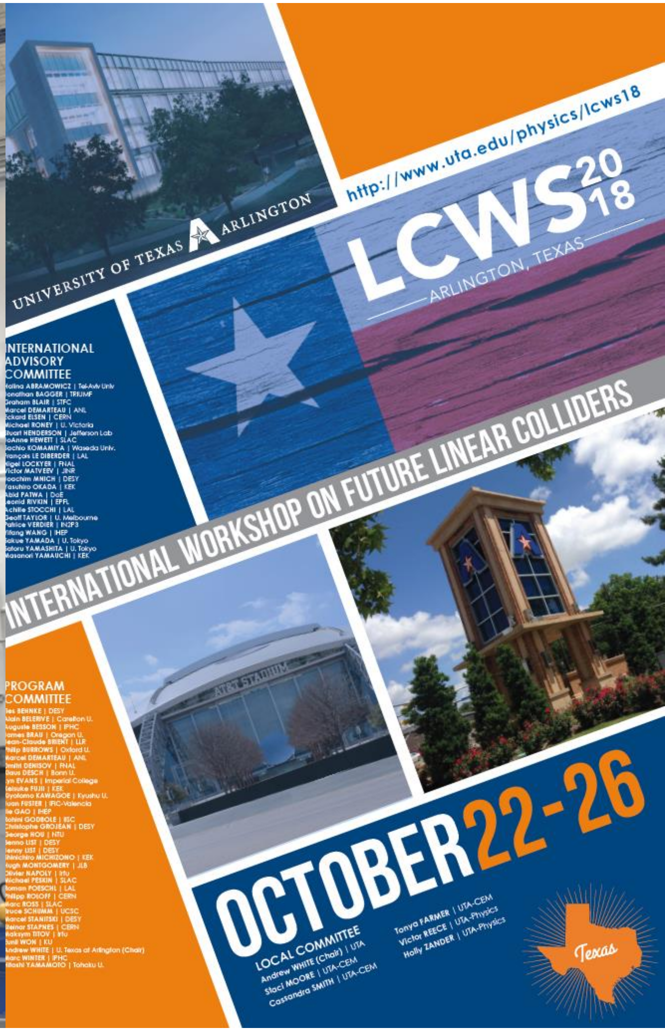
Low-Surface-Field (LSF) Shape Cavity Development: Recent Results and Future Plan

High-Efficiency High-Gradient SRF Development

JLAB-KEK Collaboration Supported by DOE

under US-Japan HEP Cooperation Program: Advanced Accelerator Technology

Rongli Geng, JLAB
Hitoshi Hayano, KEK
Zenghai Li, SLAC

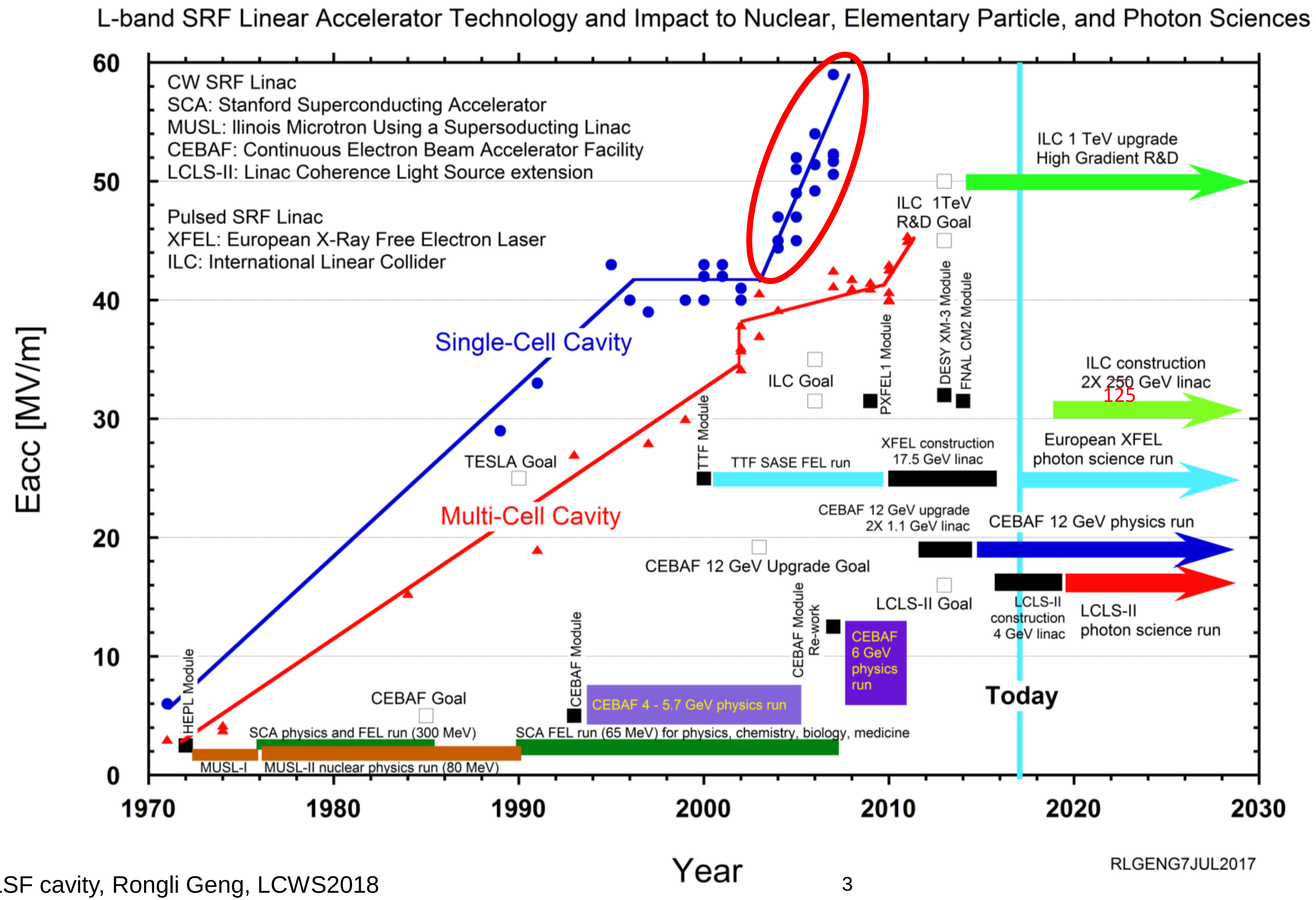


Jefferson Lab

Outline

- Long march of SRF technology and success brought by new cavity shapes in realizing 50-60 MV/m gradient
- Challenge met by new shapes when applied to 9-cell cavities
- LSF emerged as a good shape and LSF shape cavity development
- Material choices for LSF shape cavities
- First sight of 50 MV/m in 5-cell cavity LSF5-1 and next step
- 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

