DESIGN OF SUPERCONDUCTING CW LINAC FOR PIP-II *

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Abstract

Proton Improvement Plan (PIP) -II is a proposed roadmap to upgrade existing proton accelerator complex at Fermilab. It is primarily based on construction of superconducting (SC) linear accelerator (linac) that would be capable of operating in continuous wave (CW) mode. This paper presents reference design layout and beam optics of SC linac and discusses some of the underlying requirements and motivations.

INTRODUCTION

An ambitious program is proposed to develop a high intensity proton beam facility that would support, over the next two decades, a world-leading neutrino program and rich variety of high intensity frontier particle physics experiments at Fermilab. This program, referred to as Proton Improvement Plan -II (PIP-II), is primarily based on construction of 800 MeV SC linac that would provide flexible platform for further enhancement of the existing Fermilab accelerator complex. A schematic of PIP-II facility is shown in Fig 1. A detailed description of site layout is presented elsewhere [1].

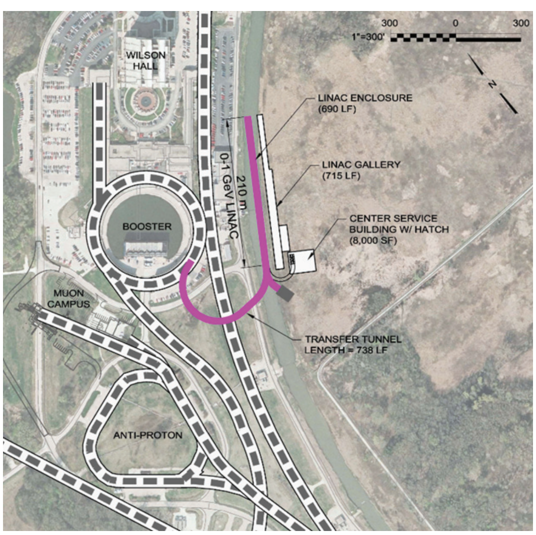

Figure 1: Schematic of PIP-II facility.

To reconcile a stringent budgetary situation and an immediate requirement for high beam power by existing operating experiments, we plan to expedite construction by leveraging the existing Fermilab infrastructure. In particular, the cryogenic infrastructure of the now decommissioned Tevatron will be re-purposed for the PIP-II SC linac. While the machine is designed to be fully compatible with continuous wave (CW) operation, limitations in the capacity of the Tevatron system will require that the linac initially operate in pulsed mode. Success of the PIP-II facility depends critically on the robustness of the SC linac design. While the reference design parameters [1] have been established, the optics is still evolving to incorporate technical constraints and to address issues that may potentially cause degradation of beam quality and result in beam losses. In this paper we discuss baseline configuration of PIP-II SC linac and present results of preliminary beam optics studies.

LINAC ARCHITECTURE

A schematic of linac baseline configuration is shown in Fig 2. It consists of room temperature front-end and SC linac. Each superconducting section in Fig 2 is represented by optimal beta of respective cavities except LB and HB section which are shown for geometrical beta of corresponding cavities. The room temperature front-end is composed of

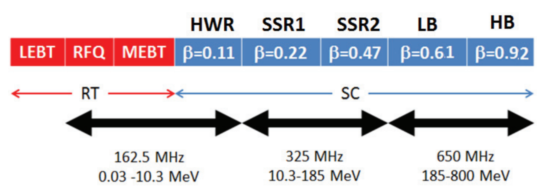

Figure 2: Technology map of PIP-II linac.

an ion source, a low energy beam transport (LEBT) section, an RFQ and a medium energy beam transport (MEBT) section. The DC ion source delivers a nominal current of 5 mA at 30 keV. The beam is transported through the LEBT and matched to the RFQ. The RFQ operates at a frequency of 162.5 MHz and accelerates the beam up to 2.1 MeV. The beam then enters the MEBT where it gets chopped to acquire the time structure required to drive different experiments.

