Cavity development for TESLA

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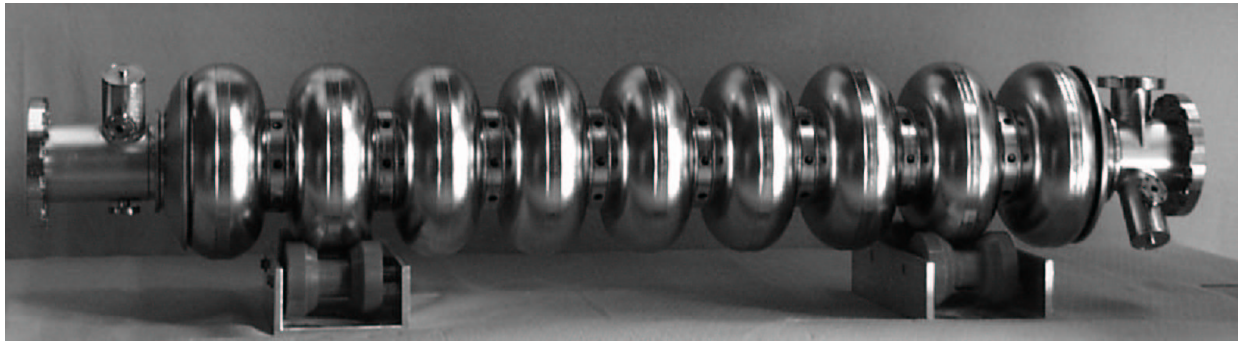
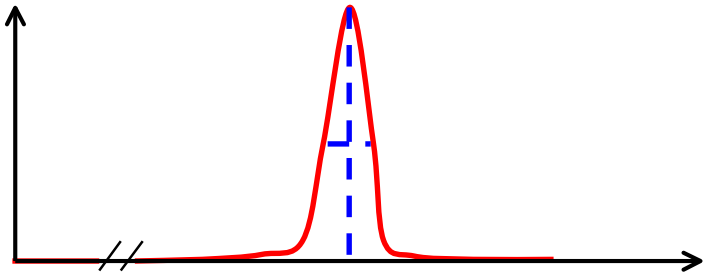
DESY -FDET-

- Cavity basics
- History:
  - Limitations and solutions
    - »Material inclusions
    - »Weld defects
    - »Field emission
    - »Increased surface resistance at high field
- Performance of 9-cell cavities (TESLA-500)
- R&D for TESLA-800
  - Surface Preparation
  - Manufacturing techniques
  - Superstructure
  - Piezoelectric tuner

TESLA Cavities

Cavities for TESLA -RF surface resistance





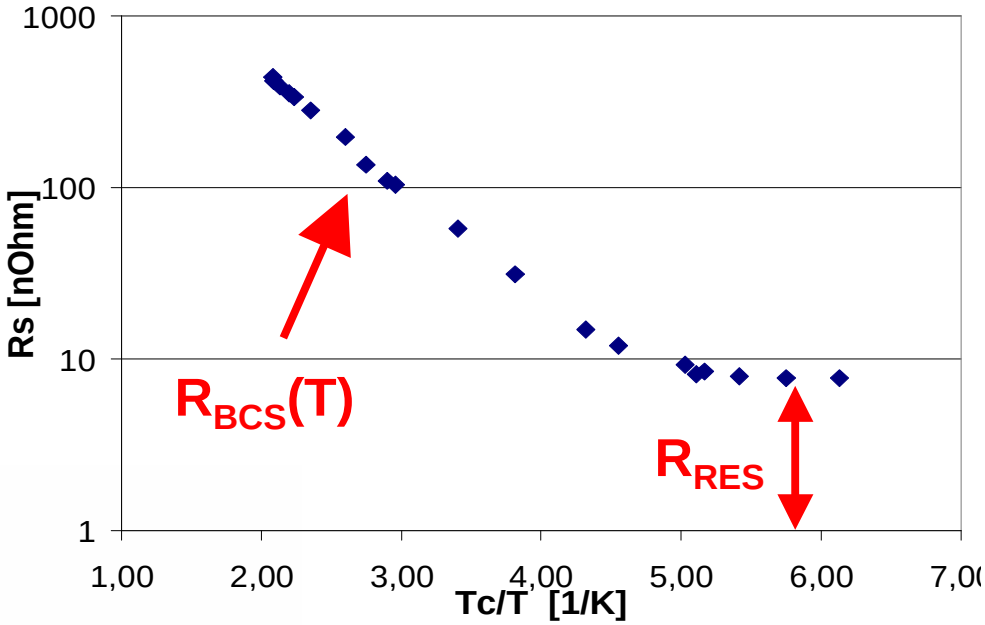
$f_o = 1.300.000.000\,\text{Hz}$

Quality factor:

$$Q_o = \frac{f}{\Delta f} = \frac{270\ \text{Ohm}}{R_S}$$

RF surface resistance:

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



'Natural' Bandwidth:

$\Delta f \approx 0{,}1$ Hz

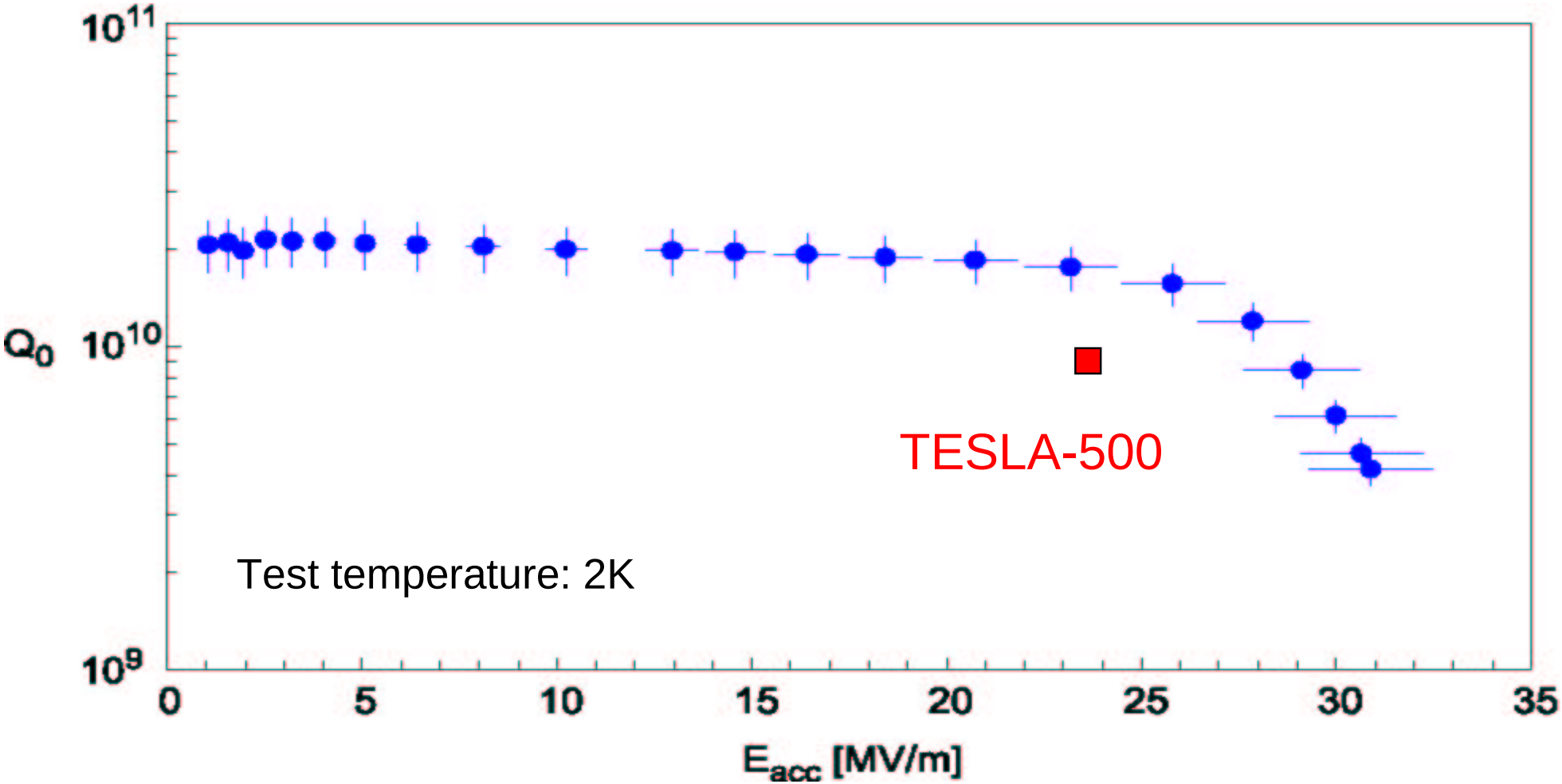
$\Rightarrow$ **$Q_0 \approx 10^{10}$**

Line width with main coupler

$\Delta f \approx 300$ Hz

$\Rightarrow$ **$Q_0 \approx 10^{6}$**

Best continuous wave test of TESLA cavity



Specifications:

E_{acc} = 23,4 MV/m @ $Q_0 = 1 \cdot 10^{10}$ for TESLA-500

E_{acc} = 35 MV/m @ $Q_0 = 5 \cdot 10^{9}$ for TESLA-800

Theoretical limit: $E_{acc} \approx 50$ MV/m

RF magnetic field exceeds first critical field of niobium

Challenges for TESLA cavities

- Accelerating gradient
  - For 500 GeV center-of-mass
    - E_{acc} = 23 MV/m @ $Q_0 = 1 \cdot 10^{10}$
  - For energy upgrade to 800 GeV
    - E_{acc} = 35 MV/m @ $Q_0 = 5 \cdot 10^{9}$
- Pulsed operation
  - Frequency detuning due to Lorentz force requires additional RF power

- What material quality is really needed?
- What is the best manufacturing technique ?
- How to prepare the best surface for RF superconductivity?
- How to compensate the Lorentz-force detuning?

Production and preparation of TESLA cavities

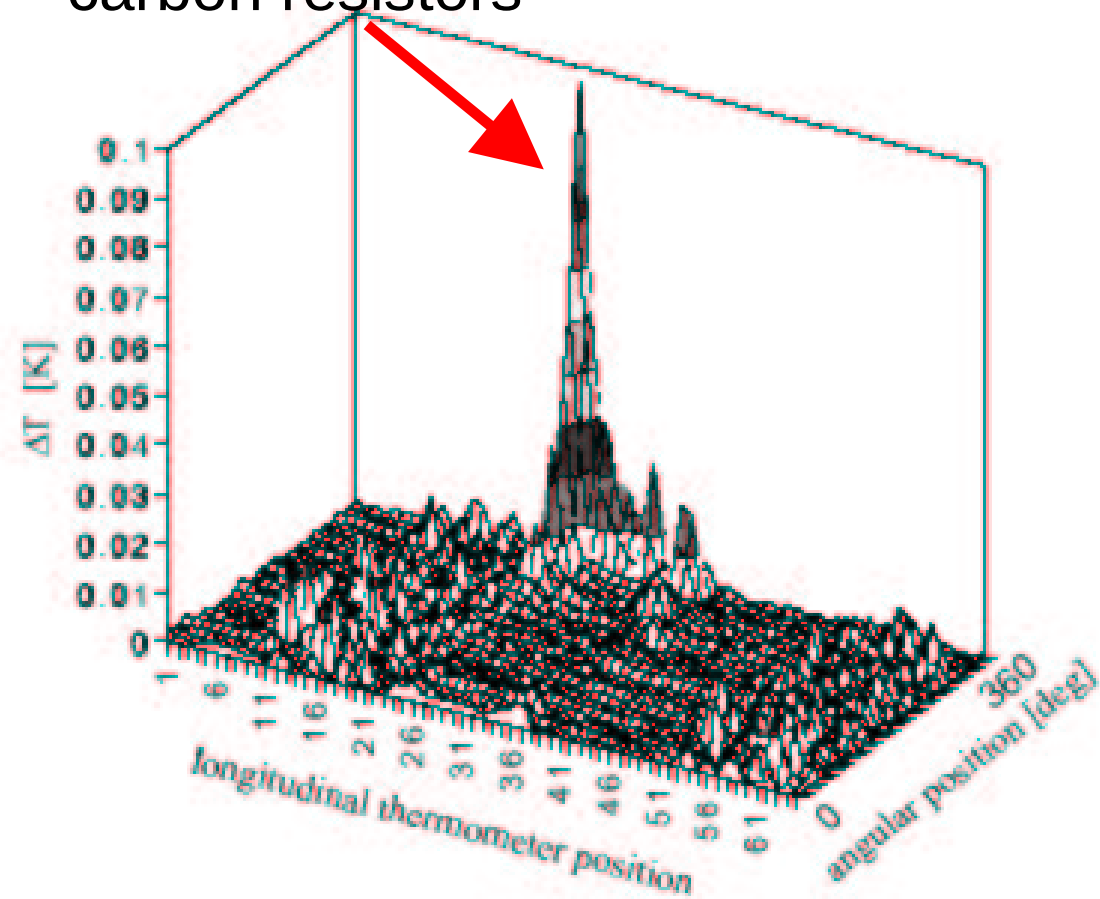
- Niobium sheets (RRR=300) are subjected to eddy-current scanning to avoid foreign material inclusions like tantalum and iron
- Deep-drawing of subunits (half-cells, etc.) from niobium sheets
- Electron-beam welding according to detailed specification
- 800 °C high temperature heat treatment to stress anneal the Nb and to remove hydrogen from the Nb
- 1400 °C high temperature heat treatment with titanium getter layer to increase the thermal conductivity (RRR=500)
- Chemical etching to remove damage layer and titanium getter layer
- High pressure water rinsing as final treatment to avoid particle contamination