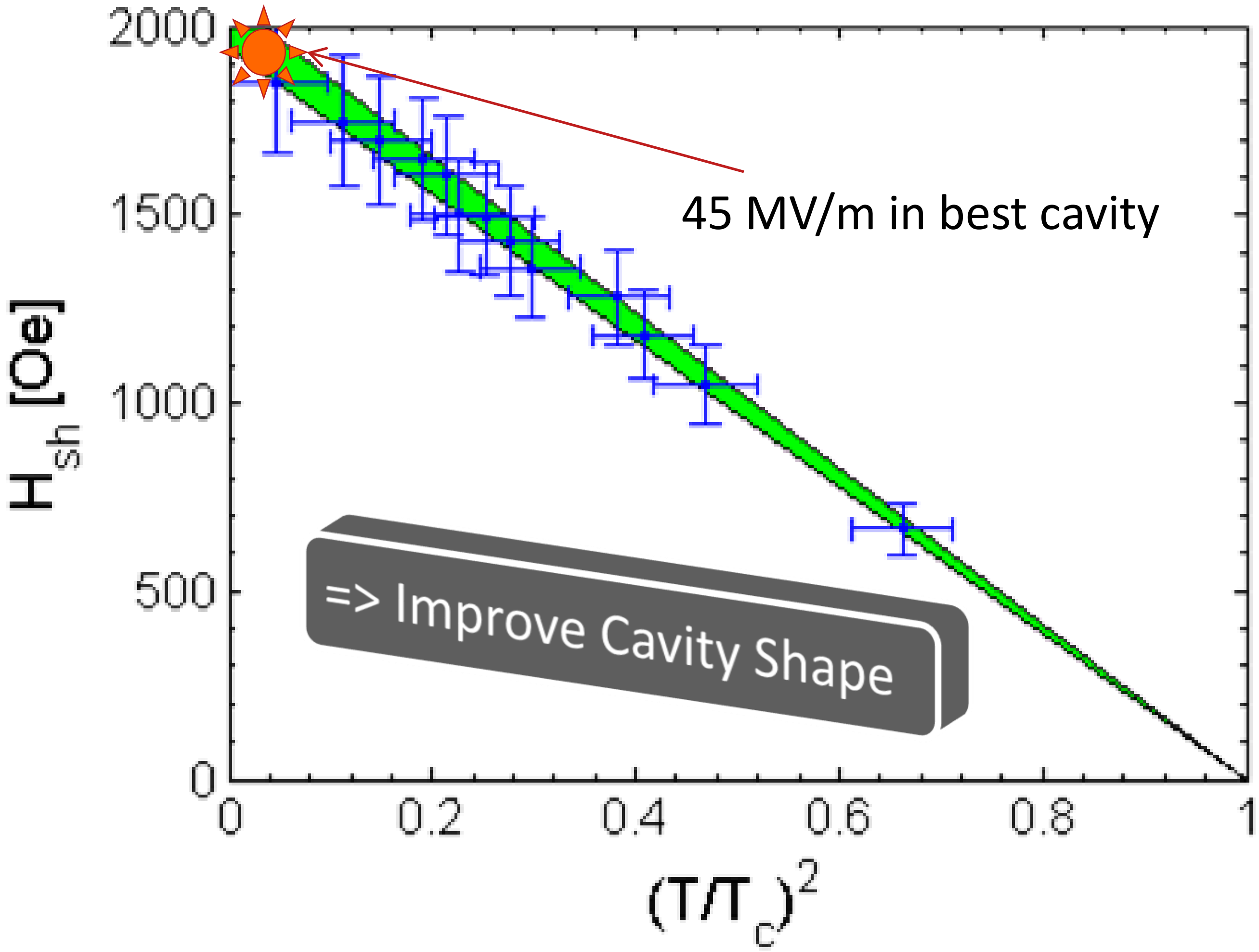
EBW, EP

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, HPR, elliptical shape

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

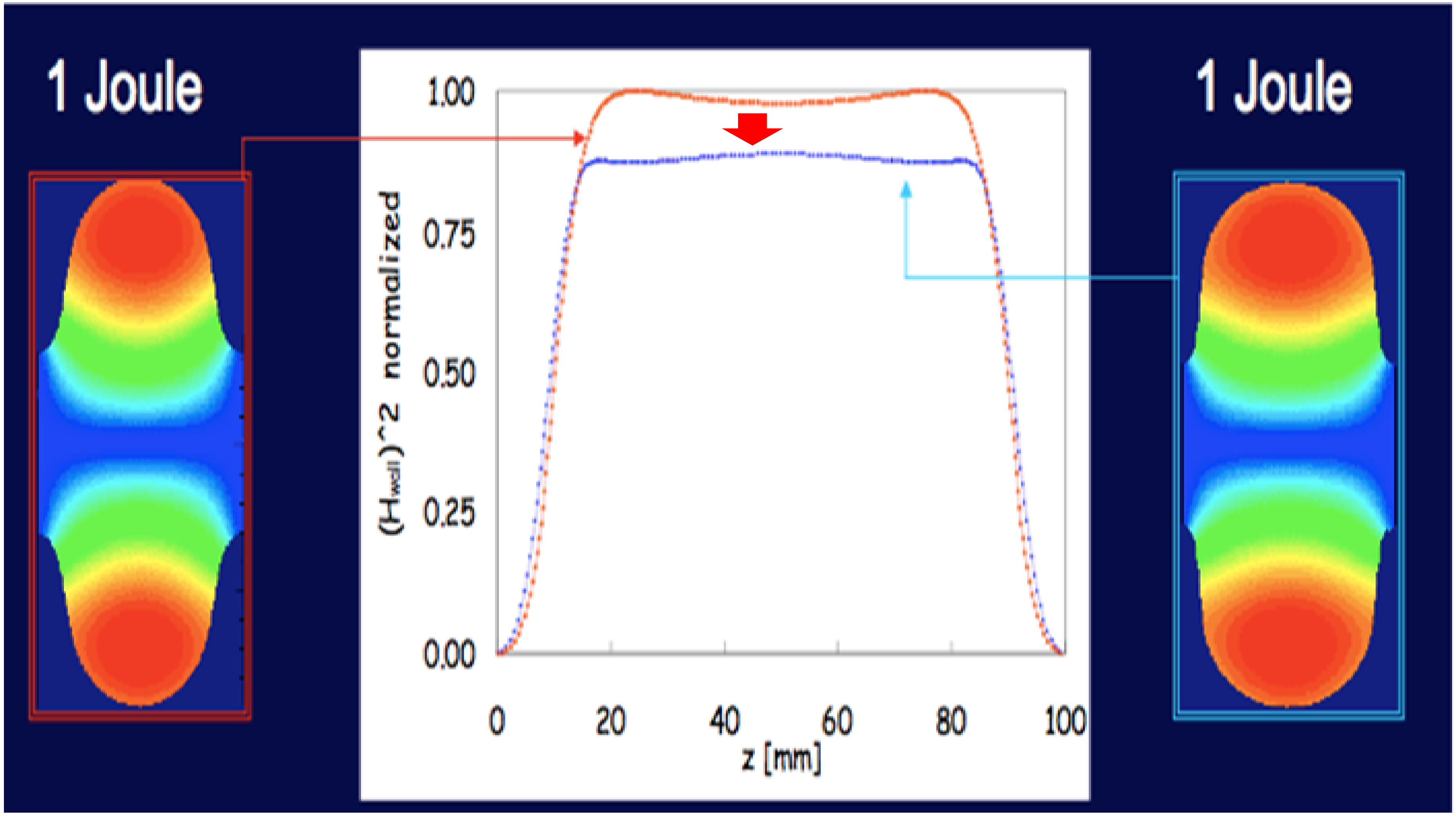
The Physics



Max surface surface magnetic field reached with TESLA-shape cavities is close to "theoretical limit" Fundamental RF Critical Field ($H_{superheating}$) Measurement

Hasan Padamsee, LCWS2015, Whistler, Canada.

