CHALLENGES ASSOCIATED WITH 8 GEV H- TRANSPORT AND INJECTION FOR FERMILAB PROJECT-X *

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Abstract

The Fermilab Project X R&D program is focused on the design of a new proton source utilizing a superconducting linac to accelerate H-minus ions to 8 GeV kinetic energy for injection into the permanent magnet Recycler ring. The initial specifications[1] for the project are a 5 Hz rep-rate with a 1.25 ms pulse length and 20 mA average current which produce a modest beam power of 1 MW at 8 GeV. This beam power will ultimately provide 2.3 MW at 120 GeV from the Main Injector for the neutrino program in addition of up to 860 kW at 8 GeV for an 8 GeV physics program. The challenges faced with the transport and injection of 1 MW of 8 GeV beam power will be discussed. The topics will include uncontrolled beam losses and their mitigation in both the transport and injection processes, injection stripping options, and transverse phase space painting options. A review of the issues that have been highlighted and addressed by numerous authors will be presented

INTRODUCTION / HISTORY

In 2003, after several years of Proton Driver studies [2][3], the Fermi Long Range Planning committee endorsed the development of a Proton Driver based upon an 8 GeV H- superconducting linac. The function of the Proton Driver would be as a high intensity replacement of the aging Fermilab Proton source (Linac and Booster), provide 8 GeV protons for a 120 GeV Neutrino program, an 8 GeV Physics progrm , and serve as a 1% test bed for the ILC superconducting linac beam tests. The first H^- Transport and Injection Workshop was held at Fermilab in December of 2004. This workshop was attended by experts from 8 Universities and National Labs. The workshop concluded that although there are many challenges with the transport and injection of 8 GeV H^-, no show stoppers were identified[4]. The Proton Driver project would initially deliver 9 mA in a 3 ms pulse (or 1.5E14) to the Main Injector every 1.4 seconds to provide 2.1 MW at 120 GeV for the neutrino program. As additional klystrons became available, the linac current would increase to 27 mA in a 1ms pulse and be capable of a 10 Hz rep rate. This would still support the 120 GeV neutrino program an additionally provide 2 MW beam power at 8 GeV for other programs. In 2006, due to the impending fast track status of the ILC, Proton Driver effort was directed toward the most technically challenging aspect of the project, the front-end linac for the project. An R&D program was established to build a 90 MeV H^- linac utilizing a single klystron and vector modulators to control multiple warm and superconducting cavities. [5] The R&D effort on the front end continued under the High Intensity Neutrino Source program. Several MOU's were established with LBNL , Argonne, and BNL for the design of buncher cavities, electron cloud calculations, continued linac design, transport line review, H^- injection optimization, and the construction of a laser wire profile monitor for the HINS project, etc.

In an effort to provide an intensity frontier physics program at FNAL in the era between the end of the Tevatron Collider Run II and the turn on of the ILC and the contribute toward the fast track industrialization of superconducting RF cavity production, Project X was introduced in mid 2007, and endorsed by the Accelerator Advisory Committee. The new Project would utilize ILC cryo modules and power couplers at the 31.5 MV/m gradient and would accelerate 9mA of H^- beam current in a 1ms pulse at a 5 Hz rep rate. This would produce 360 kW of beam power at 8 GeV. The lower beam current meant that three linac cycles would have to be accumulated to reach the MI intensity requirement of 1.5E14 per MI cycle. To accomplish this, the Recycler would be used as a H^- stripping and accumulation ring, requiring 3 linac cycles for single turn injection into the Main Injector rather than direct injection into the Main Injector as in the Proton Driver scenario. This would leave 200 kW 8 GeV beam power for an 8 GeV Physics program.

In November 2007 Fermilab held a Project X Accelerator Physics workshop with 175 people from 28 institutions. [6]

In mid- 2008, the Project X team was encouraged to investigate alternative configurations that maintain the "ILC like" cryo- modules, but not restrict the linac current to 9mA as had been required in the previuos incarnation. By increasing the linac current to ~20 mA and the beam pulse length to 1.25 ms at the same 5 Hz rate, the 8 GeV beam power is increased to 1 MW, with the option of upgrade to 2 MW. In addition, the required gradient has been relaxed from 31.5 MV/m to 25 MV/m to facilitate existing cavity technology. The Recycler is still to be used as a stripping ring. With only a single linac cycle required for 120 GeV neutrino program from the Main Injector, the Recycler would immediately transfer the beam into the MI after the 1.25 ms injection period. This leaves 6 linac cycles (860 kW) available for an 8 GeV Physics program, assuming a 1.4 sec MI cycle time.

