BEAM DYNAMICAL ASPECTS OF THE SIN INJECTOR II

S. Adam, M. Humbel, W. Joho
Swiss Institute for Nuclear Research, CH-5234 Villigen, Switzerland

Summary

Some key points of the beam dynamical activities in connection with SIN Injector II are presented. As it is a fixed energy machine, the isochronism has been adjusted to high precision by shimming the magnet-edge, requiring only small residual trimcoil corrections. In order to regularize the accelerated orbits the width of the individual sector magnets has been adapted. The conical shim at the tip of the first sector magnet has been optimized to achieve the proper bending and focussing of the injected beam. The behaviour of the accelerated particles in the first few turns has been studied using a numerical simulation method. Results from the first beam tests are reported.

Isochronizing

In the SIN Injector II the proper isochronism is achieved in three steps: pole shape, shimming and trimcoils.

In order to simplify construction, the gap of the sector magnets is constant and the pole edge at the beam entrance side follows a straight line. Using a simple polygonal shape for the pole edge at the beam exit side the sector magnets are isochronized to an accuracy of 2%. The shims have to reduce these errors down to .05%. The high precision shimming allowed for a simpler trimcoil construction.

Twelve pairs of iron shims of 12 cm height and 30 cm radial extent with a variable thickness of .2 to 4 cm are screwed onto the flat surface of each magnet pole at the beam entrance side above and below the magnet gap. For each shim the thickness as a function of radius should be determined by three straight lines. This restriction simplifies the machining of the iron pieces. The resulting polygonal shape of the isochronism correction of each sector magnet has about 36 segments which is enough to achieve the desired accuracy. The final configuration of the shims has been found through iterative refinement using orbit integration based on field maps. From orbit calculations with the final field, phase excursions of only a few degrees can be expected [M1].

A special mathematical procedure has been developed which determines the change of the shim thickness which is needed to correct a known isochronism error. It is similar to the method using a dTdB matrix [1,Z1]. First, the effect of a shim variation on the changing of isochronism is established. This effectivity function is represented by the dTdS matrix. The method to find this matrix is based on orbit geometry. The field changes due to an azimutal variation of the magnet edge are proportional to the azimutal derivative of the field. (For the dTdB matrix field changes proportional to the local field had to be taken into account).

Given the dTdS matrix and an isochronism error there remains a so called "ill posed problem" to find the corresponding correction of the magnet width. The proper solution of such a problem can be found by using a least squares fit which includes an additional stabilisation [2]. For the shimming case a second difference scheme provides the proper stabilisation. It is highly insensitive to the weight which is given to the stabilizing matrix and it tends to diminish fluctuations in the correcting radial function of shim thickness.

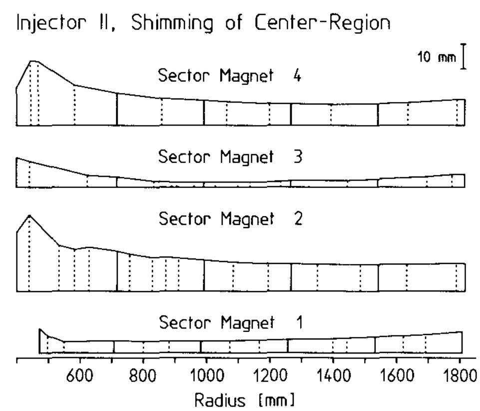

Fig. 1: Shim thickness as a function of radius. The first five shim pairs of all four sector magnets are displayed. The full vertical lines show the boundaries between individual iron pieces; the dotted lines indicate the corners of the polygonal shape. Due to the correction of the orbit asymmetry caused by acceleration, the shims of the magnets 2 and 4 are thicker than the ones on the sector magnets 1 and 3.

Regularization of accelerated orbits

Between the first few turns of Injector II there is an extremely high radial gain. In combination with the 180 degree symmetry of the accelerating structures a large difference between a centered accelerated orbit and the corresponding static equilibrium orbits evolves.