Detailed preparation sequence for niobium cavities

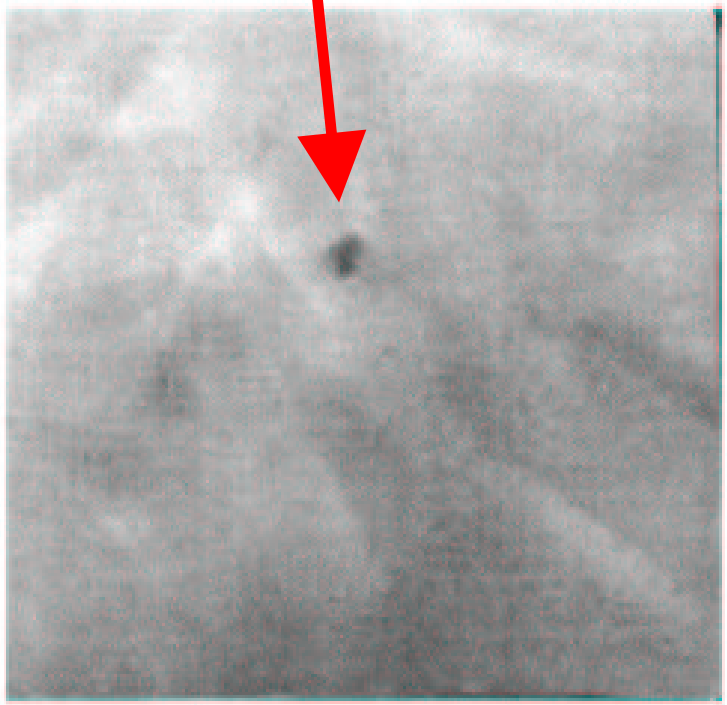
- removal of the damage layer by chemical etching
- 2 hours heat treatment at 800 C - remove hydrogen and stress anneal
- 4 hours heat treatment at 1400 C with titanium getter for higher thermal conductivity to stabilize defects
- removal of the titanium layer by chemical etching
- field flatness tuning
- final 20 □m removal from the inner surface by etching
- high pressure rinsing (HPR) with ultrapure water
- drying by laminar flow in a class 10 cleanroom
- assembly of all flanges, leak-check
- 2 times HPR, drying by laminar flow and assembly
- of the input antenna with high external Q

Example of a material defect

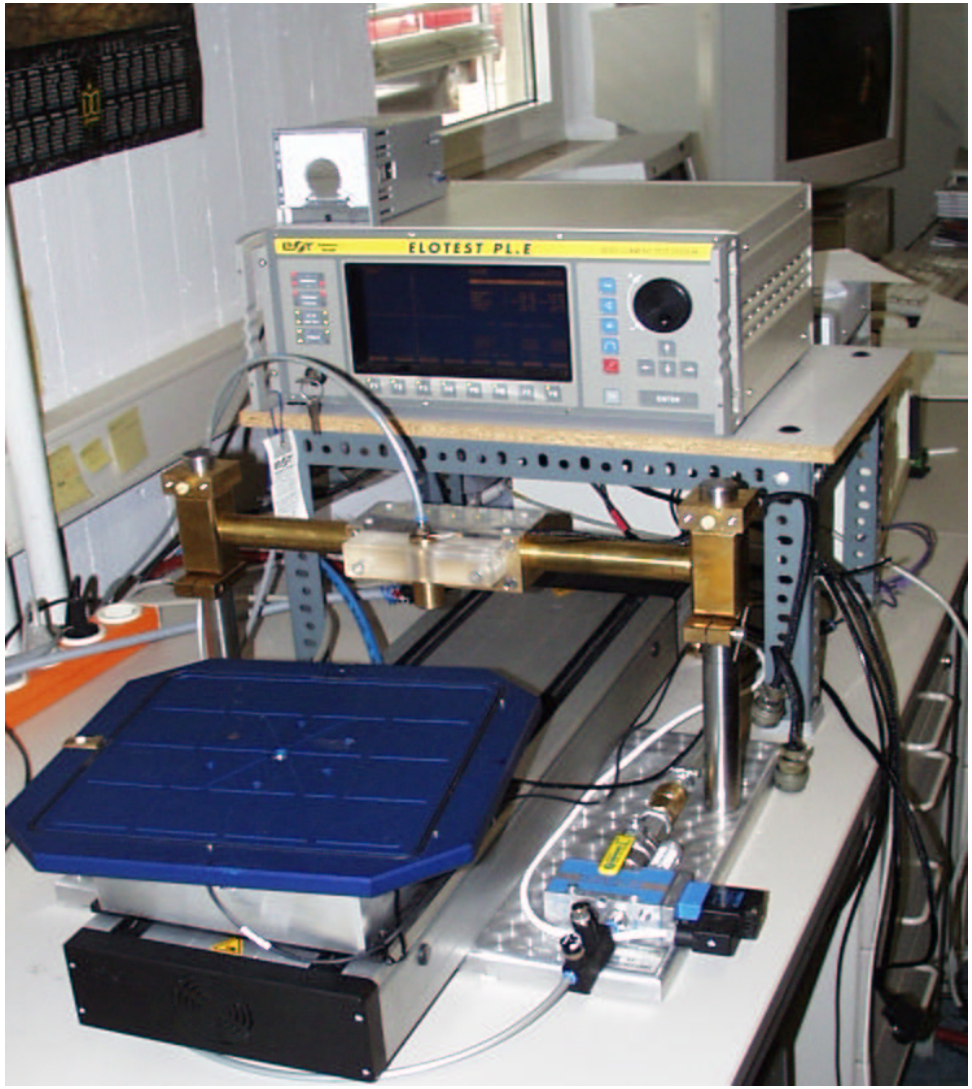
Heating on the outside surface measured with carbon resistors



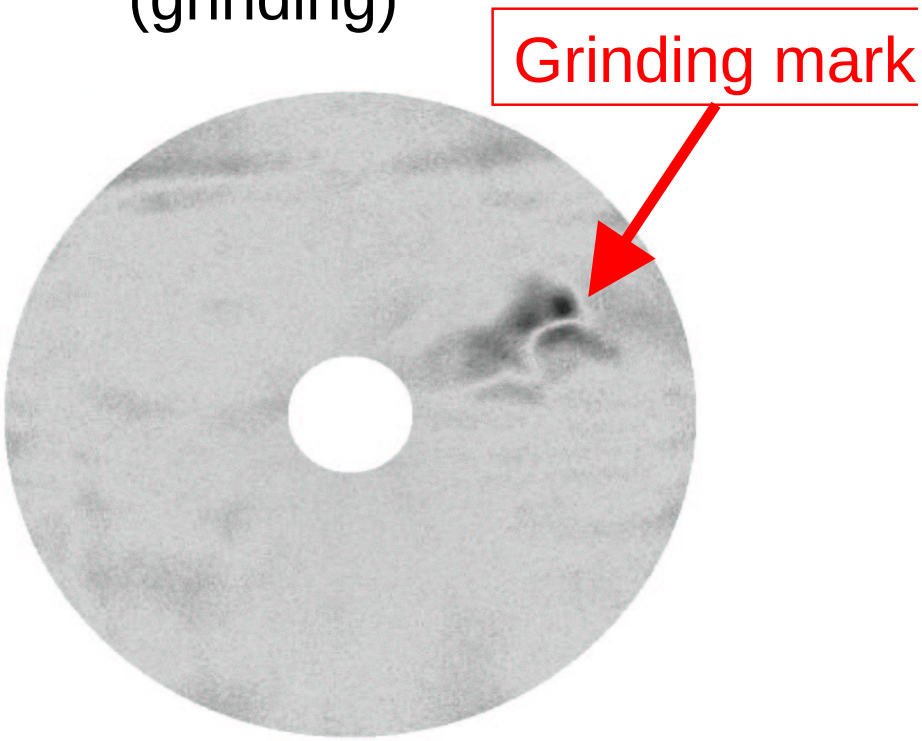
Defect found with X-ray technique: Tantalum



