# ILC SRF Cavity Gradient R&D

**Rongli Geng*, Akira Yamamoto****

*** GDE & Jefferson Lab**

**** GDE & KEK**

ILC Project Advisory Committee Meeting

May 19-20, 2011, Academia Sinica, Taipei, Taiwan

# What was reported @ 5th PAC

REPORT OF THE FIFTH MEETING OF THE ILC PROJECT ADVISORY COMMITTEE (PAC)

11/12 November 2010; Eugene, OR, USA

B. A report on SCRF progress since the previous PAC meeting was given by Akira Yamamoto; he noted that the 600-cavity production order for the XFEL had been placed. Yamamoto said that the Fermilab NML CM1 cryomodule cooldown was about to start, and MHI-12 at KEK reached 37.5 MV/m on the first pass. The goal of 50% yield at 35 MV/m has been reached; JLab has had an 81% yield, and 9 out of 10 ACCEL/RI cavities have exceeded 35 MV/m. Yamamoto described the S1 global test, where eight 9-cell cavities in the S1 global…

MHI cavities since MHI-12 now included for global gradient yield analysis

With a vertical cavity gradient of 35 MV/m, and a 28-42 MV/m allowed spread, this should give an operational 31.5 MV/m average, and a spread of 25-38 MV/m. Yamamoto gave the RF capacity requirements to accommodate this spread. His presentation is in Attachment VIII.

This is now the new baseline for cavity gradient and spread

# What was advised @ 5th PAC

- From PAC summary and recommendations
  - **General**

2. It is important that consideration be given by ILCSC, GDE and RD to maintaining global coherence of the ILC accelerator and detector R&D efforts past the 2012 design report.

Agree, cavity gradient R&D program beyond 2012 in support of 1 TeV ILC requires global coherence. GDE started ILC 1 TeV cavity gradient R&D discussion at ALCPG2011.

  - **Accelerator**

2. The PAC is very impressed by the recent progress on SCRF cavity gradients; 9 out of 10 cavities from one manufacturer meeting the nominal ILC gradient requirement is an outstanding achievement.
3. There is a need to pay attention to the issue of field emission in the SCRF cavities.

All lab groups involved in ILC cavity R&D now started field emission instrumentation
Goal: unique quantification and cross-facility checking of field emission
A TDP-2 gradient R&D priority and a necessary subject for 1 TeV gradient R&D
No results yet – expect to report next PAC meeting

# Outline

- **Highlights since the 5th PAC meeting**
  - Formal adoption of average gradient 35 MV/m and spread ± 20% for cavity acceptance test
  - Inclusion of MHI/KEK cavity data for global yield analysis
  - DESY demonstrated 45 MV/m gradient at Q0 > 1E10 in a large-grain 9-cell cavity
  - Global ILC cavity gradient yield updated
- **Toward TDP-2 gradient goal**
  - Fabrication QA/QC at DESY for XFEL production cavity
  - Mechanical polishing for increased fabrication tolerance
  - Fight against field emission at very high gradient
  - Cost saving R&D and value engineering
- **R&D plan to support 1 TeV ILC upgrade**
  - Gradient, $Q_0$, and field emission R&D goal
  - Cavity R&D plan
  - ILC SRF cavity R&D beyond 2012
- **Summary**

# Global Plan for ILC Gradient R&D

| Year | 07 | 2008 | 2009 | 2010 | 2011 | 2012 |
|---|---|---|---|---|---|---|
| Phase | TDP-1 | | | TDP-2 | | |
| Cavity Gradient in v. test to reach 35 MV/m | → Yield 50% | | | → Yield 90% | | |
| Cavity-string to reach 31.5 MV/m, with one-cryomodule | | Global effort for string assembly and test (DESY, FNAL, INFN, KEK) | | | | |
| System Test with beam acceleration | | | FLASH (DESY) , NML (FNAL) STF2 (KEK, test start in 2013) | | | |
| Preparation for Industrialization | | | | Production Technology R&D | | |

**New baseline gradient:**

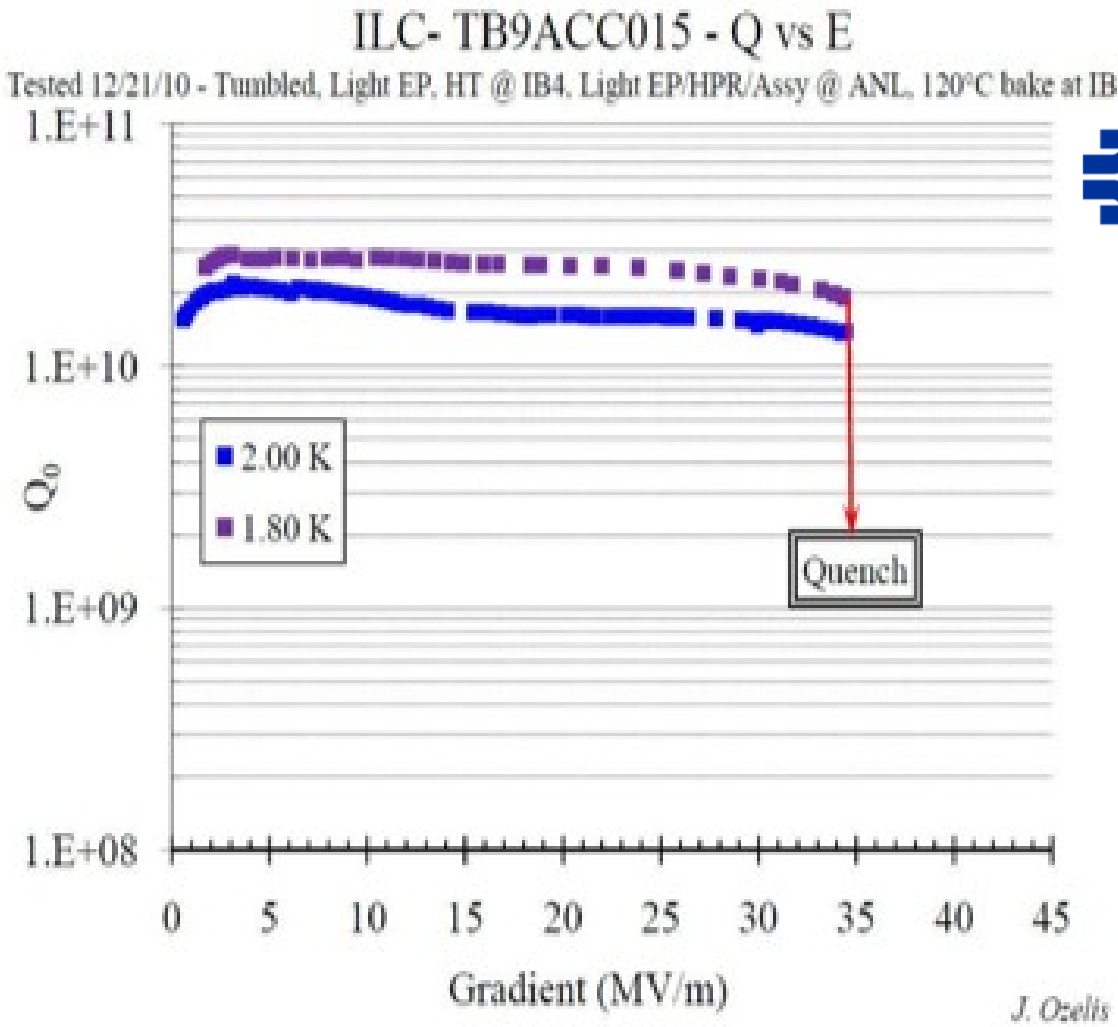
Vertical acceptance: 35 MV/m average, allowing ±20% spread (28-42 MV/m)

Operational: 31.5 MV/m average, allowing ±20% spread (25-38 MV/m)

# SRF Cavity and Gradient Highlights since November 2010

- Americas
  - **FNAL mechanical polishing improved 9-cell cavity ACC15 gradient from 19 MV/m to 35 MV/m**
  - **JLAB started processing and testing DESY seamless 9-cell cavity built from DESY 3-cell seamless units**
  - **6 9-cell cavities of AES 3rd production & 4 remaining 9-cell cavities of Niowave-Roark 1st production received by FNAL**
- Asia
  - **KEK MHI-12 reached 40.7 MV/m gradient at Q0 6.2E9**
  - **KEK-JLAB: ACD shape cavity ICHIRO7 reached 40 MV/m gradient at Q0 8E9**
- Europe
  - **DESY large-grain 9-cell cavity AC155 reached 45 MV/m gradient at Q0 > 1E10**

# ACC15 Reached 35 MV/m after Mechanical Polishing at FNAL




Fermilab

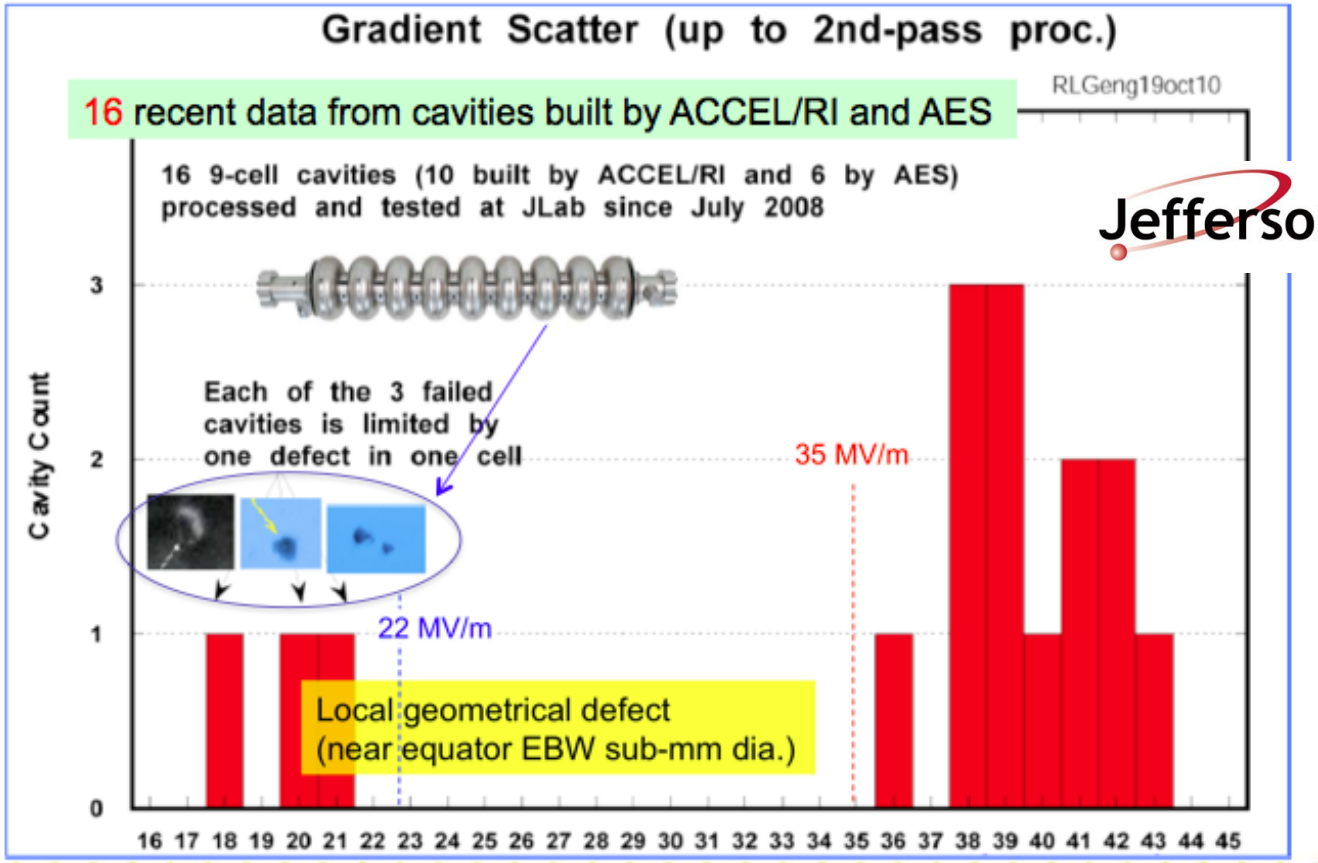
More cavities by FNAL mechanical polishing on the way…

