CAVITY OPTIMIZATIONS AND BEAM DYNAMICS SIMULATIONS FOR LANSCE UPGRADES*

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Abstract

The Distributed Drive Linear accelerators (DDLs), in which each accelerating cell is independently powered, offer the flexibility to set the phase and amplitude of the RF fields in each cavity individually. In the limiting case of a linac composed entirely of independently-driven single-cell cavities, the RF power required per individual cavity can be a good match to the capabilities of solid-state amplifiers. For these reasons, the possibility of upgrading the current Coupled-Cavity Linac (CCL) in the LANSCE accelerator at Los Alamos National Laboratory to a DDL architecture is being investigated. Here we report results from cell profile optimizations and beam dynamics simulations carried out to study the potential advantages of a DDL architecture in the LANSCE accelerator.

INTRODUCTION

The Los Alamos Neutron Science Center (LANSCE) accelerator complex supports a wide variety of applications. These include applications for national security, medical, and scientific research. In an effort to explore possible upgrades to LANSCE, the replacement of a Coupled-Cavity Linac (CCL) section with a Distributed Drive Linac (DDL), where each cell is individually powered by solid state amplifiers, is being investigated. Previous studies of the CCL can be found in Ref. [1]. One aspect of the upgrade investigation consists of optimizing the cell profile using the approach described in Ref. [2]. Here we report results of these optimizations as well as some preliminary beam dynamics simulations.

CELL PROFILE OPTIMIZATION

The desired resonant frequency of the cell is f_0 = 805 MHz. The cell length is 8.0274 cm and the bore radius is 1.5875 cm, matching the cell design described in Ref. [1]. This cell design is used in the CCL Module 5 Tank 1 (M5T1) in LANSCE. The cell was assumed to have ideal copper walls with a resistivity of 1.7241 μΩ cm. The optimization used Superfish [3] to perform the radiofrequency field simulations, and the results were verified using CST Studio Suite [4].

The objectives in this optimization were to maximize the time-dependent shunt impedance per unit length and to minimize the ratio of peak surface field, E_{peak}, to accelerating gradient E_{acc}. We define the time-dependent shunt impedance as $R_s = V_{\mathrm{acc}}^2/P_{\mathrm{diss}}$, where P_{diss} is the dissipated power, and $V_{\mathrm{acc}} = \int_{-L/2}^{L/2} E_z(z)\cos\left(\frac{2\pi f_0 z}{\beta c}\right) dz$. E_z is the on-axis longitudinal electric field, L is the cavity length, and β is equal to 0.4311 [1], corresponding to the velocity of a 101.6 MeV proton beam. We can express E_{acc} in terms of these quantities as V_{acc}/L. The resonant frequency was constrained to be within 1 MHz of the target frequency. As described in Ref. [2], the optimization is performed by varying the endpoint coordinate and tangent slope values of elliptical and linear segments that define the cell profile. Let the endpoint coordinates of a given point be (r_i, z_i) and let the slope of the tangent at that point be s_i. The values for these parameters are given by

$$z_i = u_i Z,$$

$$r_i = v_i(R - r) + r,$$

$$s_i = t_i R/Z,$$

with R, r, Z defined as shown in Fig. 1 and the set of parameters u_i, v_i, t_i being the optimization variables. The ranges of optimization variables are shown in Table 1.

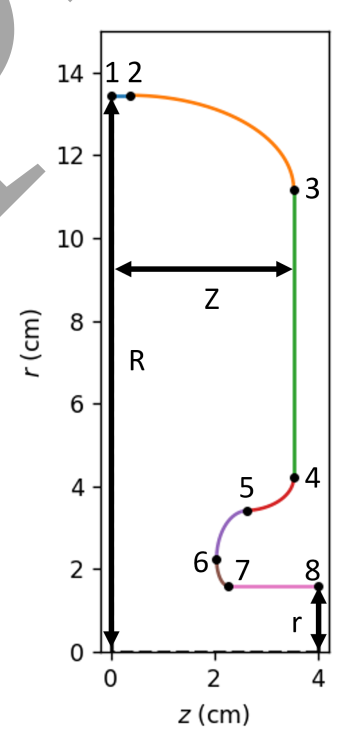

Figure 1: Reference figure for cell optimization parameters. R was allowed to vary in the range 12 cm–13.5 cm and Z was allowed to vary in the range 3 cm–3.537 45 cm. The bore radius r was fixed at 1.5875 cm.

