# Toward Higher Gradient and $Q_0$


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U.S. DEPARTMENT OF ENERGY

Jefferson Lab

# Outline

- Why higher gradient and Q0 R&D
- Challenges faced
- Current activities
- Outlook

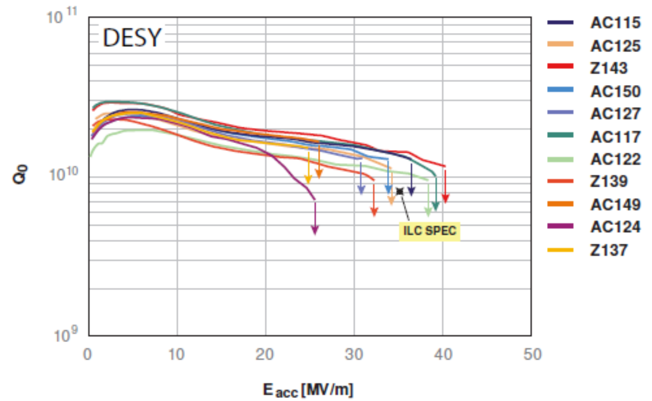
# Why higher gradient and Q0 R&D

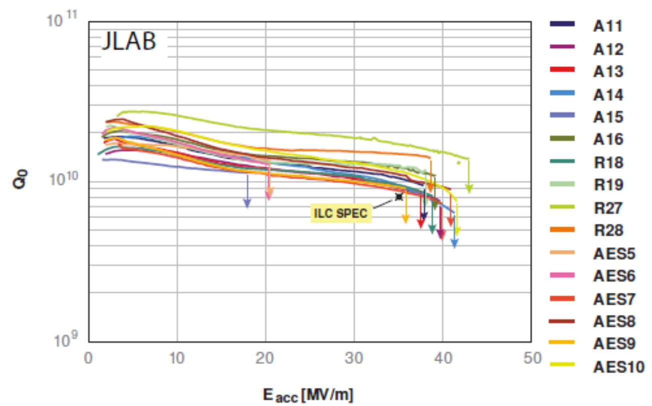
- Enable ILC 1 TeV energy upgrade → Performance
- Enable higher luminosity within cryogenic limit
- Enable reliable and repeatable cavity fabrication

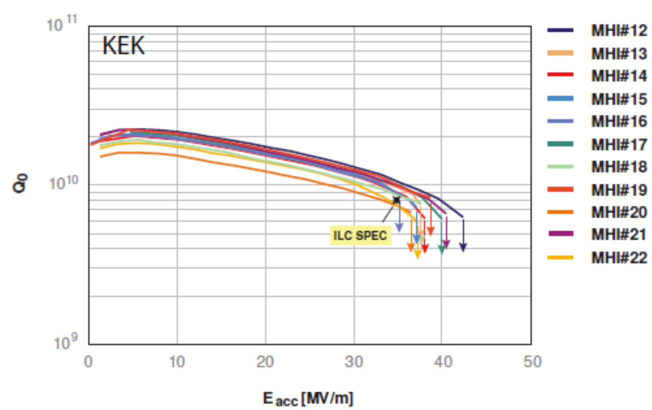
→ Cost

- Preserve cavity gradient and Q0 → Operation performance

# ILC Cavity Gradient R&D under GDE

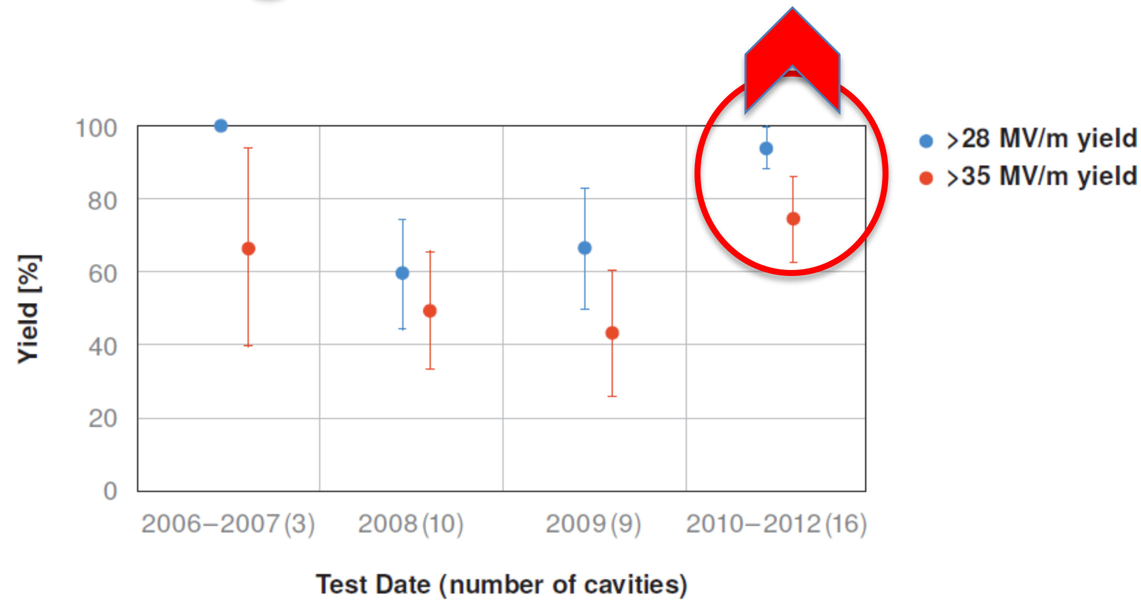



- Reliable cavity processing – clearly demonstrated
- Second-pass processing – clearly defined

## ILC S0 Program (2006-2012): Average Gradient: 37 MV/m

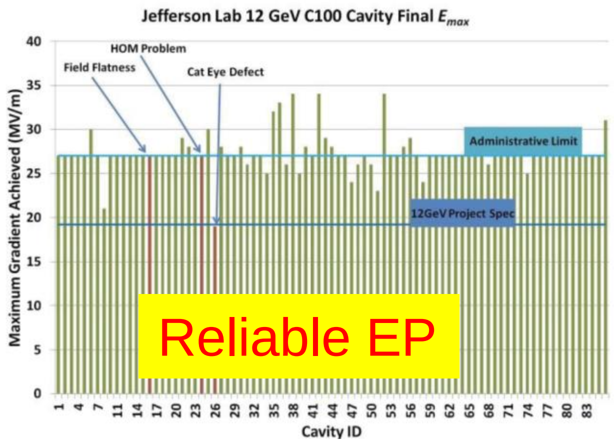



**(b)** Second-pass yield

The International Linear Collider Technical Design Report, ISBN 978-3-935702-77-5 (2013).

