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HIGH INTENSITY PROBLEMS IN CYCLOTRONS

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Abstract.- Cyclotrons have so far produced currents up to the order of 200 micro-amps, this limit mainly be given by extraction losses and the brightness of the ion source. Future cyclotrons will operate with average currents in the milli-ampere region. To achieve these intensities injection from an external ion source into a ring cyclotron is the most promising route. For conventional extraction, without stripping, single turn extraction is necessary in order to keep losses and thus activation levels within tolerable limits. Longitudinal space charge forces tend to spoil the turn separation. They can be partially compensated with a high accelerating voltage and a flattopping higher harmonic. At beam power levels reaching 1 MW the problem of beam loading puts stringent tolerances on the RF-system. Additional problems arise with cooling of the targets as well as with space charge forces in the beam transport lines and in the cyclotron.

1. Introduction

In 1931 M.S. Livingston and E.O. Lawrence accelerated a 1 nA proton beam to 1.2 MeV in their 11 inch cyclotron [1]. 50 years later the SIN cyclotron delivered 170 µA protons at 590 MeV representing a beam power of 100 kW compared with the original 1.2 mW. With the new injector under construction at SIN [2] the intensity goal is even 2 mA or 1.2 MW of beam power. Progress thus seems easier to be made on the intensity rather than on the energy front.
In the paper by M. Craddock from TRIUMF [3] future trends and limits in the energy of cyclotrons will be discussed, while in this paper it will be shown, that further progress in beam intensity will not come the easy way. - In terms of average beam power cyclotrons can even compete with existing high energy accelerators as fig. 1 shows. So far the highest beam intensities required in cyclotrons are protons for the meson facilities at TRIUMF and SIN and for isotope production at lower energies. There seems to be no need yet for very intense heavy ion beams and therefore I will concentrate my discussion on proton accelerators. For specific examples let us look at the following four cyclotrons:

a) The TRIUMF 500 MeV H^--cyclotron [4].
This is a unique machine in many respects. Extraction is easy, but the weakly bound H^--ion requires a good vacuum and low magnetic fields. So far 150 µA have been extracted at 500 MeV. A beam current of 300 µA at 450 MeV looks feasible in the near future, since a 700 µA, 300 keV DC beam has already been obtained at the center of the cyclotron. Transmission between DC beam and beam on target is typically 40% with a combination of two bunchers [5].

With an improved design of cooled collimators in the 40 m long injection line the TRIUMF group is confident to reach an extracted beam intensity of 500 µA. The routine intensity level will be lower and mainly dictated by the activation level.

b) The Philips 72 MeV injector at SIN [6].
The design of this machine is typical for many single stage cyclotrons. Originally planned for 100 µA operation the SIN injector group under T. Stammbach succeeded to boost the intensity limit to 190 µA. This limit is

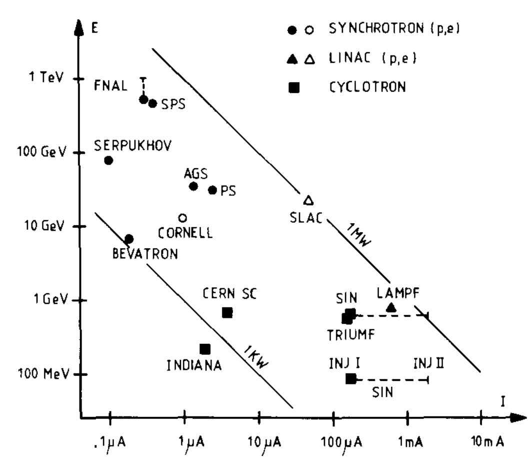

Fig. 1: Energy versus average beam intensity for some medium to high energy accelerators. The two slanted lines indicate points for 1 kW and 1 MW beam power respectively.

presently given by problems in matching the output of the internal source to the vertical acceptance of the center region.

c) The 590 MeV ring cyclotron at SIN [7].
This cyclotron is fed by the Philips injector and has easily accelerated the 170 µA beam it got so far. It obviously waits for the injector II to see where the intensity limits are! In order to achieve the goal of 1 MW of beam power the RF-system has to be upgraded correspondingly. The addition of a third harmonic flattop cavity [8] to the ring in 1979 made the setting of the machine parameters very "forgiving" and has boosted the routine value for the extraction efficiency to 99.98%.

d) The SIN injector II for 72 MeV protons.
Despite the remarkable beam performance of the present injector SIN constructs a new one with an intensity goal of 1 - 2 mA in order to exploit the full potential of the 590 MeV ring cyclotron. The project is described in detail in a separate paper [2] at this conference. First beam from this cyclotron is expected in late 1983.

In general, a cyclotron facility can be structured in the way shown in fig. 2. In the following chapters I will discuss those areas which play an important role in determining the intensity limits of cyclotrons. Special emphasis will be given to longitudinal space charge effects since they play a key role in high intensity cyclotrons.

2. Ion Source

This subject will be covered at this conference in a special paper by Dave Clark [9]. Therefore only a few aspects concerning high intensity ion beams will be mentioned. Three alternatives for the arrangement of the ion source as seen in fig. 2 are: internal source, external source at the few keV level with axial injection and external source at a level of 10 - 100 keV combined with further acceleration prior to injection into the cyclotron.

Internal sources are known for years to give beams in the few mA region. But matching the output of the source to the acceptance of the cyclotron requires a rather strong collimation with slits. This leads to a big loss of transmission in the first few turns. Transit time effects, especially phase dependent vertical focusing forces add complexity to the system. But if one optimizes the center region for a fixed particle energy and hence fixed frequency and accelerating voltage one can reach respectable currents in the region of a few hundred µA, as the example of the Philips injector at SIN shows.

Axial injection at the few keV level suffers from space charge effects and is not recommended for very high currents.

