TRANSFER LINE DESIGN FOR PIP-II PROJECT*

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Abstract

The recent U.S. Particle Physics Community P5 report encouraged the realization of the Proton Improvement Plan II (PIP-II) project to support future neutrino programs in the United States. PIP-II includes the construction of a new 800 MeV H^- Superconducting (SC) Linac at Fermilab and an upgrade of its current accelerator complex mostly focused on upgrades of the Booster and Main Injector synchrotrons. The SC Linac will initially operate in pulsed mode at 20 Hz. The design should be compatible with upgrades to CW mode and higher energy. A new transport line will connect the Linac to the Booster. This line has to provide adequate collimation and be instrumented for beam parameter measurements. In addition, to support beam based Linac energy stabilization, the line should provide a mechanism to redirect the beam from the dump to the Booster within one pulse. In this paper we present the design of the transport line developed to meet the above requirements. Tracking simulations results are reported to confirm the validity of the design.

INTRODUCTION

PIP-II [1] immediate goal is to provide more than 1 MW of beam power on the target at the start of LBNF operations [2], maintaining the flexibility of the Fermilab accelerator complex necessary to support long-term neutrino physics and being cost-effective. The main limiting factor for an increase of beam power to LBNF is the current Linac/Booster system. Increasing the injection energy from the current 400 MeV to 800 MeV, together with some modifications in the existing Booster, Recycler and Main Injector, would allow higher beam intensity and power. To provide the 800 MeV proton beam, PIP-II assumes the construction of a new SC Linac operated in pulsed mode but built with CW-capable accelerating structures and cryomodules, minimizing the cost of a future upgrade to CW mode. The SC Linac will accelerate a 2 mA H^- beam, requiring a multi-turn strip-injection in the Booster. The repetition frequency will be 20 Hz and the beam duty factor of 1.1%.

TRANSFER LINE DESIGN

The siting of the SC Linac has been selected because of its proximity to existing electrical, water and cryogenic infrastructure and the possibility it offers for future development. To connect the end of the Linac to the injection position in Booster a new beam line has been designed. Figure 1 shows a layout of the Fermilab site together with the existing beam lines. In green the footprint of the PIP-II SC Linac and Transfer Line are presented. In cyan the footprint of the alternate design is shown. The alternate design is around 24 m shorter than the baseline.

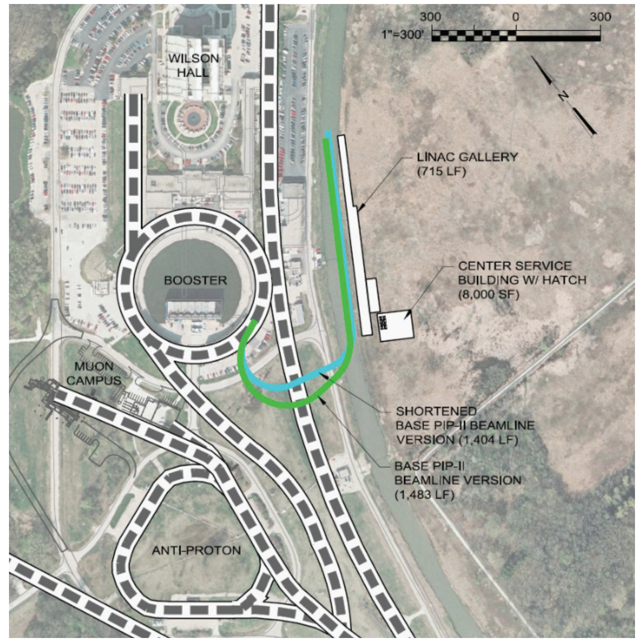

Figure 1: Layout of Fermilab site with PIP-II beam lines.

