Cavity Gradient R&D Status and Future Plans for TDP-2

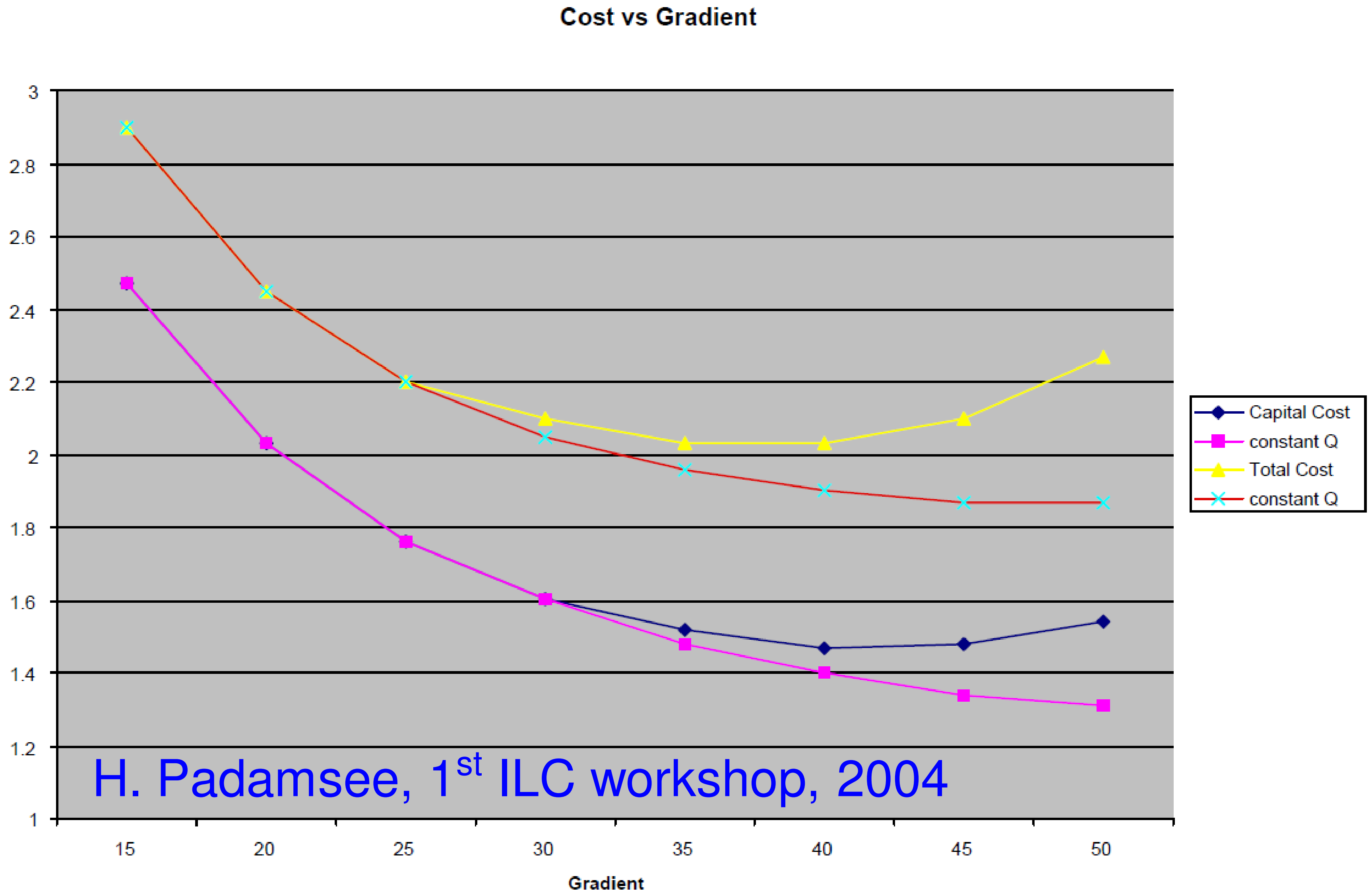
Rongli Geng
Jefferson Lab

Outline

- Brief history since 1st ILC workshop in 2004
  - BCD & ACD proposal, RDR, SB2009
  - Gradient scatter & S0
  - Efforts of FE reduction and results
  - Flat top operation with spread of gradients – ACD HLRF impact
- R&D status
  - Success of US industry built cavities
  - Understanding of gradient limit due to quench
  - Yield definition & global data base
- TDP-2 strategy and plan
  - Major issue: yield drop at ~ 20 MV/m due to quench
  - Path forward and high priority R&D issues
  - Resources
- Gradient choice considerations
  - Snowmass assumptions revisited
  - ACD issues

Brief history since 1st ILC workshop at KEK in 2004

Gradient a Major Cost Driver for ILC



ILC Gradient Goals

500 GeV: Gradient and Q

Based on BCD cavity shape (TESLA cavity)

- BCD: Linac operating performance
  Eacc = **31,5** MV/m; Q = **$1x10^{10}$**
- BCD: Installed performance
  Eacc ≥ **35** MV/m; Q ≥ **$0.8x10^{10}$**
  - Required R&D
    - Reduction of field emission and multipacting
    - Reduction of scatter of cavity performance

H.Edwards, D.Proch, K.Saito,
ILC snowmass 05, Wg5

Parameter	Value
Type of accelerating structure	Standing Wave
Accelerating Mode	TM_{010}, π mode
Fundamental Frequency	1.300 GHz
Average installed gradient	31.5 MV/m
Qualification gradient	35.0 MV/m
Installed quality factor	$\geq 1\times10^{10}$
Quality factor during qualification	$\geq 0.8\times10^{10}$
Active length	1.038 m
Number of cells	9
Cell to cell coupling	1.87%
Iris diameter	70 mm
R/Q	1036 Ω
Geometry factor	270 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT $MV^{-1}m^{-1}$
Tuning range	±300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Number of HOM couplers	2

2005 Snowmass BCD proposal → 2007 RDR → SB2009

4.1.2 Issues of Main Linac System Design

In conjunction with the (GDE and AAP) review process in 2010, based on the current R&D results we propose to keep the cavity gradient goals at 35MV/m in vertical test,S0, and 31.5MV/m in operation in an installed cryomodule, S1. We note that as the R&D progresses, including horizontal testing of

2006: S0 for ILC Cavity Gradient

The 'S' R&D Task Forces

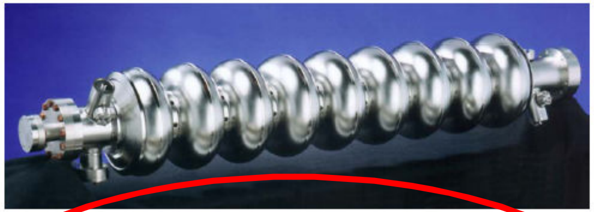
- **S0** High-Gradient Cavities
- **S1** High-Gradient Cryomodule
- **S2** Test Linac
- **S3** Damping Ring
- **S4** Beam Delivery
- S5…Sn

Priority: high

ILC Valencia 7th November 2006 **Globa**

The 'S' R&D Task Forces

- **S0 High-Gradient Cavities**
- S1 High-Gradient Cryomodule
- S2 Test Linac
- S3 Damping Ring
- S4 Beam Delivery



- Addresses current 'poor' yield for EP cavities
- Primary goal: establish parameters for routinely producing 35 MV/m EP'd cavities
  - **required ≥ 80% yield**

Yield is Key Word

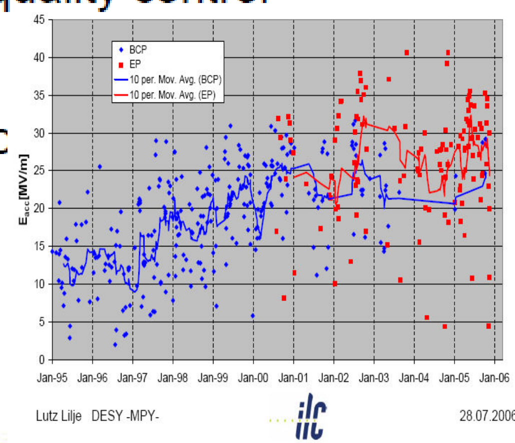
H. Hayano, T. Higo, L. Lilje, J. Mammosser, H. Padamsee, M. Ross, K. Saito

ILC Valencia 7th November 2006 **Global Design Effort** 55

Major Issue in 2006

Agreed High Priority R&D Issues

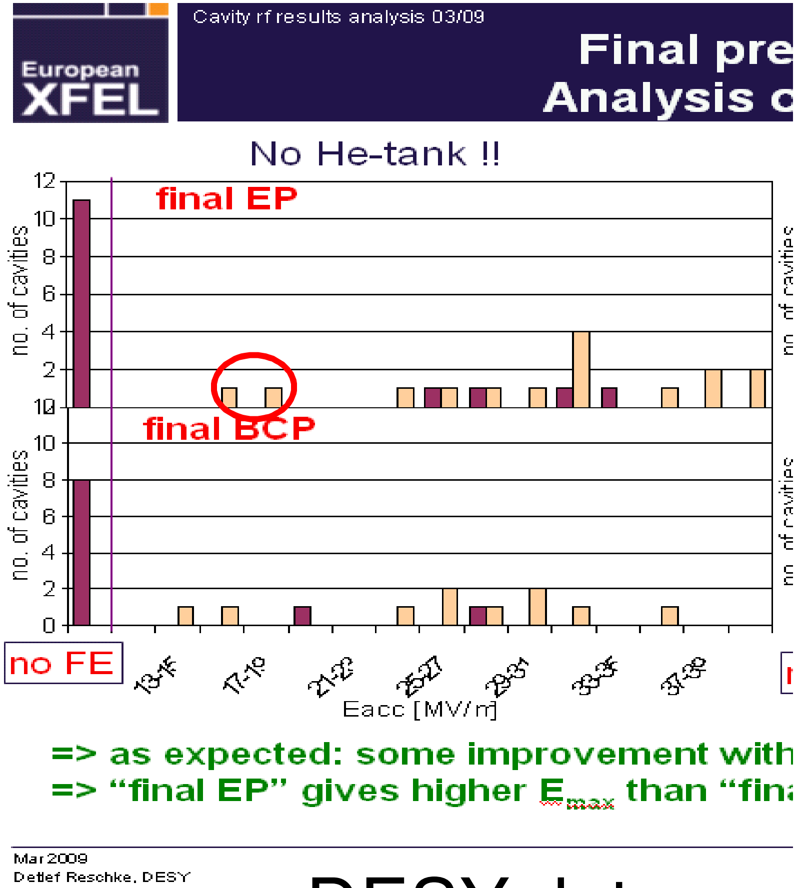
- Field emission control is the major R&D issue
  - Field emission is the major source for a large performance spread of cavities
- Quality control issues for surface preparation needs a major effort
  - E.g. acid quality control
  - Surface quality after several preparation steps needs to be controlled
    - Roughness control before final EP
  - Rinsing procedures need quality control
    - E.g. online-monitoring of particles in water from water draining out of the cavity
  - Reduction of cross-contamination due to integration of quality control steps (e.g. frequency tuning) inside the cleanroom
- Mass production issues for many steps need work
- Basic R&D needed for understanding ‘recipes‘ that wc etc.



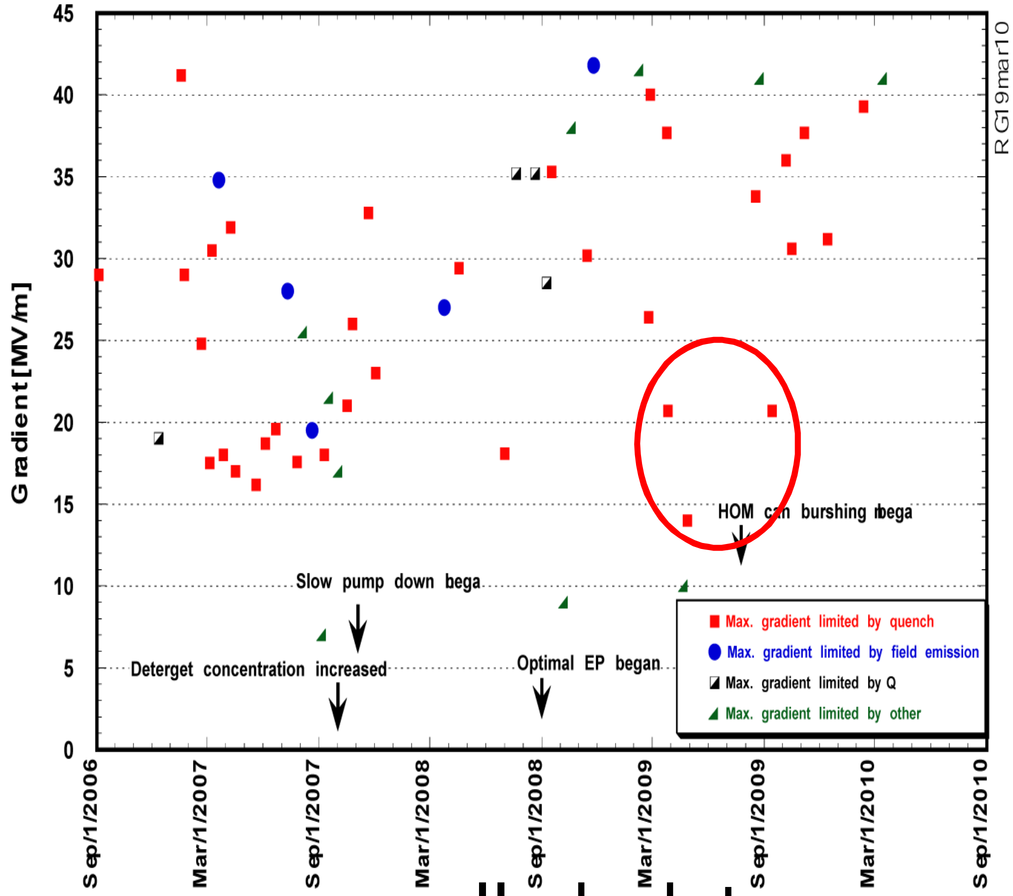
Lutz Lilje

Progress since 2006

- FE limit much reduced (Post-EP rinsing, assembly, optimal EP)
- Scatter remains - due to quench (more later)



