High-Gradient
Superconducting Radiofrequency Cavities
for Particle Acceleration

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EPAC'06
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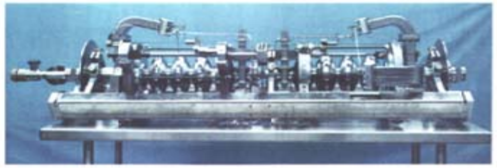
- Why Superconducting Accelerating Cavities?
- Limiting Mechanisms
- High Gradient Cavities
  - Surface Preparation
  - Fast Frequency Tuning
- Outlook

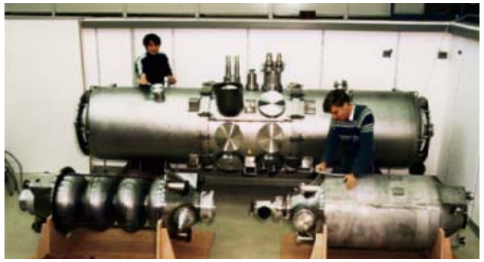
EPAC 06 Edinburgh, Scotland
10th European Particle Accelerator Conference
A Europhysics Conference

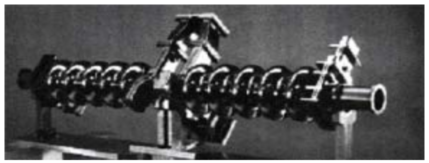
Thank You!

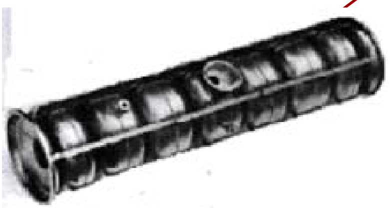
- To the TESLA Technology Collaboration for the support during the last years
- To many people for viewgraphs
  - J. Sekutowicz, K. Saito, E. Kako, A. Matheisen, H. Weise, D. Kostin, R. Lange, P. Sekalski, M. Liepe, M. Kelly, K. Shepard, H. Padamsee

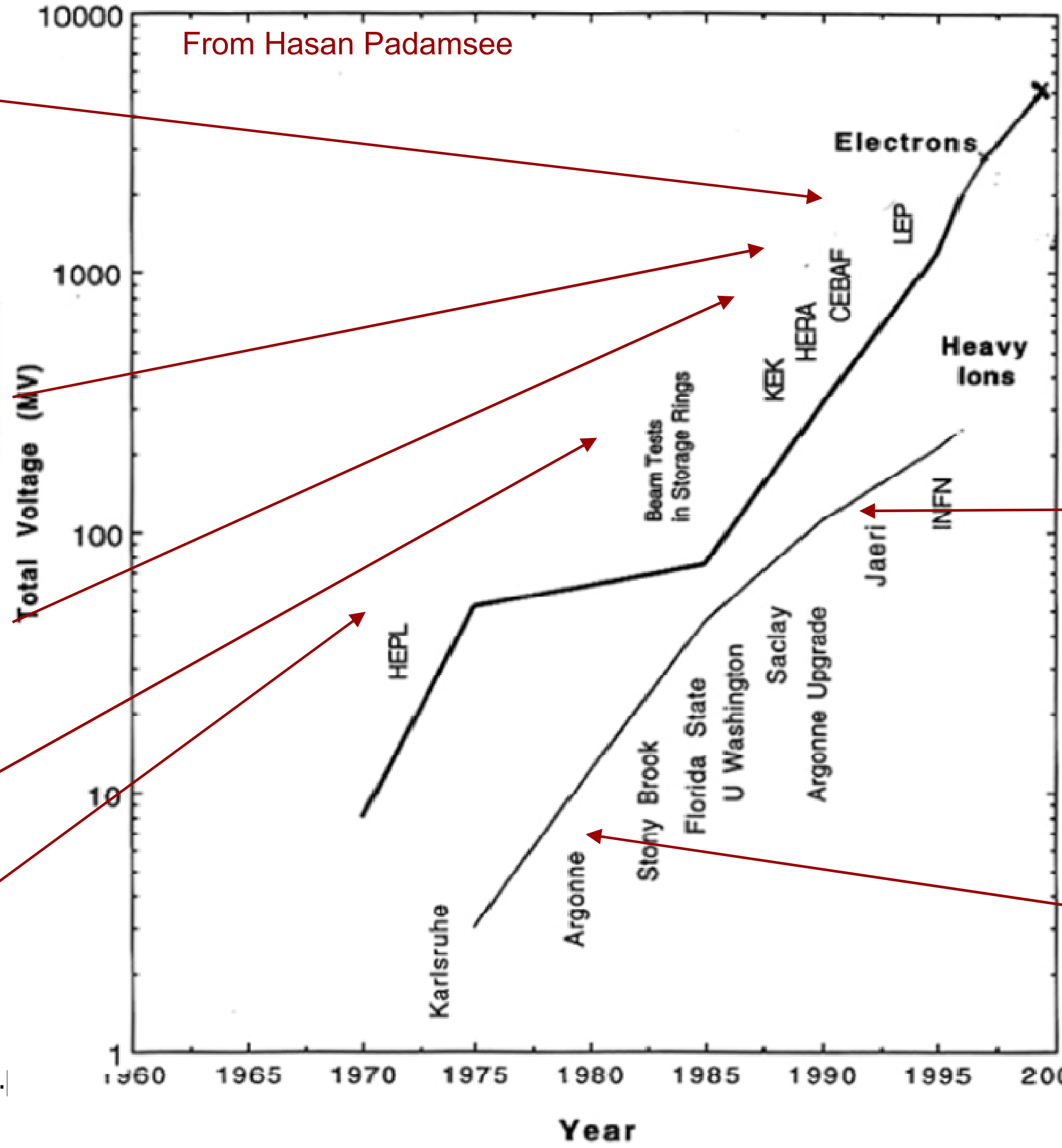
Superconducting RF History : Installed Accelerating Voltage











Total >1000 meters
> 5 GV

Superconducting RF Present and Future: Accelerator Projects Featuring SRF Cavities

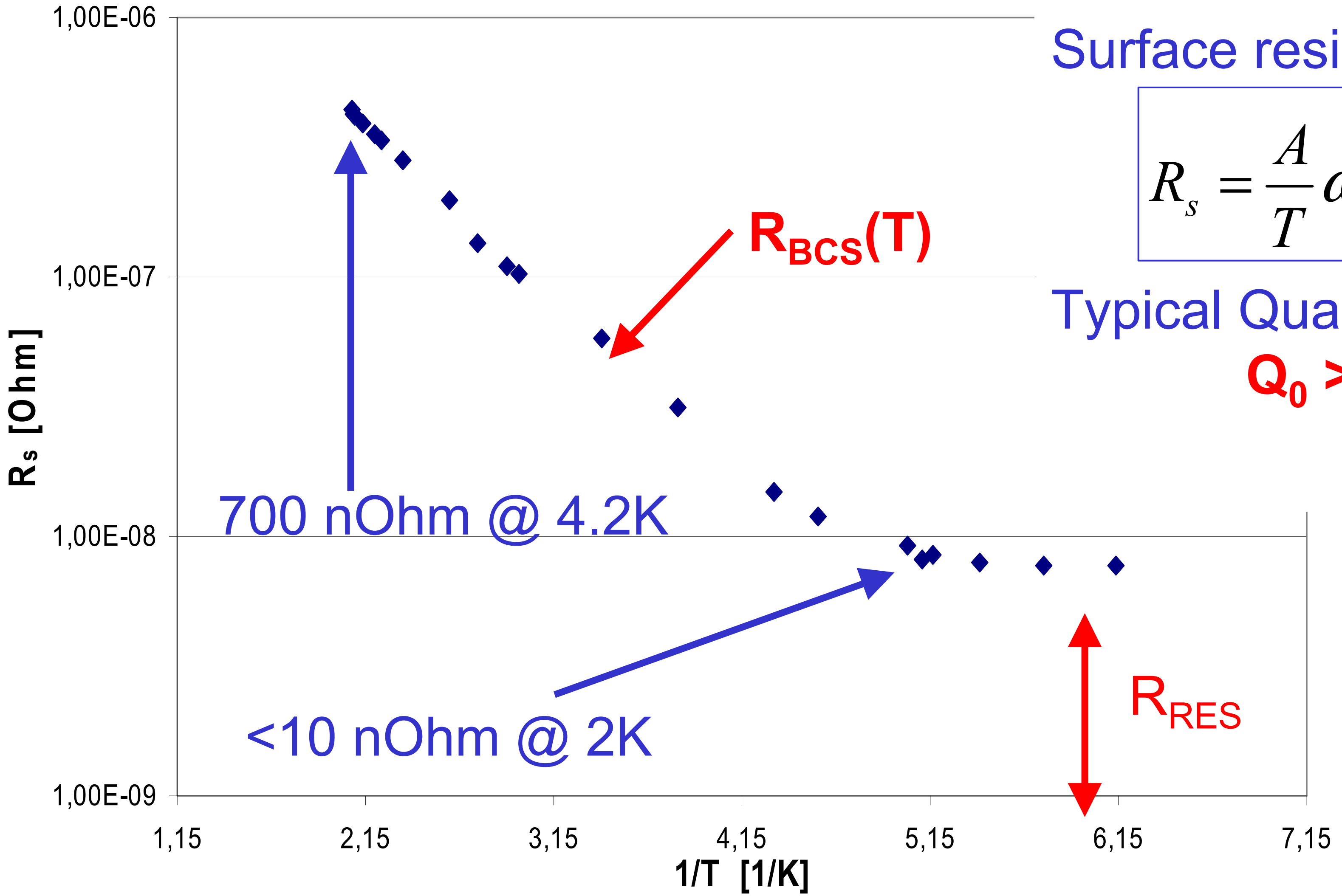
- Disclaimer: The focus is mostly on electron machines with beta =1
- LINACs
  - ILC, European XFEL, FLASH, ELBE, BESSY-FEL, MIT Bates, FERMILAB 8 GeV, SNS
- Recirculating LINACS
  - S-DALINAC, CEBAF, LUX, Arc-en-Ciel, Neutrino Factory/Muon Collider
- ERLs
  - JLAB FEL, JAERI, Cornell FEL, PERL (BNL), 4GLS, KEK-ERL, RHIC-II
- Storage rings
  - HEP
    - KEK-B, CESR, HERA, Tristan, LEP
  - Synchrotron Light
    - SOLEIL, CHESS, Canadian Light Source, Taiwan Light Source, DIAMOND

No guarantee for completeness...

Superconducting Cavities

- SC cavities offer
  - a surface resistance which is six orders of magnitude lower than normal conductors (NC)
  - high efficiency, even when cooling is included
    - large currents can be accelerated
    - high duty cycle up to continuous wave (cw) operation
  - low frequency, large aperture
  - high accelerating gradients
  - attractive for a wide range of projects and a lot of ideas
    - E.g. XFEL, Linear collider, Energy Recovery LINACS

Surface Resistance $R_s(T)$



Geometry factor:

G = 270 Ohm

$$Q_o = \frac{G}{R_s}$$

Surface resistance:

$$R_s = \frac{A}{T}\omega^2 e^{-\frac{\Delta}{k_B T_C}\frac{T_C}{T}} + R_{res}$$

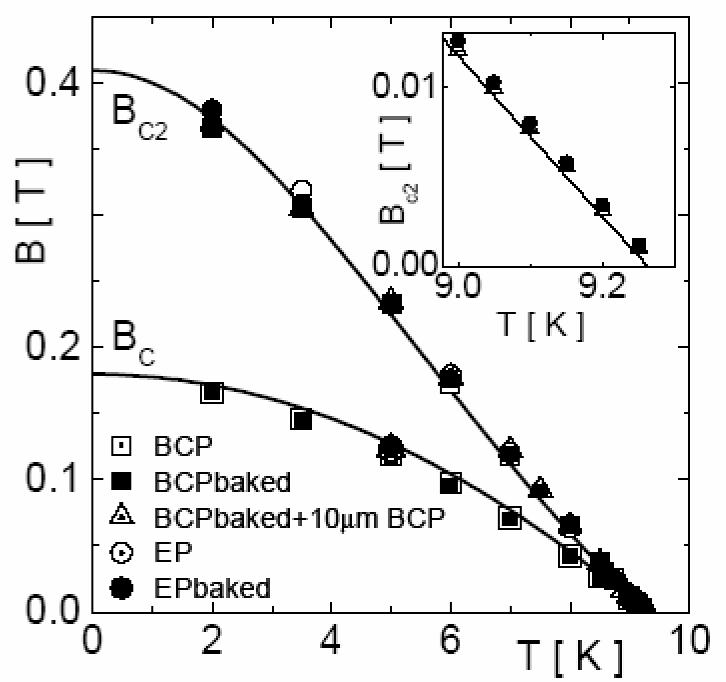
Typical Quality factor:

$Q_0 > 1*10^{10}$ at 2K

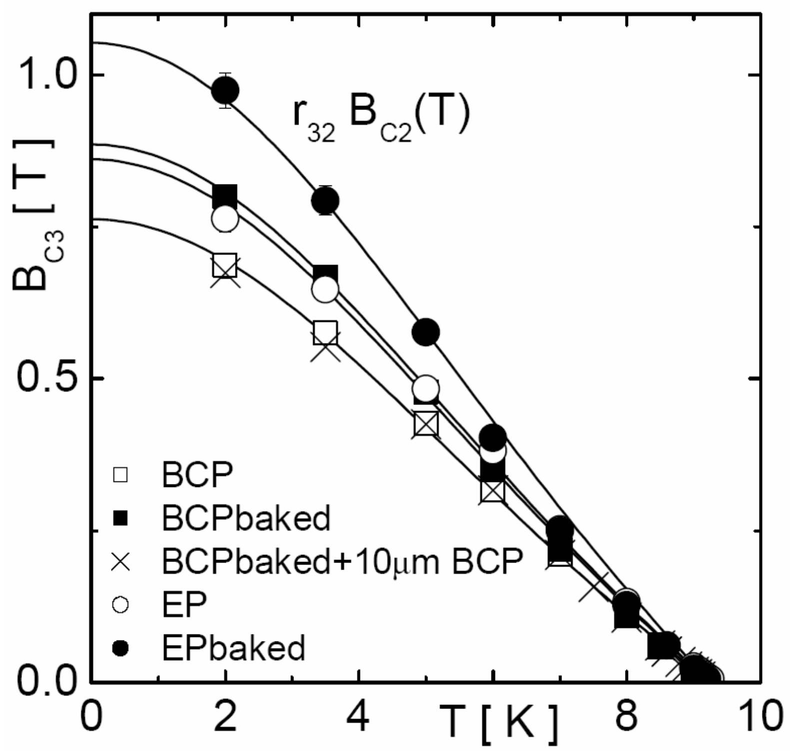
S. Casalbuoni,
L. von Sawilski,
P. Schmüser,
B. Steffen et al.