The H^- ion is non-relativistic at kinetic energy of 2.1 MeV and its velocity changes rapidly with acceleration along linac. In order to achieve efficient acceleration SC linac employs several families of accelerating cavities optimized for specific range of velocities. On the basis of these families, SC linac is segmented into five sections. The first SC section is based on Half Wave Resonators (HWR) operating at frequency of 162.5 MHz.

The choice of this frequency was motivated by several factors, including reducing transverse RF defocusing. It can be observed from equation 1 [2] that RF kick is directly proportional to the frequency. Operation at lower frequency helps making maximum use of the available accelerating gradient in cavities. HWR section accelerates the beam from 2.1 MeV to 10.3 MeV. It is required eight HWR cavities assembled in single cryomodule to cover this energy range.

$$\Delta(\gamma\beta r') = -\frac{\pi E_0 T L sin(\phi)}{mc^2\gamma_s^2\beta_s^2\lambda} r \qquad (1)$$

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The HWR section is followed SSR1 and SSR2. Both sections are based on single spoke resonators operating at frequency of 325 MHz. SSR1 section is composed of two cryomodules and each cryomodule consists of eight SSR1 cavities. This section covers the energy range from 10.3 - 35 MeV. SSR2 section is made up of seven cryomodules with each cryomodule containing five SSR2 cavities. The beam is accelerated from kinetic energy of 35 MeV to 185MeV in SSR2 section. Figure 3 shows lattice period topology in HWR, SSR1 and SSR2 sections. Superconducting solenoids provide transverse focusing in these sections.

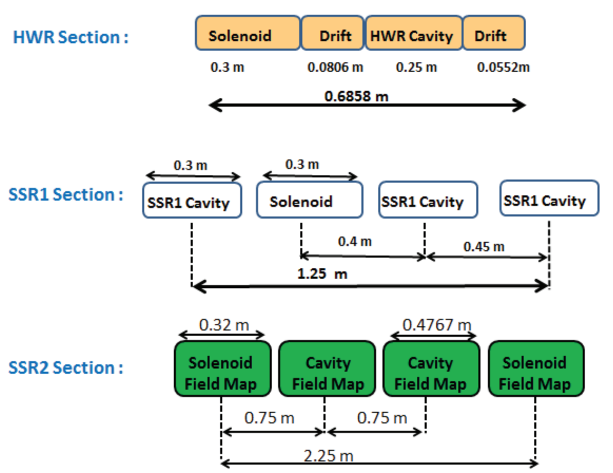

Figure 3: Focusing periods in low energy section of SC Linac.

The final two sections, referred as low beta (LB) and high beta (HB), are based on two families of 5-cell 650 MHz elliptical shaped cavities. The LB section accelerates the beam from 185- 500 MeV and it requires eleven cryomodules to cover this energy range. Each cryomodule is composed of three 5-cell 650 MHz elliptical shaped cavities which are designed for $\beta_G = 0.61$. Transverse focusing in LB section is provided by normal conducting (NC) quadrupole doublet. HB section is used for rest of beam acceleration. It employs four cryomodules of $\beta_G = 0.92$, 5-cell 650 MHz cavities to reach final beam energy of 800 MeV. Each cryomodule consists of six cavities.

A preliminary layout of superconducting cryomodule in LB and HB section is shown in Fig 4. Mechanical design of cryomodules are still evolving and therefore, distances shown are subject to change.Element types, counts as well as transition energies between sections are summarized in Table 1.

