High-Gradient High-Efficiency SRF Cavity Development at JLAB

Latest Results on LSF-Shape Nb Cavities

JLAB-KEK Collaboration Under US-Japan HEP Cooperation Program

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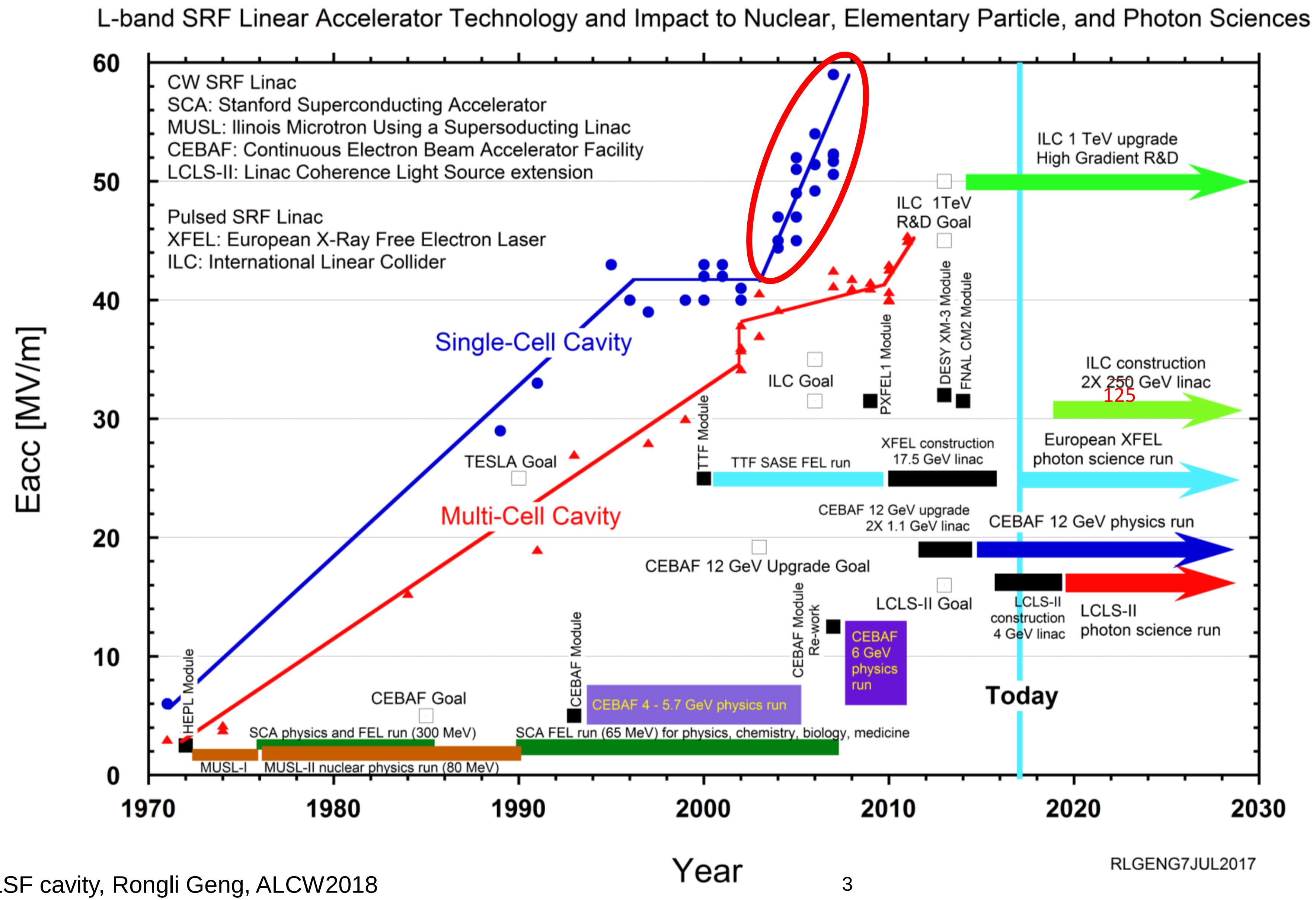
Outline

- Long march of SRF technology and great success of new cavity shapes
- Struggle for new shape demonstration in 9-cell cavities
- LSF emerged as best cavity shape and its potential for high gradient & high efficiency
- Moving forward, JLAB chose LSF+LG Nb approach – on ground of GDE SRF success
- Single-cell LSF+LG Nb cavities
- LSF5-1 first multi-cell LSF and its first tests
- Conclusion and outlook

The Long March of SRF Technology



Breakthrough brought by new cavity shapes

- RE @ Cornell
- LL/ICHIRO @ KEK

Jefferson Lab

The Idea (as viewed though a "phenomenological law for gradient")

