H⁻ CHARGE EXCHANGE INJECTION FOR THE NSNS ACCUMULATOR*

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Abstract

A scheme for injection into the FODO cell of the National Spallation Neutron Source(NSNS) Accumulator ring is discussed. A 400 μg/cm^2 carbon foil is chosen for a high stripping efficiency and for heating of the foil consideration. Additional schemes to reduce losses due to nuclear and Coulomb scattering at the foil are discussed. Subsequent loss from magnetic field ionization of the residual H^o component is estimated to be small comparable to nuclear loss. A method for sweeping and collecting the stripped electrons from the foil is presented.

1 INTRODUCTION

Injection into the NSNS accumulator ring is H$^-$ charge exchange process where one can accumulate even on top of occupied phase space. As described in the linac section the beam from the linac is chopped in revolution frequency of the ring insuring there be a gap in the accumulated proton. The injection will take place in one of the dispersion free straight sections just upstream of the center quadrupole which has a large aperture. Because of the dumping scheme of the excited H^o from the stripping foil the injection shall take place exact radial position where the magnetic field of the quadrupole is 2.43 KG which is exactly 10 cm from the reference orbit. The magnetic field value is important because the electric field felt by the excited H^o is such that principal quantum number n=4 or less survives the field where n=5 or higher strip immediately. It is working a assumption that the stripping will take place between DC dipole and the quadrupole. However we may consider placing the stripping foil inside of the dipole upstream in order to avoid the effect of fringe field, however it is much more complicated mechanically. A set of 4 pulsing and one fixed field dipole are used to create orbit bump to paint optimum phase space of the injected proton population. The pulsing dipoles are programmed to paint the phase space to reduce the space charge effect of the circulating proton beam. The optimum distribution would be determined later by computer simulation and by experiment. The bump scheme should be able to accommodate a wide range of distribution from uniform phase space density to a so called smoke ring distribution. Likewise a set of four vertical pulsing dipoles are utilized to paint the vertical phase space. The basic scheme of painting the phase space is shown in the fig.1, and the proposed orbit bump is illustrated in fig. 2. Table I lists the location and kick angle of the orbit bumps both for the start and end of the injection process.

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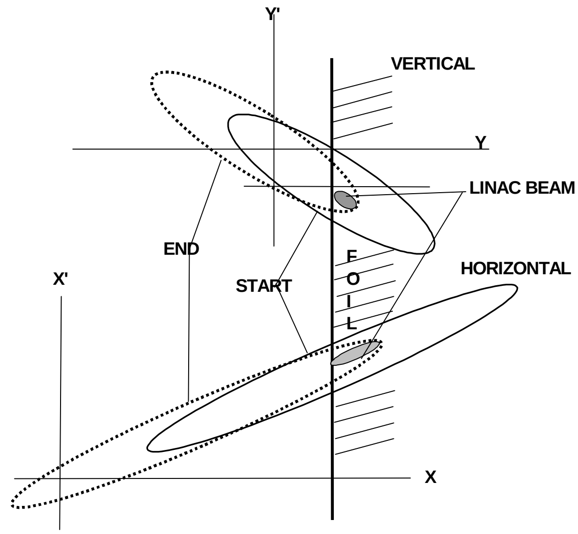

Fig. 1 X and Y injection Phase Space diagram

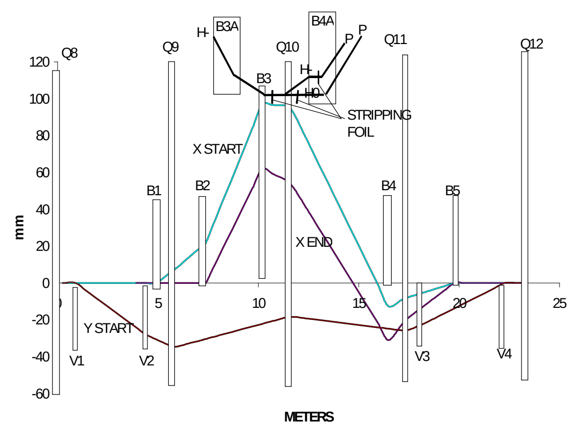

Fig. 2 Schematic Injection Bump Scheme

Table I Injection Bump Kicker Specifications

BUMP	LOCATION#	θ start	θ end
B1	Q_8 + 4.9m	7.75 mr	0.0
B2	Q_9 + 1.6m	17.35 mr	22.1 mr
B3	Q_9 + 4.4m	-27.15 mr	DC
B4	Q_{10} + 4.9m	27,05 mr	24.05 mr
B4A	Q_{10} + 2.0m	177 mr	DC
B5	Q_{11} + 2.4m	-2.67 mr	-7.78 mr
V1	Q_8 + 0.9m	8.0 mr	0.0
V2	Q_8 + 4.4m	-3.0 mr	0.0
V3	Q_{11} + 0.9m	-1.0 mr	0.0
V4	Q_{11} + 4.9m	5.5 mr	0.0

#Distance is from center of the quadrupole to the center of the bend. Q8 through Q11 are quadrupoles in the straight section starting from last quadrupole of preceding arc.

