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FEATURES OF THE BEAM DYNAMICS FOR THE SNS SYNCHROTRON

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Abstract

The following features are described of the fast cycling proton synchrotron under construction at the Laboratory for a spallation neutron source facility: choice of lattice, Q-values and beam emittances; injection and ejection schemes; correction elements; scrapers; beam loading compensation; longitudinal space charge compensation; impedances; a possible storage ring mode of operation for heavy ion fusion simulation studies.

Introduction

The 50 Hz, 800 MeV proton synchrotron has a mean radius of 26 m, an injection energy of 70.44 MeV, a multi-turn charge exchange H^- injection process and an estimated space charge limit of 2.3 10^{13} protons per pulse corresponding to 184 μA average current.

The main features of the beam and its environment that influence the dynamics are:

a. The low momentum spread at injection to limit the subsequent longitudinal emittance.
b. The relatively long injection interval of approximately 0.4 ms.
c. The relatively high level of the longitudinal space charge forces.
d. The large transverse emittances to give the required space charge limit.
e. The use of octupoles to combat transverse instabilities.
f. The large reactive longitudinal and transverse coupling impedances due to the space charge.
g. The reduction of these impedances by tailoring the vacuum walls to approach the beam envelope.
h. The proposed use of longitudinal space charge compensation to improve the trapping efficiency.

These features and related points are discussed in the report, together with the possibility of using the SNS synchrotron in a 70.44 MeV storage ring mode for studying aspects of heavy ion fusion drivers.

Choice of Lattice, Q-Values and Beam Emittances

The design of the magnet lattice had to take into account the following constraints:

a. The use of an existing 50 Hz magnet power supply with 10 symmetrical outputs.
b. The use of an existing magnet hall with defined directions for injection and extraction beam lines.
c. The need for efficient beam loss collection because of the associated activation levels.
d. The fast extraction of a very large emittance 800 MeV beam.
e. The requirement of long straights for injection, acceleration and extraction components.
f. Space considerations which suggested a mean radius requirement of 26 m.

It proved difficult to find a lattice meeting all these constraints, particularly one in which the peak stored energy in the bending magnets had to be minimised. Lattice periodicities of 5, 10 and 20 were considered and 10 was finally chosen. An initial missing dipole magnet scheme of periodicity 5 had some undesirable features and was discarded, while the use of 20 lattice cells gave inadequate straight sections.

Betatron Q values greater than 3.5 were required to provide reasonable values of the β-functions and 10 FODO-type cells were inappropriate for this condition. The lattice finally chosen had 10 cells of the form:
Quadrupole Doublet - Long Straight - Quadrupole Singlet - Gradient Magnet - Medium Straight.
The gradient magnet has a bend angle of 36° and a low profile parameter to provide some horizontal focussing. There is more focussing provided by the DF quadrupole doublet than the D singlet - BF gradient magnet combination.

A major consideration in choosing the lattice was the aim to provide almost loss-free fast extraction by minimising the extraction requirements and maximising the clearances for the halo of the kicked beam. Vertical extraction was chosen with the quadrupole doublet the only lattice element in the path between the fast kicker magnets and the extraction septum unit.

The basic lattice is:

Element Type	Magnetic Length (m)	Actual Length (m)	Focussing Par.(m^{-2})
D quadrupole	0.7256	0.6086	0.63766
Straight section	-	0.8368	-
F quadrupole	0.7068	0.5898	-0.63766
Straight section	-	5.9381	-
D quadrupole	0.4024	0.314	0.72624
Straight section	-	0.54328	-
BF gradient magnet	4.4	4.4	-0.06875
Straight section	-	3.1057	-

The betatron tunes are $Q_h = 4.31$ and $Q_v = 3.83$. Splitting of the Q-values by a half integer is not often adopted and has the disadvantage that Q_v lies just below an integer with a low threshold for the vertical resistive wall instability. Among the considerations that influenced the choice were: optimising the β-functions and focussing strengths in the lattice and obtaining equal pole profiles in the two quadrupoles of a doublet. An option remains open to lower Q_v to 3.4 by introducing shunt elements in the resonant magnet network. The particular choice of the Q-values leads to no period-resonances in the working diamond for resonances up to order four. The most significant non-periodic resonance is expected to be that of $Q_h + Q_v = 8$.

The beam transverse emittances ($\pi\varepsilon$) have been set by factors such as the peak capability of the magnet power supply and the constructional tolerances of the ceramic vacuum chambers. The values have decreased as the design has progressed:
ε_h 950 → 540 μrad m., ε_v 535 → 430 μrad m.,
The nominal transverse space charge limit for the final emittances is estimated at 2.3 10^{13} protons per pulse, under the assumptions:

a. A beam of uniform transverse density.
b. A δQ limit set by $\sqrt{\delta Q_h^2 + \delta Q_v^2} = 0.25$

c. An RF trapping sequence leading to maximum space charge at 85 MeV after 1 ms of acceleration.

