State of the Art SRF Cavity Performance

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DESY

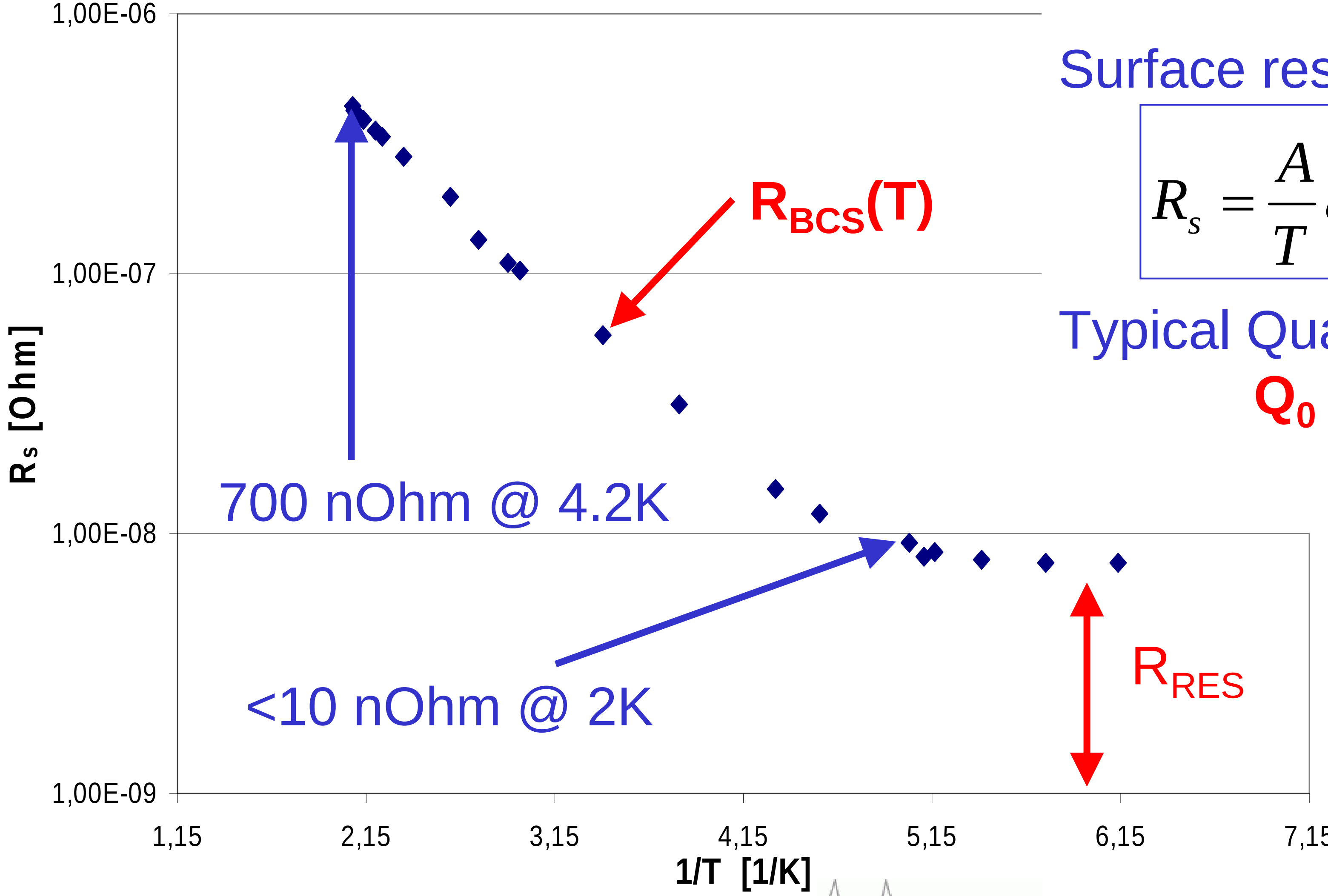
LINAC 2004

- SRF features
- State-of the-art beta=1 cavities
- Projects and new challenges

Thank You…

- … to the colleagues from the TESLA collaboration
- ... to the colleagues in the field of superconducting RF cavities for the material provided esp. P. Kneisel, J. Sekutowicz, G. Hoffstätter, M Kelly, H. Padamsee.

Surface Resistance $R_s(T)$



Geometry factor: $Q_o = \frac{G}{R_s}$

G = 270 Ohm

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

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
    - Theoretical limit for the TESLA shape is between 45-50 MV/m
  - energy recovery
  - attractive for a wide range of projects....

Accelerator Projects Featuring SRF Cavities

- Disclaimer: Focus of this talk is mostly on electron machines with beta =1
  - for beta <1 see J. Delayen TH301
- LINACs
  - TESLA, European XFEL, TTF, 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

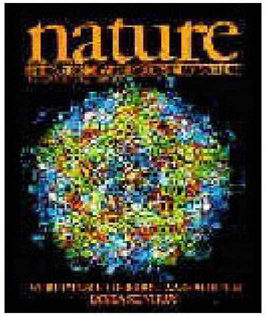
No guarantee for completeness...

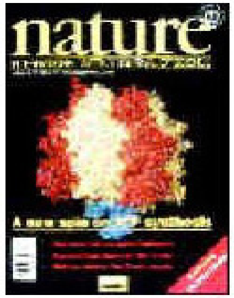
New Applications for SRF Cavities

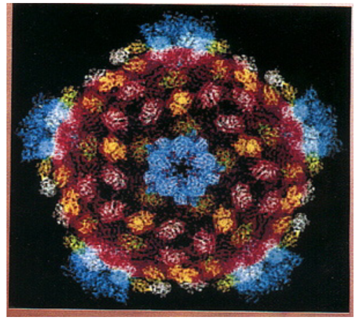
- high energy physics and synchrotron radiation physics (chemistry, biology...) have taken profit of this technology already since a long time
- technology is well advanced and available
  - the small surface resistance of the superconducting necessitates avoidance of NC contaminations larger than a 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
- new projects are aiming at
  - high gradient (e.g. TESLA)
    - further improvement of the surface preparation
  - increasing electron currents (ERLs)
    - Higher-Order-Mode (HOM) damping
  - high duty cycle (CW FELs)

Storage Ring Light Sources

H. Padamsee,
PAC2001







Taiwan Light Source

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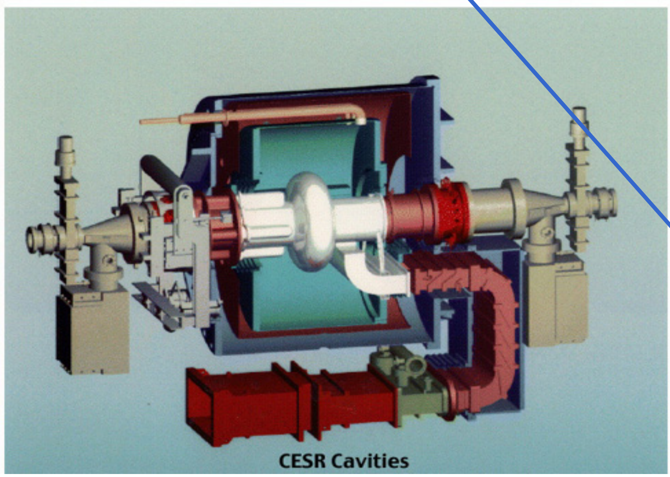
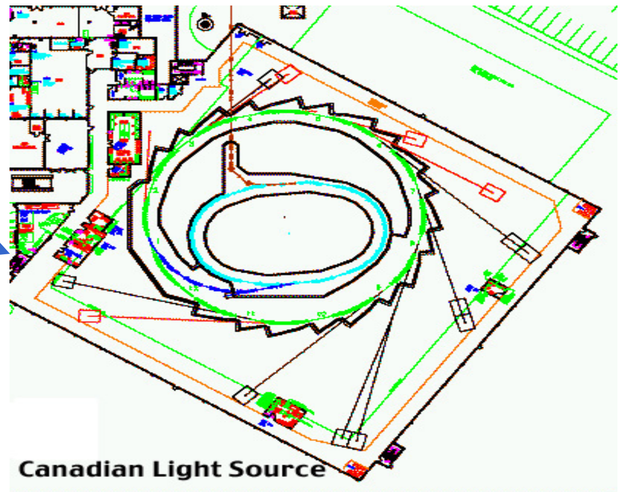
Diamond Site





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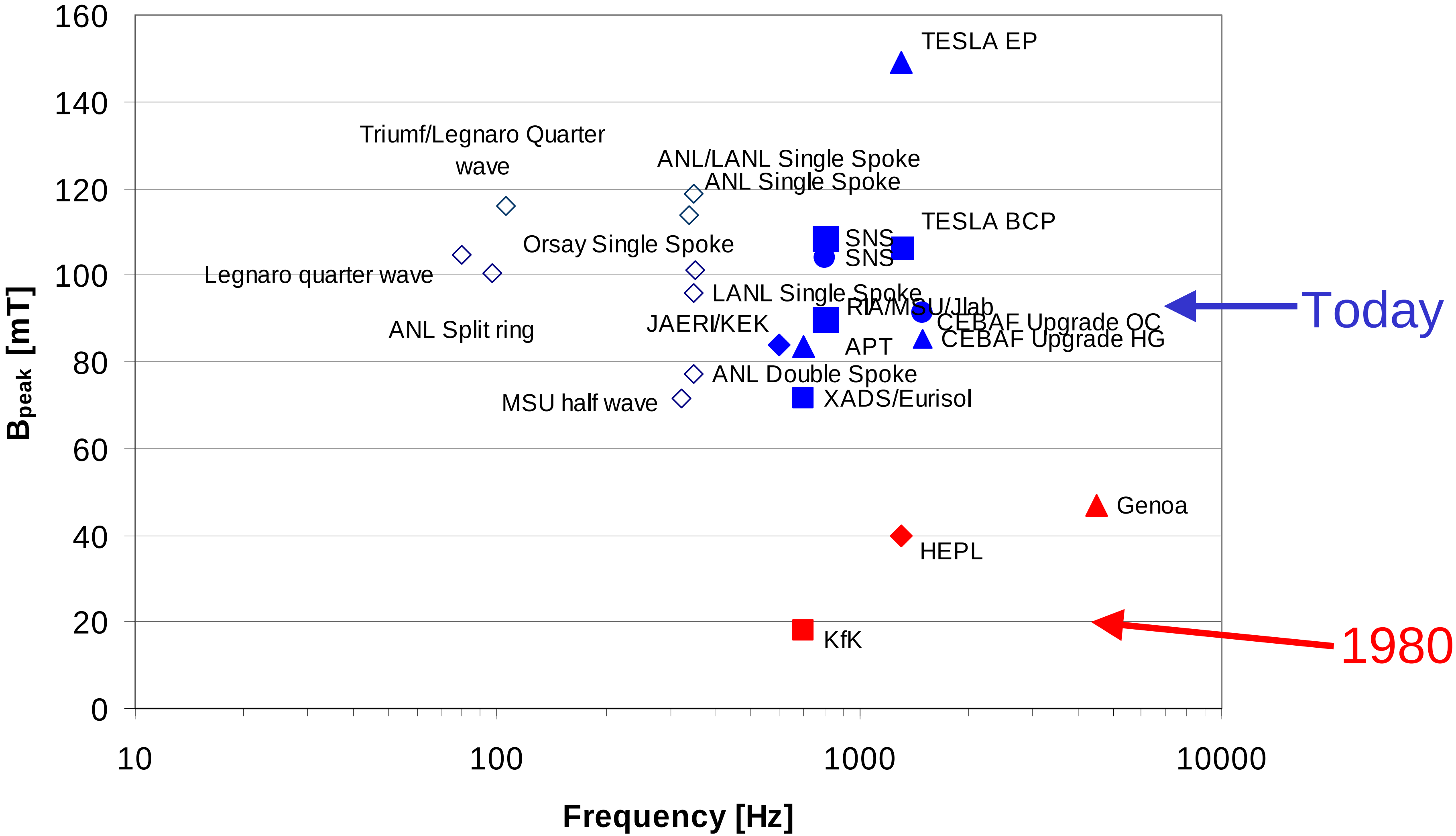
Light Source

