SPALLATION NEUTRON SOURCE

Preliminary Change Request for the Chromatic Sextupoles and Trim Quadrupole Elements of the SNS Accumulator Ring

BNL/SNS TECHNICAL NOTE

NO. 075

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May 30, 2000

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Abstract

In view of the adopted modified design for the 1.3 GeV compatible accumulator ring of the SNS [1], complementary studies have been undertaken, in order to justify the need of high-field chromatic sextupoles for chromaticity correction. Furthermore, as these chromatic sextupoles introduce a first order quadrupole "feed-down" effect, the trim quadrupole elements specifications had to be reviewed in order to accommodate this change.

1 The SNS accumulator ring lattice

The SNS accumulator ring has a hybrid lattice design consisting of four identical arcs and straight sections. The arc has a FODO structure, with four cells (eight quadrupoles and dipoles) plus a quadrupole that matches the arcs with the straight sections. The later contains two quadrupole doublets, setting the total number of quadrupoles at fifty-two. The magnetic elements are placed and powered in a way to preserve a four-fold symmetry. A schematic presentation of one super-period is presented in Fig. 1. The lattice has been matched for four working points: (6.3,5.8), (6.3,5.27), (5.82,4.8) and (5.82,5.8). The optical functions for the nominal working point (6.3,5.8) are shown in Fig. 2.

In the proposed lattice design, five chromatic sextupoles are placed downstream to the arc quadrupoles, at areas of large dispersion (Figs. 1 and 2). These "strong" sextupoles have been foreseen for adjusting the chromaticities to desired values, minimizing off-momentum optical mismatch and control resonance effects and instabilities [2].

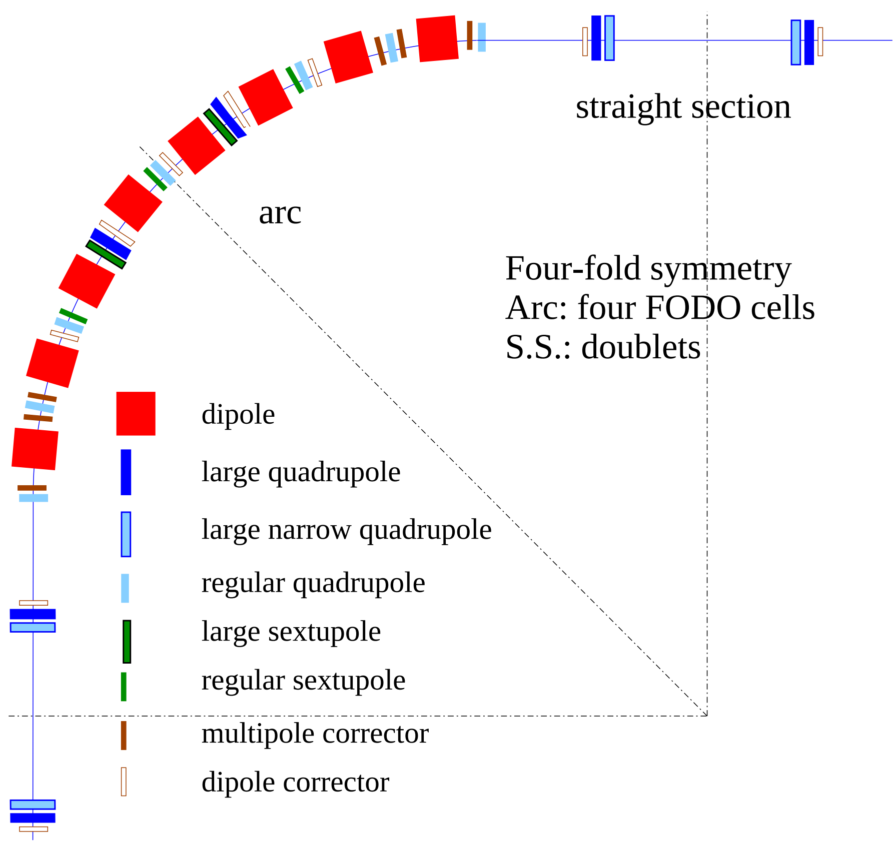

Figure 1: Schematic layout showing dipole, quadrupole, sextupole, and corrector magnets of one lattice super-period. The chromatic sextupoles are shown in green.

