POLYHEDRAL CAVITY STRUCTURE FOR LINAC COLLIDERS*

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Abstract

A polyhedral superconducting cavity is being developed for possible use in linac colliders. The side view of the cavity has the ellipsoidal contour of a Tesla-type multi-cell string, yet the end view has the shape of a dodecahedron. Each of the twelve copper wedges has the TESLA contour cut out by EDM. The copper segments have refrigeration channels gun bored through them and the solid structure eliminates Lorentz detuning. A niobium foil is bonded to the inner surface of the wedge and then the twelve are assembled to create the superconducting cavity. There are no welds, and the seams between adjacent segments do not affect the high Q of the accelerating mode but at the same time block the azimuthal currents of deflecting modes. The power coupled into deflecting modes can be slot-coupled at the seams into waveguides integrated in the copper segments and conveyed to a warm termination. This open geometry makes each segment readily available for cleaning, polishing, inspection, and characterization. The accessibility to the surface accommodates advanced superconductors that may allow for higher gradients. The performance of these materials can be tested in a superconducting test cavity.

GRADIENT AND DEFLECTING MODES: PACING ISSUES FOR LINAC COLLIDERS

ILC has been endorsed as the next new facility for high energy research. The TESLA technology [1] has been chosen for the project as the most cost-effective basis for the ~500 GeV linacs. The design is based upon a 1.3 GHz ellipsoidal cavity, made of pure Nb, operating at 1.8 K. Prototype ILC cavities have attained an accelerating gradient of ~30 MV/m and up to ~50 MV/m with high-power conditioning. The latter is reaching the superheating limit.

The capital cost of a TESLA linac collider will be dominated by the cost of the Nb cavities, cryogenics, power couplers, and RF power systems. The operating cost will be dominated by the cost of refrigerating the accelerating structures to superfluid helium temperature. The performance of a linac collider is determined by the accelerating gradient and the beam brightness that can be sustained through the acceleration process.

The TESLA cavity's compound ellipsoidal geometry is a figure of revolution, as shown in Figure 1. A 9-cell cavity string is the basic module of the linac structure. Fabrication begins by forming half-cell contours from flat niobium sheet. The half-cells are e-beam welded at the equator (Figure 1) to form single cells and then 9 cells are welded at the necks to form a module.

The attainable gradient can be limited by contamination of surface chemistry and by irregularities in grain structure, both of which can be generated by the equatorial weld. These issues can affect both the surface electric and magnetic fields that can be sustained. Defects, impurities, and irregularities can lead to multipacting, field emission, and thermal breakdown, all causing quench. Once a module is complete, cleaning, polishing, inspection, and characterization of the critical surfaces are performed blindly through narrow end apertures.

POLYHEDRAL STRUCTURE

The equatorial weld and access to the critical surfaces motivated us to consider an alternate structure with the same ellipsoidal *r-z* contour but with a polyhedral *r-φ* geometry. A polyhedral ellipsoid should perform as a high-Q resonator with a mode structure very similar to the TESLA cavity, yet the entire 9-cell module fabricated from copper wedges with strips of superconducting material bonded to the interior. Fabrication of each segment follows the procedure shown in Figure 2.

Each copper segment is EDM-machined to create the TESLA profile and the cooling channels are gun-drilled along its length creating a closed circuit plumbing manifold, thereby eliminating the need for pool-boiling cryostat. Then a foil of copper backed Nb, which has been explosively bonded, is die-formed to the contour and is low-temperature eutectic bonded to the Cu segments.

A gap is milled in the side face of each segment creating a slot in between adjacent wedge, which naturally suppresses the defecting mode. The slot is connected to HOM waveguide bored into the copper. The edges of the bonded Nb foil near are precision-ground to the rounded contour creating good coupling to the slot (Figure 4).

Once the twelve wedges are completed they are stacked in a locking Roman arch to form the 9-cell module (Figure 3). Note that the solid Cu segments provide rigid support for the Nb surface, eliminating issues of Lorentz detuning. The polyhedral seams provide a natural means for suppression of deflecting modes and the open geometry creates several opportunities for advanced techniques.

