POLYHEDRAL CAVITY STRUCTURE FOR LINAC COLLIDERS*

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Abstract

A polyhedral cavity structure has been devised for use in superconducting linacs. It has the same ellipsoidal side contour as a TESLA cavity but is configured as a polyhedron in its end view. Each segment of the polyhedron consists of a Nb foil bonded to a Cu wedge that has been machined to the desired ellipsoidal inner contour. There are no welds, and the seams between adjacent segments do not affect the high Q of the accelerating mode but 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 warm termination. The inner surface of each segment is accessible for polishing and characterization. It accommodates application of improved superconducting surfaces, such as the multi-layer thin-film Nb_3Sn proposed by Gurevich. Refrigeration can be provided by gun-bored channels within the copper segments. The copper segments provide a rigid assembly that eliminates Lorentz detuning.

GRADIENT AND DEFLECTING MODES: PACING ISSUES FOR LINAC COLLIDERS

The ILC project 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 capital cost of a TESLA-based linac collider will be dominated by the cost of the Nb cavities and the associated cryogenics, power couplers, and RF power systems. The operating cost will be dominated by the cost of refrigerating kilometers of accelerating structure to superfluid helium temperature. The performance of a linac collider is determined by the accelerating gradient that can be sustained and by the beam brightness (emittance density) that can be sustained through the acceleration process. Dilution of the beam brightness can arise from transverse forces due to deflecting modes that are excited by electron bunches traversing the superconducting cavities with slight misalignment from the cavity axis.

The TESLA cavity geometry is a figure of revolution in which the side contour is a compound ellipsoid, as shown in Figure 1. A 9-cell cavity string is the basic module of the linac structure. Decades of effort have been devoted to perfecting the techniques by which these modules are fabricated. 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 field that can be sustained (multipacting near the iris) and the surface magnetic field that can be sustained by supercurrents in the surface layer of Nb (slow onset of quench near the equator). Cleaning and inspection are complicated by the fact that the critical surfaces are *inside* the module when it is complete. Operations of cleaning, polishing, inspection and characterization must be done through the narrow end apertures.

POLYHEDRAL STRUCTURE

The considerations of equatorial weld and of access to the critical inside surfaces motivated us to consider an alternative structure with the same ellipsoidal r-z contour but with a polyhedral r-φ geometry. Such a polyhedral ellipsoid has the interesting property that it should perform as a high-Q resonator with a mode structure very similar to the figure of revolution, yet it could be fabricated from flat strips of superconducting material.

The concept for fabrication of the polyhedral cavity is illustrated in Figure 2 for a dodecahedral cavity. Each segment of the entire 9-cell module is fabricated from a flat strip of superconducting material. The foil is bent in the easy direction and bonded to the curved surface of a solid copper wedge on which the desired ellipsoidal contour has been formed. 12 segments are then 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.

Provision for refrigeration can be integrated directly into the copper segments by gun-drilling cooling channels, so that refrigeration can be provided as a closed-circuit plumbing manifold and no pool-boiling cryostat is necessary. The polyhedral seams provide a natural means for suppression of deflecting modes and for coupling of power from those modes to an external load.

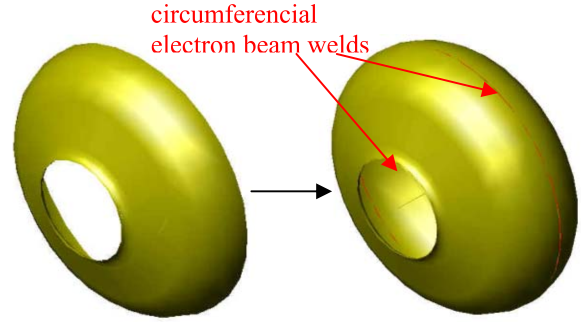

Figure 1: TESLA cavity cell construction.

