Cavity Process
and
General R&D Plan and Proposal

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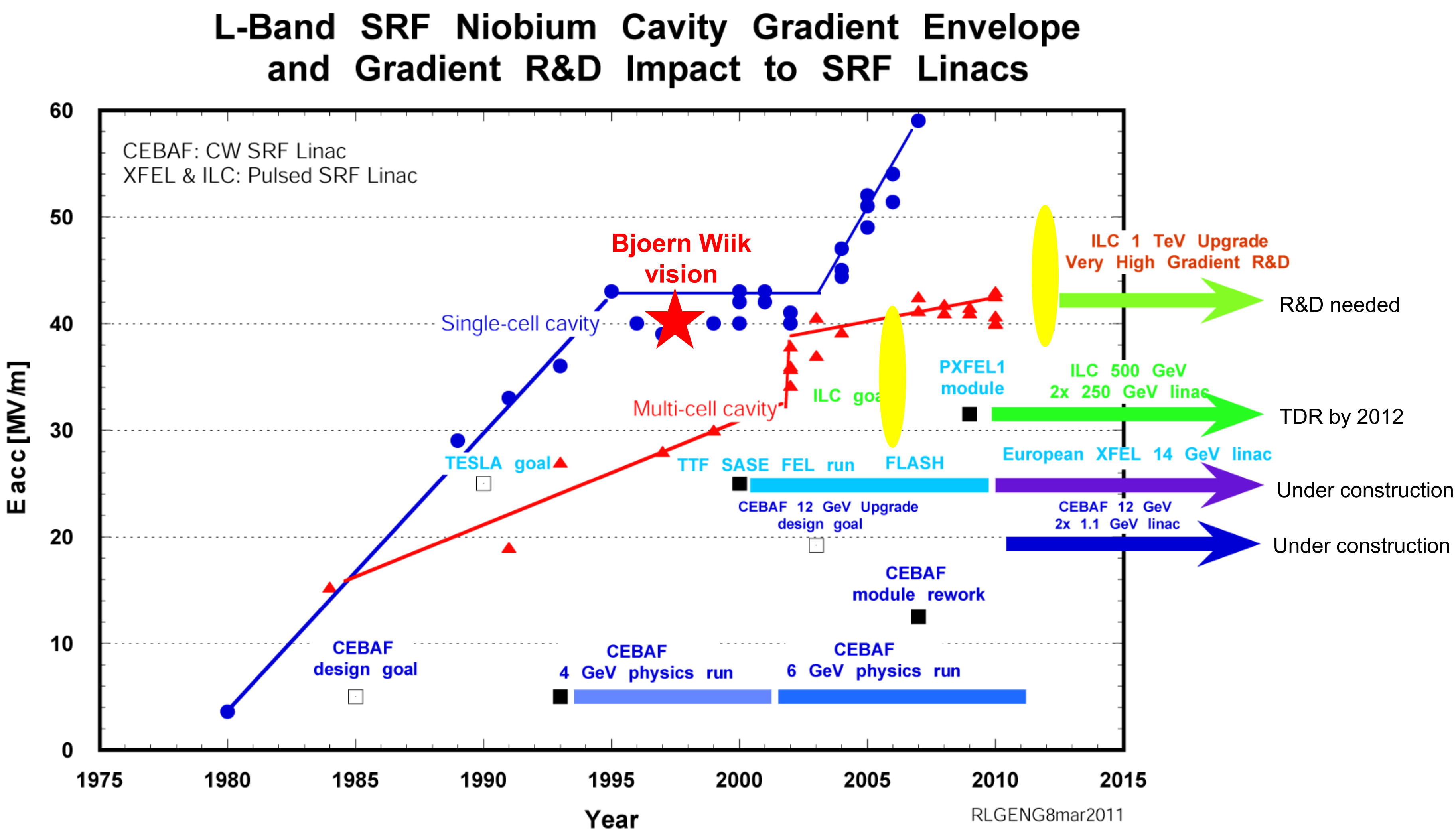
Outline

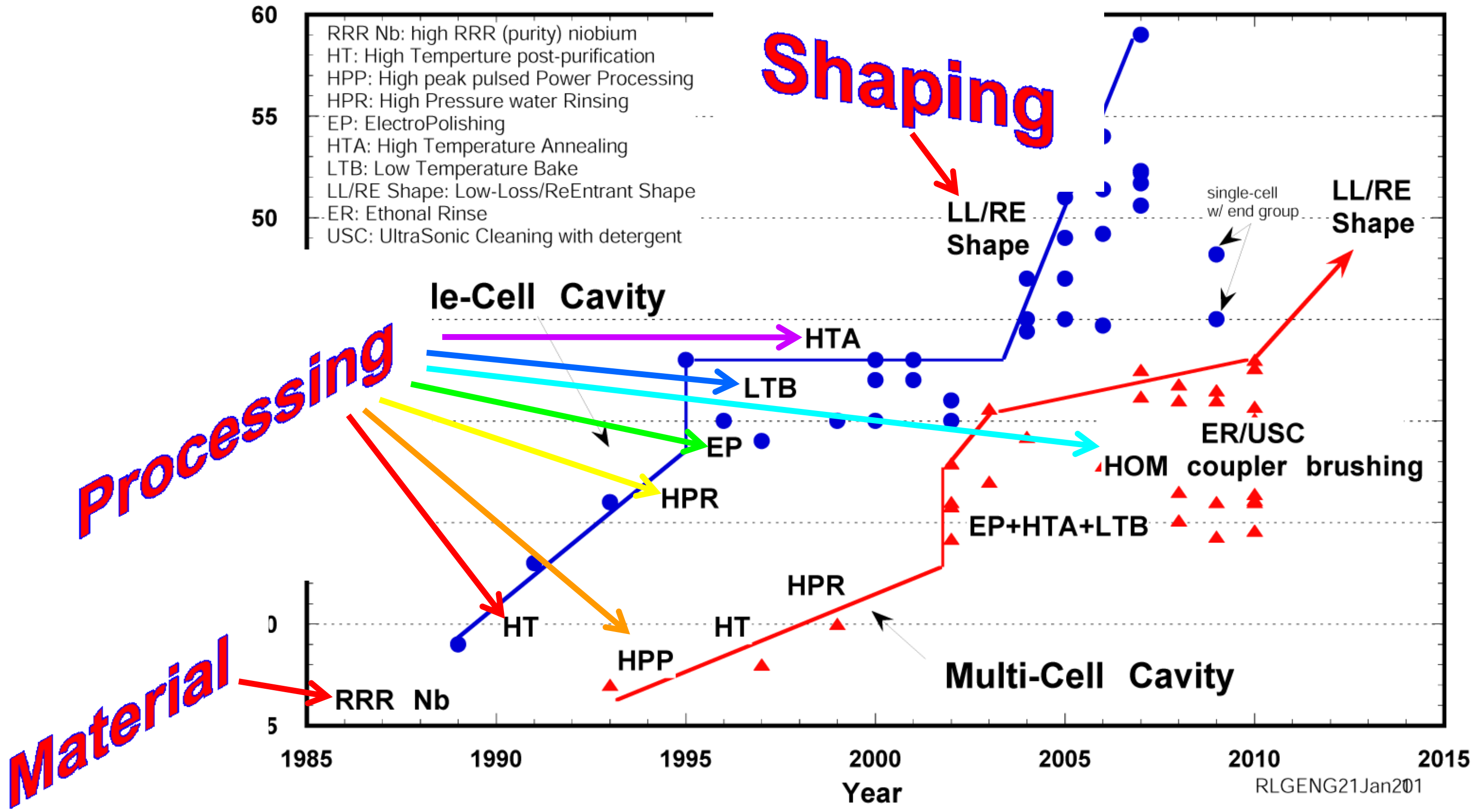
- **SRF cavity gradient frontier**
  - Cavity gradient progress and impact to SRF electron linacs
  - SRF cavity gradient R&D and technology innovation
  - State-of-the-art gradient results
  - Baseline ILC Nb cavity processing procedure
  - High gradient SRF cavity R&D impacts and benefits
- **Main issues at very high gradient**
  - Field emission
  - Q drop
  - Quench limit
  - Economics from linac system point of view
- **R&D plan to support 1 TeV ILC upgrade**
  - Gradient, Q_0, and field emission R&D goal
  - Cavity R&D plan for pushing quench limit
  - Cavity R&D plan for raising Q_0
  - Cavity R&D plan for suppressing field emission
- **High gradient SRF cavity R&D beyond 2012**

