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THE DESIGN OF PARALLEL-FEED SC RF ACCELERATOR STRUCTURE*

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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. We are experimentally verifying the concept using an X-band SC RF design to be tested at SLAC.

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 [3-4]. 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 [5]. 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.

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Table 1: Comparison between the SCPF and TESLA Cavities, Assuming both are Fabricated from Bulk Nb. At 2 K, Rs is set to 27 nΩ (BCS)

Parameter	SC-PF	TESLA
f (GHz)	1.3	1.3
Mode (phase advance)	2π/3	π
a (cm) (aperture radius)	0.66	3.5
Q_0	8.0e9	1.0e10
R_{sh} (Ω/m)	2.4e13	9.8e12
E_{pk}/E_{acc}	2.05	1.98
B_{pk}/E_{acc} (mT·m/MV)	2.41	4.17
R_{sh}/Q_0 (Ω/m)	3050	983
G (Ω)	217	271
$G \cdot R_{sh}/Q_0$ (Ω^2)	5.08e4	3.07e4
P_{loss}/E_{acc}^2 (mW·m/MV^2)	41.1	102
U/E_{acc}^2 (mJ·m/MV^2)	40.2	124

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 described in [6], and optimized for either maximum shunt impedance, R_{sh}, or maximum accelerating gradient, E_{acc}, relative to the peak surface magnetic field, H_{pk}. In all cases, the electric field ratio, E_{pk}/E_{acc}, was limited to a maximum value of about 2.0 (similar to the TESLA cavity).

We also investigated phase advances other than π – because RF power is fed directly to each cell, their relative phase is controlled by the manifold design. A phase advance of 2π/3 yielded the optimum cell topology, with both high R_{sh} and high E_{acc}. Table 1 lists several key parameters for this cell design and draws a direct comparison with the state-of-the-art TESLA cavity. Assuming both are fabricated from bulk niobium and operated at a temperature of 2 K, our optimized cell shape achieves both 60% less RF power dissipation and 70% greater accelerating gradient.

PROTOTYPE DESIGN

After completing the initial design study, we considered various options for constructing the prototype: S-band or X-band, 2π/3-mode or π-mode. Given the limited physical space in our cryostat and the simplicity of the RF manifold, we chose the latter option in both cases: an X-band π-mode structure. The prototype will consist of two cells fed by a single RF feed port.

Table 2 lists several key parameters for this cell design, while Fig. 1 shows both the (a) E- and (b) H-field temperature maps and (c) a plot of the surface field amplitudes along the cell wall.

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Table 2: X-band Prototype Parameters Assuming Bulk Nb at 4 K and a Surface Resistance (Rs) of 34 $\mu\Omega$

Parameter	Value
f (GHz)	11.424
Mode (phase advance)	π
a (cm) (aperture radius)	0.15
Q_0	7.16e6
R_{sh} (Ω/m)	1.20e11
E_{pk}/E_{acc}	2.05
B_{pk}/E_{acc} (mT·m/MV)	3.57
R_{sh}/Q_0 (Ω/m)	1.67e4
G (Ω)	240
$G{\cdot}R_{sh}/Q_0$ (Ω^2)	5.26e4
P_{loss}/E_{acc}^2 (mW·m/MV^2)	8360
P_{loss}/E_{acc}^2 (mW/cell/(MV/m)^2)	110
U/E_{acc}^2 (mJ·m/MV^2)	10.9

The manifold was optimized to equally split power between the two cells, achieve the proper phase advance (180°), and minimize the reflected power. We also designed a waveguide coupler that transitions from standard WR-90 to the custom size used in the manifold. The coupling ports were designed targeting a Q_{ext} of 2.8e5. (For the RF power source, we will use a TWT with 2.5 kW peak power and 11.7 μs pulse width – the latter sets the coupling strength.) The port is located at the cell equator (see Fig. 2), and with sufficient rounding the local magnetic field enhancement is only 8.6% above the peak surface field on the cavity wall.