BEAM OPTICS

One of the most challenging task of PIP-II facility is to deliver a high quality beam to several experiments with different requirements. Hence a careful design of linac optics is important to achieve this objective. In a high intensity ion linac, non-linear forces play a crucial role in beam stability. Thus short focusing periods are used at low energy part of

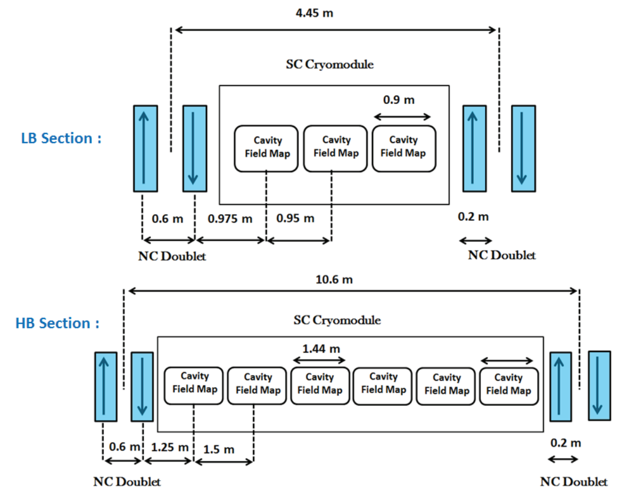

Figure 4: Focusing periods in LB and HB section of SC Linac.

Table 1: Number of Elements in Each Section of SC Linac

	HWR	SSR1	SSR2	LB	HB
No. of CM	1	2	7	11	4
Cavities/CM	8	8	5	3	6
Freq. (MHz)	162.5	325	325	650	650
Max.Energy gain per cavity (MeV)	2.0	2.05	5.0	11.9	19.9
Solenoids/CM	8	4	3	-	-
Quads doublets per CM	-	-	-	1	1
Energy range (MeV)	2.1-10 3	10.3-35	35-185	185-500	500-800

PIP-II SC linac where space charge force is significant and might result in beam instability. Beam halo formation is also a major concerned in high intensity linac. Longitudinal halo formed at low energy results in beam losses at high energy. In order to avoid beam halo formation, lattice is designed with smoothly varying longitudinal and transverse focusing. Beam is properly matched with subsequent sections in order to avoid any abrupt changes in beam envelope that otherwise may drive beam halo formation.

Beam optics is designed for baseline configuration of linac. Simulation studies are performed to analyze beam profile through linac (MEBT and SC linac) using beam dynamics code TRACEWIN [3]. Figure 5 shows 3σ transverse and longitudinal beam envelope along the MEBT and SC linac. No beam losses are observed in SC part of linac. Figure 6 shows evolution of longitudinal and transverse RMS normalized emittance along the linac. While some emittance exchange between the longitudinal and transverse planes takes place in the early stages of acceleration, space charge forces become progressively weaker as the beam energy increases and there is no further emittance variation in either plane through rest of the linac. Normalized particle density projection in horizontal plane with aperture limitation along

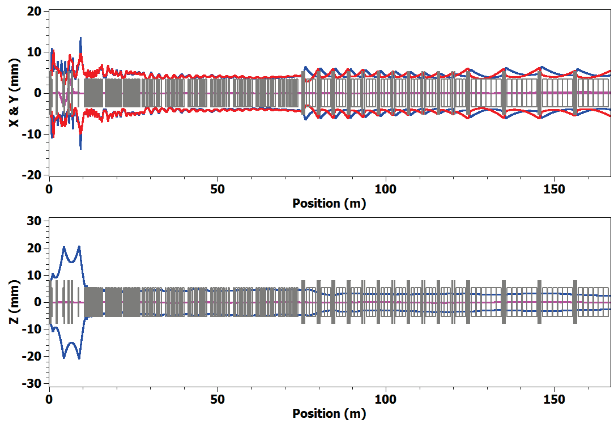

Figure 5: Beam envelope (top) in horizontal (blue) and vertical (red) plane, (bottom) in longitudinal plane.

