RESIDUAL FOCUSING ASYMMETRY IN SUPERCONDUCTING SPOKE CAVITIES[*]

J-F. Ostiguy[†], N. Solyak,
Fermilab, Batavia, IL, USA

Abstract

Project-X is a proposed high intensity proton source at Fermilab. Protons (H-) are first accelerated from 2 MeV to 3 GeV in a superconducting linac operating in CW mode. While most of the particles are delivered to a variety of precision experiments, a fraction ($\sim$ 10 to 20 %) is further accelerated to 8 GeV in a second stage superconducting linac operating in pulsed mode. In the the first stage CW linac, single-spoke cavities are used for acceleration. Solenoids provide transverse focusing in the low energy front-end, and quadrupole doublets are used at higher energy. The transverse rf defocusing arising from the spoke cavities has a small residual asymmetry whose effect can become noticeable in periods where the transverse phase advance is low. In this paper we discuss this effect, its practical consequences, as well as possible mitigation strategies.

INTRODUCTION

Project-X is a proposed high intensity proton source at Fermilab. The current concept involves two stages of acceleration in superconducting linacs. In the first stage, H- are accelerated from 2 MeV to 3 GeV in a superconducting machine operating in CW mode. Most 3 GeV particles would then be dispatched to high precision experiments while a fraction would be further accelerated up to 8 GeV and transferred into the existing recycler/Main Injector complex with the objective of providing intense beams for neutrino experiments.

Significant efforts have been invested in the development of the CW linac, and in particular, of the low energy front end, which, in contrast to other machines currently in development (such as ISS or Linac4) is fully superconducting. A number of cavities have been developed for this application; at the time of this writing, the design is based on acceleration in three families of 325 MHz single-spoke resonators (labelled SSR0, SSR1 and SSR2, $\beta = 0.11, 0.21, 0.42$ respectively) followed by two families of 650 MHz elliptical cavities ($\beta = 0.61, 0.90$). The CW linac lattice has undergone a large number of iterations and revisions; this process is still ongoing. One iteration, which was somewhat pathological and therefore abandoned, attracted our attention to an interesting phenomenon that was traced to a small residual asymmetry in the field of the spoke cavities.

SINGLE SPOKE RESONATOR

A conceptual view, representative of the three proposed families of single spoke resonators is shown in Fig. 1. The single-spoke and its close relative, the half-wave resonator, have emerged in recent years as a good choice for acceleration of low velocity ions. As can be seen from the figure, the resonator is topologically equivalent to a coaxial transmission line, terminated by a short at both ends. Along the central post, a quasi-TEM wave bounces up and down. The electric field lines extend perpendicularly from the surface of the post while the magnetic field lines surround it. The chief advantage of this topology is that it results in manageable cavity volume at low rf frequencies (typically 100s of MHz) compared to a hollow resonator. It is also mechanically robust and geometrically stable. As should be obvious from the diagram, the symmetry of the post in the x-y and plane prevents dipole steering i.e. a particle accelerated on axis will not experience a dipole kick. However, the symmetry does not preclude a "quadrupole" asymmetry, even though near the axis, one would expect the effect to remain be relatively small. As we shall see, this is indeed the case, but in some cases, the residual asymmetry can have a noticeable impact on the beam envelope.
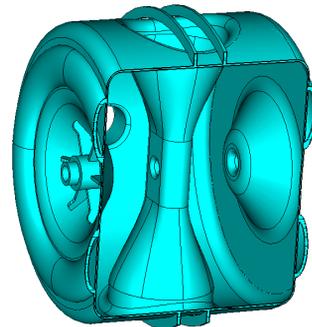

Figure 1: Concept of a single spoke resonator for Project-X.

ENVELOPE PERTURBATION

Fig. 2 shows the transverse beam envelopes obtained for a lattice corresponding to an iteration of the Project-X CW linac. The region from 0 to 60 m encompasses the first three sections of the linac, where all periods are based on single spoke resonators and solenoidal focusing. The result was obtained by tracking 10^4 particles; all cavity fields were modeled using a standard Fourier-Bessel expansion based on the axial electric field. Note that from 0 to 60 m,

04 Hadron Accelerators

A08 Linear Accelerators

both the horizontal envelope (red) and the vertical (blue) are precisely identical. Beyond 60 m the focusing is provided by quadrupole doublets which introduce a phase shift between the horizontal and vertical oscillations. Fig. 3
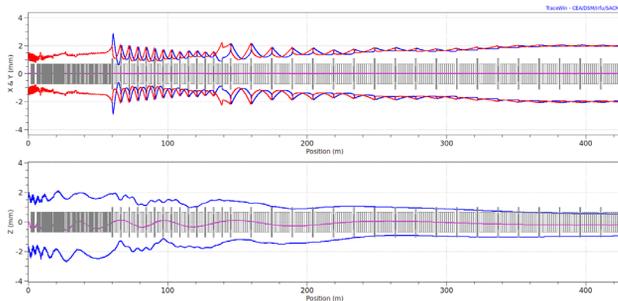

Figure 2: Beam envelopes for an early iteration of the Project-X CW linac lattice. This version was obtained with axially symmetric field maps.

shows the result of same calculation, this time performed using fully 3D field maps. We note that from $40 < z < 60$ m, the span of the last family of single spoke resonators (SSR2) , the horizontal and vertical envelope amplitude begin to diverge, leading to a visible mismatch downstream. Fig. 4, a magnified view of Fig. 3 clearly shows the envelope asymmetry developing.

