High Gradient Programme for the ILC

Lutz Lilje@desy.de
DESY -MPY-

ILC Meeting@DESY
18.2.2005

- Cavity Design Options
- Review on test results for TTF cavities
  - Surface treatments
  - Integration into accelerator modules
- Work on Auxiliaries
  - e.g. Frequency Tuner

Cavity Design Options

- Established baseline parameters
  - Frequency: 1.3 GHz
  - Operating temperature: 2K
    - Maybe minor changes
- Parameters under discussion
  - Gradient
    - TESLA-500: 25 MV/m
    - TESLA-800: 35 MV/m
    - ILC: ???
      - Cost optimum is between 30-40 MV/m
        - » Depends on your cost model….
  - Cavity cell shape
    - Increase E_{peak}/E_{acc} :
      - field emission under control !?
    - Reduce B_{peak}/E_{acc}:
      - magnetic surface field limit achieved !?
      - This would increase the operating gradient
    - Very good summaries by J. Sekutowicz:
      - http://lcdev.kek.jp/ILCWS/Talks/13wg5-05-Shape_Sekutowicz.pdf
      - http://www.slac.stanford.edu/grp/ara/structures_meeting/JSekutowicz.pdf
  - Number of cells per accelerating structure
    - Superstructure

Surface Resistance of Niobium: $R_s(T)$

Geometry factor:

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

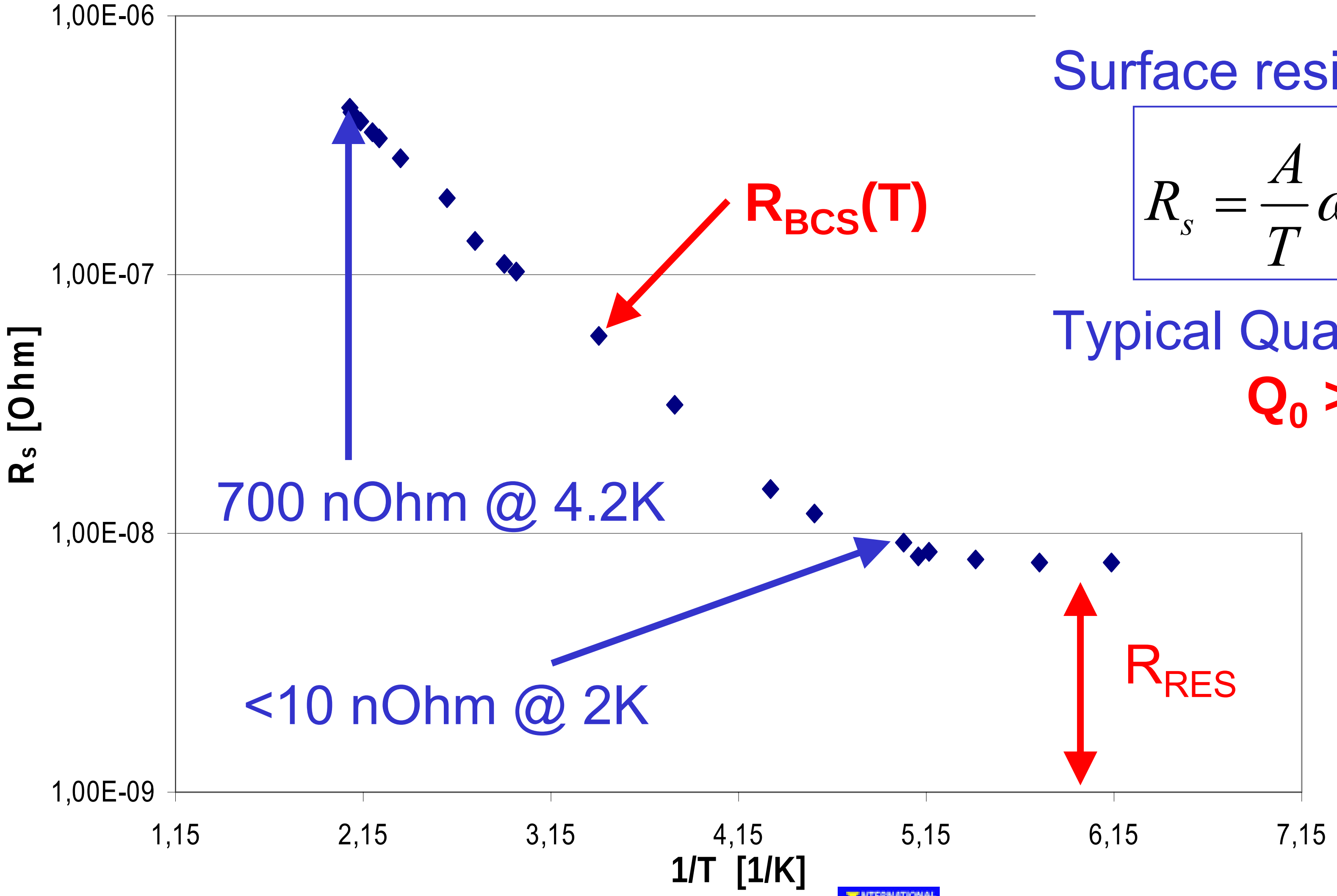
G = 270 Ohm

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



$R_{BCS}(T)$

700 nOhm @ 4.2K

<10 nOhm @ 2K

R_{RES}

Cavity Design

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

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

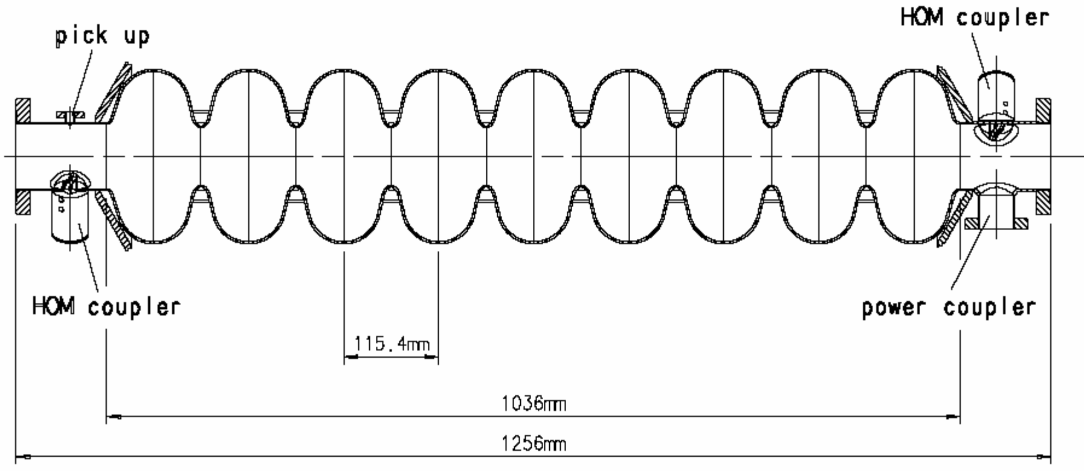
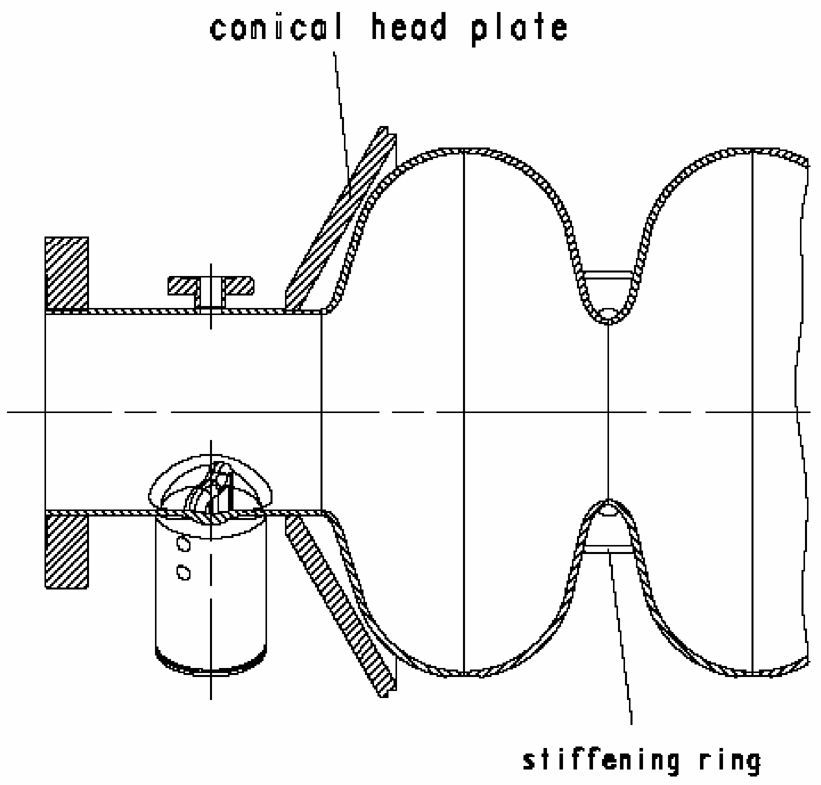
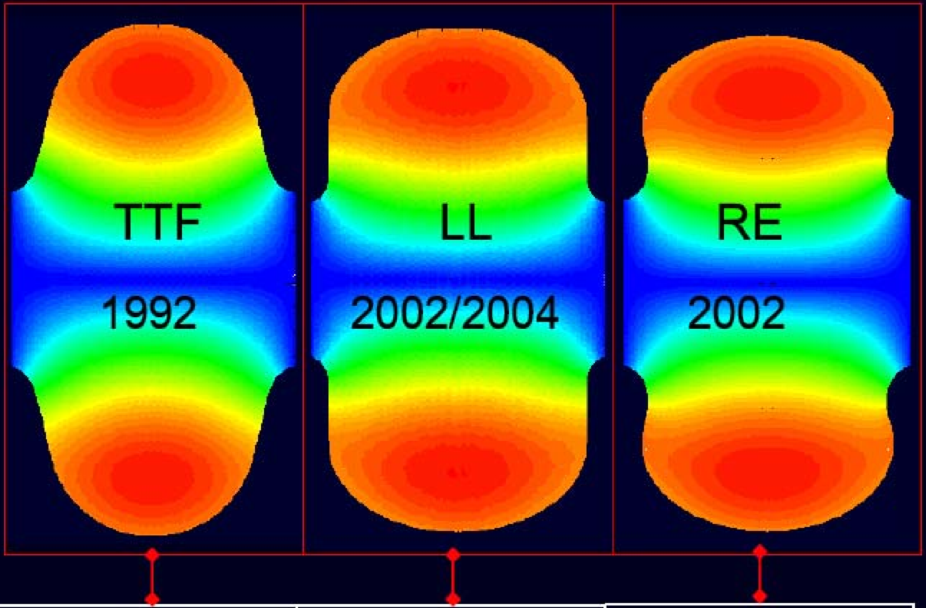


Figure 2.1.3: *Side view of the 9-cell cavity with the main power coupler port and two higher-order mode couplers.*



1. Introduction: Evolution of the elliptical cavities cont.

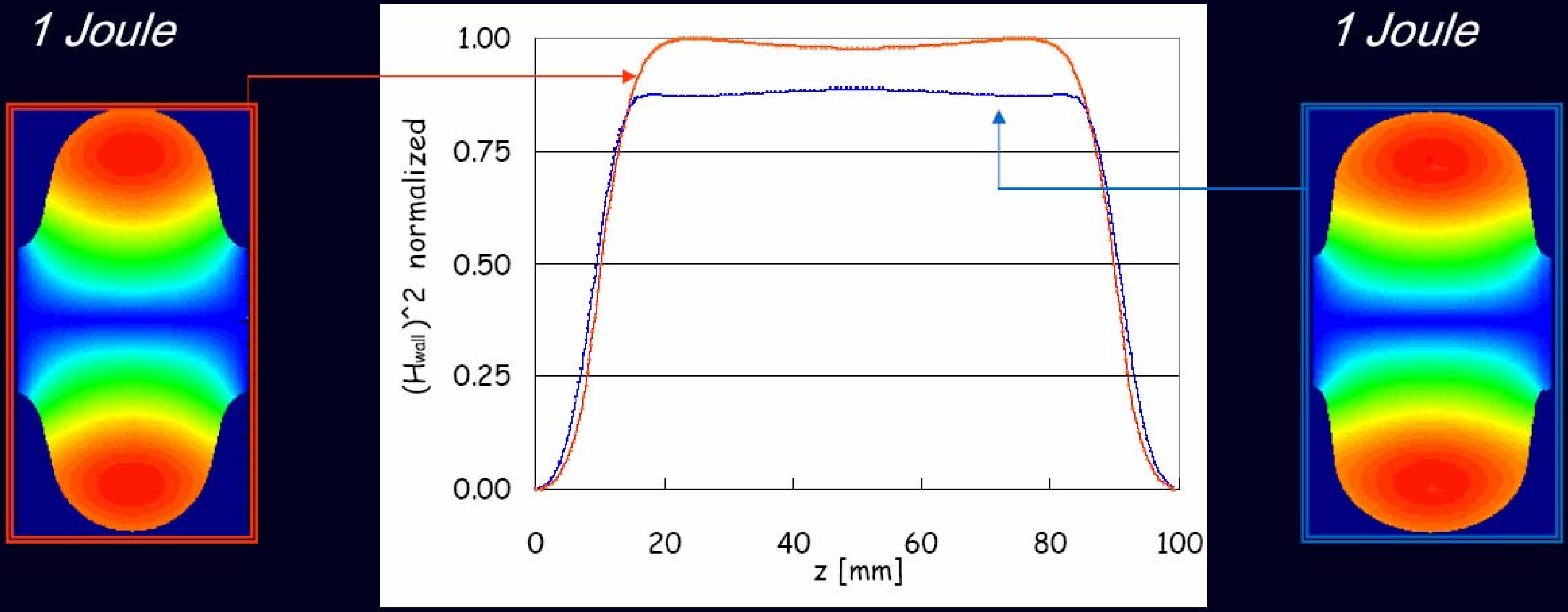
Example: 1.3 GHz inner cells for TESLA and ILC



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.