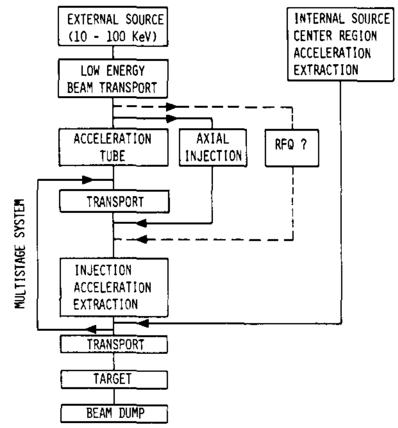

Fig. 2: Structure diagram for cyclotron facilities with internal and external ion sources. RF-quadrupoles (RFQ) are possible future candidates as low energy injectors.

The third approach with an external source and injection at a few hundred keV looks to me the most promising route for high intensity operation. The external arrangement leaves the greatest flexibility in the choice of ion source type. TRIUMF uses an Ehlers type source, capable of delivering around 1 mA DC of H^--ions. This intensity is adequate for the near future. For its new injector SIN will install a cusp-field ion source [10][11]. This type of source is being extensively developed for neutral beams in the magnetic confinement fusion program. - Beam intensity is not a problem, since these sources have produced DC-currents up to more than 100 mA for a single aperture with current densities in the order of 200 mA/cm^2. Efforts are being undertaken to produce intense H^--ion beams from these cusp-field sources as well. The absence of a magnetic field at the extraction region helps to produce a quiet plasma surface which is beneficial in producing beams of high quality and small intensity fluctuations.

3. Acceleration tubes

For high intensity cyclotrons, pre-accelerators of the Cockcroft-Walton type are good candidates as injectors. A critical point is the high voltage break-down of the acceleration tube in the presence of the beam [12]; the sparking rate depends mainly on the accelerating voltage, the vacuum conditions and the average beam current. In contrast to Cockcroft-Walton injectors for high energy accelerators, which operate typically at 750 kV with pulsed beams of relatively low average currents, cyclotrons require DC-operation.

Representative acceleration tubes with high average beam currents are:

Los Alamos	V=750kV,	I= 2mA (7% duty cycle)
Chalk River	V=750kV,	I=10mA
TRIUMF	V=300kV,	I= 1mA (H^-)
SIN Inj. II	V=800kV,	I=25mA (planned)

Backstreaming electrons, arising from the collisions of the primary beam either with the residual gas or with the accelerating electrodes, are probably the main cause for beam induced tube breakdowns. Bremsstrahlung, if not properly shielded, can charge up, via photoelectric effect, the insulators causing eventually a flashover. Measures which have been taken against this problem are: good vacuum in acceleration tube, good electron trapping and labyrinths with high-Z material to absorb x-rays and charged particles.

The Chalk River group [13] reports rather high sparking rates at DC-currents as low as 10 mA. The difficulties arise probably because the source, producing a variety of parasitic ions, is attached directly to the tube. Additional problems arise because space charge forces require a Pierce configuration with narrow electrode apertures. One new trend in injector layouts is to decouple the source from the acceleration tube which has the following effects:

- large aperture, high current sources can be used
- parasitic ions like H_2^+ and H_3^+ can be filtered out prior to acceleration.
- The vacuum in the tube can be improved.
- The acceleration tube can be of the simple constant gradient, large aperture type.
- The beam can be properly matched to the tube with a transport system between source and tube. Space charge forces in this section are well neutralized already at pressures in the order of 10^{-5} torr.

This approach has been adopted for the preinjector at SIN [10] where it is hoped to obtain a high quality DC-beam of 25 mA at 860 keV. A second trend which is being followed by the groups at Los Alamos [14] and Chalk River is the use of an RF-quadrupole structure (RFQ) instead of the DC accelerator. This new development looks very promising for high current linear accelerators, because an RFQ not only accelerates particles from a few tens of keV to a few MeV, but it does so with an almost 100% bunching efficiency. The main drawback of such a system is that present designs produce energy spreads in the order of 2 to 3%, which is above tolerance for beams to be injected into cyclotrons. Giving up bunching efficiency it might be possible to improve on the energy spread of the RFQ [15]. An additional tricky problem is the debunching of high current beam pulses between the output of the RFQ and the first acceleration gap in the cyclotron. It remains thus to be seen, if RFQ-structures can be used effectively as high current injectors for future cyclotrons.

4. Space charge effects in transport systems

The beam transport between cyclotrons has been discussed at the 1975 cyclotron conference [16] and is the subject of a review paper at this conference [17]. We are concerned here only with the intensity aspect, i.e. with space charge forces. These effects have been incorporated into the computer program TRANSPORT [18] which allows detailed calculations. Space charge forces are most pronounced at low velocities and for a specific example the reader is referred to numerical results for the 860 keV beam line at SIN [19]. At this energy beams of already a few mA require intensity dependent quadrupole settings if one wants to preserve the topology of an optical solution. At very low energies one even has to rely on neutralization of the beam by the residual gas [20]. This implies that electrostatic elements should be avoided if possible. It is advantageous to keep an intense low energy beam unbunched as long as possible, since short bunches spoil neutralization and through the longitudinal space charge force can introduce an energy spread [16].

The need for very intense particle beams in the Heavy Ion Fusion program has renewed the interest in space charge forces over the last few years. Many computer simulations with Monte Carlo methods have shown collective effects at high currents, which can lead to emittance growth in long beam lines [21][22]. The effect depends critically on the particle distribution in phase space, on the intensity parameter ω (defined in equation (5) of the next chapter) and it is enhanced if the so-called phase advance angle is larger than 90^0.

