Alternative Cavity Shapes for High Gradient
Low-Surface-Field (LSF) Shape Cavity Development Status

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High-Gradient High-Efficiency SRF Development

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Jefferson Lab

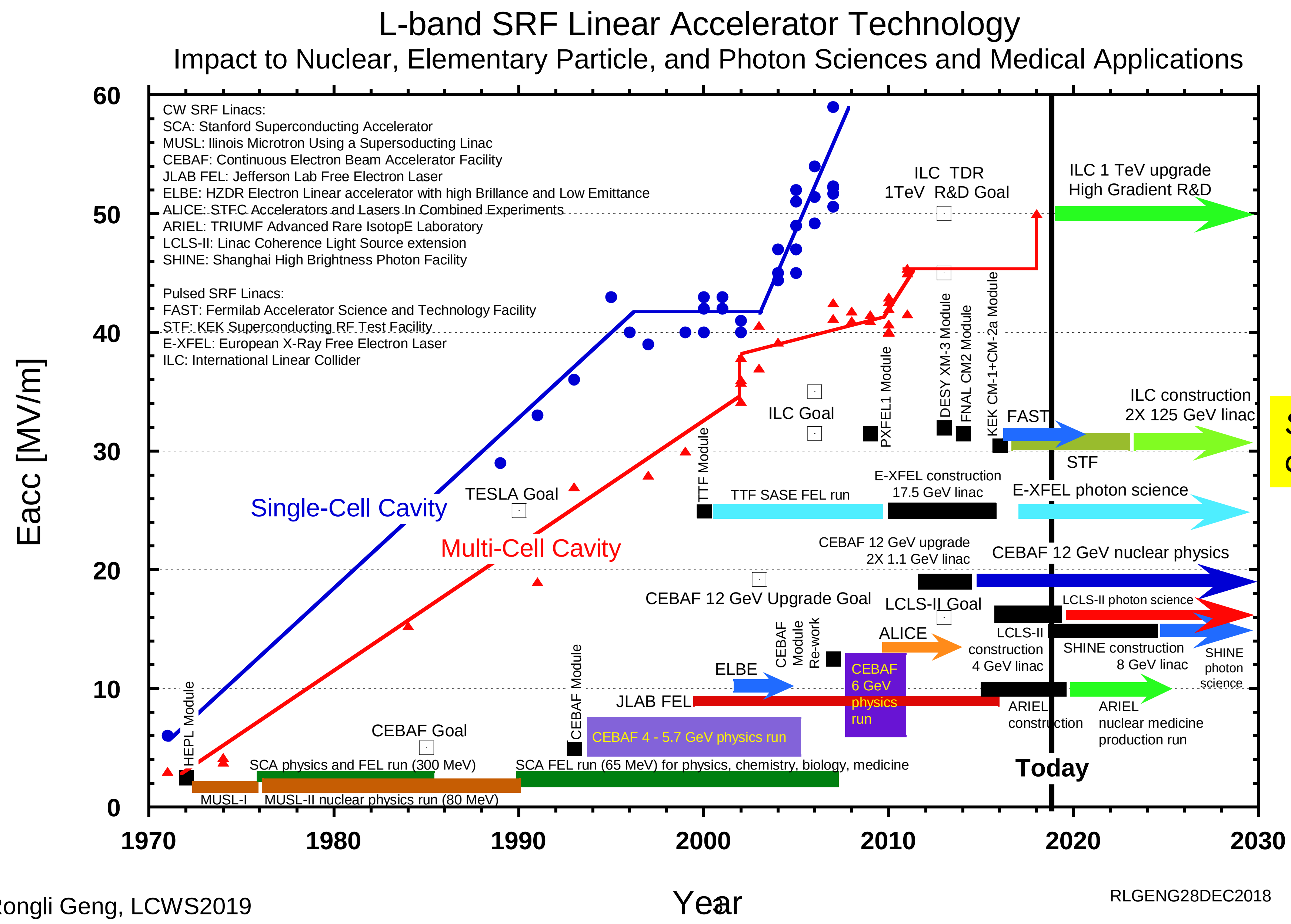
U.S. DEPARTMENT OF ENERGY Office of Science

JSA

Outline

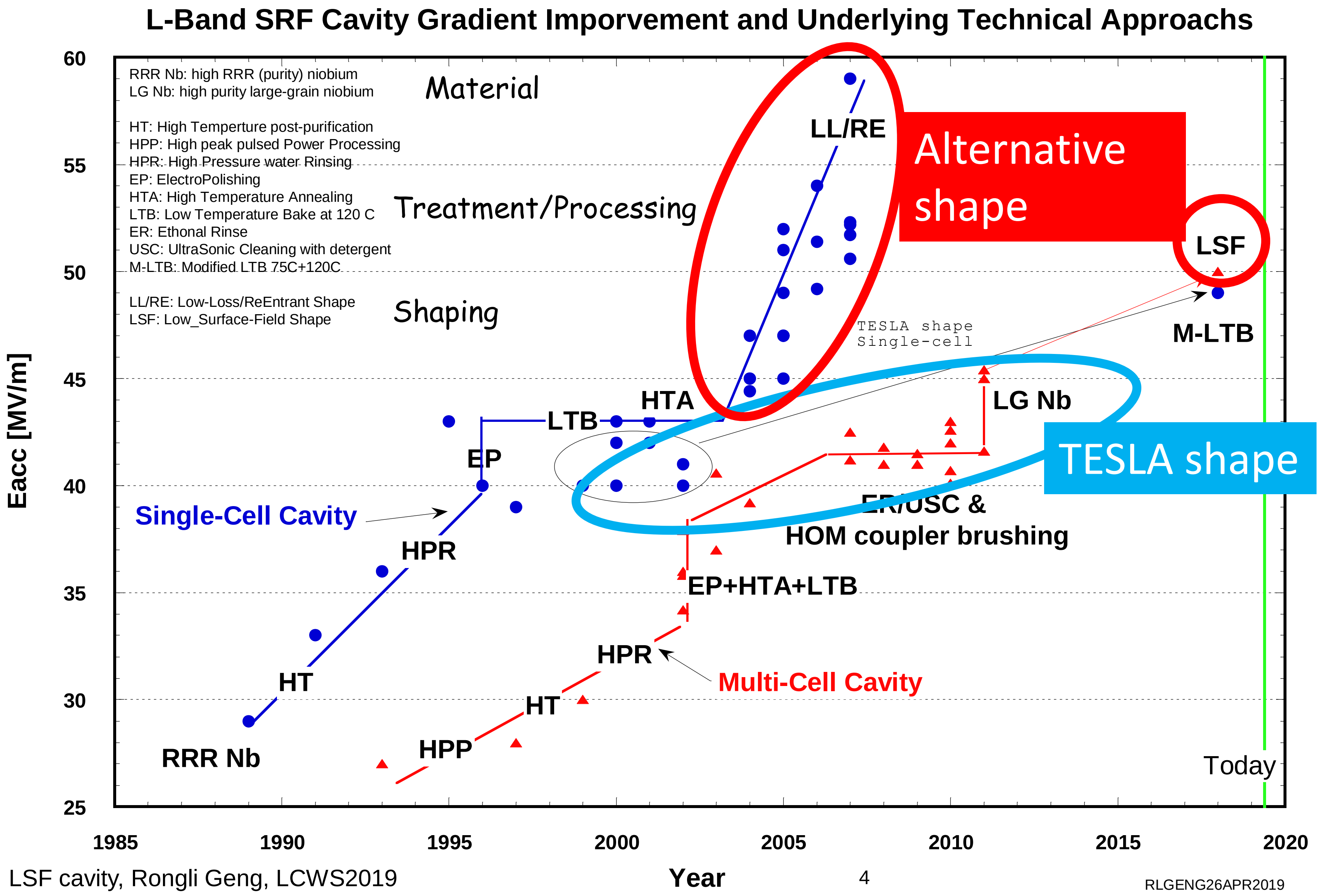
- Rise of SRF gradient and current landscape
- Technical approaches to gradient and role of cavity shaping
- Outcome of initial effort in cavity shaping
- LSF shape cavity development
- Birth of the first 9-cell LSF shape cavity
- Conclusion and outlook

