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**A PULSED SPALLATION NEUTRON SOURCE.
SOLUTION WITH A 1.25 GeV ACCUMULATOR.**

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ALTERNATING GRADIENT SYNCHROTRON DEPARTMENT

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A Pulsed Spallation Neutron Source. Solution with a 1.25 GeV Accumulator.

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A. Computer Tracking Study of the Injection.

Simulation by Tracking

In a previous report [A1], a Spallation Neutron Source consisting with a 600 MeV Linac followed by two fast cycling synchrotrons was presented. Later, an alternate scheme with a 1.25 GeV Linac plus two accumulator rings was proposed. The results of a computer simulation of the injection and the capture of protons in these rings are discussed in this paper.

The lattice of one of the proposed rings [A2] is shown in Fig. A.1, together with a plot of the optical functions, β and dispersion. The ring has three super periods with FODO cells and long straight sections, with a total length of 180 m. One straight is dedicated to the injection, one straight to the extraction and one contains the RF cavities. The injection of H^- ions, converted to protons in a stripping foil, and the fast orbit bump associated with the process are described in detail in a following section. The main parameters of the machine are described in the Appendix.

The simulation has been performed with the code *Accsim*, developed at TRIUMF [A3]. It is a full 6-dimension simulation, with tracking of a certain number of macro particles through the lattice in the presence of space charge forces and beam to wall interaction. The initial distribution in the transverse and longitudinal phase space of the representative particles was random. Then, the tracking was done by representing the lattice with a certain number of transfer matrices built from a description of the lattice with the code *Mad* [A4]. *Accsim* also takes into account the scattering in the injection foil, that is traversed many times by the injected and stored beam during the first turns.

Main goals of the simulation were: (i) strictly limit particle losses in order to avoid radiation contamination, since the required injected beam current is very high, (ii) inject a long pulse to decrease the average current that the linac should deliver, and (iii) experiment with various beam energy spreads, and with beams carrying some halo.

Losses arise from two main sources, H^- ions missing the foil, or not being converted to protons and protons hitting the walls during the accumulation process. This latter effect was simulated by inserting suitable aperture diaphragms along the ring circumference, in the location where the beam envelope

was larger. *Accsim* counts and records foil mishits and particles hitting the apertures and take them off the tracking cycle.

Injected pulse was made as long as possible, both increasing the number of injected bunches and by increasing the longitudinal phase range of acceptance in the RF bucket. The height of the bucket itself was kept as small as possible, to limit the RF power requirements, compatible with the beam energy spread. The harmonic number used was one, to make use of the longest possible bucket.

The strategy used in the simulation was the following.

A stripping foil was placed offset, both in the horizontal and vertical position and the foil was hit by particles with gaussian random distribution in the transverse phase space. A fast orbit bump with various time shape was applied, in order to adiabatically bring the final beam after the injection to the equilibrium orbit, and the losses were recorded. Changing the bump shape determined the particle distribution inside the beam and strongly affected the loss rate, since it controlled the space charge forces and therefore the diffusion of the beam.

The longitudinal phase space was filled with a uniform random distribution in phase, corresponding to a chopping of the linac beam, and a gaussian distribution in energy.

At first, the emittance of the beam, the extension in phase and the energy spread of the beam were set to small values. Also, the foil was assumed rather thin to minimize scattering. From the beginning we tried to inject 1,000 turns, a comfortable value for the average current in the linac. We started to change the bump shape and the foil position in order to generate different particle distributions, while watching the losses during injection and accumulation, and also discarding those cases that generated a maximum space charge tune shift greater than 0.1.

We were guided by the experience with the AGS Booster at Brookhaven that showed how a very intense proton beam seems to be accepted more easily if the beam distribution in the transverse phase space is somewhat hollow, a sort of "smoke ring". Using 10,000 macro particles in the simulation we could after some attempts reduce the losses to zero ($<10^{-4}$).

Following this first stage, we proceeded by gradually increasing beam emittance, energy spread and bunch length. Also the foil was made thicker. After some trials, we again succeeded in the simulation to

inject and store the total charge with no losses and with a controlled tune shift. We repeated the best case with 100,000 particles and again saw no losses at the level of 10^{-5} .

