MAGNET RAMPING WITH VARIABLE OPTICS IN THE SIS

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Abstract

For a synchrotron lattice with optics varying from triplet to doublet focusing it is necessary to replace fixed values of the normalized focusing strength of quadrupoles for a given tune by a table of values describing the range of optics variation. This table should also include the sensitivity of chromaticity and closed orbit position to correcting or perturbing sextupoles and dipoles resp.

Using this table the settings for quadrupoles etc. as a function of time according to the dipol fields can be calculated with sufficient accuracy for any desired optics variation scheme.

For the particular interesting case of leaving one quadrupole at constant injection field during acceleration the tune is calculated using a realistic model of the behaviour of power supplies and control system. The expected tune errors are small enough to be tolerated.

Introduction

At GSI in Darmstadt (Germany) the heavy ion synchrotron SIS is under construction as a part of the new SIS/ESR accelerator facility extending the energy range of the existing heavy ion linac UNILAC to energies of 1 to 2 GeV/u.

As described earlier [1] the focusing scheme used for the SIS lattice does not exactly match to one of the usual categories of FODO, doublet, or triplet. Since all these schemes have their special advantages and disadvantages, we employed the method of optics variation between triplet and doublet in order to combine the good properties of both focusing schemes.

In this paper special aspects of variable optics and in particular the expected tune behaviour during the first part of the magnet cycle under realistic assumptions on power supplies and their control will be discussed.

The Focusing Schemes

The lattice of SIS is formed by twelve identical focusing periods as shown in fig. 1 consisting of two dipoles (B) and three quadrupoles (F, D, and T) each.

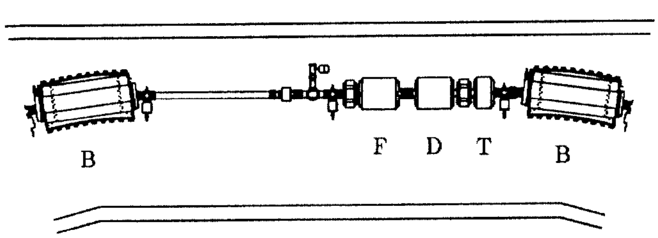

Fig. 1: One of twelve focusing periods of SIS

Thus there are many ways of exciting the quadrupoles to give the desired horizontal and vertical tune of 4.2 and 3.4 resp. The focusing strengths of the three quadrupoles in the range from nearly symmetric triplet to pure doublet focusing as a function of an arbitrary parameter p are shown in fig. 2.

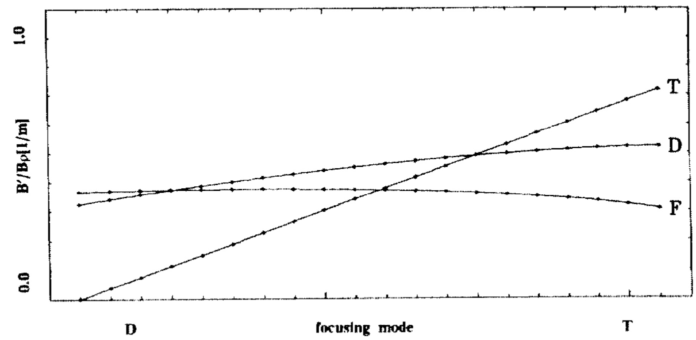

Fig. 2: Quadrupole settings for tune $Q_H = 4.2$ and $Q_V = 3.4$

Though the the tune is the same for all p, the amplitude functions are considerably different as shown in fig. 3. This enables us to choose the appropriate value of p according to the different requirements at injection and extraction.

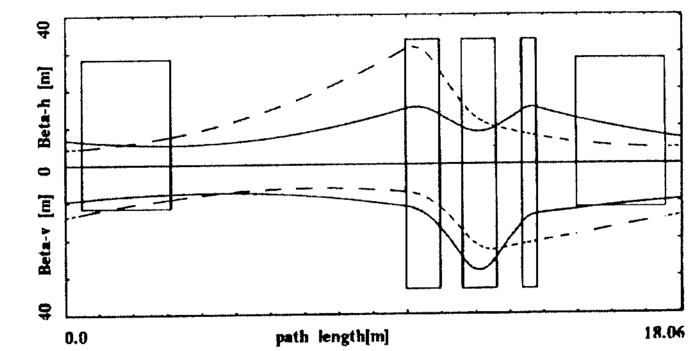

Fig. 3: Horizontal and vertical amplitude functions for triplet and doublet focusing (dashed lines)

Triplet focusing will be used at injection, because here the largest acceptance provided by smooth and low amplitude functions is needed. At maximum energy the situation is opposite: the acceptance may be lower because the emittance shrinks during acceleration, but larger and more modulated values of the amplitude functions increase the efficiency of correction elements and the extraction of the beam considerably.