Rise of SRF Gradient and Current Landscape



Steady gradient progress drives broad applications

Technical Approaches to Gradient



Cavity shaping delivered gradient breakthrough of > 50 MV/m

Reason for Pursuing Cavity Shape

Achievable gradient

EP

Cavity surface chemistry

Nb: > 2000 Oe (exp.)
2400 Oe (the.)
Nb_3Sn: > 4000 Oe (the.)

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Cavity wall thermal conductance

High purity (RRR) Nb

Cavity surface smoothness

EBW, EP

Cavity shape

Significant past effort to master material & treatment/processing for reliable cavity gradient

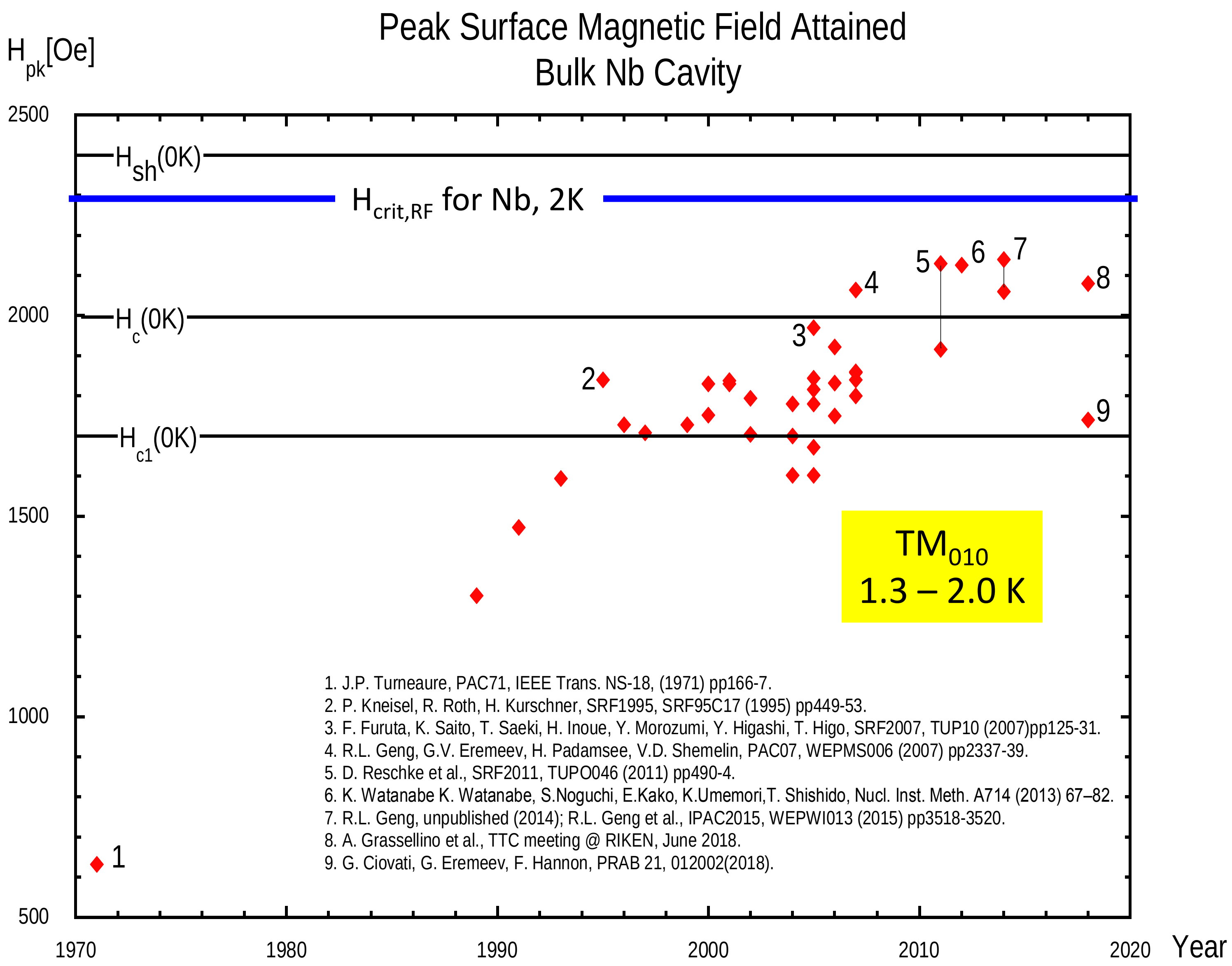
Decades of R&D + hundreds of M$ investment*, solutions in addressing $(d, r, \beta_{MAG,})$ for high gradient SRF now converged and in hand :

Hi purity Nb, EBW, EP, LTB, HPR

* Peter Kneisel, Hot Topics, SRF2009, Dresden, Germany.

- While one's desire is to get E_{acc} from a cavity device in its vacuum space, its inner surface must bear an RF magnetic field, peak value being Hpk.
- Whenever E_{acc} is raised, H_{pk} increases in proportion. The ratio H_{pk}/E_{acc} a fixed value, determined by shape, solely.
- When H_{pk} reaches this value $H_{crit,RF}$, superconductivity is destroyed.
- Hence the desired E_{acc} has a limit, specific to cavity surface material.
- Role of cavity shaping is to seek those possessing smaller ratio H_{pk}/E_{acc}.
- When a good shape is united with proven material and process, a gain in E_{acc} is achieved effectively in a coherent manner.