In the sector magnets following the cavities the accelerated orbit has a lower and in the other ones it has a higher radius than the reference. Usually cyclotron magnets are designed with identical magnet sectors. This makes the equilibrium orbits completely regular. In a fixed energy machine with known accelerating voltage there is no reason to keep a purely theoretical orbit regular. The actual orbits of the particles deviate always in the same manner therefore it is favourable to pre-correct the static orbit by the same amount and to have a more regular accelerated orbit [C1].

There are three different criteria which allow to judge the regularity of the orbit. One of them is the purely geometric one which asks for the successive radii and angles of the orbit at intervals of 90 degrees to vary monotonically. (An accelerated orbit cannot have a perfect symmetry since it spirals out.) The two other criteria consider the variation of the phase advance angle for the radial and the vertical focussing. The optimum is not exactly identical for the three regularity requirements, but a good compromise has been found.

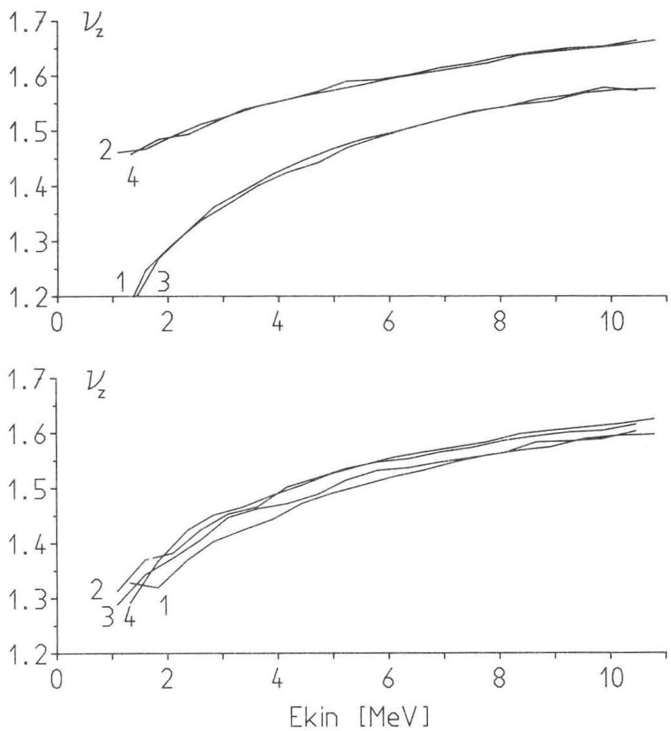

Fig. 2: Effect of the orbit regularization. The effective vertical tunes over the individual sector magnets are plotted. The upper frame shows the case of four identical magnets. In the lower frame the differences in the focussing between magnets has almost disappeared due to orbit regularization with the shim pattern of figure 1.

The conical shim at injection

The innermost part of sector magnet 1 is specially shaped to leave room for the conical shim. This shim enhances the field from 10.4 kG in the normal gap to 15-17 kG in the region of the injected beam. The enhanced field bends the 860 keV beam coming from the machine center by 135 degrees into its first orbit [C1,C2]. This high bending angle would produce excessive x-focussing if there were not a strong gradient in the magnetic field around the injected beam. The proper bending and focussing of this injection element has been established in several rounds of changing the shim and analyzing the measured magnetic field.

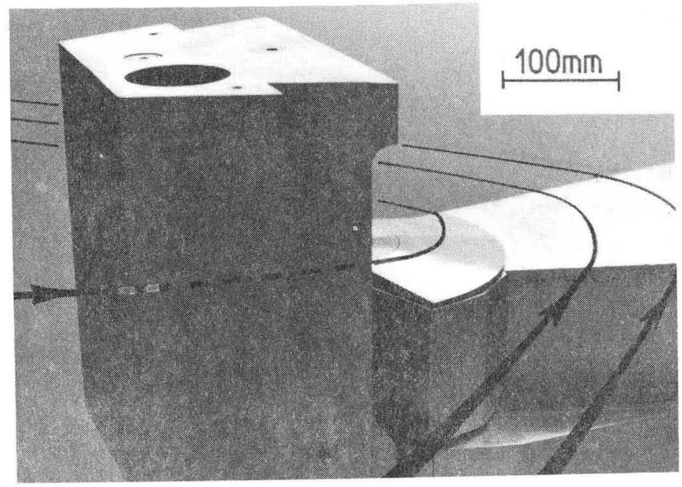

Fig. 3: Location and shape of the conical shim. From the wooden model the upper pole has been removed and the lower piece of the conical shim pair has been put in place. On the left side one sees the special gap spacer of sector magnet 1 with a horizontal hole for the injected beam and a vertical hole for diagnostics. The injection orbit and the first accelerated orbits are drawn.

