HIGH INTENSITY PROBLEMS, REVISITED OR CYCLOTRON OPERATION BEYOND LIMITS

TH.STAMMBACH

PSI, 5232 Villigen-PSI, Switzerland

High intensity problems in cyclotrons are reviewed in response to the growing interest in new applications like neutron spallation sources, hybrid reactor systems (as e.g. the "energy amplifier"), inertial fusion and accelerator driven transmutation technologies. The feasibility of high power cyclotrons is discussed based on the experience gained from the upgrade of the PSI accelerator facility and on an overview is given on the progress on high intensity cyclotrons and possible limitations. Subjects to be treated are space charge effects, halo formation, activation and questions related to beam generation.

1 Introduction

The question on possible performance limitations of cyclotrons has always played an important role in the history of cyclotrons. Today new applications of high power particle beams in various fields focus the interest on the question of high beam intensities and possible limits on the beam power. Such applications like spallation neutron sources, accelerator driven hybrid reactor systems and accelerator driven transmutation technologies are described in section 2.

High intensity problems in cyclotrons have been summarized by W.Joho in the 9th Int. Cycl. Conference that was also held in Caen in 1981 [1]. The progress since then is reviewed based on the experience gained in the upgrade of the PSI accelerator facility from 0.15mA in 1981 to 1.5mA in 1995. The feasibility of high power cyclotrons and possible limitations are discussed on three typical examples: 1) the PSI Injector 2, a 72 MeV cyclotron specifically designed for high beam intensities [2], 2) the PSI 590 MeV Ringcyclotron routinely operated at a beam current of 1.5mA corresponding to 0.9 MW beam power [3] and 3) the conceptual design of a 1 GeV cyclotron for the production of a 10mA beam corresponding to 10 MW beam power [4]. A tentative layout of such a cyclotron is shown in fig.1. This cyclotron has been named the "dream-machine" by H.Blosser, a name to be used further in this text.

Important subjects to be covered in this work are space charge effects, halo formation and maintenance of activated components. As has happened often in the history of cyclotrons, new concepts and changing strategies were essential to circumvent limiting effects. Prominent examples are the development of synchrocyclotrons, the introduction of AVF focusing and the use of external ion sources. In the PSI cyclotrons, new concepts like separated magnet sectors, a large orbit radius and a high energy gain per turn have resulted in well separated turns allowing beam extraction with extremely low beam losses and low activation levels. Finally, as a step into the future, the change of the setup strategy in the PSI Injector 2 based on investigations of strong longitudinal space charge effects [5] has led into a new regime for a cyclotron, where expected limits disappear and the beam quality is improved by the space charge forces. Apart from the experience with the PSI cyclotrons little is known about halo formation. Further investigations and simulation studies have to be done on this subject.

2 New Applications

The new applications mentioned above require beam intensities considerably higher than available today. They depend on beam power in the range of 1 - 100 MW. The 1 MW beam in the PSI facility is employed to drive a spallation neutron source, where the neutrons are used as probes in material research, solid state physics, chemistry and biology. The beam power needed for such applications is in the range of 1 - 5 MW. The project of an energy amplifier and similar accelerator driven hybrid reactor systems need beams in the range 10 - 30 MW. The expectation is that such inherently save reactor systems could be a possible source of energy for coming decades, with the advantages that more abundant fuels like Thorium can be used and at the same time spent fuel from classical nuclear power plants can be burnt and transmuted. Inertial fusion programs, where intense particle beams are employed to reach the necessary temperatures for fusion need around 10 - 40 MW pulsed beams. Finally, accelerator driven transmutation facilities are planned to burn up plutonium from nuclear weapons as well as other nuclides with long lifetimes present in spent fuel from nuclear power plants. These facilities would not be optimized for energy production, but rather for a high transmutation rate of the dangerous isotopes and would need beams up to 100 MW beam power.

Several facilities, mainly based on linear accelerators,

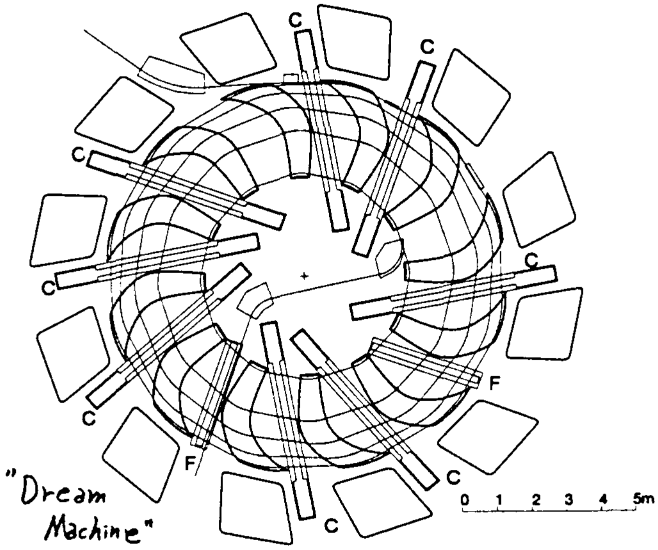

Figure 1: Conceptual layout of a high power cyclotron for 10mA beam current at 1 GeV. Its main characteristics are: 12 sector magnets with a maximum field of 2.1T, with 8 accelerating cavities (C) operating at 44.2 MHz, the 6th harmonic of the cyclotron frequency, and two 132.6MHz flattop cavities (F). The injection energy is 120 MeV and the extraction radius of 5.67m is reached after 140 revolutions.