CORNELL
UNIVERSITY

Example: Standard SC Technology

- Cornell 500 MHz system
  - developed by Cornell University
  - commercially available
  - used in:
    - Canadian light source
    - NSRRC (Taiwan light source)
    - DIAMOND (UK)
  - see EPAC 04: MOPLT041, MOPLT040
- Overview on magnetic peak field over a wide frequency range

Magnetic Peak Surface Fields Today and 1980



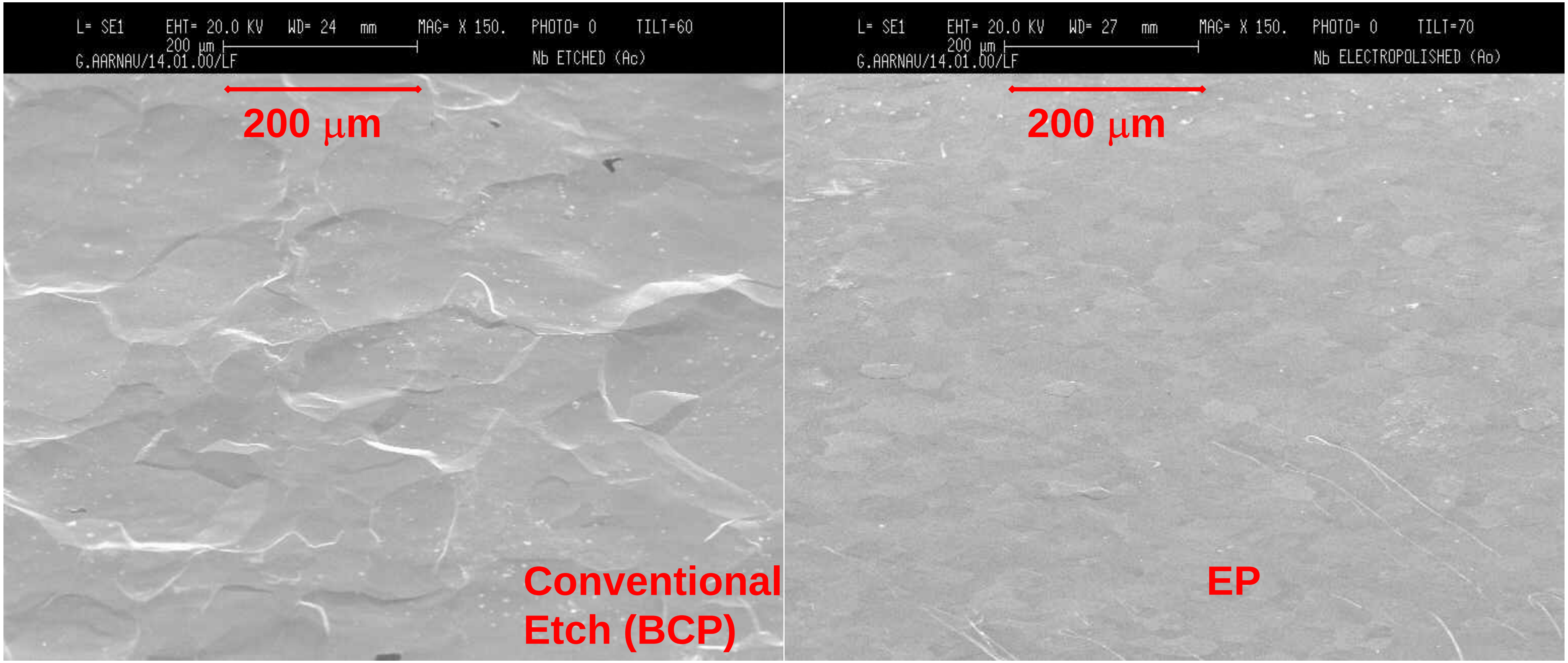
Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL

Surface Preparation: Electropolishing

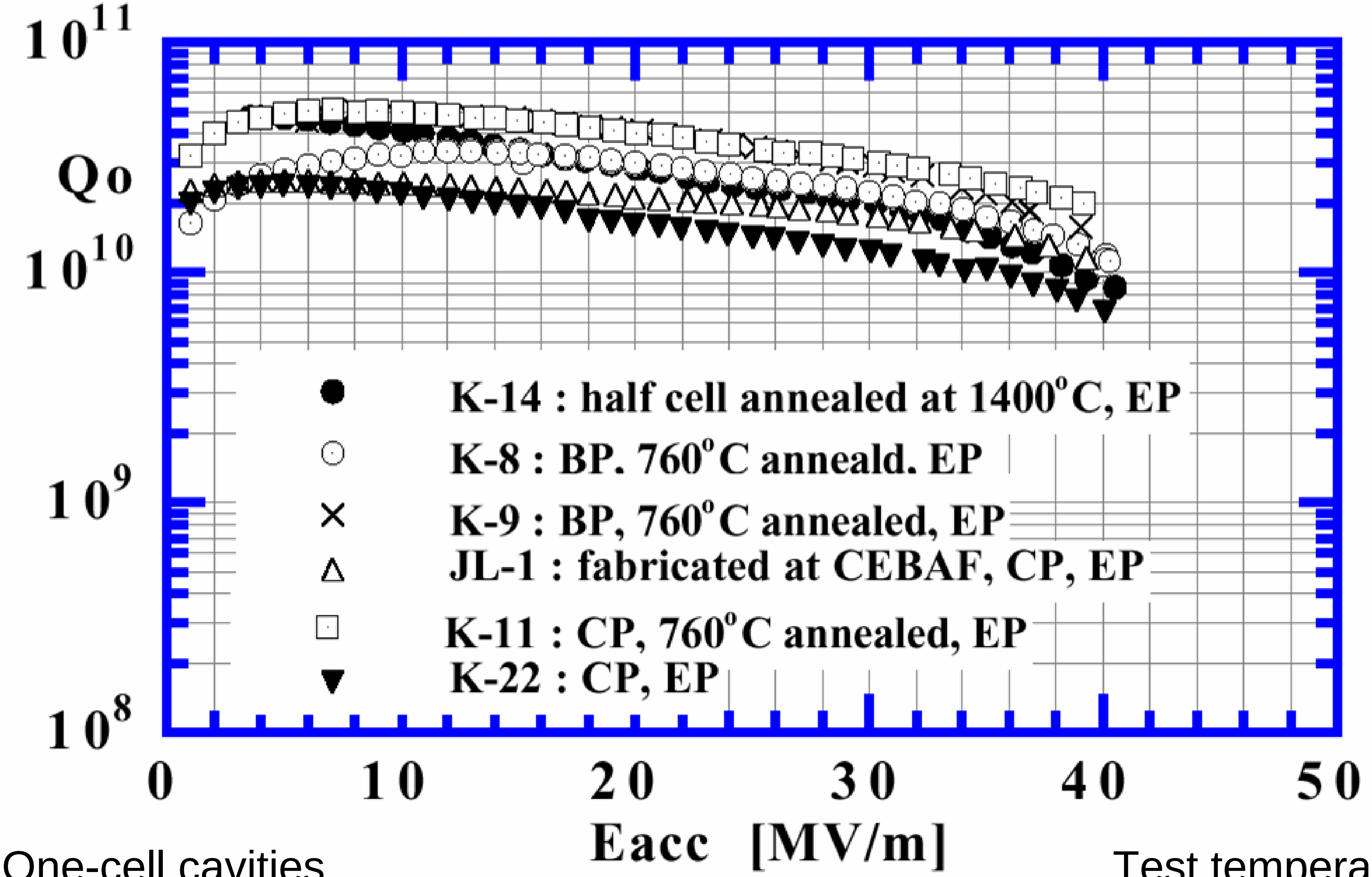
- Electropolishing (EP) of niobium surfaces is a key technology to achieve the highest electrical and magnetic surface fields
- KEK/ Nomura Plating pioneered application of EP to elliptical niobium cavities since TRISTAN using a Siemens' recipe
- EP has also been successfully applied to
  - Low-Beta 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