5. Transversal space charge force in cyclotrons

Particles at the periphery of the beam are pushed away from the center by space charge forces. This reduces their original focusing frequencies ν_r and ν_z given by external electromagnetic fields. One speaks about a shift of the incoherent frequencies. Coherent oscillation of the whole beam are affected much weaker by the presence of the vacuum chamber and neighbouring orbits. The dependence of the beam amplitudes on the beam current is calculated by solving the Lapostolle - Sacherer equation [23][24] and looking for periodic solutions, as outlined in [16].

$$(1)\quad \left| \begin{array}{l} a_x'' + k_x^2\, a_x - \dfrac{\varepsilon_x^2}{a_x^3} - \dfrac{2A}{a_x+a_y} = 0 \\[2ex] a_y'' + k_y^2\, a_y - \dfrac{\varepsilon_y^2}{a_y^3} \quad \dfrac{2A}{a_x+a_y} = 0 \end{array} \right.$$

where $a_x = 2\sqrt{\overline{x^2}}$, $a_y = 2\sqrt{\overline{y^2}}$, $' \equiv d/ds$

$\pi\varepsilon$ = emittance at given energy, $k_x(s)$ and $k_y(s)$ are the external focusing strengths. A is a dimensionless value proportional to the peak particle current I (part.) = <I(part.)> $2\pi/\Delta\phi$

$$(2)\quad A = \frac{2}{\gamma^3\ \beta^3}\ \frac{Q^2}{M}\ \frac{2\pi}{\Delta\phi}\ \frac{<I(\text{part.})>}{I_0}$$

Q is the charge state, M the atomic mass of the particle (=1 for protons) and $\Delta\phi$ the phase width of the beam. I_0 is the universal current defined as

$$(3) \quad I_0 = 4\pi\varepsilon_0\, m(\text{proton})\, \frac{c^3}{e} = \frac{938\ \text{MV}}{30\ \Omega} \simeq \pi 10^7 \text{A}$$

The discussion of eq's (1) is simplified if we make the following assumptions: similar emittances and focusing frequencies in x and y i.e. $\varepsilon_x=\varepsilon_y=\varepsilon$, and $\nu_x=\nu_y\equiv\nu_0=kR$. Where k is the average focusing strength and R is the radius of the orbit. We further introduce the normalized emittance $\pi\varepsilon_N = \pi\varepsilon\beta\gamma$, a critical current I_T and a dimensionless space charge parameter ω:

$$(4) \quad I_T = \frac{M}{Q^2}\,\frac{\varepsilon_N\nu_0}{R}\,\beta^2\gamma^2\,\frac{\Delta\phi}{2\pi}\, I_0$$

$$(5) \quad \omega = \frac{\langle I(\text{part.})\rangle}{I_T} = \frac{A}{2\varepsilon k}$$

The dependence of the average beam amplitude, a, and the focusing frequency ν on the beam current is found by setting a"=0 in eq. (1):

$$(6) \quad a^2(I) = a_0^2\,[\omega+\sqrt{1+\omega^2}]$$

$$(7) \quad \nu(I) = \nu_0[\sqrt{1+\omega^2}-\omega]$$

$a_0=\sqrt{\varepsilon R/\nu_0}$ is the amplitude and ν_0 the focusing frequency at zero current. The transversal space charge limit is reached if ν gets depressed down to a dangerous resonance value or if the amplitude a becomes too large. At ω=1 the collective emittance growth effects mentioned in chapter 4 become critical as well. Since R is proportional to β eq. (4) shows, that the critical current I_T is proportional to β and $\Delta\phi$, i.e. transversal space charge effects dominate at low velocities and strongly bunched beams. For the SIN facilities, assuming a normalized emittance of π mm mrad, we obtain as transversal space charge limits average currents of 5 mA for the injector II and 20 mA for the 590 MeV ring, if we allow ω to raise up to a value of .4.

6. Extraction

6.1 Stripping of H^--ions (TRIUMF).
For H^--ions extraction is achieved simply by stripping with a foil. The last turns in the cyclotron do not have to be clearly separated. The heat load on the foil is negligible and the experience at TRIUMF has shown, that the lifetime of the foil is not a problem even at intensities above 100 µA. The price for this elegant extraction method is the loss of H^--ions through stripping by the magnetic field at high energies and by the residual gas at low energies. For TRIUMF [5] this loss amounts to about 2% of the extracted beam at 450 MeV and 10% at 500 MeV.

6.2 Extraction by an electrostatic septum.
With this conventional method it is of vital importance to have a large turn separation at extraction in order to avoid an excessive heat load on the septum by the intercepted particles and also to avoid critical activation levels. The natural solution for a large turn separation is a high acceleration voltage. To enlarge this turn separation further one uses either resonance extraction methods [25][26][27] or eccentric injection in the case of a ring cyclotron [28]. As an example the turn separation at the extraction radius of the injector and the ring cyclotron at SIN are 3 mm and 8 mm respectively. As typical examples of the state of the art, the two septa in operation at SIN are described. The electrostatic deflector (ESD) of the Philips injector cyclotron is 70 cm long, water cooled and made out of solid copper. Its curvature was made with a numerically controlled milling machine to fit the path of 72 MeV protons. The voltage on the cathode is 52 kV across a 4 mm gap. A 10 cm long V-slit helps to reduce the average power density at the entrance of the septum. The new version of this septum, designed by T. Stammbach of SIN, has a thickness of about .15 mm compared with the .3 mm of the old version. This smaller thickness not only reduces the fraction of intercepted particles, but increases the chance for these particles to escape again by Coulomb scattering. The fate of all particles reaching the extraction radius is as follows [29]:

1%	intercepted and absorbed in septum
4%	intercepted but scattered out by septum
2%	absorbed in collimators or the magnetic focusing channel
93%	extracted to an energy analyzing slit where about another 2 - 3% are removed from the main beam.

Thus even at 200 µA only about 200 W of beam power are absorbed in the septum hence giving no cooling problems. Since the injector cyclotron seems to be intensity limited by the central region [6], one can only speculate about the limit of the extraction septum. The critical point is the Bragg peak 7 mm after the end of the V-slit, creating a hot spot.

