Review of New Shapes for Higher Gradients

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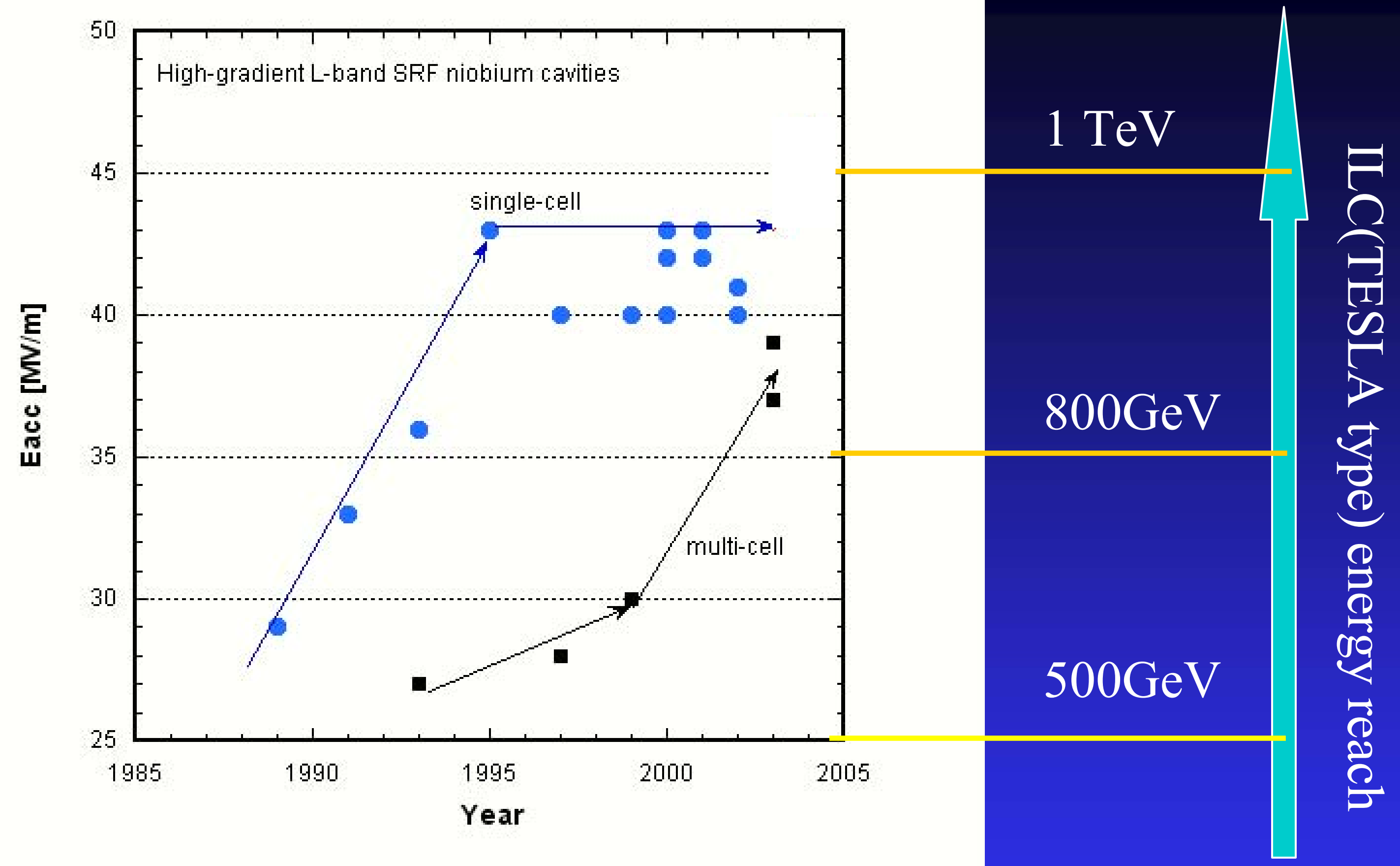


- Rapid advances in single-cell cavities until 1995.
- Single-cell gradient envelope saturated at 42 MV/m for last 10 years.
- While multi-cell cavity performance advances rapidly.
- Would it be possible for 45 MV/m and beyond?

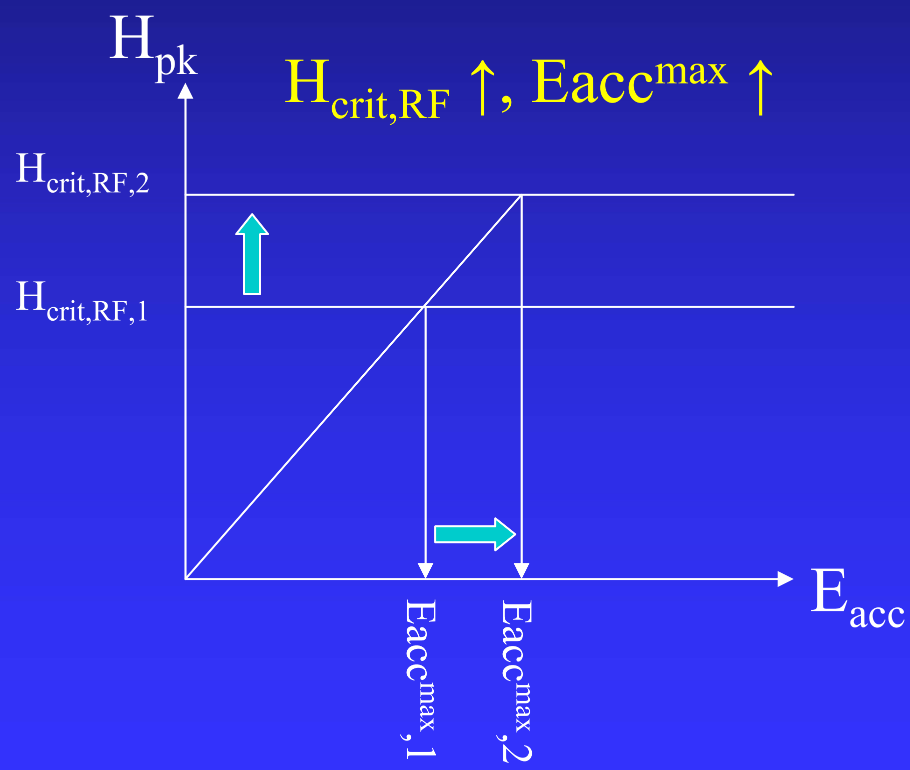
Paths toward higher Eacc (I)

The maximum feasible Eacc is determined by the RF critical magnetic field $H_{crit,RF}$. When the surface magnetic field exceeds $H_{crit,RF}$, superconductivity breaks down into normal conductivity.

