BEAM TRANSFER BETWEEN ACCELERATORS AT CYCLOTRON FACILITIES

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Abstract

A short review is given of some design criteria for beam transfer lines between accelerators. The importance of good matching in the 6-dimensional phase space is pointed out. For high intensity beams, some approximate space charge formulas are given. Examples of specific transfer lines at cyclotron facilities are illustrated.

1. Introduction

For the construction of high energy accelerators, it proves to be advantageous to split up the acceleration process into two or even more stages. This calls for beam transfer systems between the different accelerators. We can distinguish two main categories:

a) Pulsed beams:
The most commonly used accelerator combinations are: LINAC-synchrotrons, Booster synchrotrons - Main Synchrotron, Synchrotron-Storage-rings. One can take full advantage of the pulsed structure in the beam by using pulsed elements in a multi-turn injection mode. Space charge effects, which limit the beam intensities, favour an injector with high energy.

b) Continuous beams (CW):
From now on we restrict ourselves to this category and furthermore, we treat only accelerator combinations involving cyclotrons. Table 1 shows a list of operating or planned cyclotron facilities which have beam transfer systems between different accelerators. A special case is the class of injection systems where the injector is just an external ion source: a novel medium plane injection scheme was applied at Saclay[1], while axial injection into a cyclotron was pioneered at Birmingham[2] with further developments at Grenoble, the Cyclotron Corporation in Berkeley, Karlsruhe, etc. Practically all newly developed solid pole cyclotrons provide the opportunity for axial injection. Since such systems were discussed at earlier conferences, we will not consider them any further in this report.

All elements involved in a beam transfer system are shown in the block diagram of Fig. 1. Obviously the first step for an accelerator builder will be to choose the proper transition energy between injector and main accelerator. Criteria for this choice are:

- minimization of total cost for injector, beam line and main machines, taking engineering complexity into account,
- reliability and access to machine components,
- beam performance, stripping efficiency for heavy ions, space charge effects and matching of the two RF-systems, if both machines are cyclotrons[3].

The two extreme cases are:

i) Low energy injector. For voltages below 1 MV, a Cockroft-Walton DC-stage is the obvious choice. These accelerators are cheap and reliable. Examples are the 300 KeV H^--injector at TRIUMF[4], the 450

Pre-Accelerator \ Main Accelerator	Solid Pole Cyclotron	Ring Cyclotron	Superconducting Cyclotron	Van de Graaff
Cockroft Walton	TRIUMF (DELFT)	Indiana 1 (SIN 1)		
Van de Graaff	Oak Ridge 1	VICKSI	(Chalk River) (Michigan State)	
Linac	ALICE, Orsay			
Compact Cyclotron		(GANIL 1) (South Africa)		DUKE CYCLOGRAAFF
Solid Pole Cyclotron	DUBNA (CYCLONE) (ORIC REC.)	SIN (Oak Ridge 2)	(Michigan State)	
Ring Cyclotron		Indiana 2 (GANIL 2) (SIN 2)		

Table 1

List of cyclotron facilities using beam transfer between different accelerators. Projects under consideration or construction are mentioned in parenthesis.

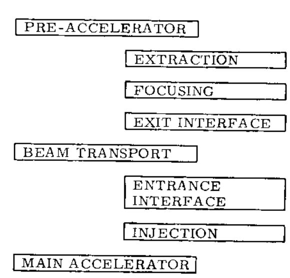

Fig. 1

Block diagram of structures involved in a beam transfer between two accelerators. The exit and entrance regions contain diagnostic equipment to check the beam properties.

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and 800 KV stages at Indiana and the 800 KeV injector for the proposed new injector at S.I.N.[5] Problems are: a crowded center in the following cyclotron stage and space charge effects for high intensity beams.

ii) High energy injector. Examples are the 72 MeV injector at S.I.N., ring I for 15 MeV protons at Indiana, the Van de Graaff injector at VICKSI and the new folded 25 MV Tandem at ORIC. Among the proposed facilities, GANIL, the South African project and the superconducting cyclotrons at MSU and Chalk River fall into this category. Orbital stability of the beam at high injection energies is generally very good. ν_r is not close to 1 and ν_z is high for ring cyclotrons. Problems are: a costly injector and the energy gain in the second stage has to be substantially higher than the energy spread of the injector in order to ensure a good injection efficiency.

2. Layout of Beamline

Once the decision about the injector energy has been made, one can go back to the block diagram of Fig. 1 and tackle the three main problems of extraction from the injector, beam transfer line and injection into the main machine.

Injection into cyclotrons is, in many cases, the most difficult part because the magnetic field has to bend the injected beam more than the internal beam (see e.g. Fig. 3 or the layout of the center region for the proposed separate sector cyclotron at GANIL[6]).

