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Brookhaven National Laboratory
Upton, New York 11973

BNL Interdepartmental Study of a Spallation Neutron Source

September 1995

Alessandro G. Ruggiero

Negative-Ion Injection by Charge Exchange at 2.4 GeV

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Negative-Ion Injection by Charge Exchange at 2.4 GeV

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Abstract

The present technical note describes multi-turn injection by charge exchange of 2.4-GeV negative ions in a Accumulator Ring used as an intense Pulsed Spallation Neutron Source. The major concern of beam loss due to magnetic stripping of the negative ions is addressed. It is demonstrated that, despite the high energy of the ions and the limitation on the magnitude of the magnetic field, it is possible to control the amount of beam losses to a fractional value of better than 10^{-5} , as it is required to avoid latent activation of the accelerator components. The injection magnet system which accomplish this is described. The paper addresses also the concern of beam loss due to the same effect in the 2.4-GeV injector linear accelerator, and in the transport from the Linac to the Accumulator Ring.

Introduction

A scenario for a 5-MW Pulsed Spallation Neutron Source based on a 2.4-GeV Superconducting Linac injecting in a single Accumulator Ring has recently been proposed [1]. The advocated advantage of the scenario is that, for the same power level, high beam energy reduces the demand on the beam current intensity and thus removes one of the major source of technical risk. To compress the beam to the required length (μs) in the Accumulator Ring, multi-turn injection by charge exchange of negative ions is required. It is known that there is always a finite probability that beam loss may occur due to the stripping of the negative ions induced by the magnetic field the beam encounters on its path. The beam loss, and the consequent latent activation effects, can be controlled to a sufficiently low and safe level if the integrated magnetic field is kept sufficiently low.

The example discussed here, is the demonstration that it is indeed possible to inject by charge exchange a 2.4-GeV beam of negative ions by imposing that it travels on a trajectory which includes an integrated field not exceeding 1 kG-m. Under this assumption, beam losses due to magnetic stripping are then negligible.

The Spallation Neutron Source

Figure 1 outlines the proposed 5-MW Pulsed Spallation Neutron Source which makes use of a 2.4-GeV Superconducting Linac injecting in a single Accumulator Ring [1]. General parameters of the Linac and of the Accumulator Ring are given respectively in Tables 1 and 2. The following regions need estimate of beam losses due to magnetic stripping (see Figure 2):

- Normal-conducting Linac Front-End
- Superconducting Linac
- Beam Transport
- Injection into the Accumulator Ring

Because of the low energy (~ 100 MeV), we do not expect any significant effect in the normal conducting front-end linac section, and we shall leave this component out of our analysis. As we shall see the effect is completely negligible in the Superconducting Linac and in the Beam Transport. The problem of magnetic stripping can be handled during injection with a proper design of the magnet system.

Tutorial

A negative ion, traversing a distance l in a region where there is a magnetic field B , has a probability to be stripped, and thus lost, given by [2, 3]

$$P = 1 - \exp(-l/l_s), \quad (1)$$

where the stripping length

$$l_s = (A_1 / B) \exp(A_2 / \beta\gamma B), \quad (2)$$

with $A_1 = 2.704 \times 10^{-5}$ kG-m, $A_2 = 149.3$ kG, and B is expressed in kG and l_s in meter. Typically $l \ll l_s$, and the stripping probability is small.

Let us assume that the ion is travelling through a sequence of magnets of different length, field, and at different energies, then the total stripping probability is

$$P = 1 - \prod_i \exp(-l/l_s)_i, \quad (3)$$

where each element of the product corresponds to a magnet in the sequence. In the approximation that $(l/l_s)_i \ll 1$ for all magnets, we have

$$P \sim \sum_i (l/l_s)_i. \quad (4)$$

The Superconducting Linac

The Superconducting Linac [1] is made of three sections: the first from 100 to 300 MeV, the second from 0.3 to 1.2 GeV, and the last from 1.2 GeV to 2.4 GeV. Each section is made of a number of periods, as shown in Figure 3: respectively 16, 59 and 60. Each period consists of a cryomodule, which includes a number of accelerating cavities, and of a normal-conducting drift where quadrupole magnets are located. There are no bending magnets. The length of the periods varies from section to section, namely 5.746 m in the first two sections, and 6.499 m in the last section.

Transverse focussing is provided by arranging quadrupoles in FODO cells with one quadrupole per period. The length of the quadrupoles is always the same, $l_Q = 0.3$ m. The gradient G varies from quadrupole to quadrupole with the beam energy. Denoting with $B\rho$ the particle magnetic rigidity, the focussing parameter $k = G l_Q / B\rho$ is constant. In the low- and medium-energy sections $k = 0.2462 \text{ m}^{-1}$, and in the high-energy section $k = 0.2176 \text{ m}^{-1}$. With a phase advance per cell of 90° , these parameters yield value of the amplitude function $\beta_{\max} = 19.62$ m in the first two sections, and 22.19 m in the high-energy section.