SRF Cavity Gradient Progress



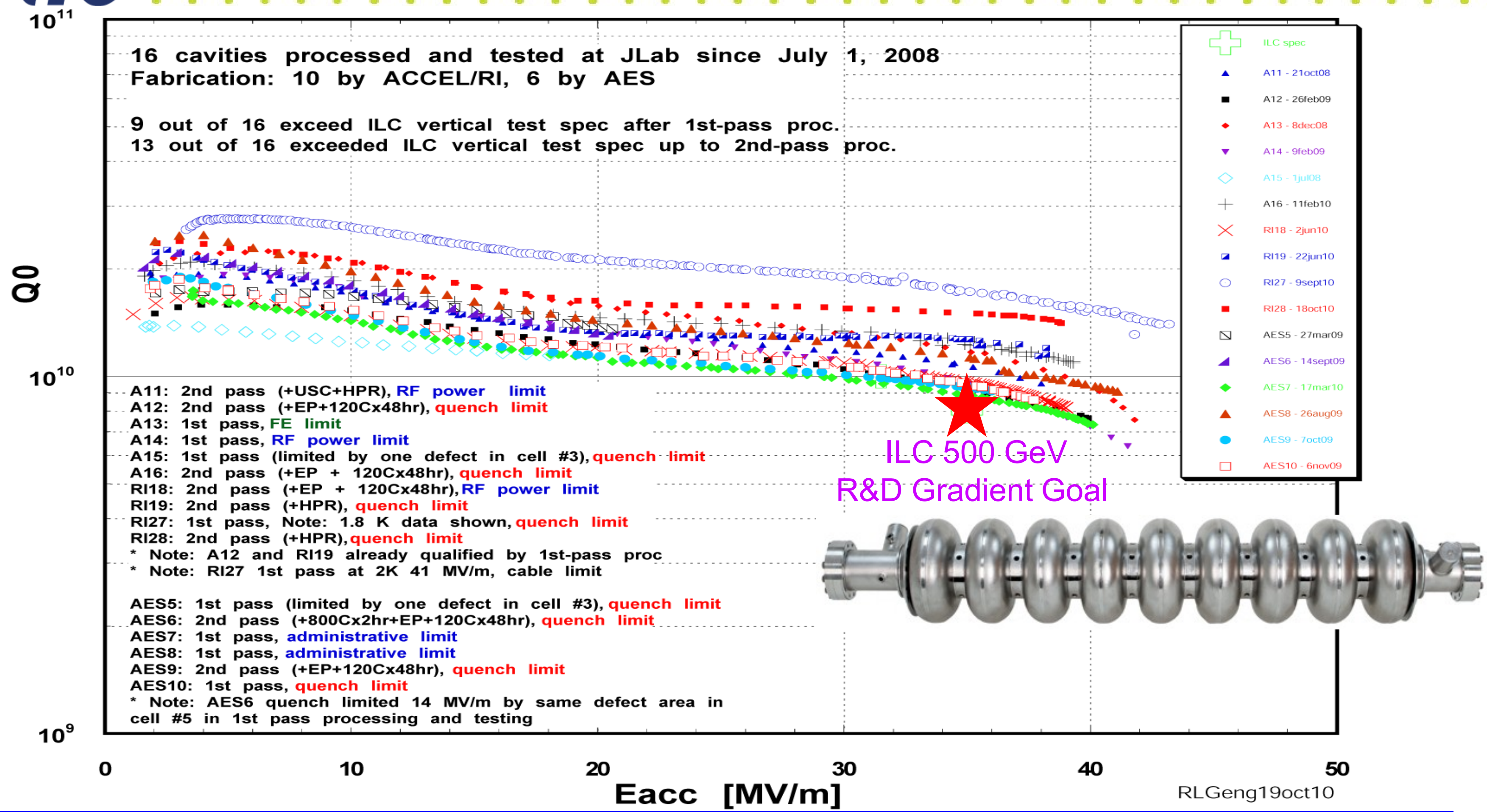
Steady progress in SRF cavity gradient makes SRF an enabling technology
SRF based electron linacs (CW & pulsed) have track record of successful operations

SRF R&D Behind Gradient Progresses



Understanding in gradient limits and inventing breakthrough solutions are responsible for gradient progresses. This has been a tradition in SRF community and rapid gradient progress continues. Up to 60 MV/m gradient has been demonstrated in 1-cell 1300 MHz Nb cavity. 45-50 MV/m gradient demonstration in 9-cell cavity is foreseen in next 5 years.

