Injection and Extraction in Cyclotrons

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Abstract

After an introduction to the related basics of cyclotrons, this article describes injection and extraction schemes in cyclotrons. Often these represent the critical aspects of cyclotron designs. For injection, we discuss internal sources, electrostatic inflectors, horizontal injection and matching. For extraction, we cover the scaling of turn separation, electrostatic septa and charge-exchange extraction. Low loss extraction of high-intensity beams is discussed in particular detail.

Keywords

Cyclotron; injection; extraction.

1 Introduction

Cyclotrons have a long history in accelerator physics and are used for a wide range of medical, industrial, and research applications [1]. The first cyclotrons were designed and built by Lawrence and Livingston back in 1931 [2]. The cyclotron represents a resonant accelerator concept with several properties that make it well suited for cost-effective and compact accelerator installations, but also for the acceleration of hadron beams with high average intensity. It is a powerful concept for the following reasons. The circulation time of the beam can be kept constant by arranging the scaling of bending radius and velocity in proportion. Thus neither frequency nor magnetic field must be varied in the process of acceleration and the beam can be accelerated continuously. A simple-shaped vertically oriented magnetic field plus a pair of electrodes for acceleration by a radiofrequency (RF) field are sufficient to construct a classical cyclotron. The acceleration device can be used repetitively, thus presenting a cost-effective solution. The most significant limitations of cyclotrons are the limited energy range and the relatively weak focusing, which imposes a limit for the bunch charge. While the acceleration process can be realized in a straightforward way in cyclotrons, clean injection and extraction into and out of this continuous accelerating scheme are challenging.

In the series of the CERN accelerator school CAS, the topic of injection/extraction for cyclotrons have been considered already several times in depth [3–5]. This paper touches on all relevant techniques, but focuses a bit more on specific issues with high-intensity beams. Most of the cited papers are available in electronic format on the internet, and related links are given in the references section.

2 Related cyclotron basics and magnetic versus electric deflection

The revolution frequency of an ion beam in a classical cyclotron is given by

$$\begin{aligned} f_c = \frac{\omega_c}{2\pi} &= \frac{qB_z}{2\pi\gamma m_0} \\ &\approx 15.2\,\text{MHz} \cdot B(\text{T})\ (\text{for protons}). \end{aligned} \tag{1}$$

Here m_0 and q are ion rest mass and charge, and B_z the vertically oriented bending field. The frequency is constant for low energies, a fact that made the construction of the first classical cyclotrons relatively easy (Fig. 1). But as soon as γ deviated by a few per cent from 1 the particles would run out of phase, and extended concepts had to be implemented, in the form of the isochronous cyclotron
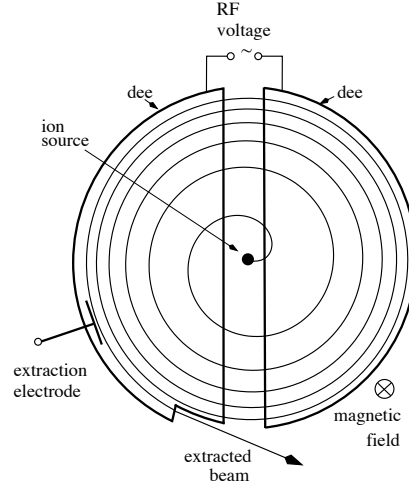
Fig. 1: Conceptual sketch of a classical cyclotron in plan view. Thanks to the simple concept, the first cyclotrons were constructed as far back as the 1930s.

and the synchro-cyclotron. In the isochronous cyclotron the average magnetic field is raised radially in proportion to γ, to keep the circulation time constant. Vertical focusing is provided by azimuthal variation of the bending field. The radial betatron frequency ν_r can be computed by expanding the equation of motion around the orbit radius R and by taking into account the radial slope of the bending field [6]. The result is

$$\nu_r \approx \sqrt{1 + \frac{R}{B}\frac{\mathrm{d}B}{\mathrm{d}R}} \approx \gamma. \tag{2}$$

The relation to γ is computed from the square-root term by taking into account the isochronous condition, i.e. $R \propto \beta$ and $B \propto \gamma$. In comparison to alternating gradient synchrotrons the focusing in cyclotrons is relatively weak since the beam energies are usually below 1 GeV. Also the vertical tune ν_z is typically a low number. This is important for injection matching and for acceleration of high-intensity beams, since the transverse space-charge forces counteract the relatively weak focusing of cyclotrons. Average beam optics parameters as beta-function and horizontal dispersion are estimated by $\beta_r \approx R/\gamma$ and $D_r \approx R/\gamma^2$. In order to prevent emittance blowup the injected beam must be matched to the appropriate optics on the first turns.

For clean extraction of high-intensity beams the turn separation is the most relevant parameter. To extract the beam by electrostatic deflection a thin electrode has to be placed in between the turns. To understand the basic scaling we consider here first the non-relativistic case with $\gamma = 1$, $B = \mathrm{const}$ and ΔE_k a constant energy gain per turn:

$$
\begin{aligned}
BR &= \frac{p}{q} = \frac{1}{q}\sqrt{2mE_k}, \\
\frac{\mathrm{d}R}{R} &= \frac{1}{2}\frac{\mathrm{d}E_k}{E_k}, \\
\Delta R(R) &= \frac{m}{q^2 B^2}\frac{\Delta E_k}{R}, \quad \Delta R_{\mathrm{extr}} = \frac{1}{2}R_{\mathrm{extr}}\frac{\Delta E_k}{E_{k,\mathrm{extr}}}.
\end{aligned}
\tag{3}
$$

Thus, during the acceleration process the turn separation is reduced as $1/R$. For a given final energy $E_{k,\mathrm{extr}}$ the turn separation scales with the extraction radius, i.e. with the size of the cyclotron.