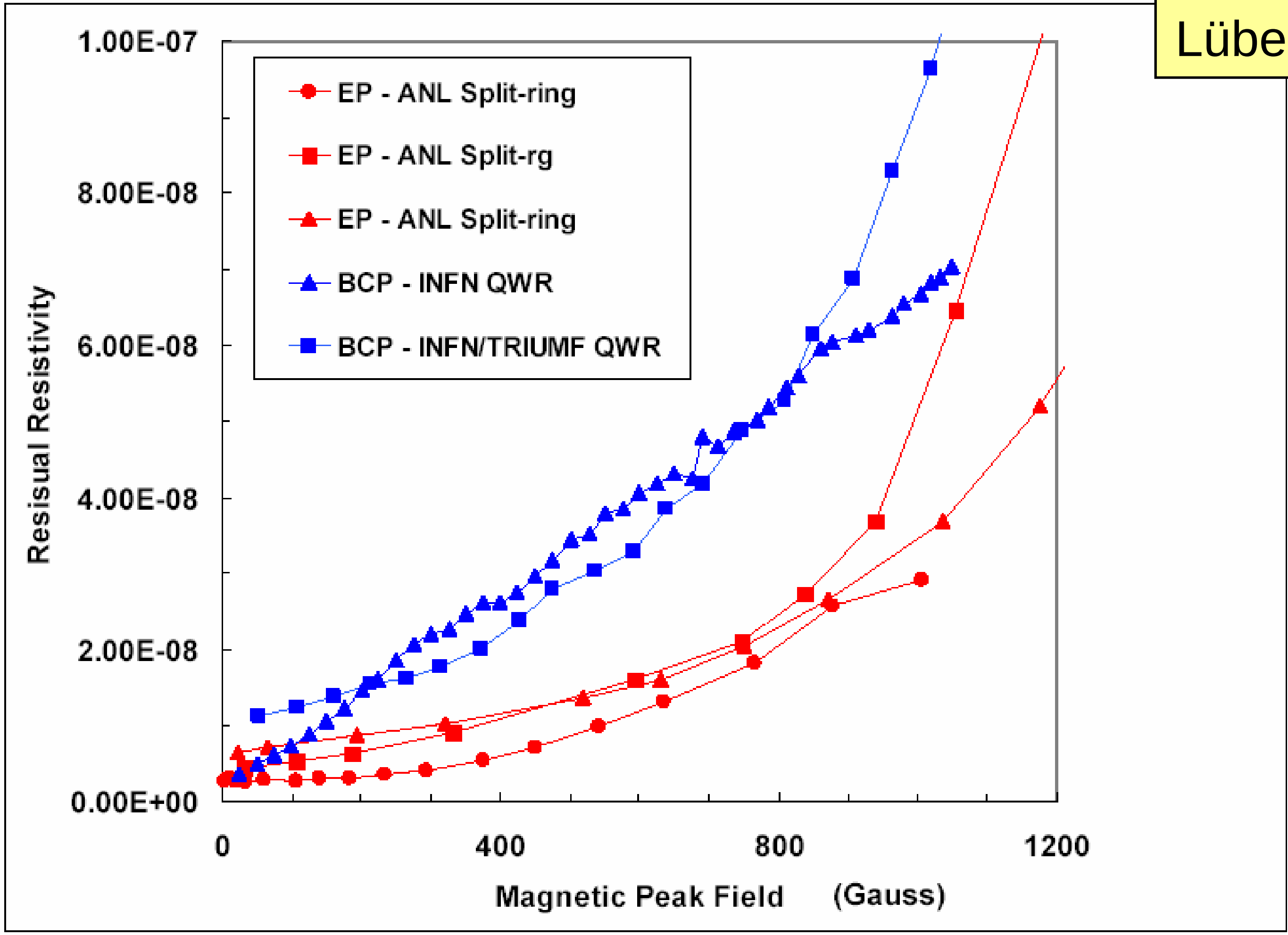


One-cell cavities

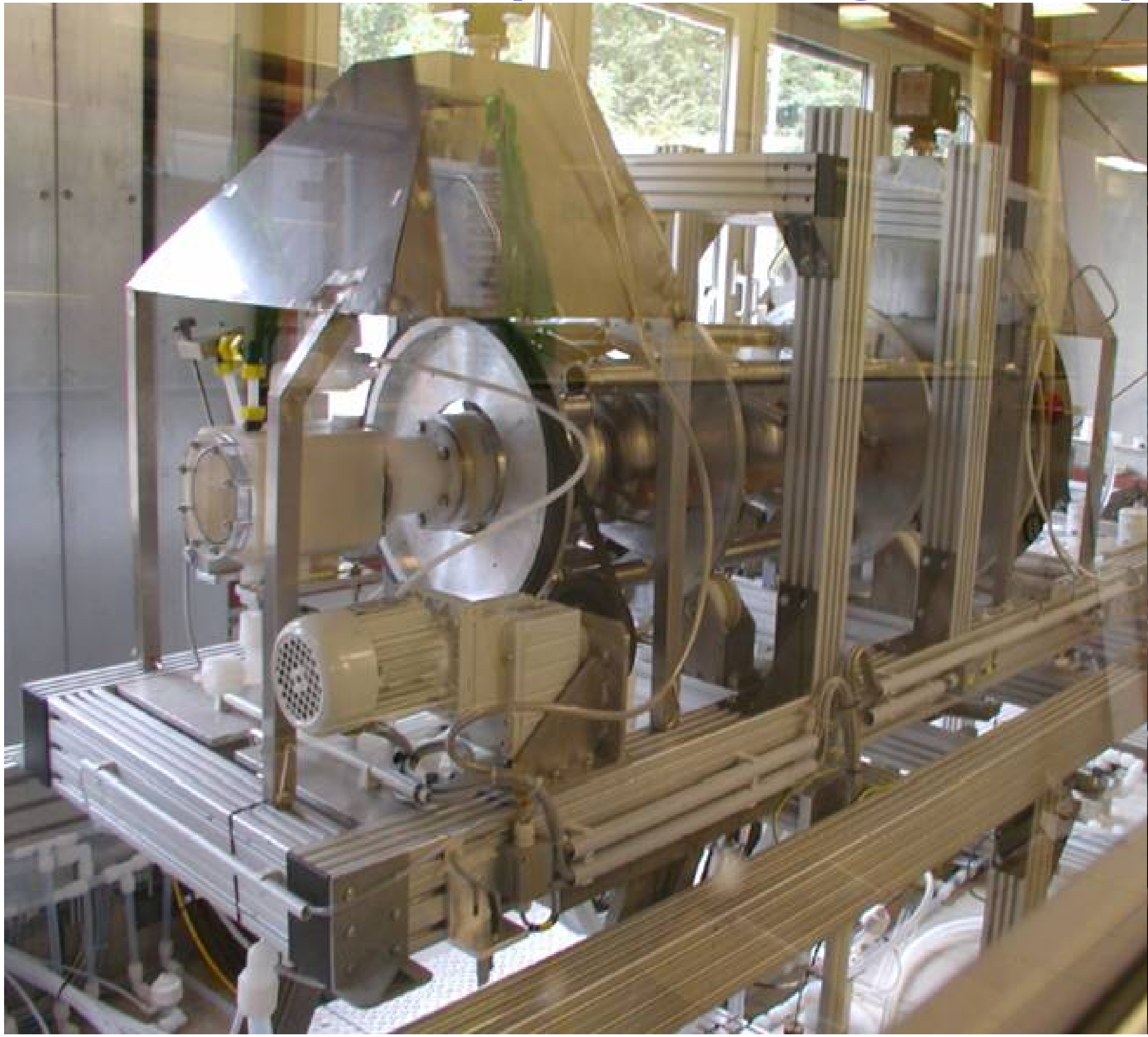
Test temperature: 1.6 K

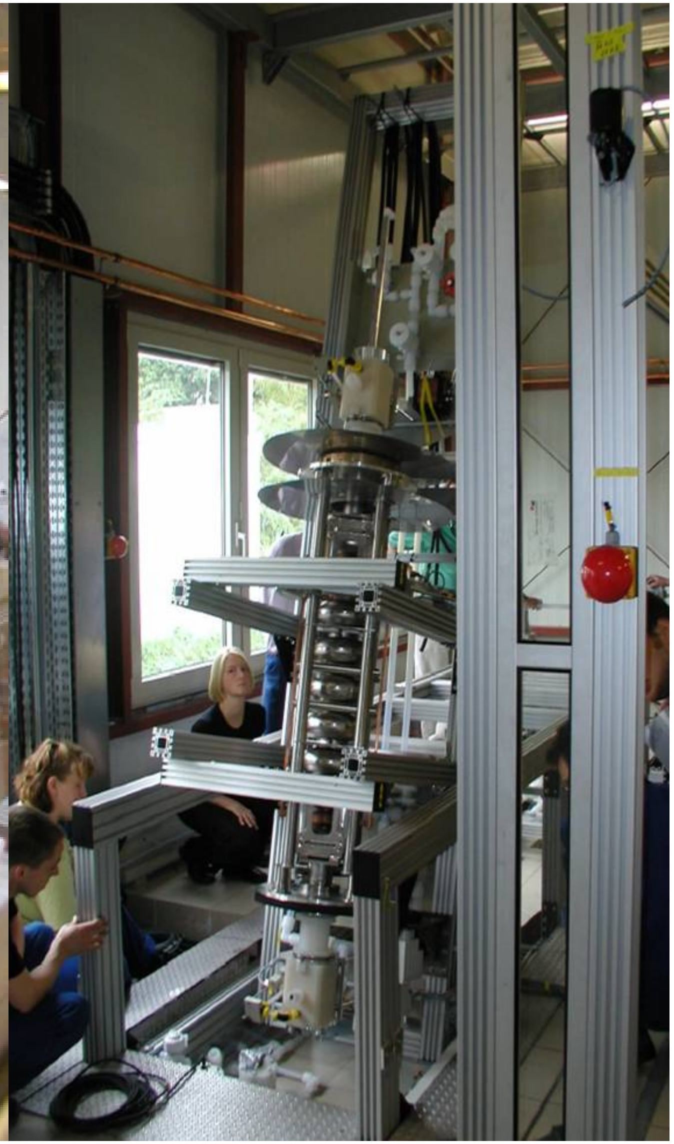
4.2 K Residual resistivity – 80-100 MHz Quarter-wave structures