The individual δQ-shifts, estimated from envelope equations with uniform transverse space charge, are $\delta Q_h = 0.15$, $\delta Q_v = 0.2$.

The longitudinal emittance has been chosen to limit $\Delta p/p$ during the cycle and to reduce the RF system requirements. A total longitudinal phase space area of 0.75 eV sec in two bunches corresponds to a peak $\Delta p/p$ value of $\pm 6\ 10^{-3}$ at approximately 90 MeV. In practice, this figure may be exceeded due to error tolerances of the linac and synchrotron and due to the effect of longitudinal space charge during debunching of the injected linac beam. Such effects may increase $\Delta p/p$ (max) to $\pm 8\ 10^{-3}$ and would require some reduction in ε_h. During acceleration there may be further longitudinal dilution and the RF system is designed to cater for bunches of total area 1.5 eV sec.

Injection and Ejection Schemes

Injection occurs as the guide field decreases during the interval 0.5 to 0.1 ms ahead of the field minimum. The natural chromaticity leads to a continuous Q-shift of the injected beam and trim quadrupoles correct for the shift. The injection components are all located in one long straight section: an input septum magnet, a series of 4 bump magnets and a central stripping foil. In reference 1, the dynamics of the injection process is described, in particular the attempt to reduce the peak density at the centre of the beam transverse density distribution.

Extraction at 800 MeV is achieved by three fast kicker magnets and an extraction septum magnet. A closed orbit bump at the septum reduces the kicker requirements. There will be some emittance dilution between 70 and 800 MeV; dilution up to a factor two will still allow loss-free extraction. Any further dilution is to be handled by scraping the halo prior to extraction.

Correction Elements

Correction elements include steering dipoles (a set of 4 for each transverse plane), a few remotely adjustable quadrupole supports, 20 trim quadrupoles, a pair of skew quadrupoles and two sets of 4 octupoles. Also there is space for 2 sets of 3 sextupoles. Steering magnets are used in setting the closed orbit with respect to beam-loss collection units. For the vertical plane they also provide the vertical orbit bump that aids extraction.

Routine correction of the closed orbit is made via 6 remotely adjustable jacks, 4 under singlet quadrupoles and 2 under doublet units. The singlets have the greater range of movement and they are adequate for full correction of fourth harmonic orbit errors and for partial correction of the third and fifth harmonics. Use must also be made of the 2 doublets to complete the third and fifth harmonic corrections. After repeated corrections it may be necessary to adjust the positions of further magnets or to resurvey the ring.

The 20 trim quadrupoles are pulsed over the injection interval to keep the Q-values constant. In addition they correct throughout the cycle for gradient errors in the lattice quadrupoles. The important gradient errors are the harmonic components exciting the $2Q_h = 8$, $2Q_h = 9$, $2Q_v = 8$ and $2Q_v = 7$ resonances. Trim quadrupole currents are controlled by function generators and two such units are adequate to control the harmonic excitation for any one second order resonance. The second order coupling resonance $Q_h + Q_v = 8$ is corrected by a pair of skew quadrupoles appropriately placed.

Octupoles produce Q-spreads for combatting transverse instabilities. The proposed 2 sets of 4 octupoles are located at equivalent lattice positions in 8 of the 10 medium straight sections. The distribution gives zero excitation of betatron resonances driven by the fourteenth, sixteenth and all odd integer harmonics. Peak normolised octupole strengths are 32 m^{-4} and the resulting Q-spreads are of order 0.03. Sets of sextupoles are not considered necessary unless unexpected sextupoles error fields occur in the ring.

Scrapers

Beam loss is to be localised over a restricted region of the ring. The major loss is expected in the energy range 70-100 MeV and provision is made for betatron and trapping losses of up to 180 μA average. The operating intensity will be that which keeps the average loss at higher energies to less than 2 μA.

A similar scheme is to be used for low and high energy collection. Protons that migrate from the beam envelope first strike a thin scattering foil. About half the beam is scattered into a collector 1 m downstream while most of the remainder is scattered through the beam to emerge at 0.45 or 0.95 of a betatron wavelength downstream to strike a further collector. For vertical collection 1 foil and 2 collectors are used with the second collector at 0.45λ from the foil. For horizontal collection 3 foils and 4 collectors are used and the spacing of 1 foil to final collector is 0.95λ.

The 70-100 MeV collection system uses copper foils and graphite collectors. There is a high temperature braze in the collector between the graphite and a water-cooled copper section. At 800 MeV the foil and collectors are both of stainless steel and the collectors are 0.5 m long. High energy collection is provided only in the vertical plane and is achieved with the help of the extraction vertical orbit bump. Typical activation levels of the individual collectors, after extended operation at the design intensity, are 10 to 20 rem/hr at 1 m one day after shutdown.