These results were initially a bit surprising; in our experience beam envelopes obtained with fields based on a Fourier Bessel expansion usually do not deviate meaningfully different from those obtained with full 3D field maps. Interestingly, the observed envelope asymmetry with 3D fields does not develop in the first two sections (SSR0 and SSR1) even though all the spoke cavities are geometrically very similar. Clearly, the phenomenon must be related
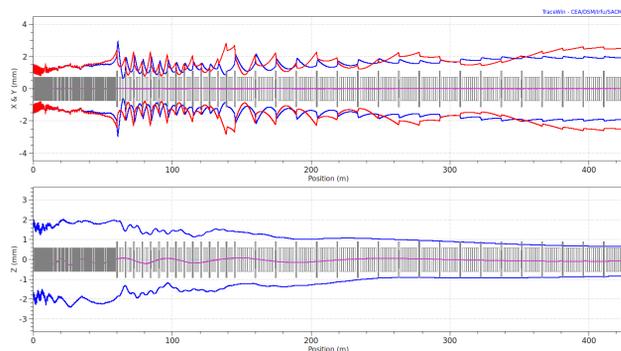

Figure 3: Beam envelopes for the same lattice as Fig. 2, this time with 3D field maps.

to some residual asymmetry in cavity focusing. To confirm that an asymmetry is present and observable in the 3D fields, we compared the the field interpolated from the 3D field maps to those obtained from a Fourier-Bessel expansion about axial accelerating field $\mathbf{E}_z$. The results are shown in Fig. 5 and Fig. 6 which compare respectively, the electric and magnetic fields transverse to the cavity axis.

04 Hadron Accelerators
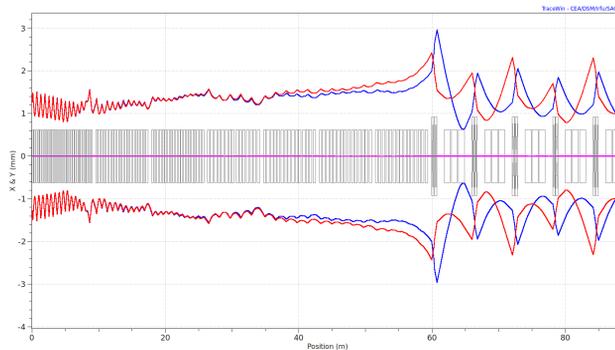
A08 Linear Accelerators

Figure 4: Magnified view of Fig. 3.

In both cases, the deviations between the two transverse planes are clearly observable and, as expected, the fields obtained from the Fourier-Bessel expansion are about the average of the 3D fields between the two planes.
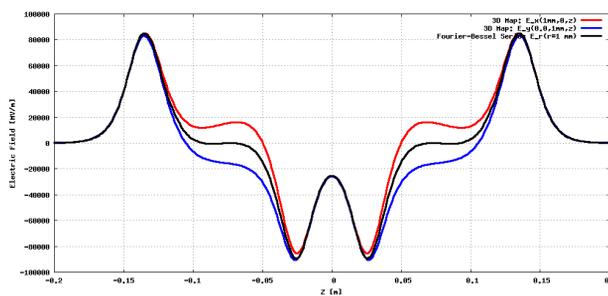

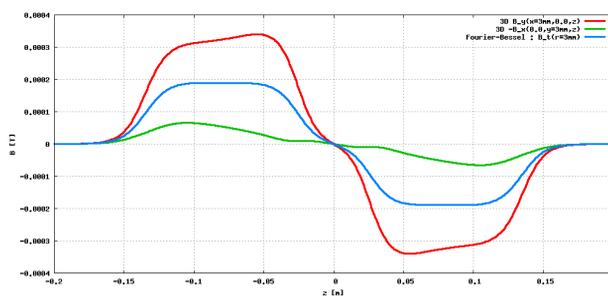Figure 5: 3D radial electric field along x and y vs symmetric radial field obtained from an axial expansion.

Figure 6: 3D transverse magnetic field along x and y vs symmetric polar field obtained from an axial expansion.

