High gradients in multi-cell cavities

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- A look into the past
- Cavity shape, material and preparation
- Cavity limitations
- SRF projects using elliptical multi-cell cavities
- Recent cavity performance tests
  - – e.g. high power performance test of an electropolished TESLA cavity
- Outlook

TESLA

Disclaimer

- This is a compilation of data available since the last SRF workshop in Tsukuba.
  - Focus on multi-cell cavity tests
  - Try to watch out for specialties in treatment, manufacturing etc.
  - If you think your tested multi-cell is missing, please tell me.
- Overview on new projects on friday
- The basics of SRF are described elsewhere:
  - P. Schmüser - Monday Tutorial (MoT01)
  - H. Padamsee et al., RF superconductivity for accelerators, Wiley
  - B. Aune et al., Superconducting TESLA cavities, PRST - AB, Vol. 3, 092001 (2000)

Thank you!

- For providing me with data, plots and information
  - Peter Kneisel
  - John Mammosser
  - Hans Weise
  - Detlef Reschke
- For the preparation of the EP of TESLA nine-cells at KEK/Nomura Plating
  - Eiji Kako
  - Kenji Saito
- For helping with the high power test
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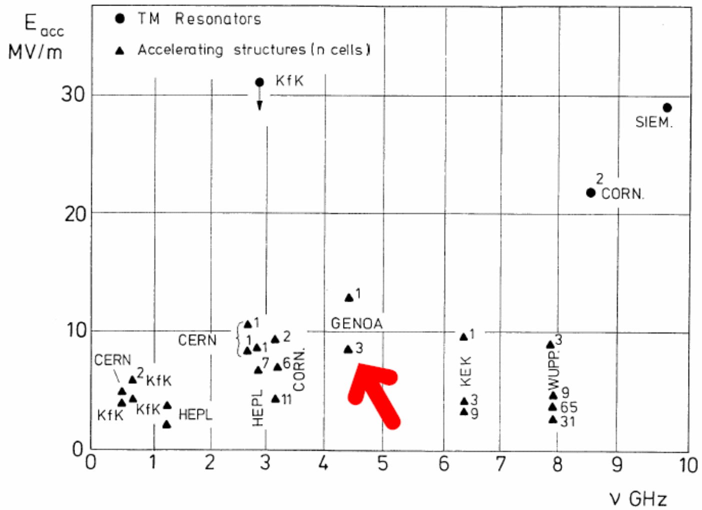
A look into the past

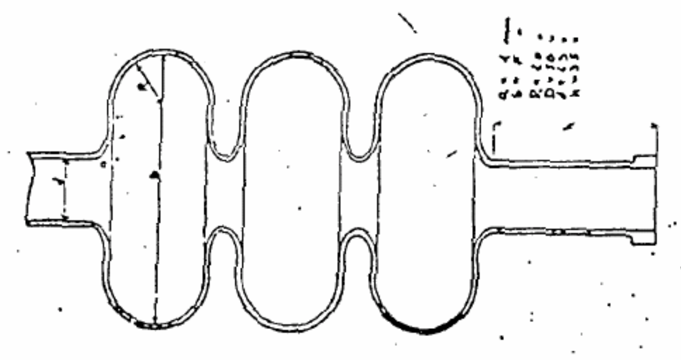
- At the time of the SRF80 (KfK 3019, November 1980) Multipacting (MP) was one severe limitation for cylindrical and muffin-tin cavities.
- But one spherical three-cell cavity has shown good performance (Parodi et al., IEEE Trans. on Mag., Vol. MAG-15,1,June 1977)
  - ‘Genoa still looks very favourable’ wrote A. Citron, referring to the shape of a C-band three-cell cavity
  - ‘The [..] geometrical approach to suppressing multipacting is paradoxically to round out the outer wall rather than to make the corners sharper.’ C.M. Lyneis
  - Simulations (Klein and Proch, Proc.Conf. on Future Possibilities for Electron Accelerators, 1979) could explain the reduced sensitivity to one-point-MP



Accelerating gradient vs. frequency

from A. Citron, Compilation of experimental results and operational experience
First Workshop on RF Superconductivity, Karlsruhe, Germany, 1980

C-band Structure
Genoa, about 1980
the first spherical geometry
realized because of easier manufacturing



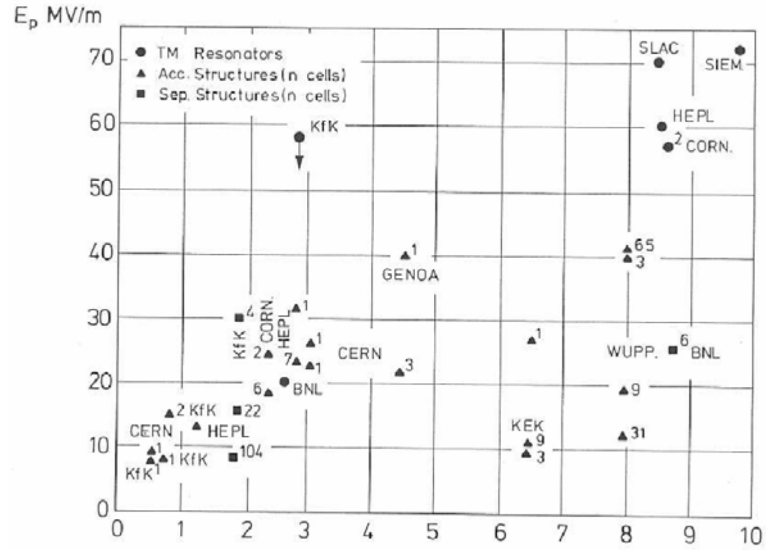


Fig. 15: Electric peak-fields vs. frequency

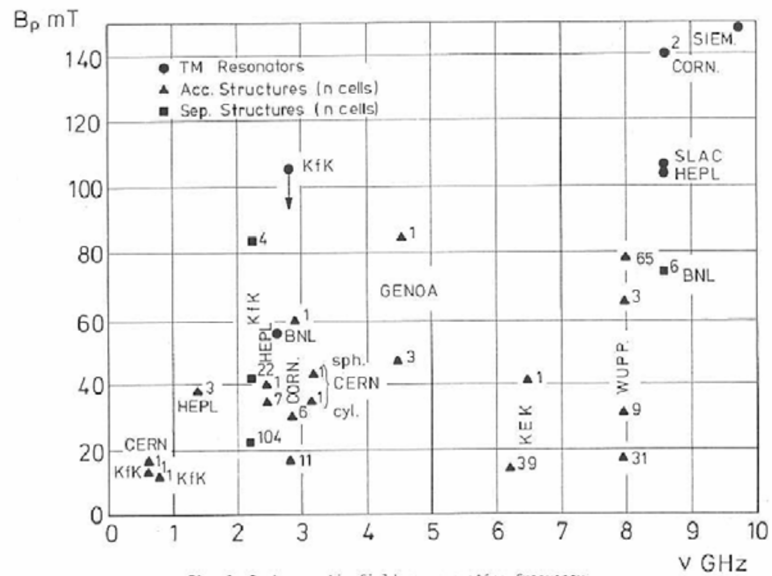


Fig. 1: Peak magnetic field vs. operating frequency

Elliptical multi-cell cavities

- Since this discovery the SRF community concentrated on this shape for beta=1 applications and is pursuing many different projects
  - high current storage rings
  - TESLA linear collider
  - synchrotron light sources
  - XFEL Driver Linacs
  - CW Linacs
- More recently, this cavity shape is becoming more attractive also for 0,47<beta<1
  - Protons (SNS,KEK/Jaeri, XADS/Eurisol, APT/AAA, Trasco)
  - Ions (RIA/MSU)

Material

- For the time being, gradients above 10 MV/m in multi-cell cavities can reliably achieved only with bulk niobium cavities (despite the success of the LEP film cavities)
- Improved niobium material control has led to a significant improvement in niobium sheet quality and therefore cavity performance
  - RRR=200-300(400) is standard
  - e.g. eddy current scanning
- Typically high temperature treatments for stress annealing, hydrogen degassing (600-800°C) and in some cases for post-purification (>1000°C with getter materials) are part of the fabrication process
- Still, some effects like the 'Q-slope at high gradients' still need further investigation (see Posters and B. Visentin)

Preparation of niobium surfaces

- Typically 100-200 µm of damage layer are removed to obtain high gradients
  - etching is still the most commonly used method
  - electropolishing – due to the impressive results at KEK on single-cells – becomes more and more popular (for good reasons – see below)
- One major limitation of cavities is still field emission:
  - High pressure rinsing with ultrapure water is a necessity
  - Dust-free assembly with quality control is needed

Operational issues / Auxiliaries

- A multi-cell cavity needs several interfaces to the outside:
  - He Tanks, mechanical stiffness
  - RF Couplers for cavities are critical elements
    - larger power handling capability
    - heat conductivity etc.
    - B. Rusnak tutorial this evening (TuT01)
  - HOM dampers
    - guarantee beam quality
  - Tuners for frequency adjustment
    - e.g. Lorentz force detuning