Ken Shepherd,
SRF 2003,
Lübeck

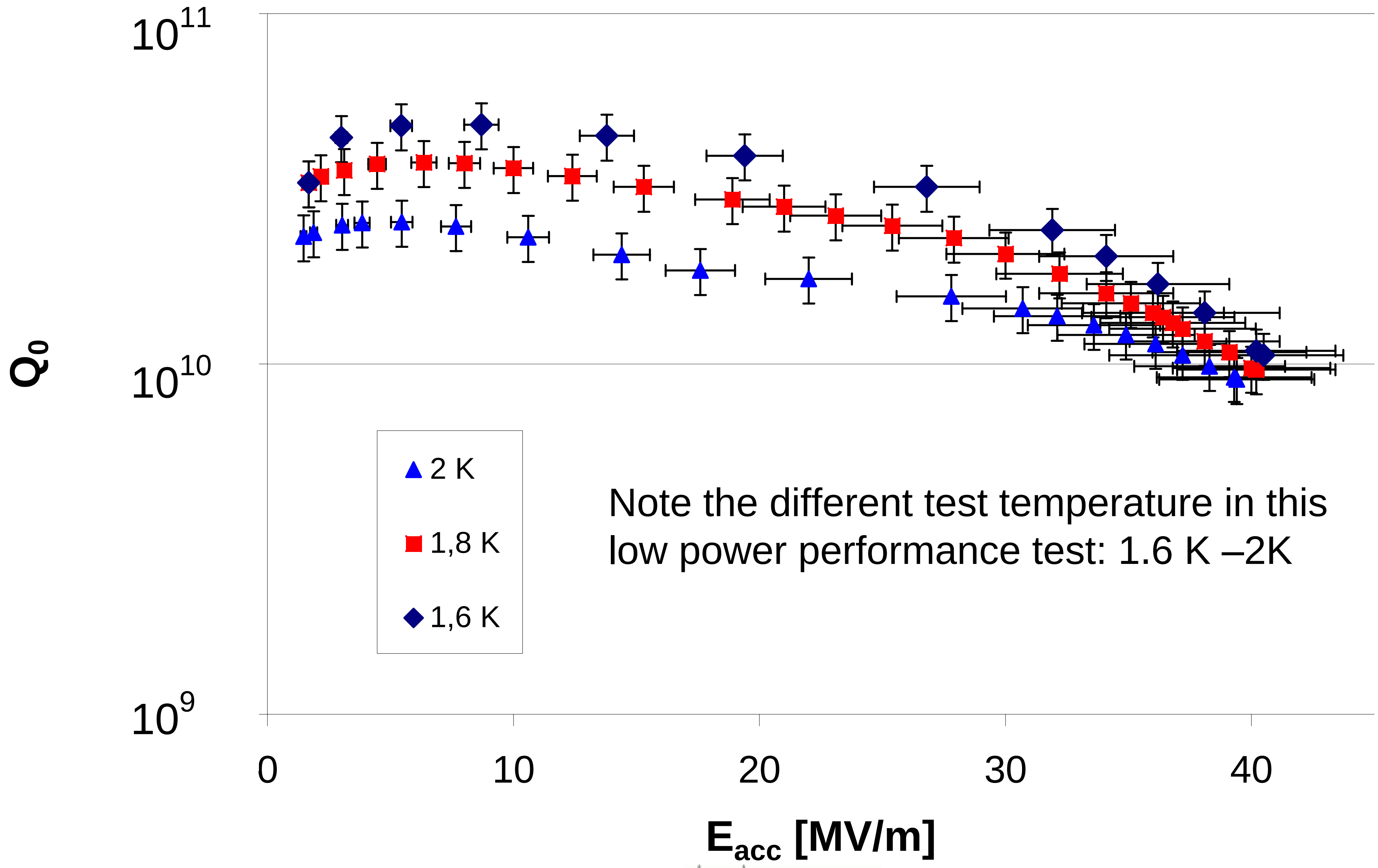


Electropolishing Setup at DESY



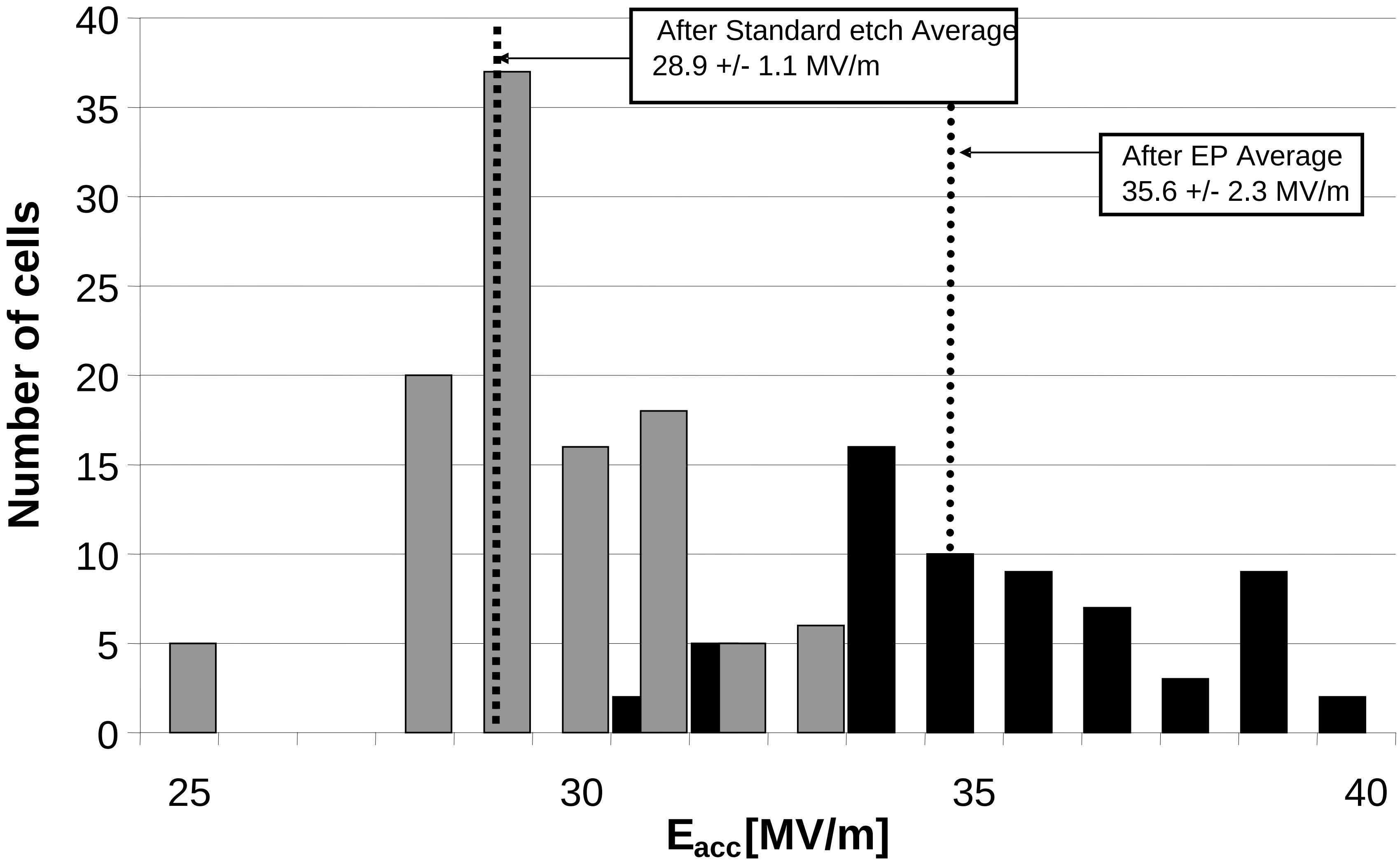


AC70: EP at DESY



Comparison of EP to Standard Etch

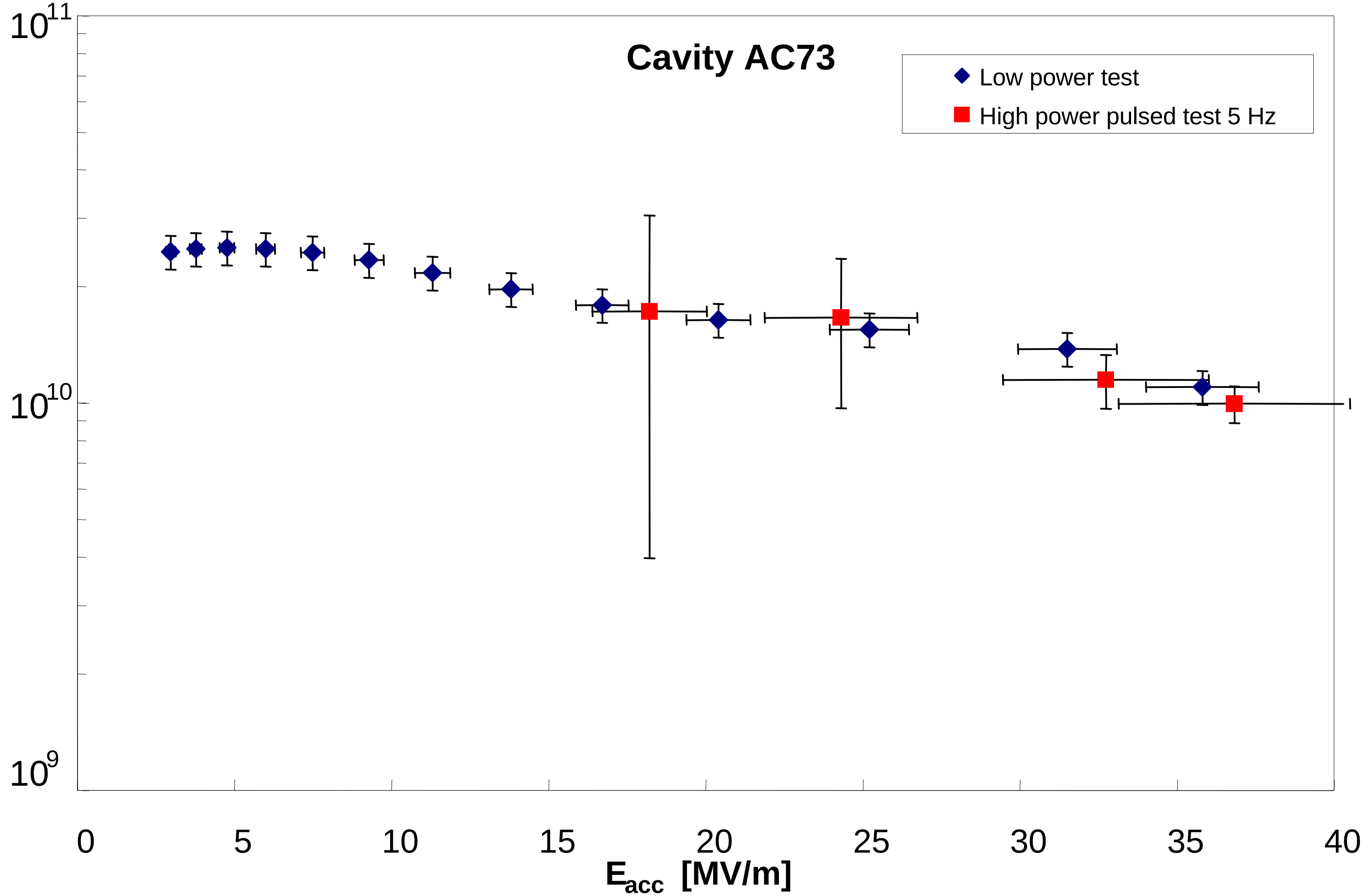
(Results from the KEK-DESY Collaboration)



- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells)

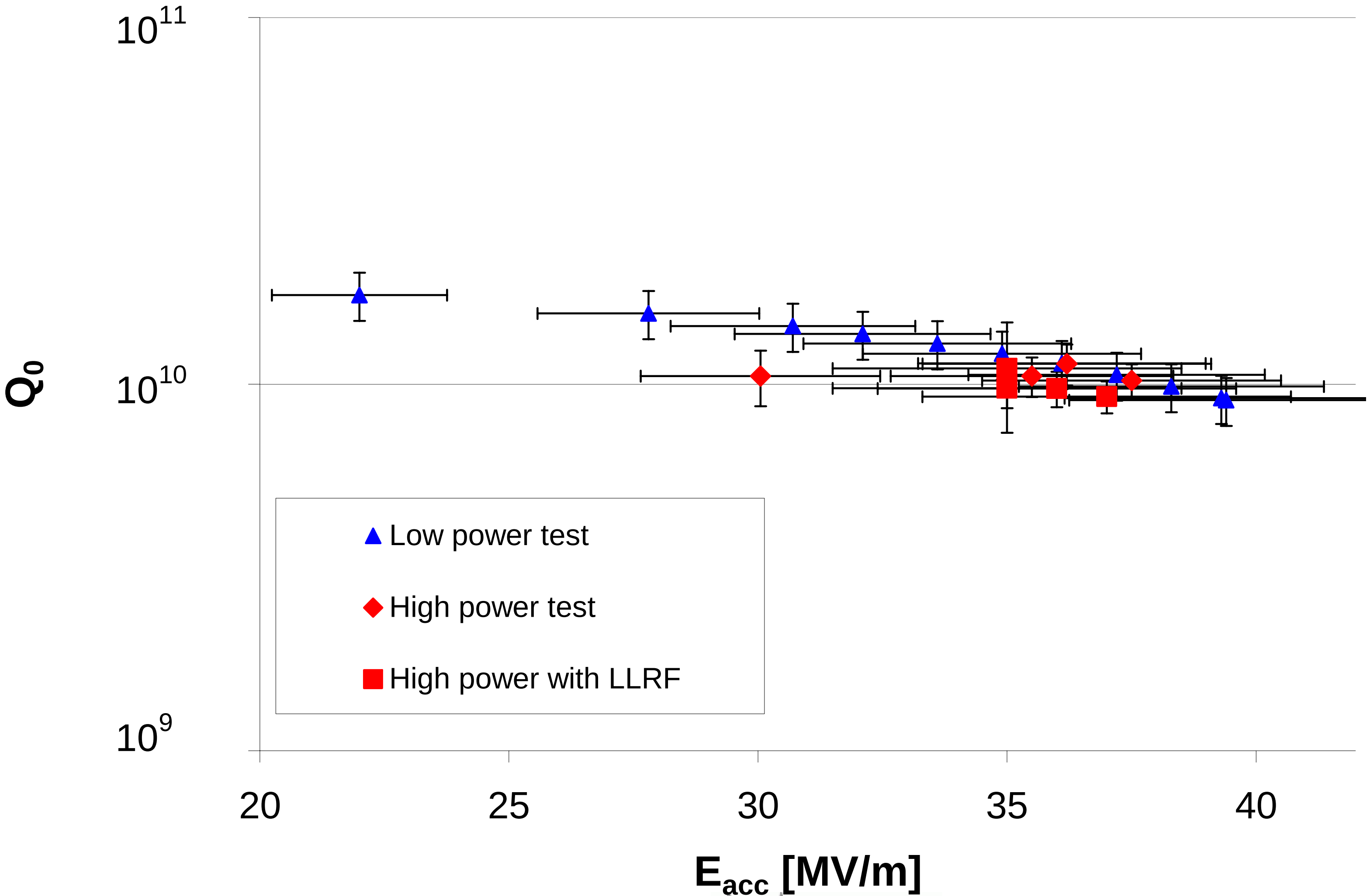
High Power Test Results

- High power tests give Cavity-Coupler-wise the full information about the system's behaviour e.g. it corresponds to 1/8th of an accelerator module
- Longterm test:
  - No breakdown in 1100 hours at 35 MV/m (neither the Cavity nor the Coupler)
  - No degradation was observed when breakdowns were forced (thermal quenches and coupler breakdowns)

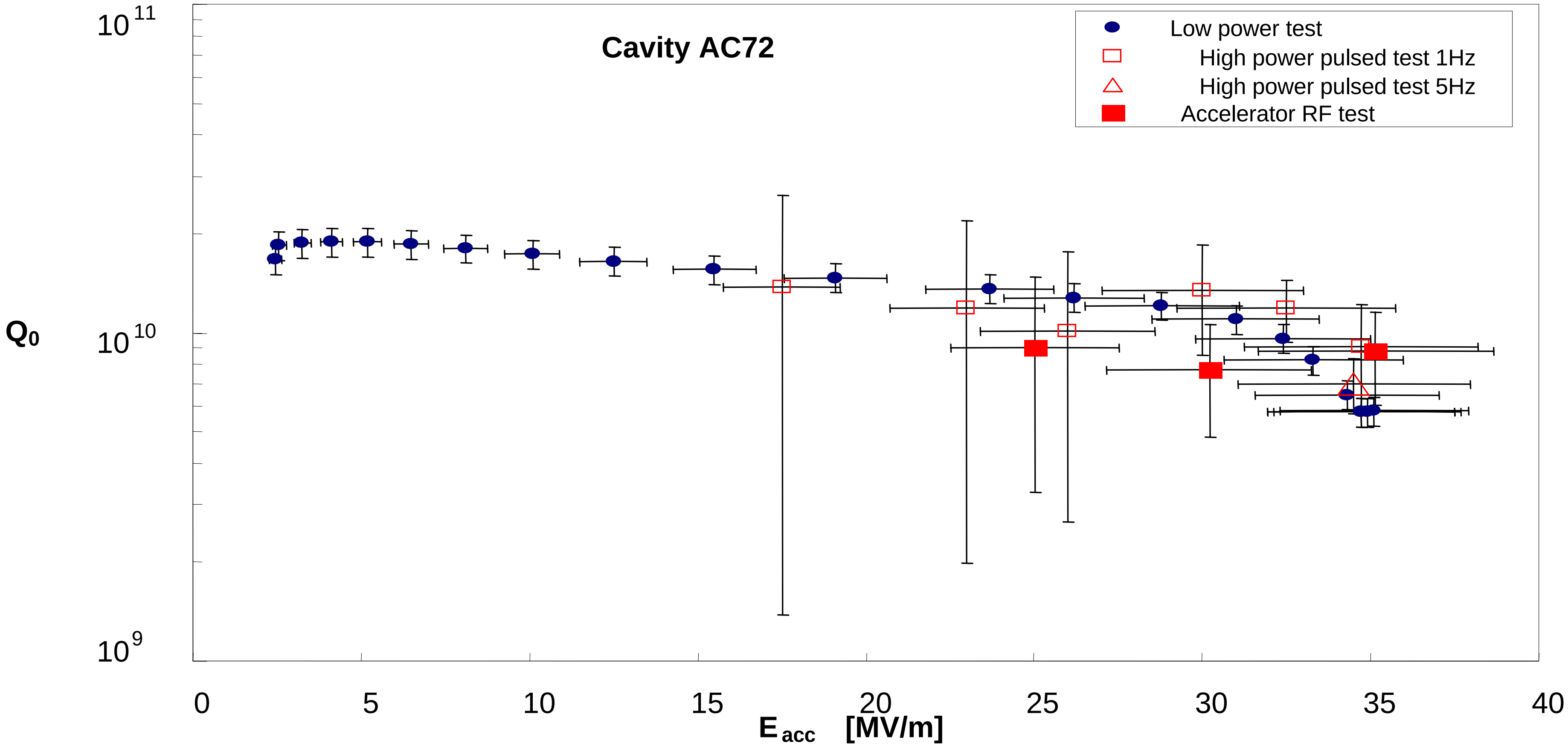


High Power Test Results

- One cavity without post-purification achieved a gradient of more than 35 MV/m with a Q_0 of 10^{10}. This a about a factor of 2 above the TESLA specification.



Cavity Test Inside a Module (ctd.)