DESY data

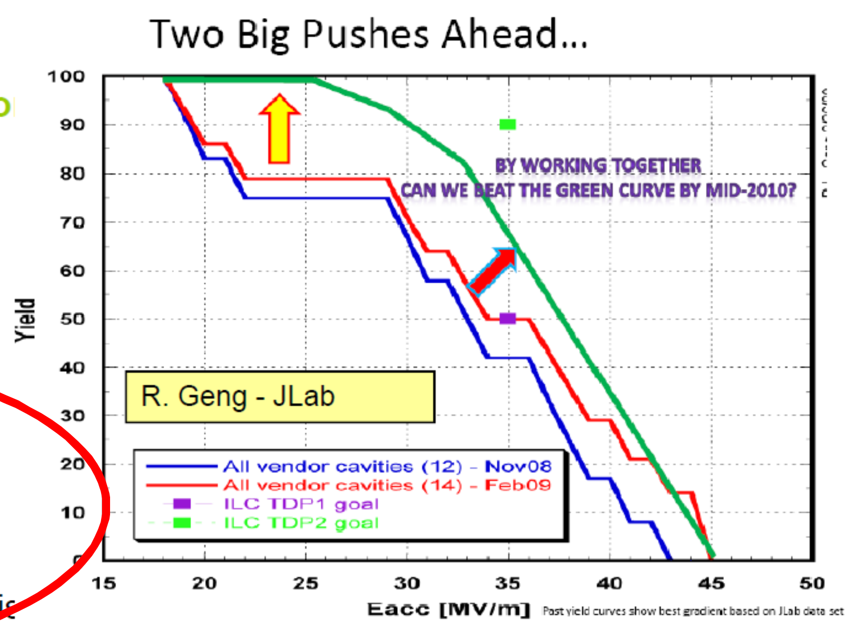


JLab data

Introduction of Diagnostics in 2008

Strategy to Improve Performance

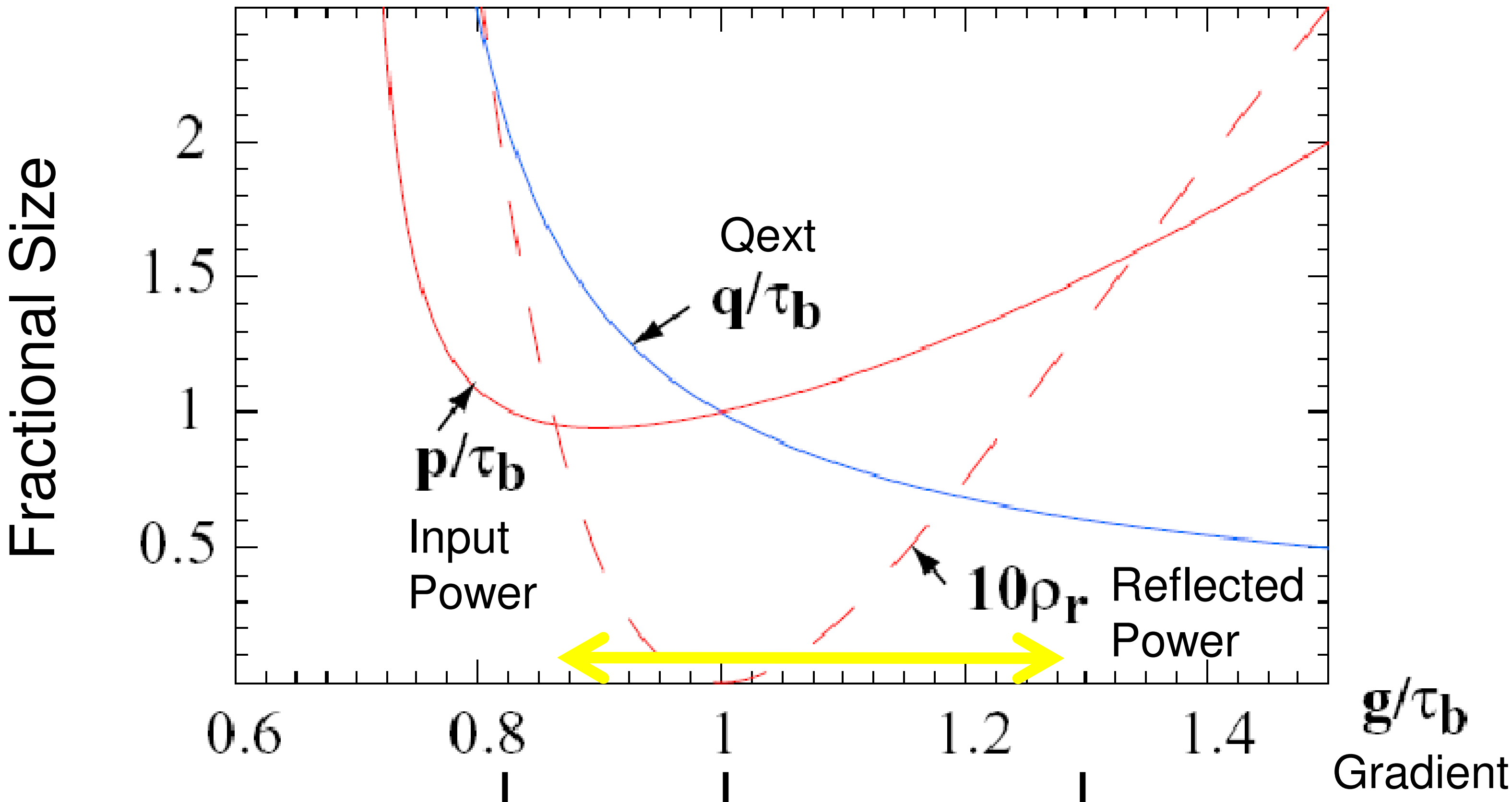
- The lower gradient part
  - **Vendor qualification**
  - **Improvement of fabricatio and weld quality**
  - **Typically larger defects, ‚easily‘ detectable**
- The higher gradient part
  - **More systematic studies needed**
- Tools are available
  - **Surface Mapping**
    - T-Map
    - Second Sound
  - **Optical inspection**
    - Common data evaluation is the way
- In addition:
  - **Study repair options**
    - Local grinding
    - Tumbling



T-mapping and optical inspection in routine use in past year with fruits…

SB2009 ACD HLRF
Flattop Operation with a Spread of Cavity Gradients

reported by C. Adolphsen



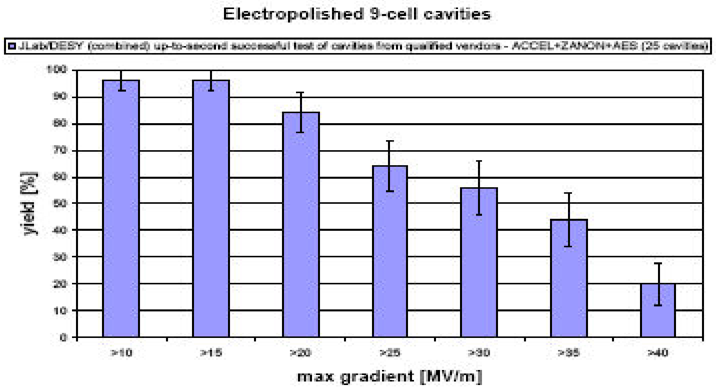
31.5 MV/m Average → 24.5 MV/m | 29.8 MV/m | 38.5 MV/m

Operation with Gradient Spread Increases Cavity Acceptance

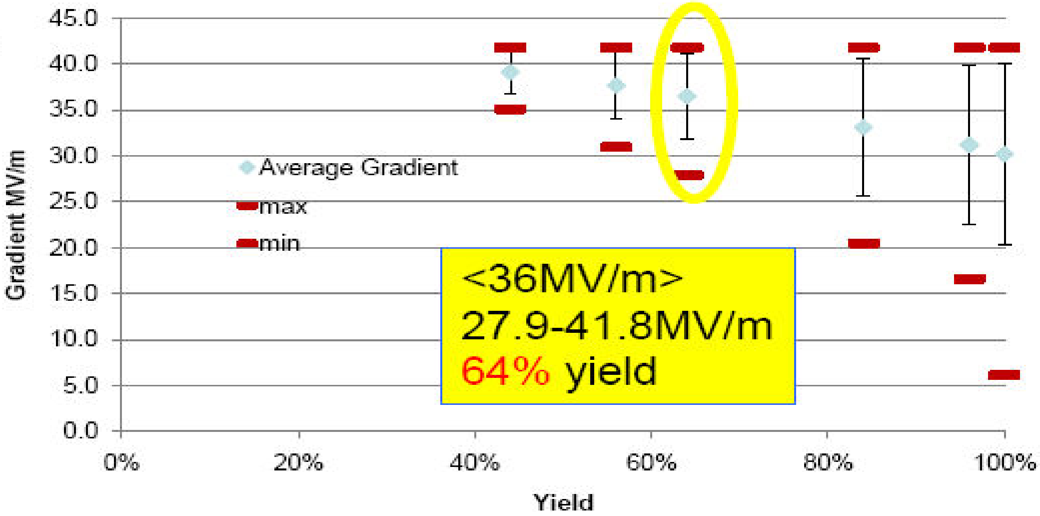
Alternative Yield Plot Analysis

originated by N. Walker

Dec 2009 Data:
1st +2nd Pass, 1st pass cut 35MV/m, vendors w/ 1 cavity > 35MV/m



>35MV/m
35-41.8MV/m
44% yield



-Yield: estimated assuming a specific lower cut-off in cavity performance, below which cavities are assumed 'rejected'.
- Error bar: +/- one RMS value (standard deviation of the population) of the remaining (accepted) cavities (gradient above cut-off).
- Additional bars (min, max) indicated the minimum and maximum gradients in the remaining cavities.

Cavity Gradient R&D Status

TDP Cavity Gradient R&D Goal and Milestone

ILC Research and Development Plan for the Technical Design Phase

Release 4

July 2009

ILC Global Design Effort

Director: Barry Barish

Prepared by the Technical Design Phase Project Management

Project Managers: Marc Ross, Nick Walker, Akira Yamamoto

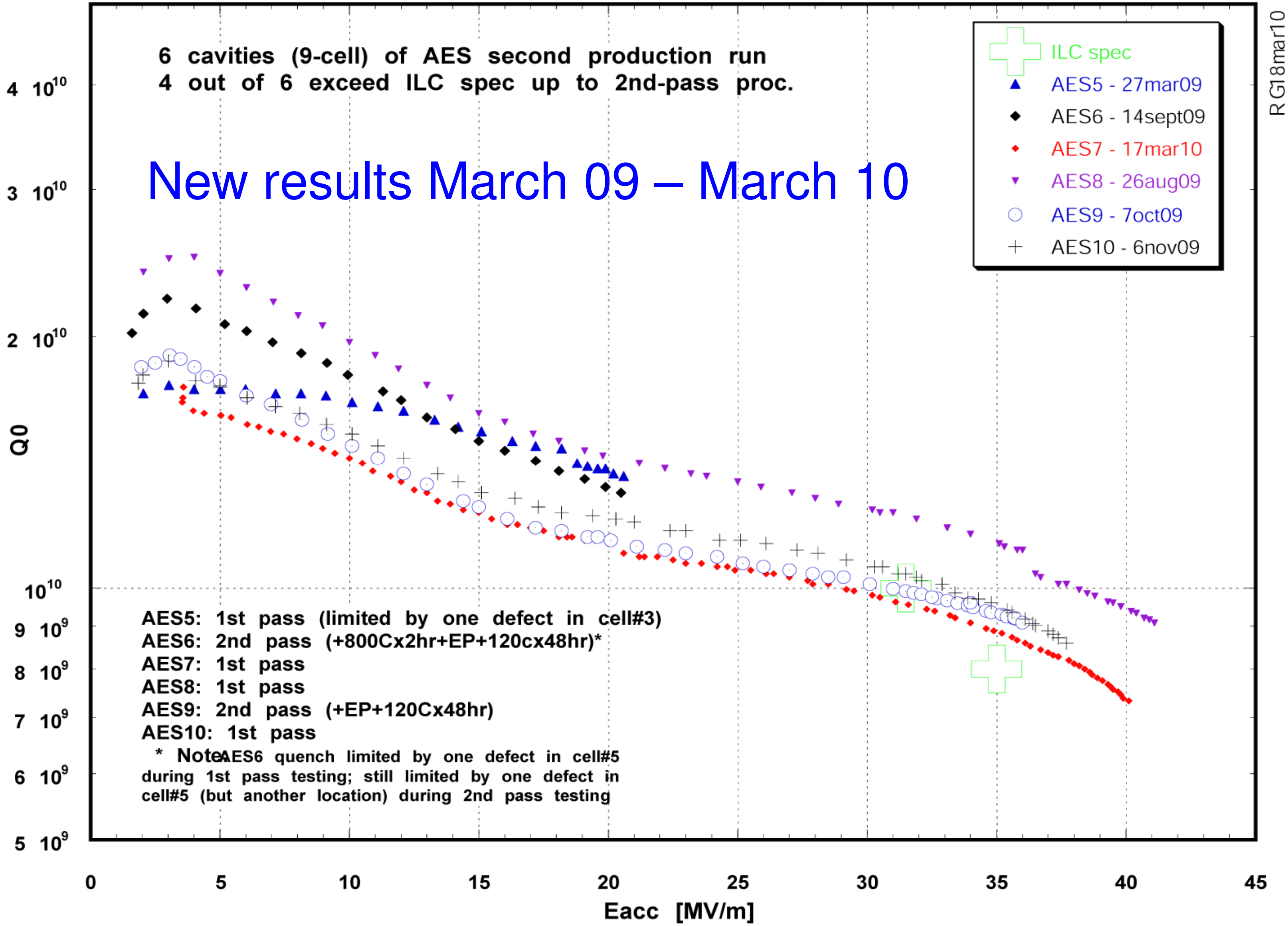
Table 3-1: Milestones for the SCRF R&D Program.