Susceptibility Measurements: Niobium Properties

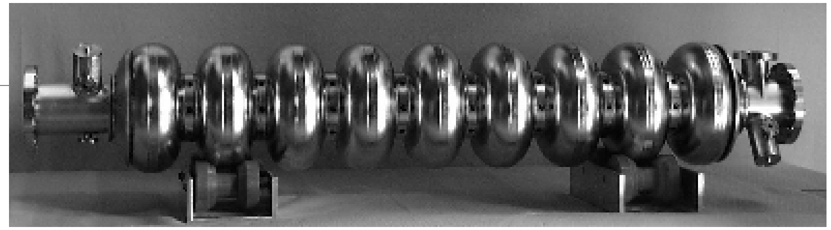
- Surface treatment does not change the bulk properties e.g. B_c and B_{c2}
- Surface critical field B_{c3} depends on surface preparation
  - Electropolishing (EP) vs. Standard etch (BCP)
  - Baking

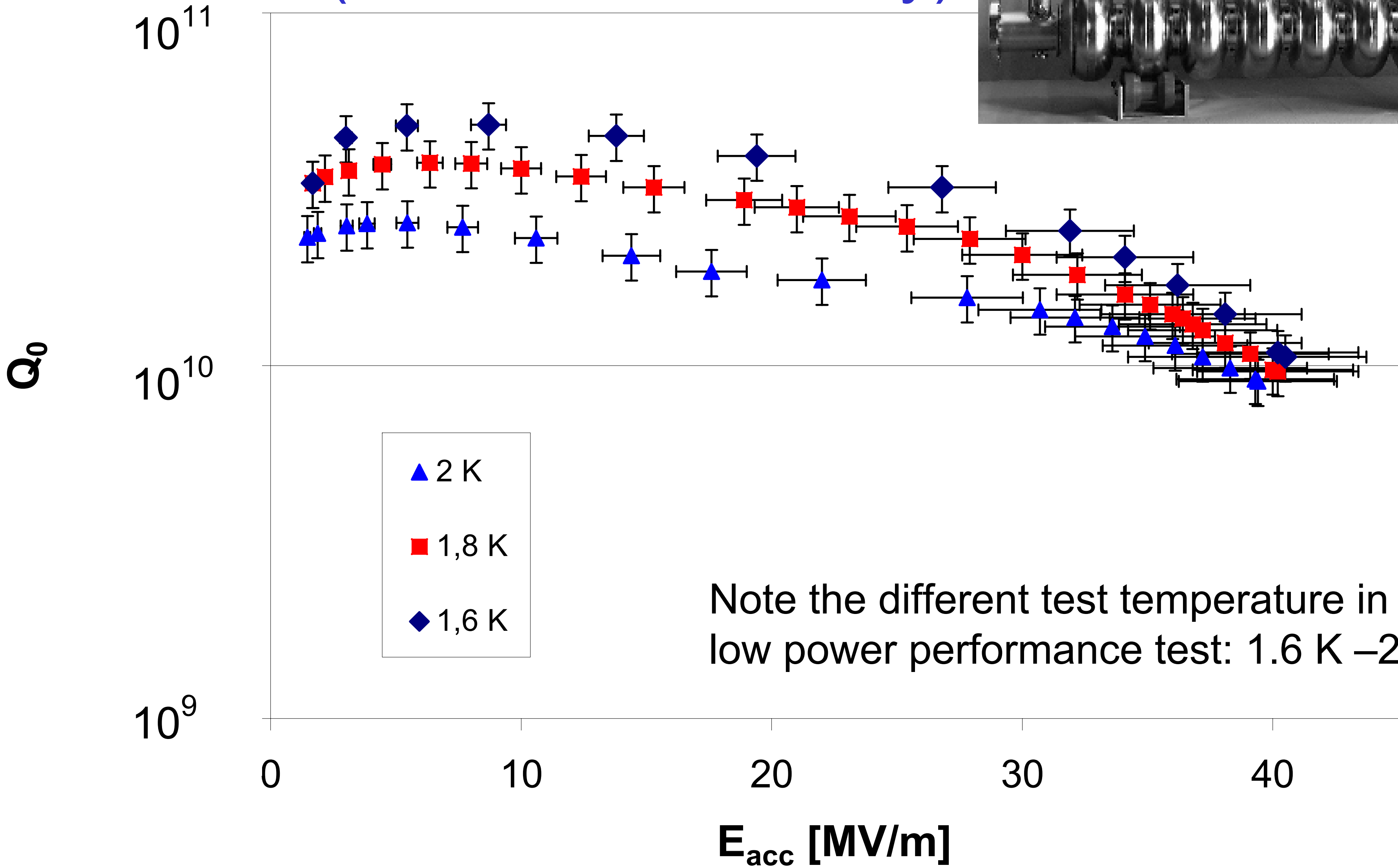


	BCP	EP
T_c [K]	9.263 ± 0.003	
RRR	≈ 300	
surf. roughness on grain [nm]	≈ 1	
steps at grain bound.	1-5 μm	$\lesssim 0.1 \mu$m
$B_c(0)$ [mT]	180 ± 5	
$B_{c2}(0)$ [mT]	410 ± 5	
$J_c(0,0)$ [A/mm^2]	240 ± 10	180 ± 10



Proof-of-Principle: TESLA Nine-cell Test (ILC Baseline Cavity)

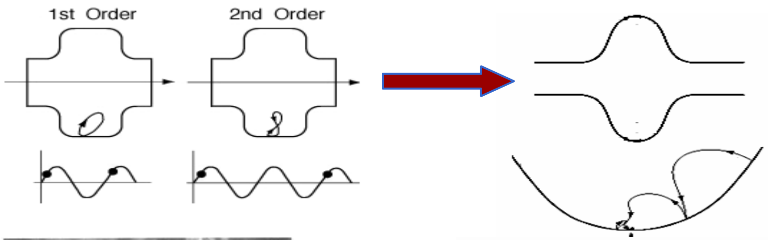




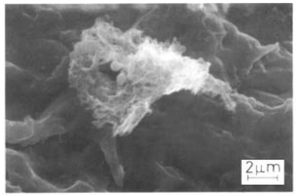
Note the different test temperature in this low power performance test: 1.6 K –2K

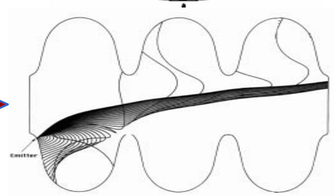
Examples for Limiting Mechanisms

- Understanding Multipactoring
  - A few computer codes developed
  - Spherical shape realized at Genova and qualified at Cornell & Wuppertal

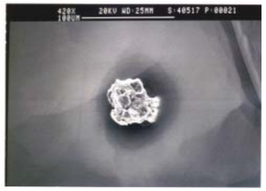


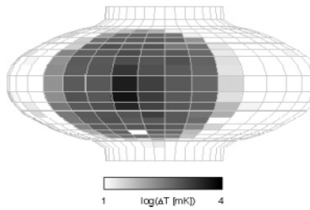
- Understanding Field Emission
  - Emitters were localized and analyzed
  - Improved treatments and cleanness



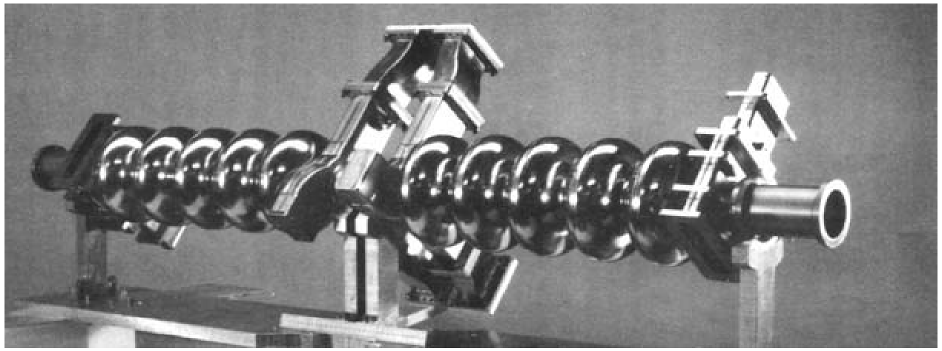


- Cure thermal Breakdown
  - Higher RRR Nb
  - Deeper control for inclusions





E_{acc} > 5 MV/m



1984/85: First great success

- A pair of 1.5 GHz cavities developed and tested (in CESR) at Cornell
- Chosen for CEBAF at TJNAF for a nominal E_{acc} = 5 MV/m

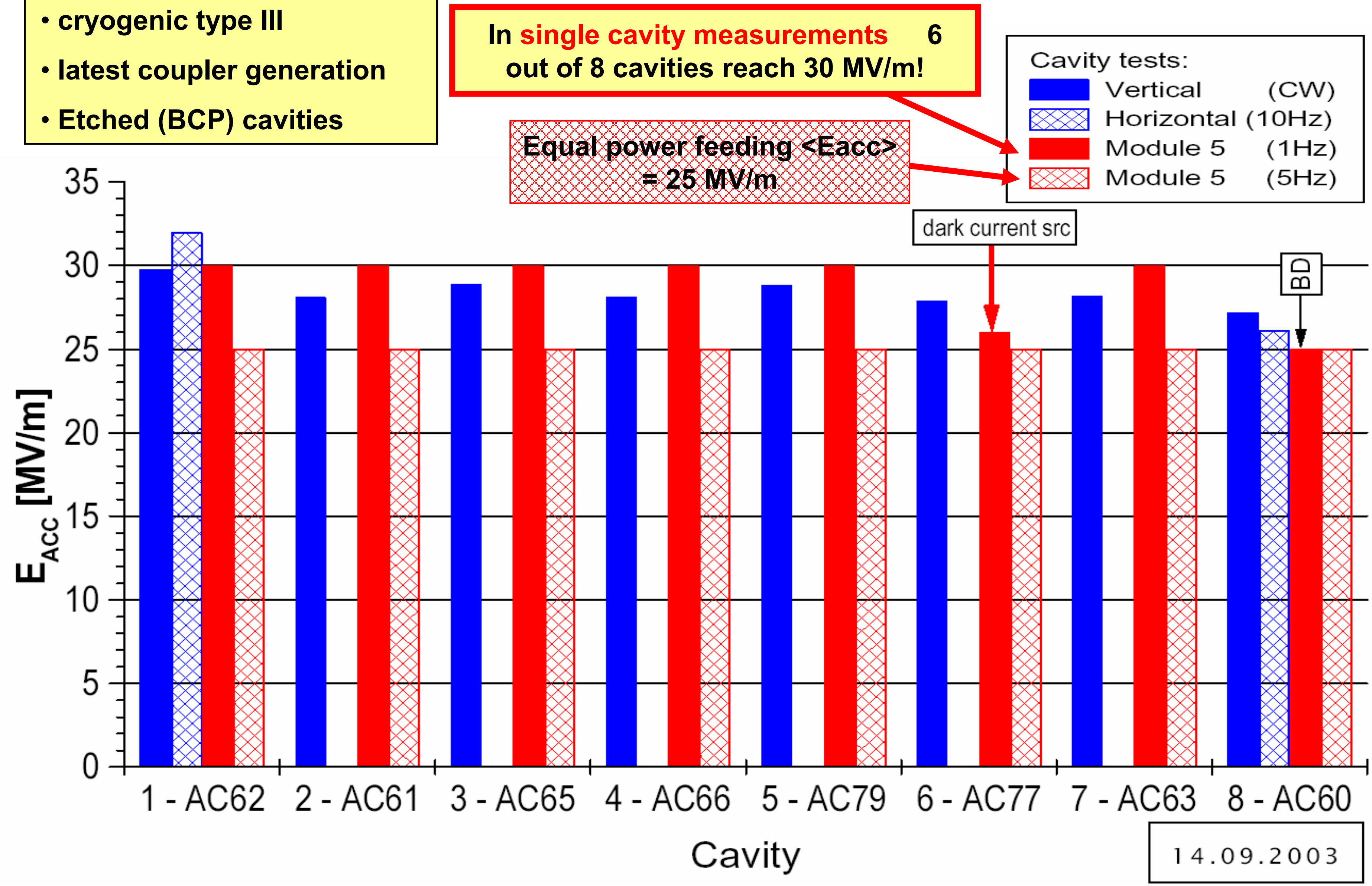
Cleanroom Technology for SC Cavities

- the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a few µm
    - detailed material specification and quality control are done
    - tight specification for fabrication e.g. welds have been implemented
    - clean room technology is a must (e.g. QC with particle counts, monitoring of water quality, documentation of processes)

The inter-cavity connection is done in class 10 cleanrooms

Performance of FLASH Accelerator Modul From H. Weise/ D. Kostin

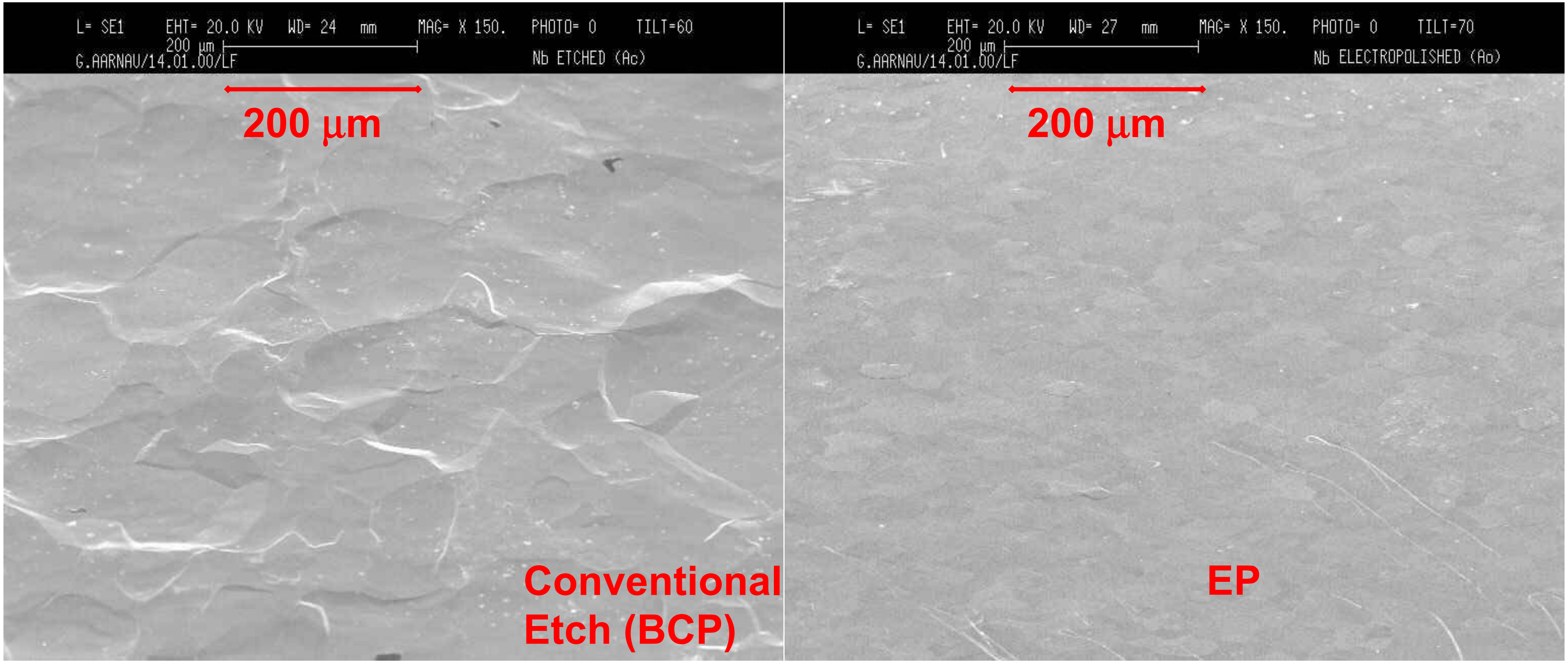
A State-of-the-art module
- cryogenic type III
- latest coupler generation
- Etched (BCP) cavities