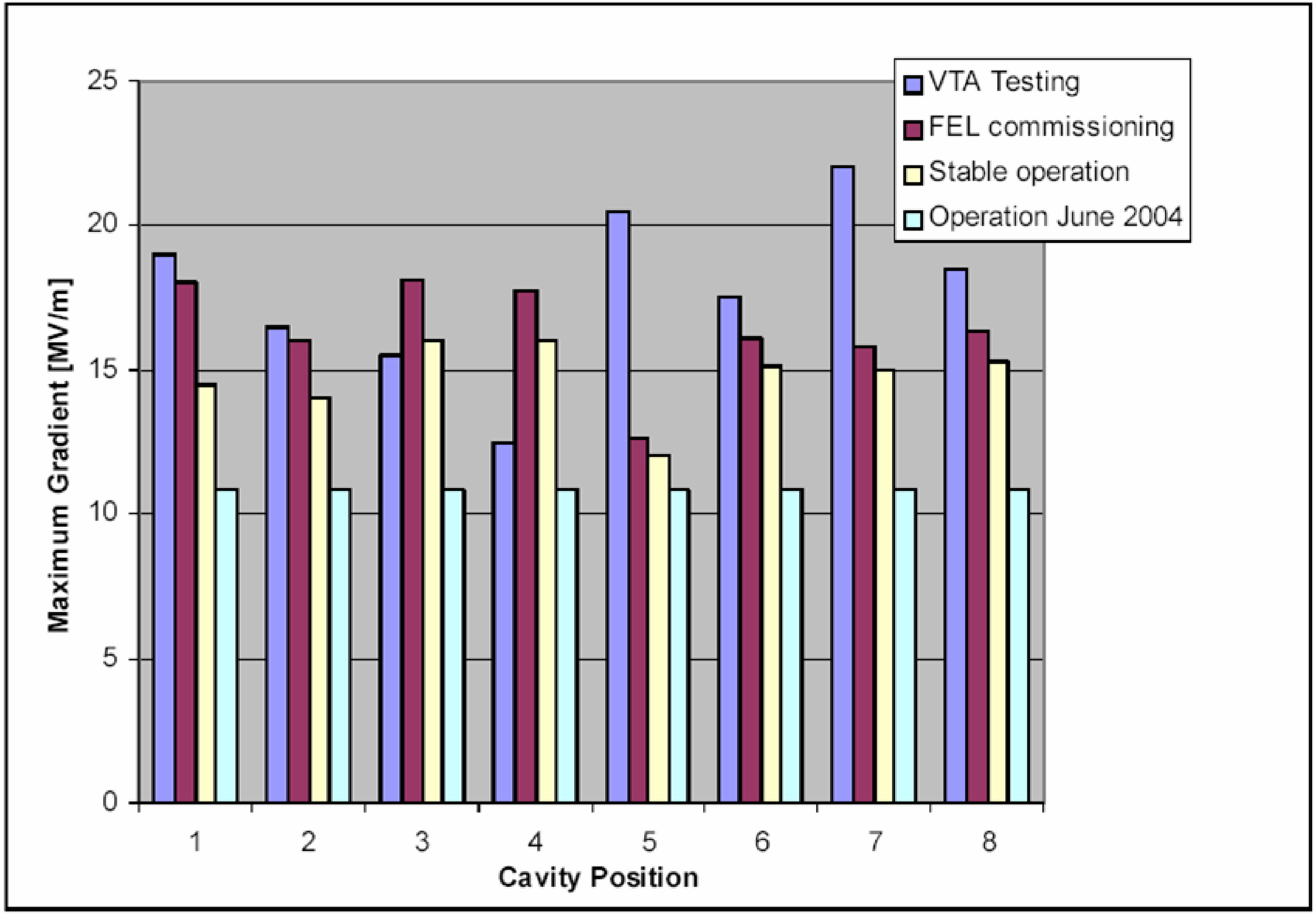


- One of the electropolished cavities (AC72) was installed into an accelerating module for the VUV-FEL
- Very low cryogenic losses as in high power tests
- Standard X-ray radiation measurement indicates no radiation up to 35 MV/m

From Pulsed to Continuous-Wave (CW)

- TESLA is a pulsed machine
  - large heat losses due to high gradient
  - gradient is the major research issue
- for CW operation
  - high quality factor at intermediate gradients is crucial
  - ultimate dream is $Q_0 >> 10^{10}$ at 15 MV/m
- often this means the same thing:
  - avoid field emission
  - good niobium quality i.e. eddy-current scanned material
  - detailed welding specification

CW Modules



A.-M. Valente et al., EPAC'04

- stable CW operation at 15 MV/m achieved at JLAB-FEL
  - etched cavities
  - no postpurification using titanium furnace treatment
- most of the operation at lower gradient by user request so far, but not limited by the cavities

Recent Developments and Challenges

- Surface preparation improvement
- CW modules
- Superstructures
- New elliptical cavity shapes
- CW ERL

Superstructures

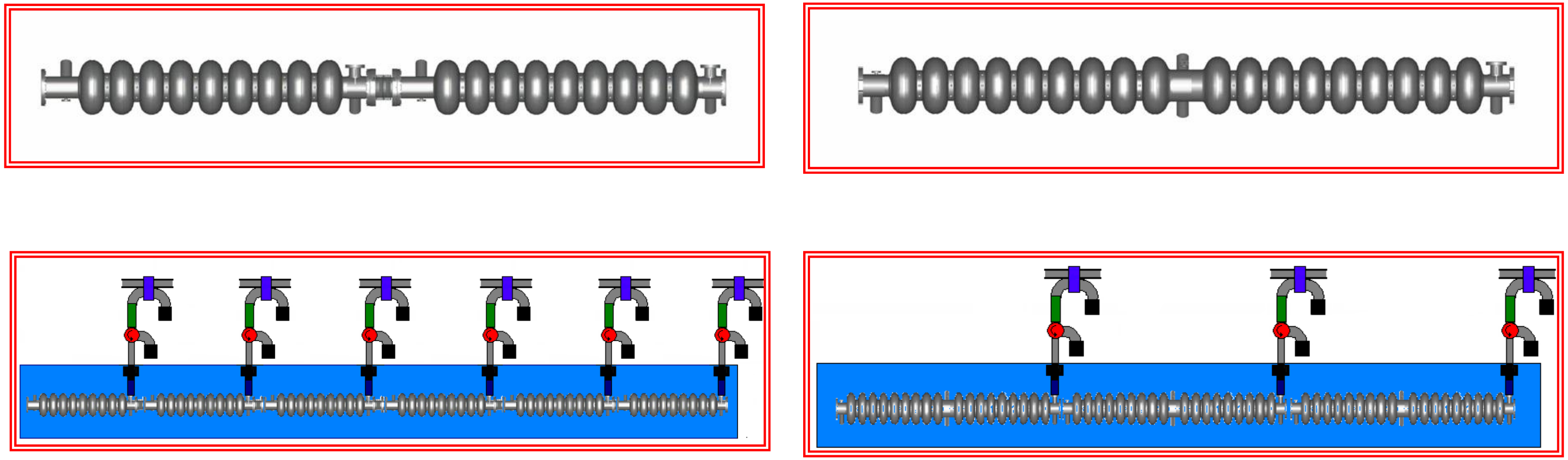
J. Sekutowicz et al.,
Phys.Rev. ST-AB,
Vol. 7, 012002 (2004)

J. Sekutowicz,
SRF2003, Lübeck

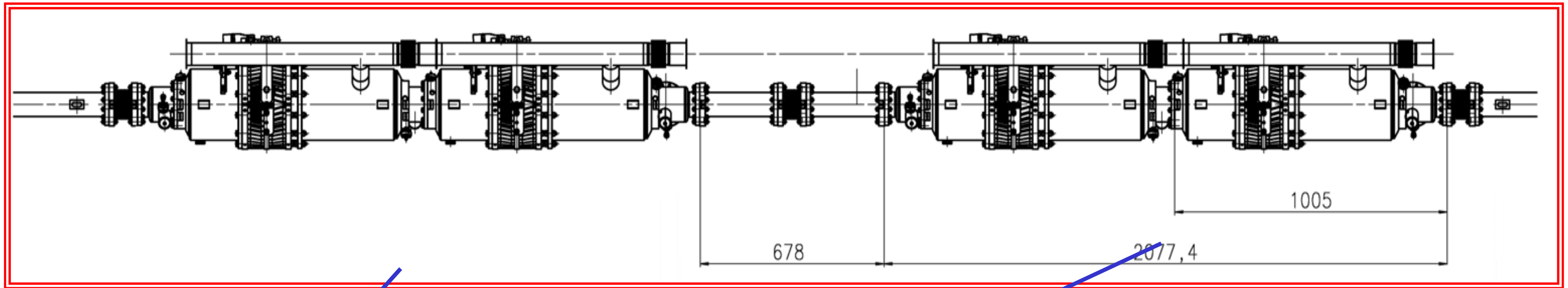
- more economical (e.g. less high power couplers)
- higher fill factor of the accelerator
- improved HOM damping
- demonstrated that
  – energy refilling does work even with weakly coupled sub-units

Superstructure Layout

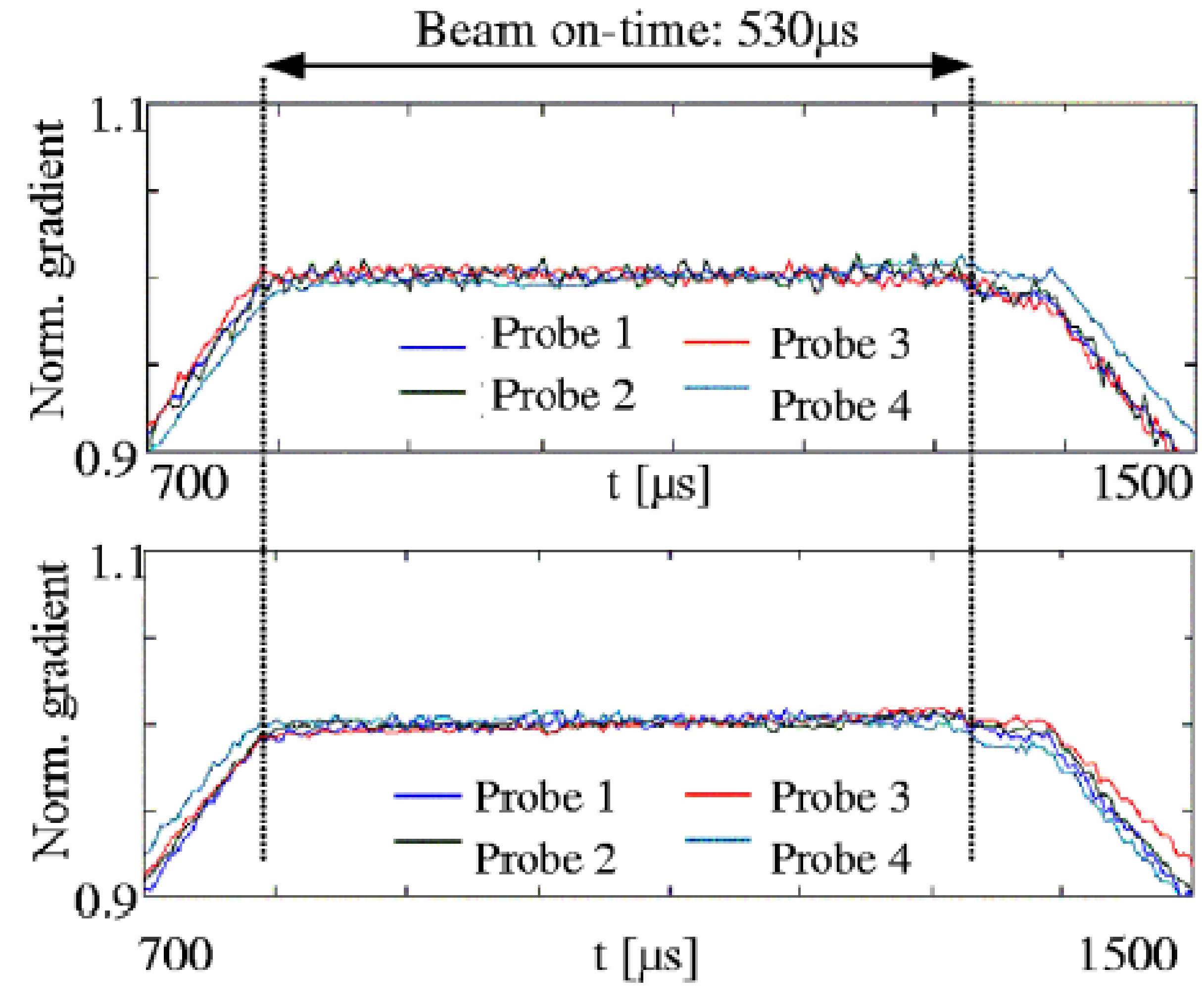
- Cell-to-cell coupling: ~2%
- Structure-to-structure: ~0.04%
- Compare standard nine-cell with superstructure:



2x7-cell Superstructure Prototypes at TTF



Energy Transfer

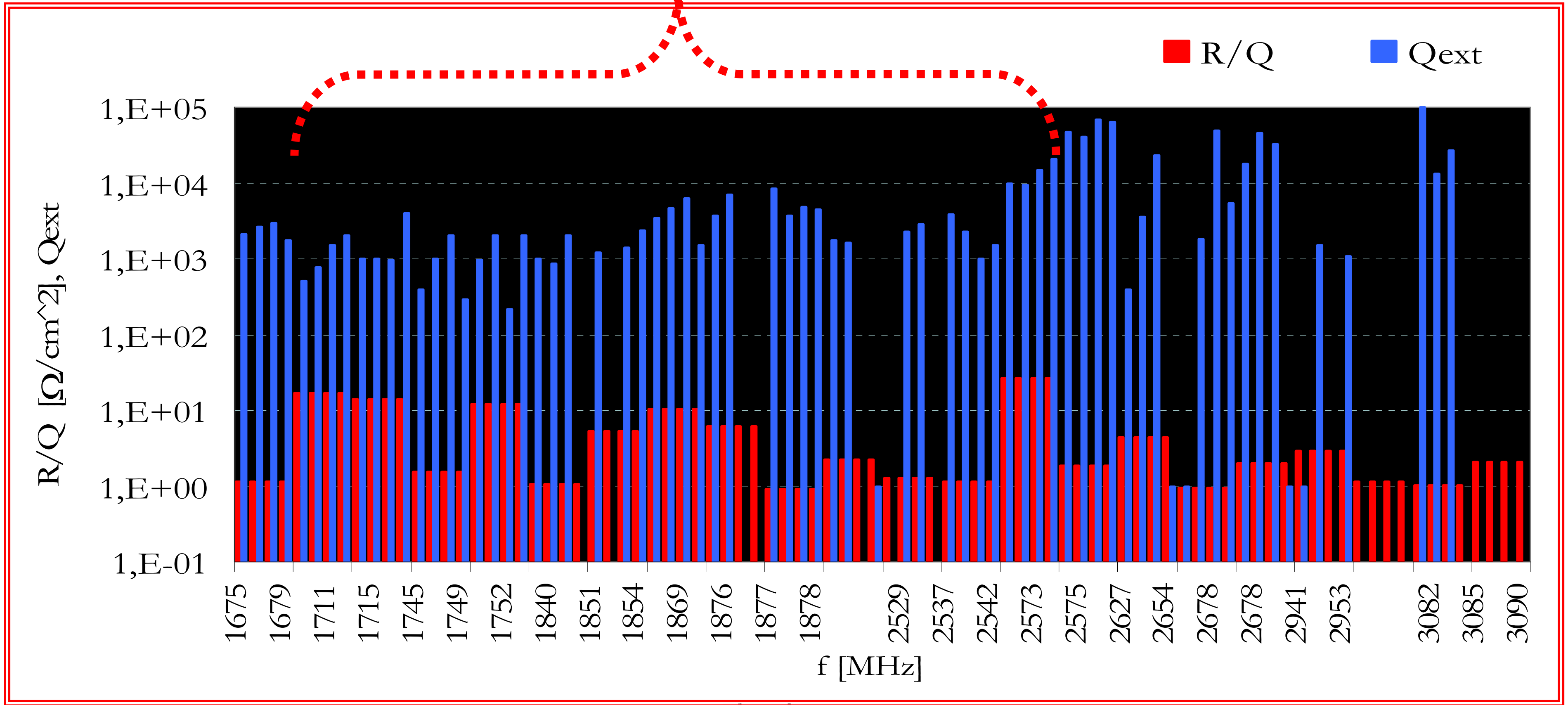


- **Measured:**
  - **ΔE/E (rms) ≤ $2{\cdot}10^{-4}$**
- **TESLA-Specification:**
  - **ΔE/E (rms) ≤ 5 ·10-4**

HOMs

- damping of dipoles with (R/Q) ≥ 1 Ω/cm2 which are relevant for the TESLA beam was by factor 5÷100 better then spec.

Beam Dynamics limit $Q_{ext} \leq 10^5$



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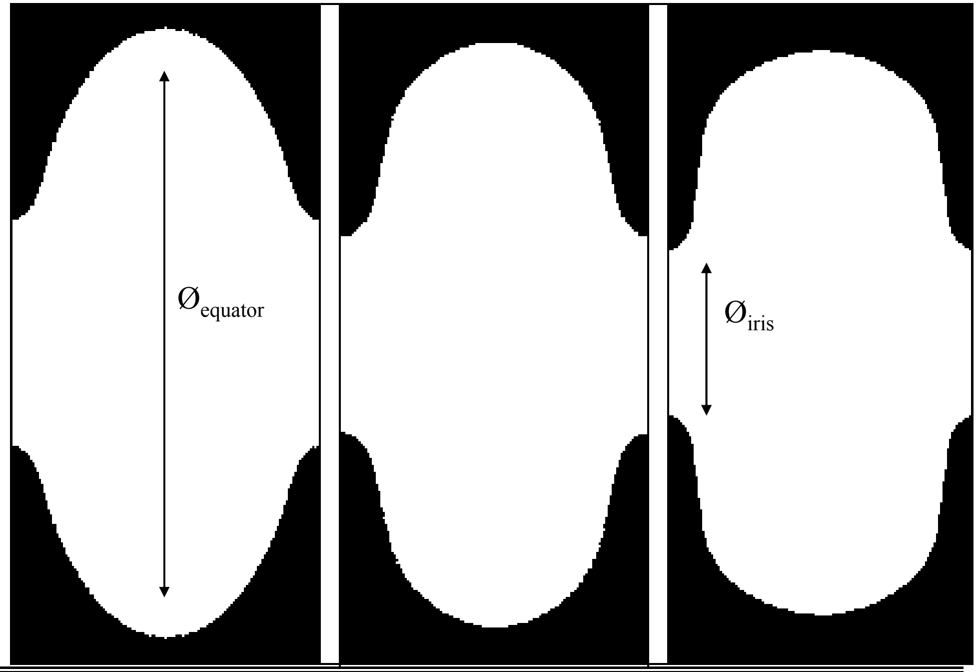
New Elliptical Cavity Shapes

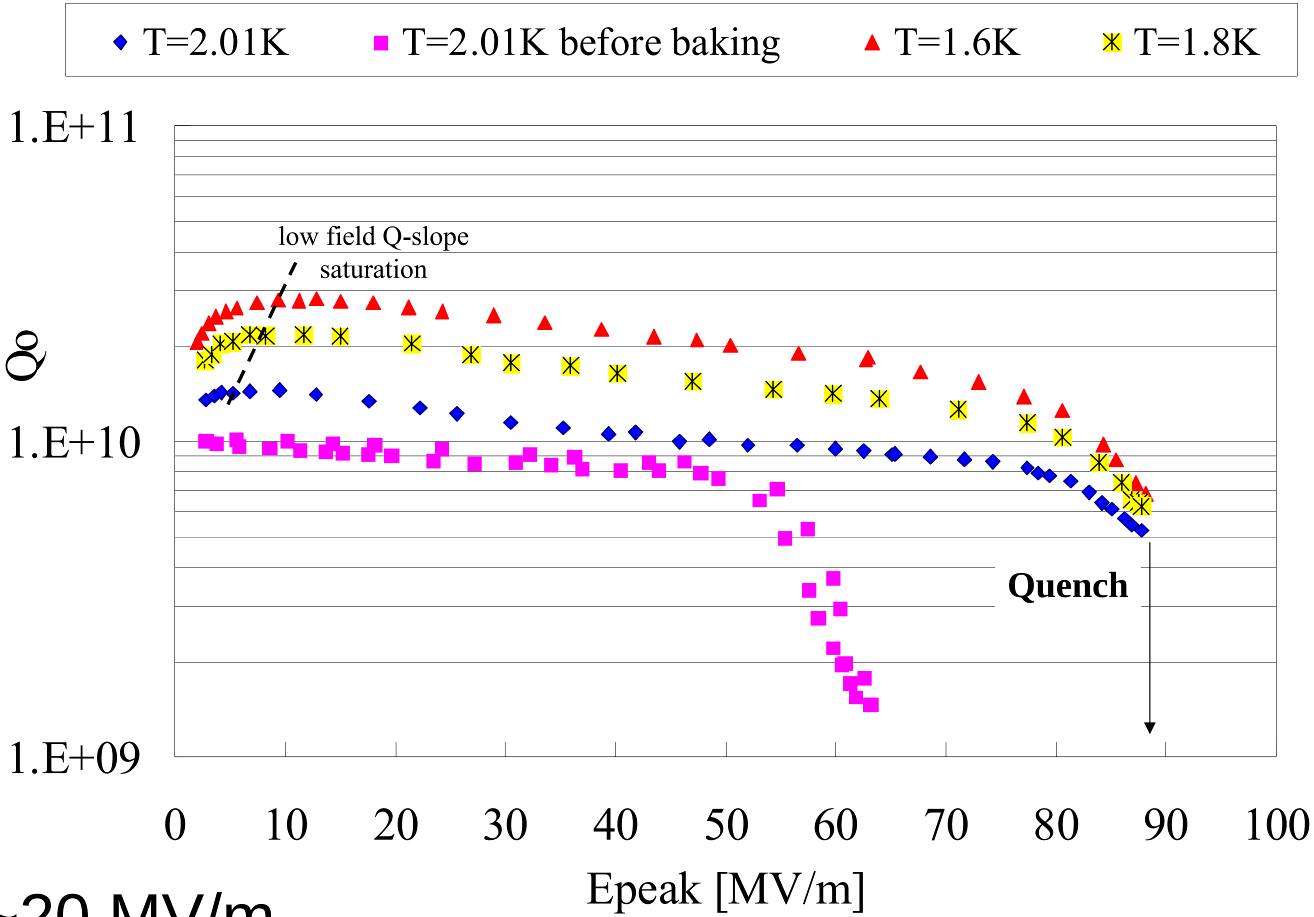
- Example: CEBAF upgrade
  - high-gradient operation (HG):
    - lower E_{surf}
    - reduce field emission
  - low-loss (LL)
    - maximize shunt impedance and geometric factor
    - with a given cryo power maximise achievable gradient