EP

Achievable gradient

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

Cavity surface smoothness

Cavity shape

High purity (RRR) Nb

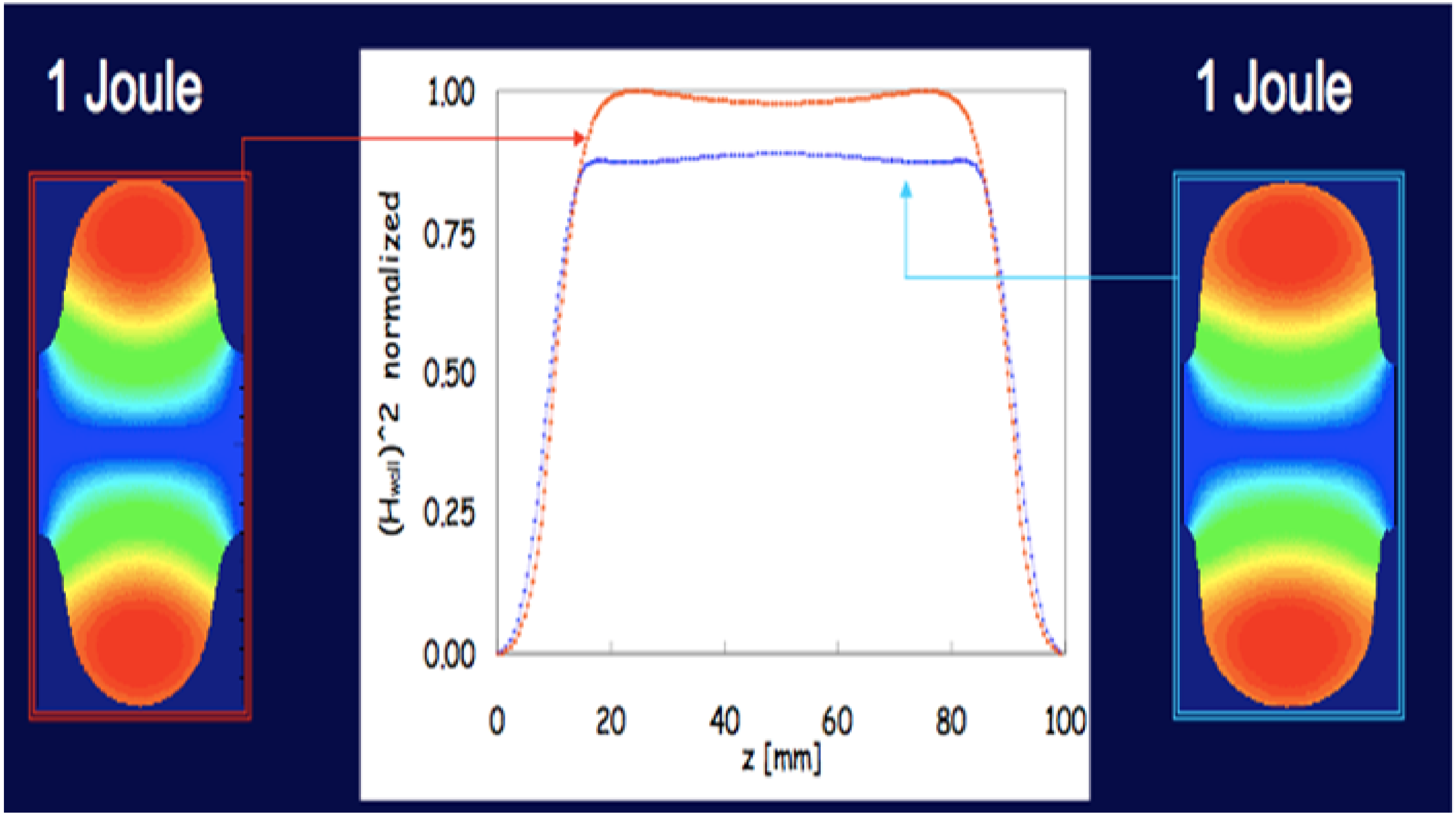
EBW, EP

Tune down H_{pk}/E_{acc} for higher E_{acc} as $H_{rcit,\ RF}$ is a fundamental material property setting limit

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

* Kneisel, Hot Topics, SRF2009.

The Approach



Enlarge equator to "dilute" surface RF current hence to Lower H_{pk}

Courtesy J. Sekutowicz

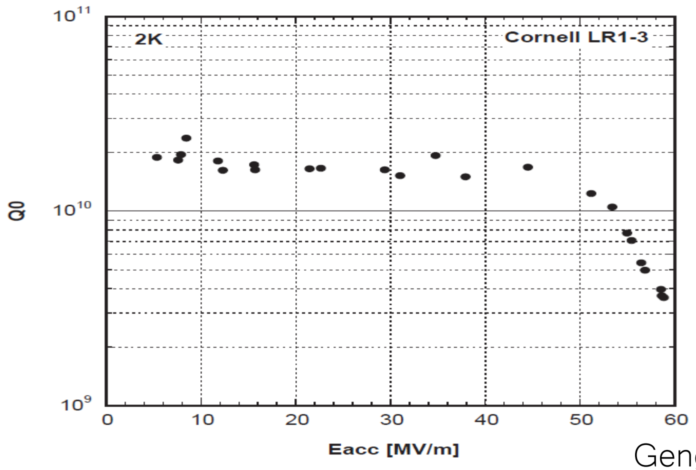
The Early Shape-Players in 2002-2003 and Great Success

		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

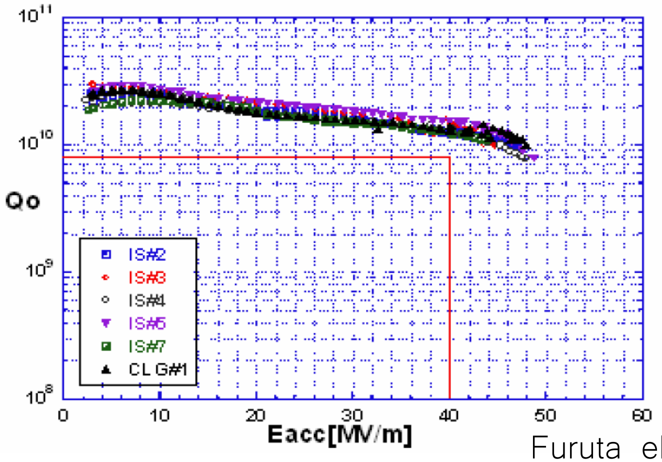
Lowering H_{pk}/E_{acc} by 13-15%

E_{acc} 50-60 MV/m Achieved

- 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, 2014.
- TESLA
  - Haebel et al., Proc. HEACC vol.2 , Hamburg (1992).
  - Proch, Proc. 6th SRF Workshop, Newport News, VA, USA (1993).



Geng et al, PAC2007



Furuta el al, SRF2007

The Struggle in Extending Success to Full-Scale 9-Cell

		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!

