SEGMENTATION IN THE PROJECT-X LOW ENERGY CW LINAC FRONT END *

J-F. Ostiguy†, N. Solyak and B. Shteynas
Fermilab, Batavia, IL, USA

Abstract

The low-energy front-end of the Project-X 2.5 MeV-3 GeV linac utilizes superconducting single-spoke resonators for acceleration and solenoids for transverse focusing. To take maximum advantage of the available accelerating field in the cavities, it is necessary to minimize the period length. This leads to a compact arrangement of cavities and solenoids with minimal available open longitudinal space. While beam position monitors and correctors can be integrated to solenoid assemblies inside a cryostat, instrumentation –e.g beam profile monitors– require some dedicated longitudinal space. In this paper, we describe an arrangement where the front-end is segmented in cryostats comprising about half a dozen lattice periods separated by longitudinal space ”gaps”. We discuss the impact of introducing such gaps and present an optical solution integrating them. The strategy and constraints leading to this solution are outlined.

INTRODUCTION

Project-X is proposed high-intensity proton (H^-)accelerator complex that would support a diverse physics program. The facility would simultaneously provide beam at different energies and with a different time structure to a number of experiments, including 3 GeV protons to kaon- and muon-based precision experiments. In addition, it would provide higher energy protons to create high-intensity neutrino beams for neutrino oscillation experiments such as NOvA and the Long Baseline Neutrino Experiment. The current concept involves two stages of linac acceleration. The first stage is a superconducting, 2.1 MeV to 3 GeV CW machine. A fraction of the beam emerging from this linac would be multiplexed, using rf separators to a number of experiments; the balance would be accelerated in a second, pulsed superconducting linac from 3 to 8 GeV and subsequently injected for accumulation and further acceleration into the existing Main Injector accelerator complex. Aside from providing inherently superior stability, CW operation allows for considerable flexibility in beam temporal structure. In practice, the main limitation is the performance of a high bandwidth beam chopper located upstream, in the MEBT section.

In contrast with conventional DTL structures, low beta superconducting structures such as spoke and half-wave resonators can efficiently produce very high accelerating gradients. Unfortunately, high gradient also implies strong longitudinal focusing. In the presence of space charge forces, allowing the intrinsic (zero current) betatron phase advance per spatial period (either longitudinal or transverse) σ_0 to exceed 90° can drive an envelope instability.

Given the ”softness” of the beam at low energy, the constraint on the longitudinal phase advance dictates an arrangement of cavities and transverse focusing elements that is, in the low energy front-end, longitudinally as compact as possible. Superconducting solenoids are the focusing element of choice in that context, as their pure radial focusing compensates for the radial rf and space charge defocusing forces. Although nearly radial focusing may also be obtained with quadrupole doublets or triplets, for a given net focusing strength, the arrangement is not as compact. More problematic is that to deliver enough net focusing, the transverse magnetic field in neighbouring quadrupoles of a multiplet needs to be rather high, leading to magnetic stripping losses.

In practice, a superconducting proton linac comprises a number of sections optimized for a suitably chosen relativistic β. Each section in turn, is assembled from a number of cryo-modules encompassing N periods. For practical reasons, a cryomodule length is limited to a maximum of $\sim$ 10 m. Longitudinal gaps (either warm or cold) between cryomodules may be required in order to accommodate not only mechanical interconnections but also collimation and/or instrumentation. The introduction of open longitudinal space in the linac lattice perturbs the periodicity and is especially problematic at low energy.

OPTICS REFRESHER

In a linear optical system, the beta function (in any plane) in a drift space obeys the relation

$$\beta(z) = \beta^* + (z - z^*)^2/\beta^* \qquad (1)$$

where β^* and z^* are respectively the value of the beta function and the position at the location of the beam waist. This result can easily be derived by substituting the ansatz

$$x(z) = \sqrt{\beta(z)\epsilon}\cos\int_0^z \frac{dz}{\beta} \qquad (2)$$

into the equation of motion

$$x'' + k^2(z)x = x'' = 0 \qquad (3)$$

since $k(z) = 0$ in a drift region. For convenience, one can choose the origin of z to coincide with the waist and and the coordinates of the extremities of the open region to be respectively $-L_1$ and L_2. Then, for a fixed value of

---

[*] Work supported by DOE under contract DE-AC02-07CH11359.

