SETTING UP THE SIN 590 MeV RING CYCLOTRON FOR SINGLE TURN EXTRACTION

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Abstract

Several strategies to optimize the parameters of the SIN 590 MeV ring cyclotron have evolved from tuning experience and beam studies. The step-by-step procedures for obtaining single turn extraction with extraction rates close to 100 % are described. Optimal values of the main magnetic field and the accelerating voltage can be determined with an accuracy of 10^{-6} and 10^{-4}, respectively.

Introduction

In a cyclotron it is obviously advantageous to have well separated orbits at extraction. Thus it is necessary to produce beams with a narrow phase width, unless an RF system with flattopping[1] is available. Furthermore the so-called single turn condition[2] has to be fulfilled. Let us briefly summarize this condition and its consequences. We assume the beam to have initially a central phase ϕ_i and a phase width $\delta\phi_i$. The optimal turn separation at extraction is reached when both the particle with phase $\phi_i + \delta\phi_i/2$ and phase $\phi_i - \delta\phi_i/2$ reach the extraction radius after the same number of revolutions n. This is the case (to first order) when the central particle at ϕ_i reaches the extraction energy E_f with the minimum number of turns.

$$\int_{E_i}^{E_f} dn = \text{minimum} . \quad (1)$$

After some calculations one gets the corresponding single turn condition

$$\int_{E_i}^{E_f} \frac{\sin \phi(E) dE}{E_G(E) \cos^3\phi(E)} = 0 . \quad (2)$$

This condition maximizes as well the final energy for a given number of turns (maximum acceleration efficiency). Condition (2) can still be fulfilled by a variety of different phase histories $\phi(E)$. For optimum energy spread,

$$\delta E \sim \int \frac{1+2 \sin^2\phi(E) dE}{\cos^5\phi(E)} , \quad (3)$$

a phase history close to isochronism is favoured.

Condition for Minimum Phase Advance

In the SIN ring cyclotron it was possible to enhance the turn separation at extraction by injecting the beam off center. In order to avoid degradation of beam quality from precessional mixing, the induced betatron oscillation should remain coherent up to the extraction energy for the entire phase width of the beam. This means that the phase advance angle μ_x should have a minimum for the central phase $\phi i (\mu_x/2\pi$ is the total number of betatron oscillations between injection and extraction)

$$\mu_x = \int_{E_i}^{E_f} \nu_r(E) dn = \text{minimum} \quad (4)$$

where $\nu_r(E)$ is the horizontal betatron frequency which is fully determined by the magnetic field properties. (4) is essentially the same condition as (1) except for the weighting factor $\nu_r(E)$. Analogous to (2) we have thus a condition for minimum phase advance

$$\int_{E_i}^{E_f} \frac{\nu_r(E) \sin \phi(E) dE}{E_G(E) \cos^3\phi(E)} = 0 \quad (5)$$

In the SIN ring cyclotron ν_r starts at a value of 1.12 at injection, increases up to 1.7 and reaches about 1.4 at extraction. Deviations from isochronism have thus a stronger weight in the extraction region. We notice that for a perfectly isochronous cyclotron ($\phi(E) = 0$), conditions (2) and (5) are simultaneously fulfilled. It is thus necessary that the local phase $\phi(E)$ is as close to zero as possible, especially for eccentric orbits. Figure 1 shows an example of two phase histories, both fulfilling the single turn condition (2) but one of them fulfilling also (5).

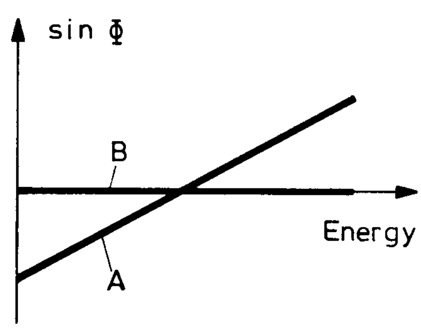

Fig. 1
Two possible phase histories $\phi(E)$, both fulfilling the single turn condition. The perfectly isochronous curve B is preferable to A. It has a minimum energy spread, maximum turn separation at injection and extraction and fulfills the minimum phase advance condition for eccentric orbits.