The direction of the Linac forms an angle of 217 deg. with the direction of injection in the Booster. In order to avoid Lorentz stripping, the magnetic field used to bend the beam has been chosen to be 2.36 kG, corresponding to a loss rate of $3 \cdot 10^{-13}$ m^{-1}. With these parameters the total bending angle can be completed with 32 bending dipole magnets of 2.45 m length (baseline) or with 24 dipoes 3.27 m long (alternate). To fit into the geometrical constraints of the site, the Transfer Line has been divided into a first matching straight section, a first arc, a second straight section, a second arc and an injection line to the Booster. The optics chosen for the transport is a FODO lattice for all the line but the first matching straight section, in which a doublet focusing system similar to the one in the Linac is used, and the injection line. The cell length has been determined by the geometrical constraints resulting in 12 m for both the options. The strength of the quadrupoles has been chosen to determine about 90 deg. phase advance per cell both horizontally and vertically. With this choice, the first arc is composed of 4 cells and the second arc of 12 or 8 cells for the baseline and alternate design respectively. Such choice assures achromaticity of the arcs. The vacuum chamber will be manufactured from 1.5” stainless steel pipe, leaving a transverse aperture of 17 mm for the beam. Figure 2 presents the optical functions of the Transfer Line (baseline) computed with the code OPTIM [3].

*Work supported by Fermi Research Alliance, LLC under Contract No. De-AC02-07CH11359 with the United States Department of Energy.
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ISBN 978-3-95450-168-7

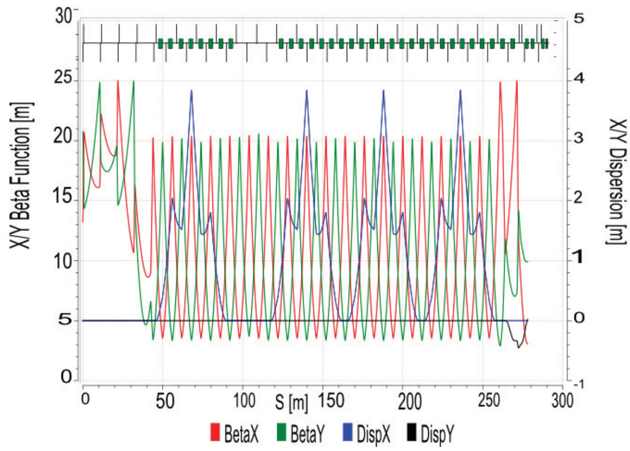

Figure 2: Optics of the Transfer Line (baseline).

Low power momentum collimators are placed at the center cells of the first arc, where the dispersion reaches its maximum value of 3.8 m. The space needed for these collimators is around 1 m. With the choice made for cell and bend lengths the packing factor for the baseline arcs is 41%, leaving enough space for correctors after each quadrupole, ion pumps, BPMs and other instrumentation other than additional collimators and debunching cavities if necessary. For the alternate design the space available is reduced by the higher packing factor.

The injection into the Booster will be vertical, with the last section of the Transfer Line aligned with the Booster injection section (see Fig. 3).

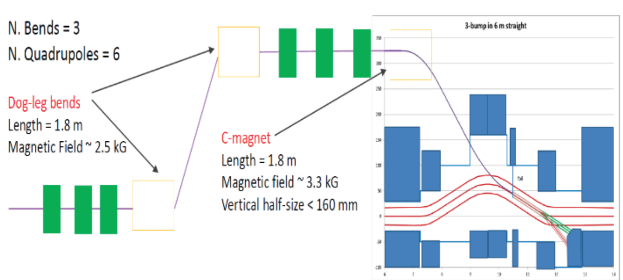

Figure 3: Layout of the injection in to the Booster.

A C-magnet placed 33 cm above the Booster beam line will bend the beam toward the injection point where a stripping foil for Booster injection is located.

The beam will be brought to the elevation of the C-magnet by a vertical dogleg consisting of 2 bends of length 1.8 m and magnetic field around 2.5 kG. The C-magnet length will be 1.8 m and its magnetic field will be around 3.3 kG. Triplets of quadrupoles are placed before the dogleg and the C-magnet for correct matching.

