STATUS OF THE PROJECT-X CW LINAC DESIGN*

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Abstract

Project-X is a proposed proton accelerator complex at Fermilab that would provide particle beams to support a diversified experimental program at the intensity frontier. As currently envisioned, the complex would employ a CW superconducting linac to accelerate a 1 mA average, 5 mA peak H^- beam from 2.1 MeV to 3 GeV. A second superconducting linac, operating in pulsed mode would ultimately accelerate a small fraction of this beam up to 8 GeV. The CW linac is based on five families of resonators operating at three frequencies: half-wave (1 family at 162.5 MHz), spoke (2 families at 325 MHz) and elliptical (2 families at 650 MHz). Accelerating and focusing elements are assembled in cryomodules separated by short warm sections. A long open region ($\sim$ 15 m) allows beam extraction at 1 GeV in support of a nuclear experimental program. In this paper, we present the latest iteration of the CW linac baseline lattice. We also briefly compare it to an alternative where the 162.5 half-wave resonators are replaced with 325 MHz spoke resonators.

INTRODUCTION

The Project-X 3 GeV linac operates in CW mode. The front-end MEBT incorporates a high bandwidth chopper with the ability of rejecting single bunches. In conjunction with CW operation, this chopper enables a variable, flexible bunch structure that can simultaneously accommodate the needs of a variety of experiments. The beam structure can be complex; the sole requirement is that the average current over a time interval $T \sim \frac{Q_L}{2\omega_0}$ remains 1 mA. While the overall linac concept is now relatively mature, details are still evolving. We will highlight recent developments.

Two recent and related decisions provided the motivation for the current lattice iteration. The first one is to use 162.5 MHz half-wave resonator technology from Argonne National Laboratory to handle acceleration from 2.1 to 10 MeV. The considerations that led to this change were many and include improved acceleration efficiency and taking advantage of ANL's expertise and infrastructure for fabrication. The second decision is to build a test facility[1], dubbed PXIE (Project X Integrated Experiment), to validate the concept of wide bandwidth chopping in the MEBT and better understand a number of technical risks. PXIE comprises a source, LEBT, MEBT followed by one 162.5 MHz cryomodule (HWR) and one 325 MHz (SSR1) cryomodule. It is our intent to eventually reuse parts of the PXIE infrastructure for Project-X.

In the interest of allowing PXIE to fit into existing available space, minimize its cost and eventually that of the Project-X CW linac itself, our current lattice attempts to make maximum use of the available cavity gradient and to accelerate rapidly, even if this means deviating from usual design rules. This is discussed in details later.

A high level block diagram of the linac layout, starting, for completeness, at the ion source, is shown in Fig. 1. Relevant details for each regular sections are summarized in Table 1. Overall transverse and longitudinal rms beam envelopes are shown in Fig. 2.

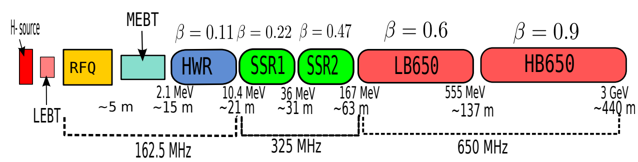

Figure 1: High Level Block Diagram of the 3 GeV CW Linac.

Table 1: Details of Linac Sections. Key: CM: Cryomodule; D: Doublet, S: Solenoid, R: Resonator, R^n: n-Resonators Sequence.

Section	**f[MHz]**	**Cav/mag/CM**	L_{CM}**[m]**	**Cell**
			w/o flanges	
HWR	162.5	8/8/1	5.26	S-R
SSR1	325	16/8/2	4.76	R-S-R
SSR2	325	36/20/4	7.77	S-R^2
LB650	650	42/14/7	7.1	R^3-D
HB650	650	152/19/19	11.21	D-R^8

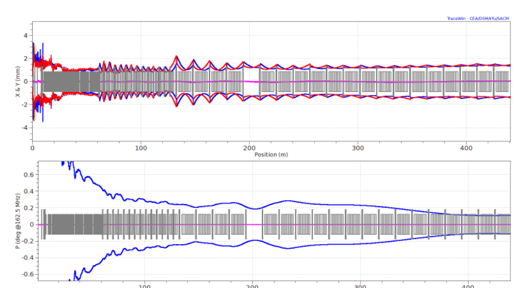

Figure 2: Beam Envelopes.

SOURCE AND RFQ

The design of the source subsystem, including the RFQ, is led by LBNL. The ion source –which has been fabricated and tested– nominally supplies 5 mA of H^- at 30 keV continuously. It is followed by a LEBT section whose primary function is to match the beam into a RFQ operating at 162.5 MHz. Beam chopping is provided in the LEBT primarily to reduce beam power during machine commisioning and

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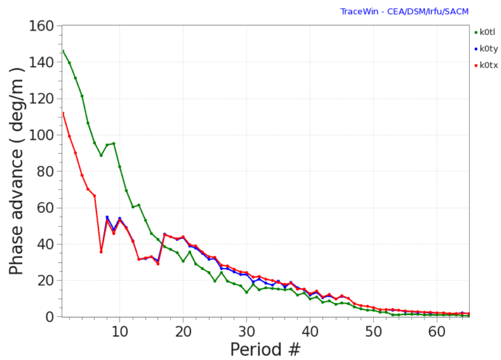

Figure 3: Structural phase advances along the CW linac.