High-gradient cavity performance at 35 MV/m according to the specified chemical process with a process yield of 50% in TDP1, and with a production yield of 90% in TDP2 (S0, see section 3.1.3 for definition of process yield)	2010 2012

Global Gradient R&D Highlights

- Americas
  - **4 out of 6 9-cell cavities of AES second production exceed ILC spec.**
  - **FNAL/ANL joint facility 33 MV/m 9-cell EP processing and testing.**
  - **Improved understanding by T-mapping and optical inspection of 9-cell cavities.**
  - **Cornell OST's distributed to other labs.**
- Asia
  - **STF facility 38 MV/m 9-cell (MHI#8 after local grinding) EP processing and testing.**
  - **Improved understanding by T-mapping and optical inspection of 9-cell cavities.**
  - **Successful multi-wire slicing of ingot niobium.**
- Europe
  - **Improved understanding by T-mapping and optical inspection of 9-cell cavities.**
  - **Second sound detector commissioning.**
  - **XFEL cavity call for tenders.**
- GDE SCRF Cavity Technical Area
  - **Yield definition (1st-pass & 2nd-pass) proposed at AD&I meeting in May 28-29 2009.**
  - **Formed global cavity database team in summer of 2009.**

Results of AES Cavities EP and VT at JLab



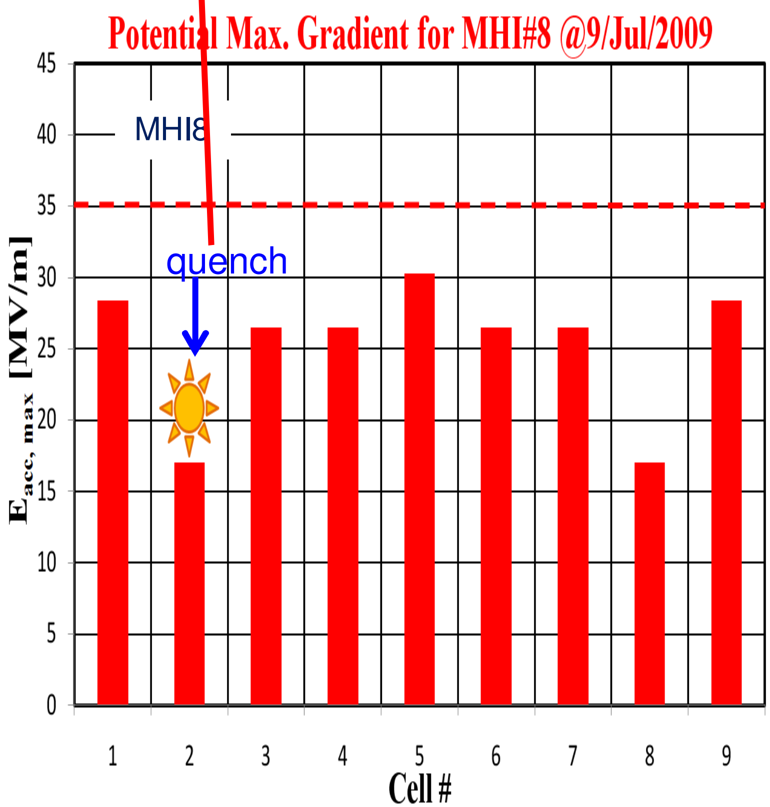
Understandings of Quench Limit

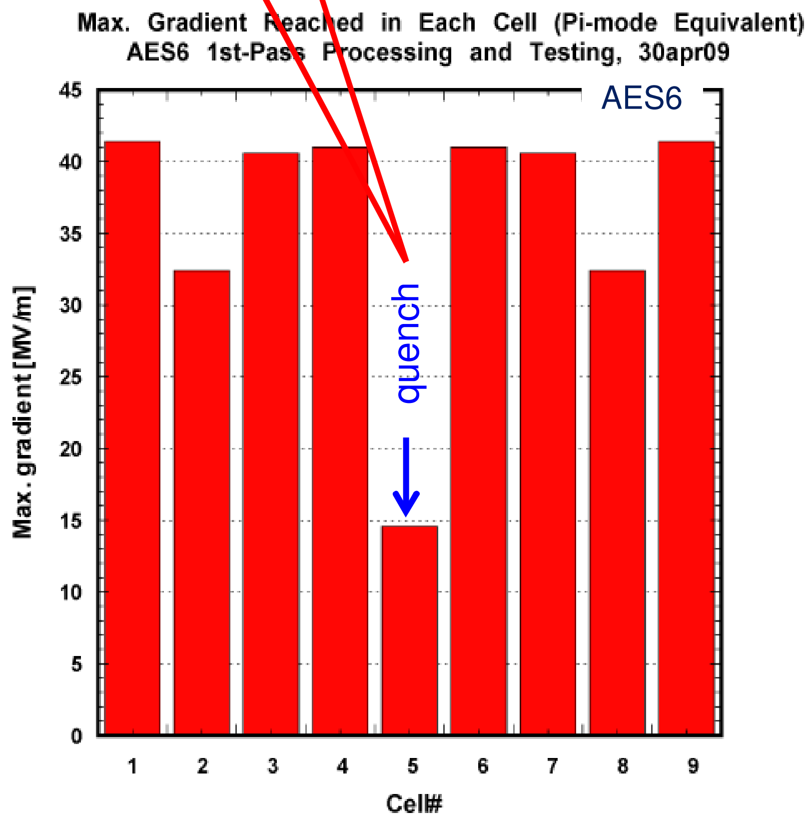
- Gradient limited by one defect in one cell
  - Other superior cells often reaching 30-40 MV/m already
  - Quench location often near equator weld
    - Some in the weld (due to obvious EBW error)
    - Some within 20 mm distance from seam (not so clear how they come about)
    - Many features observed on as-built surface – but they are not harmful
- Often times geometrical features observed at quench location for ~ 20 MV/m limit
  - Sub-mm sized pit or bump
  - Repeated EP has little effect
  - Examples found in cavities from all vendors
  - Local grinding removes defect for raised gradient
    - MHI8 for example (more later)
- Sometimes no observable (~10μm scale) irregularity
  - In this case, it is possible to raise gradient to > 35 MV/m by re-EP

Examples with Observable Defect

Deep pit at boundary of under-bead of equator EBW

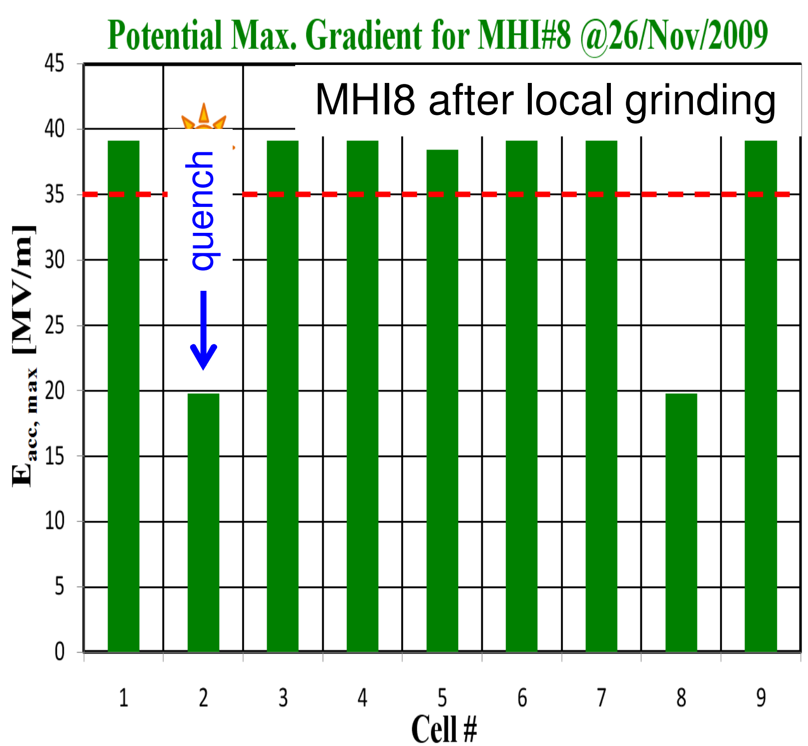
Twin defects 300-500μm dia. 8mm from equator EBW seam

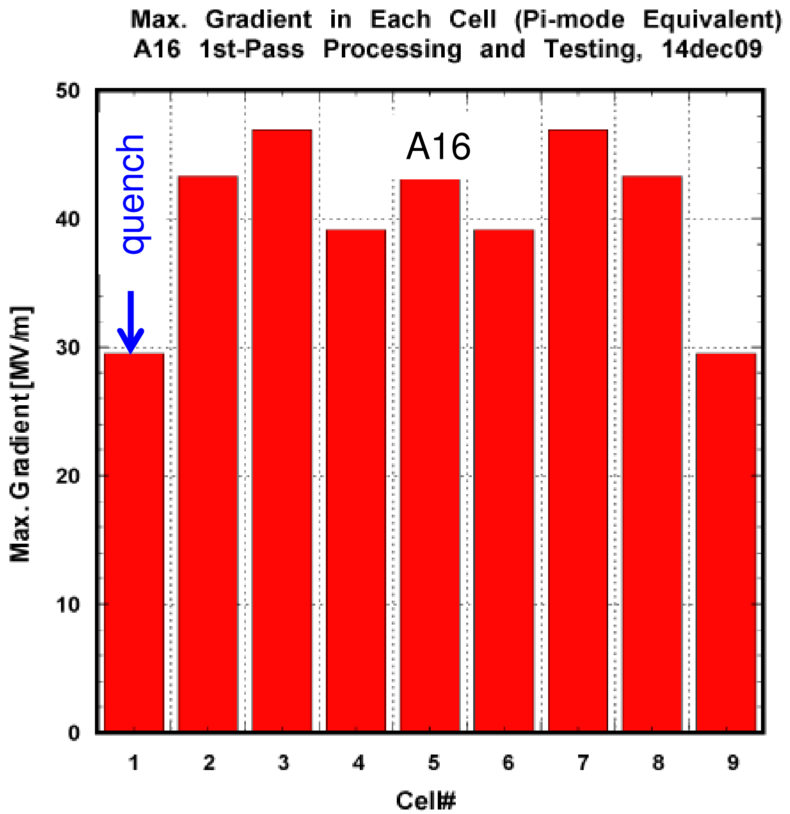




More Examples

- No geometrical defects (down to ~10μm) observed at quench location
- Re-EP effectively raises cavity gradient
    - MHI8: 18 MV/m >>> 38 MV/m
    - A16: 31 MV/m >>> 39 MV/m





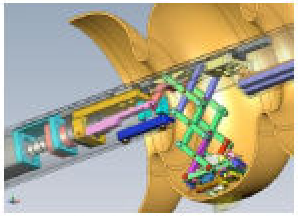
Defect Treatment Methods being Explored

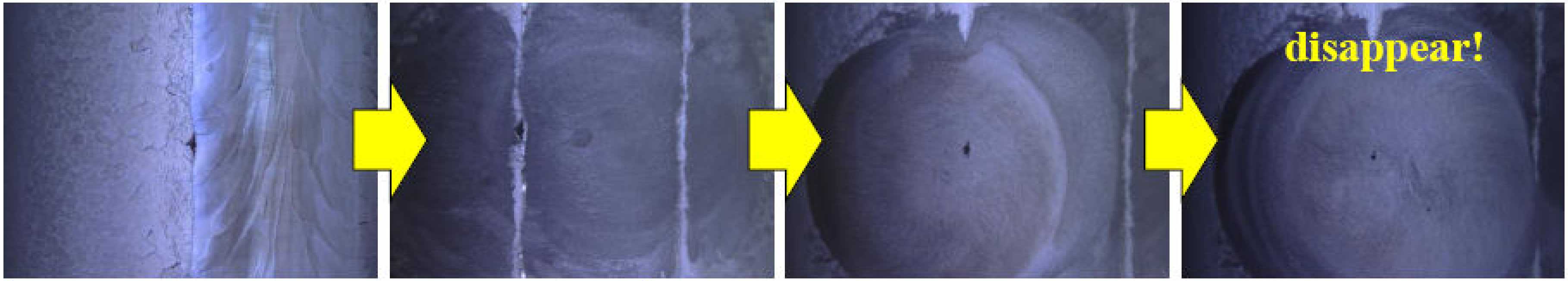
- Local treatment
  - **Local grinding**
    - Successful 9-cell demonstration at KEK
      - MHI8 (more later)
      - AES3: 20 MV/m >>> 30+ MV/m
  - **Local re-melting**
    - using electron beam
      - Successful 1-cell demonstration at JLab
    - using laser
      - Successful 1-cell demonstration at FNAL
- Global treatment
  - **Tumbling**
    - Successful 9-cell demonstration at Cornell

MHI8 Local Grinding at KEK

cell #2, 172° (triangle pit)

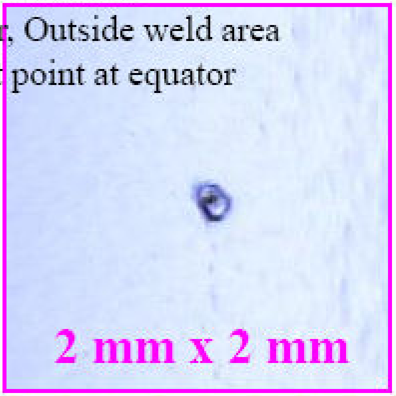
Local grinding was performed to remove it!



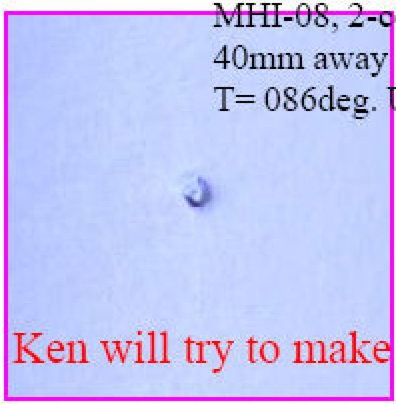


cell #2, 86° (ellipse bump)

After 2nd V.T. 195 um removed
MHI-08, 2-cell equator, Outside weld area
40mm away from joint point at equator
T= 086deg. Upstream



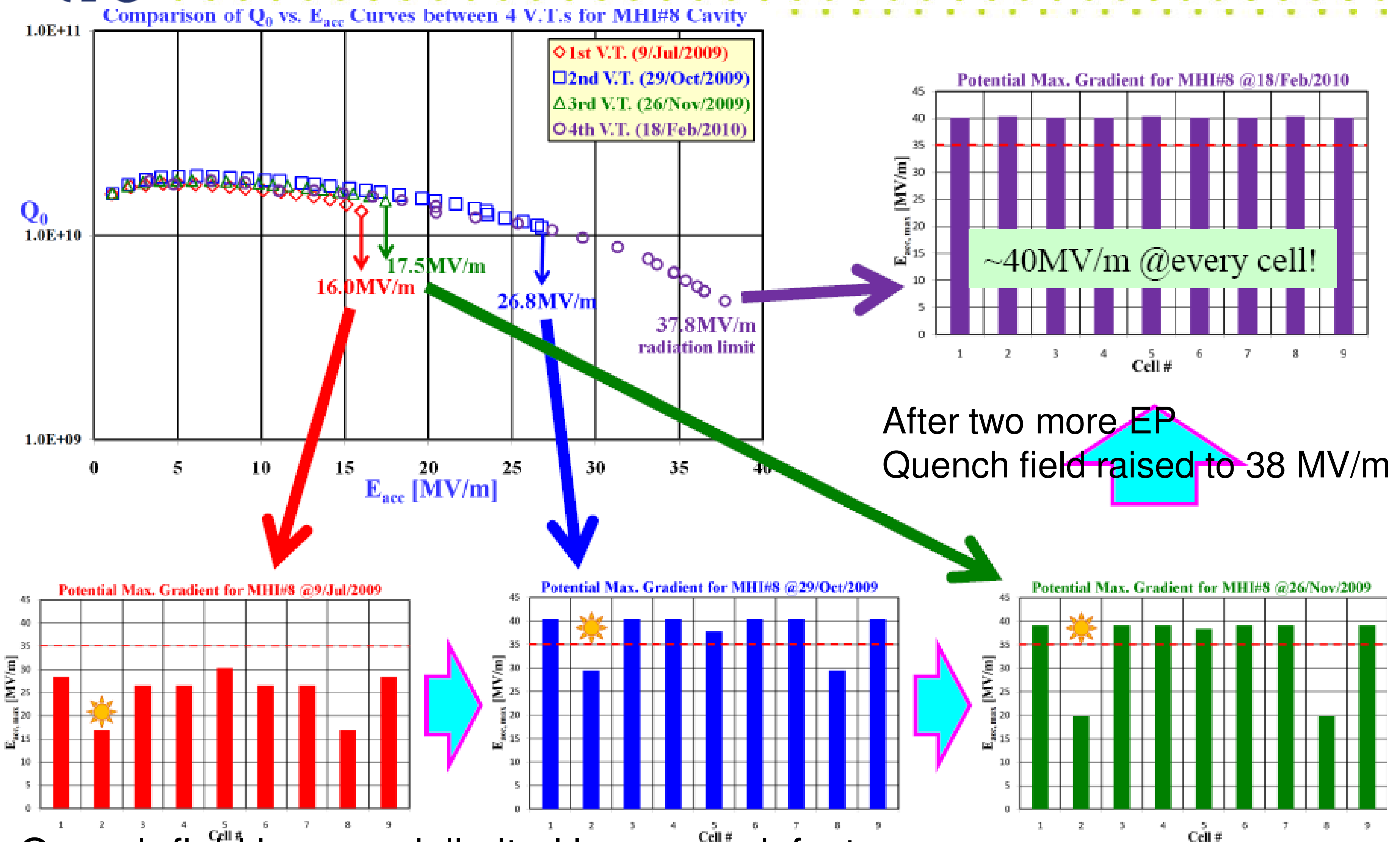
After 4th V.T. 235 um removed
MHI-08, 2-cell equator, Outside weld area
40mm away from joint point at equator
T= 086deg. Upstream



Ken will try to make the replica of the bump!

