DESIGN OF AN 8-GEV H^- TRANSPORT AND MULTI-TURN INJECTION SYSTEM*

D. E. Johnson #, Fermi National Accelerator Lab, Batavia, IL 60500, U.S.A.

Abstract

An 8 GeV superconducting linear accelerator (SCL) has been proposed as a single stage H^- injector into the Main Injector (MI) synchrotron. This could be a multi-use facility which would, among other things, support a 2 MW Neutrino program at Fermi National Accelerator Lab (FNAL) [1,2,3,4]. This paper describes a solution for a transport line which is capable of low loss transmission of an H^- beam from the linac to the MI, transverse and momentum collimation, and provides for flexible matching into the MI lattice. The required modifications to the MI accelerator complex to accommodate the transfer line, multi-turn injection utilizing carbon foil stripping (and/or potentially laser stripping), and the injection layout are discussed.

INTRODUCTION

The SCL has been designed for an initial 3 ms (ultimate 1 ms) macropulse width delivering 1.54E14 protons to the MI each 1.5 sec. for a 120 GeV MI ramp. The average linac current during a macropulse is 8.7 mA (27 mA). The beam is bunched at 325 Mhz and chopped at 325 Mhz with a 53 Mhz, and 89 khz modulation for injection into MI. This pulse produces a beam power of 131 kW at injection and 2MW at 120 GeV.

The optimization of the transport and injection system has been included in the High Intensity Neutrino Source (HINS) R&D program. Although the construction of the linac and portions of the transfer line could take place simultaneously with Accelerator Operations, the final tie-in into the MI requires an accelerator shutdown. The current effort is to optimize the transport and injection designs while minimizing the impact on civil construction and the length of the facility downtime. The selection of the footprint for the linac and the motivations and design choices for the transport line design have been described elsewhere [4,5].

TRANSPORT LINE

The transport line from the linac to the injection chicane magnet, just upstream of the foils is 1163 meters. The linac and transport line lie in the same plane MI. The geometry has been defined such that it places the linac in the southern part of the inside of the Tevatron ring, with enough real estate to the south for additional missions such as a proton buncher ring and muon target station for muon cooling experiments [6]. The location of the transport line at the interface of the MI has been chosen to minimize impact on existing structures. Figure 1 shows the layout of the linac and transport line on Fermi site.

*Work supported by Universities Research Association, Inc., under contract DE-AC02-76CH03000 and with the U.S. Department of Energy. # dej@fnal.gov

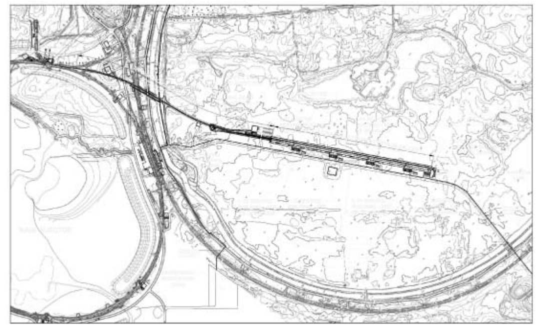

Figure 1: Linac and transfer line on FNAL site.

The transport line is made up of five sections indicated by magenta lines in Figure 2: 1) a matching straight section from linac used for betatron collimation and the upstream end of the straight ahead linac beam absorber, 2) a 2π achromatic bending section for momentum collimation, 3) a 2π straight section that could be used for betatron collimation and a bunch rotator cavity, 4) a second 2π reverse bend achromat for momentum collimation, and 5) an achromatic injection matching section.

Optics

The majority of the transport line is made up of 60 degree FODO cell structure with a 21.83 m half-cell length. The minimum and maximum beta within the FODO cell is 25 meters and 75 meters. The maximum dispersion is 6 meters. All quads are connected to either a QF or QD bus except the first four or last eleven which are used for matching to the linac and MI, respectively. The first three dipoles in the first achromat are powered independently from the main dipole bus to switch beam between the transfer line and linac dump.

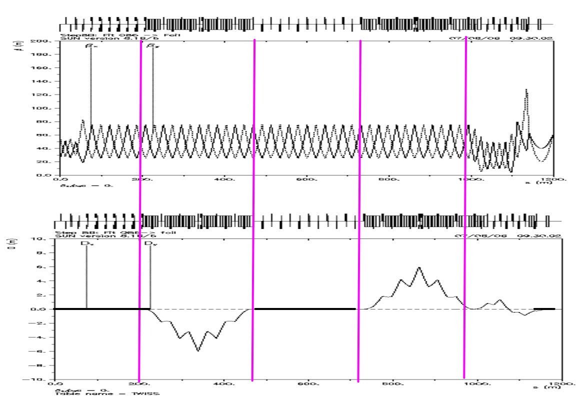

Figure 2: Lattice functions (top) and dispersion (bottom) of transfer line.