- Eacc ↑, Hpk ↑
- Eacc=Hpk/(Hpk/Eacc)
- H_{pk}/E_{acc} determined by geometry
- $Hpk \le H_{crti,RF}$ for superconductivity

$$Eacc^{max} = \frac{H_{crit,RF}}{H_{pk}/Eacc}$$

$H_{crit,RF}$ ↑, $Eacc^{max}$ ↑

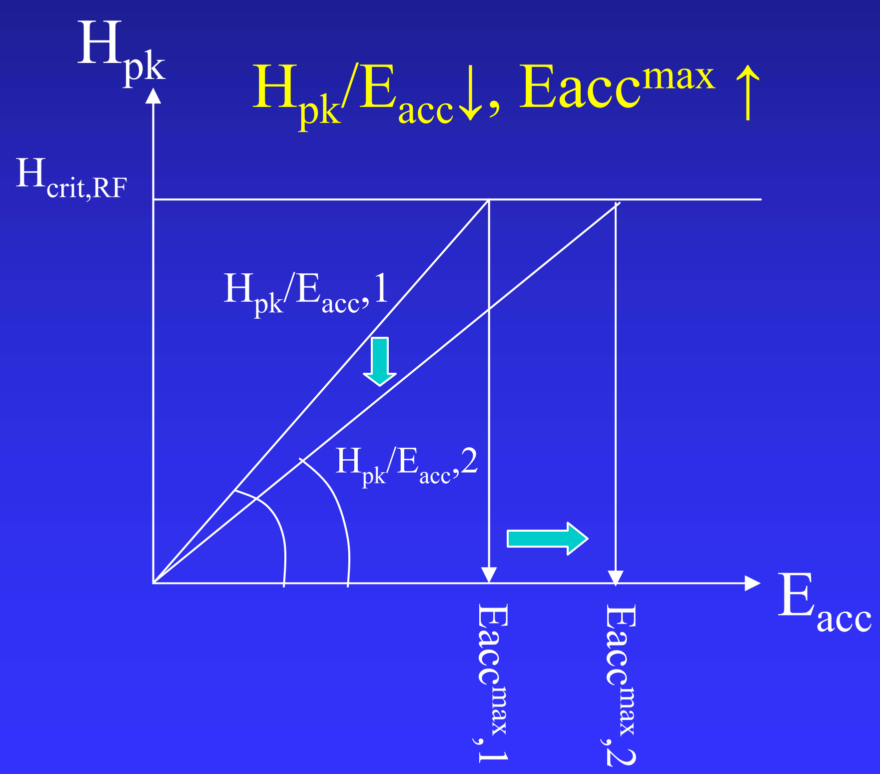


Paths toward higher Eacc (II)

Reducing H_{pk}/E_{acc} delays breakdown of superconductivity and allows a higher E_{acc} to be tolerated.

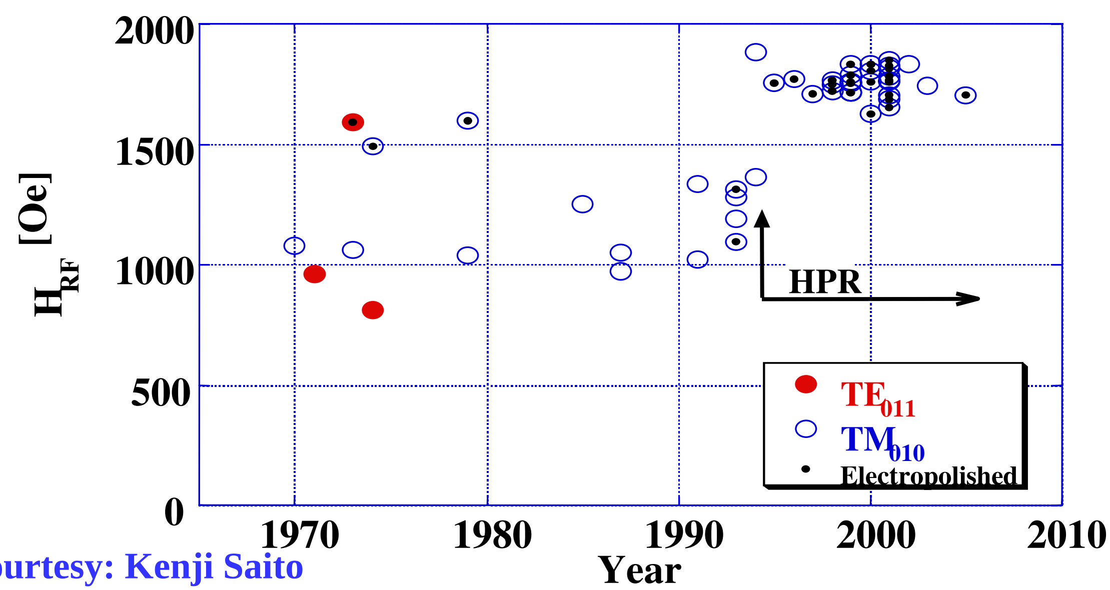
- Eacc ↑, Hpk ↑
- Eacc=Hpk/(Hpk/Eacc)
- H_{pk}/E_{acc} determined by geometry
- $Hpk \le H_{crti,RF}$ for superconductivity

$$Eacc^{max} = \frac{H_{crit,RF}}{H_{pk}/Eacc}$$



$H_{crit,\,RF}$ intrinsic material property

- Theoretical limit is ~ 2000 Oe for Nb.
- Many cavities reached 1750±100 Oe.
- Record Hpk in Nb cavity: 1850 Oe (Kneisel, 2005).