In the ring cyclotron a foil septum (EEC) designed by M. Olivo [30] is used for extraction. The range of the 590 MeV protons in Tungsten (W) and Molebdynum (Mo) is 15 cm and 24 cm respectively. The 1 m long straight septum consists of 129 Mo-strips .05 mm thick and 7 mm wide. There are two W-strips in front of the septum, each .03 mm thick and 3 mm wide. The first strip is isolated and delivers a signal proportional to the intercepted proton current. This strip is protected from the 100 kV cathode voltage by the second strip and therefore the current signal is very clean and allows excellent tuning of the cyclotron for minimal beam losses. The septum is cooled primarily by radiation. The temperature limit depends strongly on the tension applied to the spring loaded strips. For the applied 10 Kp/mm^2 the experimentally measured limit is 1200^0 C for Mo (melting point 2700^{0}C) and 1600^0 C for W (melting point 3380^0 C). Calculation with a Monte Carlo program [31] indicates that this temperature limit is reached when the strips intercept about 5 μA of beam. During routine operation we are far from these limits, since beam losses are about 20 nA with flattop acceleration [8] and 200 nA without flattop. In beam development experiments at 100 μA, up to 3 μA have been intercepted and scattered by the septum without observing any damage. But the scattered particles created an additional heat load on the focusing magnet downstream. This problem could get cured though if the situation demands it. M. Olivo estimates, that with an improved design septa withstanding up to 20 μA beam loss could be constructed. In conclusion one can say, that the extraction septum is probably not a limiting factor for reaching mA beams at SIN.

7. Longitudinal space charge (LSC)-forces

The effect of longitudinal space charge in cyclotrons was first mentioned by T.A. Welton [32] and studied in detail by M.M. Gordon [33] for the MSU cyclotron, where the first experimental identification of this effect occured at the few μA level. At SIN the LSC-forces are, even at the 170 μA level, still masked by other effects, but should become very important around 1 mA. As explained by Gordon LSC leads to a vortex motion of the space charge cloud as viewed in the rotating frame of the beam bunch. The coherent radial force due to the curvature of the beam bunch leads to an azimuthal displacement of the particles. This rearrangement of the azimuthal charge density is usually small and can be neglected in most cases.
The effect of the azimuthal electric field component ϵ_θ resulting from LSC is a voltage gain $dU_{SC}/dn = 2\pi R\epsilon_\theta$ which has to be added to the voltage gain arising from the RF-sytem. ϵ_θ is strongly dependent on the azimuthal charge distribution. Leading resp. lagging particles always gain resp. loose energy against the center of the bunch. Because an isochronous cyclotron operates always like a synchrotron on transition energy there is no phase stability and the front particle ends up with a net energy increase over the average energy of the bunch. A certain fraction of this space charge effect can be compensated with the accelerating RF-field, as shown later. If one depends on separated turns for a very good extraction rate, like at SIN, then the LSC-limit is reached, when the remaining total energy spread is of the order of half the energy gain per turn. In what follows some analytical formula for the voltage gain from LSC will be given for the sector model, followed by some numerical examples from the so-called DISCS-model [34].

The sector model.- This model is an extension of an idea by H. Blosser from MSU and assumes that the electrical field ε_θ at the peripheral point P in fig. 3 is given by the local charge density ρ. For a nonrelativistic cyclotron the turn separation δr is proportional to R^{-1}, and for closely packed turns ρ is thus independent of radius. To obtain a numerical estimate of ϵ_θ we assume this field to be given by an uniformly charged oblate spheroid of diameter 2w and thickness 2a as indicated on the left of fig. 3. Integration yields:

$$(8) \qquad \epsilon_\theta(p) = \frac{\rho a}{2\varepsilon_0} g_1(p)$$

where p = a/w and $g_1(p)$ is the ellipsoidal form factor shown in fig. 4.

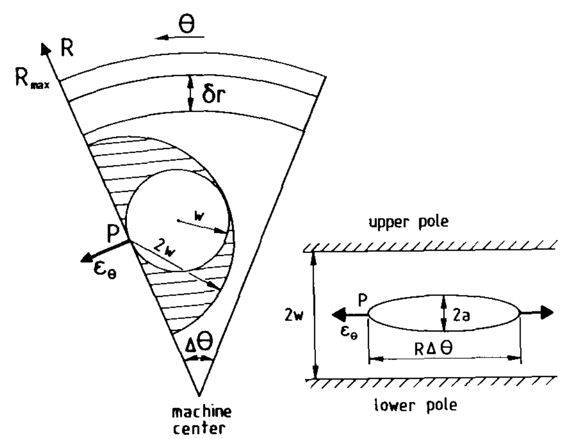

Fig. 3: The sector model for longitudinal space charge forces. A rotating beam sector of angular width Δθ and vertical width 2a is seen in top view at left and in side view at right inside a magnet gap of width 2w. The azimuthal electrical field ϵ_θ at point P is calculated by assuming a constant charge density ρ inside the ellipsoidal disc of radius w and thickness 2a. Particles outside the range 2w from P are shielded by the vacuum chamber and contribution to ϵ_θ from particles in the shaded area are neglected. δr is the radial gain per turn.

In cyclotrons the beam fills typically 1 to 20% of the vacuum chamber gap. For this range of p-values (.01 to .2), $g_1(p)$ can be approximated by a constant value $g_{1c} \approx 1.4$. Making use of the relations $(4\pi\varepsilon_0 c)^{-1} = 30\ \Omega$, $\beta = v/c$ $R = \beta R_\infty$ we finally obtain with I(peak) as the peak current

$$(9)\quad \epsilon_\theta(p) = \frac{4\ g_{1c}\ 30\ \Omega\ I\ (peak)}{\beta\delta r}$$

for the electric field and

$$(10)\quad \frac{dU_{sc}(p)}{dn} = g_{1c}\ 8\pi\ 30\Omega\ I(peak)\ \frac{R_\infty}{\delta r}$$

$$\cong 1000\ \Omega\ I(peak)\ \frac{R_\infty}{\delta r}$$

for the voltage gain per turn sustained by the leading particle at P. Since the lagging particle looses the same amount of voltage the spread across the beam is twice as large. The total voltage spread ΔU_{sc} after n revolutions is:

$$(11)\quad \Delta U_{sc} = g_{1c}\ \frac{64\pi}{3}\ 30\Omega\ I(peak)\ \frac{n^2}{\beta_{max}}$$

$$= 2800\ \Omega\ I(peak)\ \frac{n^2}{\beta_{max}}$$

This is a remarkably simple formula with the following properties:
- ΔU_{sc} depends only on n, the final velocity and the peak current I(peak) = $\langle I\rangle\ 2\pi/\Delta\phi$
- ΔU_{sc} does not depend on a, w and R_{max} therefore it does not depend on the magnetic field, the RF frequency and harmonic number!
- the relevant value for single turn extraction is $\Delta U_{sc}/V_1$ and thus proportional to n^3. This shows the big advantage of a large RF voltage V_1.
- the experimental and numerical results for the MSU cyclotron are rather well explained.