In order to compute the turn separation for the case of the isochronous cyclotron with higher energies we have to include relativistic factors and the radial change of the magnetic field. As a starting point we use the total differential of the expression for the magnetic rigidity (6):

$$\frac{\mathrm{d}B}{B} + \frac{\mathrm{d}R}{R} = \frac{\gamma \, \mathrm{d}\gamma}{\gamma^2 - 1}. \tag{4}$$

This single equation relates the three parameters kinetic energy (through γ), orbit radius R and magnetic field B. With n_t denoting the turn number, the radius increment per turn is computed as

$$\begin{aligned}
\frac{\mathrm{d}R}{\mathrm{d}n_\mathrm{t}} &= \frac{\Delta E_k}{m_0 c^2} \frac{\gamma R}{(\gamma^2 - 1)\nu_r^2} \\
&= \frac{\Delta E_k}{m_0 c^2} \frac{R}{(\gamma^2 - 1)\gamma}.
\end{aligned} \tag{5}$$

The first line in (5) is a more general expression, indicating the option to change the radial slope of the magnetic field that affects ν_r and the turn separation. If the condition of isochronicity is applied through (2) one obtains the second line in which the slope of the field is not a free parameter. However, in the vicinity of the outer radius in a cyclotron this condition can be violated over a few turns in order to increase the turn separation locally for better extraction efficiency. For larger energy the strong dependence on γ leads to quickly diminishing turn separation. A practical limit is reached for proton cyclotrons at an energy of $0.8 \ldots 1$ GeV. For fixed final energy the turn separation also scales with the orbit radius at extraction, so it is generally easier to extract from a large cyclotron. The derivation of this relation is given in more detail in [6]. For example in the PSI Ring cyclotron with protons of 590 MeV kinetic energy and an extraction radius of 4.5 m this number is about 6 mm. The scaling with the size is illustrated in Fig. 2 for a hypothetical cyclotron that accelerates to 800 MeV with different maximum field strength at extraction, thus a varying overall size.

In compact cyclotrons with a factor 1000 less intensity, turn separation is not as critical and one can even allow overlapping turns with acceptable extraction losses. In order to realize extraction and injection schemes the beam must be deflected onto the first turn or out of the last turn. For this deflection static electric or magnetic fields are used. The challenge is to deflect only one turn and to minimize the effect on neighboured turns. Magnetic fields are used in septum magnets and the bending strength is given by the well-known magnetic rigidity, here given as a function of the relativistic γ factor:

$$B\rho = \frac{m_0 c}{q} \sqrt{\gamma^2 - 1}. \tag{6}$$

For injection and extraction elements the application of electric fields has some advantages. More complex field shapes can be realized, for example using a spiral inflector as described later. An electrostatic electrode can be very thin in cases where a neighboured turn passes closely. The corresponding electrostatic rigidity is calculated as follows:

$$E\rho = \frac{m_0 c^2}{q} \frac{\gamma^2 - 1}{\gamma}. \tag{7}$$

At low energies, e.g. at ion source energies, (7) can be approximated by $E\rho \approx 2U_\mathrm{acc}$, where U_acc is the accelerating voltage in the source. As it turns out, electrical fields are more effective at lower energy. For protons a few numerical examples for attainable bending strength are given in Table 1.

3 Internal sources

Internal ion sources are often used in compact cyclotrons. That is possible since the magnetic field covers also the central region of the cyclotron, and the beam can be accelerated from very low energy.
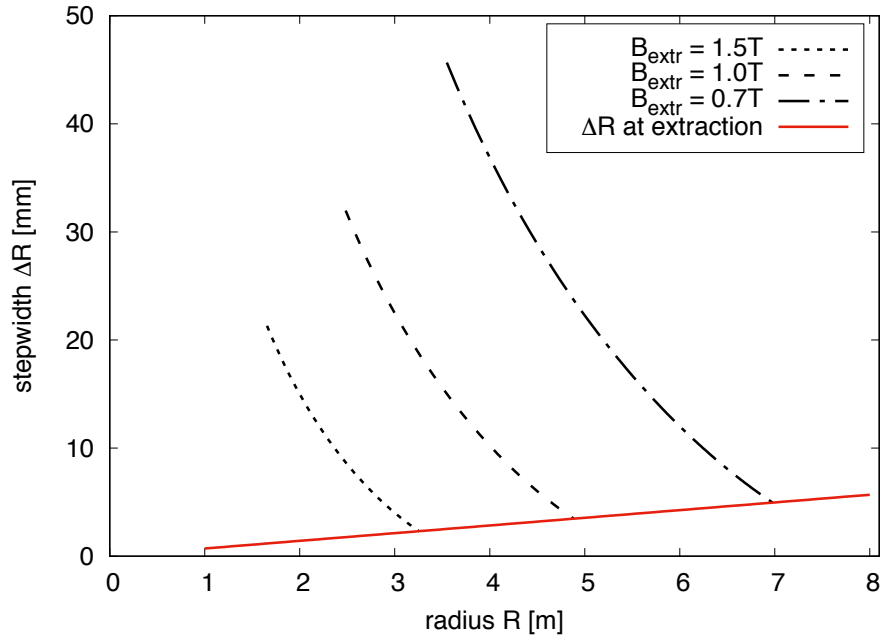
Fig. 2: During the course of acceleration, in all examples from 100 MeV to 800 MeV, the turn separation decreases as a function of radius. However, the final turn separation at the extraction radius is proportional to this radius, i.e. a larger cyclotron with lower magnetic field is advantageous for clean extraction.