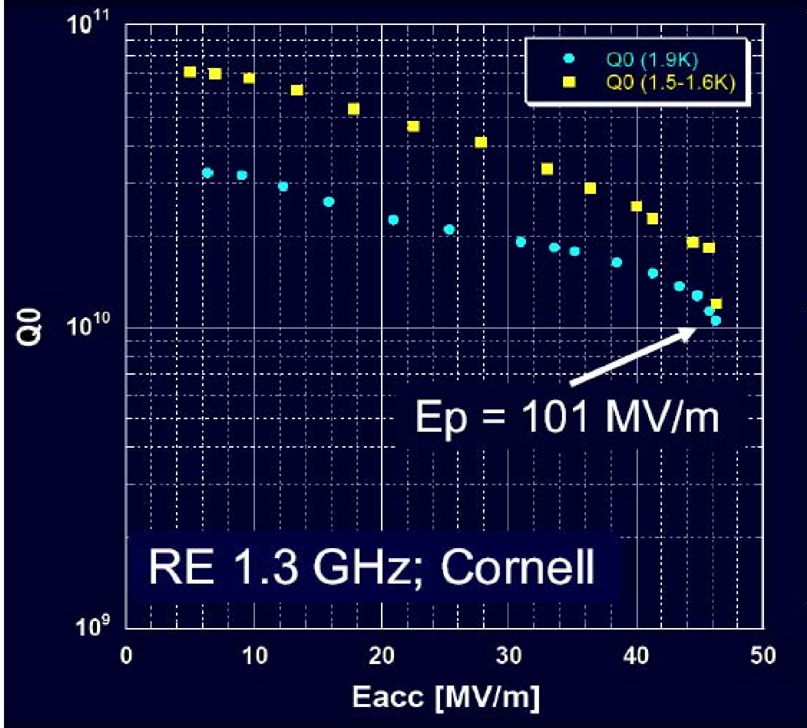


H^2 on the Nb wall

2. Low Loss cavity: Fundamental Mode, cont.

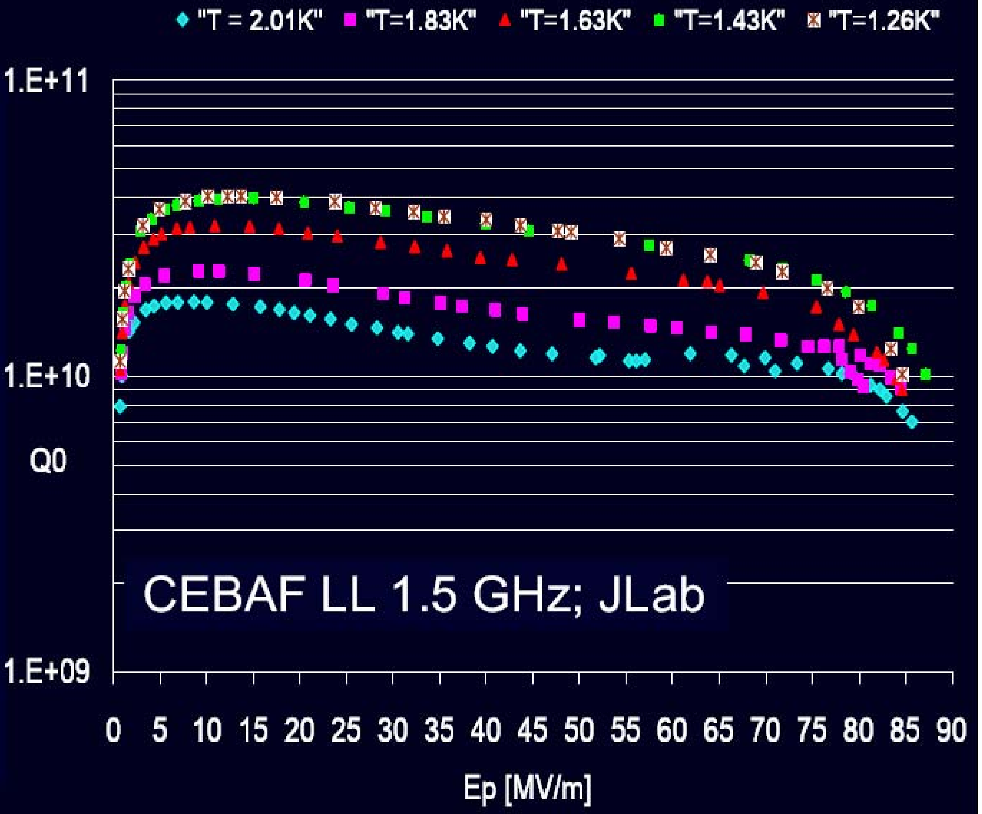
Single-cells!!!

$E_{peak}/E_{acc} = 2.36 \longrightarrow E_{peak} = 83$ MV/m at Eacc = 35 MV/m



RE 1.3 GHz; Cornell

Ep = 101 MV/m



CEBAF LL 1.5 GHz; JLab

2. Low Loss cavity: Fundamental Mode, Multi-cell parameters

		LL	TTF
Type	-	symmetric	asymmetric
f_π	[MHz]	1300.0	1300.0
Number of cells, Nc	-	9	9
k_{cc}	[%]	1.52	1.9
E_{peak}/E_{acc}	-	2.36	1.98
B_{peak}/E_{acc}	[mT/(MV/m)]	3.61	4.15
R/Q	[Ω]	1166.5	1012
G	[Ω]	284.8	271
(R/Q*G) / Nc	[Ω*Ω]	36913	30472

5. Summary and the next steps

What is good about this structure ?

- Lower cryogenic loss by ~20% (as compared to TTF structure).
- Shorter rise time by 13% due to higher (R/Q) (as compared to TTF structure).
- Less sensitive to microphonics due to higher (R/Q) and thus lower Qext.
- Less stored energy by 13%.
- B_{peak}/E_{acc} lower.

What is critical for this structure ?

- Higher $E_{peak}/E_{acc} = 2.36$, (TTF structure 2).
- Weaker cell-to-cell coupling $k_{cc} = 1.52\%$ (TTF structure 1.9%).
- HOM loss factors are higher: $k_\perp$ by 65% , $k_\parallel$ by 18 %.

Open questions:

- Vibrations ?
- Preparation and cleaning ?

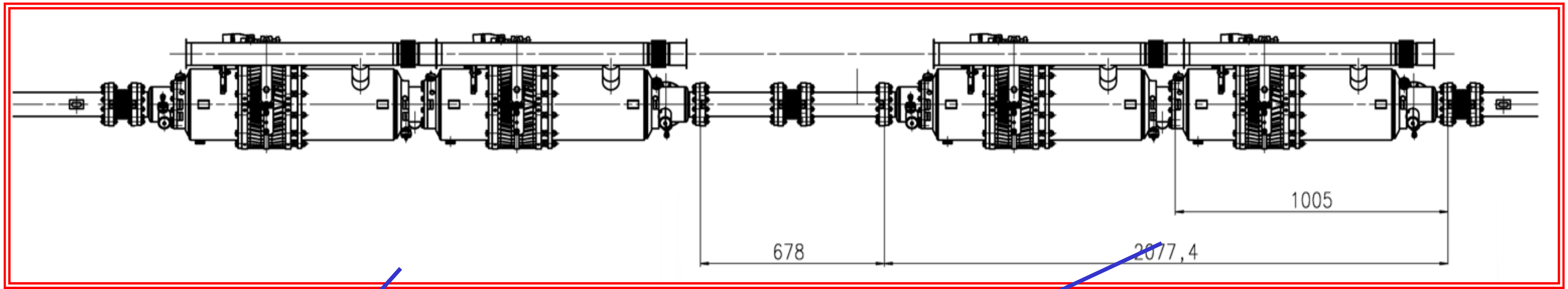
TESLA Upgrade Option: Superstructures

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

J. Sekutowicz,
SRF2003, Lübeck

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

2x7-cell Superstructure Prototypes at TTF



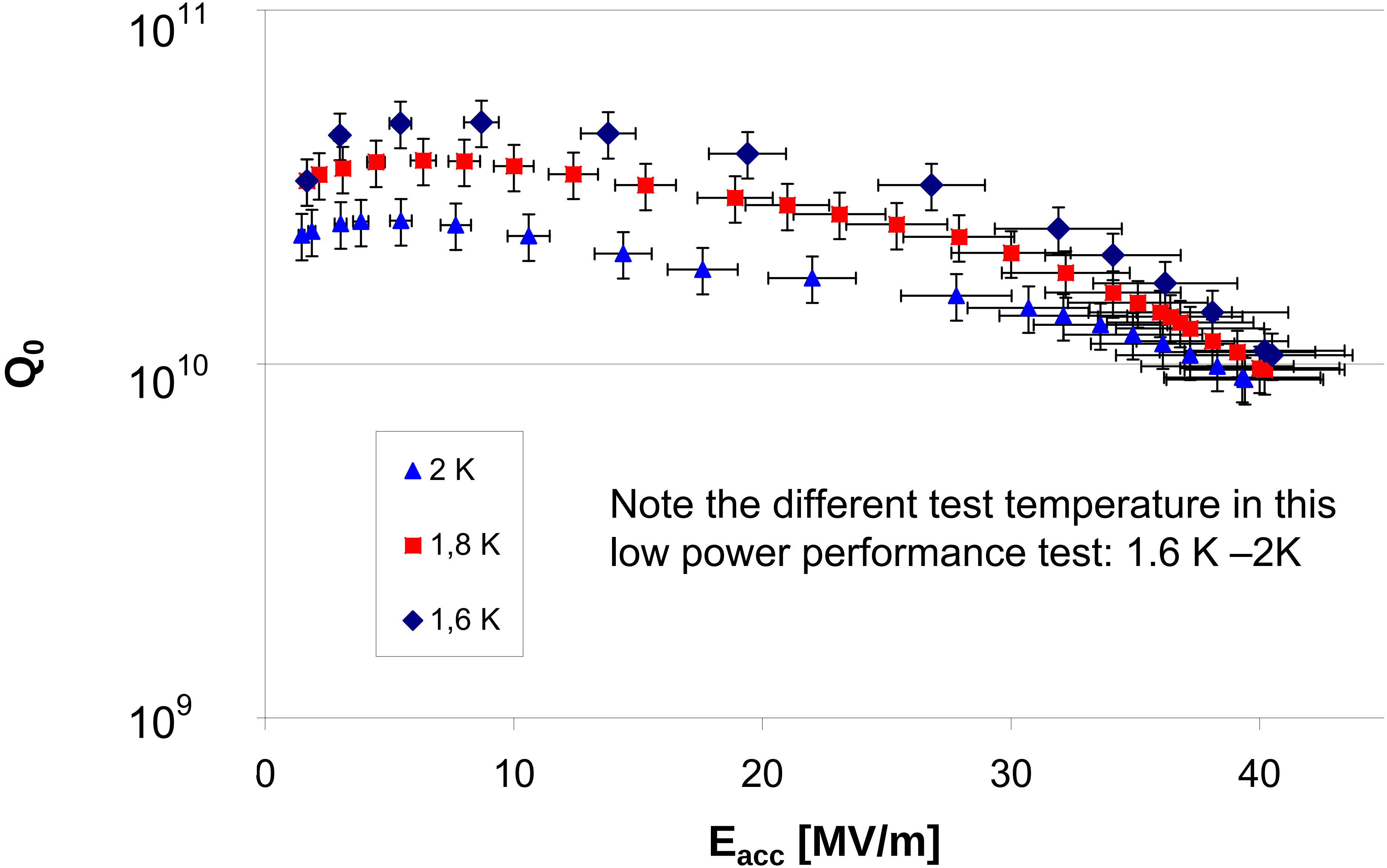
Cavity Design Options Summary

- A lot of work is underway
  - DESY (Jacek): Design
  - KEK: Prototype
    - » KEK is also very actively pursuing other fabrication techniques
  - JLab: Prototypes (1.5 GHz)
  - SLAC: Computations
  - FNAL: Computations
  - Cornell: Single-cell prototyping
- Open issues
  - Detailed design for HOM damping
    - » Prototyping on copper cavities
  - Multi-cell niobium prototype testing
    - » 4 units in September 2005 (KEK)?
  - Superstructure ?

Review on Tests for TTF Multi-Cell Cavities

- Surface preparation is critical
  - Electropolishing (EP) is needed for high gradients
    - Some statistics available
    - Proof-of-principle: One EP cavity in the accelerator reached 35 MV/m!
  - Cleaning and assembly is critical
    - Risk of particle contamination
    - Causes field emission
- Integration into accelerator modules needs to be done carefully
  - Avoid contaminations
  - Quality control measures for all components and their assembly procedures need improvement

CW Test: AC70: EP at DESY



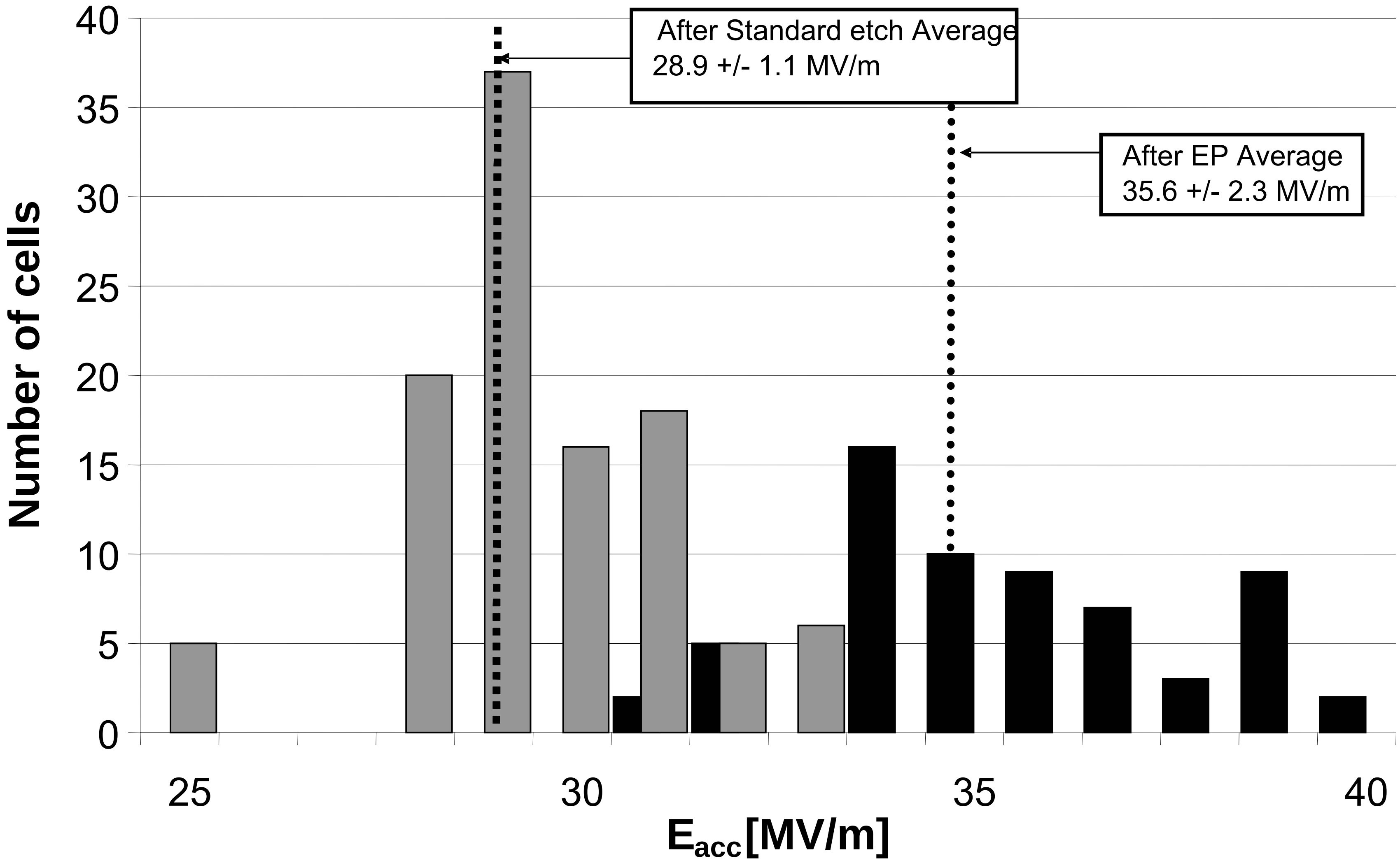
Note the different test temperature in this low power performance test: 1.6 K –2K