State-of-the-Art Gradient Results



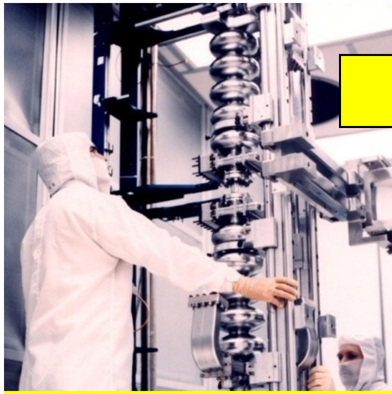
As a result of continued SRF cavity R&D at CERN, Cornell, DESY, JLAB, KEK, SACLAY and other labs, modern 9-cell TTF-style cavities increasingly exceed 35 MV/m at $Q_0 \geq 8\times10^9$. Gradient in the range of 40-43 MV/m demonstrated and confirmed independently in real 9-cell (and 7-cell) cavities, corresponding to a surface magnetic field of 160-180 mT.

Baseline ILC Nb Cavity Proc. Procedure

- Cavity manufacture (EBW) using RRR 300 Nb
- Initial light chemistry 5-30 μm (BCP)
- Heavy chemistry 80-150 μm (EP)
- Post-EP cleaning
- Vacuum furnace heat treatment 750-800 °C
- Light chemistry 20-50 μm (EP)
- Post-EP cleaning (ER/USC+HOM coupler brushing)
- Initial HPR
- Clean room assembly
- Final HPR
- Pump down
- 120°Cx48hr bake-out

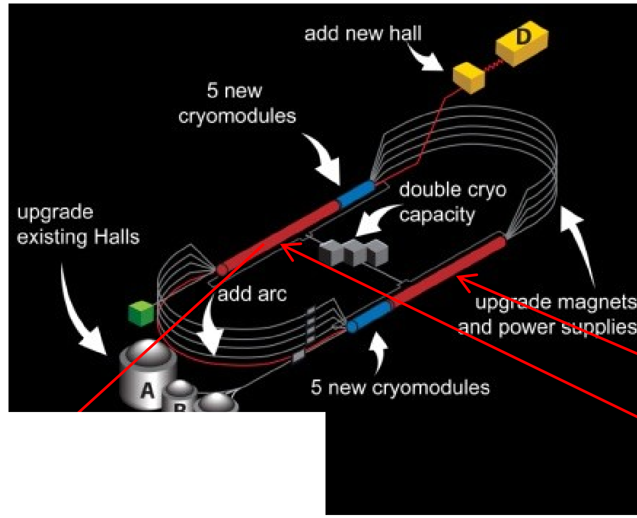
This processing procedure has been established in processing/testing facilities at DESY, JLAB, FNAL/ANL, KEK for 9-cell processing to > 35 MV/m. There is example of reproducible processing of 9-cell cavities to > 35 MV/m which is transferrable to industry.

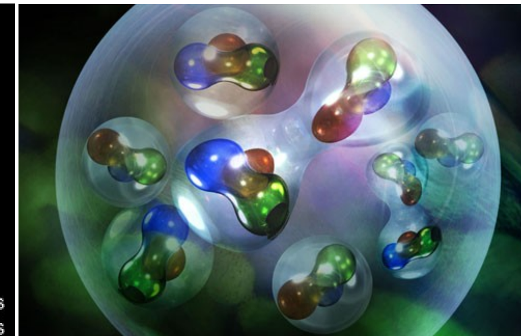
SRF Cavity Gradient R&D Impacts & Benefits

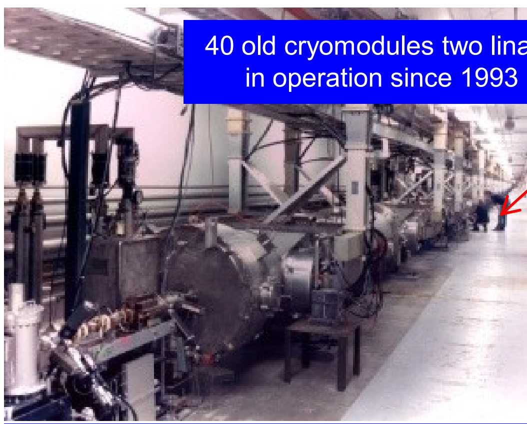


1991 (BCP)
Cryomodule cavity 5 MV/m
320 cavities installed in linacs

2011 (BCP+HTA+EP+HPR+LTB)
Cryomodule cavity 19.2 MV/m
80 cavities needed, many qualified to >25 MV/m, some up to 35-43 MV/m

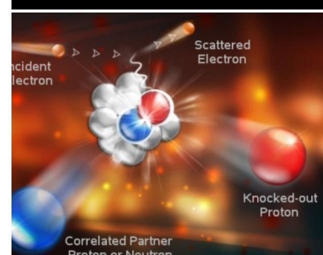


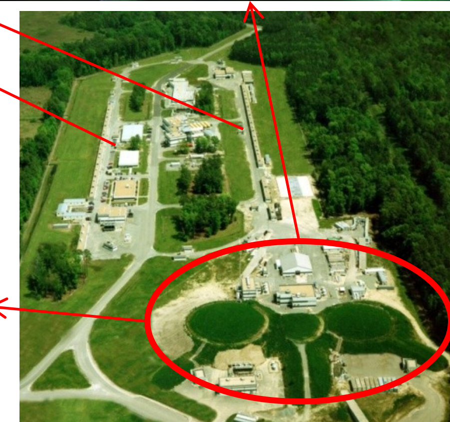




40 old cryomodules two linacs in operation since 1993

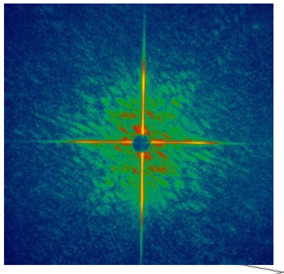
CW SRF Linac

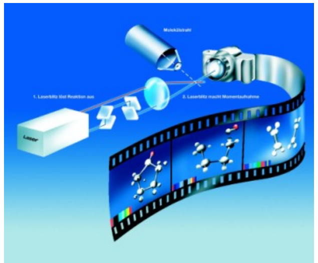


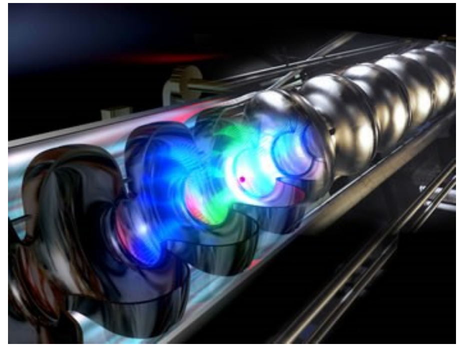


CEBAF upgrade, under construction now, will double its energy to 12 GeV. The present 6 GeV machine has 42 old cryomodules. The additional 6 GeV is achieved by adding only 10 new modules with high gradient cavities.

