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PARALLEL-FEED SRF ACCELERATOR STRUCTURES*

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Abstract

Development of SRF accelerator technology that enables both higher gradient and higher efficiency is crucial for future machines. While much of the recent R&D focus has been on materials and surface science, our aim is to optimize the cavity geometry to maximize performance with current materials. The recent demonstration of a highly efficient parallel-feed normal-conducting RF structure at SLAC has served as a proof-of-concept. Instead of coupled elliptical cells, the structure employs isolated re-entrant cells. To feed RF power to the cavities, each cell is directly coupled to an integrated manifold. The structure is made in two parts, split along the beam axis, which are then joined. Applied to SRF, simulations suggest such a structure could nearly double the achievable gradient, while reducing cryogenic RF loss by more than half.

INTRODUCTION

For high-β electron-positron accelerators, [1] where $\beta = v/c \approx 1$, the best-known and most widely used SRF structure is the TESLA cavity [2]. The 1.3 GHz TESLA cavity and variations of it are the basis for the International Linear Collider (ILC), the European X-ray Free Electron Laser (XFEL), and the 2nd generation Linac Coherent Light Source (LCLS-II). The TESLA cavity is about 1.3 m long and consists of nine coupled elliptical cells. Power is fed to the cavity from one end by a coaxial input coupler, with the coupling strength between cells optimized in order to obtain the necessary dispersion and a uniform field distribution.

Recently, researchers at SLAC have considered completely novel topologies for accelerator structures, with methodologies that are different from the conventional wisdom [3]. Genetic optimization algorithms that focus on efficiency or high gradient performance produce cavity shapes that are generally incompatible with either travelling-wave or standing-wave structures with a pre-defined coupling between cavities. Instead of employing coupled-cells, the new SLAC topology feeds each cell in the accelerator structure independently. Such a structure has been demonstrated with normal-conducting bulk copper, but we seek to demonstrate this parallel-feed technology for use in SRF applications. Below we describe the cell and structure design, the simulation results that show tremendous promise in terms of high gradient and low RF loss, and our plans for fabricating and testing a two-cell S-band structure in the near future.

SRF-CELL OPTIMIZATION

We started our research efforts focusing on cell design and understanding the potential of an SRF parallel-feed accelerator. The cell shape was parameterized using a series of elliptical and straight segments as shown in Fig. 1, and optimized for either maximum shunt impedance, R_{sh}, or maximum accelerating gradient, E_{acc}, relative to the peak surface magnetic field, B_{pk}. In all cases, the electric field ratio, $E_{\mathrm{pk}}/E_{\mathrm{acc}}$, was limited to a maximum value of about 2.0 (similar to the TESLA cavity). For our simulations, we also assumed an operating frequency of 2.86 GHz, a wall thickness, t, of 3 mm, and a beam aperture radius, a, of 3 mm ($a/\lambda = 0.029$).

We also investigated phase advances other than π – because RF power is fed directly to each cell, the relative phase between cells is controlled by the manifold design. A phase advance of $2\pi/3$ showed improvement in terms of both gradient and shunt impedance, but going further, to $\pi/2$, gave only an incremental increase in gradient and reduced shunt impedance due to increased wall losses. In the end, we picked a $2\pi/3$ design for the SRF prototype demonstration, with both high shunt impedance and high gradient. Table 1 lists several key parameters for this cell design, while Fig. 2 shows both the (a) E- and (b) B-field temperature maps and (c) a plot of the surface field amplitudes along the cell wall.

For the prototype we have chosen S-band (2.86 GHz) for several reasons. First, our pulse-tube cryostat has both limited space (~ 1 cubic foot) and cooling power (1.35 W at 4.2 K) – the choice of S-band will allow a two-cell structure to be built and tested. Second, the smaller size

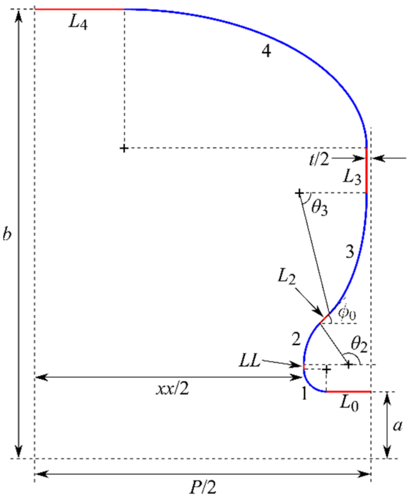

Figure 1: Cell parameterization includes both elliptical (blue) and straight (red) segments, with up to 12 free parameters.

