens one behind the other provide some net focusing in both planes and b) the defocusing lens is weaker due the fact that the particle has higher velocity in the second part of the gap. However, the dee-voltage is not DC but varying in time and this may provide an additional focusing term that is more important than the previous two effects. This is obtained by letting the particle cross the gap at the moment that the dee-voltage is falling (instead of accelerating on the top). In this case the defocusing effect of the second gap half is additionally decreased. In order to achieve this, the first few accelerating gaps have to be properly positioned azimuthally. This makes part of the central region design.

Fig. 7: Illustration of vertical electrical focusing in the cyclotron accelerating gap

Fig. 8: Normalized vertical electrical forces obtained from orbit tracking of a particle during 5 turns in a central region with two dees (four accelerating gaps). Dee crossings are indicated in blue and gap crossings (two per dee) in green. It is seen that each gap is focusing at the entrance and defocusing at the exit.

The vertical electrical focusing is also illustrated in Fig. 8. This figure shows the (normalized) vertical electrical force acting on a particle during the first 5 turns in the cyclotron (IBA C18/9). A minus sign corresponds with focusing (force directed towards the median plane). The dee crossings (two dees) as well as the gap crossings (four gaps) are indicated. It is seen that each gap is focusing at the entrance and defocusing at the exit. It is also seen from the amplitude of the force that the electrical focusing rapidly falls with increasing beam energy. However, after a few turns the magnetic focusing already becomes sufficient.
2.1.4 Burning paper

When a new central region has been designed and is being tested in the machine it does not always immediately function correctly and it may happen that the beam is lost after a few turns. Due to space limitations, it is not always possible to have a beam diagnostic probe that can reach the centre of the cyclotron and it may be difficult to find out why and where the beam is lost. In such case it may help to put small bits of thin paper in the median plane; they will change colour due to the interaction with the beam. This is illustrated in Fig. 9 showing the central region layout of the IBA self-extracting cyclotron. The bits of burned paper (7 in total) have been collated on the central region design drawing. In this way the position of each turn as well as corresponding beam sizes are nicely indicated.

![Figure 9: Small bits of thin paper are placed in the pole gap and burned by the beam in order to find the beam position and size during the first few turns](image)

2.2 Cyclotrons with an external ion source

In many cases the ion source is placed outside of the cyclotron. There may be different reasons for this choice: i) higher beam intensities are needed, which can only be realized in a more complex and larger ion source than the simple PIG source, ii) special ion species such as heavy ions or highly stripped ions are required or iii) good machine vacuum is needed (as is for example the case for H-minus acceleration). Of course the external ion source is a more complex and more expensive solution since it asks for an injection line with all related equipment such as magnetic or electrostatic beam guiding and focusing elements, vacuum equipment, beam diagnostics etc.

2.2.1 Different ways of injection

There are a few different ways to inject into a cyclotron.

1. **Axial injection**: this case is most relevant for small cyclotrons. The beam travels along the vertical symmetry axis of the cyclotron towards the cyclotron centre. In the centre the beam is bend by an angle of 90 degrees from vertical to horizontal into the median plane. This is done by an electrostatic or magnetostatic inflector

2. **Horizontal injection**: the beam is travelling in the median plane from the outside towards the cyclotron centre. Generally speaking, this type of injection is more complicated than axial injection, due to the vertical magnetic field that is exerting a horizontal force on the beam thereby trying to bend it in the horizontal plane. It has been tried to cancel this force with electrical forces from an electrode system installed near the median plane [13]. It has also
been tried to live with this force and to let the beam make a spiral motion along the hill-valley pole edge towards the cyclotron centre. This is called trochoidal injection and is illustrated in Fig. 10. In the centre an electrostatic deflector places the particle on the correct equilibrium orbit. Both methods are very difficult and therefore are no longer used.

3. Injection into a separate sector cyclotron: this must be qualified as a special case. Much more space is available in the centre for placing magnetic bending and focusing devices. Injection at much higher energy (MeV range) is possible. Here it is considered as out of the scope of small accelerators.

