PHYSICS DESIGN OF THE PROJECT X CW LINAC*

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Abstract

Project X is a proposed high-intensity H^- accelerator complex that aims at providing high intensity beams for a diverse physics program which includes neutrino, kaon and muon-based precision experiments. In the current proposal, a 3 MW, 1 mA superconducting linac operating in continuous wave (CW) mode would accelerate beam from 2.5 MeV up to 3 GeV. The status of this CW linac is presented. Lattice design and components are discussed, supported by results from beam dynamics simulations.

INTRODUCTION

Project X is a multi-MW proton source under development at Fermilab [1] that would enable a world-class program of precision experiments in neutrino, kaon and muon physics. At the heart of the proposed facility is a 3 GeV, 1 mA (average) CW superconducting linac. While the bulk of the H^- beam emerging from this linac is directed at up to three concurrent experiments at 3 GeV, a modest fraction (5-9%) is accelerated in a second stage SC pulsed linac and injected into the existing Recycler/Main Injector complex. This would provide high intensity, multi-MW beams for neutrino and muon experiments.

GENERAL

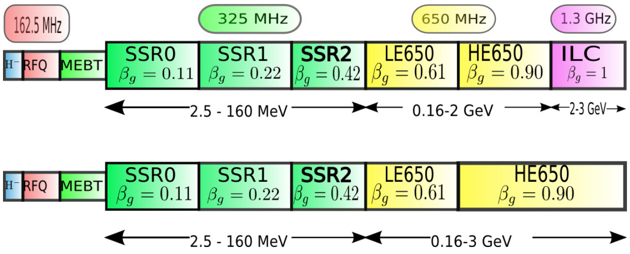

Figure 1: Top: baseline. Bottom: preferred variant.

Table 1: Counts for the preferred HE650 lattice variant. Note: 1 doublet = 1 element.

Section	f MHz	E_{in} MeV	Cav/Elm/CM	Acc,Foc
SSR0	325	2.5	18/ 18/ 1	1-spoke, Sol
SSR1	325	11.4	20/ 20/ 2	1-spoke, Sol
SSR2	325	42.9	44/ 24/ 4	1-spoke, Sol
LB650	650	178.7	42/ 14/ 7	5-cell , Dblt
HB650	650	558.5	152/19 /19	5-cell, Dblt

Project X 3 GeV CW linac provides H^- beam with average current of 1 mA endowed with a special and flexible time structure [2] to satisfy diverse experimental needs. The pulse current can reach a peak of 5 mA, corresponding to a maximum 162.5 MHz bunch frequency. A block diagram of the linac configuration is shown in Fig. 1. It includes: (i) an ion source, (ii) a 162.5 MHz RFQ, (iii) a medium energy beam transport (MEBT) section, (iv) three accelerating sections based on 325 MHz single-spoke resonators (SSR) and (v) two sections of 650 MHz elliptical cavities. It should be noted that although our efforts are converging, a number of lattice variants continue to be studied. In a previous report [3] we described a baseline lattice where 2-3 GeV acceleration is handled by 1.3 GHz ILC 9-cell elliptical cavities. Although no final decision has been made, the current favoured alternative is a lattice where $\beta = 0.9$ cavities are used all the way to 3 GeV . For the sake of conciseness, we emphasize this variant in the paper. While the baseline lattice differs in details, both lattices are essentially identical at energies below 0.5 GeV. The ion source provides 5 mA of H^- to a 162.5 MHz RFQ. Our previous lattice iterations featured a 325 MHz RFQ; the decision to reduce the frequency was made to reduce the required chopper bandwidth. From the RFQ emerges a 2.5 MeV beam with transverse and longitudinal normalized emittances of 0.25 and 0.27 mm-mrad respectively. In the MEBT, 325 MHz bunching cavities are used to support the beam longitudinal dynamics while quadrupole triplets provide transverse focusing. The MEBT operates at room temperature and comprises a chopping section, upstream and downstream matching optics and necessary diagnostics. A high-bandwidth, bunch-selective chopper is needed to produce a flexible time structure for concurrent experiments; almost 90% of the beam is chopped out in the process. The chopping section –a key technical challenge – has four periods; each period includes a 0.5 m long deflector with ± 250 V applied across a 15 mm gap. With this arrangement, the transmitted beam fraction upon chopping is estimated to be $< 10^{-4}$. Details of the current chopper concept are presented in reference [4]. Further acceleration takes place in a SC linac. The low-energy part of the linac consists of three 325 MHz single-spoke resonators (SSR) sections with focusing provided by SC solenoids to minimize the period length. The high-energy part of the linac consists of two sections, based on two families of elliptical cavities (β =0.61 and 0.9) operating at 650 MHz [7, 8]. Focusing in these sections is provided by superconducting doublets. The breakpoints between cavity families are optimized to maximize efficiency and acceptance; counts for sections and components are presented in Table . To ensure more reliable performance and minimize power losses, accelerating gradient limits are selected for operation below the high-field Q-slope region [3]. Based on experimental

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results, the maximum surface magnetic field limits were set respectively at 60 mT and 70 mT for the 325 MHz and 650 MHz cavities. Furthermore, the peak surface electric field is limited to 40 MV/m to prevent strong field emission; this was a consideration in the cavity design.