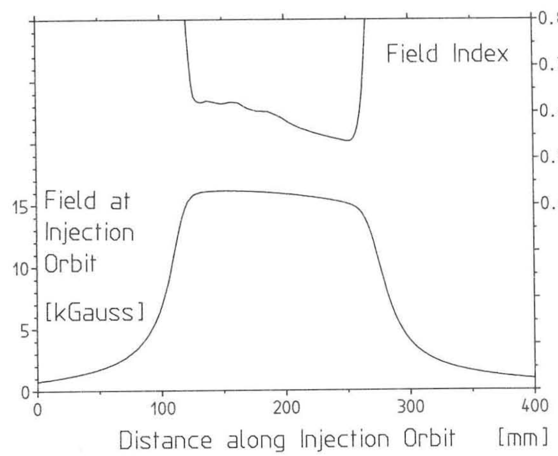

Fig. 4: Magnetic field and field index along the injection orbit in the region of the conical shim.

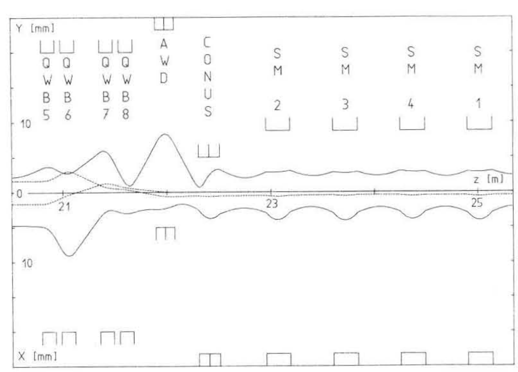

Fig. 5: An example of the graphic output from TRANSPORT results. Beam amplitudes and dispersion are plotted from the center of the vertical beam line to the first orbit in the cyclotron [C2]. The representation of injection elements and sector magnets in TRANSPORT notation allows to extend the beam optical calculations into the cyclotron.

Phase dependent centering

The accelerated orbit which has served as a reference for the regularization of the actual orbit has been determined such that it is centered i.e. its radii and radial momenta execute the least possible oscillations over successive turns. Usually this reference trajectory is calculated for zero RF-phase which yields maximum acceleration.

Particles with different starting phase need another starting point in r-pr-phase space. When the energy gain is not 100% the corresponding kicks in betatron phase space are different.

In many cases the differences between the centered starting points in phase space are smaller than the oscillation amplitudes in the beam. In the SIN Injector II, a high radial gain per turn and a small beam diameter are combined with the aim to accept a wide range of phases. It has therefore been planned to improve centering at injection using deflecting electrodes with time dependent (150 MHz RF) fields [3].

Radial longitudinal coupling

Beam dynamical effects caused by the coupling between the radial and the longitudinal motion of the particles have recently been discussed in many publications [C3,C4,C5,4,5,].

In the Injector II such effects become important because of the high harmonic number of 10 of the accelerating RF relative to the particle revolution frequency. The high radial gain between the turns in combination with its rapid change in the inner region causes nonlinear phase space distortions. In the inner region the acceleration cannot really be considered to be adiabatic.

A simple method for the numerical simulation of phase space deformations at injection has been developed similar to the program COMA from Vancouver [6]. This simulation uses transfer matrices and approximates the effect of acceleration by sudden changes of energy and betatron amplitudes at the two effective gaps. The double gap cavities of SIN Injector II are summarized in a single gap at the center line of the RF structure.

In order to clearly separate radial longitudinal coupling effects from non adiobatic ones, groups of particles should be compared which have all the same center position phase. A constant center position phase is established if each particle of a group has the appropriate difference in actual phase from the others depending on its difference in radius and radial momentum. This correlation can be represented by a vector. For each particle the product of this correlation vector with the vector of betatron phase space yields the corresponding phase deviation.