K. Yamamoto, this workshop

Local Grinding Removes Responsible Defect



After two more EP
Quench field raised to 38 MV/m

Quench field improved, limited by a new defect

Yield Definition – 1st-Pass

- **First-pass processing following "ILC recipe"**
- **If cavity qualified (35 MV/m @ Q0≥8E9) by first-pass, stop further proc.**
  - Different from "tight-loop" (earlier S0 approach)
  - Qualified cavity move on for S1
- **Failed proc./test due to known facility error excluded**
- **If cavity not qualified by first-pass then 2nd-pass**

ILC Processing & Testing Recipe (major steps)

- Heavy EP
- Vacuum furnace heat treatment
- Light EP
- Post-EP cleaning
- HPR and clean room assembly
- In-situ bake 120Cx48hr
- Cool down to 2K
- RF test
- (Further test with T-mapping)
- (Optical inspection for defect)

Yield Definition – 1st-Pass Yield

of cavities passing Eacc at 1st-pass processing

$$FPY(Eacc) = \frac{N(Eacc)}{N\_tot}$$

1st-pass yield at Eacc

# of cavities counted for yield

Yield Definition – 2^{nd} -Pass

- **First-pass test result drives second-pass processing (including treatment other than just EP)**
- **If cavity qualified by second-pass, stop further proc.**
  - Qualified cavity move on for S1
- **Failed proc./test due to known facility error excluded**
- **If cavity still not qualified by 2^{nd}-pass then further decision**

Possible second-pass treatments:

- For FE limited cavity in 1^{st}-pass
  - Re-HPR
  - Re-EP + 120cx48hr
- For quench limited cavities in 1^{st}-pass
  - Re-EP +120cx48hr
  - Local grinding + re-EP +120cx48hr
  - Tumbling + re-HT + re-EP + 120Cx48hr
  - Local e-beam re-melting (+ re-EP +120Cx48hr)
  - Local laser re-melting (+ re-EP +120Cx48hr)

Yield Definition – 2^{nd} -Pass Yield

2^{nd}-pass yield at Eacc

# of cavities passing final gradient of Eacc up to 2^{nd}-pass proc.

$$SPY(Eacc) = \frac{N2,1(Eacc)}{N\_tot - N\_no\_spp}$$

# of cavities counted for yield

# of cavities requiring 2^{nd} –pass proc. but 2^{nd}-pass processing not done yet

Data Cut for Yield Analysis

- No ACD cavities
  - **LL/RE**
  - **Large-grain**
- No BCP processing
  - **For damage layer**
  - **Or for final chemistry**
- Only cavities manufactured by experienced vendors
  - **ACCEL/RI**
  - **ZANON**
  - **AES**
  - **(MHI)**

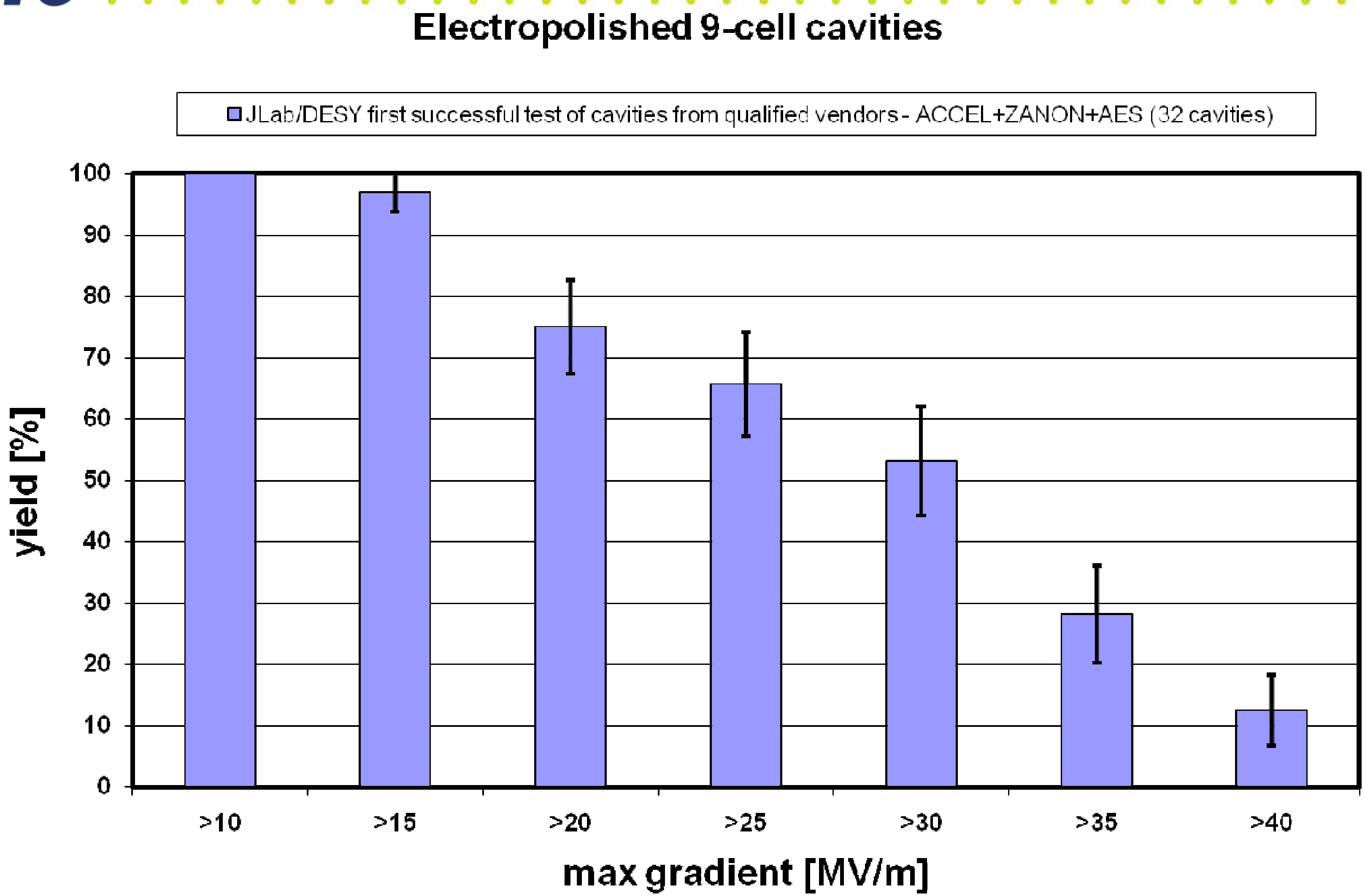
Global Data Collection

- Proposition 2: accept known variability
  - **Fine grain niobium ~~irrespective of vendors~~**
  - **EBW irrespective of prep design welding para.**
  - **Cavities w/ or without helium tank**
  - **With or without pre-EP treatment (BCP, CBP…)**
  - **EP irrespective of parameters & protocols**
    - Horizontal EP or vertical EP
    - $H_2SO_4/HF/H_2O$ ratio, pre-mixing or on-site mixing
    - Cell temp. control or return acid temp. control
    - W/ or w/o acid circulation after voltage shut off
    - Post-EP cleaning: ER or USC or H_2O_2 rinsing
  - **H2 out-gassing irrespective of temp. & time**
  - **HPR irrespective of nozzle style, HPR time**
  - **CR assembly irrespective of practice variability**

7/31/09 R.L. Geng **14th Cavity Group Meeting** 5

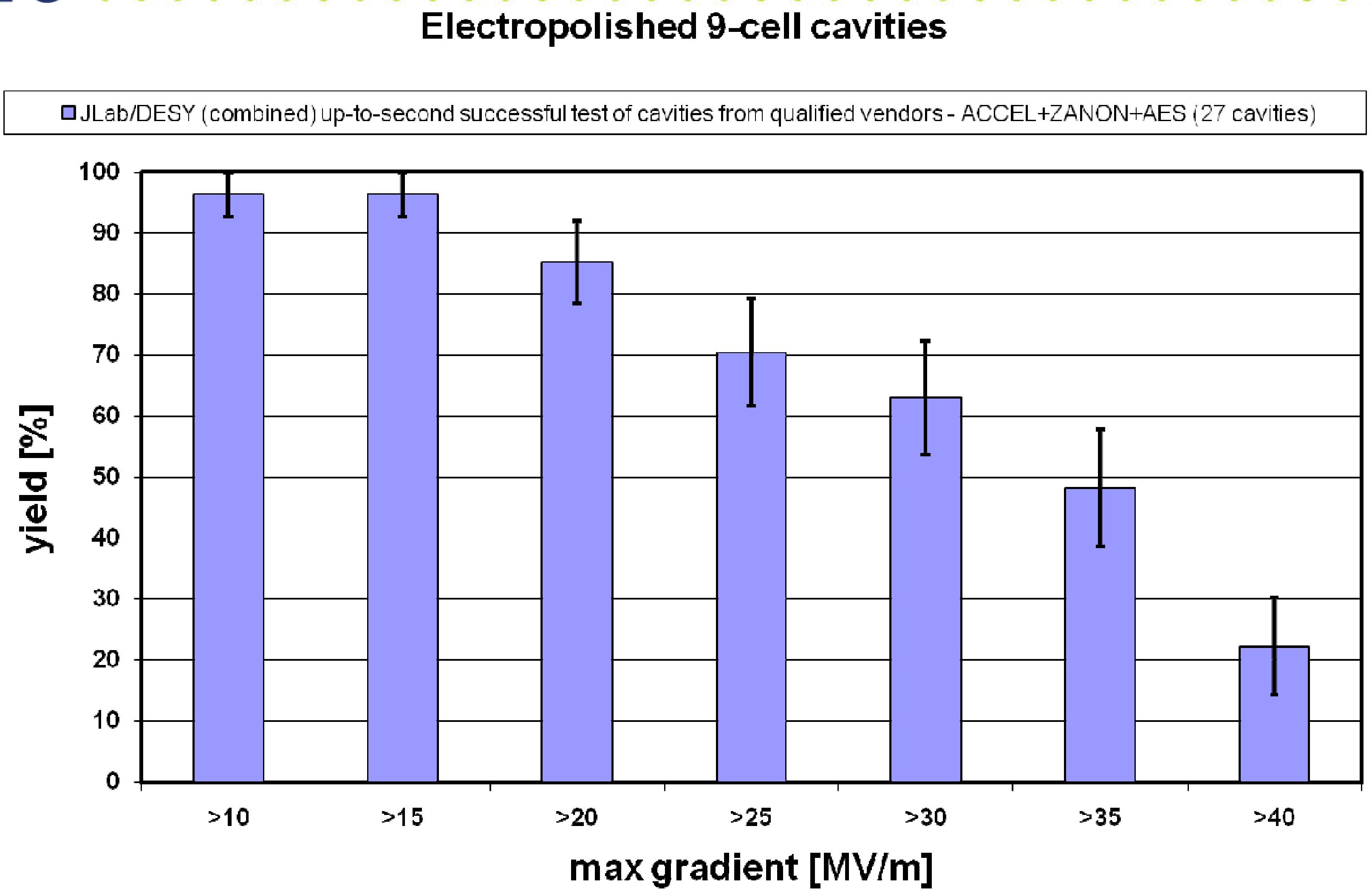
- Despite these cut, still known large variability in fab and proc
  - **<u>Large number of cavities required to reduce statistical error</u>**
  - **Some variability may be facility specific**

Global Gradient Yield Plots:1st Pass



Updated by C. Ginsburg as of March 2010

Global Gradient Yield Plots: 2nd -Pass



Updated by C. Ginsburg as of March 2010

TDP-2 Strategy and Plan

Major Challenge in TDP-2

- Yield drop at 15-20 MV/m is a major issue
  - **Shared issue with XFEL and CEBAF upgrade cavities**
- Solution requires actions in cavity fabrication
  - **EBW QA/QC**
  - **Finished weld inspection**
  - **Early correction**
- Feedback enables change and then progress expected
  - **Experienced vendors**
  - **New vendors**

Guideline: Standard Procedure and Feedback Loop

	Standard Fabrication/Process	(Optional action)	Acceptance Test/Inspection
Fabrication	Nb-sheet purchasing		Chemical component analysis
	Component (Shape) Fabrication		Optical inspect., Eddy current
	Cavity assembly with EBW	(tumbling	Optical inspection
Process	EP-1 (Bulk: ~150um)		
	Ultrasonic degreasing (detergent) or ethanol rinse		
	High-pressure pure-water rinsing		Optical inspection
	Hydrogen degassing at 600 C (?)	750 C	
	Field flatness tuning		
	EP-2 (~20um)		
	Ultrasonic degreasing or ethanol	(Flash/Fresh EP) (~5um))	
	High-pressure pure-water rinsing		
	General assembly		
	Baking at 120 C		
Cold Test (vertical test)	Performance Test with temperature and mode measurement	Temp. mapping	If cavity not meet specification Optical inspection