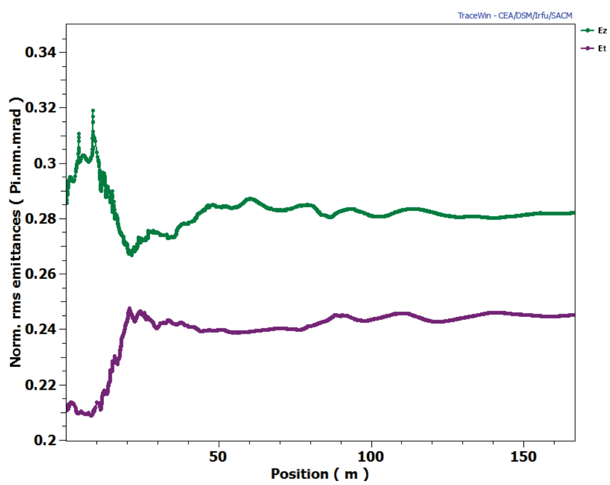

Figure 6: RMS normalized transverse (magenta) and longitudinal (green) beam emittance along linac.

the linac is shown in Fig 7. It can be noticed that there is no abrupt changes in particle density profile and beam propagates smoothly along the linac. There is no particle that hits aperture in SC linac. All the particles are well confined in core that implies absence of beam halo for nominal operation of linac.

Intra Beam Stripping

Experience from SNS operation suggests that intra-beam stripping [4] is one of the major source of beam losses in well matched and tuned machine. Intra-beam losses are estimated for PIP-II SC linac. Figure 8 shows the predicted beam loss power density due to intra-beam stripping. As one can see the losses due to this mechanism are below $0.1W/m$ everywhere along the linac. Even for CW operation, integrated beam losses due to intra-beam stripping along the linac remain below $10W$. Thus, we conclude intra-beam stripping losses are well within requirement for PIP-II SC linac. However, in order to further minimization of beam losses in cryogenic environment, the fixed aperture beam collimators will be installed between each cryomodule in

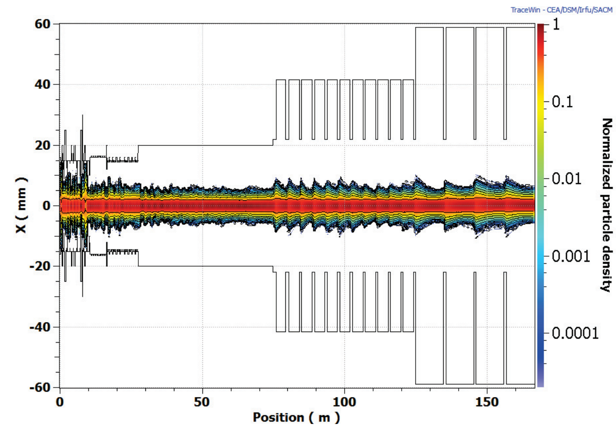

Figure 7: Normalized particle density projection in horizontal plane and aperture limitation along the linac from MEBT to linac end.

HWR, SSR1 and SSR2 section. The collimator aperture is chosen to be 5 mm smaller than the aperture of downstream cryomodule. Thickness of collimator increases with energy and it reaches about 4cm of steel at the end of SSR2 section. There are no dedicated collimators in the LB 650 and HB 650 sections.

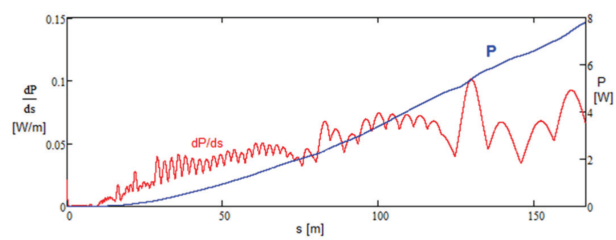

Figure 8: : The beam power loss per unit length due to intra-beam stripping (red) and its integrated value along the linac (blue); RFQ beam current 5 mA, CW beam of 2 mA in the SC Linac (60% of bunches are chopped off).

CONCLUSION

The heart of PIP-II facility is a SC linac which is designed for CW operation, but initially operating in pulsed mode. Robust optics, validated by simulations ensures reliable operation of SC linac. Results of these simulations show that the beam quality meets the requirement set for project. In particular, predicted beam losses are well within requirement set to allow for hand-on maintenance of the machine and alleviate other safety concerns.

REFERENCES

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