In a final run, we tried to address the problem of a possible halo in the injected beam, checking the behavior of a beam with 10 times the beam emittance and 10% of the charge. The losses that were seen in this case gave a rough indication of the losses that we could expect from the halo.

Results are given in Table A.I and in the figures A.3-4.

Conclusions

In comparison to the synchrotron, the fixed energy accumulator seems a much easier machine. On the other hand, the higher energy linac is much more demanding in the latter case. The level of losses that we could see in the accumulator was much lower than in the synchrotron.

However, the comparison is not completely fair, since the simulation for the synchrotron was done in only the longitudinal phase space, in the presence of space charge forces, using the Fermilab code *Esme* [A5], while the present simulation was in full 6 phase space dimensions. We feel that a simulation only limited to the longitudinal motion is somewhat pessimistic as far as losses are concerned. To stress this point, the important effect that we observed by using smoke rings in the transverse space could not be observed with *Esme* and the like.

The halo may play an important role in the minimization of the losses. It is difficult to predict what

kind of halo the beam will carry, and clearly our attempt to represent it is barely adequate. This point requires further studies.

Another area that deserves more attention is the stripping of the H^- beam in the foil. A first problem arises from the survival of a percentage of unstripped ions and a second from the analysis of the scattering mechanism. *Esme* only computes the effects of Coulomb and atomic scattering, but not those of nuclear scattering, that may affect the long term behavior of the beam. This is in turn affected by the total time of storage required before extraction.

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Table A.I. Injection and accumulation parameters

Kinetic Energy, Protons	1.250 GeV
No of Injection Turns	1,000
Total Injection Time	0.665 msec
Total Injected Charge (H ⁻)	$2.08 \cdot 10^{14}$
Foil Center Position	31 mm(x), 23.8 mm (y)
RF Voltage -(Harmonic No.)	30 KV (1)

Table A.II. Accsim Simulation. "Smoke Ring" Optimization

Norm Emittance Gaussian [mm-mrad]	Injected Bucket Rectangular	DE (99%) Gaussian	Foil Size Thickness	No. of Macropart.	Losses
Case "I": Ref.					
0.35 π (x) 0.42 π (y)	240°	4.16 MeV	6 x 9 mm ² 300 $\mu\text{g}/\text{cm}^2$	10,000 = $2.08 \cdot 10^{14}$	no
Case "L": Thick foil					
"I"	"I"	"I"	6 x 9 mm ² 600 $\mu\text{g}/\text{cm}^2$	"I"	no
Case "M": Larger Emittance					
π (x) π (y)	"I"	"I"	9 x 12.6 mm ² 300 $\mu\text{g}/\text{cm}^2$	"I"	no
Case "N": Larger Energy Spread					
"I"	"I"	8.32 MeV	"I"	"I"	no
Case "O": "L" + "M" + "N"					
"M"	"I"	"N"	9 x 12.6 mm ² 600 $\mu\text{g}/\text{cm}^2$	"I"	no
Case "O+": "O" + More Macro particles					
"O"	"O"	"O"	"O"	100,000	no
Case "P": Pseudo Halo					
3.5 π (x) 4.2 π (y)	"O"	"O"	"O"	10,000 = $2.08 \cdot 10^{12}$	135
Losses were calculated for particles hitting 60 mm radius diaphragms placed at locations around the Ring where β is largest. Ring Acceptance (Case "O" in Table II) resulted in 240 π mm-mrad (x), 100 π mm-mrad (y). Maximum Tune Shift due to space charge at injection end was $\Delta\nu_x = -0.080$, $\Delta\nu_y = -0.102$. RF Bucket Half Height @ 13 KeV.

Fig. A.1. Layout of the Spallation Neutron Source Accumulator Ring.

Fig. A.2. Fast Injection Bump. Time Shape.

Fig. A.3. Accsim Tracking. Case "O". Transverse and Longitudinal Space. After 500 turns (upper 4 Plots), and after 750 turns (lower 4 Plots).