At extraction, on the other hand, the beam has to be bent less than the internal beam and has a natural tendency to be extracted by the fringe field. Therefore, one should concentrate very early on the injection method. Possibilities are: axial injection at low energies, injection through the medium plane with magnetic and electric elements, injection by stripping for heavy ions. Especially for superconducting cyclotrons, only the latter method seems to be possible.

A new method of a precessional injection without any injection elements has just recently been tried out successfully by Van Kampen at the Delft cyclotron[8]. Fig. 2 shows how protons of 200 KeV are injected in a trochoidal motion along the edge of a sector and finally centered with a strong first harmonic bump. This method shows great promise for the injection of heavy ions at higher energies than is possible with an axial injection system.

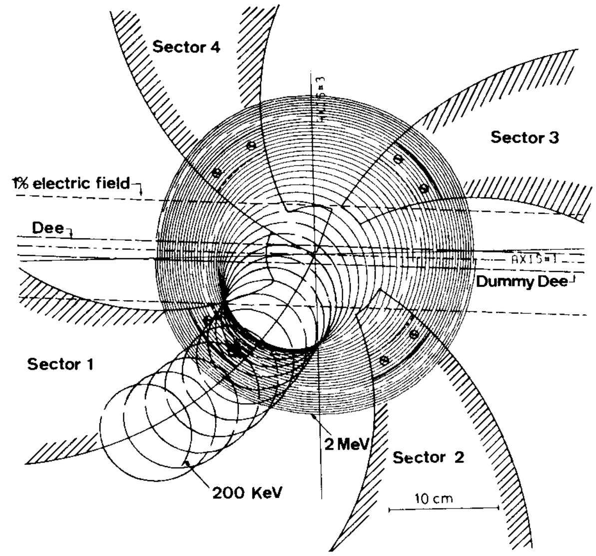

Fig. 2:
New injection scheme without injection channels for the Delft 4 sector cyclotron. 200 KeV protons drift along a sector edge towards the cyclotron center, where the electric field of the dee starts to increase the orbit radius. Due to a strong first harmonic bump, produced by the extension of the sectors 1 and 4, the orbits drift further until they are properly centered.

Injection into the TRIUMF cyclotron contains two innovations, both proposed by G. Dutto[9]:

a) Vertical steering electrodes correct for dee misalignments,

b) particles gain 100 KeV on their first dee gap crossing and 200 KeV on subsequent crossings at the same azimuth. This scheme, which is only possible for dees operating in a push-pull mode, allows optimal centering of particles with a wide phase range.

Extraction from a cyclotron injector has to be studied early in some detail, too, because the direction of the extracted beam gives an important input for the orientation of the accelerators in the experimental hall. Under all circumstances, vertical and substantial horizontal steering capabilities have to be provided immediately at the exit of the injector, since the final fringe field of the cyclotron field is known only very late in the game.

Beam transfer between accelerators is traditionally being studied too late in most projects. The designer of the transport line has then to fight against established boundary conditions and try to make the best out of it. In order to safeguard against this unlucky situation, the following guidelines should be adopted: The distance between the two accelerators should be on the high side. Empty space has a tendency to be filled very quickly! Foresee all possible future extensions, like an alternate injector (reserve the building space!), a separate exit for the injector beam for diagnostic purposes or isotope production, etc. Even beam sharing with a beam splitter can be considered at a place where the beam is rather broad in diameter.

Start very early with a zero order layout of the beamline with ruler and compass. Split up the line according to Fig. 1 into generous interface regions at extraction and injection where all measurements concerning intensity, beam quality and time structure can be done. Try to divide the rest of the system into modular subsections (waist to waist transport). After these preparations, the real work on beam optics with the program TRANSPORT[14] as the primary tool can start.

3. Beam Optics and Matching between Accelerators

The magnetic configuration of the main cyclotron determines the so-called acceptance of this accelerator. In the static case, the injection energy defines a closed equilibrium orbit and, in the dynamic case, the acceleration voltage defines a spiral-like quasi-equilibrium orbit[10]. Particles with small deviations from their equilibrium orbits will exhibit betatron oscillations. In the transverse phase space (x, P_x) or (y, p_y), so-called eigenellipses[11] will be traced out if the particle coordinates are plotted at periodic azimuthal intervals (see Fig. 10). It is the duty of the beam transport designer to match the incoming beam to these eigenellipses. This ensures periodic beam envelopes inside the cyclotron (see Fig. 4, 7 and 14) with a minimum of amplitude modulation and avoids deterioration of beam quality through precessional mixing[11].

Since the energy and time structure of the particle bunches also have to be adapted to the main accelerator, we speak of a matching process in six dimensions. Unfortunately, there is a coupling between energy and radial position of a particle at injection, because particles with higher energy have to be injected on correspondingly larger equilibrium radii. This energy-radius relation is called dispersion. The terms d and d' are used for the horizontal displacement and divergence of a particle with higher energy (or momentum) from a reference particle.