Progress in Treatment & Processing toward Theoretical Limiting Field



Data Point	material	Freq [GHz]	# of cells	Treatment
1	Nb	1.3	1	HT+LTB
2	Nb	1.3	1	BCP
3	Nb	1.3	1	EP+LTB
4	Nb	1.3	1	EP+LTB
5	LG Nb	1.3	9	EP+LTB
6	Nb	1.3	2	EP+LTB
7	LG Nb	1.5	1	EP+LTB
8	Nb	1.3	1	EP+M-LTB
9	Nb	3.0	1	EP+LTB

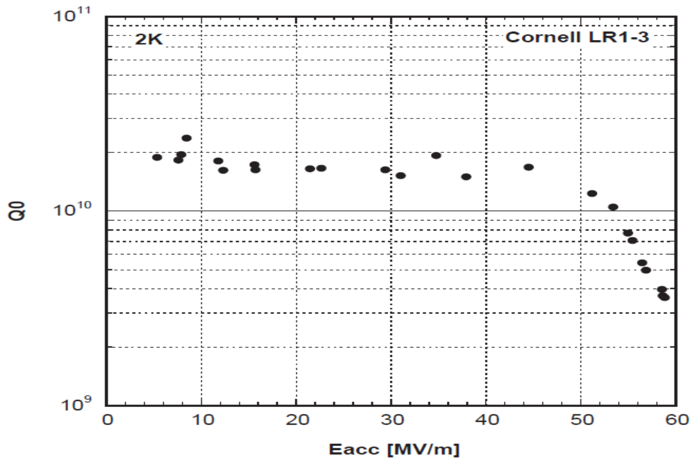
Nb: Fine-grain nNb
LG Nb: large grain ingot Nb
HT: UHV firing 1800 °C
CP: Buffered chemical Polishing (HNO_3+HF+H_2O)
EP: Electropolishing (HF+H_2O+H_2SO_4)
LTB: Low temperature bake 100-120 °C
M-LTB: Modified LTB (75°C + 120 °C)

Outcome of Initial Effort in Cavity Shaping: Achievement

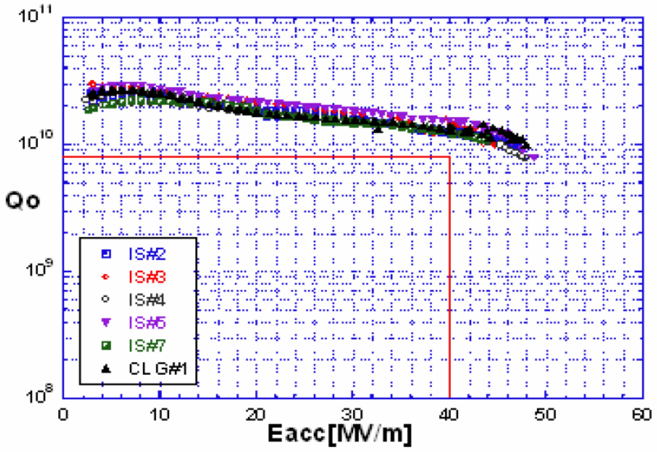
		TESLA	Low-loss/ICHIRO	Re-entrant
frequency	MHz	1300	1300	1300
Aperture	mm	70	60	60
Epk/Eacc	-	1.98	2.36	2.28
Bpk/Eacc	mT/(MV/m)	4.15	3.61	3.54

Lowering the ratio H_{pk}/E_{acc} by 13-15%

E_{acc} ~ 60 MV/m achieved w/ proven processing



Geng et al, PAC2007



Furuta el al, SRF2007

- RE
  - Shemelin, Padamsee, Cornell Internal Report, SRF020128-01 (2002).
  - Shemelin, Padamsee, Geng, NIM-A496(2003)1.
- LL
  - Sekutowicz, Kneisel, Ciovati, Wang, JLAB Tech Note, TN-02-023 (2002).
  - Sekutowicz, Talk 1st ILC Workshop at KEK, Japan, Nov. 13-15, 2004.
- TESLA
  - Haebel et al., Proc. HEACC vol.2 , Hamburg (1992).
  - Proch, Proc. 6th SRF Workshop, Newport News, VA, USA (1993).

Outcome of Initial Effort in Cavity Shaping: Challenge

		TESLA	Low-loss/ICHIRO	Re-entrant
frequency	MHz	1300	1300	1300
Aperture	mm	70	60	60
Epk/Eacc	-	1.98	2.36	2.28
Bpk/Eacc	mT/(MV/m)	4.15	3.61	3.54

- 50 MV/m not realized in 9-cells
- Best 9-cell result 40 MV/m by ICHIRO7
- Old enemy: Field Emission!

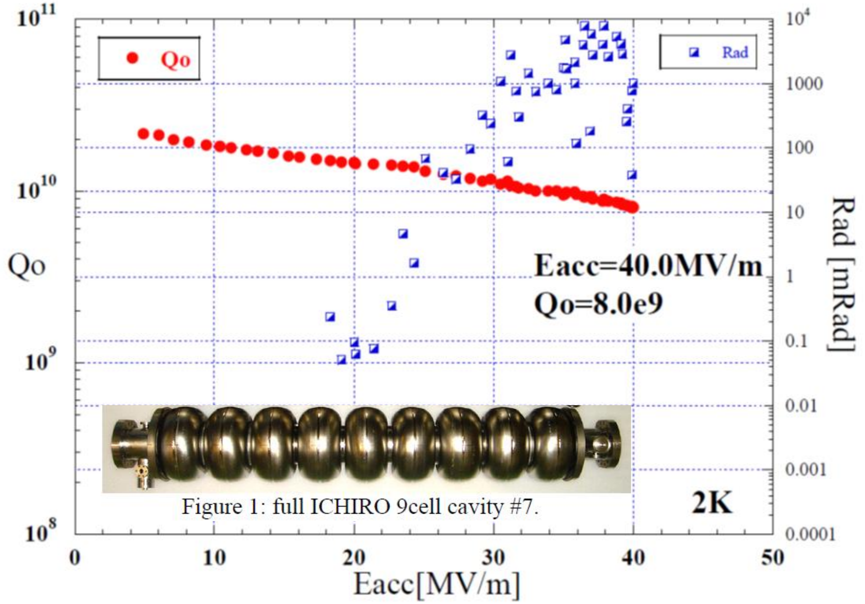


Figure 1: full ICHIRO 9cell cavity #7.

Furuta el al, SRF2011

- H_{pk}/E_{acc} 13-15% reduction in RE & LL at cost of 15-20% increase in E_{pk}/E_{acc}.
- Lessons learned: To materialize the full potential of new shapes, it is still required to fight against field emission, though it not being a fundamental limit.