The projection of the uniform ellipsoid assumed in this model leads to a parabolic azimuthal charge density. $\Delta\phi$ is the total RF phase width, defined by the footpoint of the charge distribution.

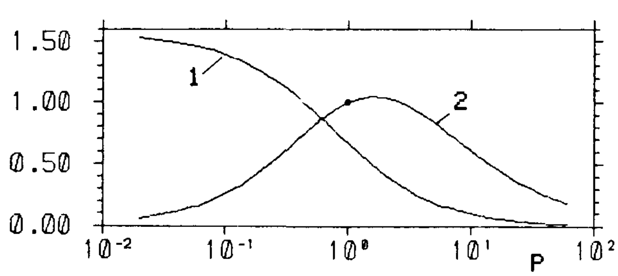

Fig. 4: Geometrical form factors $g_1(p)$ for curve 1 and $g_2(p)$ for curve 2 are used to calculate the electric field at the edge of rotationally symmetric ellipsoids. p is the ratio of the longitudinal to transversal diameter. For p>1 the ellipsoid has a cigar shape.

The cigar model (uniformly charged spheroid).- In this model we neglect neighbouring orbits and assume the beam bunch to be a uniformly charged prolate spheroid of length 2b and diameter 2a. If this diameter is small compared with its length and the vacuum gap, we get for the LSC-field ϵ_θ(FP) seen by the front particle (FP)

$$(12)\quad \epsilon_\theta(FP) = \frac{Q_B}{4\pi\ \epsilon_0\ ab\gamma^2}\ g_2(p)$$

where Q_B is the total charge of the ellipsoid, $g_2(p)$, with p=b/a, is a formfactor shown in fig. 4 and related to the usual factor f(p) in ref.35 by g_2 = 3 p f(p). The voltage gain over one turn is then

$$(13)\quad \frac{dU_{sc}}{dn} = 4\pi\ 30\Omega\ I(peak)\ \frac{g_2(p)\ R_\infty}{a\gamma^2}$$

and the total voltage spread across the beam over n revolutions as

$$(14)\quad \Delta U_{sc} = 8\pi\ 30\Omega\ R_\infty\ n \left\langle \frac{I(peak)\ g_2(p)}{a\gamma^2}\right\rangle$$

The smooth conducting wall model [36].
This model has been worked out for single beam bunches in pipes of circular cross-sections. The assumptions are: - Long bunches compared with the pipe diameter - smooth azimuthal variation of the local current I(θ) - perfectly conducting walls and negligible inductive wall impedance. Adapting this model for cyclotrons with well separated turns we can write for the LSC-field

$$(15)\quad \epsilon_\theta(\theta) = -g_0\ \frac{30\ \Omega}{\beta\gamma^2 R}\ \frac{dI}{d\theta}$$

g_0 is a geometrical factor typically in the range 3 to 8 as numerical calculations with the DISCS-model have shown. Eq. (15) indicates, why the model of a uniformly charged ellipsoid is quite popular: In the projection we obtain a parabolic azimuthal variation of I(θ) leading to a field ϵ_θ which is linear in θ.

Partial compensation of LSC-forces with the accelerating RF-field.- For bunches with a small RF-phase width $\Delta\phi$ one can compensate the linear part of the LSC-forces with the fundamental of the accelerating RF voltage alone:

$V(\phi) = V_1\cos\phi = V_1 v(\phi)$

V_1 is the peak voltage gain per turn. One shifts the phase ϕ_0 of the center of the bunch towards negative values in order to reduce the voltage gain for the leading particles. But this shift increases the turn number n ($n \sim v^{-1}(\phi_0)$) and the relevant parameter for this compensation is therefore

$$(16)\quad K \equiv v(\phi_o)\frac{dv(\phi_o)}{dn} = v_o v_o' = -.5\sin 2\phi_o$$

and has a maximum value of 0.5 for $\phi_o = -45^o$. Compensation of the linear part of LSC requires

$$(17)\quad \Delta U_{sc} - n\,V'(\phi_o)\Delta\phi = 0$$

For the disc model one obtains using (11):

$$(18)\quad \sin 2\phi_o = -\frac{18\ k\Omega\ \langle I\rangle\ U_o\beta_{max}}{V_1^2\ \Delta\phi^2}$$

where $qU_0 = m_0c^2$ (U_0 = 938 MV for protons). The maximum average current which can be compensated is reached when $\phi_0 = -45^o$. When using the MSU data [33] for 36 MeV protons, one obtains for $\Delta\phi = 2^o$ an upper limit of 8 µA, which agrees with the observation.