A beam is called dispersionless if d = d' = 0. If the energy spread for the injector beam is relatively large, which is the case for cyclotrons or linacs, somewhere along the beamline, it is advantageous to have a place where the energy spread can be measured and limited with a slit. The beam must be bent in order to produce a large dispersion at this energy slit.

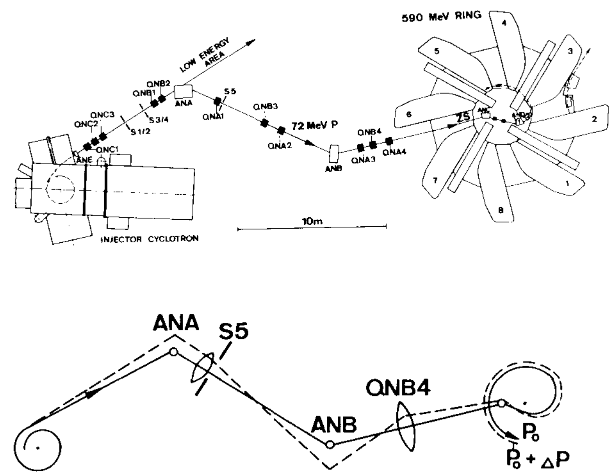

Fig. 3:

Layout of the beam transfer line between the S.I.N. injector cyclotron and the 590 MeV ring cyclotron. 72 MeV protons are guided in a 35 m long Z-shaped line toward the center of the ring. The top figure shows the geometrical arrangement of the beam line with quadrupoles drawn in solid black. The bottom figure shows schematically how the dispersion is matched. A particle with slightly higher momentum Po + ΔP (broken line) is brought to a higher injection radius in the ring.

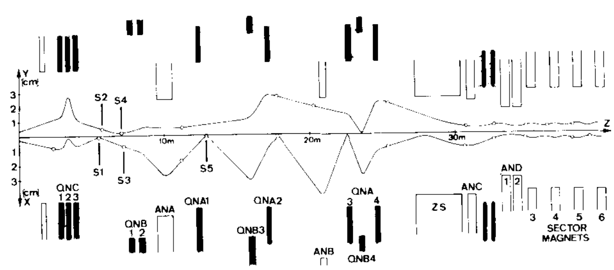

Fig 4:

Beam envelopes for the S.I.N. 72 MeV beam line. The emittance is measured with slits S1-S4. The energy spread can be measured at slit S5 where the dispersion is large (see Fig. 3). All beam profiles indicated by open circles can be observed with profile monitors.

The approximate formula for the momentum resolution of a single bend is given by Steffen[12] as:

$$(3.1) \quad \frac{dp}{p} = \frac{\varepsilon_x}{a \sin\frac{\varphi}{2}}$$

φ= bending angle, a=horizontal beam amplitude inside the bending magnet and $\pi\varepsilon_x$ is the horizontal beam quality. A good resolution requires, therefore, a large beam amplitude in the bending magnet.

It is crucial for the layout of the whole beamline to understand how the dispersion is affected by the different bending magnets and quadrupoles. Possible layouts are shaped in the form of a U, Z or W. Fig. 3 shows a simplified layout of the Z-shaped S.I.N. beamline for 72 MeV protons. It shows (as a broken line) how the dispersion is matched to the ring cyclotron.

In many cases, especially with van de Graaff or DC-injectors, the beam is practically dispersionless to start with. One often wants to keep this property as long as possible along the beamline, with dispersion matching with the main accelerator occurring only shortly before injection. For this purpose, symmetric, dispersionless bends are used. For example, a 90° bend is split into two 45° bends, with quadrupoles placed symmetrically between the two bends. The two most popular versions are:

i) A single quadrupole at the symmetry point between the two bends. This version is used at ALICE (see Fig. 6) and at VICKSI (see the bends A-Q2 - B and C-Q5 - D in Fig.15). Vertical focussing is provided by the edges of the bending magnets.

ii) Four quadrupoles between the two bends. A double beam waist and angular dispersion d' = o is produced at the symmetry point. This arrangement is more complex but offers more flexibility. A single energy slit at the symmetry point can filter out unwanted energies. This 90° bend version is used in the TRIUMF injection line with electric elements throughout (see Fig. 12). Fig. 5 shows a 90° bend with two rectangular magnets[13]. Its virtue is small geometrical aberrations. Similar layouts are used for some secondary beamlines at LAMPF (P3-beam) and S.I.N. (πE3 beam).

