Polyhedral Cavities for Linac Colliders

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Ellipsoidal cavities have reached an advanced state-of-art

Ultimate limits: Q ~ 10^{10} at 1.3 GHz, 2 K

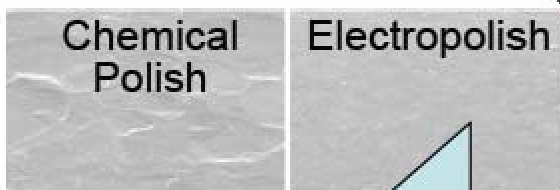
E_{acc} ~ 50 MV/m (best-of-show) ~ BCS limit

Surface fields to 200 MV/m in particular geometries

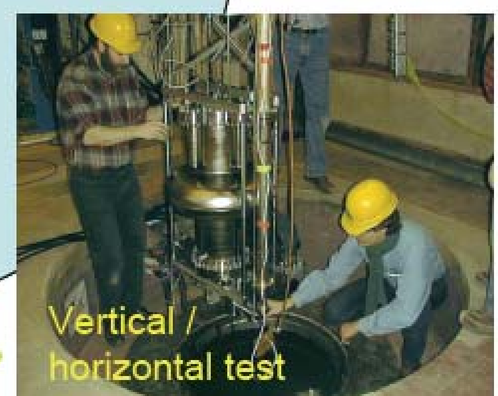
Critical surface field from rf superheating ~2300 Öe

Learning to make reliable Cavities

Intensive R&D; extensive test facilities

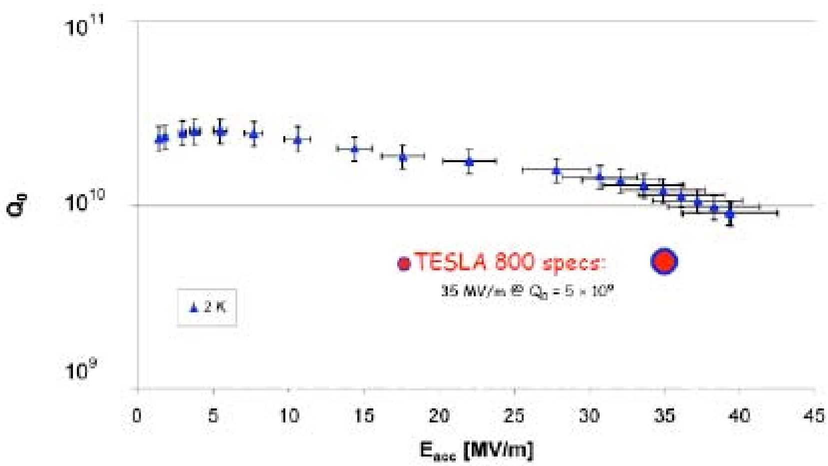


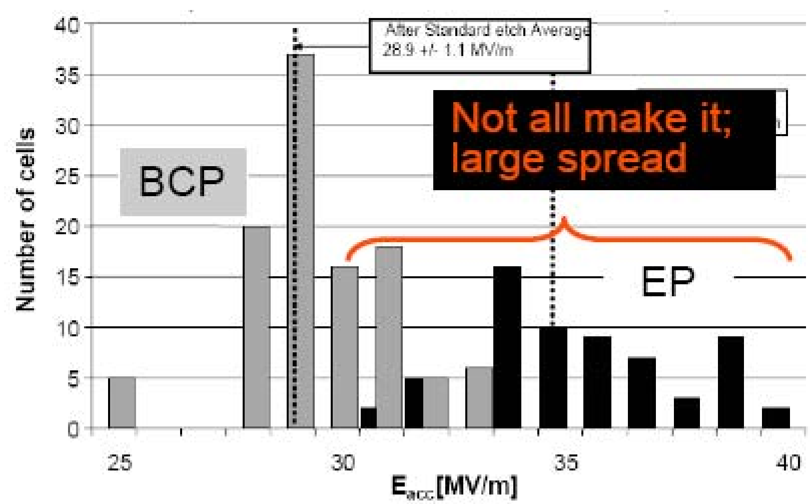
DESY photos



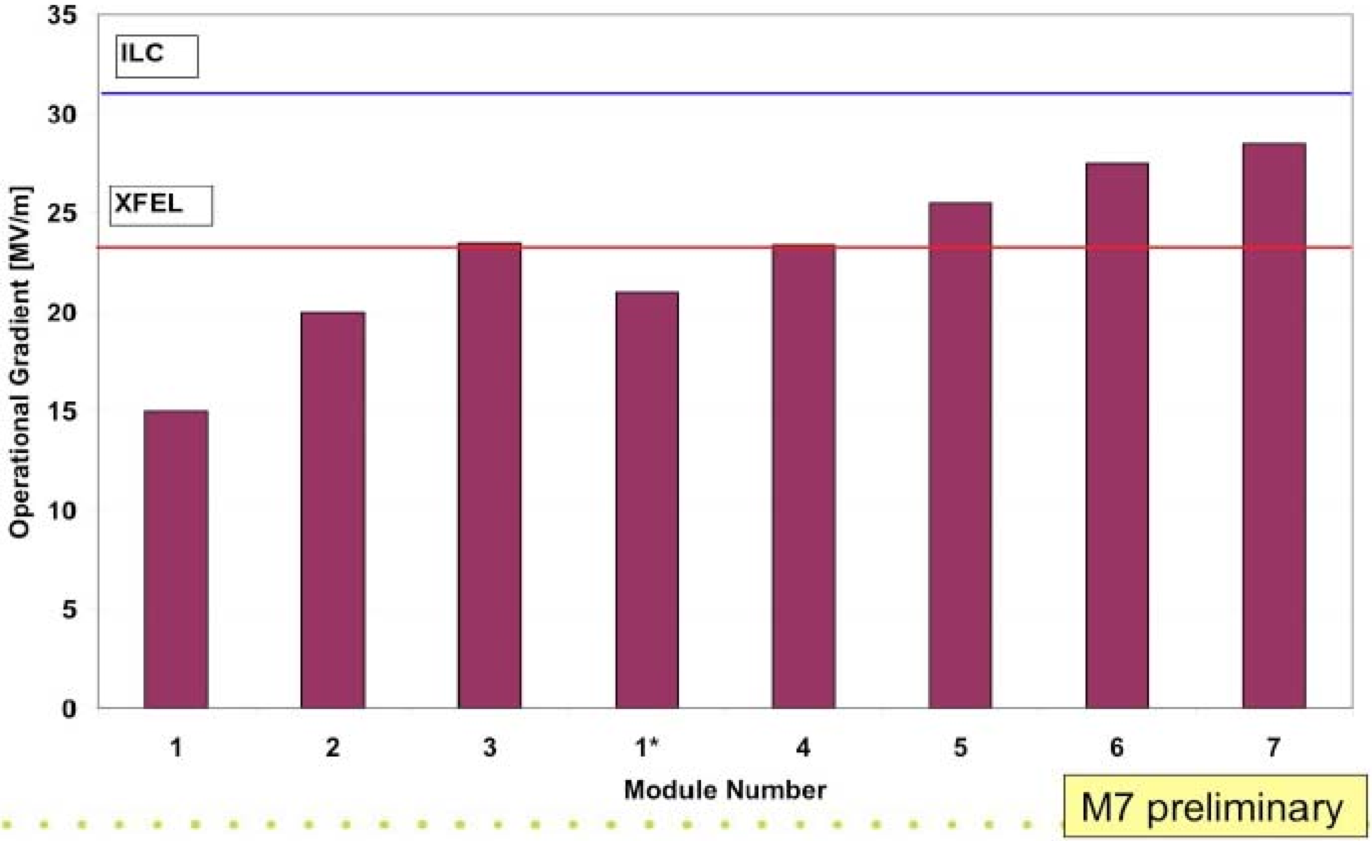
Cavity Gradient & Yield

Learning how to prepare smooth, pure Nb surfaces to get the high gradient was a decade-long effort. One recent advance uses electropolishing as well as (rather than?) chemical polishing for smooth surface. (Alternate cavity shapes have reached >50 MV/m.) But the process is not under good control. One still worries about field emission from surface imperfections giving large dark current.





