LATTICE DESIGN AND BEAM DYNAMICS STUDIES FOR PROJECT-X*

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Abstract

Project-X is a proposed proton accelerator complex at Fermilab 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). We discuss the latest iteration (v 6.0) of the CW linac baseline lattice.

INTRODUCTION

From 2.1 MeV up to 3 GeV, Project X employs SC linac technology operating in CW mode. The front-end MEBT incorporates a high bandwidth chopper with the ability to reject individual bunches. In conjunction with CW operation, this arrangement enables a variable and flexible bunch structure that can simultaneously accommodate a variety of experiments. The (multiplexed) beam structure can be quite complex; however, the average current over a time interval $T \sim \frac{Q_L}{2\omega_0}$ must remain 1 mA. While the overall concept is by now relatively mature, details are still evolving.

Some recent developments are worthy of mention. The first one is the decision to rely on 162.5 MHz half-wave resonator technology from Argonne National Laboratory to handle acceleration from 2.1 to 11 MeV. The considerations that led to this decision were many and include improved acceleration efficiency and longitudinal acceptance. It also allows the project to leverage ANL's expertise and infrastructure for fabrication. The second is the decision to build a test facility[1], dubbed PXIE (Project X Injector Experiment), to validate the concept of wide bandwidth chopping in the MEBT and to mitigate technical risks. PXIE comprises the ion source, LEBT and MEBT followed by one 162.5 MHz cryomodule (HWR) and one 325 MHz (SSR1) cryomodule. The intent is to maximally re-use the PXIE infrastructure for Project-X. In the interest of allowing PXIE to physically fit into existing available space and to minimize its cost – and eventually that of the Project-X CW linac itself – our recent lattice iterations strive to make maximum use of available cavity gradient even at the expense of some deviation from traditional design rules. Finally, it is becoming clear that in the current budgetary context the 3 GeV CW linac should be planned and build in stages. The existence of a compelling nuclear physics experimental program at 1 GeV makes this energy a logical choice for a first stage. Our most recent lattice iterations therefore assume 1 GeV as output energy. The default option for acceleration from 1 to 3 GeV would be to continue with cryomodules based on $\beta_g = 0.9$, 650 MHz cavities, as described in [3]. Recently, a number of other projects including NGLS at LBNL and X-FEL at DESY have been seriously looking into CW operation with 1.3 GHz ILC-style cavities. Given the larger size and overall cost of 650 MHz cavities, standardized CW 1.3 GHz technology and power sources from 1 to 3 GeV might prove a better and more cost-effective choice. We intend to study this option at a later time.

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LINAC LAYOUT

A high level block diagram of the latest linac layout (dubbed "v6.0"), 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.

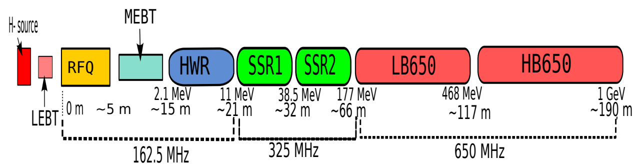

Figure 1: High Level Block Diagram for the (stage 1) 1 GeV CW Linac.

Table 1: Details of Linac Sections. Key: CM: cryomodule; D:doublet, S:solenoid, R:resonator, R^n: n-resonator sequence.

Section	f[MHz]	Cav/mag/CM	Period [m]	Cell
HWR	162.5	8/8/1	0.686	S-R
SSR1	325	16/8/2	1.250	R-S-R
SSR2	325	36/20/4	1.720	S-R^2
LB650	650	30/20/5	5.1	D-R^3
HB650	650	40/10/5	14.3	D-R^8

Ion source, LEBT, RFQ and MEBT

The ion source –which has been obtained from industry 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 tuning. The 4.4 m RFQ, which is designed and ready for

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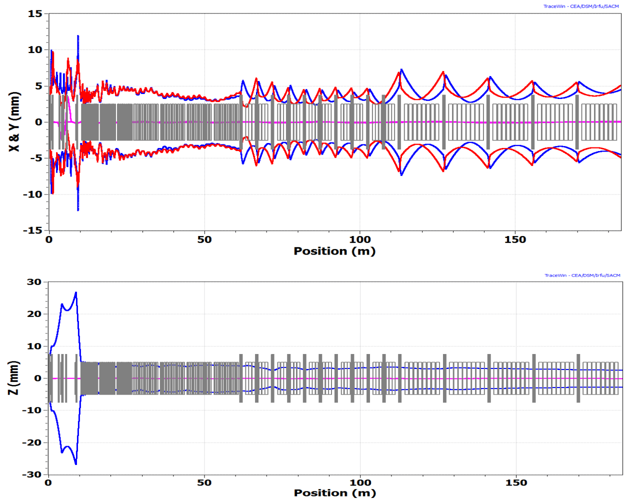

Figure 2: Beam Envelopes.

fabrication, accelerates the beam from 30 keV to 2.1 MeV in CW mode. Both the LEBT and RFQ are designed and constructed by LBNL, which is also responsible for the integration of the source. The output energy was selected to lie below the neutron production cross-section threshold in Cu. The beam transverse and longitudinal emittances at the RFQ output are expected to be 0.15 and 0.21 mm-mrad respectively, under nominal operating conditions. These values were obtained from simulations by tracking a distribution matching the *measured* beam parameters downstream of the ion source all the way to the RFQ output.