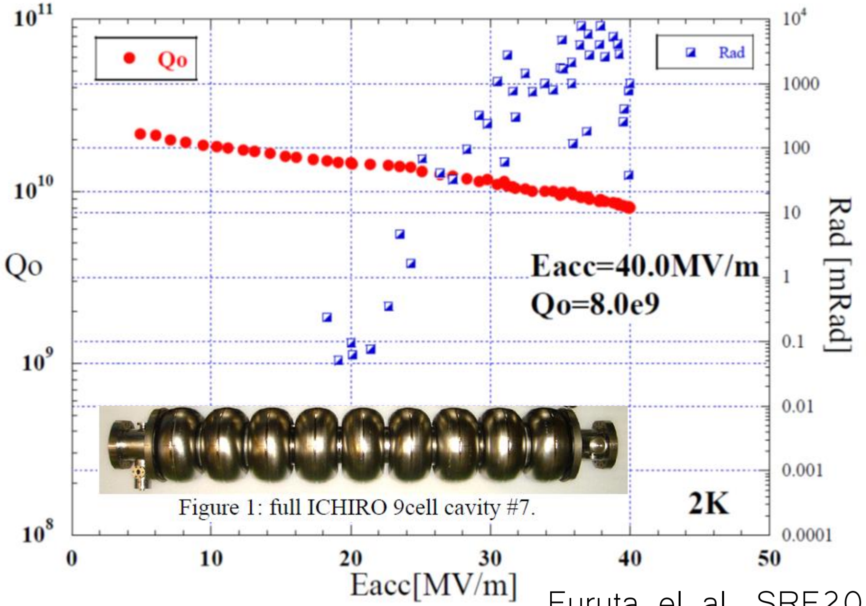


Figure 1: full ICHIRO 9cell cavity #7.

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 LSF Emerged as Best Shape

		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}

Li, Adolphsen, LINAC08 (2008).

All new shapes offer additional benefits in higher efficiency 20-34% saving in power dissi.

JLAB Chose LSF + LG Nb as the New Approach in 2013

- ILC S0 program concluded and TDR published in 2013
  - 90% yield vertical qualification test at avg gradient 35 MV/m (TESLA shape + FG Nb + EP).

- Moving forward, built upon successful outcome of SRF R&D under GDE, and in recognition of
  - Solid knowledge in cell shape properties.
  - 10-year's global experience in new shape cavity prototyping and testing since 2003.
  - Observed higher Q_0 in LG Nb cavities in 2011-2013 (its origin subsequently understood).
  - (See more in backup slides).

- A new approach chosen at JLAB for demonstrating higher SRF gradient and for help lower ILC project risk and cost via more gradient margin and better efficiency:

LSF shape + LG Nb (high purity) + EP

JLAB Selected LSF + LG Nb as the New Approach in 2013 (cont.)

- Goal: 11% more gradient margin and 45% better efficiency 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

