LATTICE DESIGN OF A 1 GEV PROTON SYNCHROTRON

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Abstract

A 25Hz, 100MeV - 1 GeV proton synchrotron is proposed to be built as a spallation neutron source at Centre for Advanced Technology. A lattice with 4-fold symmetry is proposed for this synchrotron. The lattice has four dispersion free long straight sections for accommodating the injection system, the extraction system, the RF cavities and beam scraping system. The FODO structure of lattice provides a smooth variation of beta functions over the entire synchrotron and good tunability. The lattice is designed to deliver a beam power of 100 kW at the spallation target and taking in to consideration the space charge effects and requirement of high transition energy.

INTRODUCTION

The main accelerator in the Indian Spallation Neutron Source (ISNS) will be a Rapid Cycling Synchrotron (RCS) with repetition rate of 25 Hz, which will capture the H⁻ particles from the linac at 100 MeV and will deliver a proton beam of 1 GeV. The average current will be 100 μA and the average beam power will be 100 kW with pulse duration of nearly 1μ s [1]. Moderate repetition rate of 25 Hz is chosen from considerations of magnet and vacuum chamber design. This rate (25 Hz) is also the half of the main line frequency of 50 Hz in India. The previous lattice for the ISNS was designed to be a three-fold lattice [2]. That lattice does not provide sufficient space for accommodating the betatron collimators. Thus a new lattice with four-fold symmetry is chosen. In addition the four-fold symmetry also provides better stability against structural resonances than a three-fold symmetry.

LATTICE

Space Charge Tune Shift

At the injection energy of 100 MeV, there will be nearly 2.4×10^{13} protons in the synchrotron and thus space charge problems become severe. The first estimation of the space charge is made by the space charge tune shift of the synchrotron. This shift is given by

$$\Delta v_{x,y} = -\frac{N r_p \overline{R}}{\pi \beta^2 \gamma^3 v_{x,y} B_f a_{x,y} (a_y + a_x)}$$

Here symbols have their usual meanings. We allowed this shift up to –0.2. This will also decide the working point of the synchrotron and RF program, so that maximum number of particles can be captured keeping the loss of particles minimum at the injection.

Magnetic Lattice

The lattice for the accelerator is designed to be a FODO type and dispersion is matched with a missing dipole scheme [3]. The FODO lattice has the advantage of smooth variations of lattice functions, which makes it less prone to the field errors and also less prone to the envelope instability due to space charge. The additional advantages of a FODO lattice are that the strength of quadrupoles is moderate and chromaticity correcting sextupoles are weak. This lattice has four superperiods. Each super period consists of a large (3.875×4=15.5 m) dispersion free straight section, needed for the installation of the injection system, betatron collimators, RF systems and extraction systems.

One superperiod consists of six FODO cells, two for a dispersion free straight section and four for making an arc. The arc is designed with six rectangular type-bending magnets, each with a 15° bend. The maximum field strength is nearly 0.8 T at the extraction energy. Parameter list of the lattice is given in the table-1. The basic layout of superperiod with lattice parameters is shown in the figure 1.
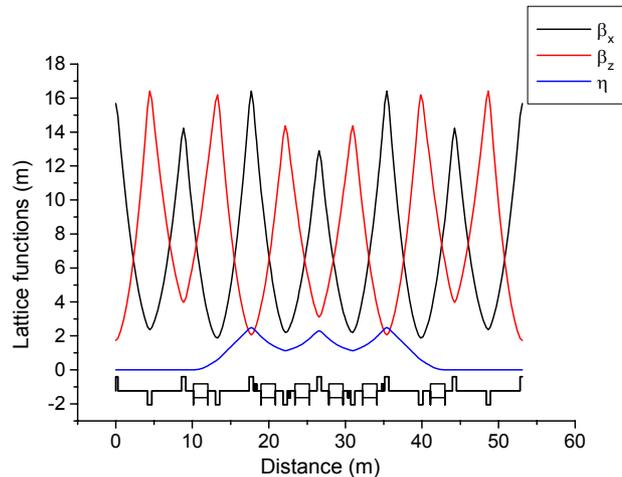

Figure 1: Lattice parameters of 1 GeV proton synchrotron.

The lattice has five families of quadrupoles (two defocusing and three focusing) by which synchrotron can be tuned in a wide range without affecting the lattice parameters much. The maximum field gradient in quadrupoles is kept below 4.5 T/m. The beta functions and dispersion of the synchrotron is optimised in the way so that maximum aperture does not exceed ±100 mm anywhere in the synchrotron for ±1% momentum acceptance. The lattice is optimised in such a way that the gama transition is also high to keep the synchrotron operation well below transition. The linac RF frequency

of 300 MHz is almost integer multiple (496 times) of the revolution frequency of proton in the synchrotron.