Lutz Lilje DESY -MPY-

18.02.2005

Comparison of EP to Standard Etch

(Results from the KEK-DESY Collaboration)

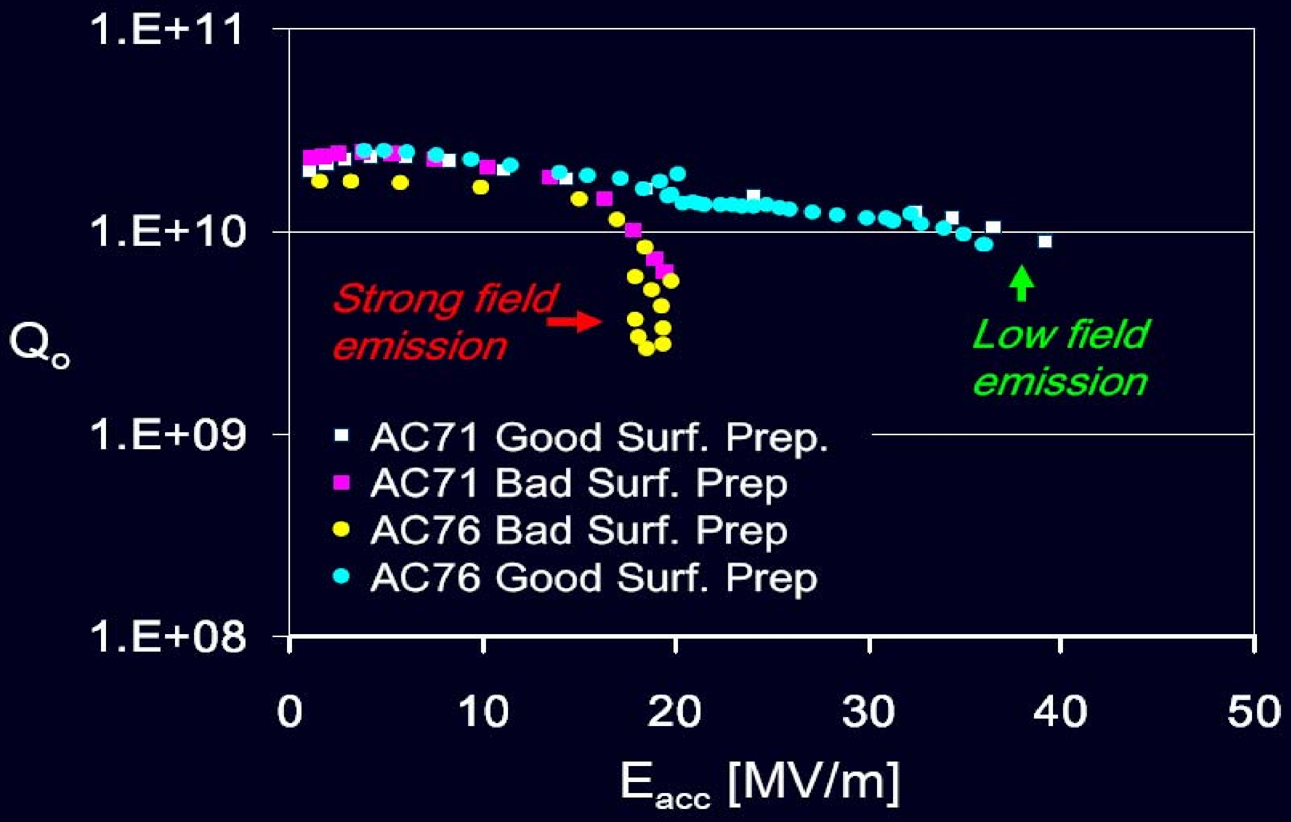


- EP offers systematically higher gradient than standard etch (single cell results from mode analysis of multi-cells)

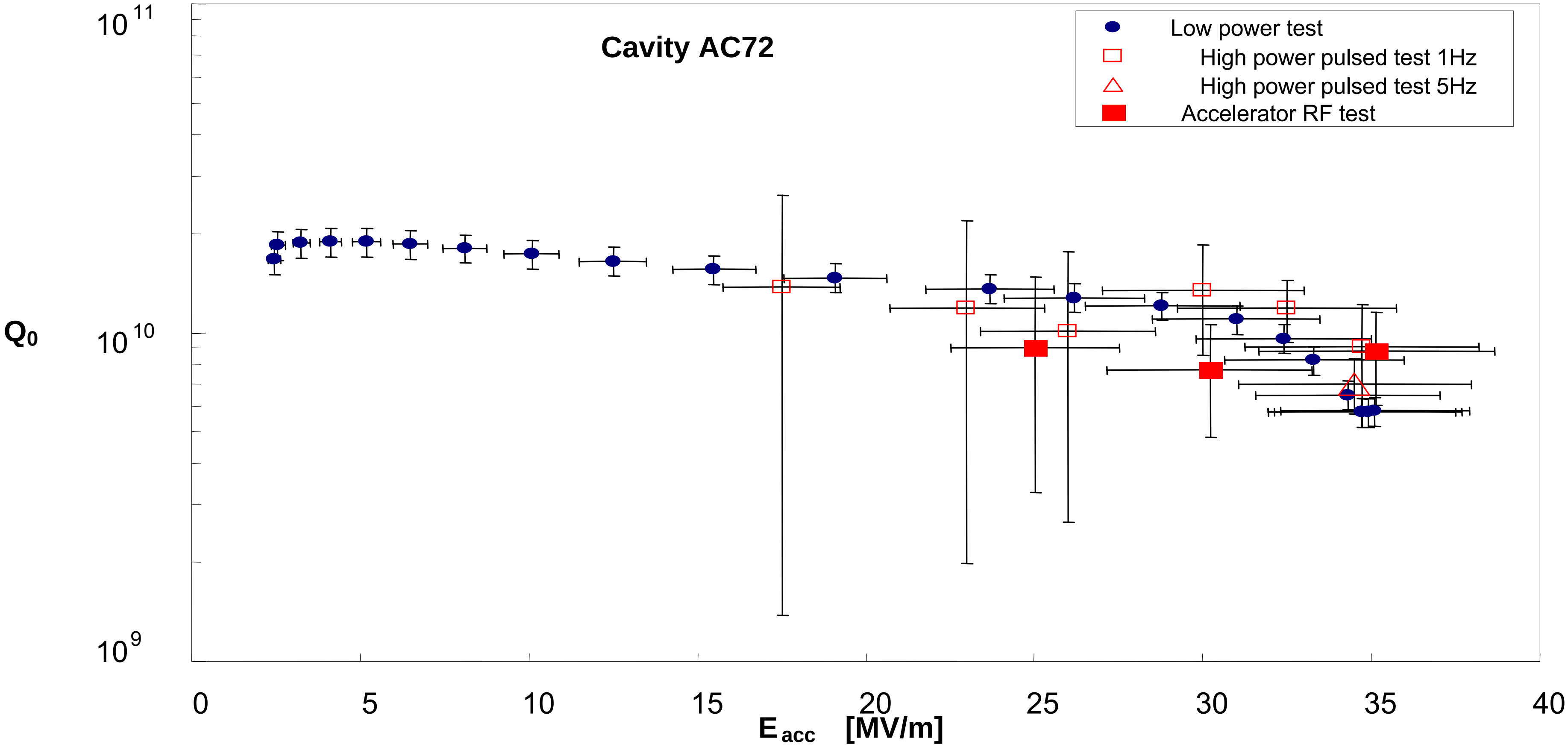
1. Introduction: Criteria cont.

Avoiding field emission is an ongoing struggle !

Some examples: 2002/2005



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

Complete Accelerator Modules - Tests in TTF

- Gradient performance
- HOM measurements
    - Use as BPM
- …

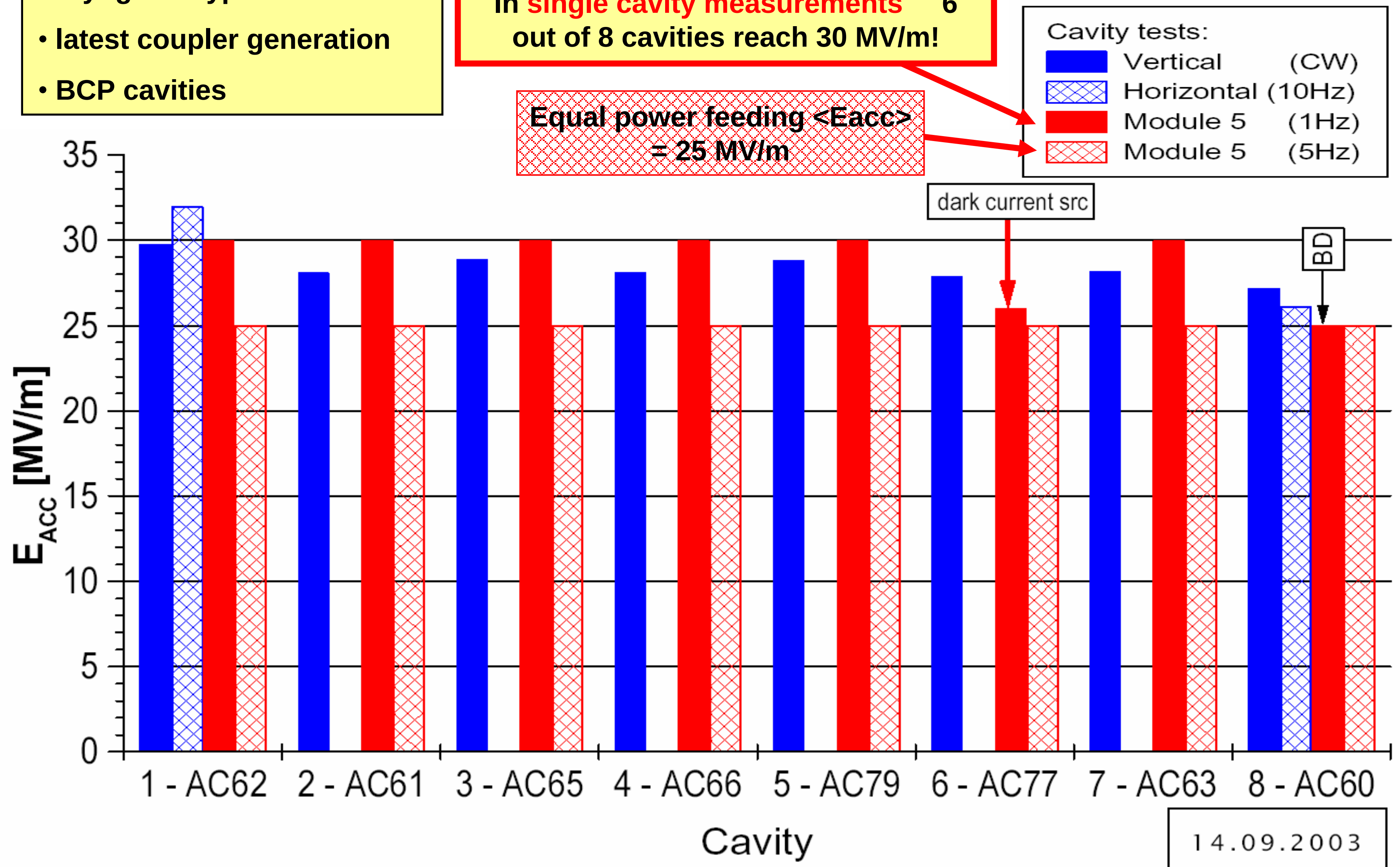
Performance of Accelerator Module 5

From H. Weise/ D. Kostin

A State-of-the-art module

- cryogenic type III
- latest coupler generation
- BCP cavities

In single cavity measurements 6 out of 8 cavities reach 30 MV/m!