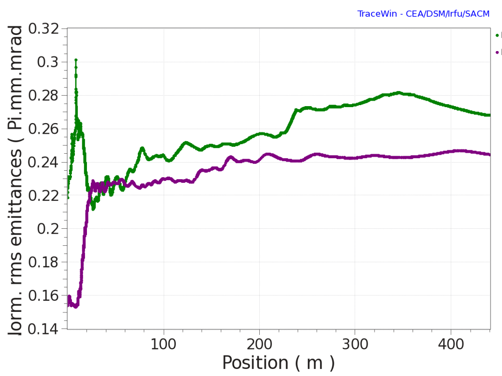

Figure 4: RMS emittances along the CW linac.

tuning. The RFQ is approximately 4-m long, and accelerates the beam from 30 keV to 2.1 MeV in CW mode. The output energy was selected to lie below the neutron production cross-section threshold in Cu. Beam transverse and longitudinal emittances at the RFQ output are expected to be 0.15 and 0.22 mm-mrad respectively, under nominal operating conditions. These values are derived from RFQ simulations using as input the measured distribution with (transverse) emittance of 0.11 mm-mrad.

MEBT

Details of the MEBT concept and operation are presented elsewhere. We only mention here two significant changes. The first is a decision to shorten and simplify the MEBT by using a 2 kicker configuration where both the rejected and the transmitted beam are kicked. The second is to use 162.5 MHz quarter wave resonators rather than 325 MHz cavities as bunchers. This provides longitudinal acceptance better matched to that of the new downstream 162.5 MHz HWR section. Although the 162.5 MHz cavities are physically larger, they consume about half the power (< 2 kW vs 5 kW).

HWR SECTION

Previous iterations[2] of the CW linac lattice were based on three families of 325 MHz single spoke resonators with $\beta_g = 0.12, 0.22, 0.40$ respectively labelled SSR0, SSR1 and SSR2. In the current lattice, the SSR0 section is completely replaced with a new one based on 162.5 MHz half-wave resonators. The HWR section comprises a single 6m cryomodule and uses 8 half-wave resonators to accelerate the beam from 2.1 to 10.3 MeV. Cavity failure is most difficult to handle in the HWR section; it is important to ensure that operations can proceed. Fig. 5 shows the beam envelopes after retuning neighbouring elements following hypothetical failure of the (most critical) first cavity in the HWR cryostat. A cavity failure in a downstream higher energy cryomodule can be handled in a similar manner, with less difficulty.

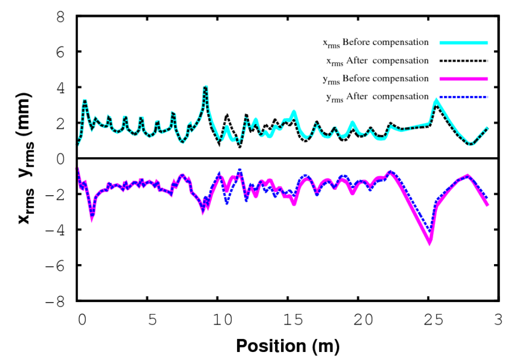

Figure 5: Envelopes in HWR section after reconfiguration to compensate for failure of the first cavity.

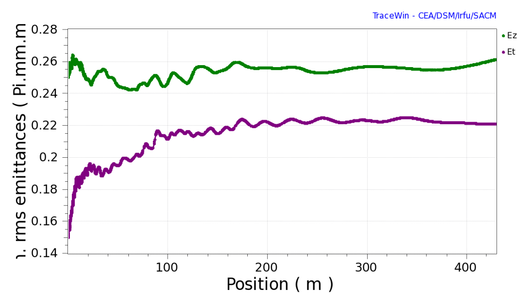

Figure 6: Emittance evolution in SSR0 lattice variant.

SSR1 AND SSR2 SECTIONS

These sections are based on 325 MHz single-spoke cavities developed at Fermilab. The SSR1 section comprises 2 cryomodules spanning 4 periods each. The SSR2 section comprises 4 cryomodules spanning 9 periods each. Both sections employ solenoids for transverse focusing. Of note is that in contrast with previous lattices, an SSR1 period now contains two cavities rather than one. The SSR2 cavity, which in previous iterations had $\beta_g = 0.40$ has also been re-optimized to $\beta_g = 0.47$. The transitions upstream of SSR1 and downstream of SSR2 both involve frequency jumps; from a matching standpoint, the transition between SSR2 and LE650 is delicate since it also involves a change from solenoidal to magnetic doublet focusing; matching is accomplished with independently powered doublet magnets in the first cell of the LE650 section.