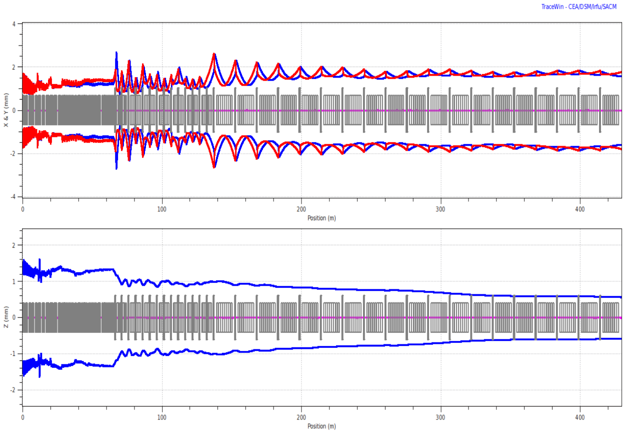

Figure 2: Beam envelopes. Top: $\sigma_{x,y}$. Bottom: σ_z.

COMPONENTS STATUS

Some of the components required for Project X were designed and tested in the context of the HINS program, a feasibility demonstration for the front-end of a future proton driver. Specifically, two of the required solenoid types and two prototypes of SSR1 single-spoke resonators have been built and tested. The cavities gradient reached about twice the nominal value. Invaluable experience was acquired while developing 1.3 GHz cavities and cryomodules for the ILC program. Fermilab has completed the electromagnetic design for all cavities mentioned above; the mechanical design is ongoing.

Power requirements for the cavities is discussed here [5]. Solid-state amplifiers are favoured for the front-end. For the 650 MHz sections, IOTs will be used. Due to a low average beam current, the quality factor under load Q_L remains high (3×10^7), and special efforts to reduce microphonics are necessary. Amplitude and phase stabilization is also possible: such stabilization has been contemplated [6] for energy recovery linacs applications where $Q_L \simeq 10^8$. Rf couplers for all cavities are under development. The design has to allow for assembly and sealing of the cavities in a clean room for later installation in a cryomodule. The linac comprises five types cavities at two different frequencies (six and three if ILC cavities are used); the objective is to produce couplers that are as simple, reliable, and universal as possible.

All cryomodules in the low-energy part of the linac (325 MHz) are separated by short RT sections. This arrangement (i) allows for easier maintenance and reliability, (ii) provides space for beam profile diagnostics or halo cleaning. The first high energy section (650 MHz $\beta = 0.61$) is assembled from cryomodules comprising two groups of 3 cavities separated by a SC doublet. A separate warm doublet is positioned between cryomodules, preserving the 3 cavities-1 doublet pattern. In the $\beta = 0.9$ section, each cryomodule comprises 8 cavities. In that case, the warm doublets are always located between cryomodules. Counts for each section are presented in Table .

LATTICE AND BEAM DYNAMICS

The lattice design is based on principles summarized below; the transverse and longitudinal envelopes are shown in Fig. 2. The focusing period length is kept short, especially in the front end. Transversely, the beam envelope transverse dimensions are kept as uniform as possible. The transverse phase advance is set to start at about 90° per cell (at zero current) at the beginning of each section and is allowed to decrease down to about 20° at the end of a section. Longitudinally, the bunch length decreases monotonically. To minimize the potential for mismatches arising from pertubations (e.g. change in current) the wavenumbers change smoothly and monotonically (Fig. 4). Abrupt changes in the longitudinal synchronous phase are avoided to prevent corresponding variations in transverse rf focusing strength. The ratio of longitudinal to transverse phase advance is kept in the range 0.6-0.8 to avoid exciting the $n = 1$ parametric resonance between longitudinal and transverse planes. Emittance exchange between these planes via space-charge resonances is prevented either by providing beam equi-partitioning or by avoiding unstable areas in Hofmann stability charts.

Proper matching in the transitions between sections is critical to avoid exciting envelope oscillations and halo formation. Matching between sections is achieved by adjusting parameters of the outermost elements of each section (solenoid or doublet fields, and rf phase). At a frequency jump, a reduction in bunch length is achieved, at the cost of some loss in acceleration efficiency, by setting the synchronous phase toward -90° in one or more of the upstream cavities.

