DESIGN CONSIDERATIONS FOR THE FERMILAB PIP-II 800 MeV SUPERCONDUCTING LINAC*

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Abstract

Proton Improvement Plan (PIP)-II is a proposed upgrade of existing proton accelerator complex at Fermilab. It is primarily based on construction of a superconducting (SC) linear accelerator (linac) that would be capable to operate in the continuous wave and pulsed modes. It will accelerate 2 mA H^- ion beam up to 800 MeV. Among the various technical and beam optics issues associated with high beam power ion linacs, beam mismatch, uncontrolled beam losses, halo formation and potential element's failures are the most critical elements that largely affect performance and reliability of the linac. This paper reviews these issues in the framework of PIP-II SC linac and discusses experience accumulated in the course of this work.

INTRODUCTION

The Proton Improvement Plan –II is an aspiring program proposed for further enhancement of the existing Fermilab accelerator complex to support a world leading neutrino program and rich variety of high intensity frontier particle physics experiments at Fermilab. The most important part of the PIP-II is to build a new superconducting (SC) linear accelerator that would be capable to operate in the continuous wave (CW) regime.

A schematic of the linac baseline configuration is shown in Fig. 1. It consists of a room temperature front-end and an accelerating SC linac. The front-end is composed of a low energy beam transport (LEBT) section, an RFQ and, a medium energy beam transport (MEBT) section. The main accelerating part of the linac utilizes five families of superconducting cavities to accelerate the H^- ion beam from kinetic energy of 2.1 MeV to 800 MeV. On the basis of these families, SC linac is segmented into five sections i.e. half wave resonator, single spoke resonator (SSR) 1 & 2, low beta (LB) and high beta (HB). Each section in Fig. 1 is represented by optimal beta of respective cavities except LB and HB sections which are shown for geometrical beta of corresponding cavities. A detailed description of the PIP-II is presented elsewhere [1, 2].

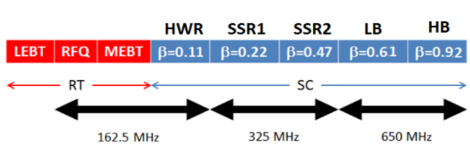

Figure 1: A schematic of acceleration scheme in the PIP-II SC linac. Red-coloured sections operate at room temperature while blue-coloured sections operate at 2K.

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GENERAL

One of the major concerned related with the high intensity ion-linacs is the uncontrolled beam loss. An excessive beam loss might result in radio-activation that leads to interruptions in hands on maintenance, hazard to personal health and environment. This, in turn, keeps stringent limit on tolerable beam loss along the linac. A cumulative experience with high intensity beam operation at existing facilities such as LANSCE [3] was utilized to set a threshold limit of beam loss. An average beam loss below 1W/m at beam energy of 1GeV is considered a safe-operational limit across the accelerator community over the world.

LINAC DESIGN CONSIDERATIONS

A rigorous study is required to obtain a robust design of the ion linac that not only preserves the beam quality but also deals with different mechanisms which induce beam loss along the linac. In this paper we discuss the high intensity ion linac design considerations based on our experience gained over the years for a quest of a robust design of the PIP-II SC linac. Those considerations assist to control implications of principal beam loss mechanisms such as halo formation, beam mismatch, beam stripping, fault scenario etc.

SC Linac Acceptance

Acceptance of the linac is determined by the largest beam size that can be transmitted through the linac without any beam loss. Thus, acceptance is a vital parameter to measure the linac tolerances against potential errors. A large acceptance suggests less possibility of the uncontrolled beam loss and therefore, achieving a large acceptance is one of the primary considerations of the linac design.

Longitudinal Acceptance In an ion-linac, longitudinal acceptance is primarily outlined by its low energy part where beam is non-relativistic and bunch length is relatively longer. In order to achieve large acceptance, a strong adiabatic longitudinal focusing is required. Longitudinal phase advance (k_z) per meter for a non-relativistic ion beam is given as:

$$k_z^2 = \frac{2\pi q E_0 T_s \sin(-\phi_s)}{(\beta\gamma)^3 mc^2 \lambda}; \tag{1}$$

where β, γ are Lorentz factors for synchronous particle, ϕ_s, T_s are synchronous phase, transit time factor for synchronous particle respectively and, E_0 is accelerating field gradient. It can be noticed from eq. (1) that accelerating cavities need to be operated at large synchronous phases to avoid the phase slippage. Figure 2 shows synchronous phases of accelerating cavities in the PIP-II SC linac. It can be easily observed from Fig. 2 that phases are large enough to accommodate 6σ beam.

