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H⁻ INJECTION SIMULATION FOR A 5 MW SPALLATION NEUTRON SOURCE*

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I. Introduction

BNL has conducted a study of a "green field" pulsed Spallation Neutron Source with a design objective of 5 MW of average proton beam power on a heavy element production target. We propose H^- injection from a 600-MeV CCL linac into a pair of rapid (30 Hz) cycling synchrotrons with final energy 3.6-GeV and total output current of 1.394 mA. With a total throughput of $8.7 \cdot 10^{15}$ p/s from the two 3.6-GeV rings, it is important that losses - particularly distributed loss around the rings - be minimized both for reasons of shielding requirements and activation of components. A reasonable limit for fractional distributed losses is $\leq 10^{-3}$. A major source of such losses would be scattering of the incident H^- beam and subsequent multiple traversals of the stripped protons out of the ring acceptance ellipses by multiple coulomb (MCS) and nuclear elastic scattering (NES). Indeed, Yamane, et al.¹ have made an estimate of these losses for the Japanese Hadron Facility at 1-GeV incident H^- energy through a $250 \mu\text{g}/\text{cm}^2$ C^{12} stripper foil and obtain scattering losses of $5.4 \cdot 10^{-4}$. Such losses could be higher for the 600-MeV H^- injection contemplated here. We, therefore, did a detailed Monte-Carlo simulation of multiturn injection through a carbon stripper foil to obtain quantitative loss estimates. We find that under optimal conditions with a rapidly (exponentially) collapsing orbit bump of the ring horizontal (x) and vertical (z) acceptance ellipse through a $300 \mu\text{g}/\text{cm}^2$ "postage stamp" (10mm x 10mm) C^{12} foil and with 300 turn injection of an H^- beam tracking the ellipse axis $y' = -(\alpha/\beta)y$, the scattering losses out of an $A_{x,z} = 400\pi$ mm-mrad acceptance ellipse with 50% filling is only $(2.9 \pm .3) \cdot 10^{-5}$. Under worst case conditions with a large area (20mm x 160mm) foil, no tracking of the ellipse axis, and with 600 turn injection through a $600 \mu\text{g}/\text{cm}^2$ foil, the losses are $(3.3 \pm .1) \cdot 10^{-3}$. The computed losses are systematically about 10% too large due to an overestimate of the nuclear elastic losses resulting from an overestimate of the nuclear radius of C^{12} .

II. Formulation of Multiple Coulomb and Nuclear Scattering

We use the Moliere² series expansion of the probability for MCS scattering into an angle between θ and $\theta + d\theta$ as

$$P(\delta)d\delta = \delta d\delta \left[2e^{-\delta^2} + \sum_{n=1}^{\infty} f_n(\delta)/B^n \right] \quad (1)$$

where the $f_n(\delta)$ are universal functions of the normalized angle $\delta = \theta/\theta_{\text{mcs}}$ with the rms multiple coulomb scattering angle $\theta_{\text{mcs}} = \langle \theta^2 \rangle^{1/2} = \theta_1 \sqrt{B}$. The θ_1 function as well as a function (θ_1/θ_0) required to obtain B are elucidated by Bethe and Ashkin.³ The evaluation of the $f_n(\delta)$ and Moliere B functions are given in detail elsewhere⁴; here we note that the present calculation evaluates all $f_n(\delta)$ functions over a larger angle interval, $0 \leq \delta \leq 1000$, in smaller angle increments $\Delta\delta$ ($= .01$ for $\delta \leq 20$) and with considerably better numerical accuracy than used in a previous calculation⁵. Also, we evaluate all terms up to $n=10$ here. Random angles are sampled from the integral of the probability function Eq.(1) using an improved random number generator⁶. The transcendental equation for Moliere's B does not allow solutions with $B \leq 1$ which, indeed,

would result in a diverging series for Eq. (1); this limit corresponds to $\tau \approx 245 \mu\text{g}/\text{cm}^2$ for the C^{12} foils of the present calculation, and we therefore do not consider foils thinner than $\tau = 300 \mu\text{g}/\text{cm}^2$, for which $B = 1.7994$ and $\theta_{\text{mcs}} = 17.82 \mu\text{rad}$.