Fig. A.4. Accsim Tracking. Case "O". Transverse and Longitudinal Space. After 1,000 turns (upper 4 Plots), and after 2,000 turns (lower 4 Plots).

B. Injection Losses in 1.25-GeV Accumulator from HMINUSINJ Code

One run was made with the transverse phase space injection code HMINUSINJ [B1], which selects horizontal and vertical phase space coordinates of incident 1.25-GeV H^- particles at random from a pulse train of N_T turns, and evaluates multiple coulomb and nuclear elastic scattering in the stripper foil for each of N_{TV} traversals of the foil experienced by the sampled proton during the collapse of the injection orbit bump. The injected proton is tracked around the ring using linear transport matrices based on the MAD code model of the 3-superperiod, 180-m circumference ring presented by van Steenberg [B2].

For the present case, a Gaussian profile is assumed for the incident beam and normalized RMS emittances of $E_{nx} = 0.35\pi$ -mm-mrad and $E_{ny} = 0.42\pi$ -mm-mrad as estimated by Alessi [B3,B4] based on a Penning surface plasma H^- source used at LANL. The resulting unnormalized RMS reduced emittances are then $\epsilon_{ux} = 0.1661$ -mm-mr and $\epsilon_{uy} = 0.1993$ -mm-mr and lead to RMS sizes of $\sigma_x = \sqrt{\epsilon_{ux}\beta_x} = 0.5297$ -mm and $\sigma_y = \sqrt{\epsilon_{uy}\beta_y} = 0.8155$ -mm, where $\epsilon = E/\pi$ and use is made of the betatron functions $\beta_x = 1.689$ -m, $\beta_y = 3.336$ -m at the stripper foil position.

The transverse dimensions of the stripper foil, taken here to be a 300- $\mu\text{g}/\text{cm}^2$ C^{12} foil, are obtained from the RMS H^- beam size by requiring that the foil be approximately

$\pm 5\sigma$, a dimension for which the number of incident particles missing the foil is $< 10^{-7}$. For the present run the foil was taken to be a "postage stamp" 6-mm horizontal and 9-mm vertical. The foil center is positioned at $x = 31$ -mm outside the DC-bumped horizontal equilibrium orbit to give about 2-mm clearance between the foil inner edge and the outer dimension X_m of the ring acceptance ellipse of area $A = 400\pi$ -mm-mr, $X_m = 26$ -mm. The initial amplitude of the exponentially collapsing horizontal bump is taken as $A_H = 29$ -mm to produce a 2-mm radius hole in the ring circulating beam and thereby avoid excessive space-charge density at the beam center. The rate of collapse of the exponential bump is set so that no more than 200 π -mm-mrad of the acceptance is filled during the 626 turn injection interval of 416 μsec duration. Concurrently, the vertical phase space is filled with an exponentially rising bump since the H^- beam and the center of the stripper foil are both located in the median plane.

The filling of the horizontal ring acceptance is illustrated in Fig. B.1 where the phase space coordinates of the first 20,000 injected particles are plotted. The

results of the total run of 10^7 incident H^- particles, sampled in about 40 hours of HP-750 computer CPU time, are: NLOST = 182, NINT = 524, NSCAT = 189, and $\langle N_{tr} \rangle = 8$. Here, NLOST is the number of protons outside the 400π -mm-mrad acceptance at the end of injection and therefore lost on some aperture within the ring circumference (a distributed loss). NINT is the total number of elastic plus non-elastic nuclear interactions, NSCAT is the total number of nuclear elastic scattering events and $\langle N_{tr} \rangle$ the average number of foil traversals per proton. The fraction of particles lost by scattering is thus $f_L = (1.82 \pm 0.13) 10^{-5}$. It should be noted that multiple coulomb scattering (MCS) is very small for 1.25-GeV protons on C^{12} , in contrast to the 600-MeV case (see section D). For the present results only the lead term (Gaussian) in the Molière expansion was used since the Molière B parameter is undefined for the present conditions.