Each achromat is made up of six cells with either 2 or 3 bend magnets per cell symmetrically distributed about the center of the achromat. The injection achromat is composed 90 degree cells with a half cell length of 14.8 meters. The last two quads in the MI matching section form a D-F doublet for matching into the new MI straight section. This provides for independent control of H &V beam size and divergence at the foil.

H- Stripping Losses During Transport

The second electron of the H^- ion has a relatively low binding energy of 0.75 eV. At 8 GeV this electron becomes easier to detach because of blackbody radiation and magnetic stripping. Collisions with residual gas also contribute to uncontrolled losses. These sources of uncontrolled loss and mitigation plans were discussed at a workshop held at Fermilab in 2004 and documented elsewhere [7,8]. By keeping all magnetic fields below 550G and the addition of a LN_2 cooled beam screen will reduce both the blackbody and residual gas by a factor of ~100 so that a loss rate of ~1.7E-9/m can be maintained through out the transport line, which corresponds to a loss rate of about 3 mW/m for an intensity of 1E14 /sec.

INJECTION SYSTEM

The existing MI lattice was designed as a pure FODO lattice with six dispersion free straight sections of either 3, 4, or 8 half-cells in length. The half-cell length in the arcs and straight sections are 17.288 m. The operational tunes (H/V) are 26.425 and 25.415. The lattice functions of the current straight section are shown in Figure 3. Current injection is a bucket to bucket transfer with a horizontal Lambertson (L) and vertical kicker (K) as shown Figure 3.

Straight Section Modifications

The current straight section configuration would require the installation of the stripping foil just upstream of the quad in the middle of the straight section. This is problematic because the quad becomes the limiting aperture. Other problems include: coupling the tune adjustment to injection trajectory, fixed lattice functions at the foil determined by the standard MI lattice, and radiation dosage to the quad. In addition, the limiting dipole field (<550G) of the injection dipole does not allow the H^- injection line to clear the adjacent lattice quad.

A symmetric straight section was created by splitting the central quad and moving the halves (and increasing the quad length) outward toward the adjacent quads creating a symmetric doublet. This created a 38 meter injection straight between the inner doublet quads. The doublet, along with the inner 4 quads in the dispersion suppressor on either side of the straight, are removed from the main QF and QD quad bus and symmetrically powered using six new power supplies. These supplies must track the main ramp. The symmetric insert provides for a waist at the foil position. The values of the beta function at the foil are independently tuneable over the range of about 10 to 50 meters in each plane. One solution is shown in Figure 4. In addition, the main quad bus outside this region and the trim coils in the dispersion suppressor quads must be adjusted to maintain the machine tune and matched lattice.

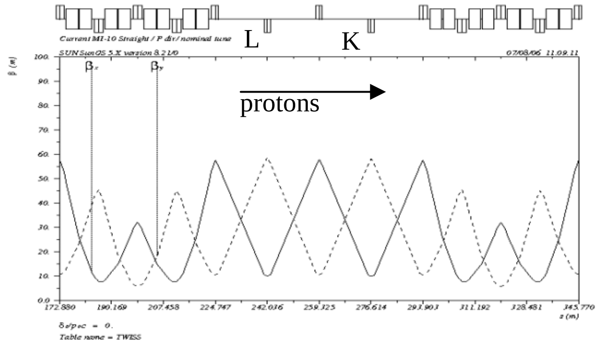

Figure 3: Current MI-10 injection straight section lattice functions.

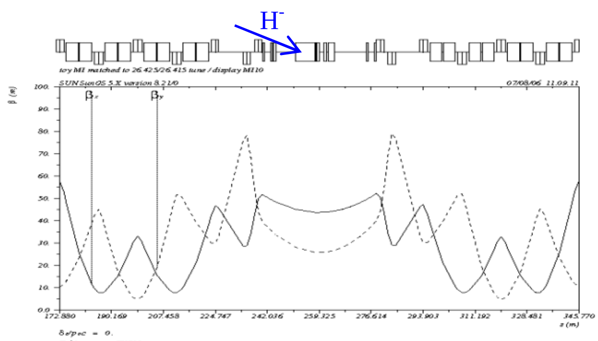

Figure 4: Proposed symmetric injection straight section.