090528 ADI Meeting at DESY 17

Path Forward

- Successful cavity result involves three aspects
  - **Material production**
  - **Cavity fabrication**
  - **Cavity processing**
- Yield improvement requires QA/QC in all aspects
- *Address them systematically for end results*
  - **Two examples**
  - **Heat treatment recovers/improves bulk material properties**
    - This increases defect tolerance
    - Standard heat treatment: DESY 800x2hr, JLab 600ºCx10hr , KEK 750ºCx3hr
    - Recent heat treatment change (600°Cx10hr to 800°Cx2hr) at JLab
  - **Post-fab treatment removes fabrication flaws**
    - EP removes burs and galling
    - Tumbling removes pits/bumps

High Priority R&D Issues for TDP-2

- Fabrication QA/QC
- EBW optimization
- Local repair method development
- ACD damage layer removal
  - **Barrel polishing**
  - **Tumbling**
  - **BCP ?**
- In parallel, continue final EP QA/QC for improved proc. stability and reproducibility
- Further suppress field emission up to 40 MV/m

Prospect of New Cavities in TDP-2

Progress and Prospect of Cavity Gradient Yield Statistics

	PAC-09 Last/Best May 2009	FALC 1st Pass Jul 2009	ALCPG 2nd Pass Oct 2009	Current Dec 2009	Coming Prod/Test Jun 2010	Research cavities	Coming Prod/Test till 2012
DESY	9 (AC) 16 (ZA)	8 (AC) 7 (ZA)	14 (AC/ZA)	10-6 (Prod-4)	5	8 (large grain)	24+800-x ?
JLAB FNAL/ANL/ Cornell	8 (AC) 4 (AE) 1 (KE-LL5) 1 (JL-2)	7 (AC)	7 (AC)	5 (AE) 1 (AC)	12 (RI) 6 (AE) 2 (AC)	6 (NW) (including large-G)	40+y ?
KEK/IHEP /PKU			(4 -4:MH)	5 -5 (MH)	2 (MH)	~5 (LL) 1 (IHEP) 2 (PKU)	15+z?
Sum	39	22	21	21 -11	27	**~ 22**	
G-Sum				42-11 = 31	69-11=58		

Statistics for Production Yield in Progress to reach ~ 60, within TDP-1.
We may need to have separate statistics for 'production' and for 'research',

Resources

- On-going globally coordinated S0 effort
  - **ANL, Cornell, DESY, FNAL, JLab, KEK**
- XFEL cavity production (800 cavities)
- EU ILC-HiGrade
- FNAL new cavity orders and US new vendor development
- CEBAF 12-GeV cavity production (80 cavities)
- KEK new cavity orders from Japanese industry including new vendor development
- New vendor development in Canada, China and India

Gradient Choice Considerations

Snowmass Assumptions Revisited

2005 limit assumption

Cavity Performance

- Theoretical RF magnetic limit: ~45 MV/m for BCD supported by recent experience at DESY including 1-cell result
  - Tesla shape: 41 MV/m ➔
  - LL,RE shape: 47 MV/m ➔ ~60 MV/m for ACD supported by 2007 Cornell 1-cell data
- Present practical limit in multi-cell cavities -10%
  - TESLA shape. 37 MV/m ➔ 40 MV/m
  - LL, RE shape: 42.3 MV/m
- Lower end of present fabrication scatter (σ = 5%)
  - TESLA shape: 35 MV/m
  - LL, RE shape: 40 MV/m
- Operations margin -10 %
  - TESLA shape: 31.5 MV/m
  - LL, RE shape: 36 MV/m

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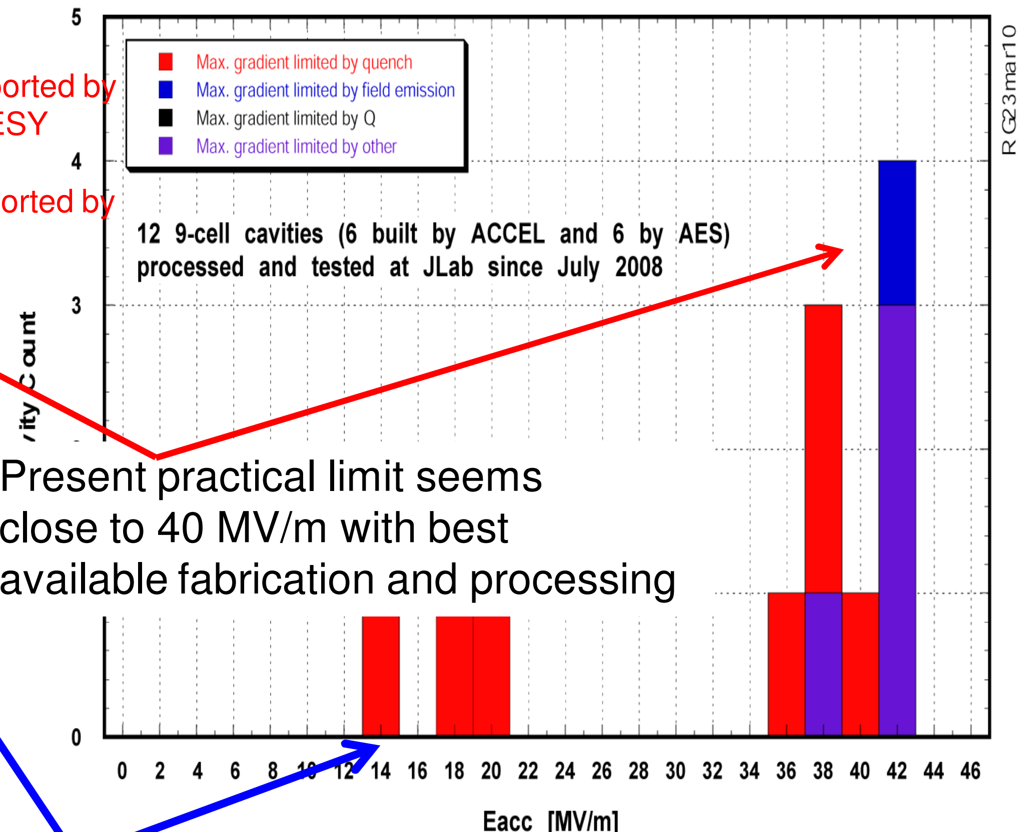
ILC snowmass 05, Wg5

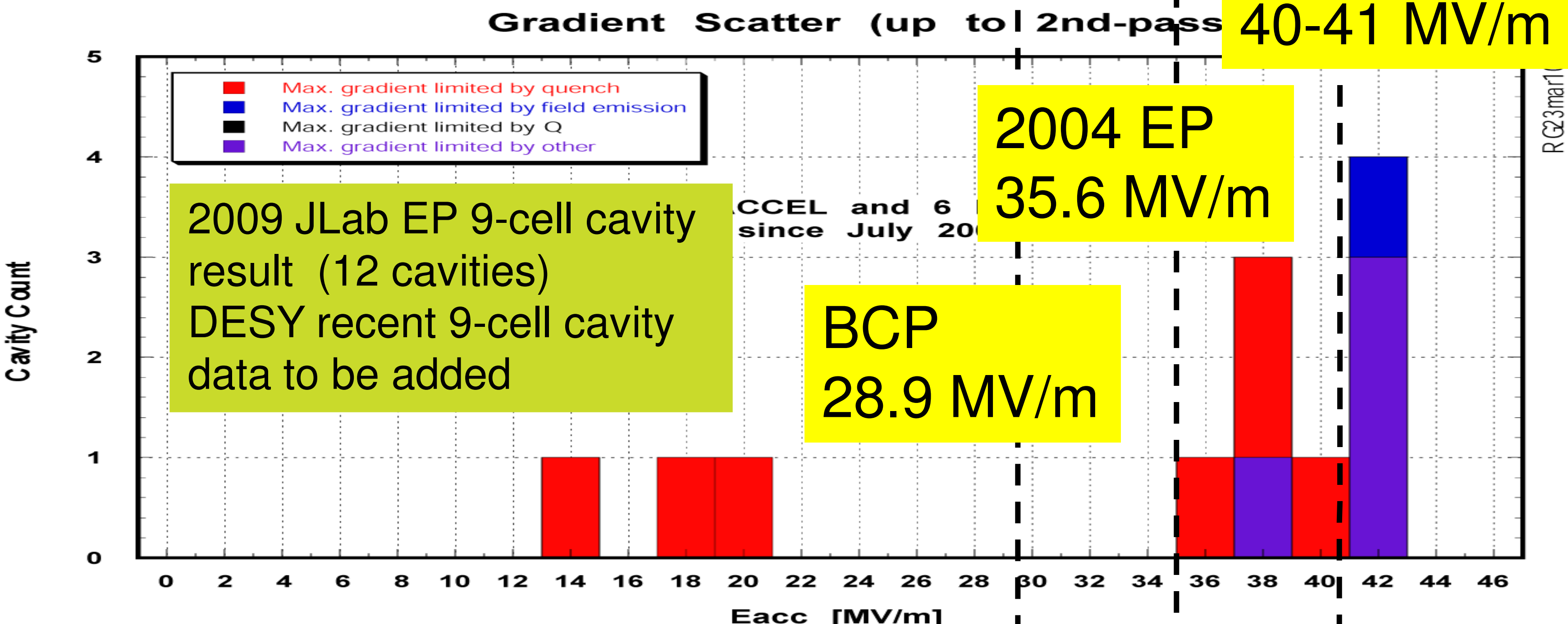
2009 update from
12 cavities by ACCEL & AES EP at JLab



Present practical limit seems close to 40 MV/m with best available fabrication and processing

Further R&D may be required to achieve this

“practical limit” update

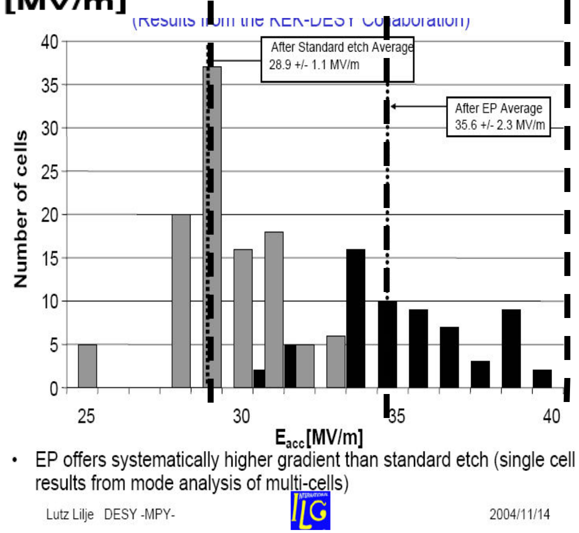


2009 EP
40-41 MV/m

2004 EP
35.6 MV/m

BCP
28.9 MV/m

2009 JLab EP 9-cell cavity result (12 cavities)
DESY recent 9-cell cavity data to be added



2004 DESY EP 9-cell cavities
Gradient distribution in cells from pass-band measurements (~ 8 cavities)

ACD Issues

Further progress in yield improvement and FE reduction requires accelerated R&D in ACD topics

BCD Proposal

- Hottest topics
  - Damage layer Removal
    - BCD: Electropolishing (EP)
    - ACD 1: Mechanical Grinding + small etch or EP
    - ACD 2: Etch
  - Furnace treatment
    - BCD: 800°C
    - ACD: 1400°C
  - Final surface preparation
    - BCD: EP
  - Final cleaning
    - BCD: High Pressure Rinsing with ultra-pure water
    - ACD 1: Dry-ice cleaning
    - ACD 2: Megasonic rinsing
  - Bakeout
    - BCD: 'In-situ' bakeout 120
    - ACD: Air bakeout as part of the drying process

Cavity Performance

- Theoretical RF magnetic limit:
  - Tesla shape: 41 MV/m
  - LL,RE shape: 47 MV/m
- Present practical limit in multi-cell cavities -10%
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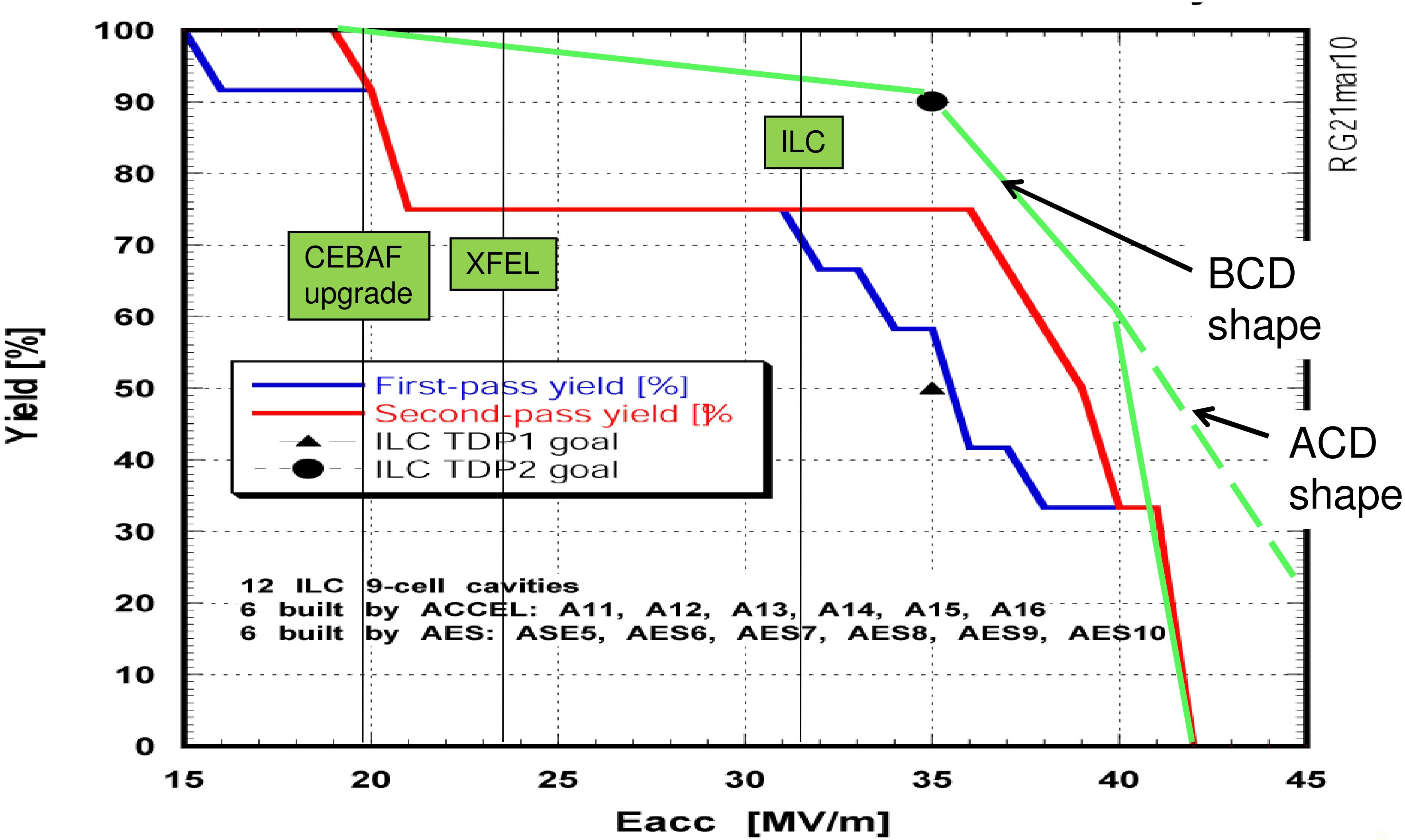
- Lower end of present fabrication scatter (σ = 5%)
  - TESLA shape: 35 MV/m
  - LL, RE shape: 40 MV/m
- Operations margin -10 %
  - TESLA shape: 31.5 MV/m
  - LL, RE shape: 36 MV/m