4. Injection by stripping: a stripper foil positioned in the centre changes the particle charge state and its local radius of curvature so that the particle places itself on the correct equilibrium orbit. This method is mostly applied for separate sector cyclotrons where the beam is injected horizontally.

Fig. 10: Illustration of horizontal (trochoidal) injection. The beam travels along the hill-valley pole edge. In the centre an electrostatic device places the beam on the equilibrium orbit.

2.2.2 Inflectors for axial injection

The electrical field between two electrodes bends the beam 90 degrees from vertical to horizontal. The presence of the cyclotron magnetic field creates a complicated 3D orbit and this makes the inflector design difficult. Four different types of electrostatic inflectors are known.

1. The mirror inflector: two planar electrodes are placed at an angle of 45 degrees with respect to the vertical beam direction. In the upper electrode is an opening for beam entrance and beam exit (see Fig. 11). The advantage of the mirror inflector is its relative simplicity. However, due to the fact that the orbit is not following an equipotential surface, a high electrode voltage (comparable to the injection voltage) is needed. At the entrance the particle decelerated and at the exit it is re-accelerated again. Furthermore, in order to obtain a reasonable electrical field distribution between the electrodes, a wire grid is needed across the entrance/exit opening in the upper electrode. Such a grid is very vulnerable and easily damaged by the beam.

2. The spiral inflector: this is basically a cylindrical capacitor that is gradually twisted in order to take into account the spiralling of the trajectory, induced by the vertical cyclotron magnetic field. The design is such that the electrical field is always perpendicular to the velocity vector of the central particle and the orbit therefore is positioned on an equipotential surface. The
The electrode voltage can be much lower for a mirror inflector. A simple formula for the electrode voltage is:

\[ V = 2 \frac{E}{q} \frac{d}{A}, \]

where \( V \) is the electrode voltage, \( E \) is the injection energy, \( q \) is the particle charge, \( d \) is the electrode spacing and \( A \) is the electric radius of the inflector. It is seen that the ratio between electrode voltage and injection voltage is equal to twice the ratio of the electrode spacing and height of the inflector. An important advantage of the spiral inflector is that it has two free design parameters that can be used to place the particle on the correct equilibrium orbit. These two parameters are the electrical radius \( A \) and the so-called tilt parameter \( k' \). This second parameter represents a gradual rotation of the electrodes around the particle moving direction by which a horizontal electric field component is obtained that is proportional to the horizontal velocity component of the particle. Varying the tilt parameter \( k' \) therefore is equivalent (as far as the central trajectory is concerned) to varying the cyclotron magnetic field in the inflector volume. Another advantage of the spiral inflector is its compactness. On the other hand, the electrode surfaces are complicated 3D structures which are difficult to machine. Nowadays however, with the wide availability of computer controlled 5-axis milling machines this is not really a problem anymore. Figure 12 show a scale 1:1 model of the spiral inflector that is used in the IBA C30 cyclotron.

3. The hyperboloid inflector: the electrodes are hyperboloids with rotational symmetry around the vertical z-axis (see Fig. 11). As for the spiral inflector, the electrical field is perpendicular to the particle velocity and a relative low electrode voltage can be used. However, for this inflector, no free design parameters are available. For given particle charge and mass, injection energy and magnetic field, the electrode geometry is fixed and it is more difficult to inject the particle on the correct equilibrium orbit. Furthermore, this inflector is quite large as compared to the spiral inflector. On the other hand, due to the rotational symmetry, it is easier to machine.

4. The parabolic inflector: the electrodes are obtained from bending sheet metal plates into a parabolic shape. This inflector has the same advantages and disadvantages as the hyperboloid inflector: relatively low voltage and ease of construction, but no free design parameters and relatively large geometry.

Fig 11: Illustration of the mirror inflector (left) and the hyperboloid inflector (right)
2.2.3 A magnetostatic inflector?