Table 1: Bending radii achieved with typical magnetic and electric fields for protons at different kinetic energies

E_k	$B = 1\,\mathrm{T}$	$E = 10\,\mathrm{MV/m}$
60 keV	0.035 m	0.012 m
1 MeV	0.14 m	0.2 m
1 GeV	5.6 m	150 m

As compared with the external injection of a quality beam, an internal source delivers a diffuse cloud of ions. Typically a mixture of different charge states is created. An important aim of the central region design in a compact cyclotron is therefore the efficient capture of the desired ion species at low energies. If unwanted ions are accelerated to higher energies, e.g. beyond $\approx 7\,\mathrm{MeV}$, these will create secondary activation. Fig. 3 shows a sketch of a cold cathode ion source and the concept of the central region in a 250 MeV cyclotron for cancer treatment (Varian).

In the 'chimney', electrons emitted from cathodes ionize injected hydrogen gas. The vertical magnetic field in the compact cyclotron is essential for this process since the electrons follow a spiral path in the field, which greatly enhances the ionization rate. The principle is similar to the function of an ion getter pump, or Penning ionization. The generated ions leave the chimney though a narrow slot. The first step of acceleration is achieved by a so-called puller electrode which is part of one of the four Dees in this cyclotron. Repetitive acceleration of the beam is performed by applying a high voltage RF potential to the Dees. The paths of the other charge states H_2^+ and H^- are also indicated in the figure. Unwanted ions are collimated at an early stage. For certain applications like fast pencil-beam scanning of cancer tumours, the stability of the beam current on a fast time-scale is important. Several parameters must be optimized for high stability and a high current for the Penning discharge seems to be particularly beneficial. Due to the injected gas the internal ion source is a limiting factor for the vacuum quality in a cyclotron. Another limitation of internal sources is the fact that heavier ions and specific charge states like H^- cannot be injected in this way. In summary internal sources present an elegant and cost-effective
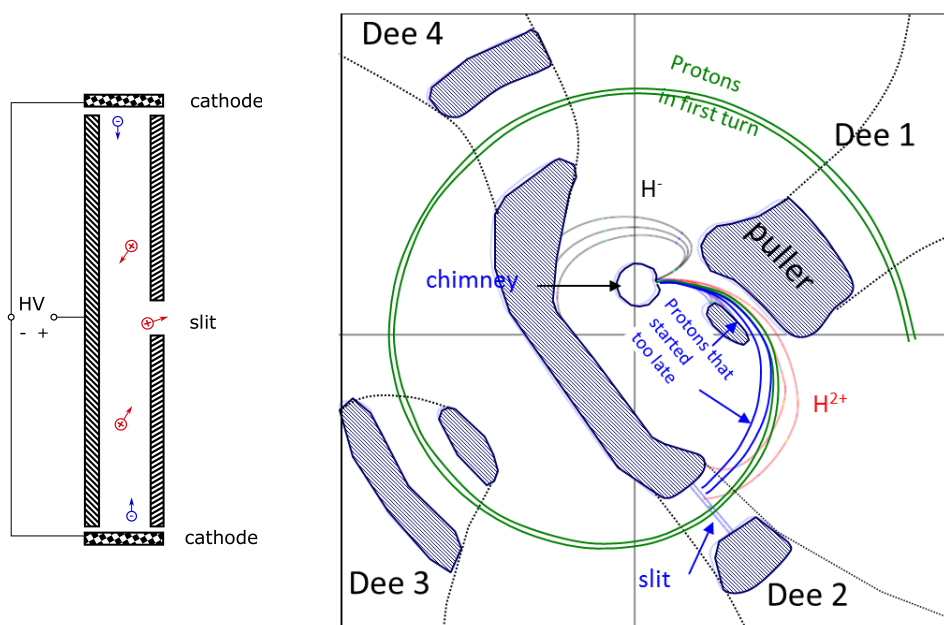
Fig. 3: Hydrogen atoms are ionized by electrons and emerge from the slit in the centre of the tube (left). The inner region concept of the compact superconducting 250 MeV Varian cyclotron is shown on the right (courtesy of M. Schippers, PSI). Collimation of unwanted charge states and deviating protons must be done at low energy.

solution for compact cyclotrons, but several limitations exist.

4 Injection

In many situations an external ion source or even a pre-accelerator must be employed. The reasons can be high intensity requiring a complex source, better beam quality, the need for specific ions or charge states. Separated-sector cyclotrons with a field-free region in the centre require a minimum beam energy, excluding the use of internal sources. Axial injection (compare Fig. 4) is often used for small cyclotrons with magnetic field in the centre. The beam enters vertically and is bent by $90 \deg$ into the plane of the circulating orbits. The bending is realized by an electrostatic or magnetostatic inflector. The vertical magnetic field supports radial bending at the same time, turning the beam towards the direction of the first turn in the cyclotron. For horizontal injection the beam enters the cyclotron radially in the plane of the circulating orbits. It passes the centre region and is bend by magnetic elements towards the first turn orbit. The last step is often realized by an electrostatic deflector with the challenge not to affect the second and other circulating turns. Another option is stripping injection, where the beam passes a foil to remove electrons from the ion. The change in charge state brings the ion on the orbit of the first turn.