# Impact of Mechanical Polishing Report at 5th PAC Meeting in Eugene

R. Geng

## 81 % Yield at 35 MV/m achieved at JLab

**Main Issue, now: Quench Limit ~ 20 MV/m**




A, Yamamoto, 10-11-11 ILC-PAC: SCRF 17

# Impact of Mechanical Polishing Today at 6th PAC Meeting in Taipei

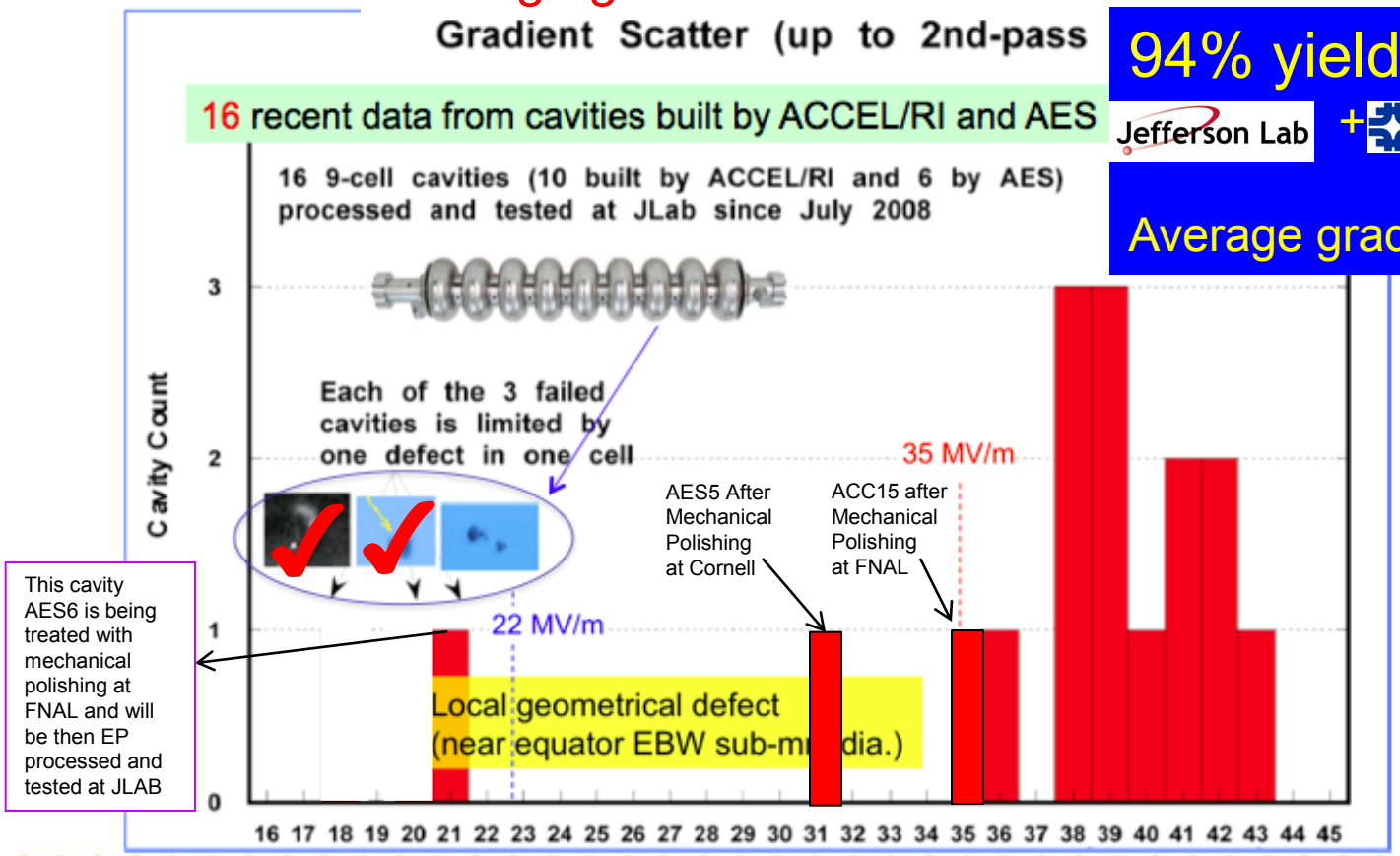
88% **Yield at 35 MV/m achieved at** JLAB + FNAL

Average gradient 39 MV/m

94% yield at ≥31 MV/m

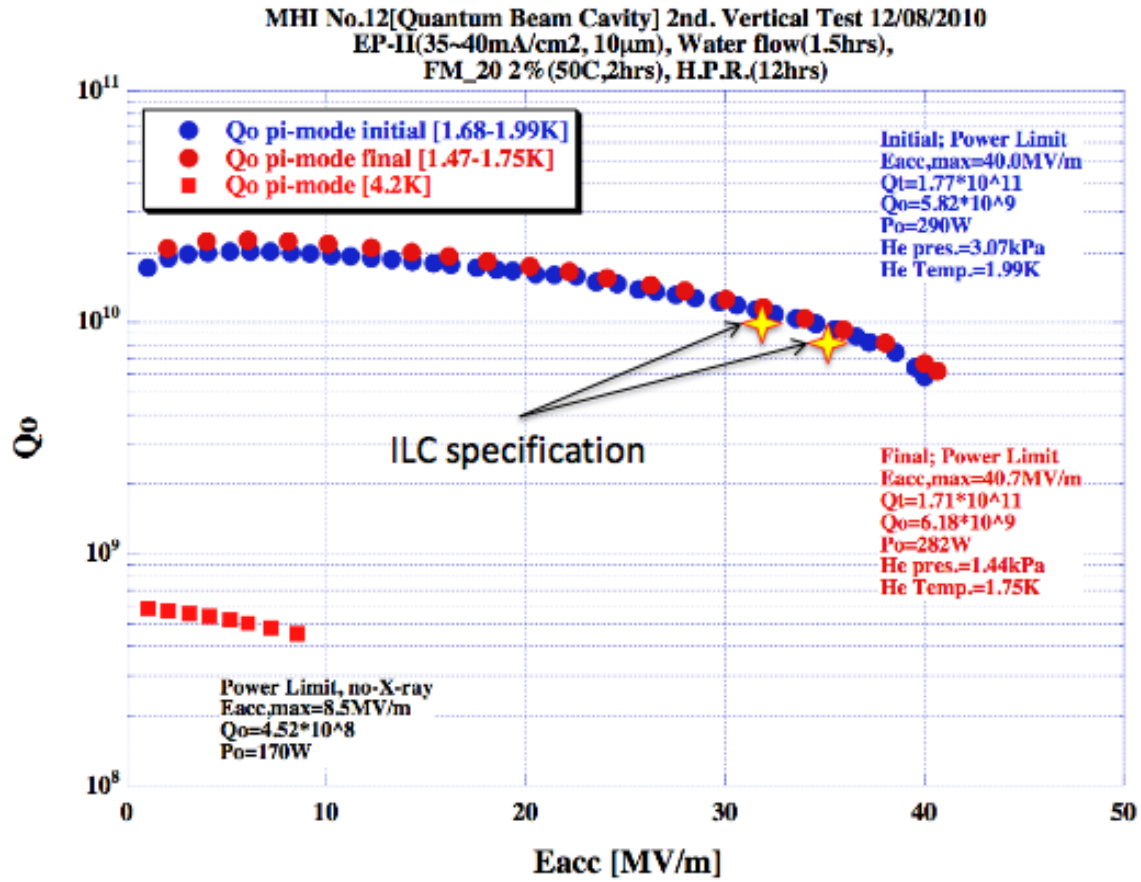
Jefferson Lab + Fermilab + Cornell University

Average gradient 38.8 MV/m



# KEK MHI-12 Exceeded 40 MV/m

## MHI-012 2nd VT reached 40.7MV/m




MHI-13 reached 36.5 MV/m at Q0 7.5E9 after first-pass processing

Intentional power stop at 40MV/m

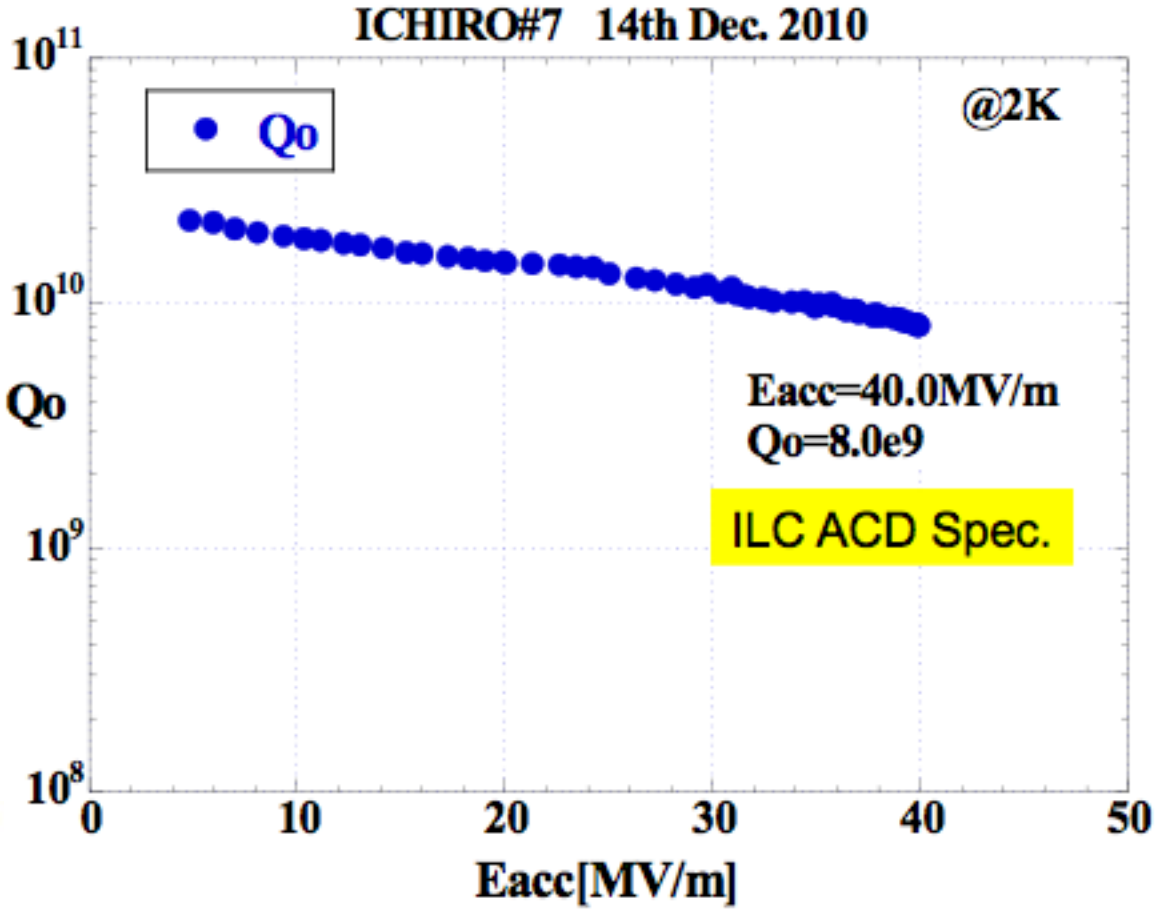
# KEK/MHI Cavity Data Now Included for Global Yield Analysis

- Most recent update was TDP/R&D plan release 5 [June 30, 2010]
  - 35 cavities for 1st pass, 27 cavities for 2nd pass
- ALCPG 2011
  - Cavity updates
    - TB9RI027, TB9RI028 (1st and 2nd pass) from JLab
    - one cavity, TB9ACC015, was found to have no standard second pass process (mistake of data entry)
    - MHI012, MHI013, MHI014, (1st and 2nd pass), MHI015 (1st pass only) from KEK
      - MHI data were added to database using TTC talk [Feb. 2011] by Kirk Yamamoto-san; due to the nature of this update, I would like to wait for confirmation before making these "official"
  - 41 cavities for 1st pass, 31 cavities for 2nd pass

# KEK ICHIRO7 Reached 40 MV/m

Photo courtesy
Kenji Saito & Fumio Furuta
of KEK

CBP(80μm)+ CP(10μm)+AN(750°C, 3hr)+EP(80μm)+HPR Bake+VT @ KEK, then sent Jlab.