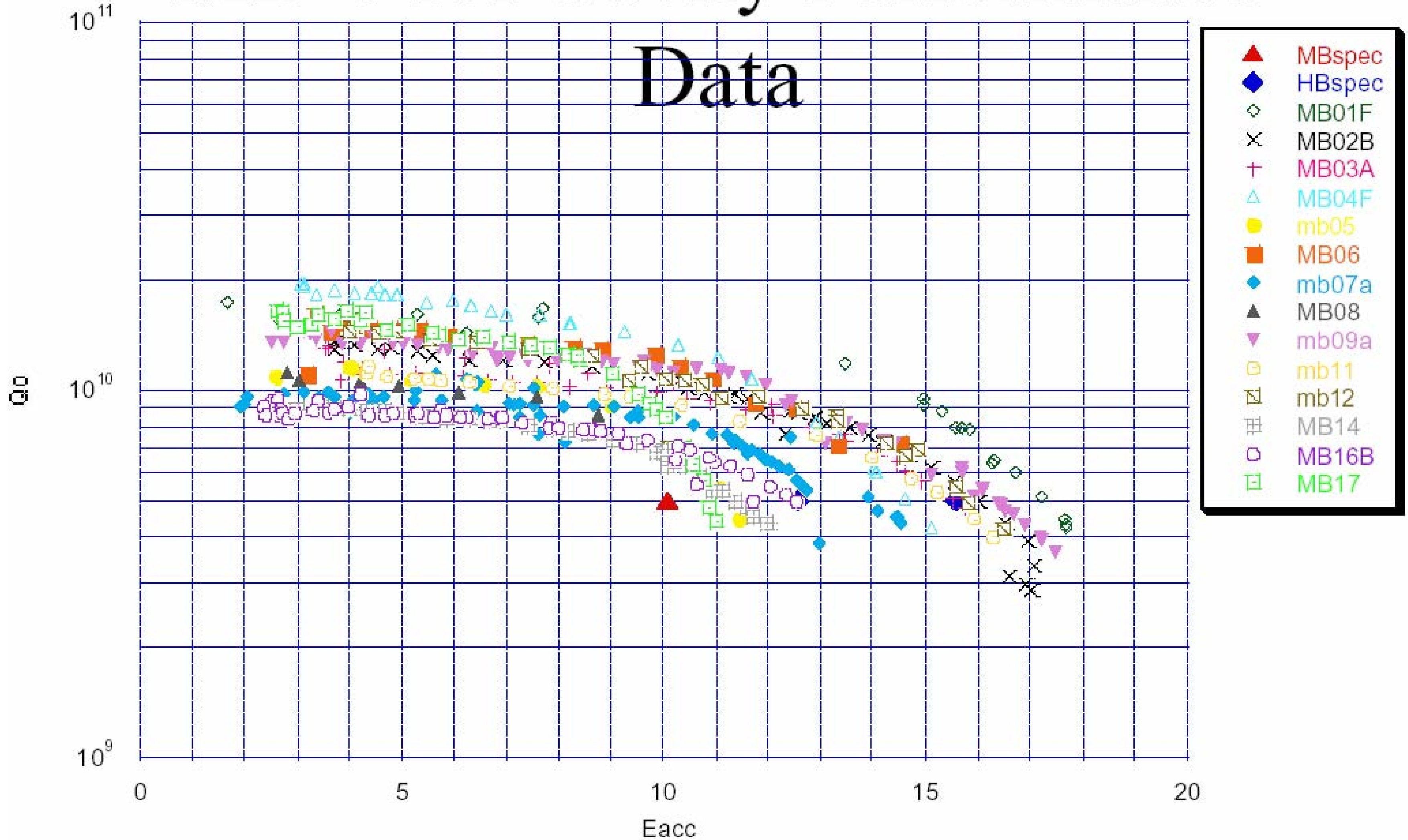
Available data

SNS

- Sneak Preview: See detailed report (J. Mammosser WeO01) and posters (e.g. TuP31,TuP32,TuP33)
- Basic preparation: 600°C firing, etching
- 805 MHz Medium Beta (0,61)
  - Vertical test results show that the design goal of 10 MV/m is routinely reached with some safety margin (best 17MV/m)
  - Currently the first medium beta modules are under test and show good performance: 15 MV/m
- 805 MHz High beta (0,81)
  - One cavity reached 20 MV/m after standard etch...
  - ... and 22 MV/m with higher Q after electropolishing
  - Specification has been increased from 12,5 to 15,5 MV/m

SNS

MB VTA Cavity Performance Data



SNS

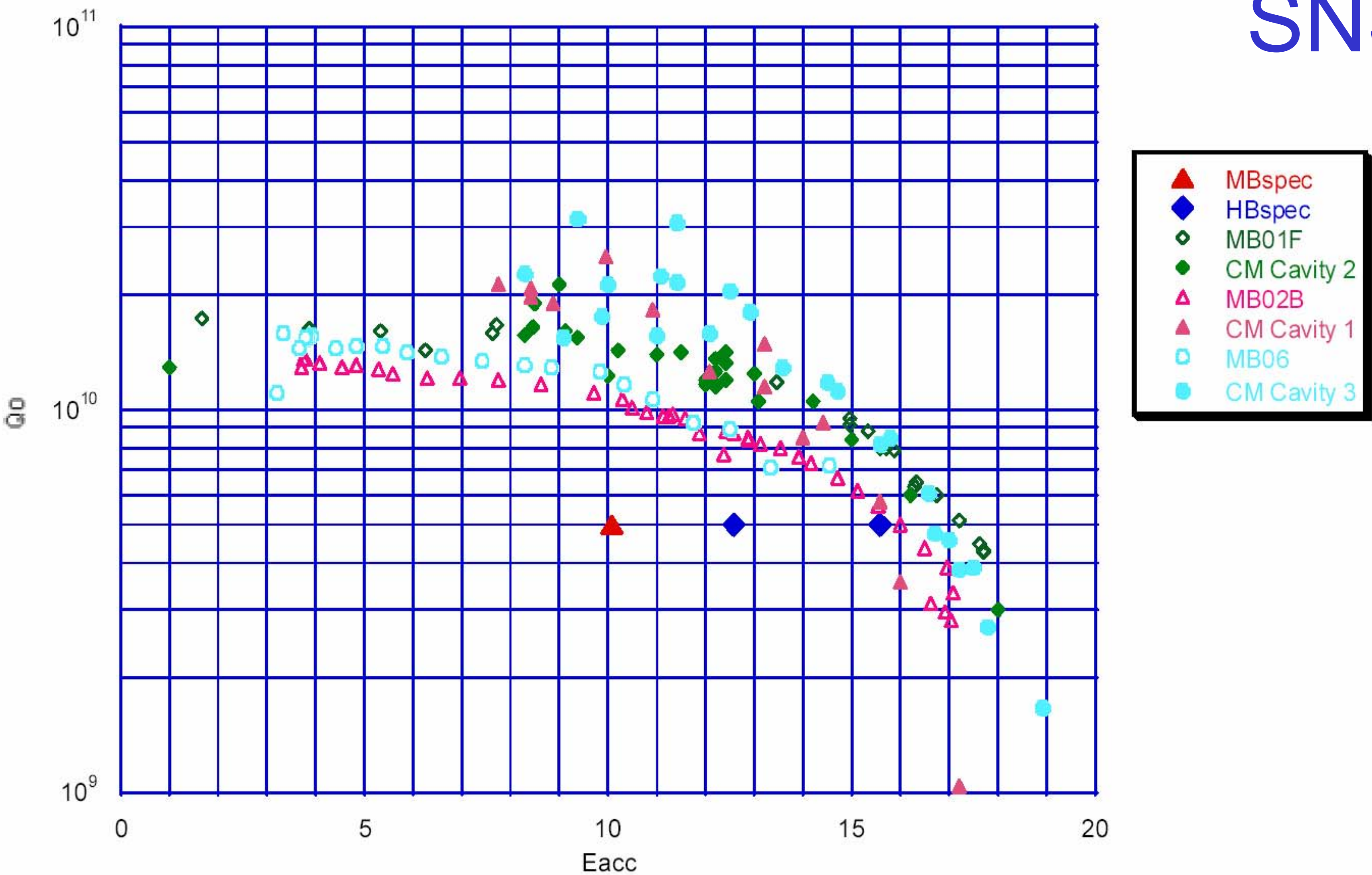
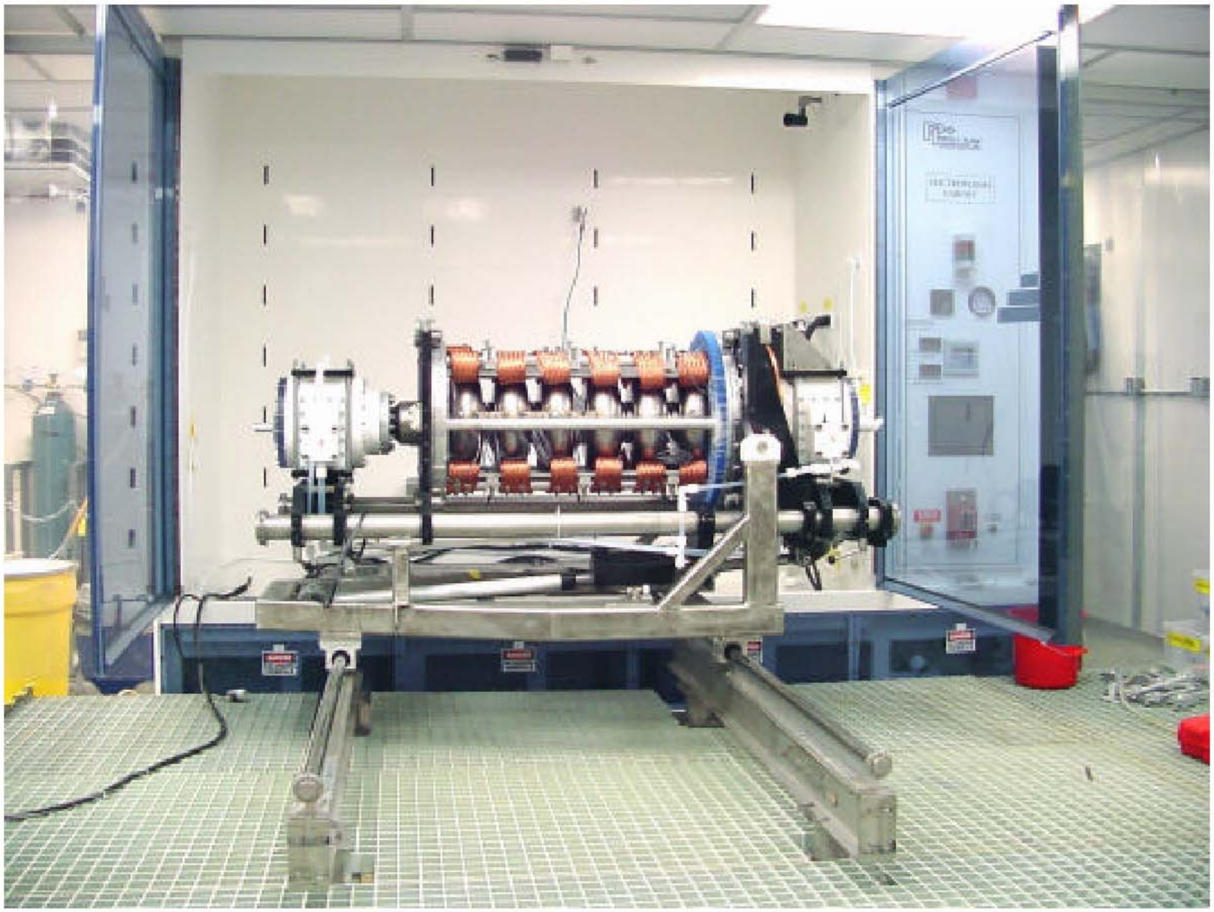