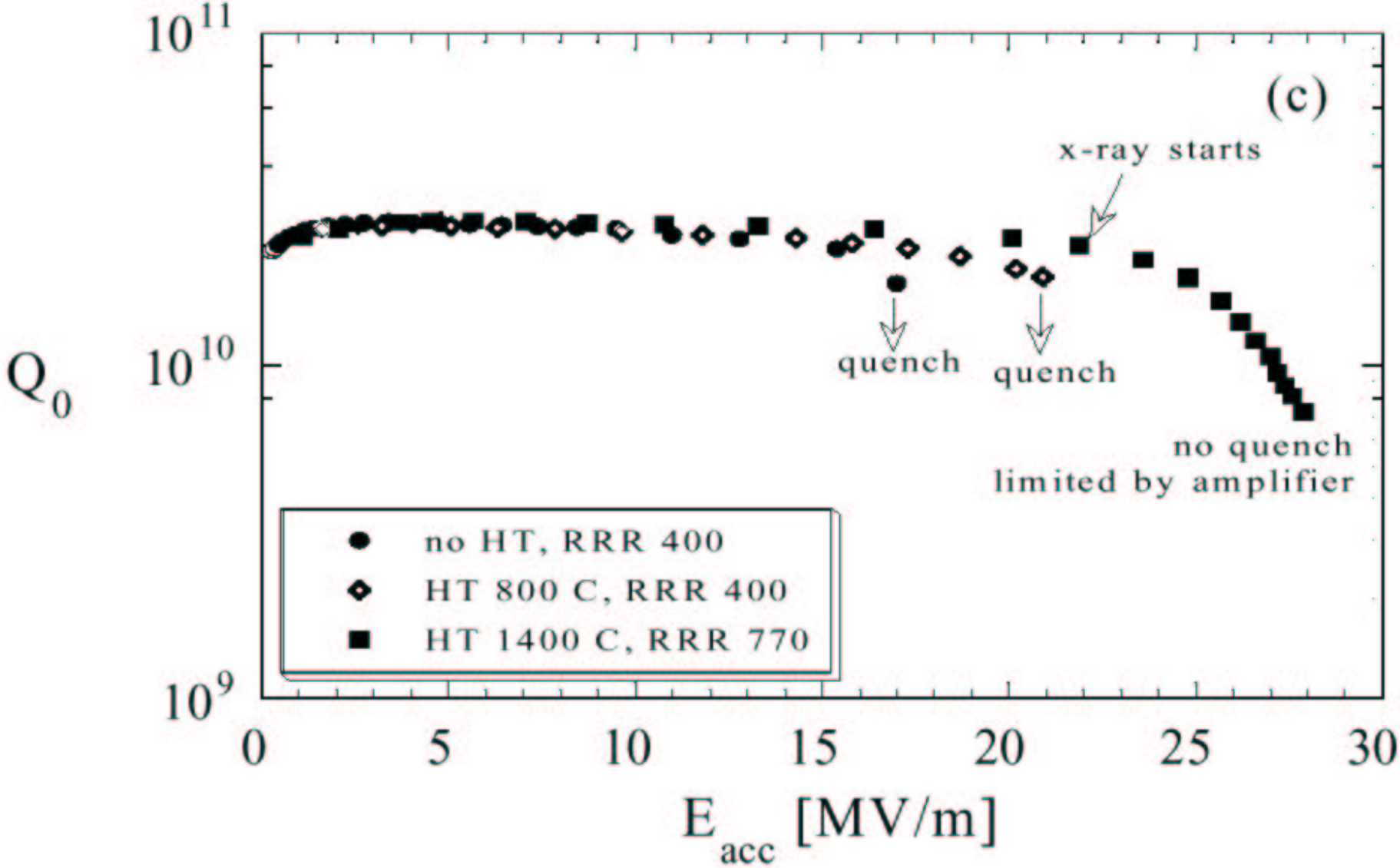
Eddy current scanning



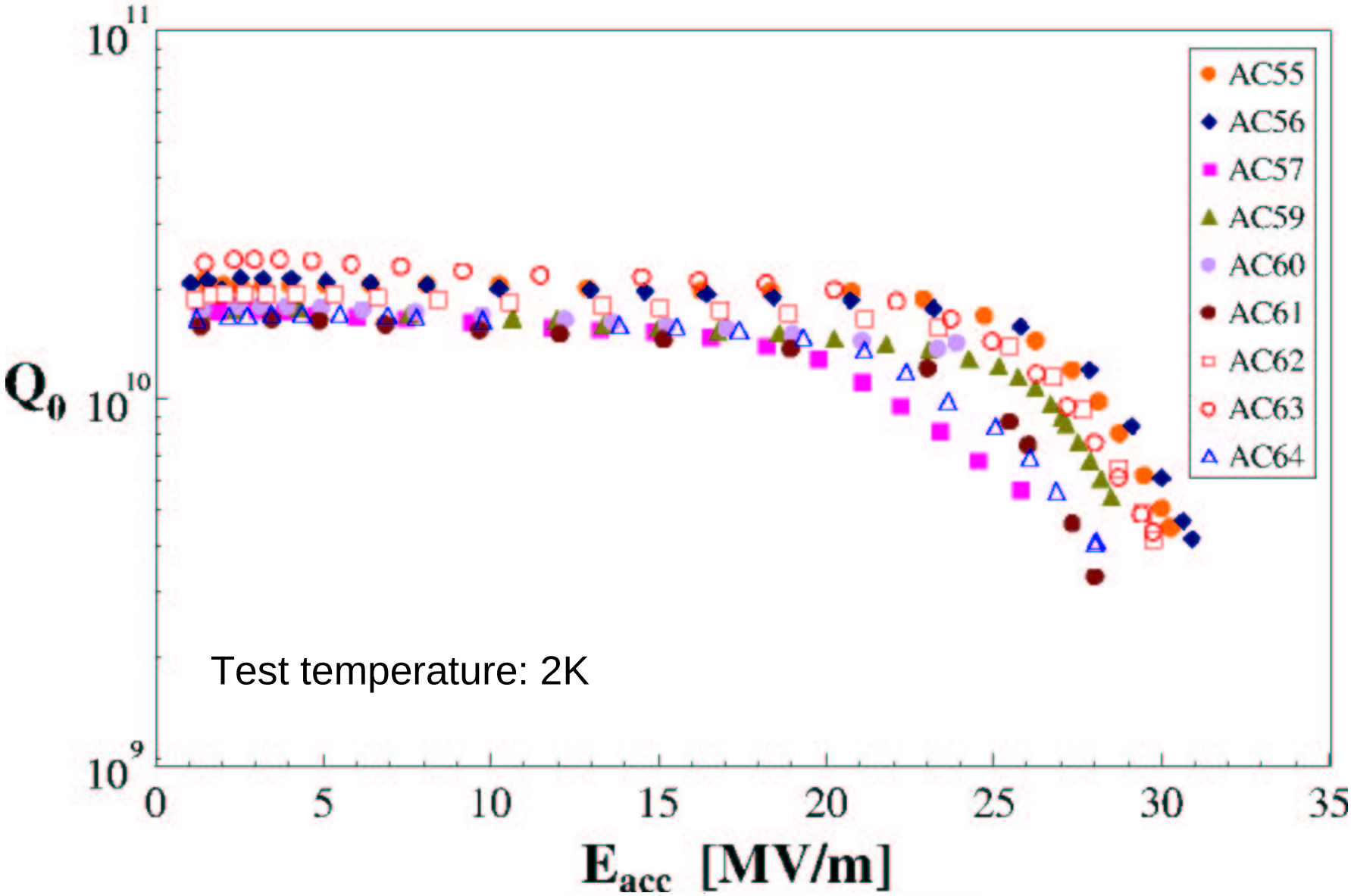
- Large tantalum inclusions (~200 µm) and places with irregular patterns from surface preparation (grinding)



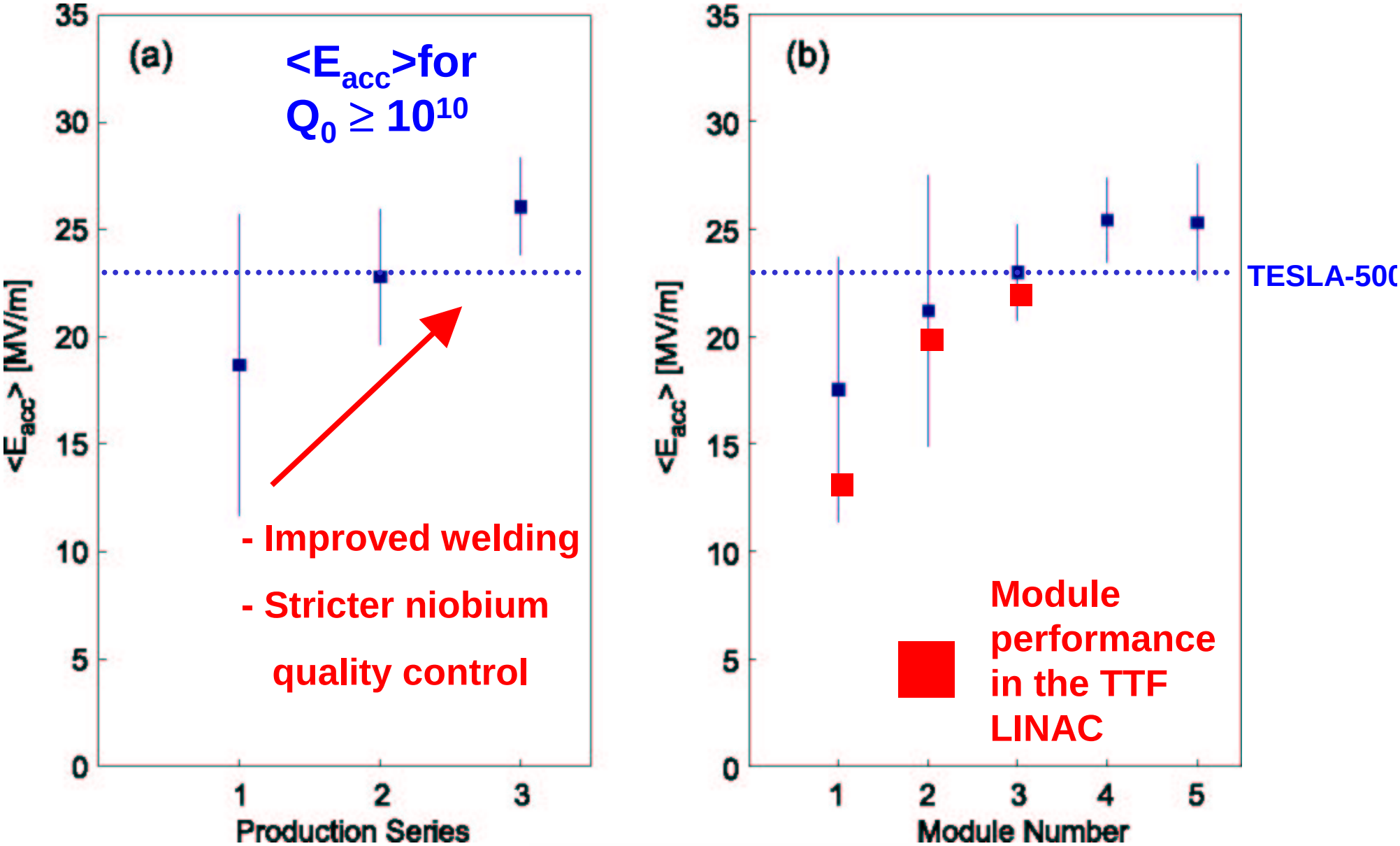
Benefit of the high temperature heat treatments



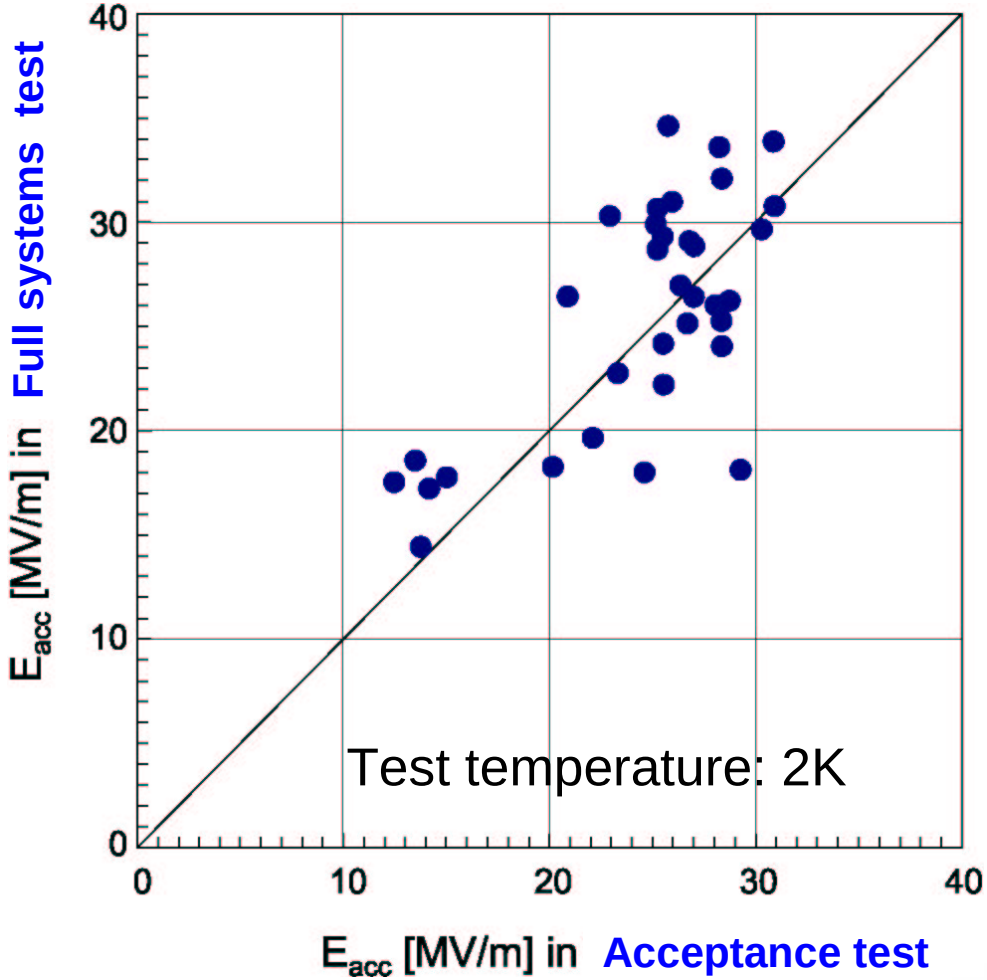
Latest production of TESLA-type nine-cell cavities



