DESIGN ISSUES OF HIGH INTENSITY SC CW ION LINAC FOR PROJECT-X FACILITY*

A. Saini†, N. Solyak, V. P. Yakovlev, Fermilab, Batavia, IL 60510 U.S.A.

Abstract

Project-X is a high intensity proton facility which is primarily based on superconducting (SC) continuous wave (CW) linac. One of the most challenging tasks of Project-X facility is to have robust design of SC CW linac which can provide high quality beam to several experiments and subsequent pulsed linac simultaneously. Among the various technical problems associated with the SC CW linac, halo formation, beam mismatch, uncontrolled emittance growth and beam losses are the most crucial as they can limit overall performance and reliability. Scope of this paper is to address these issues for reference design of Project-X SC CW linac.

INTRODUCTION

The application horizon of particle accelerators has been widening significantly in recent decades. Where large accelerators have traditionally been the tools of the trade for high-energy nuclear and particle physics, applications in the last decade have grown to include large-scale accelerators like synchrotron light sources and spallation neutron sources. Applications like generation of rare isotopes, transmutation of nuclear reactor waste, sub-critical nuclear power, tritium production, radiation damage studies, studies of rare processes and generation of neutrino beams etc. are the next area of investigation for accelerator scientific community all over the world. Such applications require high beam power in the range of few mega-watts (MW). One such high intensity proton beam facility is proposed at Fermilab, named as Project-X [1]. The success of Project-X facility is primarily dependent on reliable operation of 1 GeV CW linac at first stage which is capable of delivering 2 MW beam power. A detailed description of baseline design of the CW linac is presented elsewhere [2].

Design of the high beam power accelerators are based on stringent beam losses limit. High beam losses can result in severe problem in terms of radio-activations. The cumulative experience of high intensity operation with existing facilities such as LANSCE [3] is utilized to set threshold limit of beam losses. In order to ensure hand-on-maintenance in safe environment, beam losses must be limited to 1 W/m for beam energy at 1 GeV. This paper addresses main characteristics and crucial beam dynamics design issues for the high intensity ion linac in framework of 1 GeV SC CW linac for the Project-X facility.

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† asaini@fnal.gov

EMITTANCE GROWTH

A low beam emittance ensures good output beam quality. Thus, minimal emittance growth along the linac is one of the primary objectives of optics design. The ion source determines initial transverse emittance of the beam which is transported to the RFQ through the low energy beam transport (LEBT) section. The magnets aberrations and non-linear space charge forces can result in a increase of transverse emittance in LEBT. It can be controlled, keeping beam size small and applying space charge neutralization. The longitudinal emittance is formed in the RFQ. A good beam matching at the upstream end of the RFQ minimizes transverse and longitudinal emittance growth along the RFQ. It is followed by the medium energy beam transport (MEBT) section which is comprised of bunching cavities and focusing magnets. Following is a SC CW linac. A robust design is capable to conserve emittance along the linac. It can be achieved using short regular focusing periods especially at low energy part of the linac. It results in smooth and linear changes in phase advance per meter (k). However, zero current phase advance in a focusing period should be kept below 90^0 to avoid envelope instability [4]. In order to avoid parametric resonance, focusing in linac is chosen such that $k_l \neq 2k_t$. Where k_l, k_t are wave numbers of the longitudinal and transverse oscillations respectively. Furthermore, non-linear space charge forces can result in excitation of coupling resonances which causes coupling between longitudinal and transverse motion. It results in abrupt emittance transfer between the planes. Figure 1 shows emittance coupling between longitudinal and transverse plane in first few sections of one of the variants of Project-X CW linac. It can be noticed that longitudinal emittance ϵ_l reduces at the expense of transverse emittance ϵ_t. In order to mitigate free energy transfer from one

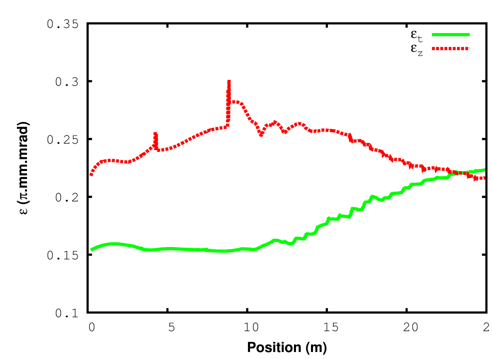

Figure 1: Emittance coupling between longitudinal and transverse plane.