Preparation of the Beam After the Injector Cyclotron

Setting up the ring cyclotron on a routine basis for single turn extraction is made easier if the beam coming from the injector cyclotron is prepared in a reproduceable way[3]. After the injector the beam is brought to fixed focal points in the x and y directions

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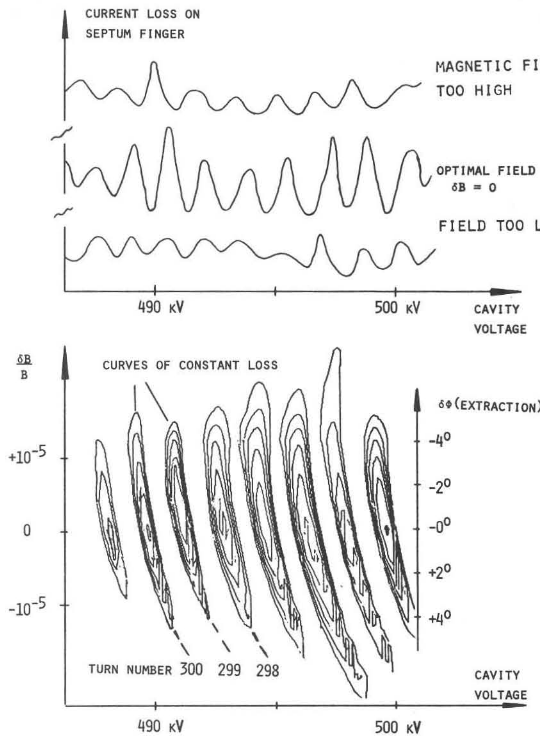

Fig. 7

Single turn extraction for centered beam. Optimization of main magneic field and cavity voltage in the ring cyclotron. In a so-called "cavity scan" the cavity voltage is varied for a given magnetic field. Simultaneously the beam current lost on an isolated finger in front of the extraction septum is plotted. With every change of the revolution number by one unit, this current plot reaches a new local minimum, corresponding to an optimum position of the septum between the last two turns. For the optimal magnetic field these local minima are especially deep, as seen in the upper part of the figure. The lower part of the figure shows a two-dimensional contour plot of the septum losses versus cavity voltage and magnetic field. All levels with extraction losses over 5 % are omitted to bring out more clearly the "islands" of single turn extraction with minimal losses. This optimization technique has a very high sensitivity of 10^{-4} in the cavity voltage and 10^{-6} in the magnetic field. Due to saturation this corresponds to an accuracy of $4 \cdot 10^{-6}$ in magnet current.