providing such beams have been proposed. The feasibility of cyclotrons for the production of high power beams has been discussed in references [4],[6] and [7]. Based on a performance extrapolated from the PSI facility it was concluded that the cyclotron shown in fig.1 should produce a 10 MW beam without intolerable beam losses. Applications that need higher beam power would most probably be based on multiple accelerators, i.e. a cyclotron farm with more than one accelerator in order to reduce the power fluctuations on the target of such a facility. This is expected to be very important due to the considerable problems related to the power deposition in the target assembly and related to mechanical stress introduced by too frequent interruptions of the high power beam if a single accelerator were used.

3 History of Limits in Cyclotrons

In the discussion of limits it is worthwhile to look back on the history of cyclotrons and to recall how new concepts and strategies have been employed to overcome existing limits. As early as 1932, only two years after the first publication on the 'apparatus for the multiple acceleration of ions' as the cyclotron was called at that time, Lawrence and Livingston [8] already observed the contradiction between vertical focusing and the acceleration of particles to relativistic energies. The conclusion that this imposes an energy limit was then stated in 1937 by Bethe and Rose [9] in their publication on 'The Maximum Energy Obtainable from the cyclotron' where they predicted an energy limit of 12 MeV for protons. The invention of the synchrocyclotron is the first typical example of a new concept that removed existing barriers. The introduction of azimuthally varying fields about two decades later was another new concept that helped to go beyond this limit and today cyclotrons operate at proton beam energies up to 520 MeV at TRIUMF, 590 MeV at PSI, and synchrocyclotrons reach 1 GeV as e.g. in Gatchina. The progress in the production of high intensity proton beams, of beams of negative hydrogen ions and in the production of highly charged heavy ion beams would not have been possible with the limitation imposed by internal ion sources in cyclotrons. The introduction of axial injection systems and the use of external ion sources have removed this limitation. Finally, the superconducting cyclotrons broke the economic limitations imposed by the size of heavy ion facilities using normal conducting cyclotrons.

The conclusion is, that the question 'what are the limits' should be replaced by the alternative question 'what strategies are available to go beyond limitations'.

4 Cyclotrons for High Beam Power

In order to generate high beam power three parameters have to be considered: beam current, energy and the number of beams. On one side multiple beams will be important in applications in which a continuous uninterrupted beam is essential, but on the other side the beam current is the least expensive way to high beam power. In most cases the beam current in cyclotrons is limited by the amount of beam lost at extraction. Both, power deposition and activation due to beam losses impose severe problems, but generally it is thought that most probably the radiation dose to the personnel involved in repair and maintenance work would be the limiting factor. When meson factories were designed in the sixties new concepts had to be introduced and developed in order to overcome this limitation. One way was the acceleration of negative ions that can be extracted by stripping, another way the concept of separated magnet sectors that allow to have clearly separated turns.

The acceleration of negative ions has been employed successfully in a large number of low energy, high current cyclotrons and in the large 520 MeV cyclotron of the meson factory at TRIUMF in Canada. The use of this principle for the generation of high power beams will be discussed in detail by M.Craddock in another contribution to this conference [10].

Clearly separated turns can be achieved in separated sector cyclotrons as proposed by H.Willax [11] in 1963.

These cyclotrons generally have a large orbit radius and the free space between the sectors allows to install large RF resonators with a high Q-value for an acceleration with a high energy gain per turn. Both factors, large radius and high energy gain, improve the turn separation given by the equations

$$\begin{aligned} dR/dn &= R_{\text{av}} \frac{E_{\text{gain}}}{E} \frac{\gamma}{(\gamma+1)(1+k)} \\ k(r) &= \frac{r}{B} \frac{dB}{dr} \quad , \end{aligned}$$

where R_{av} is the average orbit radius, E_{gain} the energy gain per turn, E the energy and γ the relativistic factor. k is the field index of the cyclotron field and $(1+k) \simeq \nu_r^2 \simeq \gamma^2$, where ν_r is the radial betatron frequency. Beam losses can be kept low, as long as the turn separation remains larger than the size of the beam.

