Progress in the Design and Simulation of a 1 GeV Superconducting Proton Linac for a Nuclear Waste Transmutation ADS

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Abstract

We present the status of the design of a 1 GeV superconducting (SC) proton linac with a design current of 25 mA. Focusing is performed with SC solenoids. Five types of SC cavities are used over three different periodic sections of the linac; the three sections have cavities-per-solenoid ratios of 1, 2, and 3. Simulations with TRACK code show longitudinal emittance growth constrained to around 30% along the linac. Strong mismatch effects are observed in transverse RMS envelope and emittance fluctuations, likely because solenoid field strengths were not matched after the longitudinal matching was modified in attempts to reduce emittance.

1 Introduction

The advent of superconducting cavities for low to medium relativistic β proton and ion acceleration has inspired a number of proposals for accelerator-driven systems (ADS). Spallation neutron sources, radioactive beam production mechanisms, neutrino physics experiments, and nuclear waste transmutation applications all utilize some type of ADS.

The design of a nuclear waste transmutation ADS involves several components. These are best split into three parts: an accelerator, a spallation target, and a nuclear reactor with a subcritical core. All of these require large design processes, and in this article we present the design of the accelerator component. As noted by [1], we follow the general trend and choose to accelerate protons up to energies of 1 GeV with an operational current of 25 mA. The rest of this article will ignore the transmutation and ADS aspects of the overall system, and instead focus on fundamental accelerator design. As the cavities have already been developed, our discussion will concentrate on the design principles of the linac lattice. We will conclude with analysis of the current design and future directions in theory and simulation to continue the work.

2 Design Principles

The most general design requirements for a high-intensity proton linac, in order to avoid RMS emittance growth, are reviewed in Ref. 2, and are given as follows:

- The zero current phase advance per period of transverse and longitudinal oscillations (σ_{T0} and σ_{L0}, respectively) should be below $\frac{\pi}{2}$ to avoid parametric instabilities at operational current [3].
- Transverse and longitudinal wavenumbers k_{T0} and k_{L0}, with $k_0 = \frac{\sigma_0}{L_f}$ (and L_f the focusing period) should change adiabatically throughout the linac to minimize the chance of mismatch [4].
- Ensure that the $n = 1$ parametric resonance between transverse and longitudinal motion is avoided. This resonance happens for the following condition [5]:

$$\sigma_{T0} = \frac{n}{2}\sigma_{L0} \tag{1}$$

The $n = 1$ resonance is the most concerning, and can be avoided by choosing good operational tunes.

- Provide matching in the lattice transitions to avoid halo formation and transverse RMS emittance and envelope fluctuations.
- Keep longitudinal RMS emittance as low as possible.

The above requirements will yield an accelerator that is hopefully free of major mismatches, emittance growths, resonances, halos, and other undesirable effects such as beam losses.

3 Design Procedure

All of the design of the linac will be carried out in TRACK, a 3-D code with many useful features. A brief overview of the code is presented in [2].

Design of an accelerator is most efficiently performed by splitting the process between zero current design before moving to the maximum current design. The optimal zero current design should be relatively close to the optimal max current design, and it is important to confirm several of the design principles of zero current operation before moving on to consider space charge effects. During the zero current design, the synchronous phases of the cavities and cavity field strengths are varied in order to provide a smooth wavenumber and avoid resonances related to phase advances per period. Importantly, proper adjustment of phases and strengths can prevent the $n = 1$ resonance given by (1). After proper tuning of the 0 mA case, we can move to the full 25 mA case. When considering space charge effects, variation of the synchronous phases and cavity strengths will have a larger effect on the operation of the linac. Additionally, if emittance growth is still occurring at lattice transitions, one can adjust the lattice periodicity via adding or removing periods, or even changing the solenoid-to-cavity ratios of periods. Since the design space is so large, certain heuristics, such as adiabatic decreasing synchronous phases, are used to get a rough idea for what will improve operation. When the design at 25 mA is finalized, tests are run at 0 mA again to ensure that operation is as expected and has not somehow worsened with the 25 mA improvements.