[†] ostiguy@fnal.gov

L_1 the minimum value of the beta function at the upstream extremity occurs when

$$\frac{d\beta}{d\beta^*} = 1 - \frac{L_1^2}{\beta^{*2}} = 0 \; \beta^* = L_1, \; \beta = 2L_1 \tag{4}$$

and similarly for the downstream extremity. Clearly, a minimal extremal β for the entire open region is obtained in the symmetric case where $L_1 = L_2 = L$ i.e. when the waist is located in the center of the open region. In that case one has:

$$\frac{\beta(\pm L)}{\beta^*} = \frac{2L}{2} = 2 \tag{5}$$

which in terms of rms beam size corresponds to a ratio $\frac{\sigma}{\sigma^*} = \sqrt{2}$. Again, with $L_1 = L_2 = L$, if one is willing to accept $\beta > L$ at the extremities of the open region, there are two possible solutions for β^*. Inserting $z = L$ into the relation (1) yields

$$\beta^{*2} - \beta(L)\beta^* - \beta^{*2} + L^2 = 0 \tag{6}$$

and therefore

$$\beta^* = \frac{\beta(L)}{2} \pm \sqrt{\beta^2(L) - 4L^2} \tag{7}$$

this result confirms that $\beta(L)$ can never be smaller than $2L$ (β^* must be real). It should be reiterated that the results in this section apply either to the longitudinal or the transverse planes.

CONSTRAINTS

To produce smooth beam envelopes with slowly varying amplitudes, linacs are generally designed so that the wavenumbers (i.e. phase advances per unit length) decrease monotonically and adiabatically. This quasi-periodic optics ensures minimal sensitivity to errors and perturbations. Transversely, the acceptance is limited by the bore of cavities and/or the physical elements; while longitudinally, the synchronous (accelerating) phase plays the role of the physical aperture i.e. particles with amplitudes $> |\phi_s|$ are lost.

Optimally, one would like to minimize the impact of a longitudinal gap on the beam envelope i.e. allow it to remain as uniform as possible, This implies minimizing the beam size ratio $\sigma(\pm L)/\sigma(z)$ while keeping $\sigma(z)$ as close as possible to the value it would assume without the extra space. Assume that $\beta(\pm L)$ is fixed and chosen so that $\sigma = \sqrt{\beta\epsilon}$ lies within the available aperture. Then (7) shows that the *maximum achievable distance* is $2L = \beta(\pm L)$ with $\beta^*/\beta(\pm L) = 0.5$. Of course, if $L < 2$, $\beta(\pm L)$ then, $0.5 < \beta^*/\beta(\pm L) < 1$.

Space Charge and Nonlinear Focusing

In the presence of space charge, the rms envelope equation (transversely or longitudinally) takes on the form

$$R'' - \frac{K}{R} - \frac{\epsilon}{R^3} = 0, \quad R = \sqrt{\beta\epsilon} \tag{8}$$

where $K = \frac{2e\hat{I}}{mc^3\beta^3\gamma^3} > 0$. Rearranging a bit, one gets

$$R'' - \frac{KR^2 + \epsilon^2}{R^3} = R'' - \frac{\hat{\epsilon}^2}{R^3} = 0, \quad \hat{\epsilon} > \epsilon \tag{9}$$

which shows that provided space charge is a small enough perturbation, its effect is roughly equivalent to a relative emittance increase $\sqrt{K}R/\epsilon$. At fixed aperture, this reduces the maximum allowable β value at the extremities of the gap, and, consequently, the maximum achievable gap. Transversely, the focusing strength remains, to a very good approximation, linear. In contrast, longitudinally, especially at low energy where the bunch is longest and tends to occupy a more significant fraction of the available rf phase acceptance, the nonlinear focusing due to rf curvature is noticeable. Asymmetric focusing with respect to the bunch center triggers centroid oscillations. Nonlinearity also causes an increase in emittance that may result in particle loss downstream.