H.Edwards, D.Proch, K.Saito,
ILC snowmass 05, Wg5

An Optimistic Expectation at end of TDP-2



Conclusion

- Gradient R&D history (focus on 9-cell and yield) since 1st ILC workshop briefly reviewed
- Successful FE reduction due to past S0 effort presented
- Global competence in high gradient EP processing in place
- US vendor qualified for cavity production meeting ILC spec
- Yield definition clarified and global cavity database in place
- Quench detection (T-mapping/Cornell OST) and optical insp. in routine use and quench limit understanding improved
- Major issue for future gradient R&D identified
- High priority R&D issues for TDP-2 presented
- Some ACD topics identified for more aggressive push
- And finally, Continued gradient progress expected in TDP-2

Acknowledgement

Many thanks to colleagues from Cornell, DESY, FNAL, KEK, JLab for contribution

Especially Detlef Reschke for critical comments and Camille Ginsburg and the global database team for input

Backup Slides

2004 State-of the-art EP 9-Cell Cavities at DESY Foundation of RDR Gradient Choice

CERN COURIER

Jan 27, 2004

Superconducting cavities exceed 35 MV/m

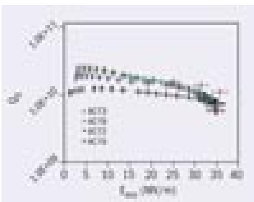


Figure 1

Development work for the TESLA linear collider has recently made substantial progress. After a surface treatment called electrolytic polishing, four superconducting nine-cell niobium cavities reached accelerating gradients of more than 35 MV/m. This is the performance required for an upgrade of TESLA to 800 GeV (*CERN Courier* November 2003 p22).

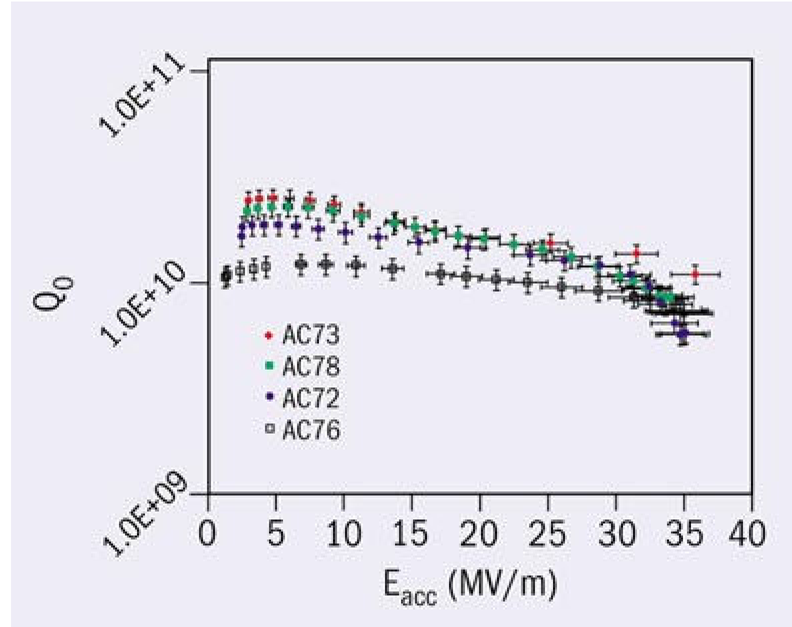
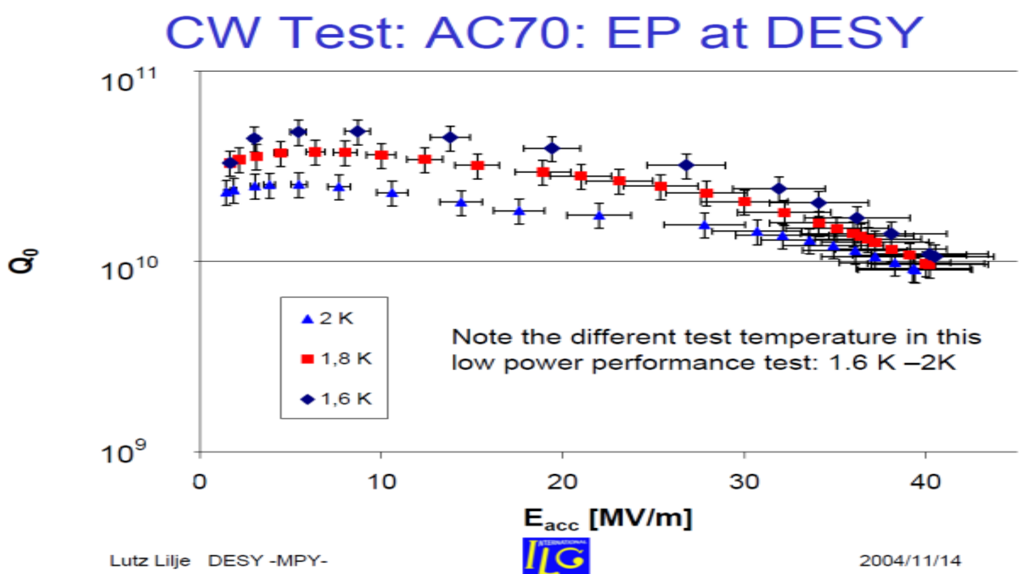
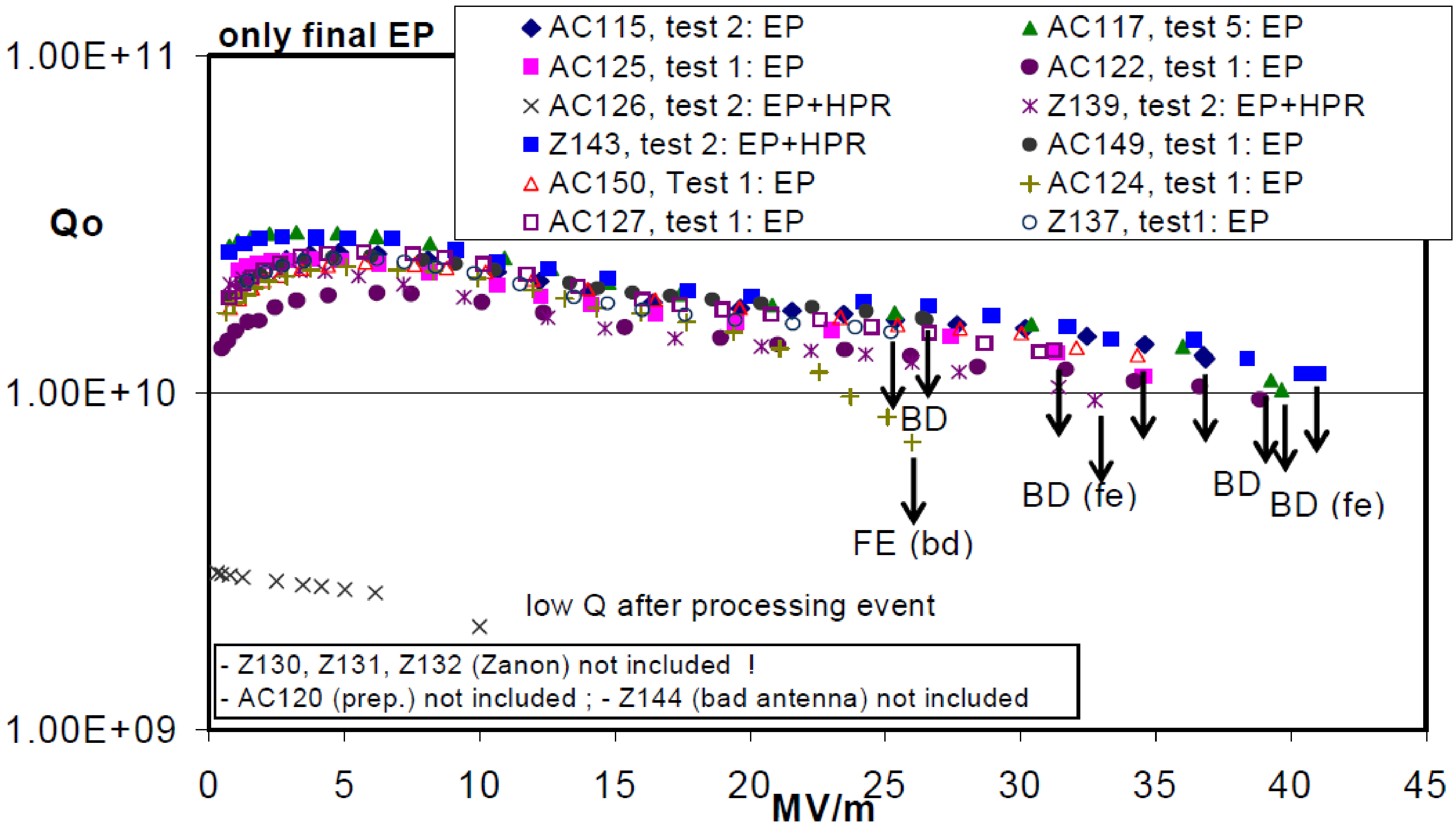


Fig. 1. Excitation curves of the four best nine-cell cavities after electropolishing at Nomura Plating, Japan. The quality factor Q_0 is shown as a function of the accelerating field. The tests were performed at 2 K.