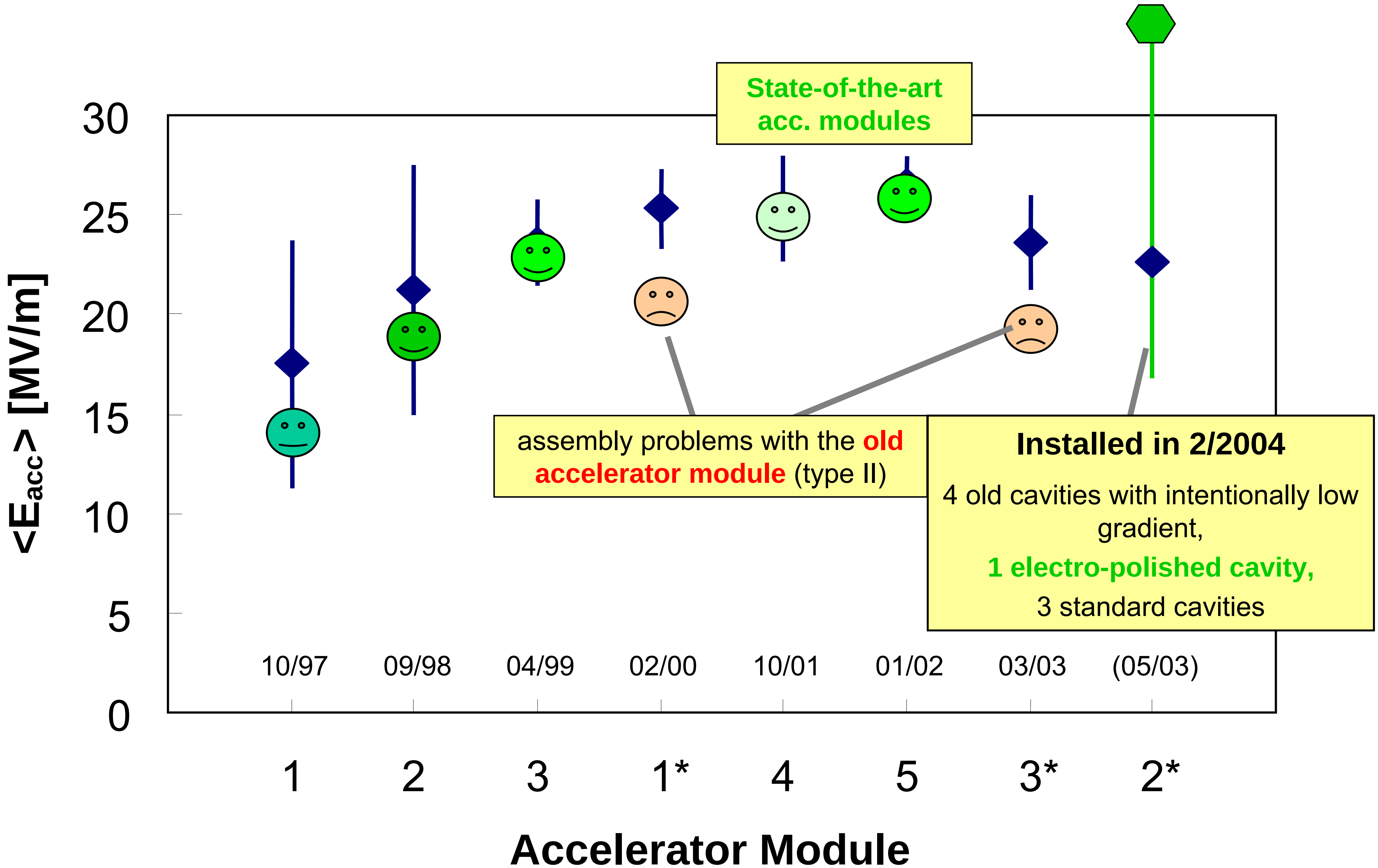


Equal power feeding <Eacc> = 25 MV/m

14.09.2003

Gradients of Accelerator Modules

From H. Weise



State-of-the-art acc. modules

assembly problems with the **old accelerator module** (type II)

Installed in 2/2004

4 old cavities with intentionally low gradient,

1 electro-polished cavity,

3 standard cavities

Summary of Available Gradients today

- For TTF shape multi-cells:
  - Individual cavities with electropolishing
    - Continuous wave tests: up to 40 MV/m
    - Accelerator: Proof-of-Principle 35 MV/m
  - Full modules: 25 MV/m (etched cavities)
- But:
  - More reproducibility needed for cavity preparation
    - Still a large scatter in results
    - most of this is due to field emission

Open Issues: Surface Preparation and Module Integration

- Basic research on EP and ‘In-Situ‘ bakeout:
  - What are the fundamental limiting effects?
    - Measurements on superconducting properties of samples are needed
      - Some work has been done at Uni Hamburg (Casalbuoni, Steffen, Schmüser et al.), but programme discontinued
    - Tests on single-cells
      - Work ongoing in several labs (DESY: D. Reschke et al.)
  - Are there other cleaning techniques worth considering?
- Engineering
  - Module integration needs more quality control procedures
    - Esp. Field emission
  - Industrialisation of EP
    - Work on single-cells has started in Germany
    - Status in Japan is not quite clear
  - Module assembly in industry
    - Industrial study is just being launched
  - These are of course major goals for the XFEL

Frequency Tuner

- Tuner consists of 2 parts
  - Slow tuner
    - Allow for different thermal shrinkage
    - Correct slow drifts e.g. He pressure
    - Specification:
      - Range: 820 kHz
      - Resolution: 1 Hz /step
    - 2 basic types have been tested
      - Lateral (Saclay)
      - Coaxial (INFN, DESY)
  - Fast tuner
    - Compensate Lorentz-forces
      - df <= 1 kHz in 1 m
    - Piezoelectric

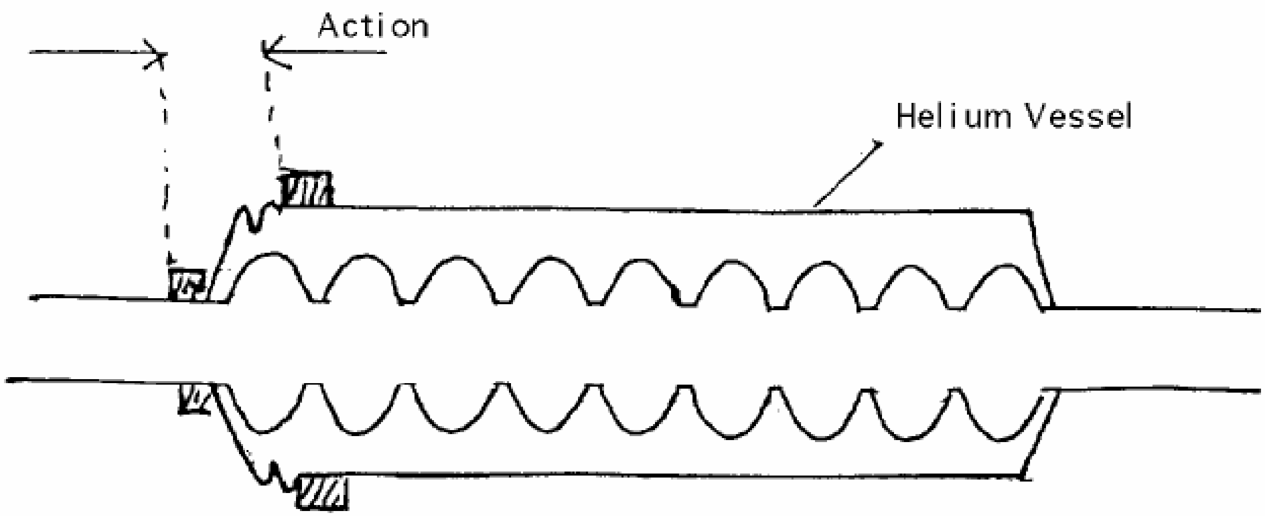
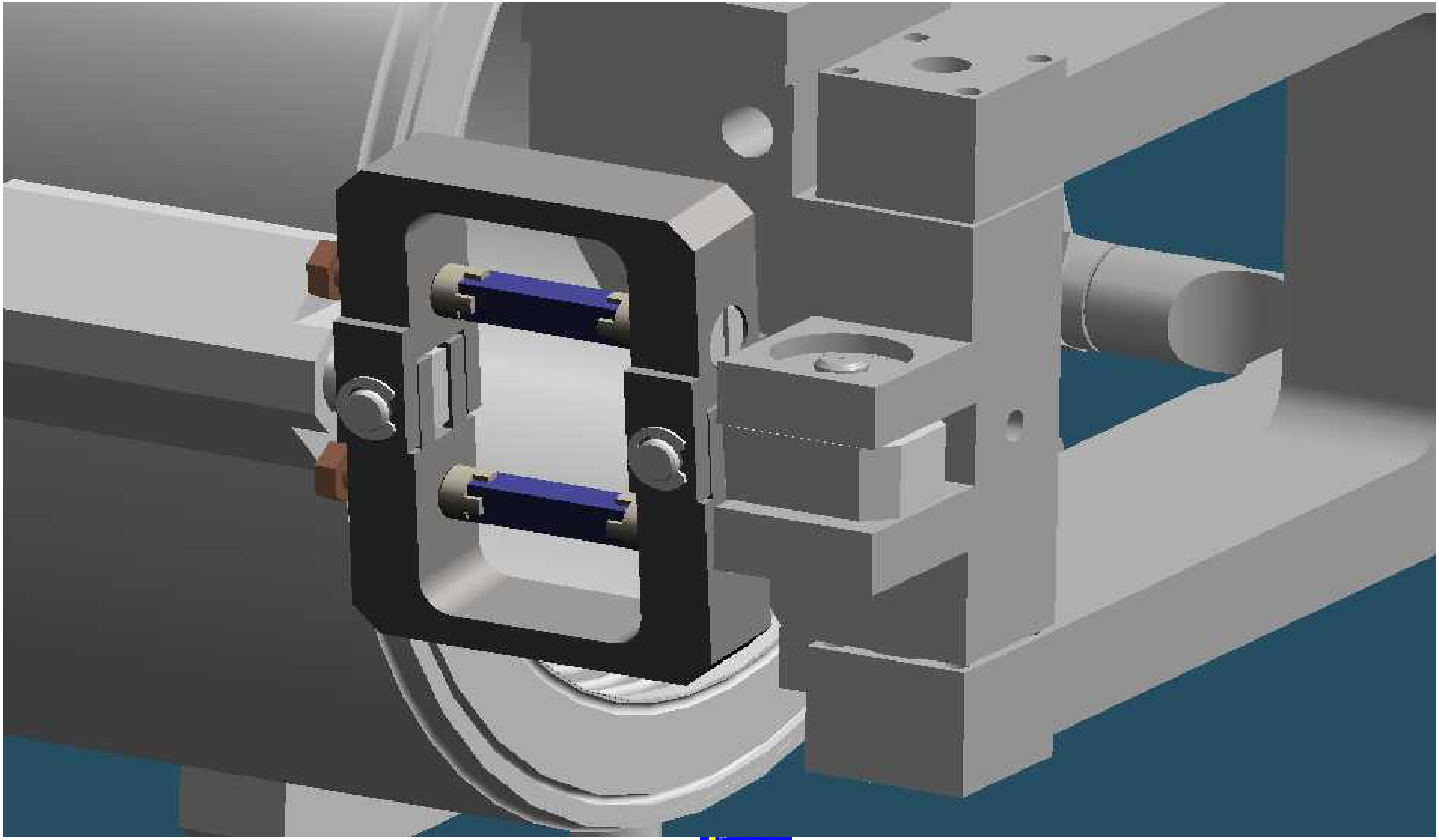


Figure 4.21: How the CTS is acting on the cavity length.

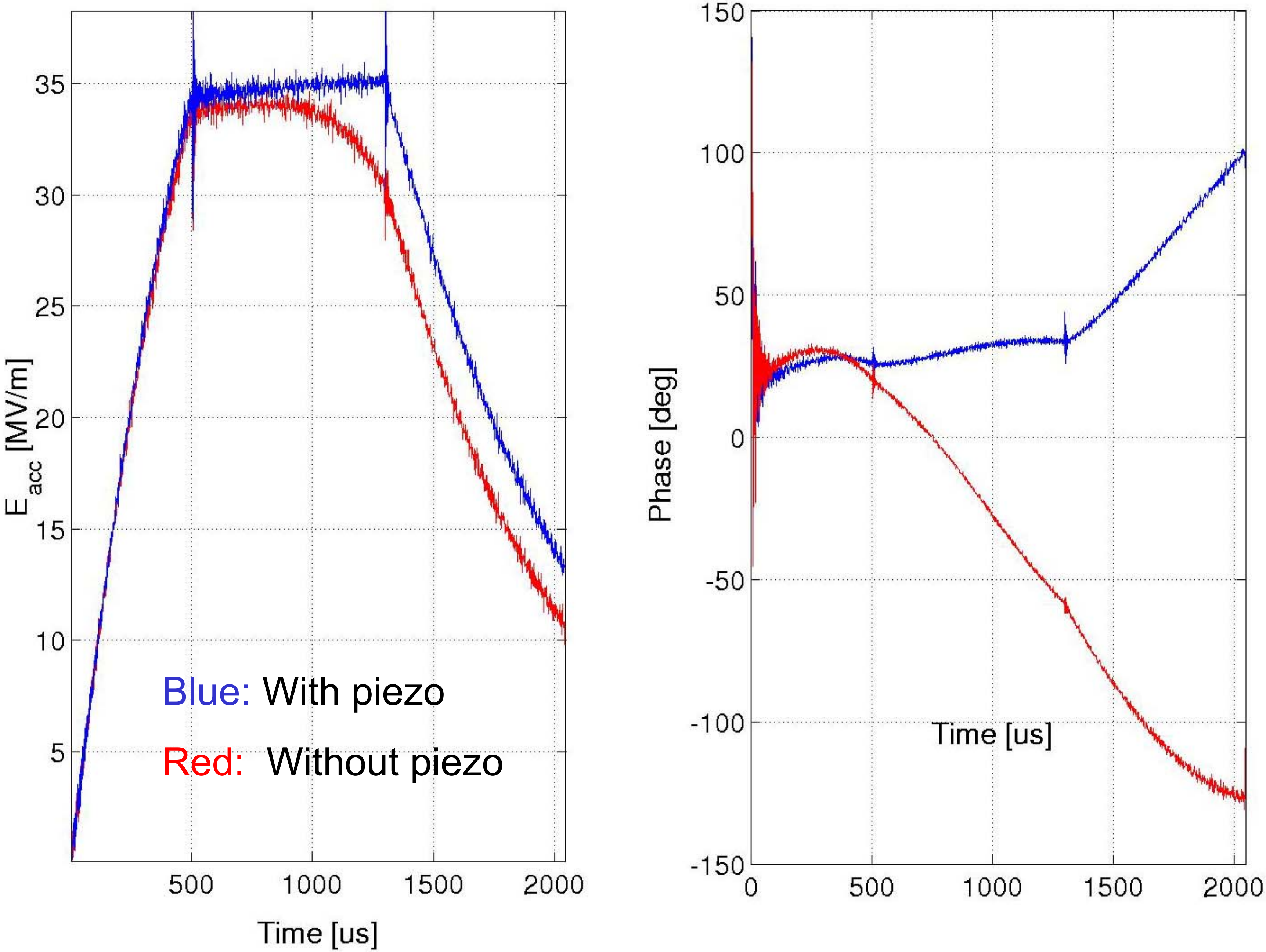
Active Tuner

- Actively compensate the detuning of the cavity during the RF pulse by mechanical means to reduce power consumption
- Piezoelectric elements are suitable for this application (heavily used for fuel injection in car industry)
  - Magnetostrictive materials can be an option
- Proof-of-principle done
- A lot of engineering needed
  - Choice of tuner
  - Choice of Actuator
  - …