PRACTICAL REALIZATION

As a practical application, we applied our analysis to the problem of segmenting the lowest energy section of the current version of the Project-X CW linac. Fig. 1 shows a concept of a lattice for the so-called SSR0 section of the linac, which is responsible for acceleration from from 2 to 10 MeV. An ideal, spatially periodic version of the section lattice ignoring segmentation would be constituted of 18 cells, each made of one solenoid followed by a 325 MHz single-spoke resonator. To introduce gaps, this arrangement was divided into three cryostats each containing seven periods followed by an additional solenoid for a total of 8 solenoids and 7 cavities per cryostat. So as to minimally perturb the transverse periodicity the length of the two longitudinal gap between cryomodules was chosen to correspond to that of one of the spoke cavities. The amplitude of the (longitudinal) beta function was set to L at both extremities of each longitudinal gap. Note that from the point of view of longitudinal dynamics, the gap length $2L$ is equal to the length of the missing cavity plus that of the two solenoids on each side. In order not to reduce the longitudinal "aperture", the cavity synchronous phases were left untouched; rather, the voltages of two cavities on both sides of each gap were used for matching. The result is shown in Fig. 2 in envelope mode. A corresponding plot obtained by tracking a

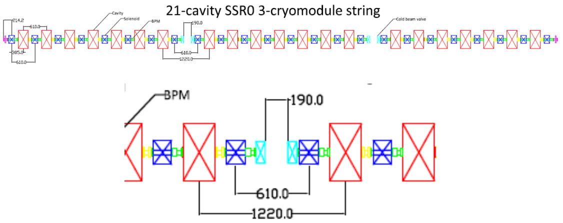

Figure 1: Top: Schematic of the segmented section. Bottom: magnified view of the first longitudinal gap.

particle distribution is shown in Fig. 3; note the significant disturbance on the centroid due to the rf curvature that is not picked up by the envelope calculation. Fig. 4 shows the transverse and longitudinal structural phase advances. The longitudinal perturbation is noticeable. Fig. 5 shows the cavity voltage profile along the linac. The voltage drop on both side of each gap provides the reduction in focusing necessary to let the β function reach its peak value on the edges of each gap. While the procedure we outlined works as expected, the segmentation "missing cavity" segmentation scheme has some obvious shortcomings. Using cavity fields for longitudinal matching is costly in terms of acceleration efficiency. Even with 3 additional cavities (21 vs 18) the segmented lattice barely reaches the final energy as the non-segmented version. A more serious issue is that the ratio of longitudinal aperture to bunch length is reduced by a factor or order $\sqrt{2}$. This is uncomfortable, especially at low energy where it is already difficult to keep this ratio > 5 in a non-segmented lattice. Finally, our initial attempt assumed an input energy of 2.5 MeV. This was revised to 2.1 MeV to mitigate activation. Unfortunately, this change increases the bunch length. These observations led us to consider a different arrangement, based on a "missing solenoid". In that case, for the same physical gap between cryostats, the original optical gap between cavities is preserved. While the disturbance is shifted to the transverse plane, only minor adjustments to the cavity fields are needed to obtain a good longitudinal match. The result, for a new segmented lattice based on this scheme is shown in Fig. 6. The fact that no cavity need operate at reduced voltage makes it possible to segment into two cryostats with nine cavities. Even though the transverse rf defocusing of the cavity upstream of the gap exacerbates the transverse beam size increase, this turns out to be a better compromise in view of a larger available transverse aperture margin and the transverse focusing better linearity.