A new concept is proposed for an inflector that does not use any electrical field to bend the beam but only magnetic field. This magnetic field is produced by two soft-iron pole elements with rotational symmetry that are placed in between the magnet poles of the cyclotron in the centre of the cyclotron and which are magnetized by the main cyclotron magnetic field (see Fig. 13). The main advantage of this system would be that the beam could be injected at much higher energies (60 kVolt). For electrostatic inflectors this is much more difficult and often impossible due to electrical sparking problems. Another interesting aspect is that orbit centring of the beam with respect to the equilibrium orbit is obtained by a steering magnet that moves the beam off from the cyclotron axis before it enters into the inflector. Detailed studies still have to be made, however.

2.2.4 Example of an axial injection line

One main goal of the injection line is to provide means to match the injected beam into the cyclotron acceptance. Fig. 14 shows an example of relatively simple axial injection line as is proposed for the IBA Cyclone 30 cyclotron. For matching of the transverse emittances in general, if no coupling is present in the optical elements, two independent knobs are needed for each of the two directions. For
this reason, four small quadrupoles (Q1 to Q4) are placed in the injection line. However, some strong transverse coupling is introduced by the spiral inflector itself. Due to this, it is not possible to match both transverse phase planes completely and a certain emittance growth cannot be avoided. The emittance growth can even be bigger than a factor 5 [14]. In order to reduce this adverse coupling effect introduced by the spiral inflector, a small skew quadrupole is included in the injection line. It is placed as close as possible to the inflector. The injection line further contains two small steering magnets (S1 and S2) in order to align the beam with the cyclotron axis. A Faraday cup is used to measure the current extracted from the ion source.

![Fig 14: Example of an axial injection line for a compact cyclotron](image)

### 2.2.5 Numerical computations

Analytical formulas exist for central orbits in a spiral inflector placed in a homogeneous magnetic field [15–18]. However, the field in the cyclotron centre is certainly not uniform, due to the axial hole that is needed for the axial injection. In practise the inflector design requires an extensive numerical effort which contains three main parts: 1) 3D modelisation of the electrical fields of the inflector and central region, 2) 3D modelization of the magnetic field in the central region and 3) orbit tracking in the central region. The complete process is tedious and requires many iterations. First, the central trajectory has to be defined and optimised. There are three main requirements, namely that the injected orbit is nicely on the equilibrium orbit, correctly placed in the median plane and also that the orbit is well centred with respect to the inflector electrodes. After an acceptable electrode geometry has been obtained, for which these requirements are fulfilled, the beam optics has to be studied. Here the main requirement is that reasonable matching into the cyclotron eigenellipse can be achieved, so that large emittance growth in the cyclotron is avoided [14].

It may be necessary to calculate several inflectors of different height $A$ and tilt parameter $k'$, in order also to optimise this process. At IBA both the 3D magnetic field computations as well as the 3D electrical field computations are done with the OPERA3D software package from Vector Fields. Often, the models are completely parametrized in order to be able to quickly modify and optimise.
Figure 15 shows such a model of the central region and the inflector. The inflector model uses the following parameters: the electrode width and spacing (both may vary along the inflector), the tilt parameter $k'$, and furthermore the shape of the central trajectory itself in terms of a list of points and velocity vectors. In order to increase the good field region in the inflector, the electrode surfaces may be curved as is shown in Fig. 15. Figure 16 shows a model of the IBA cyclone 30 cyclotron magnet.

**Fig. 15:** Illustration of the 3D axial injection modelization. In the figure on the left the inflector and central region model has been merged with the magnetic model. In reality these two models are calculated separately. The figure on the right shows the modelization of an inflector with curved electrodes.

**Fig. 16:** Illustration of the IBA Cyclone 30 magnetic field modelization

## 3 Part 2: Extraction from cyclotrons

Extraction is the process of beam transfer from an internal orbit to a target that is placed outside of the magnetic field. There are basically three reasons why extraction is considered as difficult:

1. The magnetic field itself behaves as a kind of trap. When the particles are accelerated into the falling fringe field they will run out of phase with respect to the RF wave; if the phase slip is
more than 90° they will be decelerated instead and move inward. This may be considered as a kind of reflection of the beam on the radial pole edge of the magnet.