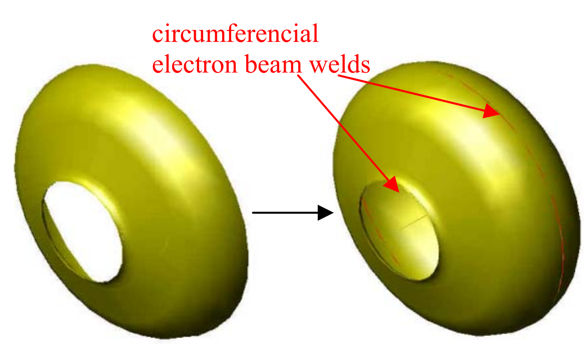

Figure 1: TESLA cavity cell construction.

*Work supported in part by Grant DE-FG03-95ER40924.
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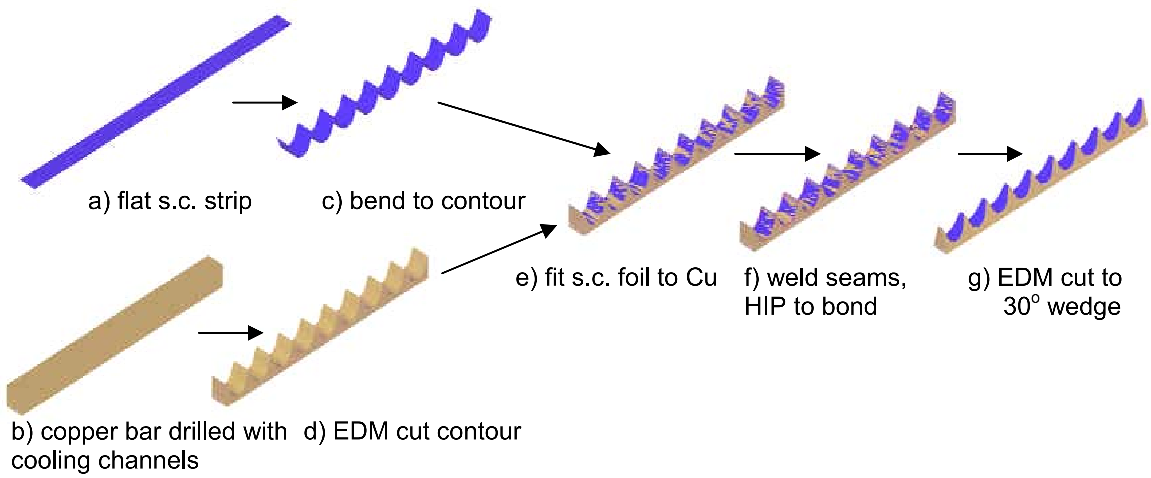

Figure 2: Fabrication sequence for constructing each wedge segment of a polyhedral cavity module.