In order to correct any type of quadrupole perturbation and to allow a robust tuning of the SNS ring, trim quadrupole windings will be mounted in the bodies of the lattice quadrupoles. A detailed study for the evaluation of this effect was performed for the original all FODO-type

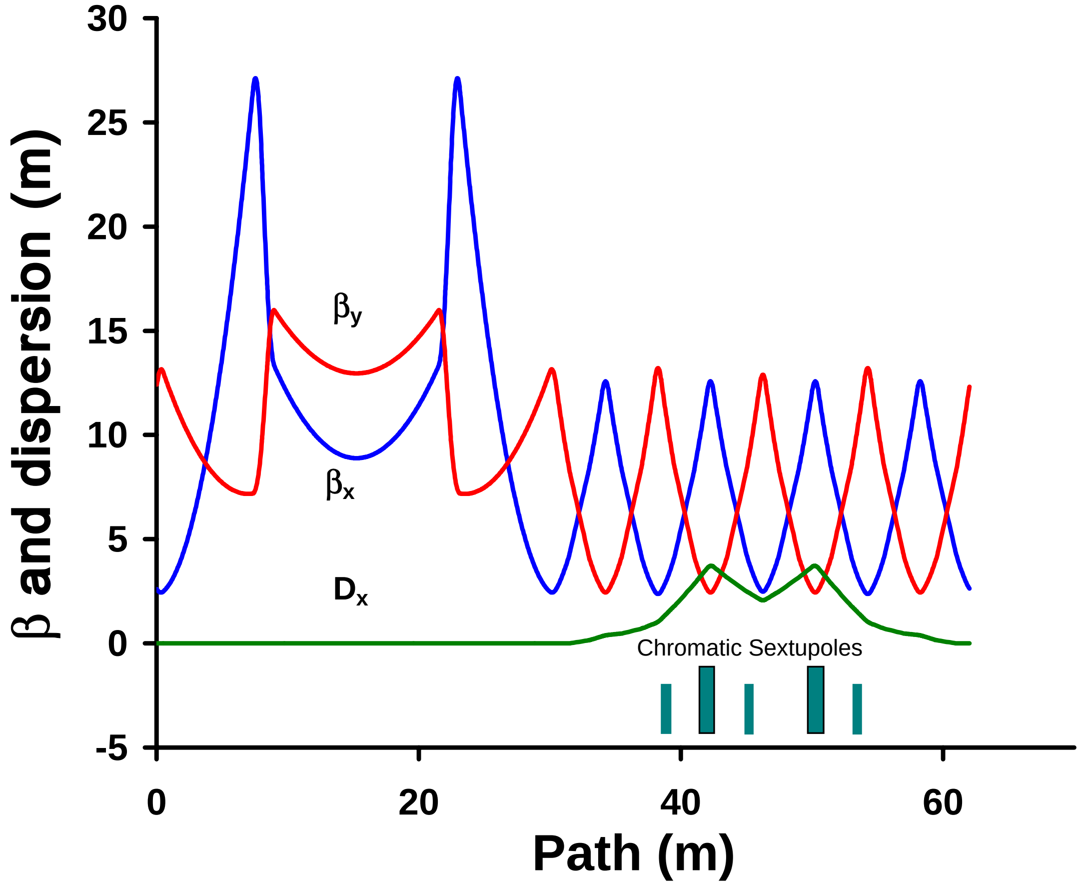

Figure 2: Lattice functions of one lattice super-period consisting of a FODO arc and a doublet straight. The horizontal phase advance across the arc section is 2π radian. The dispersion in the straight section is zero.

lattice [3]. In view of the introduction of the sextupoles in the baseline of the SNS ring, the powering and specification of the trim quadrupole elements had to be reviewed in order to accommodate this change.