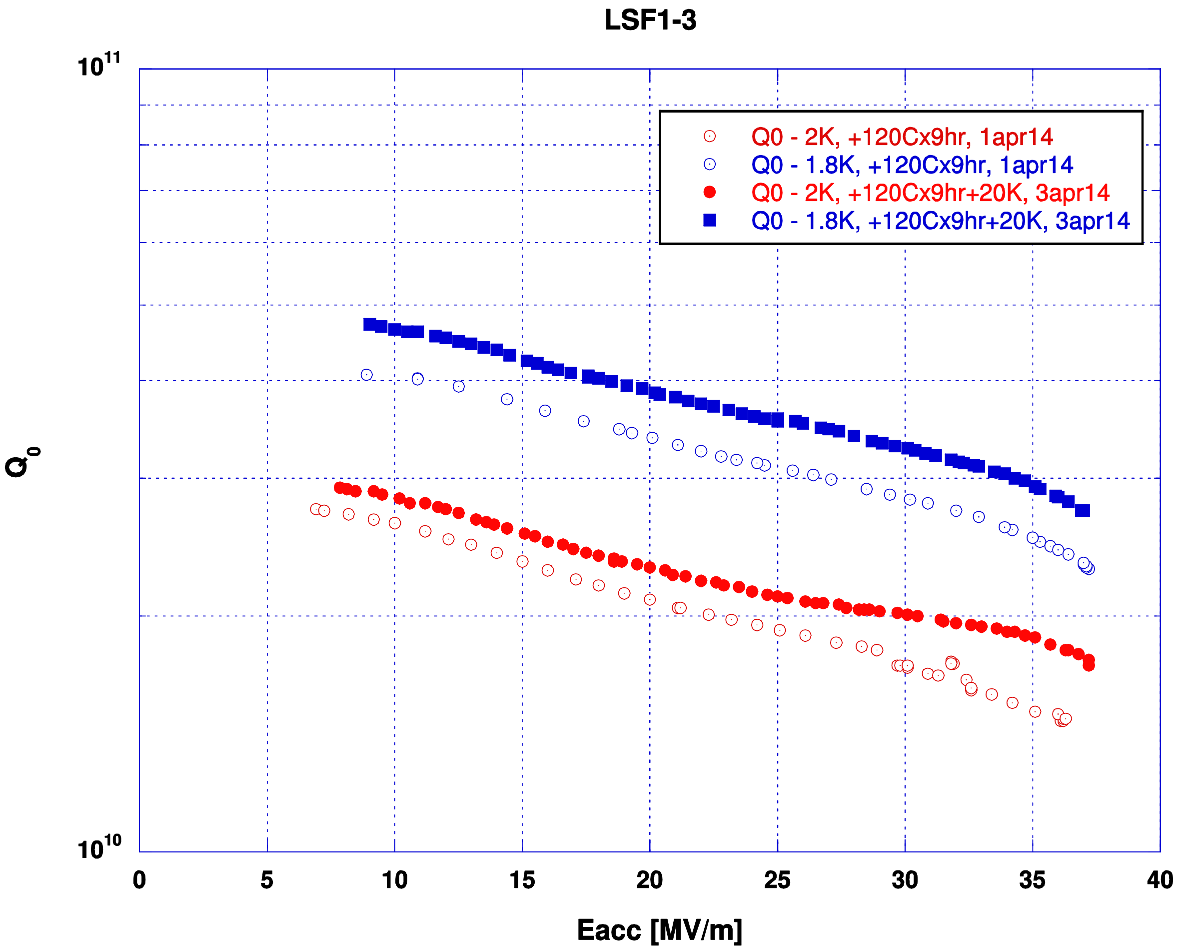
25-30% from material

15% from shape

40-45% better efficiency

Jefferson Lab

Single-Cell LSF LG Nb Cavities – Early Fruits Through a Collaboration



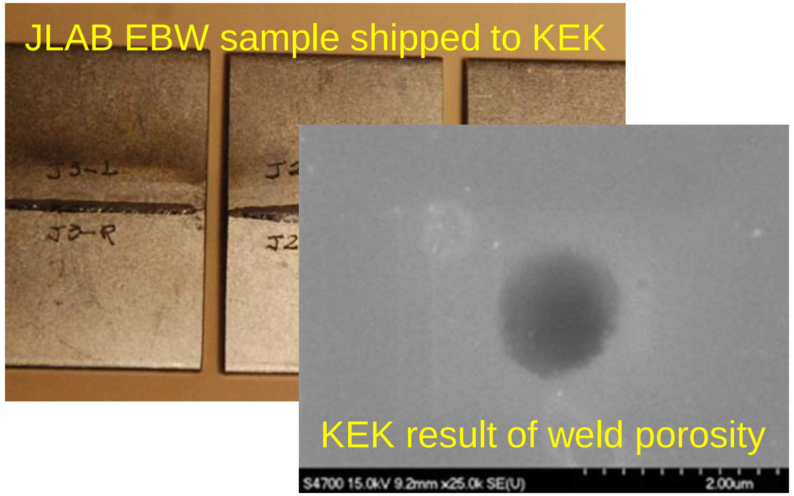
Collaborators: JLAB, PKU, SLAC

- Two 1-cell LSF LG Nb cavities built and tested.
- Ningxia high-purity LG Nb.
- ~38 MV/m @ Q0 ~2E10 after surface BCP only.
- Surface EP now in progress to raise Eacc.

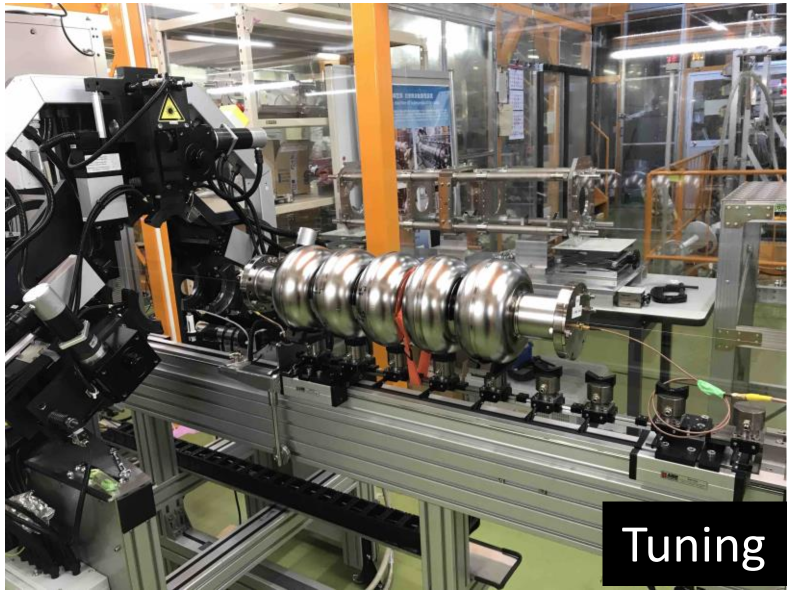
Geng et al., WEPWI013, IPAC2015 (2015)

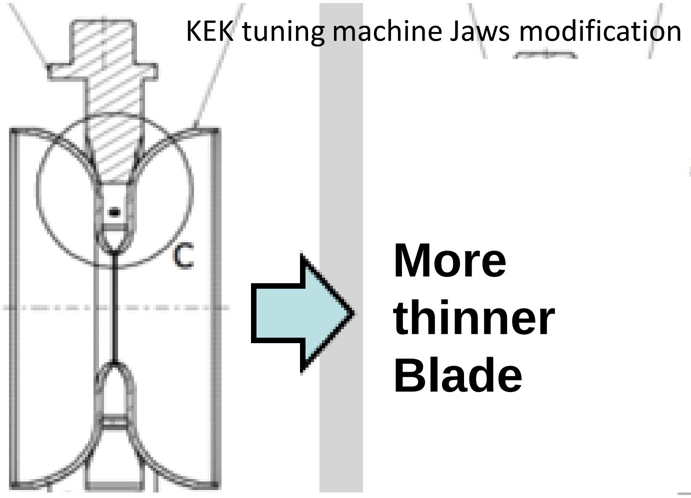
March 3, 2016 Birth of first multi-cell LSF cavity – enabled by US-Japan Collaboration

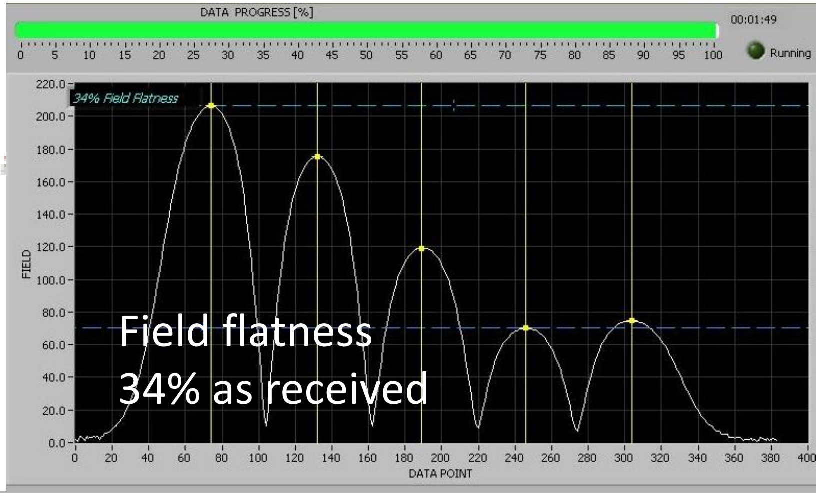
- A new pre-EBW cleaning recipe was established at JLab – an outcome of weld porosity study of prior years (2014-2015) joint study between JLAB and KEK under US-Japan collaboration.
- The new recipe was first applied to the in-house fabrication of 1-cell LSF shape cavities.
- The same recipe was applied to in-house fabrication of 5-cell LSF shape cavity LSF5-1.
- Fine-grain Nb (to allow comparison with TESLA & LL/ICHIRO).