The Development of Low-Surface-Field (LSF) Shape Cavity

		TESLA	Low-loss/ICHIRO	Re-entrant	Low-surface-field
frequency	MHz	1300	1300	1300	1300
Aperture	mm	70	60	60	60
Epk/Eacc	-	1.98	2.36	2.28	1.98
Bpk/Eacc	mT/(MV/m)	4.15	3.61	3.54	3.71
G*R/Q	Ω^2	30840	37970	41208	36995

$$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0}\times Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0}\times G}\times R_s$$

Accelerator operation requirement

Cavity material

Cavity geometry

Lowering H_{pk}/E_{acc} by 11% while preserving the same E_{pk}/E_{acc} as compared to TESLA shape

Li, Adolphsen, LINAC08 (2008).

All new shapes possess intrinsic higher efficiency, independent of material surface losses.

Power dissipation saving 20-34%

2013 Selection of LSF + LG Nb at JLAB to Advance Gradient & Efficiency

- Goal 1: 50 MV/m gradient in multi-cell cavities with Q_0 2×10^{10} at 45 MV/m and 1.8-2.0 K
- Goal 2: In reference to ILC TDR baseline, 11% more gradient margin and 45% better efficiency is reasonable as underpinned by selected shape & material

$$E_{acc}^{max} = d \cdot \frac{r \cdot H_{crit,RF}}{\beta_{MAG} \cdot (H_{pk}/E_{acc})}$$

Achievable gradient

Cavity surface chemistry

Nb: > 2000 Oe (exp.)
2400 Oe (the.)
Nb_3Sn: > 4000 Oe (the.)

Cavity wall thermal conductance

Cavity surface smoothness

Cavity shape

- 11% more gradient margin by tuning one parameter
- Other parameters untouched hence avoid provoking new risks

$$P_c = \frac{V_c^2}{R_a} = \frac{V_c^2}{\frac{R_a}{Q_0} \times Q_0} = \frac{V_c^2}{\frac{R_a}{Q_0} \times G} \times R_s$$

Accelerator operation requirement

Cavity material

Cavity geometry

25-30% from LG Nb material

15% from shape

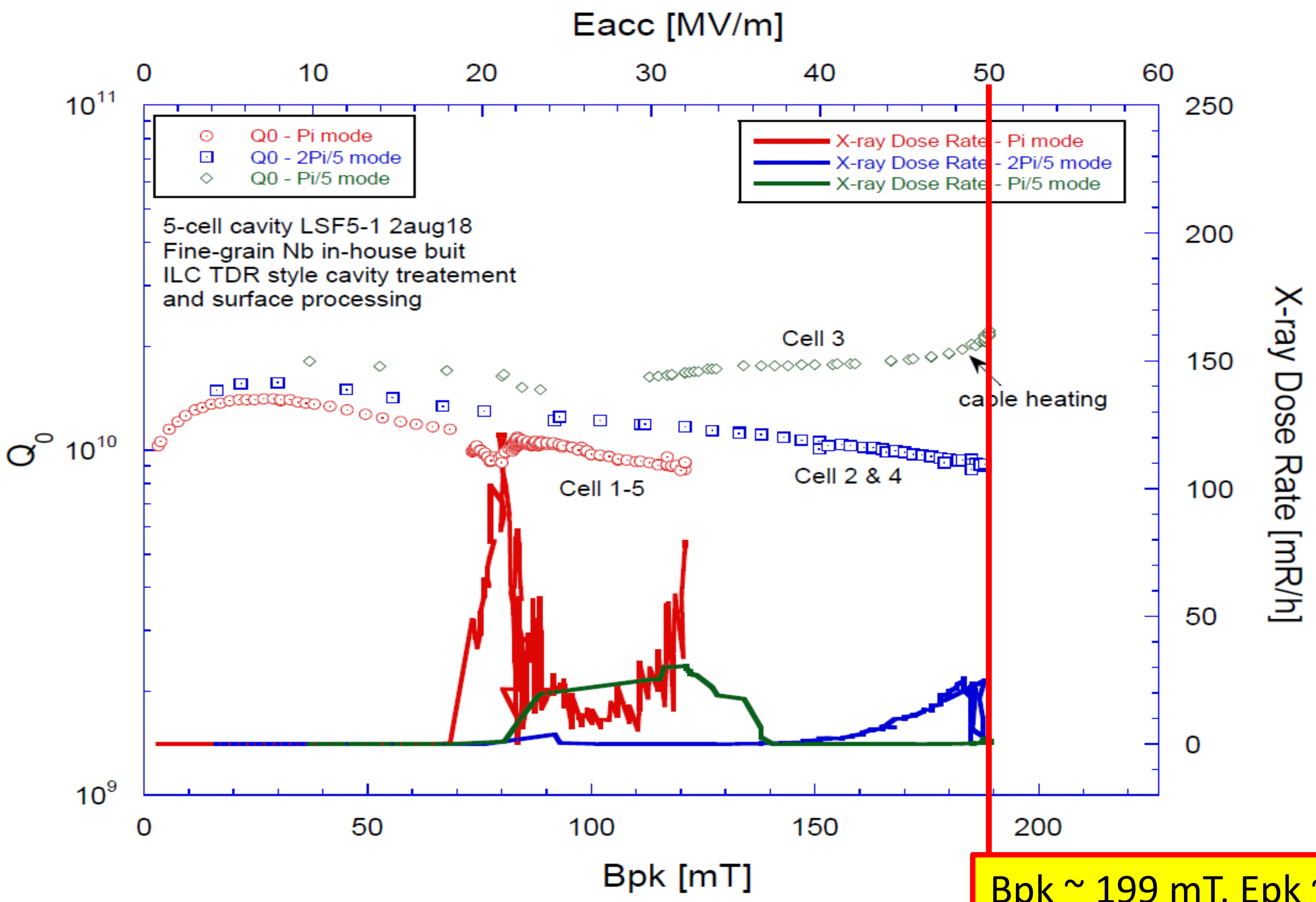
40-45% better efficiency

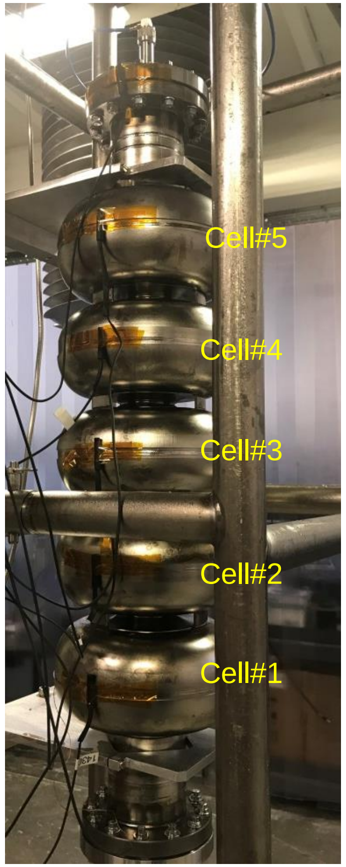
LSF Shape Cavity Development

- 2015, single-cell LSF shape LG Nb cavities prototyped, tested.
- 2016, 5-cell LSF shape FG Nb LSF5-1 cavity completed.
- 2018, LSF5-1 tested to surface field corresponding to accelerating gradient of 50 MV/m in three mid-cells.
  - Test continues on understanding & overcoming field emission limits in 2 end-cells.
  - Field emission studies using Kyoto's sX-mapping instrument (under US-Japan collaboration with Prof. Y. Iwashita, Kyoto University)
- 2019, First 9-cell LSF shape FG Nb cavity completed.