Increasing size allows to have more magnet sectors and a larger number of acceleration cavities, which results in a higher energy gain and helps to control beam losses at extraction. The scaling law of the turn separation dR/dn and the width of the beam Δx with energy is shown in fig.2 for different radii on the example of the PSI Ringcyclotron (590 MeV, $R_{\text{max}} = 4.5$m) and the 1 GeV-cyclotron shown in fig.1 (1 GeV, $R_{\text{max}} = 5.7$m). Also shown is the energy dependence of dR/dn and Δx at extraction for two model cyclotrons with fixed extraction radii of $R_{\text{max}} = 10$m and $R_{\text{max}} = 20$m. The values plotted in fig.2 were calculated based on the following assumptions: isochronous cyclotrons, $(1+k) = \nu_r^2 = \gamma^2$, the number of cavities proportional to the size of the cyclotron (and hence E_{gain} proportional to R_{max}, set to be $E_{\text{gain}} = R_{\text{max}} \cdot 0.8\,\text{MeV/m}$), and finally a beam size calculated from a reduced beam emittance $\varepsilon_n = 4\pi$ mm mrad.

In some cases the advantage of a large orbit radius in high power applications is further enhanced by the fact that the higher energy gain also reduces the deterioration of the beam quality due to space charge forces, as discussed in the following sections. The free space between the sector magnet also makes it possible to install a "flattop cavity" that operates at the 3rd harmonic of the acceleration voltage and which makes the acceleration independent on the phase of the particles. This gives narrow turns even if bunches with a large phase width are accelerated.

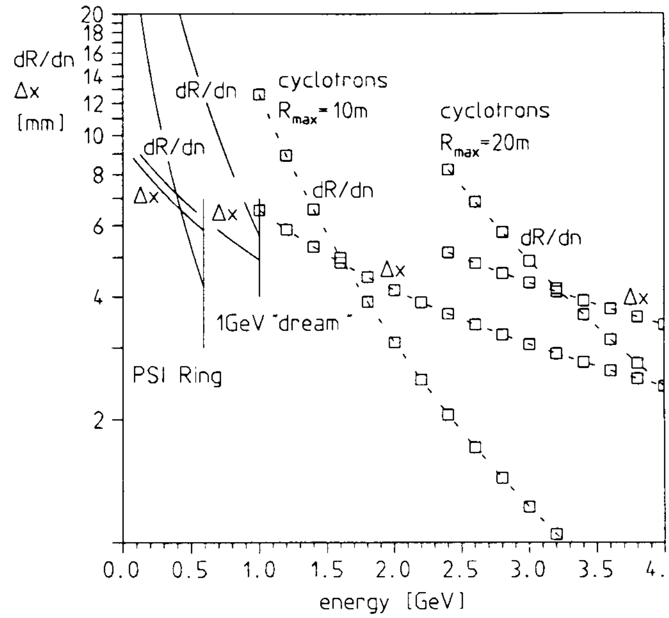

Figure 2: Turn separation dR/dn and beam full width Δx in function of energy for typical cyclotrons of variable size as specified in the text. The figure demonstrates that increasing size of the cyclotron helps to reduce extraction losses, which remain low as long as dR/dn can be kept larger than Δx.

5 Beam Losses and Activation

A possibly limiting factor which is difficult to quantify is the activation of components and the radiation dose imposed on the personnel involved in their repair and maintenance. The dose not only depends on the beam losses, but to a large degree on the design of the cyclotron, on preventive measures like concentration of activation in specially designed dumps, the installation of local shielding, optimized material selection and, last but not least, the attitude of the personnel in the handling of activated components. The serviceability after irradiation is rather related to design than to the amount of beam lost. This is also seen from the seemingly contradictory specifications of beam currents and tolerable losses: the target of the spallation neutron source at PSI is built for a beam current of up to 2mA, while in the design of linacs the beam losses are requested to remain below 1 nA/m [12].

The large range in the relation between beam losses and dose shall be demonstrated on typical data from the upgrade of the PSI cyclotron facility from around 0.1 to 1.5mA beam current. Until 1985 the facility was operated with the Injector 1, a conventional 72 MeV cyclotron with an internal ion source, at an average beam current of 0.1mA and an extraction rate around 93%. Averaged over 4 years (1982-1985) the integrated beam production was 430 mAh per year, the beam losses were 30 mAh/y and the total dose related to service on the Injector 1 cyclotron amounted to about 100 mSv per year. Today the facility is routinely operated at a beam current of 1.5 mA, but with very low beam losses. Both cyclotrons, the Injector 2 and the 590 MeV Ringcyclotron are separated sector cyclotrons with an extraction rate of around 99.95% to 99.97%. The activation of accelerator components remains within levels tolerable for normal hands-on maintenance. Only some of the components used for the injection and extraction of the beam have to be equipped with local shielding and installations for remote handling. Due to continuous improvement on the cyclotron setup and the components, the dose to the service personnel is decreasing, although the beam production is increasing from year to year. Averaged over the years 1994-1997 the integrated annual beam production for the whole facility was 4750 mAh per year. The integrated beam losses were 5 mAh/y at 72 MeV, 10 mAh/y in a specially shielded collimator in the 72 MeV beam line and 1.4 mAh/y at 590 MeV at extraction from the Ringcyclotron. The average annual dose of the accelerator division was around 45 mSv per year.