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plane to another, equipartitoning is required. Condition of equipartitioning is:

$$\frac{T_t}{T_l} = \frac{k_t \epsilon_t}{k_l \epsilon_l} = 1 \tag{1}$$

where T_t and T_l are temperatures in transverse and longitudinal plane respectively. In order to achieve efficient acceleration, focusing periods vary along the linac. Therefore, it is difficult to satisfy equipartition condition through out the linac. In this scenario, free energy transfer from one plane to another is suppressed by proper selection of working points (phase advance per period) in tune space where non-linear space charge modes are stable. The Hofmann stability diagram [5] represents stability region in tune space that distinguishes stable modes from those which lead to coupling. Figure 2 shows working points of lattice that corresponds to Fig. 1. It can be noticed that some points are placed in stop-bands (region where space charge modes are unstable). It explains the reason of emittance exchange shown in Fig. 1.

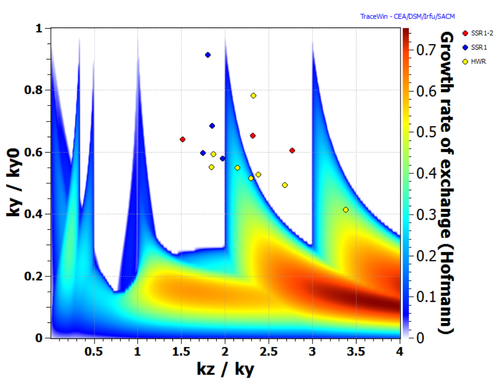

Figure 2: Hofmann stability chart: Distribution of working points in tune space.

The baseline design of Project-X CW linac involves no emittance exchange between the planes. Emittance growth [2] with respect to initial emittance is less than 4% in longitudinal plane, $\sim$ 10% and 14% in horizontal and vertical planes respectively.

ACCEPTANCE

In high intensity linac, acceptance parameter is a vital mean to measure linac performance in term of beam losses. It is determined by largest beam size that can be transmitted through the linac without any particle losses. Thus, large beam acceptance corresponds to high tolerances against errors. A choice of physical aperture of beamline elements sets transverse acceptance of the machines. Preliminary beam-dynamics studies using numerical simulation codes helps to make optimal choice of aperture. Figure 3 shows transverse acceptance of 1 GeV SC CW linac for Project-X. An input distribution (shown in red) is generated with relatively very large emittance than nominal beam emittance in horizontal plane and relatively smaller in others. Distribution is tracked through the linac. Area occupied by initial coordinates of transmitted particles (shown in green) trace the acceptance of linac in this plane. It can be observed that transverse emittance is sufficient to accommodate 6σ beam (shown in blue).

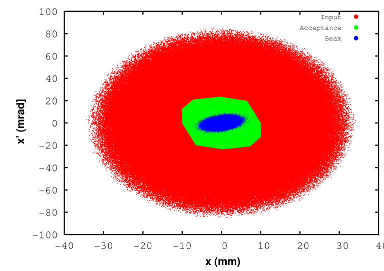

Figure 3: Transverse acceptance (green) of 1 GeV SC CW linac of Project-X with 6σ beam.

The complexity of ion linac is associated with the fact that beam velocity changes significantly during acceleration along the linac. Thus, to achieve efficient acceleration, different families of cavities are used along the linac. The Project-X SC CW linac is segmented into three section on the basis of operational frequencies of cavities (162.5 MHz, 325 MHz and 650 MHz). A careful matching is required between these sections otherwise it may introduce a discontinuity in average longitudinal force per period and limits longitudinal acceptance of the linac. In order to investigate most sensitive section in SC CW linac, longitudinal acceptance is analyzed at different locations in SC CW linac. It is found that longitudinal acceptance is primarily limited by the SSR2 section and no significant degradation is observed in subsequent sections. Figure 4 shows longitudinal acceptance after each section in linac. It is large enough to enclose 6σ beam (black). Thus no losses have been

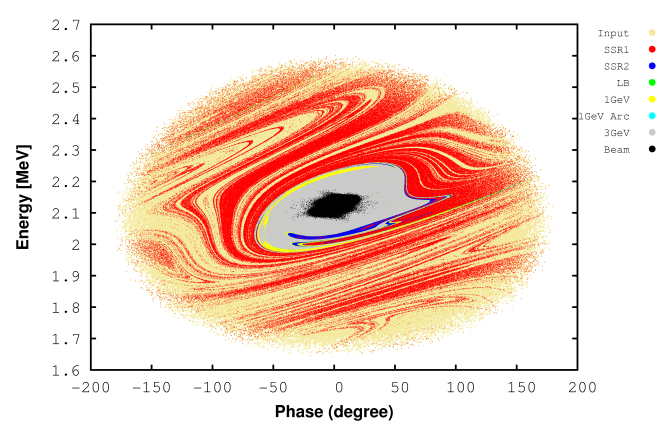

Figure 4: Longitudinal acceptance of SC CW linac of Project-X with 6σ beam (black).

observed for nominal operation of linac. Particles which fall out of longitudinal acceptance (grey region in Fig. 4) are no longer accelerated in linac, hence are not matched with downstream magnetic focusing elements which are designed for fully accelerated particles and consequently, they are lost due to transverse mismatch. Typically, the high intensity linac are designed to obtain large longitudinal acceptance in order to deal with longitudinal halo that usually results in beam losses at high energy part of linac.