4 Beam Dynamics

4.1 0 mA Design

Zero current simulations in TRACK of the present linac design are shown in Fig. 1. The phase advances per period shown in Fig. 1(a) are clearly below 90 degrees for most of the linac. The few points at which this is violated are at very sharp peaks, meaning that the linac moves away from these areas of operation fairly quickly. The $n = 1$ resonance is quite clearly avoided, since the longitudinal phase advance is always less than twice the transverse phase advance. The transverse and longitudinal wavenumbers decrease adiabatically along the linac as shown in Fig. 1(b). Note that the longitudinal wavenumber has three distinct sections; these correspond to three different lattice periodicities. Solenoid-to-cavity ratios are 1:1, 1:2, and 1:3 in these three sections. This is not too concerning, but brings up an interesting question that will be mentioned later.

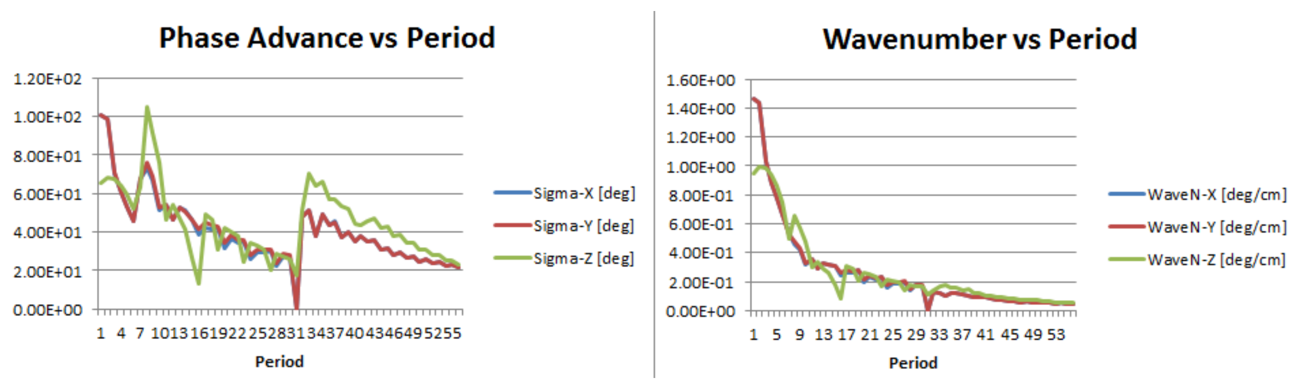

Figure 1. Phase advances per period (a) and wavenumber (b) progression along the linac.

The longitudinal and transverse emittances in the zero current simulation are in the neighborhood of 3%. These are pictured in Fig. 2. Note that the increase is steady and relatively smooth, despite some transverse envelope oscillations due to mismatching of the solenoids.

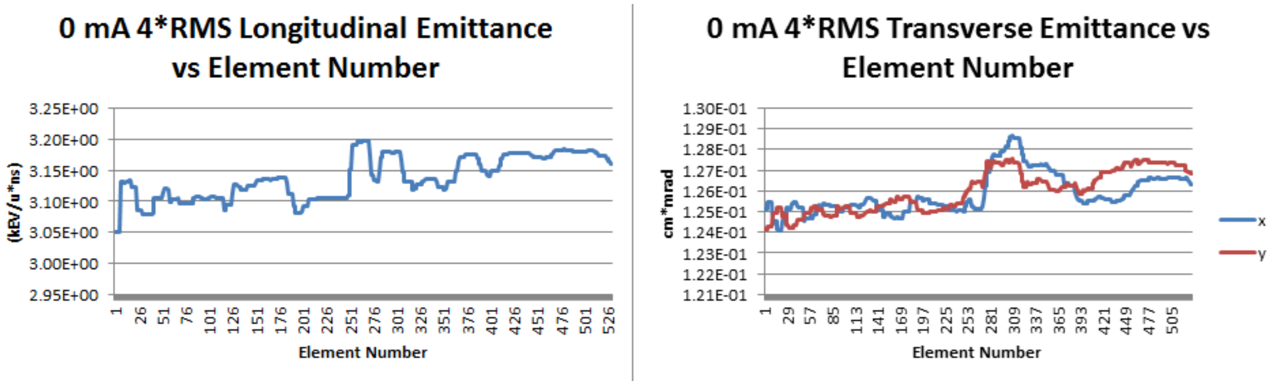

Figure 2. Longitudinal (a) and transverse (b) RMS emittances during zero current operation.