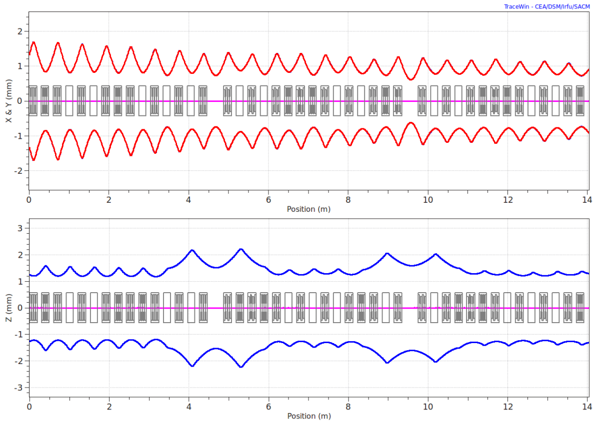

Figure 2: Transverse and longitudinal envelopes computed in the 2nd order moment approximation.

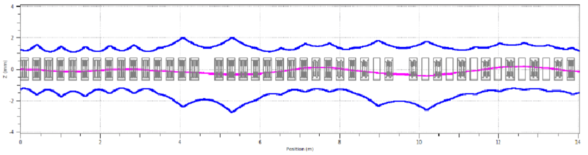

Figure 3: Longitudinal envelope obtained from particle tracking. Note the centroid oscillation due to the focusing asymmetry.

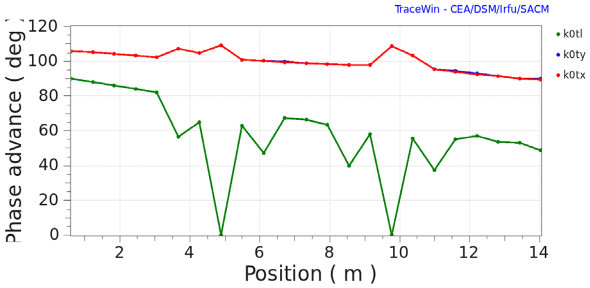

Figure 4: Structural phase advance along the section.

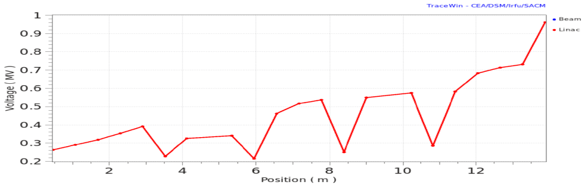

Figure 5: Cavity voltage along the segmented section.

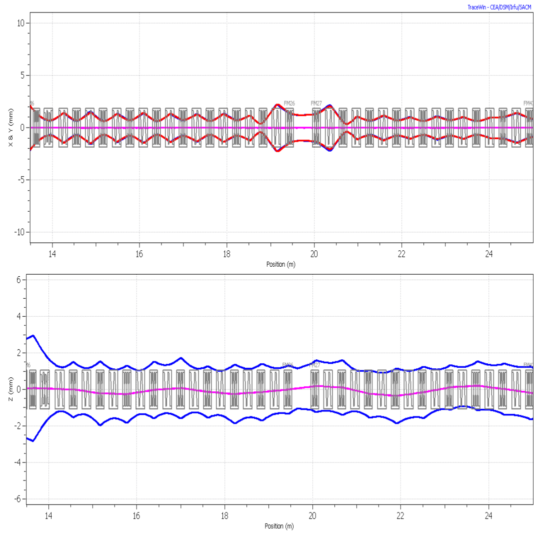

Figure 6: Missing solenoid segmentation scheme.

REFERENCES

[1] S.D. Holmes "Project-X at Fermilab: Prospects and Plans", PAC09, Vancouver, May 2009, FR1GRI02, p. 4241

[2] N. Solyak et al.," Design of the Project X CW Linac", LINAC10, Tsukuba, Japan, Sep. 2010, WE101, p. 678