For nuclear elastic scattering we use the optical model formulation of Fernbach, Serber and Taylor⁷ (FST) which assumes a complex square well potential of radius R and obtains the differential cross-section in the center-of-mass (CM)

$$\frac{d\sigma}{d\Omega} = (kR)^2 R^2 [I_1^2(\delta) + I_2^2(\delta)] \quad (2)$$

in terms of dimensionless integrals I_1 and I_2 and the normalized angle $\delta = kR \sin\theta$ which are described elsewhere.⁴ The wavenumber $k = p/\hbar$ is obtained from the relativistic kinetic energy of the reduced mass $\mu = M_p M_c / (M_p + M_c)$ of the proton- C^{12} system in the CM; we obtain $kR = 15.9778$ here with $R = r_0 A^{1/3}$ and $r_0 = 1.25 \text{ fm}$. Comparison of Eq. (2) with elastic cross section data of Jones⁸ measured at $T_p = 597\text{-MeV}$ at LAMPF are shown in Fig. 1. We see that the first minimum of the theoretical curve occurs at an angle about 10% smaller than the data, and that a decrease in R of that amount would reproduce the correct position of the minimum which is determined by the first minimum of the Bessel function $J_0(kR \sin\theta)$ in the integrands of I_1 and I_2 . A reduction in R would also bring the magnitude of Eq. (2) into better agreement with the data at smaller angles, and into better agreement with the value for r_0 found for lower energy $p + \text{C}^{12}$ scattering.⁹

III. Computation Procedure

We choose at random the coordinate and angle of an incident H^+ from an assumed Gaussian beam with center fixed in the middle of a small area carbon "postage stamp" stripper foil similar to that used successfully at the LAMPF PSR.^{10,11} A random MCS angle is added and, if required, a random NES angle if a nuclear elastic event occurred as evaluated from the total elastic⁷ cross section computed here as $\sigma_e = 145.3 \text{ mb}$. In addition, non-elastic events are calculated from the result $\sigma_{\text{ne}} = 233 \pm 5 \text{ mb}$ measured by Renberg, et al.¹² at 552-MeV. The total nuclear cross section used here, $\sigma_T = \sigma_e + \sigma_{\text{ne}} = 378.3 \text{ mb}$ is in good agreement with the measured value of $370 \pm 9 \text{ mb}$ at 1000 MeV by Palevsky, et al.¹³

We next select a random injection time t for the particle between the start of injection t_i and the end of injection t_f and compute an initial turn number based on the total number of injection turns desired. For 300 turn injection, $t_f - t_i = 458 \mu\text{sec}$ for the ring model used here.¹⁴ Use of a continuously variable injection time implies that we are including points from all azimuthal positions in the ring and thus avoiding filamentation in phase space which would result from discrete injection intervals. The injected particle coordinates are then transformed to coordinates relative to the acceptance ellipse centers $X_c(t)$ and $Z_c(t)$. We are using a rapidly collapsing function¹⁵ for the horizontal "bump", an exponential in the present case, and a corresponding exponentially increasing function for the vertical

$$\begin{aligned} X_c(t) &= A_H e^{-w_x t} \\ Z_c(t) &= A_v [1 - e^{-w_z(t+t_0)}] \end{aligned} \quad (3)$$

with $w_x = w_z$ and t_0 an initial time offset to give an initial displacement of the ellipse center and create a "hole" in the central phase space density.¹⁵ Preliminary results using a half-sinusoidal bump gave a large population peak at the ellipse center and thus an excessive space-charge tune spread. Reduced central particle density also leads to fewer subsequent foil traversals and thus lower scattering losses as well as less radiation damage and therefore longer foil lifetime.