We present in this note the studies undertaken in order to justify the need of four families of chromatic sextupoles and fifty-three power supplies for the trim quadrupole elements. We estimate the impact in the lattice functions and non-linear dynamics and show the benefit with respect to the machine performance.

2 Justification of Changes

2.1 Chromatic Sextupoles

One of the design aspects that will help avoiding beam resonances and/or beam instabilities, thereby minimizing the beam losses in the accumulator ring, is the chromaticity control. Without this control, the tune spread produced by the natural chromaticity is about ± 0.08,

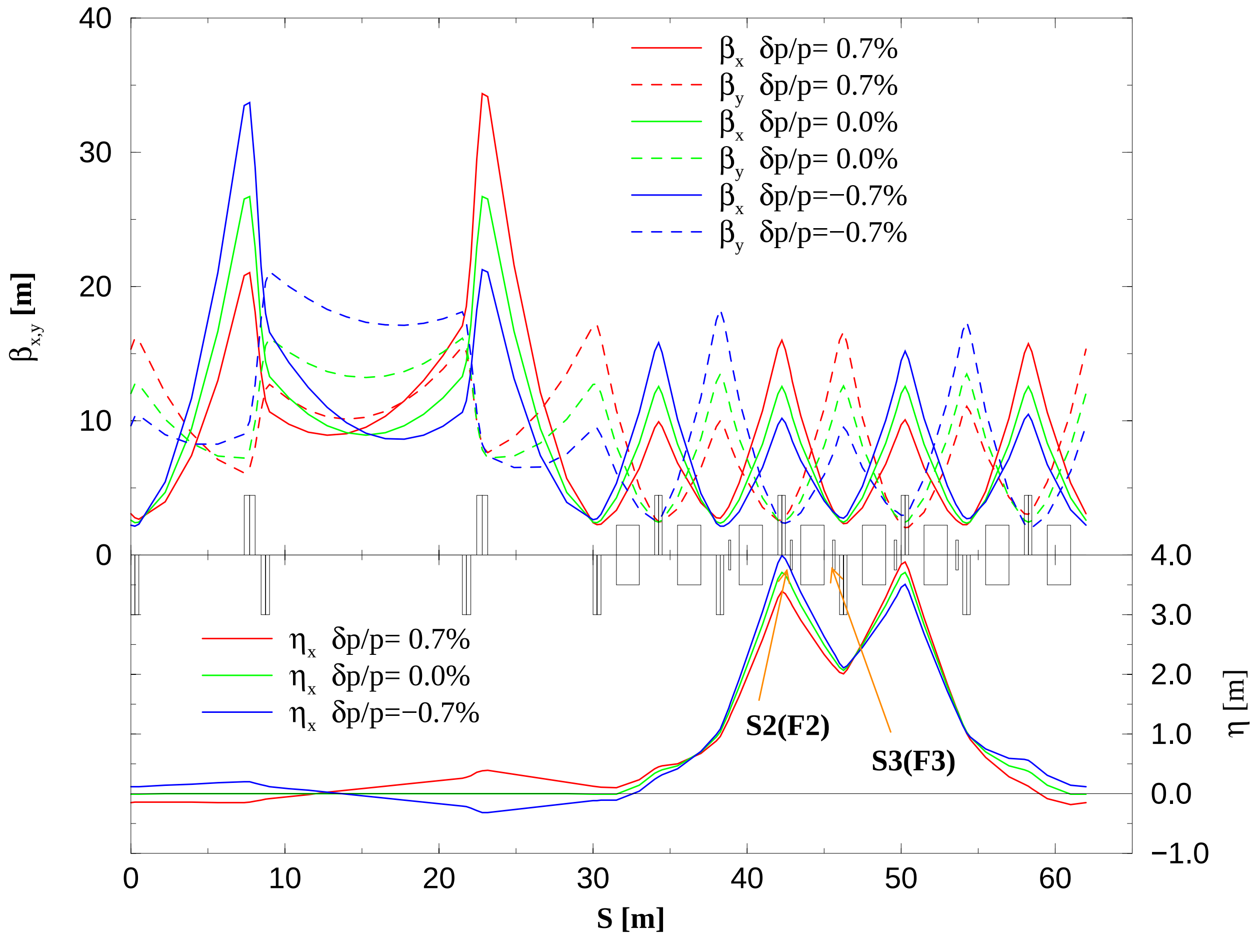

Figure 3: Lattice functions of the SNS accumulator ring for the nominal tunes (6.3,5.8) using two families of sextupoles. The beta and dispersion functions are strongly perturbed for off-momentum cases.