The multiple coulomb scattering angle θ_{MCS} computed for this case is only 7.2- μrad , and the contribution to NLOST from MCS is negligible. The losses are principally from nuclear elastic scattering as seen by comparing NSCAT and NLOST. For nuclear elastic scattering, the angle distribution probability tables previously used for 600-MeV protons on C^{12} were used, with $\sigma_{el} = 145.3$ millibarns, and we have therefore underestimated the total number of nuclear elastic events since the total elastic cross-section is increasing slowly with energy in this energy region. However, at 1.25-GeV the angular distribution of elastic scattering is more forward-peaked so that a larger fraction of scattered protons will be within the ring acceptance.

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- [B4] Proceedings of the Workshop on Ion Source Issues Relevant to a Pulsed Spallation Neutron Source: Part 1: Workshop Summary. Eds. L. Schroeder, K.-N. Leung and J. Alonso, Lawrence Berkeley Lab, Oct.24-26 (1994). See Table II-a, the LANL Penning 4X Source.

Fig. B.1. Filling of Horizontal Ring Acceptance.

C. Layout of 1.25 GeV Accumulator Ring Injection Straight Section

The proposed layout of the $L = 9.2$ -m injection straight is given in Fig. C.1. The incident 1.25-GeV H^- beam, with magnetic rigidity $B\rho = 65.943$ -kG-m, first passes through a DC septum-splitter magnet BDC1 and is deflected by an angle $\theta_{DC} = 51.25$ -mrad. A second deflection in magnet BDC2 of $-\theta_{DC}$ brings the H^- beam parallel to, but displaced by 10.25-cm from, the unperturbed ring equilibrium orbit. The 4-magnet chicane, BDC1 to BDC4, forms a local orbit deformation in the straight section centered on the stripper foil. The choice of magnetic field, $B = 3.38$ -kG in these magnets, is such that the fractional magnetic stripping probability is 10^{-4} in one meter, which leads to a stripping loss of $f_s = 1.5 \cdot 10^{-4}$ in the approximately 1.5-m of H^- path length in Fig. C-1.

This loss is much larger than obtained for the distributed ring losses from foil scattering given in the previous section; however it represents a local loss within the injection straight section of H^0 particles which are emitted tangential to the H^- orbit in BDC1 and BDC2. We could further assure that these H^0 's (and H^+ ions resulting from magnetic stripping of H^-) interact within the straight section by putting Pb shielding (not shown in Fig. C-1) along the outside edge of the beam trajectory in these DC magnets, since the absorption length for non-elastic interactions of high-energy protons is only 18.5-cm, much less than the 77-cm range of 1.25-GeV protons in Pb. It should be noted that our magnetic stripping losses are much larger than will be incurred in the European Spallation Source (ESS) straight section design [C1] of $f_s = 4.1 \cdot 10^{-12}$ with a magnetic field of $B = 1.77$ -kG and H^- kinetic energy of 1.334-GeV. Similar comments pertain for the magnetic stripping losses in the 8 m straight section provided for the Los Alamos (LANSCE-II, 1-MW) 800 MeV accumulator ring design [C2,C3].

We believe that the larger losses in the present design are tolerable because they are localized in the injection straight, in contrast to the distributed scattering losses discussed in the previous section.

Also shown in Fig. C.1 is a fast horizontal orbit bump of 32.5-mm amplitude formed by the 4-magnet chicane BHF1 to BHF4, which displaces the center of the 400π -mm-mrad ring acceptance ellipse to the center of the C^{12} stripper foil. The stationary H^- beam is also centered on this point. The magnetic field required in these fast bump magnets, $B = 4.286$ -kG, is relatively large due to the limited space available within the straight section, but is still within the range of modern ferrites [C4]. The kicker magnets for the vertical 4-bump chicane, BVF1 to BVF4, have a smaller peak field of $B = 2.11$ -kG because the vertical bump has been

tailored to the requirements of the "smoke-ring" phase space filling described in Section A.

Another major source of local losses is the foil inefficiency in conversion of H^- to H^+ . Webber and Hojvat [C5] have measured the stripping cross-sections σ_{10} and σ_{01} in C^{12} foils for the reactions $H^- \rightarrow H^0 + e^-$ and $H^0 \rightarrow H^+ + e^-$ for the Fermilab 200-MeV injection energy and have also concluded that the cross-section σ_{11} for the reaction $H^- \rightarrow H^+ + 2e^-$ is negligible and consistent with zero. They also present a theoretical curve for the cross-sections for energies < 1 -GeV. For the present design we have extrapolated their curve to 1.25-GeV and obtained $\sigma_{10} = 0.8 \cdot 10^{-18}$ cm² and $\sigma_{01} = 0.35 \cdot 10^{-18}$ cm².