Parameter		OC	HG	LL
$\varnothing_{equator}$	[mm]	187.0	180.5	174.0
$\varnothing_{iris}$	[mm]	70.0	61.4	53.0
k_{cc} *	[%]	3.29	1.72	1.49
E_{peak}/E_{acc}	[-]	2.56	1.89	2.17
B_{peak}/E_{acc}	[mT/(MV/m)]	4.56	4.26	3.74
R/Q	[Ω]	96.5	111.9	128.8
G	[Ω]	273.8	265.5	280.3
R/Q·G	[Ω·Ω]	26422	29709	36103

J. Sekutowicz, P. Kneisel, et.al.
This conference.

New Elliptical Cavity Shapes (ctd.)



- multipacting-free
- multi-cells show E_{acc}~20 MV/m
- one-cell of the low loss variety gives an E_{surf} of 87 MV/m
- HOMs
  - damping of niobium prototypes confirms calculations and copper model measurements,
  - improved feedthroughs with better thermal design under fabrication

Recent Developments and Challenges

- Surface preparation improvement
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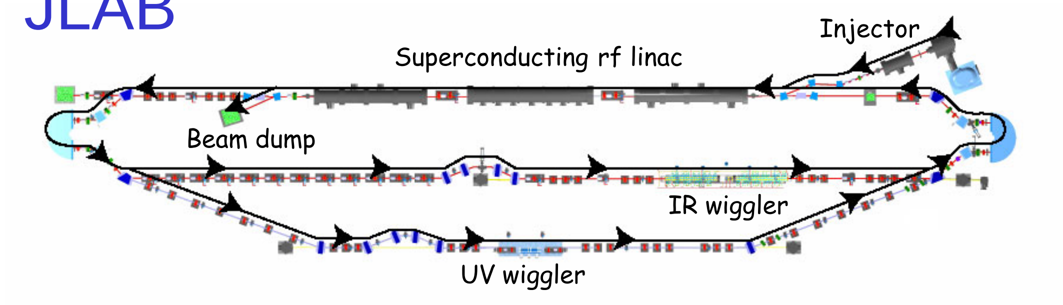
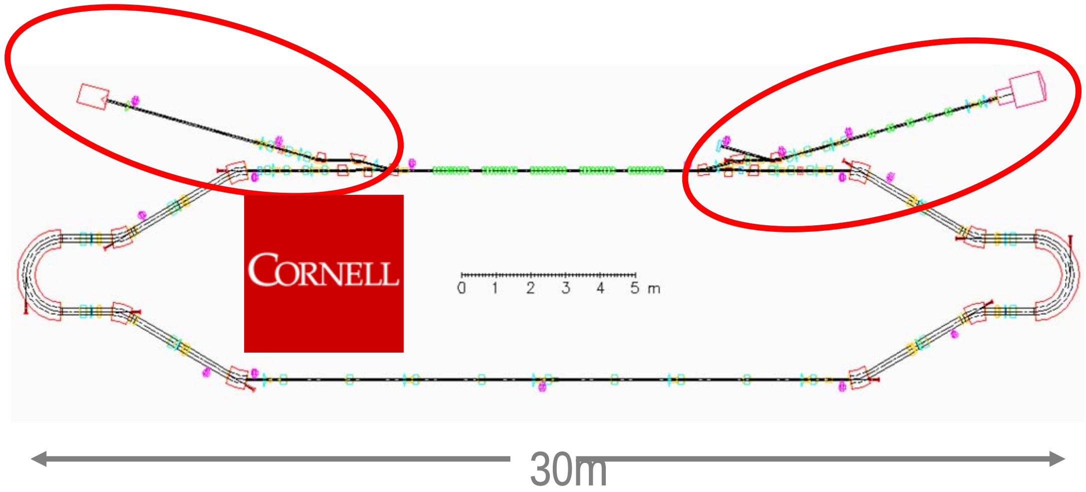
CW ERLs

JLAB

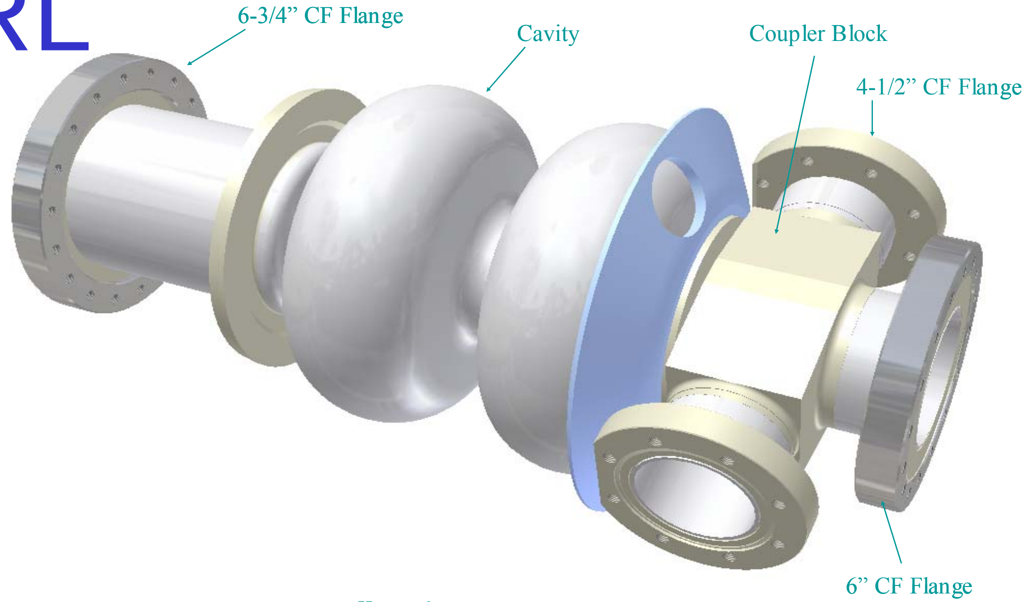




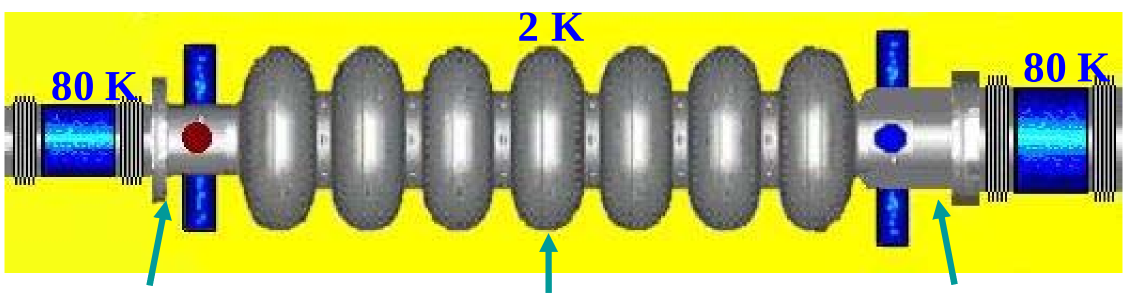
- Promises:
  - high efficiency
  - lower RF power requirements
    - nearly independent of accelerated current
    - need to compensate wall losses, therefore superconductivity
  - linac-like beam quality
  - beam power at the dump reduced
- Examples
  - existing: JLAB, JAERI
    - ~10 mA
  - proposed: Cornell ERL Prototype
    - ~100mA
- Challenges
  - higher order mode damping
  - high cw power couplers

Example: Cornell ERL Prototype Cavities

- Injector
  - two-cells ('HOM-free')
  - Ferrite broadband absorbers at 80 K
  - 130 kW CW coupler
- Linac
  - seven-cells
  - LLRF stability
    - Phase 0.06 degrees
    - Amplitude: $3*10^4$
  - $Q_{ext}=2.6*10^7$ (microphonics)
  - 140 W losses per cavity from beam-excited monopole modes
  - opposite HOM couplers to reduce transverse kicks
  - enlarged beam tube
  - 6 HOM loop couplers:
    - reduce power per coupler
    - damp quadrupole modes reliable.
  - ferrite broadband absorbers at 80 K



2-cell cavity



small 78 mm beam tube

7-cell s.c. cavity, TESLA shaped center cells

large 106 mm beam tube

Summary

- SC cavities are a standard tool becoming more and more interesting for several applications
  - CW linacs (e.g. FELs, ERLs)
  - high gradient applications (e.g. TESLA)
- this is due to:
  - surface preparation provides high gradients near the theoretical limit
    - a big variety cavities achieve B_{surf}=100mT easily
    - with EP up to 150 mT in multi-cells
    - even higher Q0 at intermediate gradients is desirable for cw applications
  - new cavity design options
    - cell shape
    - superstructures
  - improved HOM damping concepts allow to increase currents