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Table 1: Cell Profile Parameters and Optimization Ranges

Point	u	v	t
1	0	1	0
2	1 − 0.7	1	0
3	1	0.4 − 0.9	-∞
4	1	0.2 − 0.5	-∞
5	0.7 − 1	0.1 − 0.3	0 − 5
6	0.5 − 0.95	0.05 − 0.3	∞
7	0.6 − 1.1	0	0
8	$L/2Z$	0	0

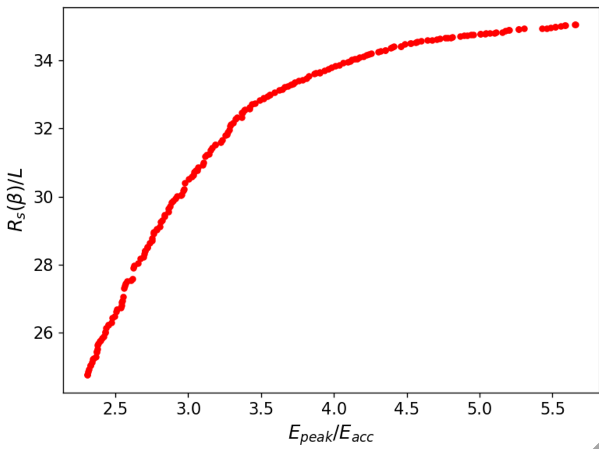

Figure 2: Pareto front showing the trade-off between $E_{\text{peak}}/E_{\text{acc}}$ and $R_s(\beta)/L$ in the set of optimized cell profiles.

Given there were two optimization objectives, the optimization yielded a set of solutions called a Pareto front spanning the trade-off between $E_{\text{peak}}/E_{\text{acc}}$ and $R_s(\beta)/L$. Figure 2 shows the Pareto front resulting from this optimization.

As reported in Ref. [1], simulations of the current cell profile design give $R_s(\beta)/L = 31.45\,\text{M}\Omega\,\text{m}^{-1}$. We selected a cell profile with a similar time-dependent shunt impedance per length of $32\,\text{M}\Omega\,\text{m}^{-1}$ for the beam dynamics simulations. Figure 3 shows the optimized cell profile corresponding to this $R_s(\beta)/L$ along with its electric field magnitude.

Table 2 compares some of the cell parameters to the corresponding ones of the M5T1 CCL cell reported in Ref. [1]. We refer to the cell optimized in this work as the DDL cell. We see that for a similar $R_s(\beta)/L$, $E_{\text{peak}}/E_{\text{acc}}$ has been significantly reduced by a factor of ≈ 46%, which indicates that

Table 2: Comparison of cell parameters for CCL cell discussed in Ref. [1] and DDL cell presented in this work. R_s refers to the time-independent shunt impedance, and $R_s(\beta) = R_s \cdot [\text{TTF}]^2$ is the time-dependent shunt impedance.

Parameter	**DDL**	**CCL**
R_s/L (MΩ/m)	46.4	42.3
$R_s(\beta)/L$ (MΩ/m)	31.96	31.45
Transit time factor [TTF]	0.830	0.862
Quality factor Q	20735	17630
$E_{\text{peak}}/E_{\text{acc}}$	3.28	6.06

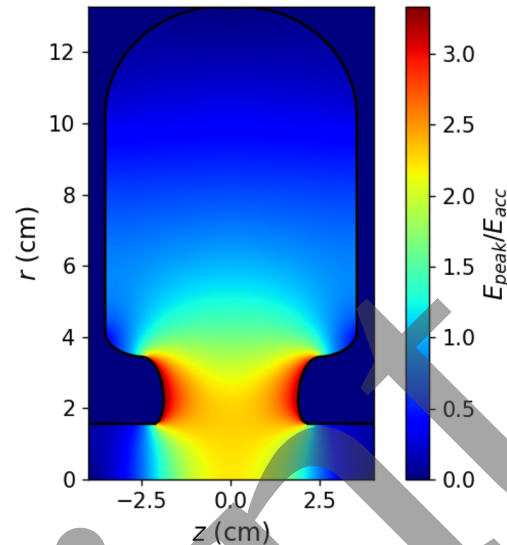

Figure 3: Optimized cell profile with $R_s(\beta)/L = 32$ showing the electric field magnitude.

the maximum allowed accelerating gradient in the optimized cell can be a factor of two higher than achievable in a M5T1 CCL cell.

PARTICLE TRACKING SIMULATIONS

We now discuss preliminary results obtained from particle tracking simulations performed with the general particle tracer (GPT) code [5] tracking 10 000 macro-particles. The purpose of these simulations was to study the emittance growth of the beam through a linac section like that described in Ref. [1]. This section consists of 36 cells, and the fields in each cavity is scaled such that $E_{\text{acc}} = 1.37\,\text{MV/m}$. For these preliminary simulations, the phase of each cavity was set to 180° relative to the previous cavity as in the CCL. The initial beam distribution was Gaussian longitudinally and radially uniform. The energy and transverse momenta were also Gaussian distributed. The initial transverse normalized RMS beam emittances $\epsilon_{n,x}$ and $\epsilon_{n,y}$ along with the beam energy spread and temporal length were obtained from simulations for LAMP reported in [6, 7]. The beam size and transverse phase space correlations were optimized to minimize the beam size variation along the DDL. This was done by optimizing the radius and Twiss parameters $\alpha_x = -\langle xx' \rangle/\epsilon_x, \alpha_y = -\langle yy' \rangle/\epsilon_y$, where ϵ_x, ϵ_y are the transverse RMS geometric emittances. Table 3 shows the beam parameters used in the simulations after optimizing for the beam radius and α_x, α_y.