We use these values in the expression obtained by M. Joy [C6] for foil conversion efficiency and obtain the results of Fig. C.2. In particular, the conversion fraction for a $300\text{-}\mu\text{g}/\text{cm}^2$ C^{12} foil is $f_c = 0.99085$ and for $600\text{-}\mu\text{g}/\text{cm}^2$ is $f_c = 0.999953$. Losses of 1% appear excessive, whereas losses of $\sim 5 \cdot 10^{-5}$ are consistent with other losses previously considered. Therefore we chose a $600\text{-}\mu\text{g}/\text{cm}^2$ foil in the calculations of Section A. The unconverted H^- ions will be predominately H^{0*} , i.e. excited hydrogen atoms and, as pointed out by the LANL group, atoms in excited states of principal quantum number $n > 4$ can be magnetically stripped to H^+ in the field of the magnet BDC3. We propose to provide Pb shielding in the 90-cm drift space between BDC4 and BVF4 to absorb the resulting H^+ ions. The unstripped H^{0*} atoms are shown in Fig. C.1 to be stripped to H^+ in a second, thick stripper foil upstream of BDC4.

In the present design we propose to bend the resulting H^+ beam out of the machine with a 170-mrad deflection provided by a pulsed field of $B = 11.21$ -kG in the upper portion of the BDC4 septum magnet. The septum in BDC4 would indeed be unnecessary if the straight section were sufficiently long to give clearance for the stripped H^+ residue. It should also be pointed out that residual H^- ions which pass through "pinholes" in the stripper foil or miss the stripper foil due to halo around the incident H^- beam will also be converted in the thick stripper and discarded in the external dump. The backup thick stripper will also be needed as a safety device if the primary stripper foil fails due to beam damage. An alternative to the beam dump scheme proposed here is to put Pb absorber (not shown in Fig. C.1) in the 1-m aperture of BDC4 and the 90-cm drift space downstream of BDC4, thereby creating a beam dump within the straight section.

Finally it must be noted that we have used two magnets, BDC2 and BDC3, for the central bend and located the stripper foil in the 20-cm gap between these magnets, in contrast to the single magnet central bend used in the ESS [C1] and LANL [C2] designs where the

foil is contained within the central magnet. In the present design the stripper foil is accessible and the foil can be readily replaced using a suitable foil-changing mechanism. (Of course, the foil is accessible in the ESS and LANL designs if the central bend is a C-magnet.) The fringe fields of magnets BDC2 and BDC3 should be sufficient at the foil position (~ 1 -kG) to sweep knock-on electrons from the circulating beam aperture, thereby avoiding electron trapping by the ring proton beam. Nonlinear instabilities observed at LANSCE have been attributed to the trapped electrons. Also, failure of the C^{12} "postage stamp" foils, regarded as a major operational limitation by the LANSCE group, has been investigated at Los Alamos [C7]. They studied 12-mm x 16-mm and 16-mm x 16-mm foils of 200- $\mu\text{g}/\text{cm}^2$ thickness with 800-MeV protons and, at fluxes of 6.0-6.6 $10^{16}/\text{cm}^2\text{-sec}$, they observe foil lifetimes of 6.0 $10^{22}/\text{cm}^2$ to 1.1 $10^{23}/\text{cm}^2$. The fluxes and foil dimensions are similar to those proposed here, i.e. we have 2 10^{14} incident H^- per pulse, 30 pulses/sec, and 8 proton traversals of the foil per incident H^- , giving 4.8 $10^{16}/\text{sec}$ on a 1.13 cm^2 foil. In the worst case reported, the useful foil lifetime at LANL was 278 hours (11.6 days).