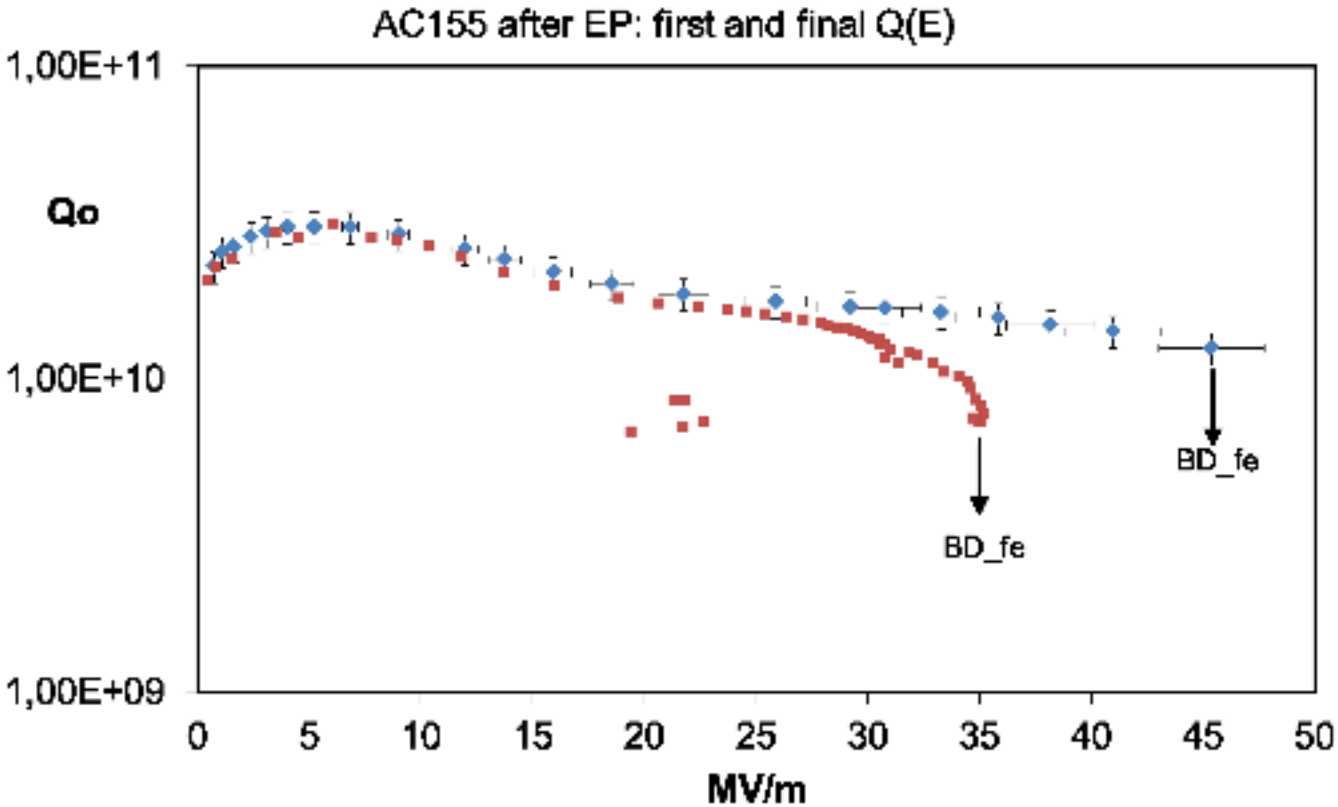

Jefferson Lab

50 MV/m in perspective as many ICHIRO 1-cell cavities achieved gradient of > 50 MV/m…

# DESY Large-Grain Cavity AC155 Reached 45 MV/m at Q0 > 1E10

**Heavy BCP + EP + low temperature bake**

> **Re-test after 300 K:** Final $Q_0(E_{acc})$ at 2K: **45 MV/m @ > $10^{10}$** ; some FE




- Final mode measurements: 47 – 51 MV/m

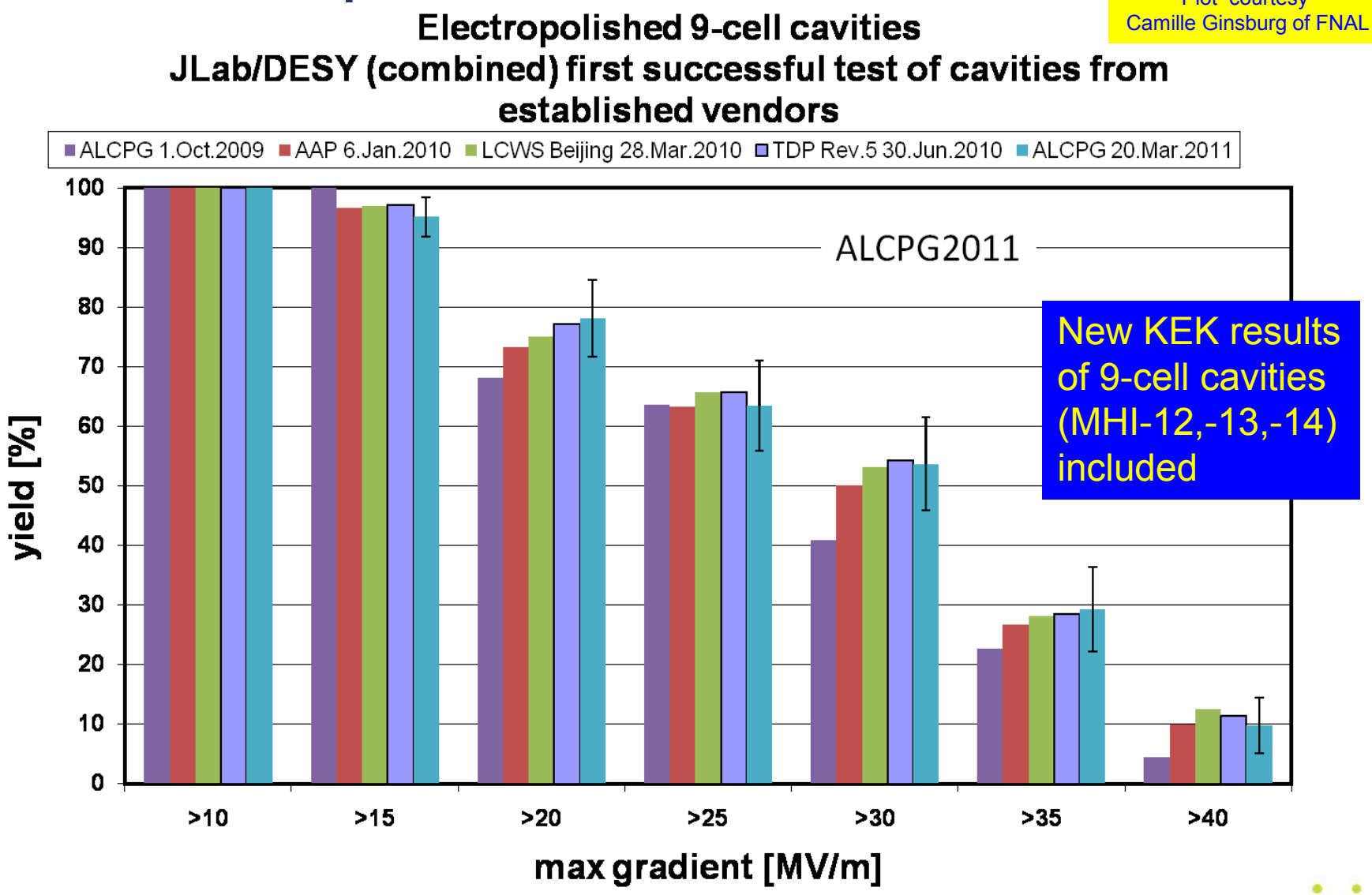
- Second Sound done

**7 more cavities on the way…**

26. April 2011 | Page 5

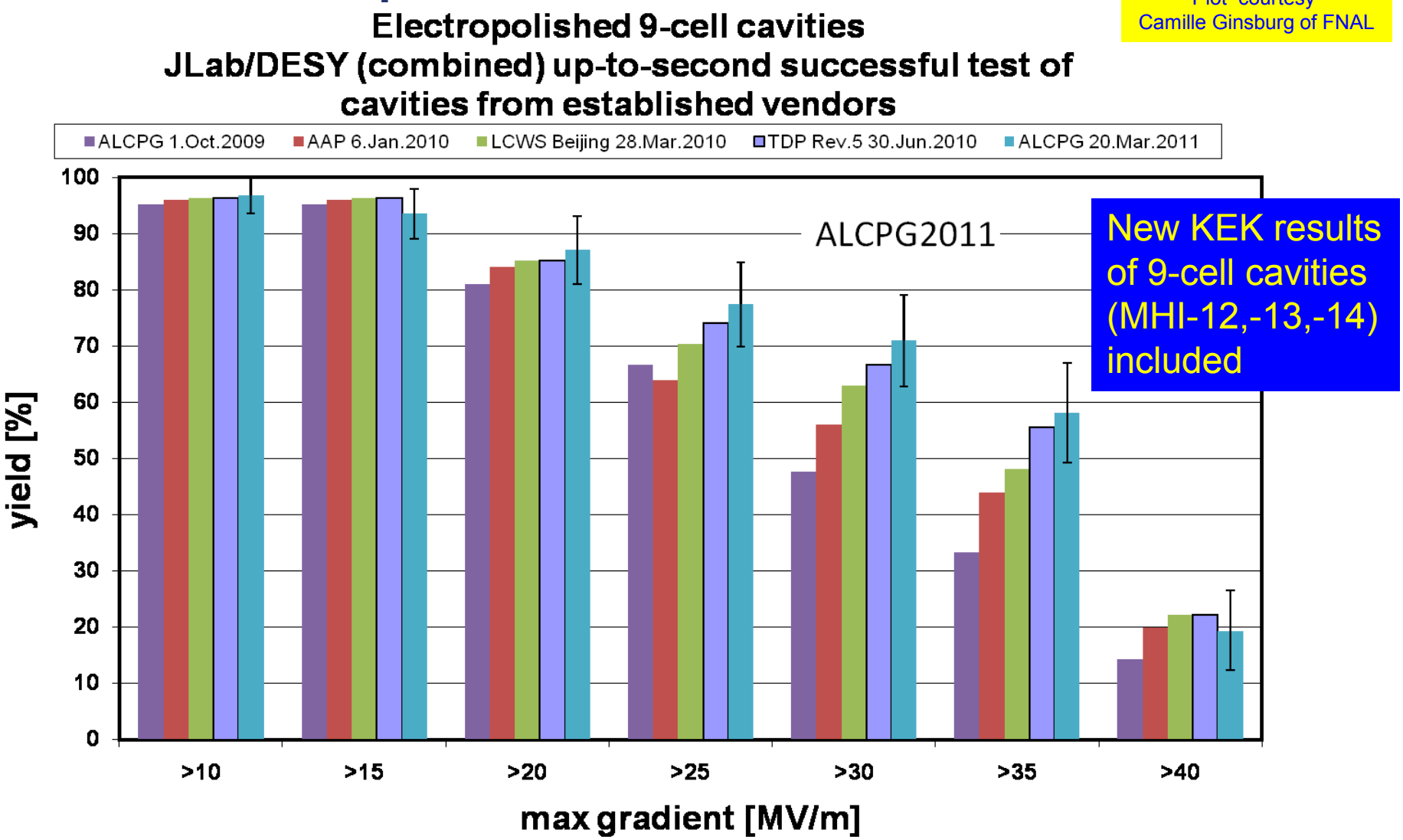
# Global ILC Cavity Gradient Yield Updated at ALCPG2011