similar to the spread produced by the space-charge. The adjustment of the chromaticity and the optical compensation can be achieved by using chromaticity sextupoles. The SNS lattice contains five 15 cm long chromatic sextupoles per super-period. Their design parameters (see [1]) are presented in Table 2.1.

Two families of sextupoles, placed at high-beta and high-dispersion regions, can control the linear chromaticity of the ring. The sextupoles however may strongly affect the first and second order of the beta and dispersion functions dependence on the momentum spread, introducing strong "beta/dispersion waves" and, thereby, reducing the dynamic aperture. In addition, this beta/dispersion variation will increase the first and higher order terms of the chromaticity. This is clearly shown in figure 3: with a two-family scheme, the optical distortion in β-function is as large as 30% for off-momentum orbits.

In order to minimize the dependence of the beta, the dispersion functions and the chromaticity on $\delta p/p$, additional families of sextupoles are required. In the proposed chromaticity correction scheme, three of the sextupoles are powered independently and two of them in

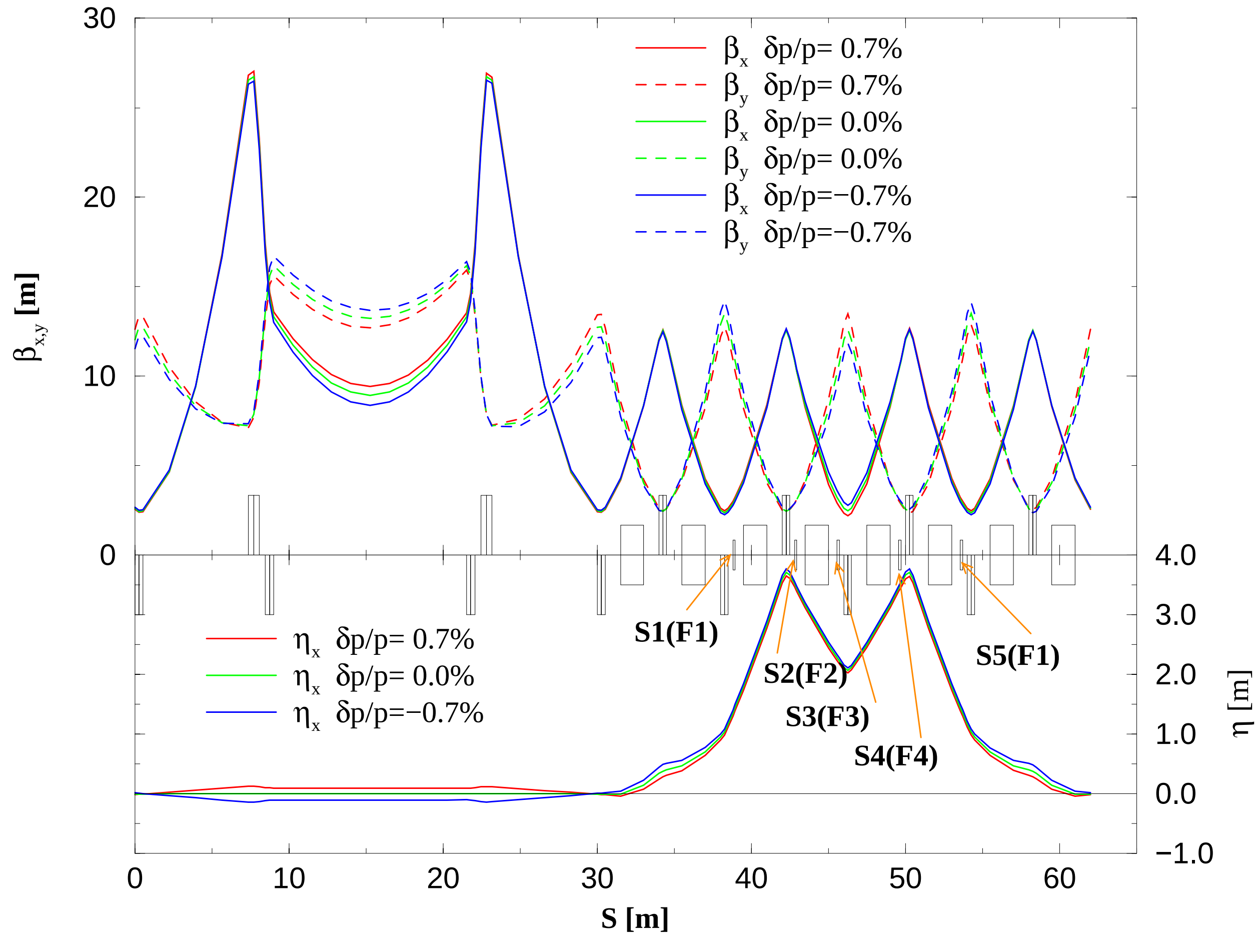

Figure 4: Lattice functions of the SNS accumulator ring for the nominal tunes (6.3,5.8) using 4 families of sextupoles. The beta and dispersion wave has been minimized by the introduction of the 2 supplementary sextupole families.

series, forming a total of four families. With a four-family scheme, the off-momentum optics is greatly improved, and the β-wave is minimal (Fig. 4).

By using the HARMON module of the MAD program [4], we have computed the required strength of the four families of sextupoles in order to adjust the horizontal and vertical chromaticity $\xi_{x,y}$ to a wide value range and at the same time to minimize the optics functions' perturbation (Fig. 5). We observe that the sextupole strengths for the most extreme cases are less than 6m^{-3}. Thus, the strength requirements of 8.3m^{-3}, given in Table 2.1, are sufficient to handle the chromaticity/optics control, leaving a comfortable 20% margin.