Working Point

The horizontal and vertical tunes can be adjusted by one unit without affecting optics parameters much. The tune can be varied from 6.3 to 7.3 and from 4.3 to 6.3 in horizontal and vertical planes respectively with only 1 m extreme change in beta functions. The two families of quadrupoles of straight sections are used for tune adjustment. The three families of quadrupoles in the arc are used to adjust horizontal and vertical beta functions and maximum dispersion. Selection of a working point is done keeping in view that the major resonances up to 4th order are avoided and the phase advance per cell remains around 90°. One of the suitable working points chosen is (6.88, 5.88), which is a split high tune. The tune is away from the sum resonance up to fourth order, but when the tune shifts by –0.2 due to space charge it can cross $\nu_x + 3\nu_y = 24$ line. Studies on other candidate tunes are also going on. Figure 2 shows the working point.

Table 1: Parameter list of the Synchrotron.

| Parameter	
Injection energy	100 MeV
Final energy	1 GeV
No. of protons in the synchrotron	2.4×10^{13}
Average power at the target	100 kW
Circumference	212.4 m
Periodicity	4
No. of bending magnets	24
Bending angle	15°
Magnet length	1.875 m
Bending field at injection	0.20 T
Bending field at extraction	0.79 T
No. of quadrupoles	48 (5 families)
Maximum gradient	< 4.5 T/m
Quadrupole length	0.55 m
No. of sextupoles	16
Sextupole length	0.20 m
Tune point	6.88, 5.88
$\beta_{x,max}$, β_{ymax}	16.4 m, 16.4 m
Maximum dispersion	2.49 m
Chromaticity	-8.95, -7.64
γ_t	5.591
Revolution time	1.65 – 0.81 μs
Harmonic number	2
RF Frequency	1.21 – 2.47 MHz
Peak RF voltage	120 kV
Linac parameters	
Energy of H- ion from linac	100 MeV
Pulse length	500 μs
Pulse current	25 mA
Emittance (normalised)	0.23π mm mrad
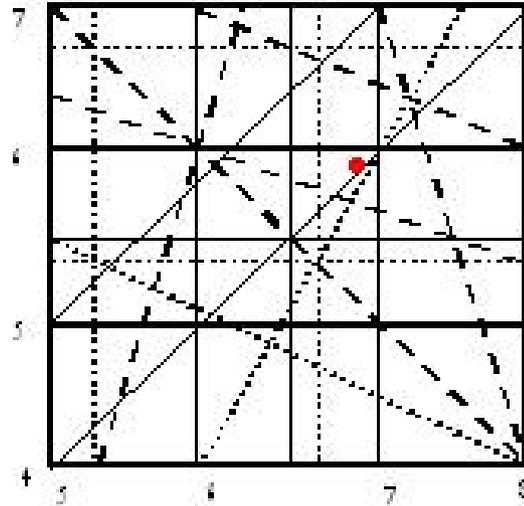
Figure 2: Tune diagram showing resonances up to 4th order

BEAM COLLIMATION

In high intensity synchrotrons the control of beam loss is an important aspect of lattice design and optimisation. As injection energy is low (100 MeV) and number of protons is high, so there exists a good possibility of halo formation due to mismatch of optical parameters and nonlinearities. Halo particles are slowly lost and cause activation of accelerator components. For removing this halo, betatron collimators are placed in the straight section of the period next to injection. Two primary scrapers, one for each plane and four secondary collectors, two in each plane are planned. Figure 3 shows the locations of these collimators. Arrows show the primary scrapers and bars show the secondary collectors. Red and blue colours are for horizontal and vertical planes respectively. The apertures of collimators are decided by the beam sizes at that location and assumption of a reasonable COD of 5 mm. The aperture ratios (n_2/n_1) of secondary collector to primary scraper in the horizontal and vertical plane are 1.1 and 1.2 respectively, which give phase advance between primary and second secondary 155° and 146° respectively in horizontal and vertical planes. Further studies are being carried out to improve the efficiency of the collimators. In the arc of the same period, a momentum collimator will be installed for collecting the off-momentum particles, which are out of the longitudinal acceptance of the synchrotron.

BEAM INJECTION

A long dispersion free straight section of one period is available for the injection system. Injection in the synchrotron has the goal to achieve such a distribution, so that space charge forces become linear. The charge exchange scheme, in which the H⁻ ions will be stripped through a thin foil, will be used to fill out the transverse phase space with K-V distribution. Linac pulse length is
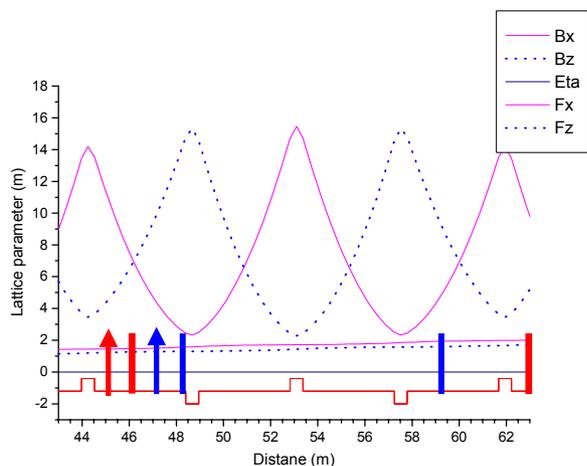
Figure 3: Locations of the betatron collimators.

taken as 500 µs and revolution time in the synchrotron at the injection is 1.65 µs, which leads to nearly 300 turns injection. The four bumper magnets located in the long straight section will achieve the painting in the horizontal plane. For vertical plane, the painting will be done by a bumper magnet, located in the linac to synchrotron transfer line.