The conclusion is, that the limit imposed by activation of components can be avoided with proper design strategies, like local shielding, installations for quick and remote removal of activated components into shielded boxes and the use of manipulators [13]. The design has to be adapted until the dose complies with that allowed by law. Based on this we assume that the radiation problems can also be controlled in a 10 MW facility provided it is operated at extraction efficiencies comparable to the PSI cyclotrons.

6 Space Charge Effects

The effects from space charge forces in cyclotrons have been summarized in ref. [1],[6],[14] and the references given therein. A full discussion of many aspects of space charge forces on particle beams, - or more generally of the self fields generated by the particles in the moving bunch -, can be found in a recent book by M.Reiser [15]. In cyclotrons longitudinal space charge effects dominate. The calculation and simulation of space charge effects is complicated for several reasons. Self fields and external focusing fields have to be accounted for. Of interest is the relative motion of the individual particles in the bunch, which has to be separated from the motion of the bunch as a whole. The relative motion, then, changes the particle distribution that defines the fields. Hence the space charge force and the particle distribution have to be treated in a self-consistent manner and the resulting forces are generally highly nonlinear. An insight in the essential features comes from simple models and from the analysis of simulation results. If the behaviour of tails and halos should be investigated, simulations have to follow a very large number of particles. An accurate prediction of the behaviour of beam losses under space charge forces is close to impossible, since the tails of the profiles are determined by nonlinearities and those could only be calculated based on a precise knowledge on the actual charge distribution in the bunch, which is hard to get for a cyclotron beam. More successful are extrapolation procedures.

Some basic features can be derived from a few simplified cases. The defocusing action from space charge forces is proportional to the beam current I_{peak} and decreases with the third power of the product of the relativistic parameters $(\beta\gamma)$. In general the space charge forces contribute most in the center region of a cyclotron. They can be described conveniently in terms of the general perveance K, which is defined by

$$K = \frac{Z}{A}\frac{I_{\mathrm{peak}}}{I_0}\frac{2}{(\beta\gamma)^3} \quad ,$$

where

$$I_0 = \frac{4\pi\,\varepsilon_0\,c\,E_{\mathrm{amu}}}{e} = 3.107\ 10^7\mathrm{A} \quad .$$

Z is the charge state, A the mass number of the particles, I_{peak} is the actual peak current (not averaged), ε_0 the permittivity of free space, c the speed of light, e the electron charge and E_{amu} the energy at rest of an atomic mass unit. Note that in contrast to other publications the factor (Z/A) has been separated out from the equation of I_0 in order to show its effect in heavy ion beams. The tuneshift $d\nu_{\mathrm{r}}$ from transverse space charge forces can easily be found for a continuous unbunched beam in a periodic focusing channel, the same formula applies to a bunch that has the shape of a sphere:

$$\nu_{\mathrm{r}}^2 = \nu_{\mathrm{r0}}^2 - K\frac{R_{\mathrm{av}}^2}{a^2} \quad ,$$

where ν_{r0} is the radial betatron frequency at zero beam current, ν_{r}=$(\nu_{\mathrm{r0}} + d\nu_{\mathrm{r}})$ at the beam current included in the perveance K, R_{av} the average orbit radius and $2a$ the diameter of the beam or the sphere. For all other cases geometry factors have to be included in the calculation of K. Difficulties with resonances arise if $d\nu_{\mathrm{r}} \geq 0.5$, an absolute limit is reached if $d\nu_{\mathrm{r}} \geq \nu_{\mathrm{r0}}$.

The effect from the bunch geometry shall be demonstrated on the example of a homogeneously charged rotational ellipsoid with the axis a in both transverse and l_m in the longitudinal directions along the path of the beam. For relativistic beams the Lorentz contraction has to be accounted for in the longitudinal axis. The electric field components on the surface of such a bunch in the radial and longitudinal directions on the main axes of the ellipsoid are

$$\begin{aligned} E_{\mathrm{r}} &= \frac{Q}{4\pi\varepsilon_0 a^2}\,G_{\mathrm{tr}} \\ E_l &= \frac{Q}{4\pi\varepsilon_0 a^2}\,G_l \quad , \end{aligned}$$

where Q is the charge contained in a single bunch. The geometry factors G_{tr} and G_l can be calculated from a

and l_m [14],[15]

$$\begin{aligned} G_{\rm tr} &= \frac{3a}{2l_m}(1 - f(p)) \\ G_l &= 3f(p) \quad , \end{aligned}$$

where p and $f(p)$ are defined by

$$\begin{aligned} &p = \frac{l_m}{a} \\ &p \geq 1 : f(p) = \frac{p}{\sqrt{(p^2-1)^3}} \ln p + \sqrt{(p^2-1)} - \frac{1}{(p^2-1)} \\ &p = 1 : f(p) = 1/3 \\ &p \leq 1 : f(p) = \frac{1}{(1-p^2)} - \arccos p \frac{p}{\sqrt{(1-p^2)^3}} \quad . \end{aligned}$$

The electric field along both, the transverse and longitudinal axis drop roughly with $1/l_m$, i.e. they vary inversely to the phase width of the beam. The effect of mirror charges to reduce the longitudinal space charge fields can be estimated using the geometry factors g and g_0 derived by M.Reiser [15]. G_l has to be multiplied by g/g_0, where g_0 is related to $f(p)$ by $g_0 = 2\,p^2 \cdot f(p)$. Note also, that in this model of a homogeneous charge distribution the fields inside the bunch increase linearly with the distance from the center.