DESIGN CHALLENGES

Project X is a large project which must be integrated into an existing facility. This places a number of design

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constraints on the accelerator systems and civil construction that might not be present in a "green-field" design. The design must match into constraints imposed by existing accelerators (which might include upgrades) such as injection energy, bunch structure, and transverse and longitudinal acceptance. When expanding an existing facility with an operational control system, the design team must consider the integration of the new facility into the existing system, converting the entire complex to a more modern system, or something in between. The design must have a footprint which meets the accelerator design goals but minimizes impact to the existing infrastructure, including existing service buildings, underground tunnels, and existing service utilities. The design must also allow for upgrades and expansion for future facilities which would utilize its beam power, for example, a neutrino factory or muon collider. Figure 1 shows the current footprint on the Fermilab site inside the Tevatron ring. The injection point into the Recycler is at the 10 straight section, indicated by the red circle.

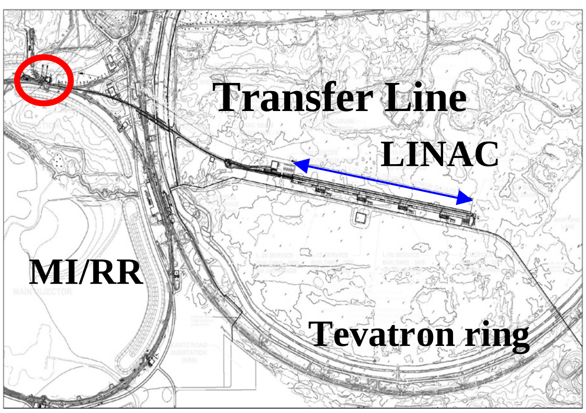

Figure 1: Current footprint of the Project X linac and transfer line relative to the Tevatron, Main Injector and Recycler.

At the Conceptual Design level of Project X, the overall project requirements are defined and the major systems are developing physics and engineering designs and operational parameters which will meet or exceed the project requirements. Sub-system requirements will be developed and designs initiated. During this stage the initial component requirements and specifications will be defined at a level where an initial cost range may be estimated.

Although there are many design and engineering challenges associated with all components of Project X, [i.e. the front end linac, the superconducting linac, RF distribution, cryogenic fluid distribution and other utilities, the high intensity operation of both the Recycler and Main Injector, and the civil construction, plus the integration of the facility into an existing complex] this report concentrates on the design and engineering challenges associated with transporting 8 GeV H^- ions, along almost a kilometer of transport line, and their injection into the Recycler. The transport line system and the injection system will be treated separately in the text. In each of these systems, the design team faces both physics and engineering challenges, which at times are intertwined and require optimization.

The major challenges with the transport line are concerned with beam loss control and the implementation of an efficient collimation system. This does not imply that these are (or will be) the only engineering challenges faced in the transport line design, but none are envisioned to be technical show stoppers. In addition, the optical design is assumed to be robust and function according to design, so does not pose a technical risk.

The major challenges in the design of a multi-turn 8 GeV H^- charge exchange injection system are

- the design of an injection straight section in the ring which is decoupled from the ring tune system, provides enough space for the injection system, provides adequate physical aperture, and is optically flexible,
- the design of a system that will efficiently convert the H^- into H^+, with minimal losses in the injection region due to injected or circulating beam, and create the desired phase space,
- the design of an efficient waste beam collection system.

It is clear that each of these systems contain physics design issues such as the magnitude and longitudinal distribution of the transverse magnetic fields and the impact on the H^-, H^+, and H^0 ions or the temporal structure of the injection closed orbit, and engineering issues such as the design of the foil changing and electron catcher system or power supplies which generate the required temporal fields in the painting magnets. All of these systems must be seemlessly integrated together to satisfy the project requirements concerning energy, intensity, final transverse emittance, longitudinal emittance, all within the defined loss budget. Although there are significant technical design challenges associated with each of these components, the complete system design or integration task provides a unique challenge. The remainder of the report will discuss some of the technical issues and indicate how these issues are being addressed.

TRANSPORT DESIGN CHALLENGES

The transport line is required to cleanly transport 8 GeV H- ions from the linac to the injection stripping foil with specific, but flexible, beam parameters at the foil that are required for matching into the Recycler and optimized for phase space painting. In addition, the transport line must be able to: 1) protect the Recycler from linac pulses outside the energy acceptance of the ring, 2) provide efficient transverse collimation of large amplitude particles, 3) provide a capability for pulse-to-pulse energy correction, and 4) provide a flexible lattice for beam characterization and matching.

The phrase "cleanly transport" may be interpreted as low loss. Any beam loss poses risks from prompt radiation in adjacent uncontrolled areas and the residual activation of accelerator components. There are multiple ways to mitigate prompt radiation in uncontrolled areas with enclosure shielding, electronic detectors, and administrative access controls, etc.. The activation of components relate directly to beam loss interacting with accelerator components. A residual activation of 100 mrem/hr at a foot has generally been accepted as a level where extraordinary controls are not required for maintenance [7].