The foil preparation method at LANL has been electron-beam evaporation of 100- $\mu\text{g}/\text{cm}^2$ foils which are then superimposed to make a two-layer 200- $\mu\text{g}/\text{cm}^2$ "sandwich". The foil is then supported by an array of 4-5- μm carbon fibers. Other methods of foil preparation have been studied [C8, C9] which suggest that longer foil lifetimes can be attained using heavy ion sputtering or laser-plasma ablation. It has been suggested [C10] that the thicker, 600- $\mu\text{g}/\text{cm}^2$ foil proposed in the present design will result in larger energy deposition per proton

traversal and may lead to shorter foil lifetime. The energy deposition rate dE/dx is only 10% less at 1.25-GeV than at 800-MeV. Clearly, the problem of foil lifetime vs. foil thickness needs further study.

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$\beta_x^* = 1.589\text{mm}$ $\beta_y^* = 3.336\text{mm}$ $L_{SS} = 9.2\text{m}$
 $\alpha_x^* = \alpha_y^* = 0$
 $\eta_x = 0.09\text{m}$ $\eta_y = 0$ $B\rho = 65.9427\text{ kG-m}$

$\epsilon_H = \epsilon_V = 1.0\pi\text{ mm-mr (norm,RMS) H}^- \text{ BEAM}$
 $A_H = A_V = 400\pi\text{ mm-mr ACCEPTANCE}$

- ⊗ - MAGNETIC FIELD INTO PAGE
- ⊙ - MAGNETIC FIELD OUT OF PAGE

VERTICAL SCALE: 1mm = 0.5cm
 HORIZONTAL SCALE: 1mm = 2.5cm
 DIMENSIONS IN CENTIMETERS

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Fig. C.1. Layout of the Injection Straight. Injection Bump.

Fig. C.2. H⁻ to H⁺ Conversion Fraction, 1250-MeV, C¹².

D. Injection Losses vs. Number of Injected Turns and Emittance of Incident H⁻ Beam in 3.6-GeV Rapid Cycling Booster

For the original BNL Spallation Source Design Study [D1] only 300 turn injection from a 600-MeV Linac of normalized RMS emittance 0.35π -mm-mr horizontal $\times$ 0.42π -mm-mr vertical was considered for injection into the 30-Hz, 363-m circumference, 3.6-GeV ring. It is of interest to determine how rapidly distributed losses in the ring increase with increasing injected turns (and consequently lower average Linac current), and further to determine how strongly our loss predictions depend on the assumed emittance of the incident H⁻ beam—a property which in turn depends on the performance of the H⁻ ion source and subsequent dilution in the Linac and beam transfer systems.

A series of runs were undertaken using the HMINUSINJ code [D2] and a sample of $4 \cdot 10^6$ incident particles to assure better than 10% accuracy in the computed loss fraction. The computer time required using the BNL NSLS VAX-8600 was greater than 50 hours of CPU per run, thus limiting the number of variations of parameters attainable. Results were obtained for 300, 400, 500 and 600 injected turns at each of five H⁻ normalized RMS emittances: $\epsilon_n = E/\pi = 0.16, 0.35, 0.55, 0.75$ and 1.0 -mm-mrad. C¹² stripper

foil sizes of about $\pm 5\sigma$ were used and correspond to square foils of sides 10, 15.4, 19.3, 22.56 and 26-mm. The thickness of the foil was held fixed at 300 μ g/cm for these runs. The results are given in Fig. D.1 where the lines are simply drawn through the points and do not represent fits to the data. The ring acceptance was taken as $A_H = A_V = 320\pi$ -mm-mr and the injected beam initially filled no more than 50% of the acceptance. An exponentially collapsing bump was used in the horizontal plane and an exponentially rising bump in the vertical.

The losses vary from as low as $(3.07 \pm 0.28) \cdot 10^{-5}$ for the 300-turn, 10-mm $\times$ 10-mm foil to $(3.87 \pm 0.07) \cdot 10^{-4}$ for the 600-turn, 26-mm $\times$ 26-mm foil. Limiting the fractional ring losses to $< 10^{-4}$ will require a Linac normalized emittance of $< 0.35\pi$ -mm-mr for the number of turns considered here. The losses increase nearly linearly with emittance but less rapidly with increasing number of injected turns. It should be noted that the losses extrapolate to zero as the emittance, and hence the foil size, approach zero—as expected.