2. In a cyclotron, the turn-separation is inversely proportional with the radius. Due to this the turns pile up closely together near the extraction radius. Therefore it is difficult to deflect the last orbit, without influencing the inner orbits and without important beam losses.

3. During extraction the beam has to cross the fringe field. This is an area where there are very large gradients and non-linearity’s in the magnetic field. Special precautions have to be made to avoid substantial beam losses, beam blow-up or loss of beam quality.

There are a few different ways to solve the problem of extraction namely:

1. avoid the problem by using an internal target;
2. extraction by stripping;
3. use one (or more) electrostatic deflectors that peel off the last orbit;
4. self-extraction.

Cases 3 and 4 require some way to increase the turn-separation between the last and before last orbit. The four methods will be discussed in more detail below.

3.1 The use of an internal target
The target is placed between the poles of the cyclotron at a radius where the field is still isochronous. The method is applied quit frequently for the production of radioisotopes such as palladium-103 or thallium-201. The method is relatively simple and also non-expensive. The energy can be selected by choosing the correct radius of the target in the cyclotron. On the other hand it is a dirty way of working because of radioactive contamination of the cyclotron. If the target is perpendicular to the beam, the beam spot is very small and local heating will pose a problem. In order to avoid this, the target is placed at a small grazing angle with respect to the beam. In this case however, a certain percentage of the incoming beam will reflect on the target surface due to multiple scattering. This in turn will activate the cyclotron. Figure 17 shows IBA C18+ cyclotron with an internal rhodium target that is used for the production of palladium-103. The target can be fully remotely handled. Palladium is used for brachytherapy (treatment of prostate cancer). Sixteen of these machines have been sold to one customer.

![Rhodium target](image)

Fig. 17: The IBA C18+ cyclotron with an internal rhodium target for the production of palladium
Figure 18 shows some detail of the internal Rh/Pd target. The target is heavily water-cooled in order to be able to take the beam power of 30 kWatt (2 mA/15 MeV). The target surface is profiled which is optimised in order to maximise the beam spot and minimise the beam reflection.

![Figure 18: Detail of an internal target showing the profiling of the target surface that has been optimized in order to maximize the beam spot and minimize the beam reflection on the target.](image)

### 3.2 Stripping extraction

In order to extract the beam, the particles pass a thin stripper foil by which one or more electrons are removed from the ion. Due to this there is an instantaneous change of the orbit local radius of curvature. The relation between the local radius before \( \rho_b \) and after \( \rho_a \) stripping is given by:

\[
\rho_a = \frac{Z_m m_a}{Z_b m_b} \rho_b
\]

where \( m_b \) and \( m_a \) are the particle mass before and after stripping, respectively. As an example, for H-minus we have \( H^- \Rightarrow H^+ + 2e^- \) and the local radius of curvature changes sign \( (\rho_a = -\rho_b) \). Due to this, the stripped particle is immediately deflected outward, away from the cyclotron centre. This is illustrated in Fig. 19. Multiple targets can be placed around the machine. A given target is selected by rotating the corresponding stripper foil into the beam. H-minus extraction is applied in many commercial isotope production cyclotrons fabricated for example by IBA (Cyclone 30, C18/9, C10/5) or Ebco (TR30, TR13) and General Electric (PETtrace).

Another example is the acceleration of the molecular hydrogen \( H_2 \)-plus and the related extraction by stripping: \( H_2^+ \Rightarrow 2H^+ + e^- \). In this case the radius of curvature does not change sign but is divided by two \( (\rho_a = \rho_b/2) \). In this case, extraction is more difficult, because the beam initially remains in the machine because the particle is deflected inward immediately after stripping. Note that in this case, the K-value of the cyclotron magnet must be 4 times higher than the energy of extracted protons.
The most important features and advantages of stripping extraction are the following:

- very simple extraction device
- 100% extraction efficiency
- variable energy
- multiple targets can be placed around the machine
- simultaneous dual beam extraction
- good beam optics.