The first straight section of the Transfer Line consists of 4 doublet cells, with the same distance of the doublets in the SC Linac. The quadrupoles are used to match the beam at the end of the SC Linac to the first arc. This configuration allows a possible energy upgrade of the linac by inserting up to 4 additional cryomudules between the doublets. It allows reaching an energy of 1.2 GeV.

High beam energy stability is required for efficient injection into the Booster. It will be achieved by the time-of-flight energy measurement performed in the straight section at the linac end. Energy corrections will be applied to the last cryomodule of the SC Linac. The beam will be initially directed toward a beam dump until the required energy stability is reached. It will require about 20 μs. Then the beam will be switched from the dump to the transport arc. A fast dipole corrector with fall time ~0.5 μs will be placed in the second doublet period. During its flat top it will kick the beam vertically so that it will reach a Lambertson septum magnet, placed in the last doublet period, off axis thus being bent horizontally toward the beam dump. The integrated strengths of the kicker and the Lambertson are 0.18 and 3.4 kG·m, respectively. This system is similar to the one used to switch the beam to the Mu2e target line as explained below.

The energy measurement time-of-flight system will use 2.6 GHz resonant cavities excited by the beam. A distance of 20 m will be sufficient to achieve the required accuracy.

SWITCH TO MU2E TARGET LINE

PIP-II can provide a possible upgrade for Mu2e experiment at Fermilab [4] by directing part of the H^- beam to the Mu2e target. A transfer line connecting the PIP-II SC Linac to the Mu2e complex is compatible with the present design. Figure 4 shows the footprint of the baseline design (green) with a future beam line connecting PIP-II to the Mu2e transport line (magenta) directed to the Mu2e target.

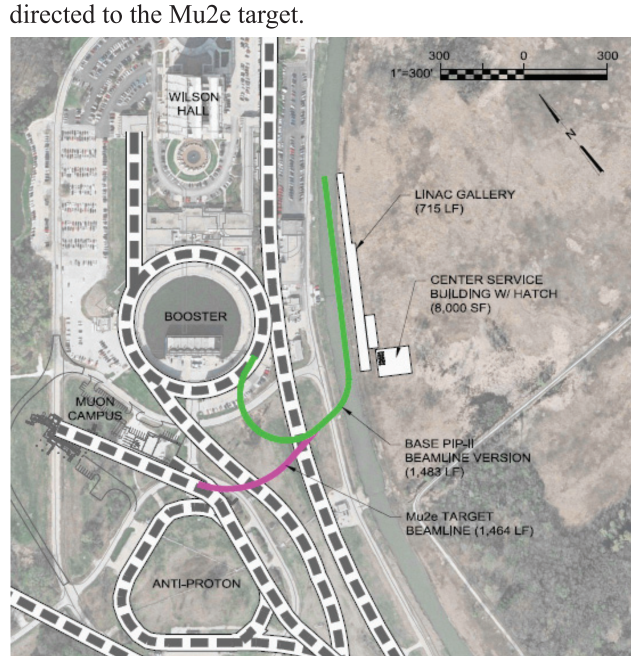

Figure 4: Layout of Fermilab site with Transfer Line to Booster (baseline) and Mu2e target.

Similar to the described above dump switch, the switch between the Booster and Mu2e target will be performed with a combination of fast vertical kicker and a

Lambertson septum magnet. Fig. 5 shows the trajectory of the deflected beam with respect to the undeflected one.

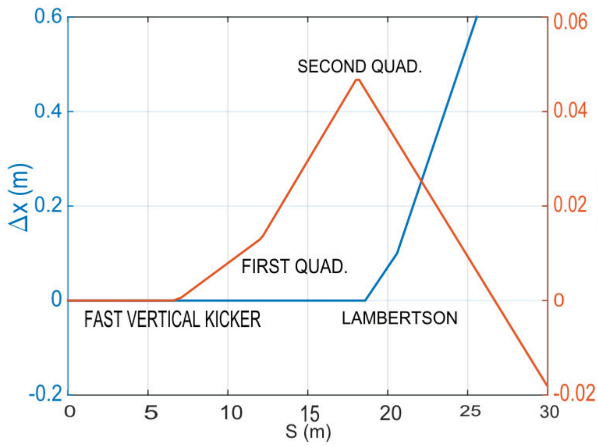

Figure 5: Trajectory of the deflected beam in the Mu2e switch.