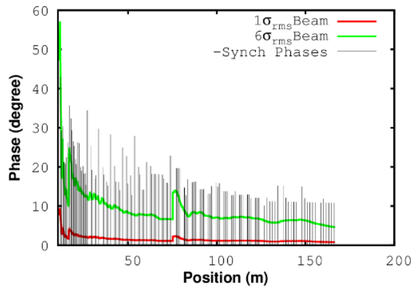

Figure 2: Accelerating phases in cavities for nominal configuration of the PIP-II SC linac.

A longer bunch is more susceptible to experience the curvature of the RF field which results in a non-linearity in the longitudinal focusing. This, in turn, requires operation of cavities at lower frequency. Furthermore, operation at lower frequency helps making maximum use of available accelerating gradient by reducing transverse RF defocusing which is a prominent effect at the low energy. As beam energy increases and bunch length reduces, operation of cavities at higher frequency becomes more favorable. Thus, a typical high energy ion linac is segmented into several sections on the basis of operating frequency of cavities.

The PIP-II SC linac uses three frequencies i.e. 162.5, 325 and 650 MHz. A frequency jump in the linac, if not designed carefully, may introduce a abrupt change in longitudinal focusing and can shrink longitudinal acceptance. Figure 3 depcits that longitudinal acceptance of the PIP-II linac is large enough to accommodate 6σ beam easily.

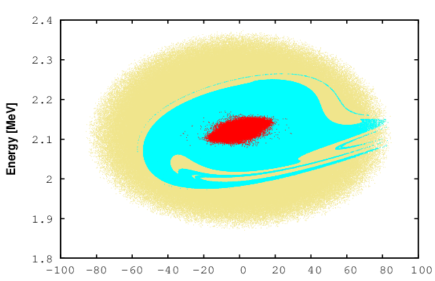

Figure 3: Longitudinal acceptance of the PIP-II SC linac (cyan) with 6σ beam at upstream of the linac (red). Initial particle distribution is shown in khakee.

Transverse Acceptance A choice of element's aperture determines transverse acceptance of the linac. Figure 4 shows normalized particle density along the PIP-II SC linac. One can observe variation in apertures along the linac. The limited aperture at the low energy part of the PIP-II linac is 30 mm imposed by SSR1 cavity while it is 44 mm at the high energy part enforced by quadrupole magnets.

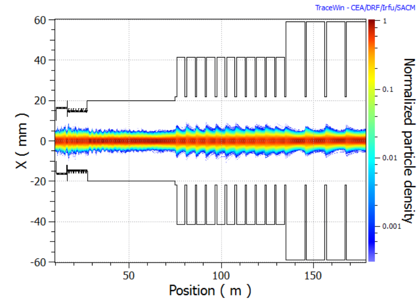

Figure 4: Normalized particle density along the linac.

Transverse acceptance of the PIP-II SC linac is shown in Fig. 5. It is about 16µm while the maximum action of 6σ distribution at the end of MEBT is 2 µm. It leaves a large margin that allows a spread in initial beam parameters. A beam scraping system placed prior to the SC linac limits the maximum action of the injected beam and therefore, further increases this margin (ratio of acceptance to beam phase space area).

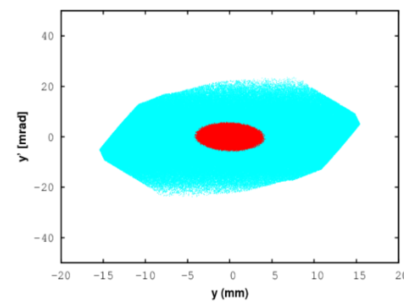

Figure 5: Tranverse acceptance of the PIP-II SC linac (cyan) with 6σ beam at upstream of the linac (red).

Beam Mismatch

It has been discussed elsewhere [4] that beam-mismatch is primary source of emittance growth and halo development in the ion-linac. Thus, optics design should be robust enough to allow a spread in design parameters. One needs to perform a careful matching at the transitions between sections. Also, abrupt changes in beam focusing should be avoided in order to minimize potential beam-mismatch.

A study has been performed for the PIP-II SC linac to analyse the halo formation due to initial beam mismatch. A specific mismatch is introduced by varying initial beam Twiss parameters in all planes. Beam is then tracked through the linac with nominal operational parameters. Figure 6 shows evolution of particles in longitudinal size at the end of linac for three cases i.e. no mismatch, 20 % and 40 % mismatch in initial Twiss parameters in all planes. Though, maximum radius almost remains constant in all cases but initial beam mismatch populates more particles in outer-core (radius >3) of the distribution. A beam loss of 0.03% is also observed for the case of 40 % initial beam mismatch.

