EXPLORATION OF DESIGN ALTERNATIVE FOR AN 8 GEV PROTON LINAC AT FERMILAB*

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Abstract

An 8 GeV proton linac is being considered as the primary element of a possible Project X at the Fermi National Accelerator Laboratory (FNAL). The present Project X driver linac baseline design uses five superconducting cavity types: three types of half-wave and two types of multi-cell elliptical structures. The elliptical cavities have a frequency of 1.3 GHz with a $\beta = v/c = 0.81$ and $\beta = 1$ and provide acceleration from 420 MeV to 8 GeV. An alternative design proposed here is to use an additional 1.3 GHz elliptical cavity type with $\beta = 0.61$ starting at ~156 MeV instead of 420 MeV in the baseline linac design. The alternative design may reduce project cost and risk. In addition it would increase the technology overlap between Project X and the International Linear Collider (ILC). Preliminary investigations show that the alternative linac lattice has the potential to provide the beam accelerations required by Project X. This paper will discuss beam dynamics studies for the alternative linac layout in comparison with the baseline layout.

INTRODUCTION

The Project X baseline linac [1] uses a 325 MHz linac followed by a 1.3 GHz linac to accelerate H^- from 2.5 MeV to 8 GeV, as shown in Figure 1. The 325 MHz linac accelerates H^- from 2.5 MeV to 420 MeV using a 2.5 MeV Radio Frequency Quadrupole (RFQ), a room temperature crossbar-H (RT-CH) section, a $\beta = 0.22$ single-spoke resonator (SSR-1) section, a $\beta = 0.4$ single-spoke resonator (SSR-2) section, and a $\beta = 0.6$ triple-spoke resonator (TSR) section. The 1.3 GHz linac accelerates H^- from 420 MeV to 8 GeV using a section with $\beta = 0.81$ ILC-like (S-ILC) elliptical cavities, and a section with $\beta = 1$ ILC cavities.

The proposed alternative linac accelerating lattice, discussed at the Project X Collaboration Meeting in November 2008, uses an additional 1.3 GHz elliptical cavity type with $\beta = 0.61$ starting at ~156 MeV, replacing the triple-spoke structures used in the baseline linac configuration, as shown in Figure 1. Figure 2 compares the 1.3 GHz 6-cell elliptical and 325 MHz triple-spoke cavities. For $\beta > 0.55$, the elliptical structure offers better (smaller) E_p/E_a and B_p/E_a, and the simpler geometry and smaller size leads to the possibility to reduce the linac cost and technical risk. In addition, the proposed alternative accelerating lattice will provide the opportunity to increase the overlap with the ILC effort.

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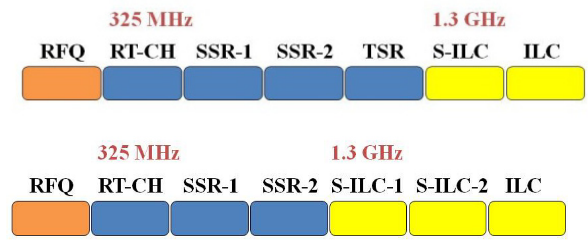

Figure 1: Project X baseline linac (above) and the alternative linac layout (bottom).

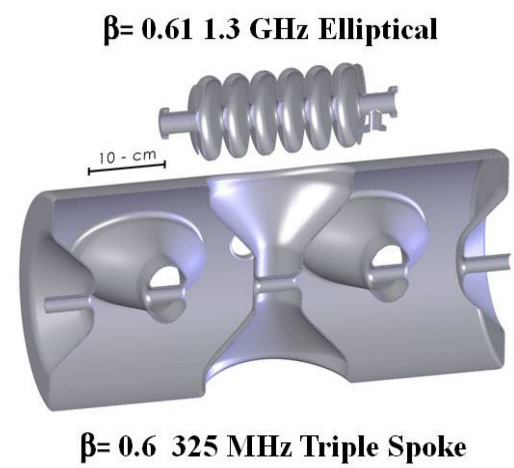

Figure 2: 1.3 GHz $\beta = 0.61$ Elliptical structure (top) and 325 MHz $\beta = 0.6$ Triple-Spoke structure (bottom).

The alternative lattice will need a modified SSR-2 section to accelerate the beam to ~156 MeV and to match it into the downstream elliptical accelerating structures.

SSR-2 SECTION MODIFICATIONS

The Project X baseline linac uses three cryomodules of SSR-2 cavities to accelerate beam from ~30 MeV to ~126 MeV. Each cryomodule consists of 11 SSR-2 cavities and six superconducting solenoid magnets [1]. The alternative lattice will use an additional SSR-2 cryomodule to bring the beam energy to ~156 MeV. In addition, a matching section, consisting of four room temperature quadrupole magnets and four SSR-2 cavities in two separate cryomodules, will be used to match the beam transversely and longitudinally into the elliptical accelerating structures. Figure 3 shows the simulated output phase space [2, 3] of the baseline linac at the end of the SSR-2 section where the beam energy is ~126 MeV using the computer code TRACK [4]. The beam has a transverse emittance ($4\varepsilon_{rms}$) of ~1.2 π mm-mrad and longitudinal emittance ($4\varepsilon_{rms}$) of ~7.0 π keV-ns. The formation of the beam longitudinal tails may be the result of mismatch between the different sections during the low-energy beam acceleration from the RFQ [2].