Surface Preparation: Electropolishing

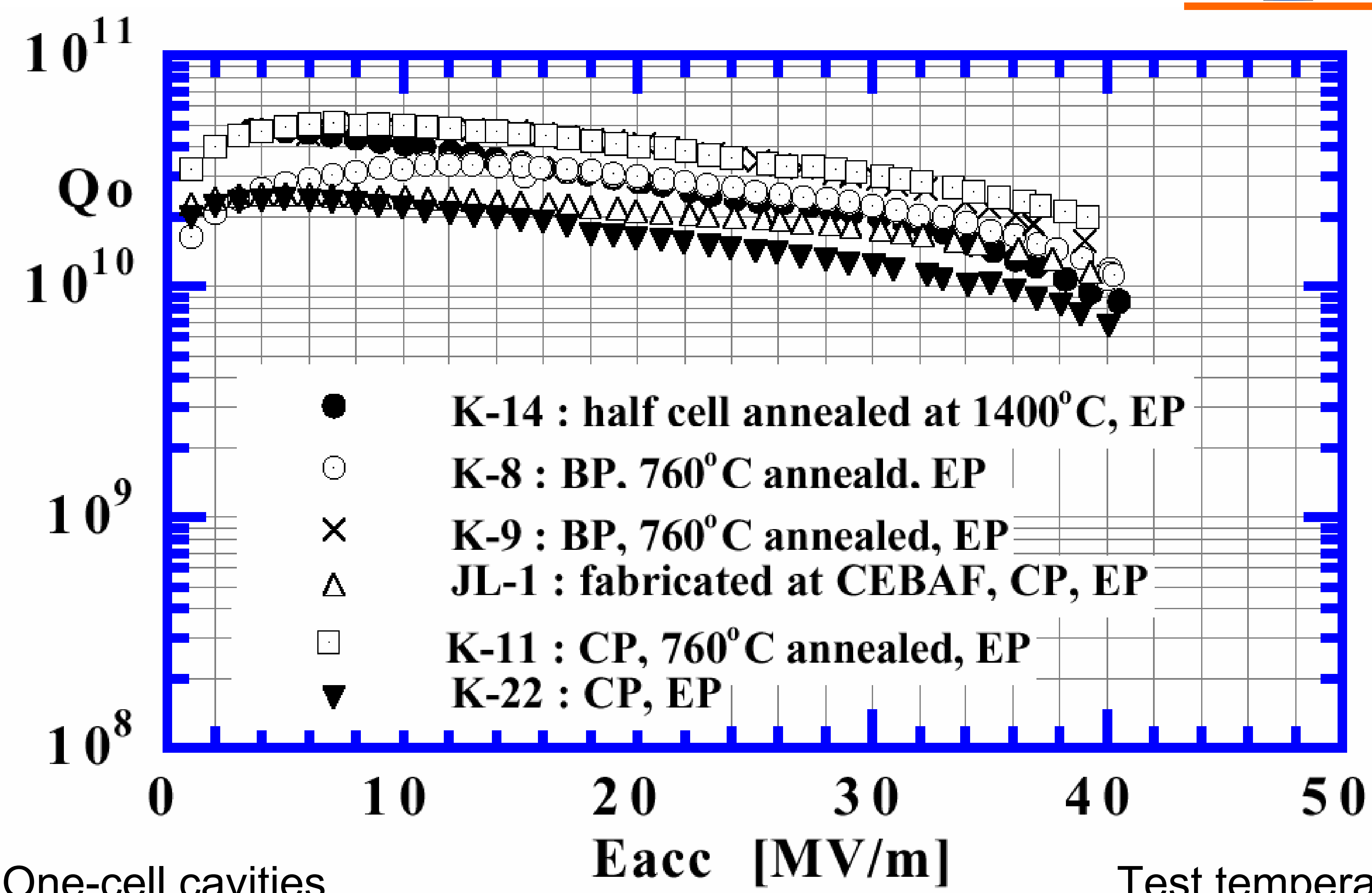
- Electropolishing (EP) of niobium surfaces is a key technology to achieve the highest electrical and magnetic surface fields
- KEK/ Nomura Plating pioneered application of EP to elliptical niobium cavities since TRISTAN using a Siemens' recipe from the 1970s
- Since then EP has also been successfully applied to
  - Low-Beta Quarter wave structures
  - TESLA nine-cells

Electropolishing Offers Improved Surface Quality



Electropolished 1,3 GHz Elliptical Niobium Cavities

K. Saito et al. KEK 1998/1999

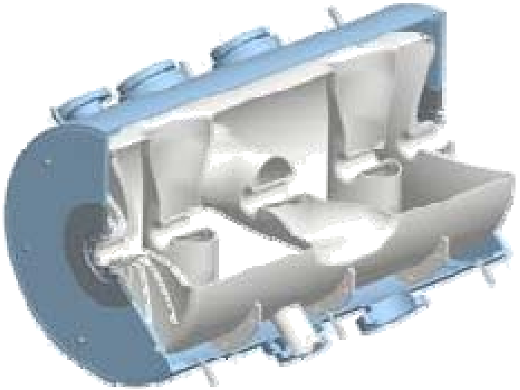


One-cell cavities

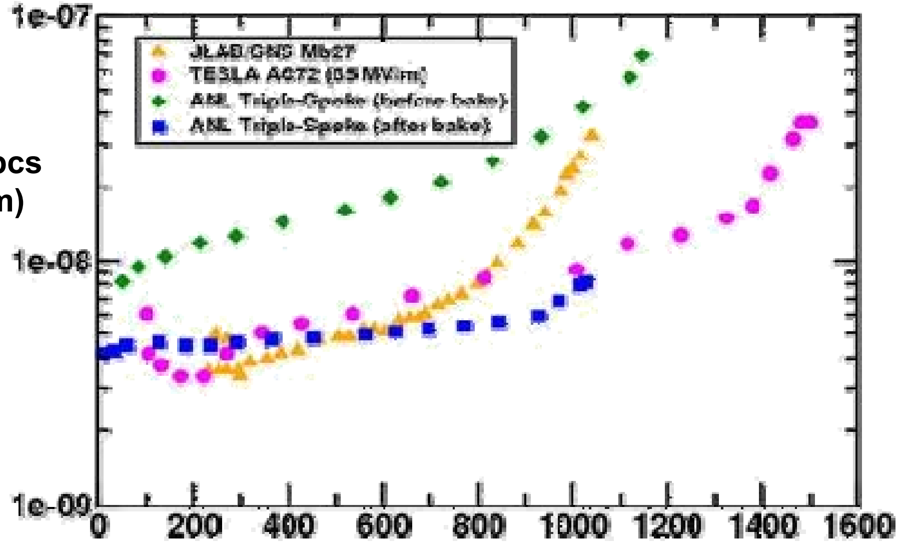
Test temperature: 1.6 K

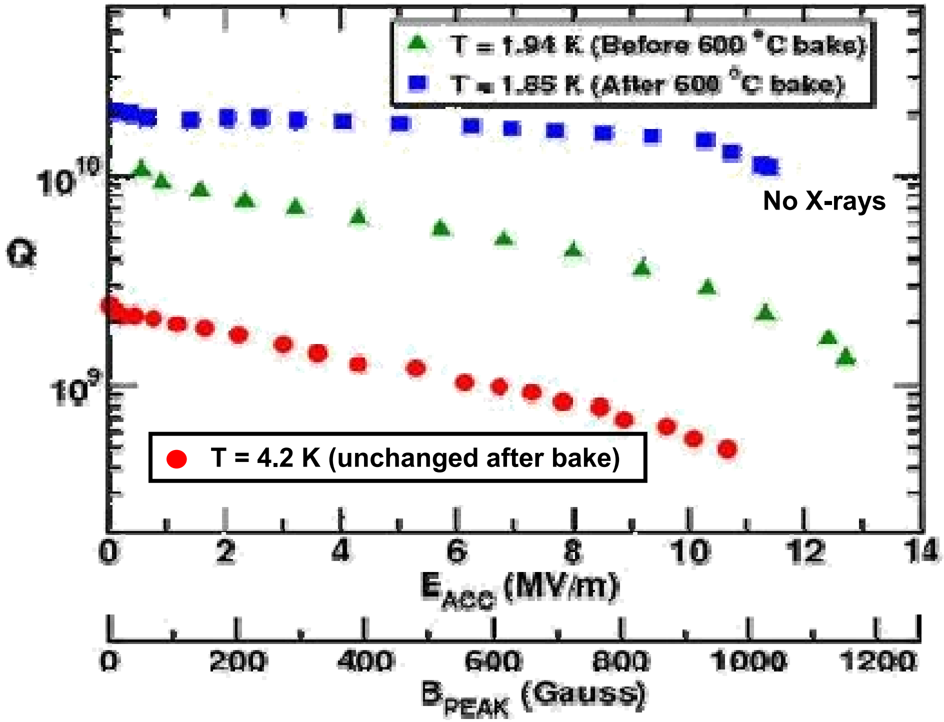
Cavity Processing:
ANL β=0.63 Triple-Spoke Cavity, Area ~1.5 m^2

ANL EP: Beta=0.63 Multi-Spoke Cavity

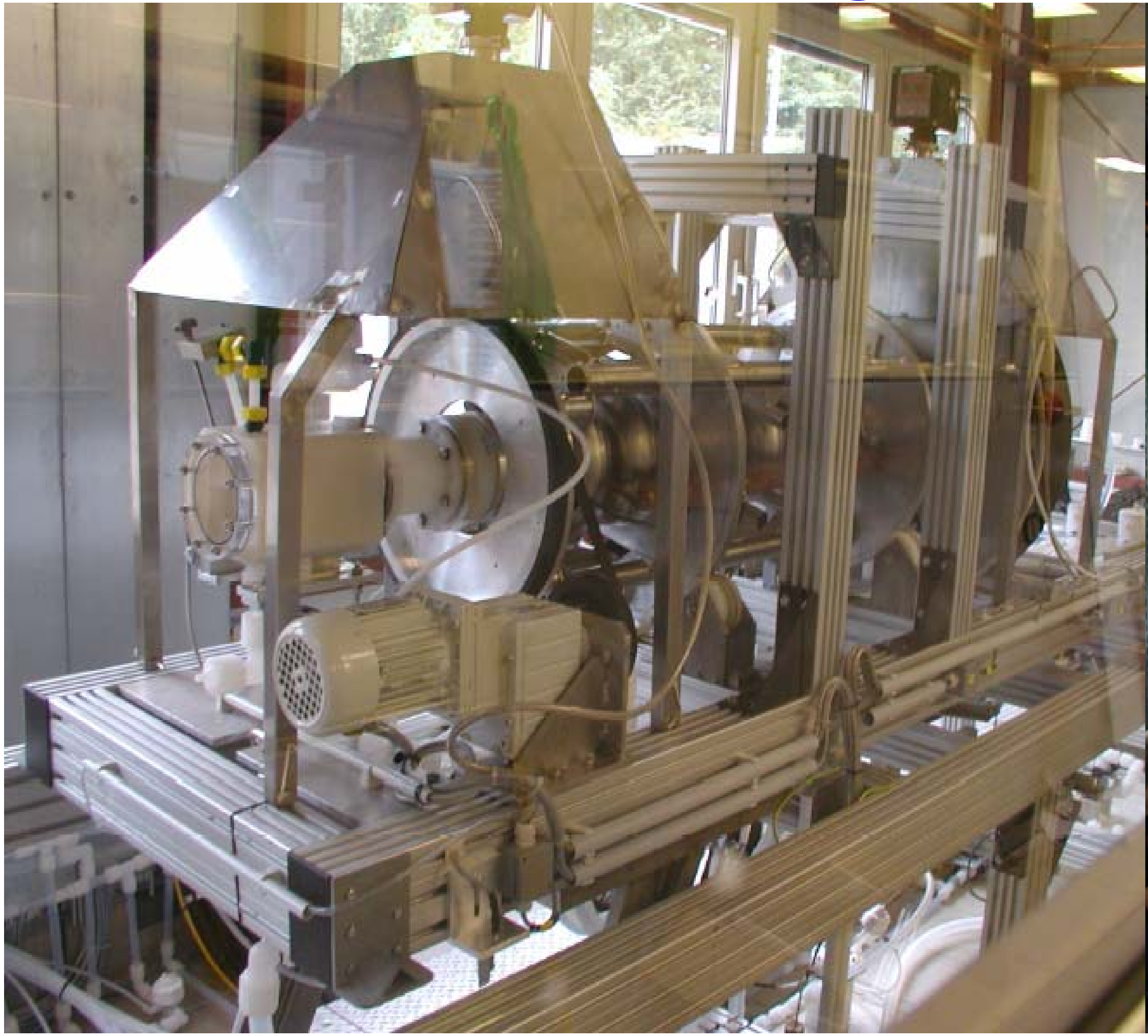


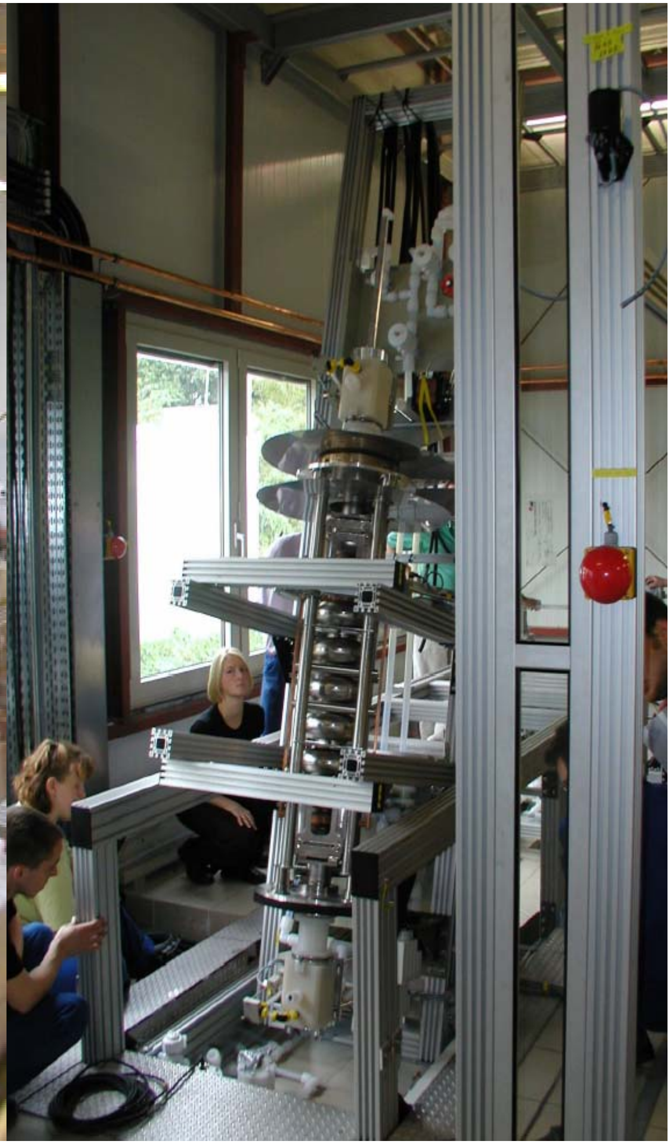
- Q-disease was observed; hydrogen degassing at 600 °C was performed at ANL
- 2 K surface resistance decreased substantially after 600 °C bake.