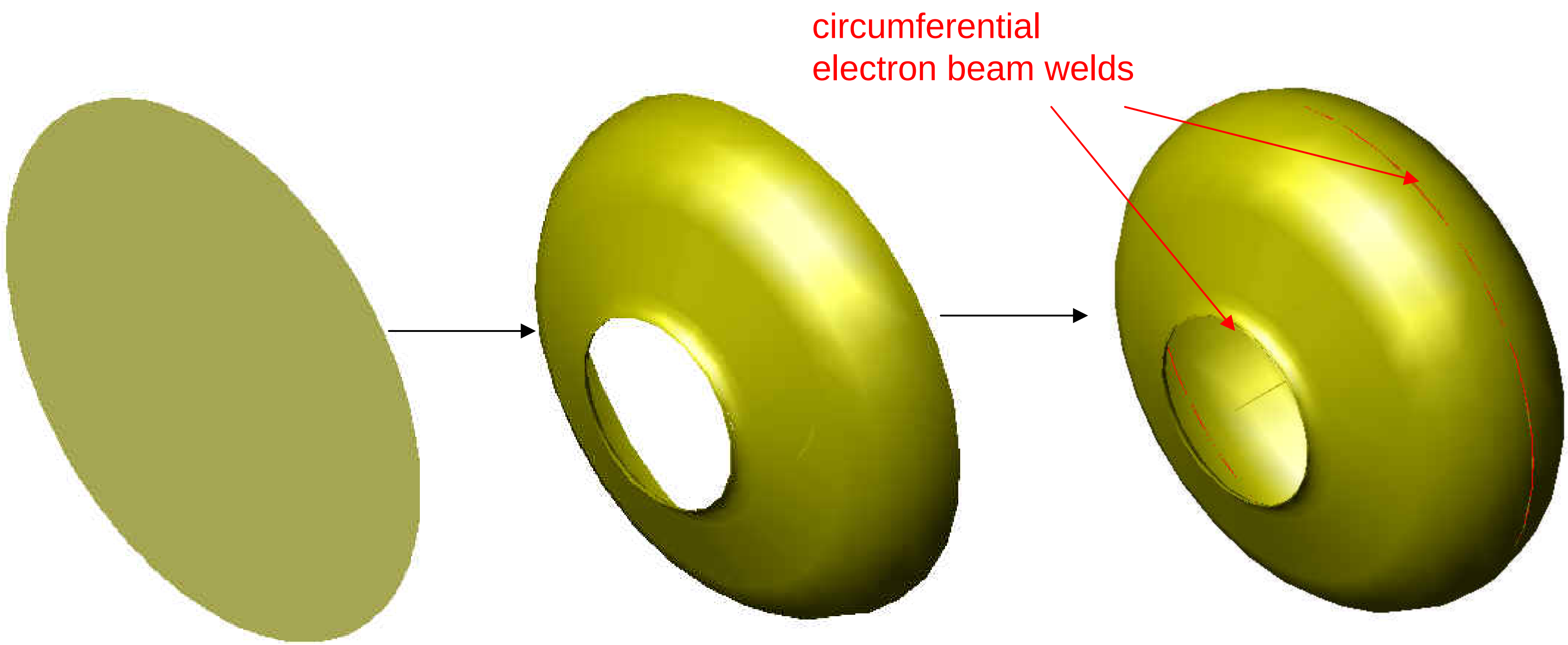
Accelerator Module Operational Gradients



Pacing challenges for cost/performance of a linac collider

- *The linac cavities and associated cryogenics dominate the capital cost.*
  - How to attain pristine surfaces on inside when you can't reach them after each cavity string is welded?
  - Can we push gradient to reduce length?
  - Each module must be immersed in superfluid He (boiler code?)
  - Lorentz detuning requires that every cavity be deformed in a feed-forward control to keep it on resonance.
- *The rf energy to cavities dominates the operating cost.*
  - The bunch spacing is limited by long-range wake fields.
  - How to kill deflecting modes so bunches could be closer?
  - How to improve Q?

Surface properties limit practical gradients



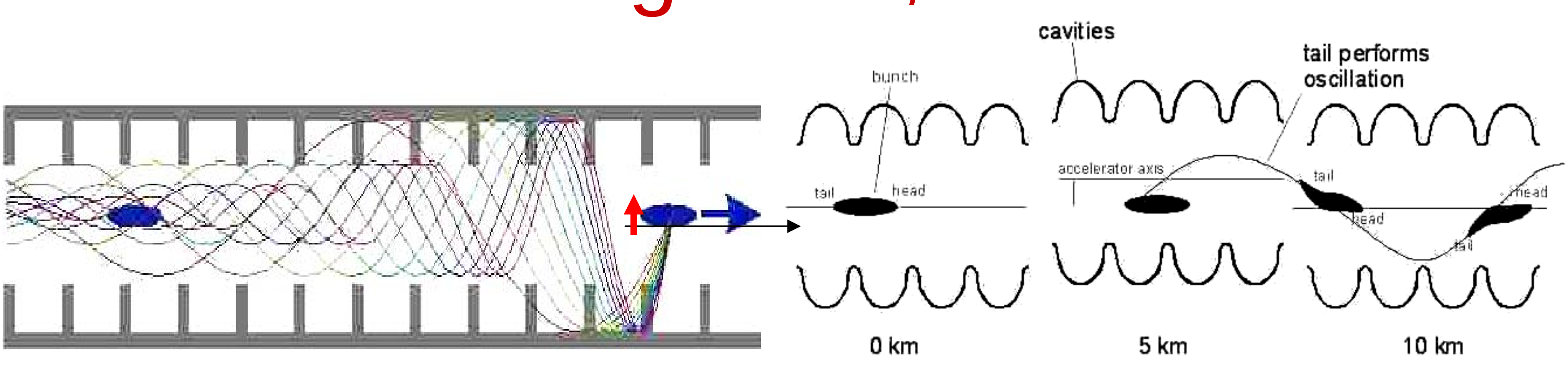
•Heat-affected zone of e-beam welds alters grain structure, oxides in surface.

•Electropolishing produces step discontinuities at grain boundaries.

•Inspection and polishing of inner surfaces must be done in a blind hole.

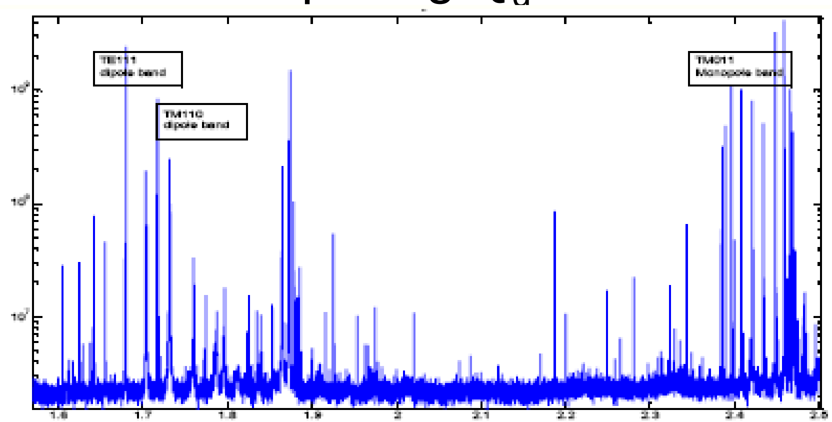
•Suppose we could fabricate the cavity string so that the inside is visible & accessible?

Transverse wake fields cause emittance growth, instabilities

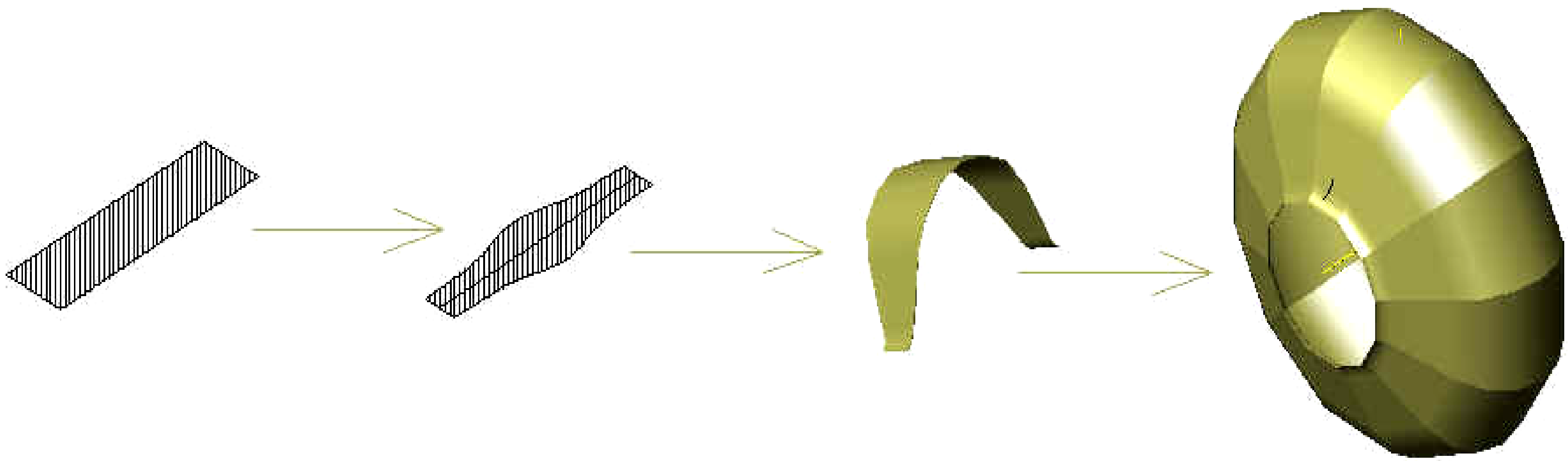


If a cavity string has transverse misalignment, each bunch drives *dipole modes* which are resonant with $Q_d \sim Q_a$.