Figure 4 shows the on-axis electric field in the DDL and the kinetic energy of the beam along the DDL. We see there is an approximately 4 MeV total energy gain, corresponding to and energy gain of 0.11 MeV per cell, in agreement with Ref. [1]. Figure 5 shows the transverse RMS beam size in x and y along the DDL. As stated earlier, the beam radius and α_x, α_y were optimized to minimize the variation in the beam size along the DDL. Specifically, they were optimized to minimize $\sqrt{\text{Var}(\sigma_{xy})}$, where $\sigma_{xy} = \sqrt{\sigma_x \sigma_y}$ and σ_x, σ_y

Table 3: Beam parameters used in the particle tracking simulations.

Parameter	Value	Unit
Bunch charge	128	pC
RMS temporal length	38	ps
Kinetic energy	100	MeV
RMS energy spread	0.256	MeV
$\epsilon_{n,x}$	1.17	µm
$\epsilon_{n,y}$	0.91	µm
Beam radius	5	mm
α_x	0.55	-
α_y	0.53	-

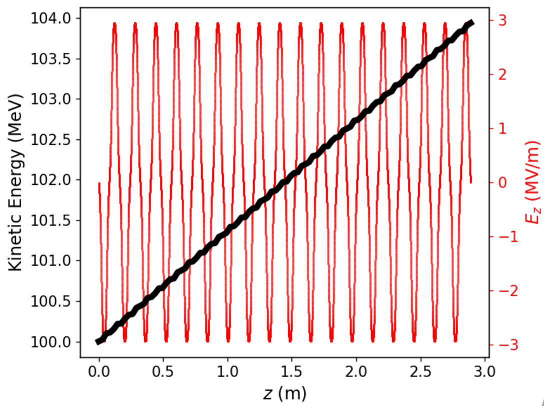

Figure 4: On-axis electric field and beam kinetic energy in DDL.

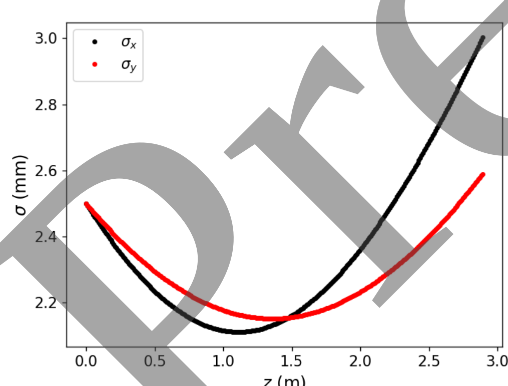

Figure 5: Transverse RMS beam sizes along the DDL.

are the transverse RMS beam dimensions. The variance was computed from a set of values for σ_{xy} sampled at eight equally spaced locations along each cell in the DDL. The difference between the maximum and minimum beam size is within 1 mm, and it is in x as expected because $\epsilon_{n,x} > \epsilon_{n,y}$ in the initial beam distribution. The objective, $\sqrt{\mathrm{Var}(\sigma_{xy})}$, was 0.17 mm for the optimized case shown in Fig. 5. The emittance growth in both x and y was below 5% as seen in Fig. 6 where the initial emittance is denoted ϵ_n^0.

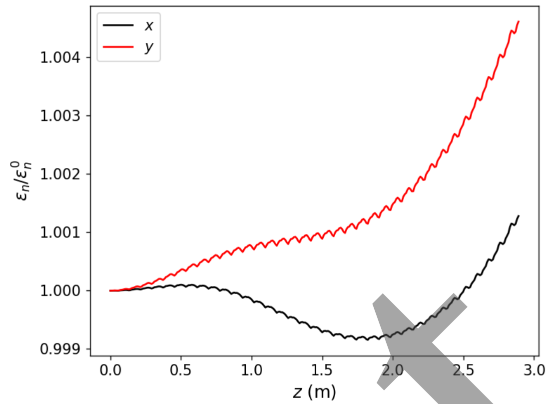

Figure 6: Transverse RMS beam sizes along the DDL.

CONCLUSION

We optimized the cell profile for a Distributed Drive Linac (DDL) being designed to replace the current Coupled-Cavity Linac (CCL) in the Los Alamos Neutron Science Center (LANSCE) accelerator complex. The cell profile was optimized to maximize the time-dependent shunt impedance and minimize the ratio of the peak surface field to the accelerating gradient. The results were compared with simulations for the current cell design in the CCL. We found that for a similar shunt impedance, the optimization resulted in a decrease of the peak surface electric field by approximately 46%. We then performed preliminary beam dynamics simulations for a 36-cell DDL section operating in π-mode and found the beam size peak-to-peak variation and emittance growth could be limited to less than 1 mm and 5% respectively.

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