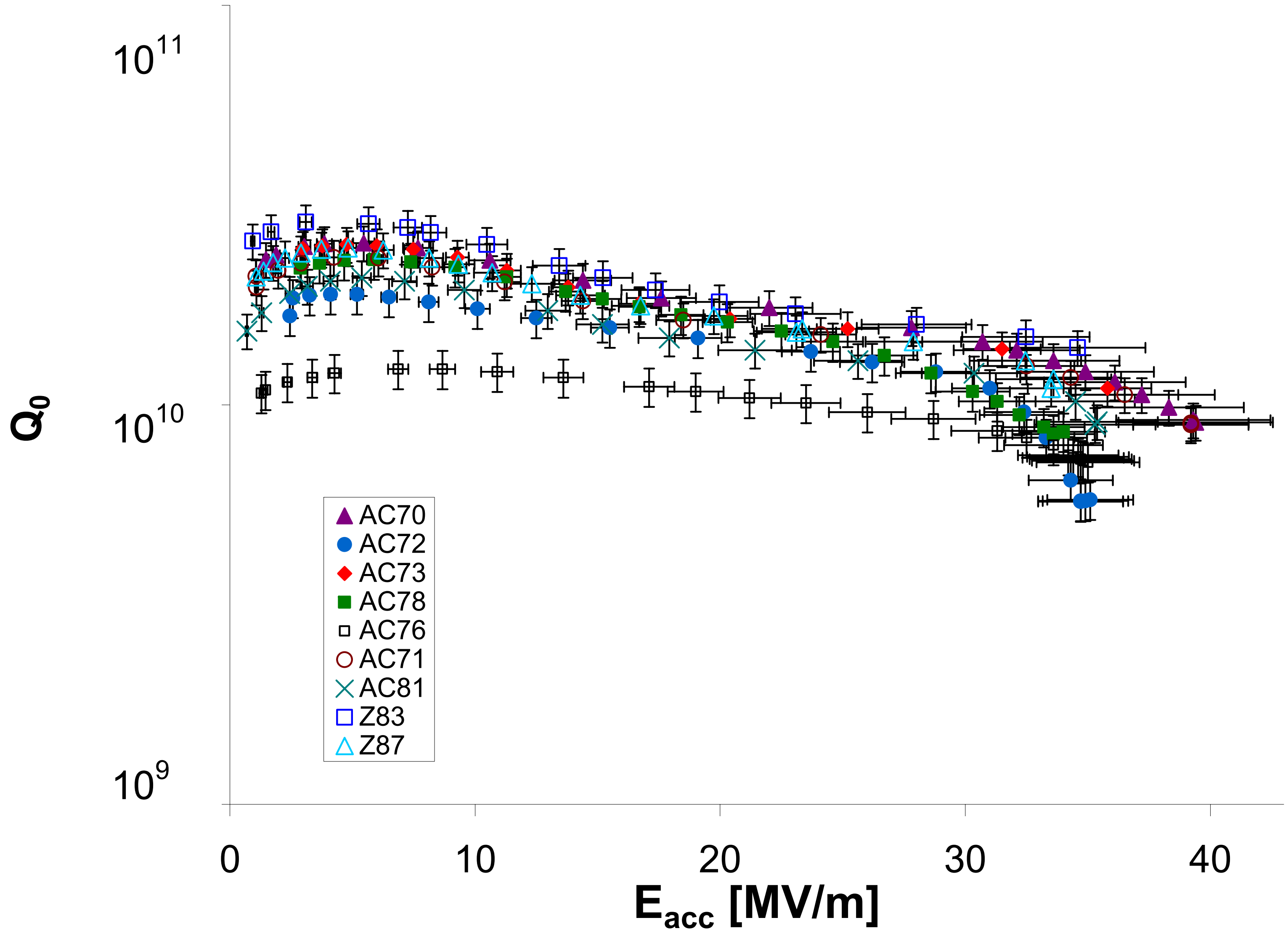


Electropolishing Setup at DESY

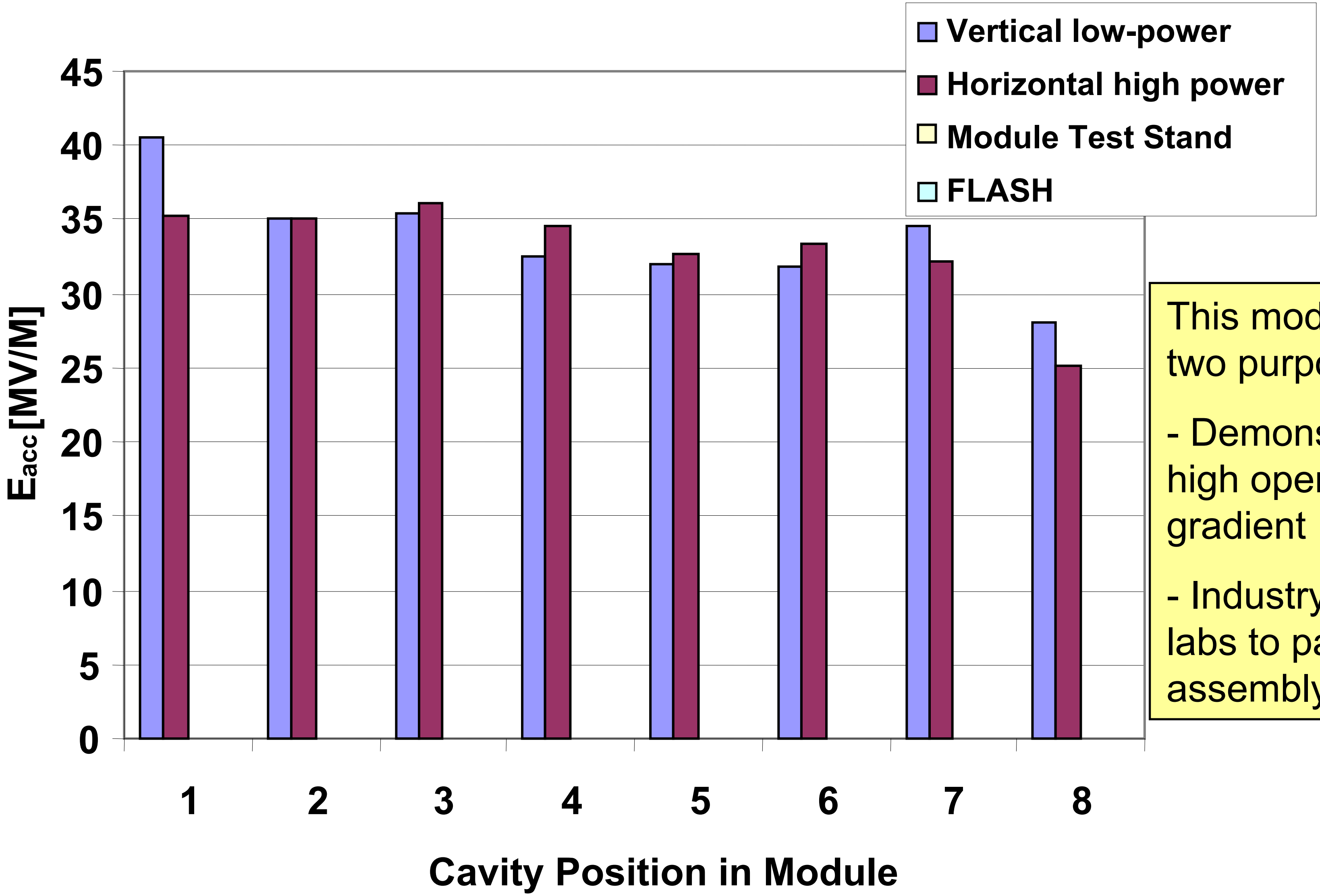




TESLA Nine-Cells: Low-Power Results



FLASH Module 6: High Gradient Module

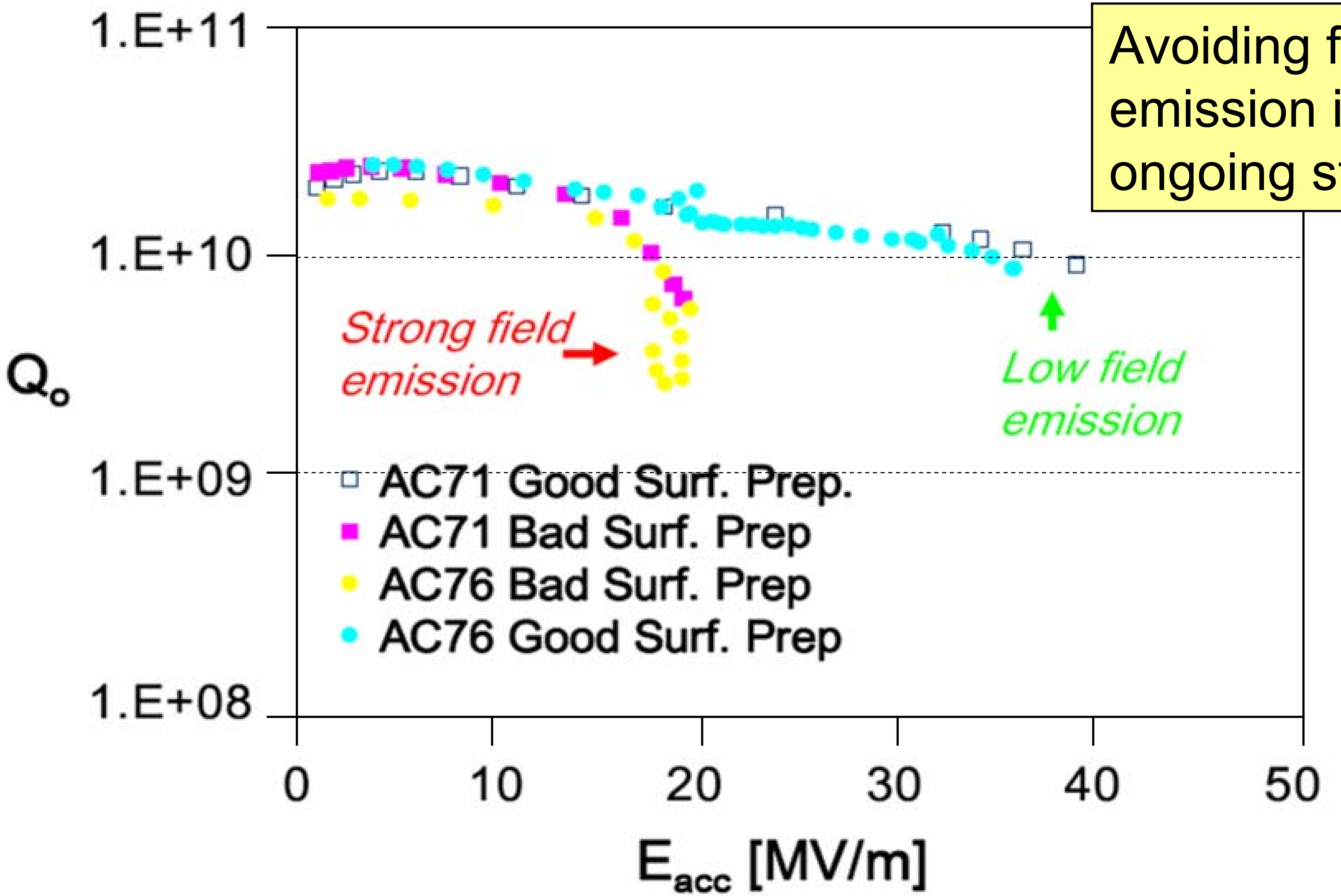


This module serves two purposes:

- Demonstration of high operational gradient

- Industry and partner labs to participate in assembly process

Work needed: Reproducibility in the EP Process



Avoiding field emission is an ongoing struggle !

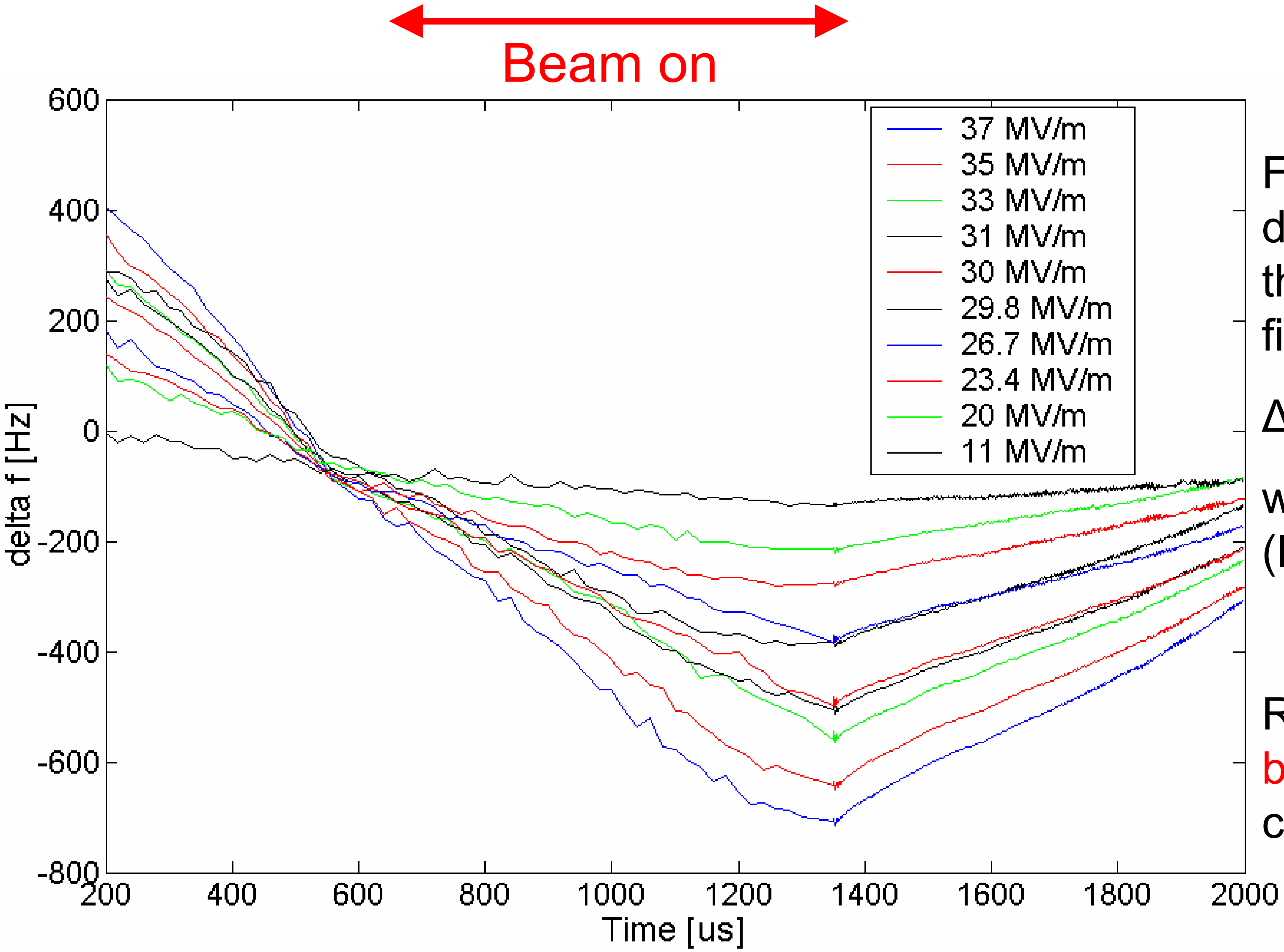
Active Tuner

- Lorentz force detunes the cavity during one RF pulse
  - If detuning is too large extra RF power would be needed

- Actively compensate the detuning of the cavity during the RF pulse by mechanical means

- Piezoelectric elements are suitable for this application

Frequency Detuning during RF Pulse



Frequency detuning due Lorentz forces of the electromagnetic field in the cavities:

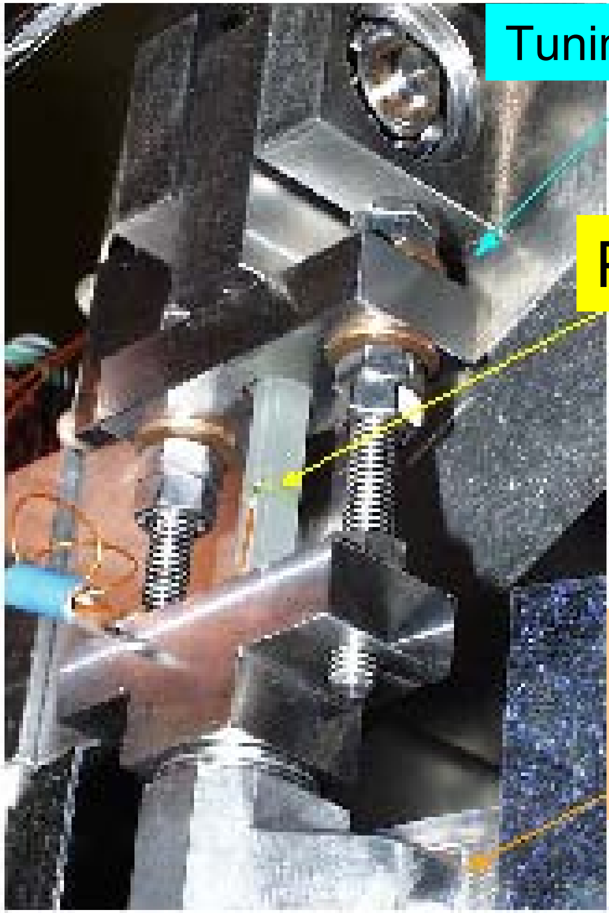
$\Delta f = -K \cdot E_{acc}^2$

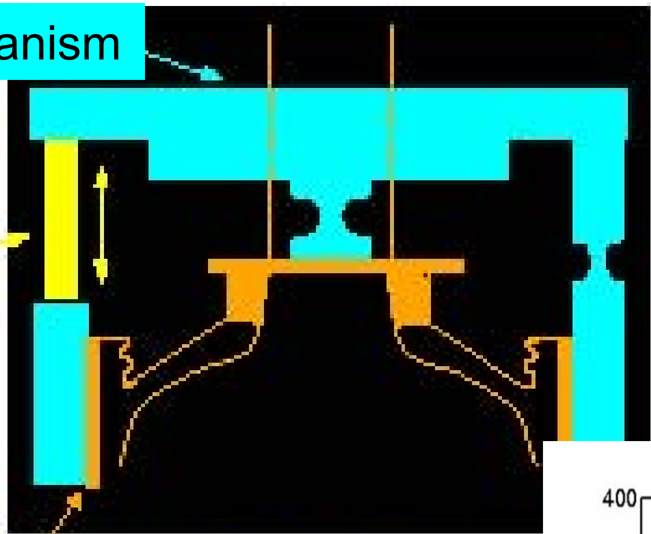
where K ≈ 1 Hz / $(MV/m)^2$

Remember: Cavity bandwidth with main coupler is ≈ 300 Hz

Proof-of-Principle: Piezoelectric Tuner

M. Liepe, S. Simrock, W.D.-Moeller





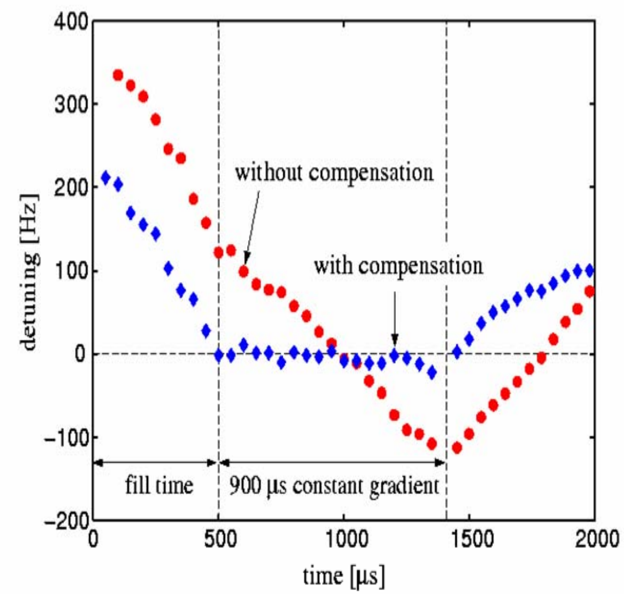
Piezo-Actuator:

l=39mm

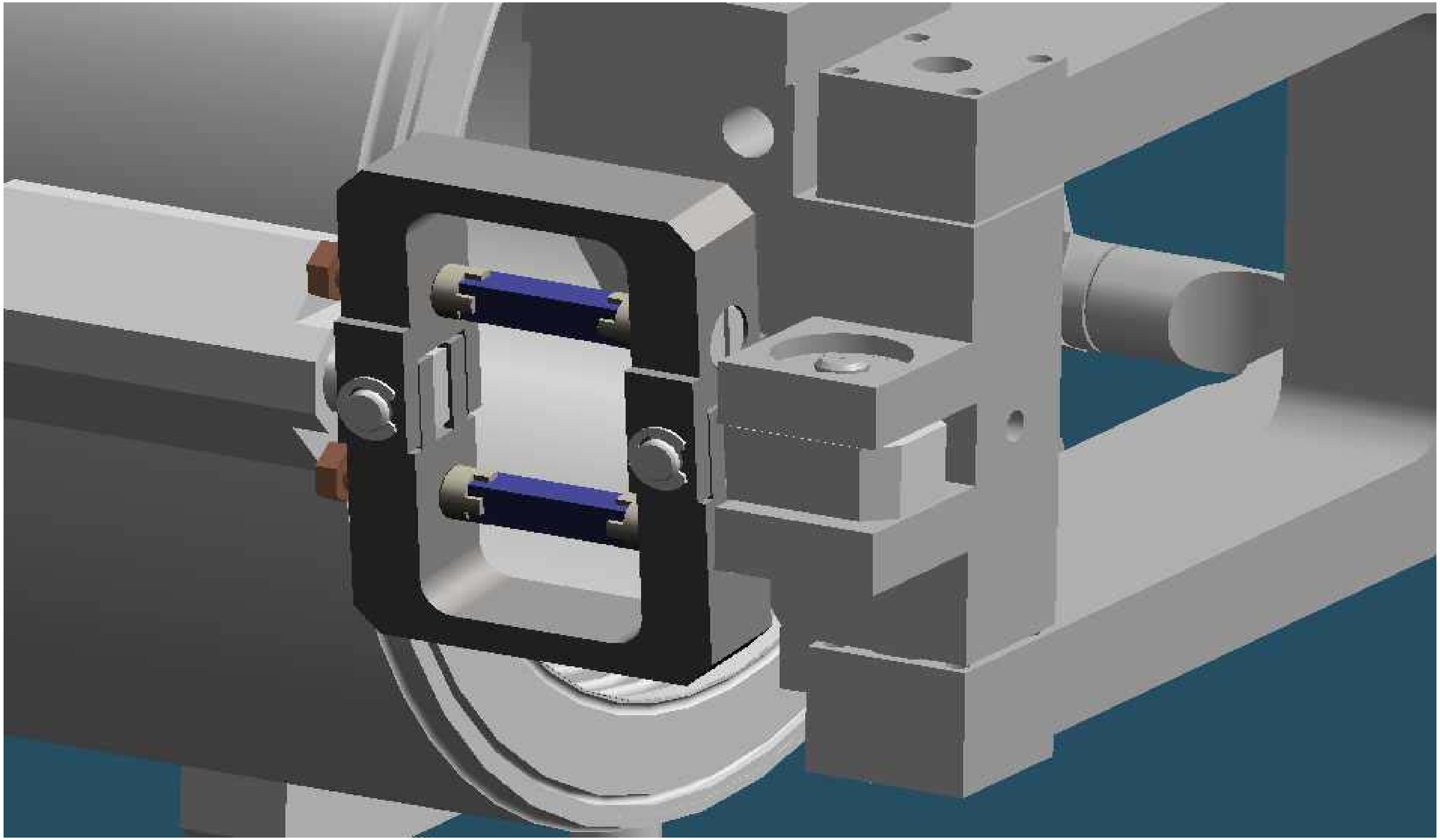
U_{max}=150V

Δ l=3µm at 2K

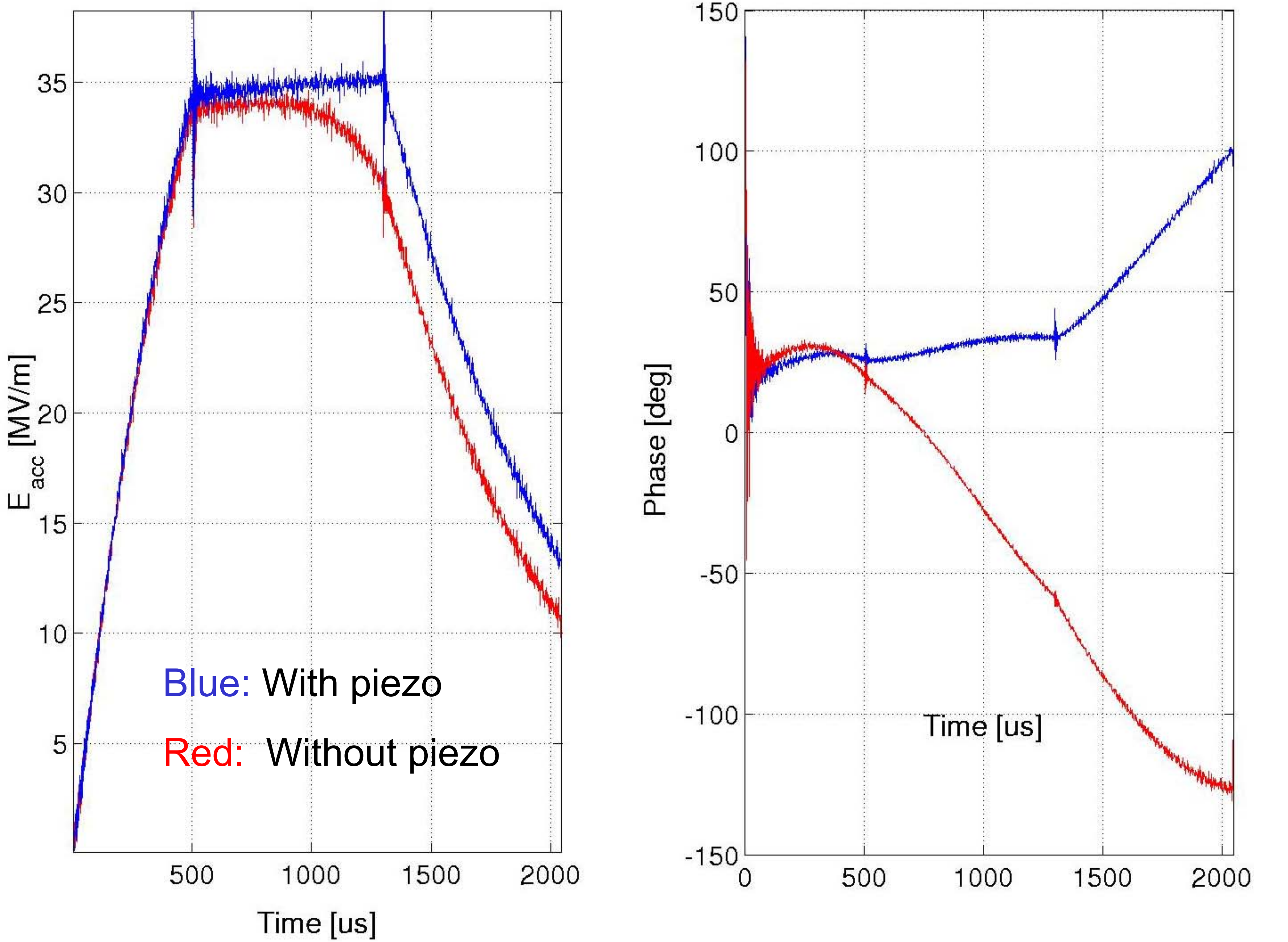
$\Delta f_{max,static}$=500Hz



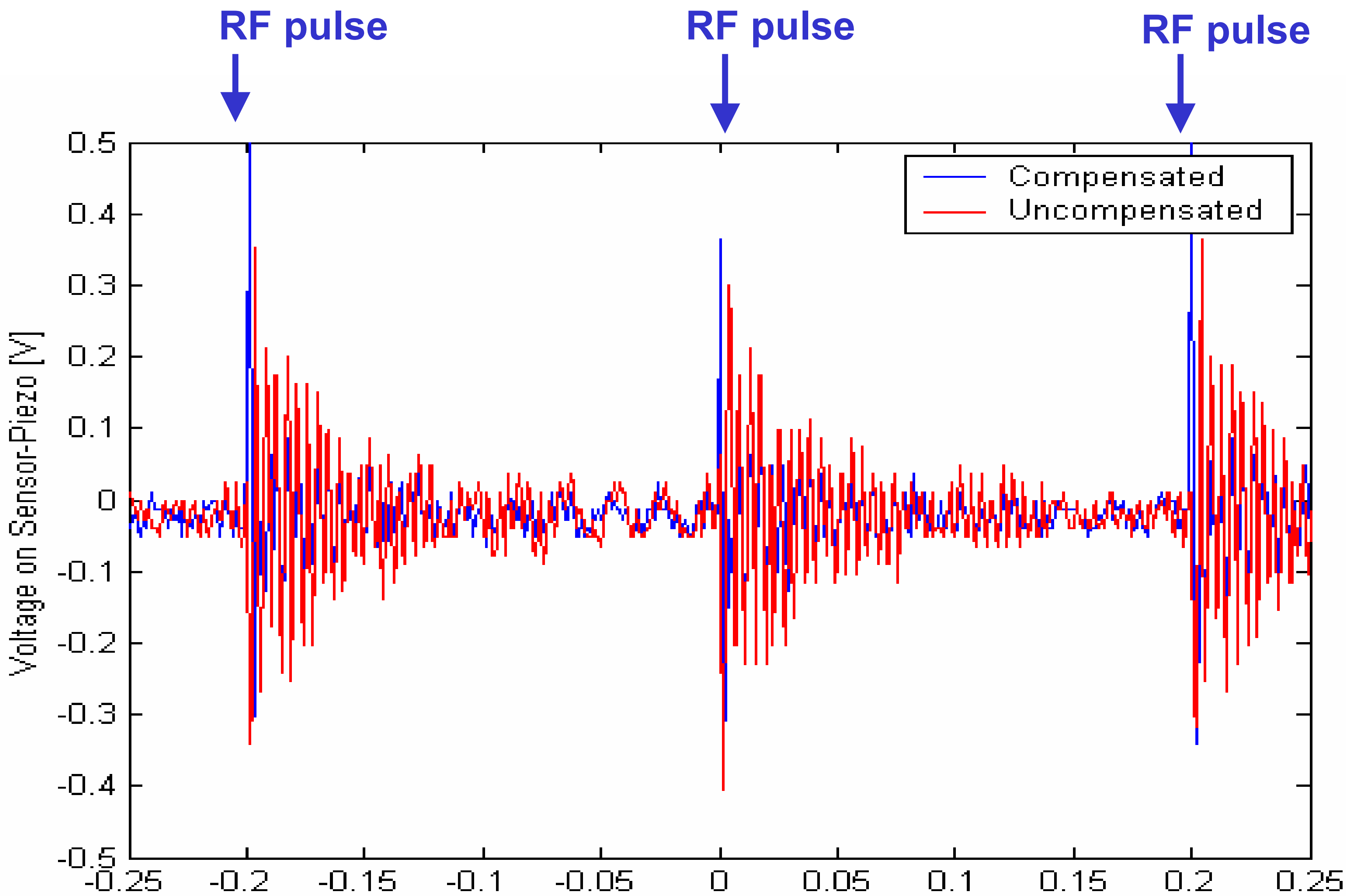
Sensor-Actuator: Piezoelectric Elements in the Tuning Mechanism



RF Signals at 35 MV/m



Damping of the ringing between pulses (5Hz operation)