# ILC-style Processing Applied to Project

LINEAR COLLIDER COLLABORATION



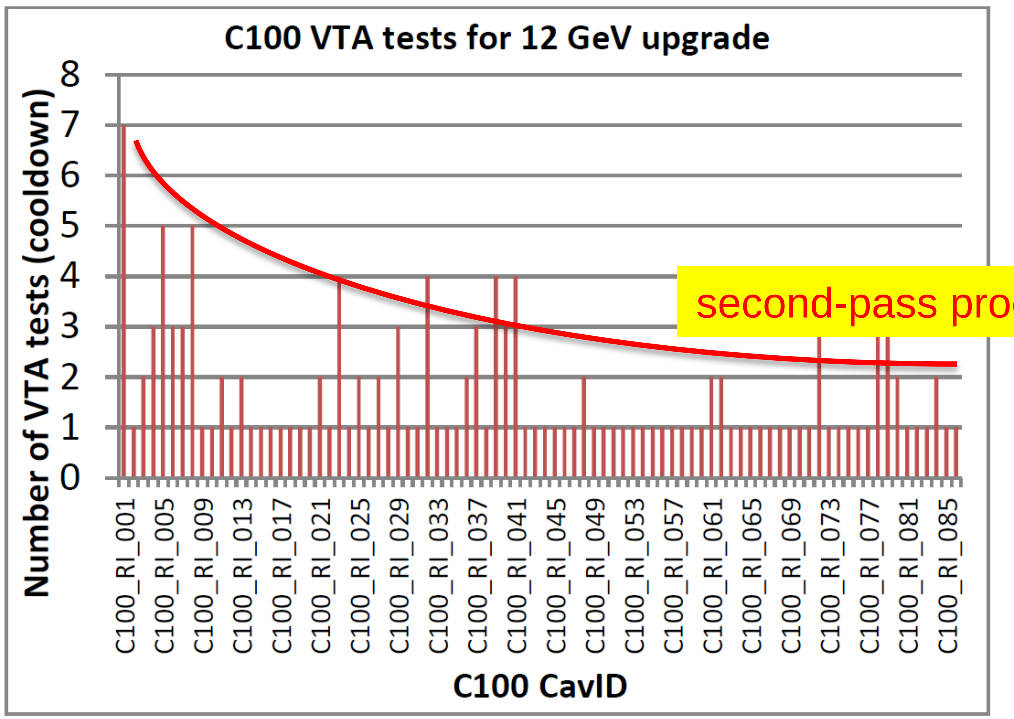

JLab 86 7-cell Low-loss shape 1.5GHz cavities

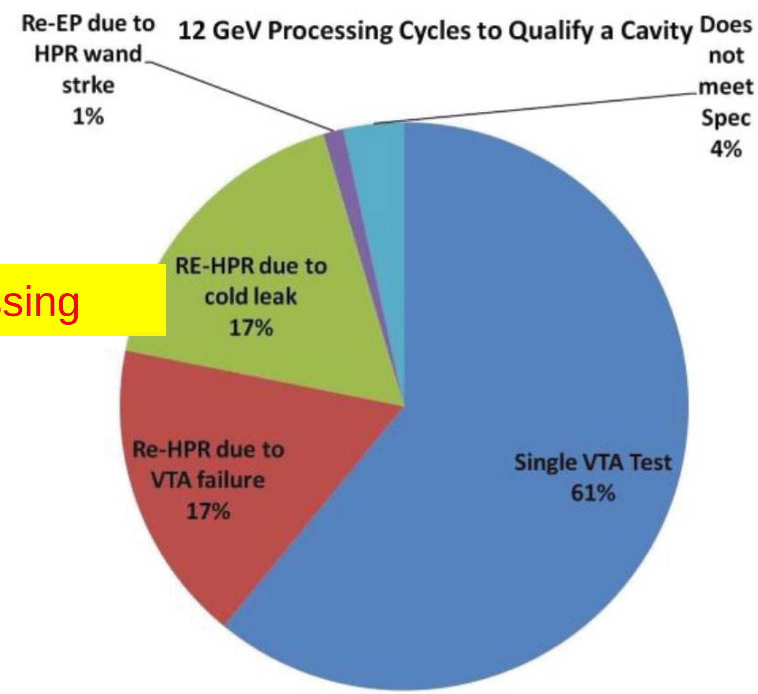
Bulk BCP + "ILC style" final cavity processing: EP + bake

80 cavities installed in 10 cryomodules

All modules now in CEBAF tunnel

Operation with beam Jan 2014




Hogan et al., NA-PAC2013

Burrill et al., IPAC2012

# ILC-style Processing Applied to Project

Status Oct 31, 2013: Test Results for the Testing of 800 Series Cavities for the European XFEL

European XFEL

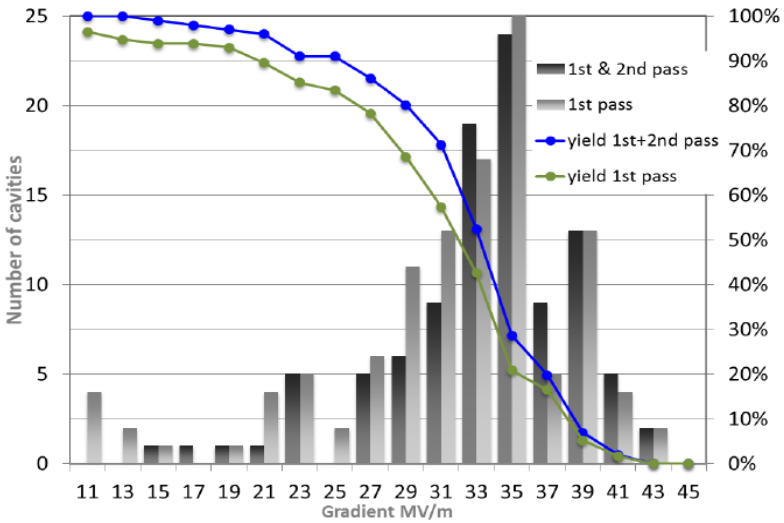
## Yield of gradients: After re-treatment (2. pass)

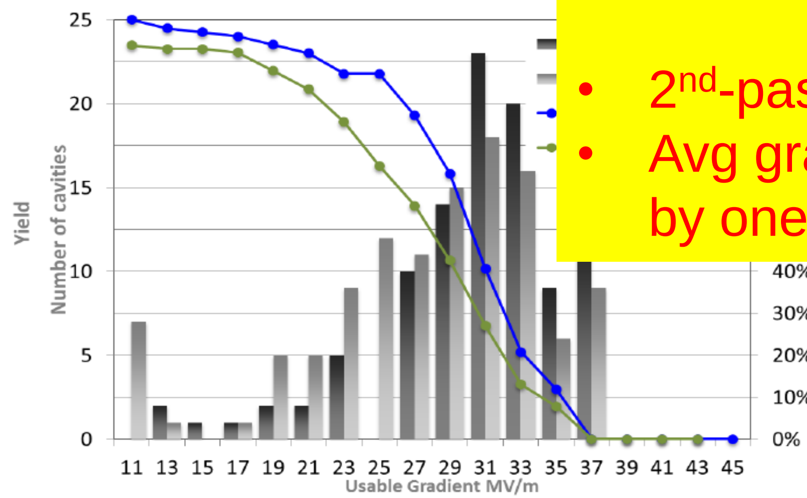
6

- Yield of usable and maximum gradient of 100 cavities (2.pass): 73 cavities passed in 1.pass + 27 cavities after re-treatment
- **Average** gradients **increased + spread reduced** (standard de

Industrial fab. and proc., first 100+ cavities:

- 2nd-pass processing
- Avg gradient 35 MV/m by one vendor already




Average **maximum** gradient:

**(31.9 ± 5.5) MV/m**

EZ: (30.1 ± 5.2) MV/m

RI: (34.5 ± 4.7) MV/m

Average **usable** gradient:

**(28.8 ± 5.2) MV/m**

EZ: (27.8 ± 5.1) MV/m

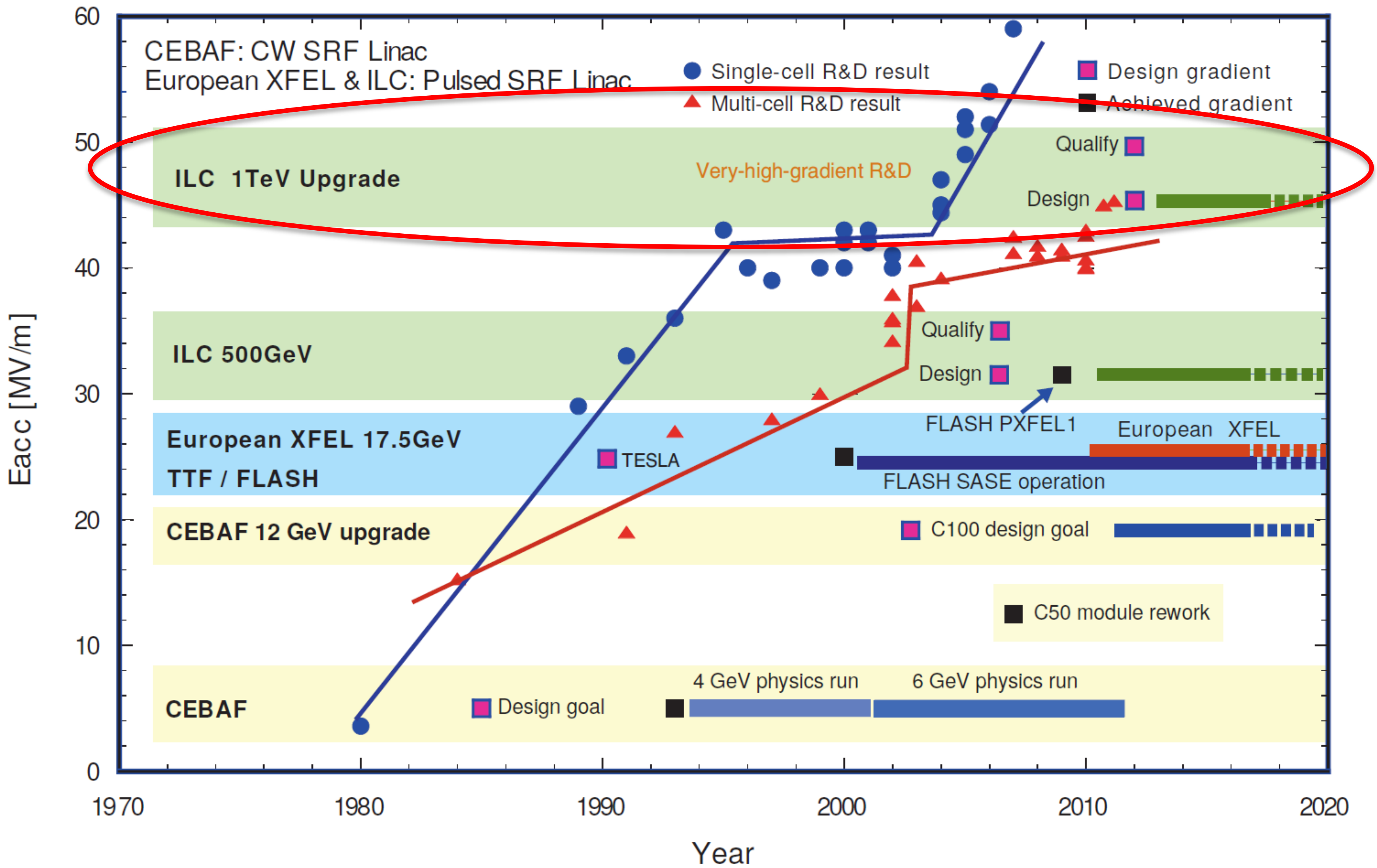
RI: (30.2 ± 5.0) MV/m

Detlef Reschke, DESY *Preliminary data; results are not published* CRISP DESY HELMHOLTZ ASSOCIATION

Reschke, Presented at the 2nd LCC ILC Cavity Group Meeting, Nov. 6, 2013

LINEAR COLLIDER COLLABORATION

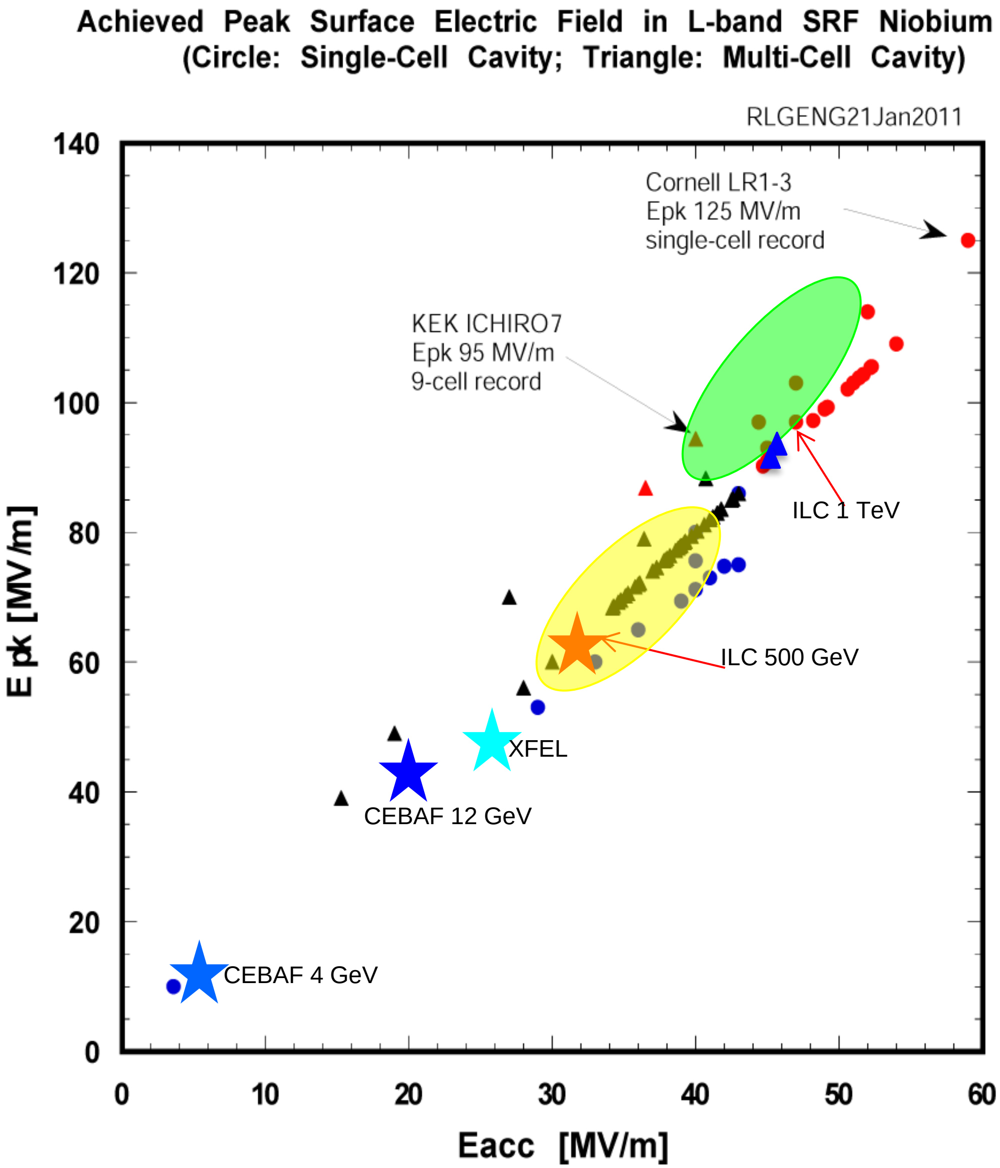
# What is next?



# Challenges faced

- Field emission
- Scatter in quench limit
- Ultimate gradient limit
- Q-drop
- HOM coupler limit
- Lorentz force detuning limit

# Field Emission Understanding and Control




- ❑ Intensive R&D in past years resulted in reduced field emission
  - Post-EP cleaning
  - No longer a main limit for vertical test
- ❑ But still not under complete control
  - Causes additional cryo loss
  - Risk increases rapidly with peak surface electric field due to exponential nature of the process

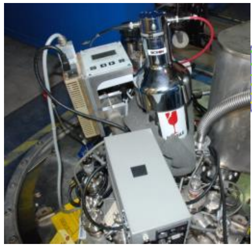
$$I_{\mathrm{FN}} = j_{\mathrm{FN}} A_{\mathrm{FN}} = A_{\mathrm{FN}} \frac{e^3 (\beta_{\mathrm{FN}} E)^2}{8\pi h \Phi t^2(y)} \exp\left(-\frac{8\pi\sqrt{2m_e \Phi^3}\, v(y)}{3he\beta_{\mathrm{FN}} E}\right)$$

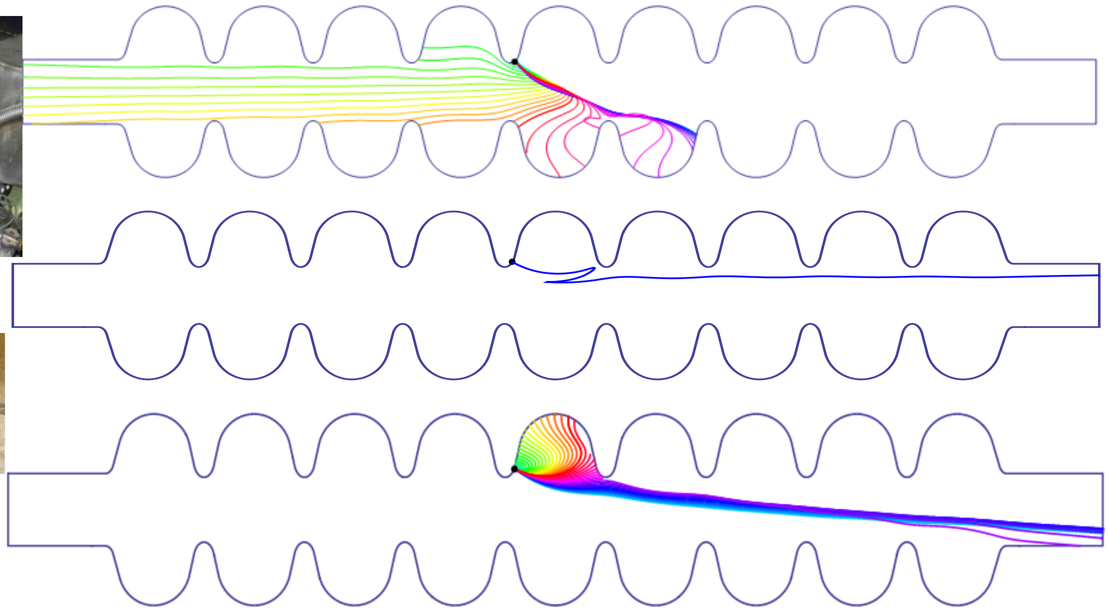
- ❑ Critical issue for accelerator operation
  - Dark current
  - Radiation damage to electronics
  - Beam line activation from neutron
- ❑ For ILC operation Epk avg 63 MV/m and up to 76 MV/m
  - For XFEL, Epk 47 MV/m
  - For CEBAF upgrade, Epk 42 MV/m