Results of cavity productions



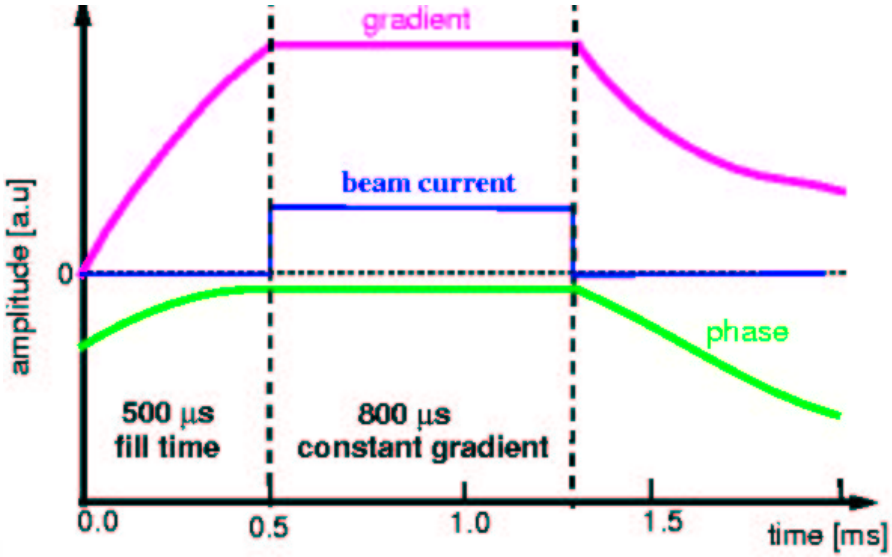
Preparation for LINAC operation



1 continuous wave acceptance test with low power

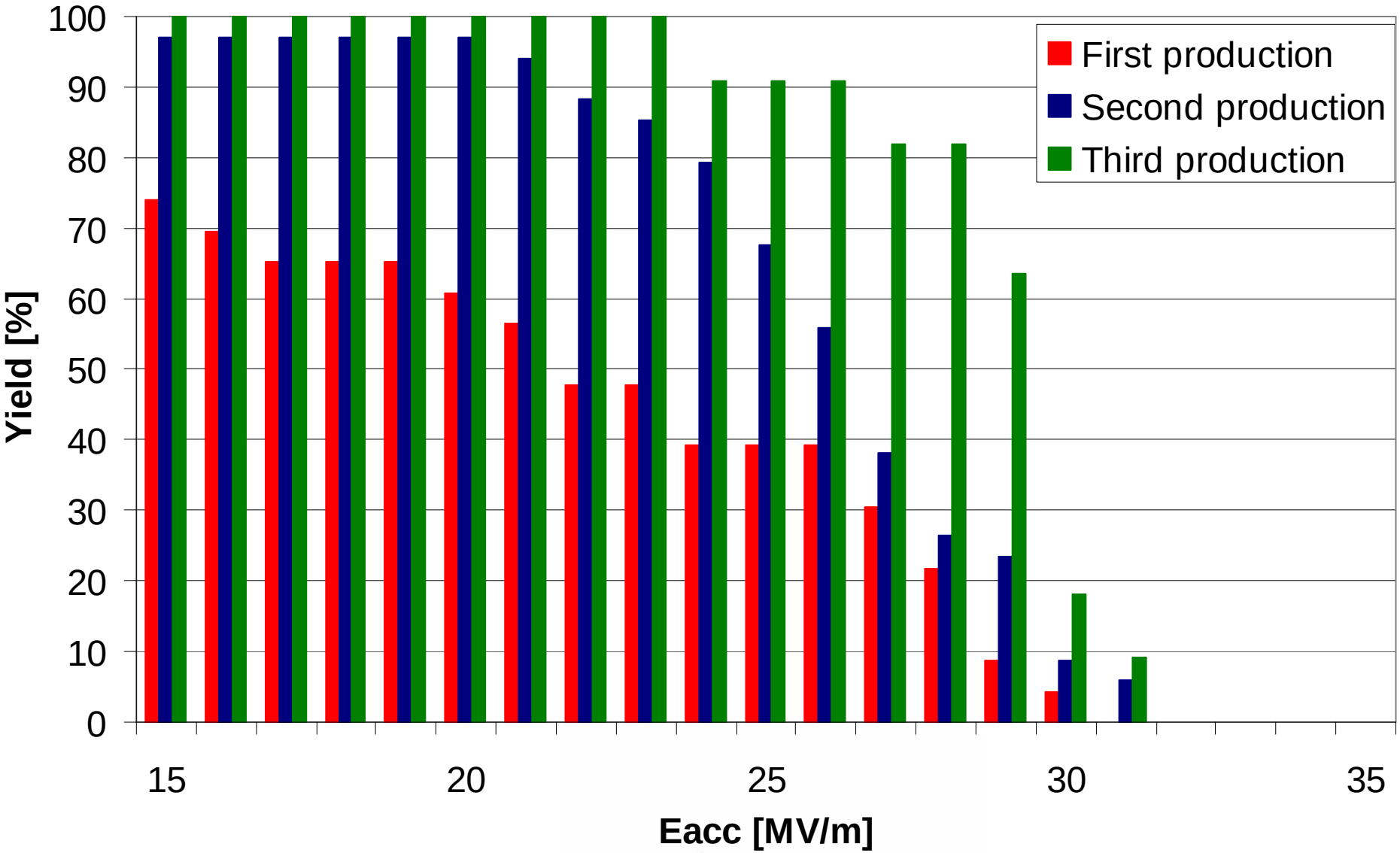
2 full systems test with high power coupler

- pulsed test with:
  - 500 µs rise time
  - 800 µs flat-top
  - 10 Hz repetition rate



- Results scatter around $E_{acc,\ cw} = E_{acc,\ pulse}$

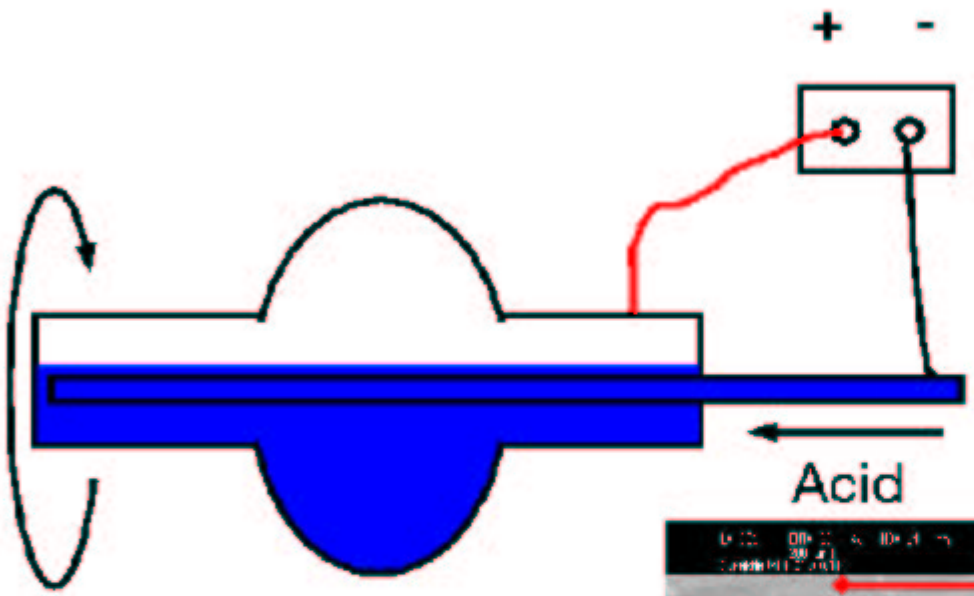
Yield of cavities from CW test



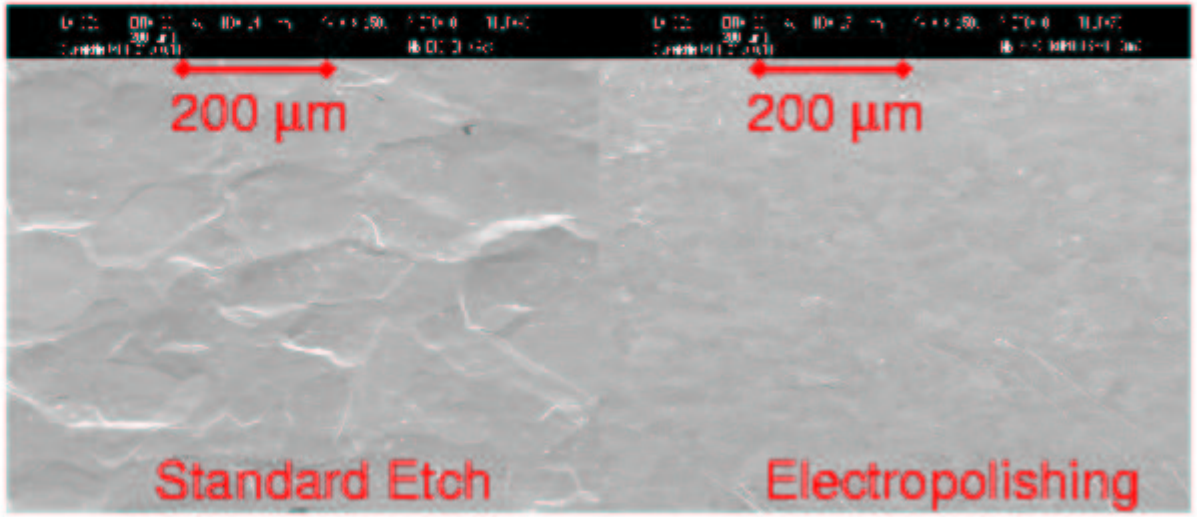
R&D

- Surface preparation
  - Electropolishing
  - ‘In-situ’ Bakeout
- Cavity Production
  - Spinning
  - Hydroforming
  - Nb-Cu clad cavities
- Pulsed operation
  - Stiffening
  - Piezo-electric tuner
- Linac fill factor -> Superstructure

Electropolishing of 1-cell cavities (Scheme)

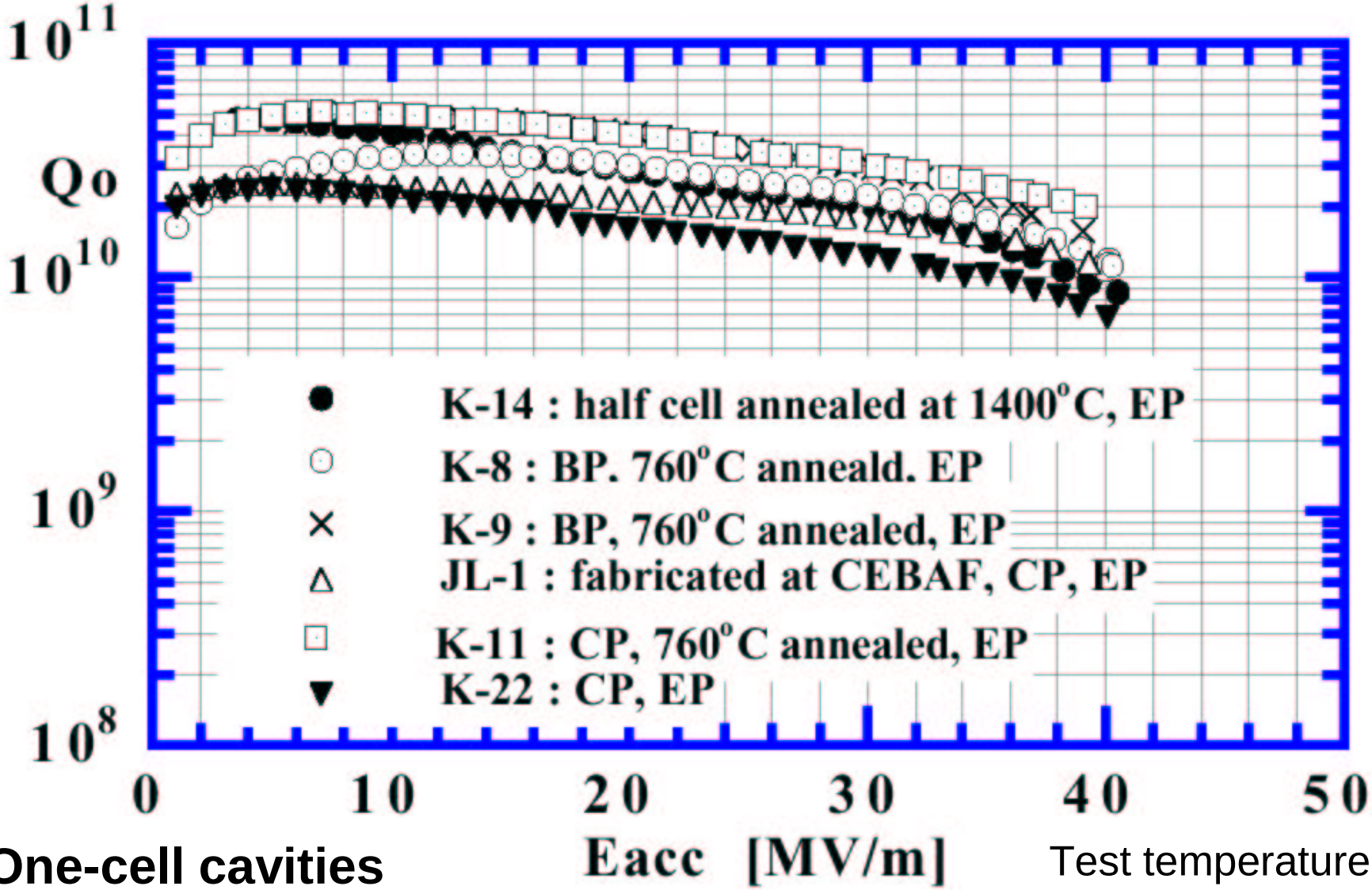


- EP electrolyte
- 90 % H_2SO_4
- 10 % HF
- 30 °C
- 0,5 µm/min removal of material