The following table shows the normalized focusing strengths $B' \times \ell / B\rho \ [m^{-1}]$ for triplet and doublet mode.

	F	D	T
triplet	-0.306	+0.520	-0.308
doublet	-0.366	+0.323	0

(Note that triplet focusing at maximum energy would require substantially higher focusing power than doublet focusing.)

Consequently it is desirable to change the focusing during the acceleration cycle.

The Focusing Table

The functions in fig. 2 can be considered as the parameter representation of a curved line in the 3-dimensional (F,D,T)-space and the quadrupole settings have to stay on this line during the cycle. In other words: once the strength of one quadrupole has been chosen the remaining two must be set simultaneously to the right values in order to keep the tune constant.

Since it is not reasonable to perform a lattice calculation each time a new set of values is needed, a table should be set up and all values of quadrupole strengths can be obtained by interpolation. To check how many exactly calculated points are needed for this table, a comparison was made between tunes obtained from interpolated values and the reference value for the tune.

Fig. 4 shows the result for exact calculation at 20 points and interpolation in between. The maximum relative tune deviation is $\Delta Q/Q = 5 \times 10^{-5}$ which is small compared to the specified accuracy of the power supplies. Therefore, the values interpolated from a table of 20 points are accurate enough to obtain reference values for the control system.

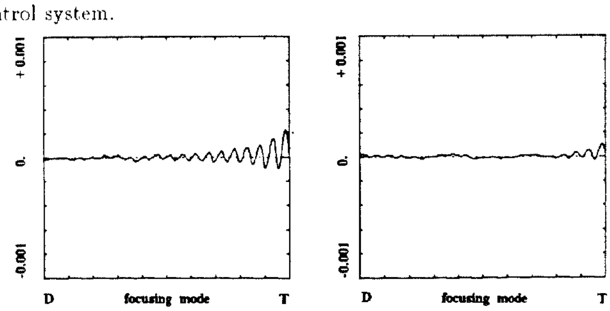

Fig. 4: Calculated tune errors due to table interpolation as a function of the focusing mode
Left: Horizontal, right: vertical - $\Delta Q/Q \leq 5 \times 10^{-5}$

It should be noted that this tune modulation is not unavoidable, but it can be reduced down to computer accuracy by choosing more points for the table calculation or different interpolation methods.

As a consequence of the varying amplitude functions at constant tune a couple of other lattice parameters has to be calculated. The complete table will contain the following entries:

- ▷ normalized strengths of the three quadrupoles
- ▷ natural chromaticity
- ▷ transition energy
- ▷ dependence of chromaticity on correction sextupoles
- ▷ dependence on sextupoles in the dipoles to calculate the influence of eddy currents and remanent fields
- ▷ sensitivity of the closed orbit at the pickup positions to the dipole correctors

To obtain actual values for correction elements the same procedure of table interpolation as for the main quadrupoles will have to be performed.

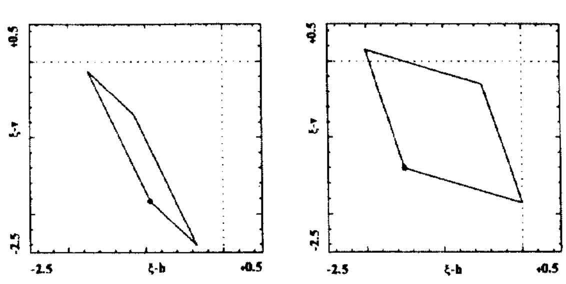

Fig. 5: Effect of two families of sextupoles of equal strength on the chromaticity for triplet (left) and doublet focusing

An example is shown in fig. 5. The range in chromaticity that can be covered by the same sextupole strengths strongly depends on the focusing scheme. The efficiency of sextupoles is much better for doublet focusing.

The Time Functions

There are no tight restrictions for the way one has to take from triplet to doublet focusing during acceleration. Only a few conditions should be met:

Leaving the triplet mode means increasing the amplitude functions in some places of the lattice. In order to avoid beam losses this increase has to be compensated by the shrinkage of emittance during acceleration. This imposes an upper limit on the speed of changing.