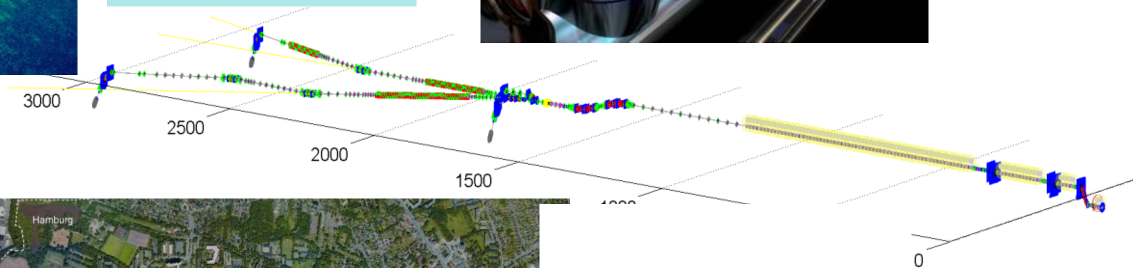
SRF Cavity Gradient R&D Impacts & Benefits







2011 (EP+HTA+EP/BCP+HPR+LTB)
Cryomodule cavity 24.3 MV/m
640 cavities needed
DESY qualified many cavities up to 35-43 MV/m



Pulsed SRF Linac

80 cryomodules needed

As a result of DESY's TTF experience and FLASH operation, European XFEL, under construction now, will reach 14 GeV with 640 high gradient cavities.

Photo courtesy Hans Weise of DESY

SRF Cavity Gradient R&D Impact & Benefits

ANL's 1st heavy ion QWR cavity EP in March 2011.
This is built on techniques developed for ILC.

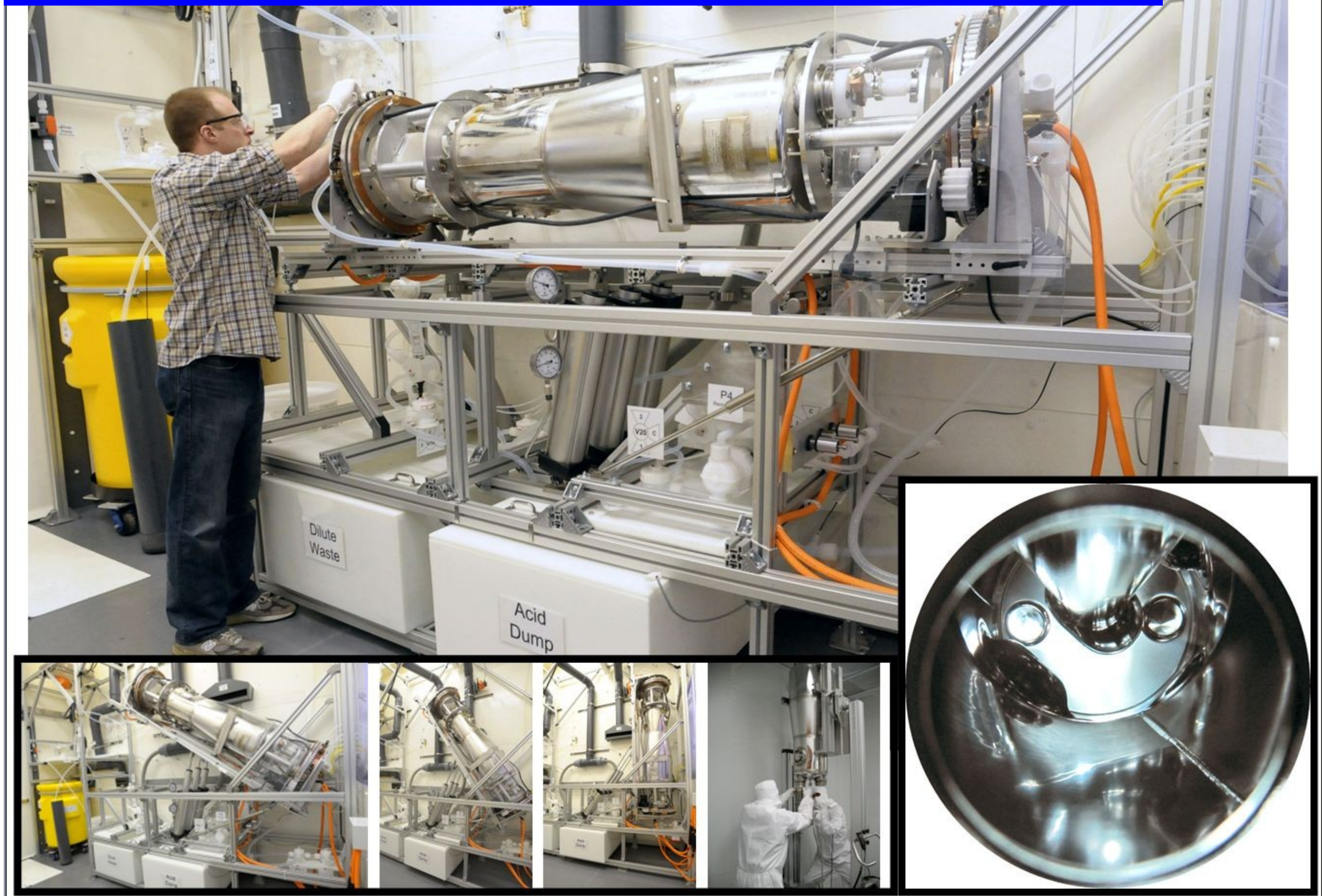


Photo courtesy
Mike Kelly of ANL

Main Issues at Very High Gradients (1)