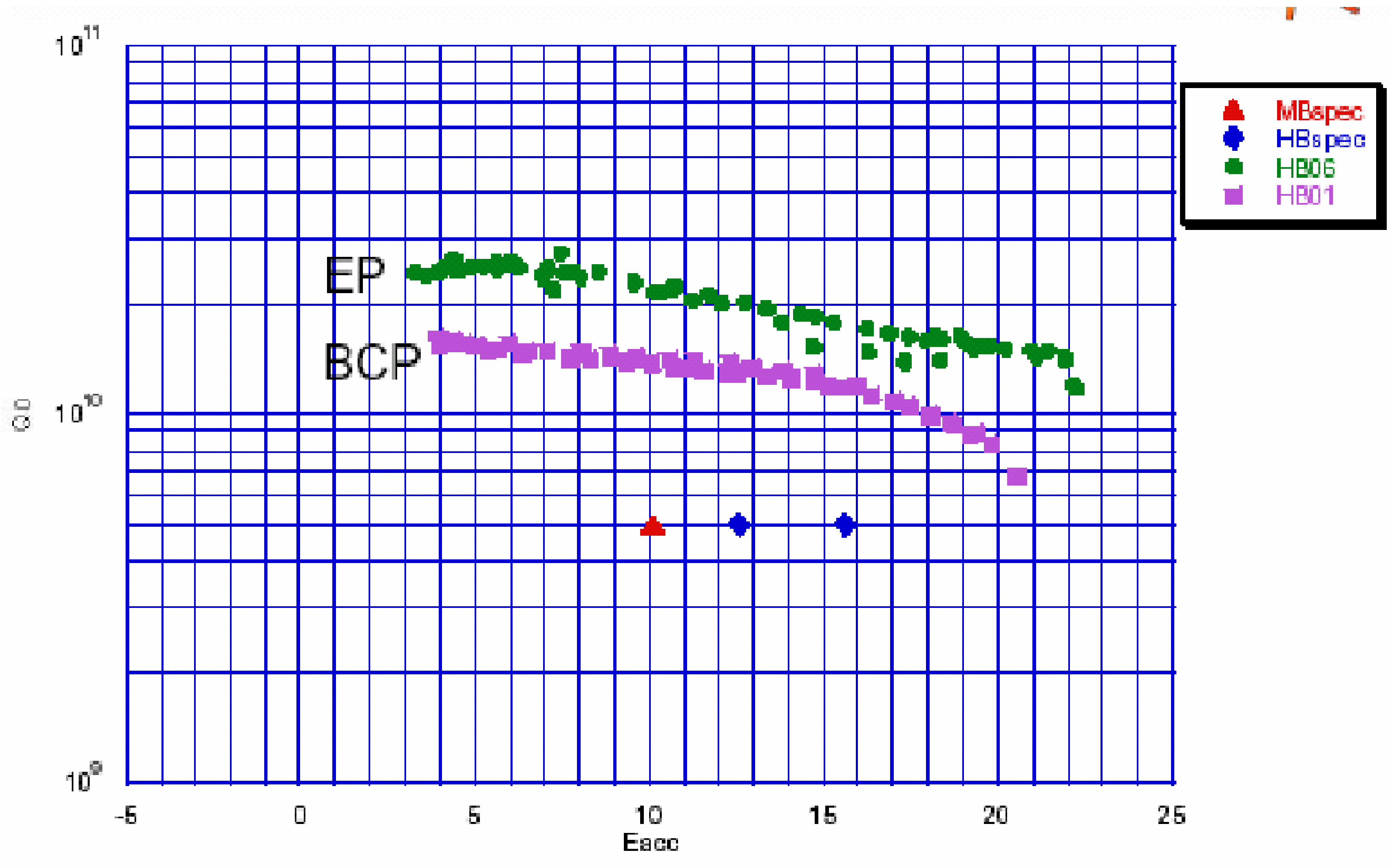
Figure 11. Cavity Q_0 in Final Assembly

SNS/JLab

EP cabinet



SNS



10^11
10^10
10^9
Q0
-5
0
5
10
15
20
25
Eacc
EP
BCP
MBspec
HBspec
HB06
HB01

KEK/JAERI: J-PARC

- Old design uses 600 MHz, five-cells
  - achieved 40 MV/m E_{peak}, ~11MV/m E_{acc}
- New ADS design will use 972 MHz
  - under design and manufacturing
  - beta=0,725
  - nine-cells
  - gradient goal: E_{peak}=30 MV/m, E_{acc}=10MV/m

JAERI/KEK Joint Project

Fig. 1 600MHz 5-cell cavity (β=0.604)

Table 1 Design parameters for cavity

Resonant Frequency, [MHz]	600
E_{peak}/E_{acc}	3.45
H_{peak}/E_{acc}, [Oe/(MV/m)]	72.28
R/Q, [Ω]	154
Geometrical factor, [Ω]	166

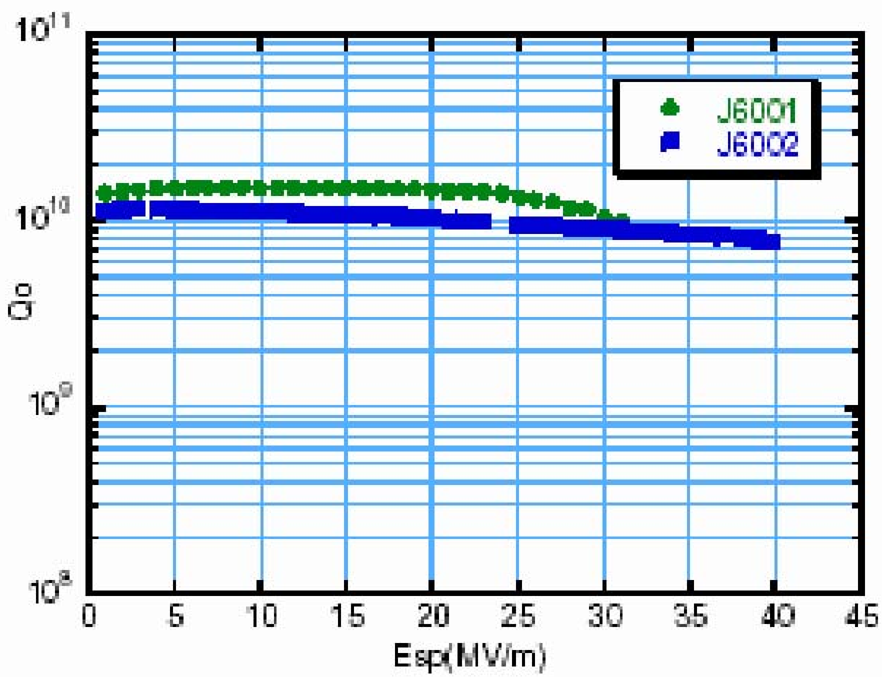
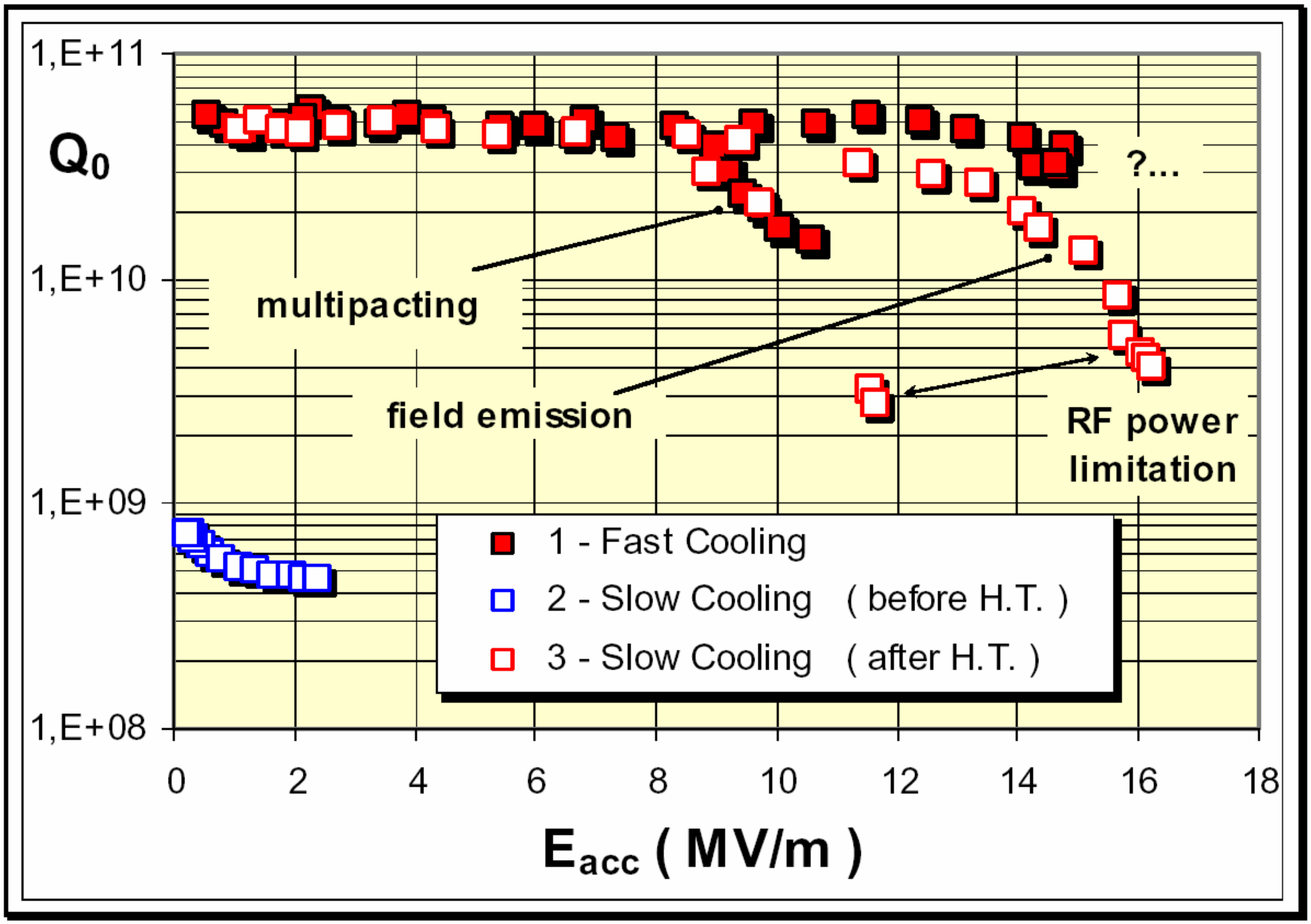


Fig. 5 Results of the vertical test

EURISOL/ XADS

- 700 MHz, beta=0,65
- five-cell prototype
  - no stiffening
  - coupler ports
  - copper brazed stainless flanges
- inside BCP only