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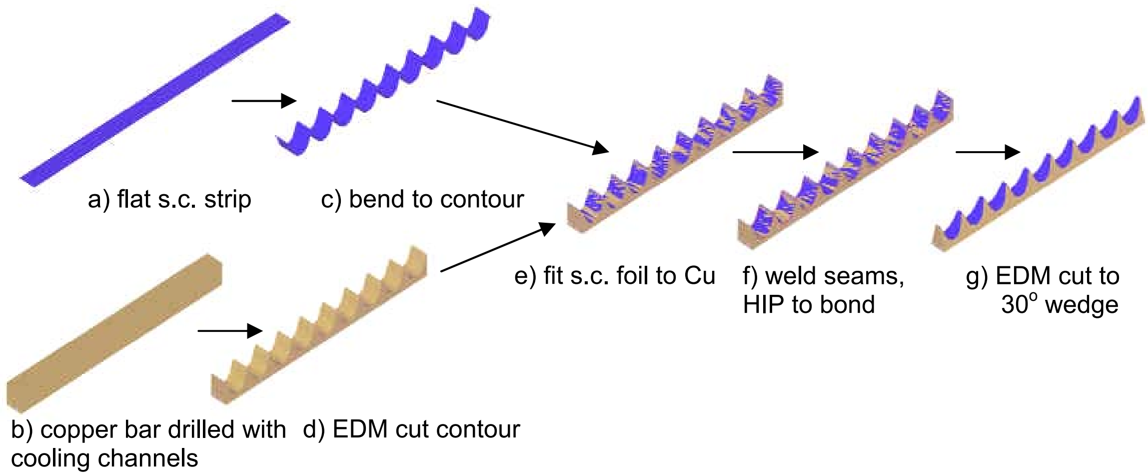

Figure 2: Fabrication sequence for constructing each wedge segment of a polyhedral cavity module.

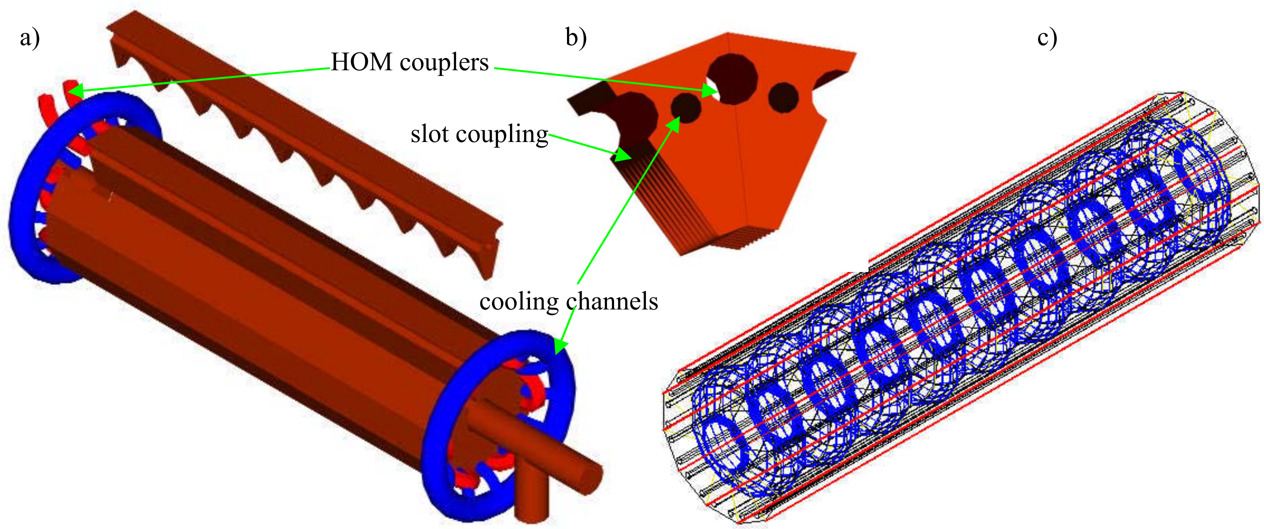

Figure 3: Assembly of 12 segments to make a polyhedral cavity module. a) polyhedral assembly, one segment withdrawn; b) detail of slot-coupled HOM waveguide and cooling channels; c) wire-frame showing interior cavity surface.

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 that 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; there are *no azimuthal currents*. Since the slots between faces of the polyhedral structure are oriented along contours of constant azimuth, no currents would cross the slots and there should be little or no impact on the Q of the accelerating mode.

Consider $\vec{E}$ in the accelerating mode near a slot between adjacent polyhedral segments. 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.

Deflecting Modes

One limitation to the performance of linear accelerators for high-energy applications is the phenomenon of 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 gaps between segments strongly suppress all deflecting modes.