Before beam optics circulations can be started with a program such as TRANSPORT, one has to know the desired beam conditions at the beginning and the end of the beamline. The problem is that the magnetic fields of cyclotrons are measured very late in a project schedule, after the beamline geometry has been determined. Improvisations and reasonable assumptions have to be made in order to get started. (The architect is waiting for input!) The following steps for a first order matching between accelerators are recommended:

Assume that the beam from the preaccelerator can be matched to x - and y - slits in the interface region, with a triplet, for instance. This decouples any uncertainty in the extraction process of the injector from the rest of the beamline (see Fig. 4). Assume that the dispersion of the extracted beam is zero for a LINAC, van de Graaff or DC-injector. For a cyclotron, the dispersion is roughly given by the natural energy-radius dependence at the

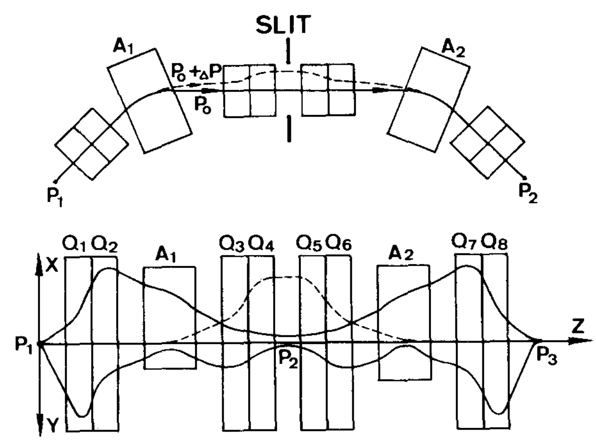

Fig. 5:

Example of a dispersionless 90°-bend with two rectangular bending magnets A_1, A_2 and eight quadrupoles. The broken line shows the trajectory of a particle with momentum $P_o + \Delta p$. At the symmetry point P2, there is a double beam waist and the momentum resolution has a maximum. A momentum slit allows removal of particles with an excessive energy spread.

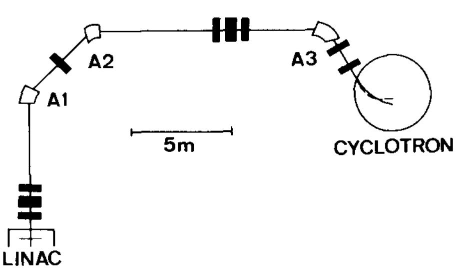

Fig. 6:

Layout of the beam transfer line at ALICE, Orsay. Quadrupoles are shown as solid boxes. The 90° bend is made dispersionless with the quadrupole between the bending magnets A1 and A2. The injection path is shown for two different ions.

entrance of the extraction system. Estimate the behaviour of the dispersion through further extraction elements and through the cyclotron fringe field.

At the other end of the beam line, the x - and y-envelopes have to be matched to the periodic solution inside the cyclotron (see Fig. 4, 7, 14). The modulation of the envelopes is given by the amount of flutter produced by the cyclotron sectors. Since the envelopes x_o, y_o are given by the beam quality $A_x = \pi\varepsilon_x$ and $A_y = \pi\varepsilon_y$) at the injection radius R, one can obtain the following approximate matching conditions:

At the first valley position inside the cyclotron, the beam should have a horizontal (and vertical) waist with amplitude x_o and divergence Θ_{max} given by:

$$(3.2) \quad x_o = \lambda_x \sqrt{\frac{R\,\varepsilon_x}{\nu_r}}, \quad \Theta_{max} = \frac{\varepsilon_x}{x_o}$$

with corresponding formulas for the vertical waist. ν_r is the horizontal focusing frequency (typically around 1) and λ_x (and λ_y) depends on the flutter strength. It is 1 for a homogenous cyclotron field and about 0.8 for ring cyclotrons with a very high flutter. (If you do not know what flutter means, take $\lambda_x = \lambda_y = 0.9$). One can verify this approximation (3.2) by simulating the cyclotron in TRANSPORT with a periodic system of sector magnets. The field index and the edge angle β can be chosen to give the desired ν_r and ν_z values. The desired dispersion in the valley can again be calculated from the energy-radius relation inside the cyclotron, and assuming d' = 0. If the final magnetic field of the main cyclotron is known, one can, of course, integrate a centered beam backwards through the injection elements into the interface region.

Fig. 8 shows typical radial turn patterns inside the main cyclotron for:

a) a perfect beam,
   and beams lacking:

b) centering,

c) horizontal matching,

e) dispersion matching.

In the last two cases, quadrupoles must be adjusted to get a perfect match.

It should be noticed, however, that perfect centering and matching are not necessary when one operates in the so-called single turn extraction mode[10]. This mode is achieved with either a very narrow phase width or a flattop accelerating system. All particles make the same number of revolutions and any mismatch or coherent amplitude at injection persists until extraction.

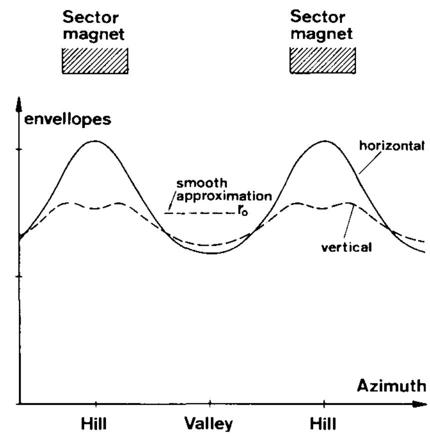

Fig. 7:

Matched beam envelopes in a ring cyclotron. This example is taken from the proposed new S.I.N. injector[5]. There are 4 straight sectors with a sector width of 26°. These narrow sectors produce a very high flutter giving strong vertical focusing with $\nu_z > 1$. Nevertheless, the modulation of the beam envelopes around the smooth approximation value is moderate.