Drawing of Piezoelectric Elements in the Tuning Mechanism



RF Signals at 35 MV/m



Blue: With piezo

Red: Without piezo

Summary

- For the high gradient programme work is ongoing
  - Cavity shapes
    - Prototypes tested by the end of the year
  - Surface preparation
    - Proof-of-Principle: 35MV/m in the accelerator
    - Quality control needs improvement
    - Basic research on samples/single-cells is needed
      - Superconducting properties of niobium
      - Other cleaning techniques
  - Module Integration
    - Quality control needs improvement
  - Auxiliaries
    - A lot of engineering needed

Thank you…

- … to Hans-Bernhard Peters, Jacek Sekutowicz and Hans Weise for their viewgraphs
- … and the TESLA Collaboration for the work that has been done to date

References

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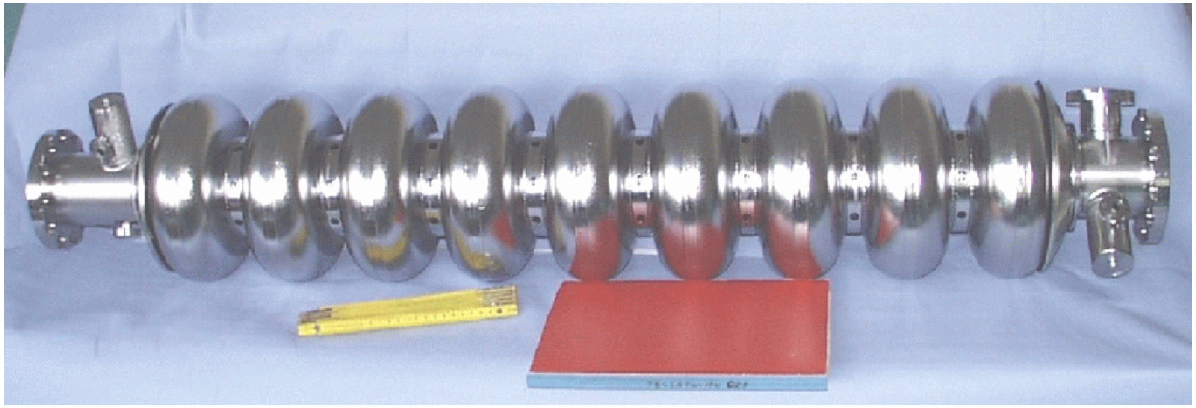
  - L. Lilje, E. Kako, K. Saito, P. Schmüser, et al.; Achievement of 35 MV/m in the Superconducting Nine-Cell Cavities for TESLA; 2004; published in NIM A; Volume 524, Issues 1-3 , 21 May 2004, Pages 1-12, DOI: 10.1016/j.nima.2004.01.045
  - S. Casalbuoni, B. Steffen, P. Schmüser et al., Surface superconductivity in niobium for superconducting RF cavities, NIM A , Volume 538, Issues 1-3 , 11 February 2005, Pages 45-64

TESLA Baseline – Overview

- Cavity
- Coupler
  - High power coupler
  - HOM (most of this will be covered in more detail by Jacek's talk in WG 2)
- Magnetic Shielding
- Tuner
  - Slow mechanical tuner
  - Fast tuner (Piezo)

TESLA Cavities



Made of solid, pure (RRR >300, high thermal cond.) Niobium

Nb sheets are deep-drawn to make cups (≈**100 µm tolerances**), which are electron beam welded to form structures.

Fill time with coupler 420 µs, i.e. $Q_{ext} = Q_{beam} \approx 3 \times 10^6$, $\Delta f \approx 400$ Hz

RF pulse length (400 µs filling + 920 µs flat top) = 1320 µs.

Operated at 2 K in superfluid Helium bath.

RF losses approx. 1 W/m.

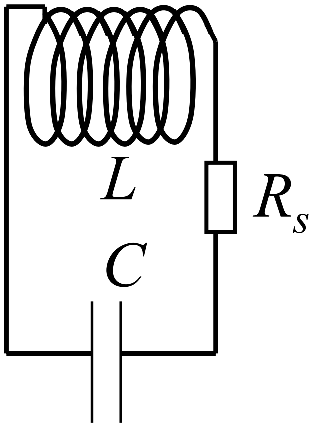
RF amplitude and phase adjusted during filling and flat top to compensate beam loading. In steady state **essentially 100% rf input power goes into the beam.**

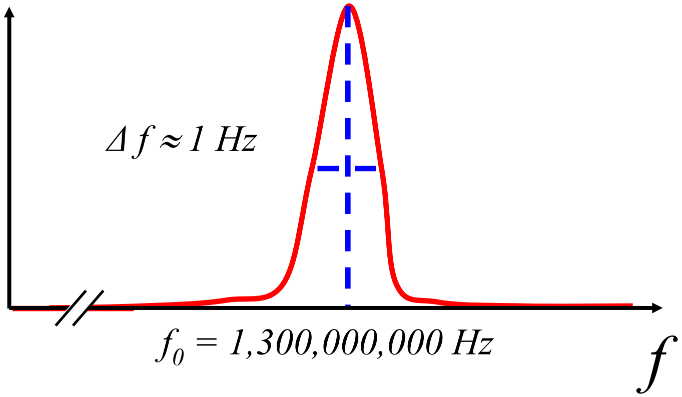
$$f_o = \frac{1}{2\pi\sqrt{LC}}$$

frequency

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

quality factor





Natural bandwith

$$\mathbf{Q_0 \approx 10^9 - 10^{10}}$$

Cavity Parameters

type of accelerating structure	standing wave
accelerating mode	TM_{010} , π-mode
fundamental frequency	1300 MHz
nominal gradient E_{acc} for TESLA-500	23.4 MV/m
quality factor Q_0	$> 10^{10}$
active length L	1.038 m
cell-to-cell coupling k_{cc}	1.87 %
iris diameter	70 mm
R/Q	1036 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	4.26 mT/(MV/m)
tuning range	± 300 kHz
$\Delta f/\Delta L$	315 kHz/mm
Lorentz force detuning constant K_{Lor}	$\approx 1\,\mathrm{Hz/(MV/m)}^2$
Q_{ext} of input coupler	$2.5 \cdot 10^6$
cavity bandwidth at $Q_{ext} = 2.5 \cdot 10^6$	520 Hz FWHM
fill time	420 μs
number of HOM couplers	2

Mechanical design

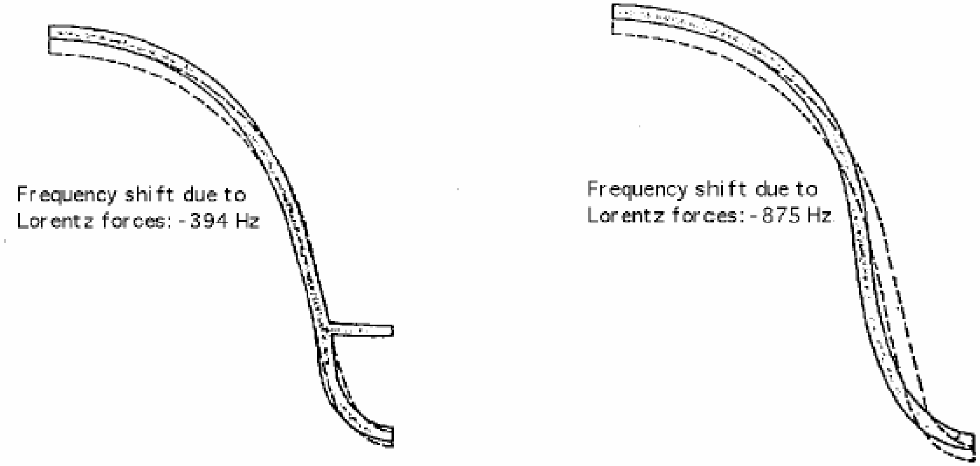
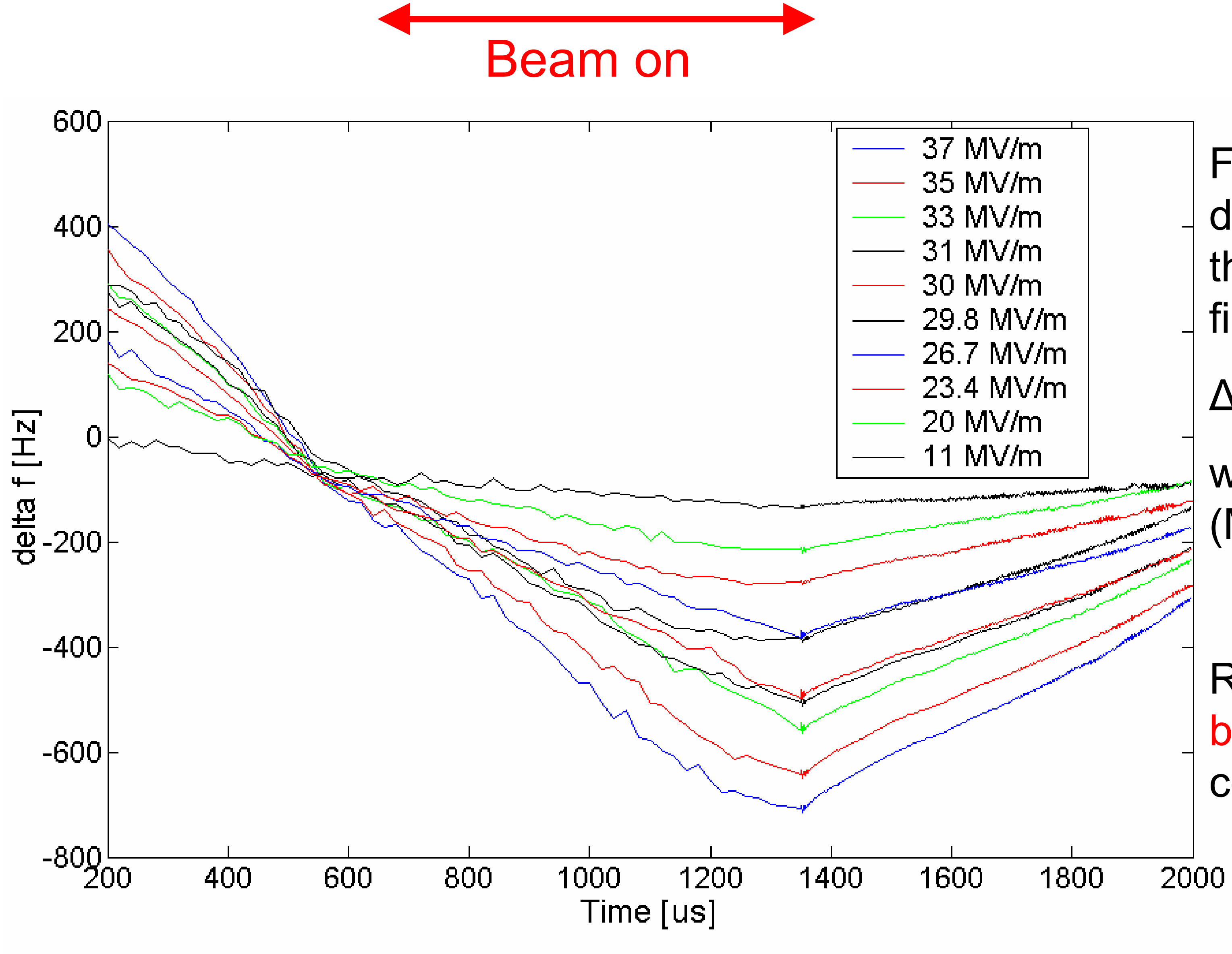


Figure 4.16: a) Deformation of a 2.5mm thick stiffened cell wall due to Lorentz forces of $E_{acc} = 25MVm^{-1}$ (gray = deformed). b) Deformation of a 2.5mm thick unstiffened cell wall due to Lorentz forces at $E_{acc} = 25MVm^{-1}$ (gray = deformed).

- Made of Niobium
  - RRR >300
  - high thermal conductivity
  - Wall thickness ~2.5 mm
- Nb sheets are deep-drawn to make cups (≈100 µm tolerances), which are electron beam welded to form structures.
- For Lorentz force detuning additional stiffening rings have been introduced
- Flange system
  - NbTi flanges with diamond shape Al gaskets

Frequency Detuning during RF Pulse



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

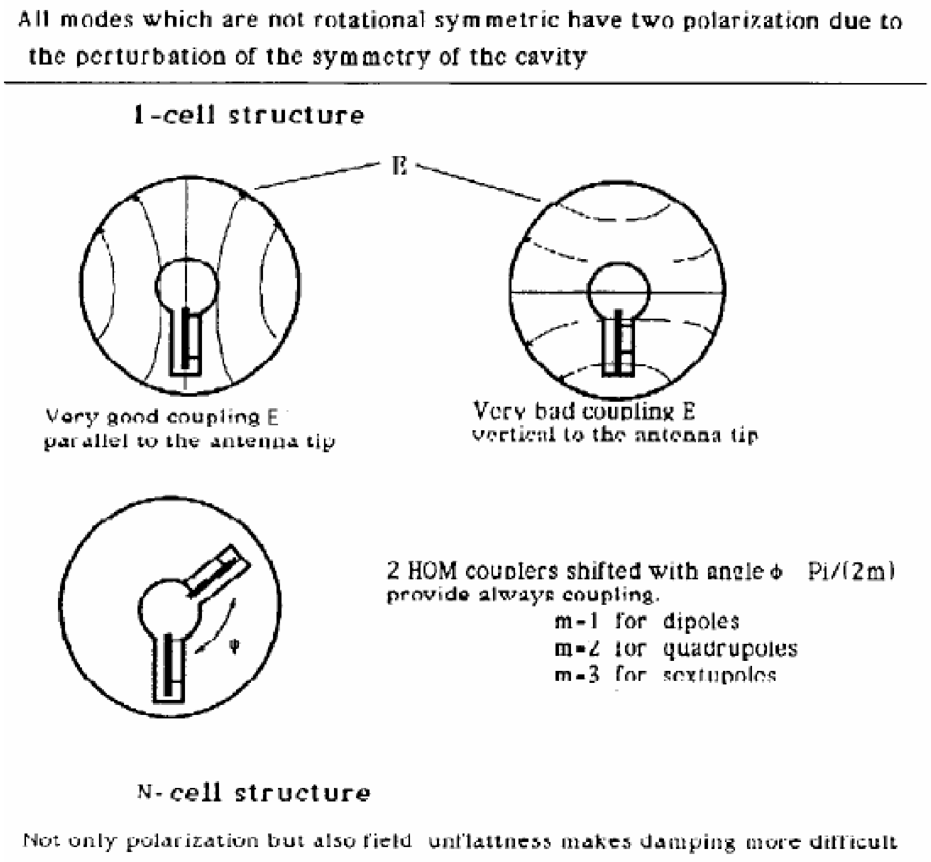
$\Delta f = -K \cdot E_{acc}^2$

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

Remember: Cavity bandwidth with main coupler is ≈ 300 Hz

HOM Coupler Design

- Requirement
  - $Q_{ext} < 10^5$ for HOMs
- Concept
  - Asymmetric end-cells to free ‘trapped‘ HOMs
  - Need 4 couplers on each cavity to damp all polarities efficiently
  - Use neighbouring cavity HOM couplers
- Coaxial type HOM coupler
  - More compact
  - Good experience from HERA
  - Integrate Notch filter
    - $Q_{ext,1.3\ GHz} > 10^{11}$