The introduction of non-linear elements as chromatic sextupoles can perturb the motion of particles in the ring. By using classical perturbation theory, we can show that sextupoles introduce a second order (quadratic in the sextupole strength) tune-shift with amplitude which is linear with the particles' emittance, equivalent to a first order octupole effect. This tune-shift may be quantified by the anharmonicity coefficients, $a_{hh} = dQ_x/d\varepsilon_x$, $a_{vv} = dQ_y/d\varepsilon_y$ and $a_{hv} = dQ_x/d\varepsilon_y$, the first derivatives of the tune with respect to the emittance. These

Table 1: Sextupole magnet parameters for the proposed hybrid lattice SNS ring.

Quantity	Value	unit
Sextupole:		
Regular ring sextupole:		
number	12	
magnetic length	0.15	m
magnetic strength, $B''/B\rho$	8.3	m^{-3}
magnetic gradient	47 – 57	T/m^2
pole inscribed diameter	21	cm
peak field at pole tip	0.26 – 0.31	T
Large ring sextupole:		
number	8	
magnetic length	0.15	m
magnetic strength, $B''/B\rho$	8.3	m^{-3}
magnetic gradient	47 – 57	T/m^2
pole inscribed diameter	26.4	cm
peak field at pole tip	0.41 – 0.49	T

three quantities have been computed for all range of chromaticity values and plotted Fig. 6. The maximum anharmonicity values are found to be a factor of five smaller than the ones introduced by the quadrupole fringe-fields [5], indicating that the introduction of chromatic sextupoles will not have an important non-linear impact on the SNS ring. This residual octupole-like tune-shift can be corrected by dedicated octupole correctors [5]. Additional tracking studies are in progress in order to further justify the small impact of the chromatic sextupoles in the non-linear dynamics of the SNS ring.