Plot courtesy
Camille Ginsburg of FNAL



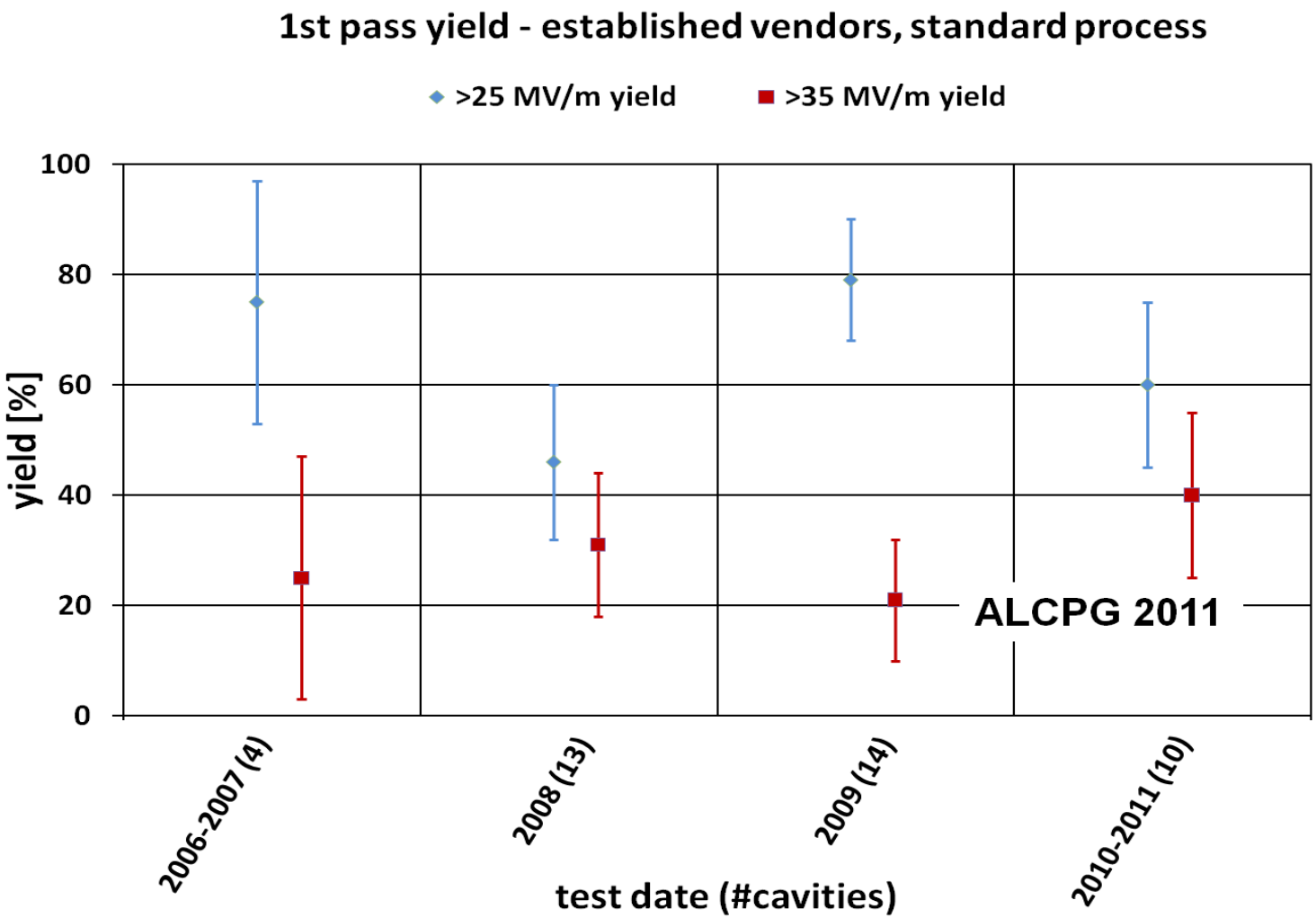
# Global ILC Cavity Gradient Yield Updated at ALCPG2011

Plot courtesy
Camille Ginsburg of FNAL



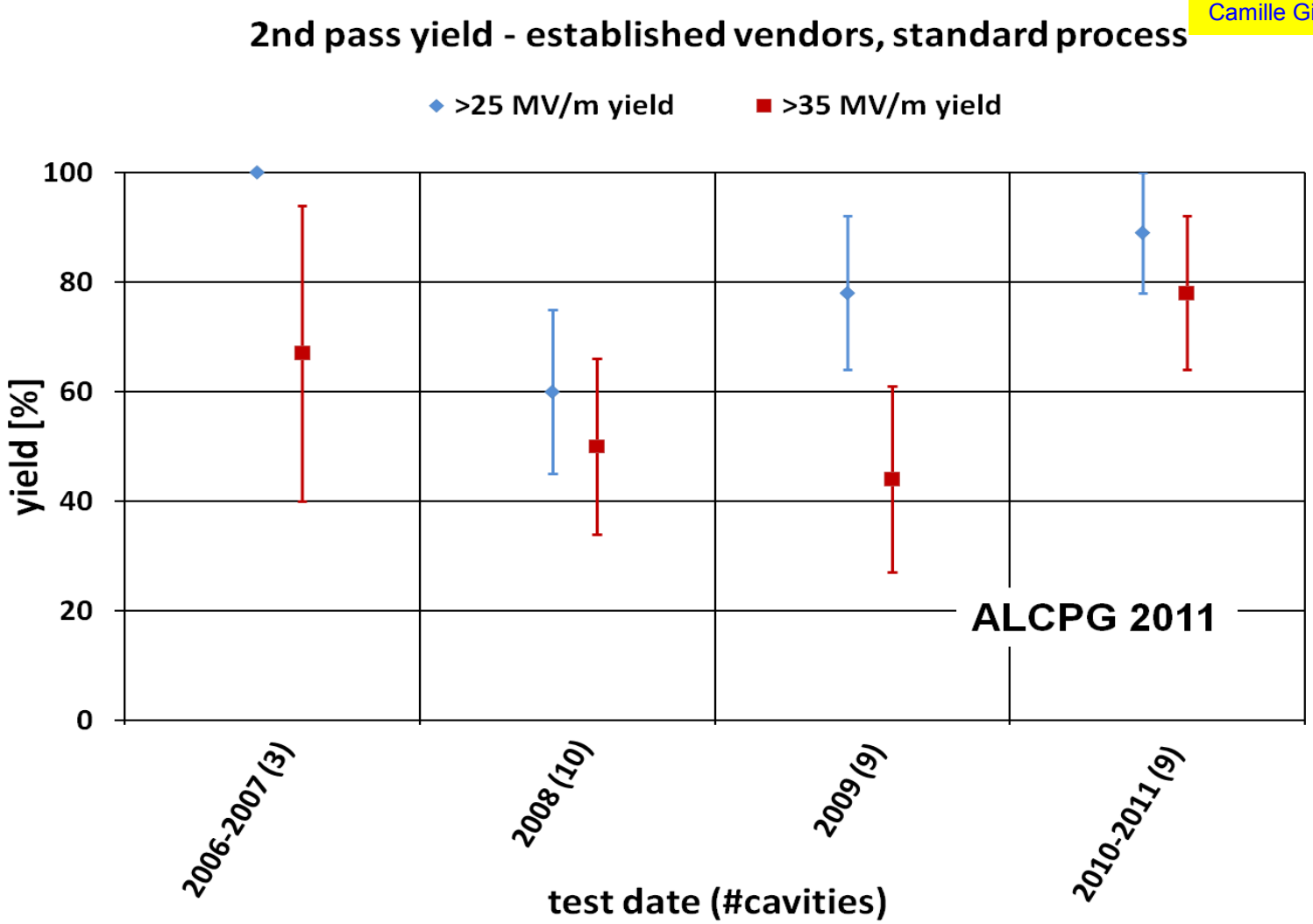
# Gradient Yield Yearly Trend (1)

Plot courtesy
Camille Ginsburg of FNAL



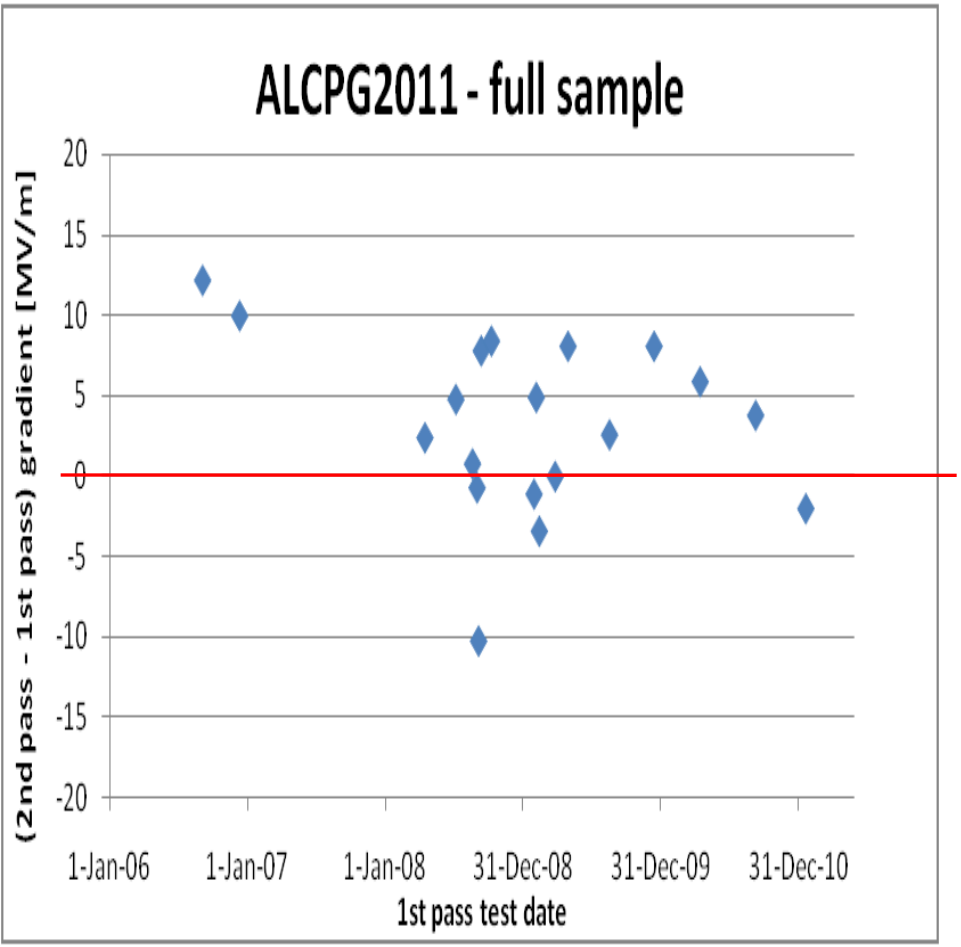
# Gradient Yield Yearly Trend (2)