In the case of adiabatic acceleration, the center position phase is defined by that correlation vector which maps onto itself in one period of the accelerator. A non adiabatic equivalent of the phase correlation vector can be found in a least squares fit. This fit investigates how an arbitrary correlation vector at injection is transformed from turn to turn. It optimzises the starting values such that the the corresponding correlation vectors have the smallest fluctuations.

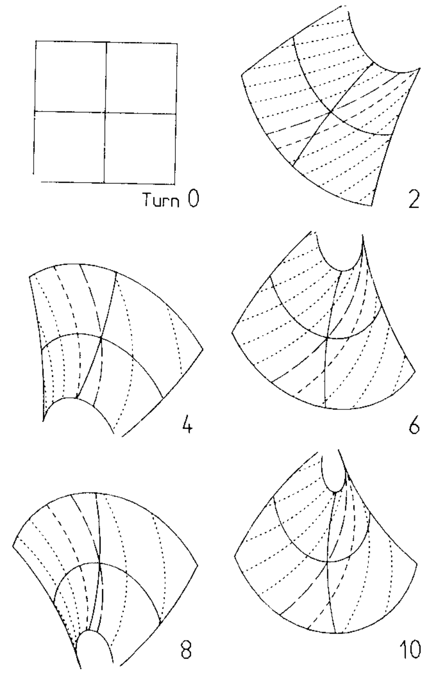

Fig 6: Phase space distortion between injection and turn 10 of a group of particles having different center position phases. The particles start with amplitudes of 3 mm in x and 0.6 mCU in px all with the same value of the actual phase. The broken lines correspond to equal phase deviation. The long dashed line marks 0 degrees, the short dashed line +2 degrees. All other equal phase lines are dotted. The difference in phase from line to line is 2 degrees.

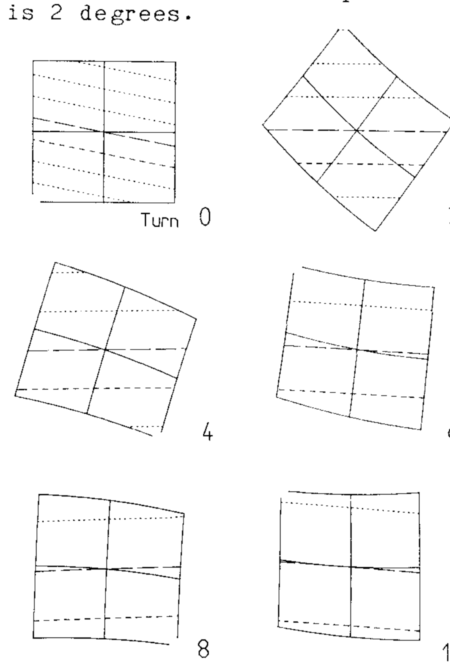

Fig 7: Phase space deformation for particles with matched center position phase. The broken lines indicate the deviation in actual phase from the central particle. Their pattern remains nearly constant relative to the phase space. This reflects the constant correlation between betatron amplitude and deviation of actual phase. For such a group of particles the deformation of phase space is much smaller than for the group of figure 6 above.

First beam tests

The first beam tests have been restricted to 5 turns where there is a beam dump inside the cyclotron. They have shown that the precalculated settings of magnet currents and of positions of injection elements provide a well centered beam inside the cyclotron. This enhances our confidence in the other beam dynamical and beam optical calculations.

The first few turns of actual beam provided a good means to test the working of the new three wire probes. One wire is vertical and the two other ones are at angles of ±45 degrees [M1]. A quick evaluation of the probe signals provides a rough estimate of the horizontal and vertical position and width of the beam. For a more detailed analysis of the beam program MENT from Los Alamos is used [7]. In a first step each turn is reconstructed from three cuts in the geometric plane x-z. This reconstruction can also provide a vertical profile of the beam. Later on a reconstruction of the radial and vertical phase spaces (x-x',z-z') will be tried.