KEK results for electropolished niobium cavities

K. Saito et al. KEK 1998/1999

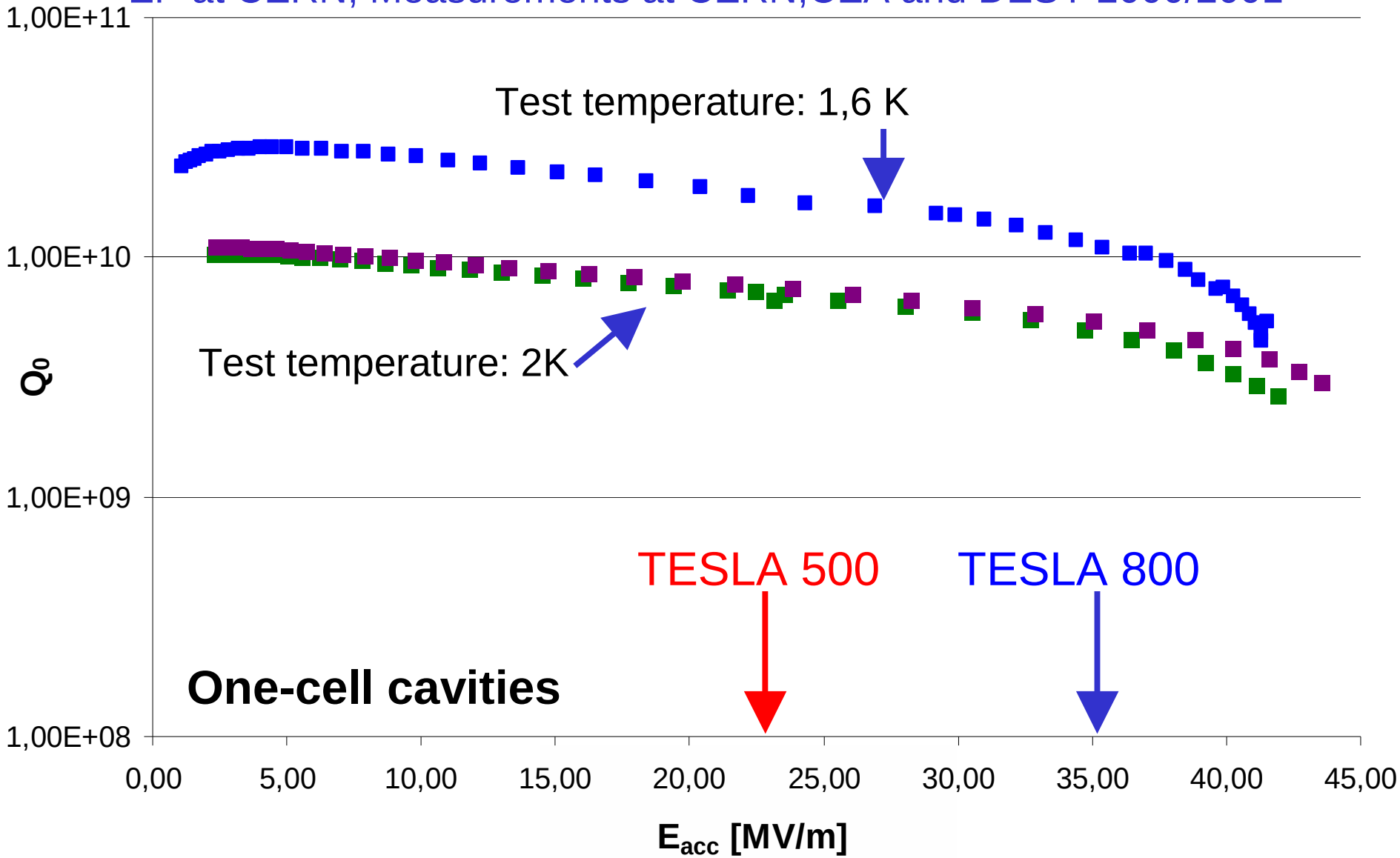


One-cell cavities

Test temperature: 1,6 K

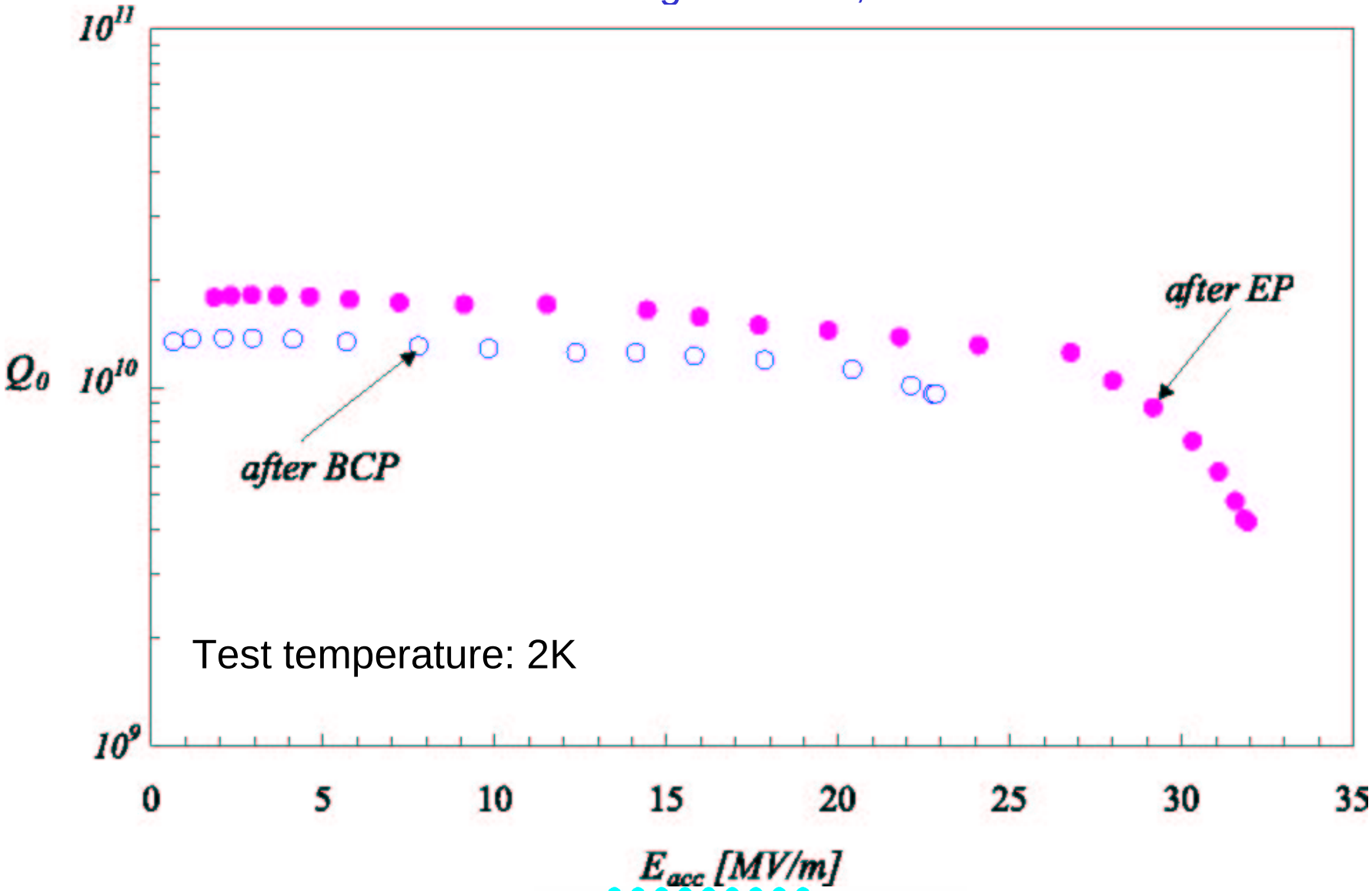
Electropolished cavities

EP at CERN, Measurements at CERN,CEA and DESY 2000/2001

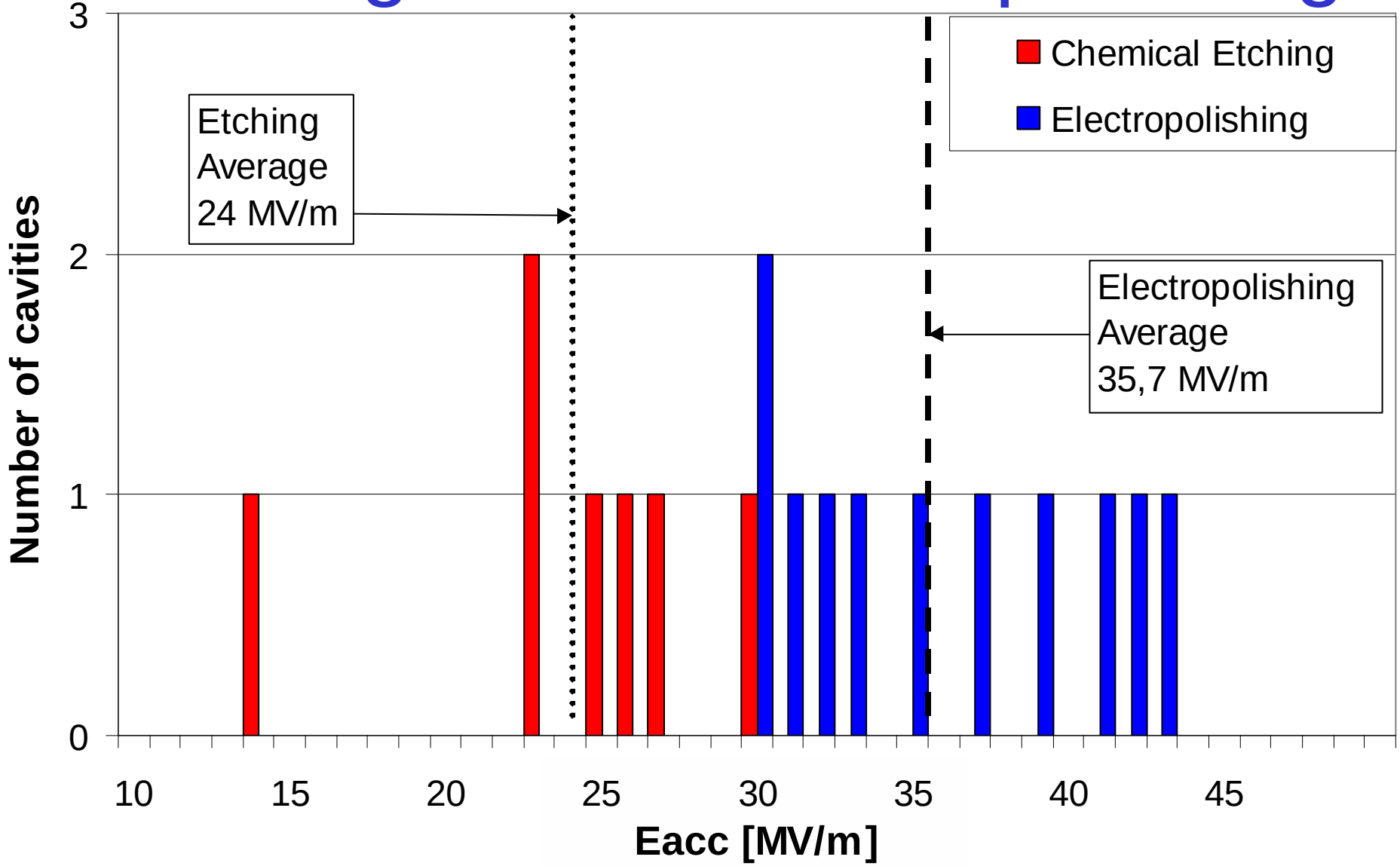


Electropolished TESLA nine-cell cavity

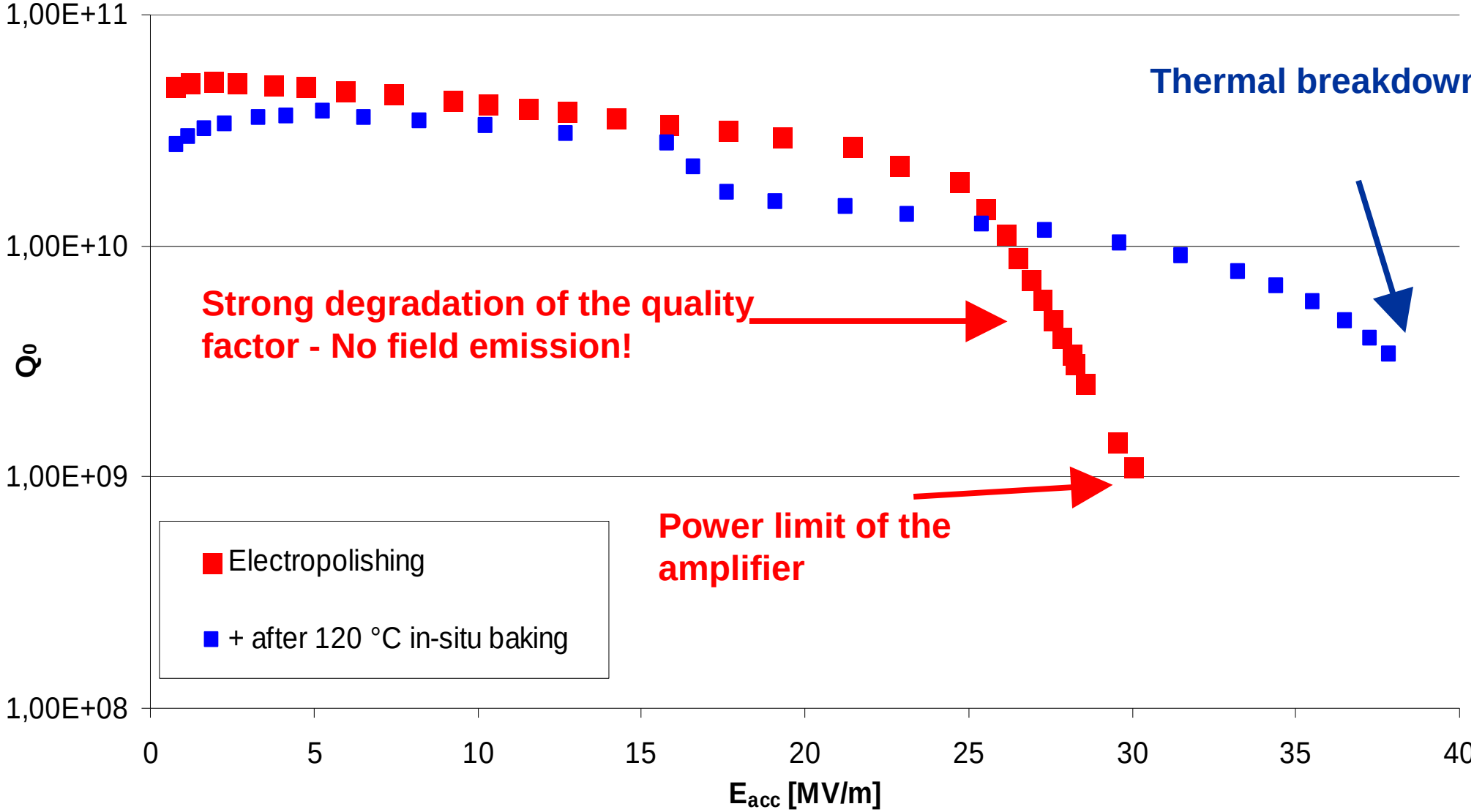
EP at Nomura Plating and KEK, Test at DESY