A general guideline for a uniformly distributed beam loss has been reported as 1 watt/m [8], however, for 8 GeV beam, it has been shown that 1 watt/meter loss rate corresponds to a residual dose rate of ~ 400 mrem/hr at a foot on a bare beam tube (such as magnet interfaces and straight sections) and 10 to 30 mrem/hr at magnet locations [9]. In order to reach a residual activation of 100 mrem/hr at a foot the beam loss rate must be limited 0.25 w/m. However, following the radiological control practice of As Low As Reasonably Achievable, ALARA, we have adopted a philosophy to reduce this by a factor of five or more to a maximum of 20 mrem/hr which leads to a loss rate of 0.05 w/m on a bare beam pipe and 0.6 to 2 w/m inside a magnet. Therefore, if we restrict ourselves to a maximum uncontrolled loss rate of 0.05 w/m, which will guarantee a maximum residual dose rate at a foot of 20 mrem/hr or less.

Loss Mechanisms

Beam loss can be characterized as controlled or uncontrolled beam loss. The controlled beam loss refers to intentional beam loss due to transverse or longitudinal collimation or waste beam disposal. Here, large amplitude or off momentum particles are lost in a controlled fashion and disposed of in a well shielded absorber. Similarly, waste beams, from the injection process are steered cleanly into a well shielded injection absorber.

Uncontrolled beam losses fall into two categories, multiparticle and single particle beam loss mechanisms. The multiparticle beam loss mechanisms are due to steering, focusing, or alignment errors and are assumed to be mitigated by careful optics design, aperture design, and component alignment and will not be discussed here. Single particle loss mechanisms are those which have a finite probability of electron detachment during the transport process. These processes give rise to almost a uniform loss throughout the transport line and determine the background residual activation. Since the second electron of the H^- ion is bound by only 0.75 eV, care must be taken not to detach this electron from the ion during transport, creating H^0 to be lost in the transport line. Three processes have been identified [4] as sources of single particle loss. Photodetachment of the outer electron by Blackbody radiation inside the beam pipe, collisional detachment due to the residual gas atoms, and detachment due to a potentially large electric field in the ions rest frame generated by the ions motion through a transverse magnetic field. Many authors have discussed these processes, their impact on the transport of 8 GeV H^- ions, and parameter choices for transport line design [10][11][12] . This report discusses the current selection of design parameters intended to mitigate the losses from single particle interactions.

Blackbody Radiation

During the preparations for the Proton Driver H- transport workshop, an important source of H- stripping was uncovered [13][14]. The room temperature beam pipe is filled with a Blackbody spectrum of thermal photons with typical energies of kT ~0.05 eV. Since the binding energy of the electron in the H- ion is 0.75 eV, negligible number of Blackbody photons are available to strip the H^-. However, since the H^- is traveling at relativistic speeds, the Blackbody photons are Doppler shifted to a higher energy such that they overlap the photodetachment cross section of the H^- in its rest frame, and the probability for stripping becomes non-negligible. Figure 2 shows the room temperature spectral density of the Blackbody photons, the spectral density of the Doppler shifted photons for 1, 4, and 8 GeV along with the photodetachment cross section for H^- [15].

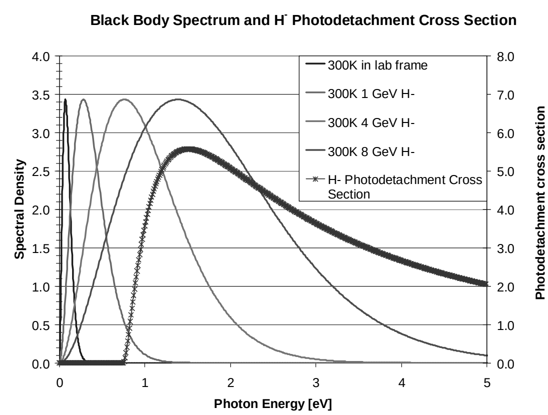

Figure 2: Spectral density of 300K Blackbody photons in H- rest frame and the spectral density shifted into the rest frame of 1, 4, and 8 GeV H^- ions as a function of photon energy.

Calculations of the photodetachment rate and fractional beam loss have been reported by C. Hill [13] and H. Bryant [14] and replicated by J. P. Carneiro [12] for implementation into the beam tracking code TRACK[16]. Figure 3 shows the results of the calculation for three energies, 1, 4, and 8 GeV as a function of beam pipe temperature.

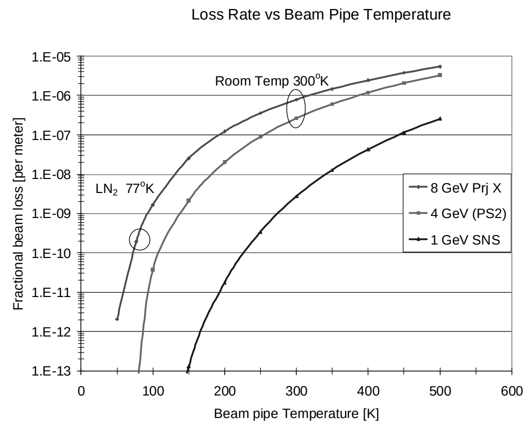

Figure 3: Loss rate as a function of beam pipe temperature for 1, 4, and 8 GeV H- ions.