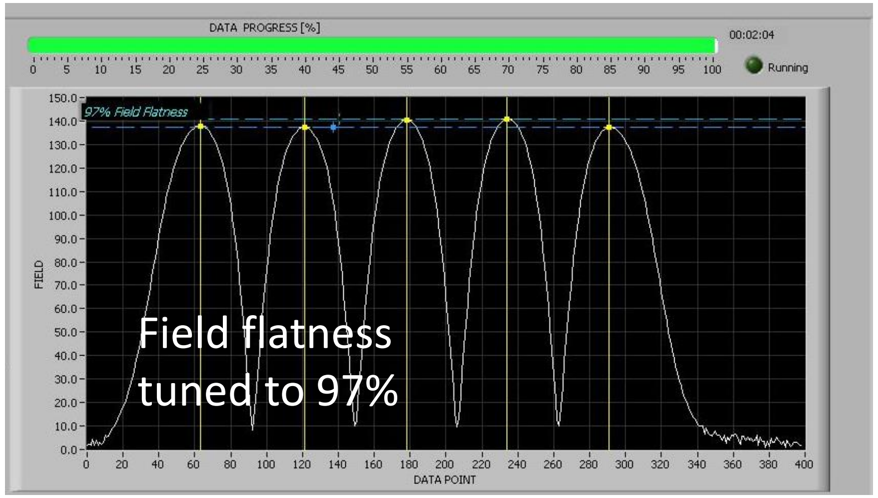


LSF5-1 Processing at KEK with Its Proven High Gradient Yield ILC-Style Recipe





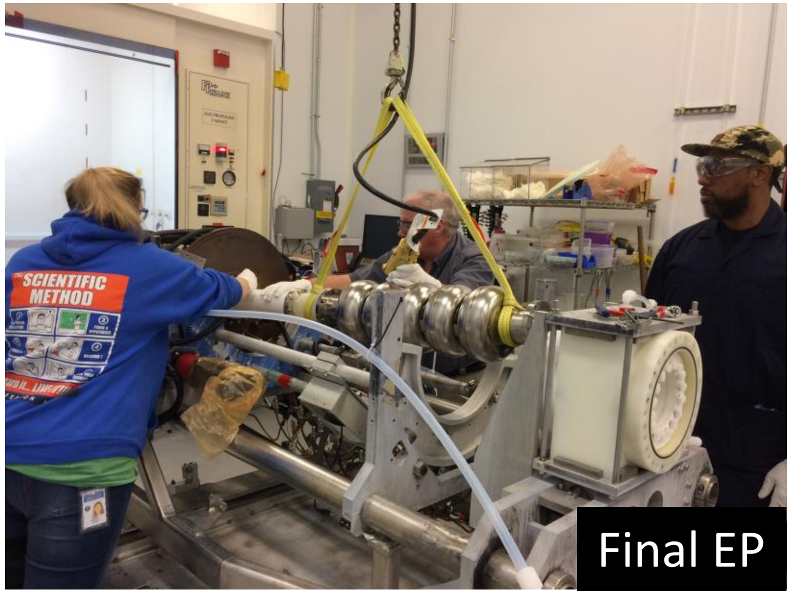




LSF5-1 Processing and Preparation for First Vertical Test at JLAB in 2018

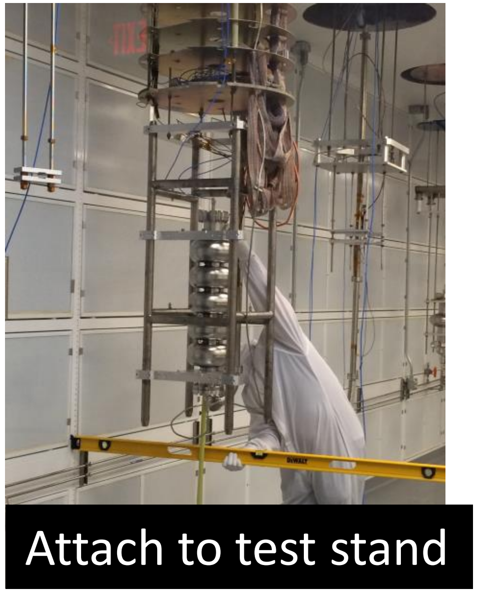
Vertical bead pull

Prep for final EP



Final EP

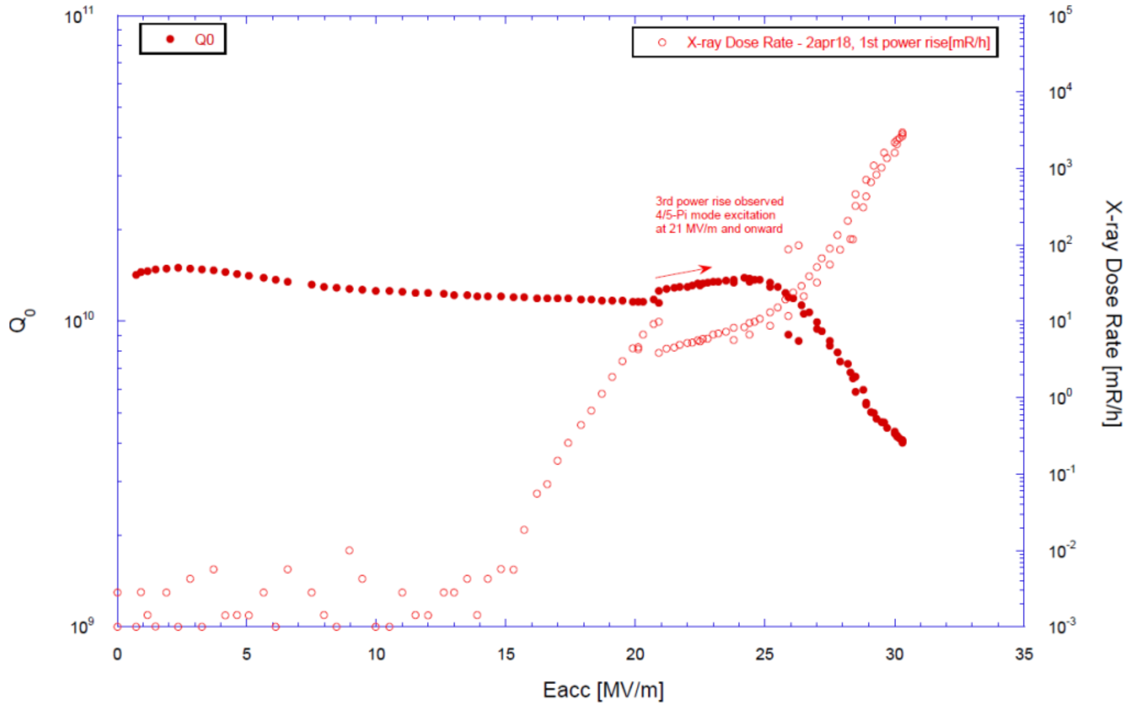
HPR



Attach to test stand

Dewar Mag survey

Results of First Cold Tests of LSF5-1



Hayato Ito,
graduate student of SOKENDAI/KEK at JLAB for prep and testing in January - February 2018

- Pressure detuning df/dp -186 Hz/torr; Lorentz force detuning coeff. -4.4 Hz/(MV/m)^2.
- Highest Eacc achieved 30 MV/m.
  - Limited by pass-band mode (4/5-π) excitation and evidence of end group heating.
- Gradient reach probed by pass-band technique: 33 MV/m end cells; 36-38 MV/m inner cells.
  - Pointing toward end group limitation as well.

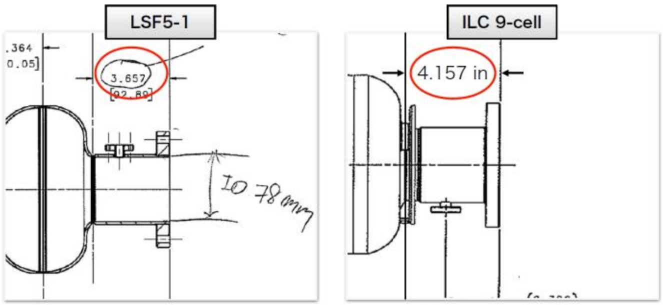
Understanding LSF5-1 First Tests and Actions for Next Steps

- High gradient reach of 36-38 MV/m by inner cells confirmed high quality equator weld & surface processing.

- 30 MV/m cavity gradient limitation by pass-band mode (4/5-π) excitation and end group heating.
  - Field emitters in end cells (contaminants in test stand).
  - Missing the 0.5 inch length in beam tube has consequence!