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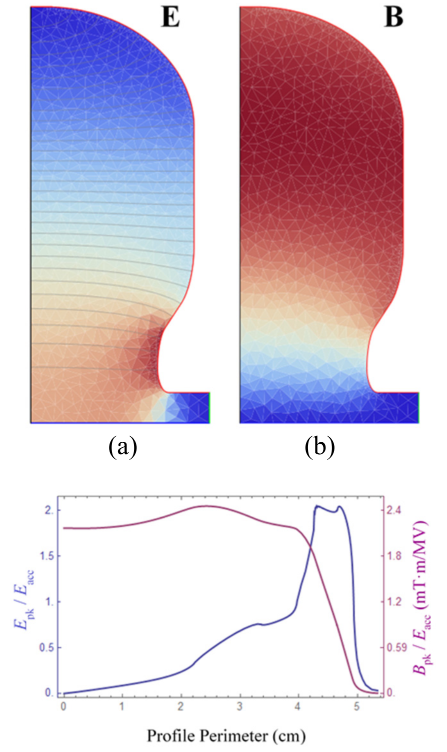
Table 1: Parameters for the $2\pi/3$ Cell Design. Utilizing High-RRR Bulk Nb at 4.2 K, R_s is set to 2 $\mu\Omega$ (BCS)

Parameter	**Value**
f (GHz)	2.86
Mode (phase advance)	$2\pi/3$
Q_0	1.04e8
R_{sh} (Ω/m)	6.95e11
E_{pk}/E_{acc}	2.05
B_{pk}/E_{acc} (mT·m/MV)	2.41
R_{sh}/Q_0 (Ω/m)	6710
G (Ω)	217
$G{\cdot}R_{sh}/Q_0$ (Ω^2/m)	5.09e4
P_{loss}/E_{acc}^2 (mW·m/MV^2)	1440
U/E_{acc}^2 (mJ/(MV/m)^2)	0.291

will also reduce fabrication costs – for the demonstration our plan is to mill the structure from high-RRR bulk niobium. And third, at SLAC we have existing RF components and power supplies at this frequency, though we are also investigating a solid-state power amplifier for feeding the SRF prototype.

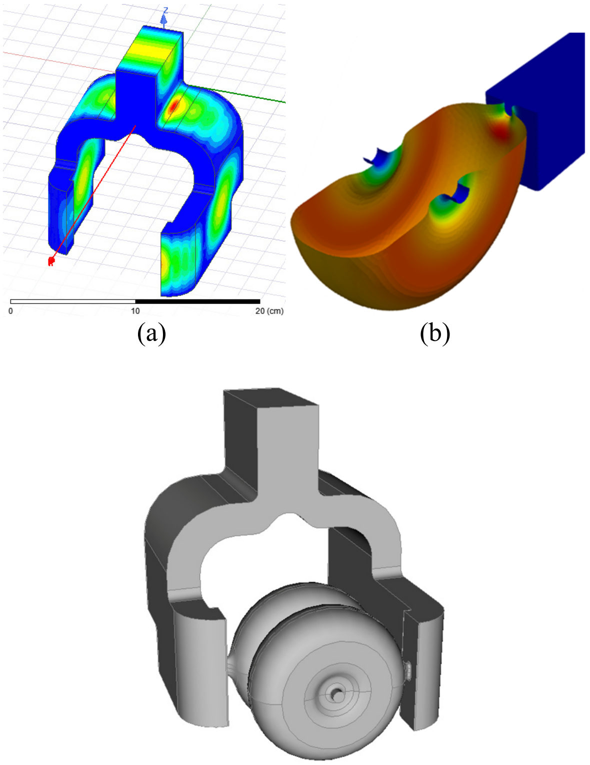
Given the cell design and frequency choice, we have also completed the design of the RF manifold and coupling port. The manifold was modelled in HFSS as shown in Fig. 3(a) and consists of a 3 dB splitter with asymmetric arms. The asymmetry is designed to provide the 120° phase shift between the two cells. The coupling port has been designed using the ACE3P simulation suite, targeting a Q_{ext} of $6{\times}10^6$. The port is located at the cell equator as shown in Fig. 3(b), and with sufficient rounding the local magnetic field enhancement is only 10% above the peak surface field on the cavity wall. With this increase, B_{pk}/E_{acc} = 2.65 mT·m/MV which is still 38% lower than for the TESLA cavity, meaning 60% higher gradients for the same quenching field (neglecting cryogenic loading).