The kicker is placed after the defocusing quadrupole of the first cell of the straight section, after the first arc. The beam is kicked vertically and passes through the 2 subsequent quadrupoles off axis, enters the Lambertson magnet, placed after the defocusing quadrupole of the second cell, 3.3 cm higher than the undeflected beam and is, then, bent horizontally to the Mu2e target line. These positions of the magnets minimize the kick necessary to separate the trajectory of the deflected beam at the Lambertson. The integrated strengths of the kicker and the Lambertson are 0.12 and 4.9 kG·m, respectively.

The remaining part of the Mu2e transport line consists of a straight transport and a final arc merging to the target line of the Mu2e complex, as showed in Fig. 4. The length of these sections is determined by the geometrical constraints. The final Mu2e transport arc is realized with 16 bends similar to the bends in the arcs of the transfer line to the Booster. Since the Mu2e target line has an elevation of 1.78 m with respect to the Transport Line, the first and last bends of the arc will be rotated around the longitudinal axis of about 20 deg. in order to create a helical trajectory of the beam line and reach the correct elevation and vertical/horizontal orientation.

TRACKING SIMULATION

To verify the correctness of the design tracking simulations with the code TraceWin [5] have been performed. A simulation of the SC Linac with 1 million macro-particles has been run using the expected output of the RFQ as initial beam parameters. The output particle distribution in that simulation has been used as initial distribution for the Transfer Line simulation presented here. The results are showed in Fig. 6. The transmission efficiency from the end of the linac to the Booster injection point is bigger than 99.9% using the aperture of the vacuum chamber. Beam parameters at the end of the SC Linac and at the injection are reported in Table 1. Values given for transverse parameters are the average of horizontal and vertical ones. Since RF cavities are not planned in the current design bunch length experiences a considerable growth.

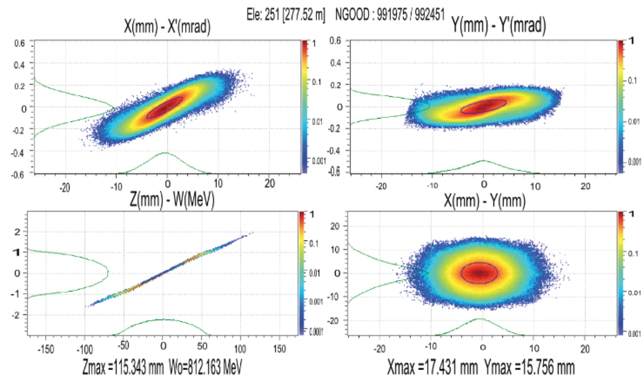

Figure 6: Output distribution of the Transfer Line tracking simulation with TraceWin.

Table 1: Input and Output Beam Parameters

Parameter	Unit	Initial	Final
Energy	MeV	812	812
Size (rms)	mm	1.6	4
Length (rms)	mm	0.83	28
Energy spread (rms)	MeV	0.27	0.52
Transverse Normalized Emittance (rms)	mm mrad	0.245	0.30

CONCLUSION

In this paper we presented the design (baseline and alternate) of PIP-II Transfer Line that connects the end of SC Linac to the Booster. The line provides efficient transport of the beam. It comprises sufficient space for collimators, instrumentation and fast switch to the beam dump, as well as space for the time-of-flight energy measurement required for beam based energy stabilization. The line design accounts for a possible energy upgrade and eventual transport to the Mu2e target. A space for debunching RF cavities (allowing additional improvement of energy spread and stability) is allocated.

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ISBN 978-3-95450-168-7