Higher-order mode (HOM) couplers are used to extract the HOM fields from each module to a termination, spoiling Q_d to reduce wake fields on following bunches.



The Polyhedral Cavity

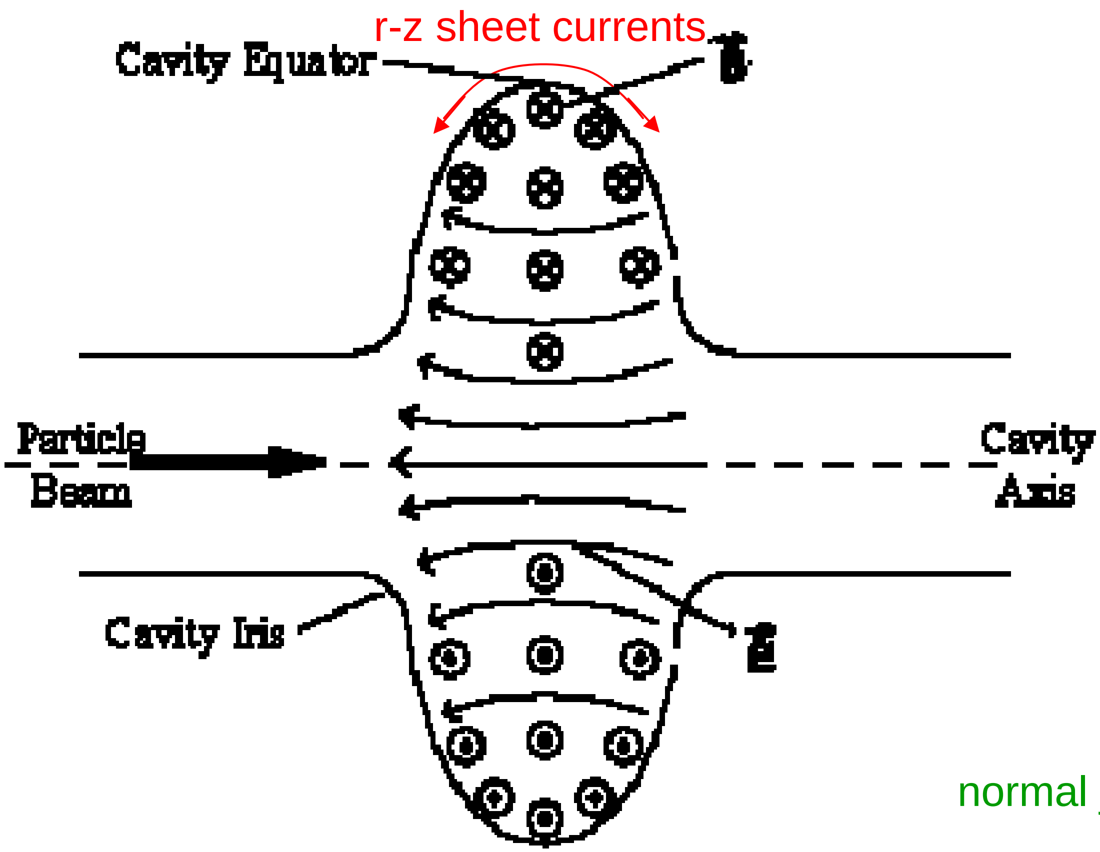


flat rectangular strip → trim strip → contour strip → assemble 12 strips

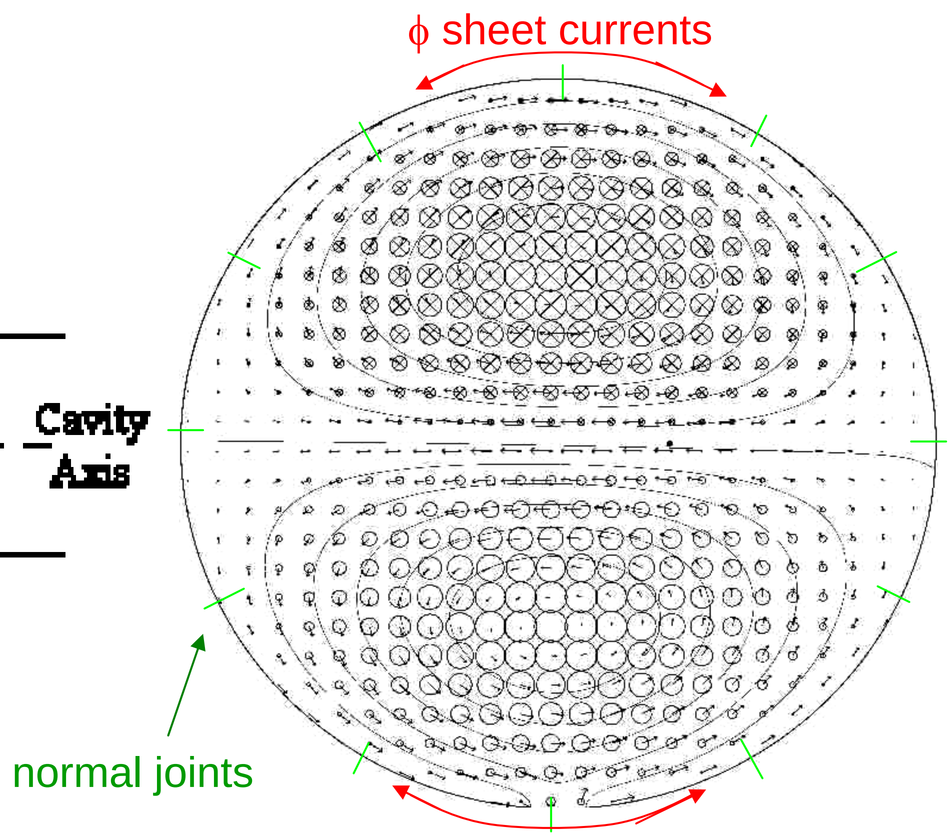
Replace the ellipsoidal figure of revolution by a polyhedron.

The electrodynamics of the resonant modes is unaffected except at extremely high order.

Accelerating mode unchanged; Deflecting mode suppressed strongly

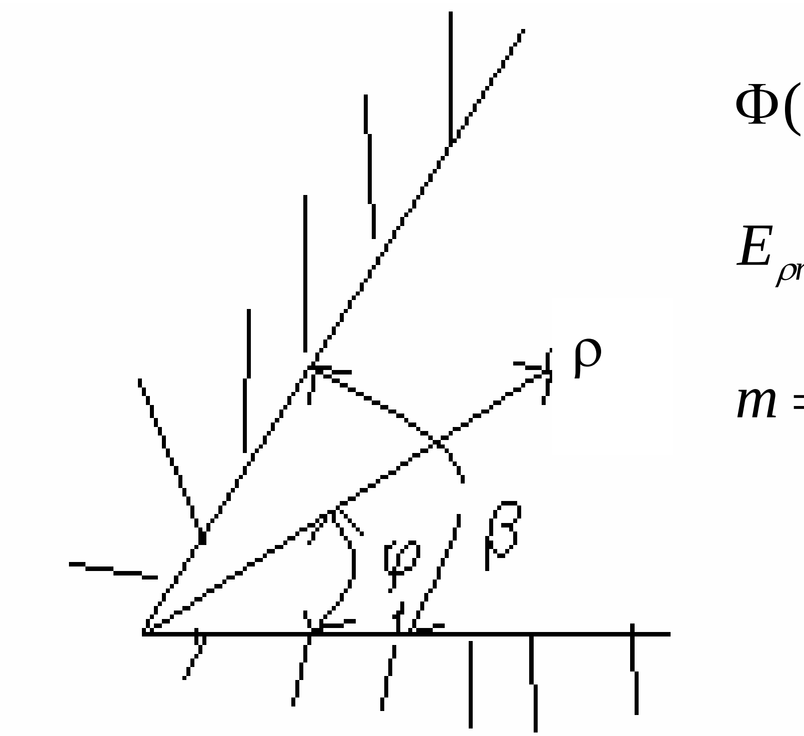


Accelerating Mode



Deflecting Mode

$\vec{E}$ at joints between hedra



$$\Phi(\rho,\varphi) = V + \sum_{m=1}^{\infty} a_m \rho^{m\pi/\beta} \sin(m\pi\varphi/\beta)$$