Field Emission / Dark Current

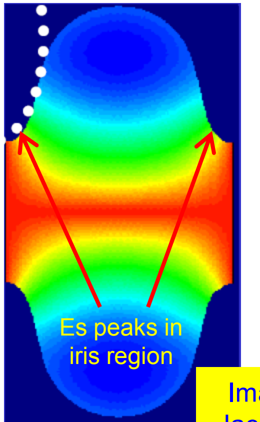


Image courtesy
Jacek Sekutowicz

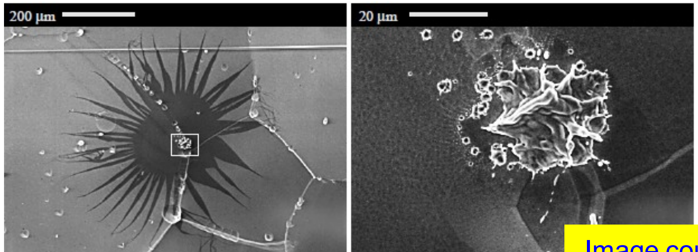
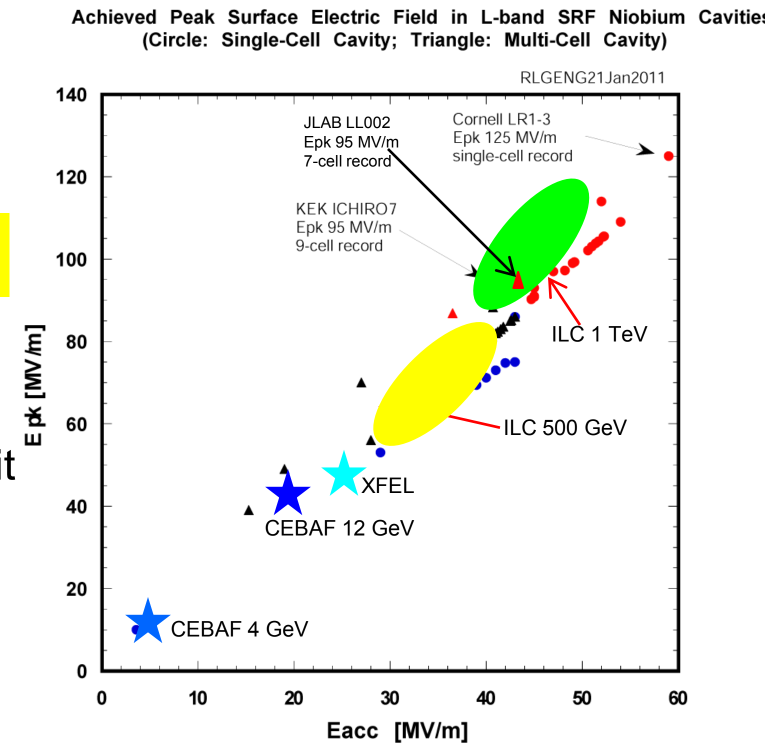


Image courtesy
Jens Knobloch

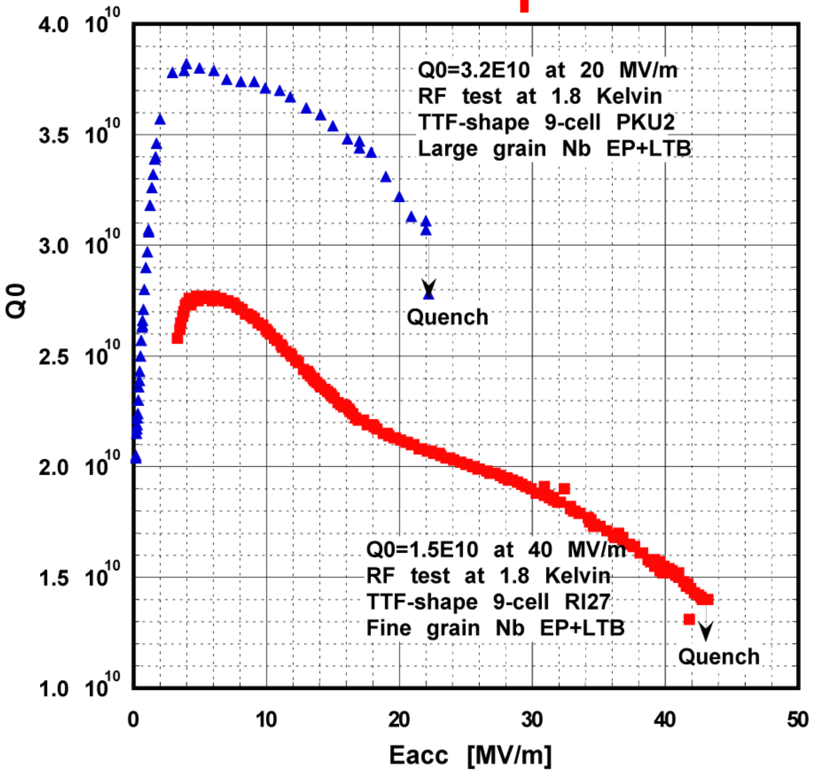


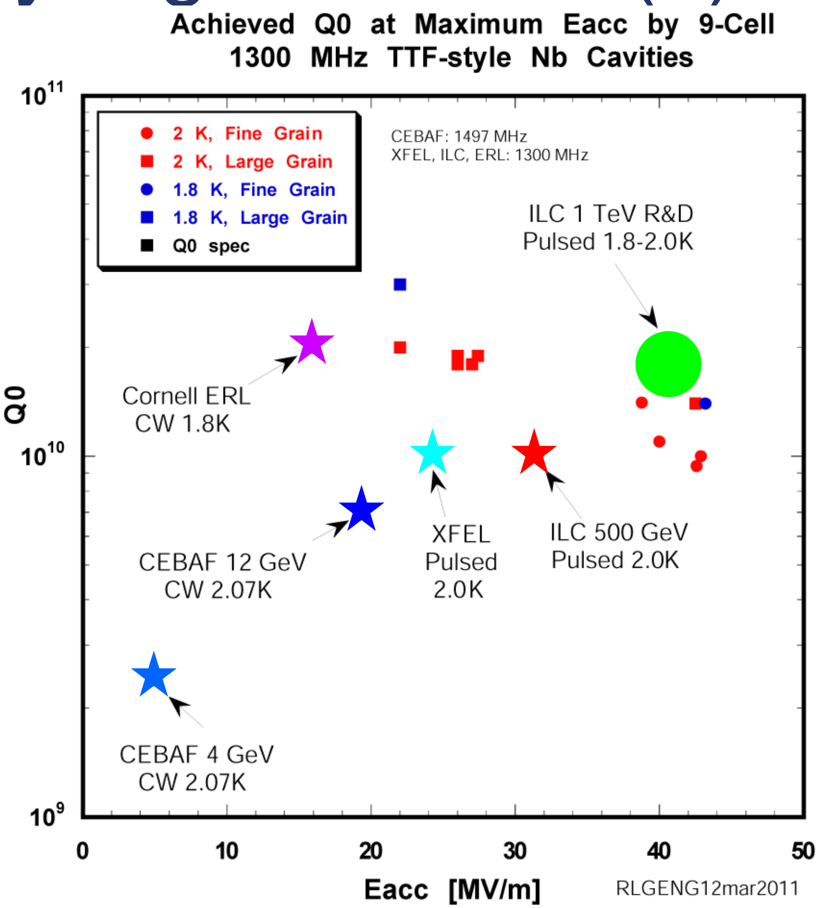
- Peak surface electric field (Epk) a governing parameter
- Physics fairly understood and no known fundamental limit
- Microscopic particles an important family of field emitters
- Epk 100-120 MV/m demonstrated in 1-cell Nb cavities
- Epk100-120 MV/m needed in multi-cell for ILC 1 TeV
  - Record Epk reached in 9-cell cavity 95 MV/m (KEK ICHIRO7)
  - Improved HOM coupler cleaning is necessary