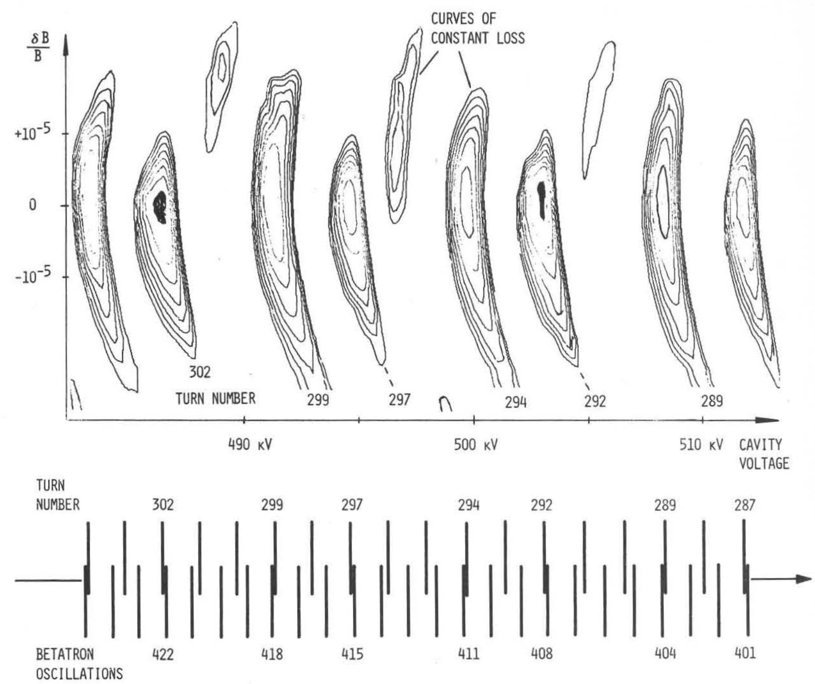

Fig. 8

Single turn extraction for an eccentric beam. As in Fig. 5 the upper part of the figure shows the beam loss at extraction as a function of magnetic field and cavity voltage. An eccentric injection into the ring generates a coherent betatron oscillation of 2.5 mm which persists till extraction due to the narrow phase width of 6° FWHW. The lower part of the figure shows the conditions for an integer number of turns and betatron oscillations. Minimum extraction losses at the septum occur if both conditions are fulfilled simultaneously. The deep minima shaded in black correspond to losses of about 0.2 %. Production runs with losses under 0.1 % have been obtained. By chance the average focusing frequency $\bar{\nu}_r$, which is responsible for the spacing between betatron oscillations happens to be 1.40, leading to an interference pattern with a period of 5 turns and 7 betatron oscillations. From this interference pattern $\bar{\nu}_r$ and the turn number n can be calculated to an accuracy of better than 1 % without moving any beam probe!

References

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with the help of a quadrupole triplet. A 57° bend analyzes the beam in energy and the energy spread can be controlled with slits at the image point. The energy itself can be determined with the excitation of the bending magnet or with a time of flight measurement[4] of the beam over a length of 21 m. The horizontal and vertical beam emittances as well as the energy spread and phase width of the beam are optimized with the extraction process of the injector cyclotron. With a series of computer programs the beam is then centered at injection into the ring cyclotron[5]. The phase signals from the 11 internal phase probes[6] allow a quick first order setting of the magnetic field for isochronous acceleration. Probably due to some vertical mis-alignment of the 8 sector magnets, the beam has to be injected a bit off the median plane. The optimal vertical beam position is obtained by tuning the transmission through the ring with the help of two vertically steering magnets (see Fig. 2).

The next problem is to fix the correct relative phase between the RF system of the injector and the ring. This is done by optimizing the radial gain in the ring over the first six revolutions. The beam is stopped on a differential probe at a fixed radius. Shifting the phase results in a current signal which is symmetric around the optimum phase. Stopping the beam on the downward slope of the 6th turn, as shown in Fig. 3, gives more accurate results than stopping it on the upward slope as in Fig. 4. After all these procedures the ring cyclotron is ready to be optimized for single turn extraction.

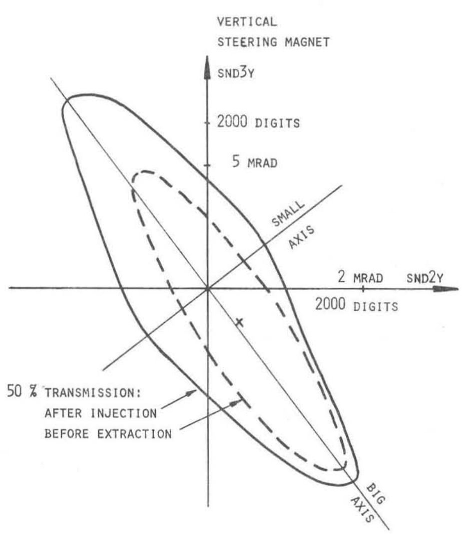

Fig. 2

Vertical beam acceptance in ring cyclotron. With two steering magnets SND2Y and SND3Y a vertical coherent amplitude can be produced at injection into the ring. 50 % of the beam is lost at collimators for a beam amplitude of 12 mm (solid line). A horizontal field component of the order of 1 Gauss, coming most probably from vertical mis-alignment of the 8 sector magnets, shifts the acceptance area by about 2.5 mm (broken line). Optimal transmission through the ring corresponds to injection at point marked with an x. Tuning the transmission is simplified by searching along the big and small axis of the acceptance ellipse corresponding to a coupled variation of the two steering magnet currents.