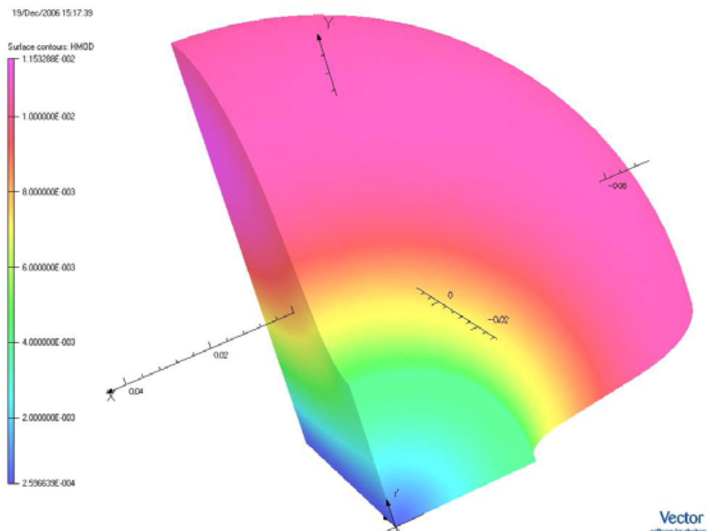
$$E_{\rho m} = -6ma_m \rho^{1.2m-1} \sin(6m\varphi)$$

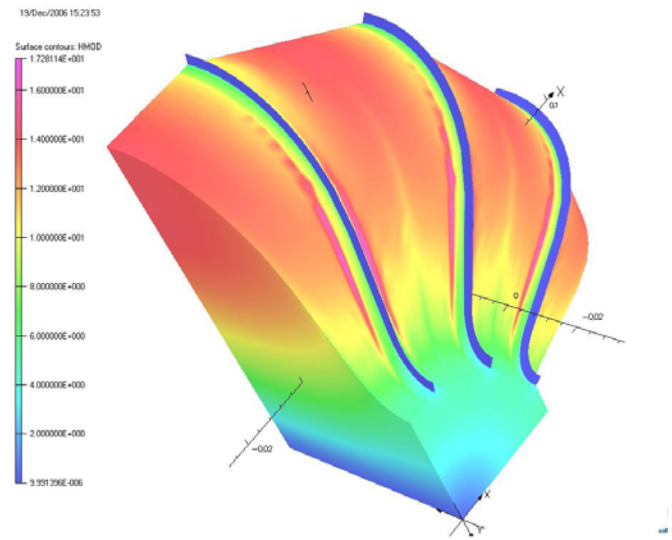
$$m = 12: \qquad \mathrm{E}_{\rho} \propto \left(\frac{\rho}{R}\right)^{0.2}$$

$\vec{E}$ reduced to half-value at distance 0.6 mm from joint.

Joint is shielded against breakdown from micro-irregularities.