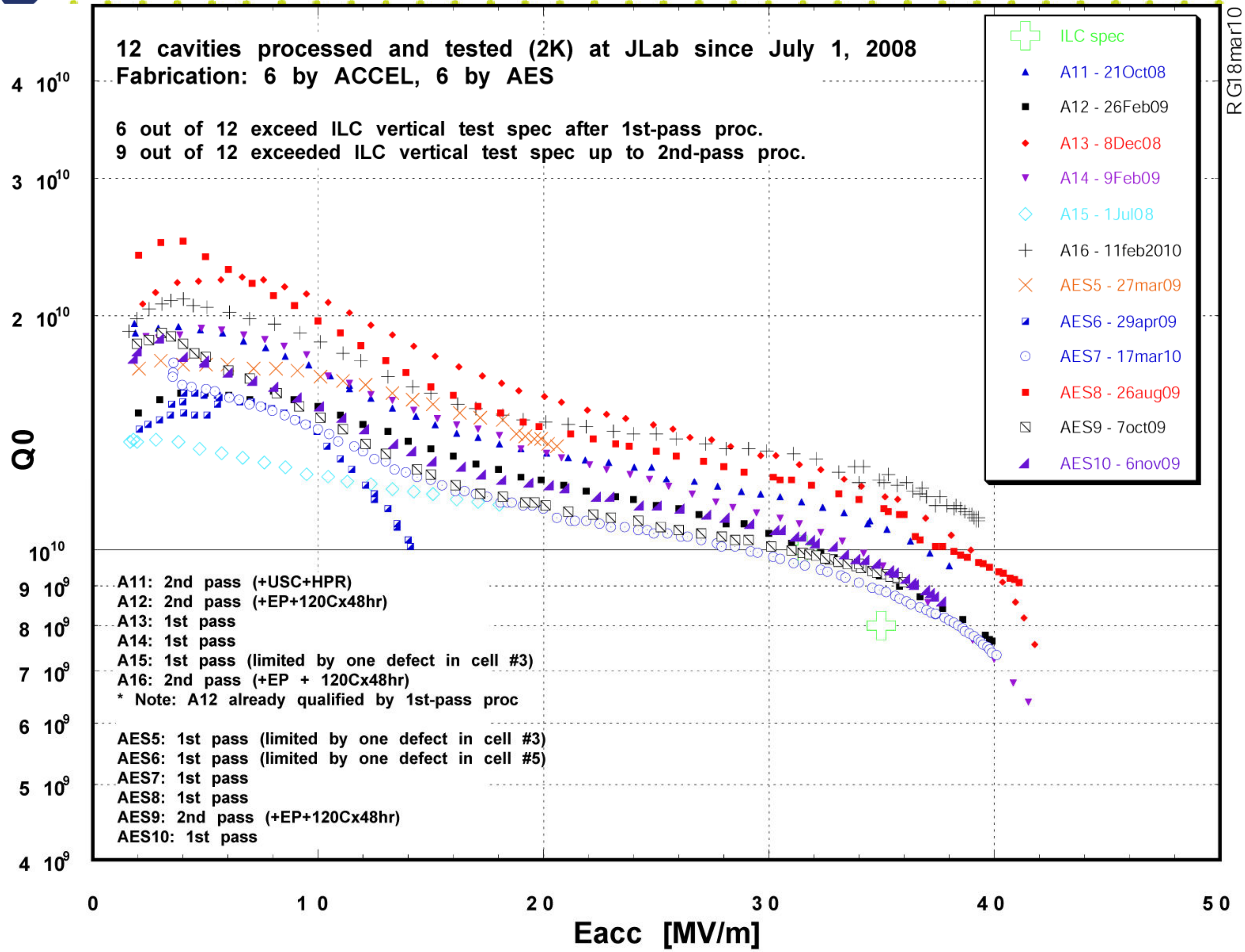


Latest Results from DESY



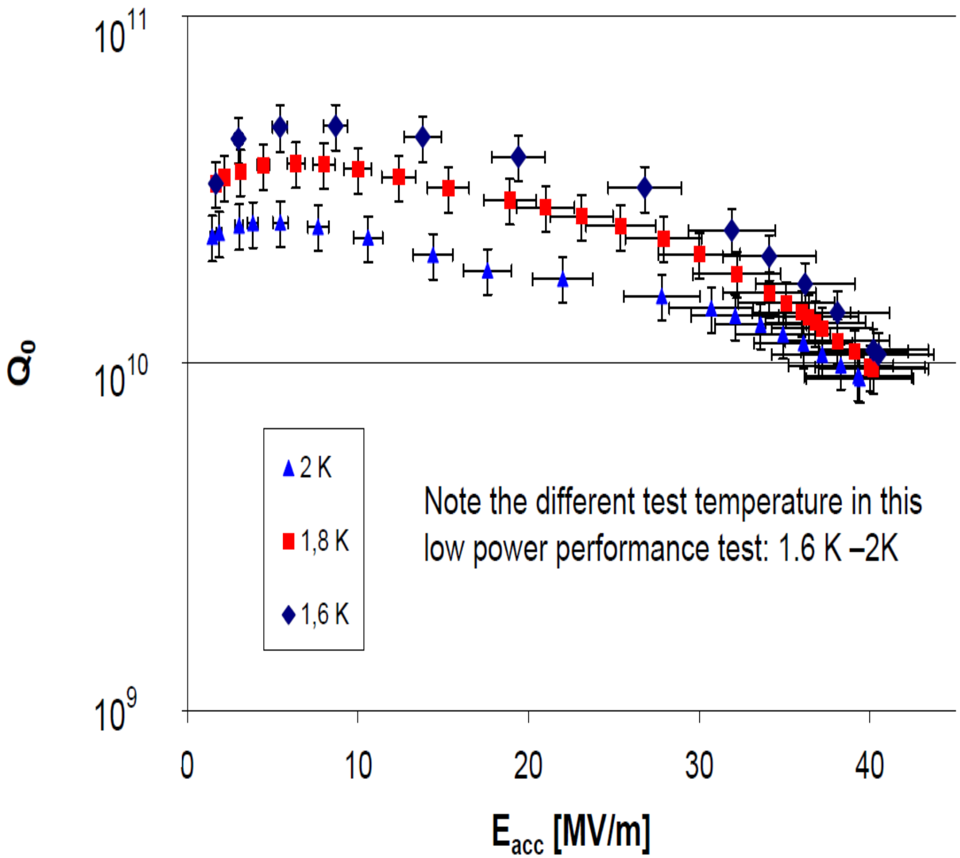
D. Reschke et al., SRF2009

Latest Results from JLab/FNAL



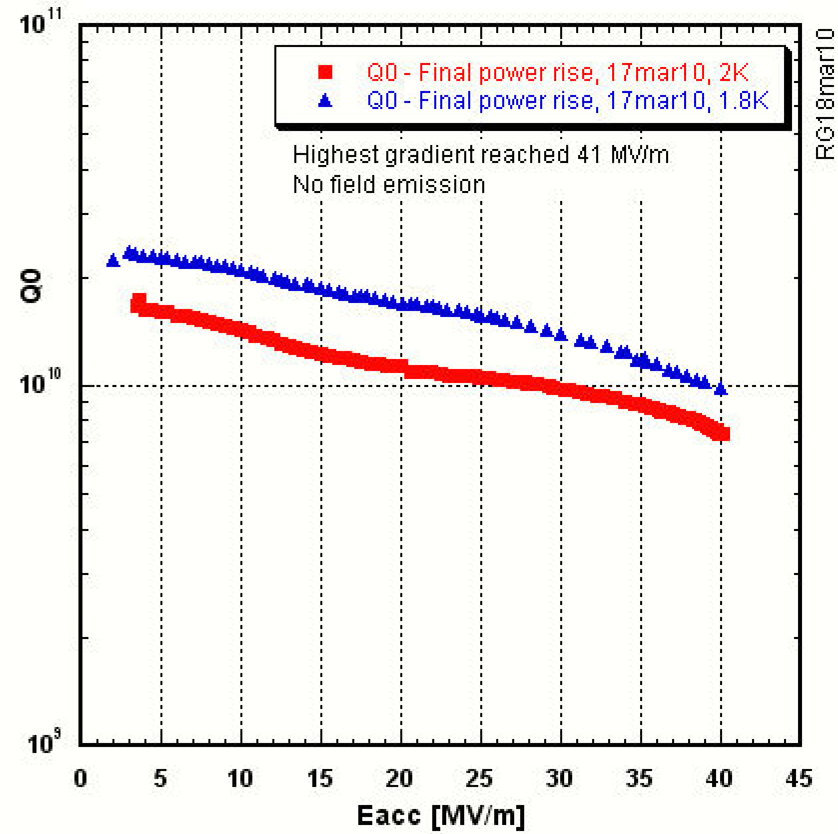
Demonstrated Q up to 40 MV/m

CW Test: AC70: EP at DESY

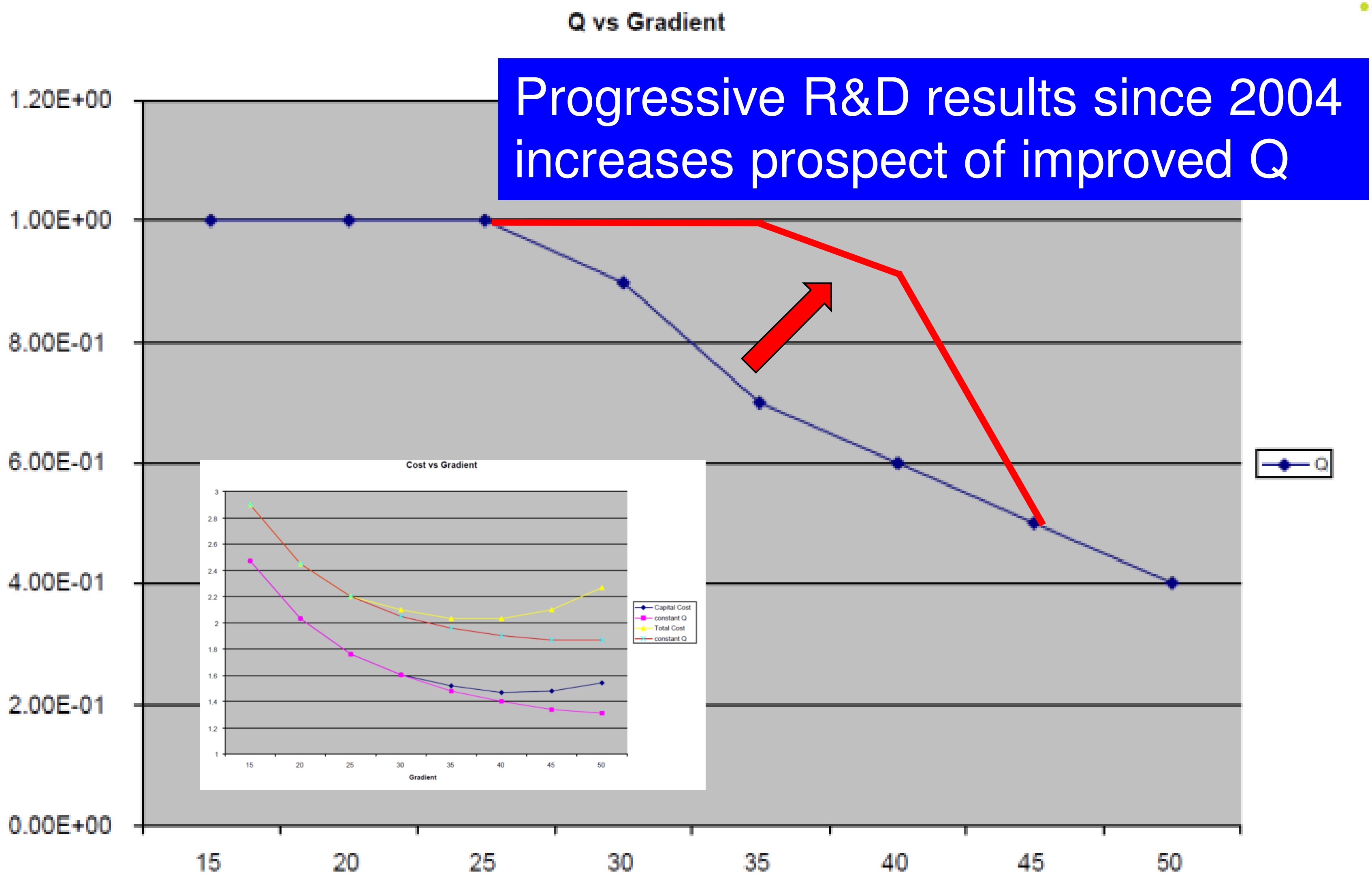


Lutz Lilje DESY -MPY- 2004/11/14

AES7 EP at JLab

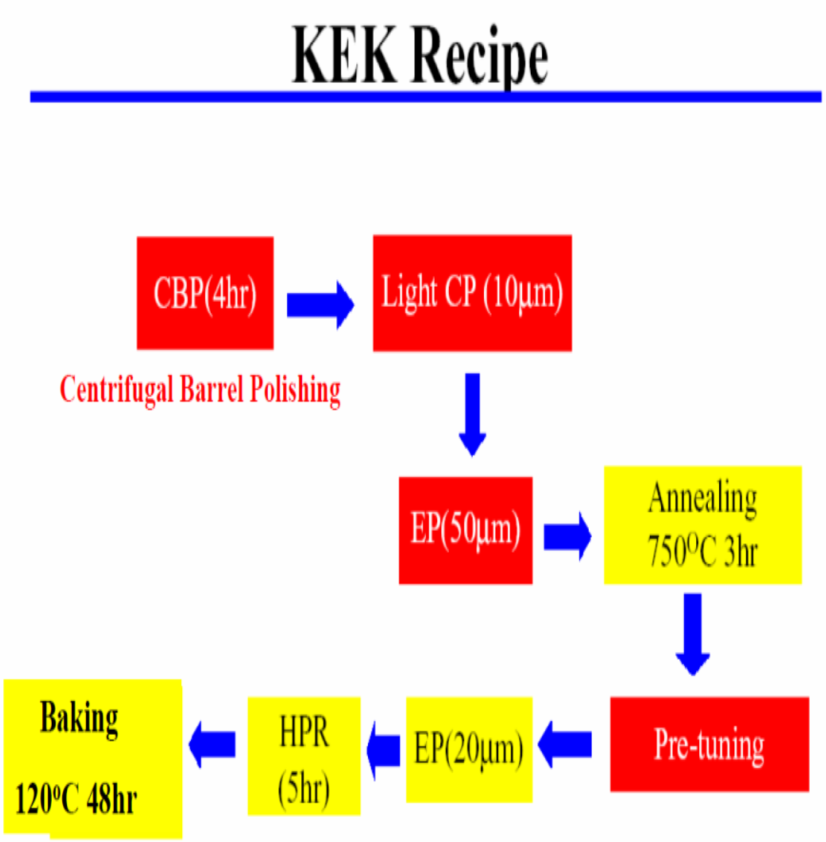


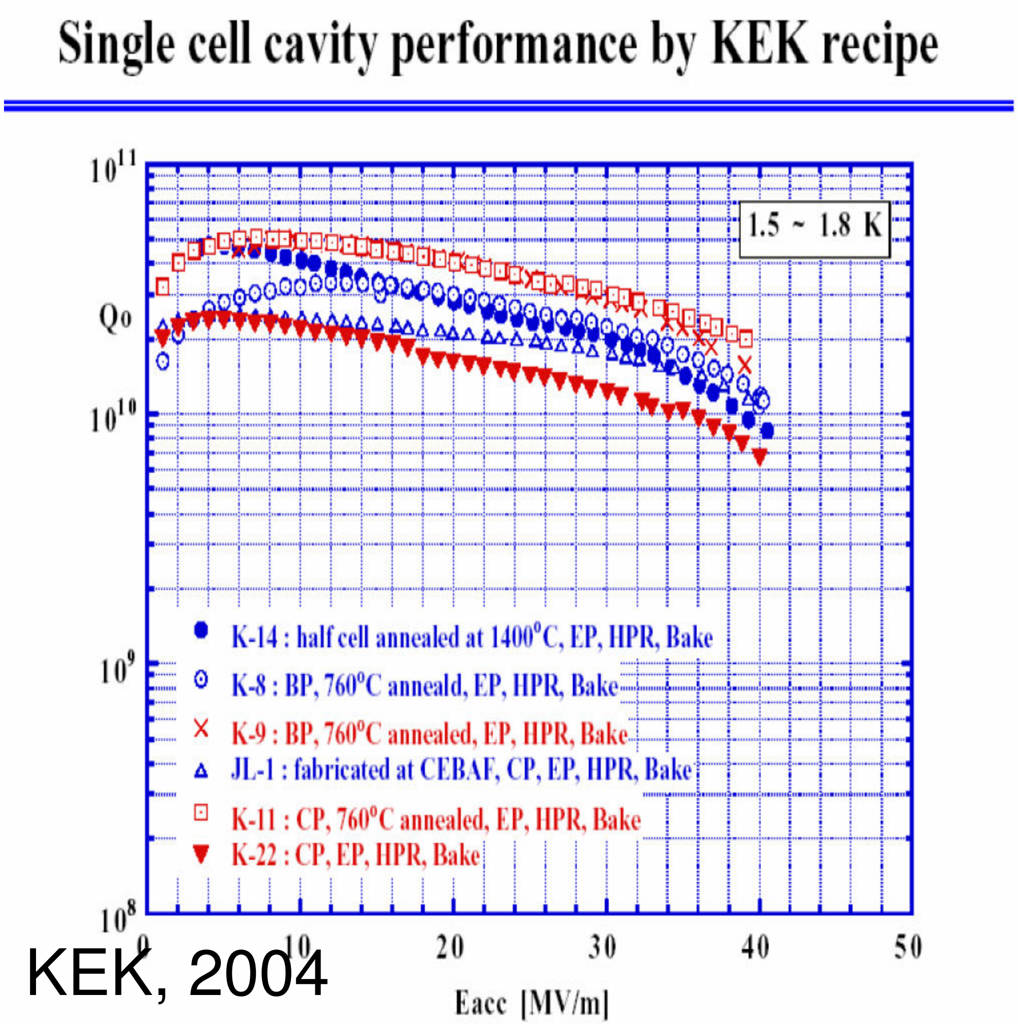
Improved Q pushes up Optimal Gradient



H. Padamsee, 1st ILC workshop, 2004

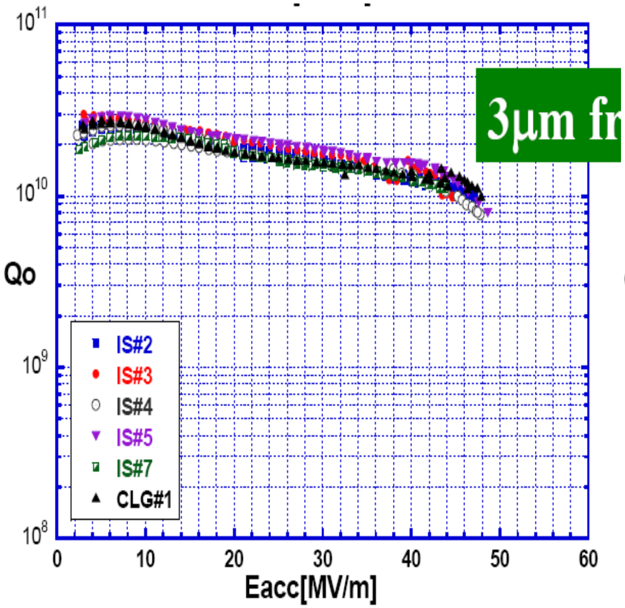
Pre-2004 Prospect of 40 MV/m from KEK 1-Cell Cavity Results