The design of a cyclotron injection requires consideration of many aspects, some of which affect the design of the entire cyclotron:

- longitudinal bunching and optimization of capture efficiency;
- optics matching including space charge for high-intensity beams;
- choice and design of the inflector element;
- central region design, radial and vertical centring.

An ion source delivers a DC beam, but for acceleration in a cyclotron the beam must be bunched. In the simplest case, similarly to the function of an internal source, the bunches are formed in the cy-
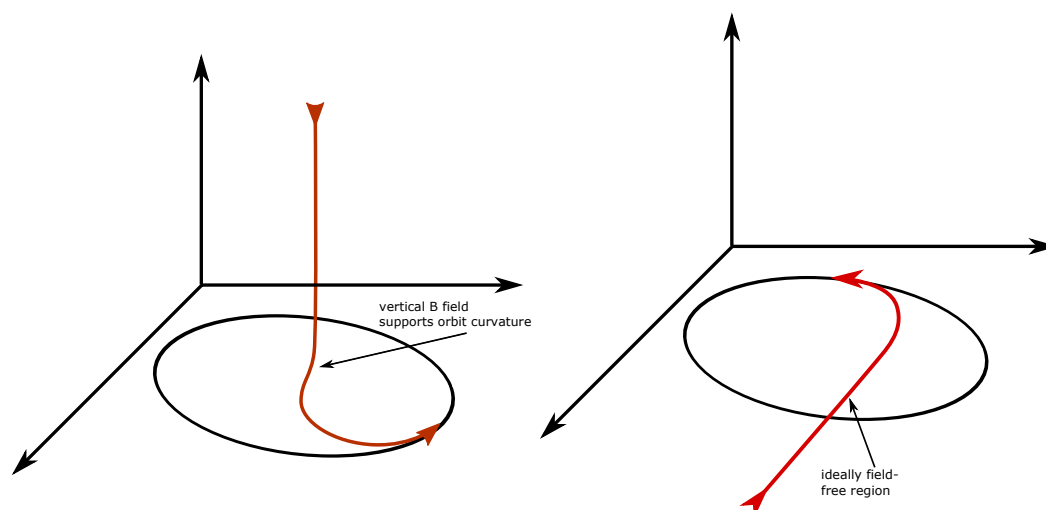
Fig. 4: Beam orbit paths for axial (left) and horizontal injection (right)

clotron itself since only ions arriving within a certain RF phase window will be accelerated. However, this scheme has low capture efficiency and one risks unwanted beam losses throughout the acceleration process.

The beam can be bunched by utilizing a buncher cavity outside the cyclotron. The buncher cavity introduces a velocity modulation resulting in the formation of bunches. Due to the acceleration in the cyclotron and the decrease of the relative velocity spread, the bunches sustain their shape. In the PSI high-intensity accelerator the beam is provided by a Cockcroft Walton pre-accelerator at an energy of 870 keV with low energy spread. In order to maximize the capture efficiency in the Injector II cyclotron one uses a third-harmonic buncher cavity at 150 MHz in addition to a fundamental-mode 50 MHz buncher. The harmonic cavity increases the linear region of the voltage modulation seen by the beam particles. The central region of the cyclotron has several adjustable collimators to remove protons with deviating phases from the beam at low energy. As an alternative to a Cockcroft Walton pre-accelerator, an RFQ pre-accelerator, providing an already-bunched beam, could be used.

Also in the transverse planes the injected beam must be matched to the envelope functions of the circulating beam. If the beam is not properly matched, the bunches will rotate in phase space, resulting in tails and potential difficulties at extraction. Complete filamentation of mismatched bunches is normally not an issue in a cyclotron, due to the short acceleration time. In comparison, the focusing strength in a cyclotron is much weaker than in alternating gradient synchrotrons. Beam envelope functions are thus just mildly modulated around the circumference. An example calculation is given in Fig. 5. In the case of high-intensity beams, space-charge forces must be taken into account. Transverse space-charge forces act against the focusing of the magnetic lattice and alter focusing frequency and envelope functions. Strong space-charge effects set an intensity limit for cyclotron, e.g. [9].