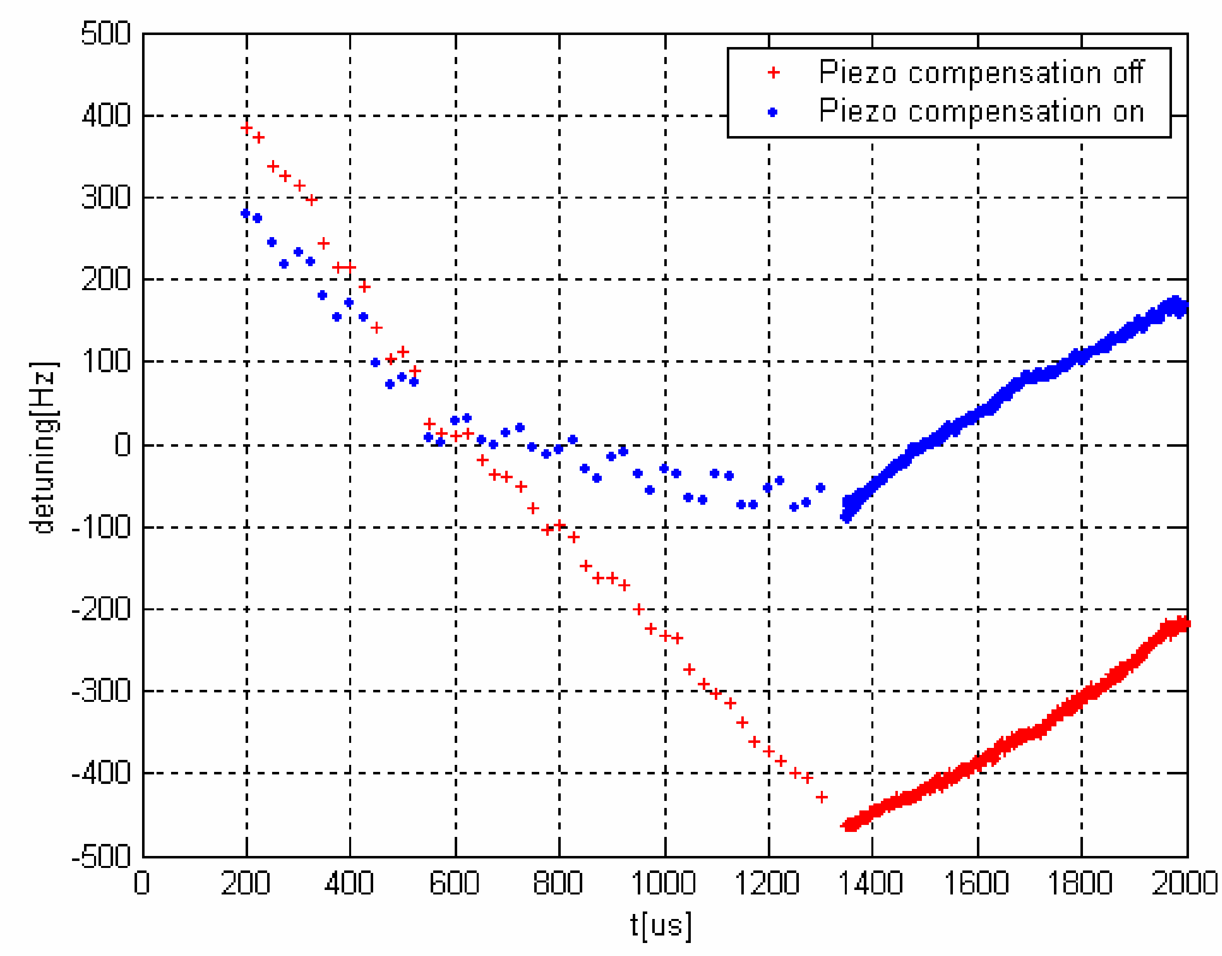


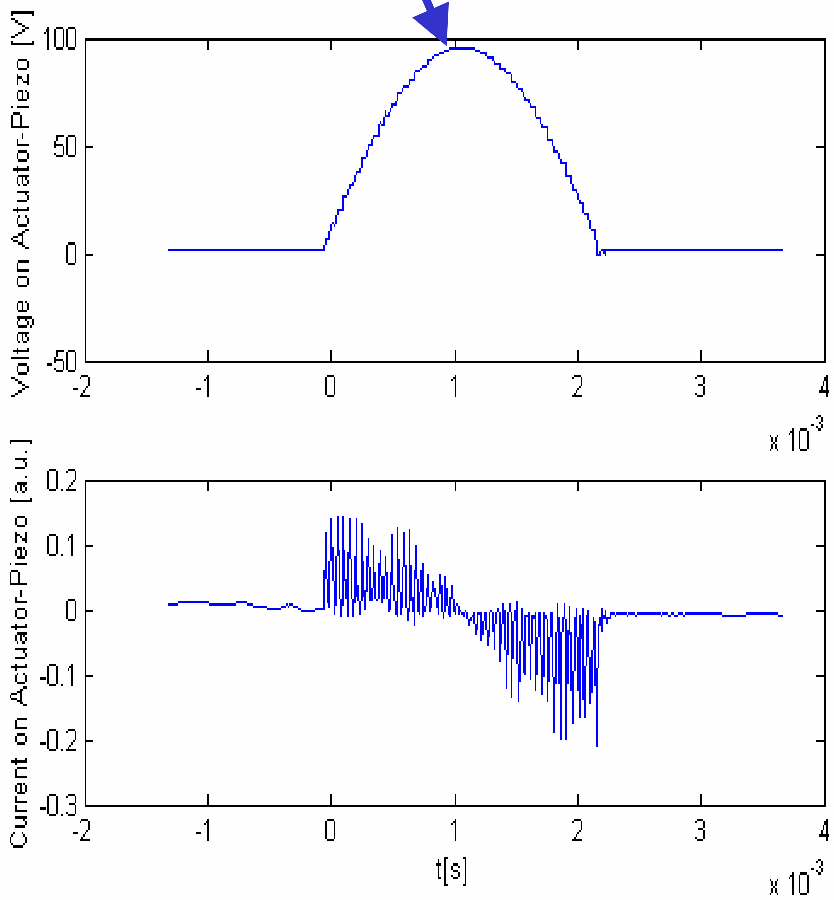
Frequency stabilization during RF pulse using a piezoelectric tuner

Blue: With piezo

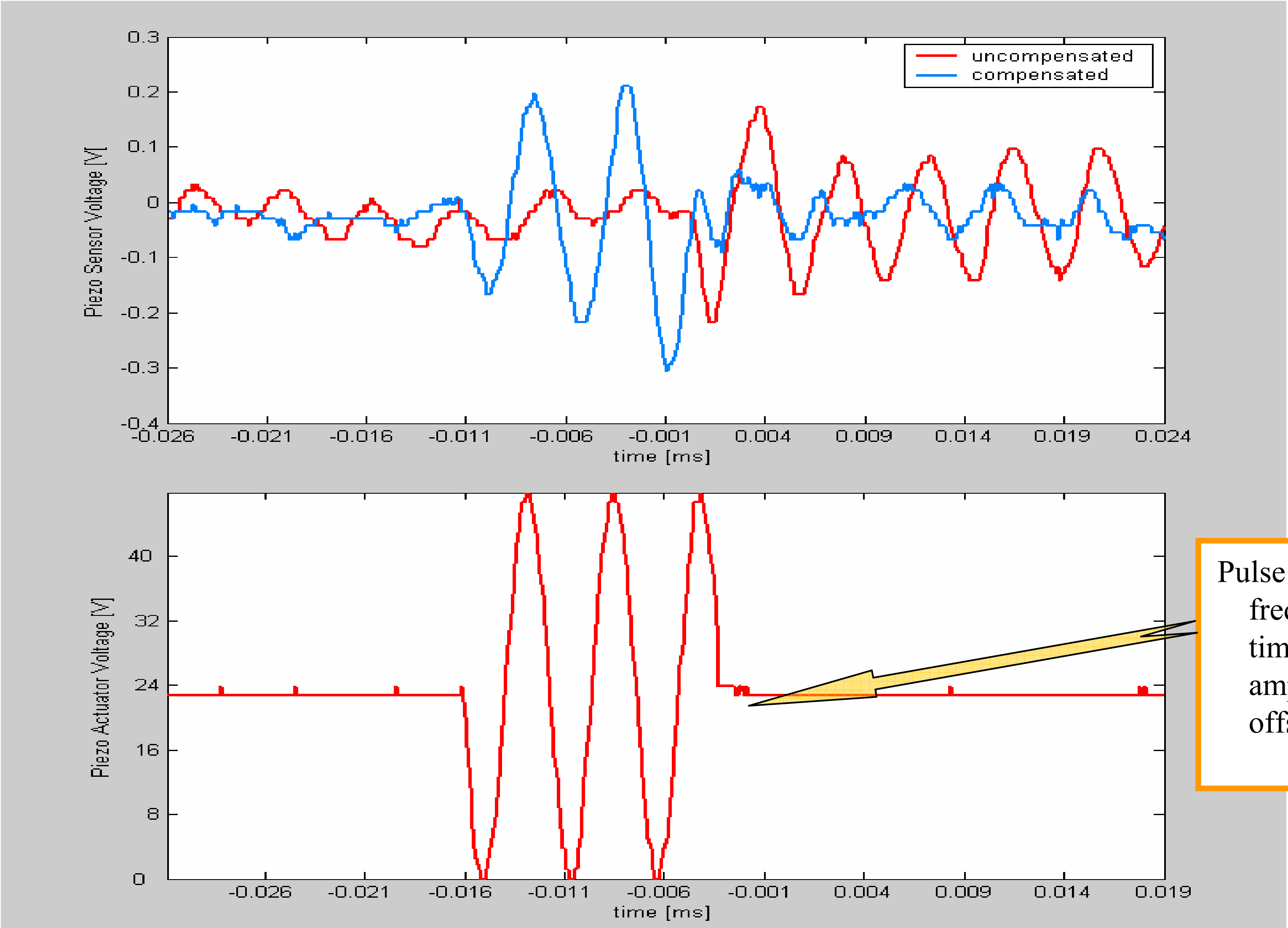
Red: Without piezo

Frequency detuning of ~ 500 Hz compensated voltage pulse (~100 V) on the piezo. No resonant compensation

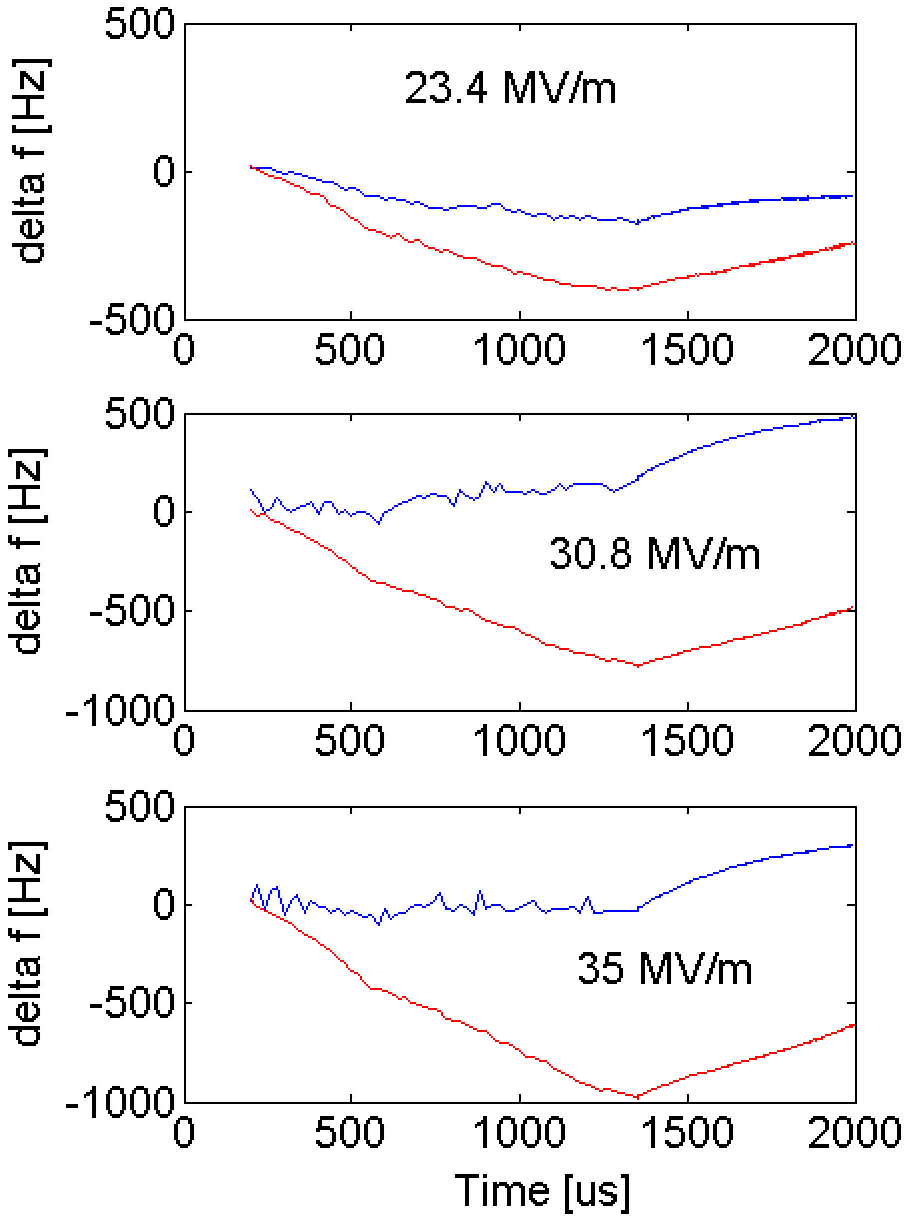




Resonant Excitation of the Cavity



Pulse Parameters:
- frequency = 219 Hz
- time shift = -9.5 ms
- amplitude = 24V
- offset = 24V



Frequency stabilization at 35 MV/m

Blue: With piezo

Red: Without piezo

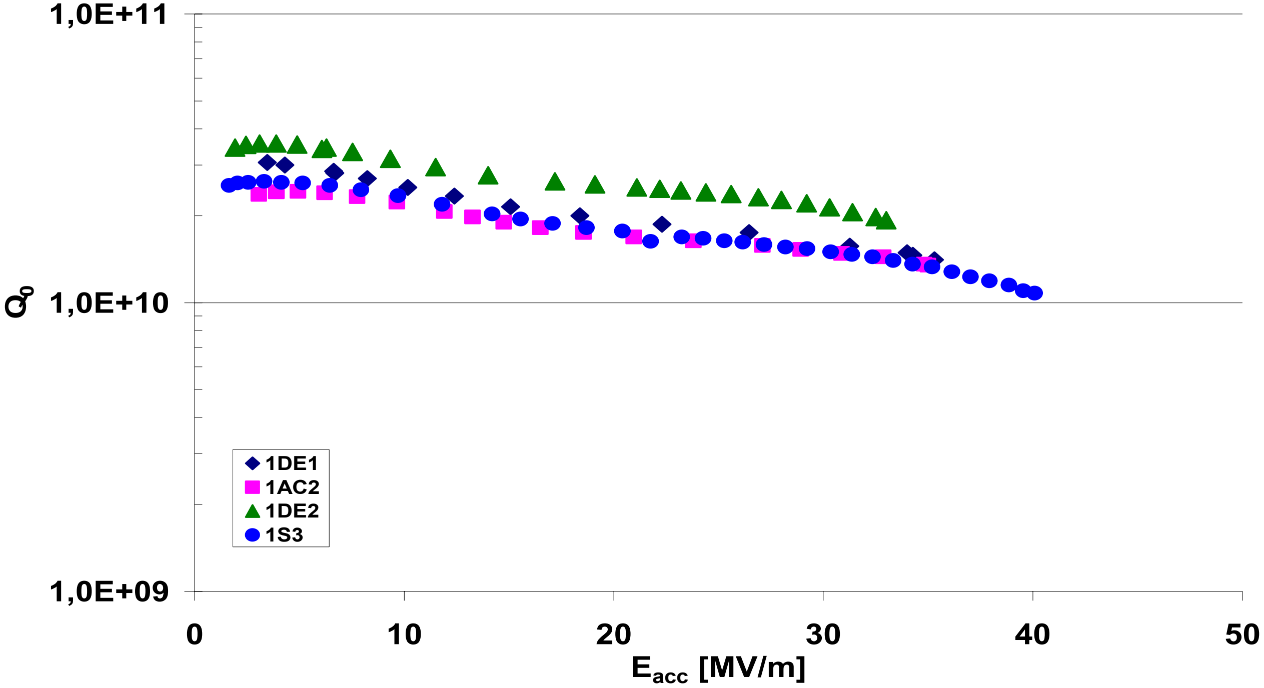
Frequency detuning of ~1000 Hz compensated with resonant excitation of a mechanical cavity resonance at 230 Hz.