We estimated magnetic stripping of negative ions that are constantly displaced by 5σ from the quadrupole axis, with σ is the rms beam size. The cavity internal diameter is $d = 10$ cm. The ratio d/σ of aperture to beam size is shown in Figures 4, 5 and 6, together to the quadrupole gradient for each of the three linac sections. This information is used to determine G and σ , and, thus, the beam loss due to the stripping in the magnetic field of the quadrupoles. The result is an integrated fractional beam loss of less than 10^{-100} in the low-energy section, about 9.8×10^{-70} in the medium-, and 1.4×10^{-32} in the high-energy section. These losses are entirely negligible.

From these considerations, we would like to advise against the use of quadrupole doublets for focussing, since typically they require a considerably higher field gradient, and are more numerous.

The Beam Transport

The Beam Transport takes the beam from the end of the Linac to the point of injection into the Accumulator Ring. Because of the higher energy, space-charge effects are expected to be considerably less important. The following table compares the kinematic parameters for two different energy values, that may correspond to two different projects,

Kinetic Energy, GeV	1.35	2.4
Protons / bunch, N	1.8×10^9	4.5×10^8
β	0.91207	0.95969
γ	2.4388	3.5579
$\beta\gamma^2$	3.9728	9.8499

Space charge effects are expected to vary about linearly with $N/\beta\gamma^2$. Moreover, as it can be seen from the plots of Figures 4, 5 and 6, the bunch length is considerably smaller the cavity internal diameter, so that image effects are not important, one being in the free-space dominated regime. The bunch momentum spread is also very small ($\sim 10^{-4}$). Thus, it appears that there is no need of a special insertion for debuncher cavities and for achromatic bending. The bunch length and momentum spread can be easily controlled by adjusting the rf phase angle of the last few Linac cryomodules. Thus the Beam Transport does not need to include bending magnets and can be made straight.

Focussing is again provided with quadrupoles arranged in FODO cells with the same spacing of the last Linac section. Let N_Q be the total number of quadrupoles in the Transport Line. We adopted the same $5\text{-}\sigma$ procedure to estimate beam losses, as in the Linac. The fractional beam loss per quadrupole is then 7.6×10^{-33} . This should be multiplied by N_Q to obtain the total expected fractional loss. The effect is very small and entirely negligible.

Injection into the Accumulator Ring

We require that the negative ions, during injection, encounter an integrated bending field of 1 kG-m before they are stripped by a carbon foil. From Eq. (1), the expected fractional loss is then 3.8×10^{-15} , that is very negligible. (*)

The magnet system for injection of the 2.4-GeV beam is shown in Figure 6. It is assumed that injection occurs in the horizontal plane, so that bending is horizontal. Figure 6 gives then the plane view. What is being shown is an example that does not really need detailed design of the Accumulator Ring lattice. We only assume that the straight section is 26 meter long, with magnets arranged symmetrically around the middle-point. The insertion is dispersionless with a waist in the middle corresponding to $\beta^* = 20$ m in both the horizontal and the vertical plane. The injected beam emittance is given in Table 1, with the same value assumed in the two planes. These conditions should be easily accommodated by a detailed design of the ring lattice and the transport line.

The injected beam is directed straight from the end of the Linac to the horizontal bending magnet Bh_1 which is shared with the circulating beam. We allow enough clearance and safety margin by taking as the beam dimension 6 times the rms value.

The stripping foil is located between the two Bh_1 dipole magnets and has an area of $16 \times 16 \text{ mm}^2$ which matches the beam footprint at that location. The two Bh_1 dipoles are separated by 1 meter. A trajectory bump is initially created in the Accumulator Ring with a displacement $x_0 = 50$ mm, going through the centre of the stripping foil. The edge of the stripping foil is thus $b = 42$ mm away from the equilibrium orbit, corresponding to a betatron acceptance of $85 \pi \text{ mm mrad}$, which has been taken to be exactly 4 times the total beam emittance at the end of the multiturn injection process. Indeed the total emittance of the circulating beam was estimated assuming a bunching factor of 0.3, to yield a space-charge tune shift of 0.2. Beam parameters are listed in Table 2.

The horizontal bump is created by four dipole magnets. As shown in Figure 6, they are Bh_2 , Bh_1 and, then, placed symmetrically around the stripping foil, Bh_1 and Bh_2 again. The magnets have a maximum field of 1 kG and a length of 1m. To get the initial displacement of 50 mm the two dipoles Bh_1 and Bh_2 are to be separated by 4.26 m.

With a waist $\beta^* = 20$ m, the amplitude function does not vary appreciably along the length of the insertion. The aperture requirement of the Bh_1 dipoles is thus: a width of 140 mm and a gap

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(*) As a comparison, if the integrated field is raised to 1.9 kG-m, the fractional beam loss increases to 0.7×10^{-5} .

of 84 mm (*) to preserve the vertical and betatron acceptance, and to allow room for beam injection and the orbit bump. The aperture requirement of the Bh_2 dipole is 86 mm in width as well for the gap. To avoid intercepting the incoming beam, the width of the backleg of this magnet is 42 mm. Such a magnet can be designed and built without difficulties.