An electrostatic inflector for axial injection can be realized in different ways [3, 4]. The mirror inflector is the most simple design, consisting of a pair of charged plates. Geometry and voltage are adjusted so as to achieve the desired bending angle, normally $90 \deg$. As soon as the beam deviates from the vertical direction, the magnetic bending field of the cyclotron starts to deflect the beam as well, which forces the beam onto a spiral path. The magnetic force can be utilized to gradually bend the beam into the direction of the first turns orbit. The electrostatic force is applied in an optimal way if it acts perpendicular to the velocity vector of the particles at each point of the orbit. Only in this way a change of the kinetic beam energy is avoided. Such scheme is realized in the spiral inflector, e.g. Fig. 6, in which the two electrode plates are gradually bend with the changing direction of the beam. A detailed treatment
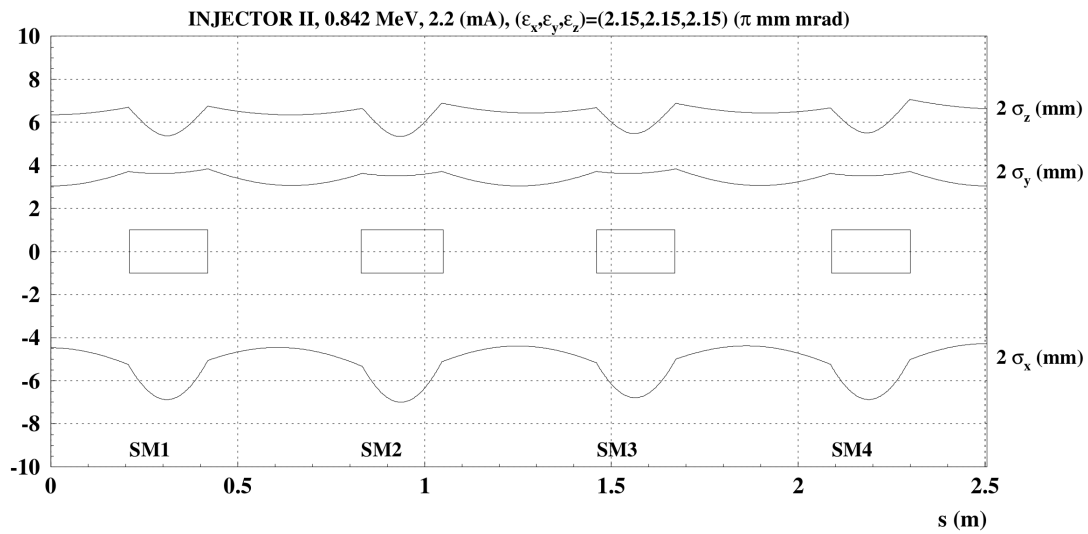
Fig. 5: Matched beam size in the PSI Injector II cyclotron as a function of azimuth at 0.84 MeV. The simulation includes space-charge forces [8].
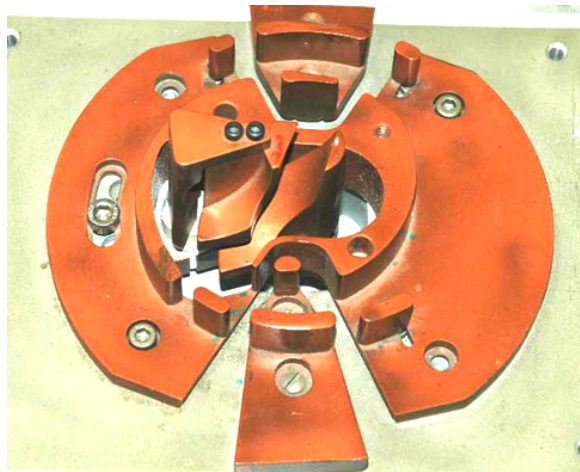
Fig. 6: Spiral inflector as used in a 30 MeV cyclotron (courtesy: IBA). The pair of curved electrodes is visible in the centre of the image.

of the beam dynamics in a spiral inflector is given in [7].

For horizontal injection in a separated-sector cyclotron the free space in the central region can be used to install magnets for bending and focusing of the beam to be injected. In order to finally deflect the beam onto the first turn orbit, often an electrostatic deflector with a thin electrode placed between the first and second turns is used. The design of this injection element can be similar as the electrostatic extraction channel in Fig. 7.
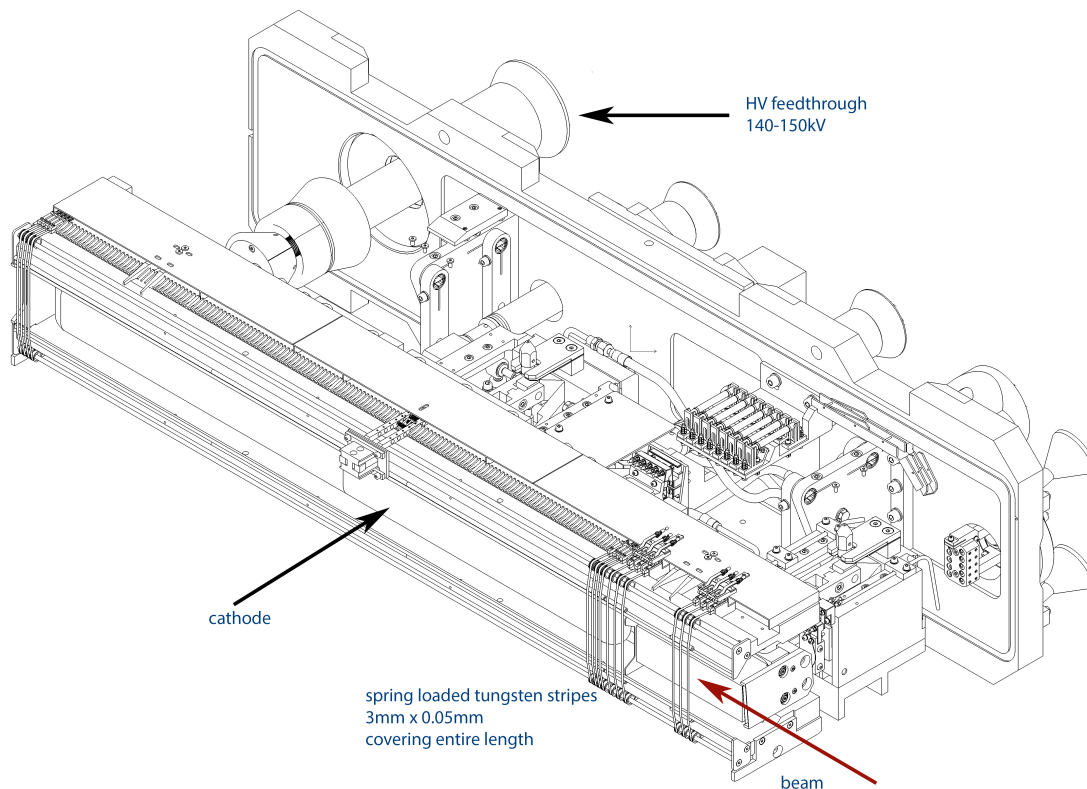
5 Extraction

For some applications, for example isotope production with low beam intensity, it is even unnecessary to extract the beam. The target can be inserted into the cyclotrons vacuum chamber for irradiation by a proton or ion beam. For compact, low-cost cyclotrons internal targets are the most effective solution. In

this case the main effort has to be spent on a reliable mechanism to exchange the targets.