The Approach



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

Courtesy J. Sekutowicz

The Commitment

SMTF Mtg@Jlab "KEK" view - N.Toge (Sep.30, 2004)

45MV/m issues

- With the known H(rf) limit ~ 1750 Oe, with suitable (i.e. non-crazy) cavity shaping, Eacc ~ 50MV/m appears to be within our reach.
- Hence, shoot for 45MV/m goal.
- Adequate cavity shape + careful surface treatment.

JLab-style LL cavity-shaped half cells x 4 (Nb, 4mm-t)

KEK

PUSHING the LIMITS of RF SUPERCONDUCTIVITY

September 22-24, 2004
Argonne National Laboratory

Workshop Chair: Kwang-Je Kim
Scientific Program: Helen Edwards, Kwang-Je Kim, Hasan Padamsee
Workshop Coordination: Cathy Eyberger (chair), Kelly Jaje, Renee Lanham

The Workshop will be held in Conference Room A of the Argonne Guest House.

Cornell

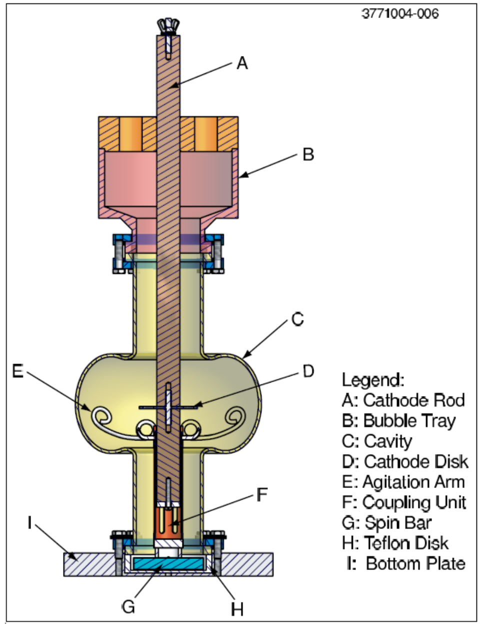


FIGURE 2. Vertical Electropolish of a single-cell niobium cavity.

CONCLUSIONS

The results of these experiments demonstrate that the accelerating gradient can be improved by reducing the H_{pk}/E_{acc} ratio. Exploration in this direction is thus warranted. A new RF design has already shown that H_{pk}/E_{acc} can be further reduced to 35 Oe/(MV/m) by reducing the iris diameter to 60 mm.

The achieved 44.4 MV/m represents the highest accelerating gradient ever realized in a niobium RF resonator although field emission is strong. Q_0 remains $> 10^{10}$ up to $E_{acc} = 35$ MV/m. Further improvement into the regime of 50 MV/m can be anticipated by additional surface treatment.

The current optimization prerequisite of maintaining a large iris diameter results a penalizing higher E_{pk}/E_{acc}. Not surprisingly, excessive field emission was observed. But field emission was found to be not responsible for the gradient limit. The high peak surface electric field ($\sim$ 100 MV/m) on a broad area in CW mode is believed to impose no fundamental limit, but further tests are needed to carefully examine its effect.

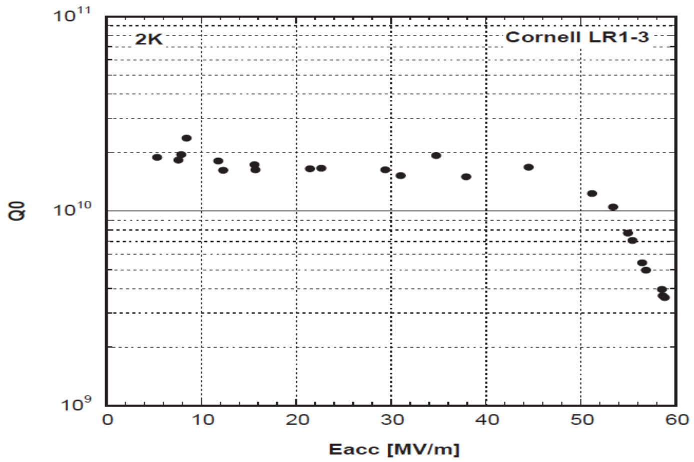
https://publications.anl.gov/anlpubs/2005/04/52906.pdf

The Outcome: 50 MV/m Vision Realized in 2007 following Five Years R&D

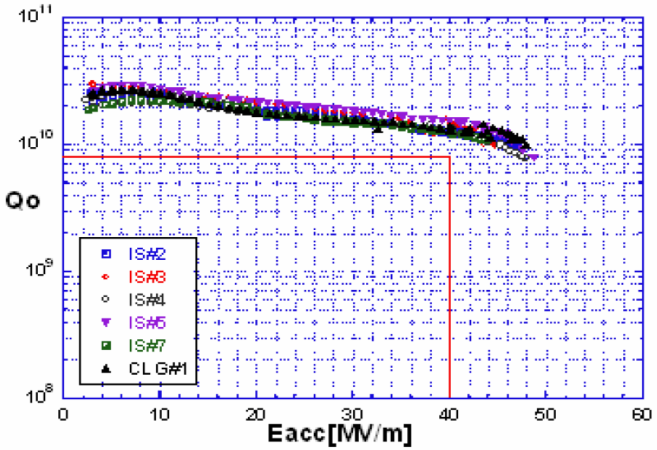
		TESLA	Low-loss/ICHIRO	Re-entrant
frequency	MHz	1300	1300	1300
Aperture	mm	70	60	60
Epk/Eacc	-	1.98	2.36	2.28
Bpk/Eacc	mT/(MV/m)	4.15	3.61	3.54

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

E_{acc} 50-60 MV/m Achieved



Geng et al, PAC2007



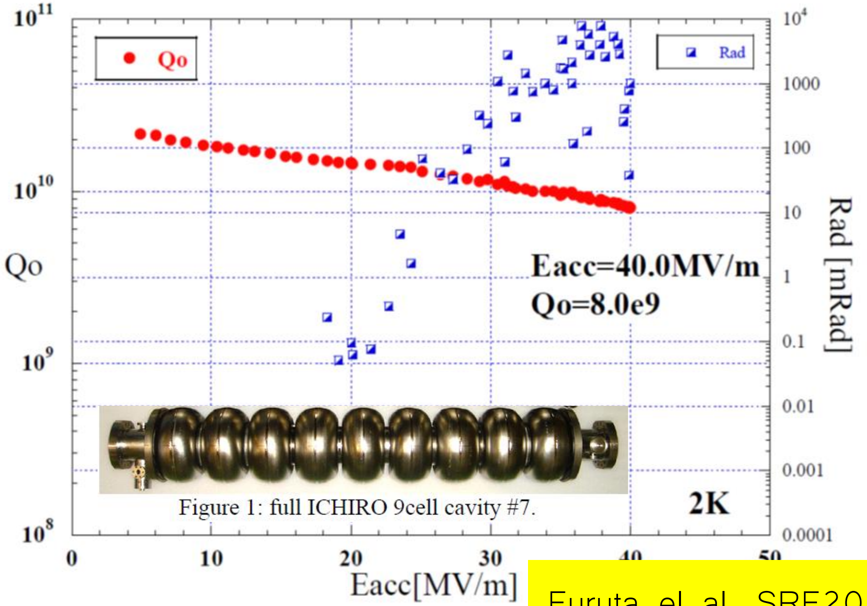
Furuta el al, SRF2007

- 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).