Etching versus Electropolishing



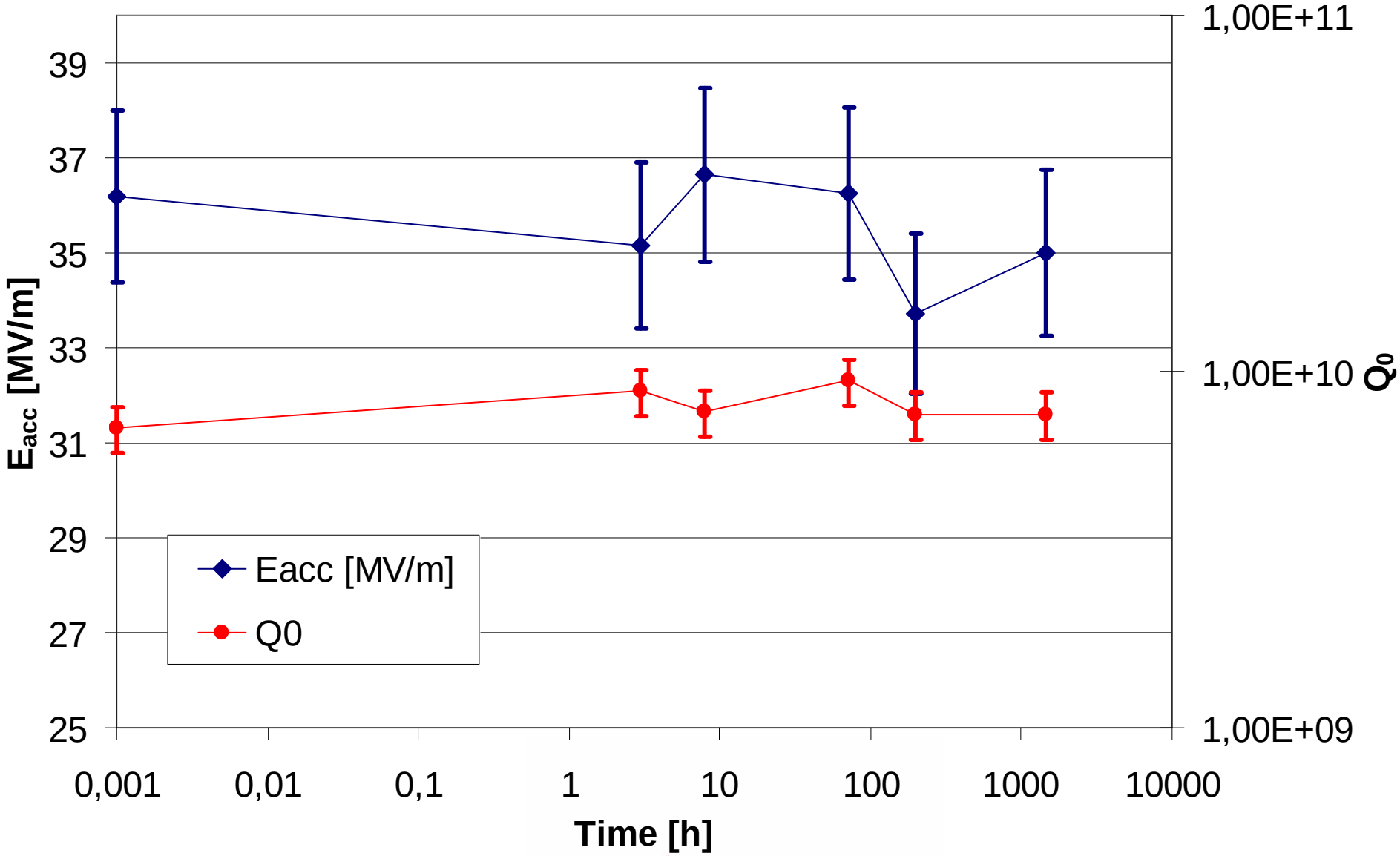
Improvement by ‘In-situ’ baking



In-situ Baking

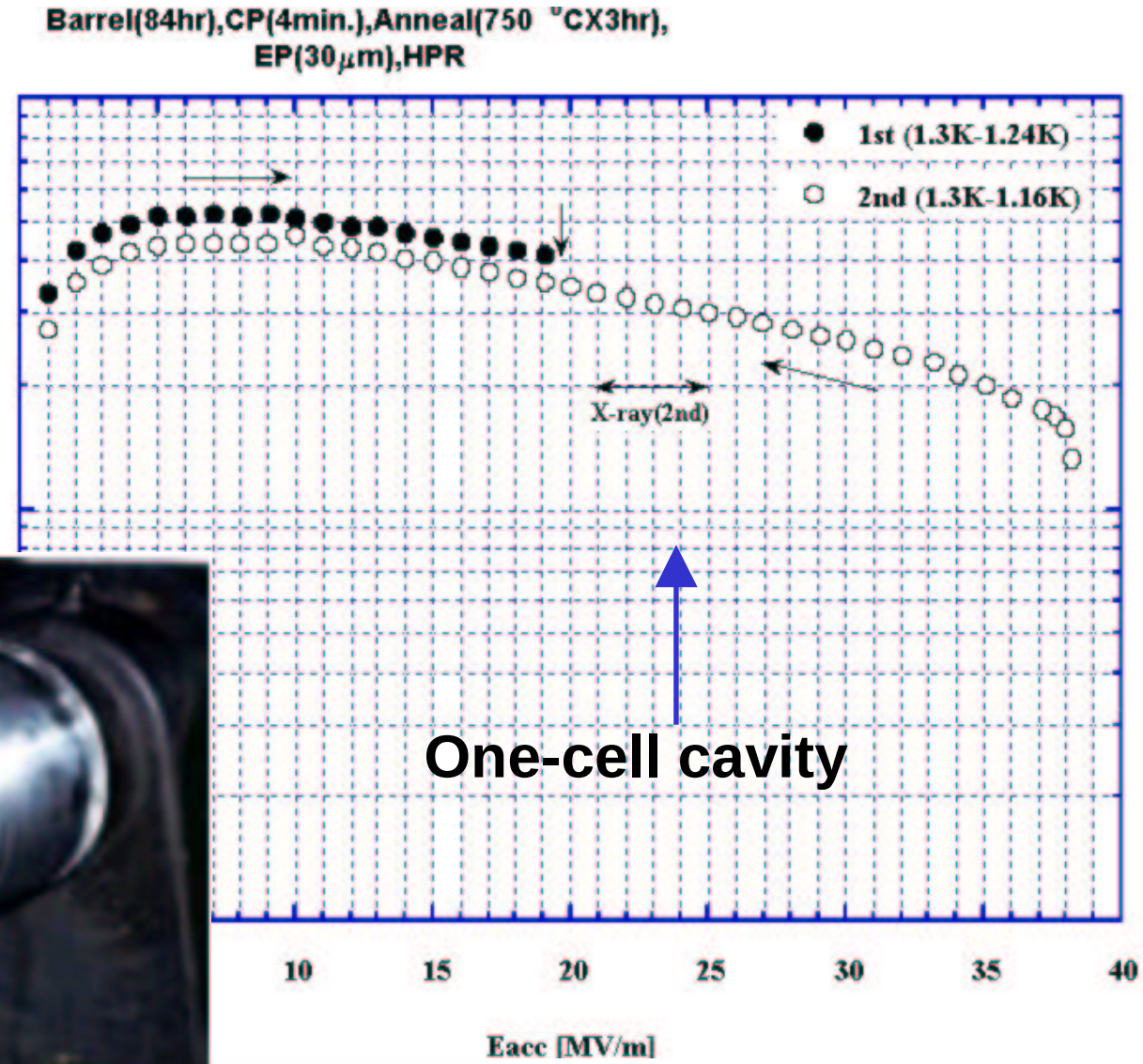
- Heating of the cavity to 100 - 120 °C
- Duration: ca. 40 hours
- Pressure below 10^{-6} mbar
- Inert gas atmosphere on the outside

Air exposure of a baked niobium surface



Spun and EP cavities

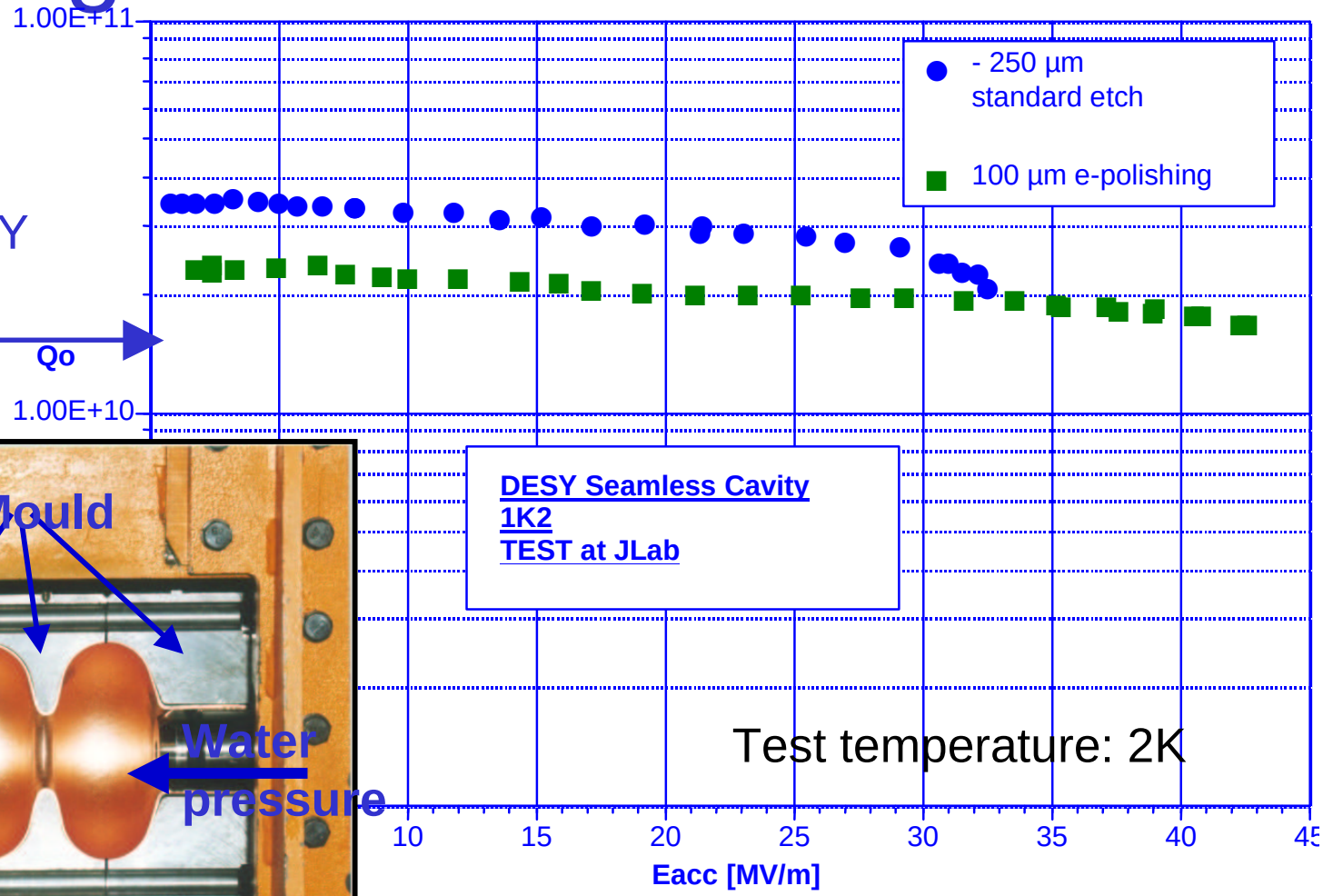
Palmieri (INFN-LNL),
Saito (KEK)