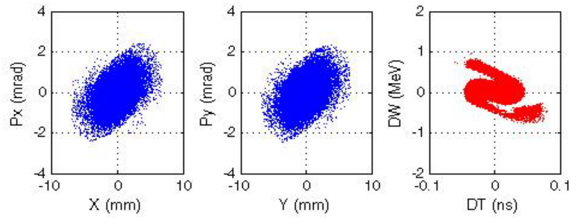

Figure 3: Horizontal (left), vertical (middle) and longitudinal (right) phase spaces at the exit of the SSR2 segment in the baseline linac, at a beam energy of ~126 MeV.

Figure 4 shows the phase spaces simulated using IMPACT code [5] after the matching section of the alternative accelerating lattice, at a beam energy of ~156 MeV prior to further acceleration in the 1.3 GHz elliptical cavity section. No noticeable emittance degradation is observed in the beam simulations.

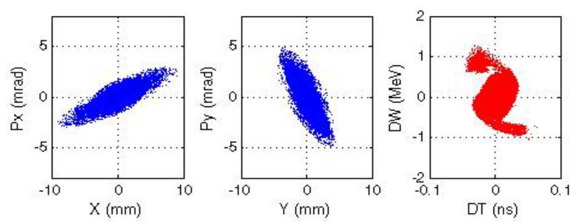

Figure 4: Horizontal (left), vertical (middle) and longitudinal (right) phase space after the matching section of the alternative accelerating lattice, at a beam energy of ~156 MeV.

ELLIPTICAL ACCELERATING STRUCTURE

In the alternative lattice, two elliptical accelerating structures are used to accelerate the beam from ~156 MeV to 1.2 GeV. As shown in Figure 5, each cryomodule consists of 8 elliptical cavities and six superconducting quadrupole magnets with two quadrupoles in the warm region between the cryomodules to provide periodic transverse focusing. To limit the production of H^0 from strong magnetic focusing [6], quadrupole focusing gradients are limited to 12 T/m for the S-ILC-1 section and 15 T/m for the S-ILC-2 section, so that the maximum magnetic field is less than 0.6 T and 0.3 T, respectively. Table 1 lists the main parameters of the cavities and cryomodules. Figure 6 shows the voltage gain and Transit Time Factor (TTF) for the elliptical accelerating structures.

A β = 0.61 six-cell elliptical cavity at 805 MHz is used for the superconducting linac at the Spallation Neutron Source (SNS) at ORNL [6]. For the alternative accelerating lattice evaluations, the SNS β = 0.61 cavity was scaled from 805 MHz to 1.3 GHz. The β = 0.81 seven-cell cavity was developed for Project X. The cavity design was done by MSU, in collaboration with Fermilab. Four single-cell prototype cavities have been fabricated and tested (via an MSU/Fermilab/Jefferson Lab collaboration). All four cavities reached reasonably high gradients and quality factors [7, 8]. Two 7-cell cavities have also been fabricated [8], but they have not yet been tested.

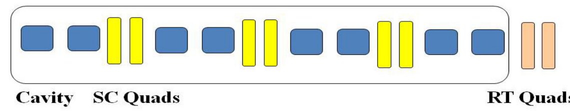

Figure 5: Layout of the elliptical cryomodule for the alternative accelerating lattice including the room temperature (RT) quadrupoles.

Table 1: Main Cavity and Cryomodule Parameters

Cavity	S-ILC-1	S-ILC-2
β_G	0.61	0.81
Number of cells	6	7
Frequency (GHz)	1.3	1.3
E peak (MV/m)	52	52
Accelerating voltage (MV)	7.31	15.84
Number of cavities	48	64
Number of cryomodules	6	8
Cryomodule length (m)	9.2	11.7

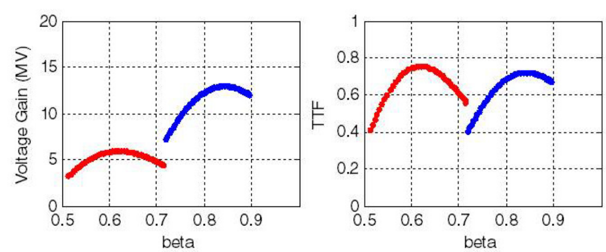

Figure 6: Voltage gain (left) and transit time factor (right) for the alternative accelerating lattice.