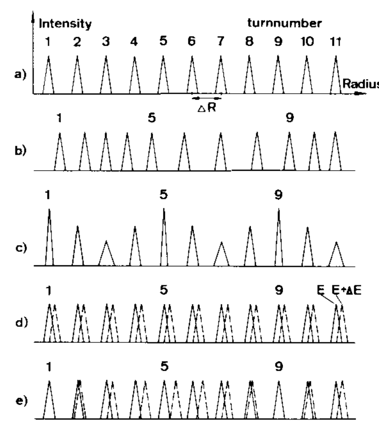

Fig. 8:

Idealized turn pattern of a beam injected into a cyclotron. For simplicity's sake the radial gain per turn ΔR is assumed to be constant. The radial betatron frequency ν_r is chosen as 9/8.

a) Monoenergetic beam, matched and centered.
b) Monoenergetic beam, matched but not centered on its equilibrium orbit. The turn pattern repeats after 8 turns.
c) Monoenergetic beam, centered but not matched. The pattern repeats after 4 turns.
d) Beam with an energy spread ΔE. The dispersion from this spread is matched.
e) As d), but the dispersion is not matched. The turn pattern repeats after 8 turns.

This fact can even be exploited to produce an increased turn spacing at extraction through an excentric injection. This feature will be tried out at S.I.N. as soon as the new flattop cavity is installed in 1977.

Fig. 9 shows a measured turnpattern with reasonably good matching for the S.I.N. ring cyclotron.

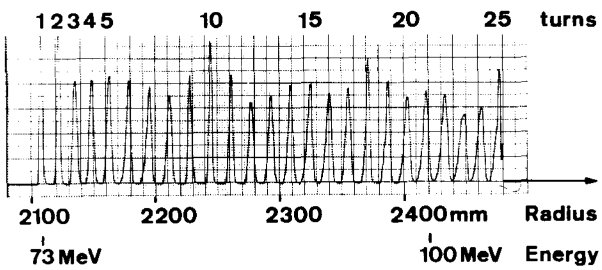

Fig. 9:

The first 25 turns in the S.I.N. ring cyclotron, measured with a 1 mm wide differential probe. Displayed is the beam current versus radius.

A few more points should be considered for the layout of a beam transfer line:

- "Orthogonality" of quadrupoles. At at least two quadrupoles, the horizontal beam amplitude should be large and the vertical amplitude small. At two other quadrupoles just the opposite should be true. These two "orthogonal" pairs of quadrupoles allow separate adjustment of the horizontal and vertical beam matching (e.g., quadrupoles QNC2, QNA3 and QNB3/4 for the S.I.N. layout in Fig. 4). Similarly, a quadrupole close to the energy slit, where the dispersion is large and the horizontal amplitude is small, is ideal for adjusting the dispersion property.
- Good positioning of all beam line elements. Quadrupoles which steer the beam are a nuisance. Furthermore, any parameter not controllable from the control room is a dead parameter, and the position of a quadrupole is certainly one of them.
- Stability of all components. Do not gamble on cheap power supplies.
- Quadrupole filling factor. Quadrupole apertures should not be filled to more than 50 % with beam, especially for high intensities where even the beam halo can activate parts of the quadrupoles. Large apertures also supply flexibility in beam optics and insurance against changes in injector beam properties. Lastly, aberrations are minimized.

4. Bunching, Debunching and Chopping

Quadrupoles are used to modify the beam in the four dimensional transverse phase space. In a similar way, bunchers and debunchers can match the beam between two accelerators in the two longitudinal phase space dimensions of energy and time (or phase with respect to the accelerating system). A special case of this matching is a so-called isochronous beamline, where all particles have the same transit time between the two accelerators. Deviation from isochronism comes from two effects:

a) Particles with large horizontal or vertical deviations from the center of the beam normally have an increased path length. In the horizontal phase plane, combinations of quadrupoles and bends can be designed such that this effect is minimized[15], while in the vertical direction, without any bends, the beam amplitude and divergence have to be kept within acceptable limits.

b) Due to the energy spread from the injector, particles start with different velocities at the beginning of the beamline. This leads to a debunching process which is quite severe for low energy particles and long beamlines. Compensation of this effect can be achieved with one or more bunchers along the beamline.

With a combination of bunchers and debunchers[16] one can cope with the general case where bunch length and energy spread have to be adapted to the main accelerator Compromises in the layout of such a system have to be made if transportation of a variety of particles at different energies is foreseen[17]. The following variety of bunchers (or debunchers) are in operation or under consideration:

- sinusoidal bunchers operating at a single frequency. Double gap bunchers are used at low voltages and resonating cavities at high voltages;
- saw tooth bunchers[18, 19];
- harmonic bunchers operating at different frequencies and placed at different positions.