HALO DEVELOPMENT

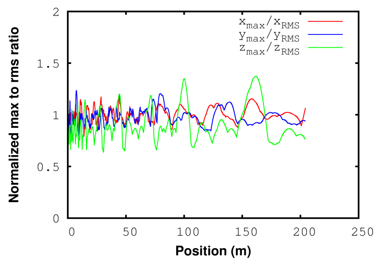

Figure 5: Normalized *maximum to RMS ratio* in all planes along 1 GeV SC linac.

The existence of beam halo is an important characteristics of the high intensity ion beam. Typically, beam halo is developed in low energy section and it is acquired large amplitude in high energy section that results in particle losses. It is most concerned aspect of the design of high intensity machine in the regime of stringent beam losses limit. There are several definition to quantify beam halo [6] but an important figure of merit that can be incorporated during lattice design is *max to RMS ratio*. It is ratio of maximum displacement to the RMS size of matched beam. Figure 5 shows *max to RMS ratio* normalized to initial value along the 1 GeV CW linac. Keeping this ratio close to one ensures that halo amplitude does not grow up along the linac. It is also useful to identify location of halo formation. It can be noticed from Fig. 5 that location around 100 m and 160 m is sensitive to longitudinal halo formation in linac.

Beam Mismatch

Beam mismatch is major source of halo development in linac. Studies are performed in order to analyze the impact of initial mismatch on halo formation for 1 GeV SC linac. Variation of 20% and 60% in initial Twiss Parameters in all planes are applied. All simulations are performed using a 6σ Gaussian distributed beam of 10^6 particles. Figure 6

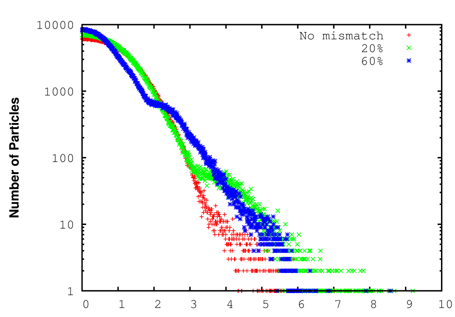

Figure 6: Longitudinal particle distribution at the end of 1 GeV linac (Radius = $|\sigma|$).

shows longitudinal particle distribution at the end of linac for three cases no mismatch, 20% and 60% beam mismatch. Redistribution of particles can be observed in presence of mismatch which results in more particles in tail of distribution (radius >3). It is due to core oscillations that results in energy transfer from core movement to single particle orbit. It can also be noticed that redistribtion occurs faster in case of 60% mismatch (radius $\sim$ 2) than 20% (radius $\sim$3). It is a consequences of additional "free energy" introduced via mis-matched in the system. Similar

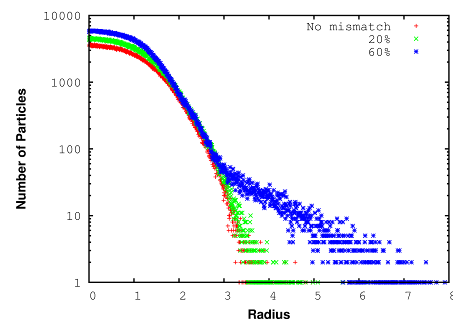

Figure 7: Transverse particle distribution at the end of 1 GeV linac (Radius = $|\sigma|$).

behavior is observed in horizontal plane. Figure 7 shows horizontal particle distribution at the end of linac. It can be noticed that only 60% mismatch results in significant halo development.

CONCLUSION

Controlled emittance growth and low beam losses are main objectives of the design of high intensity ion linac. Equipartition among the planes and avoiding stop-bands in the Hofmann stability diagram are possible way to avoid emittance exchange in presence of non-linear space charge forces. Large machine acceptance and suppression of mechanisms that lead to halo development are essential for reliable operation of the linac. Design of 1 GeV SC CW linac for Project-X is sufficiently robust to sustain stable operation even in presence of spread in design parameters. No beam losses are observed along the linac even in presence of 60 % initial mismatch of the beam.

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