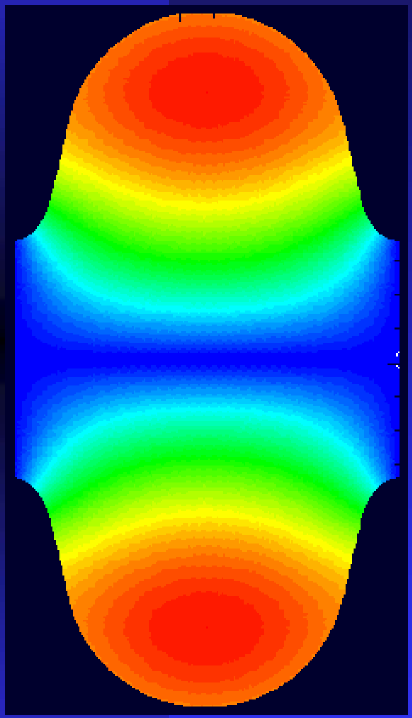


Courtesy: Kenji Saito

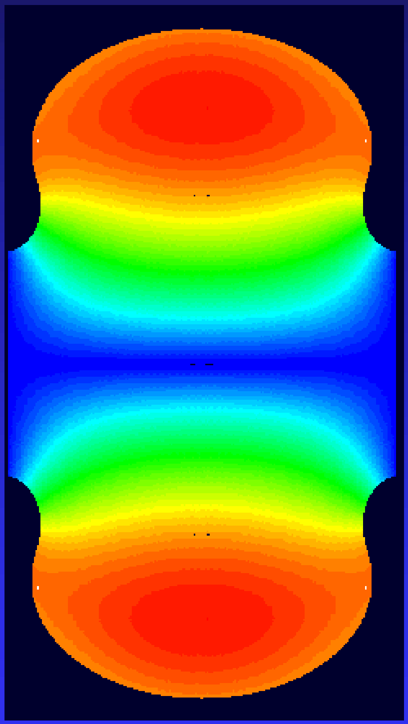
Why new geometry

- It seems that, at 90% of the theoretical limit level, a rather hard magnetic barrier is encountered.
- To avoid this brick wall…
- New geometry is a possibility to boost Eacc.
- The trick is to alter cavity shape for a reduced Hpk/Eacc.
- With new geometry, 10-15% improvement in Eacc possible.
- Two leading approaches: Low-loss and re-entrant

Re-entrant geometry



TTF
1992



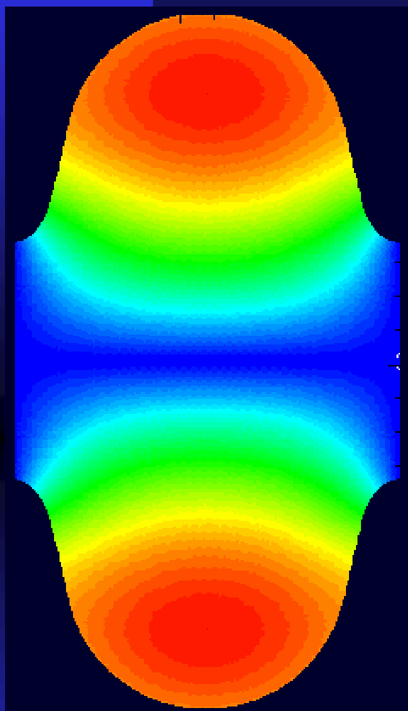
Re-entrant
2002

- 2002, Cornell University.
- 1300 MHz for ILC.
- goal is to reduce Hpk/Eacc.
- keeps large 70mm aperture.
- for small HOM loss factor

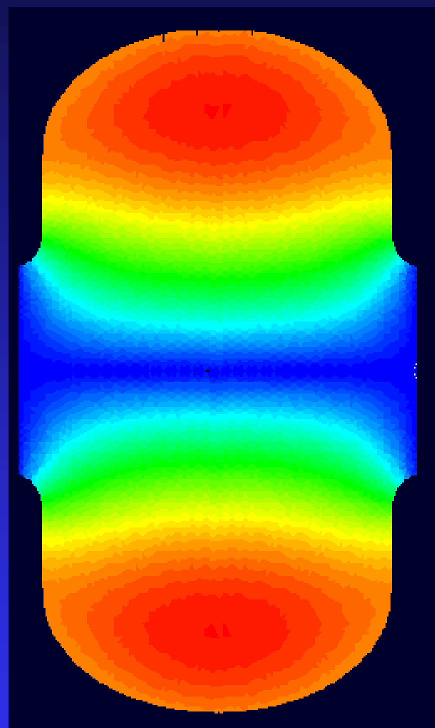
- also a higher (R/Q)*G.
- means lower cryogenic loss.

Shemelin, Padamsee, Geng, NIMA 496(2003)1-7.

Low-loss geometry



TTF
1992



Low-Loss
2002/2004

- 2002, JLab/DESY.
- 1500 MHz for CEBAF upgrade.
- goal is to maximize (R/Q)*G.
- so as to reduce cryogenic loss.
- small aperture strategy.
- also a reduced Hpk/Eacc.

Sekutowicz, Kneisel, Ciovati, Wang,
JLAB TN-02-023,(2002).

- 2004, KEK/DESY/JLAB.
- 1300 MHz for ILC.
- highlight lower Hpk/Eacc feature.

Sekutowicz, Workshop on pushing the limits of RF superconductivity, September 22-24, 2004.
Sekutowicz et. al., PAC2005, May 16-20, 2005.

Cavity parameters

Shape	Hpk/Eacc	(R/Q)*G	Epk/Eacc	k	Iris dia.
unit	Oe/(MV/m)	Ω^2	-	%	mm
TTF	41.5 (ref)	30840 (ref)	1.98	1.90	70
R70	37.8 (-9%)	33762 (+10%)	2.40	2.38	70
LL	36.1 (-13%)	37970 (+23%)	2.36	1.52	60

- R70(70 mm aperture reentrant): 10% improvement in Hpk/Eacc; 10% improvement in (R/Q)*G; better cell-to-cell coupling.
- LL(60mm aperture low-loss): 13% improvement in Hpk/Eacc; 23% improvement in (R/Q)*G; cell-to-cell coupling is weaker.
- Both shapes have a higher Epk/Eacc.

Down side of a higher Epk/Eacc

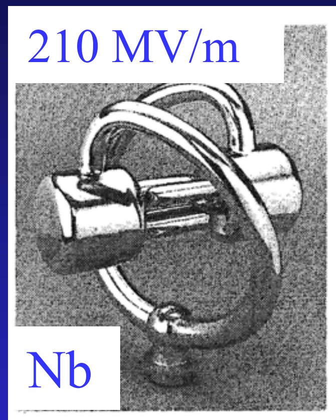
• Both new shapes have a higher Epk/Eacc compared to TTF.
• This means higher Epk for the same Eacc.
• E_{acc}=40 MV/m, Epk=80 MV/m (TTF).
• Eacc=40 MV/m, Epk= 96 MV/m (new shapes).
• Field emission is a practical challenge because of exponential dependence of surface electric field.