2.2 Trim Quadrupole Elements

The SNS hybrid lattice contains fifty-two quadrupoles, eight per arc and five per straight section. In order for the arcs to be an achromat and at the same time to adjust the tunes to the desired values, five families of quadrupole magnets are needed. The focusing and defocusing quadrupoles of the FODO arc form the two families. The other two families correspond to the doublet quadrupoles and the remaining family is formed by the four quadrupoles which match the arc with the straight section. The quadrupole magnet parameters are given in Table 3 (see [1]). The range of the values mentioned for the magnetic gradient and pole tip field represent the change of these parameters in order to accommodate the upgrade of the energy to 1.3 GeV.

Since the first design of the SNS lattice (a pure FODO), main and trim quadrupole windings have been foreseen to be installed on the core of the quadrupoles [3] in order to correct any type of quadrupole perturbation in the lattice.

Quadrupole perturbations can be mainly caused by a random or systematic variation of the quadrupole gradients around the ring. This can cause a β-wave and dispersion distortion.

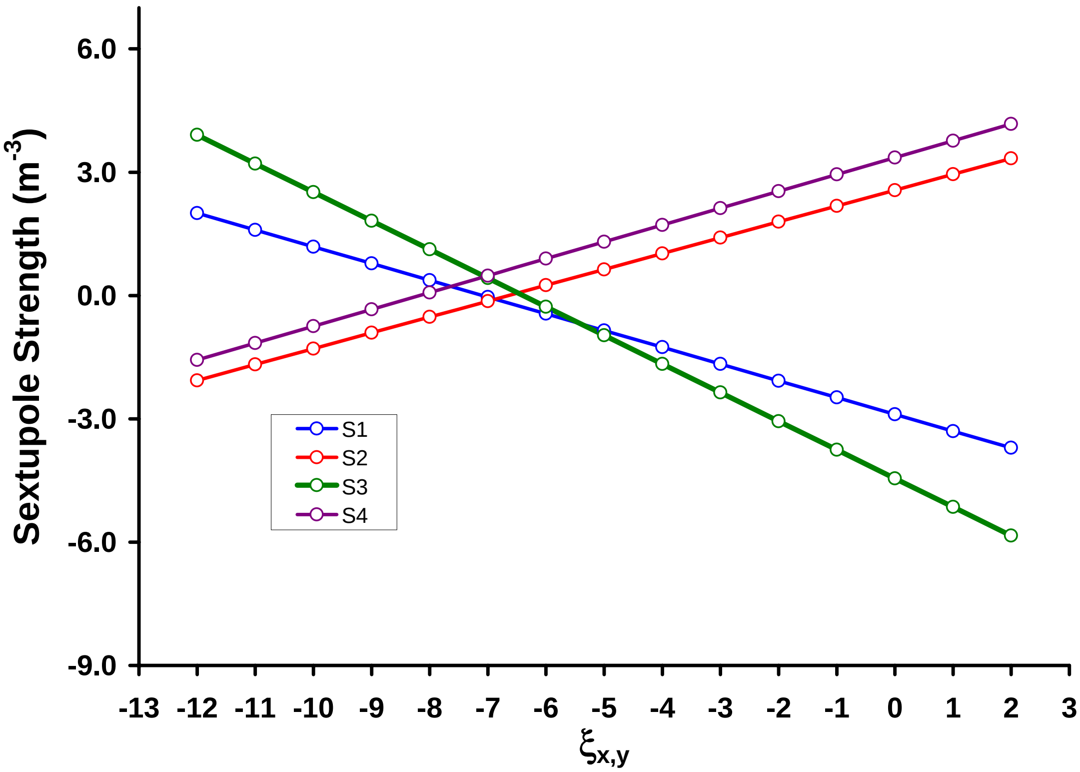

Figure 5: Sextupole strengths for the four families of chromatic sextupoles versus the chromaticity. The maximum values are within the strength requirements (Table 2.1).

Furthermore, the introduction of chromatic sextupoles can cause a feed-down quadrupole effect, for any type of closed-orbit distortion. On the other hand, if the tunes are close to quadrupole resonances of the form $2Q_{x,y} = p$ (*i.e.* for the working points (5.82,4.8) and (5.82,5.8)), the quadrupole perturbations may excite these resonances and produce significant β-beatings.