Details of the MEBT concept and operation have been presented elsewhere [2]. We only mention here two significant changes. The first is a decision to shorten and simplify the MEBT by using a two, rather than four, kicker configuration; with this configuration both the rejected and the transmitted beam are kicked. The second is to use 162.5 MHz rather than 325 MHz quarter wave bunchers. This results in a longitudinal acceptance better matched to that of the downstream 162.5 MHz HWR section; furthermore, although 162.5 MHz cavities are physically larger, they consume about half the power (< 2 vs 5 kW) of the 325 MHz versions.

HWR, SSR1 and SSR2 Sections

The HWR section comprises a single 6 m cryomodule and uses eight half-wave resonators to accelerate the beam from 2.1 to 11 MeV. The SSR1 sections comprises two cryomodules, each spanning four periods. The SSR2 sections consists of four cryomodules spanning four and a half periods each. Both sections are based on 325 MHz single-spoke cavities developed at Fermilab and employ solenoids for transverse focusing. The transitions upstream of SSR1 and downstream of SSR2 both involve two-fold frequency jumps; from a matching standpoint, the transition between SSR2 and LE650 is delicate since it also involves a change from solenoidal to quadrupole doublet focusing.

LB650 and HB650 Sections

Both the ("low beta") LB650 and the ("high beta") HB650 sections are based on 5-cell elliptical cavities operating at 650 MHz. The LB650 section uses $\beta_g = 0.6$ cavities to accelerate the beam from 177 to 468 MeV. An LB650 cryomodule spans two periods. While the first doublet is external and warm, the second is superconducting. In the HB650 section –based on $\beta_g = 0.9$ cavities – the beam ultimately reaches a final energy of 1 GeV; each HB650 cryomodule spans almost a single period (contains only cavities). Transverse focusing is handled by warm quadrupole doublets which provide natural locations for collimation and instrumentation. Matching from the upstream SSR2 into LE650 section is accomplished using independently powered magnets in the first doublet of the LE650 section. A notable change in this current v6.0 iteration with respect to the v5.3 iteration [3] is that the last two cryomodules of the LB650 sections ($\beta_g = 0.6$) have been replaced with a single ($\beta_g = 0.9$) HB650 cryomodule, resulting in a reduction by four in cavity count and by one in cryomodules. While the transit time factor is now a bit less favorable in the first HB650 cryomodule, the loss in acceleration was easily compensated by slightly raising the field in the downstream cavities.

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 effectively sets a limit on achievable acceleration. In high peak current machines, $\sigma_{\ell 0}$ is generally conservatively kept below 90° even though the permissible advance is actually higher at low tune depression. Our modest peak current of 5 mA ($\frac{\sigma}{\sigma_0} \simeq 0.75$) provides some headroom to increase $\sigma_{\ell 0}$ beyond 90°/period in the HWR and SSR1 sections. Accordingly, the longitudinal struc-

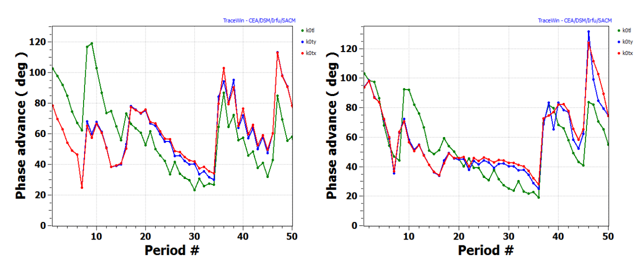

Figure 3: Structural phase advances along the CW linac.

tural phase advance per period starts around 100°. To get stable transverse envelopes and to avoid exceeding a practical field limit for the solenoids ($\sim$ 6 T), the corresponding transverse structural advances cannot initially be higher than the longitudinal. While having $\sigma_t < \sigma_\ell$ may excite 2nd order synchro-betatron resonances, the later are weak.