# Field Emission R&D Goals

- **Near term goal: Reduce field emission reliably up to a surface electric field of 80 MV/m in 9-cell cavity so as to insure operation of cryomodules at average gradient of 31.5 MV/m with acceptable field emission induced cryogenic loss and field emission induced radiation dose**
- (Cryogenic loss due to FE) / (Cryogenic loss due to dynamic + static heat) per cryomodule < 10%
- Dark current per cavity < 50 nA
- **Long term goal: Push the field emission onset gradient reliably beyond Epk = 50 MV/m in 9-cell cavities; Demonstrate Epk = 100-120 MV/m in 9-cell cavities**
- Requires deeper fundamental understanding of FE phenomenon
- Requires advanced surface processing

# Locating Field Emitter in 9-cell Cavity

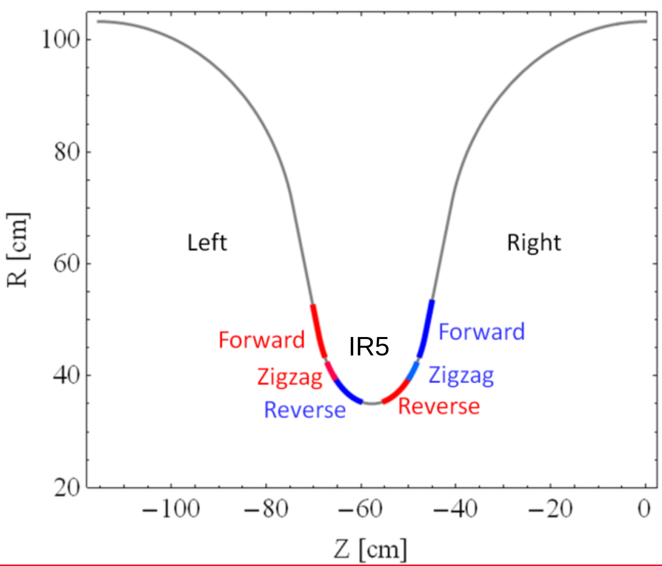


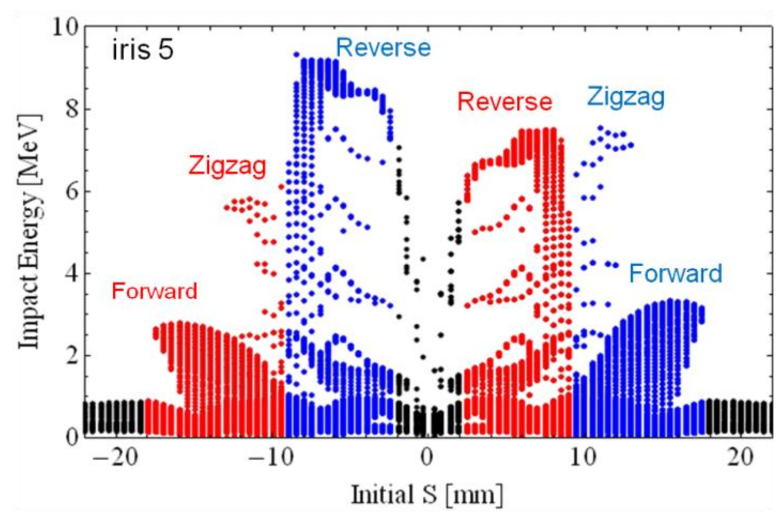


Emission in region >>> "Reverse" type"

Emission in region >>> "Zigzag type"

Emission in region >>> "Forward type"