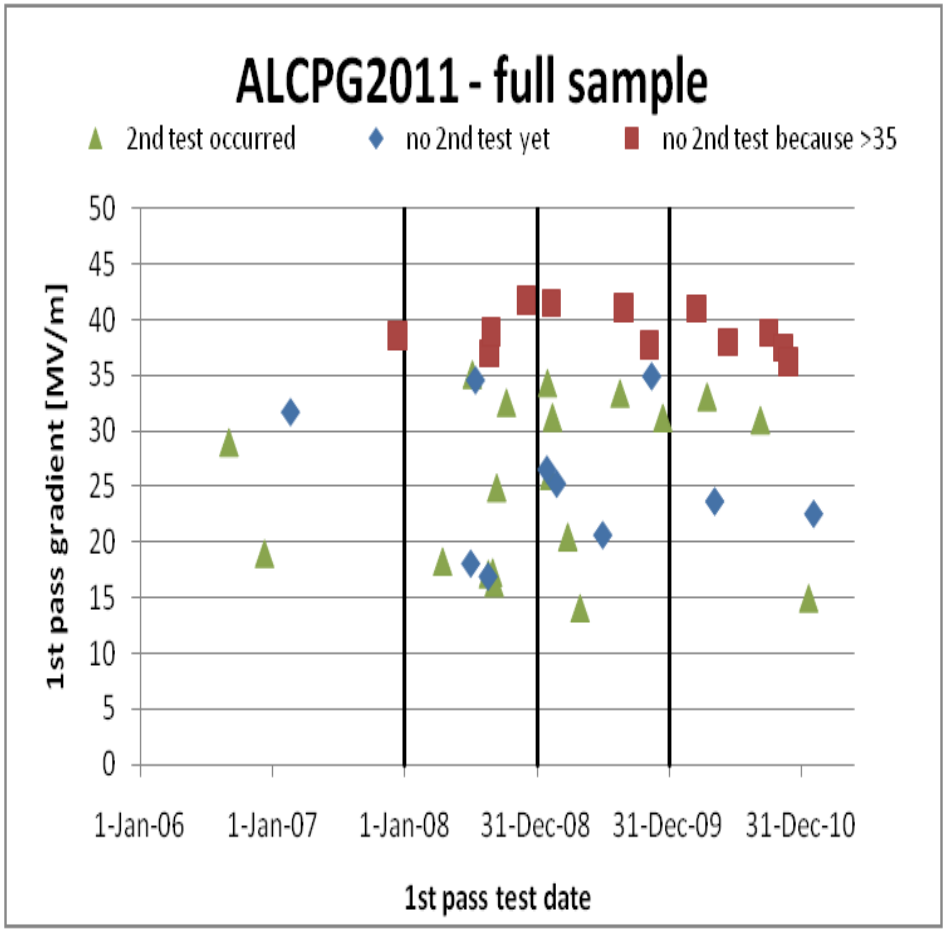
Plot courtesy
Camille Ginsburg of FNAL



# Effect of 2nd Pass Processing

Plot courtesy
Camille Ginsburg of FNAL



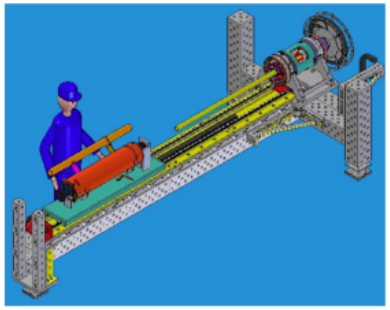



# Toward TDP-2 Goal of 90% Yield (1)

- Fabrication QA/QC development at DESY in association with XFEL production cavities

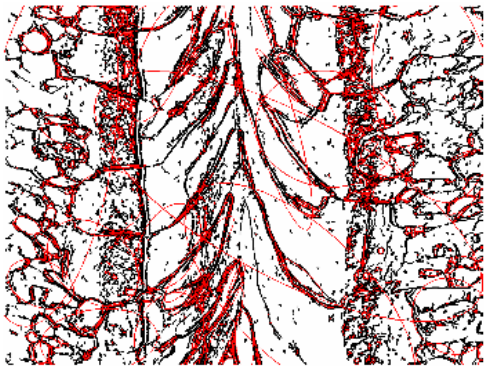
## Optical inspection at DESY

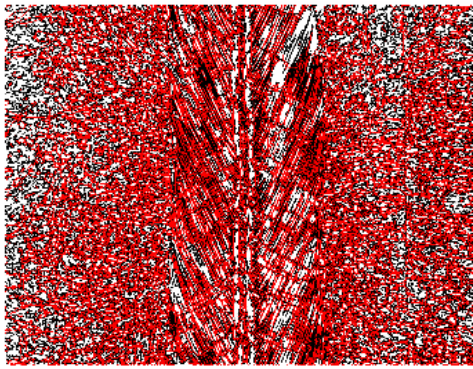
- Kyoto/KEK-camera system in use since August 2008
- More than 25 cavities inspected
- Correlation between hotspot in Tmap-measurement and defect found by optical inspection in several cases
  - See talk by Y.Yamamoto and S. Aderhold for examples
- Automated inspection set-up under development
  - Reproducibility, speed, robustness
  - Suitable for application in cavity mass production



Eckhard Elsen, Sebastian Aderhold, Detlef Reschke | Activities for ILC at DESY | Page 5

## Regions: Surface Properties





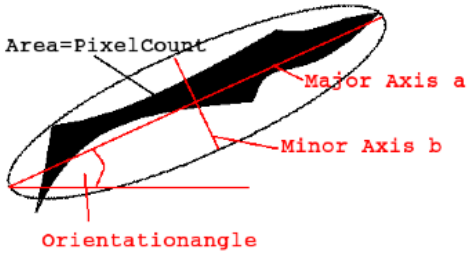



Photo courtesy
Marc Wenskat of DESY

skat | ALCPG11 | 19.-23. March 2011 | Page 7

**Automated inspection**

**Feature recognition**

# Toward TDP-2 Goal of 90% Yield (2)

- Mechanical polishing
  - **Global reset of cavity surface**
  - **Increase fab flaw tolerance**
    - Cost saving potential
  - **Pioneering work at KEK**
    - CBP by Kenji Saito group
    - All ICHIRO cavities were CBP'ed
  - **Recent improvement at FNAL**
    - "mirror finish" inner surface
  - **Almost every lab has a machine**
    - Cornell, DESY, FNAL, JLAB, KEK
- Guided repair
  - **Local grinding (KEK)**
  - **Cell mechanical polishing (Cornell)**
  - **Local laser re-melting (FNAL)**
  - **Local e-beam re-melting (JLAB)**

Photo courtesy
Charlie Cooper of FNAL

Cost-effective
cavity recover

# Toward TDP-2 Goal of 90% Yield (3)

- Fighting against field emission (FE)
  - **Issues**
    - Baking induced FE
    - Sudden field emitter turn on
  - **Solutions needing further R&D**
    - HOM can horn cleaning
    - CO2 snow cleaning
    - Plasma cleaning
  - **Instrumentation for understanding and comparison**
    - “at cavity” X-ray monitoring
      - Diodes
      - Many labs started this: DESY, FNAL, JLAB, KEK
    - “inside cavity” Faraday cup