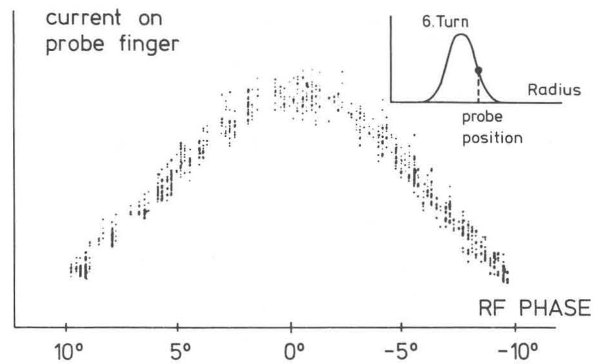

Fig. 3

Determination of proper timing between injected beam bunches and cavity voltage. The injected beam is stopped on a differential probe after 6 revolutions. The radial position of the probe finger with respect to the beam profile is indicated in the insert. With a phase shifter the arrival time of the bunches from the injector can be varied. This is indicated as RF phase on the horizontal axis. If particles arrive at the RF gap at the moment of peak voltage, they get optimally accelerated. The radial position of the beam after 6 revolutions reaches a maximum, giving a maximum signal on the fixed probe finger. Zero phase is thus defined as the symmetry point of the probe signal versus phase and can be determined with an accuracy of about ± 0.5°.

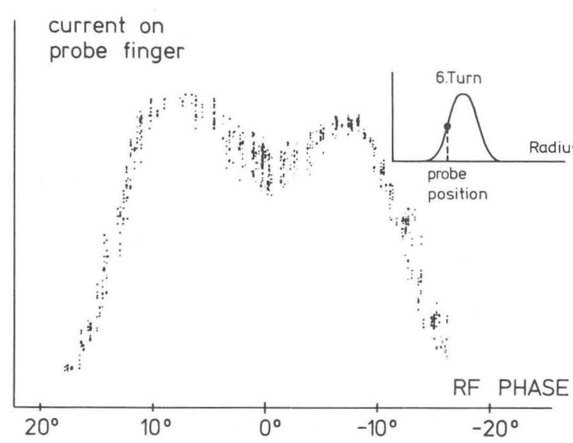

Fig. 4

Same situation as in Fig. 3 except that the radial position of the probe finger with respect to the beam is now towards the center of the ring, as indicated in the small diagram. Phase shifting the RF voltage leads correspondingly to a double hump in the probe curve versus phase. Determination of zero phase is less accurate than by method of Fig. 3.

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Setting-Up the Ring for Single Turn Extraction

Extraction losses in the ring cyclotron occur entirely at the extraction septum. In order to measure these losses, ionization chambers were installed around the periphery of the cyclotron and carefully calibrated[7]. These ionization chambers respond logarithmically to the current losses. In order to have a linear indication of the losses, an isolated 30 μm thick finger of tungsten was mounted in front of the septum[8]. The current signal from this finger is approximately linear with the overall extraction losses. This fact is used in the next procedure of the set-up. In a so-called cavity scan the voltage of the acceleration cavities is varied for a fixed given magnetic field. The upper part of Fig. 7 show plots of finger current versus cavity voltage. The computer program CAVITY SCAN completes about one trace per minute. For a well centered beam we obtain equally spaced minima corresponding to the variation of the turn number by one unit. Varying now the magnetic field as well gives the two-dimensional plot in the lower part of Fig. 7. The "islands" of minimal losses correspond to parameter settings which fulfill the single turn condition (2). The banana-shaped contour lines of equal losses are bent towards the right, due to the fact that for a non-isochronous field a higher cavity voltage is required to reach the extraction septum with a fixed number of revolutions. The banana shapes are not quite symmetric with respect to the optimal field setting $\delta B/B = 0$, since the beam is extracted at a phase of about 5^o and not at 0^o at the peak of the voltage (see Fig. 5). This same figure shows a typical phase history of the beam after optimizing the field. The single turn condition (2) for the phase history gives a nice consistency check for the calibration of the phase probes.