Beam Loading Compensation

As the bunches are forming, the voltage on the 6 RF cavities is low and the beam loading is high. Each double cavity is powered by a pair of tetrodes in parallel, one operating in Class B and one in Class A. The Class B stage is adequate at low intensity and the Class A stage compensates for the high intensity beam loading.

The compensation is obtained by sensing the beam current pulse at one point on the orbit and feeding an inverse signal via a variable delay line and amplifier to arrive at the Class A stage at the instant the beam pulse arrives. This feed-forward technique reduces the output impedance of the cavity within a given bandwidth and the coupling impedance depends on the gain and stability of the compensation.

A reduction of impedance is needed to prevent self-bunching in the injection interval and to reduce beam loading effects during acceleration. The feed-forward systems act to cancel the beam induced voltages and they must be effective in the presence of beam loss. Tuning systems act to keep each of the ferrite loaded cavities on tune. This is in contrast to when there is no compensation, in which case each cavity is detuned to counteract the reactive component of beam loading.

The systems have been designed with adequate power systems to operate throughout the acceleration cycle. In the second half of the cycle the RF voltage is high and the beam loss is small so it may be possible to reduce the duty cycle of the Class A systems with consequent power saving.

Longitudinal Space Charge Compensation

A possible future development is to provide longitudinal space charge compensation and so improve the trapping efficiency at high intensity. At energies below transition, longitudinal space charge forces are defocussing. The forces are a maximum at the end of the bunch where they may be greater than the focussing forces provided by a sine wave accelerating field.

The beam coupling impedance due to the longitudinal space charge is equivalent to a negative inductance. Such an impedance may be compensated over a limited frequency range by an inductive wall impedance. At 70 MeV in the SNS the negative inductance is large, approximately -154 μH, which is not practical to compensate by an inductive wall. Instead , a smaller inductance may be introduced, 14 μH, and a feed-forward system with a gain of 10 used to effectively amplify the inductance value. The beam current I and an amplified signal 10 1 excite the 14 μH cavity to give the equivalent of 154 μH.

The 14 μH may be provided by 2, 7 μH cavities. These have a resonant frequency of order 6 MHz which must be heavily damped. At 70 MeV the beam pulse has frequency components 1.34 MHz and harmonics up to 4 for which the cavity remains inductive.

The longitudinal space charge compensation need not cover the 10 ms acceleration cycle but only the first 1.5 ms. The bunch extent is then reduced to a level that the longitudinal space charge may be compensated via the main RF system.

Impedances

As a consequence of the low proton velocities (β = 0.367 to 0.842) there are large reactive space charge components of the longitudinal and transverse beam coupling impedances. The space charge contribution to the longitudinal impedance, Z/n, varies over the cycle from -j700 Ω to -j170 Ω; these numbers correspond to the case where the vacuum chamber walls are relatively close to the beam. The numbers are enhanced at a given energy for a reduced emittance beam.

The impedance values are such that the design currents are above the threshold levels for longitudinal and transverse instabilities. Thus it is important to minimise the impedances as much as possible, both the reactive and resistive components. The rapid cycling magnets have ceramic vacuum chambers which include special RF shields. These approximately follow the beam profile to reduce the reactive impedances and they make good RF contact to neighbouring chambers to reduce the resistive impedances.

Reducing the resistive component of impedance leads to slower growth rates for the instabilities. Reducing the reactive impedance corresponds to lowering the space charge forces in the longitudinal case but not in the transverse case. In the latter case it is still desirable, however, for it minimises the difference between the shifts in the transverse incoherent and coherent betatron frequencies and so reduces octupole requirements.

H.I.F. Storage Ring Simulations

The synchrotron may be operated in a 70 MeV proton storage ring mode when it becomes highly suitable for simulating the conditions in the type of storage rings proposed for heavy ion fusion drivers. The topic is discussed in some detail in reference 2 where suitable operating parameters are derived.

Among the topics that may be simulated and investigated at the SNS are:

a. Bunch compression and longitudinal space charge compensation.
b. Transverse and longitudinal emittance dilution during compression.
c. Transverse and longitudinal instabilities.
d. Debunching of the linac beam in an accumulator ring.
e. Beam transport under conditions of high space charge.
f. Operation of induction linac sections in an external beam line.

References

1 V Kempson, C Planner and V Pugh, Injection Dynamics and Multiturn Charge Exchange Injection into the Fast Cycling Synchrotron for the SNS, Proceedings of this Conference (1981).

2 C W Planner and G H Rees, Possible Use of the SNS Synchrotron for Feasibility Tests on Aspects of Heavy Ion Fusion Drivers, Rutherford Laboratory Report RL-80-042 July 1980.