Also of interest is the relative importance of multiple coulomb scattering (MCS) and nuclear elastic scattering (NES) in the loss process, as well as the correlation of losses with average number of foil traversals $\langle N_{tr} \rangle$ per incident H⁻. The particle losses are summarized below.

Table D.I. Protons Lost by Scattering and Nuclear Interactions vs. Injected Turns and Incident H⁻ Beam Emittance.

Emittance $\epsilon_n = E/\pi$ (normalized, RMS) in mm-mrad						
NTURNS		0.16	0.35	0.55	0.75	1.0
300	NLOST	123	285	393	521	780
	NSCAT	59	113	175	223	319
	NINT	141	286	458	595	844
	$\langle N_{tr} \rangle$	5.40	10.12	15.44	22.11	32.38
400	NLOST	157	315	493	726	1050
	NSCAT	67	142	210	312	422
	NINT	164	352	559	792	1162
	$\langle N_{tr} \rangle$	6.47	12.42	19.45	28.44	42.23
500	NLOST	199	375	588	876	1342
	NSCAT	76	162	245	395	579
	NINT	201	421	646	1005	1481
	$\langle N_{tr} \rangle$	7.44	14.61	23.42	34.75	52.16
600	NLOST	214	437	720	1041	1547
	NSCAT	83	180	293	422	652
	NINT	231	474	766	1141	1705
	$\langle N_{tr} \rangle$	8.35	16.77	27.39	41.11	62.04

In the above, NLOST is the number of particles outside the 320π -mm-mr ring acceptance after injection is completed, NSCAT is the total number of nuclear elastic scattering events, and NINT is the total number of nuclear interaction, elastic plus non-elastic, experienced by the $4 \cdot 10^6$ sample. The losses appear to track the number of foil traversals $\langle N_{tr} \rangle$ quite well. The foil traversals are in turn reasonably correlated with foil area. Also, nuclear elastic scattering appears to account for no more than about 40% of the losses; thus coulomb scattering is an important effect at 600-MeV, in contrast to the higher energy results of Section B.

For the above runs, the nuclear elastic scattering angular distribution at 600-MeV was obtained from measurements of Jones [D3] at LAMPF and fitted to the diffraction scattering theory of Fernbach, et al. [D4]. The data give a total elastic cross-section of $\sigma_{el} = 145.27$ -millibarns. Additional data on non-elastic cross-sections for ~ 600 -MeV protons on C^{12} by Renberg, et

al. [D5] at CERN give the total cross-section σ_T of 378.3 millibarns used here. The value of σ_T is consistent with BNL measurements by Palevsky, et al. [D6] at 1-GeV.

References

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Fig. D.1. Fractional Scattering Loss. 600-MeV H^- , $300 \mu g/cm^2 C^{12}$.

Appendix

5 MW Pulsed Spallation Neutron Source Parameters Accumulator Design Option

As a possible alternative design approach for the 5 MW PSNS, the use of an intermediate energy Linac, in conjunction with two accumulator rings has been studied.

The lower final beam energy necessitates the use of higher beam current. This disadvantage is greatly offset by the use of dc rings, reducing by an order of magnitude the RF requirements, simplifying greatly the ring magnets and associated power supplies, and eliminating the use of aperture demanding, impedance compensated, ceramic chambers.

The reduced magnet/magnet power supply cost and reduction of ring beam energy, permits greater sophistication in ring lattice structure design, easing the beam injection configuration and permitting greater control over localizing unavoidable beam loss.

Parameter optimization studies yielded the combination:

1.25 GeV (60 Hz) Linac $\Rightarrow$ two 1.25 GeV (dc) Accumulators

Design Scenario PSNS, Phased Construction
Linac-Accumulator(s) Alternative Design

Phase I Beam Power 1 MW

Linac, 0.8 GeV.; Rep.Rate 60 Hz

1.25 GeV Accumulator Ring:

Phase I Operation at 0.8 GeV, $\langle I \rangle = 1.25$ mA.