Finally, a tune value ν is assigned to the particle so that a one-turn matrix can be constructed to transport the particle around the assumed linear machine for as many turns as is required to move the acceptance ellipse off of the stripper foil. An amplitude-dependent tune as obtains for a non-uniform space charge density is used here (constant tune leads to phase space filamentation) although the form of the density function is not a priori known; we assume¹⁶ a Gaussian density function

$$n(r) = n_0 e^{-\alpha^2 r^2}$$

and obtain⁴, from a generalization of Laslett's¹⁷ derivation of uniform space-charge tune shift, as elucidated by Bruck¹⁸, the expression

$$\begin{aligned} \nu &= \nu_0 - \Delta\nu = \frac{1}{2} \left[\nu_0 + \sqrt{\nu_0^2 - 4A(r)} \right] \\ \text{where } A(r) &= \frac{r_0 C N_0 (1 - e^{-\alpha^2 r_m^2})}{(2\pi)^2 \beta^2 \gamma^3 B (1 - e^{-\alpha^2 r_m^2}) r^2} \end{aligned} \quad (4)$$

and where C is the ring circumference, B is the bunching factor, β and γ the usual relativistic factors, r_m the maximum radial extent of the machine acceptance, N_0 the total number of protons in the ring, $\alpha^2 = 1/2\sigma^2$ with σ the rms width of the Gaussian, and $r_0 = e^2/m_p c^2$ = classical radius of the proton. Eq. (4) is based on the assumption of a circular beam and uniform longitudinal particle density in the bunch; it reduces to the Laslett expression¹⁸ in the limit of uniform density ($\sigma \rightarrow \infty$) where the tune shift $\Delta\nu$ attains its minimum value and is independent of particle amplitude. In Fig. 2 we show the tune variation for several values of the bunching factor B and corresponding beam width σ with the constraint $(\Delta\nu)_{\max} = .25$. The value of σ for $B = 0.5$ used in the loss calculations is $\sigma = 18.4$ mm. Ruggiero¹⁹ has considered the more general case of a Gaussian particle distribution transversely and longitudinally for a bunch of elliptical cross section.

The machine model used for the calculation¹⁴ has horizontal and vertical phase space acceptance ellipses of area $A_{x,z} = 400\pi$ mm-mrad with a horizontal half-width of $a_x = 56$ mm at the stripper foil position which is at the midpoint of the 4.4 m straight section downstream of

the horizontally defocussing lattice symmetry point quadrupole. The betatron functions at the stripper are $\alpha_x = -1.361$, $\beta_x = 7.960$ m, $\alpha_z = 1.401$, $\beta_z = 8.449$ m and $\eta_x = 2.21$ m and result in tilted acceptance ellipses since $\alpha_{x,z}$ are non-zero. We have therefore considered cases where the bumped ellipse centers X_c and Z_c remain on the axes $x' = z' = 0$ as well as cases where X_c and Z_c track the ellipse axes $y' = -(\alpha/\beta)y$ ($y = x$ or z). This axis is close to the symmetry axis of the tilted ellipse obtained¹⁶ by diagonalizing the quadratic form of the rotated Courant-Snyder invariant, which gives the tilted ellipse major axis as ⁴

$$y' = \frac{(1 + \alpha^2)}{\beta} \left[\frac{\alpha}{2} \pm \sqrt{1 + (\alpha/2)^2} \right] \quad (5)$$

In either case the injection is terminated at $t = t_i$ with a clearance between the H^- beam center and acceptance ellipse edge of $5\sigma_{bx}$ where $\sigma_{bx} \approx 1.0$ mm is the rms width of the H^- beam of rms emittance $\epsilon_b = .1232\pi$ mm-mrad.¹⁴ A clearance of 3.6 mm is also taken between the acceptance ellipse and the inner edge of the stripper foil located at $X_{fo} = 60$ mm. The H^- beam center is at $X_{bo} = 65$ mm at the center of a 10 mm x 10 mm carbon foil; again we allow $5\sigma_{bx}$ between the H^- beam center and foil edge to assure that losses from randomly selected H^- ions with an assumed Gaussian profile missing the stripper foil are $< 10^{-5}$. In the present calculation we also ignore momentum dispersion effects which will increase the H^- beam size at the stripper foil from the H^- beam momentum spread ¹⁴ of $\delta = \Delta p/p_0 = .005$ by $\sim \sqrt{2}$. Momentum spread will also result in a small spread in position X_c of the ring acceptance ellipse center.