From Figure 3, it can be seen that at room temperature the loss rate due to Blackbody stripping at 1 GeV, 4 GeV, and 8 GeV is ~3E-9, ~2E-7, and ~ 8E-7/meter, respectively. At 8 GeV and room temperature, this will turn out to be the dominant single particle loss. Cooling the internal beam pipe as suggested by several authors [4][11][12] can reduce the loss rate by up to a factor 4000. Currently, we investigate the temperature reduction to 77° K which drops the loss rate to ~2E-10/meter, and the effect once again becomes negligible.

Residual Gas

The most important residual gas interaction for a negatively charged ion, H^-, is electron loss [17] . The loss rate/meter is proportional to the molecular density and the ionization cross section of the various molecules in the residual gas. The molecular density is a function of temperature and pressure. It has been shown that the electron loss cross section can be scaled by $1/\beta^2$ [18][19] [12]. The loss rate can thus be predicted by determining the residual gas make up within the beamline for a given vacuum level (pressure) and temperature. The challenge will be to create a beam tube vacuum in the low 10^{-8} to 10^{-10} torr range. This is routinely accomplished in the Tevatron with a cold beam tube.

Magnetic Field Stripping

A energetic H^- ion moving through a transverse magnetic field is subject to an intense electric field in it's rest frame given by

$$E = \gamma(\beta c)B$$

where B is the transverse field and β and γ are the usual relativistic parameters. If the electric field in the ions rest frame is strong enough it can strip the weakly bound electron. This will be important in both the transport region, where we don't want to strip the electron and in the injection region where we will purposefully strip the outer electron over a short distance. In 1979 Sherk[20] published an expression for the rest-frame lifetime of a negative ion in a weak and static field given by

$$\tau_{rest} = \frac{a}{E} e^{\frac{b}{E}}$$

where both parameters a and b are functions of the electron affinity. Sherk "utilized lifetime measurements at 50 MeV [21] to improve the empirical of the electron affinity of the negative hydrogen by an order of magnitude"[20].

Two additional experimental investigations [22][23] have measured the lifetime of 800 MeV H^- in a range of transverse magnetic fields corresponding to rest-frame electric fields 1.87MV/cm to 6.7MV/m. Using the parameterization above, the data were fit and the values of a and b reported. The latest measurement by Keating, et.al obtained parameters a=3.073E-6 V-s/m and b=4.414E+9 V/m. Of interest is the loss rate per meter, which is given by

$$\frac{1}{L} = \frac{1}{(\beta c)\gamma\tau_{rest}}$$

where γ τ(rest) is just the lab frame lifetime. This parameterization has been installed in the program TRACK. Using these parameters, Figure 4 displays the loss rate as a function of the rest-frame electric field.

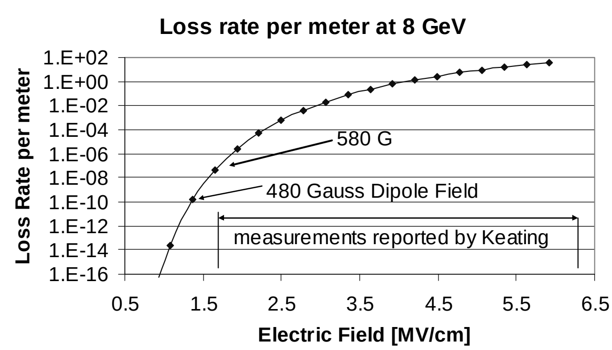

Figure 4: Loss rate per meter for as a function of the rest-frame electric field generated by an 8 GeV H- ion moving in a transverse magnetic field. The region covered by previous measurements is shown.

Although there have never been any measurements of the lifetime in a magnetic field for H^- ions above 800 MeV, the electric field generated by the proposed dipole field of 480 Gauss is 1.36 MV/cm, just outside the low field region of the previous measurements. The loss rate for the proposed field is only 1.4E-10 per meter. This field was utilized in laying out the footprint shown in Figure 1.

Single Particle Loss Summary

By utilizing a cold beam screen inside the beam tube, setting the requirements for the vacuum level a 1E-8 torr or below, and restricting the dipole magnetic field to under 500 Gauss we can mitigate the single particle loss issue. The loss distributions due to the single particle processes may be simulated using the tracking program TRACK. Table 1 shows the loss rate and watts/meter for each of the three processes for 1 MW with and without the cryo beam shield.