Special attention should be paid to longitudinal space charge effects, since isochronous cyclotrons do not have the property of longitudinal focusing. In the lowest order approximation the longitudinal space charge forces results in an additional energy spread. Leading particles gain energy and drift adiabatically to the corresponding equilibrium orbit at a larger radius. Late particles loose energy and drift inwards. These motions result in a rotation of the bunch in respect to the direction of propagation. Nonlinear effects from the Coulomb forces and the charge distribution, but also from the fact that the beam bunch in the cyclotron is curved, lead to a distortion in addition to the rotation of the bunch. The broadening of the bunch due to the linear part can be compensated by adjusting the phase away from the peak of the RF voltage or, if a flattop system is used, by adjusting the phase of the third harmonic with respect to the accelerating RF voltage [1],[14],[16]. The nonlinear part results in a deterioration in beam quality and increasing beam losses due to long tails on the beam profiles.

W.Joho [1] presented various models to approximate this energy spread, in order to find the basic scaling laws and to estimate beam current limits. The space charge induced energy spread $\Delta E_{\rm sc}$ (full width) is found by integration of the longitudinal electric field E_l over the whole path of the particles in the cyclotron, i.e. by integration over the turn number n

$$\Delta E_{\rm sc} = 2\,\frac{1}{\gamma^2} \int Ze \cdot E_l \cdot 2\pi R_{\rm av} dn \quad ,$$

where the factor $(1/\gamma^2)$ comes from the Lorentz transformation of E_l to the moving frame. The turns remain separated as long as $\Delta E_{\rm sc}$ is smaller than the energy gain per turn at the extraction radius. The result cannot be more than a rough estimate with large uncertainties for three reasons: 1) due to the fact that the electric fields depend on the charge distribution, especially on the periphery of the bunch, 2) from the shielding effect of the walls above and below the beam bunch that reduce the electric fields in the case of elongated bunches, and 3) from the contribution of neighboring orbits to the longitudinal electric field. All three effects are not known with sufficient accuracy for an exact calculation of $\Delta E_{\rm sc}$, but the models do give very useful scaling laws.

For the calculation of the effect from neighboring turns the "sector model" has been proposed [1]. This model is based on the assumption of completely overlapping turns forming a rotating beam sector. The charge density in this sector is not a function of radius as long as relativistic corrections are neglected. Based on this model W.Joho [1] deduced the rule that the maximum beam current scales with the third power of the energy gain per turn, $E_{\rm gain}$, i.e. with $1/N^3$, where N is the total number of turns. A current limit is reached when $\Delta E_{\rm sc}$ becomes too large compared to $E_{\rm gain}$. Hence the maximum current is determined by the ratio $E_{\rm gain}/\Delta E_{\rm sc}$, where $E_{\rm gain}$ is proportional to $1/N$ and $\Delta E_{\rm sc}$ is proportional to N^2 (because both, the charge density and the integration path increase proportional to N). An example is given in fig.3 which shows how the beam current could be raised with increasing cavity voltage in the upgrade of the PSI facility.

7 Operation beyond space charge limits

The PSI Injector 2 [2] gives an example of a new strategy that allows to operate a cyclotron beyond limits expected from space charge forces. The experience gained from experiments with strongly bunched beams has revealed a new mode with very interesting properties [4],[5],[16]. It turns out that in a cyclotron under strong space charge forces the radial and the longitudinal effects can not be treated separately. The vortex motion [17], introduced by the combined action of space charge forces and the strong coupling between radial and longitudinal motion, produces very compact and clean beam bunches. Such a beam has a very small phase width, no far reaching tails in the particle distribution and it can be extracted with extremely low beam losses. Three conditions are important: strong space charge forces (i.e. strongly bunched beams), a spherical beam bunch and well separated turns.

Detailed investigations on the particle motion in an isolated bunch have been done by many authors, mostly