For bunches with a large RF phasewidth one needs the addition of a flat-topping higher RF harmonic for partial compensation of the LSC-forces. Such a flattop system was successfully put into operation at SIN, and fig. 5 shows an experimental verification of the wide RF-phase acceptance leading to a very monochromatic extracted beam. In general the voltage gain per turn with harmonic j is:

$$(19)\quad V(\phi) = V_1[\cos\phi - \varepsilon_j\cos(j\phi-\varphi_1)] = V_1 v(\phi)$$

Assuming that the azimuthal charge distribution is symmetric around the central phase the LSC-field $\mathcal{E}_\theta$ has the property that $\mathcal{E}_\theta''(\phi_0) = 0$. For optimum cancellation of LSC-effects one requires therefore $v''(\phi_0) = 0$ as well. This leads to v_o being independent of ε_j:

$$(20)\quad v(\phi_o) = v_o = (1-1/j^2)\cos\phi_o$$

The current dependent parameter for the cancellation of the linear part of $\mathcal{E}_\theta(\phi)$ is again $K = v_0 v_0'$. We have thus three free variables (ϕ_0, ε_j and φ_j) to fulfil two conditions ($v''(\phi_0) = 0$ and K given by the current and the detailed charge distribution). Choosing ϕ_0 as the independent variable one can solve explicity for φ_j and ε_j. Introducing $\psi_j = j\phi_0 - \varphi_j$, the beamloading angle between beam center and the RF harmonic j, one obtains

$$(21)\quad \psi_j = \tan^{-1}\left[\frac{j^3K}{(j^2-1)\cos^2\phi_0} + j\tan\phi_o\right]$$

$$(22)\quad \varepsilon_j = \frac{\cos\phi_o}{j^2\cos\psi_j}$$

For the SIN ring cyclotron we have chosen the third harmonic (j = 3) for flat-topping. The relation between ϕ_0 and ε_3 for constant K-values is shown in fig. 6. For minimum turn number a solution with ϕ_0 close to zero is advantageous. One still has the flexibility of local variations in $\phi_0(R)$, since the compensation of LSC is an integral effect. Two examples of a "flattop" RF voltage are shown in fig. 7 for K = .055 and .55 respectively.

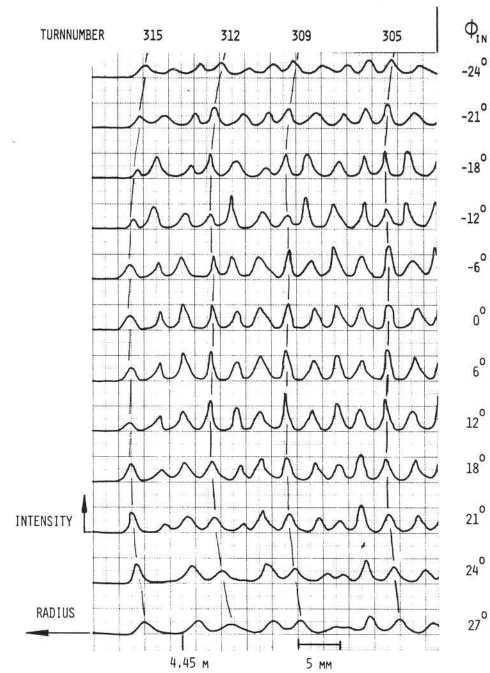

Fig. 5: Demonstration of large phase acceptance of flattop system. Shown are the last 11 out of 315 turns in the SIN ring cyclotron for different injection phases ϕ_{in}. The phase range for single turn extraction is more than 40^o. The clear distinction of separate turns for the extreme phases proves the excellent phase stability.

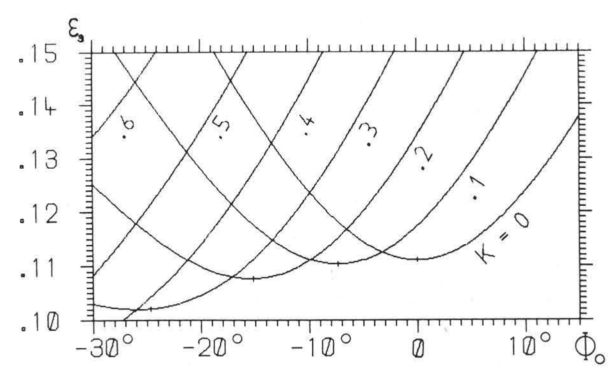

Fig. 6: Compensation of the linear part of the longitudinal space charge forces with a third harmonic RF-component ε_3 and a shift in the central beam phase ϕ_0 with respect to the fundamental RF. K is a dimensionless parameter porportional to the slope of the accelerating voltage at ϕ_0. The optimum K depends on the detailed shape of the azimuthal charge density and increases proportional to the beam current.

The DISCS-model (numerical) [34].- In this model the beam is represented as a cylinder of constant diameter 2a. The azimuthal charge distribution is described with a binomial distribution [37]. The cylinder is sliced into a series of short discs. Neighbouring orbits are neglected but image forces from the vacuum chamber as well as flattop RF voltages are incorporated. Figures 8, 9 and 10 show some results for the SIN Injector II with a 2 mA beam. Nonlinear contributions from LSC-forces depend critically on the shape of the charge distribution. The LSC-induced voltage spread can typically be reduced by a factor ranging from 5 to 15. Higher compensation factors can perhaps be obtained by properly shaping the charge distribution with high harmonic bunchers. Assuming a compensation factor of about 10 for an unneutralized 2 mA beam we obtain the following results for the SIN cyclotrons:

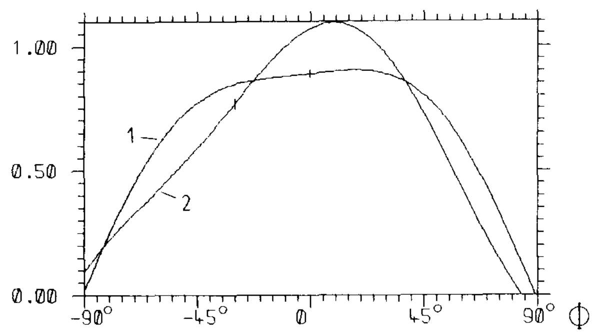

Fig. 7: Accelerating voltage with third harmonic component ε_3: $V(\phi) = \cos\phi - \varepsilon_3 \cos(3\phi - \varphi_3)$ The parameters are chosen such that at ϕ_0 marked by a vertical tick, $V''(\phi_0) = 0$. $K = v(\phi_0)\cdot v'(\phi_0)$ is a current dependent parameter describing the compensation of longitudinal space charge forces.
Curve 1: $\varepsilon_3 = .113$, $\phi_0 = 0^0$, $\varphi_3 = -10.5^0$, K=.055
Curve 2: $\varepsilon_3 = .12$, $\phi_0 = -30^0$, $\varphi_3 = -126.7^0$ K=.55