  - Moving forward: Add 0.5 in ring in beam tube; restore test stand.
- Lorentz force detuning coeff. 10% better than ICHIRO7.
  - Validating design & fabrication of new stiffening components.

- Field flatness preserved within 3% from handling/evacuation
  - Indicating design efficacy in dealing LSF's small cell-to-cell coupling.

- Beam tubes wire EDM cut, EBW in progress, re-test coming.



4.157 - 3.657 = 0.5 inch

Conclusion and Outlook

- JLAB has chosen LSF shape +LG Nb as a new approach for advancing high gradient SRF to the next level. Steady effort since 2013. New boost from US-Japan collaboration.

- Two 1-cell LG & one 5-cell FG cavities are being tested. 9-cell (FG & LG) is next.

- While on the one hand, this LSF cavity development has been driven by the goal of shifting performance frontier beyond 50 MV/m in full-scale 9-cell cavities,

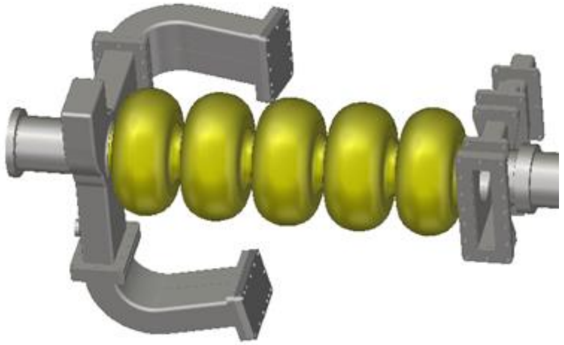
- There is, on the other hand, a second motivation of shifting ILC project risk in the right direction (fraction of quench limited cavities still large, see XFEL cav. data analysis*).
  - 11% more margin in gradient.

* Walker, TTC at CEA Saclay, July 5-8, 2016.

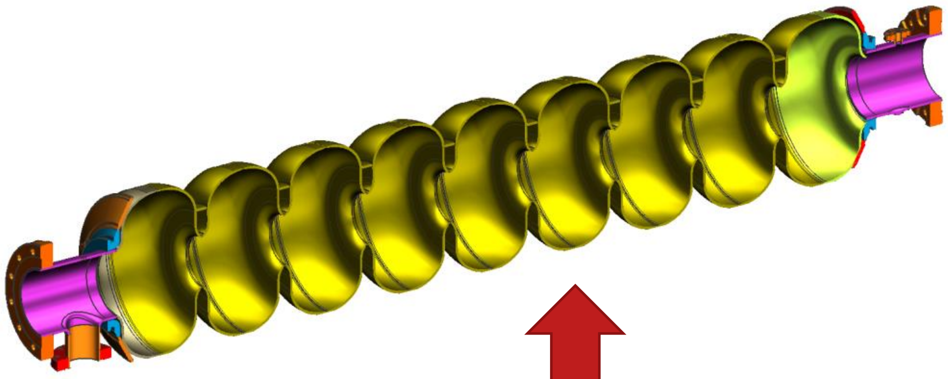
- This work is as well expected to save ILC accelerator cost, still a largely unfilled need.
  - 40-45% cryo loss saving underpinned by selected shape and material.