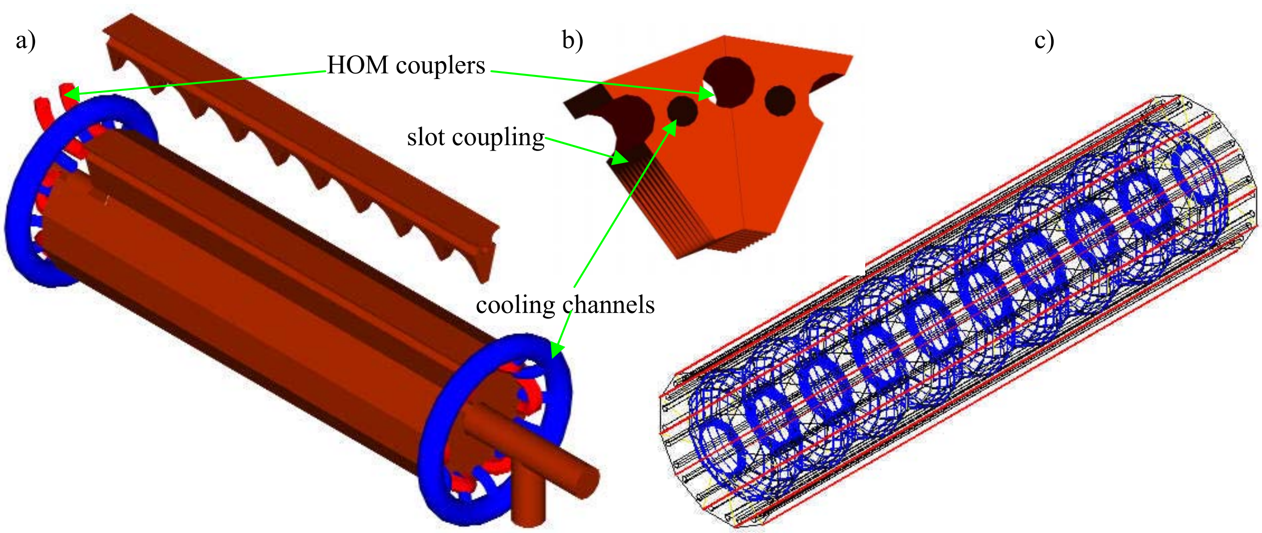

Figure 3: Assembly of 12 segments to make a polyhedral cavity module. a) polyhedral assembly, one segment withdrawn; b) detail of slot-coupled HOM waveguide and cooling channels; c) wire-frame showing interior cavity surface.

RESONANT MODES

Comparing the polyhedral cavity structure of Figure 3 to the cylindrical ellipsoidal structure of Figure 1, the resonant mode structure and resonant Q of the dominant modes are very similar. The most important difference is the boundary joint between adjacent faces of the polyhedral structure is not superconducting (indeed a narrow slot gap there can be used to remove deflecting modes). We have used the 3-D code SOPRANO [2] to calculate the accelerating mode and the deflecting modes in both the TESLA and the polyhedral geometries.

Accelerating Mode

The accelerating mode (TM_{010}, shown in Figure 4a) is carried by surface currents traveling in the r-z plane only. Since the slots between faces of the polyhedral structure are oriented along contours of constant azimuth, these currents would not cross the slots. However the slots must be narrow enough and have precision ground edges so as not to affect the Q, for the accelerating mode is sensitive to the slot size and shape. At the interior fold between two planar surfaces, both E and H vanish as a power law $(\rho/R)^n$, where ρ is the distance from the slot and R is the radius of the cavity. The surface field near a joint decreases to half its nominal value at a distance ρ=0.6 mm from the slot (Figure 4b). The slot region is thus self-protecting against surface breakdown (Figure 4b). Thus comparing models of the TELSA geometry, Q = 4.3 x 10^{10}, to the polyhedral cavity, Q=3.3 x 10^{10}, there is no appreciable difference.

Deflecting Modes

One limitation to the performance of linear accelerators is transverse emittance growth from deflecting modes. When a cavity is slightly misaligned from the beam axis, a charged particle bunch will drive deflecting modes (*e.g.* $TE_{110,}$ shown in Figure 4c). All such modes are supported by *azimuthal currents* in the cavity walls. In the polyhedral cavity structure, the slots between wedges strongly suppress all deflecting modes. Q_{def} is reduced by 140,000.

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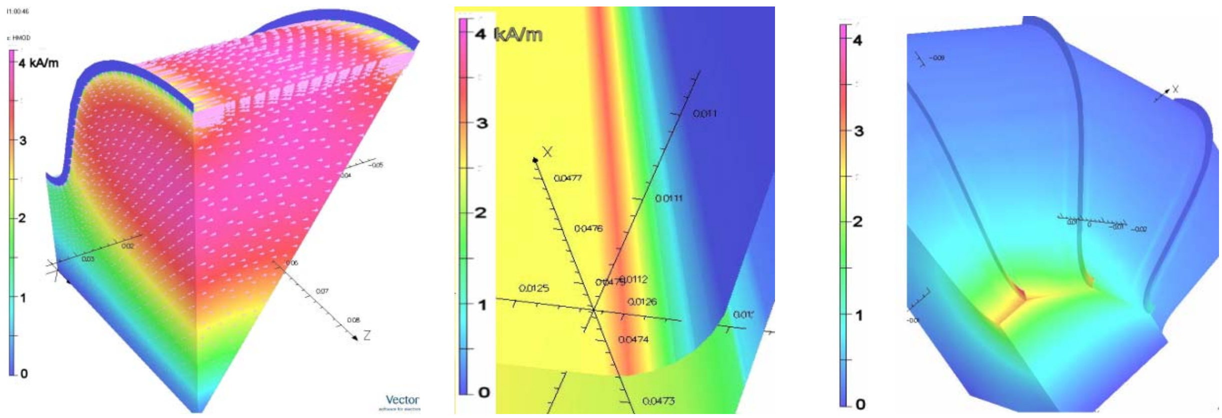