IV. Results and Conclusions on Distributed Injection Losses

A sample computer run (case 37, Table I) showing the horizontal phase space distribution of $N = 10^4$ incident particles is given in Fig. 3 to illustrate the geometry described above and the affect of the exponential "bump" of Eq. (3) and tune spread of Eq. (4) in producing a nearly uniform density distribution. Although a 2-mm radius "hole" was introduced at the ellipse center, there is still evidence of higher density in the central region. This is also apparent from the horizontal profiles produced by the program which are generally peaked above the $n(x) \sim [1 - (x/x_{max})^2]^{1/2}$ profile expected for a uniform phase space density. Lee and Ratner¹⁵ suggest that a parabolically collapsing bump will more closely approximate a uniform phase space population. In table I we summarize results from some of the computer runs in which foil thickness τ , injected turns, foil area and trajectory of incident H^- beam are varied (NBC = 0 means ellipse centers X_c and Z_c move along $x' = z' = 0$; NBC = 1 means X_c and Z_c movement along ellipse axis $y' = -(\alpha/\beta)y$). In runs 33-39 (except 37) the injected beam filled 50% of the acceptance with lost particles outside the $A_{x,z}$ area; in runs 28-31 losses are evaluated as all particles with final coordinates outside the filled phase area. Although the calculation uses specific model parameters for ellipse shape and ring tune, we feel that the loss results are reasonably model-independent except for acceptance area and foil size.

TABLE I. COMPUTED INJECTION LOSSES FROM PROGRAM HMINUSINJ

RUN	N (10 ⁶)	τ ($\mu\text{g}/\text{cm}^2$)	TURNS	Ax,z (mm-mr)	EBx,z (mm-mr)	foil size (mmxmm)	NBC	$\bar{N}_t$ (trav/p)	NLOST	NINT	NSCAT	loss function f_L (in 10^{-5})
36	4	300	300	400	200	10x10	1	4.91	117	144	47	$2.92 \pm .27$
38	4	300	600	400	200	10x10	1	7.35	148	211	69	$3.70 \pm .30$
33	2	600	600	400	200	10x10	1	7.33	135	174	59	$6.75 \pm .58$
35	3	300	600	320	160	10x10	1	8.35	168	183	68	$5.60 \pm .43$
39	2	300	300	400	200	10x10	0	12.16	129	172	61	$6.45 \pm .57$
37	3	300	600	400	400	10x10	1	4.03	116	89	38	$3.87 \pm .36$
34	.5	600	600	400	200	20x160	0	251	1644	1603	638	329 ± 8
29	3	300	300	200	200	10x10	1		130	94	31	$4.33 \pm .38$
28	3	300	600	200	200	10x10	1		216	139	45	$7.20 \pm .49$
31	1.5	300	600	200	200	10x10	0		490	256	99	32.7 ± 1.5
30	3	300	600	200	200	20x160	1		2903	1110	404	96.8 ± 1.8

(1) Run 36 with $\tau=300 \mu\text{g}/\text{cm}^2$ and 300 turn injection gives the smallest fractional loss of all cases considered here, $(2.9 \pm .3) 10^{-5}$. Uncertainties quoted in the present report are rms statistical values. NLOST includes MCS and NES losses. The total number of nuclear interactions is $N_{\text{INT}} = N_{\text{non-elastic}} + N_{\text{NSCAT}}$; therefore the "local" non-elastic losses in this case is $N_{\text{ne}}=97$ which is comparable to the distributed losses NLOST. Essentially all of the elastic scattering events NSCAT are included in NLOST. The computer program also gives the average number of traversals per proton per turn and number of particles lost as a function of initial turn number of the injected particle. These functions are shown in Fig. 4 for run 36 and illustrate that the number of traversals/proton is still largest for the initial turns. However, the overall average traversals/proton, $\bar{N}_t=4.91$, is $< 2\%$ of the number of turns. Comparison of run 38 to run 36 with the number of injected turns increased to 600 shows that the fractional losses have increased by a factor of $1.27 \pm .16$, which is barely statistically different from unity and certainly small. Thus, there appears to be little penalty in transverse losses if we choose to double the length of the Linac pulse rather than double the Linac current from the specified ¹⁴ 50 mA to 100 mA pulse to accommodate the $\sim 50\%$ chopping required for efficient longitudinal capture.