EURISOL/ XADS



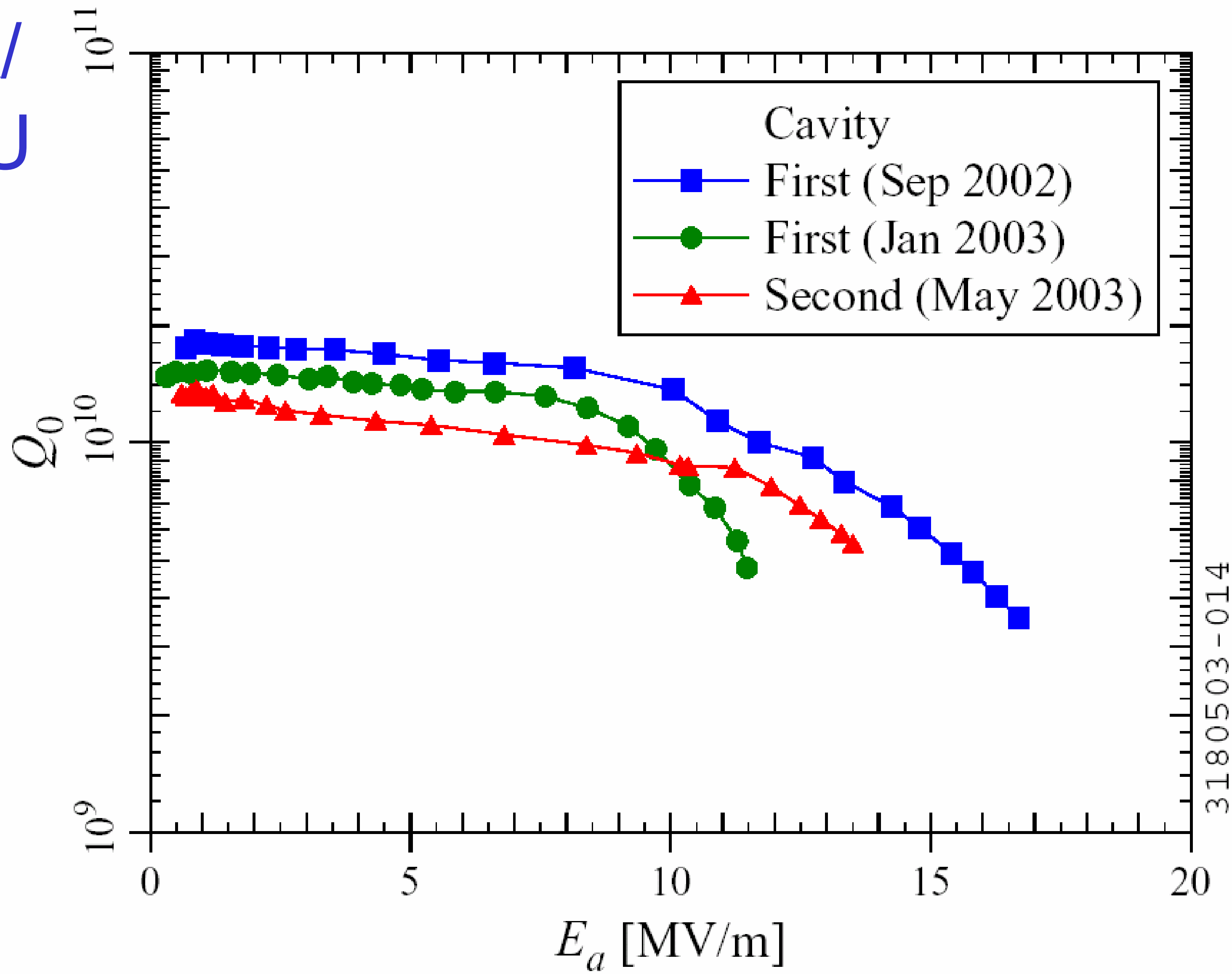
RIA/MSU

- 805 GHz
- very low beta=0,47
- 1st prototype six-cell:
  - no stiffening rings
  - no coupler ports
  - etch, 600°C for 10 hours
- 2nd prototype
  - etch, no firing

- MSU Poster (MoP03)
- RIA talk (WeO08)

E_p/E_{acc}	3.41
B_p/E_{acc} [mT/(MV/m)]	6.92
R/Q [Ω]	160
G [Ω]	136.7
Q_{BCS} @ 2 K (10^9)	21.2
k [%]	1.5
f [MHz]	805.006
Field flatness [%]	1.8

RIA/ MSU

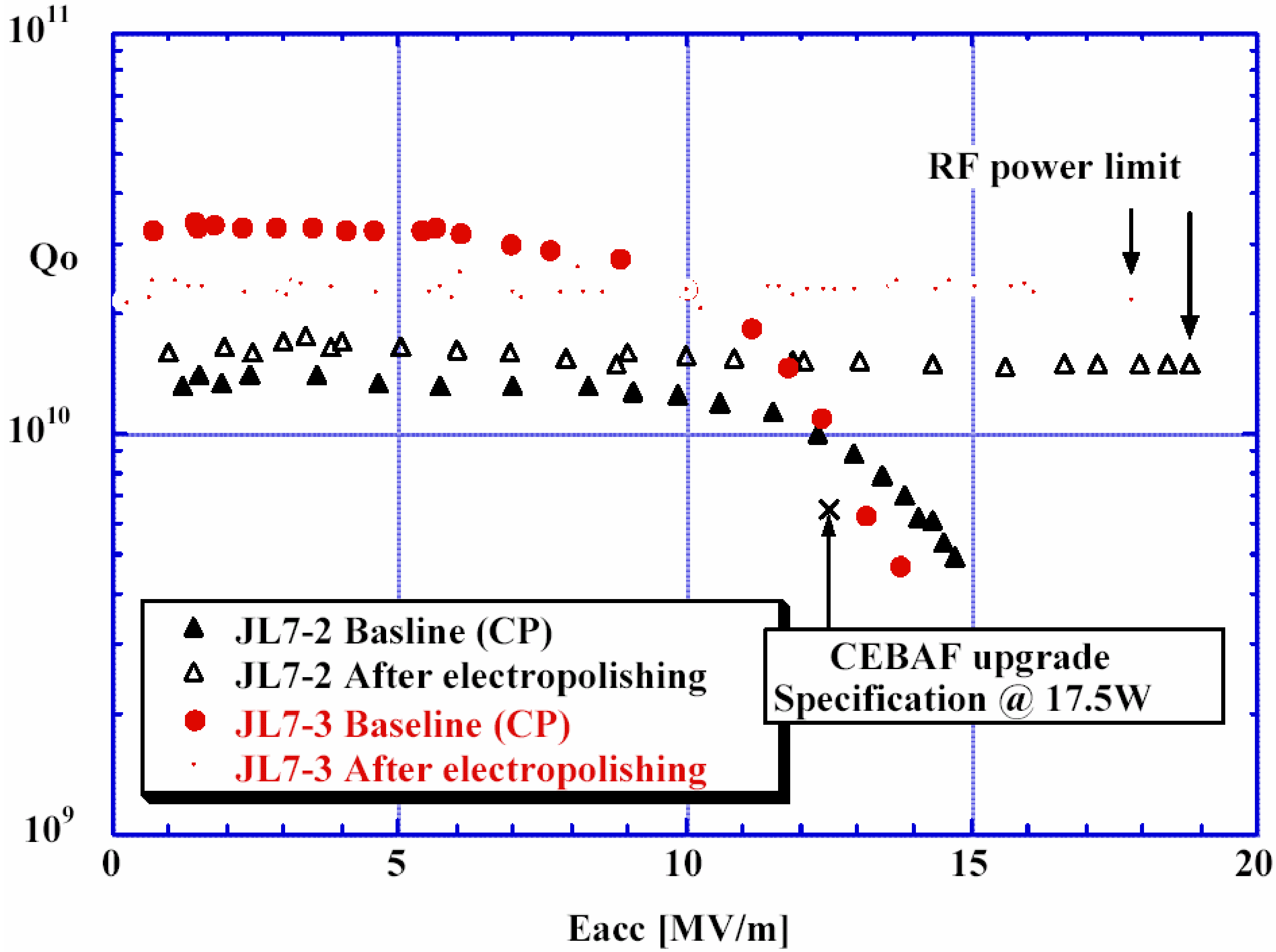


Cavity
First (Sep 2002)
First (Jan 2003)
Second (May 2003)
Q_0
10^{11}
10^{10}
10^{9}
0
5
10
15
20
E_a [MV/m]
3180503-014

Jlab Upgrade/FEL cavities

- A lot of activity on the 1500 MHz besides SNS
  - development of different cavity shapes (MoP17)
    - seven-cells
    - Original Cornell (OC) shape achieved 20 MV/m
    - High gradient (HG) shape achieved 20 MV/m
    - Low loss (LL) single-cell with very good performance: 87MV/m E_{peak}
  - usually etching, EP in some cases
  - work on superstructures

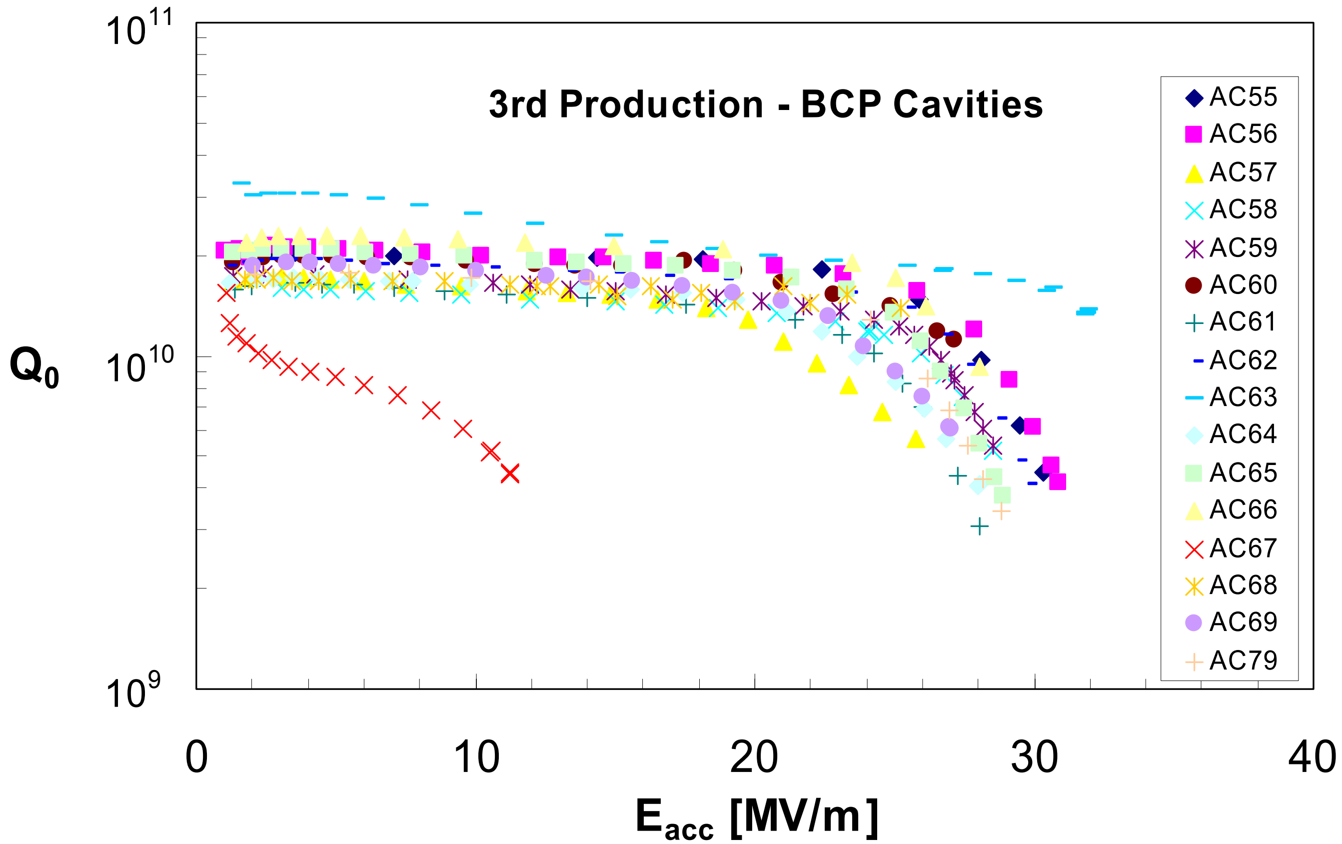
Jlab Upgrade (OC)



TESLA

- 1,3 GHz nine-cells, beta=1
  - focus on the last cavity production
    - etching (BCP), no ‘In-Situ‘ baking
    - titanisation at 1400°C
    - electropolishing (in collaboration with KEK) and baking
      - vertical test results
      - horizontal high power test