At the high energy end of the magnet cycle the maximum field gradients must not be exceeded. Therefore, the doublet mode has to be reached soon enough. Thus the choice of focusing mode is restricted in this region. Fig. 6 shows the limitations of $B\rho$ as a function of the focusing mode.

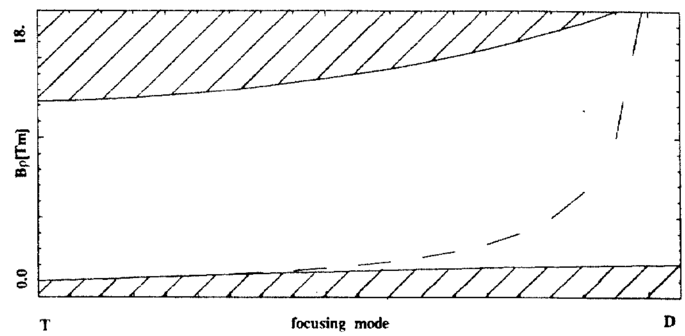

Fig. 6: Allowed range of $B\rho$ depending on focusing mode
Top hatched area: maximum focusing strength exceeded
Bottom hatched area: beam size would grow with accelerati
Dashed line: quadrupole T kept at injection field

Since for normal operation the magnetic rigidity between injection and extraction changes by a factor of about ten, there is a convenient way to realize appropriate time functions for the quadrupoles: one simply has to keep one quadrupole, denoted with T in fig. 1, on its value at injection and exclude it from ramping.

Hence the focusing strength decreases with time thus leading from triplet to doublet mode. Its final value of about 10 % of its initial focusing strength is very close to the pure doublet mode. This case is shown as the dashed line in fig. 6.

Of course many different schemes with varying strength of quadrupole T are possible, but here only the basis solution will be considered.

Fig. 7 shows the absolute field gradients of F and D quadrupole as a function of time assuming that quadrupole T is left at injection field. The dashed lines are included for comparison and show the values for constant doublet mode without any optics variation. They are exactly proportional to the dipole fields.

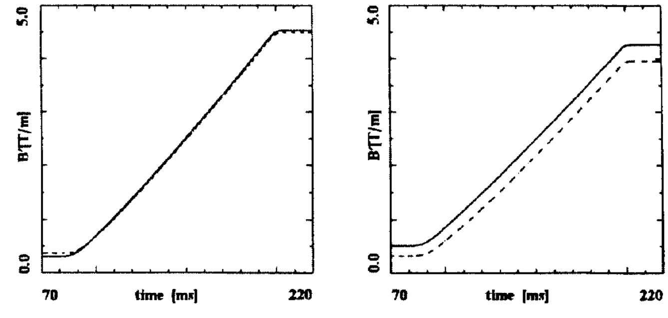

Fig. 7: Fields of the quadrupoles F (left) and D (right) as a function of time in variable optics mode
Dashed line: the same for constant optics

The remaining tune variation due to the imperfection of the focusing table (see fig. 4) is shown in fig. 8.

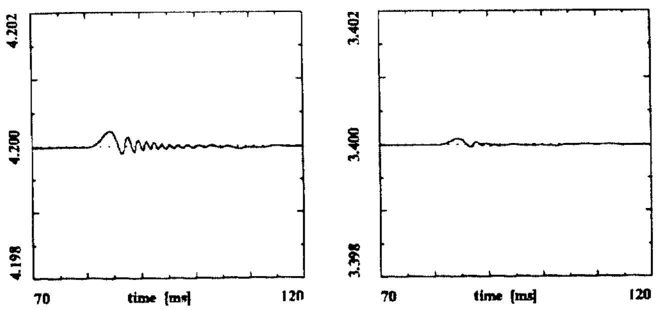

Fig. 8: Calculated horizontal (left) and vertical (right) tunes as a function of time in the first part of the cycle

Polygone Approximation

All calculations up to this point are made assuming that magnetic fields (or currents) can be made exactly equal to reference values at any given time. Unfortunately this is not quite realistic.

The reference values for the SIS magnet power supplies can be set to (almost) any value in equal steps of 1 ms (or 2,4,8,...). Between two adjacent points exact linear interpolation takes place [2].

In the case of constant optics the ratio of the dipole and quadrupole fields is constant at all times (except for small deviations due to saturation effects at high fields). Therefore, almost any function of field versus time will give constant tune values, also between the 1 ms points, provided the same functions are applied to both dipole and quadrupole power supplies.