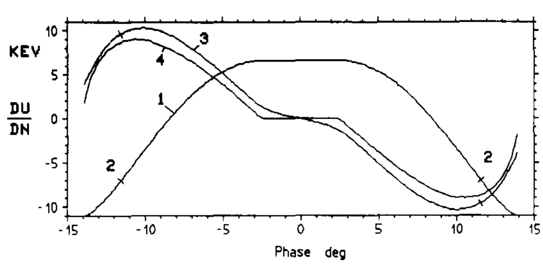

Fig. 8: Voltage gain per turn dU/dn from longitudinal space charge forces for a 2 mA beam at radius 2300 mm of Injector II at SIN.

Curve 1 shows a realistic assumption for the charge density distribution with 98% of the beam contained between the tick marks at 2, curve 3 is the voltage gain from the numerical program DISCS and 4 is the result from the smooth wall model with dU/dn proportional to the dervative of 1. The average voltage gain per turn from the RF is 850 kV.

	Inj. II	590 MeV
ΔU_{sc} (cigar model)	3.5 MV	3.5 MV
ΔU_{sc} (sector model, non rel.)	(3 MV)	(11 MV)
ΔU_{sc} (DISCS-model, numerical)	3 MV	4 MV
ΔU_{sc} (compensated)	.3 MV	.4 MV
voltage gain at extraction	1 MV	1.7 MV
$K = v_0 v_0'$ for compensation	.06	.03

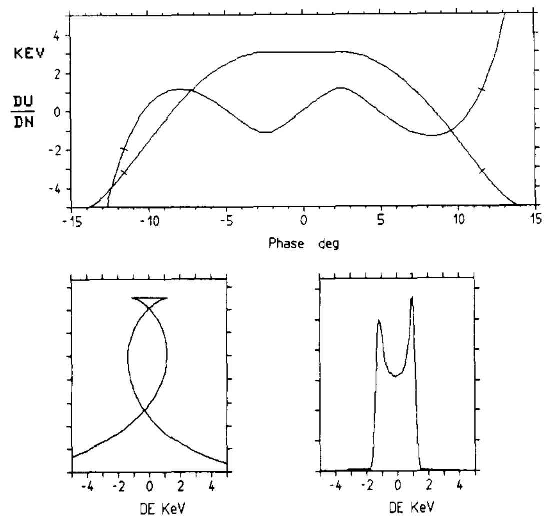

Fig. 9: Top figure shows dU/dn for same charge density as in fig. 8 but partial compensation with third harmonic $\varepsilon_3 = .113$ and K-value of .06. The lower left figure shows the azimuthal charge density versus energy deviation from central particle. The lower right figure shows the energy spectrum. The energy spread has been reduced to 3.4 keV/turn compared with 20 keV/turn for the uncompensated case.

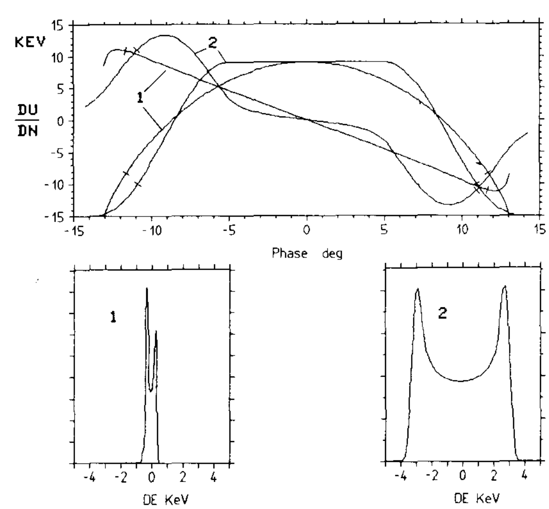

Fig. 10: Charge density and voltage gain dU/dn for an optimistic case (curves 1) and for a pessimistic case (curves 2) both with a 2 mA beam in the injector II (as in fig. 8). Lower figures show the energy spectra for the two cases with energy spreads of 1 keV/turn and 7 keV/turn respectively. The big influence of the charge distribution in the tails is clearly evident.

The sector model is not realistic in the case of the injector II, because the turns are widely separated. The agreement with the numerical result is thus more or less accidental. In the case of the 590 MeV ring cyclotron the sector model overestimates the total voltage spread ΔU_{sc} due to relativistic effects.

In conclusion we hope that even an average beam of 2 mA will have separated turns in both SIN cyclotrons.

8. Beam loading effects

When we discuss possible mechanisms which might cause current limitations due to beam loading effects, we assume that the RF-system under consideration is sufficienlty powerful to cover the losses of the accelerating system and the beam power.

Ten years ago doubts came up on the stability of accelerating systems under the influence of high beam currents in ring cyclotrons. It was assumed that the beam, when it is not exactly in phase with the accelerating voltage, exerts a reactive load on the RF-resonator which might lead to a collapse of the RF-voltage. It could be shown by theoretical considerations that accelerating systems are stable also for high beam loading factors provided that the associated amplitude and phase regulation loops are fast.

For flattop systems, whose importance was pointed out in the previous chapter, beam loading effects can be best illustrated with an example from the SIN ring cyclotron:

With 170 µA on target the total beam power at 590 MeV is 100 kW. The flattop cavity absorbs about 10 kW from the beam, which corresponds to a noticeable beam loading factor of 25%.