Fowler-Nordheim

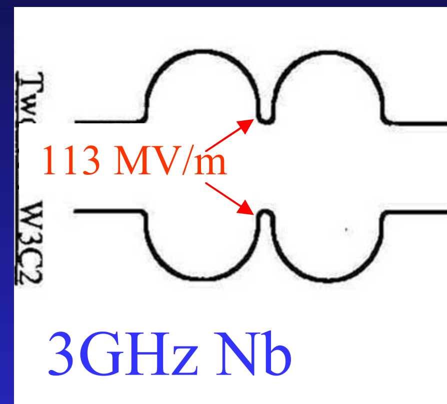
$$j_{FN} = C_1 E^2 \exp\left(-\frac{C_2}{E}\right)$$

• However, electric field has no intrinsic limit…

No intrinsic limit to Epk



Delayen, Shepard, 1990



Graber et. al., 1990

- Particulate contamination is a main cause of field emission.
- Effective methods exist to remove particulate field emitters.
- High-Pressure water Rinsing (HPR).
- High-Peak-Power RF processing (HPP).

Multipacting analysis

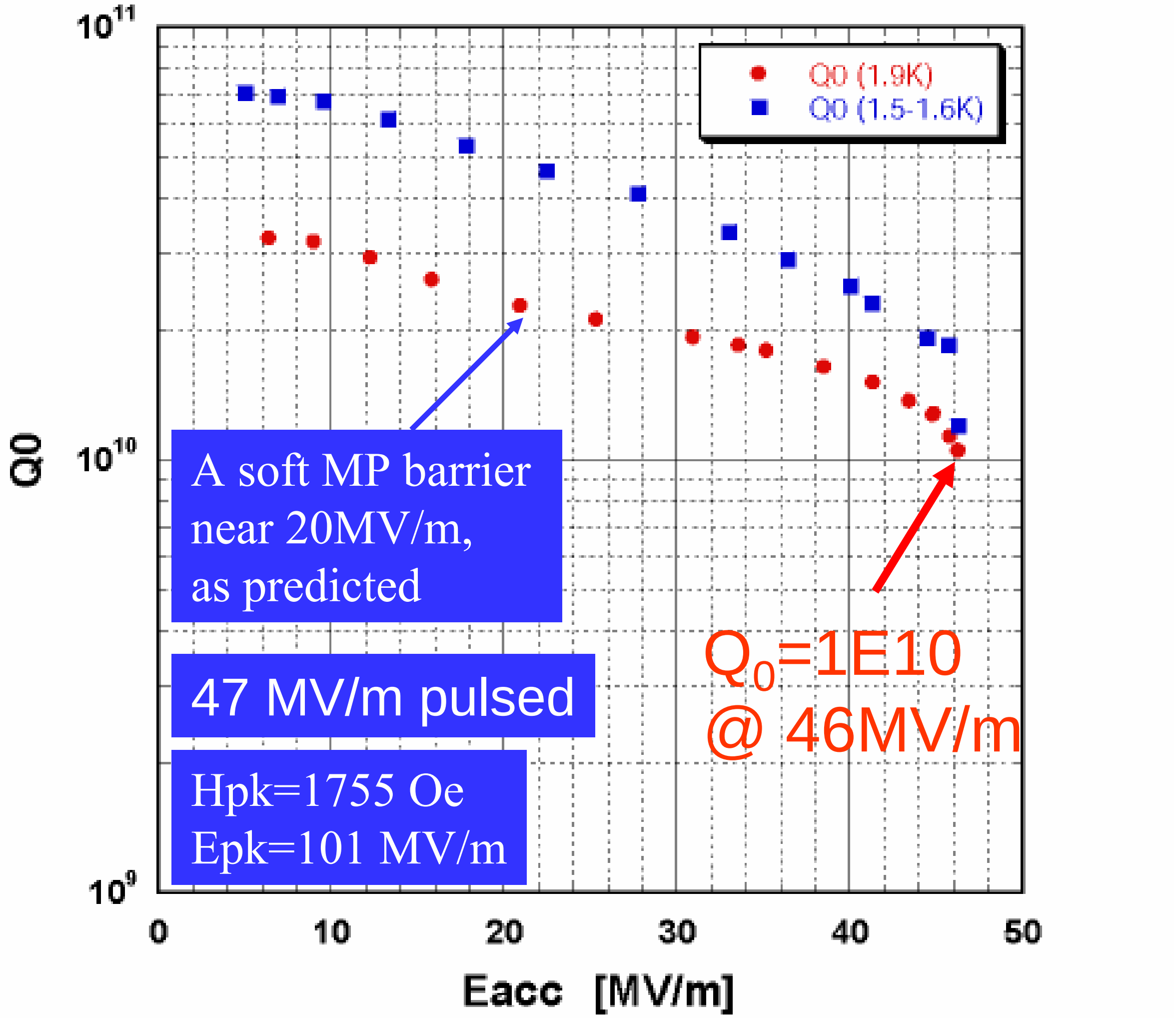
- Simulations show no hard multipacting(MP) barrier.
- For re-entrant geometry and low-loss geometry.

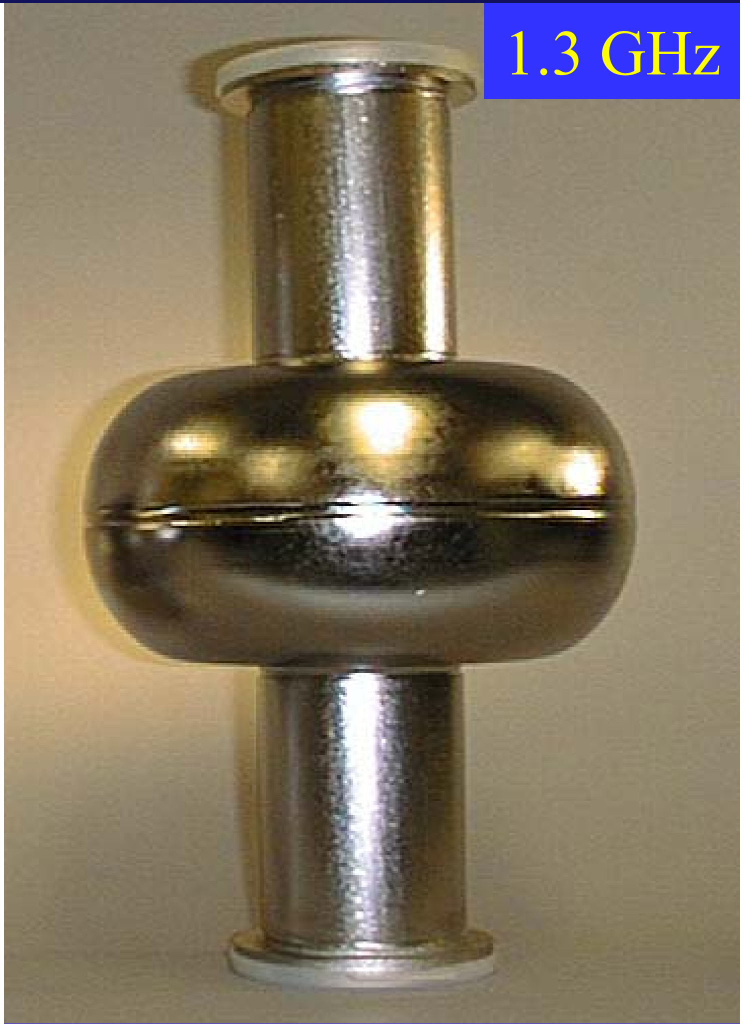
- Simulations predict the existence of two-point MP.
- Similar two-point MP barrier exists in TTF shape.