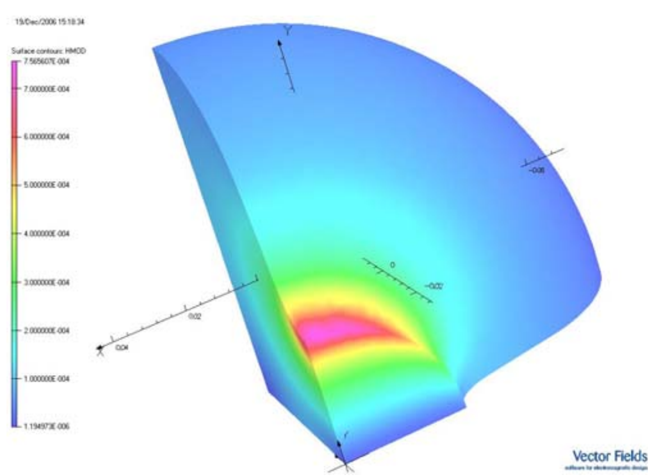
Comparison of fields

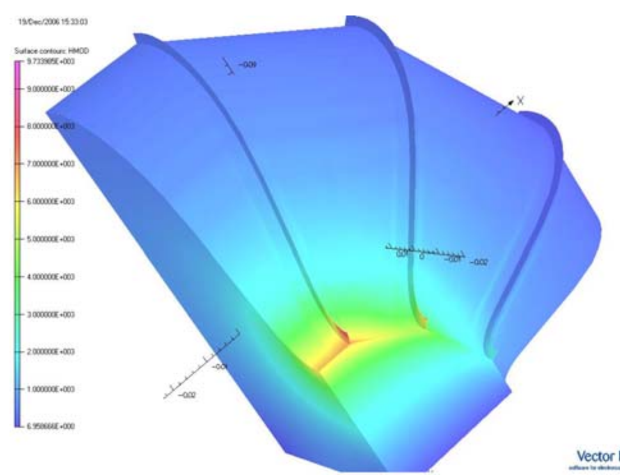




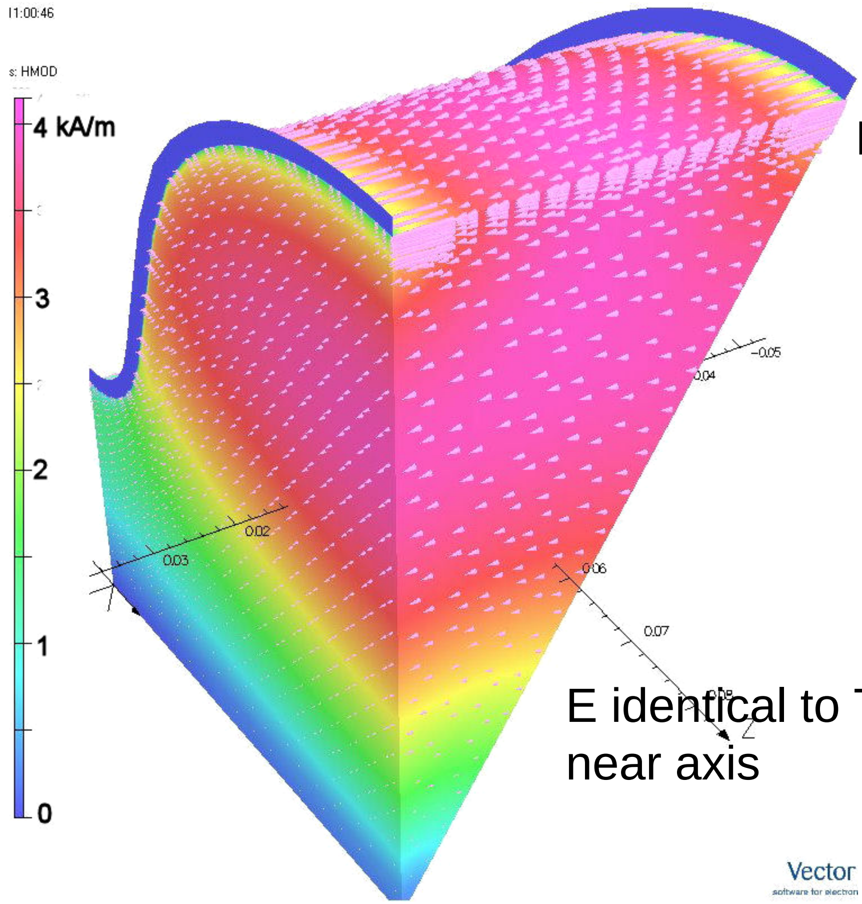
TESLA structure

Polyhedral structure



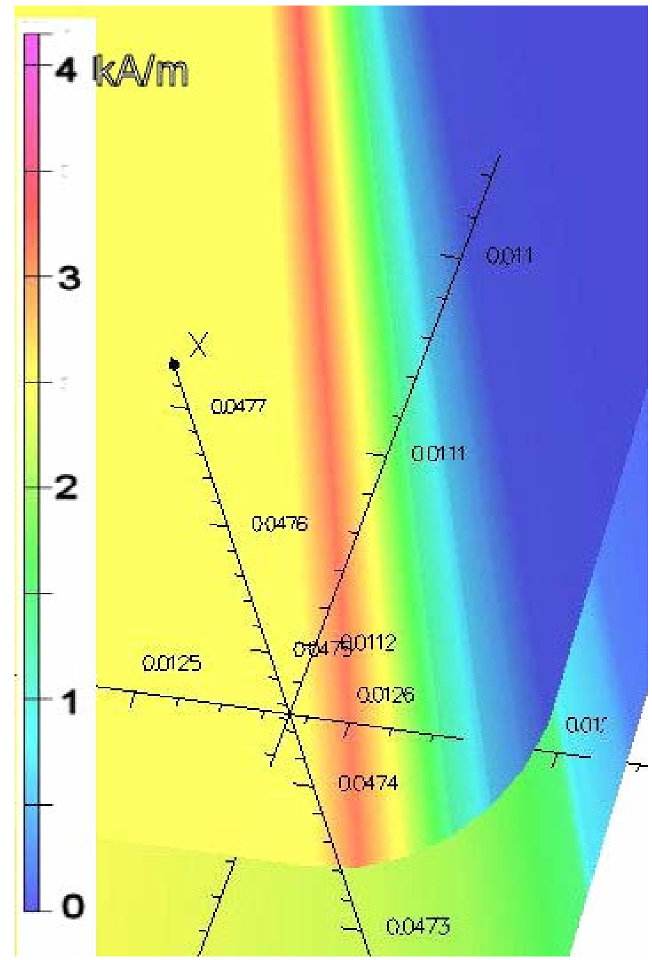


Numerical modeling of accelerating mode



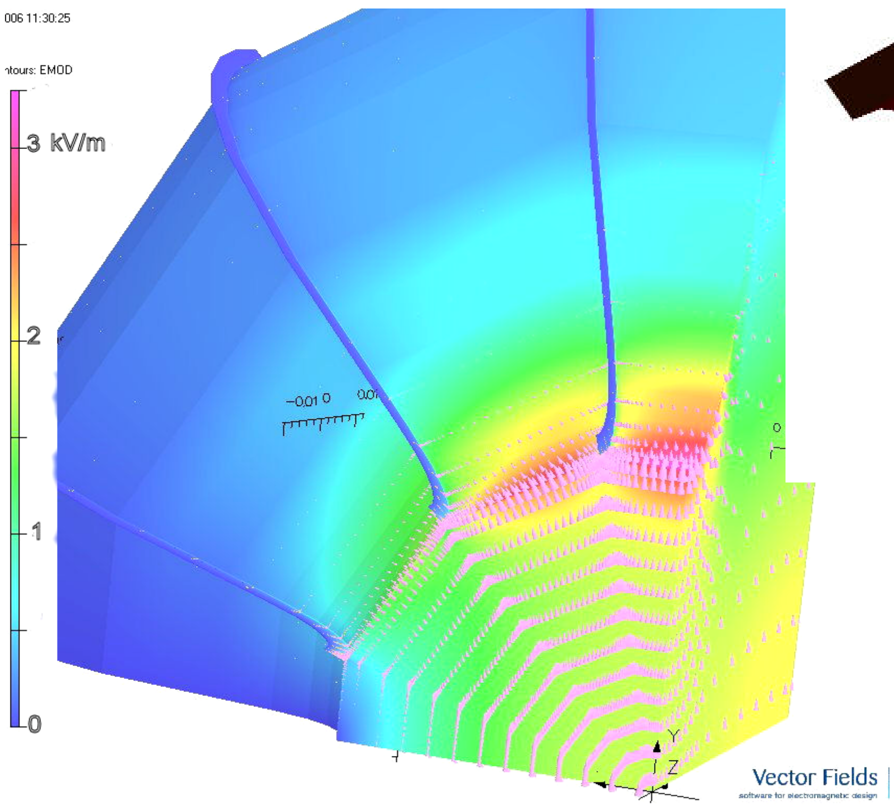
E→ 0 at slot

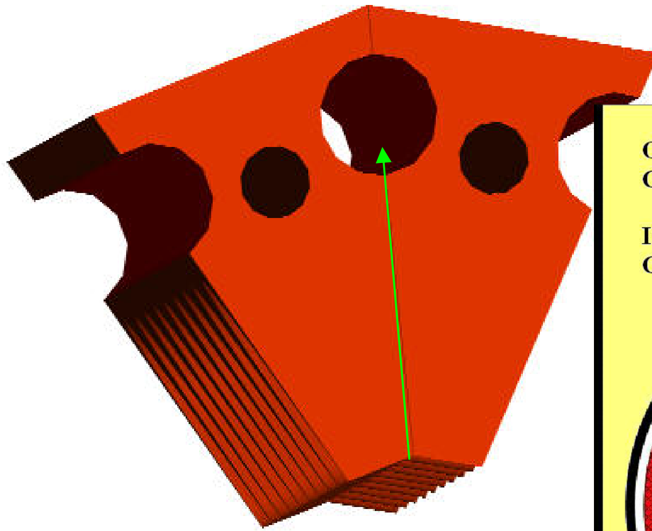
E identical to TESLA near axis

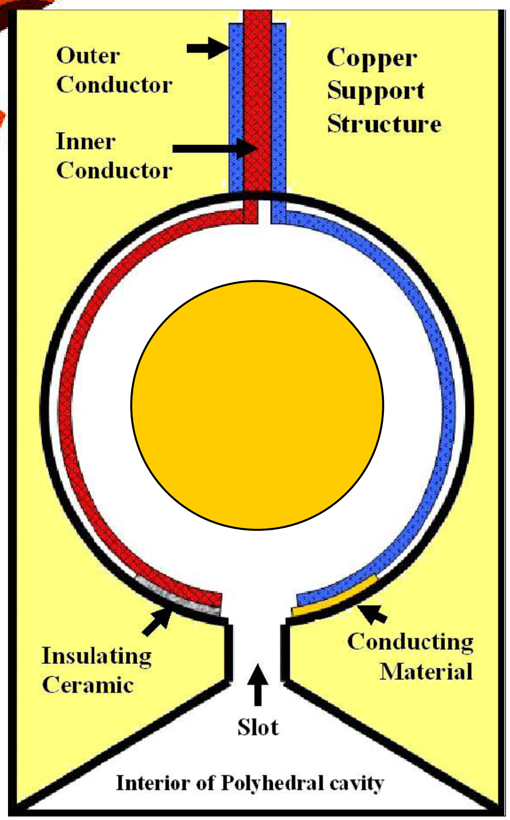


Q_a = 0.8 10^{10}, slot aperture is tapered so that fields damp exponentially into slot.

Numerical modeling of deflecting mode







Unloaded **Q_d ~ 10^5**. Couple deflecting mode fields through slot into dielectric-loaded cylindrical waveguide, out to room-temp load.

10^5 x lower Q_d → 300 x lower wake fields → could we reduce bunch spacing?

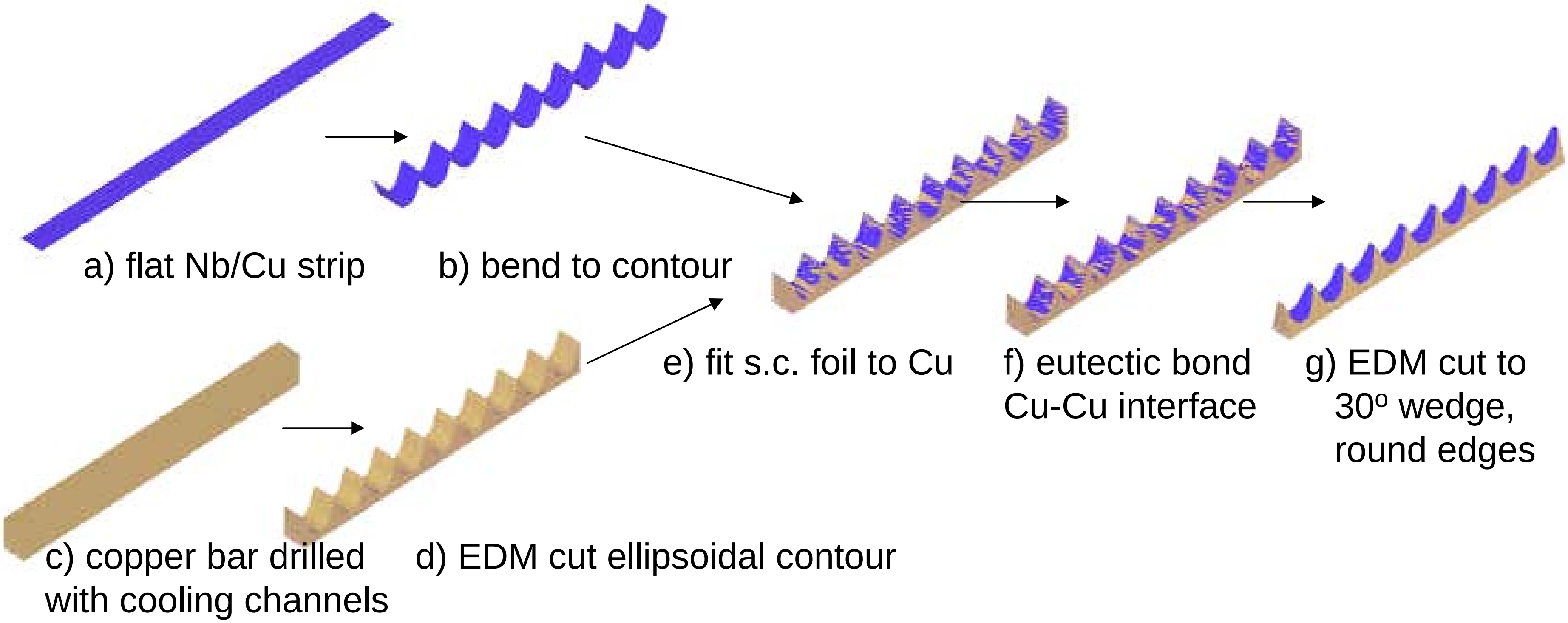
Starting material for fabrication: explosion-bonded Nb/Cu sandwich