Energy can easily be varied by moving the radial position of the stripper probe (See Fig. 20). By proper azimuthal positioning of the stripper foil, all orbits come together in the same cross-over point outside of the magnetic field. Here a combination magnet is placed that deflects the beam into the beam-line. Simultaneous dual beam operation is possible by positioning two stripper foils at an azimuth of 180° with respect to each other. Some fine tuning of the turn-pattern is needed to precisely distribute the total beam current between the two stripping foils. This may be done by fine-adjustment of the dee-voltage, or by using first harmonic coils. Since the extracted beam crosses the radial pole edge at an angle that is close to 90 degrees, the large (de-)focusing effects of the fringe field are avoided and the beam quality remains intact.

There is a serious limitation of an H-minus cyclotron due to magnetic stripping that may occur during acceleration. Due to this the magnetic field cannot be high and for obtaining high energy the pole radius of the machine must be increased. A well-known example is the TRIUMF cyclotron [20] that accelerates H-minus up to 520 MeV. The average magnetic field is only 0.3 Tesla (in the cyclotron centre) resulting in a magnet diameter of 18 m and a magnet weight of 4000 tons. The H-minus is also stripped on the vacuum rest gas and in order to limit the beam losses, good vacuum pumping and an external ion source is required (IBA Cyclone-30, Ebco TR30).
3.3 Extraction by means of electrostatic deflector devices

3.3.1 Turn separation in a cyclotron

Some qualitative aspects of orbit separation are explained in order to illustrate the general effects. In a cyclotron the position of a particle with a given energy is determined by a betatron oscillation relative to the equilibrium orbit.

\[
\Delta r(\theta) = r_0(\theta) + x(\theta) \sin(\nu_0 \theta + \theta_0) + x(\theta) \cos(2\pi n (\nu_0 -1) \theta + \theta_0)
\]

Here \( r \) and \( \theta \) are the polar coordinates of the particle, \( r_0(\theta) \) is the equilibrium orbit for a given energy, \( x \) is the amplitude of the betatron oscillation, \( \nu_0 \) is the radial betatron oscillation frequency and \( \theta_0 \) is an arbitrary offset angle. The equilibrium orbit can be ideally centred and shaped (in case of a perfectly symmetric magnetic field), or it can be displaced with respect to the centre of the cyclotron (when there is a first harmonic field perturbation in the field). The betatron oscillation is quasi-sinusoidal but the oscillation amplitude may slightly depend on \( \theta \) due to the AVF characteristic of the magnetic field. For the present purpose this effect is not important. The above describes the oscillation of one single particle. However, it can also be used for describing a coherent oscillation of the centre of the beam. The latter case is relevant for the study of turn separation. We can evaluate the radius \( r(\theta) \) at a fixed azimuth \( \theta_0 \) but for successive turns \( n \). It is easily derived that in this case [3]:

\[
\Delta r(\theta_0) = \Delta r_0(\theta_0) + \Delta x \sin(2\pi n (\nu_0 -1) + \theta_0) + \frac{2\pi (\nu_0 -1) x \cos(2\pi n (\nu_0 -1) + \theta_0)}{\text{precession}}
\]
where $\Delta r$ is the radial increase between two successive turns. In this equation there are three different terms. They relate to three different ways that can be used to generate a turn separation. The first term $\Delta r_0$ represents an increase of the radius of the equilibrium orbit and is related to the energy increase $\Delta E_0$ per turn

$$\frac{\Delta r_0}{r_0} = \frac{1}{2} \frac{\Delta E_0}{E_0},$$

where $E_0$ is the kinetic energy at the radius $r_0$. Thus the relative radial increase is only half the relative energy increase. However, for a given cyclotron the turn separation $\Delta r_0$ will double when the dee voltage is doubled.