Table 1: Summary of Single Particle Loss

loss mechanism	1MW		1MW with shield	
	$[m^{-1}]$	[w/m]	$[m^{-1}]$	[w/m]
Black body (@300K)	8.00E-07	8.00E-01	1.90E-10	1.90E-04
Residual Gas (A150 10^{-8} torr)	1.30E-08	1.30E-02	5.2E-08	5.20E-02
Magnetic (500 G)	1.30E-10	1.30E-04	1.30E-10	1.30E-04
Total	8.13E-07	8.13E-01	5.23E-08	5.23E-02

As can be seen in Table 1, for 1MW beam power, the loss rate for Blackbody dominates , the Lorentz stripping or vacuum loss. The total loss rate for the room temperature beam pipe is 0.8 watts/meter, sixteen times larger than the desired level of 0.05 watts/meter. Keeping the design magnetic field and vacuum level and adding a 77^{o}K beam shield the loss is reduced to 0.052 watts/meter.

It's clear that these design choices will impact the choice of dipole design and require a beamtube with cryo shield. The vacuum system design must now include an insulating vacuum as well as the beam tube vacuum. The level of engineering required is significant and the system will certainly be more complex, but an initial investigation did not reveal any show stoppers.

Transverse Collimation

Transverse collimation is utilized to capture large amplitude particles, halo, created in the linac that might be lost in the transport line, injection system or in the ring. The amount beam emittance dilution and halo production may be predicted by simulations and is determined by linac beam current, phase and energy errors, space charge, and linac matching, etc. However, reality does not always match the simulation results. This fact alone suggests the necessity of a flexible collimation system which is capable of accomodating whatever phase space and halo is produced in the linac.

Project X is adopting a 2 stage collimation system design utilized by the SNS which includes a thick carbon stripping foil upstream of a quadrupole to intercept large amplitude H^- ions, strip both electrons creating H^+. The downstream quadrupole bends the protons in the opposite direction from the H^- thus creating a separation at a downstream absorber [24][25]. It is critical that the H^+ generated by the collimation foils be absorbed in the downstream absorber with a significant impact parameter so that they do not scatter back out into the aperture to be lost elsewhere downstream. The separation between the H^+ and H^- at the downstream absorber is proportional to the quad gradient, the offset of the stripping foil, and initial trajectory. In the Project X design we adopt the philosophy of an adjustable absorber aperture, in addition to the adjustable stripping foil, so that we have control of the H^+ impact parameter on the absorber face depending on the required amount of collimation (i.e. foil offset from the beam centroid). Although this design philosophy leads to a more complicated engineering design, it is important to maintain this flexibility. There are currently 3 horizontal and 3 vertical foil/absorber pairs separated by 60 degrees to give complete phase space coverage. The current specification is that each foil/absorber pair should be able to take up to 1% beam load, although the expected load should be closer to a few tenths of a percent. For the initial linac power of 1 MW , this corresponds to 10 kW. The design of the collimator system provides an engineering challenge to provide the required heat removal and radiological shielding. The program MARS is utilized for shielding calculations and ANSYS for thermal design

Project X is utilizing the multi-particle tracking program TRACK feature for tracking multiple charge states through the entire collimation system. The design of the system and movable absorber are part of the current Project X R&D effort.

INJECTION DESIGN CHALLENGES

The design challenges associated with injection of 8 GeV H^- into an existing ring are to be able to create an efficient conversion of H^- into H^+ with minimal losses, minimal halo production, minimal waste beam, and create a final phase space distribution at the desired intensity which is consistent with the physical and dynamic aperture of the ring

Even though Project X is in the Conceptual Design stage (pre-CD0), the injection region design may be adapted from the design effort for injection into the Main Injector in the Proton Driver project. [26][27]. Because the ring lattice of the Recycler mirrors that of the Main Injector, modifications to the Recycler injection straight and ring lattice are reasonably straight forward and are determined utilizing the design code MAD. Of central importance is the creation of a symmetric straight section where the entire injection system may be installed between a quad doublet on either side of the straight section.

The central feature of the injection system is a dipole chicane as shown in Figure 5. This shows the four chicane magnets (H1-H4) used for:

- setting the injection closed orbit, placing the injected H- onto the stripping "foil" (here the term "foil" is used in a generic sense as the point where both electrons are stripped off the H-, regardless of the process),

- transporting the waste beam from the stripping "foil" to the thick secondary foil for creating protons going to the injection absorber,
- and closing the newly created protons back onto the closed orbit.

As discussed in the transport section, we don't want to strip the outer electron off the H^- until the "foil", so the fields before the "foil" must be low. On the other hand any of the H^- that miss the "foil" we would like to strip (turn into H^0) as close to the "foil" as possible which means that the field map between H2 and H3 is critical. Similarly, any of the H^- that doesn't get completely stripped in the "foil", exists in an excited state of H^0. These excited states are split into Stark states by the presence of magnetic field between H2 and H3. The decay rate of these states are dependent on the magnitude magnetic field they transverse. Therefore, the field after the "foil" must be taylored not to allow the decay of the excited states such that the resultant protons fall outside the acceptance of the ring to create losses in the injection region or elsewhere. In addition, the magnitude and orientation of the magnetic field at the foil should guide the stripped electrons into an electron catcher safely out of the aperture.