Last But Not The Least: Plug Compatibility

CEBAF refurbish

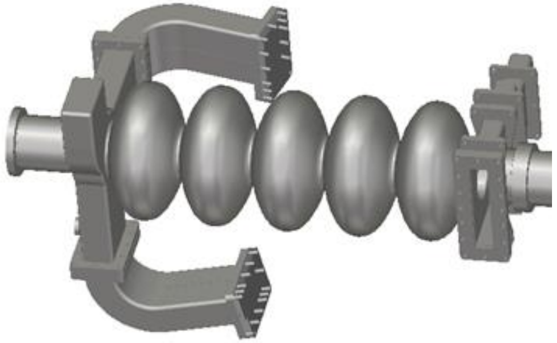


LSF



Replace center cells with LG Nb & new shape
Preserve end groups

Original CEBAF



TESLA

Ciovati, Rimmer et al, TTC at Milan, Feb 6-9, 2018.

Backup: 3 Key Elements Underpinning Perspective of LSF+LG Nb Approach

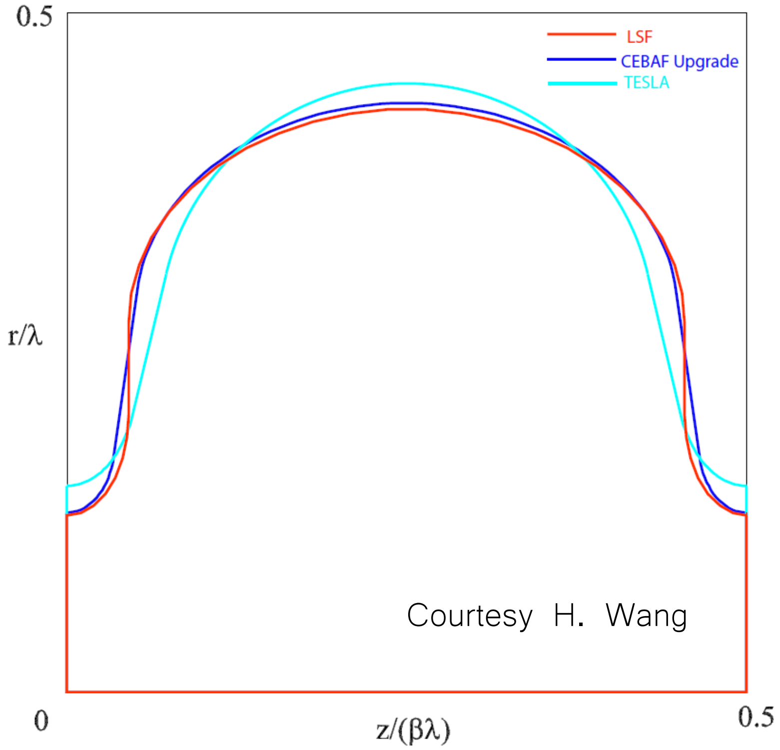
1. Solid knowledge and understandings.
   - ✓ Shape properties, aperture compatibility w/ beam*.
   - ✓ Proven ILC-style TDR baseline surface processing.
   - ✓ Origin of LG Nb's superior Q_0.

   * Zagorodnov, Solyak, EPAC06, THPCH037 (2006)

2. Extensive experiences.
   - ➢ Cornell: ~10 year on RE.
   - ➢ KEK: ~ 10 years on LL/Ichiro.
   - ➢ JLAB: 15 years on LL (CEBAF) + 5 years LSF.

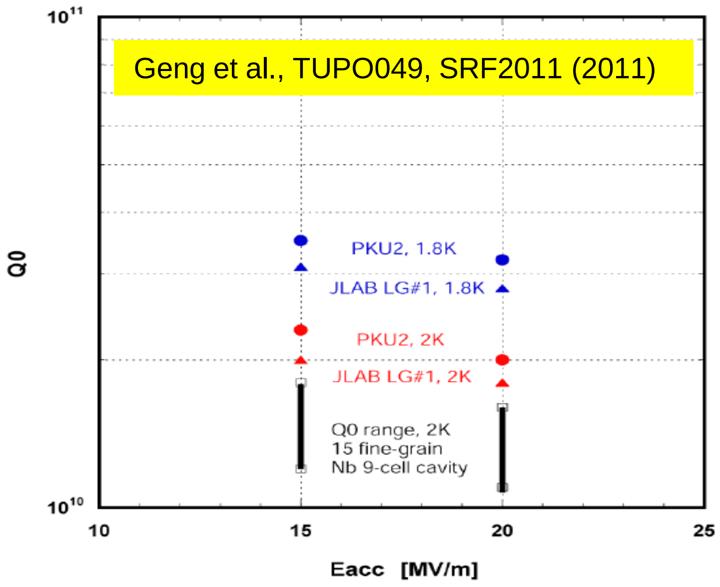
3. Actual test in real accelerator systems with beam.
   - LL shape cavities: > 4 yr in 12 GeV CEBAF.
   - LG Nb cavities:
     - ➢ 8 yr LG 9-cells (2 EA) in FLASH.
     - ➢ 3 ys LG 9-cells (2 EA) in PKU FEL (replacing now w/ two new 9-cells).
     - ➢ 1 ys LG 5-cell (2 EA) in CEBAF C50-13 (module w/ 8xLG in progress).