The second term in the above equation relates to a turn separation that is due to an increase of the betatron oscillation amplitude between two successive turns. This is in general what happens in a resonance. The resonances that are important for extraction from a (small) cyclotron are the $\nu_r = 1$ resonance and the $2\nu_r = 2$ resonance. The $\nu_r = 1$ resonance is a first order integer resonance (displacement of the beam) and is driven by a first harmonic dipole bump. The $2\nu_r = 2$ resonance is a second order half-integer resonance (exponential growth in the stop band) and is driven by a second harmonic gradient (quadrupole) bump.

The third term in the above equation describes the case where a coherent amplitude already exists, but the turn separation arises from the fact that the phase of the oscillation has advanced between two successive turns.

### 3.3.2 Different extraction methods relying on turn separation

The following classification [21] is often made for the different ways of extraction that rely on an increase of the turn separation:

- **Extraction by acceleration**: no other means than acceleration only is used to increase the turn separation. This is done for example in the IBA C235 proton therapy cyclotron.
- **Resonant extraction**: here some coherent beam oscillation is created just before extraction. Three different schemes can be distinguished:
  - **Brute force extraction**: the beam is extracted during the built up of the resonance. Due to this there is an increase of the amplitude of coherent oscillation in between the last and the before last turn. This oscillation is created on or close to the $\nu_r = 1$ resonance by applying a first harmonic dipole bump.
  - **Precessional extraction**: This is more subtle [22–24]. Also here a coherent oscillation is created with a first harmonic dipole bump on the $\nu_r = 1$ resonance. However, after passing this resonance, the beam is further accelerated into the fringe field of the cyclotron. Here the value of $\nu_r$ drops below one (typically 0.6 to 0.8). Due to this the betatron phase advance between the last two turns is substantially different from 360 degrees and a turn separation is obtained which is proportional to the oscillation amplitude and proportional to $\nu_r - 1$. Of course the number of turns in the fringe field should not be too large in order to avoid a too large RF phase slip.
  - **Regenerative extraction**: This is even more subtle. Also here the beam is extracted during resonance built up. The $2\nu_r = 2$ resonance is used. This resonance is driven by a second harmonic gradient bump. This means that the second harmonic bump should show as a function of radius a quadrupole-like dependence (linear increase with radius). This shape is more critical than for the previous two methods. If the gradient is large enough, then the
resonance will lock the real part of $\nu_r$ to value one. There also is an imaginary part of $\nu_r$ that will cause exponential growth of the betatron oscillations. It is also required that the beam has already some offset before it enters into the resonance in order that the centroid itself shows exponential growth. The betatron phase of this offset is important. Due to this complexity regenerative extraction is not used very much in small cyclotrons.

### 3.3.3 The general layout for resonant extraction

The extraction process for resonant extraction using an electrostatic deflector can generally be subdivided into four steps:

1. Use harmonic coils (placed at a radius where $\nu_r = 1$) in order to tickle the beam, create a coherent oscillation and create the required turn-separation

2. Use an electrostatic deflector to peel off the last turn and provide an initial radial kick to the beam

3. Use gradient corrector or focusing channels to guide the beam through the cyclotron fringe field. The primary goal is to locally reduce the magnetic field and to control the field gradients in order to avoid or reduce optical damage to the beam.

4. Place external focusing elements (quadrupole doublet) as close as possible to the radial pole edge (if necessary in the cyclotron return yoke) in order to handle the large beam divergences in the extracted beam.

![Fig. 21: Illustration of the extraction scheme that is used for the IBA C235 proton therapy cyclotron](image)

Figure 21 shows the extraction scheme that is used in the IBA C235 proton therapy cyclotron. In this cyclotron, turn separation is created by acceleration only. There are no harmonic extraction coils. The only extraction elements are the deflector, the gradient corrector and the permanent magnet quadrupole doublet that is placed in the return yoke. This cyclotron is a special case because the beam can be accelerated very close to the radial pole edge of the machine. This is achieved by using a pole gap with an elliptical shape. Furthermore the RF cavities are designed such that there is a strong rise of the dee-voltage with increasing radius so that a larger turn separation is obtained at extraction.