The Struggle: Challenges met 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!



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}.
  - E_{pk} 200 MV/m, small Nb surface at 2 K, Delayen, Shepard, APL, 57 (1990) 514.
  - E_{pk} 500 MV/m, X-band Cu at 45 K, Cahill, Rosenzweig, Dolgashev, Tantawi, Weathersby, PRAB, 21, 102002 (2018).
- 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.

Jefferson Lab

The New Deal: 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.

The New Approach: LSF + LG Nb Chosen at JLAB in 2013

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

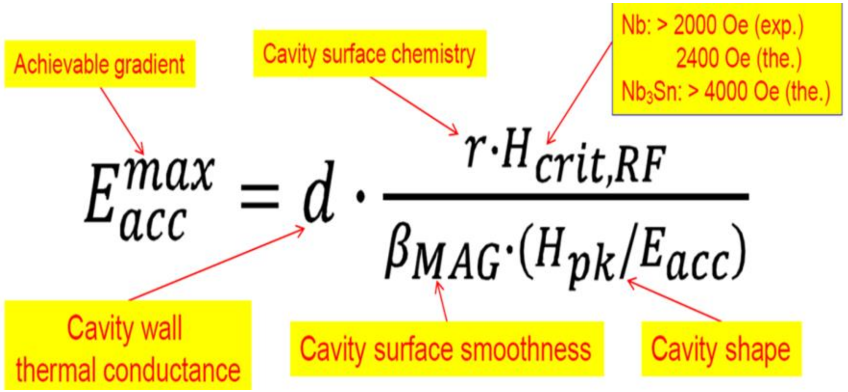
- Standing on the solid ground of ILC TDR, and in recognition of
  - Clear knowledge in cell shape properties.
  - 10-year's global experience in new shape cavity prototyping and testing since 2003.
  - Observation and understanding of higher Q_0 in LG Nb cavities in 2011-2013.

- A new approach at JLAB driven by fundamental R&D on high-efficiency high-gradient SRF cavities to reduce the ILC project risk and cost by:
  - Increasing the gradient margin
  - Increasing the efficiency (shut impedance and Q_0)

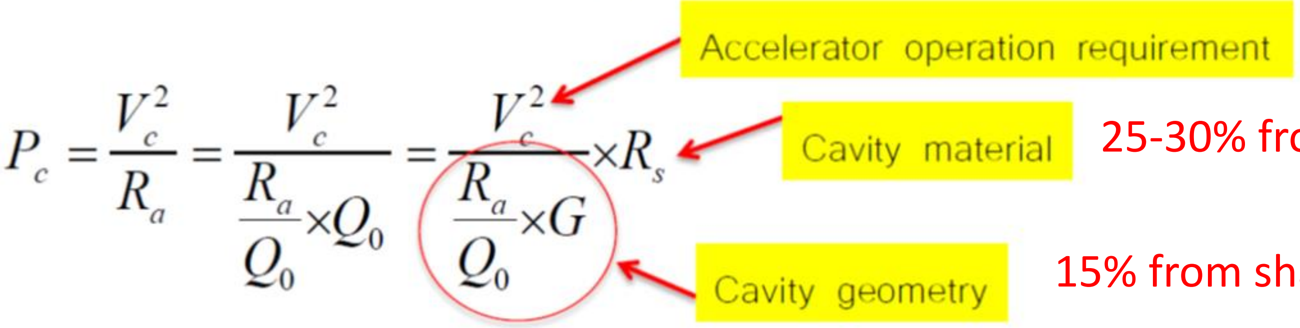
LSF shape + LG Nb (high purity) + EP

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

- 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 underpinned by selected shape & material