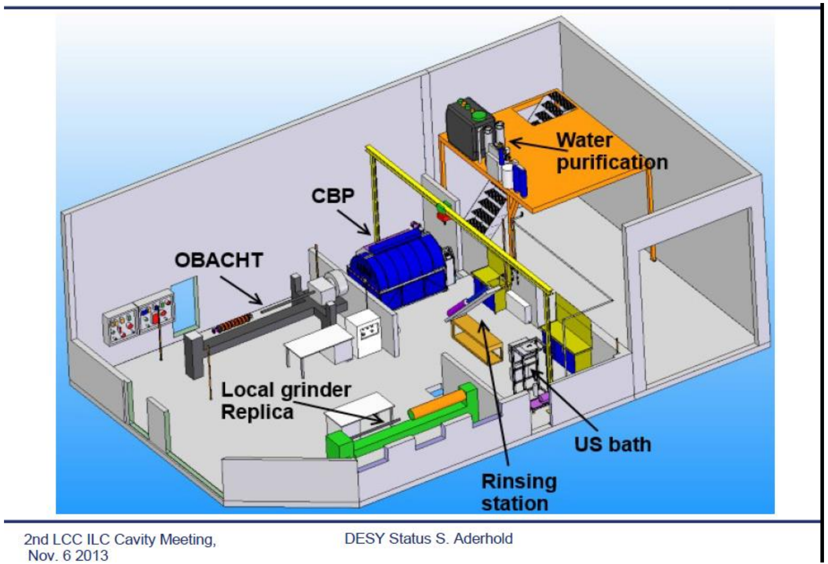


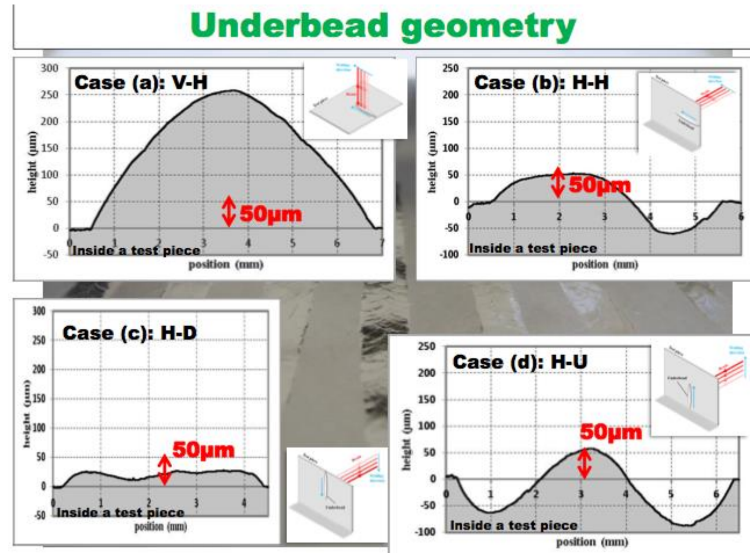

Impact position VS impact energy distribution

# Understand and reduce gradient scatter

Natural defect studies
at DESY ILC HiGrade Lab




EBW parameter systematic optimization
at KEK



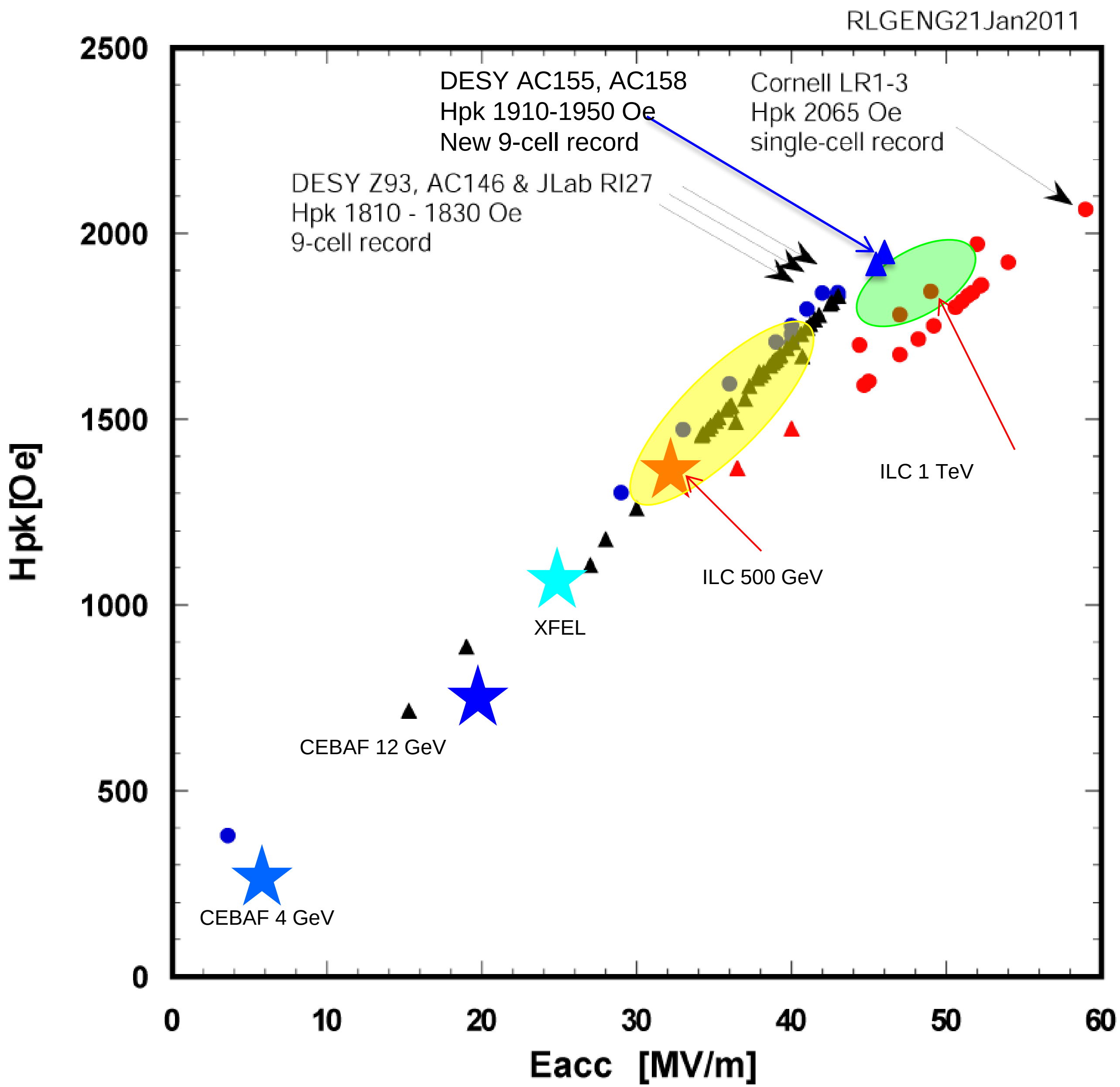

Kubo


EBW x-ray imaging for studies of Welding porosity at Kyoto University.

Welding porosity studies at JLab with controlled varied welding conditions.

Iwashita

# Ultimate Gradient (Nb)



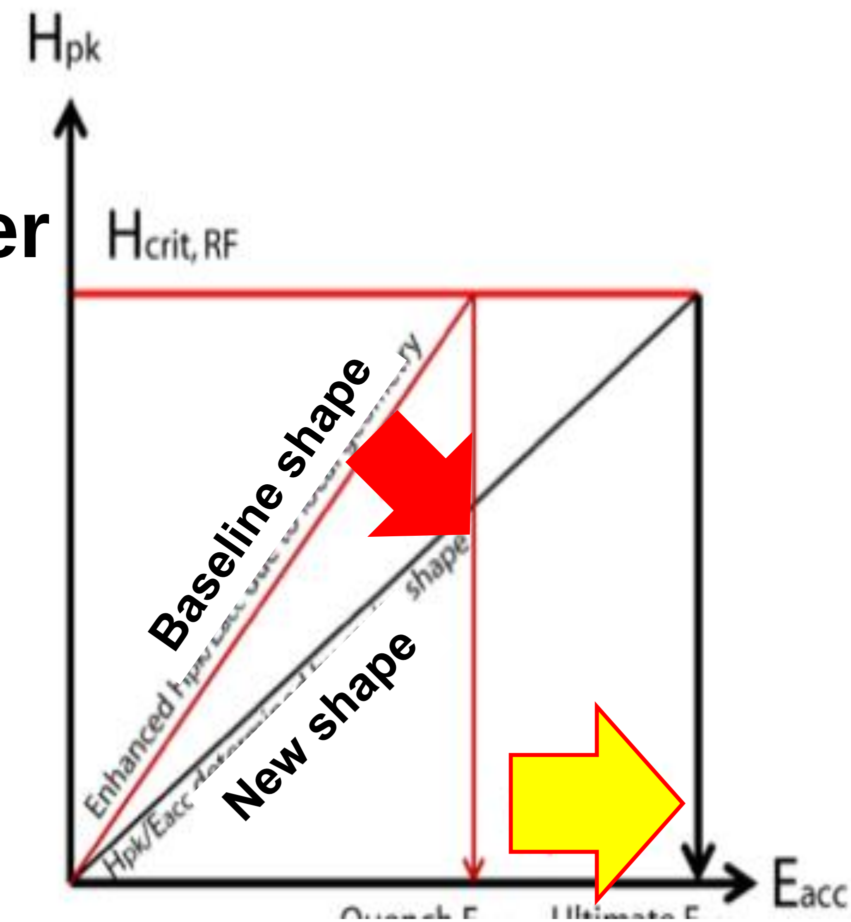

Recent cavity results established that a peak surface magnetic field of 190-200 mT is possible and practical

45 MV/m in TTF shape means effectively > 50 MV/m in Re-entrant, low-loss or ICHIRO, and Low-Surface-Field shape cavities

In fact, this is already shown in many 1-cell cavities

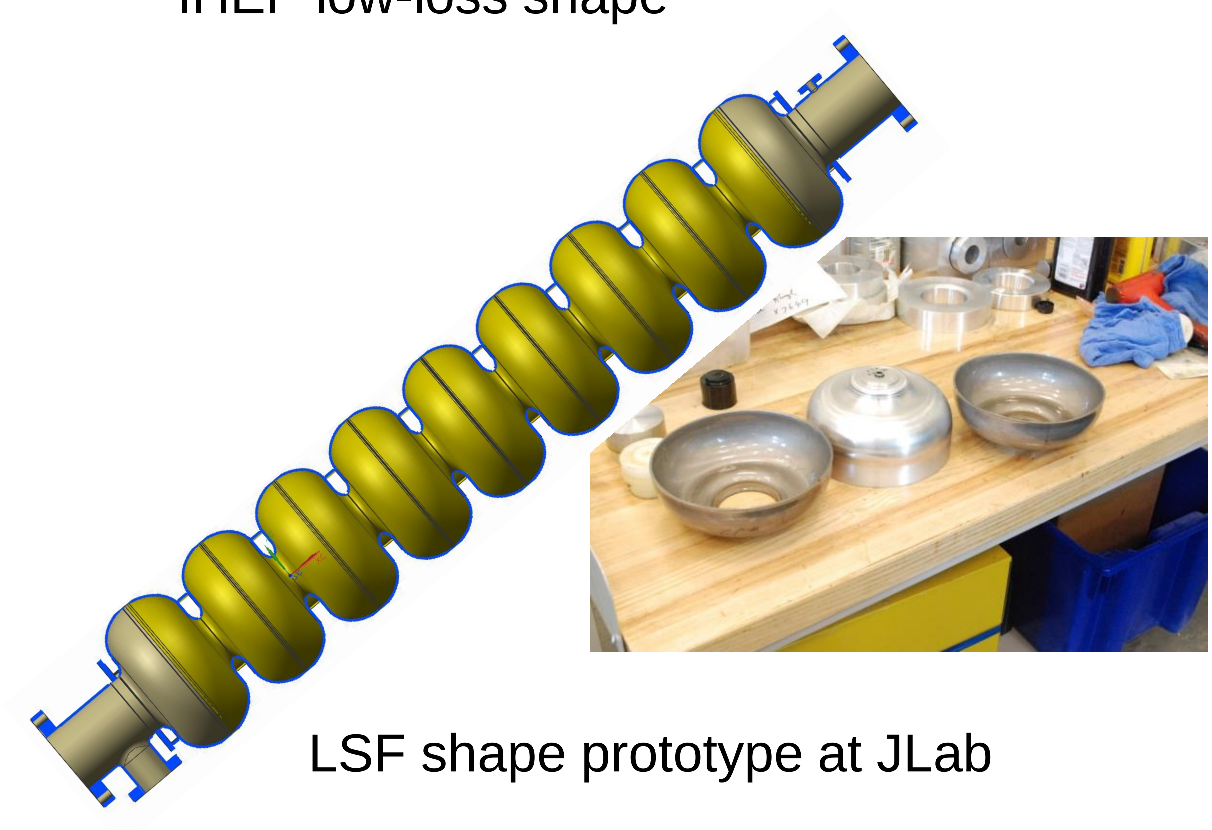
# High Gradient via New Shapes

- **Ratio of Hpk/Eacc solely determined by shape**
- **Lowering Hpk/Eacc for higher gradient up to critical RF magnetic field (material property)**
- **Three cavity shapes under evaluation**
- Low-loss (KEK, JLab, IHEP)
- Re-entrant (Cornell)
- Low-Surface-Field (JLab/SLAC)