### 3.3.4 Harmonic extraction coil

Harmonic extraction coils are used to create a coherent beam oscillation. They are placed at a radius where $\nu_r$ is close to one. The principle is simple: if $\nu_r = 1$ the radial kicks that are given to the beam are all in phase and the oscillation amplitude growth linearly with turn number. Reality may be more
difficult however. The coils cover a certain radial width (or better, a certain energy range) and $\nu_r$ will not be equal to one over the full range. Depending on the number of turns that are ‘seen’ by the harmonic coil, very quickly a situation may occur where the oscillation amplitude that was already created, is lost again due to the fact that new radial kicks are out of phase with the oscillation built up so far (Reference). To avoid this situation it is important to limit the radial width of the coil. The shape of the coil should follow the local shape of the equilibrium orbit such that the particle energy range covered by the coil is small. The coil should be placed in the pole gap in order to use the field amplification given by the iron. On the other hand this may complicate the design due to vertical space limitations. Also the heat load will be important because water cooling is often not possible. Figure 22 shows a photograph of the harmonic coil that is used in the IBA self-extracting cyclotron.

![Fig. 22: Harmonic coil used in the IBA self-extracting cyclotron](image)

3.3.5 **Electrostatic deflector**

The electrostatic deflector creates an outwardly directed DC electric field between two electrodes. The goal is to give an initial angular deflection to the beam. The inner electrode (called the septum) is placed between the last and before last turn. It is on ground potential so that the inner orbits in the cyclotron are not affected. At the entrance, the septum is knife-thin (in the order of 0.1 mm) in order to peel-off the last orbit and minimizing beam losses on the septum itself. In order to better distribute the heat due to beam losses, the beginning of the septum is often V-shaped. The septum is water cooled. The heat loss on the septum usually determines the maximum current that can be extracted from the cyclotron. The outer electrode is on a negative potential (assuming extraction of positively charged particles). Of course the shape of the electrodes must follow the shape of the extracted orbit. Figure 23 shows a photograph of the electrostatic deflector that is used in the IBA C235 cyclotron.

![Fig. 23: Photograph of the electrostatic deflector installed in the IBA C235 cyclotron](image)
3.3.6 Gradient corrector and focusing channel

The goal of a gradient corrector channel is to lower the magnetic field on the extraction path and to lower the vertical and/or increase the radial focusing through the fringe field. Often more than one magnetic channel is needed along the extraction path. Different types are used:

- **passive channel**: made of soft iron bars that are magnetized by the cyclotron magnetic field.
- **active channel**: using coils or permanent magnets.

Always, the design contains an effort to reduce the adverse effect of the channel on the internal orbits. Figure 24 shows a vertical cross section of the passive focusing channel that is used in the small ILEC cyclotron of the Eindhoven University [25]. Here the poles are shaped in order to provide a smooth and constant radial gradient at the location of the beam.

Figure 25 shows a photograph of the gradient corrector that is used in the IBA self-extracting cyclotron [7]. This is an active channel made of Samarium-Cobalt permanent magnets. It acts like a quadrupole doublet, but with the first quad being longer than the second quad. The quadrupole-like field shape is obtained by using two opposite dipole fields that are radially displaced a few centimeters with respect to each other. Some additional small magnets are placed in order to minimize the adverse effect of the gradient corrector on the internal orbits. Figure 26 shows the passive gradient corrector that is used in the IBA C235 cyclotron. The beam leaves the cyclotron by crossing the radial pole edge. Here there is a very strong magnetic field gradient that would completely defocus the beam horizontally. The gradient corrector creates a kind of plateau at lower magnetic field value. Figure 27 show a photograph of a permanent magnet quadrupole doublet that is used in the IBA C235 cyclotron to re-focusing the beam immediately after it is extracted from the cyclotron.
Fig. 25: Photograph of the lower part of the permanent magnet gradient corrector that is used in the IBA self-extracting cyclotron. The polarity of the magnets is indicated (N = north pole; S = south pole). For the upper part, the polarities are inversed.