For higher intensities extraction of the beam to an external beamline is required, and the methods of choice are then electrostatic deflection of the last turn, self-extraction in the fringe field of the cyclotron or charge-exchange extraction, 'stripping'. The latter of course requires acceleration of a not fully stripped ion, introducing specific issues.

Self-extraction of a beam can be achieved in the fringe field of the magnet at a radius where the normally positive slope of the magnetic field has decreased to a negative value at which the radial focusing stability is lost ($\nu_r = 0$, compare Eq.(2)). For this method we must avoid losing isochronicity too early. An extraction channel is machined in the magnet iron to provide a septum field and transverse focusing for the extracted beam. More details on this method are given in [3].

Fig. 7: The electrostatic extraction channel (EEC) of the PSI Ring cyclotron allows extraction of 2.4 mA CW current with relative losses below 2×10^{-4}.

For extraction with an electrostatic element (e.g. Fig. 7) the turns should ideally be separated to place the septum electrode in-between the turns, minimizing the rate of ions hitting the electrode and the resulting activation. The scaling of the average turn separation in cyclotrons was discussed in Section 2. Typical turn separation is in the range of a few millimetres. In summary, it diminishes quickly for high energy with γ^{-3} and it scales with the size of the cyclotron. Especially for compact superconducting cyclotrons with high fields the turn separation can be smaller than the beam size. But also for normalconducting cyclotrons this is a long-standing problem, and several methods have been developed to increase turn separation beyond the value generated by acceleration only. In several ways the concept of resonant extraction can be utilized. Coherent radial beam oscillations are excited by an harmonic bump. This is particularly effective in the vicinity of the integer resonance $\nu_r \approx 1$. As
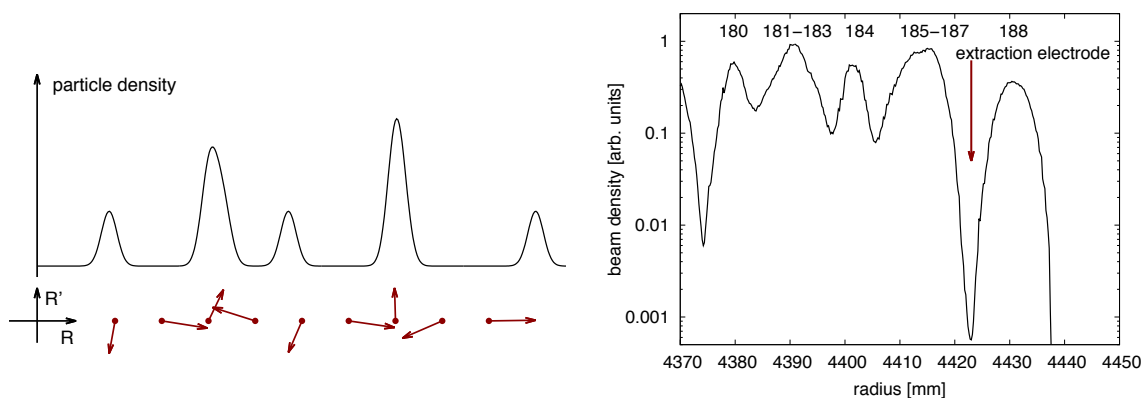
Fig. 8: Turn separation at extraction is enhanced by introducing coherent radial beam oscillations. The concept graph shows the clockwise rotating phase vector of the beam centre in the lower part. The multi-turn beam profile as a result of superimposing the shifted Gaussian beam distributions of individual turns is shown in the upper part. The right picture shows the measured beam density at extraction in the PSI Ring cyclotron on a logarithmic scale. Turn numbers and location of the electrode of the electrostatic deflector are indicated.

shown in Eq. (2), the radial tune is normally larger than 1 to keep the beam isochronous. However, close to extraction a phase slip can be tolerated for a few turns and the focusing is naturally weaker at the edge of the magnetic field. Close to the betatron resonance the amplitude of coherent oscillations is increasing quickly, thereby providing larger turn separation. In a modified version of this method, called precessional extraction, the tune drops quickly below 1 after exciting the resonance. This leads to an azimuthal shift of the maximum of the orbit oscillation from turn to turn, providing larger turn separation at the fixed azimuth of the septum. If the tune is close to a half-integer resonance, it is also possible to excite beam oscillations by introducing a gradient bump. Extraction efficiencies of 80 % can be achieved even in compact superconducting cyclotrons using these methods of resonant extraction.