All modes which are not rotational symmetric have two polarization due to the perturbation of the symmetry of the cavity

1-cell structure

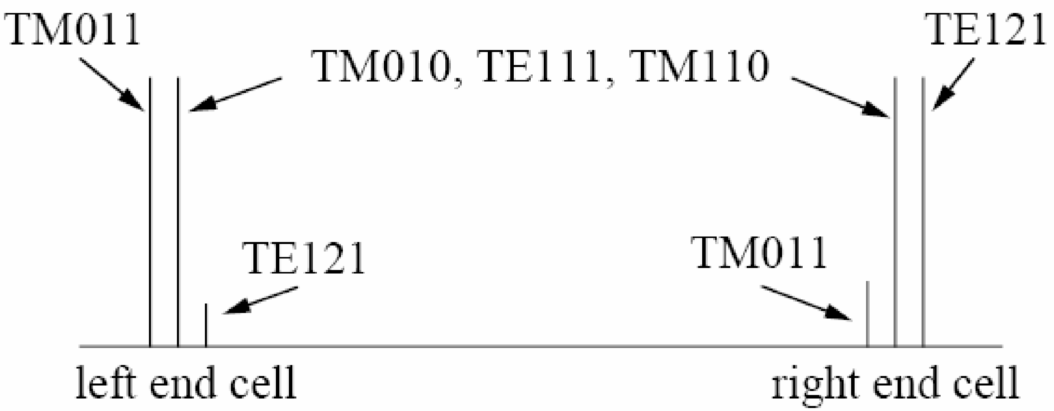
Very good coupling E parallel to the antenna tip

Very bad coupling E vertical to the antenna tip

2 HOM couplers shifted with angle ϕ Pi/(2m) provide always coupling.
m=1 for dipoles
m=2 for quadrupoles
m=3 for sextupoles

N-cell structure

Not only polarization but also field unflattness makes damping more difficult



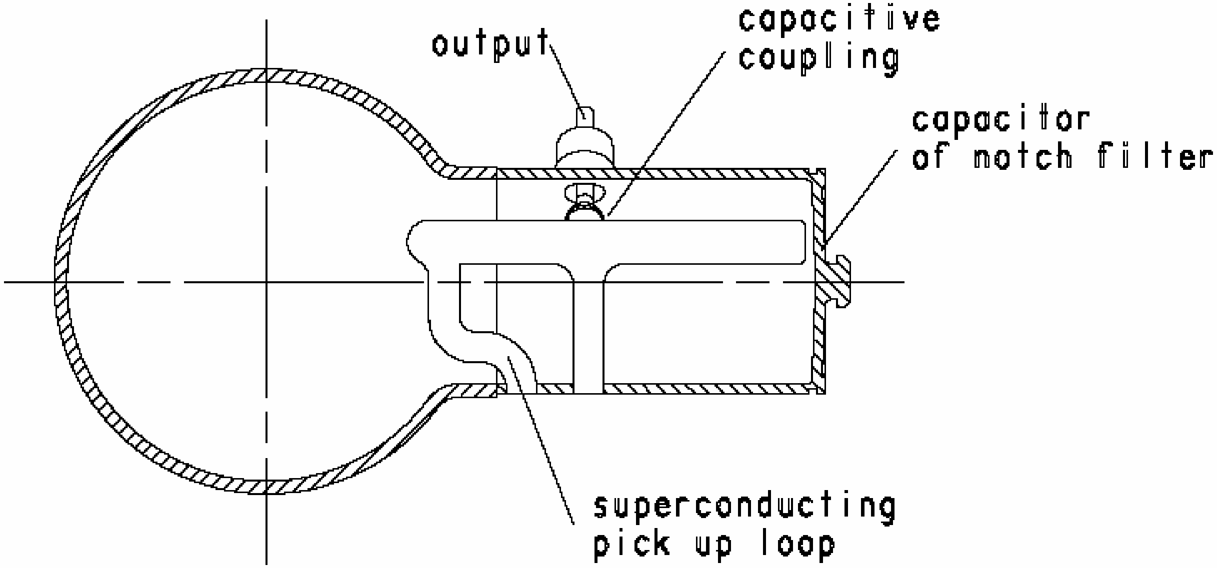


Figure 2.1.20: *Cross-section of the higher order mode (HOM) coupler.*

HOM Coupler Design Improvements

(Changes from the TDR design)

- One polarisation of a 3rd-dipole-band-mode at ~2.5GHz was insufficiently damped
  - Solution: 'Mirroring' the upstream HOM coupler
- Adjustment of Pickup antenna difficult
  - Small distance between antenna tip and 'F'-piece
  - Solution: Larger antenna diameter and larger pickup port (option:brazing of the antenna tip)

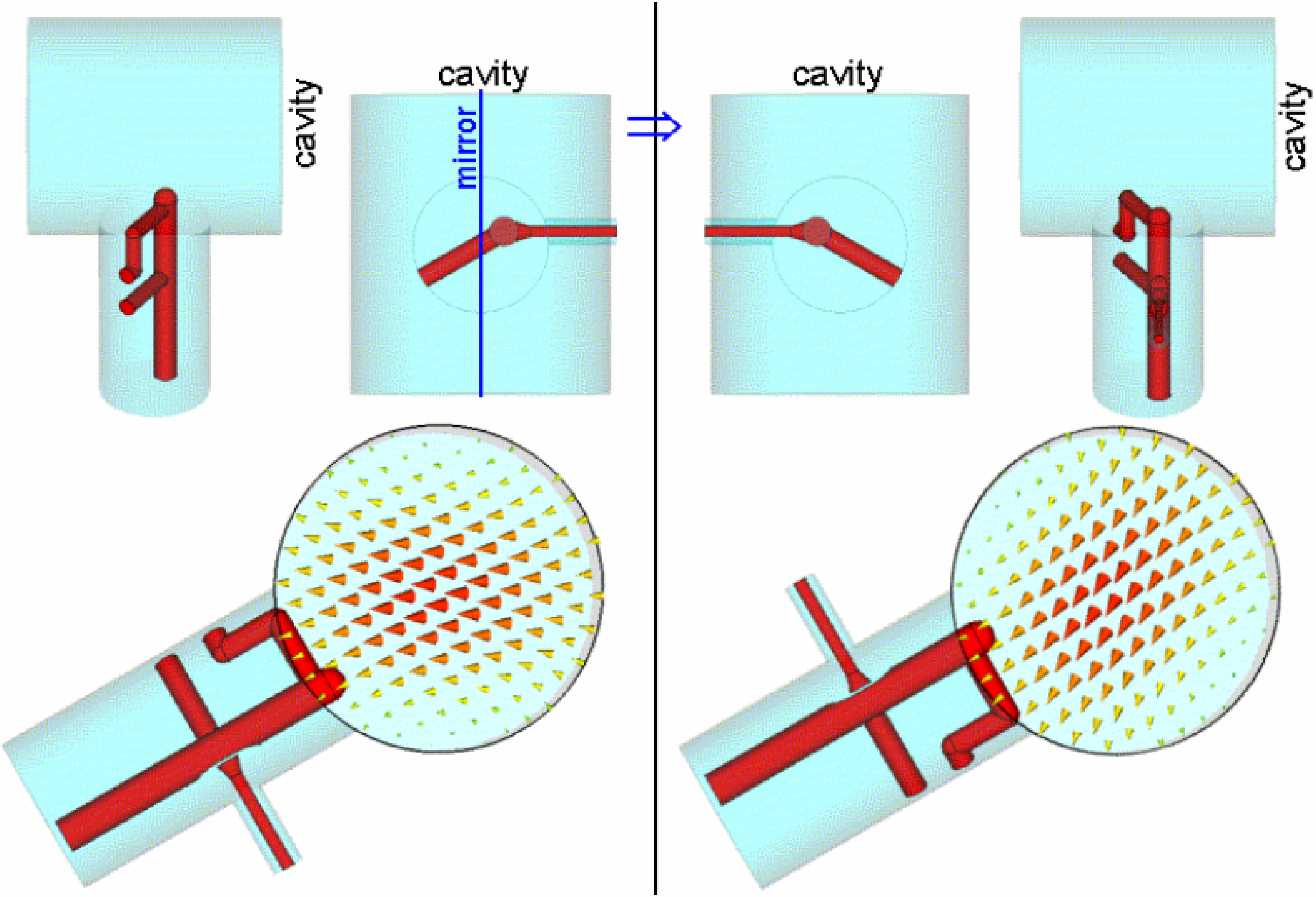


Fig. 49: Proposed modification of the upstream coupler. Due to a ‘mirror’ transformation the polarization of maximal coupling is rotated. This modification is shown for a DESY coupler, but also proposed for the SACLAY type.

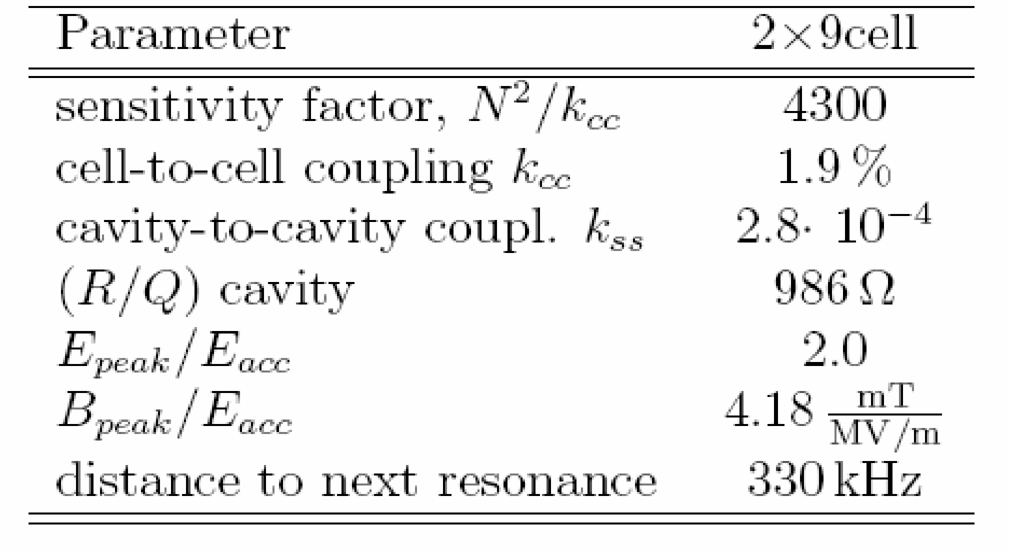

OLD
E142


NEW

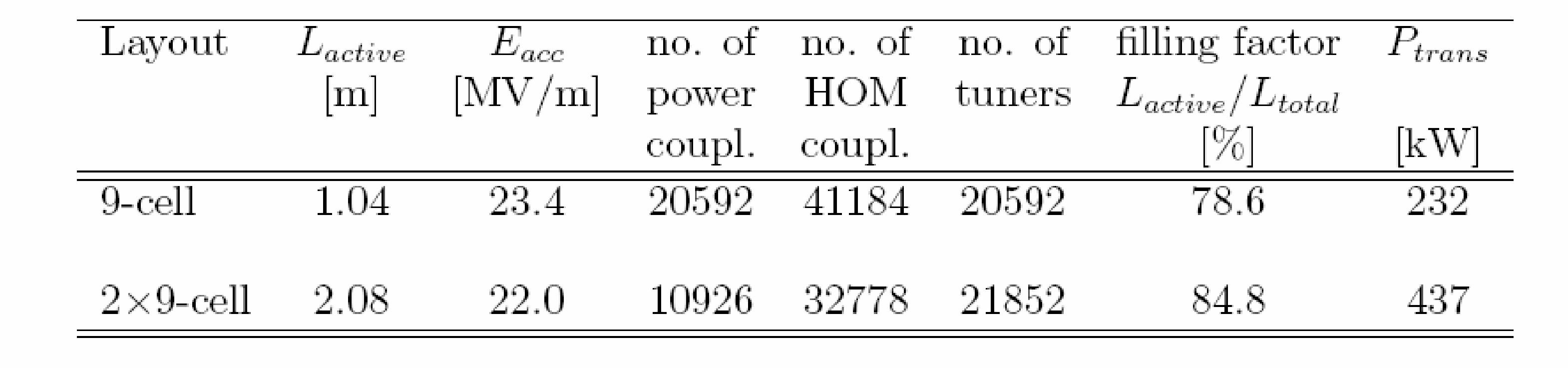
HOM Absorber

- Idea:
  - – Damp higher frequency modes >10 GHz with lossy material
    - Needed for the XFEL
    - Located in the module interconnnection
    - Cryogenic connection 4/70 K Level (not 2K!)
- Status:
  - – Under development
  - – Prototype Spring 2005
- See Jacek‘s HOM talk WG2