NOTE: This is rather an demonstration of the capability of active tuning. Application in a real machine needs investigation.

Work to be done for projects ahead

- XFEL
  - Transferring knowledge to industry
    - Cavity manufacture done in industry since the formation of the TESLA collaboration
      - Also for auxiliaries
    - Cavity Processes
      - Electropolishing has started
    - Module manufacturing and assembly
      - Studies with participation of industry in progress (see module 6)
- ILC
  - Proof-of-existence is there!
  - Need to increase yield of getting 'good' cavities
    - Surface preparation is the clue
  - Further look into cost reduction
    - Other cavity shapes
    - Other materials
  - Involve industry in an early stage
- Other projects (e.g. see Susan Smith's Talk)
  - Higher beam currents
    - E.g. HOM damping
  - CW operation
    - E.g. Higher Q_0

Example of XFEL Industrialisation: Henkel



- Very high gradient (up to 40 MV/m), high Q_0 single-cell cavities have been prepared
- Study on improved quality control measures at DESY and Henkel
  - E.g. Improved parameter-control of electrolytes
- Upto three-cell 1.3 GHz cavities can be treated currently

ILC: Shapes

- TESLA shape
  - Baseline
- Alternative Shapes
  - Main Feature
    - Designed for
      - Lower H_{peak}/E_{acc} : magnetic field limit
    - Caveat
      - Higher E_{peak}/E_{acc} : field emission
  - 'Low-Loss' shape (LL)
    - Originally designed for lower cryo losses
  - Re-entrant shape (RE)

TESLA Cavity Design

- Frequency choice
  - Lower frequency better for
    - RF losses (BCS surface resistance)
    - Lower wakefields
  - 1.3 GHz klystrons were available

- Cavity RF Layout
  - Number of cells determined by maximum cell-to-cell coupling k_{cc} (field flatness)
  - Low E_{peak}/E_{acc} (less sensitive to field emission)
  - End cells asymmetric
    - Avoid trapping of TE121 higher order mode
    - Keep TM010 and first two dipole bands mode flat

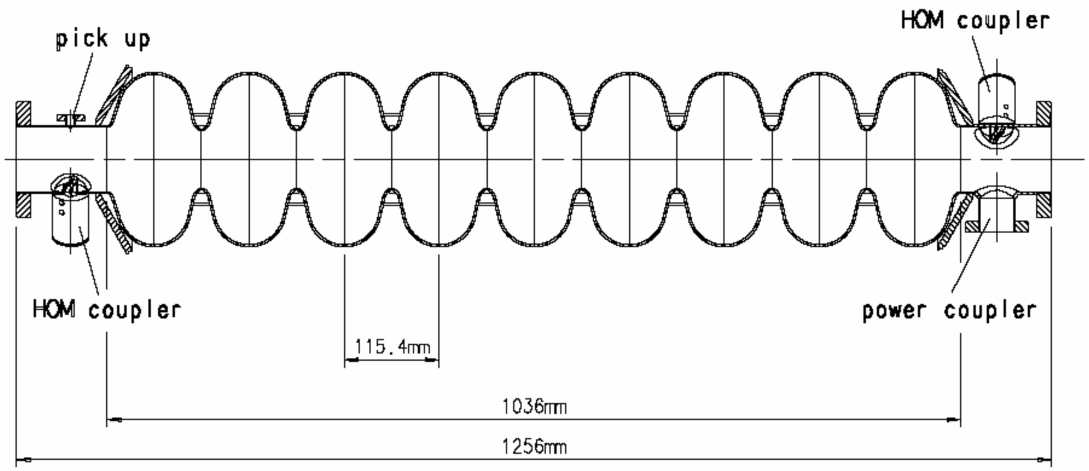
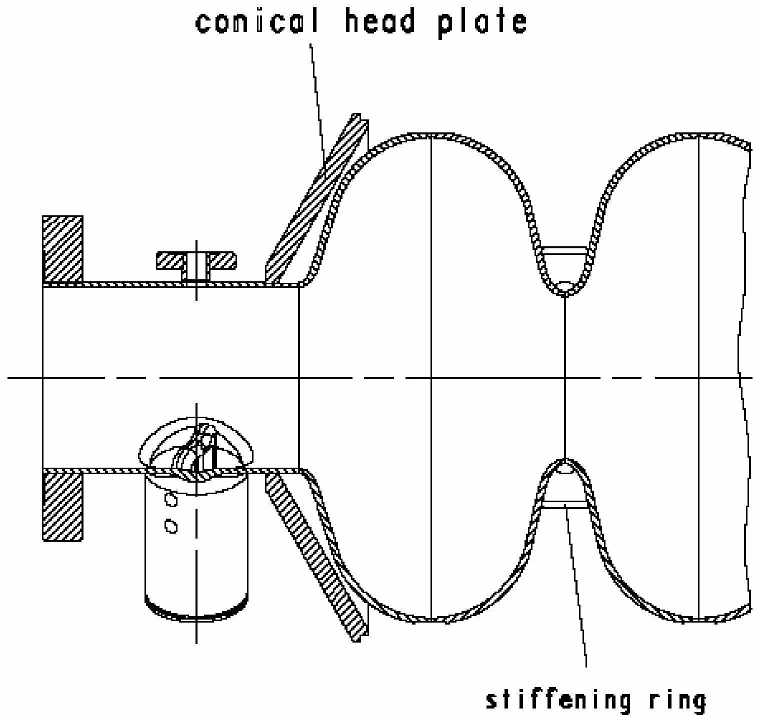
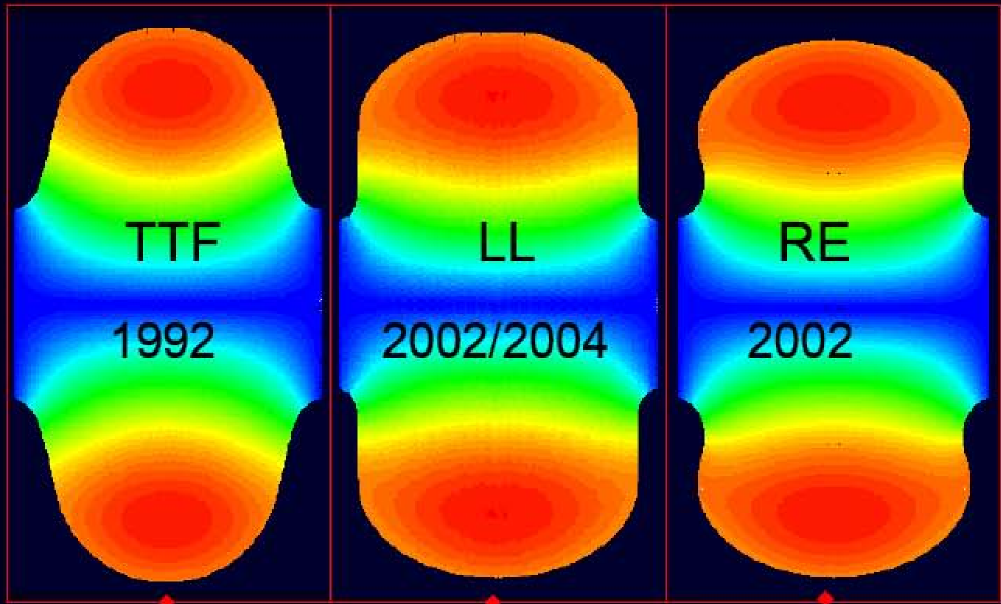


Figure 2.1.3: *Side view of the 9-cell cavity with the main power coupler port and two higher-order mode couplers.*



1. Introduction: Evolution of the elliptical cavities cont.

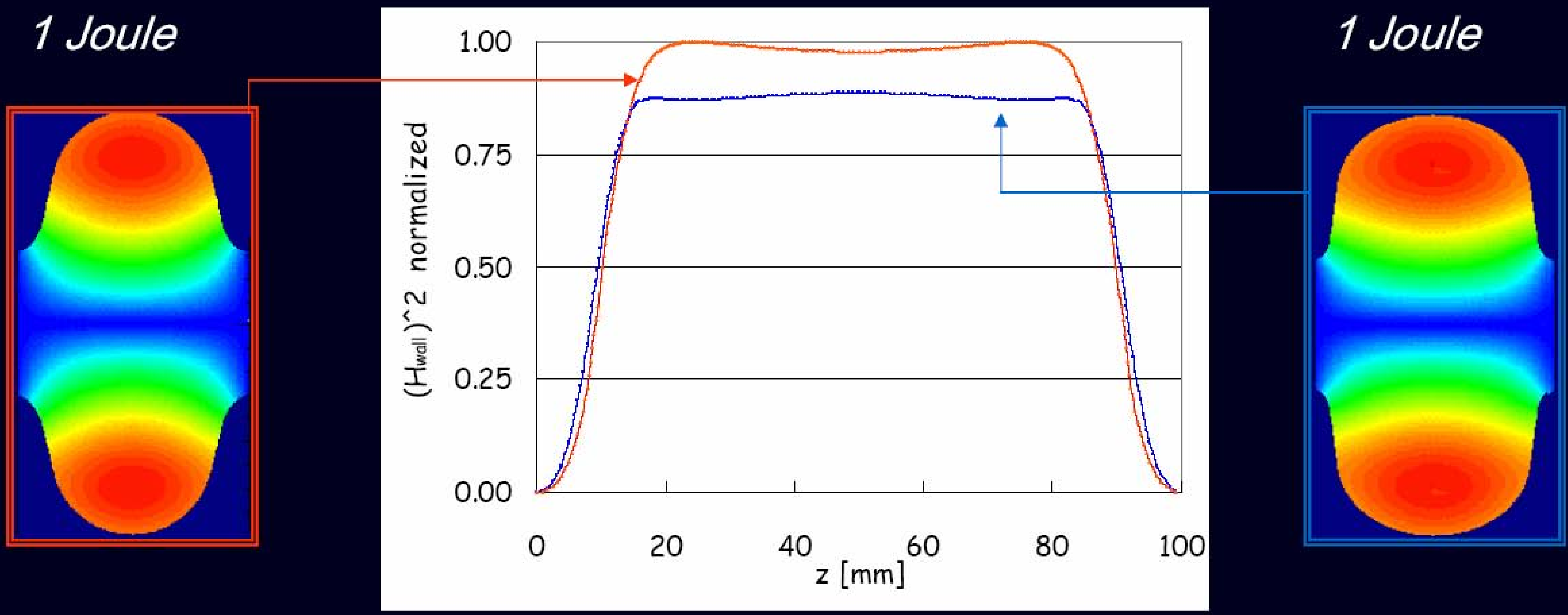
Example: 1.3 GHz inner cells for TESLA and ILC



r_{irisb}	[mm]	35	30	33	
k_{cc}	[%]	1.9	1.52	1.8	field flatness
E_{peak}/E_{acc}	-	1.98	2.36	2.21	max gradient (E limit)
B_{peak}/E_{acc}	[mT/(MV/m)]	4.15	3.61	3.76	max gradient (B limit)
R/Q	[Ω]	113.8	133.7	126.8	stored energy
G	[Ω]	271	284	277	dissipation
R/Q*G	[Ω*Ω]	30840	37970	35123	dissipation (Cryo limit)

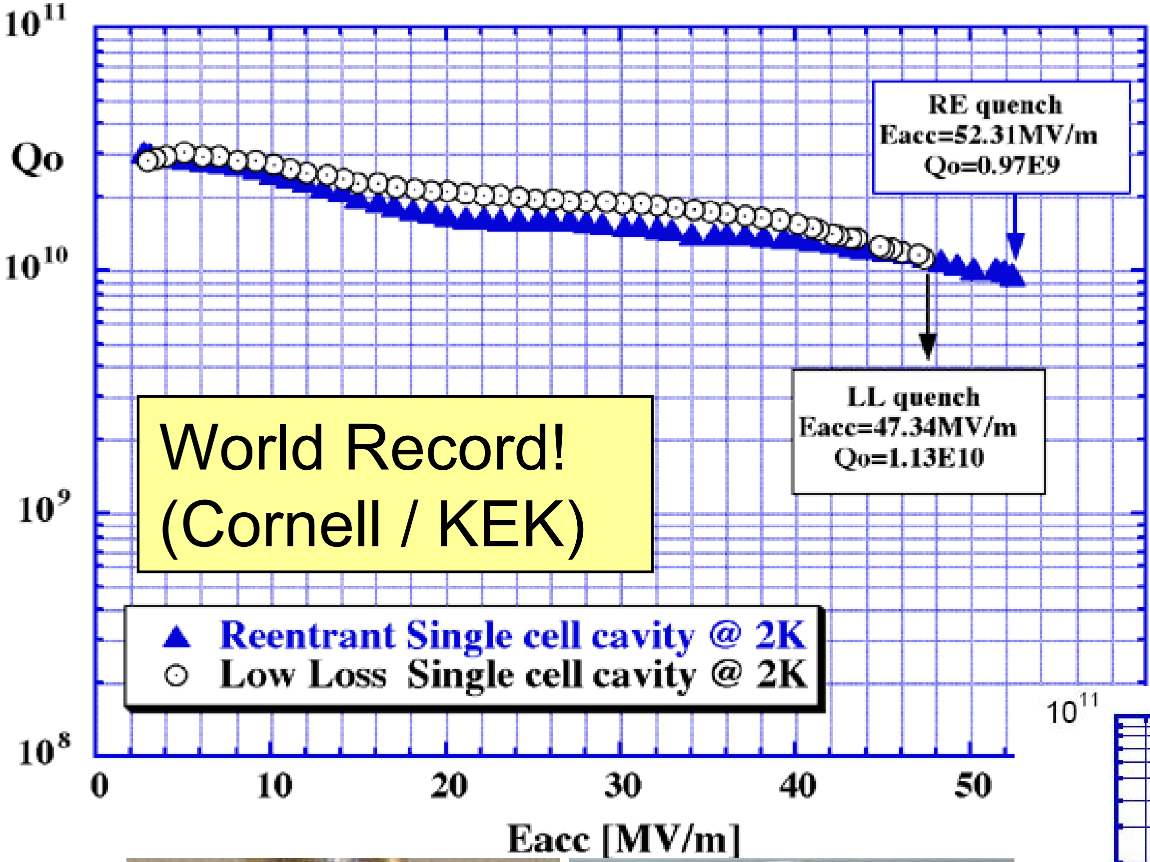
1. Introduction: Criteria, cont.

"Hunting" for high gradients goes together with "hunting" for low cryogenic loss.