- Two-point MP occurs at cavity equator region.
- The electron impact energy typically 30-50 eV.
- Two-point MP is usually surpassed by modest RF processing.

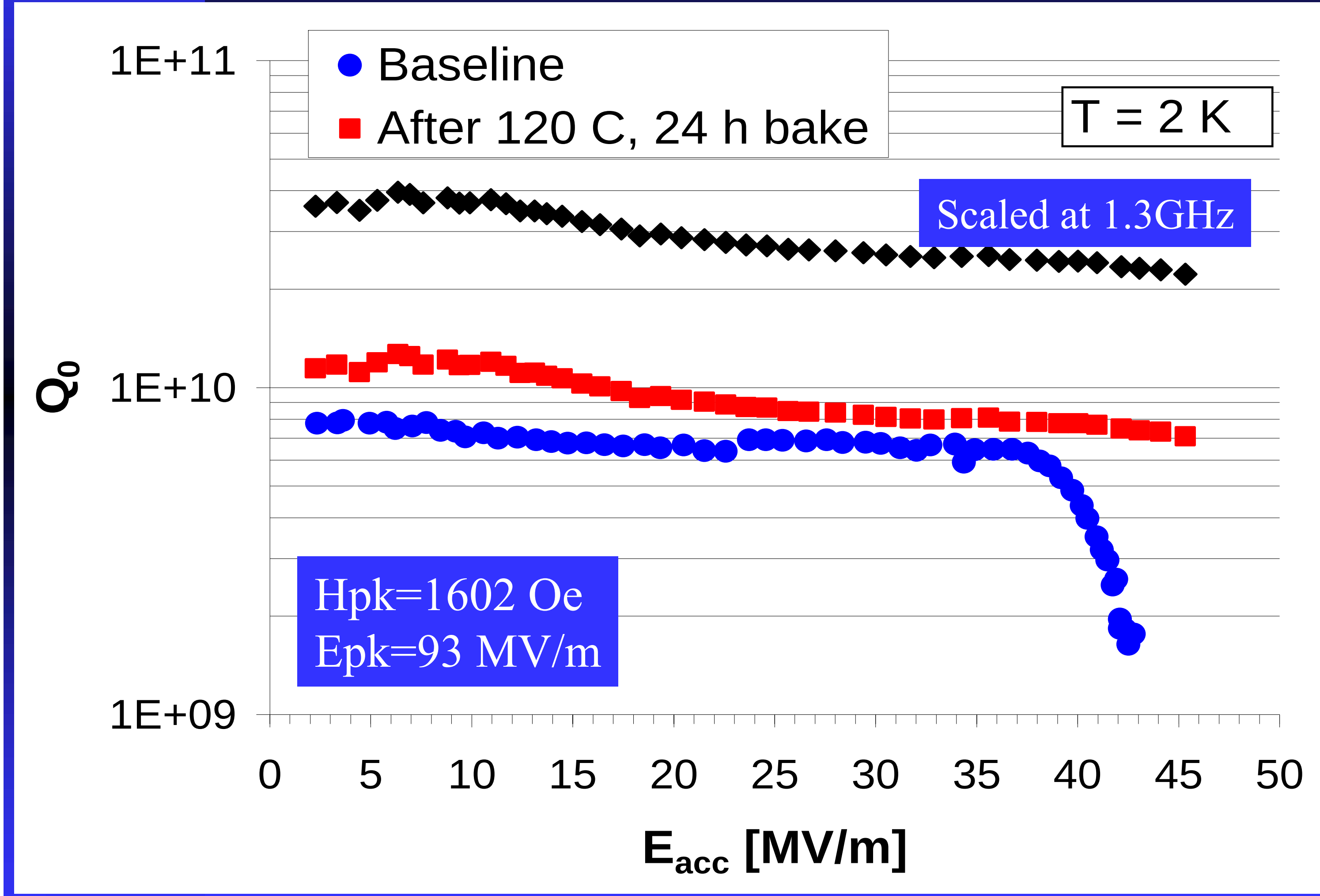
Performance of single-cell Re-entrant and Low-loss cavities