Advances since 2017 made possible due to US-Japan Collaboration in HEP, supported by US DOE

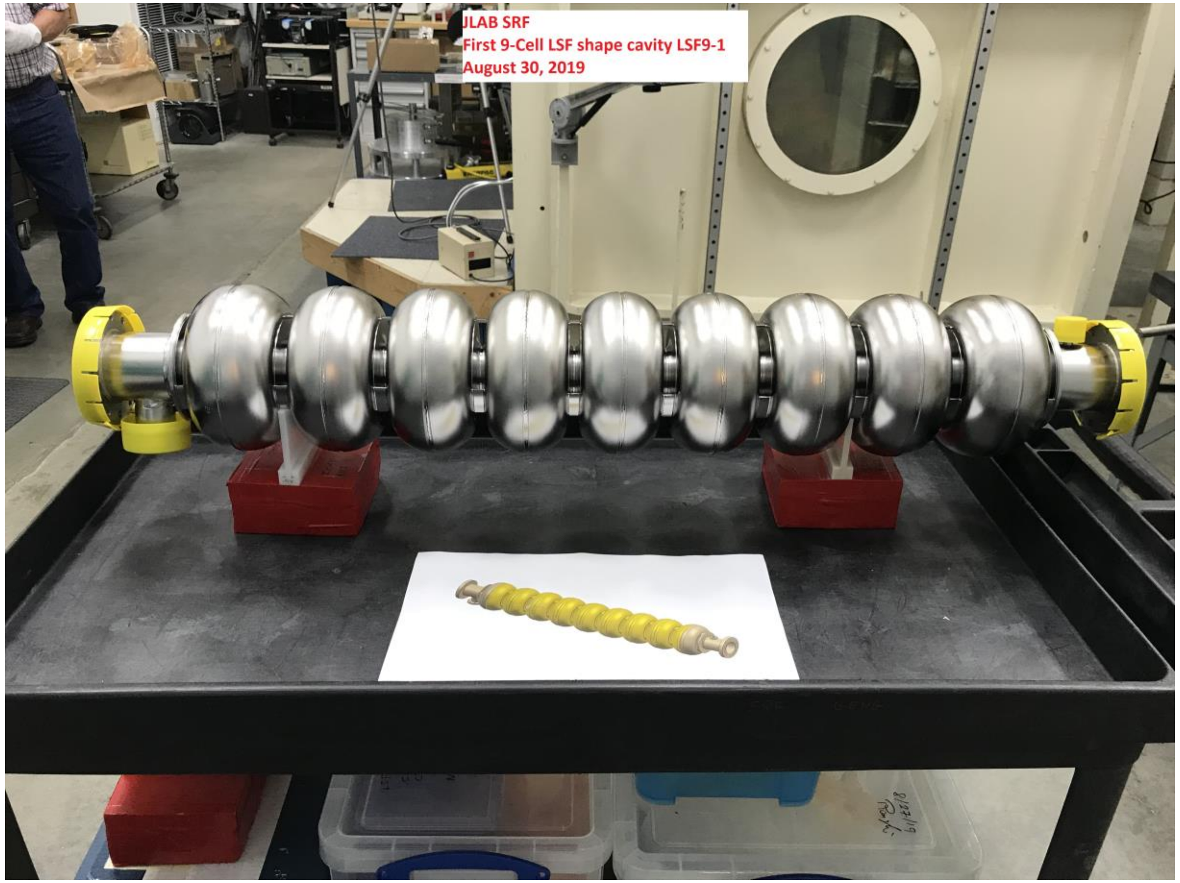
LSF5-1 Current Performance





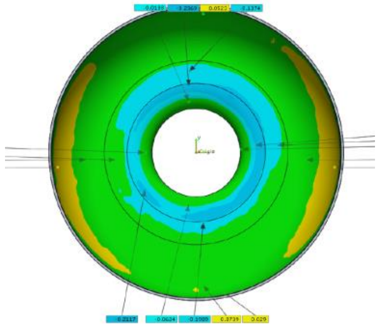
Bpk ~ 199 mT, Epk ~ 100 MV/m
Pi mode equivalent 50 MV/m

Birth of First 9-cell LSF Shape Cavity

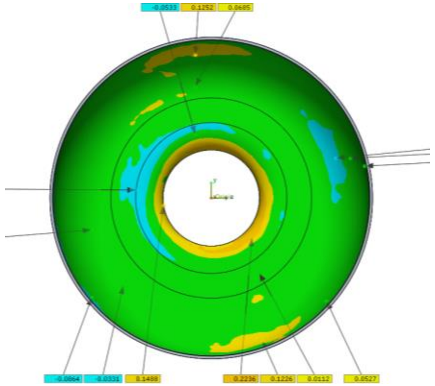


- Design Priority: Lorentz Force Detuning Coefficient
  - Reason: $\Delta f = k_{LFD} \cdot E_{acc}^2$
  - Approach: choosing stiffener radial location
- Fabrication Priority: Shape Accuracy
  - Reason: small cell-to-cell coupling
  - Approach:
    - Cup anneal then re-stamping
    - Piecewise stiffener, light weld
- Fabrication Priority: Cost Effectiveness
  - Reason: present standard fab expensive
  - Approach:
    - Eliminate dumbbell shaping
    - Eliminate dumbbell machining