Phase II Beam Power 5 MW

Linac, 0.8 GeV plus 0.45 GeV addition ; Rep.Rate 60 Hz

Add 1.25 GeV Accumulator Ring:

Phase II Operation , 2 rings at 1.25 GeV, $\langle I \rangle = 4.0$ mA.

PSNS, Accumulator Option

Linac/Injection Parameters

Beam Power	1	5	MW
E(linac)	0.8	1.25	GeV
<I(linac)>	1.25	4	mA
Protons/sec.	7.8 E15	2.5 E16	
Repetition rate	60	60	Hz
Protons/pulse	1.30 E14	4.17 E14	
Number Acc. rings	1	2	
Protons/pulse/ring	1.30 E14	2.08 E14	
I(linac), chopped	60	100	mA, ch.factor 65%
Ring, τ (orb.)	0.7132	0.6646	μ sec
τ (micro), ch.pulse	0.4636	0.4320	μ sec
Inject.protons/turn	1.74 E11	2.70 E11	" $n_p = I \cdot \tau(\text{micro})/e$ "
Injected turns/ring	747	770	
τ (macro), Linac	533	1024	μ sec
I(linac), exit RFQ	60	100	mA
Linac, RFQ effic.	~0.85	~0.85	
H ⁺ source current *	70	120	mA
H ⁺ source, duty fact.*	3.2	6.1	%

Accumulator Parameters

Beam Parameters

Kinetic Energy	0.8	1.25	[GeV]
β , velocity	0.8419	0.9034	
γ , energy	1.853	2.332	
Momeum	1.463	1.976	[GeV/c]
Magnetic Rigidity	48.810	65.916	[kG.m]

Accumulator Parameters

Circumference	180	[m]
Bending Radius	5.7296	[m]
Transition, γ_t	3.915	
Ring Excitation	dc	
Dipole Field	8.519	11.504 [kG]
Lattice Structure	Triple Achromat with zero dispersion insertions	
Number of Dipoles/Quads	24B(1.5)/18Q(0.8),24Q(0.4)	
Betatron Tunes, $\nu_{x,y}$	4.85/4.85	
Chromaticities, $\xi_{x,y}$	-6.72/-7.77	

Beam-Stay-Clear Aperture	$400\pi \cdot 10^{-6}$; $\Delta p/p = \pm 0.01$	
BSC(dipole) _{x,y}	9.5 * 7.5	[cm*cm]
BSC(quad) _{x,y}	11.5*10.5	[cm*cm]
Chamber & Clearance	0.5	[cm]
Dipole "GF" * Gap	20 * 16	[cm*cm]
Quadrupole, R _{pole}	12	[cm]
Magnet Gap	16	[cm]
B _{pole} (max), Quadrupole	8	[kG]

Revolution Period	0.7132	0.6646	[μ sec]
Harmonic Number	1		
RF frequency	1.4022	1.5047	[Mhz]
RF max. Voltage	30	30	[kV]
Bunch Area		4.35	[eV-sec]
Bunch Length, rms		313	[nsec]
Bunch $\Delta p/p$		1.2	[%full]
Bucket Area		6.1	[eV-sec]
Bucket 1/2 Height		14.5	[MeV]
Space Charge Δv		0.1 - 0.2	
Number of Protons/sec	$7.81 \cdot 10^{15}$	$2.5 \cdot 10^{16}$	
Number of Protons/pulse	$1.30 \cdot 10^{14}$	$4.17 \cdot 10^{14}$	
Number of Protons/pulse/ring	$1.30 \cdot 10^{14}$	$2.08 \cdot 10^{14}$	

Pulsed Spallation Neutron Source, schematic

Beam Time Structure

Pulsed Spallation Neutron Source

0.8 [1.25] GeV Linear Accelerator Injector

Repetition rate = 60 Hz
 Beam pulse width = 1024 μ sec
 RF pulse width = 1050 μ sec
 RF duty factor = 6.3 %
 H- current = 120 mA (peak)
 Chopper duty factor = 65 %
 Average Beam current = 4.0 mA

Pulsed Spallation Neutron Source
Tentative Site Plan