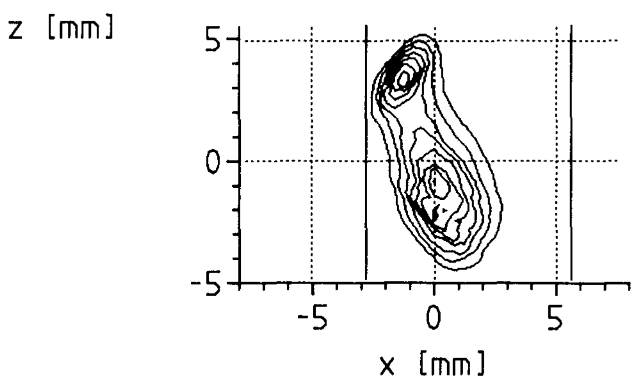

Fig. 8: Reconstruction of a beam cross- section from the signals of three wires at different angles mounted on the same radial probe. This picture is produced by the beam tomography program MENT which is normally used for reconstruction in phase space.

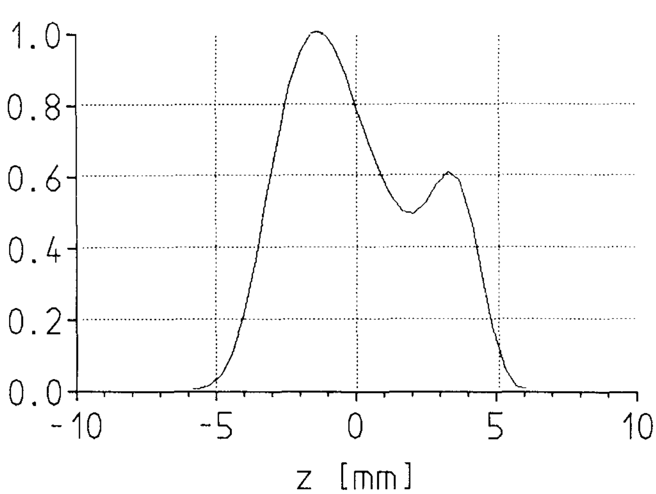

Fig. 9: Vertical profile of a beam inside the cyclotron which cannot be scanned vertically. The beam tomography program can provide arbitrary projections of the reconstructed x-z space. The input to this reconstruction is again from the 3 wire probes.

Acknowledgement

U. Rohrer has added many interactive graphic features to the beam line program TRANSPORT. He has also adapted the beam tomography program MENT [7] from Los Alamos to our computer. Both programs have become essential tools at SIN. The authors would also like to express their gratitude to F. Killer, G. Rudolf and L. Rezzonico.

References

[1] J.L. Bolduc and G.H. Mackenzie, Some orbit calculations for TRIUMF, IEEE, NS 18 (1971) p. 287

[2] A. Bjorck, Least squares Methods in Physics and engineering, CERN yellow report 81-16

[3] M. Zach, Centering electrodes for Injector II, SIN int.rep. TM-04-38

[4] W.M.Schulte and H.L. Hagedoorn, The theory of accelerated particles in cyclotrons, NIM 171(1980)p. 409-437

[5] M.M. Gordon and F. Marti Radial longitudinal coupling and focusing complementarity, Particle accelerators 12(1982)p. 13-26

[6] J.C. Kost, COMA, a KOSTLIB FORTRAN program, TRIUMF, Vancouver

[7] G. Minerbo, MENT: A maximum entropy Algorithm for reconstructing a source from projected data, Computer graphics and image processing 10 (1979) p. 48-66

[C.] 9th International Conference on Cyclotrons and their Applications, Caen (France) 1981

[C1] U. Schryber, Status report on the new Injector at SIN, p. 43

[C2] C. Markovits, Design of a high intensity 860 keV proton beam transport line for the new SIN injector, p. 525

[C3] P.Lapostolle Recent developments on beam dynamics in cyclotrons, p. 317

[C4] G. Hinderer,Phase space matching between pre-accelerators and cyclotrons, p. 327

[C5] S. Adam, New proofs for old facts in acceleration theory, p. 431

[M1] U. Schryber, Upgrading the SIN facilities to higher intensities, this conference

[Z1] S. Adam, The isochronism in the SIN 590 MeV ring cyclotron 7th Int. Conf. on Cyclotrons, Zurich, Birkhaeuser Basel (1975) p. 283