46 MV/m reached in 70mm aperture single-cell reentrant cavity at Cornell

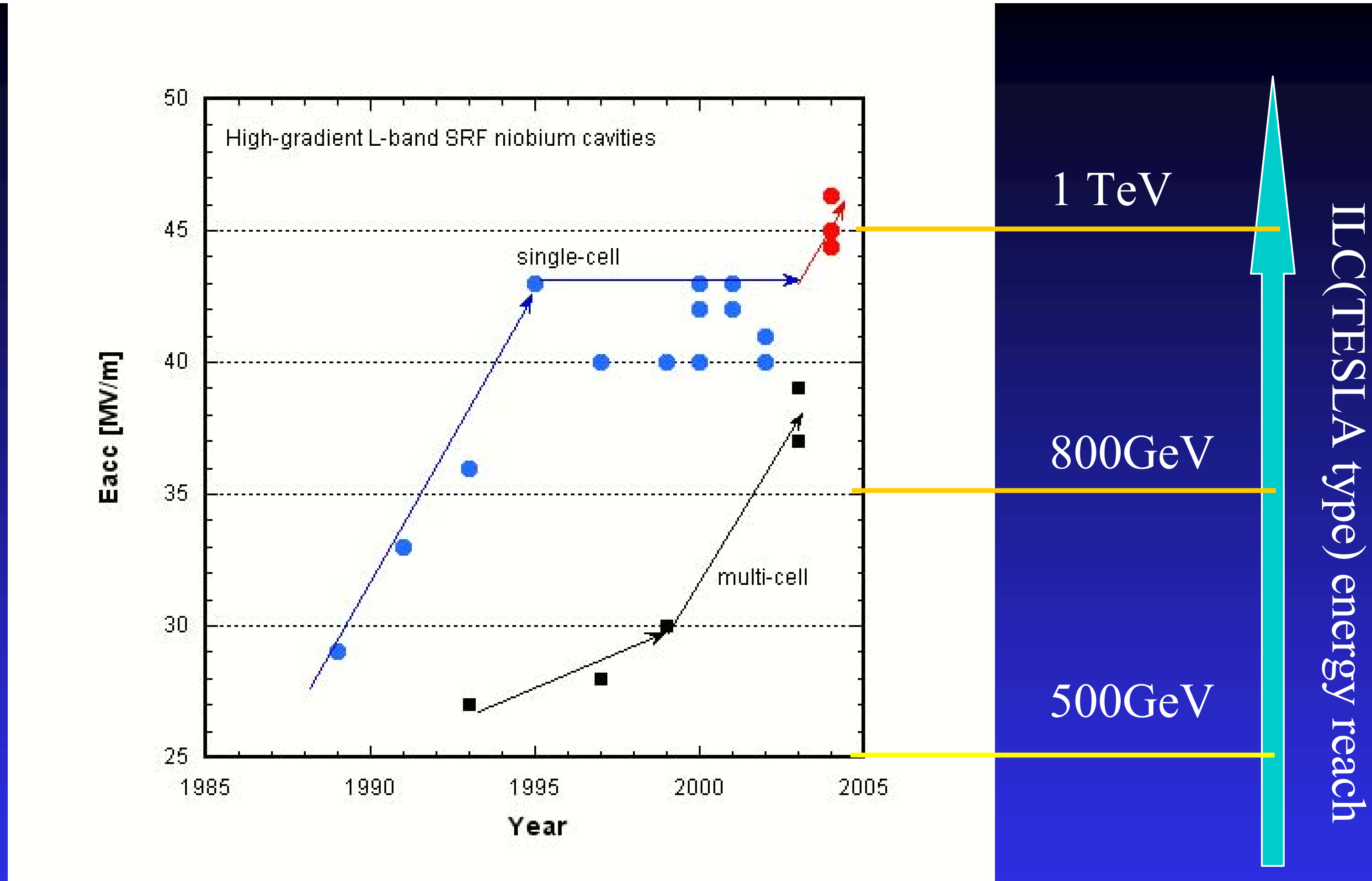




45 MV/m reached in a scaled low-loss single-cell cavity at JLab



Courtesy:
Peter Kneisel



- CW 45-46 MV/m with little field emission demonstrated in Low-loss cavity and in re-entrant cavity.
- Re-entrant cavity reached 47 MV/m in long pulsed mode.
- Unloaded Q > 1×10^{10} at 45 MV/m.

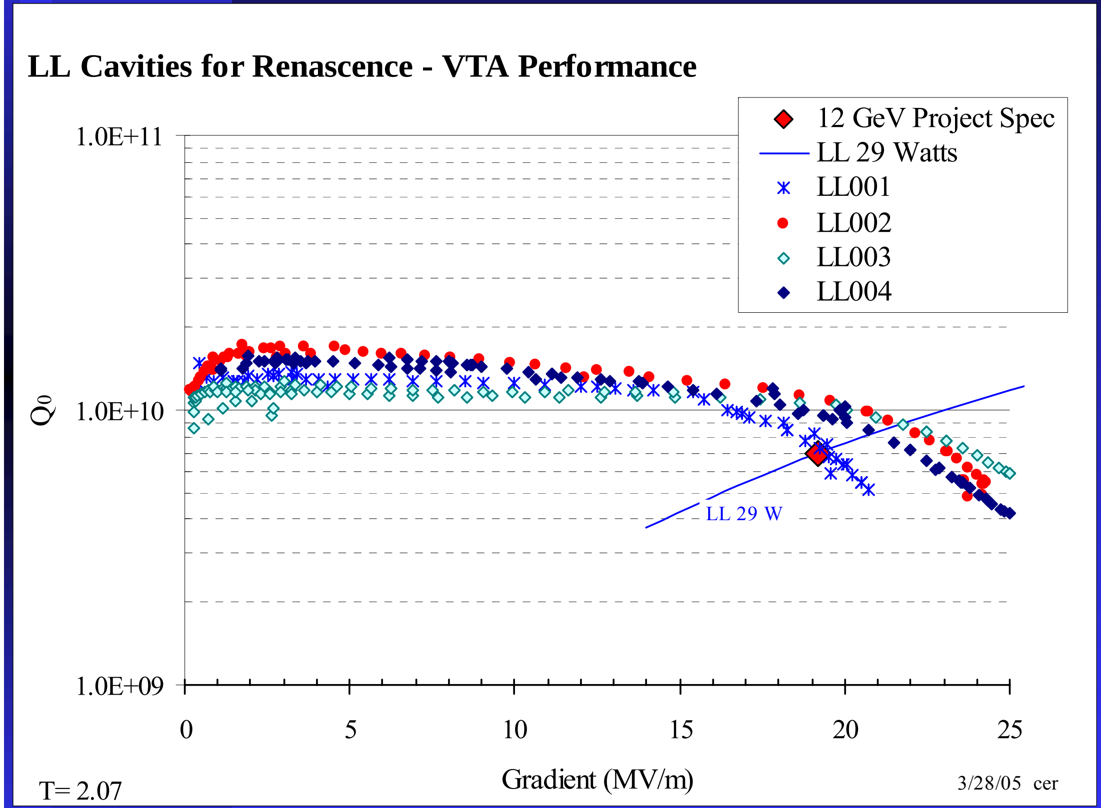
Cavity fabrication and processing

- "Standard" niobium cavity fabrication and processing.
- RRR250 high-purity sheet Nb (JLab 2.2GHz Low-loss cavity uses large grain Nb disks sliced directly from ingot).
- Deep drawing cups and trimming half-cells.
- Electron beam welding at iris and equator.
- Post-purification (Ti or Y) boosts thermal conductivity.
- Buffered chemical polishing HNO3:HF:H3PO4=1:1:2, or HNO3:HF:H3PO4=1:1:1, or electropolishing HF:H2SO4.
- High-pressure water rinsing (HPR).
- Cleaning room drying and assembly.
- Slow pump-down.
- 100°C bake-out under vacuum.

Rigorous HPR is required and re-contamination must be avoided to keep field emission at bay.