The RF program will be such that the incoming beam is captured without much loss of particles and to keep space charge tune shift smaller, Bunching factor will be around 0.5. The peak RF voltage of 120 kV at the working frequencies (1.21 to 2.47 MHz) will require a 14-15 m long dispersion free straight section for accommodating cavities and this space will be made available in the fourth superperiod. The detailed studies of longitudinal dynamics with space charge are yet to be carried out.

SEXTUPOLES AND NONLINEAR ANALYSIS

The synchrotron will work well below gama transition, so there will be no head tail instability, but in order to minimise the tune spread due to off momentum particles it is necessary to include the chromaticity correcting sextupoles. Two families of sextupoles (one focusing and other defocusing) have been considered for chromaticity correction for the present studies. There will be four sextupoles in the one period placed mirror symmetrically in each arc section for compensating the natural chromaticity. For analysing the non-linear behaviour of the synchrotron, tracking studies have been done in presence of the sextupoles by the computer code MAD. Results for an on momentum particle is shown in figure 4. The particle is tracked for 10000 turns in bare synchrotron (without space charge) with extreme displacements in both the planes. Figure shows the good stability of the tracked particle. The stable region is found to reduce considerably for the particles with –1% of dp/p. Further optimisation of the sextupole scheme for improving the dynamic aperture for off momentum particles is being done.
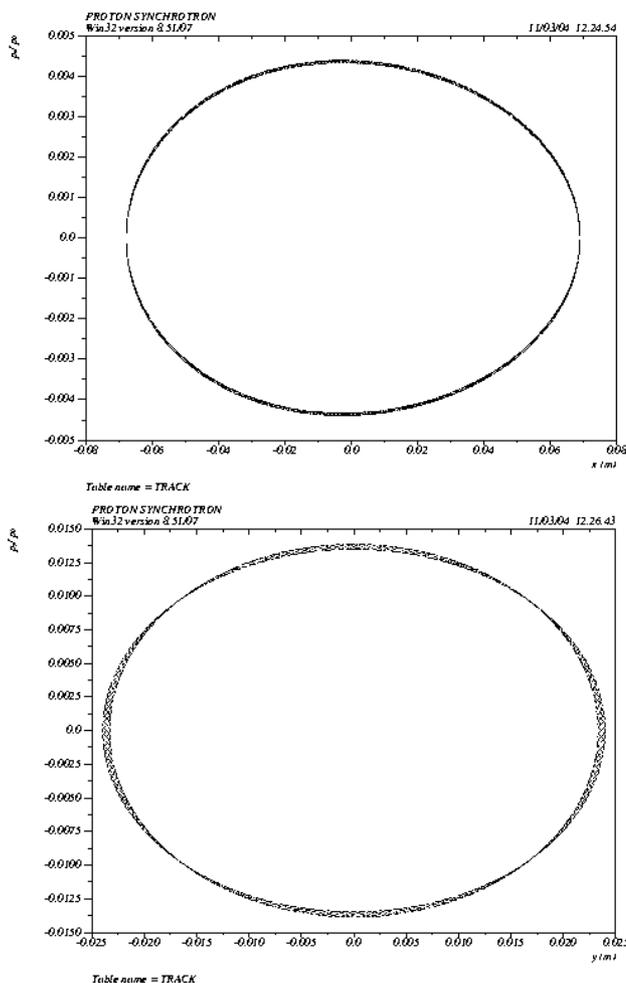

Figure 4: Tracking results in x- and y- phase space.

SUMMARY

The chosen four superperiod FODO lattice can be tuned in a wide range without much variations in lattice functions. The long dispersion free straight sections provide adequate space for placing injection system, betatron collimators, extraction system and RF systems. Nonlinear beam dynamics studies for off momentum particles and considering space charge effects have to be carried out. Besides injection, longitudinal dynamics and collimation studies are being done for minimizing beam losses.

REFERENCES

[1] D.D. Bhawalkar *et al.*, "Indian Spallation Neutron Source," InPAC'2003, February 2003, *p. 57-60*

[2] G.K.Sahoo *et al.*, "Preliminary Lattice for 1 GeV Proton Synchrotron," InPAC'2003, February 2003, *p. 79*

[3] Y. Chao *et al.*, "Conceptual Design for One Megawatt Spallation Neutron Source at Argonne," IEEE PAC'93, 1993, *p. 3757-3759*