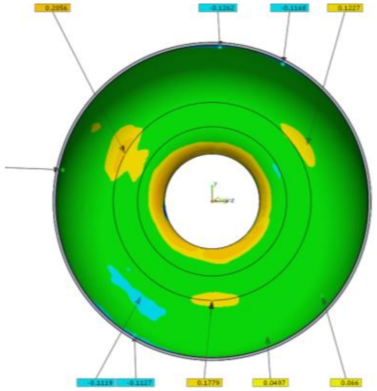
Shape Accuracy



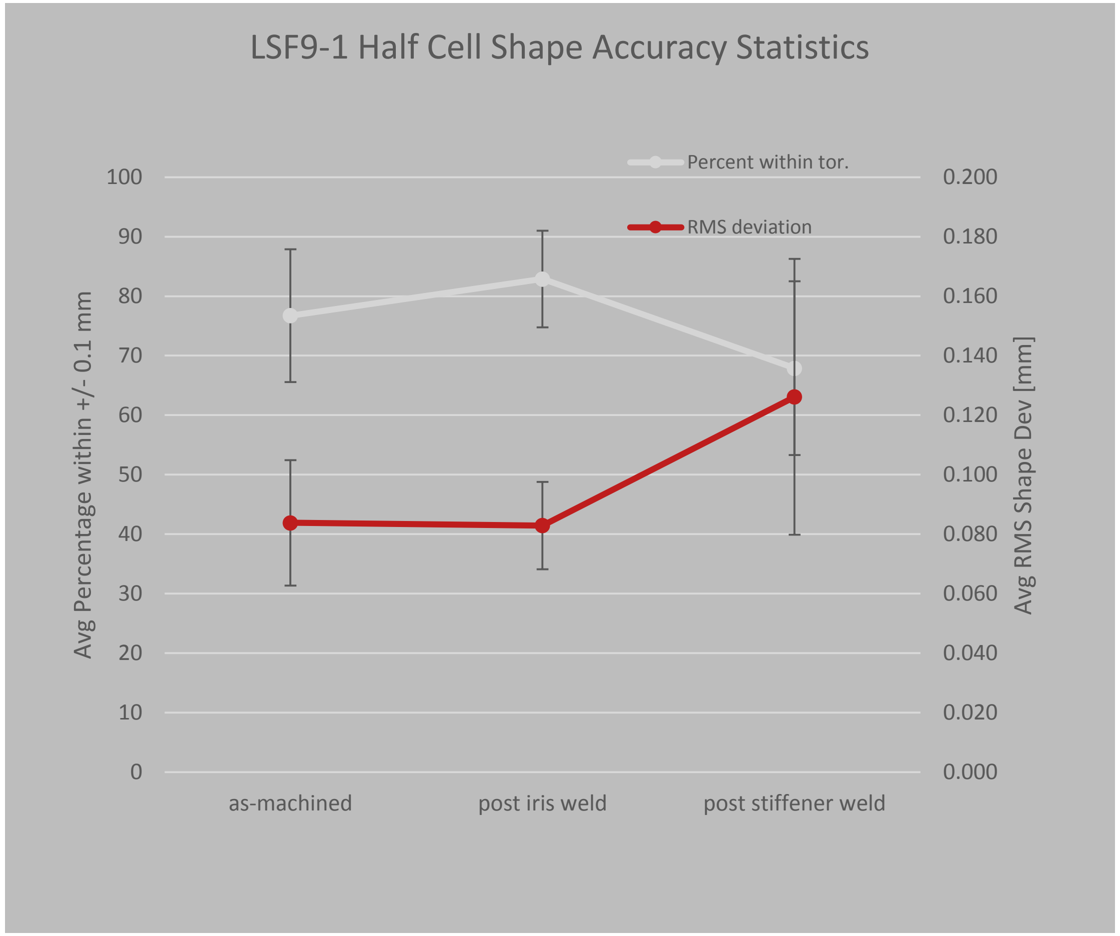
Half cell C9
RMS shape deviation 0.100 mm



Half cell C9 after iris weld
RMS shape deviation 0.071 mm



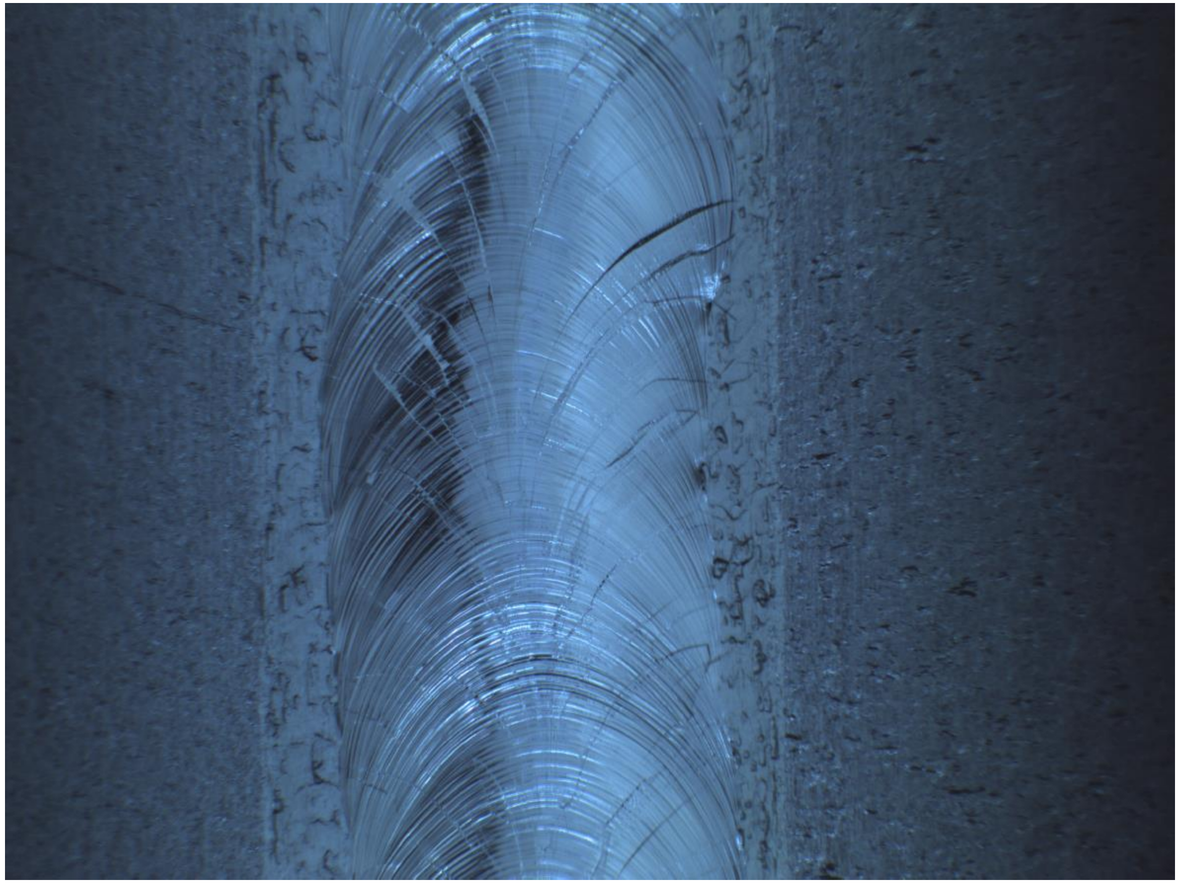
Half cell C9 after stiffener weld
RMS shape deviation 0.072 mm