Fig. 26: Photograph of the passive gradient corrector used in the IBA C235 cyclotron

Fig. 27: permanent magnet quadrupole doublet placed in the return yoke of the IBA C235 cyclotron
3.4 Self-extraction

In every cyclotron the average magnetic field starts to drop when approaching the maximum pole radius. Of course this limits the maximum energy that can be achieved in the cyclotron. There are in fact two limits:

1. There is a limit of radial stability. This limit is reached on the equilibrium orbit for which the radial betatron frequency $\nu_r$ has fallen down to zero ($\nu_r \downarrow 0$). Note that in a rotational symmetric magnetic field this corresponds with the situation where the field index equals $-1$.

$$n = \frac{r \ dB}{B \ dr} = -1$$

This occurs at the radius where the magnetic rigidity $P/q = rB$ reaches its maximum.

2. There is a limit of acceleration that occurs due to the loss of isochronism. This limit is achieved when the RF phase has slipped with 90 degrees. Of course it depends on the dee-voltage.

If the vertical pole gap is much larger than the radial gain per turn (as is the case for almost all cyclotrons that have been built so far) the second limit is achieved earlier than the first. However, when the pole gap is small and furthermore when this gap is elliptically shaped (and the dee-voltage is not too small) the first limit is achieved first and the beam is self-extracted. However, in this case the particles will come out at all possible azimuth and there is not really a well-defined coherent extracted beam. In order to achieve this, an elliptical pole gap is used which makes it possible to realize very sharp magnetic gradients close to the pole radius. At the same time a groove is machined in one of the cyclotron poles that provides an extraction channel. This channel simultaneously serves as magnetic septum and as gradient corrector. This is illustrated in Fig. 28.

![Fig. 28: In the IBA self-extracting cyclotron, a groove in one of the poles is machined in one of the poles (right) in order to create an extraction channel. This channel provides a magnetic septum at the entrance and at the same time gradient correction and focusing. An elliptical pole gap is used, allowing for sharp radial gradients in the magnetic field near the pole edge.](image)

In principle, the scheme for self-extraction is quit similar to the usual scheme for resonant precessional extraction:

- Harmonic coils create a coherent oscillation.
- The beam is accelerated into the fringe field where $\nu_r = 0.6$. 

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The groove creates a kind of magnetic septum and at the same time provides for a gradient corrector channel.

Still within the vacuum chamber, a permanent magnet doublet is placed which continues the extraction path and focuses the beam in both directions.

Figure 29 shows a photograph of the interior of the IBA self-extracting cyclotron. The part of the beam that is not well extracted is intercepted by a low activation water-cooled beam catcher. With this machine a beam intensity of 2 mA has been extracted with an efficiency of 80%.

![Photograph of the extraction elements in the IBA self-extracting cyclotron.](image)

**Fig. 29:** Photograph of the extraction elements in the IBA self-extracting cyclotron. The harmonic coils are placed underneath the pole covers. An extraction efficiency of 80% has been achieved and 2 mA of protons have been extracted. The horizontal extracted beam emittance ($2\sigma$) is about $300 \pi \text{ mm mrad}$.

## 4 Conclusion

Besides the realisation of the magnetic field, the most difficult problem in cyclotron design remains the injection as well as extraction. For industrial applications there is generally a need for higher and higher beam intensity. This implies at the same time a minimization of beam losses during injection as well as extraction. As far as theoretical and analytical methods are concerned, nothing really new has appeared during last five to ten years that were helpful in this aspect. However, more and more importance is given to the computational tools that are needed to optimise the design. This concerns 3D finite element software packages that are used to model the magnetic as well as magnetic field, but also more specialized orbit tracking codes that can take into account sufficient detail. The latter usually are developed in house.

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References