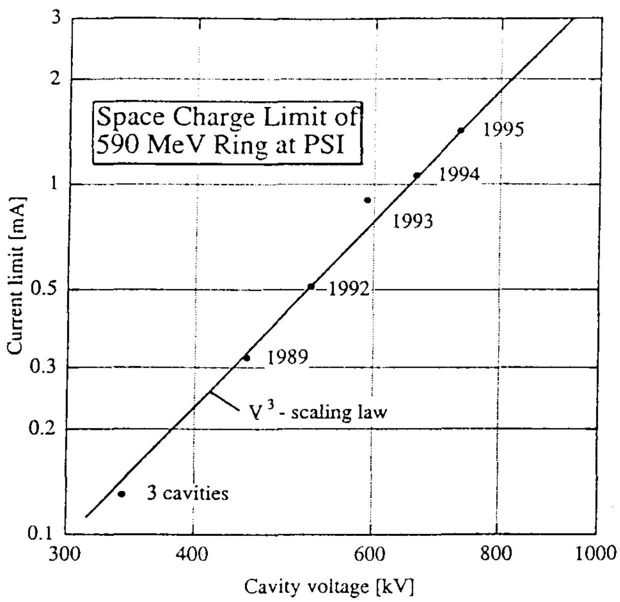

Figure 3: Maximum beam intensity that could be extracted from the PSI Ringcyclotron with low beam losses at different stages in the course of the upgrade program. Due to the effect of longitudinal space charge forces the maximum beam intensity is expected to scale with approximately the third power of the cavity voltage, i.e. the energy gain per revolution (solid line).

using particle simulation methods [5],[7],[18]. All the studies show the appearance of nonlinear effects that were expected to limit the beam current. On the case of the PSI Inj.2 S.Adam [5] demonstrated the transition of an elongated bunch towards a charge distribution that is circular in the plane given by radius and phase. Some of the special features of a spherical beam bunch have been worked out in an earlier publication by C.Chasman et al. [19]. They solved the coupled equations of motion for a particle on the periphery of the bunch in a cyclotron field including space charge forces for the nonrelativistic case. The result shows a cloverleaf oscillation of the particles around the centre of the bunch in the plane given by radius and phase. An example is given in fig.4, which shows such a cloverleaf trajectory for for the case of the PSI injector 2. This oscillation has the following important and new properties. The bunch remains spherical, which means that the phase width shrinks with increasing orbit radius. The maximum excursion of the particles from the centre of the bunch is limited, i.e. there is no escape of particles, which is a very important finding in respect to halo formation. The particle motion is not strictly isochronous anymore, as the particles oscillate around the bunch between head and tail. The period of oscillation is independent of the radius of the orbit, i.e. constant from injection to extraction. It should be noted that due to the lack of coupling between radial and vertical motion in the cyclotron field, there is little justification to assume a spherical bunch, any upright rotational ellipsoidal bunch has the same properties.

Part of these properties are also seen in the simulation work of S.Adam [5]. In a publication S.Adam and S.Koscelniak [20] point out that in space charge dominated beams the longitudinal matching in the plane given by radius and phase becomes as important as the wellknown matching in the transverse directions. They show, that an elongated, i.e. mismatched, bunch becomes circular, passing through an intermediate stage with the shape of a galaxy. The galactic arms end up as tails in the distribution. In the case of the PSI Injector 2, - which is the only cyclotron we know of that operates in this mode -, the proper matching is ensured by strong collimation of the beam that removes up to 50% of the injected beam current. Since this is done in the first few revolutions at energies below 3 MeV, an activation of the machine can be avoided.

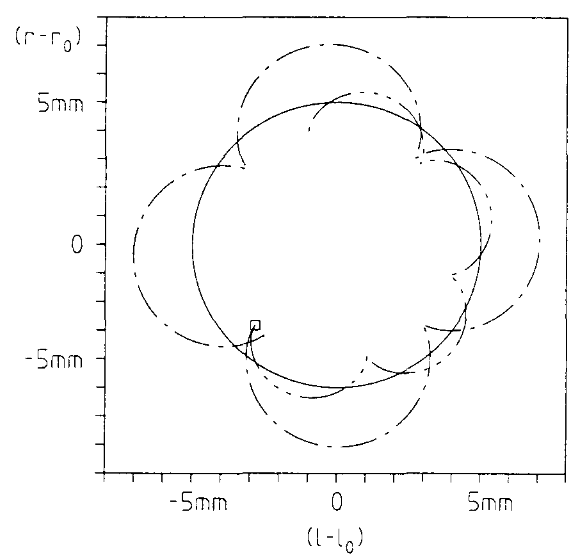

Figure 4: Typical "Cloverleaf"-trajectory of a testcharge on the surface of a spherical homogeneous beam bunch (radius 5mm) in a cyclotron field. Plotted is the case of a 1 MeV beam, coasting over 5 revolutions in the PSI Inj.2 for a beam current of 1mA — · · · — and 2mA — · —.

Experimental evidence for a circular or a spherical beam bunch is hard to find and many questions are still unexplored, as e.g. what is the effect of neighboring orbits, does a mismatched charge density lead to oscillations in the size of the bunch, to what extent can a circular beam bunch be extended along the vertical axis to form an upright ellipsoid, do the space charge forces themselves introduce enough coupling between radial and vertical motion to form a sphere and where is the limit to the charge density in such a sphere. The most striking feature in this mode, however, is that the beam appears very compact with clean beam profiles in both radius and phase [16]. Beam currents of up to 2mA at 72 MeV could be extracted with beam losses generally far below 0.1%.