4.2 25 mA Design

When considering space charge effects in a high intensity linac, one should always pay attention to the tune depression η, defined as

$$\eta = \frac{k}{k_0} \tag{2}$$

where k is the wavenumber at design current and k_0 is the corresponding wavenumber at zero current. Physically, the tune depression represents the degree to which space charge effects dominate the focusing period. A lower tune depression corresponds to a higher space charge contribution. One can easily imagine a scenario where the $n = 1$ parametric resonance defined by (1) becomes excited after considering space charge effects. For example, if $\sigma_{T0} \simeq \sigma_{L0}$, $\eta_L = 1$, and $\eta_T = 0.5$, then the resonance has been excited due to tune depression. Therefore, transverse and longitudinal tune depressions between 0.5 and 1.0 are fairly stable for our design and should avoid the resonance. The functional formulas for the tune depressions are given by [2] and reproduced as follows:

$$\eta_T^2 = 1 - \frac{3qI\lambda(1-f)}{4\pi\epsilon_0 m_0 c^3\gamma^3\beta^2(r_x + r_y)r_x r_z}\left(\frac{1}{k_{T0}}\right)^2 \tag{3}$$

$$\eta_L^2 = 1 - \frac{3qI\lambda f}{4\pi\epsilon_0 m_0 c^3\gamma^3\beta^2(r_x r_y r_z)}\left(\frac{1}{k_{L0}}\right)^2 \tag{4}$$

where I is the average current over an RF period, r_i are related to the RMS beam sizes a_i via $r_i = \sqrt{5}a_i$, f is the ellipsoidal form factor, m_0 is the particle mass, q is the particle charge, λ is the RF wavelength, and β and γ are the relativistic factors. It should be noted that, for the production of the tune depression plots, an approximation of the ellipsoidal form factor f was used. The true factor is nonlinear, but a piecewise linear function (accurate to within about 10% in the worst cases) was used for ease of calculation.

As shown in Fig. 3, most of the linac operates with both transverse and longitudinal tune depression in the desired range. There are a few points for each that fall under heavy space charge suppression, but again the linac quickly gets away from these regions of operation. These, in a similar fashion to the kinks in the zero current wavenumber curve, are related to the matching of different lattice periodicities.

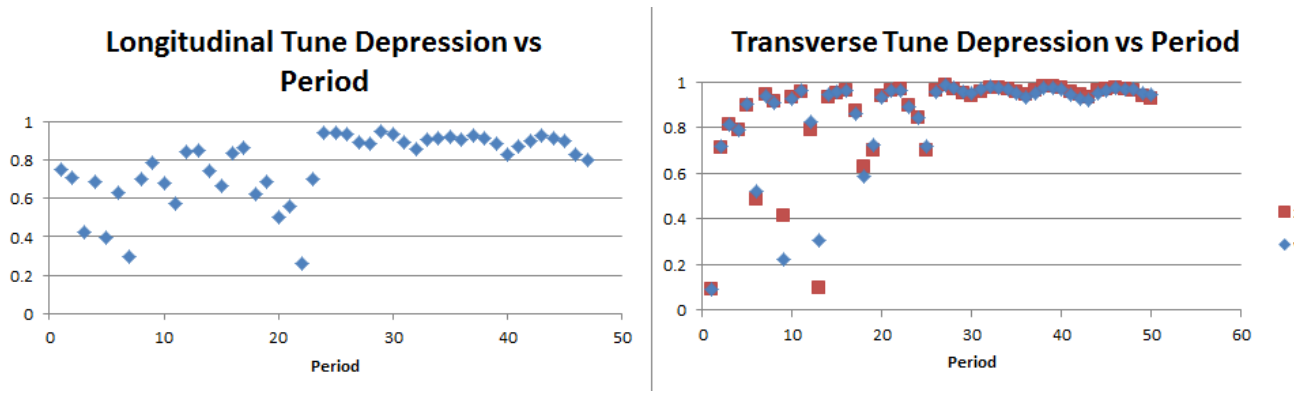

Figure 3. Longitudinal (a) and transverse (b) tune depression ratios for 25 mA operation.