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



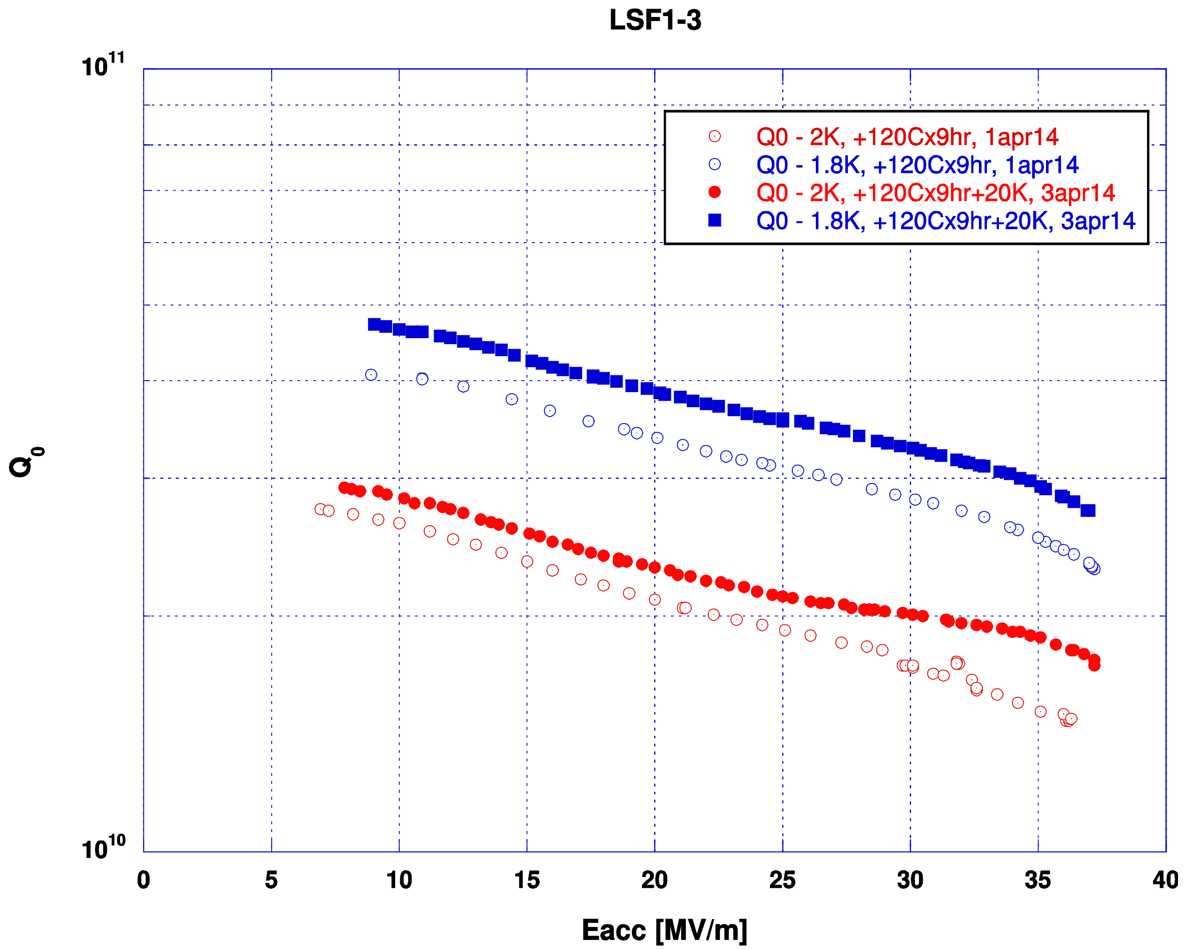
25-30% from material

15% from shape

40-45% better efficiency

Jefferson Lab

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

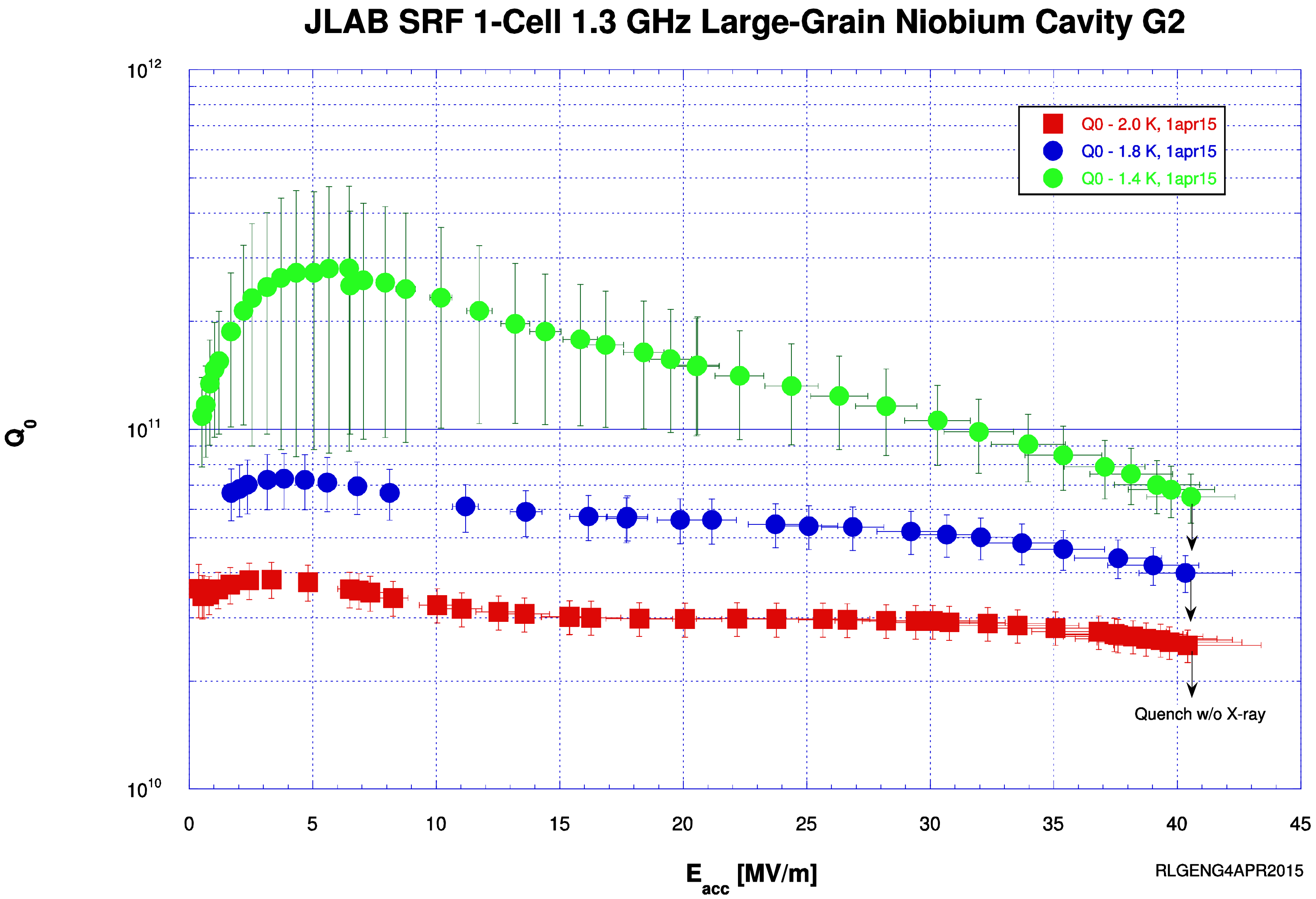


Collaborators: JLAB, PKU, SLAC

Geng et al., IPAC2015 (2015)

- 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.

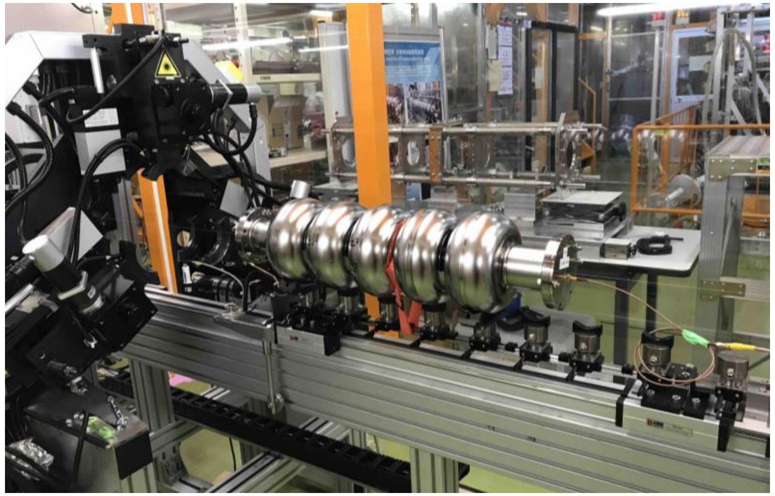
LG Nb Single-Cell Demonstrated Eacc 41 MV/m Q0 > 2E10@ 2K

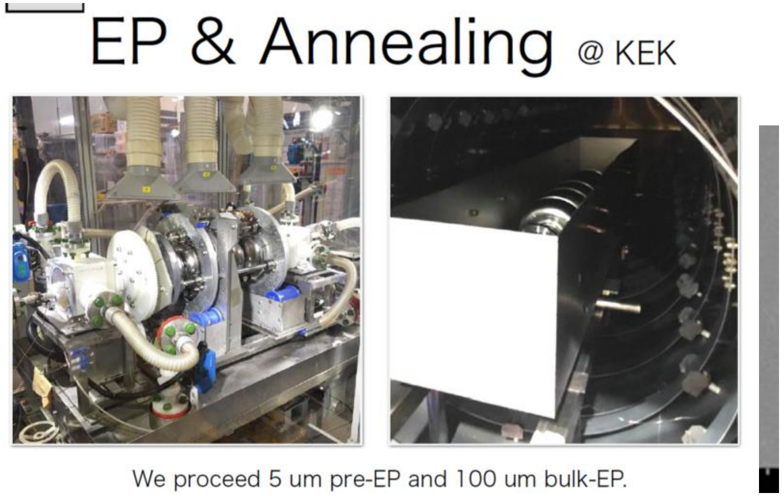


Geng et al., IPAC2015 (2015)

First multi-cell LSF cavity

- Mar 2016, LSF5-1 completed at JLAB with in-house fabrication tools supported by US-Japan collaboration fund
  - Fine-grain Nb (to allow comparison with TESLA & LL/ICHIRO)
- Oct – Dec 2017, cavity shipped to KEK where tuning, EP, and furnace annealing was carried out
- Feb – Apr 2018, final prep and first RF test at JLAB with KEK collaborator participating
- First result: Eacc 30 MV/m Pi mode, center cells 36-38 MV/m.
  - Limited by PBME and end group heating





Jefferson Lab

Lessons Learned from First Tests

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

- 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.