Bunchers have the disadvantage that they produce a phase dependent defocusing action in the transverse directions which deteriorates the beam quality. This effect can be minimized by producing a double beam waist at the buncher. Another alternative is to place grids at the buncher entrance and exit. Since the buncher affects the energy spread of the beam, it is very advantageous to place each buncher at a position where the beam is dispersionless[17]. If the injector is producing a DC-beam, then not even bunchers can bring all particles into the desired phase width at the main accelerator. Elimination of the unwanted particles can be done with slits inside the main cyclotron or with a chopper along the beamline. Choppers sweep the beam periodically across a narrow slit. They are very flexible in adjusting the phase position and phase width of the injected beam, but have the disadvantage[20] that they introduce a total energy spread $\frac{\Delta E}{E}$ which is inversely proportional to the physical pulse length Δl

$$(4.1) \qquad \left\langle \frac{\Delta E}{E} \right\rangle \Delta l = 8\varepsilon$$

$\pi\varepsilon$ is the beam quality in the sweeping direction and < > denotes the average over the pulse length. This kind of uncertainty relation (4.1) shows that choppers should not be used for extremely short pulses, very low energy particles and beams with poor quality. In this case, one has to resort to internal slits.

5. Space Charge Forces

For high intensity beams, space charge repulsion can alter the beam envelopes along a beamline, as well as introduce an additional energy spread. There exists a number of computer programs which calculate these space charge effects[21]. Rather than going into the details of these calculations, we give a few simple approximations for nonrelativistic beams which allow an estimate of space charge effects. An important dimensionless parameter is:

$$(5.1) \qquad A = \frac{V_c}{V_o} \quad \text{where}$$

eV_o = kinetic energy of particle

V_c is given by a curious version of "Ohms law":

$$(5.2) \qquad V_c = I_p \cdot \frac{Z_o}{\beta}$$

I_p = instantaneous effective peak current (incl. neutralization)

$\beta = \frac{v}{c}$ = normalized velocity

$Z_o = \frac{1}{4\pi\varepsilon_o c}$ = 30 Ohm

5.1 Transverse Space Charge Forces

For an approximately cylindrical DC-beam of radius r and uniform charge density, V_c is just the potential difference between the center and the periphery of the beam. The value of A is thus the energy spread in the beam coming from transverse space charge repulsion. It is only significant for very intense beams.

The change in the envelope radius r is given by the Kapchinsky-Vladimirsky[22] equation

$$(5.3) \qquad r'' = -K^2(z)\, r + \frac{\varepsilon^2}{r^3} + \frac{A}{r} \qquad \left(' \equiv \frac{d}{dz} \right)$$

where $k(z)$ is the specific focusing force and $\pi\varepsilon$ is the beam emittance. For a zero emittance beam in free space (with radius r_o and $r'(0) = 0$, the space charge repulsion doubles the size of the original envelope in a distance

$$(5.4) \qquad L_{DT} \simeq \frac{1.5\, r_o}{\sqrt{A}}$$

In a periodic section, one can use eq. (5.3) to calculate the smooth approximation ($r'' \simeq 0$) dependence of the matched (periodic) solution[23] from the beam current I.

$$(5.5) \qquad \left(\frac{r}{r_o}\right)^2 = \sqrt{1+\omega^2} + \omega$$

$$\frac{\nu}{\nu_o} = \sqrt{1+\omega^2} - \omega$$

$$r \cdot \Theta = r_o \Theta_o = \varepsilon = \text{constant}$$

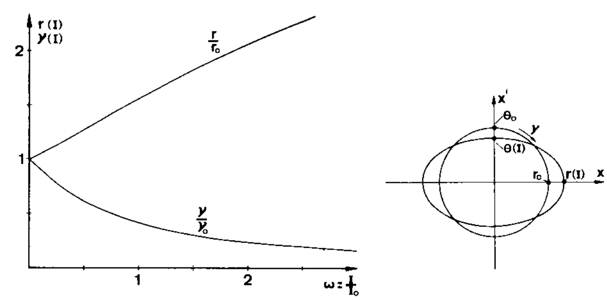

Fig. 10:

Influence of beam current I on beam amplitude r and focusing frequency ν of a matched, approximately cylindrical beam in a periodic structure. r_o, Θ_o and ν_o are the values without space charge. I_o is a characteristic current given by formula (5.7). For a high beam current I, the beam has to be made fatter in order to avoid beam blow up. The betatron frequency ν drops with higher currents and care has to be taken to avoid half integer (parametric) imperfection resonances. The figure on the right shows the eigenellipses in phase space for beams with currents 0 and I.

where Θ is the maximum beam divergence, ν is the betatron oscillation frequency and r_o, ν_o, Θ_o are the values at zero current. ω is another dimensionless parameter given by

$$(5.6) \qquad \omega = \frac{A}{2\,\Theta_o^2} \equiv \frac{I_p}{I_o}$$

This defines a characteristic current I_o:

$$(5.7) \qquad I_o = \frac{2\, V_o \beta \Theta_o^2}{Z_o}$$

Equations (5.5) are plotted in Fig. 10 and show that there are substantial space effects if the beam current I_p is comparable to I_o. If the turn separation in the main cyclotron is large compared with the beam diameter, eq. (5.5) can also be used to calculate the approximate matching conditions inside the cyclotron for different beam currents.