ANALYSIS

Transversely, focusing is the sum of three contributions: (1) radial focusing from the solenoid, (2) radial defocusing from the cavity transverse fields and (3) defocusing due to space charge. If the net focusing is purely radial, the beam is expected to remain axisymmetric. In a standard linac section, the transverse phase advance per period usually starts in the vicinity of $90°$ per period and decreases

monotonically to a minimum of typically $30°$. The exact allowable value of this minimum varies. However, to the extent that phase advance is a direct measure of focusing strength, it is clear that allowing it to go to low values significantly increases the sensitivity to lattice errors. Another, perhaps somewhat less obvious effect, is that the solenoidal focusing being perfectly radial, any residual defocusing asymmetry in the cavity becomes, in a relative sense, more important as the net focusing decreases. This can be explained, in a very crude way, in the following manner.

Let $k_s(z)$ be the focusing strength of the solenoid and let $k_c(z)$ be the defocusing due to the cavity. Then the net focusing is (very roughly) $k_s(z) - k_c(z)$. Now assume there is some asymmetry i.e. $k_{c,x} \neq k_{c,y}$. Then the ratio of the **net** horizontal to vertical focusing strengths is

$$\frac{k_x}{k_y} \simeq \frac{k_s - k_{c,x}}{k_s - k_{c,y}} \qquad (1)$$

Clearly, when $|k_s| >> |k_c|$ this ratio is 1 and the net focusing is symmetric. However, when $|k_s| \simeq |k_c|$ the net focusing ratio becomes dominated by the cavity focusing asymmetry. Fig. 7 shows the beam phase advance for the lattice iteration we considered. Note how the phase advance, therefore, the net focusing, is pathologically low in the last periods of the third (SSR2) 325 MHz spoke/solenoid section, just before the transition to the first section based on 650 MHz cavities and doublets i.e. just before period no 50. In addition, it turns out that while the SSR0 and SSR1 sections involve one cavity and one solenoid per period. the SSR2 section comprises two spoke resonators in succession followed by a solenoid, further magnifying the defocusing asymmetry. To confirm our diagnostic of the sit-
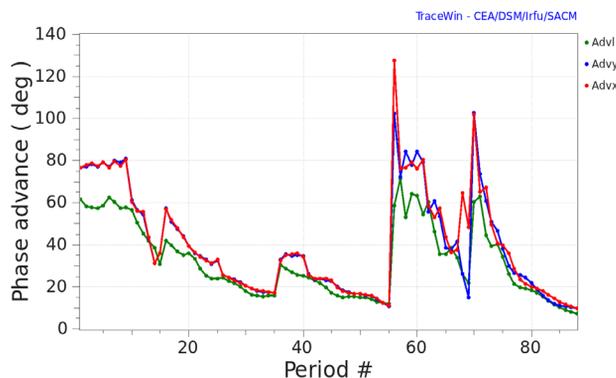

Figure 7: Beam phase advance.

uation, and mitigate the asymmetry, we performed an additional run. For this run, the cavities were rotated with respect to each other by $90°$ about the z axis, in an attempt to "symmetrize" the focusing. No element settings (e.g. field amplitudes etc) were modified. The result is shown in Fig. 8: the beam envelope asymmetry has essentially disappeared.
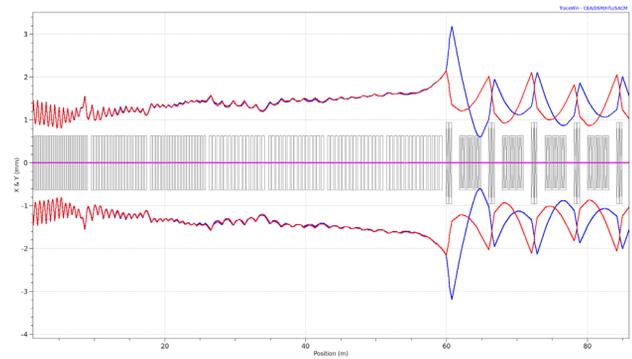

Figure 8: Beam envelopes after symmetrization.

CONCLUSIONS

When the beam phase advance per period i.e. the net transverse focusing is weakest, a small residual defocusing asymmetry in the cavity may distort the beam symmetry. Note that what matters is the net focusing, so the effect might be significant in a machine with relatively strong external focusing and strong space charge defocusing (high current). In principle, it is not difficult to operationally correct for beam asymmetry with quadrupoles; however, the latter are likely not to be available in a compact superconducting low energy front-end. A better solution is to "symmetrize" the cavity arrangement or to design out the field asymmetry. This could achieved, for example, by making the beam hole in the central post slightly elliptical.

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

[3] I. Gonin et al. "Single Spoke Cavities for the Low-energy part of CW Linac of Project X", IPAC10, Kyoto, Japan, May 2010, WEPEC057, p. 3022