- Missing the 0.5 inch length in beam tube has consequence!
  - Action: Add 0.5 in ring in beam tube

- End cell field emission
  - Action: Test stand re-cleaning

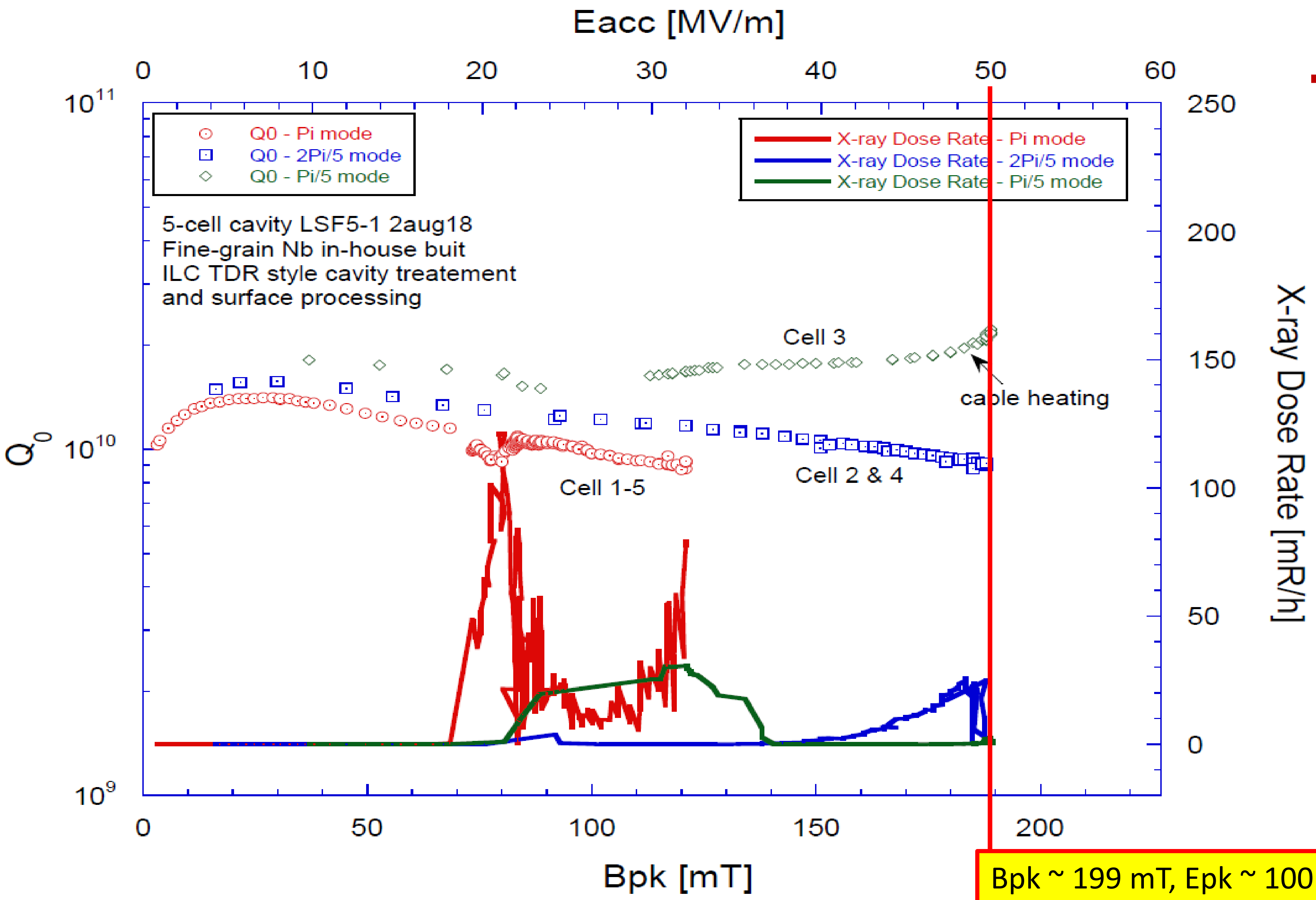
Actions in June – August, 2018 since ALCW'18 in Fukuoka

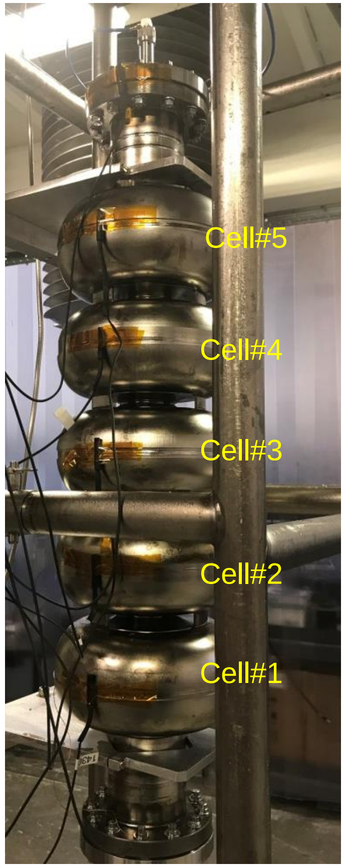
- 0.5 inch ring added at each beam tube.

- New cycle of final surface processing as per standard ILC procedure
  - New electrolyte mixed following sulfuric acid flushing
  - 20 um EP in optimal condition QA by continuous current oscillation
  - Ethanol rinse, Ultrasonic cleaning (2% Liquinox), immediate HPR (2 passes)
  - Field flatness tuned to 96%

- RF test without 120C bake
  - PBME observed again but overcome
  - Then high-field Q-slope observed (expected)
  - Very small field emission induced X-rays