One has to keep the injection loss and subsequent beam loss due to the injection mechanism manageable. There are several injection loss mechanisms. They are 1) the linac beam missing the foil, 2) H^o's emerging from the foil which is a function of the thickness of the foil, 3) H^-'s emerging from the foil which is calculated to be negligible, and 4) circulating beam loss due to Coulomb and nuclear scattering on the foil. The loss mechanism 1) is related to the stripping foil size and one should keep this loss to less than a few percent. This beam loss along with loss due to the mechanism 3) is well known and a controlled dumping of the waste beam is planed. The loss mechanism 4) is directly related to the thickness and number of circulating beam hitting the foil which is proportional to the foil size exposed to the circulating beam. The foil size is chosen such that it provides a compromise between mechanisms 1) and 4). The thickness of the foil is determined by mechanism 2), 4) and foil heating problem described later. Present working plan calls for a foil size of 8 x 4 mm and 400μg/cm^2 thick carbon foil. The bump magnets are programmable to create the best possible distribution of the proton population.

2 DISPOSAL OF UNSTORED PROTONS

The H^- ions which missed the stripping foil and H^o emerging from the foil should be disposed in proper beam dump. We place a thick stripping foil in the path of the H^o to convert entire beam to proton. The H^- bent by downstream quadrupole will travel to 10KG septum magnet, and because of the high magnetic field, they will be stripped to neutral hydrogen in the field. We place a thick stripping foil inside the septum to strip them to proton. Placement of the foil will be determined after careful measurement of the magnetic field, and to have median of the proton emerging from the septum to be parallel with the protons from H^o. A rule of thumb estimation place the foil about 12 cm inside the magnet. A set of two quadrupoles placed downstream of the septum focuses the protons to the beam dump downstream.

3 STRIPPED ELECTRON DISPOSAL

The striped electrons from incoming H^- have a momentum 0.923 MeV/c and a magnetic rigidity of 0.003 T-m. The electrons travel with the protons until they encounter a magnetic field. The first magnetic field the electrons encounter is the field of the quadrupole following the foil. The quadrupole has a 0.243 T field at the radial location, which minimizes the halo created by the excited states of H^0. The magnetic fringe field extends to approximately a distance corresponding to its gap height. The electron trajectory become right angle to the proton orbit several centimeters upstream of the magnet yoke and 8 cm outside of the foil location. We place a collection plate parallel to the proton orbit at this location. The final position of the collector plate should be determined by the magnetic measurement of the quadrupole. The collection plate is water cooled as the electron power is expected to be about 1/900 of the proton power (about 1 KW for 1 MW NSNS). One has to minimize the generation for free electrons inside the ring which can cause an instability to the stored protons. The collection plate will be electrically biased so that no secondary electrons, generated by the striped electron striking the plate, escape the plate.

4 FOIL HEATING CONSIDERATION

A carbon foil is used to strip electrons of the H^- beam because of the resiliency and high sublimation temperature of the material. The sublimation temperature of carbon is above 3500 degree K. The foil is heated by the energy deposited by the proton and two accompanying electrons. Since they all have the same velocity, they should have the same energy loss in a given material. There is no data available for what fraction of the energy lost by beam in the material contribute toward heating of the material. At higher energies, the efficiency is estimated to be as low as 30%. However, for our calculations we assume that all the energy loss contributes to the heating of the material. Furthermore, we assume that no heat dissipates by conduction along foil edge and that the black body radiation is the only mechanism which dissipates the heat. For the one megawatt NSNS injection, the linac has effective average current of 18.2 mA in the unnormalized rms emittances of 0.14π mm-mr in both planes. The peak current density at the foil, where the beta-functions are 17 and 5 meters, is about 3800 A/m^2. Temperature at the spot will rise very quickly to the equilibrium where the heat input and the black body radiation become equal. Since the heat input is proportional to the thickness of the foil while the black body radiation is proportional to the surface area, the thicker the foil results in a higher equilibrium temperature. Figure 3 shows the calculated equilibrium temperatures for the effective linac current. In this calculation we assumed the emissivity of the carbon foil to be 0.8. For the linac current assumed for the NSNS injection, up to 400μg/cm^2 carbon foil can survive the injection whereas thicker foil may reach sublimation temperature. In the case where we double the linac current for increased power, we may consider a tandem foil of two 200μg/cm^2 about a cm apart. The foil may lose

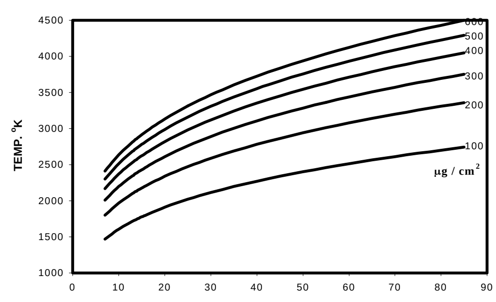

Fig.3 Peak Foil Temperature

some solid angle to radiate the heat, however, they have enough solid angle to radiate and would survive the injection process.