Based on experience from the AGS booster and calculation for the SNS ring original FODO lattice, the quadrupole strings should be able to correct a 1% perturbation of the quadrupole gradient. Additional calculations have been performed for the quadrupole perturbation introduced by the chromatic sextupoles. For a 1cm closed-orbit distortion in the sextupoles, the integrated quadrupole feed-down kick, around the machine, is found to be 0.1% of the equivalent main quadrupoles' kick. In order to control all of the above-mentioned effects and allow flexibility in tuning the lattice and minimizing the optics distortions, fifty-two small power supplies are needed to power each trim quadrupole element separately. The trim windings gradients required are of the order of 5×10^{-2} T/m.

The individual adjustment of the trim quadrupole strength can greatly assist the machine commissioning and the closed orbit tuning in operation. It is typical in the early stage of commissioning that Beam Position Monitors (BPMs) are often not fully available. Then, the trim quadrupoles adjustment becomes an essential tool to correct beam-closed orbit deviations.

Finally, special care has to be taken for the 4 "focusing" arc quadrupoles, which are

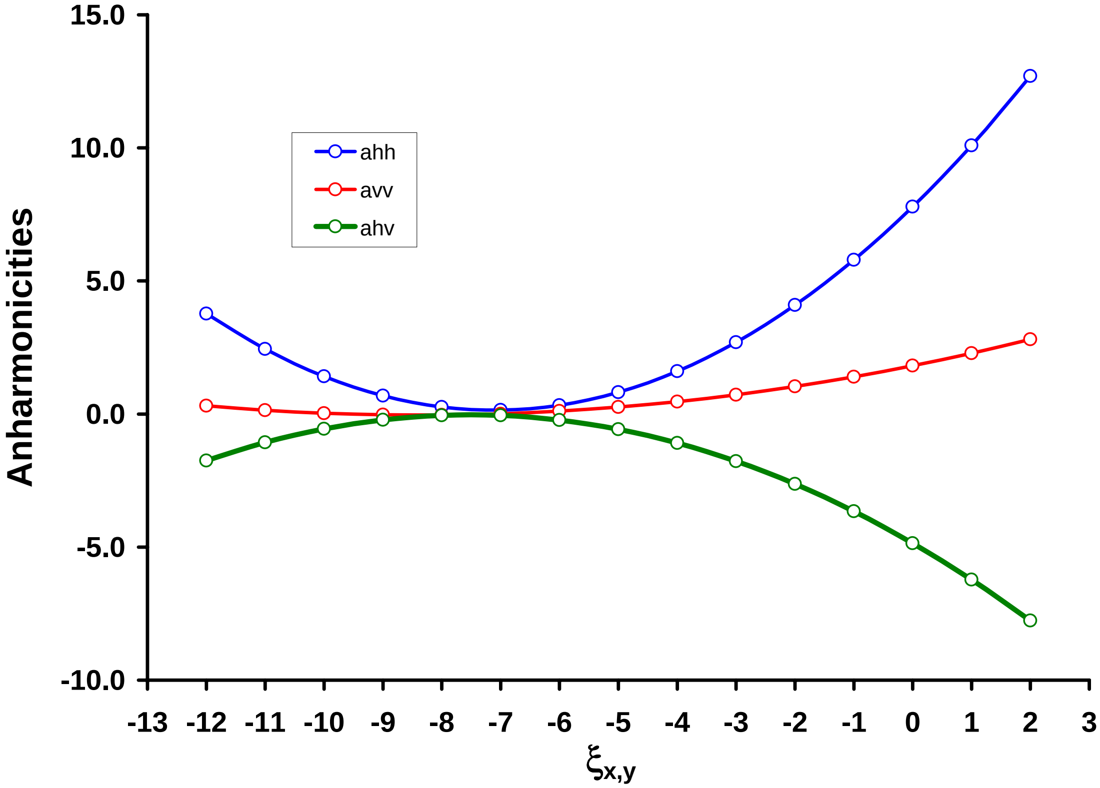

Figure 6: Anharmonicities versus the chromaticity. The maximum values are within 5% of the ones produced by the quadrupole fringe-fields.

powered in series, but have different apertures (21 versus 26 cm) and thus a 20% difference in the pole-tip field (see Table 3). A supplementary power supply will be indispensable for adjusting this difference. Thus, the number of power supplies dedicated for powering trim quadrupole elements is set to fifty-three in total.