(2) In Run 33 we double the foil thickness to $\tau=600 \mu\text{g}/\text{cm}^2$ and obtain a loss increase of a factor of $1.82 \pm .22$ compared to run 38. Although the increase is not statistically different from 2, we would expect an increase less than a factor of 2; the NES losses are proportional to τ but the multiple coulomb scattering angle $\theta_{\text{mcs}} \sim \sqrt{\tau}$. The argument in favor of a thicker stripping foil is that the $\text{H}^- \rightarrow \text{H}^+$ conversion fraction improves with increasing τ - indeed, the fractional conversion loss increases by a factor of $> 10^3$ when we go from 600 to 300 $\mu\text{g}/\text{cm}^2$. The fraction of beam converted from H^- to H^+ is given by Joy²⁰ as

$$f_{H^+} = 1 - \frac{\sigma_{-10}e^{-\sigma_{01}x} - (\sigma_{01} - \sigma_{-11})e^{-(\sigma_{-10} + \sigma_{-11})x}}{\sigma_{-10} + \sigma_{-11} - \sigma_{01}} \quad (6)$$

where σ_{-10} , σ_{01} and σ_{-11} are the cross sections for the reactions $H^- \rightarrow H^0 + e^-$, $H^0 \rightarrow H^+ + e^-$, and $H^- \rightarrow H^+ + 2e^-$ respectively, and $x = (N_A/A)\tau$ with N_A = Avogadro's number and A = target atomic weight. Webber and Hojvat²¹ report that σ_{-11} is unmeasurably small (consistent with 0) for $T_H = 200$ -MeV on C^{12} and present a graph of σ_{-10} and σ_{01} vs. T_H which gives the values $\sigma_{-10} \approx 1.2 \cdot 10^{-18} \text{ cm}^2$ and $\sigma_{01} \approx 0.5 \cdot 10^{-18} \text{ cm}^2$ at 600-MeV. The conversion fractions from Eq. (6) are then (with $\sigma_{-11}=0$) $f_{H^+}(300 \mu\text{g/cm}^2) = .9991$ and $f_{H^+}(600 \mu\text{g/cm}^2) = 1 - 6 \cdot 10^{-7}$. In Fig 5 we show f_{H^+} from Eq. (6) as a function of foil thickness τ . Note that the conversion efficiency drops rapidly below $t=300 \mu\text{g/cm}^2$ so, notwithstanding the computational difficulties noted in Section II, we would probably not choose foils much thinner than $300 \mu\text{g/cm}^2$ anyway.

The argument against a thicker stripper foil is the increase in non-elastic losses. From run 38 with $t=300 \mu\text{g/cm}^2$ these are $N_{ne}=73 \pm 12$ which leads to a fractional loss $f_{L(ne)} = (3.65 \pm .60) \cdot 10^{-5}$; in run 33 with $\tau=600 \mu\text{g/cm}^2$ we got $N_{ne}=115 \pm 15$ for a fractional loss $f_{L(ne)} = (5.75 \pm .76) \cdot 10^{-5}$. The exact result should lead to a factor of 2 increase since $f_{L(ne)} \propto \tau$. This appears to be a small penalty in losses compared to the H^- conversion losses which would be avoided.

(3) A decrease in ring acceptance to $A_{x,z} = 320\pi$ mm-mrad resulted from a new lattice design²². Again, filling this ring to 50% of the acceptance we obtain for a $300 \mu\text{g/cm}^2$ foil and 600 turn injection in Run 35 a fractional loss larger than the corresponding $A_{x,z} = 400\pi$ mm-mrad case (Run 38) by a factor $1.46 \pm .21$. We would expect MCS losses to increase as the angle extent of the acceptance ellipse decreases, i.e. $\sim 1/\sqrt{A_{x,z}}$, and losses from the large angle NES events to be unaffected. Thus a loss increase greater than $\sqrt{400/320} = 1.12$ is expected. The penalty for the decreased acceptance of the new lattice is thus small.