(a) (b)

(c)

Figure 2: (a) electric and (b) magnetic field temperature maps for the $2\pi/3$ cell, with (c) surface field amplitudes plotted vs. profile length (zero at the equatorial point).



(a) (b)

(c)

Figure 3: (a) 3 dB splitter with 120° relative phase difference between the two arms. (b) Single cell with coupling port to waveguide feed. Rounding minimizes B-field enhancement. (c) Two-cell RF design with RF manifold. Still remaining is to design the tuning mechanism.

For bulk Nb, that quenching field is about 240 mT (assuming the limit is the superheating field). This sets the maximum gradient of the TESLA cavity at about 55 MV/m, while the $2\pi/3$ parallel-field structure could reach roughly 88 MV/m. On top of that gain, the parallel-feed structure also permits a greater packing fraction (the ratio of active acceleration length to total cavity length), about 20% greater than TESLA. In total, the parallel-feed structure could nearly double the average gradient over the total cavity length.

On the RF design side, we are currently working on a cell tuning mechanism. Depending on fabrication and hardware costs, our hope is to demonstrate a plunger tuner, but we may have to resort to mechanically deforming the cavities with tuning pins, as was done with the X-band copper structure. We are in the process of finalizing

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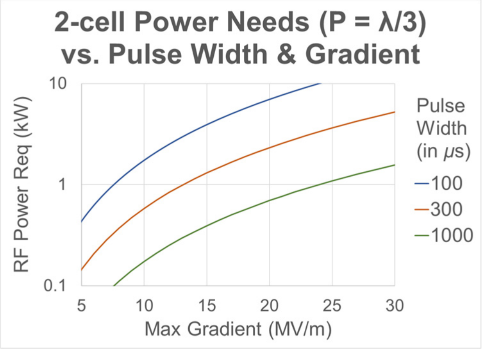

Figure 4: Power requirements for a two-cell structure vs. accelerating gradient for different pulse widths.

the mechanical design, including changes to the cryostat for mounting the cavity, maximizing thermal conductance to the base stage, and minimizing static thermal load from 40 K and room temperature. Finally, we are adding both room temperature and cryogenic magnetic shielding to minimize trapped flux in the structure.

For the RF power source, our plan is to use a solid-state power amplifier at sufficiently low duty cycle (~ 0.1%) to keep average power loss to less than 100 mW at 4 K. A GaN HEMT amplifier has been purchased from Cree, rated for an RF power output of 725 W at 2.9 GHz (with 100 μs pulse width and at 10% duty cycle). At this power level and pulse width, a two-cell S-band structure can reach a gradient of about 6 MV/m as shown in Fig. 4. Operating the HEMT at a lower duty cycle, and with enhanced transistor cooling, our aim is to reach pulse widths up to 1 ms, which would yield gradients up to about 20 MV/m.

CONCLUSION AND FUTURE WORK

Simulations of an SRF parallel-feed accelerator structure show tremendous promise, with efficiency and gradient metrics well beyond what is currently achievable with state-of-the-art cavity fabrication. We are working toward an S-band prototype and demonstration, and in the coming months will finalize structure and cryostat designs, qualify and characterize the GaN HEMT amplifier and RF hardware, and develop the measurement setup.

REFERENCES

[1] S. Belomestnykh and V. Shemelin, "High-beta cavity design A tutorial", in *Proc. SRF Conf. 05*, SUA02, 2005.

[2] B. Aune *et al.*, "Superconducting TESLA cavities", Phys. Rev. ST Accel. Beams 3, 092001, 2000.

[3] S. G. Tantawi *et al.*, "Distributed coupling and multi-frequency microwave accelerators," Jul. 2016, US Patent 9,386,682.