TESLA: Etched cavities

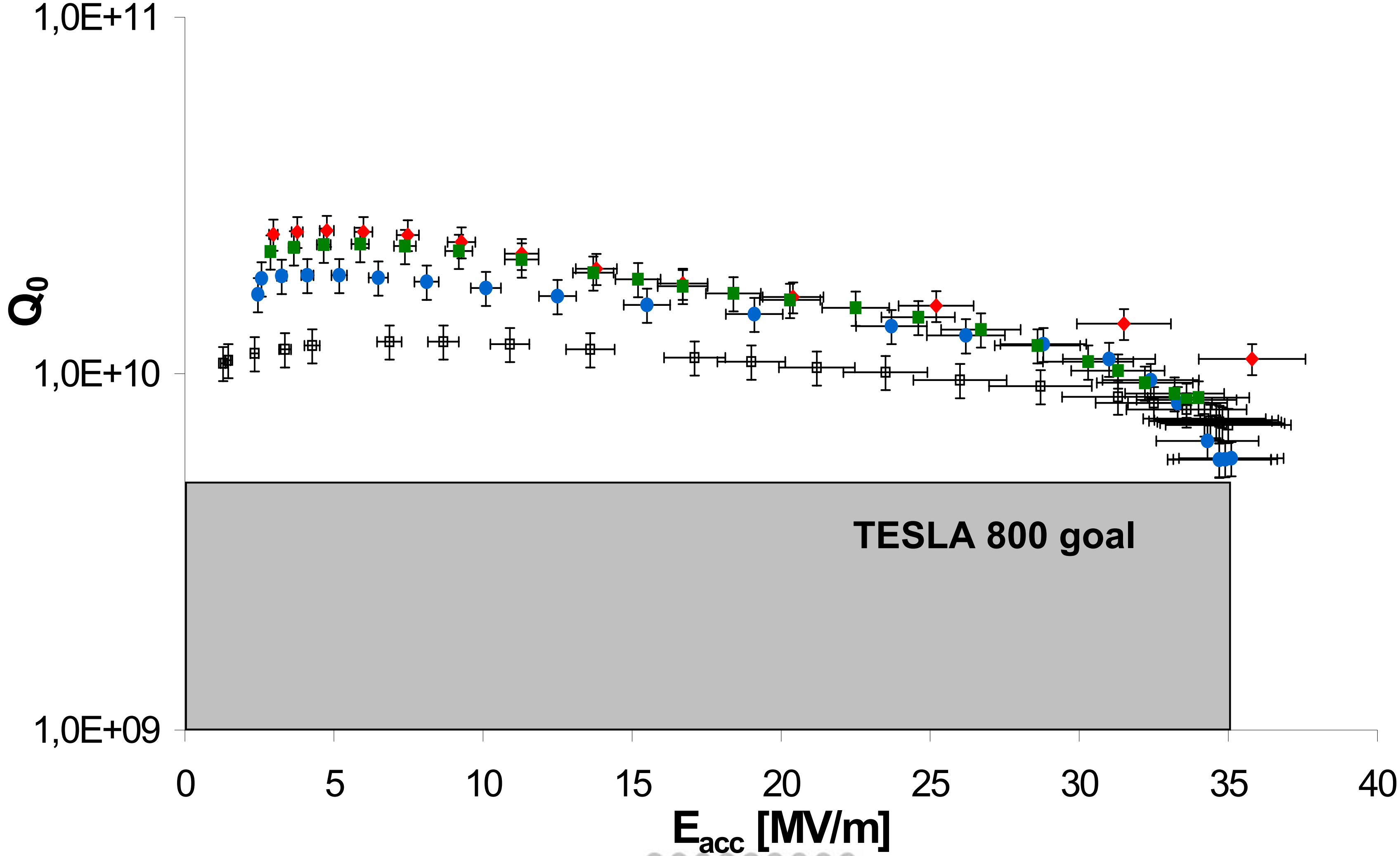


- All cavities from from the last production
- AC67 : test with He leak
- AC63 : With EP

TESLA: Electropolished nine-cells

- Electropolishing has been used on several single-cell cavities and nine-cell cavities
  - explored first at KEK (with Nomura Plating) on single-cells resulting in accelerating gradients up to 40 MV/m (1998)
  - collaboration of CEA-CERN-DESY reproduced these results (2000-2002)
  - nine-cells were electropolished in collaboration of KEK and DESY (2001-2002)
    - four cavities yielded gradients of 35 MV/m in low power cw tests
- Installation of high power coupler etc. and final high pressure rinse in DESY clean room
- Experimental setup for fast active tuning introduced

Nine-cell Cavities for TESLA-800

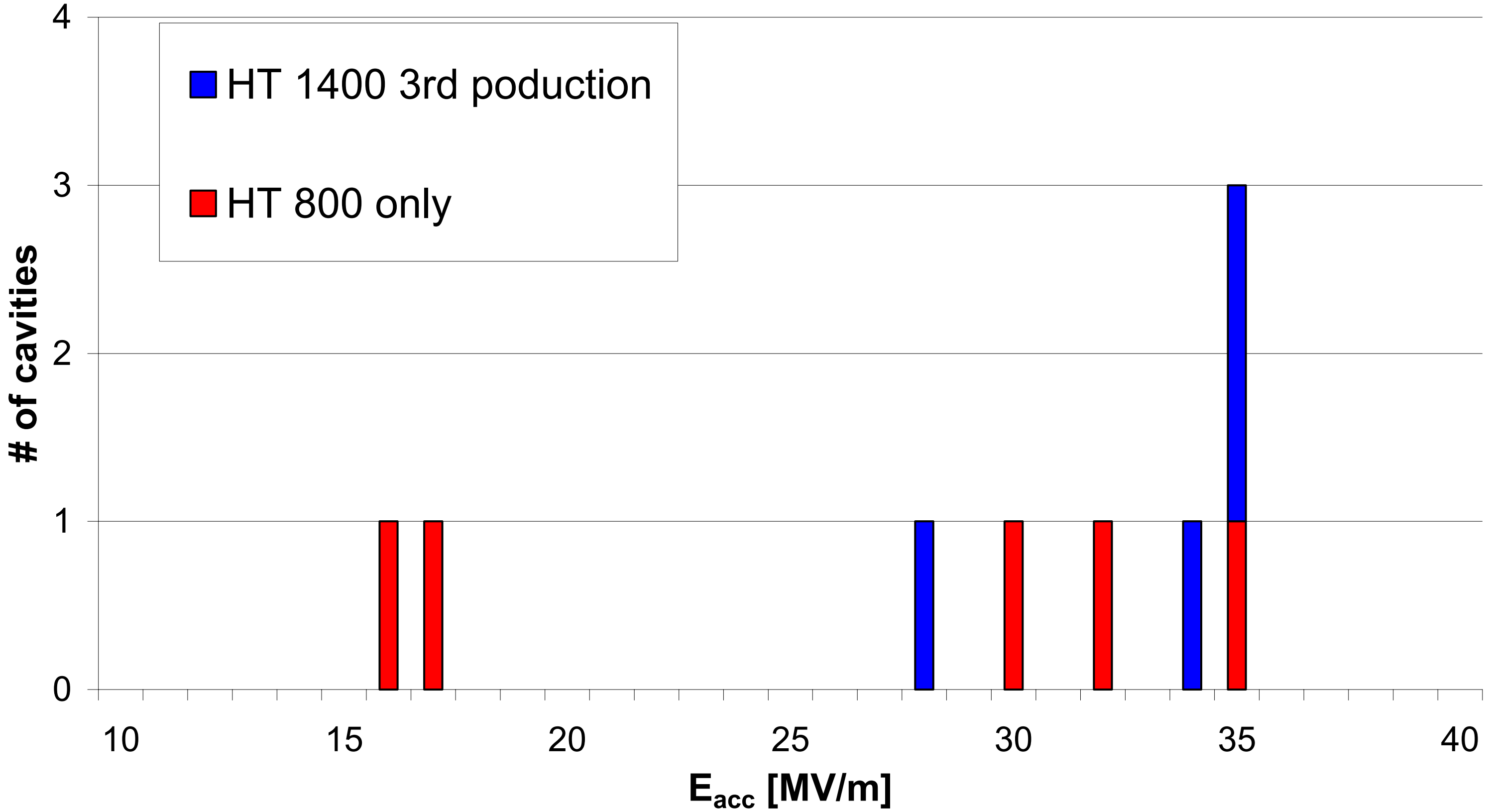


Results of Vertical Test (last Production):

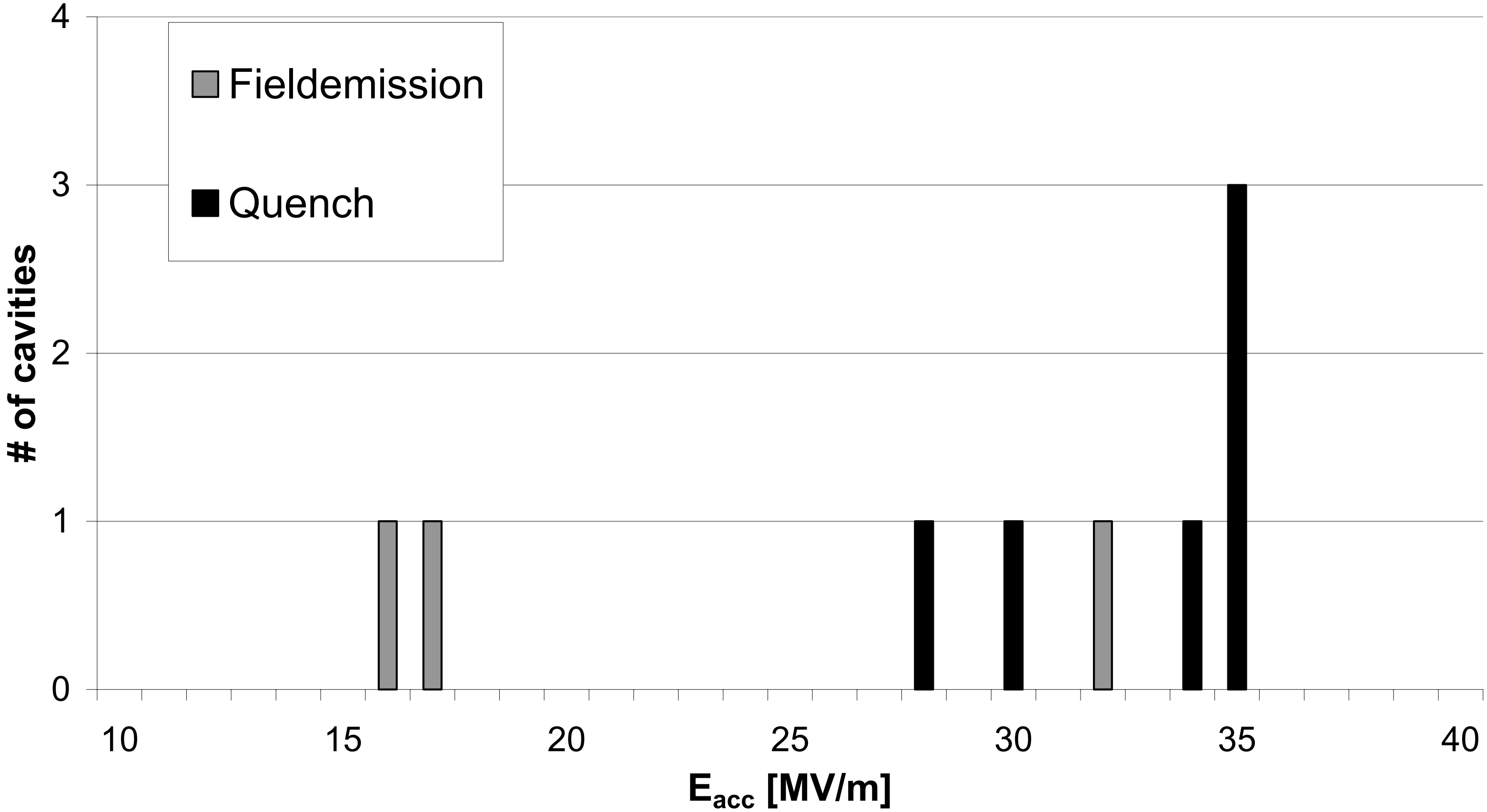
- 6 out of 9 nine-cell cavities with $E_{acc} \geq 30$MV/m
- One cavity with 800°C only achieved 35 MV/m
- 2 cavities show early and strong field emission despite high pressure rinsing
- Preliminary: From T-maps done so far indicate that the quenches are not located at the equator