# Solutions under R&D for Suppressing FE

- HOM can horn cleaning
- $CO_2$ snow cleaning
- Plasma cleaning

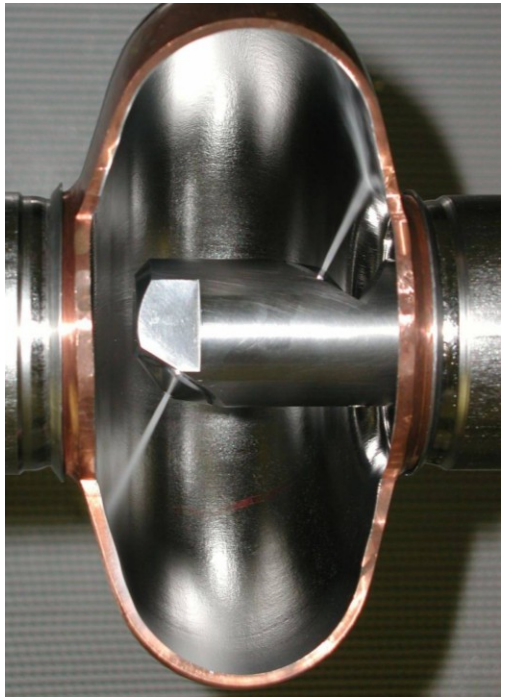


Photo courtesy
Detlef Reschke of DESY

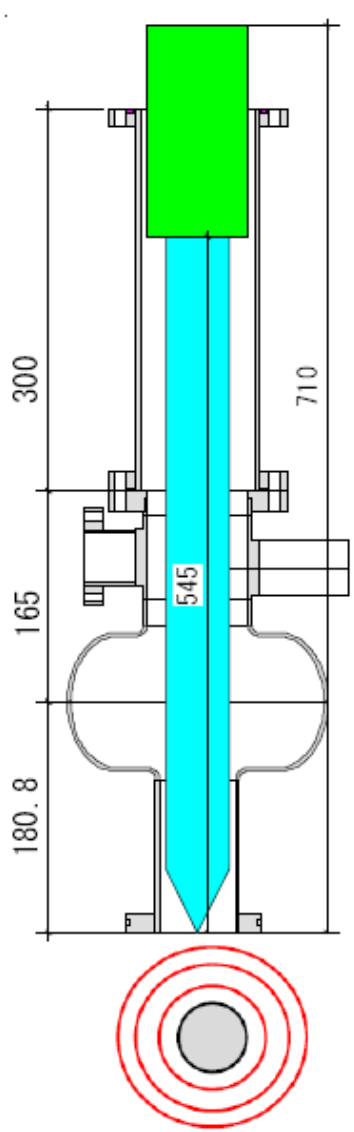


Photo courtesy
Kenji Saito of KEK

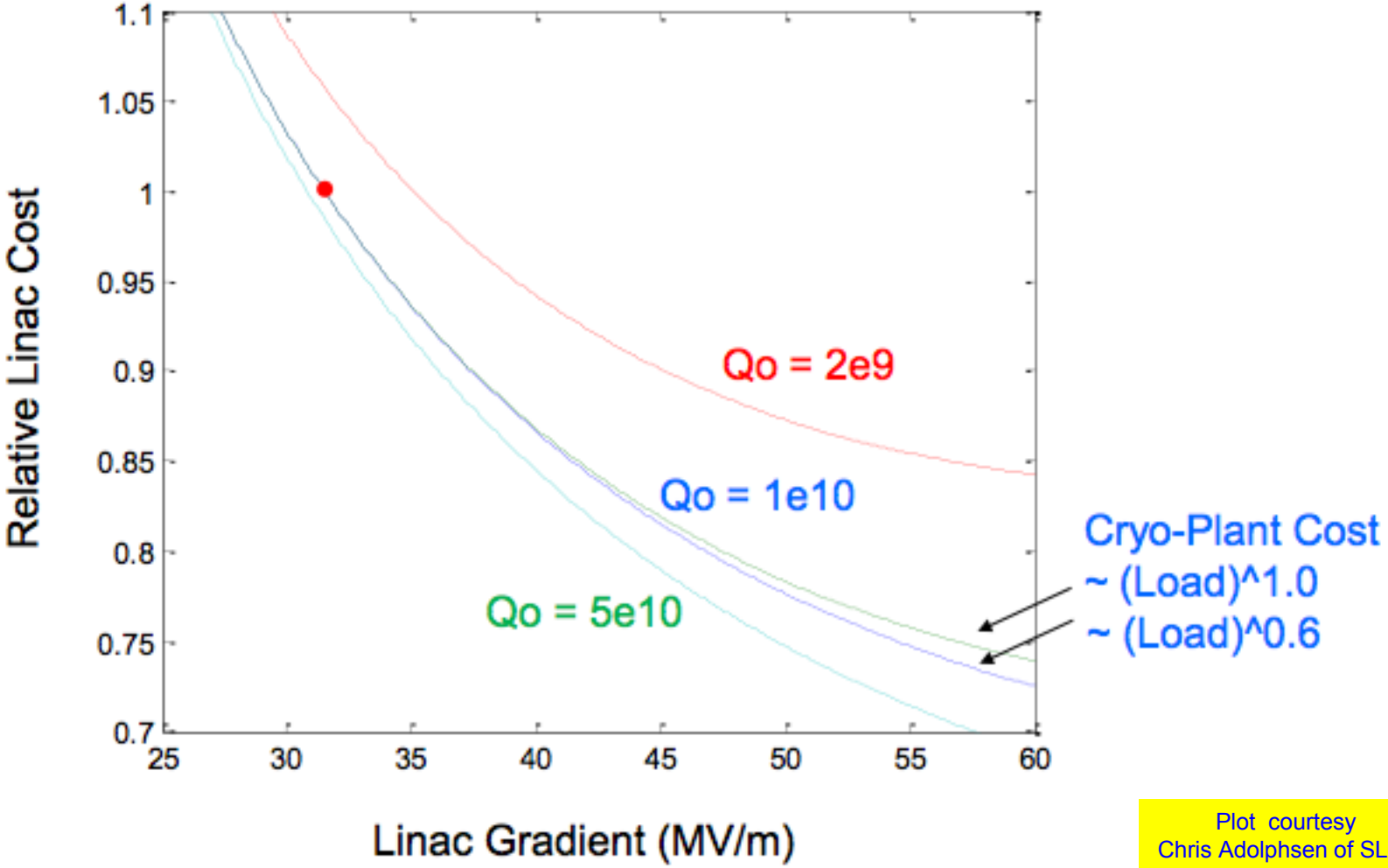
# Cost Saving R&D/Value Engineering

- Several cavity R&D topics on-going, aiming at fabrication, processing and installation cost saving
  - **Seamless cavity by hydro-forming**
    - Reduce number of electron beam welding
    - FNAL aims for complete hydro-formed 9-cells by September 2012
  - **Large grain cavity**
    - Reducing material cost by multi-wire slicing of ingot
    - DESY, JLAB, KEK all have efforts in large-grain 9-cell cavities
  - **Super-structure**
    - Increase real estate gradient and reduce # of RF couplers
    - Concept demonstrated by DESY, new interest @ ALCPG2011
- Cost saving fabrication and value engineering also pursued along with ILC SRF industrialization
  - **MHI: Seamless dumb-bell, LBW stiffening ring and flange**
  - **KEK pilot plant: several topics under R&D. More in Akira Yamamoto's talk on SCRF industrialization**

# Cavity R&D for ILC 1 TeV Upgrade

- Kick off by GDE at ALCPG2011 in Eugene, Oregon, March 19-23,2011
  - **4 GDE plenary talks**
    - Surface and material – Lance Cooley
    - Shape and configuration – Kenji Saito
    - Process and general R&D – Rongli Geng
    - Optimal linac performance – Chris Adolphsen
- Goals (to be discussed)
  - **Gradient: 40-45 MV/m (up to 50 MV/m?)**
  - **Gradient yield at 45 MV/m: 90%**
  - **Q0: 1-2E10 at 40 MV/m**
  - **Field emission: FE free at Epk 100-120 MV/m**

# Optimal Linac Gradient




Plot courtesy
Chris Adolphsen of SLAC

# Cavity R&D for ILC 1 TeV Upgrade

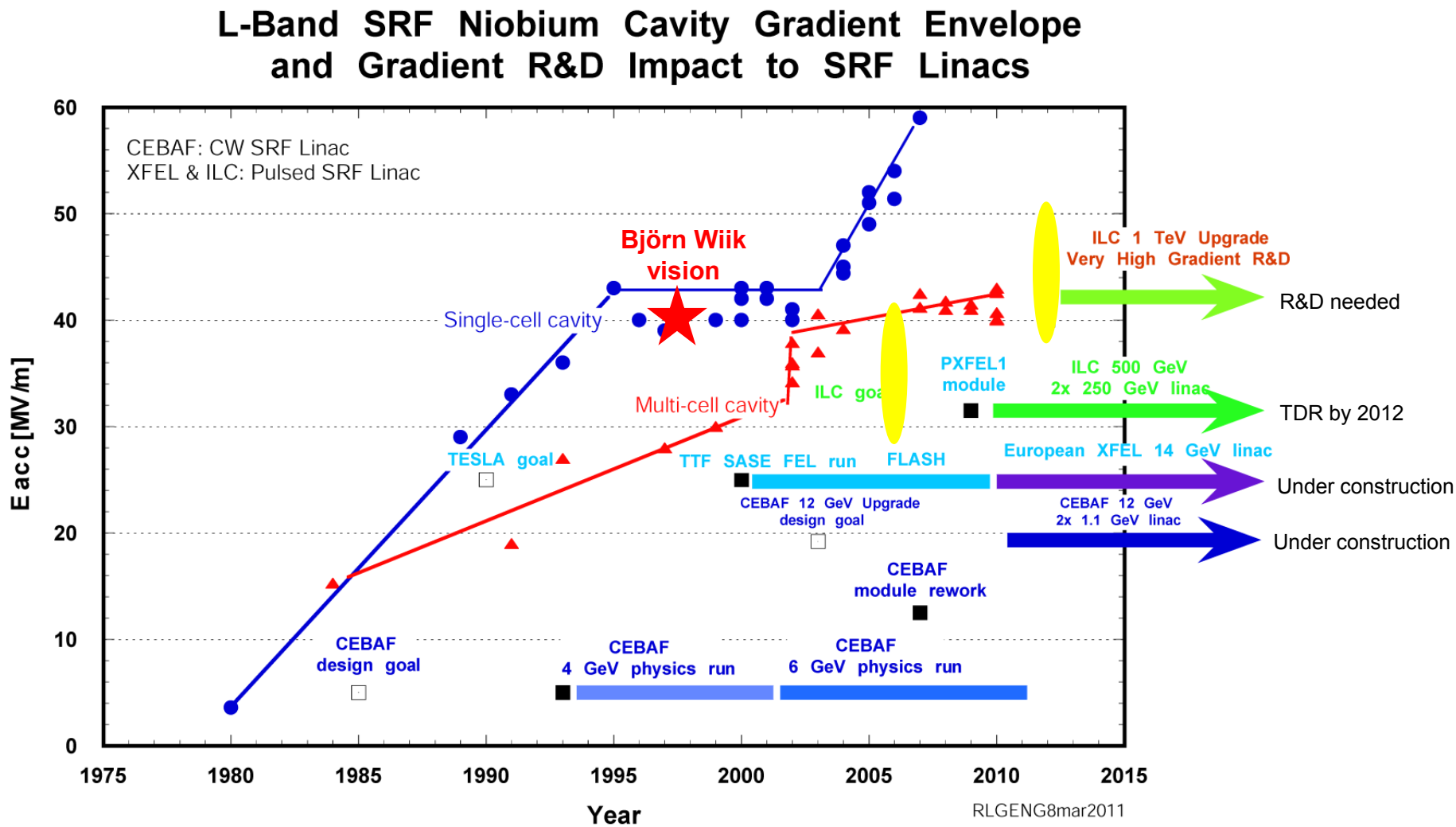
- High performance cavity R&D Plan
  - **High gradient**
    - ACD shape: LL/ICHIRO, RE, LSF – on going
    - ACD processing: Mechanical polishing – on going
    - ACD material
      - Large grain – on going
      - Nb/Cu laminate – needs re-start
      - Multi-layer and material beyond Nb – long term
  - **High Q0**
    - Large grain – on going
    - ALD over coating – R&D started
  - **Suppress field emission**
    - CO2 snow cleaning – on going
    - HOM can cleaning – R&D started

# Cavity R&D for ILC 1 TeV Upgrade

- ILC SRF cavity R&D beyond 2012
  - **GDE-like coordination important**
    - Maintain "global" nature for coherence
    - Project oriented, targeted R&D, benchmarked progress
    - Resource sharing, cross-region cavity exchange
  - **ILC the driver project for high gradient SRF cavity technology**
    - Pursuit of ultimate gradient continues to motivate innovation
    - Gradient success continues to benefit SRF based accelerators

| year | # of >35 MV/m 9-cell cavities | # of labs capable of 35 MV/m processing | # of Industrial manufacturers capable of 35 MV/m fabrication |
|---|---|---|---|
| 2006 | 10 | 1<br>DESY | 2<br>ACCEL, ZANON |
| 2010 | 40 | 4<br>DESY, JLAB, FNAL, KEK | 4<br>RI/ACCEL, ZANON, AES, MHI |

# 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

# Summary

- Globally coordinated ILC cavity gradient R&D in TDP phase not only improved gradient yield but also pushed gradient envelope, resulting in improved average gradient. With BCD cavity material, shape, manufacture and processing,
  - **90% gradient yield at 35 MV/m within reach**
  - **Average gradient of 38-39 MV/m reachable**
- ILC cavity Global Database is now truly global
  - **Cavity results from all three regions included for yield analysis**
  - **Underlining confidence of SRF technology on a global basis**
- If procedures are followed by vendors, ILC cavity design parameters are safe
  - **Funding should be made available for industry to practice**
  - **Reducing manual labor and streamlining steps for cost reduction**

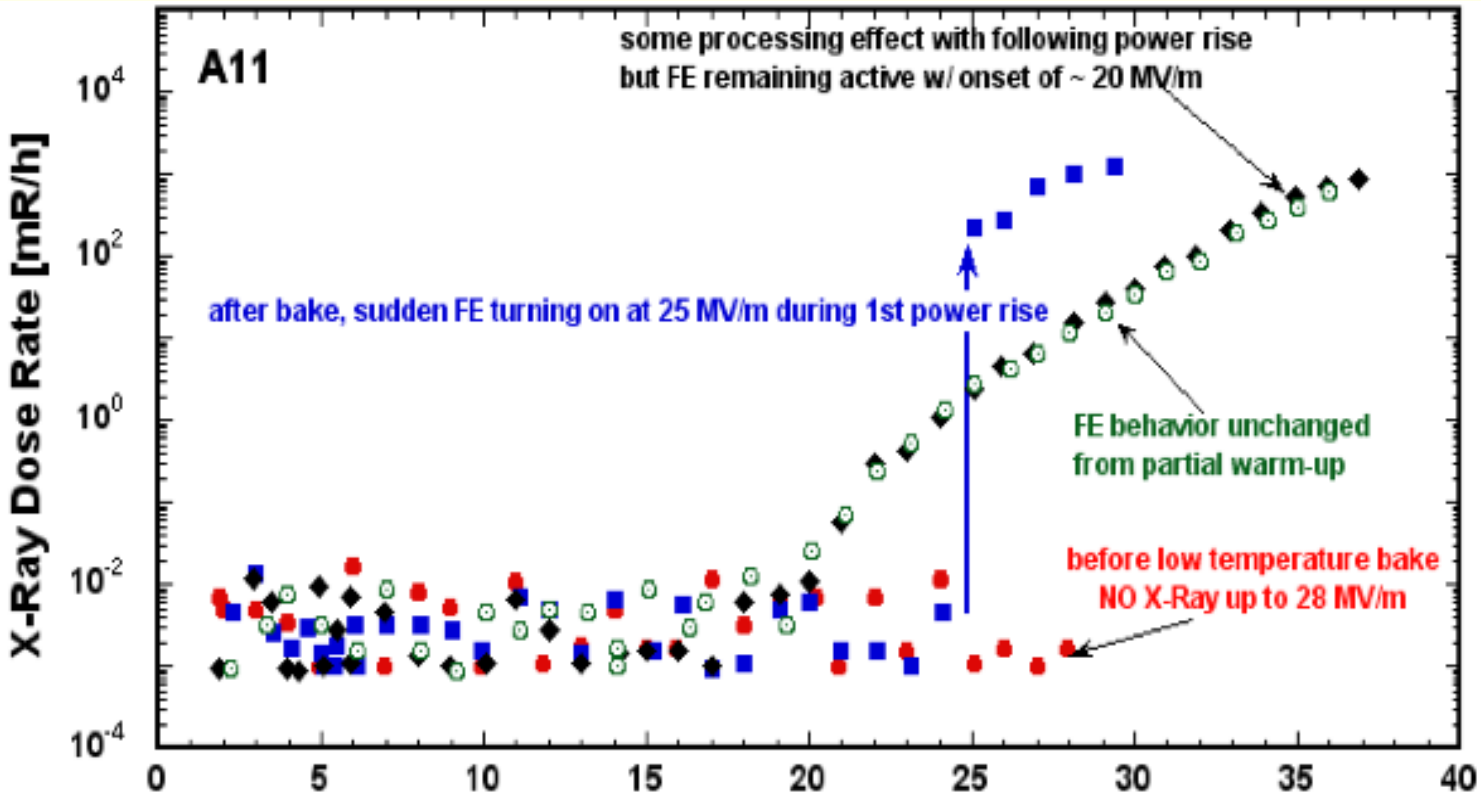
# Summary (cont.)