# New Cavities of Improved Shapes

IHEP low-loss shape

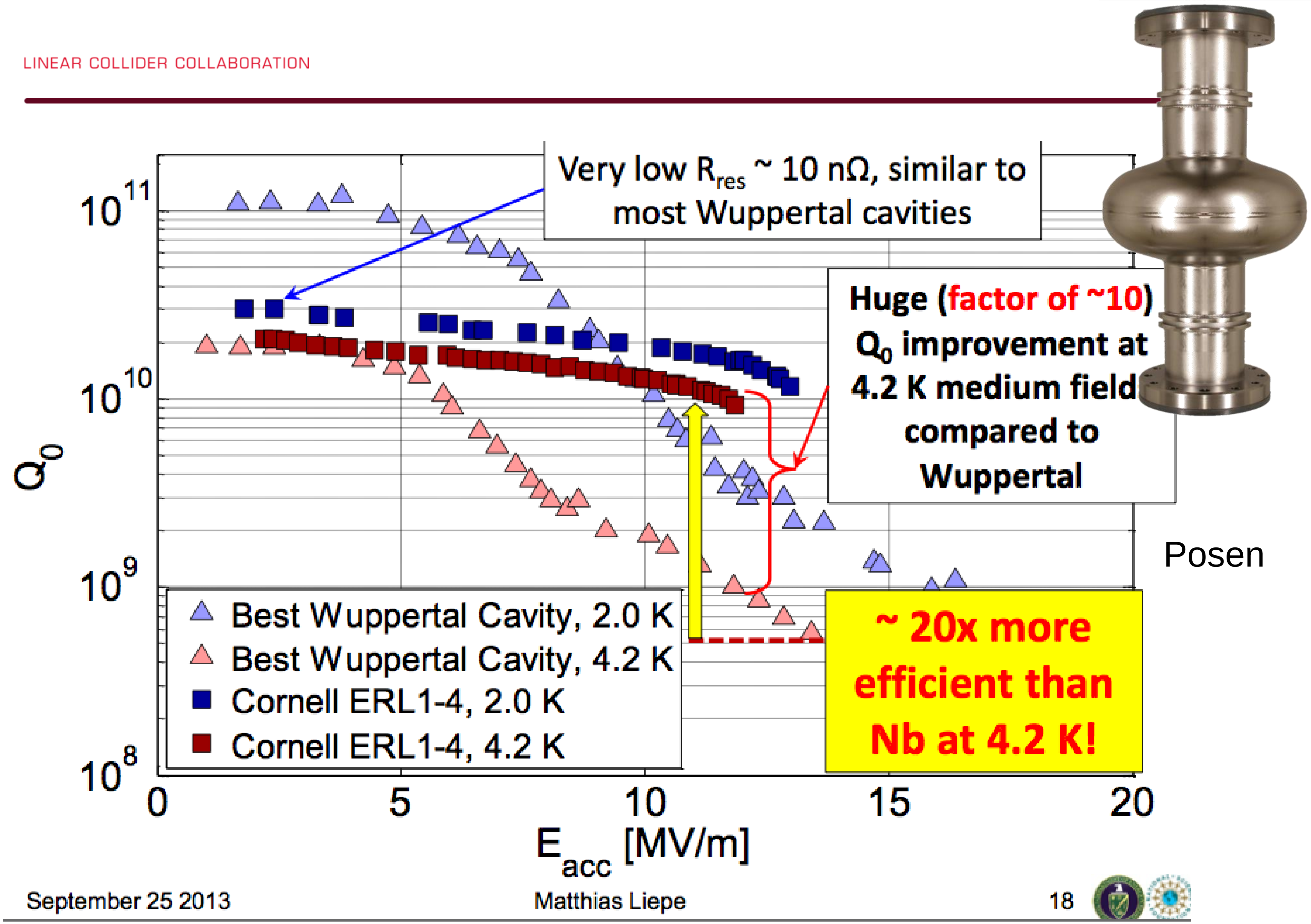


LSF shape prototype at JLab


JLab Ichiro shape
2 each under testing

# High Gradient via Materials

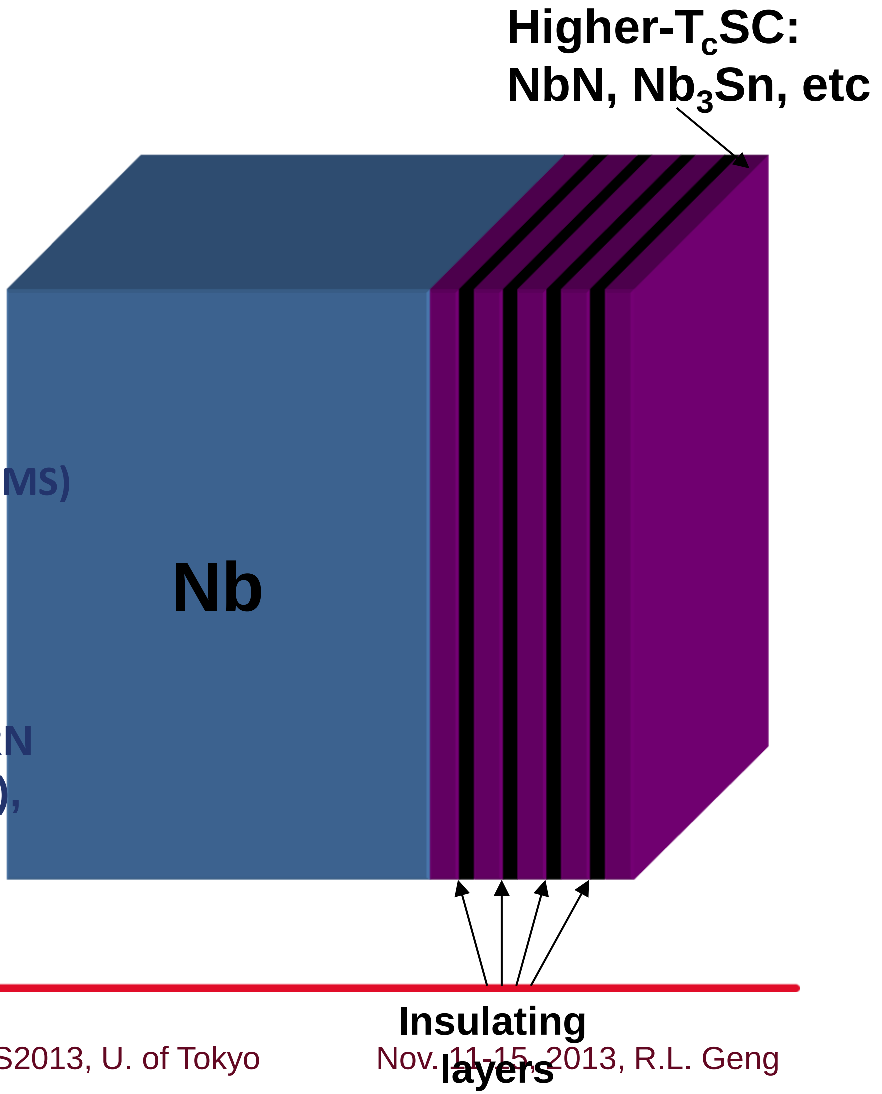
- **Ultimate gradient limit set by RF critical magnetic field**
- Nb, 240 mT predicted by superheating theory
  - Ultimate gradient 60 MV/m
  - ~210 mT (~90% theoretical limit) achieved
    - One 1-cell 1.3 GHz re-entrant cavity (R.L. Geng et al., PAC2007)
    - One 2-cell 1.3 GHz cavity (K. Watanabe et al., KEK cERL, 2012)
  - 195 mT (~80% theoretical limit) achieved
    - One 9-cell 1.3 GHz TTF-shape large grain cavity (D. Reschke et al., SRF2011)
- Nb3Sn, 400 mT predicted by superheating theory
  - Ultimate gradient 100 MV/m
  - Vapor diffusion
    - Was investigated 20 years ago
    - New efforts restarted at Cornell
      - » New test result of 1-cell cavity show new progress (next slides)