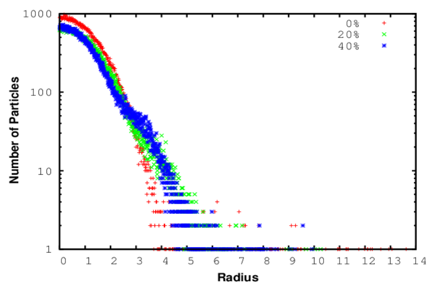

Figure 6: Longitudinal particle distribution at the end of PIP-II SC linac. (Radius = |σ|)

Intra Beam Stripping

It has been observed that intra beam stripping [5] is main source of beam loss in a well matched and tuned H^- ion linac. It is triggered by interaction of beam with black body radiation, residual gases and strong magnetic field. However, in the cryogenic environment, magnetic stripping is primary culprit that results in an uncontrolled beam loss in the SC linac. It can be suppressed by avoiding a strong focusing field and, keeping a relatively large RMS beam size at the focusing magnets. It can be observed from Fig. 7 that predicted beam loss density due to intra-beam stripping is below 0.1 W/m everywhere along the PIP-II SC linac. Even for a CW operation, integrated beam loss in the linac due to the intra-beam stripping is below 10 W.

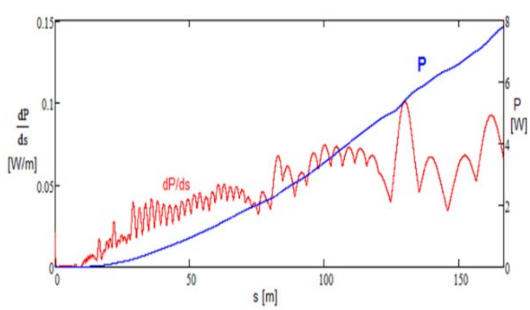

Figure 7: Beam power loss per unit length due to intra-beam stripping (red) and its integrated value along the linac (blue) for CW beam current of 2 mA.

Localized Beam Losses

The uncontrolled beam loss in the SC linac irradiates surface of cavities which causes not only a degradation in their performances but also an increase in the cryogenic heat load of the machine. Beam collimators can be deployed between cryomodules to intercept beam halo particles. This, in turn, reduces potential beam loss at the operating temperature of 2K. In the PIP-II linac, fixed aperture collimators will be installed between each cryomodule in HWR, SSR1 and SSR2 section. The collimator aperture is chosen to be 5 mm smaller than the aperture of downstream cryomodule. Thickness of the 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 and HB sections.

Fault Scenarios

The SC linac includes numerous elements and their continuous operation represents a great challenge on their reliability. There is finite probability of their temporary or permanent failures during their operation. Failure of the beam transport elements like cavity, solenoid and quadrupole alters the focusing period of beam, resulting in a mismatch of beam transport with downstream sections. This, in turn, may degrade beam quality and, in the worst case, may cause beam losses. In some cases, a faulted element at the critical location results in a significant beam losses and therefore, it becomes necessary to replace this element to continue a nominal operation. A replacement of the faulted element in the SC linac can result in a long unscheduled beam down time as it involves warming of cryomodule to the room temperature followed by its cool-down after replacing a faulted element. Thus, to assure linac's capability to deliver a high quality beam with high beam availability, fault scenarios must be considered in the design. Optics design should be capable to deal with at least one major fault in each section. An extensive study has been performed to address this issue for the PIP-II SC linac. It has been observed that implications of failures at the low energy part of the linac are more severe. It is because of the fact that beam longitudinal and transverse sizes are relatively larger and beam velocity changes rapidly at this part of the linac. Furthermore, space charge forces are significant at low energy, resulting an amplification of beam initial mismatch. However, it has been demonstrated that a local compensation scheme [6] can be successfully utilized to restore beam quality after a failure. Neighbouring elements in the vicinity of the failed elements are retuned to achieve a smooth beam envelope. Individual RF power supply for each cavity allows to adjust RF phases and field gradients to tune longitudinal optics. It can be noticed from Fig. 8 that beam emittance is restored at large extent after applying the longitudinal scheme.

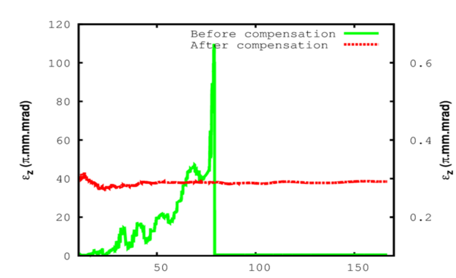

Figure 8: Normalized RMS longitudinal emittance before (green) and after (red on secondary y-axis) applying the local compensation scheme

CONCLUSION

Preservation of beam quality and minimization of beam loss below 1W/m are primary objectives for the design of the PIP-II SC ion linac. A large acceptance of the linac obtained through a careful selection of operating frequencies of cavities, synchronous phases and element's aperture, ensures a lower possibility of the uncontrolled beam loss. Furthermore, deploying a collimator system between cryomodules permits the localized beam loss in the linac. Beam loss due to the intra-beam stripping can be reduced by avoiding strong magnetic fields in focusing quadrupoles. The PIP-II linac is capable to deal with fault scenarios using a local compensation scheme.

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