Injection System Layout

The injection system (including injection absorber) is fully contained within the 38 meters between doublets and shown in Figure 5. A magnetic chicane (magenta magnets and curve) produces a DC 100 mm closed orbit bump and fast injection pulsed dipoles produce a horizontal closed orbit used for painting (green magnets and green/red curve). A vertical pulsed magnet in the transfer line (π upstream from foil) produces a vertical angle at the foil used for painting. The second chicane magnet (last low field dipole before the foil) is used to steer the incoming H- onto the stripping foil.

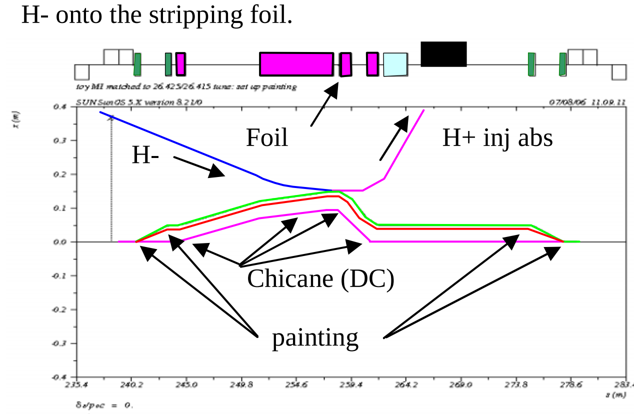

Figure 5: Layout of the injection straight section.

In an effort to minimize uncontrolled losses, the foil has been placed in the rising fringe field of the 1.2T third chicane magnet. This dipole will bend the protons created by the foil toward the MI closed orbit. Based upon the calculated lifetime of the 8 GeV H^0 Stark states [9], all states above the ground state (n>1) will be stripped within 3 mm of the foil and the protons will lie within the ring acceptance. Any H^- that miss the foil will strip immediately (3E-14 sec lab frame lifetime) and contribute to the H^0 load on the injection absorber. The last chicane magnet places the protons onto the MI closed orbit and a thick foil upstream of the magnet converts H^0 into H^+ and places them on the trajectory of the injection absorber. A single dipole in the dump line (cyan magnet) is used to steer the protons into the absorber just downstream in the MI-10 alcove (black box).

The current plan is to use a horizontal painting and vertical injection angle adjustment to produce a uniform phase space distribution [9,10]. The horizontal painting orbits are shown in Figure 5. A linac normalized transverse emittance of 1.5 π-mm-mr and a final MI emittance of 25 π-mm-mr is assumed. The start of painting (green) curve has an empty circulating phase space centered on the foil. The orbit is moved away from the foil in (initially) 270 turns and (ultimately) 90 turns to its final painting position (red). The filled MI phase space is retracted from the foil to the magenta curve in approximately 7 turns. The H^- horizontal trajectory is fixed as is the trajectory to the injection absorber. Details of the electron catcher and optimization of injected and circulating beam sizes as well as foil thickness, placement and the shaping of the chicane end fields, and painting algorithm remain.

Injection Absorber

We have investigated [11] an injection absorber design that would meet ground and surface water activation standards, prompt dose limits for external locations, and ALARA considerations for residual dosage. In addition, we wanted to minimize the impact on civil construction and avoid, if possible, the construction of an external absorber room. The main load on the injection absorber is from unstripped H^0 surviving the 3rd magnet on each injection into the MI. We consider an intensity of 5% of the full injection intensity of 1.5E14 every 1.5 sec. (134 kW) This translates into 1E20/yr. with an average beam power of ~7kW on the absorber. Of course the absorber must be able to withstand single full intensity pulse without harm. The current conceptual design is based upon a carbon core inside an aluminium cooling jacket surrounded by tungsten, steel, and marble for residual dose shielding. Figure 6 shows a MARS[12] calculation of the maximum star density in the unprotected soil as 2.7E4 star/cm^3/sec which meets standards for tritium and sodium production in unprotected soil.

SUMMARY

A revised transport line and a conceptual design for the injection region and injection absorber which minimize civil construction have been presented. The required Main Injector modifications have been described. Detailed optimization studies remain.

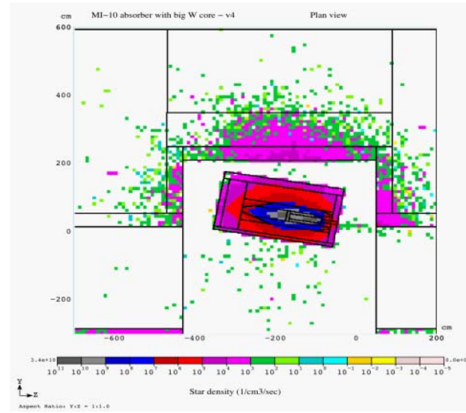

Figure 6: Mars calculation of the star density for the injection absorber.

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