Field emission is a known problem and has not been completely resolved, despite recent progress in post-EP cleaning advancement. Sudden field emitter turn-on in 9-cell cavities has been reported by almost all labs. Pushing Epk into 100-120 MV/m regime is necessary for reaching Eacc 40-45 MV/m. It is most likely new processing technology needs to be applied besides HPR. Promising work has started in this direction such as snow cleaning, plasma cleaning and HOM horn cleaning.

Main Issues at Very High Gradient (2)

Q drop

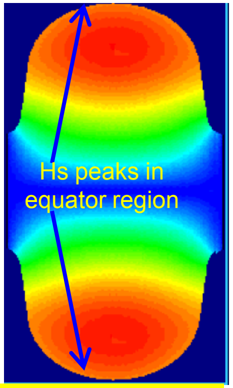




Due to surface resistance increase as gradient is raised, Q_0 values decline starting at 3-5 MV/m, even in the absence of field emission. This fundamental problem remains an open issue, despite recent progress. Raising Q_0 to $1\text{-}2\times10^{10}$ at 40-45 MV/m gradient range is necessary for ILC 1 TeV upgrade. Proof-of-principle exists with fine grain Nb cavity at a lower bath temperature of 1.8 K. Large-grain Nb seems to be a promising solution at the baseline temperature of 2K.

Main Issues at Very High Gradient (3)

Quench Limit



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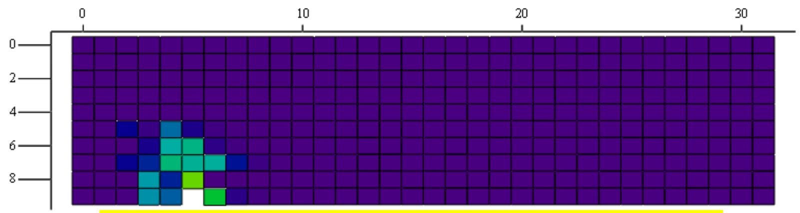
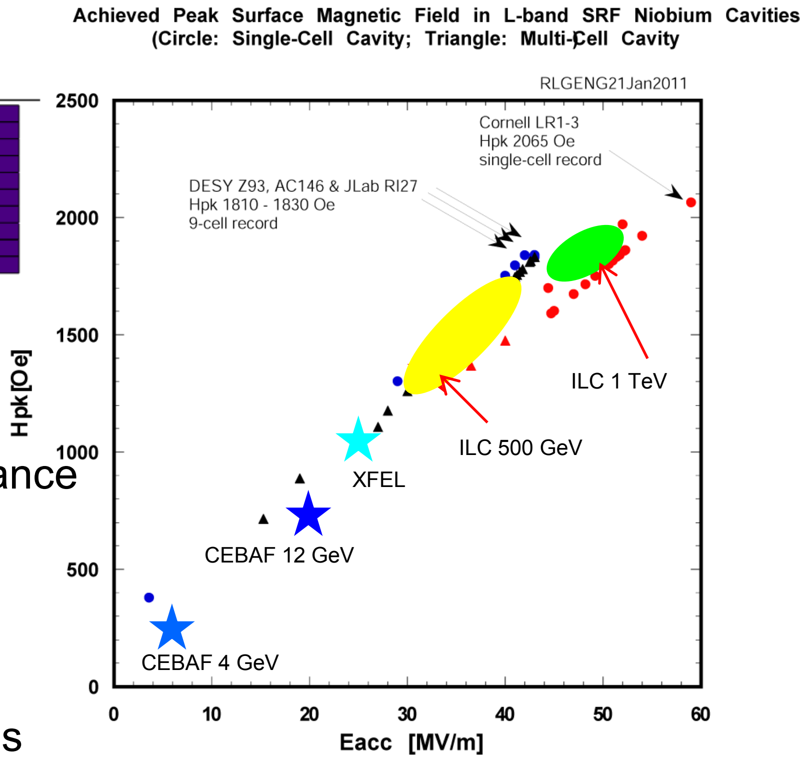
Jacek Sekutowicz



Temperature map of quench event at > 40 MV/m in 9-cell cavity RI27. Quench occurs locally in a small area of equator region.
Image courtesy Grigory Eremeev



- Peak surface magnetic field (Hpk) a parameter of importance
- Critical RF field $H_{crit, RF}$ determines the ultimate gradient
  - Above which SC to NC phase transition occurs
  - Is a fundamental limit to the achievable gradient
  - Theoretically a matter of further investigation
  - Superheating theory predicts 2300-2400 Oe for Nb at 2K
- Hpk ~2000 Oe demonstrated in 1-cell Nb 1.3 GHz cavities
- Hpk ~1800 Oe demonstrated in 9-cell Nb 1.3 GHz cavities
- Quench occurrence in 9-cell at > 40 MV/m highly localized – implies ultimate limit not yet reached

The best 9-cell TTF-style cavities have achieved 1800 Oe surface magnetic field. This corresponds to ~90% of the best values achieved in 1-cell cavities. This demonstrated peak surface magnetic field implies that ~ 50 MV/m gradient is achievable in 9-cells by using today’s proven EP processing technology and by using alternative shapes (such as LL, RE, and LSF). A main issue is to improve reproducibility at this field level – fortunately several “knobs” are available (see next slide).