5 CONVERSION EFFICIENCY IN CARBON FOIL

Recently very precise measurements of these cross sections for H^- in carbon have been obtained by Gulley et al. [1] at 800 MeV as

$$\sigma_{-1,0} = (6.76 \pm .09)10^{-19}\ cm^2$$
$$\sigma_{0,1} = (2.64 \pm .05)10^{-19}\ cm^2$$
$$\sigma_{-1,1} = (0.12 \pm .06)10^{-19}\ cm^2$$

In Fig. 4 we have evaluated the fraction of H^o beam emerging after traversing carbon foil in function of thickness. It is seen that for our choice of 400 μg/cm^2 the H^o fraction is 8.19 10^{-3}. It would, of course, be possible to reduce the H^o fraction by using a thicker foil. However, losses from nuclear interactions and Coulomb scattering would then increase. More serious, the foil temperature will increase with the larger energy deposition from protons traversing the foil. If thinner foils are required by temperature considerations, it is always possible to use several foils in tandem to achieve lower values of the fraction.

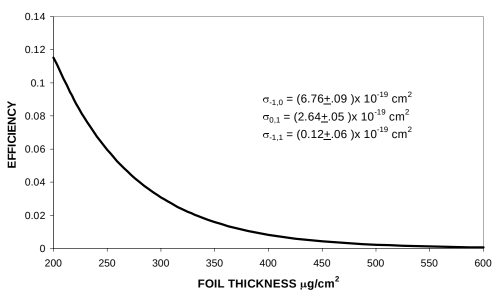

Fig. 4 Fraction of H^o

6 MAGNETIC STRIPPING OF H^O

Hydrogen atoms emerging from the stripper foil are in a distribution of excited states resulting from the stripping reaction $H^- \rightarrow H^{o*}(n) + e^-$ where n is the principal quantum number. This beam then traverses a quadrupole downstream of the foil, which bends the foil-produced protons back to the equilibrium orbit and the unstripped H^- component out of the ring. However, the neutral atoms can be magnetically stripped in the quadrupole and the resulting protons can contribute to uncontrolled losses downstream when the stripped proton is outside the acceptance ellipse of the ring. Gulley et al.[1] measured the population of H^o in quantum state n and gives distribution function as $n^{-2.8}$. We have assumed that their results at 800 MeV are valid for a 400 μg/cm^2 foil at 1 GeV. We estimated the fraction of the excited H^o decaying in .241T field of downstream quadrupole causing resulting proton to be outside of the horizontal acceptance of the accumulator ring. Using level width evaluated by Damburg and Kolosov [2]. A negligible portion (order 10^{-6}) of the states n≤4 or n≥6 decays outside of the horizontal acceptance. Though significant portion of n=5 H^0 decay proton end up outside of the acceptance. The fraction to total protons stored would be $<5x10^{-5}$ of stored protons which is less than our loss criteria of $<10^{-4}$. However, if this portion of loss becomes a problem we have an option of placing the stripping foil inside the gap of upstream dipole to avoid this problem. Since placing the foil inside the gap of a dipole creates significant complication in foil handling mechanism, present working assumption is to place the foil in the field free region between the dipole and the quadrupole.

6 COULOMB AND NUCLEAR INTERACTIONS

The injection process has been simulated with a Monte Carlo program HMININJ which tracks the transverse motion of protons from randomly selected H^- ions through the stripper foil and subsequent turns around the ring. The formulation and source code have been given elsewhere [3]. After a foil traversal the projected horizontal and vertical angles of the proton are modified by a random angle chosen from a multiple Coulomb scattering (MCS) distribution The formulation of nuclear elastic scattering (NES) in HMININJ is analogous to the MCS formulation. The elastic, non-elastic and total cross sections for 1 GeV p+C are taken from Igo, et.al. [4] as σ_e = 112 mb, σ_{ne} = 258 mb, and σ_T = 370 mb respectively. We have chosen beam ellipses of area ε_{BX} ε_{BZ} = 120π mm-mr and acceptance areas $A_x = A_z$ = 240π mm-mrad. The average number of foil traversals per proton $<N_t>$ minimized at $<N_t>$ = 2.43 when we optimized the injection bump for foil traversal. And the loss out of the ring acceptance due to Coulomb and elastic scattering is also minimum (within statistics for this N = 10^7 incident H^- run) at (2.25 ± .2)10^{-5}. For this case we can also evaluate the fractional loss from nuclear non-elastic events using non-elastic cross section = 258 mb, and the fraction is 1.26 10^{-5}, satisfying the NSNS loss criteria. The choice of the foil thickness of 400μg/cm^2 is based on comparison of losses due to H^o magnetic stripping against Coulmb and nuclear scattering loss.

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