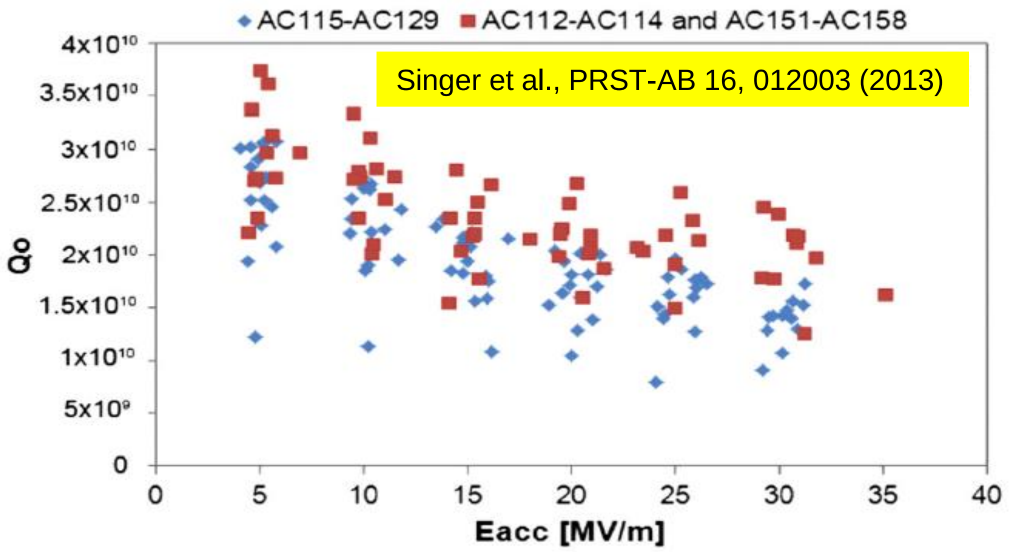
		TESLA	Low-loss/ICHIRO	Low-surface-field	CEBAF upgrade LL
frequency	MHz	1300	1300	1300	1497
# of cells	-	9	9	9	7
Aperture	Mm	70	60	60	53
Epk/Eacc	-	1.98	2.36	1.98	2.17
Hpk/Eacc	mT/(MV/m)	4.15	3.61	3.71	3.74
Cell-cell coupling	%	1.90	1.52	1.27	1.49
G*R/Q	Ω^2	30840	37970	36995	36103



Backup: A Few Words About LG Nb

- The idea of LG Nb introduced at JLAB in 2004.
- Subsequent world-wide development reviewed by Kneisel et al, NIM-A 774 (2015)133-150.
- LG Nb also known as “ingot Nb”.
- Initial motivation of LG Nb: save cost, arising from the effect of eliminating steps in producing Nb sheets by ingot slicing.
- Initially high purity (high RRR), now active work on “not so high purity” (medium- or low- RRR).
- <u>LG Nb in this talk referred to high-purity for best insurance of high gradient, as is well understood</u>.
- Observation of higher Q_0 at high gradient as compared to FG Nb similarly processed with ILC-style TDR baseline recipe and tested in identical facilities at JLAB and DESY.

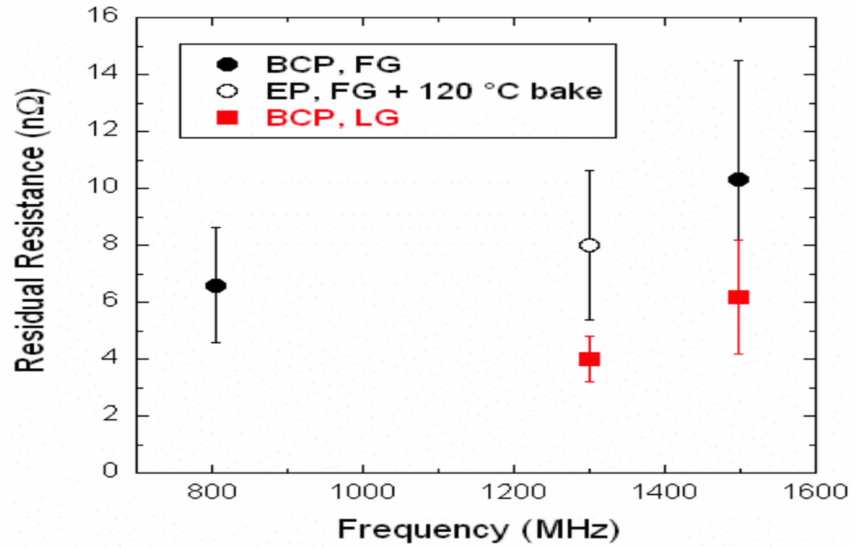




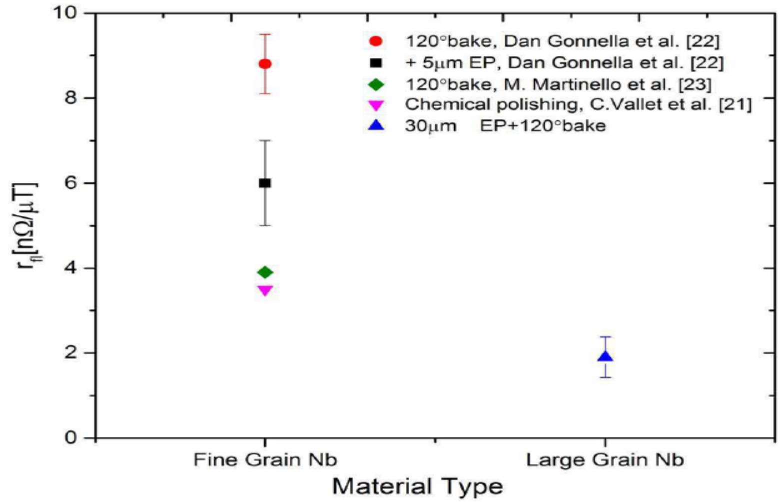
Jefferson Lab

Backup: A Few Words About LG Nb (cont.)

- The reason for observed higher Q_0 is understood.
  - ✓ Lower residual resistance
    - ➢ Ciovati, Kneisel, Myneni, AIP Conference Proceedings, 1352, Melville, NY(2011).
  - ✓ Deeper understanding for lower residual resistance: lower sensitivity to trapped flux
    - ➢ Huang, Kubo, Geng, PRAB 19, 082001 (2016).
- Further observation of stable surface resistance in LG Nb cavities against repeated quench
  - —Geng, Huang, WEPMR033, IPAC2016 (2016).
- Very large Q_0 at 1.8 K, optimal temperature at 1.9K for LG Nb?
  - —Singer et al., AIP Conference Proceedings, 1352, Melville, NY(2011).
  - — Kostin, Sekutowitz, TTC at Milan, Feb 6-9, 2018.



Ciovati et al, AIP Conf. Proc. 1352, Melville, NY(2011)



Huang, Kubo, Geng, PRAB 19, 082001 (2016)