BEAM DYNAMICS STUDIES

A key issue associated with the use of 1.3 GHz elliptical structures in lieu of the 325 MHz triple-spoke cavities at the ~156 MeV point is whether the alternative accelerating lattice has adequate transverse and longitudinal acceptance. Beam dynamics studies were performed using IMPACT [5] to evaluate the performance of the alternative accelerating lattice. Figure 7 shows the calculated longitudinal acceptance of the elliptical accelerating lattice starting at ~156 MeV, together with the beam phase space at the entrance of the linac segment. The beam has a longitudinal emittance ($4\varepsilon_{rms}$) of ~7.4 π keV-ns, while the acceptance is ~240 π keV-ns. However, the beam longitudinal tails created in the low-energy acceleration section lead to a significantly larger 99.9% emittance.

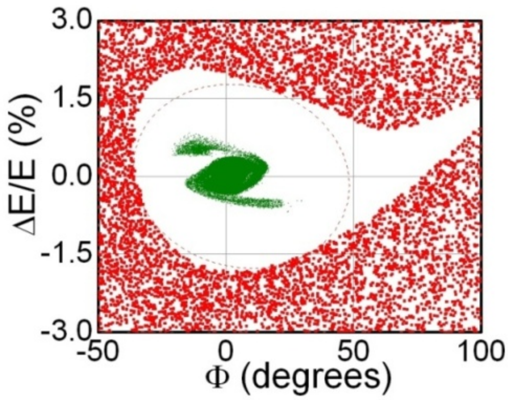

Figure 7: Longitudinal acceptance of the 1.3 GHz elliptical accelerating structure at ~ 156 MeV (white) together with the matched input beam phase space (green).

Beam simulations were performed from the output of the SSR-2 section at ~156 MeV through the alternative accelerating lattice to 1.2 GeV. Figure 8 shows the beam envelope and Figure 9 shows the beam phase space at 1.2 GeV. No beam loss or noticeable transverse and longitudinal emittance growth was observed. The transverse aperture is determined by the aperture of the quadrupole magnets, due to the maximum pole tip field allowed to avoid the production of H^0. With quadrupole gradients of 12 T/m for the S-ILC-1 section and 15 T/m for the S-ILC-2 section, the 25 cm long quadruples have radial aperture of 5 cm and 2 cm, respectively, to satisfy this requirement.

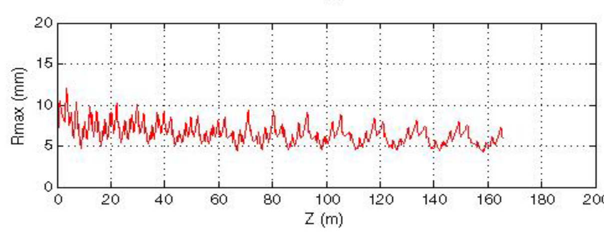

Figure 8: Beam envelope for the alternative accelerating lattice from ~156 MeV to 1.2 GeV.

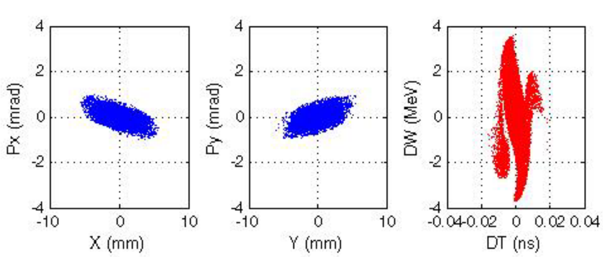

Figure 9: Horizontal (left), vertical (middle) and longitudinal (right) phase spaces at the exit of the alternative lattice, at a beam energy of ~1.2 GeV.

The rf cavity phase and amplitude errors in 325 MHz linac section will lead to a even larger initial beam longitudinal emittance for the alternative lattice. To evaluate the rf error impact, a beam with twice the longitudinal initial emittance was simulated through the alternative lattice, and no beam loss or noticeable beam emittance growth was observed. However, significant beam loss and emittance growth; were observed for a beam with 3 times the initial longitudinal emittance, mainly due to particles in the longitudinal tails created in the low-energy acceleration section.

Alternatively, beginning the implementation of elliptical structures at a higher energy of ~180 MeV in lieu of ~156 MeV will provide a longitudinal acceptance of ~300 π keV-ns in lieu of ~ 240 π keV-ns.

SUMMARY

The alternative accelerating lattice for Project X driver linac would use two types of 1.3 GHz elliptical cavities to provide beam acceleration from ~156 MeV to 1.2 GeV. Preliminary investigations show that the alternative linac lattice has the potential to provide the beam accelerations required by Project X and limit the beam loss and emittance growth. Further beam simulations with realistic errors for the complete alternative accelerating lattice from the RFQ are necessary. The lattice performance would benefit if the emittance growth in the low-energy acceleration section could be reduced. In addition, beginning the elliptical structure at ~180 MeV would lead to a larger acceptance (~ 300 π keV-ns) and better performance.

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