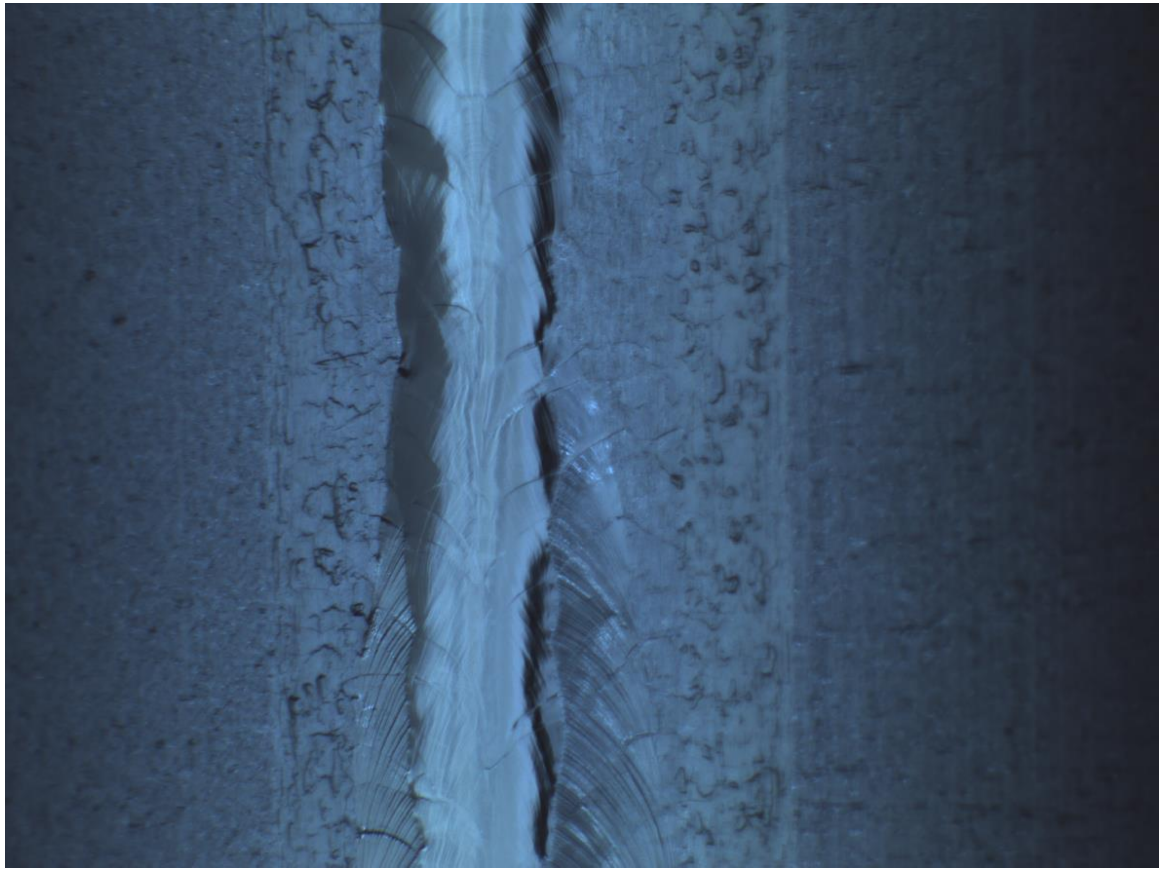
19 half cells for LSF9-1
90% points within +/- 0.2 mm tolerance (std dev 8%)
consistent with standard fabrication

Cost-Effective Fabrication by Simplification

Optical Inspection of Equator EBW Seams



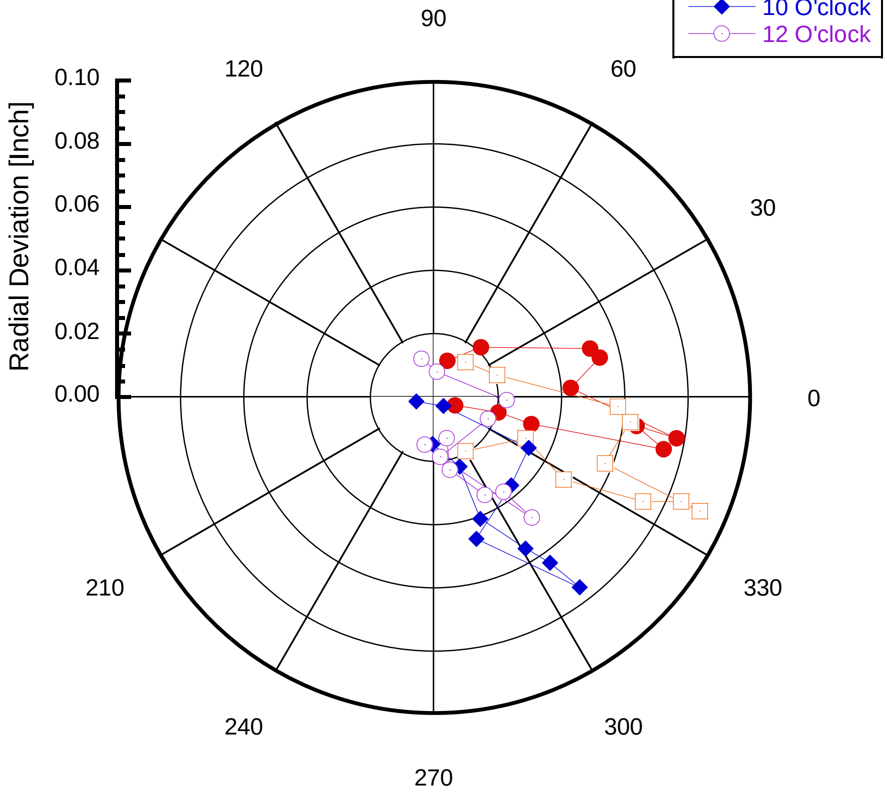
LSF9_1Cell5EQ_z631mmPhi79deg0006



LSF9_1Cell5EQ_z631mmPhi171deg_FZ neck0010

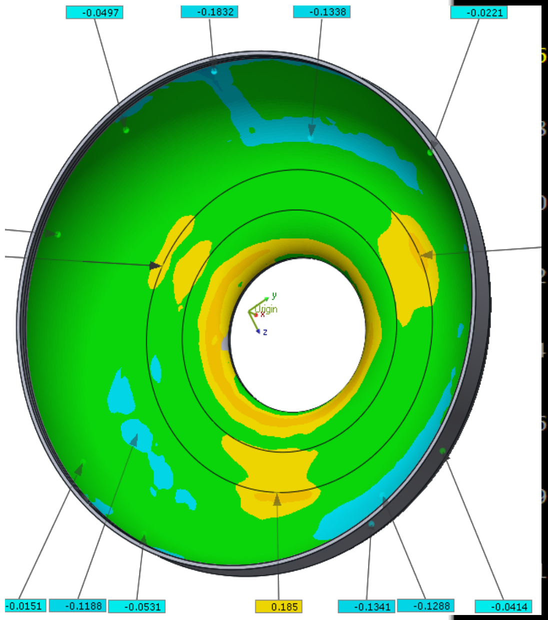
Overall good weld, notable features documented. Re-inspection to be carried out at KEK for tracking feature evolution as cavity processing progresses