Similarly there is also a vertical bump, created by Bv_1 and Bv_2 each 0.4 m long with a maximum field of 1 kG. The separation between Bh_2 and Bv_2 is taken here to be 20 cm. Contrary to the horizontal bump, which has an initial large displacement, the vertical bump has zero displacement at the beginning of injection which then increases, as explained below, as injection proceeds.

The first focussing magnet is a quadrupole Q located at a distance of 5.6 m from Bv_2 . The Q quadrupole has a bore radius of 50 mm to allow the required betatron acceptance. The width of the backleg is 102 mm to allow clearance of the injected beam.

Those negative ions that are not stripped (H^-) or that are only partially stripped (H^0) can be removed with a stopper, a 2-m long block of iron, which is located downstream of the injection point in such a way to clear the path of the circulating beam and, at the same time, to intercept both H^- and H^0 residual ions.

Excitation of the Orbit-Bump Magnets

The bending magnets, Bh_1 and Bh_2 , that create the horizontal orbit bump are excited by an exponentially-decaying pulse, namely the horizontal bending field varies according to

$$B_h = B_0 \exp(-t/\tau), \quad (5)$$

where $B_0 = 1$ kG, and $t = 0$ is taken as the start of multi-turn injection. The bending magnets, Bv_1 and Bv_2 , that create the vertical bump have, on the other hand, the following excitation waveform, with the same decay time τ ,

$$B_v = B_0 [1 - \exp(-t/\tau)], \quad (6)$$

since the vertical displacement is zero at the start and then increases as multi-turn injection proceeds.

The decay time τ is determined with the following considerations on the bump amplitude. The horizontal amplitude of the bump is given by

$$x = x_0 \exp(-t/\tau). \quad (7)$$

We require that the beam injected fills up only one quarter of the betatron acceptance in either plane, so that at the end of the multi-turn injection process, when $t = t_p = 2.315$ ms,

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(*) We have not included here the space required to accommodate the vacuum chamber.

$$x_p = x_0 \exp(-t_p/\tau) = x_0 - b/2, \quad (8)$$

which yields $\tau = 4.26$ ms. Similarly, the amplitude of the vertical bump is

$$y = x_0 [1 - \exp(-t/\tau)], \quad (9)$$

which at $t = t_p$ takes the value $y = y_p = b/2$, as it has been required.

The integrated bending field, horizontal and vertical, experienced by the negative ions as they are injected, is given by

$$\int B ds = l_v B_v + l_h B_h, \quad (10)$$

where $l_v = 0.4$ m and $l_h = 1.0$ m. From Eq.s (5 and 6),

$$\int B ds = B_0 [l_v + (l_h - l_v) \exp(-t/\tau)]. \quad (11)$$

It is easily seen that the integrated field never exceeds the value of 1 kG-m, as it was set initially as the condition to control the beam loss by magnetic stripping.

Acknowledgment

I am grateful to Dr. L. Blumberg who introduced me to the notion of orbit bump during multi-turn injection, and to the danger of beam loss by magnetic stripping.

References

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- [3] L. Scherk, Can. Journal Phys. 57, 558 (1979).

Table 1. Linac Parameters

Ion Source Peak Current	30	mA
Accelerated Peak Current	25	mA
Final Kinetic Energy	2.4	GeV
Energy of n.c. Front-End	100	MeV
Repetition Rate	60	Hz
Pulse Length	2.315	ms
Duty Cycle	13.9	%
Chopping Ratio	0.6	
Normalized rms Emittance	0.3	π mm mrad
Longitudinal rms Bunch Area	1.917	π eV-s
Superconducting Linac Frequency	700	MHz
Protons / Bunch	4.5	$\times 10^8$
Average Beam Power	5.0	MW

Table 2. Accumulator Parameters

Kinetic Energy	2.4	GeV
Magnetic Rigidity	10.69	T-m
Circumference	665.99	m
Packing Factor (ρ / R)	0.5	
Bending Field	2.0	kG
Revolution Frequency	0.432	MHz
Revolution Period	2.315	μ s
No. of injected Turns	1000	
rf Harmonic Number	1	
Transition Energy, γ_T	7.8	
Total Bunch Area	40	eV-s
Bunching Factor	0.3	
rms Bunch Length	0.280	μ s
rms Momentum Spread	0.25	%
rf Peak Voltage	12	kV
Full Betatron Emittance (norm.)	73	π mm mrad
Betatron Acceptance (4 x Full Emittance)	85	π mm mrad
Space-Charge Tune Shift	0.2	
Synchrotron Oscillation Frequency	82	Hz

Figure 1 Layout of the Spallation Neutron Source using a 2.4 GeV Superconducting proton Linac [1]

Figure 2. Configuration of the Accelerator which avoids Bending

A SC Linac Section

Figure 3. Division of a Linac Section in Periods

Figure 4. Beam Dimensions in the SC Linac Low-Energy Section

Figure 5. Beam Dimensions in the SC Linac Medium-Energy Section

Figure 6. Beam Dimensions in the SC Linac High-Energy Section