8 Discussion

In this section results from calculations using the equations given above are discussed for the three cyclotrons initially mentioned and a heavy ion cyclotron: the PSI Inj.2, the PSI Ring, the 1 GeV "dream-machine" and an $^{36}Ar^{18+}$ beam in the SSC2 at GANIL. Where available the calculations are compared to observations and measurements on the beam. The calculated values are listed in table 1 and shall be used for a discussion of the validity of the underlying models. The calculations are based on a bunch with a homogeneous charge distribution in a elongated rotational ellipsoid with the axes

$$a = \sqrt{\frac{\varepsilon_n R_{av}}{\pi \beta\gamma \nu_r}} \quad \text{and} \quad l_m = \frac{\pi R_{av}}{h}\frac{\Delta\varphi}{360^\circ} \quad ,$$

where ε_n is the normalized emittance, $\Delta\varphi$ the phase width (full width) and h the harmonic number of the cyclotron. The cyclotrons are assumed to have $\nu_r = \gamma$ and an energy gain averaged over the total number of turns N. Note that the actual turn separation in these cyclotrons differ from the calculated value due to this averaging and due to the fact, that coherent betatron oscillations and acceleration into the fringing field are used to enhance the turn separation.

The data shown in table 1 confirm that longitudinal effects dominate. In all cases the ratio ΔE_{sc} to E_{gain} is large and obviously the limiting factor. The values of ΔE_{sc} are insensitive to beam quality, but depend on the phase width. The values of ΔE_{sc} are composed of a linear part and a nonlinear contribution. The linear part can be compensated with a flattop system, the nonlinear part f_{sc} of ΔE_{sc} remains and, from experience, amounts to about $f_{sc} = \frac{1}{2}$ [14]. Including this factor the contribution to the full width of the beam is given by

$$\Delta x_{sc} = (dR/dn) f_{sc} \frac{\Delta E_{sc}}{E_{gain}} \quad .$$

In the case of the Inj.2 it is due to the low injection energy that the conditions for a circular bunch can be met using a buncher in the injection beam line. At extraction the calculated phase width is 2°, which is beyond the resolution of the existing installation for time structure measurements. A proof of an extremely small phase width is indirectly provided by the fact that today the third harmonic resonators, originally installed for flattopping, are now used to accelerate the beam. This doubles the sensitivity to phase, but although the contribution from the phase width on the radial size has doubled, no effect is observed on the beam. The size of the beam and the energy spread are roughly in agreement with a bunch circular in radius and phase with a diameter of 12mm.

The Ringcyclotron is not operated with a circular beam bunch. The phase width is about 15° and given by debunching in the beam transfer line between the Inj.2 and the Ring. It is uncertain whether a circular bunch would keep its shape in the outer region of the cyclotron where turns overlap. The values given in table 1 are calculated on the basis of separated, elongated bunches for a normalized emittance of ε_n=2.2π mm mrad. The shielding effect from mirror charges on the walls above and below the midplane is weak and reduces the listed value of ΔE_{sc} by no more than 25%. In order to account for neighboring orbits the sector model mentioned in sec-

Table 1: Turn separation, beam size and space charge effects in typical cyclotrons.

		PSI Inj.2	PSI Ring	1GeV	GANIL
beam:		p	p	p	$^{36}Ar^{18+}$
energy E		72.5MeV	590MeV	1MeV	3.42MeV
I_{av}		2mA	1.5mA	10mA	0.03mA
ions/bunch		2.5 10^8	1.9 10^8	14.1 10^8	.008 10^8
$\beta\gamma$ extr.		0.401	1.286	1.808	0.463
cyclotron:					
R_{max}		3.505m	4.463m	5.671m	3.000m
f_{RF}/h [MHz]		50.6/10	50.6/6	44.2/6	13.5/2
$E_{injection}$		0.87MeV	72.5MeV	120MeV	490MeV
N		85	216	140	440
dR/dn extr.		18mm	4.2mm	5.6mm	2.5mm
$< E_{gain} >$		0.84MeV	2.4MeV	6.3MeV	6.7MeV
space charge:					
K	inj.	34 10^{-6}	.036 10^{-6}	.108 10^{-6}	.011 10^{-6}
	extr.	0.37 10^{-6}	.001 10^{-6}	.003 10^{-6}	.001 10^{-6}
$d\nu_r$	inj.	-0.08	-0.007	-0.029	-0.001
	extr.	-0.06	-0.002	-0.004	-0.000
ΔE_{sc}	extr.	0.40MeV	3.4MeV	6.6MeV	10.0MeV
calculated bunch:					
$\Delta\varphi$	inj.	17°	15°	15°	6°
	extr.	2°	11.5°	15°	6°
a	inj.	6.0mm	3.3mm	3.9mm	2.6mm
	extr.	6.0mm	2.2mm	2.1mm	2.4mm
l_m	inj.	6.0mm	46mm	65mm	31mm
	extr.	6.0mm	74mm	124mm	78mm
measured beam:					
Δx	2.turn	12mm	12mm	-	-
	extr.	12mm	6.4mm	-	-
dR/dn extr.		22mm	11mm	-	-
ΔE	extr.	0.40MeV	2.6MeV	-	-

tion 6 can be applied, but the energy spread induced by space charge ΔE_{sc} is found to be underestimated in this case, because on the inner radii the orbits are still well separated and hence the averaged density assumed in the model is lower than the effective charge density in the individual bunch. On the outer radii, where the turns overlap, the neighboring orbits do contribute. This can be seen from the fact that the power of three dependence shown in fig.3, gives a good description of the plotted data, as predicted by the sector model, which includes the effect of neighboring orbits. Their contribution is estimated to enhance ΔE_{sc} by about a factor of 2.