- Then 120C bake for 48 hours, then re-test





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

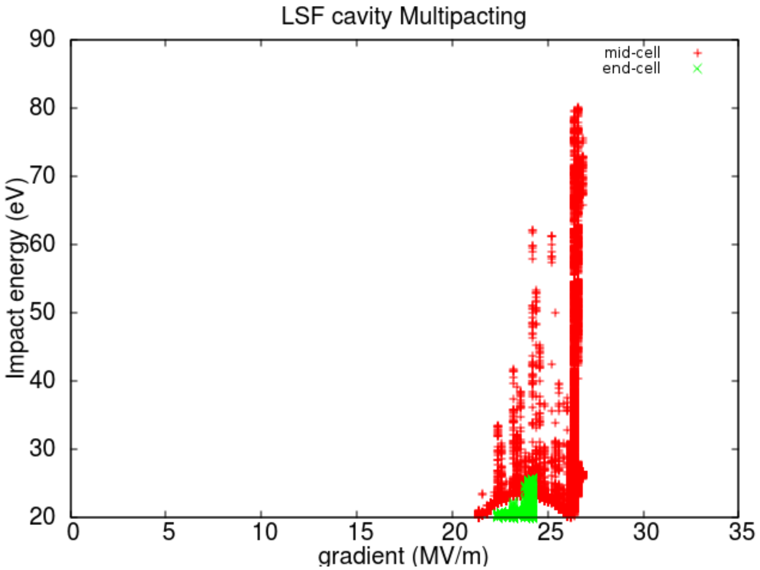
Understanding LSF5-1 Tests Results and Actions for Next Step

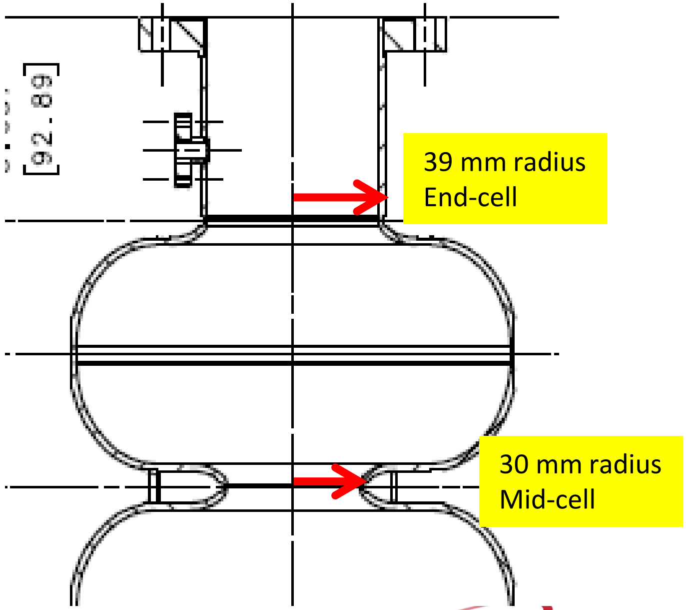
- High gradient reach 50 MV/m by three inner cells confirmed high quality equator weld, bulk EP and final EP processing.

- Small X-ray at Epk ~ 100 MV/m in center cells confirmed the adequacy of final HPR, assembly and pump down process and the test stand re-cleaning paid.

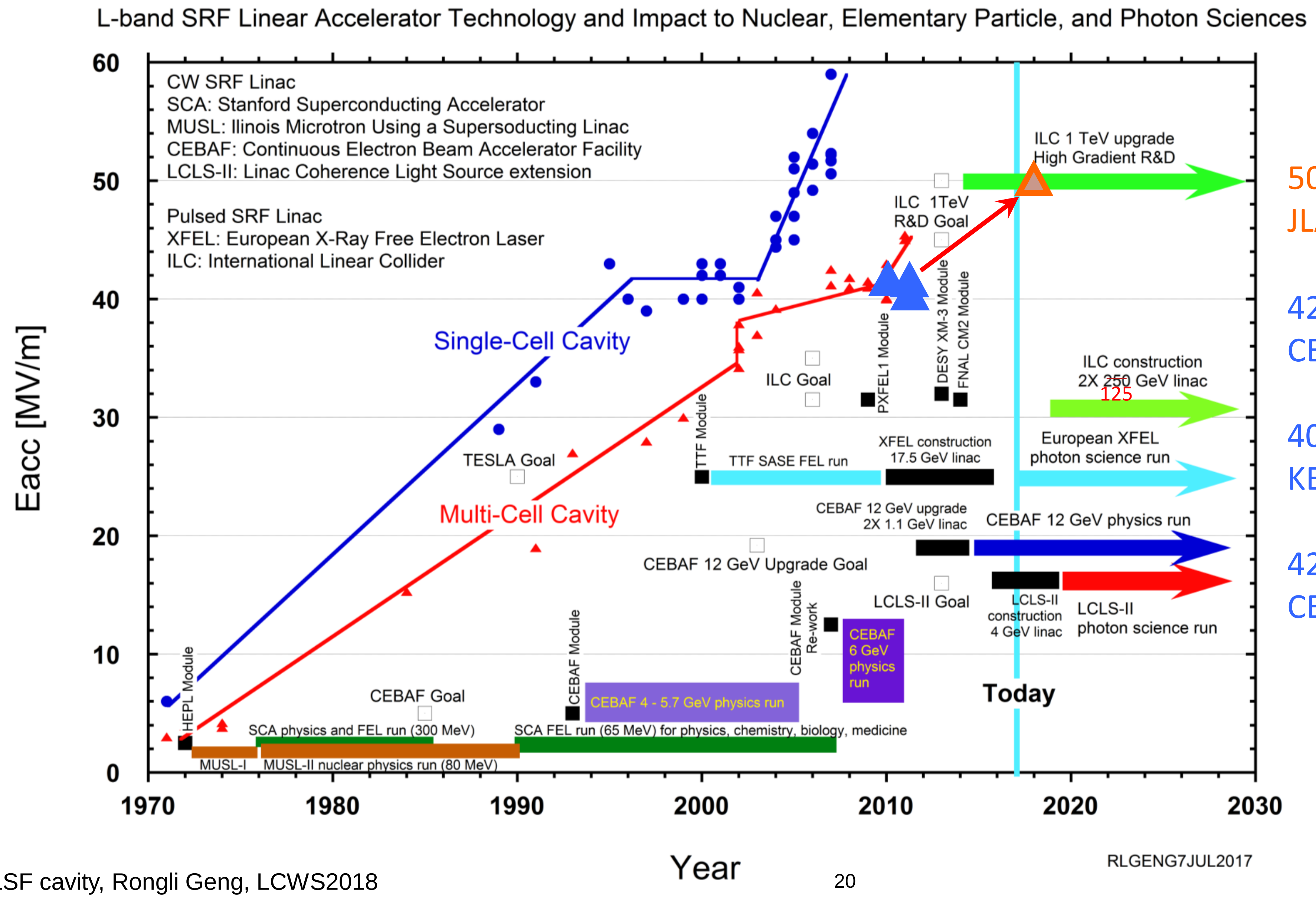
- Major issue at hand: understand and raise end cell limits
  - MP ruled out as per new calculation
  - Hydrocarbon from RGA - new procedure in place
  - Slow pump down (15 mm elbow) – re-characterized and upgraded
  - "critical distance" of HPR water jet – new nozzle and wand head
  - Re-introduce end group wiping procedure

- Next step: re-test after new prep cycle with enhanced end cell cleaning





Long March Continues – A Step Forward to useful 50 MV/m by Cavity Shaping



50 MV/m, LSF 3/5 cells @ JLAB
JLAB-KEK-SLAC collaboration, 2018

42 MV/m, LL002 @ JLAB
CEBAF 12 GeV prototype, 2010

40 MV/m, ICHIRO 9-cell @ JLAB
KEK-JLAB collaboration, 2011

42 MV/m, C100-RI-006 7-cell
CEBAF 12 GeV Upgrade, 2011

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. Boosted by new DOE support under US-Japan collaboration.