Vertical test "Statistics" on EP-cavities (last production only)

- Heat treatment at 1400°C vs. Heat treatment at 800°C only
- bad 800°C cavities are field emission loaded

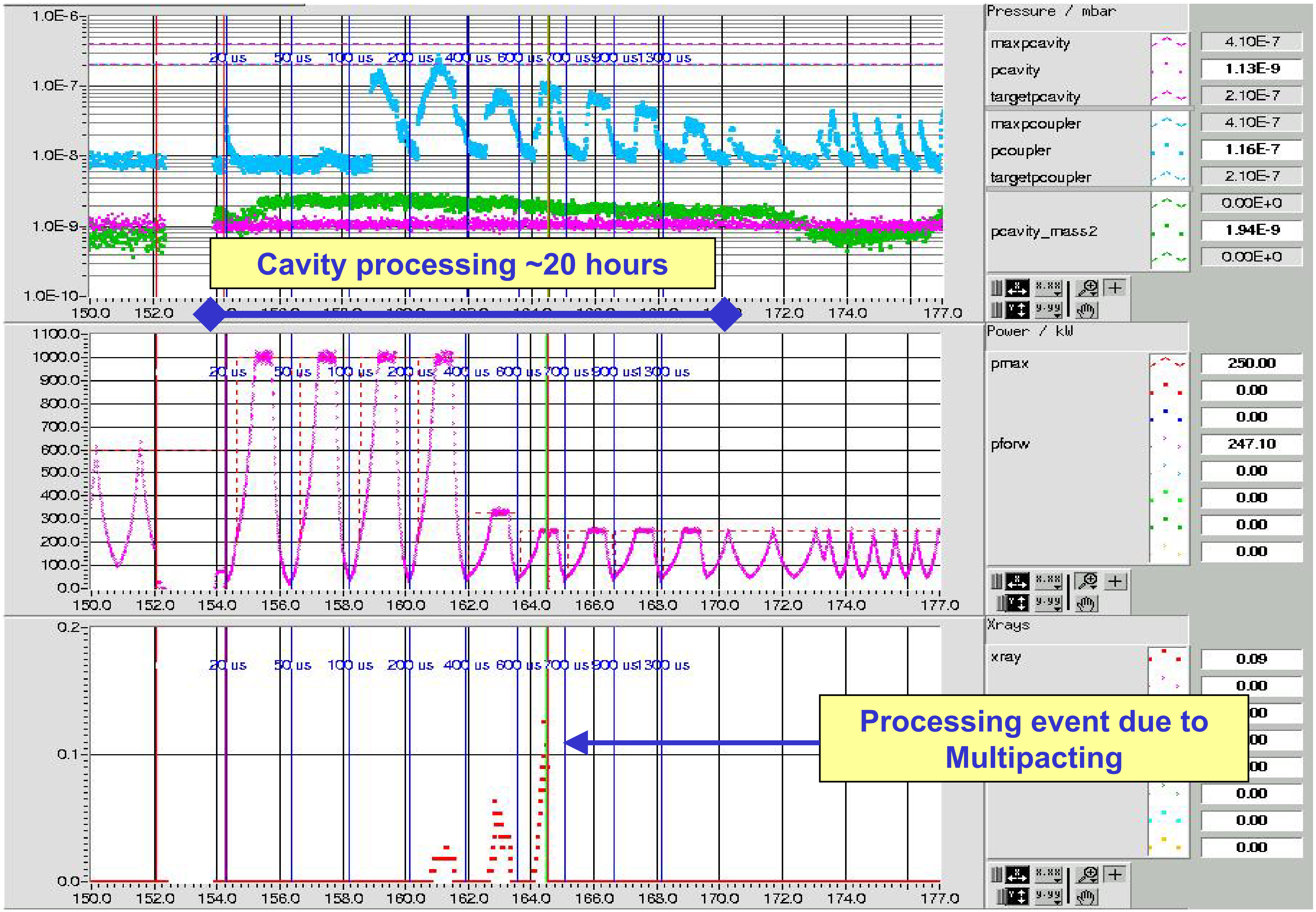


Vertical test “Statistics” on EP-cavities - limitation



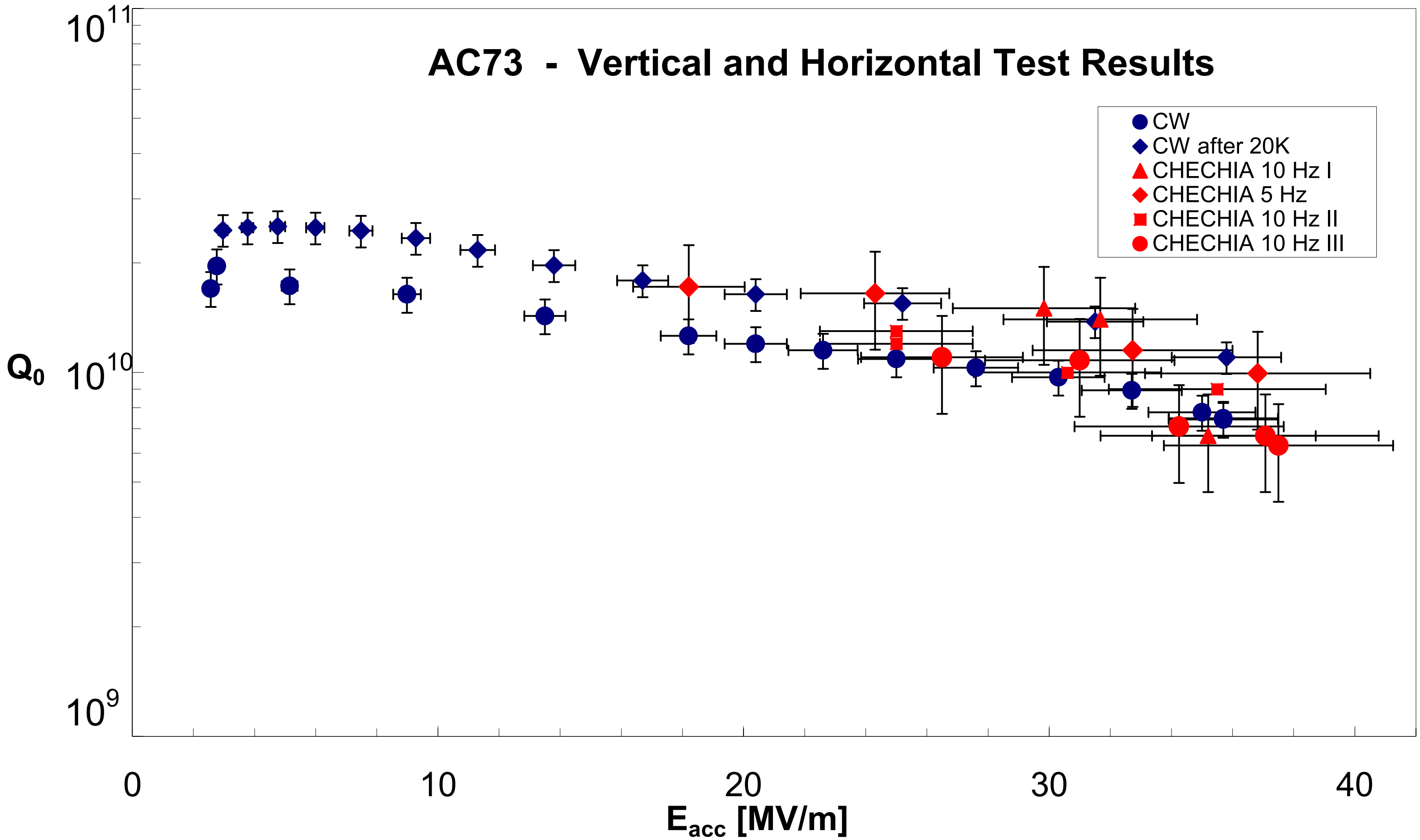
Overview on the high power test of an EP nine-cell

- Objectives of endurance test of the cavity
  - operate at maximum gradient for long time at 5 Hz, 500us fill, 800 us flat-top
  - demonstrate active detuning compensation using piezos
- Coupler and cavity processing went smoothly: 130 + 38 hours
  - heating of the coupler (standard in CHECHIA)
- Cavity has shown multipacting
  - resonant electron emission results in an avalanche
  - Xray emission at power levels corresponding to 20 MV/m disappeared after processing for a few hours (see below)
  - barrier is soft:
    - when the cavity is kept below some 100 K no new processing necessary
    - after warmup very short processing is needed (some minutes)
- Cavity performance measurements
  - 35 MV/m at $7*10^9$ stable, comparable to continuous wave test
  - max. gradient >36 MV/m
  - field emission observable only above 35 MV/m



Pressure / mbar
maxpcavity 4.10E-7
pcavity 1.13E-9
targetpcavity 2.10E-7
maxpcoupler 4.10E-7
pcoupler 1.16E-7
targetpcoupler 2.10E-7
pcavity_mass2 0.00E+0 1.94E-9 0.00E+0
Cavity processing ~20 hours
20 us 50 us 100 us 200 us 400 us 600 us 700 us 900 us 1300 us
Power / kW
pmax 250.00
pforw 247.10
Xrays
xray 0.09
Processing event due to Multipacting