In an off-line program the two-dimensional pattern of Fig. 7 was simulated and the result is shown in Fig. 6. The similarity between theory and reality is quite remarkable. Plots analogous to Fig. 7 are obtained when the initial phase ϕ_i is varied instead of the magnetic field.

A new situation occurs when the beam is injected off center into the ring. The corresponding coherent amplitude persists up to extraction. For a certain phase advance angle μ_x the turn separation at the septum can be enhanced from 4.5 to 9 mm. The upper part of Fig. 8 shows the result of a cavity scan for an eccentric beam. Only if both the number of revolutions and the number of betatron oscillations have integer values are the conditions for minimum losses fulfilled (see lower part of Fig. 8). Since the average ν_r-value is about 1.40 an interference pattern with a periodicity of 5 revolutions or 7 betatron oscillations occurs. For visual clarity the Moirée pattern formed by the turn number and betatron condition is shown with straight lines rather than with the actual parabolic ones. The intersection of these two types of parabolae, which have different curvatures, produces the satellite "islands" at turns 301, 296 and 291. Analysis of the interference pattern of Fig. 8 gives a direct method to determine the average value of ν_r. The result is $\bar{\nu}_r = 1.398 \pm 0.003$, while the predicted value from orbit calculations is 1.401. The total number of turns can also be determined with an accuracy of about ± 2.

Conclusion

Varying cavity voltage and magnetic field simultaneously and observing the losses on a septum finger gives an extremely sensitive and quick method to tune the ring cyclotron for single turn extraction. Extraction efficiencies over 99.9 % have been achieved with a suitable eccentric injection.

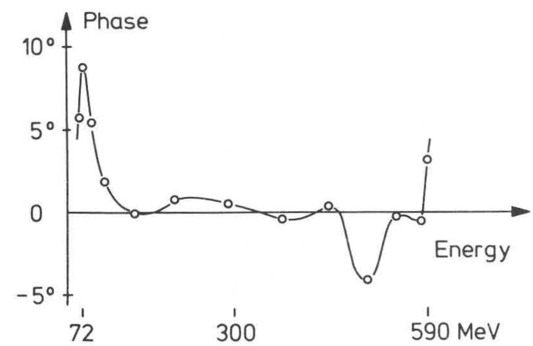

Fig. 5
Phase history of beam in the ring cyclotron. As required by the single turn condition the average phase is approximately zero. The local phase excurions depend on the history of the magnetic field.

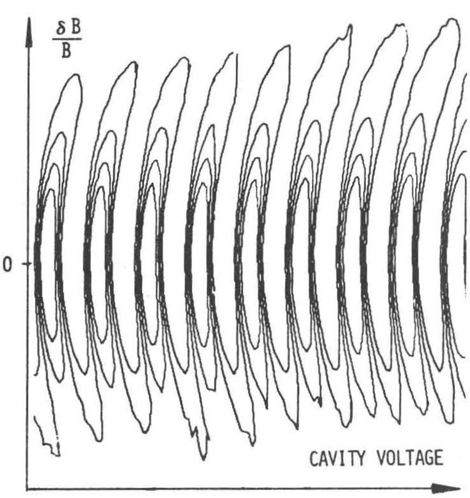

Fig. 6
Simulated cavity scan for a centered beam. As in Fig. 5 curves of constant extraction losses are plotted as a function of cavity voltage and main magnetic field. A beam of finite emittance and phase width is traced with the general orbit code from injection to extraction.