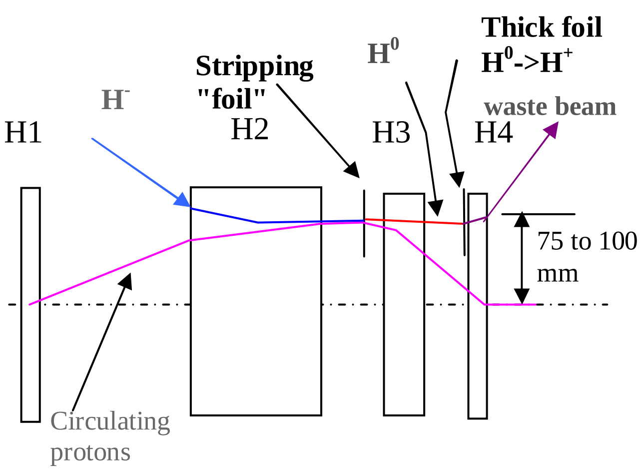

Figure 5: Cartoon of the proposed Project X injection chicane dipoles along with the location of the stripping "foil" and the predicted trajectories of the H^-, H^0, and H^+.

The configuration [25] under investigation for Project X has the foil on the midplane in the rising end field of H3 at a field of about 600 G. The peak field of H3 is 5.5 kG, between the n=2 and n=3 Stark states[25], which mean that the excited states for n=1 and 2 will not be stripped until the secondary thick foil. Tayloring the end field of this magnet will be critical in controlling losses. The field should rise such that when the n=4 and n=3 states are stripped, the resultant protons still lie within the acceptance of the ring. Taking guidance from SNS experience a full 3D model [27], e.g. in OPERA 3D, of the injection chicane and foil with a realistic field map should be generated to evaluate trajectories of H^- that miss the foil and the excited states as they decay.

Phase Space Painting

Due to the small transverse emittance of the linac beam, phase space painting during multi-turn charge exchange injection is utilized to increase the phase space density of the circulating beam. This painting is accomplished by moving the closed orbit (horizontal, vertical, or both) relative to a fixed injection point in transverse phase space during the injection period (112 turns in the case of Project X). This leads to a temporal function of the closed orbit , and potentially the injection angle, during the injection period. There have been many investigations as to the functionality of the painting algorithms[29][30] and the resultant phase space, particularly in the presence of space charge[31] for various facilities.. The ultimate selection of painting algorithm depends on the desired properties of the final phase space, i.e. gaussian, uniform distribution in x or y, the aperture of the accelerator, and the aspect ratio of the physical aperture, etc..

Project X is injecting into an existing ring with a physical aperture of 96 mm by 44 mm with a coupled lattice. Note: a "green-field" site would potentially have greater flexibility on the aperture and ultimate painting scheme. The vertical aperture, to first order, limits the ultimate phase space emittance of the beam in the ring due to choices of operation tune. Due to the "small" vertical aperture and the desire to keep the vertical closed orbit on the median plane in the injection region, the design in concentrating on painting algorithms which move the horizontal closed orbit x(t) and the vertical injection angle y'(t) keeping the vertical position on the "foil" fixed. Both correlated and anti-correlated waveforms as well as various time dependences are being investigated as part of the current Project X R&D effort.

Project X has utilized the tracking program STRUCT [32] to investigate various painting algorithms, the resultant phase space, and impact of the circulating beam "hitting" the injection foil. This program tracks an ensemble of injected phase space starting at the entrance to the foil on a turn by turn basis. It utilizes a description of the ring lattice which includes all electric and magnetic fields of physical elements and well as physical apertures and includes proton-foil interactions (from MARS), however, it presently does not include space charge effects. In a high intensity machine where the phase space is filled to the space charge limit, this must be included. The Project X design team is currently implementing the injection system into the particle tracking code ORBIT [33], which can include space charge effects as part of the Project X R&D effort. Utilizing both STRUCT and ORBIT for injection simulations will allow Project X design team to benchmark the codes and give us better confidence in the design.

H^- Stripping (Charge Exchange and Laser)

For the conversion of H^- into H^+ in a multi-turn charge exchange injection system, both electrons must be removed from the H^- ions over a short path length. A common technique for multi-turn H^- injection into a ring has been the use of thin carbon foils to collisionally detach both electrons. This suffers from the fact that both the injected beam and the circulating protons interact with the foil creating losses and foil lifetime issues. This is currently the default technique being investigated.