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Plots of the structural phase advances per period, for both the v5.3 (left-hand side) and current v6.0 (right hand side) lattice iterations are shown in Fig. 3. Using the cavity synchronous phase settings as an estimate of bucket half-width (i.e. longitudinal "aperture"), the latter is greater than $8\sigma_\phi$ in v6.0. This is an improvement over v5.3. where this ratio was somewhat smaller. Both lattices exhibit a "cross-over" point where the transverse phase advance becomes greater than its longitudinal counterpart. For the v5.3 lattice, the cross-over occurs at period no 16 (the entrance of the SSR2 section); in v6.0 it occurs later at period no 20, translating into a reduction in longitudinal phase advance in both the SSR1 and SSR2 sections. One of the objectives in v6.0 was to eliminate the emittance exchange observed in v5.3 and apparent in Fig. 4 which compares rms emittance growth in both lattices with v5.3 on the left-hand side. Fig. 5 compares Hofmann diagrams for v5.3 (left-hand side) and the current v6.0 (right-hand side) lattices. Note that while the v5.3 lattice had a few periods in high exchange rate regions, v6.0 has none. Furthermore, as seen on the right hand side of Fig. 4, emittance exchange has disappeared in v6.0. While emittance exchange is not always problematic, it does result in an increase in transverse beam size; avoiding it is preferable.

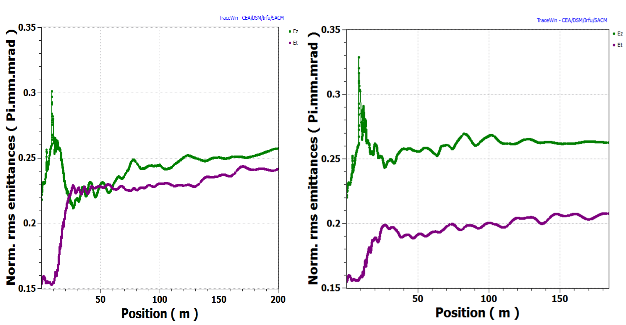

Figure 4: RMS emittances along the CW linac.

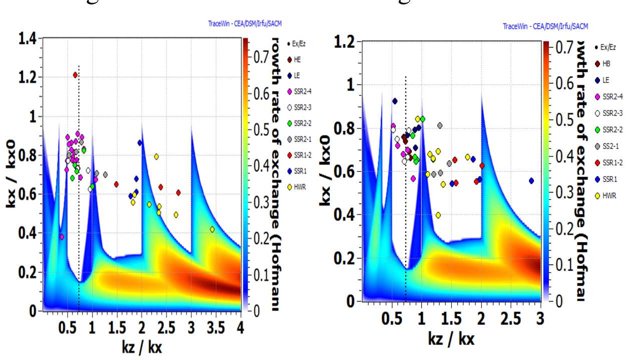

Figure 5: Hofmann Diagrams.

STATISTICAL ERROR ANALYSIS

Using the code TRACK from ANL, statistical errors studies were performed on the the FermiGrid computers. For each type of error(s) –individually and in combination– statistics from a total of 400 linacs were compiled, except for longitudinal errors where the number of linacs considered reached 5000. With a low energy beam directly injected into high gradient superconducting cavities, tolerances on dynamic rf phase and amplitude errors are expected to be an issue. No loss is observed at 0.5 deg, 0.5%; however at 1 deg, 1% 20 out of 5000 seeds cause beam losses in excess of a few W/m; in a few of those instances a significant fraction of the beam is lost. While dynamic phase and amplitude control is expected to be significantly better than 1 deg, 1%, these results suggests a possible resonant excitation. One issue is that the ratio of the longitudinal and transverse phase advance per period in the HWR section is probably too close to 1. Additional tuning will be performed in future iterations based on analysis of the problematic seeds. Preliminary runs performed to study focusing errors indicate that losses begin to appear when errors reach the 1 % level. Quadrupole misalignments have not been studied but the tolerances are expected to be similar to those of the solenoids.

Table 2: Losses due to Errors. Average over 400 Linacs

Element	Err. Type	Value	Avg. Loss (%)
Sol	δ_{xy}	$100\,\mu m$	0
Sol	δ_{xy}	$200\,\mu m$	0
Sol	δ_{xy}	$300\,\mu m$	3×10^{-3}
Sol	δ_{xy}	$400\,\mu m$	1.6×10^{-1}
Sol	δ_{xy}	$500\,\mu m$	5.7×10^{-1}
Cav	$\delta_\phi + \delta_E$	$0.5^\circ + 0.5\%$	0
Cav	$\delta_\phi + \delta_E$	$0.5^\circ + 1.0\%$	1.8×10^{-2}
Cav	$\delta_\phi + \delta_E$	$0.5^\circ + 1.5\%$	1.15
Cav	$\delta_\phi + \delta_E$	$0.5^\circ + 2.0\%$	6.25
Cav	$\delta_\phi + \delta_E$	$2.5^\circ + 2.5\%$	15.5

CONCLUSION

The Project-X CW linac lattice has been re-optimized to avoid emittance exchange, improve longitudinal aperture and reduce longitudinal phase advance. The latest lattice assumes a final energy of 1 GeV. The cryomodule count has been reduced by one by replacing the last two LB650 cryomodules with a single HB650 cryomodule. For a second phase, (1-3 GeV), the default plan is to use HB650 cryomodules and cavities; however, recent developments indicate that CW technology at 1.3 GHz might be worth pursuing. This will be the subject of future studies.

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