(4) Since the 4-bump orbit deformation we propose in Section V moves the acceptance ellipse centers along the lines $x'=z'=0$ and since we propose fixing the position of the incident H^- beam on the stripper foil, we see from Fig. 3 that the ellipse will move a smaller distance between the start and end of injection and thus the bump collapse will be slower, leading to larger losses, unless the angle of the H^- beam follows the ellipse axis. In Run 39 of Table I we show a case where the H^- beam follows the $x'=z'=0$ axis for 300 turns and compare this to Run 36 where the H^- beam tracked the line $y' = -(\alpha/\beta)y$, $y=(x,z)$. The increase in fractional loss is a factor of $2.21 \pm .28$. However, this case was previously calculated as Run 31 of Table I where injected beam filled the 50% area $EB=200\pi$ mm-mrad but all particles scattered out of that 200π mm-mrad area were considered lost. This might be a more reasonable comparison because we are filling only 200π mm-mrad of the 400π mm-mrad acceptance with the expectation that particles between $EB_{x,z}$ and $A_{x,z}$ will subsequently be lost due to ring nonlinearities, instabilities, orbit deformation, etc. So, if we compare Run 31 with Run 28 to determine the loss increase penalty for not tracking the ellipse axis, the fractional loss increase is a factor $4.54 \pm .37$. Thus,

the consequence of fixing the incident H^- angle at $x'=z'=0$ could result in a significant loss increase, and we propose programming the angle of the H^- beam spot on the stripper foil with pulsed magnets as discussed in Section V. It should be noted that this additional complication from programming the H^- beam angle at the stripper foil could be avoided if an $\alpha=0$ location for the foil were provided with a lattice insertion. In the present FODO lattice these $\alpha=0$ points are at the center of the quadrupoles, which are ring apertures.

(5) Finally, we studied the effect of increasing the stripper foil area in Run 34 to a somewhat generous width of 20 mm and a vertical size of 160 mm -- adequate to accommodate the vertical size plus vertical bump motion. Such a foil could be edge-supported on a conventional fork-shaped foil holder. Also in Run 34 the H^- beam was not tracking the ellipse axis. Compared to Run 33, the combined effect of larger area foil and not tracking gives an increased loss fraction factor of 48.7 ± 4.4 . A comparison of increased losses from only a foil area increase is given by Runs 30 and 28 as a factor of $13.44 \pm .95$. In Fig. 6 we show the average number of foil traversals/proton vs. injected turn number for the large area foil case 34. Note that the traversals/proton remains large throughout the injection period for this case.

V. Layout of the Injection System

The injection straight section shown in Fig. 7 is based on the initial lattice design¹⁴ of 4.4 m length and contains a 4-dipole D-C orbit deformation (magnets B1-B4) to translate the equilibrium orbit outward by $\Delta x = 13.28$ cm. This orbit displacement is intended to move the trajectory of the incident H^- beam outward so that it will clear the yoke of the upstream lattice quadrupole QD which has a horizontal half width of 45-cm, as well as facilitate the removal of the residual unstripped H^- beam (mainly H^0) downstream of the stripper foil. The stripper foil, located at the midpoint of the straight section between dipoles B2 and B3, is in the fringing field of these magnets to provide sweeping of knock-on electrons from the foil which, if trapped by the circulating H^+ beam, would contribute a defocusing quadrupole perturbation and thus additional tune shift as well as a driving term for half-integer resonances. The layout is similar to that proposed for the European Spallation Source^{23,24}, the TRIUMF facility²⁵, and the Los Alamos LANSE-II design.²⁶

The magnetic field $B = 5.366$ kG is the field which will result in a magnetic stripping fractional loss for the H^- ions of $f_L = 10^{-4}$ in a distance of 1-m as computed from the proper lifetime τ_0 of the H^- ion in its rest frame in an external electric field $\mathcal{E}$. Scherk²⁷ gives from the WKB approximation $\tau_0 = (A_1/\mathcal{E}) \exp(A_2/\mathcal{E})$ and, from the relativistic transformation of lab magnetic field B to H^- rest frame electric field $\mathcal{E} = \beta\gamma cB$, we obtain the lab system stripping length λ_s for the ion as