•Sandwich of Nb and Cu sheets, soap/glue release layer, sacrificial Al plates, C explosive

•Launch explosion from one end of long sheet, shock wave creates plasma at Nb/Cu interface

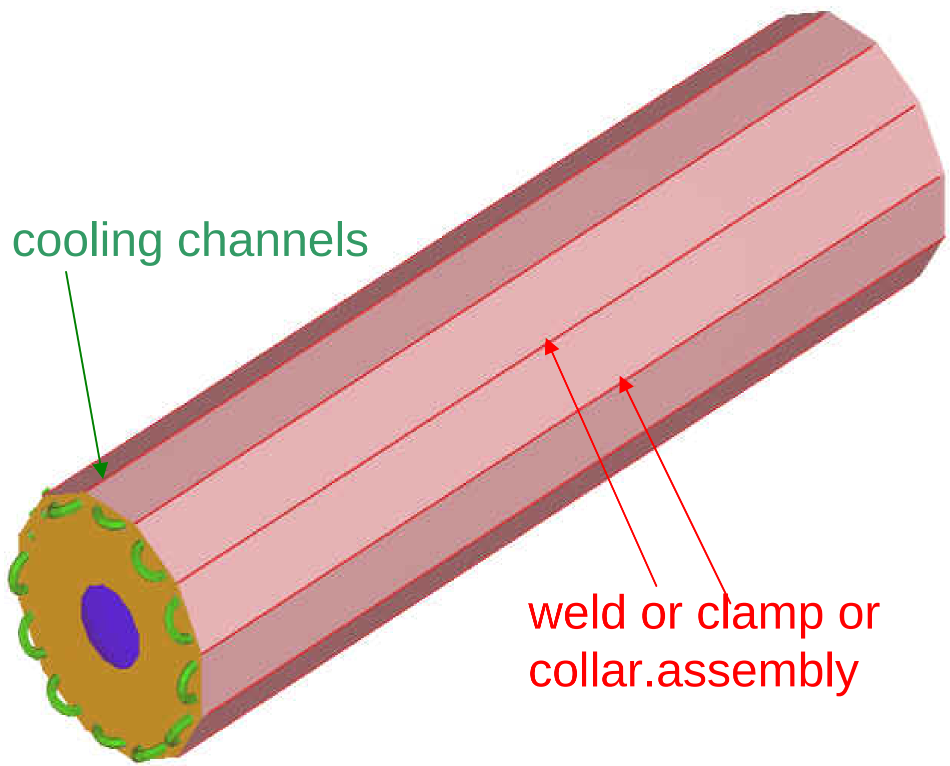
•Intimate bonding, no alteration of surface grain structure or chemistry on Nb layer.

Fabrication method for 9-cell string



- Use one continuous strip of foil for each segment of a 9-cell string.
- No joints along direction of current flow in accelerating mode.
- Form Nb/Cu foil to solid Cu blank, eutectic bond foil to blank.
- EDM Trim to form 30º wedge.

Assemble the polyhedron on an alignment fixture, weld/clamp/collar assembly.

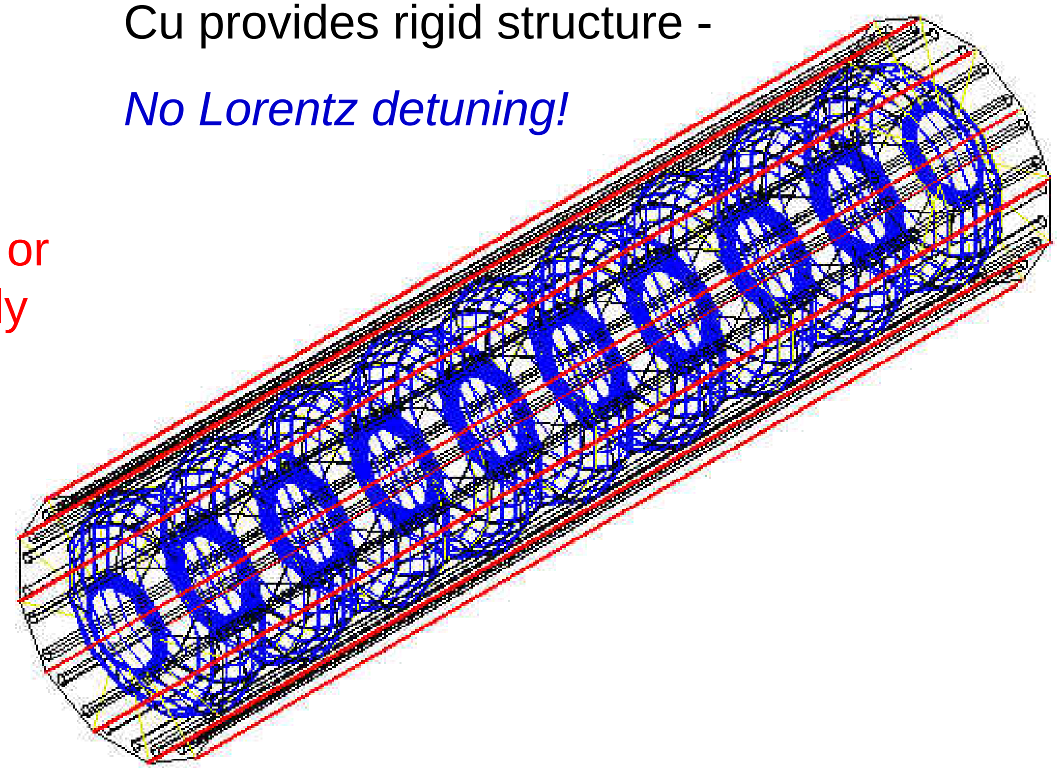


No potential for damage to Nb surfaces.

Cu provides accessible reference for alignment in cryostat, interconnection.