- First sight of 50 MV/m in 3 out of 5 cells 5-cell cavity LSF5-1 (FG Nb). Several steps are being taken for enhanced end cell cleaning before a re-test.

- The first LSF 9-cell (FG Nb) is to be completed in FY19. Will then seek LSF 9-cell (LG Nb).

- While on the one hand, this work is driven by our interest in R&D on high-efficiency high-gradient SRF aiming for shifting performance frontier beyond 50 MV/m in full-scale 9-cell cavities,

- There is, on the other hand, a practical motivation of shifting ILC project risk in the right direction (fraction of quench limited cavities still large, see XFEL cav. data analysis, Walker, TTC at CEA Saclay, July 5-8, 2016).
  - 11% more margin in gradient.

- 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.

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

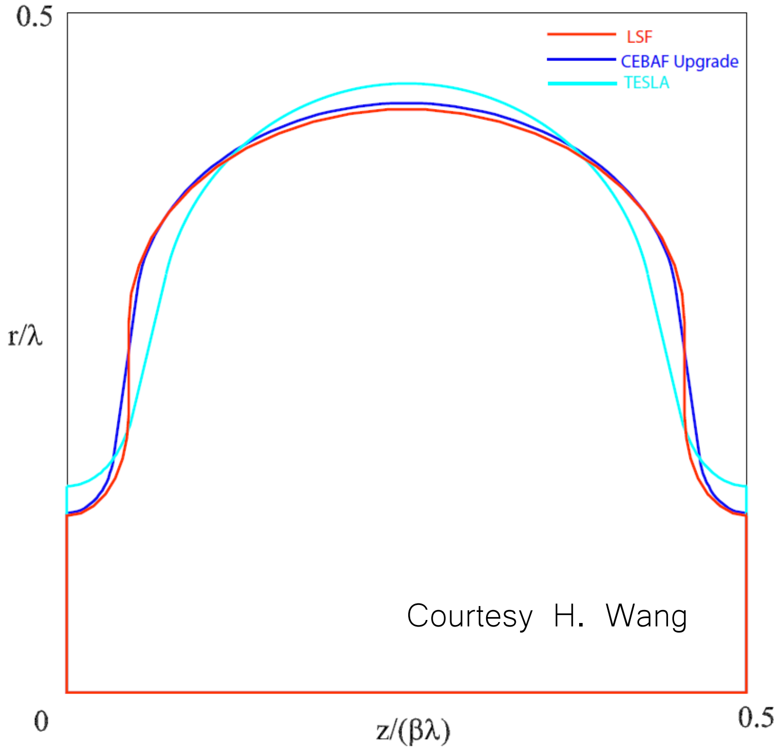
1. Solid knowledge and understandings.
   - ✓ Shape properties, aperture compatibility w/ beam*.
   - ✓ Proven ILC-style TDR baseline surface processing.
   - ✓ Origin of LG Nb's superior Q_0.

   * Zagorodnov, Solyak, EPAC06, THPCH037 (2006)

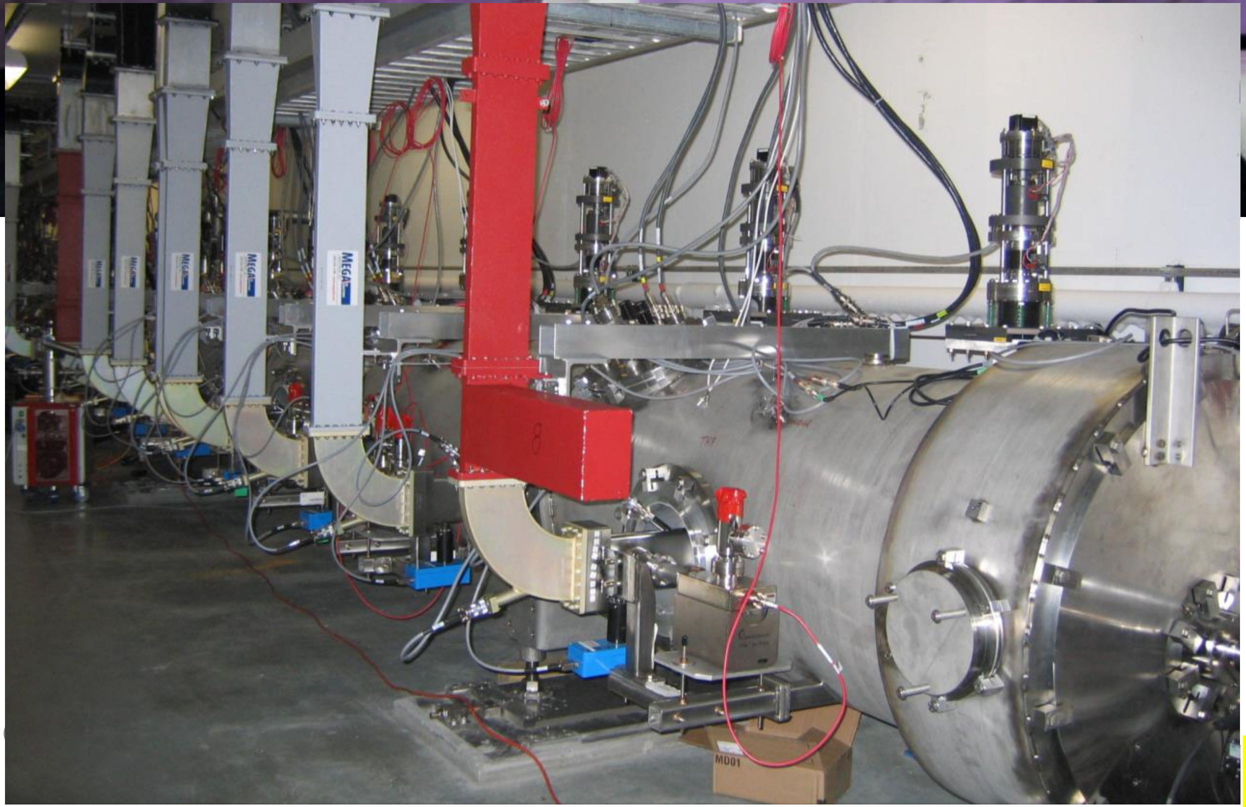
2. Extensive experiences.
   - ➢ Cornell: ~10 year on RE.
   - ➢ KEK: ~ 10 years on LL/Ichiro.
   - ➢ JLAB: 15 years on LL (CEBAF) + 5 years LSF.

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
Bpk/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: Low-Loss Shape Cavity Accelerating Beam



LSF cavity, Rongli

Table 2: C100 Commissioning Results

Cryomodule No.	Commission in CEBAF (MeV)	Operation with Beam (MeV)
C100-01	104.3	94.5
C100-02	109.6	108
C100-03	118.4	Jan 2014
C100-04	105.8	Jan 2014
C100-05	109.9	Jan 2014
C100-06	108.2	Jan 2014
C100-07	108.4	Jan 2014
C100-08	Oct 2013	Jan 2014
C100-09	113.7	Jan 2014
C100-10	109.8	Jan 2014

J. Hogan et al., PAC2013,