Multi-cell cavities of new geometry

JLab Low-loss cavity



- 1.5 GHz, 7-cell.
- vertical test results shown.
- tested to 25 MV/m.
- installed in cryomodule.
- CEBAF 12 GeV upgrade.
- H_{pk}/E_{acc}=37.4 Oe/(MV/m).
- Talk MoA04(C. Reece).

Courtesy: Charlie Reece

KEK ICHIRO cavity

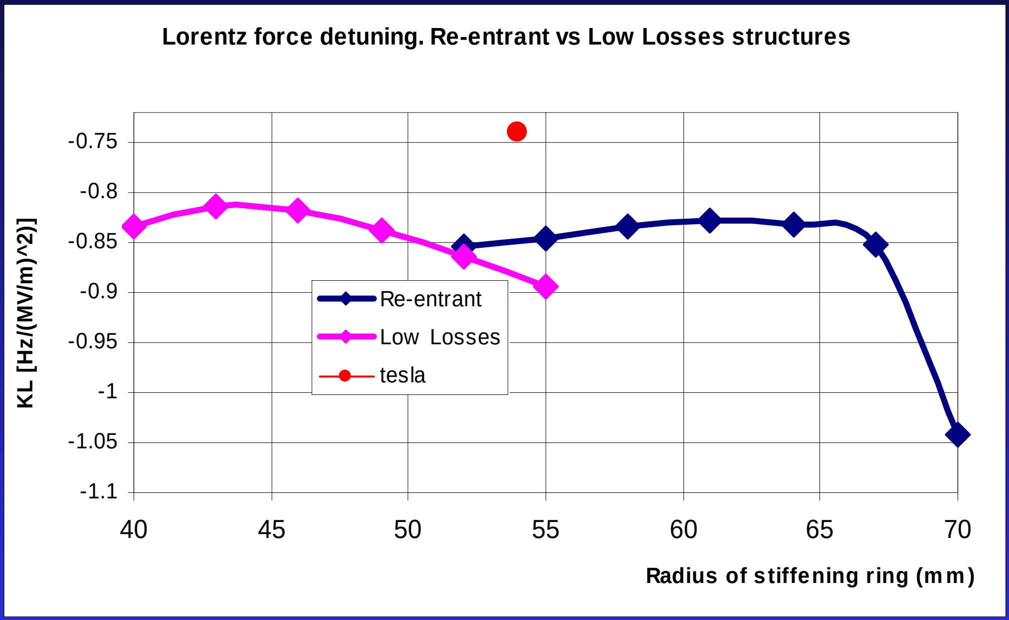
Courtesy: Kenji Saito

- 1.3 GHz, Low-loss shape.
- Single-cell cavity tested to 40 MV/m.
- Two 9-cell cavities built and test is on-going.
- Many posters in this workshop.
- TuP19 (Y. Morozumi), TuP20(T. Saeki), TuP21(K. Saito) TuP44(K. Saito), TuP45(K. Saito)

Other important cavity parameters

- Lorentz force detuning
- Wakefields and higher order modes

Lorentz force detuning

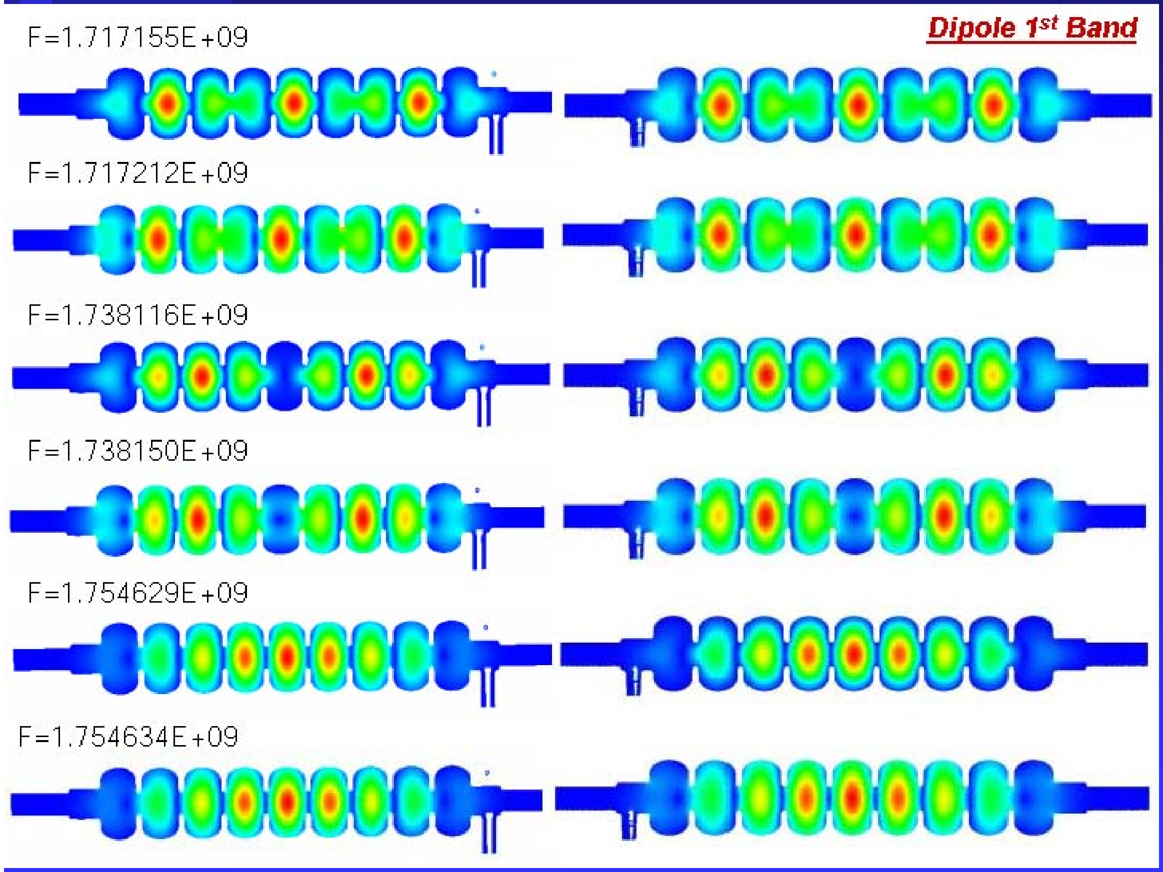


Courstey: N. Solyak Fermilab

- Wall thickness 2.8 mm.
- Similar LFD sensitivity for Low-loss and re-entrant geometry.
- Low-loss or re-entrant cavity with 3.1 mm wall thickness has the same LFD sensitivity as 2.8 mm wall TTF cavity.