- Cavity R&D for TDP-2 address gradient yield, also field emission and cost reduction
  - **Some new progress in ACD cavity shape (Low-loss/ICHIRO) and material (Large-grain niobium) cavities**
  - **Effort in ACD manufacture (hydro-forming) and processing (mechanical polishing) should ramp up**
  - **None of the above ACD item is likely to replace the BCD counterpart in ILC TDR due to limited remaining time, so these R&D topics have to continue after 2012**
- Cavity gradient R&D for ILC 1 TeV upgrade requires global planning
  - **GDE has started process at ALCPG2011 for a post-2012 program**
  - **Program should have a clear focus on cavity system development**
  - **It is necessary to have an associated SRF test facility**
  - **Global coherence important: supplemental instead of duplicative**

# Backup Slides

# Baking Induced Field Emission

- There is evidence to show this phenomenon has to do with sulfur migration/segregation due to in-situ 120 Celsius bake.
- "Hidden spaces" in end groups such as HOM coupler cans are involved.
- Wiping and brushing HOM cans seems useful.




R.L. Geng, BAW1 @ KEK
September 9, 2010

Global Design Effort

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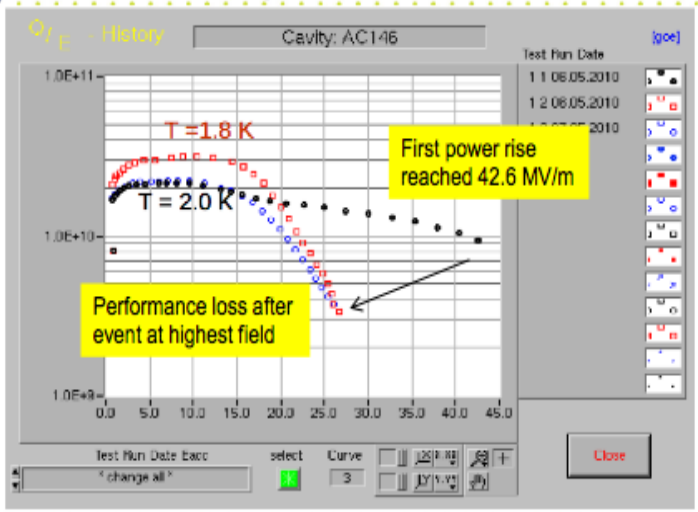
# Sudden Field Emitter Turn On




- Similar phenomenon observed in high gradient (35-42 MV/m) 9-cell cavity vertical test at JLab.
  - ✧ Explosive field emission turn on, followed by "permanent" performance loss.
- Another similar case was reported in a high gradient 9-cell cavity horizontal test at FNAL. Until 37 MV/m, no field emission, then sudden turn on followed by "permanent" performance loss.

R.L. Geng, BAW1 @ KEK
September 9, 2010

Global Design Effort

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| Cavity | $E_{FE\ Onset}$ before event | E @ event | $E_{FE\ Onset}$ after event | $E_{max}$ after event | Next process | $E_{FE\ Onset}$ latest | $E_{max}$ latest |
|---|---|---|---|---|---|---|---|
| TB9ACC9014 | 25 | 25 | 16 | 28 | HPR | 35 | 38 |
| TB9ACC9014 (part deux) | 35 | 36 | 24 | 38 | Tune, HPR | 25 | 34 |
| TB9ACC006 | 19 | 19 | 16 | 23 | EP & HPR | 29 | 32 |
| TB9ACC007 | 19 | 33 | 16 | 25 | HPR, EP & HPR | 22 | 35 |
| TB9RI026 | 22 | 29 | 15 | 20 | Grind & EP | -- -- | -- -- |
| TB9ACC015 | 20 | 32 | 9 | 25 | Tumble & EP | -- -- | -- -- |

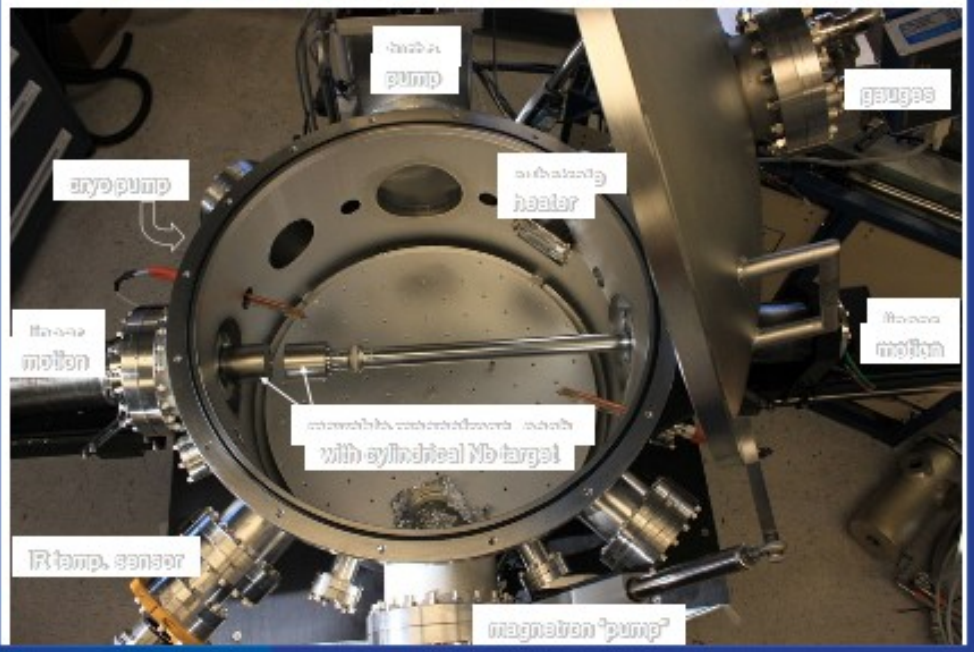
TTC Meeting, 28 February - 2 March, 2011, Milan

Summary of FNAL tests as of March, 2011
Reported by Joe Ozelis

# Thin Film Niobium Coated Cavities?

## High power impulse magnetron sputtering

**A state-of-the-art HIPIMS system for 1.3 GHz, Offering optional dual-HIPIMS and two-material HIPIMS**

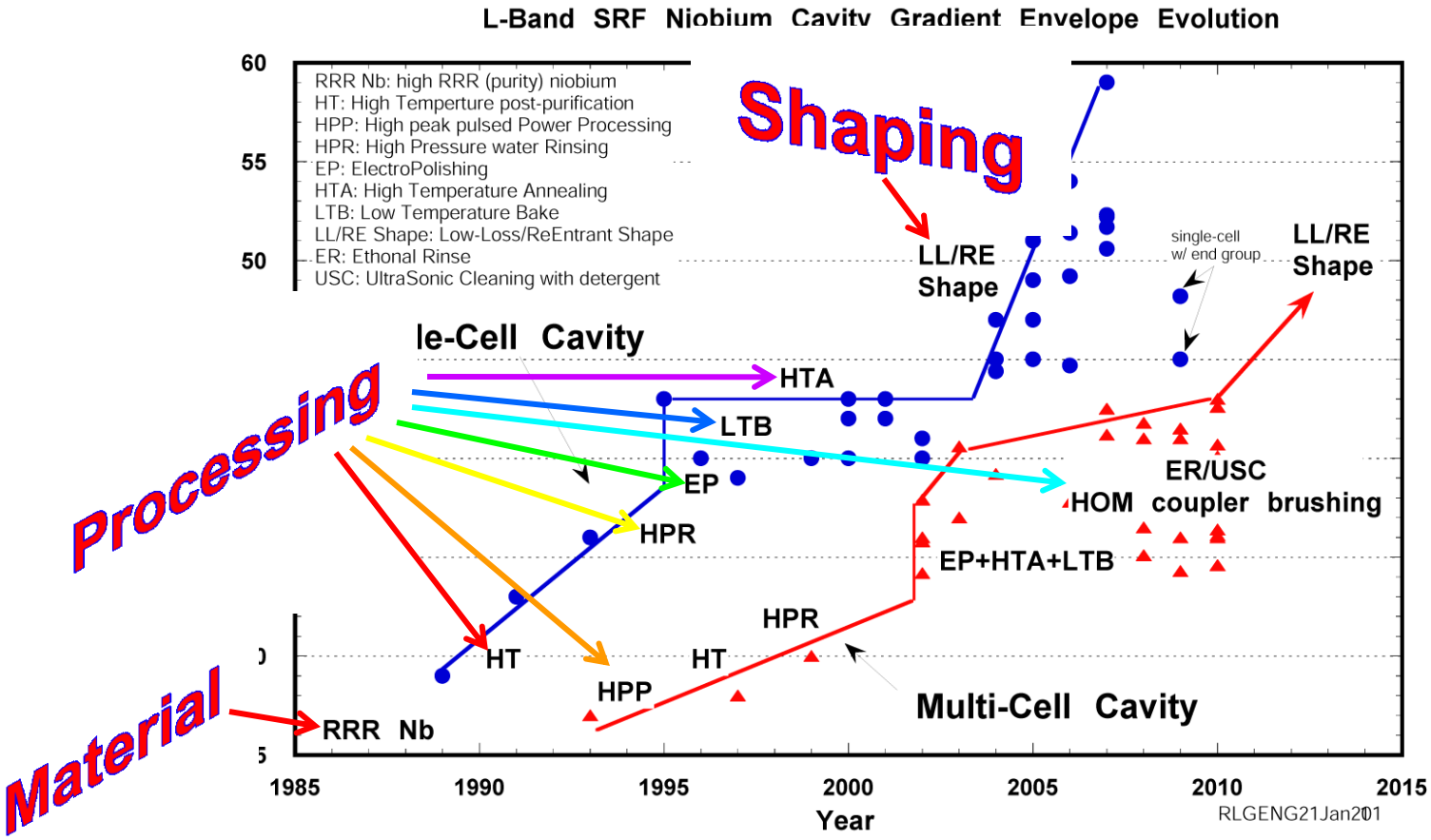



A. Anders, J. Vac. Sci. Technol. A 28 (2010) 783

- Zhou (J-Lab), with Alameda Applied Sciences: Nb films with RRR well above 300 attained for first time, Oct 2010
  - Flat films on hot sapphire
- Anders (LBL): HiPIMS system ready for cavities
- **Do the new break-throughs make Nb/Cu or Nb/Al work for ILC?**