$$\lambda_s = \beta\gamma c\tau_0 = (A_1/B) e^{A_2/\beta\gamma cB} \quad (7)$$

The constants in Eq. (7) have been measured²⁸ as $A_1 = 2.47 \cdot 10^{-6}$ volt-sec/m and $A_2 = 4.49 \cdot 10^9$ volt/m. The fraction of H^- beam lost in traversing a distance s in field B is $f_L(s) = 1 - e^{-s/\lambda_s}$. We can therefore relate the loss fraction f_L in distance $s = 1$ m, the field B and the H^- ion kinetic

energy E_K as

$$\left(\frac{A_1}{B}\right)e^{A_1/\beta\gamma cB} = -\frac{1}{\ln(1-f_L)} \quad (8)$$

with $\beta\gamma$ the usual relativistic factor

$$\beta\gamma = \left\{ 2\frac{E_K}{M} + \left(\frac{E_K}{M}\right)^2 \right\}^{1/2} \quad M = m_p c^2 \quad (9)$$

The transcendental Eq. (8) is solved numerically and given in Fig. 8 as B vs. E_K for several values of f_L . The value $B=3.75\text{kG}$ at $E_K=800\text{-MeV}$ in Fig. 8 for $f_L=10^{-5}$ is consistent with values used at Los Alamos²⁹.

Not shown in Fig. 7 are the fast bump magnets needed to give the exponential displacement of the horizontal and vertical acceptance ellipses as in Eqs. (3). The fast bumps consist of a pair of horizontal (H) and vertical (V) kickers in the straight section upstream of the injection straight and a similar pair of H and V kickers in the downstream straight - thereby comprising a 4-bump combination for each plane similar to the 4-bump D-C magnets. If the bump magnets have the same magnetic length, $\ell_m=0.8\text{m}$ - as the D-C magnets, then for the required angle deflection at the injection rigidity of $B\rho=4.066\text{ T-m}$ of 22.2 mrad , the required magnetic field is only $B_{\text{bump}}=1.129\text{ kG}$.

In Fig. 7 it should be noted that magnets B_1 , and B_4 are actually splitter magnets, or could indeed be two Septum magnets side by side which bend the H^+ and H^- beams in the same direction as B_1 and for B_4 , the circulating plus residual H^+ beams in opposite directions. We envision a second stripper foil immediately upstream of B_4 to strip the H^0 's that emerge from the primary stripper foil S_1 . Not shown in Fig. 7 are a pair of vertical and horizontal deflecting magnets in the primary H^- incident beam to provide the exponential time-dependent angle deflection of the H^- beam spot at S_1 so that the acceptance ellipse center X_c, Z_c will track the ellipse axes $(x', z') = -(\alpha/\beta)(x, z)$. The maximum deflection at S_1 as seen from the parameters in Figs. 3 and 7 is $x'_m=9.65\text{ mrad}$.