Issue Encountered: Component Alignment during Final Weld

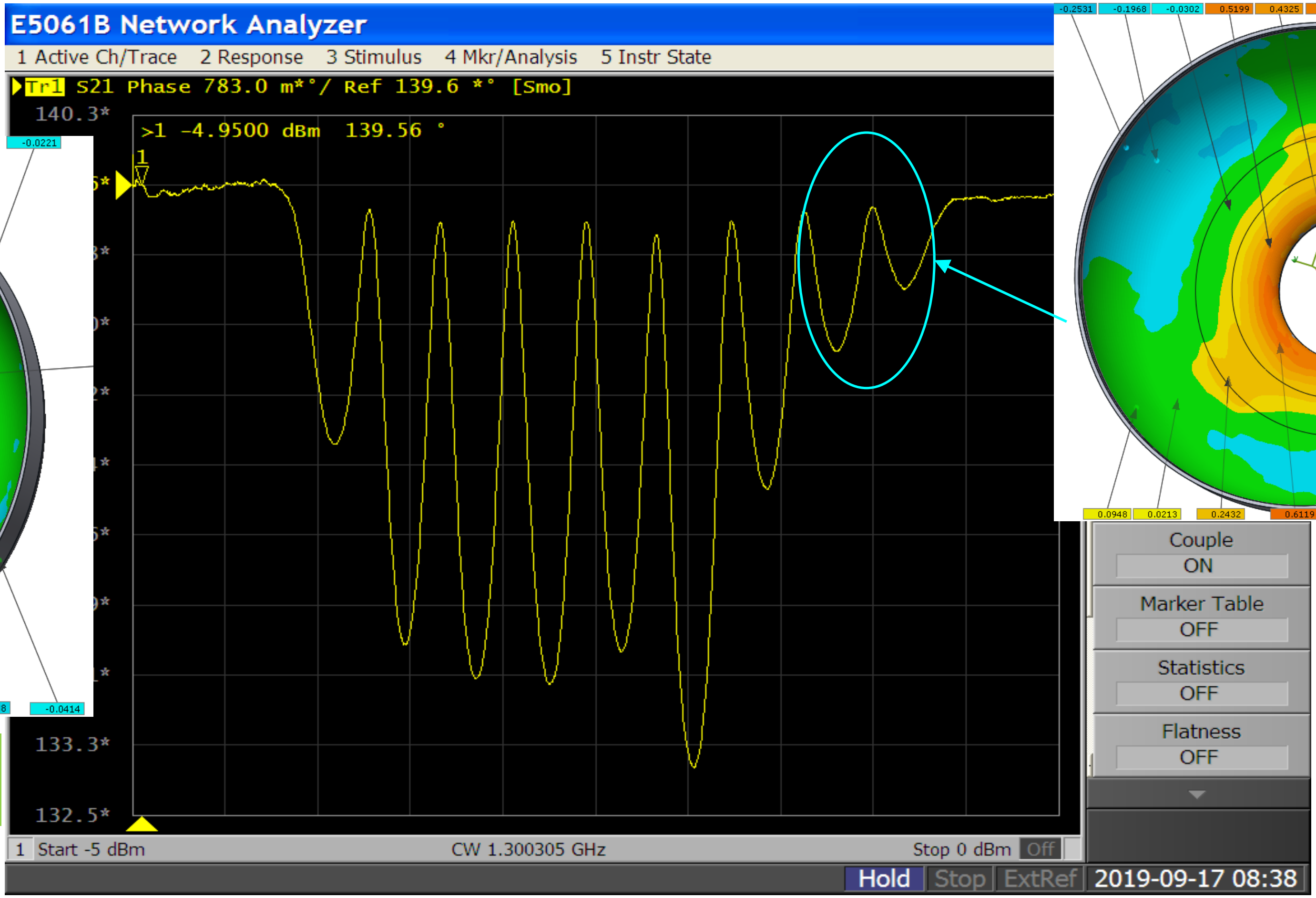


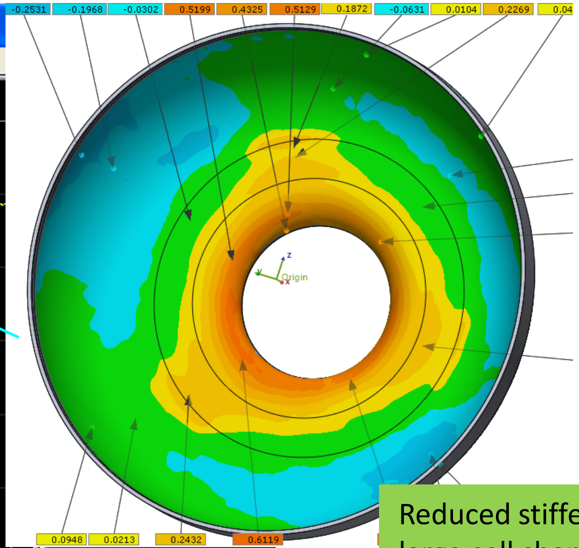
Path forward:
Short term within JLAB in-house facility, Improve alignment procedure.
Long term, seek outside facility with cavity assembly oriented vertically in EBW chamber.

Issue Encountered: Large Shape Distortion due to Stiffener Width Deviation



Nominal stiffener width resulting to better field flatness





Reduced stiffener width leading to large cell shape deviation and poor field flatness

Path forward: Revised stiffener design width based on LSF9-1 experience

Conclusion and Outlook

- The approach of LSF shape +LG Nb was chosen in 2013 at JLAB, aimed to advance high-gradient high-efficiency SRF to next level. Rapid progress since 2017 due to new US-DOE support under US-Japan collaboration.
- First sight of 50 MV/m in 3 mid-cells in the 5-cell cavity LSF5-1 (FG Nb). Its evaluation continues with focus on understanding end cell field emission using Kyoto's sX-mapping instruments.
- The first LSF 9-cell (FG Nb) cavity LSF9-1 is completed in-house fabrication at JLAB. It is being shipped to KEK for surface processing and field flatness tuning.
- Plan is to build two more 9-cell LSF shape cavities including one from FG Nb (material in hand) one from LG Nb (material to be acquired).
- We anticipate this work would allow us to make new contributions in several fronts relevant to ILC: shifting the gradient performance frontier in full scale 9-cell cavity; increase gradient margin; save cavity fabrication cost; save accelerator operation cost.