5.2 Longitudinal Space Charge Forces

Bunched beams are usually approximated with ellipsoids. If the original pulse length Δl_o is comparable with the transverse dimensions (let us say within a factor of three), then, without any bunchers, the pulse length doubles in a distance of about

$$(5.8) \qquad L_{DL} \approx \frac{.8\ \Delta l_o}{\sqrt{A}}$$

Much more severe is the energy spread $\frac{\Delta E}{E}$ coming from the longitudinal space charge repulsion (see Fig. 11). For drift distances L smaller than L_{DL} we have

$$(5.9) \qquad \frac{\Delta E}{E} \approx 4\ A\ \frac{L}{\Delta l_o}$$

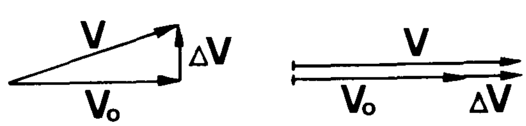

Fig. 11:
Effect of space charge forces on a particle at the periphery of a bunched beam. The initial velocity is V_o and the additional velocity from repulsion of neighbouring particles is ΔV. In the transverse case, the energy increase goes quadratically with ΔV. The longitudinal forces are more dangerous because they lead to a linear increase of the energy spread with ΔV.

This spread is quite appreciable for short bunches of high intensity, low velocity beams. It can be only partially compensated with bunchers. The conclusion is again that short pulses should be generated with internal slits in the cyclotron.

6. Diagnostics

As M. Olivo[24] points out in his review paper, it pays off to install good diagnostic equipment. One should start with an exit transition region (see Fig. 1) in order to check the output of the injector (especially if one buys it). Elements which are used to measure the six-dimensional phase space volume are:

- profile monitors and quartz-or Al_2O_3-viewers. The latter have the advantage of showing readily any x-y coupling in the beam;
- non-destructive current transformers,
- time of flight device to measure particles scattered from a foil,
- energy analyzing system with bending magnets.

At the input to the main accelerator, similar checks should be made on the injected beam. The ultimate performance of the matching process is finally measured inside the main cyclotron with probes. Fig. 9 shows a turn pattern of a reasonably well matched and centered beam in the S.I.N. ring cyclotron.

7. Specific Layouts

TRIUMF, Vancouver: The 300 keV H^- preaccelerator, the 40 m long injection line[4] and the 22 m long injection line for the 3 MeV center region model[20, 25], have been described previously. We mention only a few specific characteristics.

- A 30 cm long spiral inflector at ± 30 kV potential deflects the beam into the medium plane. It operates very reliably. Side effects are a coupling between radial and vertical phase space and dispersion produced by the deflector if the buncher and chopper are used. However, with internal slits, it is easy to cut the beam to the desired dimensions.
- Along the periodic beamline, 77 electrostatic quadrupoles produce weak focusing and keep the beam approximately cylindrical with a diameter of 1 cm.
- The characteristic beam current I_o (see eq. 5.7) is 3 mA. This means that at a DC-current of 1 mA (which will give about 100 μA average current inside the cyclotron), space charge effects have to be considered in tuning the beam line.

- An original innovation is the compensation of the 40 Gauss cyclotron stray field along the beamline by permanent magnets inside iron tubes.

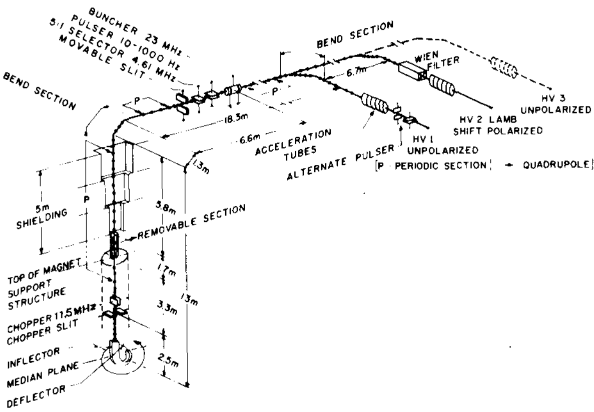

Fig. 12:

Layout of the 300 KeV injector line for polarized and unpolarized H⁻ ions at TRIUMF. All bending and focusing devices are electrostatic. Injection into the center of the 500 MeV cyclotron occurs through a spiral inflector.