3 Impact on Ring cost and Schedule

The impact on the construction schedule for both the sextupoles and trim quadrupole elements is insignificant. The total unburdened cost for the twenty chromatic sextupoles mechanical part is $ 799,471 [6]. The cost for the electrical part of the chromatic sextupoles, i.e. four 600 A power supplies (three of 40 KW/67 V and 1 of 70 KW/117 V) and cables is $ 263,753 [7]. The trim coils of the quadrupoles are already in the baseline and thus no cost change or update is required for their magnet portion. On the other hand the cost for the fifty-three power supplies of these elements is estimated to be approximately $ 890,400.

Table 2: Quadrupole magnet parameters for the proposed hybrid lattice SNS ring.

Quantity	Value	unit
Quadrupole:		
Regular ring quadrupole:		
number	28	
magnetic length	0.5	m
magnetic strength, $B'/B\rho$	0.82	m^{-2}
magnetic gradient	4.7 – 5.6	T/m
pole inscribed diameter	21	cm
peak field at pole tip	0.49 – 0.59	T
Large ring arc quadrupole:		
number	8	
magnetic length	0.5	m
magnetic strength, $B'/B\rho$	0.82	m^{-2}
magnetic gradient	4.7 – 5.6	T/m
pole inscribed diameter	26	cm
peak field at pole tip	0.61 – 0.73	T
Long ring straight quadrupole:		
number	8	
magnetic length	0.7	m
magnetic strength, $B'/B\rho$	0.77	m^{-2}
magnetic gradient	4.3 – 5.2	T/m
pole inscribed diameter	30	cm
peak field at pole tip	0.65 – 0.78	T
Narrow ring straight quadrupole:		
number	8	
magnetic length	0.55	m
magnetic strength, $B'/B\rho$	0.77	m^{-2}
magnetic gradient	4.3 – 5.2	T/m
pole inscribed diameter	30	cm
peak field at pole tip	0.65 – 0.78	T

4 Summary

The SNS accumulator ring is designed to accumulate a high-intensity beam, with large transverse emittance of 160 π mm mrad. With the required low beam loss level of 10^{-4}, the machine is designed in such a way to avoid any undesirable non-linear effects and instabilities which can limit its performance. The chromaticity control is one of the main issues in order to achieve this goal. Four families of sextupoles are needed in order to adjust the chromaticity and to keep the optical properties of the ring unperturbed. The required sextupole' strengths can be easily achieved with the proposed design properties of these magnets. The impact of these magnets with respect to non-linear dynamics is expected to be small and can be corrected with the dedicated multi-pole correctors of the SNS ring.

The other important issue discussed in this note is the requirements of the quadrupole trim elements, in order to allow tuning flexibility and correct any quadrupole perturbation. Individual adjustment of trim quad windings can greatly assist machine commissioning and closed orbit correction, especially in the early stages, when BPMs are not fully comissioned or calibrated, or even not available due to radiation damages, and the like. The quadrupole strings should be able to correct a quadrupole distortion of the level of 1% of the quadrupole gradient. The quadrupole feed-down introduced by the sextupoles for closed orbit distortions is far below that level and can be handled by the trim elements. In order to have the sufficient flexibility in correcting any systematic or random quadrupole error, fifty-two small power supplies are necessary in order to power each quadrupole string separately. An additional power supply is needed to adjust the quadrupole pole tip field difference in the family of arc quadrupoles which are powered in series but have different apertures.

5 Acknowledgments

We would like to thank Joe Tuozollo, Bob Lambiase, George Mahler and I. Marneris for many usefull discussions regarding engineering issues. We would like also to thank Kerry Mirabella for her assistance in the cost estimates.

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