For lattice design and beam physics studies, we use a number of simulation and design codes, including TRACK [9], GenLinWin, TraceWin [10] and ASTRA. For the current favoured lattice, we assumed 5 mA peak current at 162.5 MHz with an emittance ratio $(\epsilon_{n\ell}, \epsilon_{nt}) = (0.25, 0.275)$ mm-mrad at the entrance of linac. The emittance values were determined from RFQ simulations. Both TRACK and TraceWin predict no transverse emittance growth and less than 10% longitudinally in the design (error free) lattice, which is an overall indication of the quality of the matching. The Hofmann stability chart for a longitudinal to transverse emittance ratio of $\epsilon_{nt}/\epsilon_{n\ell} = 1.1$ shows that phase advances stay away from space charge resonances. In earlier iterations of our lattice, losses were somewhat sensitive to rf errors; losses at at level > 0.1 W/m would be observed in simulations with 1% amplitude and 1° phase jitter. The issue was traced to a longitudinal acceptance restriction in the last cells of the SSR2 section, just before the jump in frequency. The current lattice reflects careful longitudinal rematching and optimizations. The result can be seen in Fig. 3: the ratio $|\phi_s|/\sigma_\phi$ which used to dip to 5 just before the frequency jump now remains > 10 everywhere. The required RF power never exceeds 20 kW per cavity and the estimated cryogenic losses remain below 24 W per cavity. The magnetic gradient in the doublets is moderate ($<$ 10 T/m with a quad aperture of 100 mm). The effects of misalignments as well as those of cavity amplitude and phase jitter were principally studied using the TRACK code. Simulations indicate that, for our current favoured lattice, magnets alignment tolerances should be better than 500 μm. Left uncorrected, such tolerances result in beam centroid motion on the order of 10 mm and losses on the order of a few 0.1 W/m Assuming each transverse focusing element has a hor/ver corrector and a corresponding (or built-in) BPM with a resolution $\simeq 30\ \mu$m or better it is a straightforward matter to limit the beam centroid motion to a fraction of mm using the one-to-one correction algorithm implemented in TRACK. Post correction, no losses due to misalignments are observed. The most significant errors affecting the Project X CW linac will likely be dynamic amplitude and phase jitter for which no correction is possible. With that type of errors, TRACK simulations show that losses above 0.1 W/m begin to appear when $(\delta E/E, \delta\phi) = (1.5\%, 1.5°)$, assuming independent amplitude and phase error distributions. This represents a noticeable improvement over earlier versions of our lattice and as mentioned earlier, can mostly be attributed to higher longitudinal aperture to bunch length ratio at the downstream end of the SSR2 section compared to earlier iterations. Additional details about losses and simulations are provided in a companion contribution presented at this conference [11].

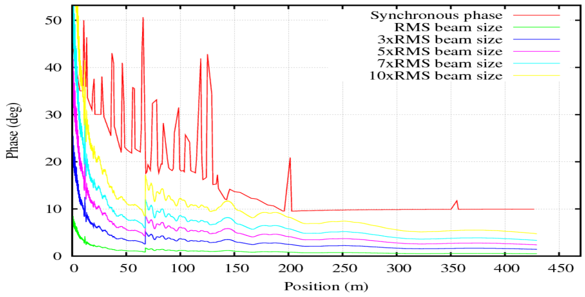

Figure 3: Bunch length and ϕ_s along the linac.

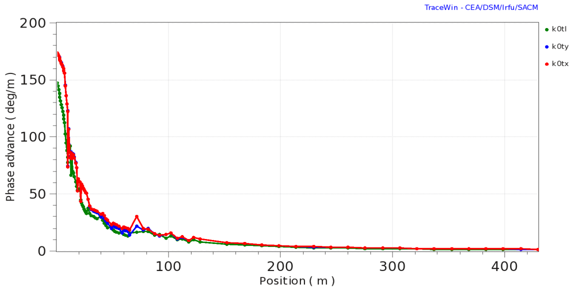

Figure 4: Structural wavenumber along the linac.

In contrast with protons, H^- ions are subject to ionization in the linac. The main physical mechanisms are: scattering with residual gas, resonant excitation by blackbody radiation, ionization by magnetic and electric fields from magnets and cavities and intra-beam stripping [13]. The results can be summarized as follow: assuming a mixture of 25% N, 25% O and 50 % H, losses due to residual gas stripping are below 0.1 W/m if the vacuum pressure in the linac is below 10^{-8} Torr at 300°K. Stripping caused by the magnetic field of solenoids and quadrupoles remains well below 0.1 W/m, even with an unrealistically large 5 mm beam offset. Stripping due to blackbody radiation is not an issue at liquid He temperatures, though the losses due this mechanism become significant in a 3 GeV room temperature transport line. Intra-beam stripping, as described in [12], was initiallya source of concern. Intra-beam striping rates were estimated for CW lattice variants assuming independent equilibrium Gaussian phase space distributions. The predicted losses are slightly below 0.1 W/m. Nevertheless, the issue deserves additional attention; a dedicated experiment is planned at the SNS.

SUMMARY

The conceptual design of the CW superconducting H- linac for 3GeV, 1mA beam, proposed for Project X is rapidly converging. The high bandwidth chopper remains a significant challenge and requires additional development and refinement. For the near future, we plan additional iterations and further optimizations with special attention paid to instrumentation, diagnostics correction and collimation schemes.

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