Wakefields and higher order modes

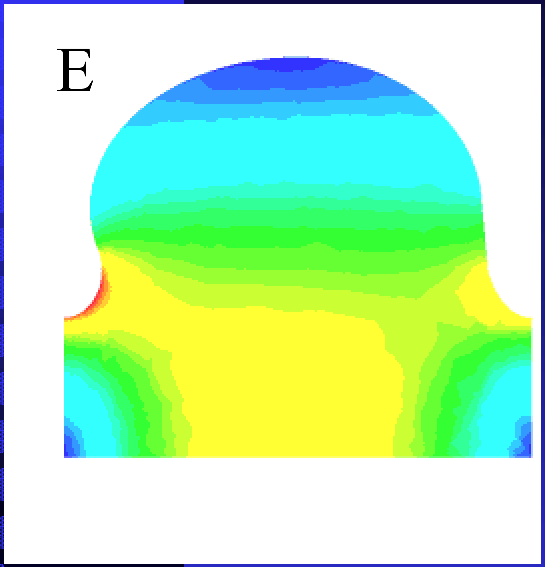
- Very important issue for beam quality and stability.
- HOM requirements limits how small the aperture can be.

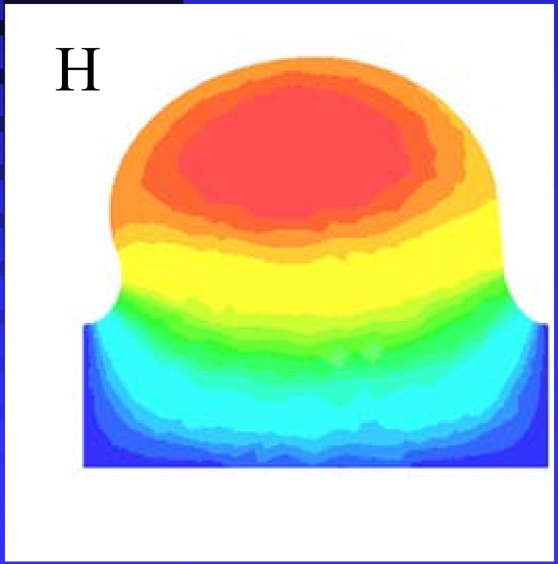


- calculation started
- SLAC/Fermi/DESY
- low-loss geometry.
- 9-cell with HOM coupler.
- SLAC code Omega3P.
- re-entrant geometry…
- Talk ThA05 (K. Ko).

Courtesy: K. Ko, SLAC

MSU Half re-entrant cavity

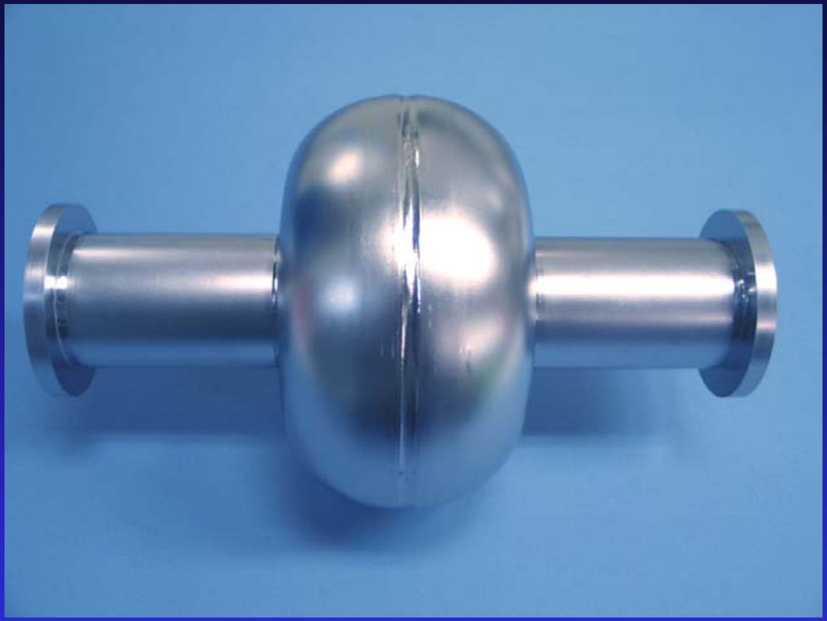




- MSU is exploring a half re-entrant geometry.
- besides improvement in Hpk/Eacc, cell-to-cell coupling and (R/Q)*G…
- this geometry allows better fluid drainage during chemistry and HPR.
- MSU plans to fabricate and test single-cell.
- Poster TuP15 (M. Meidlinger).

T. Grimm et al., Applied Superconductivity Conference, Jacksonville, FL, 2004

60mm aperture re-entrant cavity



- Cornell's next step in the re-entrant direction.
- Improves Hpk/Eacc by 15% over that of TTF.
- First single-cell cavity built and test in 2005.
- Will use the cavity prep recipe tested for Hpk 1755 Oe.
- It has potential of Eacc > 50 MV/m.
- Poster TuP43 (R.L. Geng).

Cavity parameters summary

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HR,1	37.8 (-9%)	34673 (+12%)	2.40	2.09	66.8
HR,1	36.0 (-13%)	38021 (+23%)	2.38	1.51	59.4
R60	35.4 (-15%)	41208 (+34%)	2.28	1.57	60

HR,1 and HR,2: MSU Half re-entrant geometry
R60: 60 mm aperture re-entrant geometry.

Conclusions

- Lowering Hpk/Eacc confirmed a right strategy for higer Eacc.
- Today's record Eacc is 46 MV/m CW and 47 MV/m pulsed.
- New geometry allows lower cryogenic losses.
- No hard multipacting barrier found in neither low-loss nor re-entrant geometry cavity.
- Epk=90-100 MV/m reached in new geometry cavities with little field emission.
- Cleaning and assembly of cavity for CW or long pulse Epk~100 MV/m is challenging, but it is proven possible.

Conclusions (continued)

- Unloaded Q of > 1×10^{10} at Eacc 45 MV/m is possible.

- Lorentz force detuning seems not a problem.

- Higher order modes need more study.

- Multi-cell low-loss cavity prototype being carried out aggressively in Japan.

- 50 MV/m demonstration seems to be within reach.

Acknowledgement

I am grateful to the following colleagues for providing information for the preparation of this talk:

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