High Power Test of an Electropolished nine-cell cavity



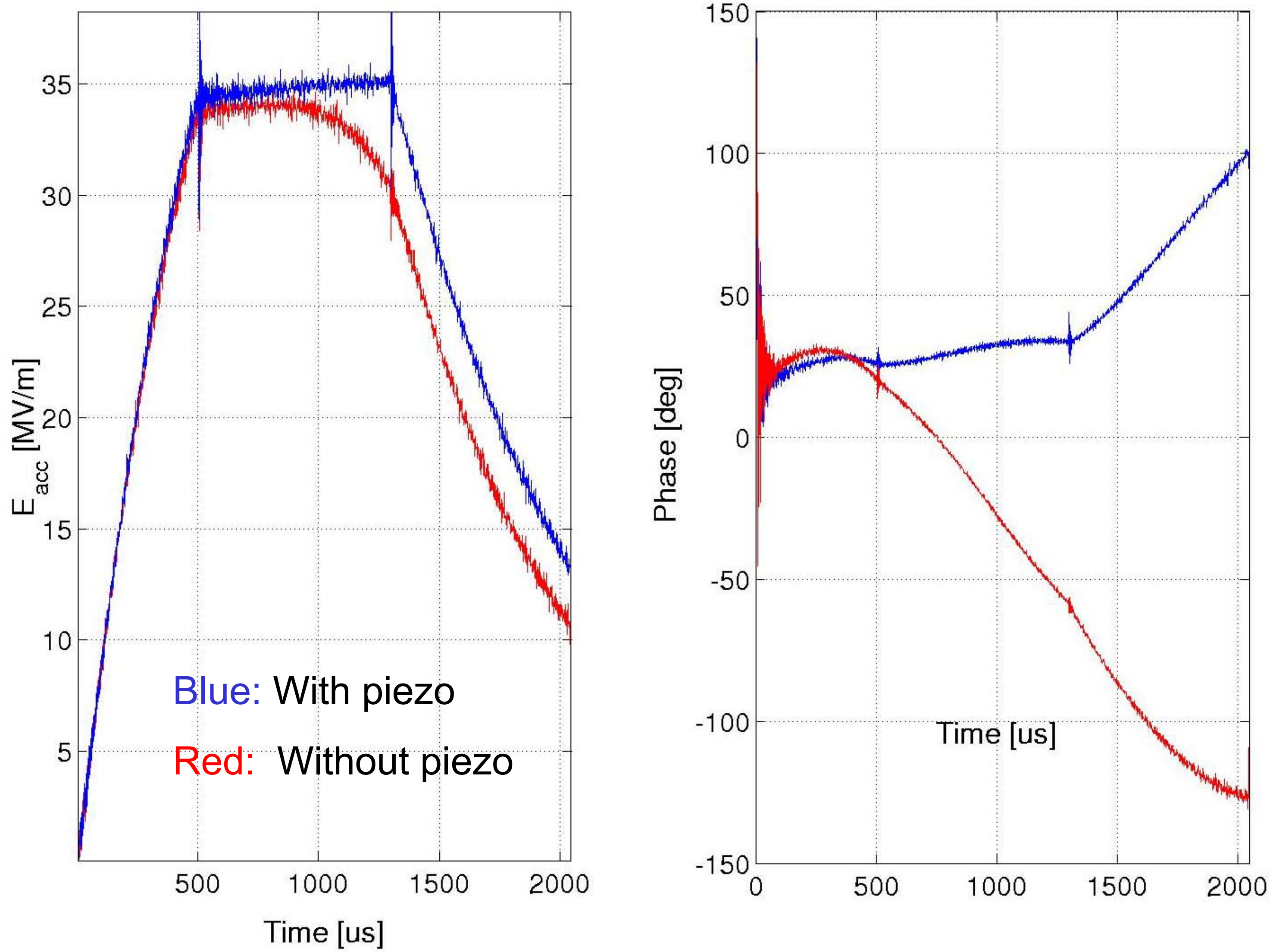
Some statistics on the test

- Test running 7.3.2003 – 14.8.2003
  - test took about 160 days (exact 3848 hours)
  - Scheduled cryo shutdown about 600 hours
  - warm-ups: 2x300 K, 4-5 times around 100 K
- Processing took about 165 hours
  - coupler 130 hours
  - cavity 35 hours
- RF operation of the coupler
  - cavity off-resonance and not at 2 K
  - power between 150 – 600 kW
  - 5 Hz operation very smooth
  - 10 Hz causes heating of the warm ceramics
  - **Total time RF on ~ 2400 hours**
- RF operation of the cavity
  - **1100 hours at around 35 +/-1 MV/m**
    - **~110 hours without interruption**
    - **57 hours at 36 MV/m +**
  - most of this is feed-forward operation
- Piezo compensation
  - **about 700 hours**

Operational Experience at high gradient

- Cavity and coupler did not cause a single event
- Of course we had cavity quenches (20-30) or coupler breakdowns (10-20), but they were caused by
  - Klystron/Pre-amp power jumps
  - LLRF problems
- No degradations were observed
  - As expected the quality factor of the cavity did not change due to these quenches
  - The breakdowns did not degrade the coupler

RF signals at 35 MV/m



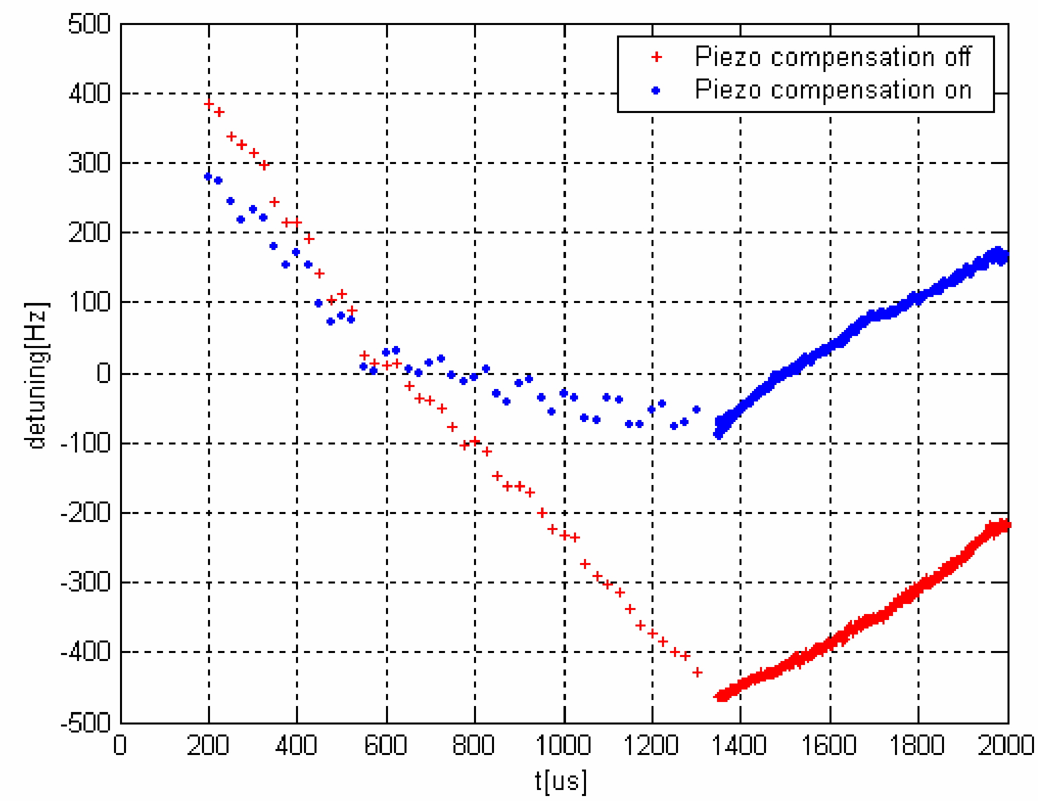
Frequency stabilization during RF pulse using a piezoelectric tuner

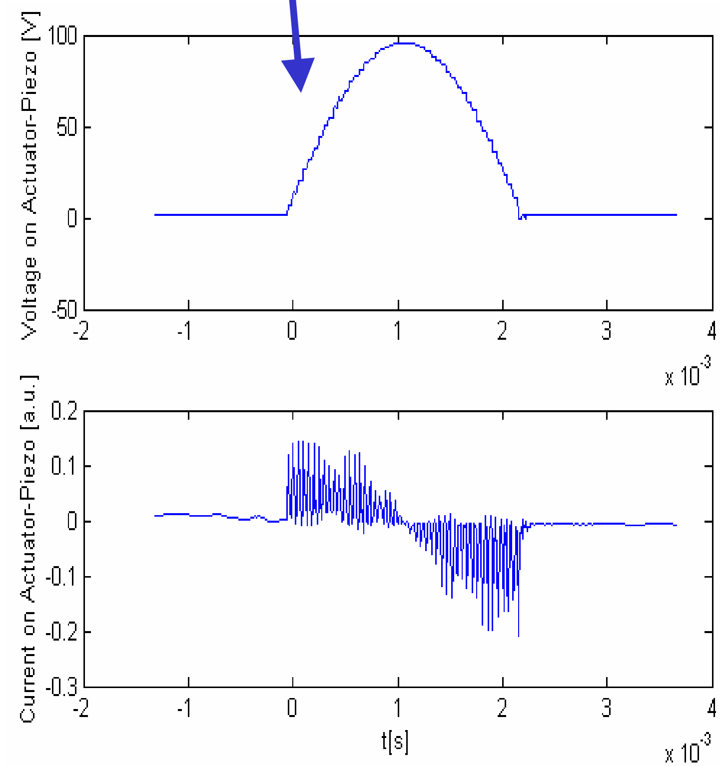
see S. Simrock (TuO09)