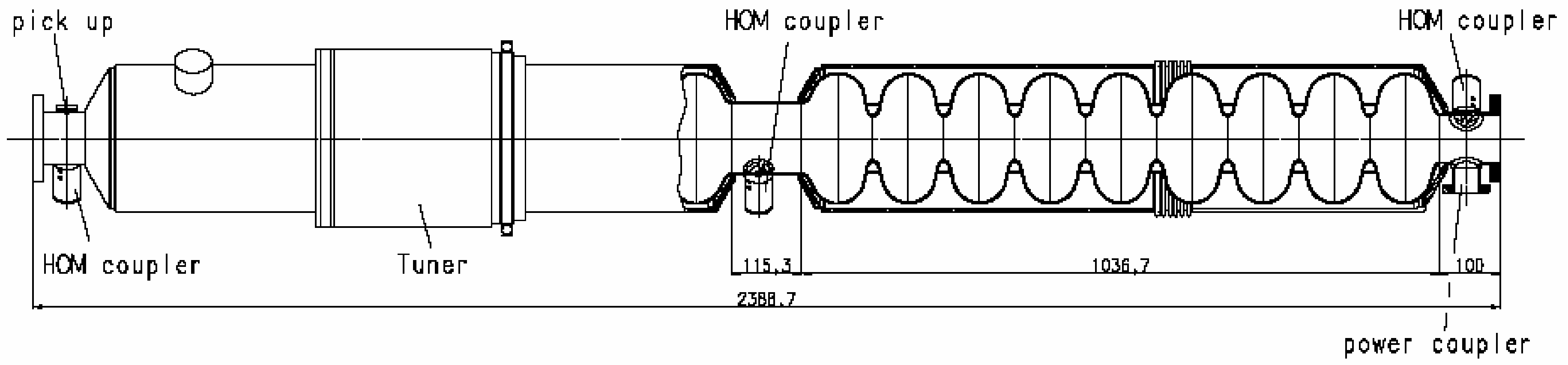
Superstructure Parameters



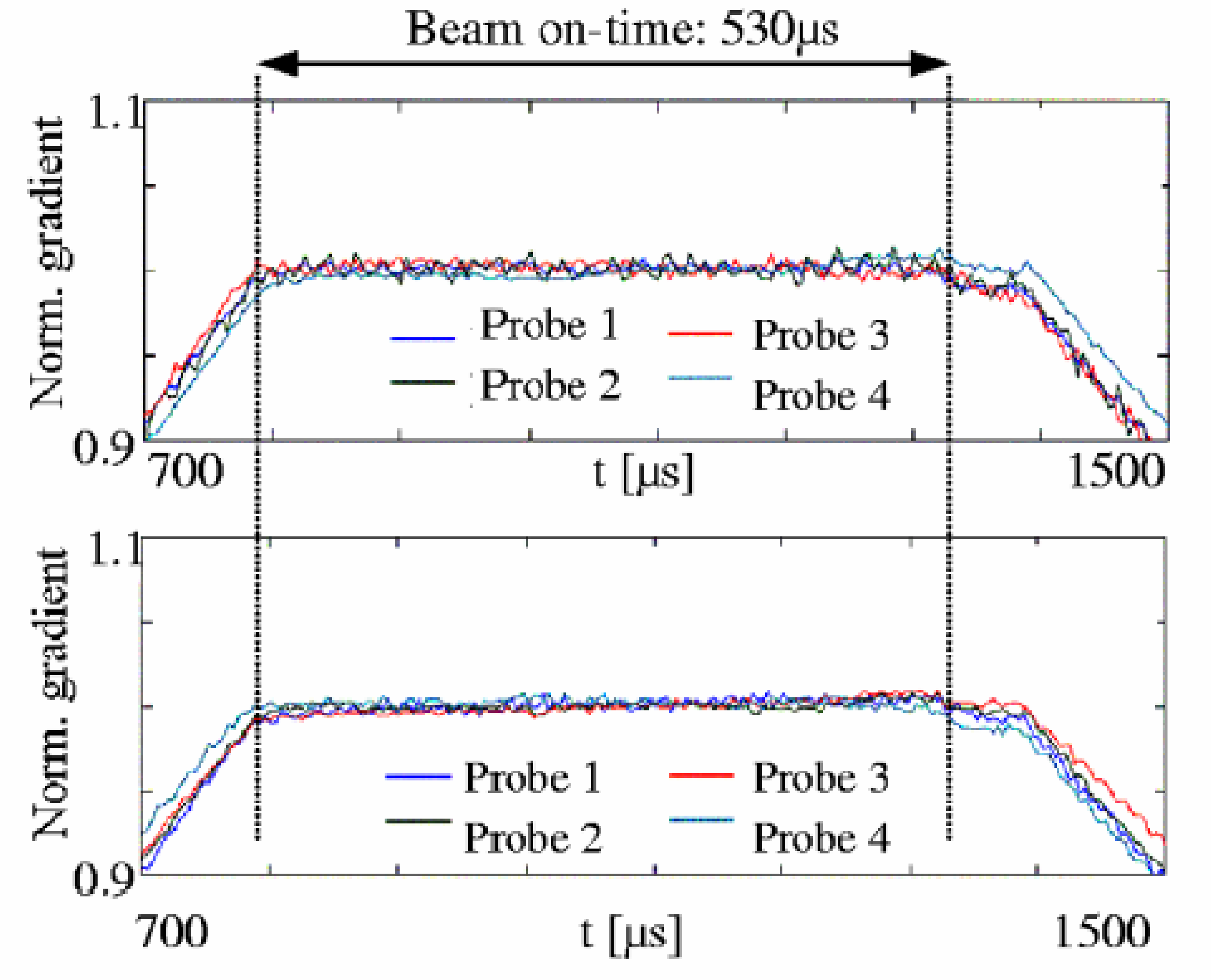
Parameter	2×9cell
sensitivity factor, N^2/k_{cc}	4300
cell-to-cell coupling k_{cc}	1.9 %
cavity-to-cavity coupl. k_{ss}	$2.8 \cdot 10^{-4}$
(R/Q) cavity	986 Ω
E_{peak}/E_{acc}	2.0
B_{peak}/E_{acc}	$4.18\ \frac{\mathrm{mT}}{\mathrm{MV/m}}$
distance to next resonance	330 kHz



Layout	L_{active} [m]	E_{acc} [MV/m]	no. of power coupl.	no. of HOM coupl.	no. of tuners	filling factor L_{active}/L_{total} [%]	P_{trans} [kW]
9-cell	1.04	23.4	20592	41184	20592	78.6	232
2×9-cell	2.08	22.0	10926	32778	21852	84.8	437



Energy Transfer

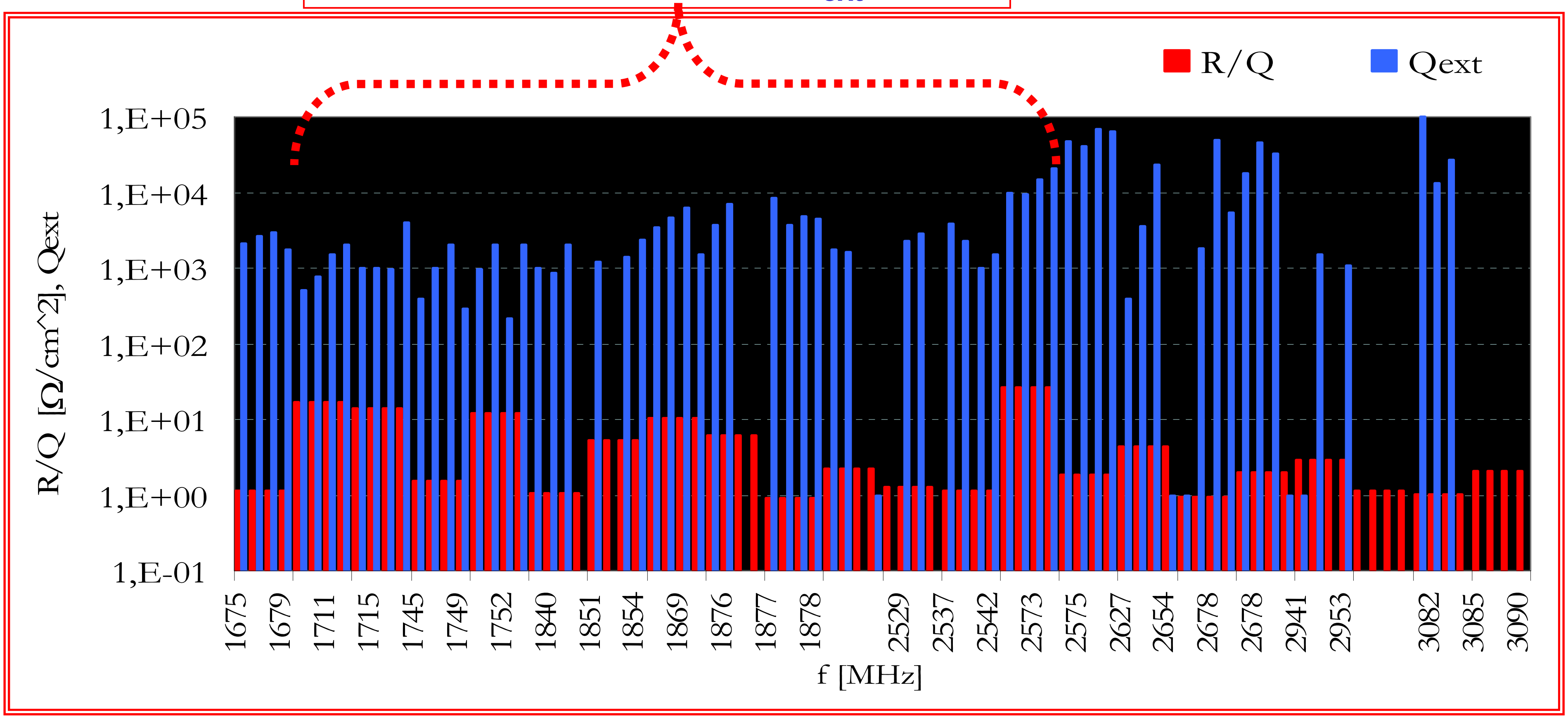


- **Measured:**
  - **$\Delta E/E$ (rms) $\leq 2 \cdot 10^{-4}$**
- **TESLA-Specification:**
  - **$\Delta E/E$ (rms) $\leq$ 5 ·10-4**

HOMs

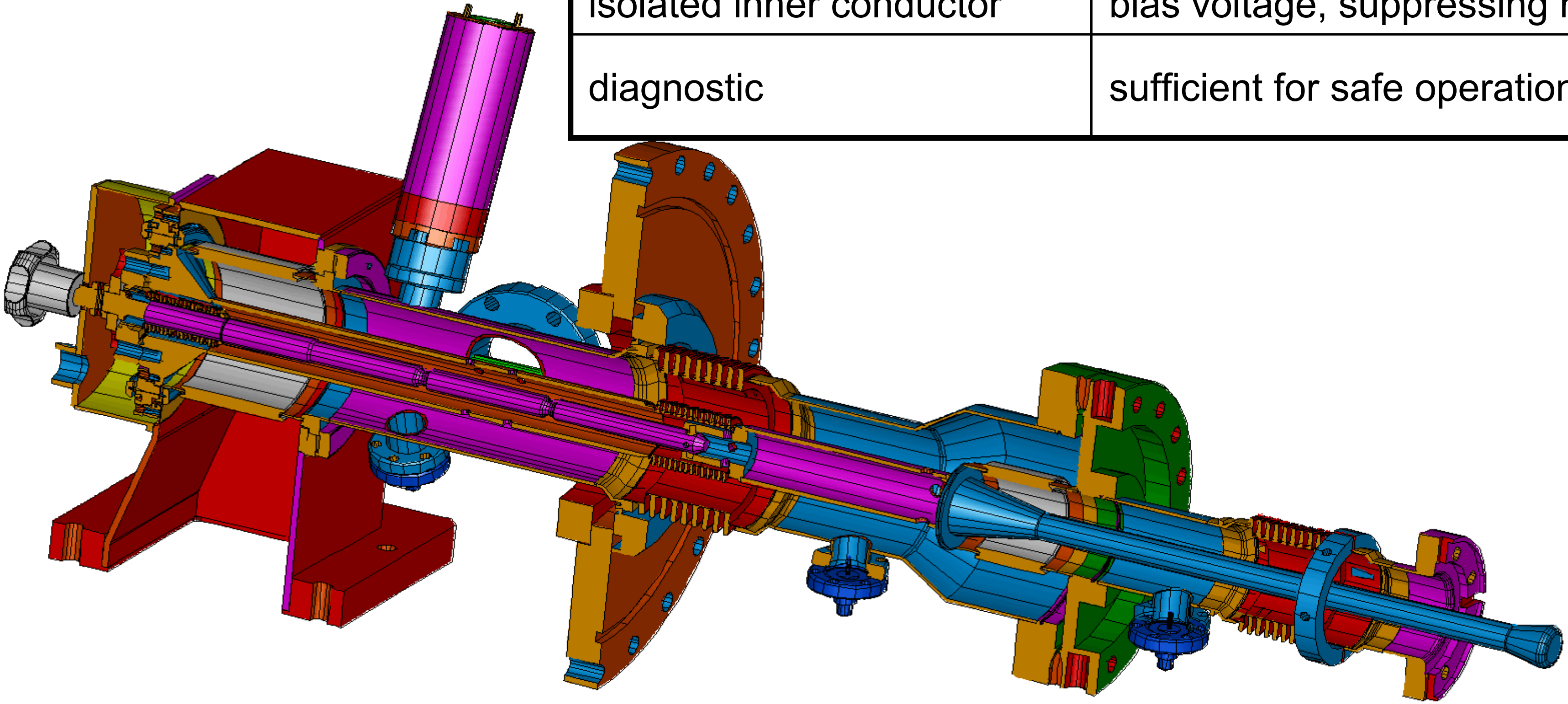
- damping of dipoles with (R/Q) ≥ 1 Ω/cm2 which are relevant for the TESLA beam was by factor 5÷100 better then spec.