18 Lance Cooley, Fermilab – ALCPG11, 20 March 2011 Fermilab

# 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.

# 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, FNAL, JLAB, 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.**

# Main Issues at Very High Gradients (1)

## Field Emission / Dark Current

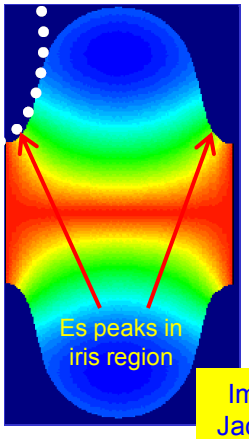



Image courtesy
Jacek Sekutowicz

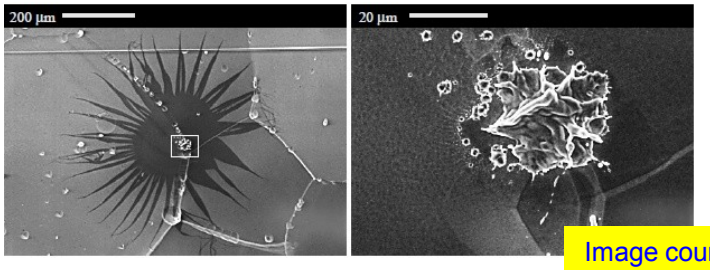
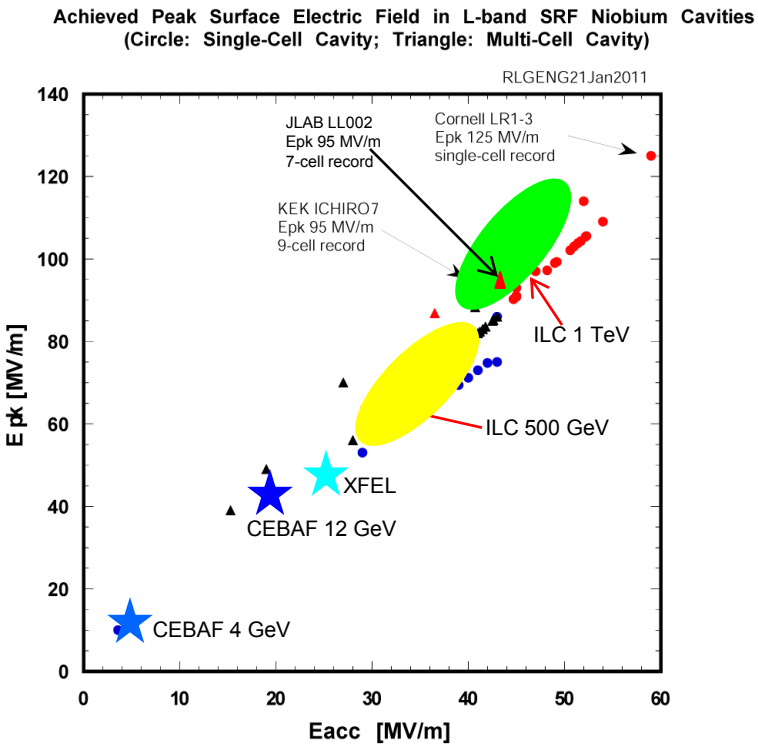



Image courtesy
Jens Knobloch

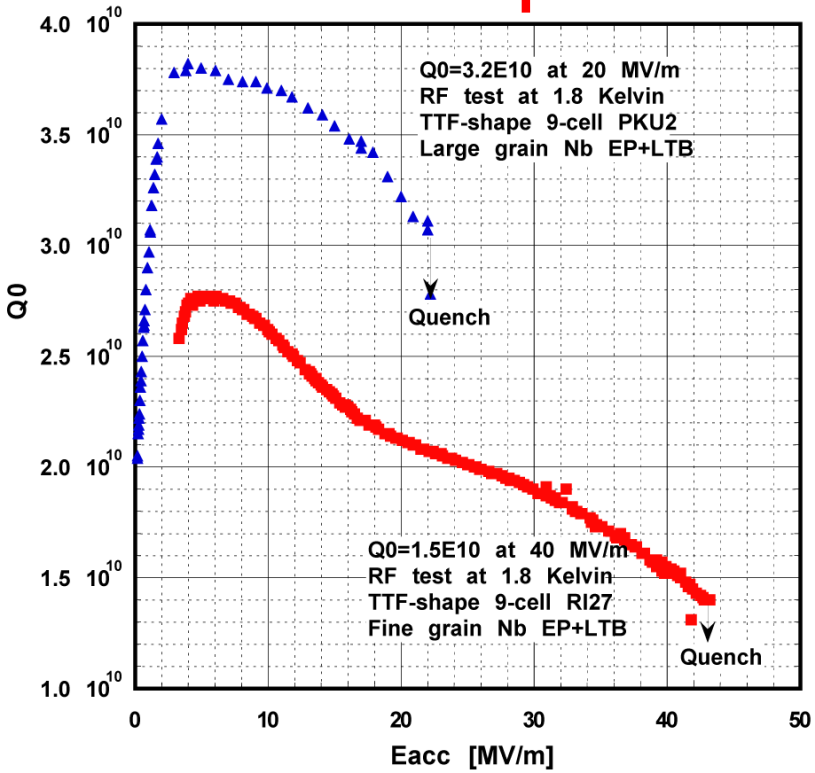


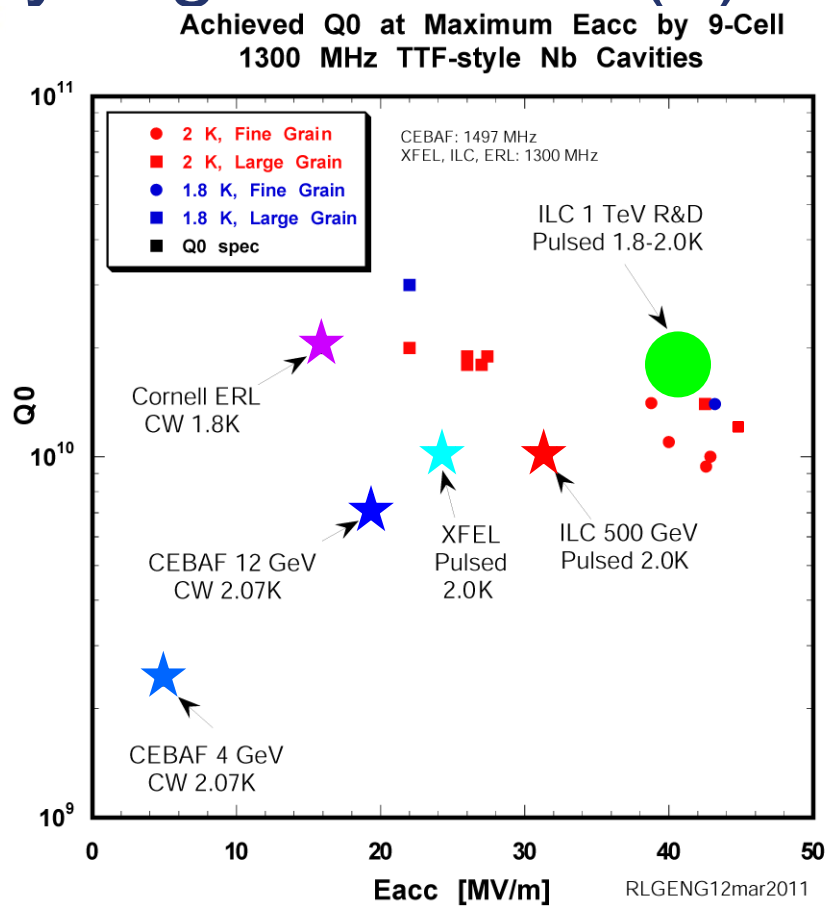

- Peak surface electric field (Epk) a governing parameter
- Physics fairly understood and no known fundamental limit
- Microscopic particles an important family of field emitters
- Epk 100-120 MV/m demonstrated in 1-cell Nb cavities
- Epk100-120 MV/m needed in multi-cell for ILC 1 TeV
  - Record Epk 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

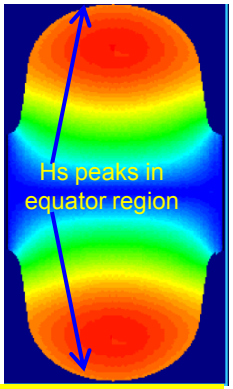
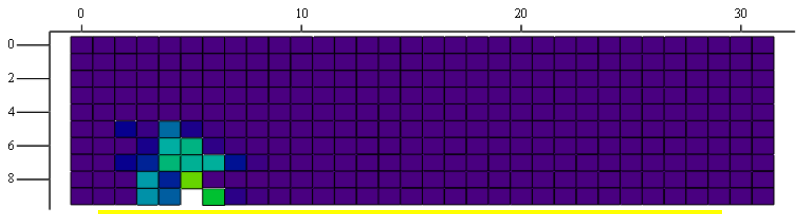
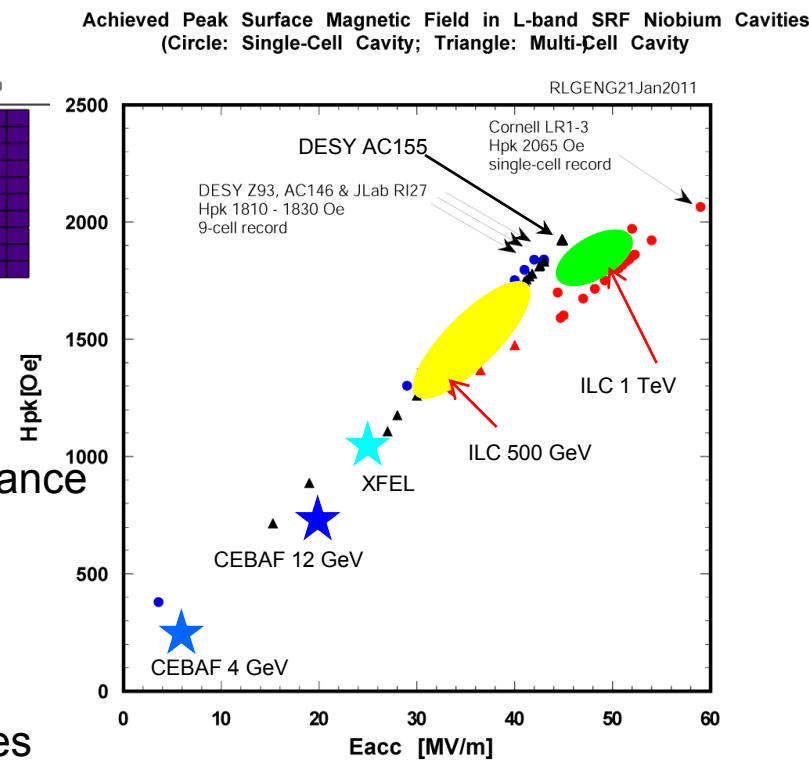



Image courtesy
Jacek Sekutowicz




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 1800-1900 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

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 local quench at very high gradient of 40-50 MV/m

Achievable gradient

Cavity surface chemistry

Material
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

(1) Alternate cavity shape for reduced Hpk/Eacc ratio. In hand (LL, RE, LSF).
(2) Uniform cavity processing for reduced local "bad" spots. In hand (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).