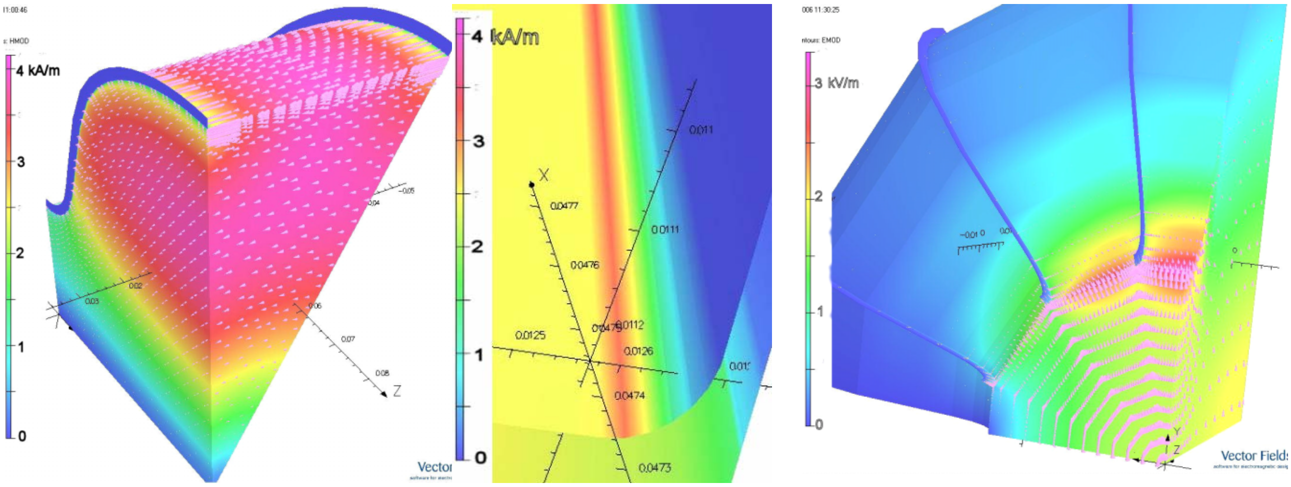

Figure 4: Field intensity distribution in the polyhedral cavity: a) $\vec{H}$ in accelerating mode; b) detail of $\vec{H}$ in slot in accelerating mode; c) $\vec{E}$ in lowest-order deflecting mode.

HOM Coupler

It is important to extract the power that is coupled into higher order modes (HOM) so that it can be dissipated on a room-temperature termination. The deflecting modes can be extracted through a narrow slot aperture at the boundary between adjacent segments, slot-coupling into a cylindrical dielectric-loaded waveguide that is formed by mating channels in the segment boundaries (Figure 3).

The slot must be narrow enough that it does not affect the Q of the accelerating mode. Figure 4b shows the distribution of magnetic field in the accelerating mode near the slot. The Q of the accelerating mode is quite sensitive to the design of the slot aperture. To evaluate the effect of the polyhedral geometry and the slot-coupled HOM coupler on Q, identical models with cylindrical symmetry and polyhedral geometry were separately calculated. Using a surface resistance of $3x10^{-9}\ \Omega$ yields Q = 4.3 x 10^{10} for the cylindrical cavity, and Q = 3.3 x 10^{10} for the polyhedral cavity.

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 adjusted 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.

FABRICATION OF THE SEGMENTS

Fabrication of each segment follows the procedure shown in Figure 2. The copper segment is EDM-machined to the required ellipsoidal contour and the cooling channels are gun-drilled along its length. The Nb foils are then die-formed to the contour and bonded to the Cu segments. One method for this bonding is to first explosion-bond the Nb foil to a Cu foil, then cold-roll the Nb/Cu laminate to an appropriate thickness, and finally to bond the laminate to the copper segment. This final copper-copper bond could be done either using low-temperature eutectic bonding or indium contact bonding. The final Nb surface can be cleaned and polished either before bonding or after bonding (or both).

The half-cylindrical channel for each HOM waveguide and the flats that will form the coupling slots are milled into the side faces of the segment. The edges of the bonded Nb foil are precision-ground to the rounded contour shown in Figure 4.

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. One example is the multi-layer laminate suggested by Gurevich [3]. Alternating thin films of dielectric (e.g. NbN) and of Nb_3Sn are sputtered onto a Nb cavity surface, each layer having a thickness small compared to the penetration depth (~50 nm Nb, 20 nm Nb_2O_5). In that case each Nb_3Sn layer should shunt ~200 mT of field and it should be possible to triple the gradient that is possible with pure Nb. Sputtering and characterizing of such thin films should be feasible on the open geometry of the polyhedral segments.

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).

REFERENCES

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