A technique of H^- stripping which avoids a physical foil and its associated issues involves the photodetachment of the electrons by various processes has been proposed and investigated [34] [35] [36] [37]. All schemes involve the basic three step process of: 1) creating H^0 via Lorentz stripping, H^- --> $H^0 + e^-$, 2) promoting the electron from the ground state to an excited state of H^0 via interaction with a photon from a laser, $H^0 + h\nu$ --> $H^0(n)$, and 3) subsequent Lorentz stripping of the excited state into protons, $H^0(n)$ --> $p + e^-$. The photon energy required to boost an electron from the ground state to the n=3 state in the H^0 rest frame is 12.1 eV. A proof-of principal demonstration has been performed [38] at SNS which produced "around 90%" conversion of H^- ions into protons in a small time slice of the linac pulse. The demonstration was carried out in the linac dump line with the H^- energy of "around 900MeV". A dipole field Lorentz stripped the outer electron, creating H^0 in the ground state. A third harmonic of a Q-switched Nd:YAG laser (i.e. 355 nm) crossed the H^- beam at an angle of 20 degrees which Doppler shifted the photons to an energy of 12.4 eV to promote the electron to the n=3 which were stripped in the downstream magnetic field. Plans for a full scale follow up test are underway at SNS [39].

The attractiveness of this technique in Project X is the removal of the charge exchange foil to mitigate the issues of beam loss and foil survival. Due to the higher energy H^- beam, Project X can utilize the fundamental Nd:YAG wavelength of 1064 nm, which when Doppler shifted to the H^- rest frame at an angle of approximately 80 degrees boosts the photon energy to 13 eV. Investigation of this technique and the expected efficiency and technical details is in the current R&D plan. The goal is to create and injection system, as described above that would be compatible with either foil charge exchange or laser stripping.

There have been several theoretical [40][41][42] and experimental investigations on the collisional detachment of electrons from and the formation of excited state H^0 ions and H^+ ions when relativistic H^- interact with thin foils up to an energy of 800 MeV. As the H^- energy of Project X is an order of magnitude larger, there has been concern about extending the predictions from the lower energies to predict the efficiency of creating H^+ and excited H^0 states at 8 GeV. Experimental measurement of electron loss cross sections exists at 200 MeV [43] and 800 MeV [44]. Fermilab hopes to soon measure the electron loss cross section at 400 MeV in the Booster. The electron loss cross section for fast H^- incident on H and He scales as $1/\beta^2$ [17]. Chou notes that "the physics governing foil stripping and residual gas stripping is the same". He utilizes the measured cross sections for 800 MeV and scales them to 200 MeV, 400 MeV, and 8 GeVand notes good agreement between the scaled and measured 200 MeV data. A theoretical description of the formation of excited states of H^0 based upon a "relativistic generalization of a previuosly developed classical transport theory" has found that the population fractions are only a function of the ratio of the foil thickness to the total mean free path between collisions. [42] They report that the scaling fails for large thickness as the magnitude of the energy an momentum transfer becomes dominant and leads to a higher degree of ionization. Figure 6 plots the calculated charge states at 800 MeV as predicted by Gulley along with the relativistic calculations at 800 MeV and 100 GeV as a function of thickness/mean free path (number of collisions).

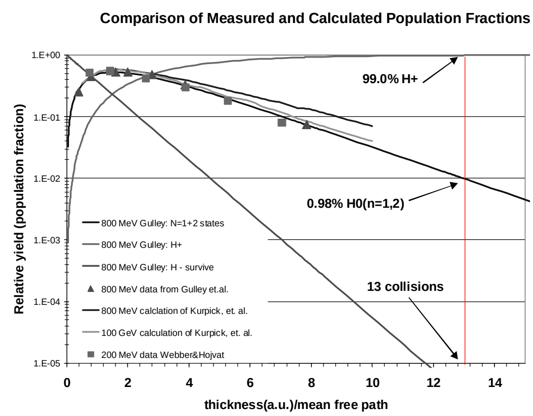

Figure 6: Comparison of calculated charge state fractions using Gulley's 800 MeV cross sections

Also plotted are the data at 200 MeV and 800 MeV which agree to both descriptions for a small number of collisions. In this plot the energy dependence is in the mean free path. For the Project X a 500 $\mu g/cm^2$ foil would experience approximately 13 collisions with ~1%H^0 produced.

Injection Losses

Losses during the injection process are due to either the interaction of the first turn H^- or circulating protons with the foil atoms. Various process contributing to beam loss and halo formation have been identified [45]. Nuclear collisions with the foil atoms result in a hadronic shower impacting the components immediately downstream of the injection foil. One MW beam power at 8 GeV corresponds to 8E14/sec injected (i.e. 1.6E14 at 5 Hz, the full linac output). With 4 to 5 hits per injected proton and the probability of a nuclear interaction of 8E-6 for a 500 $\mu g/cm^2$ foil, the number of nuclear interactions/sec could reach upwards of 3E10/sec. Two issues related to the magnitude of component activation are residual activation and component lifetime. The radiation dose to the coils of the component downstream of the stripping foil is to be evaluated using MARS or a similar code that can determine energy deposition and absorbed dose. Large angle single Coulomb scattering of the proton passing through the foil contributes to particle loss and halo formation. These and other interaction mechanisms are or will be included in the simulation codes STRUCT and ORBIT.