In the following, we discuss the extraction process in the PSI Ring cyclotron in more detail. Coherent beam oscillations and a local shift of the radial betatron frequency are used to enhance the turn separation from the normal 6 mm gain by acceleration to a tripled value of 18 mm. Using an electrostatic septum it is possible to extract a beam of 1.4 MW average power with an efficiency of 99.98 %. The lost beam power of $\approx$ 200 W leads to a peak activation of $\approx$ 10 mSv/h in magnets of the extraction beam line, which is a tolerable level for service. The design of the electrostatic septum has been optimized in several iterations to improve performance and reliability, see Fig. 7. The electrode is realised as a series of 3 mm wide and 50 μm thin tungsten stripes. Tungsten has a high melting point and tolerates best accidental beam impact. If a stripe breaks it is pulled out of the beam plane by a spring. The effective electric length is 920 mm and the deflection angle 8.2 mrad. To reduce the number of high voltage trips, the element is covered by a metallic cage inside the cyclotrons vacuum chamber, to avoid accumulation of surface charges on the ceramic insulators. In the PSI Ring cyclotron the beam is already injected off-centre at 72 MeV. The coherent radial oscillation persists throughout the acceleration process. This approach has no significant drawbacks since the machine behaves sufficiently linear. At the coupling resonance $\nu_r \approx 2\nu_z$ the large radial oscillation could potentially be coupled to the vertical plane. In practice the resonance can be crossed quickly, avoiding vertical oscillations (Fig. 9). When the beam approaches the extraction radius the tune equals roughly $\nu_r \approx 1.75$. The phase space vector rotates by 3/4 of a circle per turn as shown in Fig. 8. At the azimuth of the septum the beam oscillation results in a certain pattern, with some turns overlapping. The three turns before the last turn, 185-187, are fully

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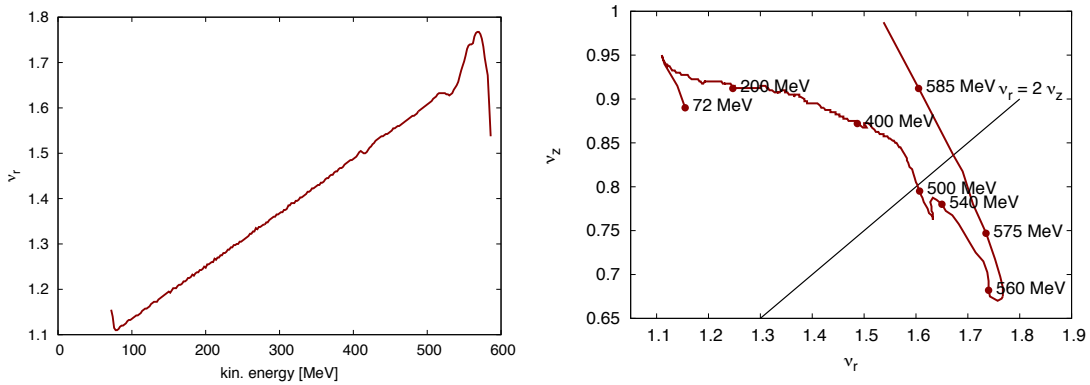
Fig. 9: The radial betatron tune in the Ring cyclotron follows closely the relativistic γ-factor (left). Over the last turns the focusing is reduced, enhancing turn separation. Coupling resonances must be crossed quickly (right) to avoid excitation of vertical oscillations.

overlapping and turn 187 is shifted inwards by the maximum oscillation amplitude. At this radius the tune is quickly reduced towards 1.5 so that the phase vector of the last turn is pointing outwards instead of downwards. As a result the normal turn separation is tripled in this scheme. In the right part of Fig. 8 a measured profile of the turns 180 to the extracted beam 188 is shown. At the location of the septum the particle density is three orders of magnitude lower than in the beam centre.

Besides the large turn separation, another ingredient of clean extraction are low beam tails. One important mechanism for tail production is longitudinal space charge, introducing energy spread, which is then converted into transverse tails. Fast acceleration is the best method to reduce these tails. Joho has shown in [10] that the attainable intensity in the PSI Ring cyclotron scales as the inverse of the cubed number of turns. Indeed, over the history of the accelerator significant improvements in intensity were achieved by raising the accelerating voltage, and the achieved intensity is in agreement with Joho's scaling law.

Stripping or charge-exchange extraction is another elegant scheme to extract a beam from a cyclotron. In this case ions are accelerated that are not fully ionized. The electrons are removed from the ions by passing them through a thin foil. The sudden change of the charge-to-mass ratio causes a change of the curvature of the ion path in a magnetic field. In this way the stripped ions are separated from the circulating beam and they are easily extracted. A prominent example for this technology is the acceleration of H^-, a proton with two bound electrons. After removing the two electrons the orbit curvature is inverted. By introducing the stripping foil at varying radius it is even possible to extract the beam at different energies, Fig. 10. While the advantages of the method are obvious, a number of difficulties must be mentioned. The second electron of H^- is bound rather weakly to the proton. In a magnetic field or by interaction with residual gas atoms, the ion is dissociated with relatively high probability. For example in the TRIUMF cyclotron the maximum magnetic field is limited to about $0.6\,\mathrm{T}$ for this reason. Another issue is the lifetime of the stripping foil, which is heated by direct interaction with the ion beam, but also by the stripped electrons. These electrons are spiralling in the magnetic field at a radius lower than the ion-bending radius by the ratio of the rest masses, which is typically just millimetres. The electron could pass the stripping foil many times until its kinetic energy is fully deposited in the foil. Thus design and positioning of the foil must be carefully optimized to obtain a good lifetime and serviceability.