Up to this point the performance of the amplitude and phase regulation loops are well within the tight specifications. But with increasing current it becomes more and more difficult for the regulation system to stabilize the cavity voltage. For a current of about 600 µA there is even no need to feed power from the transmitter into the cavity. A further problem is that the impedance of the coupling is current dependent which results in a reflected RF-wave which could damage the power amplifier. In order to solve the above mentioned problems the following measures are under consideration:

- increasing the cavity voltages of the 50 MHz and 150 MHz systems.
- lowering the Q of the 150 MHz cavity.
- loading the flattop cavity with an external resistor which can be matched to the variable beam loading. This can be done by varying the coupling or by electronically adjusting the impedance.
- the RF-power which is reflected from the flattop cavity is coupled out and dumped to a 50 Ω resistor. With presently available directional couplers only a fraction of the reflected power can be diverted.

Detailed calculations and tests will be carried out in the near future to see which method of combination of methods will be finally adopted in orderto cope with this beam loading problem.

9. Activation

The operation of an accelerator facility increases in complexity with rising activation levels induced by beam losses. K. Goebel gives an excellent review of these problems for the German project of a spallation neutron source [38]. The situation becomes critical, when "hands-on maintenance" is more and more restricted and complex remote handling is the rule rather than the exception.

At SIN the situation with the 590 MeV proton beam presents itself as follows:

In 1979, 3200 h with 90 µA ; i.e. 280'000 µAh.
losses ca. .2% i.e. 600 µAh
In 1980, 3500 h with 100 µA ; i.e. 350'000 µAh.
losses ca. .05% i.e. 180 µAh
(lower losses due to intermittent operation with flattop system).

For the future we assume (optimistically) an average loss of .3% or 6 µA at 2 mA beam current, giving a total loss of 24'000 µAh per year. This is about a factor 400 more than the losses in 1979.

As a comparison TRIUMF produced in 1979 120'000 µAh of protons with an average loss of 5% yielding an integrated loss of 6'000 µAh per year. This requires already substantial cool-down times prior to maintenance periods. Although the projected beam loss at SIN is four times higher than presently at TRIUMF, the consequences on maintenance work will be less severe, because the beam losses are localized in a few extraction elements which can be quickly removed and shielded locally.

10. Targets

The design of targets capable of withstanding beams of very high power is a technological challenge. At SIN the experience with the rotating target wheels used for pion production has shown, that the 12 cm long Be-targets cannot withstand beams of 170 µA. The two main problems are:
- thermal stress can crack the wheels
- Beryllium at high temperature evaporates a metallic Be-film onto the heat shields. This coating increases the absorptivity of the heat shield around the bearing, which leads to a temperature above 300°C, destroying the ball bearings.

It seems that for the future 2 mA beam the most promising targets are rotating graphite wheels of large diameter or stationary pyrolythic graphite targets.

To make further use of the protons after the production targets SIN is planning to construct a neutron spallation source as a beam dump.

Summary

Present cyclotrons are able to produce beams with an average beam power up to 100 kW. To improve this performance by an order of magnitude one has to cope, in addition to the technical problems, with the physical problem of space charge forces. When these intensity related effects set in, the beam losses and hence the induced activation will rise faster than linearly with the beam current. For cyclotrons which depend on single turn extraction, the longitudinal space charge forces require a careful examination. They can smear out the turn structure, hence spoiling the extraction rate. The intensity limit for routine operation will then be given by the tolerable activation levels.

At high currents the beam intensity is also an important accelerator parameter affecting the settings of other components like RF-system, trimcoils, quadrupoles etc. Varying the beam current will be a similar operation in the future as changing the beam energy in present cyclotrons. Coarse tuning at high current levels will be possible with the help of a low duty cycle pulser, maintaining the peak intensity at the operational value.

Hardware and software closed-loop control will play an even more important role than today. The time response of the beam interlock system has to be faster with increasing beam power. Diagnostic tools have to be of the non-interceptive type, like e.g. the tomography methods based on light observation from the residual gas, which are used to mesure the beam emittance [39].
A key factor for obtaining high beam intensities is the RF-system:

- the RF has to provide the necessary beam power, which can be higher than the power losses in the RF-structures.
- the tolerances on the feedback loops for RF-amplitude and phase become tighter with increasing beam loading factors.
- a high accelerating voltage is advantageous because it enhances the turn separation and thus the extraction rate. Furthermore the longitudinal space charge effect and the relative beam loading factor gets reduced.
- a flat-topping RF-system is essential (except in the case of H^-) in obtaining high intensity beams with a low energy spread.

Acknowledgements

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" DISCUSSION "

Y. JONGEN : Did you consider in your calculations, the effect of space charge neutralization by electrons in the cyclotrons ?

W. JOHO : We take neutralization into account in the beam transport at low energy with DC beams. In the cyclotron we assume, pessimistically, that we have no neutralization.

S. OHNUMA : Usually, the space of a real beam is far from an ideal six-dimensional ellipsoid. When the intensity is as high as 2 mA, the current limit would come from the extraction loss, that is, how much beam less you can tolerate. Most likely, you would have to know the detailed particle distribution (tails, whiskers etc..) of your beam. How are you going to cope with this problem in SIN ?

W. JOHO : This is of course the real issue. It is hard to predict in advance the distribution of the particles in the tails and it is these tails which determine the extraction losses. We plan to use collimators at low energy to clean up the beam and probably some bunching to obtain a favourable charge distribution in azimuth.

M. REISER : Can you please explain why the aperture (vertical acceptance) does not enter into the formula for the current limit ? It would seem that the current limit increases with the vertical acceptance. Also did you take image charge effects into account ?

W. JOHO : The vertical beam size has only a mild effect on the longitudinal field in the sector model with closely packed turns. For clearly separated turns, the influence of this vertical size is more pronounced.

G. DUTTO : You mentioned that ion source output is not a problem. However, it is our experience at TRIUMF, that the emittance of the source beam must be kept small in order to avoid halo formation through bunchers, field perturbations etc... Could you comment on the emittance of your beam ?

W. JOHO : The emittance of our new cusp-field ion source bas been measured by M. OLIVO and is 2π mm mrad, normalized, at DC-currents of 10 mA. This is better than originally specified for our new injector.