Figure 4: Field intensity distribution in the polyhedral cavity: a) $\vec{H}$ in accelerating mode; b) detail of $\vec{H}$ in slot in accelerating mode; c) $\vec{H}$ in lowest-order deflecting mode.

The deflecting modes can be extracted through the slot aperture. It is important to extract the power from these higher order modes (HOM) and dissipated on a room-temperature termination. This is done by slot-coupling into a cylindrical dielectric-loaded waveguide that is milled into each mating face of the copper (Figure 3).

The slot coupling from the cavity into each cylindrical HOM waveguide is $c \sim e^{-\ell/d}$, where d = 0.1 mm is the slot aperture and ℓ is the slot length. The geometry can thus be tailored to provide the desired HOM coupling. The waveguides are coupled in series at the module ends and brought through two transitions to 300 K termination.

By limiting the effect of long range wakefields, it should be possible to decrease bunch spacing, improving the power efficiency of the accelerator.

ENHANCED SUPERCONDUCTORS

The polyhedral cavity structure makes it possible to develop superconducting cavities using superconductors with the potential for supporting higher surface current (hence higher gradient) than Nb [3]. Alternating thin films of dielectric and type-II superconductors, with $T_c > T_c^{Nb}$ and $B_c > B_c^{Nb}$ (e.g. NbN, Nb_3Sn), are sputtered onto a Nb cavity surface, each layer's thickness being small compared to the penetration depth (~50 nm Nb_3Sn, ~20 nm NbN). In that case each Nb_3Sn layer should shunt ~200 mT of field and it should be possible to triple the gradient as well as quadruple Q of pure Nb. For ILC application, sputtering and characterizing of such thin films should be feasible on the open geometry of the polyhedral segments. This has the consequence of doubling the energy of the collider with the same length and power.

A test cavity is being designed to allow testing of these multilayer laminate films. This superconducting cavity operates at 1.3 GHz, so as to match ILC's frequency. The end face of the cavity is coated with the sample material. Currents in the cavity only flow azimuthally so as to eliminate any consequences of currents flowing across the interface between the sample and the niobium structure. The structure is powered through either a coaxial or waveguide mode converter. The magnetic field on the surface of the sample is twice in magnitude than anywhere else on the cavity surface. It is therefore possible to increase the beyond the BCS limit.

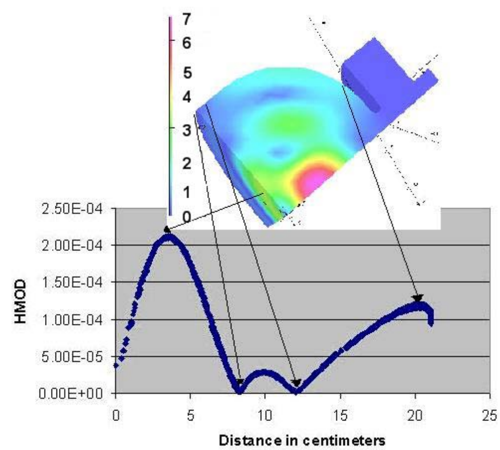

Figure 5: H field on surface of test cavity.

A second such possibility is to use a film of YBCO on a Ni substrate foil. YBCO exhibits ~300x larger rf surface resistance [4], hence lower Q, but it can be operated at ~20 K, dramatically reducing the power required for refrigeration. Trading duty factor for Q could offer an attractive alternative for some linac applications (e.g. RIA, XFEL).

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