Very low $R_{res}$ ~ 10 nΩ, similar to most Wuppertal cavities
Huge (factor of ~10) $Q_0$ improvement at 4.2 K medium field compared to Wuppertal
~ 20x more efficient than Nb at 4.2 K!
$Q_0$
$10^{11}$
$10^{10}$
$10^{9}$
$10^{8}$
0
5
10
15
20
$E_{acc}$ [MV/m]
Best Wuppertal Cavity, 2.0 K
Best Wuppertal Cavity, 4.2 K
Cornell ERL1-4, 2.0 K
Cornell ERL1-4, 4.2 K
September 25 2013
Matthias Liepe
18

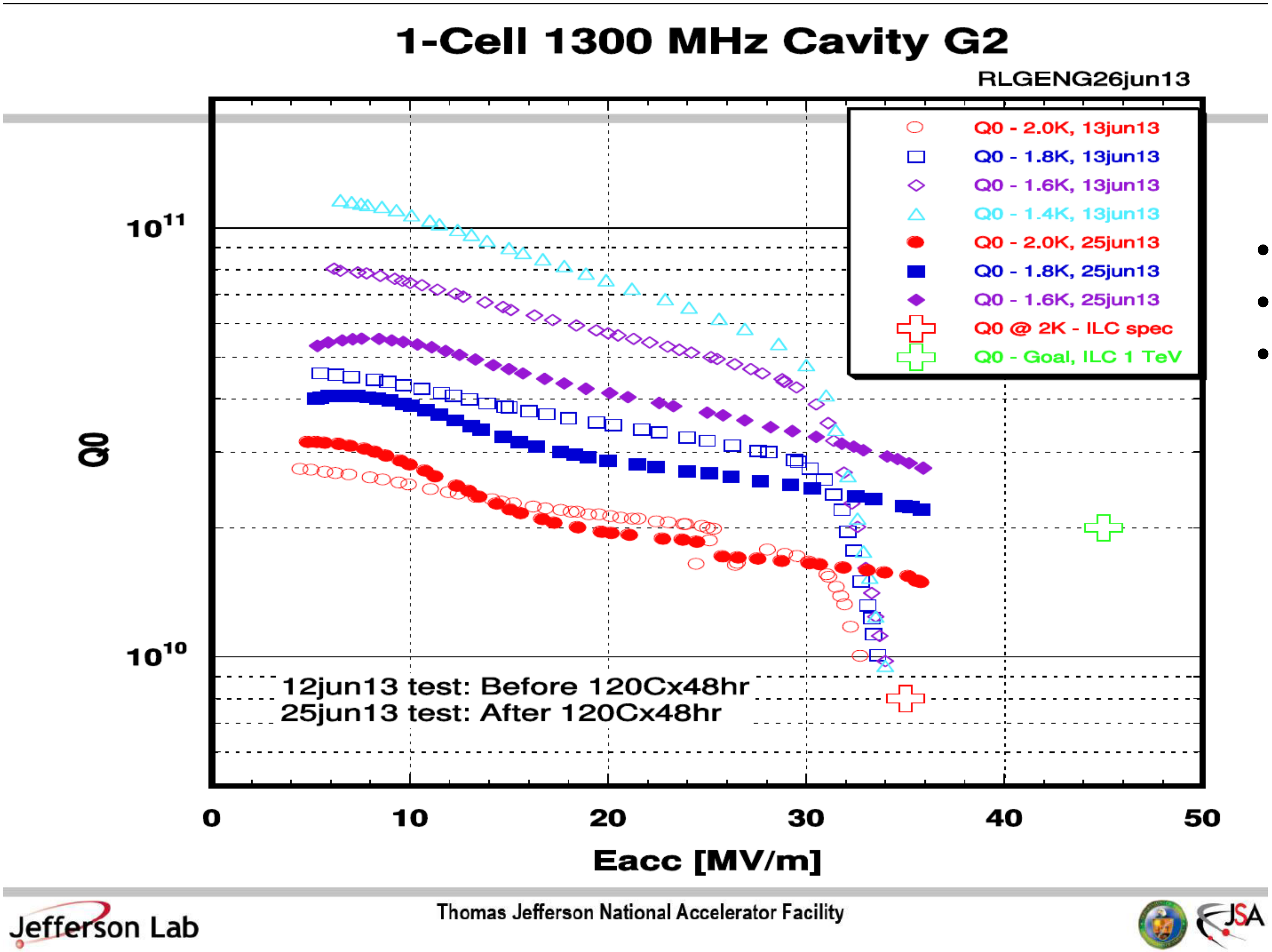
Posen

# High Gradient via Multi-Layer

- **Theory by Gurevich, APL 88, 012511(2006)**
- **Potential for magnetic limit 500-1000 mT**
- Ultimate gradient up to 200 MV/m
- **Insulating layer nm thick**
- **Thin film coated cavities**
- Coating techniques
  - **Several paths being explored at ANL (ALD), CERN (sputtering, HIPIMS), JLAB (ECR, CVD), LBNL (HIPIMS)**
- Requires RF evaluation of samples at low temperature
  - **Several apparatus being developed at CERN (Quadrupole resonator), Cornell (TE cavity), JLAB (SIC cavity)**