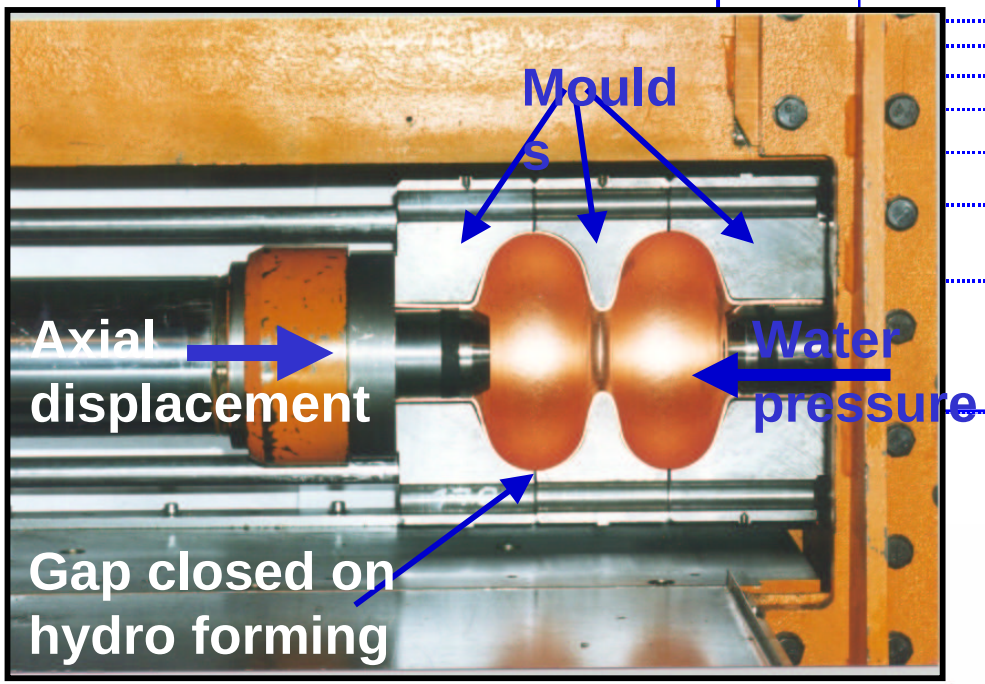


Hydroforming and EP

Kneisel TJANF
Kaiser, Singer DESY
Saito KEK

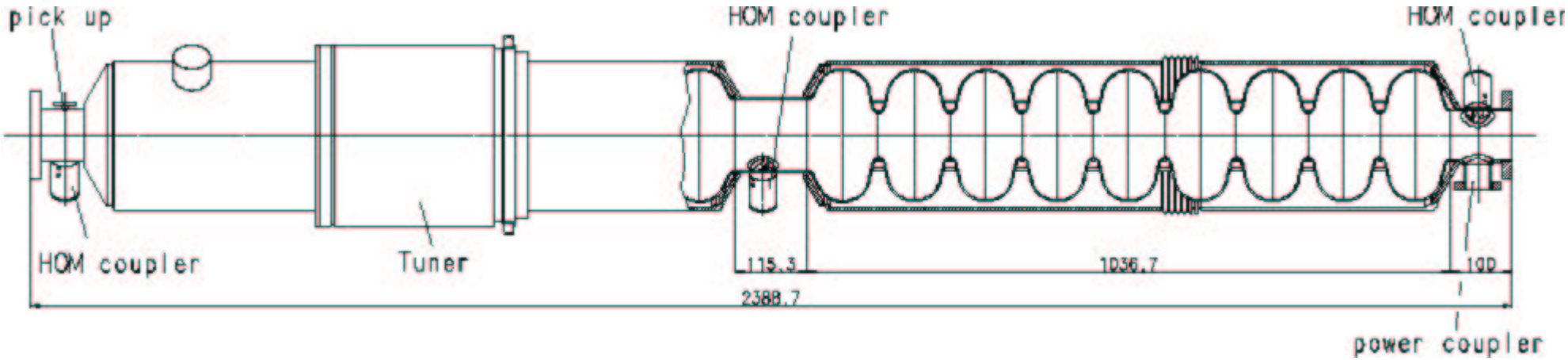
One-cell cavity



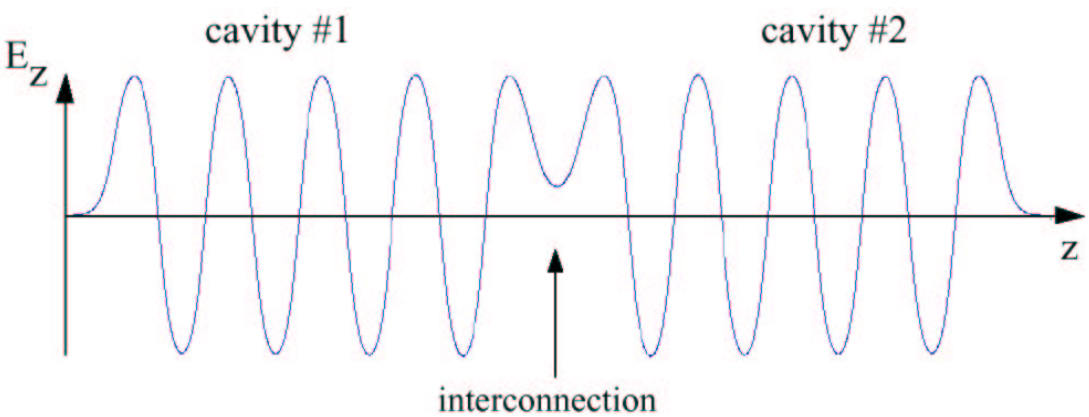


TESLA 2 x 9 Superstructure

J. Sekutowicz, M. Liepe et al.



Field profile:



Benefits:

- 6% larger active accelerating length as compared to normal nine-cell design

- less main and HOM couplers

Comparison of two accelerating schemes for TESLA-500 (nine-cell vs. superstructure)

Layout	L_{active} [m]	E_{acc} [MV/m]	No. of power coupler	No. of HOM coupler	No. of freq. tuners	Filling factor L_{active}/L_{total}	P_{trans} [kW]
9-cell	1.04	23.4	20592	41184	20592	78.6	232
2x9-cell	2.08	22	10926	32778	21852	84.8	437

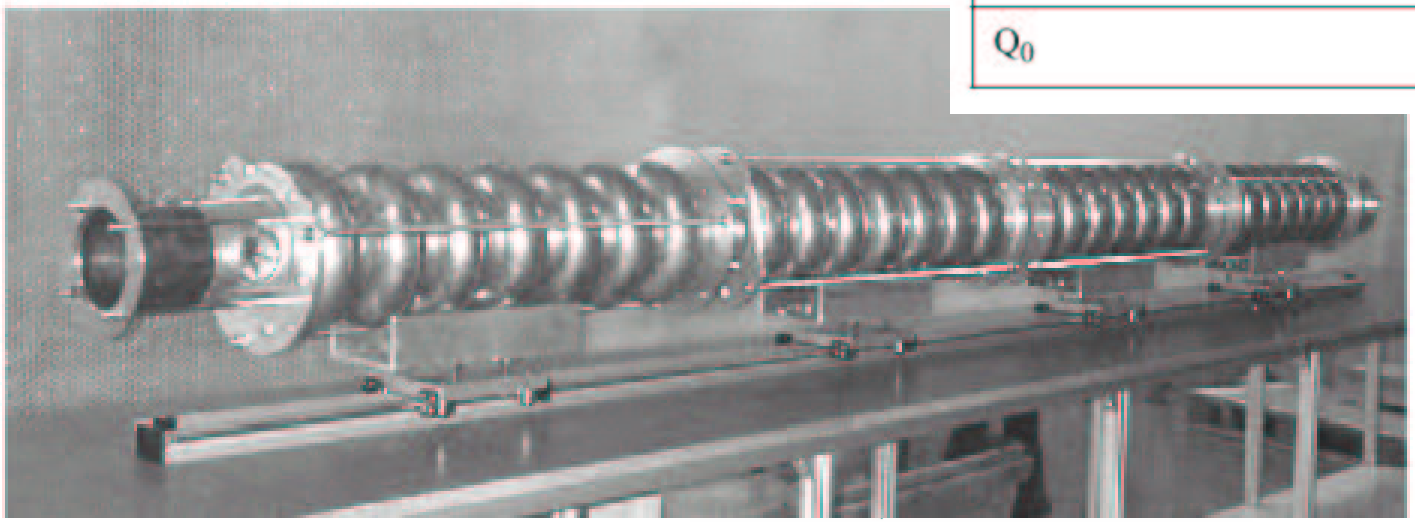
Superstructure

J. Sekutowicz, M. Liepe et al.

- higher fill factor L_{acc} / L_{total}
- less RF couplers

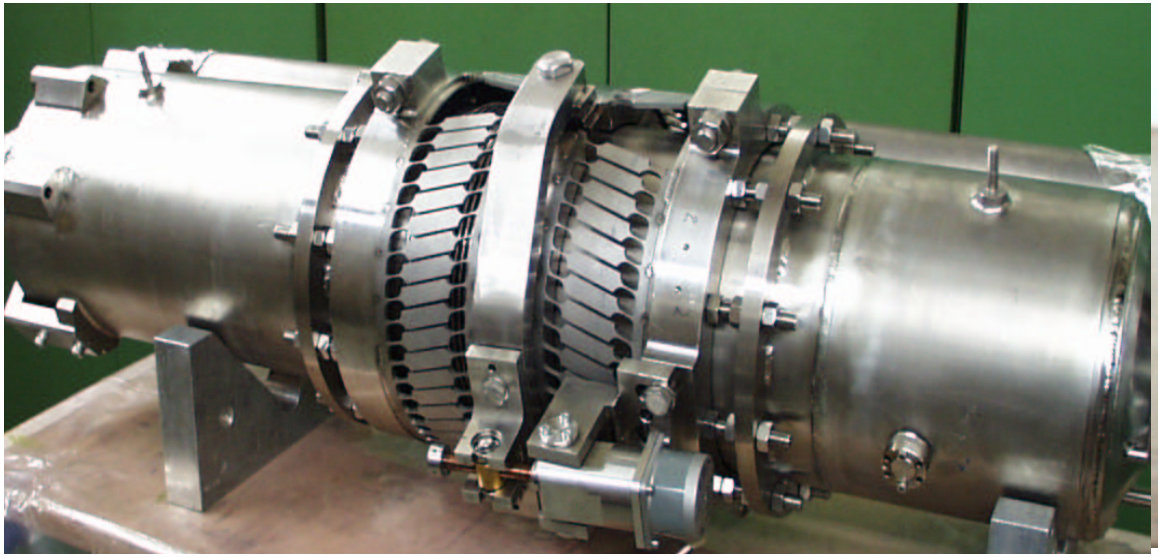
Table 1: Parameters of Cu model of the superstructure

Parameter	
number of cells, M x N	4 x 7
number of HOM / input couplers	5 / 1
radius of mid / end iris [mm]	35 / 57
fill factor	0.875
k_{cc}, cell-to-cell coupling	0.019
k_{ss}, cavity-to-cavity coupling	$3.6 \cdot 10^{-4}$
field instability factor, N^2/k_{cc} [10^3]	2.6
(R/Q)/length [Ω/m]	906
Q_0	≈ 27000



New tuner delelopment for the TESLA cavities

- mounted on the helium tank
- needed for the superstructure
- first tests succesful