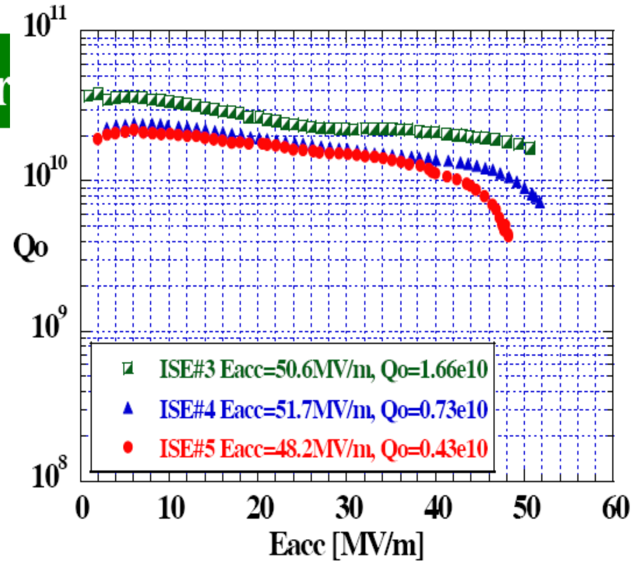


K. Saito, 1st ILC workshop, KEK, 2004

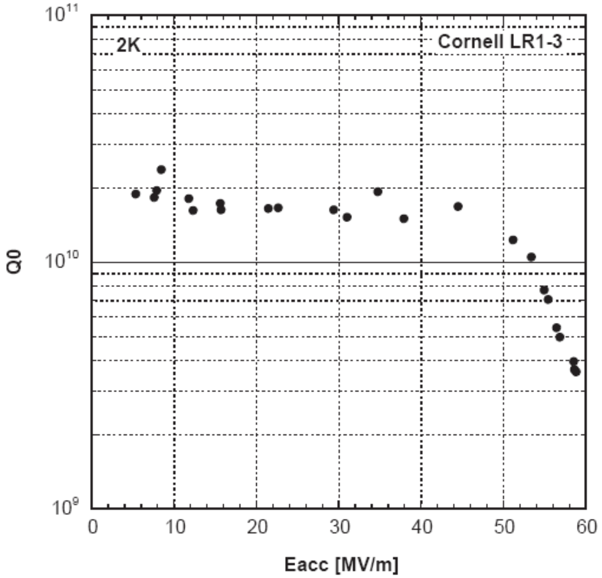
2007-2009 Prospect of 48 MV/m KEK and Cornell 1-Cell Cavity Results



F. Furuta et. al.
SRF2007

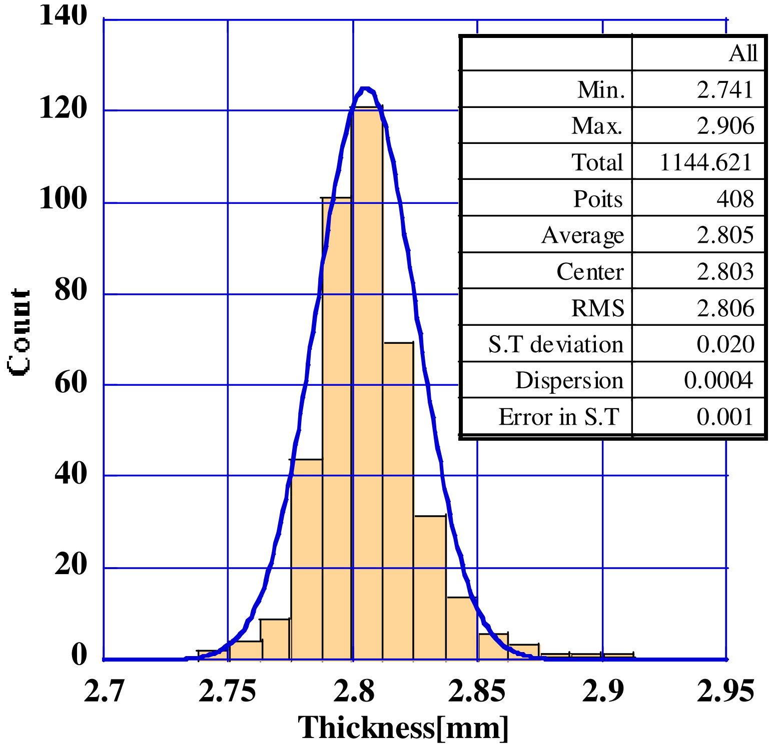


F. Furuta and K. Saito
SRF2009



R.L. Geng et. al.
PAC2007

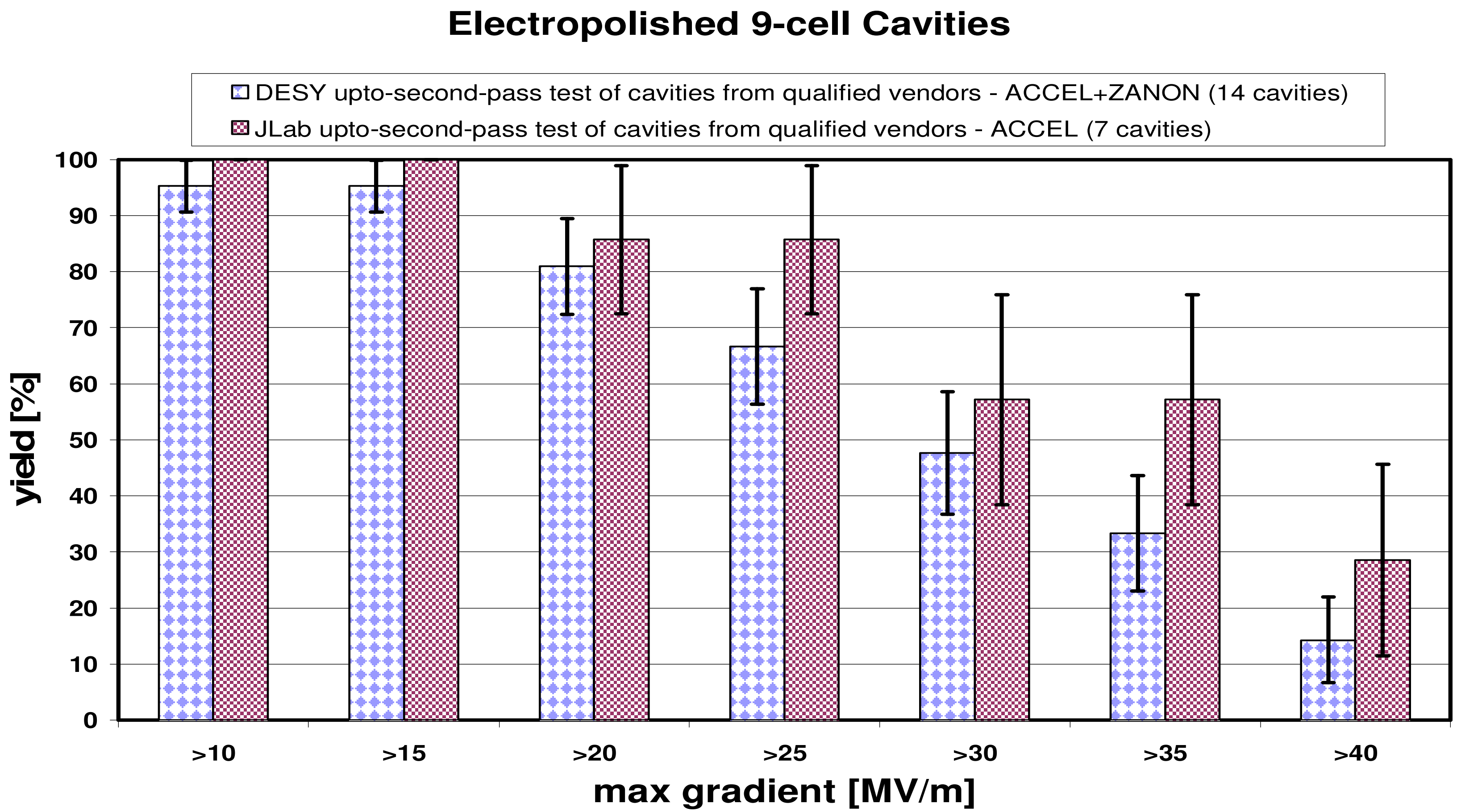
Multi-cell slicing of ingot material



Cost saving potential - also opportunity for material exploration as compared to rolled/annealed sheets

K. Saito, SRF2009

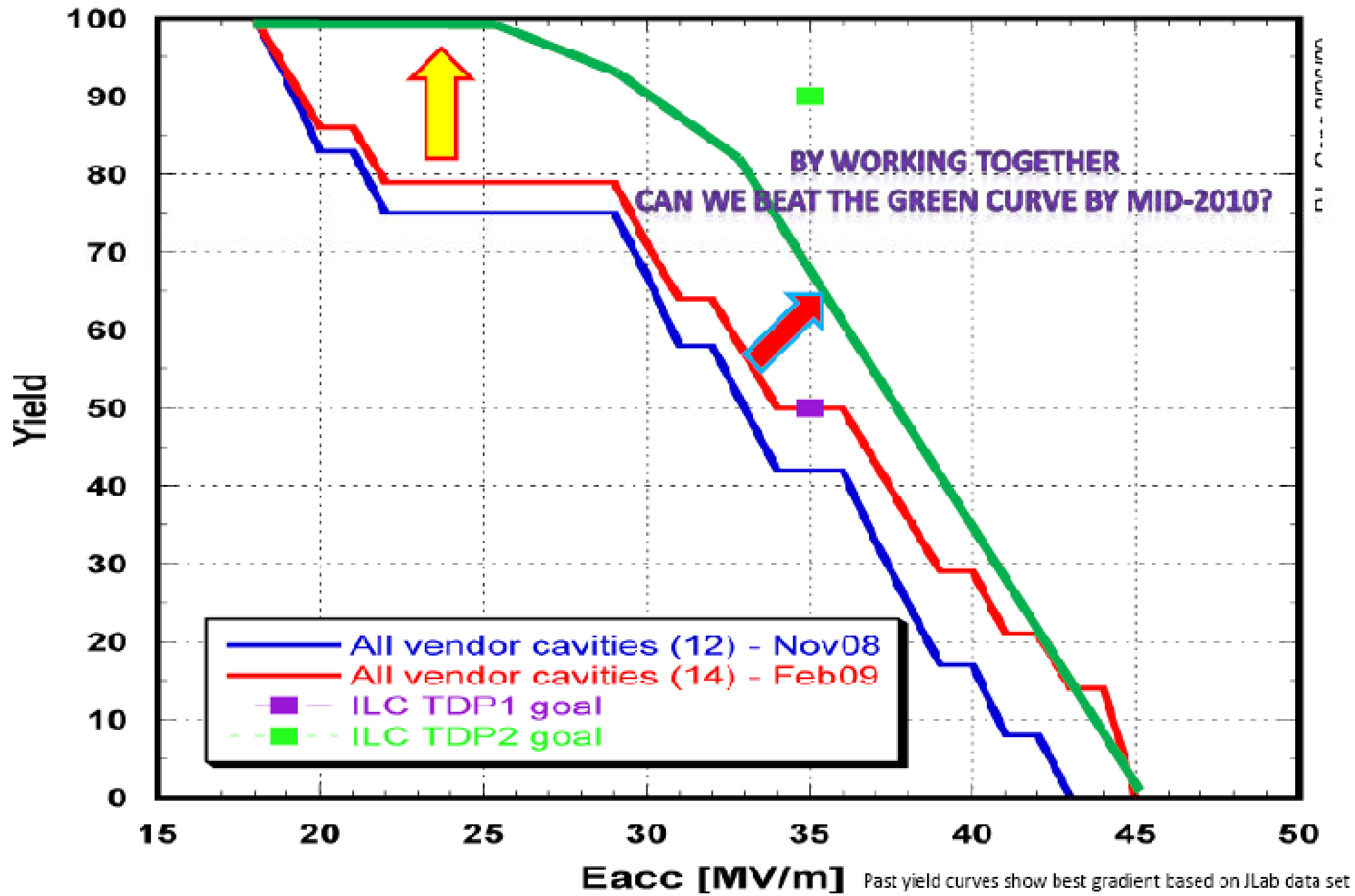
Gradient yield – up to 2nd pass



Presented by C. Ginsburg at LCWS09

New yield plot confirms need for two pushes

Two Big Pushes Ahead…



First presented at cavity vendor meeting at FNAL, March 6, 2009

Gradient Limit Equation

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

- $H_{crit,RF}$: the intrinsic RF critical field – material
- r: a dimensionless factor representing the depression effect on the *local critical field* ***within the penetration depth***, due to impurity or lattice imperfection ($r \leq 1$) – metallurgical and surface chemistry
- β_{MAG}: a dimensionless factor representing the magnetic field enhancement effect due to local geometry ($\beta_{MAG} \geq 1$) – fabrication and processing
- H_{pk}/E_{acc}:the peak surface magnetic field to accelerating gradient ratio, determined by cavity shape – reason for new shapes such as Re-entrant and low-loss shapes
- d: a dimensionless factor representing the thermal stabilization effect – bulk material

Strategy for raising limiting gradient

- Raise *r*
  - **Optimize surface chemistry.**
  - **Optimize surface metallurgical properties.**
- Suppress β_{MAG}
  - **Optimize EP for *defect correction*.**
  - **Mechanical polishing before EP as demonstrated at KEK?**
- Raise *d*
  - **Thermal conductivity near EBW.**
  - **Starting material property optimization.**
  - **Restore phonon peak by recovering/annealing?**