Injection Foil Issues

The lifetime of the carbon stripping foil is strongly dependent on the peak foil temperature and the mechanical stress due to periodic heating. The temperature rise is due to the energy deposition as the injected H- (proton and two electrons) pass through the foil. The peak temperature distribution is strongly dependent on the injected beam sigma. Circulating beam hitting the foil produces a more uniform increase in the foil temperature. Various authors have developed models to predict foil temperature and lifetime.[46][18]. An initial investigation for the Proton Driver study found that for 1.5E14 injected over 1 ms and 4 circulating beam hits/proton at a 1.5 sec. rep rate, the peak temperature ranged from ~1100^{o}K for 2mm beam sigma to ~1900^{o}K for a 1mm sigma. Increasing the rep rate to 10 Hz increased the peak temperature by about 10%. [27] A mechanical stress analysis (in ANSYS) for the Proton Driver observe displacements ~100 times the foil thickness.[19] This is clearly an area that needs additional study for Project X.

Foil types, composition, production methods, lifetime tests are being actively investigated at KEK [47], SNS[48], and TRIUMPH, and LANL. Fermilab is actively testing diamond-like foils from TRIUMPH and HCB foils from KEK in the 400 MeV Booster. [18]

The foil size, foil orientation in the accelerator, the foil support design, the foil thickness, and foil type are all interrelated. The challenge for Project X will be to incorporate beam requirements with tracking simulations from the linac to the injection foil, utilize the phase space of the injected H^- (TRACK) and the phase space from the circulating beam (ORBIT, STRUCT) which interacts with the foil to study the foil heating and mechanical stress (ANSYS). Details on the orientation and foils size and support must also be taken into account. It appears that foil technology is healthy and Project X needs to utilize the vast knowledge base and existing simulations.

Waste Beam Disposal

H^- ions that miss the injection foil or excited states of H^0 that do not strip must be turned into protons by a secondary foil for transport to the injection absorber. Although the expected stripping efficiency of the "foil will be 98 to 99% and we expect no more than 1% missing the foil, the injection absorber is designed for a routine 10% of the maximum injection intensity. Based upon the experience at SNS, the importance of controlling the trajectories of waste beam through the injection absorber transport line was emphasized. This led to the current concept of minimizing the difference in the angular trajectories of the H^- missing the foil and the H^0(n=1,2) produced in the foil by minimizing the longitudinal distance where the H^0 are formed by each process. This, coupled with the short distance to the foil and injection absorber and a large beam pipe aperture, should minimize losses along the transport line. The tracking code TRACK will be utilized to simulate the different trajectories for waste beam disposal.

Radiological and thermomechanical requirements for the previous Proton Driver project have been established.[49] The requirements for Project X are more demanding in that this project assume that all linac pulses will be delivered to the Recycler at 5 Hz with a total of 1 MW beam power. The current assumption is that the injection absorber should be designed for a routine 10% of the maximum injected beam power. This figure has a safety factor of 2 to 3 with respect to the expected waste beam intensity. In addition, the absorber must be designed to handle some number of full intensity pulses without any damage to the absorber of accelerator.

The current Project X R&D effort is investigating absorber core designs and materials in an effort to design a robust absorber core that will meet or exceed requirements. Radiological shielding design will soon follow and be based on the calculations for Proton Driver.[48]

SUMMARY

Project X continues to evolve in terms of the beam requirements and functionality. The evolution of the differing beam requirements and assumptions play an important roll for the transfer line and injection designs for Project X.

Two issues in the transport of 8 GeV H^- were addressed, one of single particle beam loss and the other concerning transverse collimation. With the proper design choices the single particle loss mechanisms may be mitigated. Significant engineering effort will be needed for both issues.

The following topics were addressed in the discussion of the injection system, 1) the general design of the current layout, 2) phase space painting, 3) H- charge exchange foils, 4) laser stripping, 5) injection losses, 6) injection foil issues, and 7) waste beam disposal. Due to all the issues with charge exchange foils, Project X continues to investigate laser assisted H^- stripping and watching closely the progress at SNS. There are many engineering challenges to be able to meet the design requirements of Project X. The largest challenge in the design of the injection is the integration of the facility into the Fermilab complex.

Conceptual designs for Project X transport and injection are well underway and some engineering for the various component systems have been initialized. There is, however, significant work remaining in physics design and engineering for both the transport systems and injection systems. The most challenging aspect will be the integration of these systems into the Fermilab complex. There is a significant amount of knowledge base due the new facilities that are being designed and the existing facilities in operation. The field of high intensity "Proton Drivers" is active and robust and Project X needs to utilize this vast knowledge base. In addition, there have been many advancements in the area of design and simulation codes MADX, TRACK, STRUCT, ORBIT, etc.. Project X plans on utilizing these codes (and others) to aid in the design and optimization of the various parameters to assure a robust design.

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