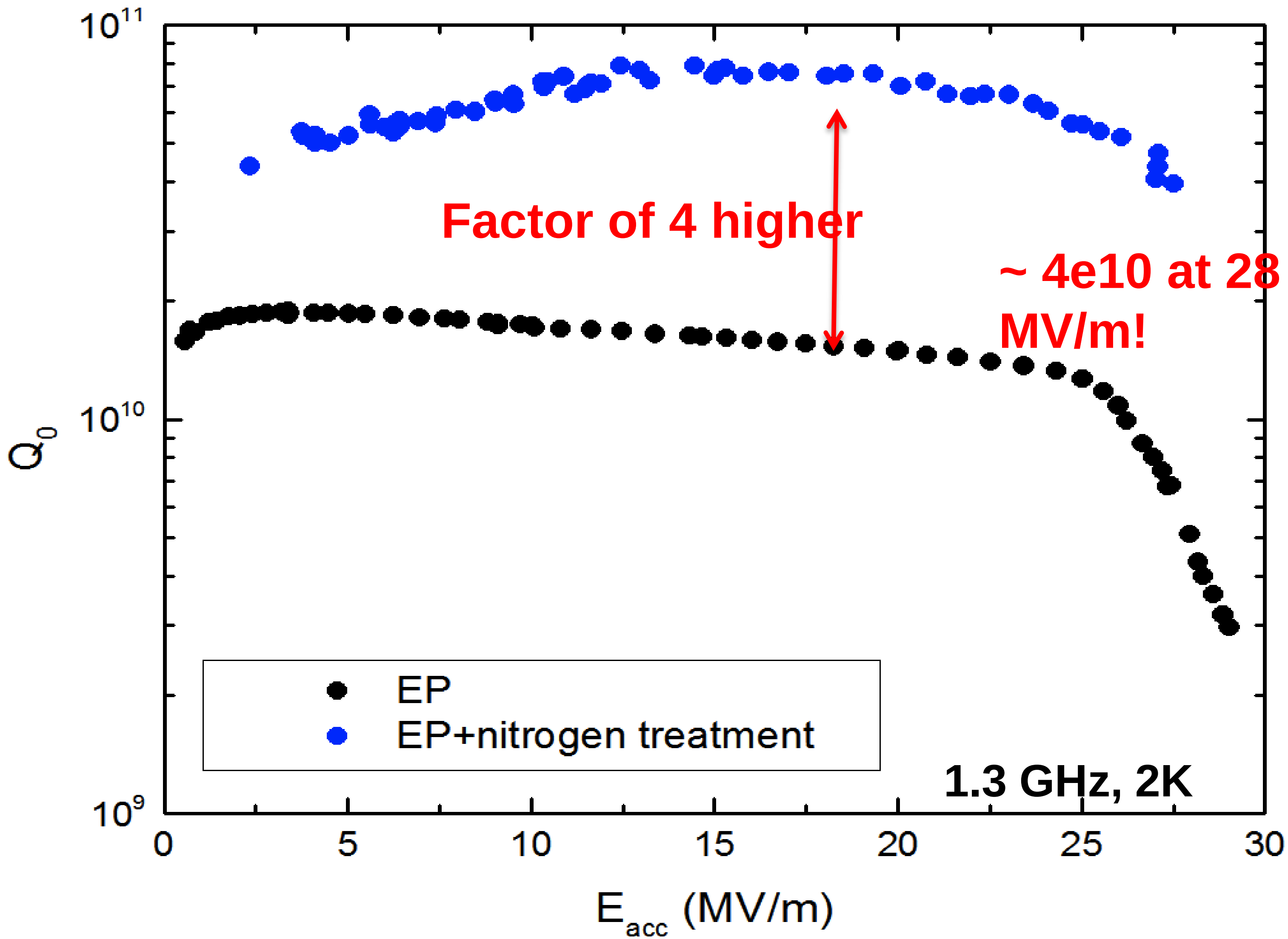


# Q-drop



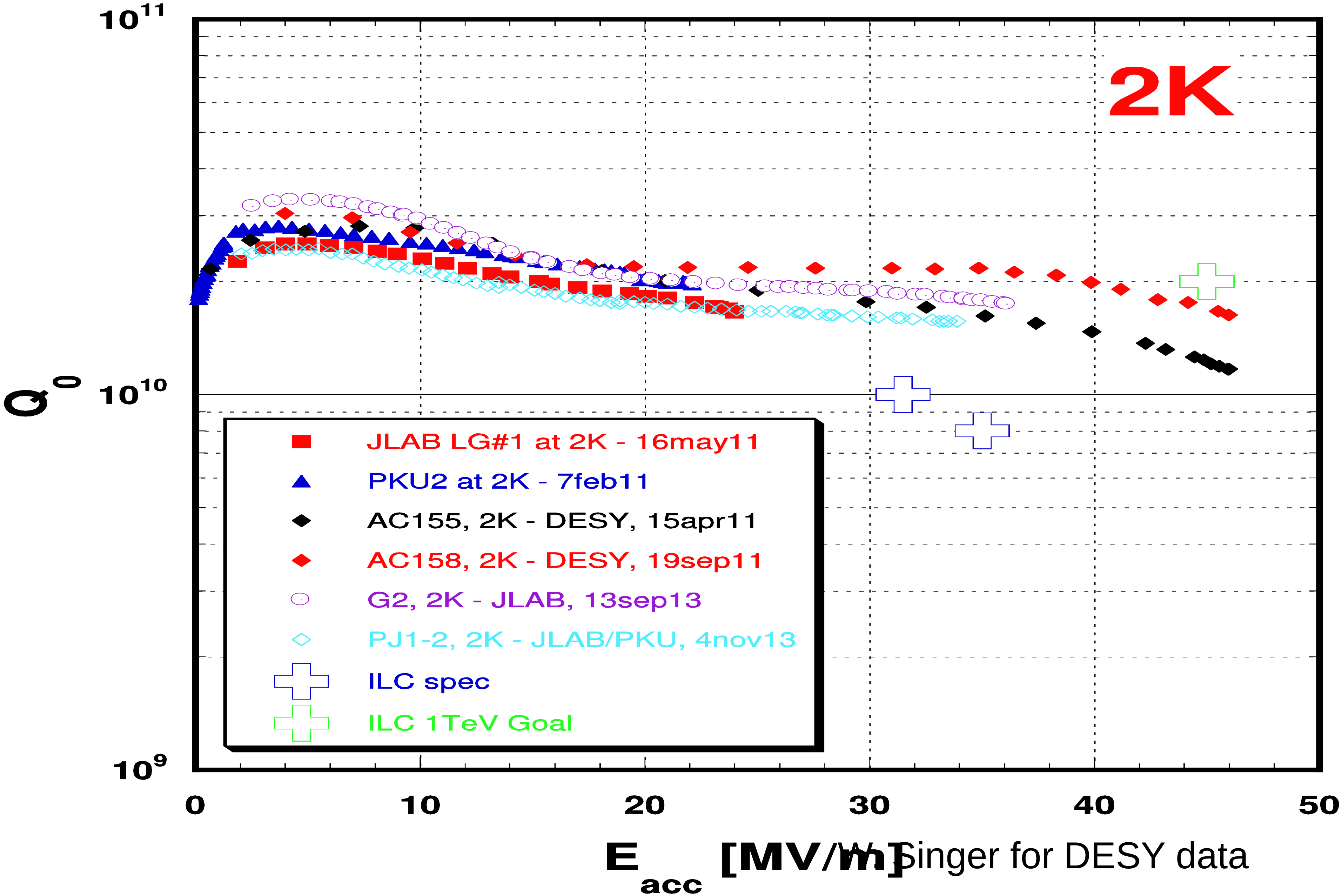

- origin of Q-drop?
- frozen flux effect
- material studies

# *Anti-Q0slope due to Nitrogen Doping*



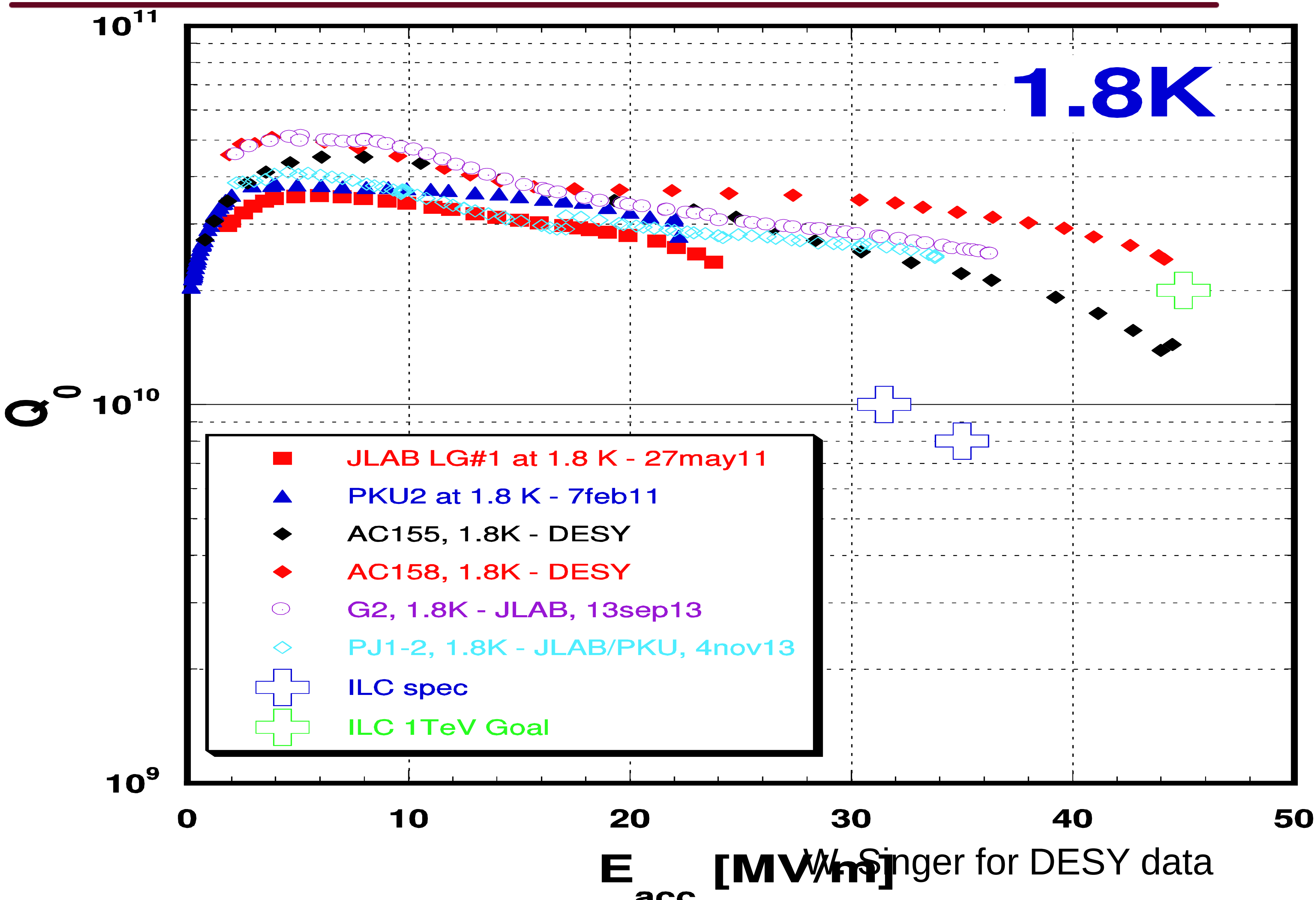

Grassellino

# Ingot Niobium Cavity Performance at 2K




W. Singer for DESY data

# Ingot niobium Cavity Perfroamnce at 1.8K




W. Singer for DESY data

# Outlook

- **Many compelling questions remain toward higher gradient and Q0.**
- **ILC continues to drive SRF frontier R&D and generate benefits to other SRF projects.**
- **Key infrastructures already in place at many lab due to GDE led effort – time to fully profit from these investments.**
- **Close collaboration in is key. This was very true in GDE era and more critical in LCC era due to resource limit.**