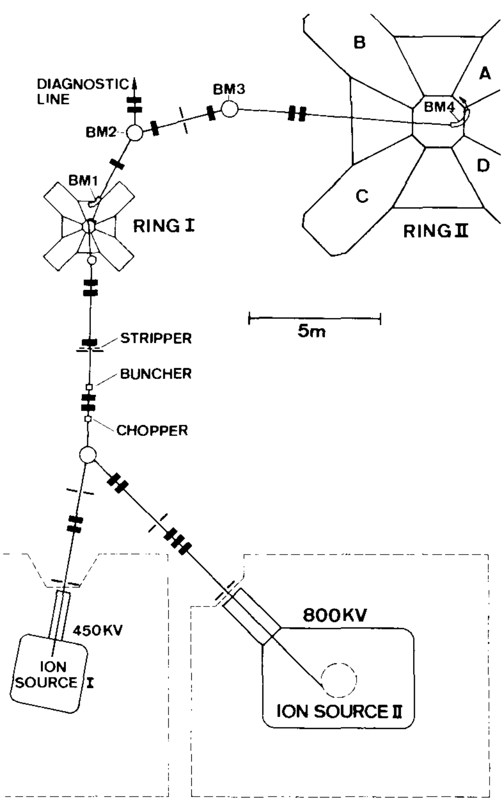

Fig. 13: Layout of the Indiana Cyclotron beam transport system.

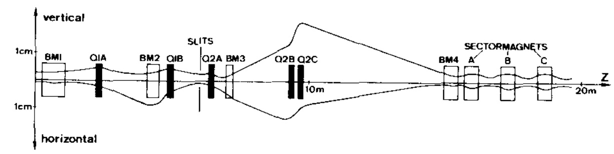

Fig. 14:

Ideal beam envelopes between ring I and II of the Indiana Cyclotron facilities. With the present five quadrupoles no perfect matching in the six-dimensional phase space will be possible for all energies and particles.

Indiana cyclotrons[26] (see Fig. 13, 14): There are a variety of beamlines with the corresponding problem of defining clear interfaces between the different machines. The chopper on the DC-beam line combines deflections in the horizontal and vertical directions. The two sweeping frequencies can be adjusted for variable energies and particles. A nice feature is the diagnostic line after Ring I.

VICKSI, Berlin (see Fig. 15, 16): The beamline between the Tandem and the ring accelerator is very nicely structured into modular dispersionless sections[27].

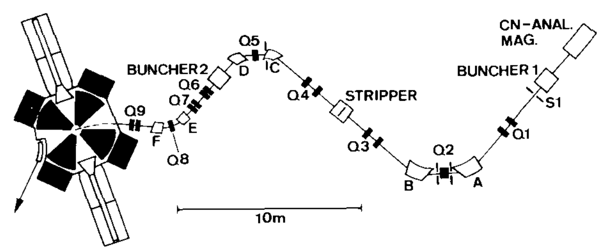

Fig. 15:

Layout of the beamline between a tandem-accelerator and a ring cyclotron at VICKSI, Berlin. The system is modular with a dispersionless waist to waist transfer from slit S1 to the stripper and further to the second buncher. At the stripper, a triple focus in the x, y and z direction is formed to minimize angle and energy straggling.

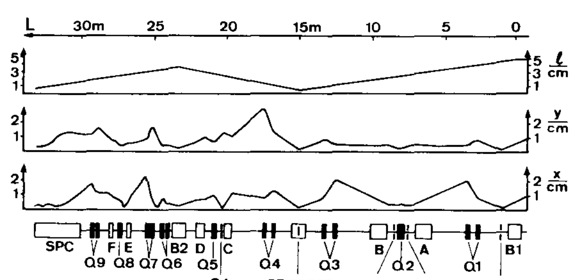

Fig. 16:

Beam envelopes x, y and bunch amplitude for the VICKSI beamline. The beam moves from right to left.

Special care has been taken to place the two bunchers at beam waist positions in order to minimize the radial defocusing effect mentioned earlier.

The stripper is placed at a focus in all three dimensions. This keeps energy- and angular straggling at a minimum. The cyclotron injection system is described by S. Lindbäck in another paper of this conference[28].

S.I.N.: The 72 MeV beamline was designed by J. Zichy and is described by him in these proceedings[29]. Since debunching along the 35 m long line is only 3°, no buncher is needed for the 20° long pulses. Matching the injector beam to the ring cyclotron is still not trivial, especially for the dispersion.

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DISCUSSION

G. DUTTO: You emphasized the need for steering at extraction. I think that it is very important to have good horizontal and vertical steering capability at injection. Could you comment about this?

W. JOHO: Yes, the problem is indeed symmetric. One should have at least two independent steering parameters for each direction, also at injection. If the situation is more complex like in your case at TRIUMF, where you have a "Dee"-misalignment and phase-dependent focusing, then your solution with vertical steering plates is needed, too.