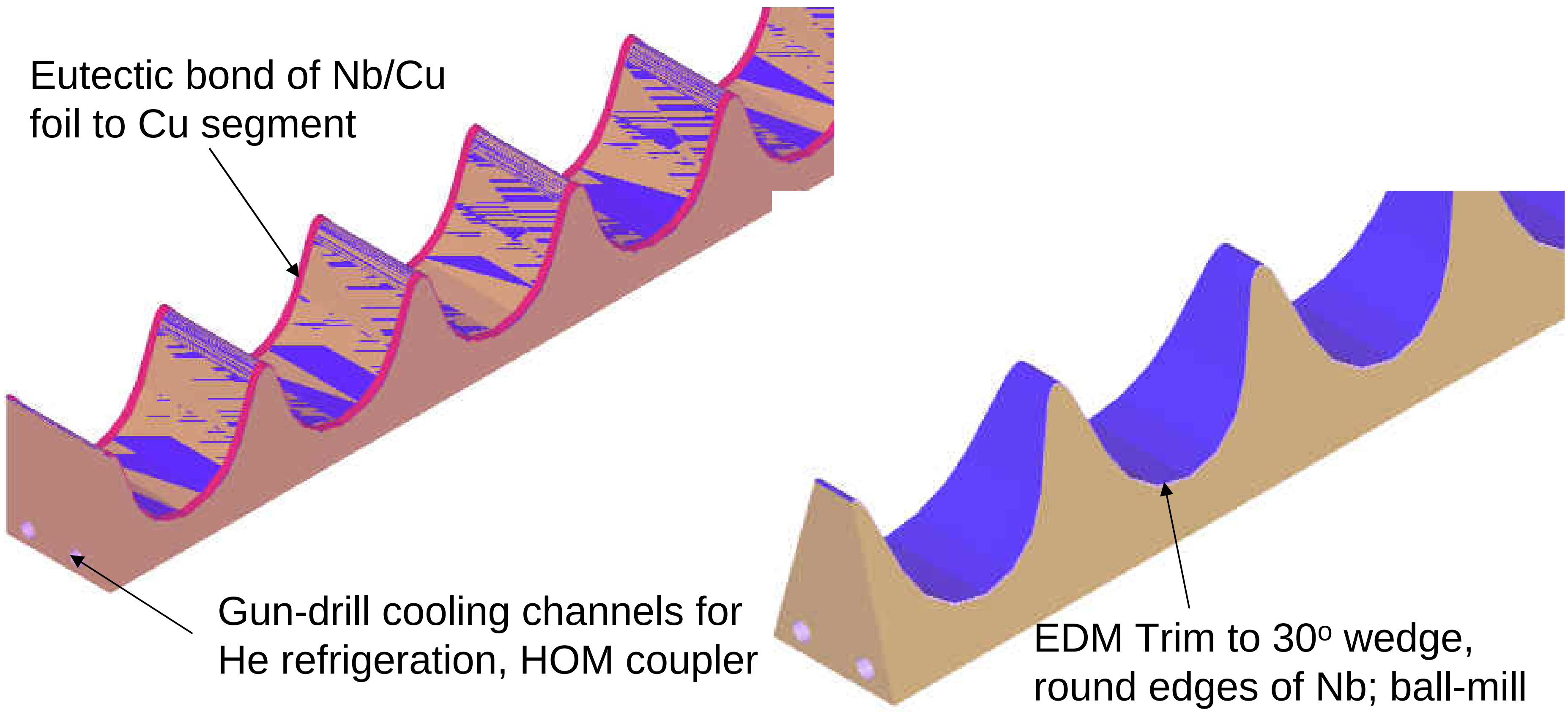
Cu provides rigid structure -

No Lorentz detuning!



He refrigeration is provided by closed-circuit flow in cooling channels – *No pool cryostat!*

Each hedron is completed free-standing

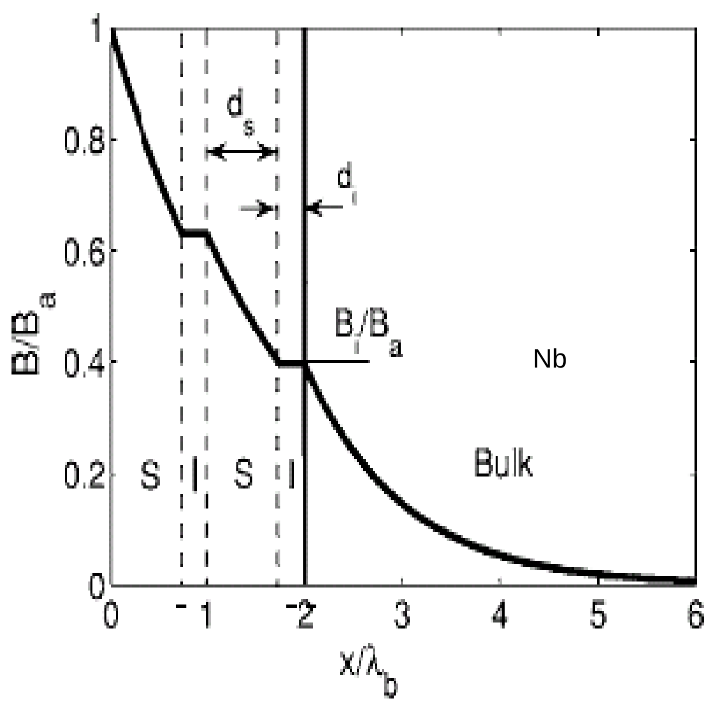


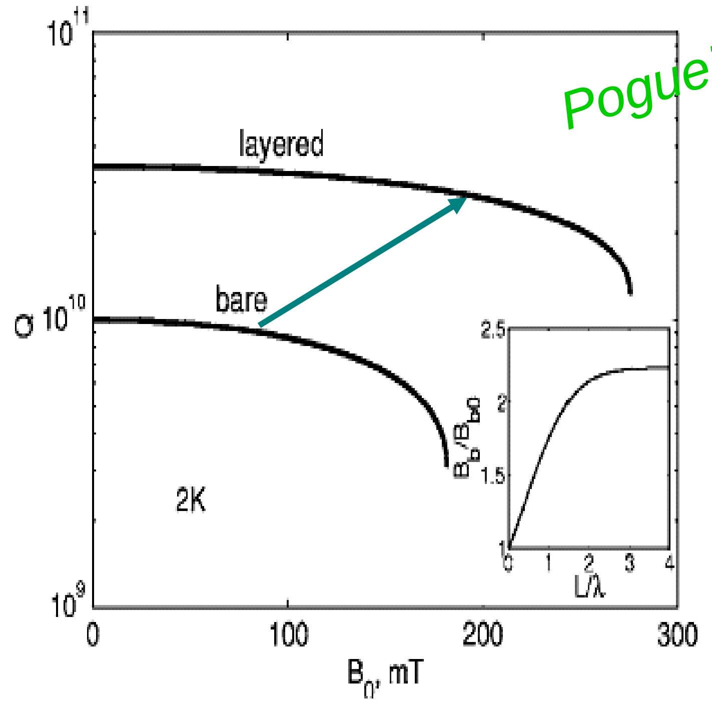
Once completed, the Nb surface can be inspected directly, electropolished, plasma polished, or any other technique.

Additional surface layers can be applied to finished surface: heterostructure superconductor, TiN dielectric, …

Polyhedral cavity opens the way for advanced rf superconductors

Gurevic proposed a heterostructure of thin films (< penetration depth λ) of Type II superconductor (NbN) and insulator (Nb_2O_5) to
double the surface fields, increase Q x4 compared to pure Nb:



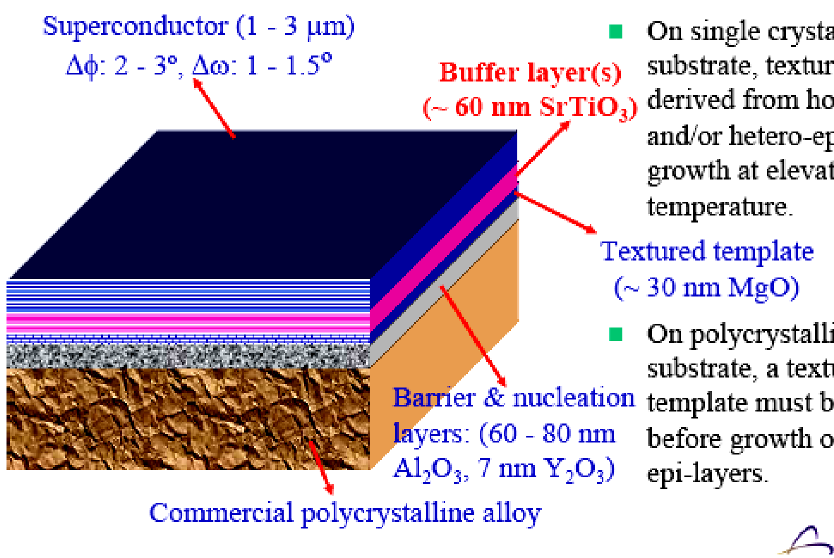


Pogue's thesis

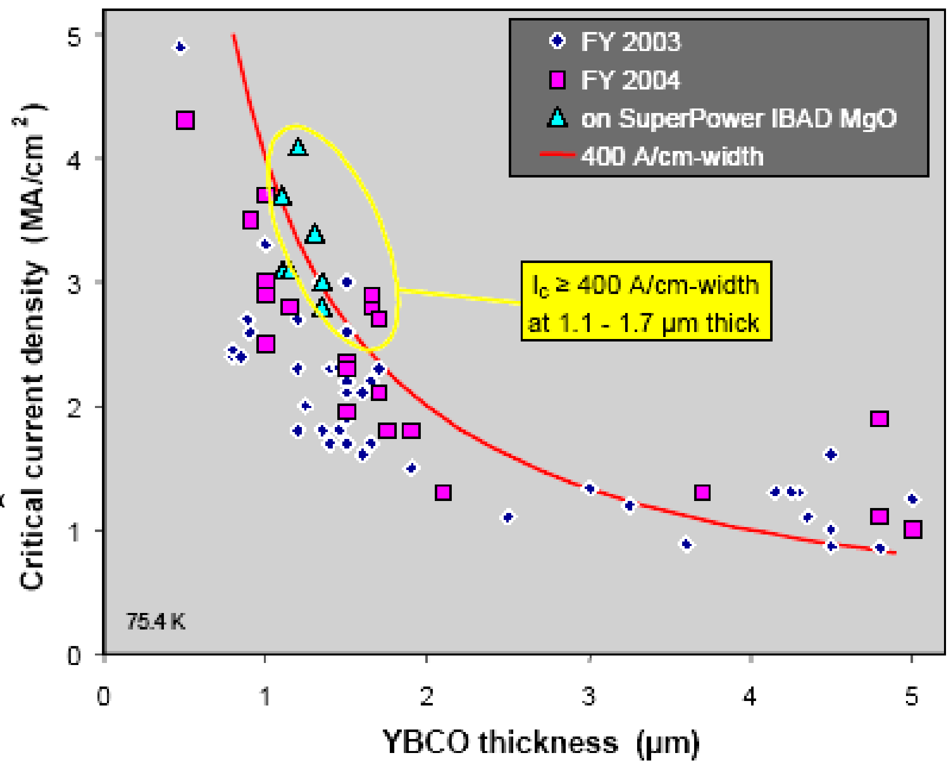
If film thickness is comparable to λ(65 nm), each Type II layer conducts sheet current to its limit then passes the rest to the next layer (analogous to multi-layer magnetic shield).

The potential: twice the gradient, same power/length

YBCO for Cavities?



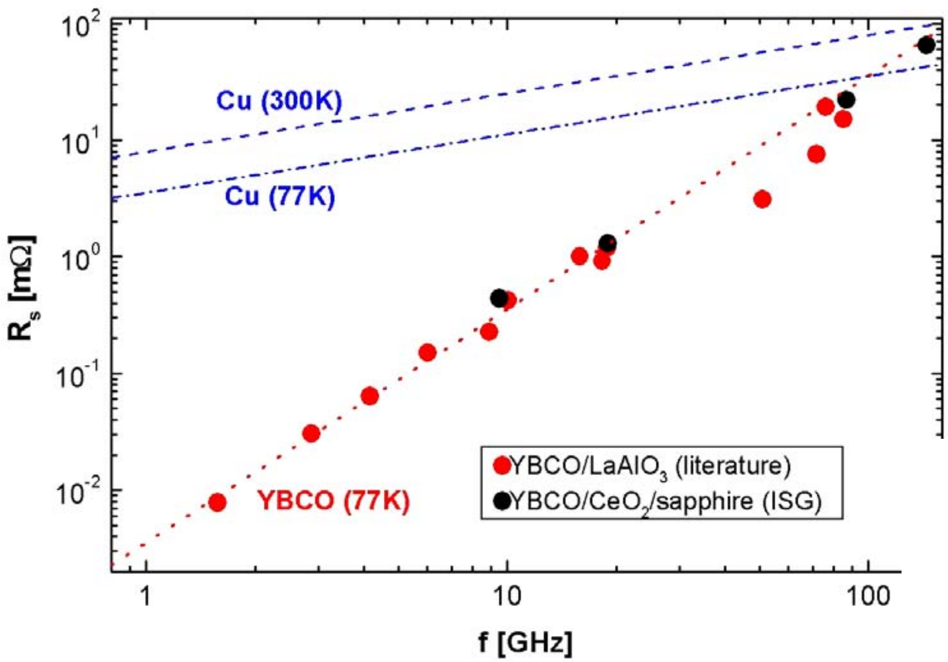
- On single crystal substrate, textured film is derived from homo- and/or hetero-epitaxial growth at elevated temperature.
- On polycrystalline substrate, a textured template must be provided before growth of desired epi-layers.

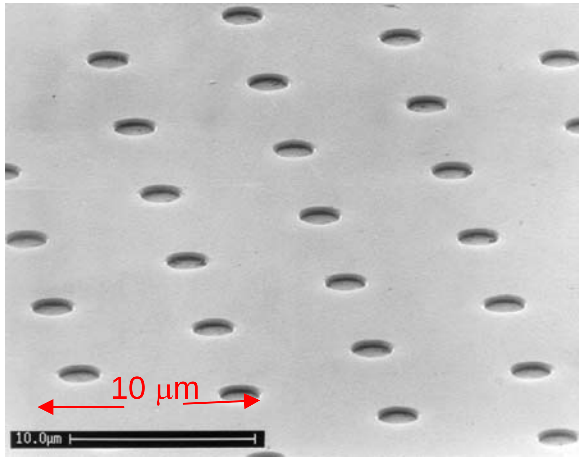


Surface currents ~40 kA/m → 500 Öe even at 77 K.

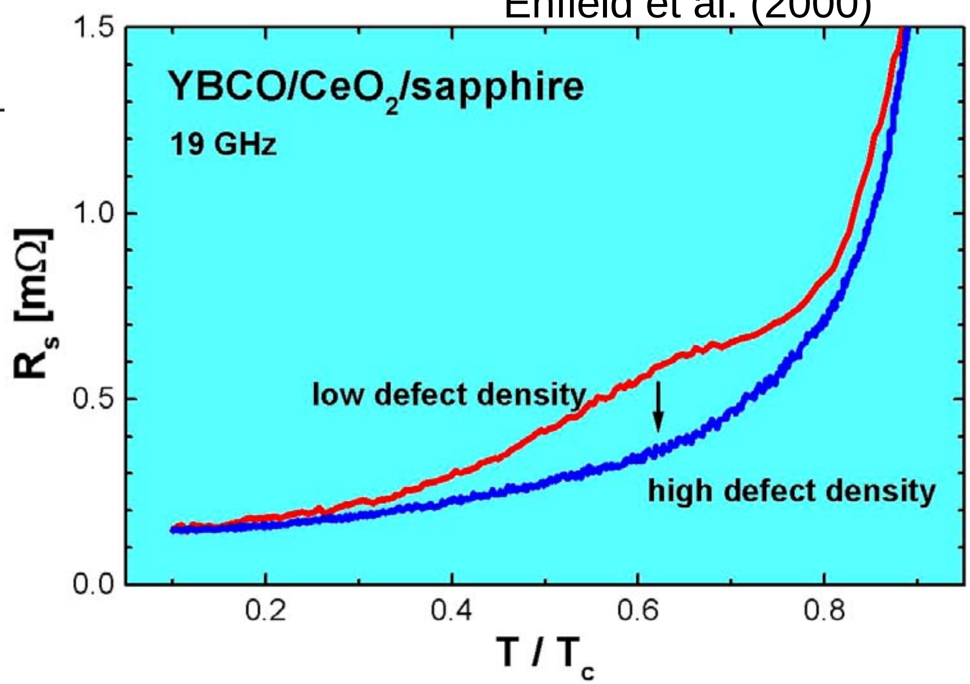
High-performance films are fabricated today with size sufficient for a hedron of a 9-cell string of 1.3 GHz dodecahedral cavity.

Improve R_s by nano-scale texture





Enfield et al. (2000)



Improve R_s by etching nanoscale holes for flux pinning.

Expect R_s ~1 $\mu\Omega$ @ 1.3 GHz, 30 K

Thin films of most high-T_c superconductors could be applied directly to the segment surface

- MgB_2 (being studied at SLAC)
- Nb_3Sn (being studied at JLab)
- Bi-2212 (high-quality films made at LANL)

The polyhedral structure provides an enabling cavity geometry to take advantage of any of these that work!

Machining capabilities

Wire EDM → machine cavity contours, trim wedges

E-beam hole drilling → 0.8 μm holes 5 μm centers, full cell in 10 minutes

Conclusions

The polyhedral cavity structure may offer significant benefits for linac colliders:

- No welds
- Compatibility for optimizing Nb surface
  - Sliced foil from billet, oriented texture, nano-scale APC
- Open access to surface of finished hedra before ass'y
  - Polishing, Inspection, Repair of damage, QC accept/reject
- Suppression of deflecting modes and Lorentz detuning
- Closed-circuit refrigeration integral to structure
- Open geometry for application of advanced superconducting layers

We are requesting $ to develop and evaluate model cavities. We would like to seek collaboration.