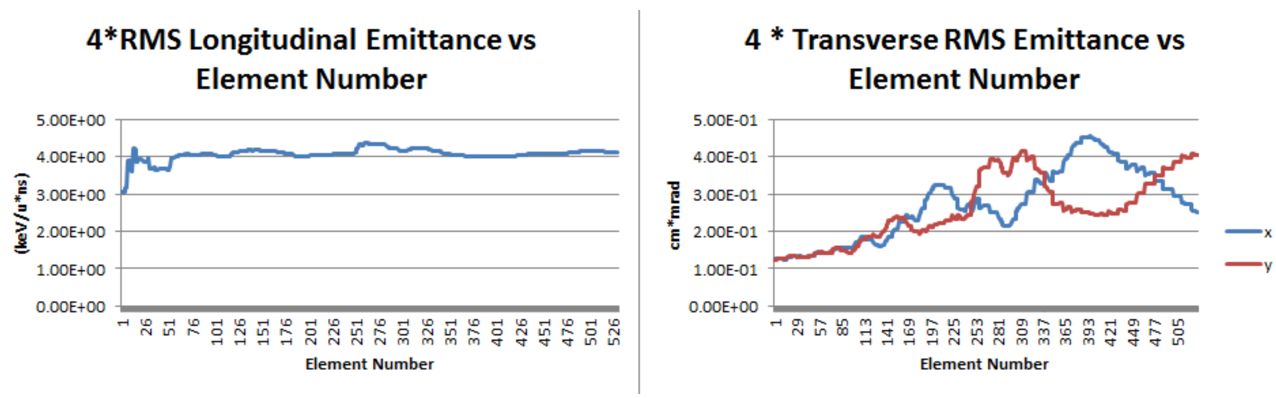

Figure 4. Longitudinal (a) and transverse (b) RMS emittances during 25 mA operation.

Fig. 4 shows the transverse and longitudinal RMS emittance growth along the linac, in the same units utilized by TRACK. We now observe that the mismatch first noted in the zero current beam envelope has propagated through to the high current case and is causing more serious issues in the transverse envelope and emittance. On the other hand, Fig. 4(a) shows that the longitudinal RMS emittance is very compact and well-behaved, only reaching a growth of about 33%.

As mentioned in [2], matching could be performed in future work by TRACE-3D or an automatic tuning procedure implemented in TRACK.

5 Conclusions

The current design of a 1 GeV SC proton linac (with design current 25 mA) for use in a nuclear waste transmutation ADS is presented. Simulations are performed with TRACK. The longitudinal emittance growth has been suppressed to about 33%, but transverse emittance growth and the transverse RMS envelope suffer from heavy mismatching, and requires a rematching of solenoid field strengths. Tune depressions in all directions are fairly healthy. Wavenumber profiles at zero current are smooth for the most part, but an interesting note with the longitudinal wavenumber is its kinks. A nontrivial theory question of interest would be to find the longitudinal wavenumber profile that gives the lowest longitudinal emittance. For further development of this linac, the first step would be to match the solenoid field strengths to the energy of the beam going through them to eliminate the transverse mismatching. Hopefully this will preserve the longitudinal gains made by altering the lattice periodicity and cavity strengths. Additionally, sychronous phases of as low as -20 degrees were used in later portions of the linac - this may cause emittance growth due to errors when that subsequent analysis is performed, due to the acceptance of the separatrix being confined. If this is found to be the case, the lattice periodicity and cavity strengths may need to be further altered to compensate for any adjustments to the phases.

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