Main Issues at Very High Gradient (3)

"Knobs" for improved reproducibility in overcoming <u>local quench</u> at very high gradient of 40-50 MV/m

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

Achievable gradient

Cavity surface chemistry

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

Cavity wall thermal conductance

Cavity surface smoothness

Cavity shape

(1) Alternate cavity shape for reduced Hpk/Eacc ratio. <u>In hand</u> (LL, RE, LSF).
(2) Uniform cavity processing for reduced local "bad" spots. <u>In hand</u> (EP).
(3) Smooth surface for reduced local magnetic field enhancement. In hand(CBP & derivative + EP).
(4) Improved wall thermal conductance for increased local heating tolerance.
- Cavity heat treatment optimization for "phonon peak engineering"
- Use Nb/Cu composite material (such as explosion bonded material)

(5) The game-changing knob is a Nb replacement material (such as Nb_3Sn or Mg_2B w/ multi-layer).

More in Chris Adolphsen's talk

- ILC cost-optimal gradient goes beyond 35 MV/m when high $Q_0 > 1\times10^{10}$ is maintained
  - **Proof-of-principle 9-cell result: Q0 > 1×10^{10} at 43 MV/m at 1.8K**
- Higher Order Modes (HOM)
  - **Calculations show cavity aperture down to 60 mm should work for tolerable emittance dilution**
- Dark current
  - **A tough battle**
    - Requires "field emitter free" cavity to begin with
    - Requires "re-contamination free" cavity string assembly
    - In-situ field emission processing needed for increased tolerance to field emitter and re-contamination
  - **New cleaning techniques are emerging (more later)**

Cavity R&D Plan for ILC 1 TeV Upgrade

Based on the past progress…

- Gradient goal: 40-45 MV/m
- Q_0 goal: $1\text{-}2\times10^{10}$
- Gradient yield goal: 90% at > 45 MV/m
- Field emission goal: field emission free surface at Epk of 100-120 MV/m

…further R&D needed

R&D Plan for Pushing Quench Limit

- Alternative cavity shapes
  - **Low-loss shape**
  - **Re-entrant shape**
  - **Low-Surface-Field Shape**

More in Kenji Saito's talk

- "Mirror-finish" surface
  - **CBP and derivative**

KEK/Jlab S0-study Schedule on ICHIRO#7

Ichiro#7: a full 9-cell cavity with LL shape

w/ end groups

W/ MO seal

Photo courtesy
Fumio Furuta & Kenji Saito of KEK

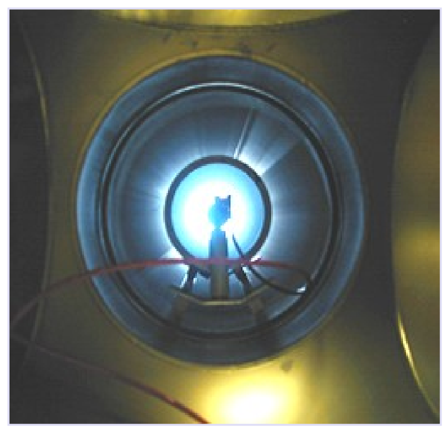
Photo courtesy
Charlie Cooper of FNAL

R&D Plan for Pushing Quench Limit (cont.)

- High cavity wall thermal conductance
  - **Heat treatment optimization**
  - **Nb/Cu laminate material cavity or Nb/Cu coated cavity**
- Nb replacement materials via coated cavity
  - **Nb_3Sn, Mg_2B etc**
  - **Coating by energetic condensation or atomic layer deposition**

More in Lance Cooley's talk

Photo courtesy
Kenji Saito of KEK & Waldemar Singer of DESY



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Mahadevan Krishnan of AASC

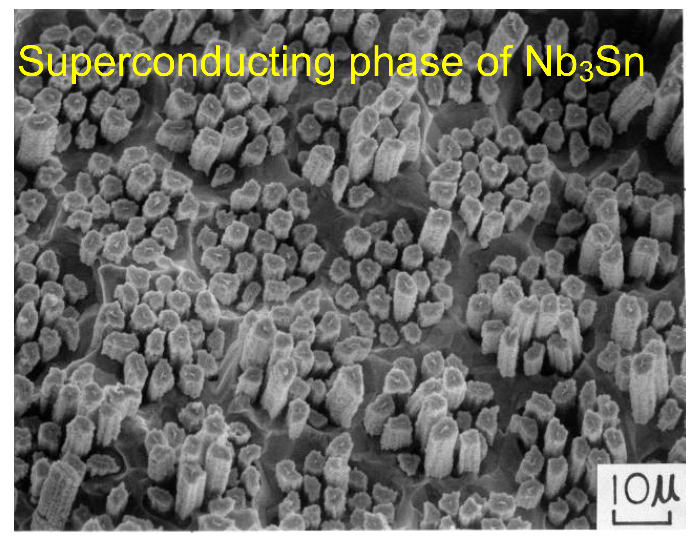

Photo courtesy LBNL

R&D Plan for Raising Q_0

- Optimal processing
  - **Electron mean free path engineering within London penetration depth, for example by optimal damage layer removal**
  - **"zero chemistry" after vacuum furnace heat treatment with nitride passivation layer**
- Large-grain niobium cavity
- Alumina over-layer coating