With variable optics these ratio changes with the time. The only values that can be set exactly according to the theoretically calculated ones are those in the 1 ms pattern. Between these points the ratio of dipole and quadrupole fields is determined by the linear interpolation and in general is different from the calcualted values.

Fig. 9 shows the calculated tune during the first part of the ramp assuming the magnet current behaviour as descibed above. The sharp maxima of the curves correspond to the points in the 1 ms pattern. They follow exactly the line determined by the focusing table. But the deviations between them are due to the unavoidable interpolation errors.

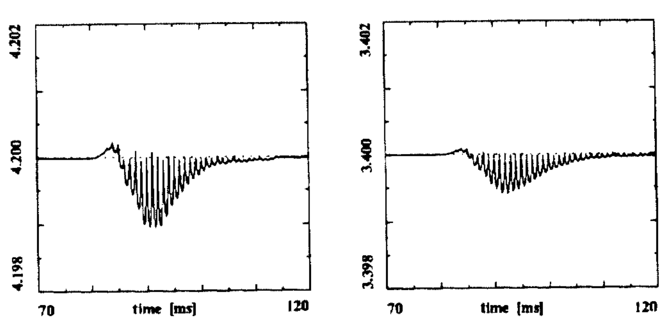

Fig. 9: Calculated horizontal (left) and vertical (right) tunes as a function of time in the first part of the cycle perturbed by polygone approximation of the time function of the quadrupoles

Since the absolute magnitude of these errors is small ($\Delta Q \leq 0.001$) we do not expect problems due to this effect with the variable optics.

But in contrast to the inaccuracy of the focusing table these errors cannot be avoided. They may only be decreased by lowering the ramping rate at the beginning of cycle or by starting with a slightly more doublet-like focusing mode.

Timing Requirements

Another source of tune error might be a systematic time difference between the time functions of different magnets. This is not specific to variable optics but also happens in conventinal operating modes. Fig. 10 shows the tune deviation in a doublet lattice assuming a time error of 10 μs between dipoles and quadrupoles.

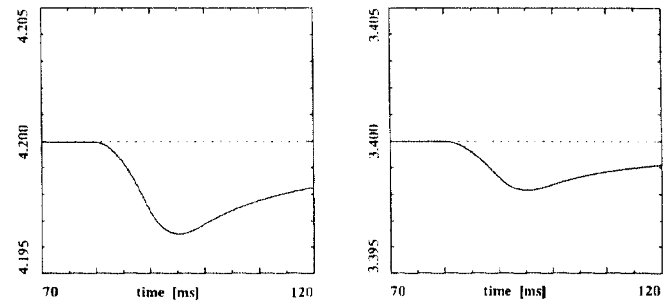

Fig. 10: Calculated horizontal (left) and vertical (right) tunes as a function of time in the first part of the cycle assuming a constant $10\mu s$ time offset for the quadrupoles constant optics mode

The effect of the same timing error in a variable optics lattice is basically the same as shown in fig. 11, only the errors already known from fig. 9 are added.

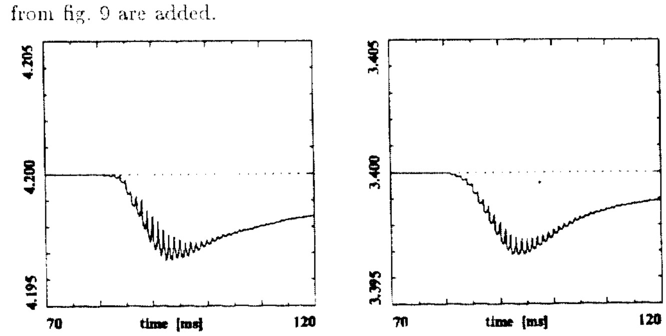

Fig. 11: Calculated horizontal (left) and vertical (right) tunes as a function of time in the first part of the cycle assuming a constant $10\mu s$ time offset for the quadrupoles variable optics mode

In practice these problems should not occur because the power supplies will follow the reference values at all times within the specified relative error limits [3]. No systematic time delay is possible this way.

Since the timing accuracy of the control system is in the order of mircroseconds, we assume that the magnets will work as synchronous as required. In particular we do not expect our lattice to be more sensitive to errors of that kind than others.

References

[1] B. Franczak, K. Blasche, K.H. Reich; IEEE NS-30, No.4 (1983) 2120

[2] R. Steiner, priv.comm.

[3] GSI Report GSI - SIS - SPEZ / 85 - 27