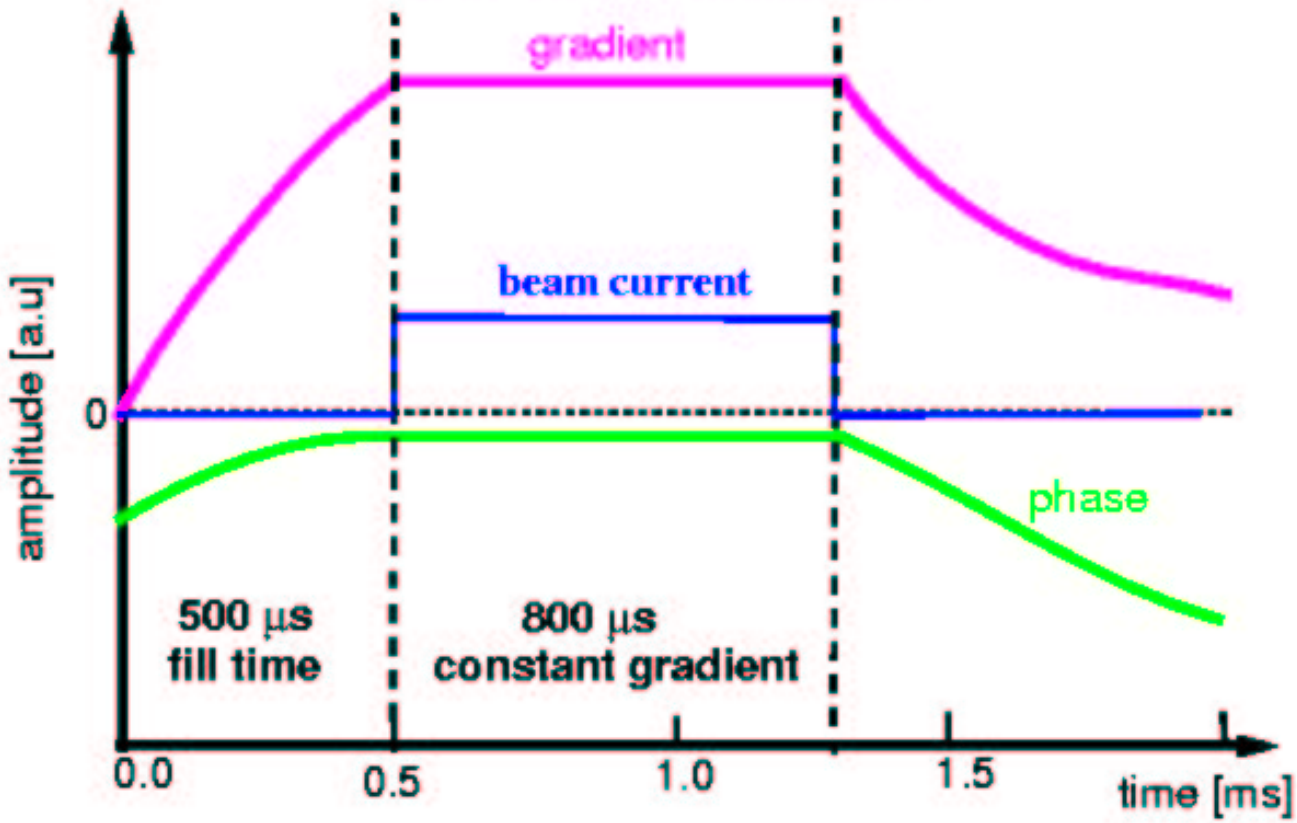
H.B. Peters DESY

H. Kaiser, W. Singer et al. DESY

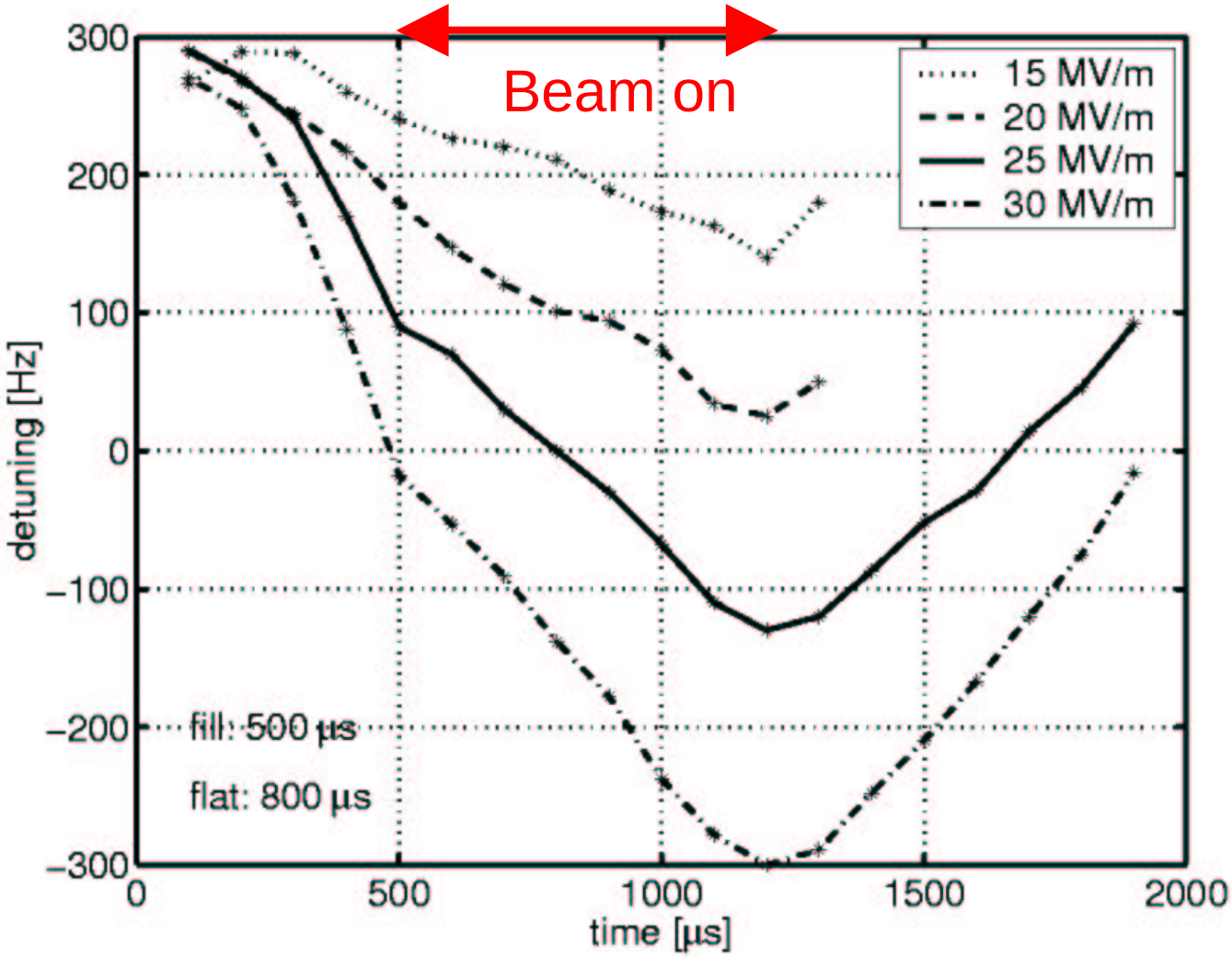
Pulsed acceleration at TESLA

Superconducting cavities at high gradients ⇒ **Pulsed operation to reduce average cryogenic losses**

Pulsed operation: 500 μs fill time + 800 μs constant gradient
10 Hz repetition rate



Frequency detuning during RF pulse



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

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

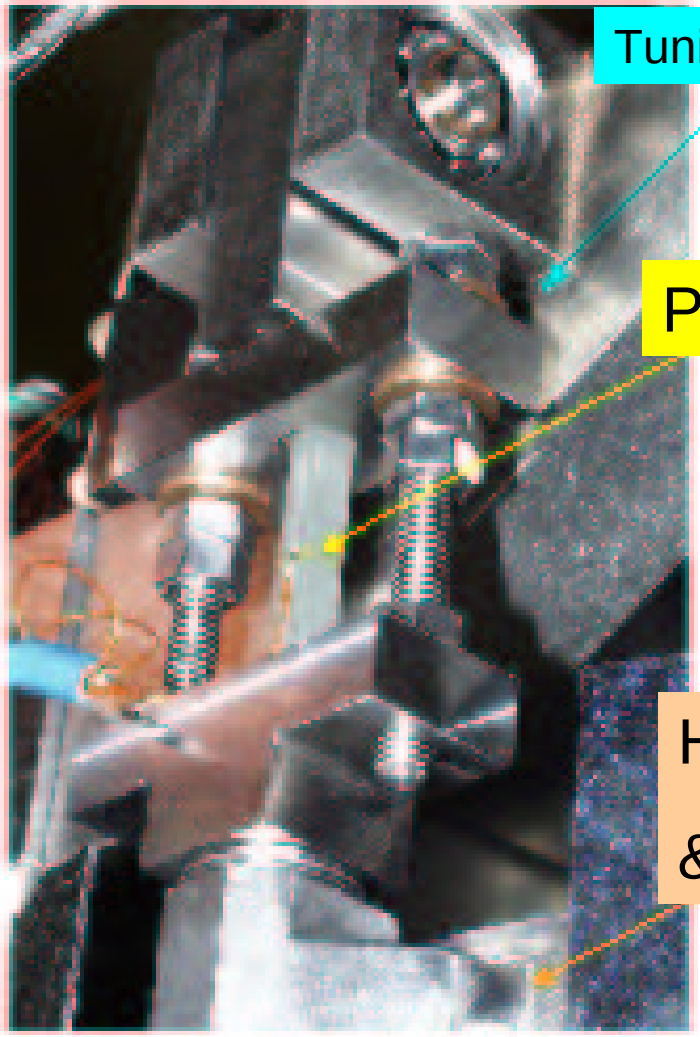
$K \approx 1$ Hz / (MV/m)^2

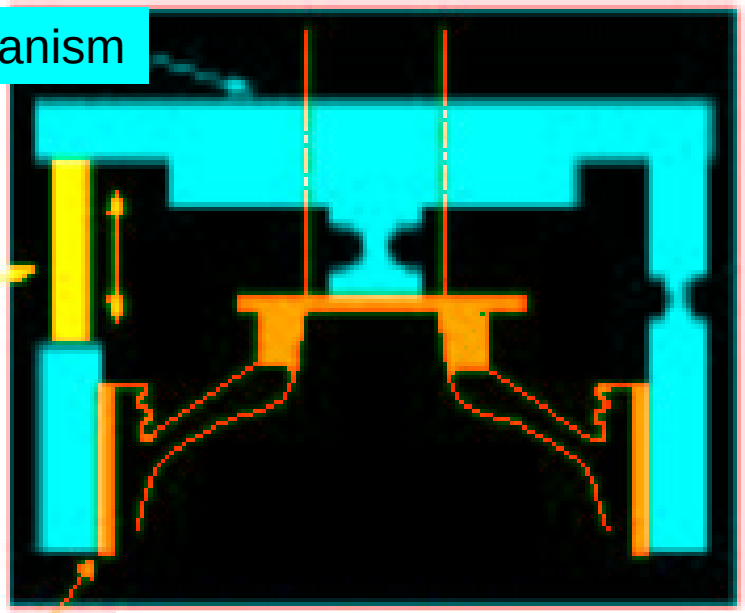
Remember:

Cavity bandwidth with main coupler is ≈ 300 Hz

Piezoelectric tuner

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





Piezo-Actuator:

l=39mm

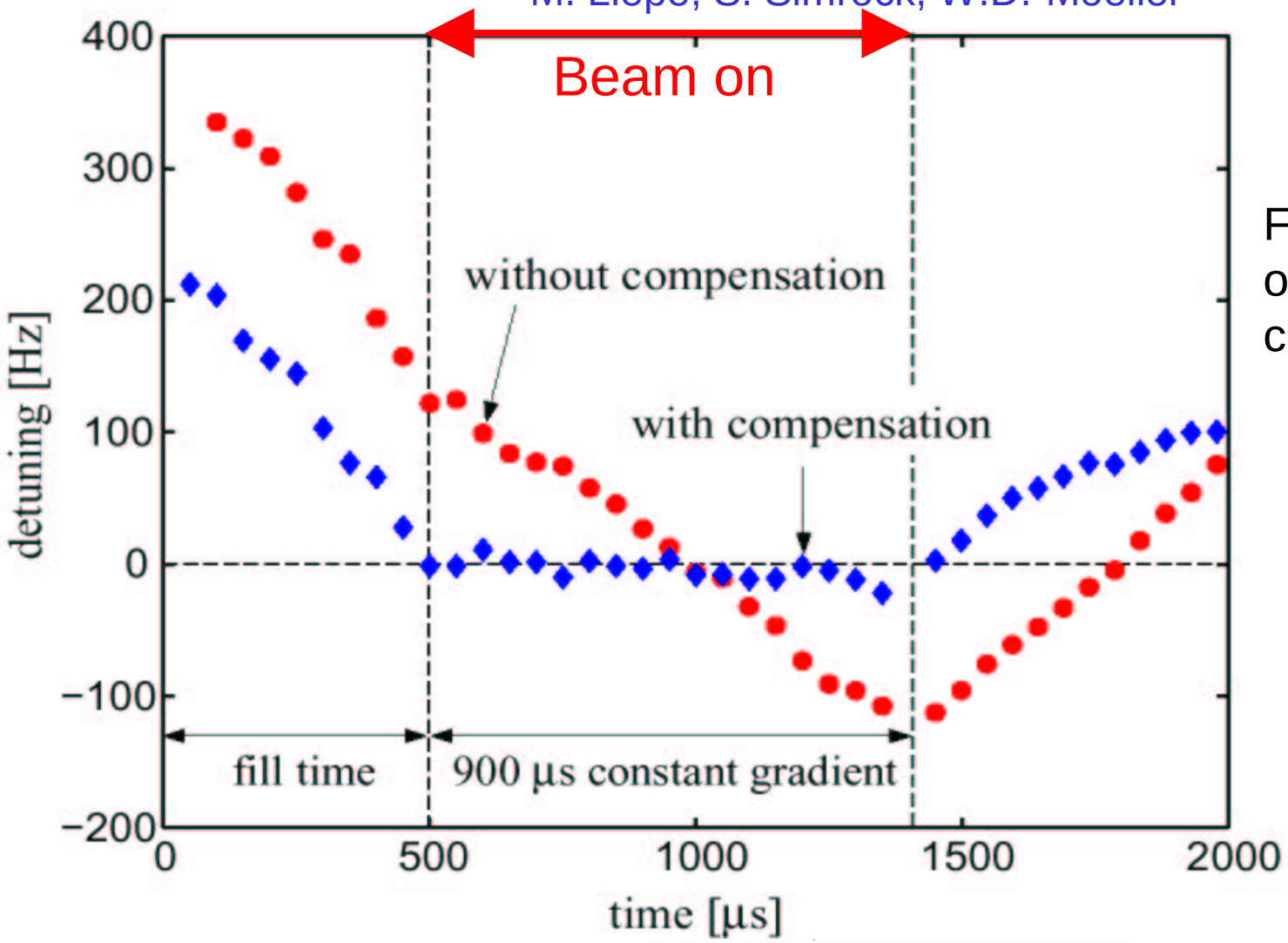
U_{max}=150V

Δ l=3µm at 2K

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

Frequency stabilisation during RF pulse using a piezoelectric tuner

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



Frequency detuning of 200 - 250 Hz compensated!

Conclusion

- Cavity technology for TESLA-500 well established
  - Third production of TTF cavities reaches specified gradient of 23,5 MV/m with a comfortable margin.
- Cavity R&D for TESLA-800 is well advanced
  - Several electropolished one-cell cavities reproducibly allow very high surface fields correspondig to accelerating gradients $E_{acc} \geq 40$ MV/m.
  - First promising results on nine-cell cavities. Test series in collaboration with KEK and Nomura Plating under way.
  - Hydroformed and spun one-cell cavities achieve E_{acc} around 40 MV/m. Multi-cell cavities are in preparation.
  - Superstructure concept increases fill factor by 6 % as compared to baseline and allows cost savings
  - Active frequency stabilisation allows pulsed operation at 35 MV/m