LB650 AND HB650 SECTIONS

Both (“low beta”) LB650 and (“high beta”) HB650 sections are based on cavities operating at 650 MHz. The LB650 section uses $\beta_g = 0.6$ cavities to accelerate the

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beam from 165.4 to 556.2 MeV. In the HB650 section – based on $\beta_g = 0.9$ cavities – the beam ultimately reaches a final energy of 3 GeV. Cavities in both the LB650 and HB650 sections are elliptical 5-cell designs. Starting in the LB650 section, transverse focusing is handled by quadrupole doublets. The doublets are all superconducting, with the exception of those belonging to the last period of each cryomodule which are located outside and operate at room temperature, providing natural locations for collimation.

To accommodate a possible 1 GeV nuclear physics program, a 15 m open region is provided between the fourth and fifth cryomodule of the HB650 section. The length is approximate and based on reasonable assumptions about the available extraction kick and the space needed to allow the beam to clear the downstream cryostat. Cavities in two cryomodules upstream and in two cryomodules downstream of the open region were adjusted so as to produce a waist at the center of the open region. The latter, clearly visible at 200 m on the envelope plot, was introduced without changing the linac cavity count by primarily using the synchronous phases as matching variables. At 1 GeV, the synchronous phase in a regular period tends to be close to the crest (typically around $-10°$). Since the longitudinal focusing strength is proportional to $\sin\phi_s \simeq \phi_s$, small changes in synchronous phase are quite effective; a few modest field amplitude changes are needed only when reducing an already low $|\phi_s|$ further would compromise the longitudinal acceptance.

BEAM DYNAMICS

Theoretically, in the presence of space charge, envelope oscillations are unconditionally stable only when the structural phase advances $\sigma_{\ell 0}, \sigma_{t0} < 90°$. In addition, to inhibit single particle synchro-betatron parametric resonances, one usually chooses $\sigma_\ell < \sigma_t$. Since longitudinal focusing is proportional to field amplitude, a limit on structural phase advance is effectively a limit on acceleration. In high peak current machines, $\sigma_{\ell 0}$ is conservatively kept below 90° even though the permissible advance is actually higher and depends on the tune depression. Our modest peak current of 5 mA makes it possible to increase $\sigma_{\ell 0}$ beyond the conservative limit in the HRW and SSR1. Therefore, in these sections the longitudinal structural phase advance per period now starts around 100° and 115° respectively. To get stable transverse envelopes and to avoid exceeding a practical field limit for the solenoids ($\sim$ 6 T), the corresponding transverse structural advances start at 90°. While having $\sigma_t < \sigma_\ell$ may excite 2nd order synchro-betatron resonances, the later are weak. Plots of the structural phase advances per unit length are presented in Fig. 3. At period 19 (the entrance of the SSR2 section), there is a "cross-over" and the transverse phase advance becomes greater than its longitudinal counterpart, the more conventional choice.

Aggressive acceleration in the first two initial sections of the linac comes at some cost. Fig. 5 shows the computed longitudinal and transverse rms emittances along the linac assuming a 6-σ Gaussian beam distribution. Emittance exchange is clearly taking place at low energy, within the first 12 periods or so. The net transverse emittance growth remains modest and although the transverse beam size increases a bit, tracking simulations including errors show no evidence of problematic halo formation downstream [3].

For comparison purposes, Fig. 6 shows the emittance evolution plot for an alternative lattice where acceleration from 2.1 to 10.3 MeV is handled in a section labelled SSR0 based on 325 MHz spoke cavities. In that variant, the longitudinal acceleration takes place more smoothly, over a total of 18 periods; in addition, the SSR1 period contains a single cavity. Fig. 7 shows the corresponding phase advances per m. The structural longitudinal advances per period at the start of the SSR0 and SSR1 are 90° and 74°. No significant emittance exchange is visible in Fig. 6; however the final emittances are comparable to those in Fig. 4. Not surprisingly, statistical studies show that the sensitivity of losses to errors in the newer lattice with aggressive acceleration is greater than for the SSR0 variant [3].

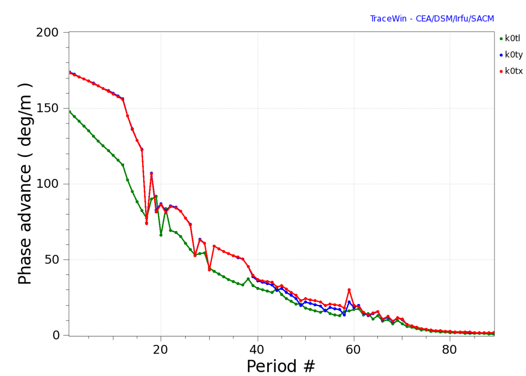

Figure 7: Structural phase advances in SSR0 variant of the CW Linac.

CONCLUSION

The latest iteration of the Project-X CW linac lattice provides rapid acceleration at low energy. It appears that a design deviating from traditional rules can keep losses below a safe level albeit at the cost of increased sensitivity to errors. Future iterations will focus on firming up these conclusions and implementing adjustments to produce the best possible compromise between cost and operational performance. Experimental measurements of beam distributions and particle losses performed at the PXIE facility will also be used to validate simulations.

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