The values listed for the 1 GeV cyclotron demonstrate that this design has been optimized for maximum energy gain per turn. This results in a lower ratio $\Delta E_{sc}/E_{gain}$, i.e. better turn separation at 10mA beam current, than that in the Ringcyclotron at 1.5mA. Of interest is the fact, that in the case of overlapping turns ΔE_{sc} does not depend on R_{max}, but a larger cyclotron of the same energy can have better turn separation as long as the energy gain E_{gain} is raised with R_{max}.

The example of the GANIL SSC2 demonstrates how ΔE_{sc} is enhanced in heavy ion beams, since the charge state Z enters quadratically in the equation of ΔE_{sc}. A high acceleration voltage is mandatory for such beams.

9 Conclusion

Cyclotrons are an excellent option for the production of high power beams. A limit is not to be expected for the next factor of 10 in beam intensity. Advantages compared to other accelerators come from their special properties in respect to low beam losses and possibly better suppression of halo formation if the radial longitudinal coupling under space charge forces is fully exploited. The most important factors in the design are maximal possible acceleration voltage and proper matching including the longitudinal phase space. The cost factor is favourable due to the compact structure of cyclotrons. The preferable solution for higher beam power is a multibeam facility made up of several 10 MW cyclotrons.

Acknowledgements. The present work is based on contributions from the whole staff of the PSI accelerator division and I wish to express my gratitude for the support. Special thanks go to S.Adam for his willingness to share his expertise on space charge effects and to A.Adelmann for providing figure 4 of this report.

References

[1] W.Joho, Proc. 9th Int. Conf. on Cyclotrons and their Application, Caen 1981, les Editions de Physique (1982) 337

[2] U.Schryber, Proc. 10th Int. Conf. on Cyclotrons and their Application, East Lansing, (1984) 195

[3] U.Schryber et al., Proc. 14th Int. Conf. on Cyclotrons and their Application, Cape Town, (1995) 32

[4] Th.Stammbach et al., Proc. 1st Int. Conf. on Accelerator Driven Transmutation Technologies 1994, AIP Conf. Proc. 346 (1994) 229, and
Th.Stammbach et al., Proc. 2nd Int. Conf. on Accelerator Driven Transmutation Technologies 1996, Kalmar, ed. H.Conde, Uppsala Univ. (1997) 1013

[5] S.Adam, Proc. 14th Int. Conf. on Cyclotrons and their Application, Cape Town, (1995) 446

[6] Th.Stammbach et al., Proc. of the 4th Int. Conf. on Accelerators in Applied Research and Technology, Zurich 1995, Nucl. Instr. & Meth. B 113 (1996) 1

[7] N.Fietier and P.Mandrillon, Proc. 14th Int. Conf. on Cyclotrons and their Appl., Cape Town (1995) 462

[8] E.O.Lawrence and M.S.Livingston, Phys. Rev. 40 (1932) 19

[9] H.E.Bethe and M.E.Rose, Phys. Rev. 52 (1937) 1254

[10] M.Craddock, this conference

[11] H.A.Willax, Proc. Int. Conf. on Sector-Focused Cyclotrons 1963, CERN 63-19 (1963) 386

[12] T.P.Wrangler, AIP Conf. Proc. 377 (1996) 60

[13] E.Mariani et al., Fig.3 in "An Electrostatic Splitter for the PSI 590 MeV Beam", to be presented at the 6th Europ. Part. Acc. Conf., Stockholm 1998, and Fig.2 in reference [3]

[14] W.Joho, Proc. Int. Acc. School, Dubna, (1988)

[15] M.Reiser, "Theory and Design of Charged Particle Beams", John Wiley and Sons, New York 1994

[16] J.Stetson et al., Proc. 13th Int. Conf. on Cyclotrons and their Application, Vancouver, (1992) 36, and Th.Stammbach, ibid. p.28

[17] M.M.Gordon, Proc. 5th Int. Conf. on Cyclotrons and their Application, Oxford, (1969) 305

[18] A.Chabert et al., Proc. 7th Int. Conf. on Cyclotrons and their Application, Zurich, (1975) 245, and IEEE Trans. NS 22/3 (1975) 1930

[19] C.Chasman et al., Nucl. Instr. & Meth. 219 (1984) 279

[20] S.R.Koscielniak and S.Adam, Proc. of the 1993 Particle Accelerator Conf., IEEE (1993) 3639