From the RF model, a mechanical design was put together – a rendering of a structure-half is shown in Fig. 2(c). The structure is under fabrication from two halves from bulk niobium block. In addition to the two accelerating cavities and RF manifold, the mechanical design includes precision machined holes for alignment, bolt holes for clamping the two halves together, pump-out ports on either end of the cells, and additional ports for diagnostics (for two-port through measurements and Faraday cups for measuring dark current). The prototype is already received and is shown in Fig. 3 before cleaning. We will begin assembly of the cryostat and the experimental RF test setup at SLAC in the upcoming months.

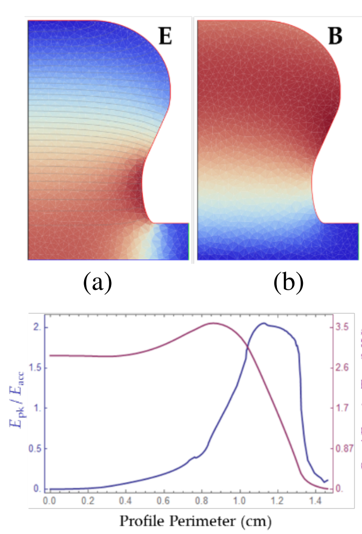

Figure 1: Field temperature maps for the X-band cell (top), with surface field amplitudes plotted vs. profile length (zero at the equatorial point).

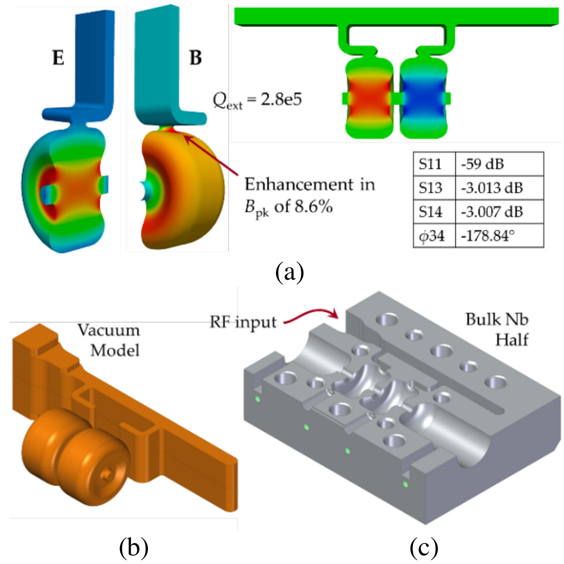

Figure 2: (a) Field temperature maps for the X-band cells with coupling ports. Note that the field enhancement is only 8.6%. When combined with the RF manifold, fields in the two-cell structure are evenly distributed with the correct phase advance and minimal reflection. (b) the vacuum model includes the waveguide adapter from a WR-90 input. (c) a mechanical model is shown for one half of the structure, with holes for alignment and clamping, and additional ports for diagnostics and pumping.

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

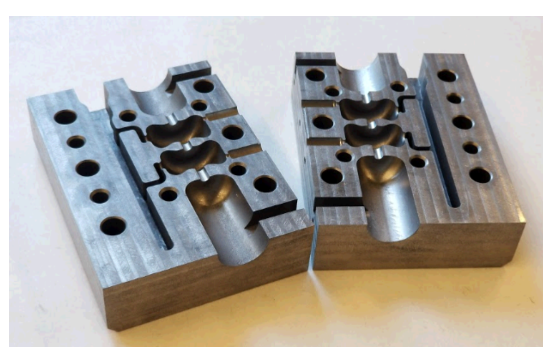

Figure 3: An image of the manufactured prototype. It is fabricated from two halves from bulk niobium block. The manufactured blocks have holes for alignment and clamping, and additional ports for diagnostics and pumping.

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state-of-the-art cavity fabrication. We worked on an X-band prototype, and in the coming months will be testing the structure at SLAC.

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