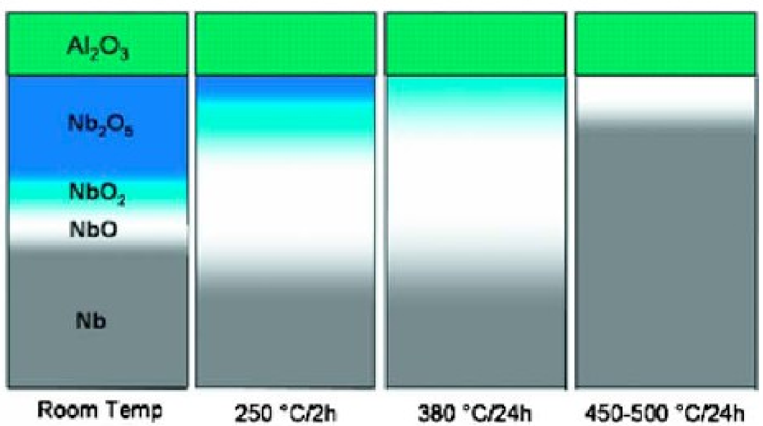

Image courtesy Thomas Proslier of ANL

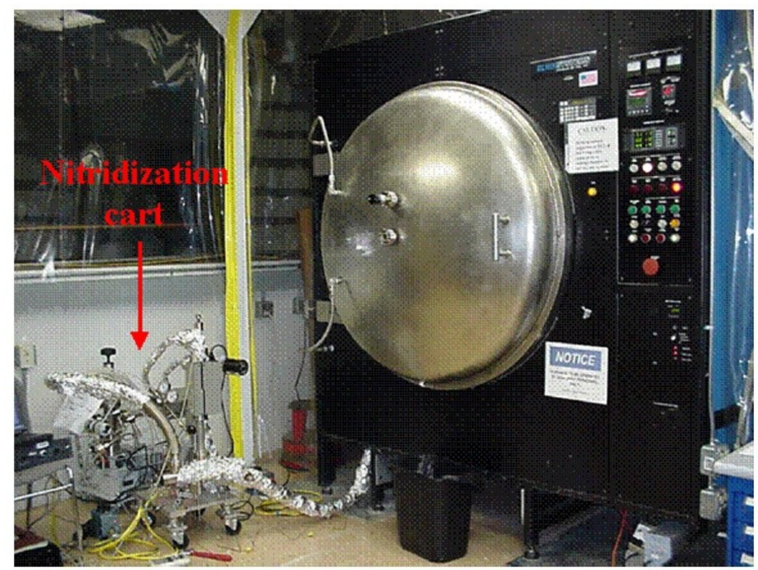

Photo courtesy Gigi Ciovati of JLAB

R&D Plan for Suppressing Field Emission

- HOM can horn cleaning
- CO_2 snow cleaning
- Plasma etching/cleaning

Photo courtesy
Anne-Marie Valente-Feliciano
of JLAB. photo shows work at ODU

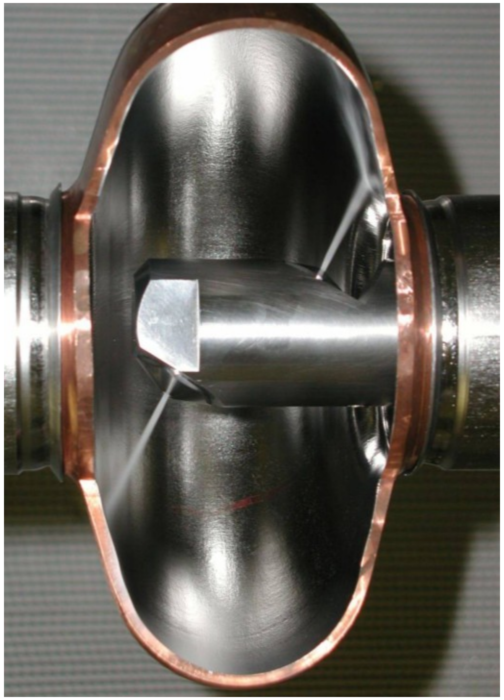

Photo courtesy
Detlef Reschke of DESY

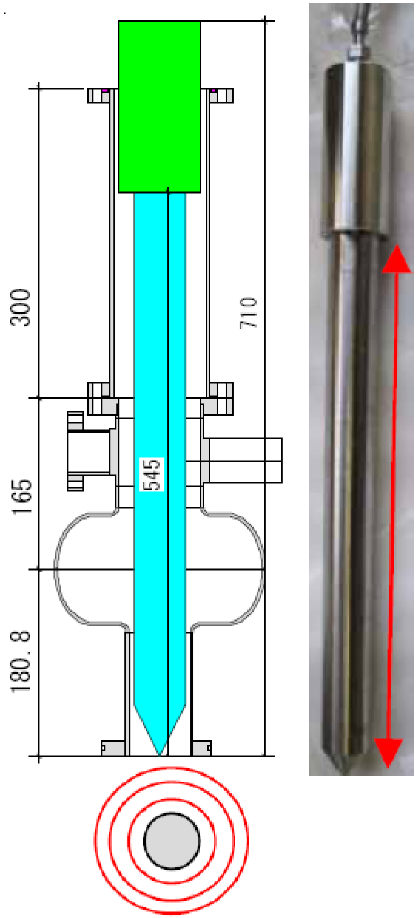

Photo courtesy
Kenji Saito of KEK

High Gradient SRF Cavity R&D beyond 2012

year	# of >35 MV/m 9-cell cavities	# of facilities capable of 35 MV/m proc./test 9-cells	# of Industrial manufacturers capable of 35 MV/m fabrication
2006	~10	1(+1) DESY, (Nomura Plating)	2 ACCEL, ZANON
2010	>40	5(+2) DESY, JLAB, FNAL/ANL, KEK, Cornell, (RI/ACCEL, Henkel)	4(+1) RI/ACCEL, ZANON, AES, MHI, (Hitachi)

- Looking backward, ILC SRF cavity R&D has made progress
  - ✓ Milestone of 50% yield at 35 MV/m in June 2010
  - ✓ Indication of 90% yield at 35 MV/m
- 35 MV/m SRF cavity technology & infrastructure fledging gloabally
- Global coordination of cavity R&D (GDE) a valuable experience
  - ✓ Project oriented, targeted R&D, benchmarked progress
  - ✓ Maximized utilization of limited resources, sharing and cross-checking
- ILC the driver for high gradient SRF cavity technology
  - ✓ Pursuit of ultimate gradient continues to motivate innovation
  - ✓ Gradient success continues to benefit SRF based accelerators

High Gradient SRF Cavity R&D beyond 2012

- Looking forward, ILC SRF cavity R&D has many opportunities
  - Continued lab/industry collaboration for cost-effective fabrication
  - First 45-50 MV/m 9-cell demonstration using alternative cavity shapes
  - Large-grain material 9-cell cavity demonstration of Q_0 2×10^{10} at >40 MV/m
  - Nb/Cu laminate material 9-cell cavity demonstration
  - Field emission free surface up to 120 MV/m surface electric field
  - Cavity system development using Nb replacement material such as Nb_3Sn
  - …
- Global coordination (GDE-like) important
  - Setting goals and recommending R&D priorities
  - Each region should develop program based on institutional strength
  - Perspective from linac system point of view
  - Framework for hardware exchanges and knowledge sharing
  - Possible synergy with NC technology such as high surface electric field physics
- ALCPG11 is the right time and place to start planning