Consequently H^- acceleration is only possible with low bending fields, but on the other hand superconducting magnet technology with high magnetic fields, is one of the major advancements in accelerator technology. As it has been shown, septum extraction is also difficult in compact cyclotrons. As a possible way out, the use of stripping extraction with accelerated H_2^+ ions is discussed. These ions have a higher binding energy ($2.7\,\mathrm{eV}$) for the electron than H^- ($0.7\,\mathrm{eV}$) and resulting dissociation prob-
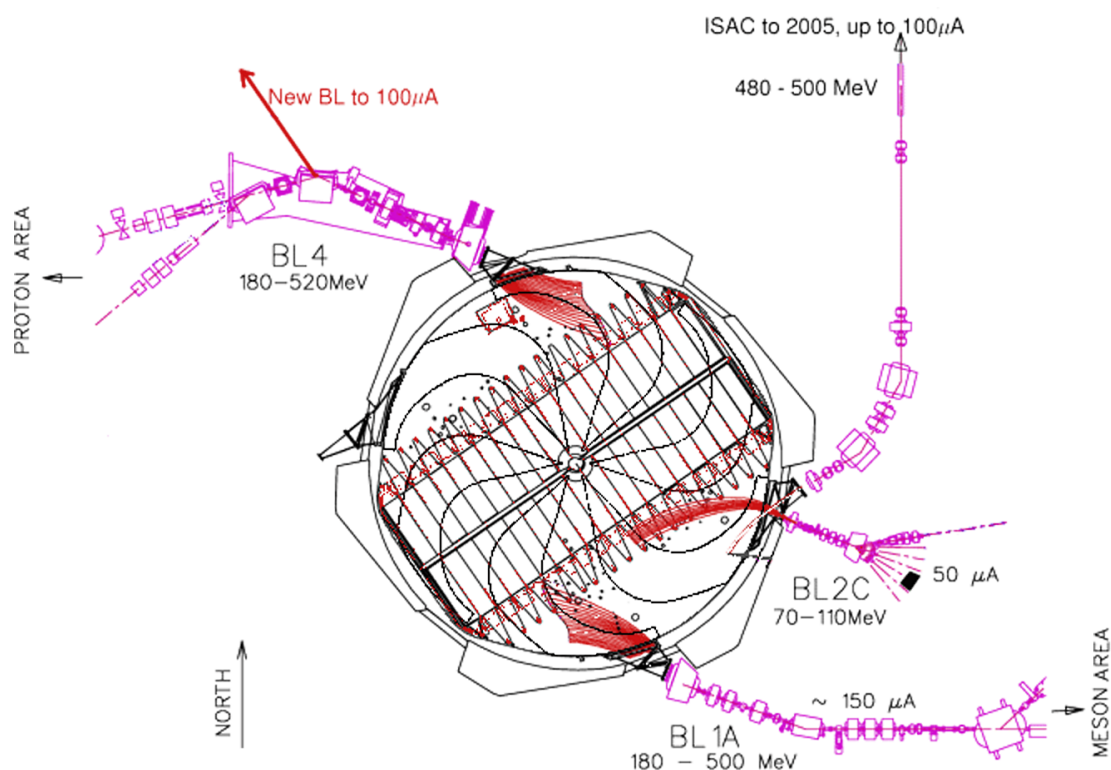
Fig. 10: Acceleration of H$^-$ ions in the TRIUMF cyclotron and stripping extraction allows to provide multiple beams in parallel at variable energy (courtesy TRIUMF).

abilities even in high magnetic fields are low, allowing the acceleration of megawatt beams in relatively compact cyclotrons. On the downside, H$_2^+$ has a charge-to-mass ratio of 1/2, requiring higher bending fields than for protons. As another complication, stripping of the electron does not invert the curvature but reduces the bending radius by a factor of 2. This is sufficient to separate the stripped ions from the circulating beam, but it leads to a complicated extraction path across the cyclotron [11]. While the statement on higher binder energy is correct for the ground state of the ion, the situation is more complicated, in particular since this ion exhibits vibrational states with relatively long lifetime. Already in the source a certain fraction of the ions is produced in an excited state, from which dissociation is possible in strong fields. Thus the details of loss mechanisms for these ions are still under discussion.

6 Summary

Owing to the simplicity of the repetitive acceleration scheme with constant frequency the cyclotron presents an effective concept for ion beam acceleration. Often the challenging aspects of a design are efficient injection and clean extraction. In the simplest case an internal ion source can be used in compact cyclotrons. For higher intensity, better beam quality or certain ion beams, the beam must be generated outside the cyclotron and injected. Axial injection is used for smaller cyclotrons while horizontal injection is typically used for separated-sector cyclotrons with field-free regions in the centre. Electrostatic inflectors provide sufficient bending angles at low energy and allow realization of complex injection paths like the case of the spiral inflector. Charge-exchange or stripping processes can also be used to inject beams.

Extraction of a beam is a challenging process as well. Excessive uncontrolled beam losses lead to secondary activation of components, which should be avoided as best as possible. The most common extraction concept involves the use of an electrostatic septum, deflecting only the last turn. Turn separation is the most critical parameter and several schemes are used to increase the gap between last and second last turn beyond the value that is given by the energy gain of the beam. Self-extraction of a beam without a septum is also possible, but requires specific shaping of the magnetic field at the radius of extraction. Another elegant method is acceleration of ions that are not fully ionized and stripping of the electrons by a foil at the desired extraction radius. While this method provides more flexibility to vary the energy of the extracted beam, it has also disadvantages such as non-negligible probabilities of Lorentz dissociation before extraction. For high beam intensities the use of stronger bound H_2^+ ions is investigated.

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