Blue: With piezo

Red: Without piezo

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

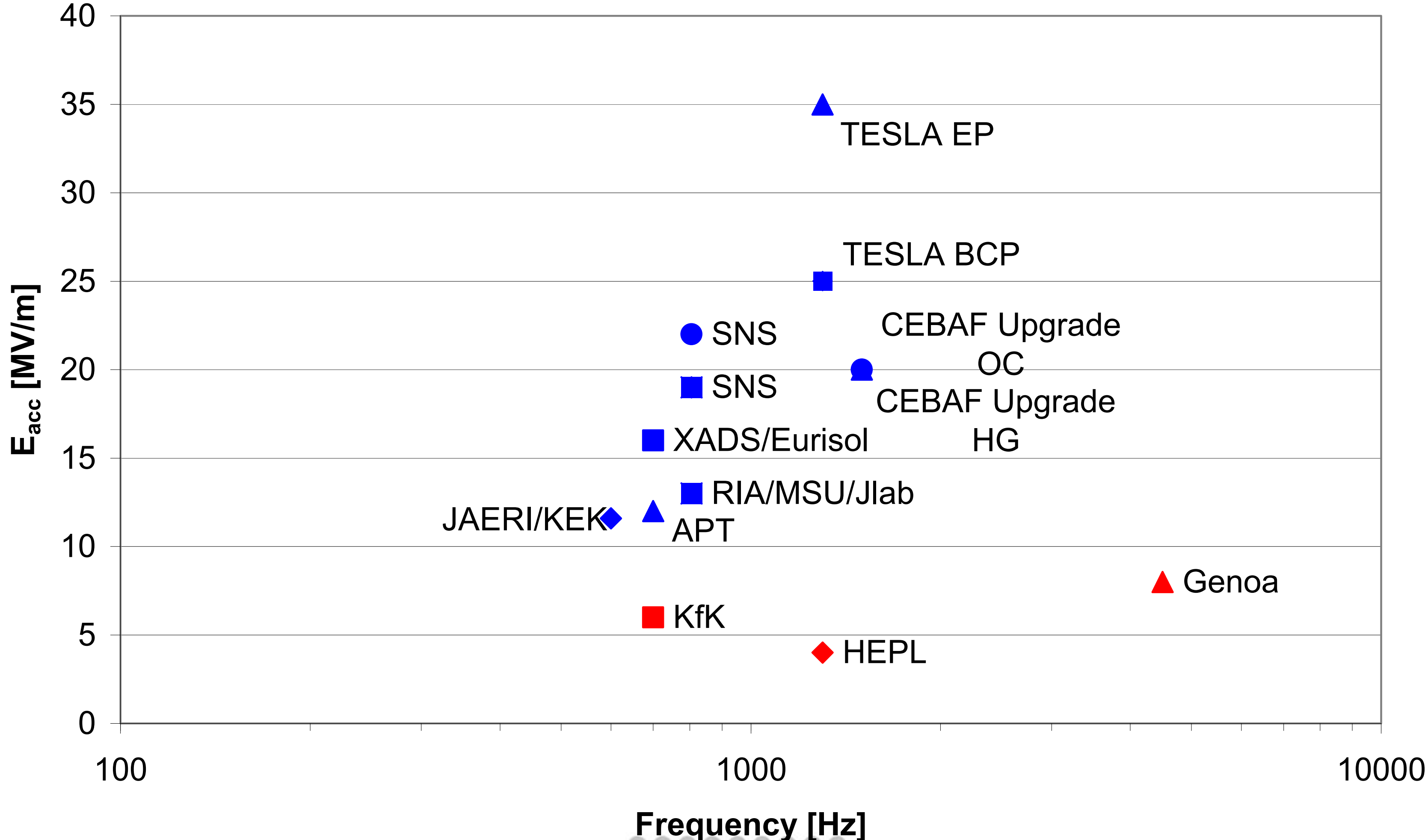




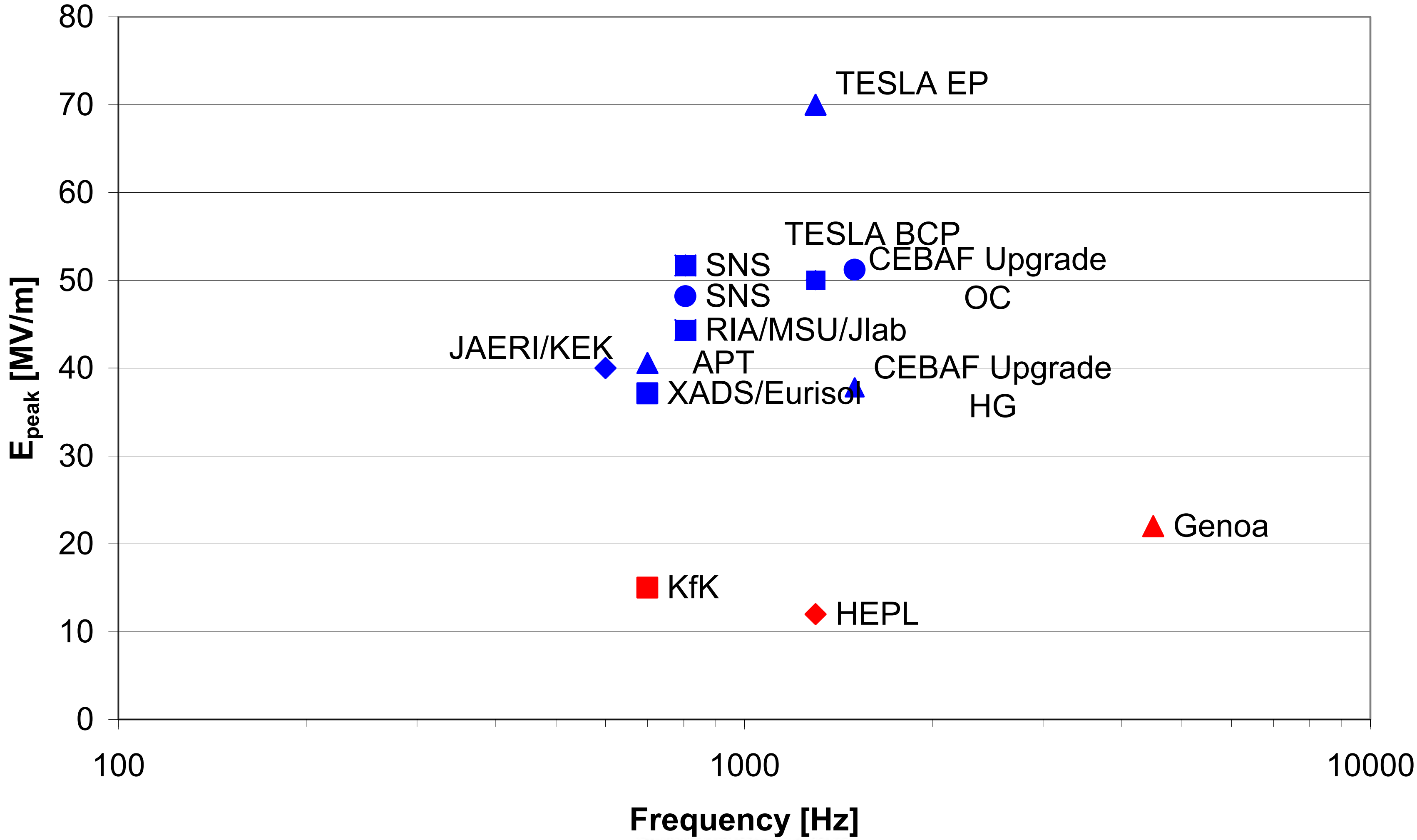
Summary

- A lot of data is available
- Where do we stand at SRF 2003 as compared to SRF 1980?

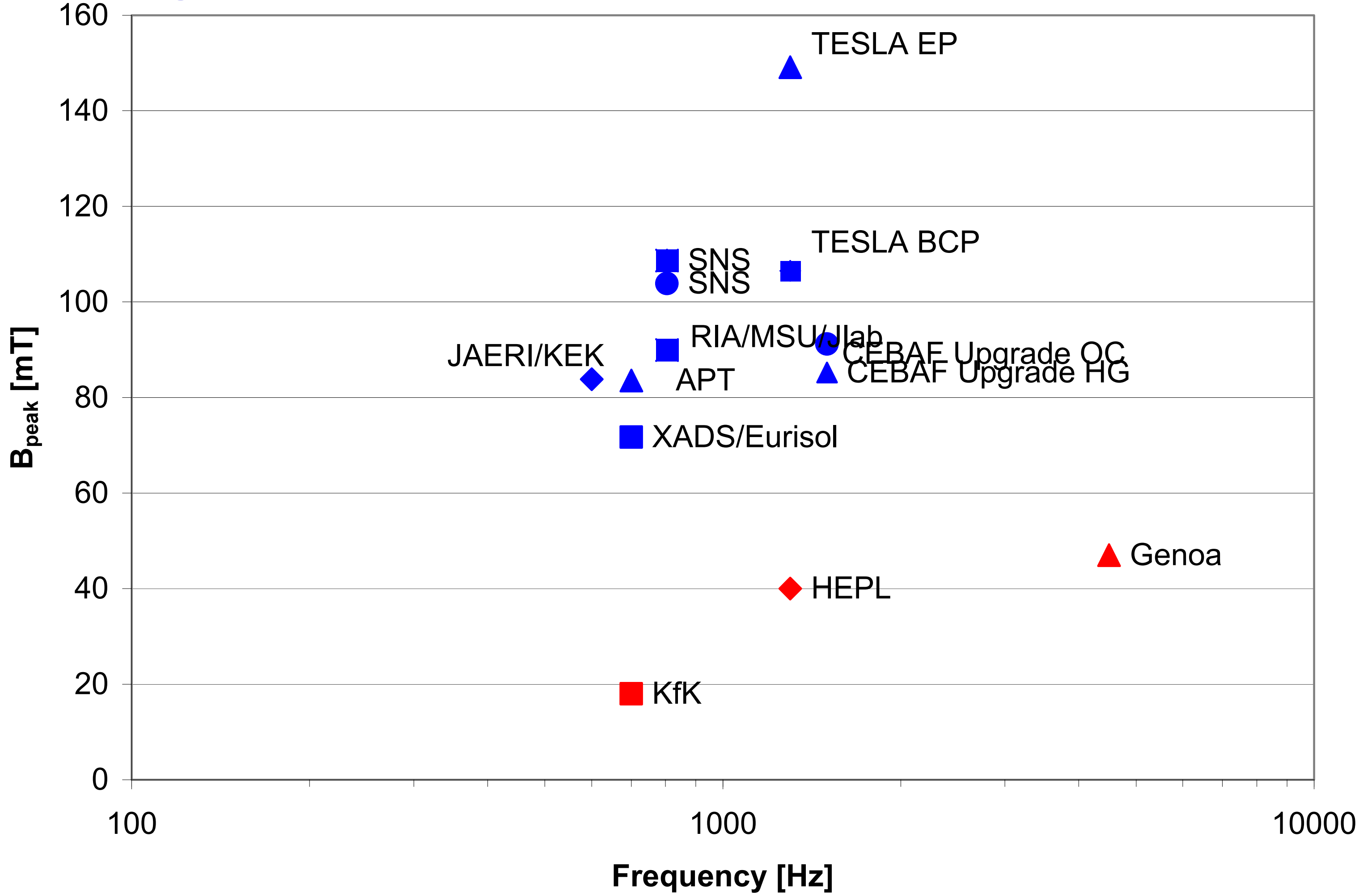
Accelerating gradients in multi-cell cavities



Electric peak field in multi-cell cavities



Magnetic peak field in multi-cell cavities



Summary

- Where do we stand at SRF 2003 as compared to SRF 1980?
  - E_{acc} upto 35 MV/m, Typical 15-25MV/m
    - electropolishing + baking is very promising
    - one cavity without titanisation at 35 MV/m
  - Typical E_{peak} around 40-50 MV/m
    - several different cavity from several projects
    - mostly etched cavities
  - Typical B_{peak} around 80-120 mT
    - several different projects
    - mostly etched cavities
    - Titanisation is not standard

Conclusion

- Proof-of existence for TESLA-800:
  - Nine-cell cavity in high power test at 35MV/m with acceptable cryogenic losses and very low field emission (only above 36 MV/m)
  - Shown stable operation at 35 MV/m for more than 1000 hours with feed forward only
  - No degradation seen in neither the coupler nor the cavity
  - Shown Piezo compensation of Lorentz force detuning is stable (more than 700 hours)
  - Non-titanified cavity at 35 MV/m in vertical test
- Several projects using standard etch as preparation yield reproducible cavity results
  - E_{acc} upto 35 MV/m, typical 15-25 MV/m
  - Typical E_{peak} around 40-50 MV/m
  - Typical B_{peak} around 80-120 mT

→ Superconducting RF is a promising *and* a mature technology at the same time !!!