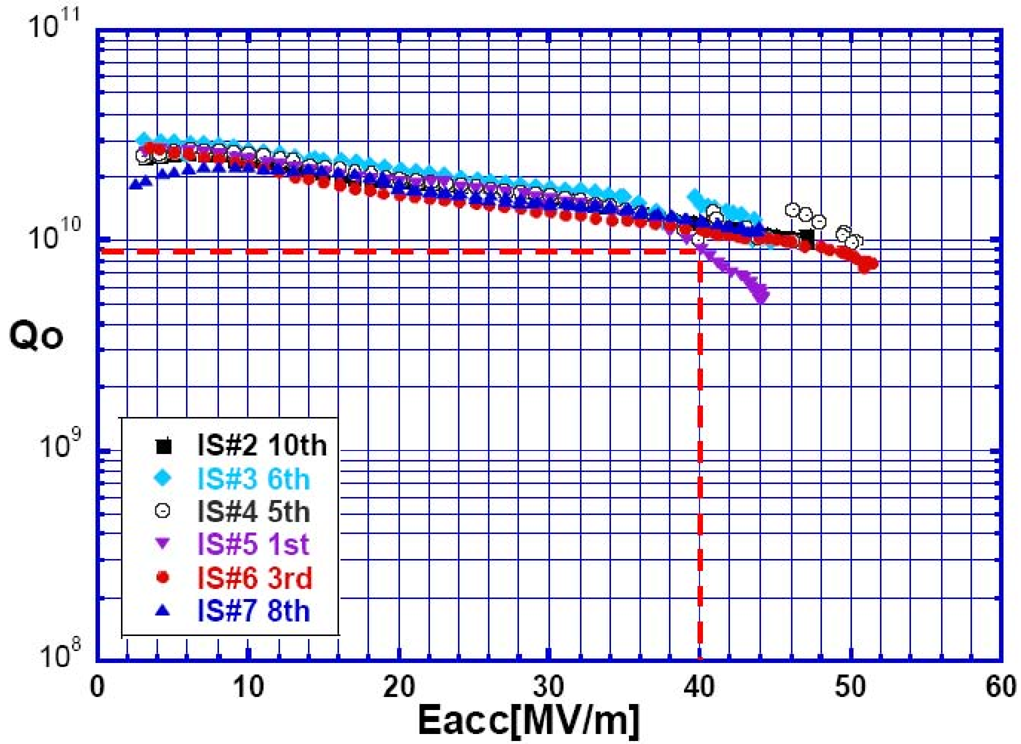
H^2 on the Nb wall

Single-Cells of Other Shapes



World Record!
(Cornell / KEK)

Several cavities achieved more than 45 MV/m at high Q! (KEK)

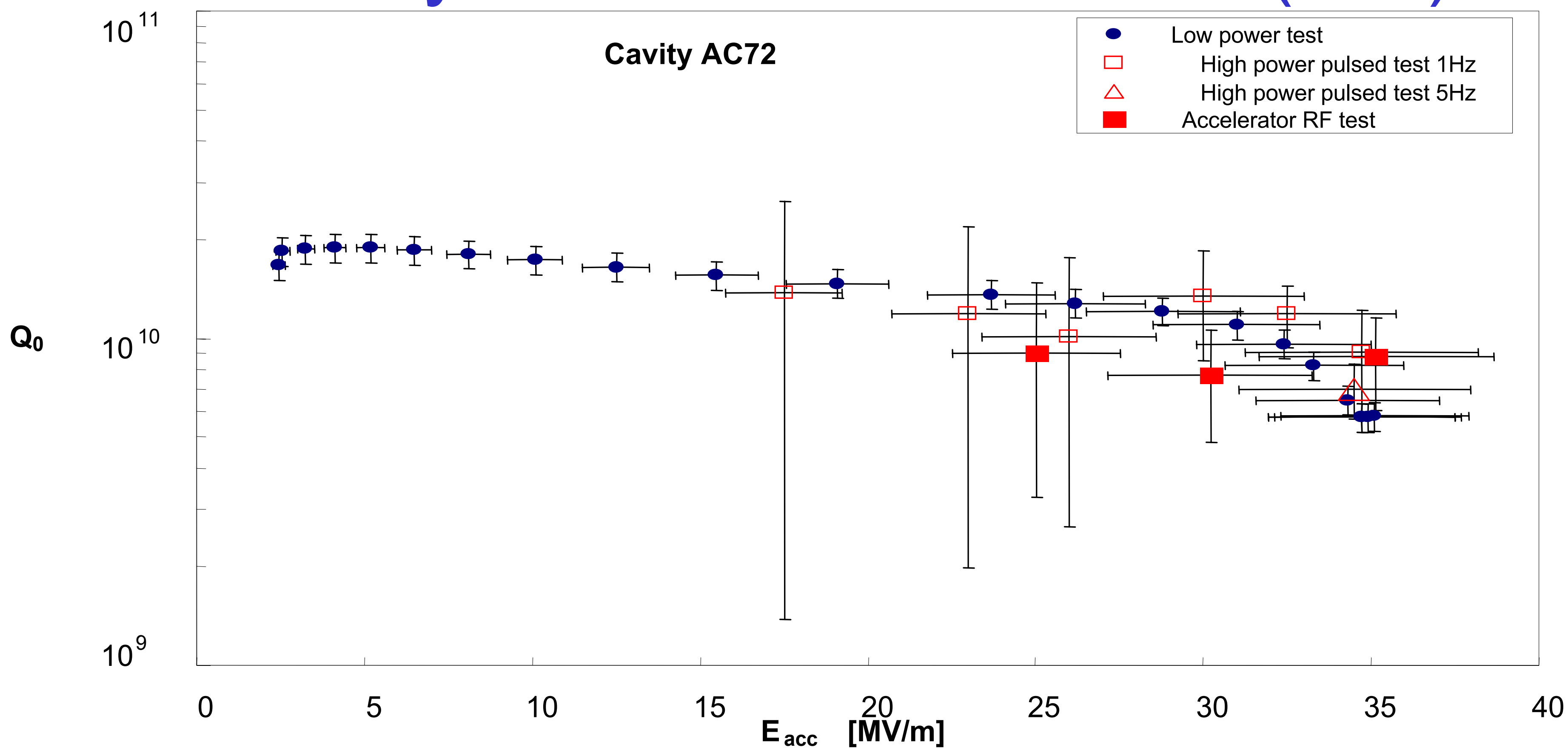


Conclusion

- SCRF cavities have a broad range of applications
- Technology matured over the recent years
  - E.g. commercially available SCRF systems
- Challenges are the reproducibility of very high gradients and cost reduction
  - 35 MV/m has been demonstrated several times
  - A production-like process is under development
- A lot of working ongoing for the XFEL and ILC
  - It is a big asset for both of them that they still can profit from each other
- Single-cells have shown more than 50 (!) MV/m
  - First tests on multi-cells are underway

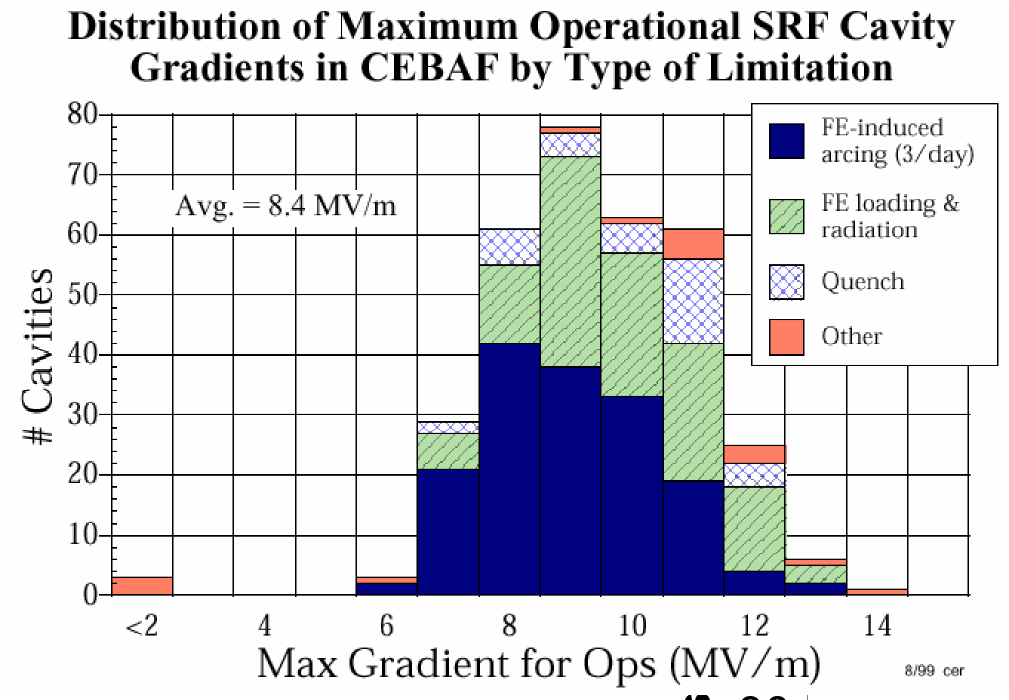
Backup

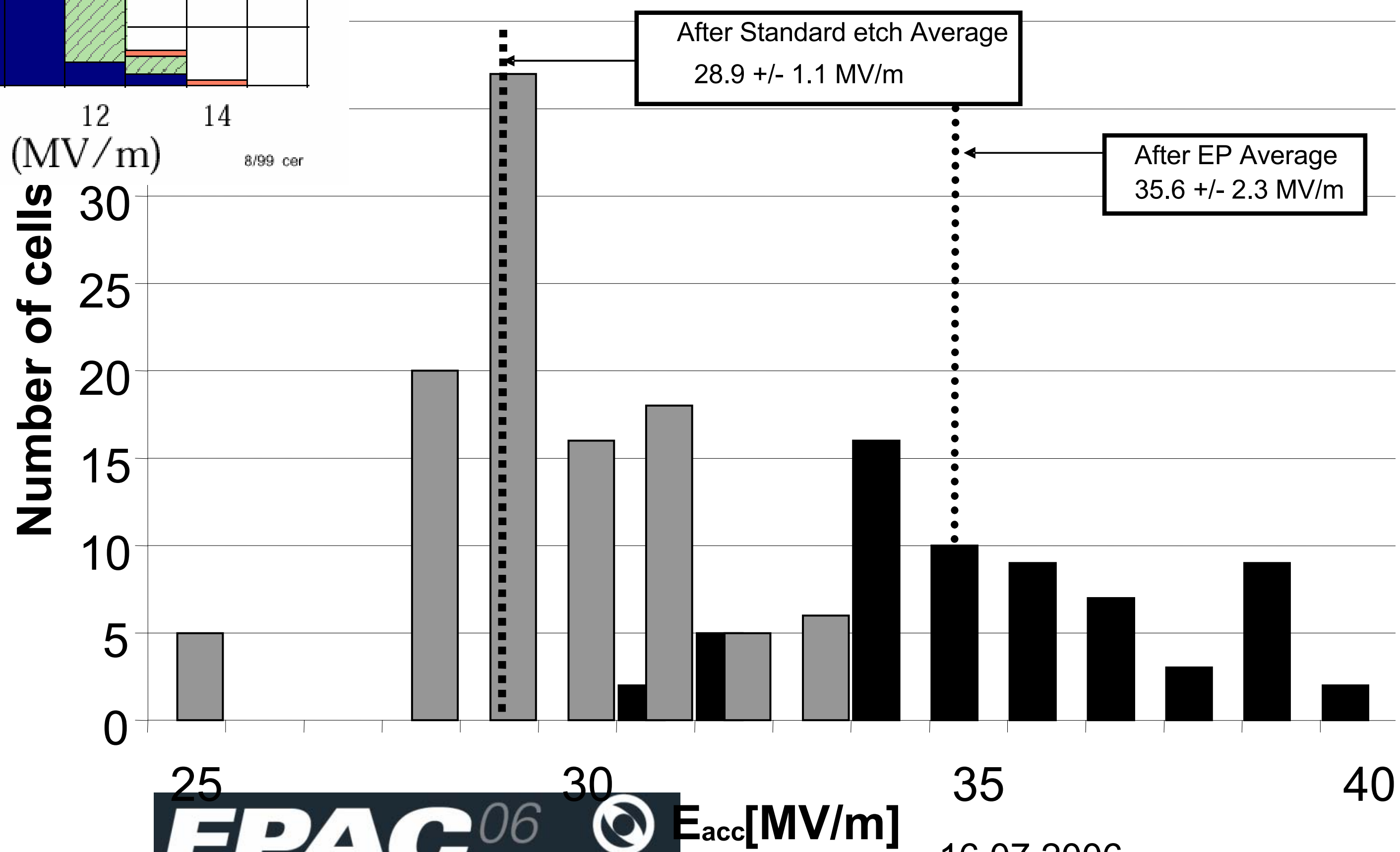
Cavity Test Inside a Module (ctd.)



- One of the electropolished cavities (AC72) was installed into an accelerating module for the VUV-FEL
- Very low cryogenic losses as in high power tests
- Standard X-ray radiation measurement indicates no radiation up to 35 MV/m

Time evolution of accelerating gradient





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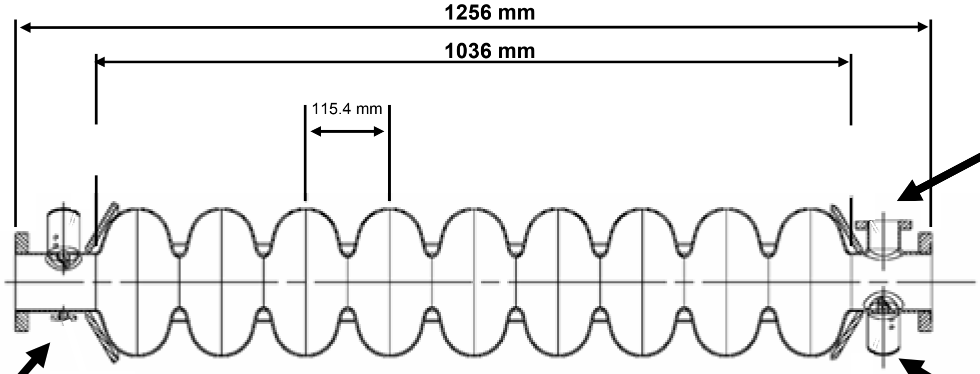
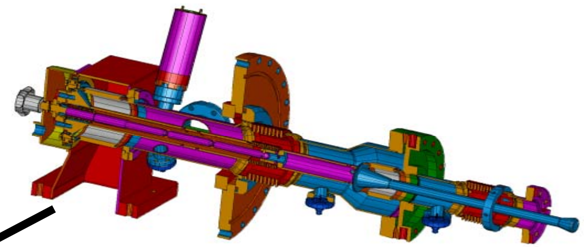
16.07.2006

Goals of the TESLA Test Facility Linac

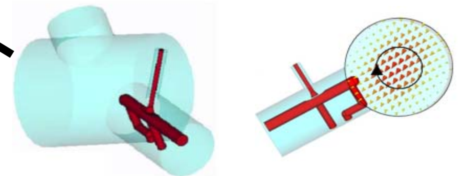
Test all the components in a real linac environment with

e⁻ - beam

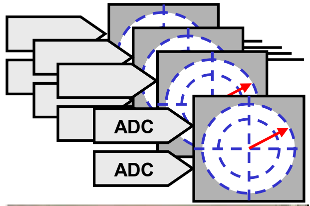




RF power coupler



HOM coupler



RF pick up & LLRF

One standard **9-cell TESLA accelerating structure** operated as a π-mode standing-wave cavity.

One 230 kW **rf power coupler**, an **rf pick up** antenna and two **Higher Order Mode antennas** are assembled to each cavity.