V. References

- ¹I. Yamane, K. Kitagawa, H. Someya and Y. Yano, KEK Report 88-8(Nov. 1988). See also I. Yamane, Proc. of ICANS-XI Int. Collab. on Advanced Neutron Sources, Vol. 1, KEK, Tsukuba, Japan, Oct. 22-26, 1990 (KEK report 90-25, March 1991) 224.
- ²G. Moliere, Z. Naturforsch. 3a(1948)78.
- ³H. Bethe and J. Ashkin, Exptl. Nucl. Phys., Ed. E. Segré (J. Wiley & Sons, Inc. 1952).
- ⁴L.N. Blumberg, H. Injection Simulation for a 5-MW Spallation Neutron Source, BAPS (Washington, APS Mtg., 18-22 April 1994); and BNL report (in preparation).
- ⁵L.N. Blumberg and F. Krausz, BNL Report 24901 (March, 1971).
- ⁶W.H. Press, B.P. Flannery, S.A. Teukolsky and W.T. Vetterling, Numerical Recipes (Cambridge Univ. Press, 1986), programs RAN2 (p. 197) and GASDEV (p. 203).
- ⁷S. Fernbach, R. Serber and T.B. Taylor, Phys. Rev. 75, 1352 (1949).
- ⁸K. Jones, Los Alamos Report LA-10064-T (1984).
- ⁹Blumberg, Gross, van der Woude, Zucker and Bassel, Phys. Rev. 147, 812 (1966).
- ¹⁰M.J. Borden, G.E. Adamson, R.N. Johnson and W.F. Nicaise, Nucl. Instr. and Meth. A303 (1991) 63.
- ¹¹M. Oyaizu, H. Muto and I. Sugai, Nucl. Instr. and Meth. A303 (1991) 59; also informal Los Alamos report PSR-92-009.
- ¹²Renberg, Measday, Pepin, Schwaller, Favier and Richard-Serre, Nucl. Phys. A183 (1972) 81; see also N.J. DiGiacomo, R.M. DeVries and J.C. Peng, Phys. Rev. Lett. 45, 527 (1980).
- ¹³Palevsky, Friedes, Sutter, Bennett, Igo, Simpson, Phillips, Corley, Wall, Stearns, and Gottschalk, Phys. Rev. Lett. 18 (1967) 1200.
- ¹⁴A.G. Ruggiero and A. van Steenbergen, BNL report 49246 (June 1993).
- ¹⁵Y. Y. Lee and L.G. Ratner, AD Booster Tech. Note 47 (June, 1986). See also M. Blaskiewicz and A. Luccio, AD Booster Tech. Note 195A (Aug. 1991).
- ¹⁶As suggested by A. Luccio (private communication, Oct. 1993).
- ¹⁷L.J. Laslett, Proc. 1963 Summer Study on Storage Rings, Accelerators and Experiments at Super-High Energy, BNL report 7534(1963), Ed. J. Bittner.
- ¹⁸H. Bruck, Circular Particle Accelerators, Inst. Nat. des Sciences et Techniques Nucléaire, Saclay, France (1966). Translation: Los Alamos report LA-TR-72-10 Rev. (1972), Chapt. XXVII.
- ¹⁹A.G. Ruggiero, AD Booster Tech. Note 104 (Jan. 1988).
- ²⁰M. Joy, Fermilab report FNAL-TM-699 (1976).
- ²¹R.C. Webber and C. Hojvat, IEEE Trans. Nucl. Sci. NS-26 (1979) 4012.
- ²²A. van Steenbergen, private communication (Dec. 1993).
- ²³G.H. Rees, Proc. of Workshop on Accelerators for Future Spallation Neutron Sources, Santa Fe, NM, Feb. 16-20, 1993.
- ²⁴V.C. Kempson, C.W. Planner and V.T. Pugh, IEEE Trans. Nucl. Sci. NS-28 (1981) 3085.
- ²⁵C.W. Planner and G.H. Rees, TRIUMF report TRI-DN-89-K98 (Dec. 1989).
- ²⁶A. Jason, Proc. of Workshop on Accelerators for Future Spallation Neutron Sources, Santa Fe, NM, Feb. 16-20, 1993.
- ²⁷L. Scherk, Can. J. Phys. 57, 588 (1979).

²⁸A. Jason, D. Hudgings and O.B. vanDyck, Proc. 1981 Part. Accel. Conf., Washington, DC (March 1981), IEEE Trans. Nucl. Sci., NS-28 (1981) 2704.

²⁹R.Macek, private communication (May, 1993).

Fig. 1. Elastic lab differential cross section, $p + C^{12}$, $E_p = 600\text{-MeV}$.

Fig. 2. Space charge tune shift vs. radius for Gaussian distribution.

Fig. 3. x - x' phase space distribution, 600 turn H⁻ injection through 300 $\mu\text{g}/\text{cm}^2$ C¹² stripper foil.

Fig. 4. Traversals/proton and proton losses vs. turn number in 300 turn H⁻ injection through 300 $\mu\text{g}/\text{cm}^2$ 10 mm x 10 mm C¹² foil at 600 MeV.

Fig. 5. H^- to H^+ conversion fraction, 600-MeV H^- on C^{12} .

Fig. 6. Traversals/proton and proton losses vs. turn number in 600 turn H^- injection through 600 $\mu\text{g}/\text{cm}^2$ 20 mm x 160 mm C^{12} foil at 600-MeV.

Fig. 7. Injection straight section for spallation neutron source with 600-MeV H^- . DC + fast bump.

Fig. 8. Magnetic stripping fractional loss for H^- ions.

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