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



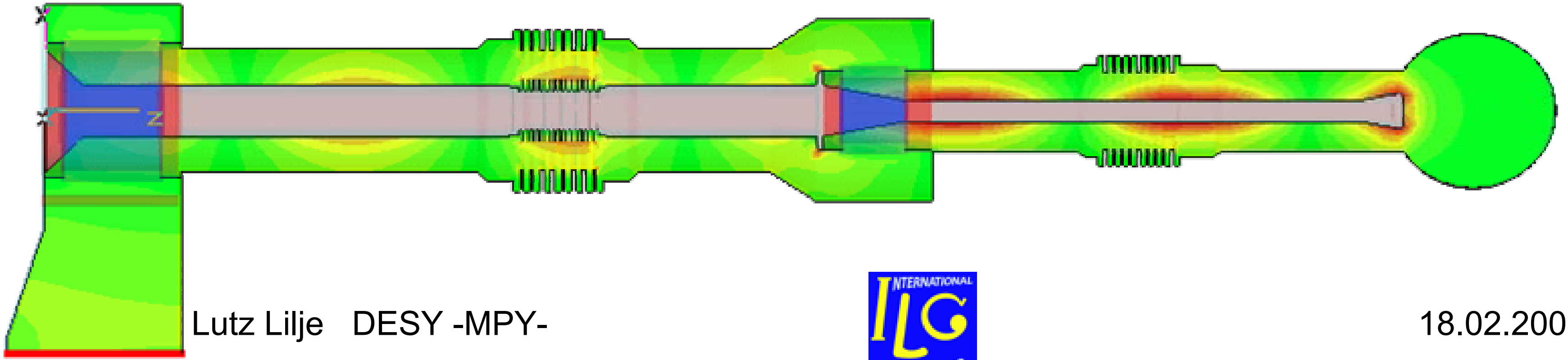
TTF III Coupler

frequency	1.3 GHz
operation	pulsed: 500 μsec rise time, 800 μsec flat top with beam
two windows, TiN coated	• safe operation • clean cavity assembly for high Eacc
2 K heat load	0.06 W
4 K heat load	0.5 W
70 K heat load	6 W
isolated inner conductor	bias voltage, suppressing multipacting
diagnostic	sufficient for safe operation and monitoring



RF Specifications

	TTF	**TESLA** 9cell / upgrade	**XFEL**
Peak power + control margin	250 kW	250 kW / 500 kW	150 kW
Repetition rate	10 Hz	5 Hz	10 Hz
Average power	3.2 kW	3.2 kW / 6.4 kW	1.9 kW
Coupling (Qext)	adjustable (10^6 - 10^7)	Fixed ($3*10^6$)	adjustable (10^6 - 10^7)



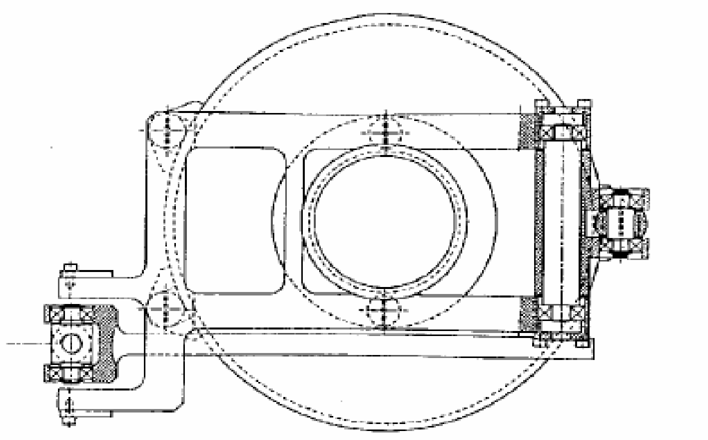
Coupler type		FNAL	TTF II	TTF III
cold part	window	conical	cyl.	cyl.
	coax diameter, mm	40	40	40
	Impedance, Ohm	50	70	70
bias		no	yes	yes
TiN coating		FermiLab	FermiLab	DESY
test stand TW	2Hz / 500µs	1MW	2MW	1MW
	2Hz / 1.3ms	1MW	1.8MW	1MW
	cold test done	yes	no	no
hiigh power test with Cavity	2Hz / <500µs	1MW	1MW	1MW
	5Hz/ 1.3ms SW	500 kW	500 kW	600 kW
	10Hz / 1.3ms	33MV/m	35MV/m	35MV/m
	cold test done	yes	yes	yes
fabricated total		16	20	62
assembled to		Mod.1*, 2	Mod.1*, 3*, 4	Mod.5, 6 (7, 8) SS
operated		1997-2004	1998-2004	2001-2004

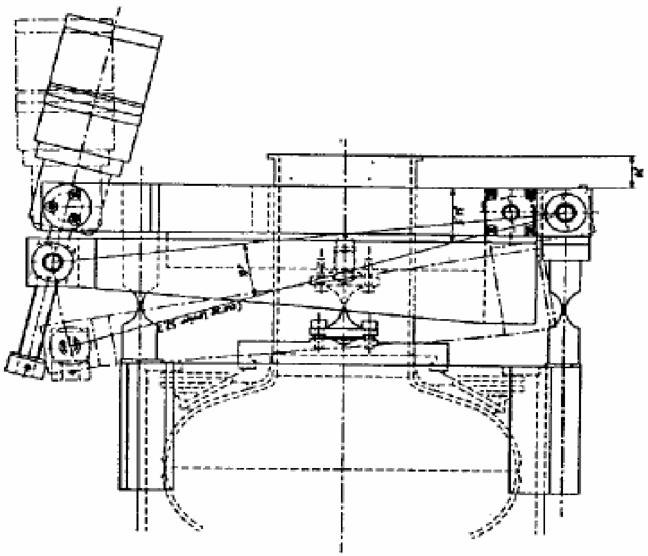
Coupler Test Results

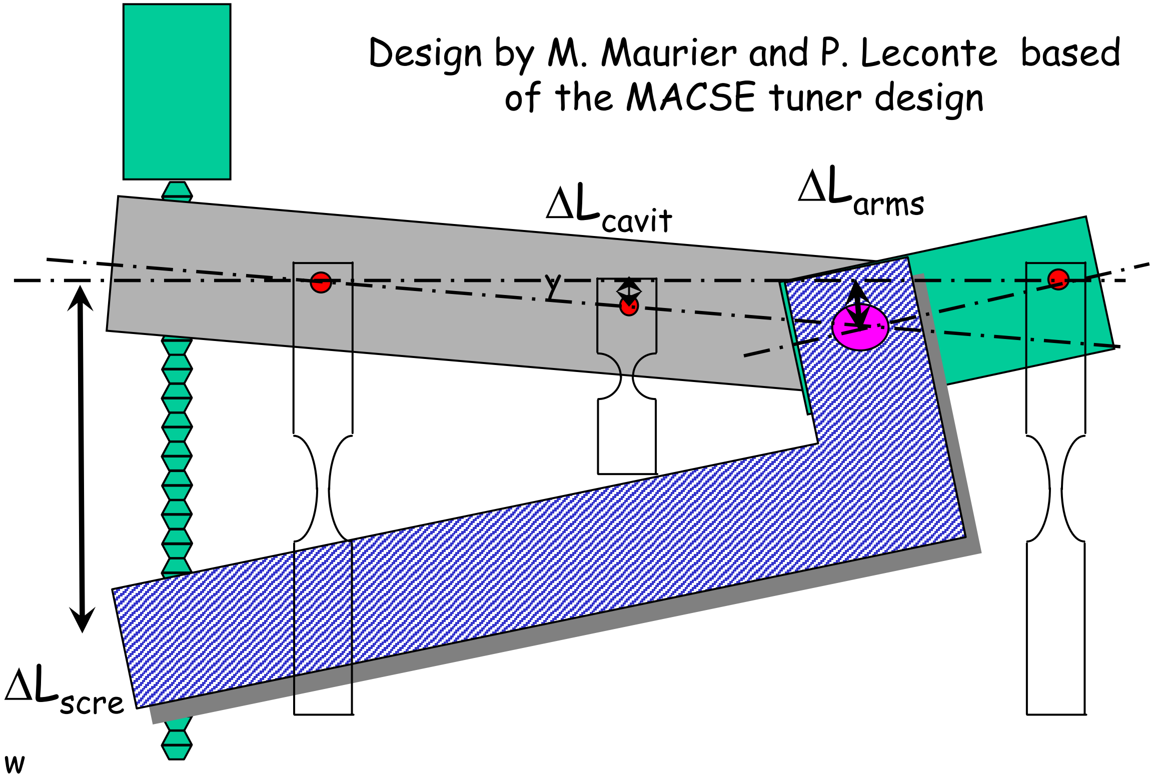
Coupler Issues

- Diagnostic
  - Temperature on cold window
  - Bias
  - Inner conductor e- pick-up
  - Open question: Is this sufficient?
- Adjustable Q_{ext}?
- Repetition rate
  - Up to 5 Hz o.k. in long-term test
  - 10 Hz needs probably cooling
- Further cost reduction
  - Orsay is working on this

Lateral Tuner
(Saclay)





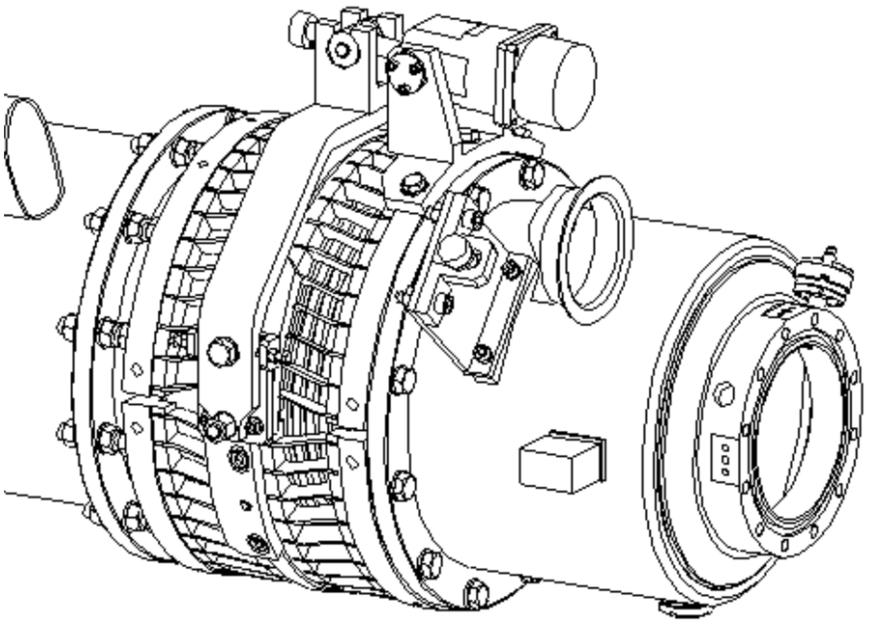


Design by M. Maurier and P. Leconte based of the MACSE tuner design

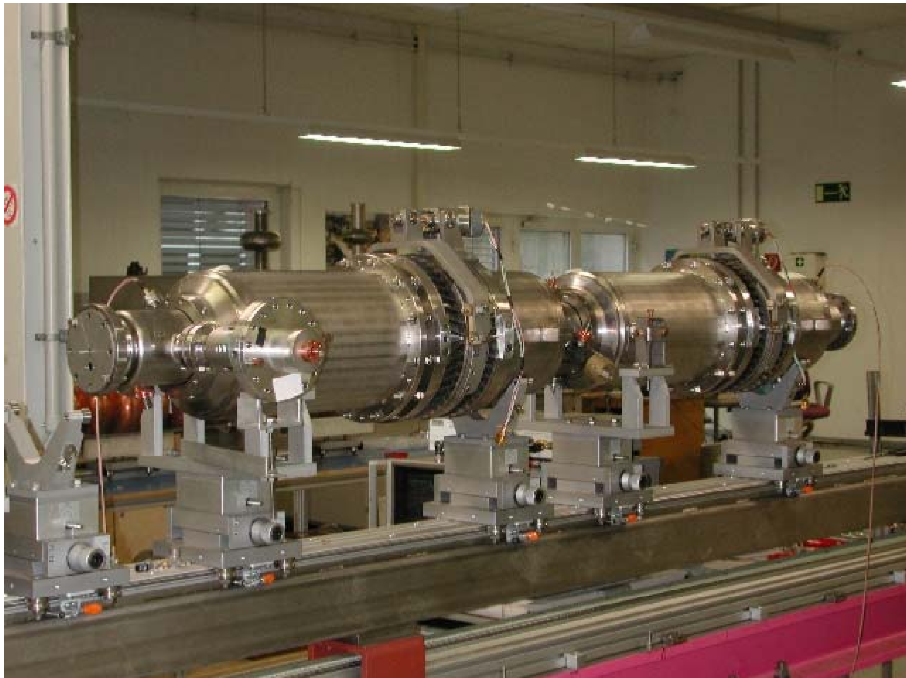
- Used in TTF
  - Double lever system: ratio ~ 1/17
  - Stepping motor with Harmonic Drive gear box
  - Screw – nut system
- Needs space between cavities
- Interferes with HOM couplers
- More compact design seems feasible

Coaxial Tuner (INFN, DESY)

- On the He vessel
- Tested on the superstructure in TTF (4 units)
- Magnetic shielding more difficult
- 2nd design exists
  - Test in CHECHIA done



	Standard	New Tuner
Tuning range [mm]	1.9	1
Tuning range [kHz]	820	440
Sensitivity [Hz/step]	0.74	0.38



Magnetic Shielding

- Superconducting niobium cavities need to be shielded from the earth magnetic shielding
- Flux frozen into the material during cooldown leads to increased surface losses ~3-5 nOhm/μT
- For $Q_0 > 10^{10}$:
  - Acceptable magnetic field: $B < 2\ \mu T$
- Use a cryoperm layer

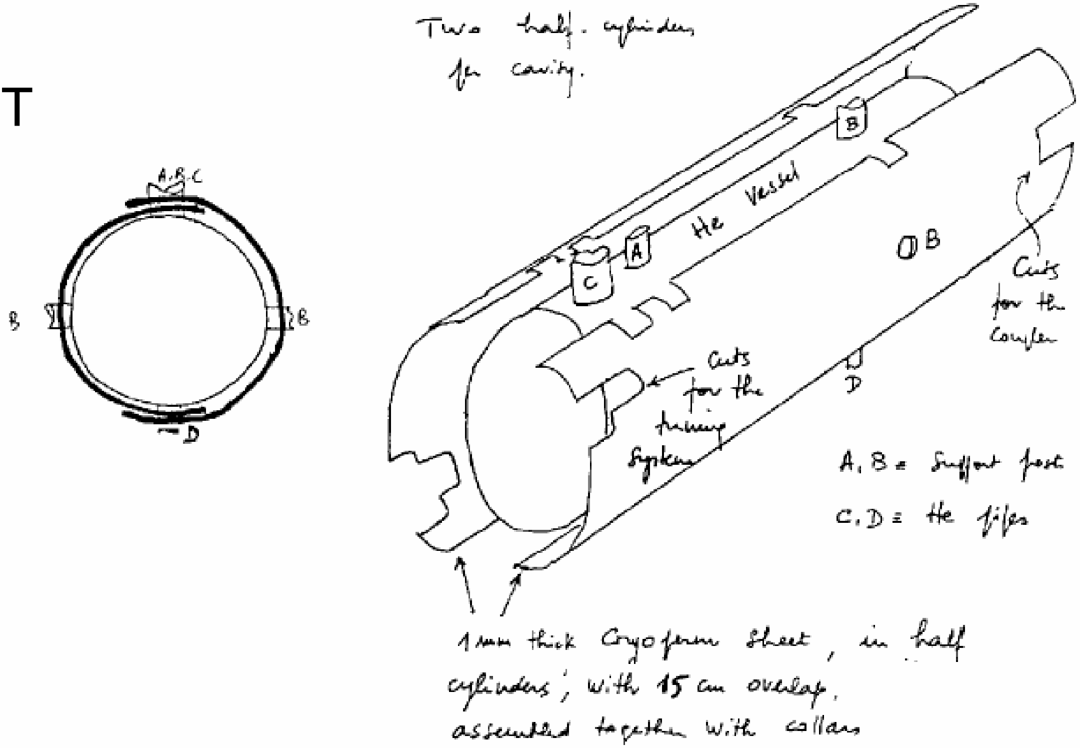


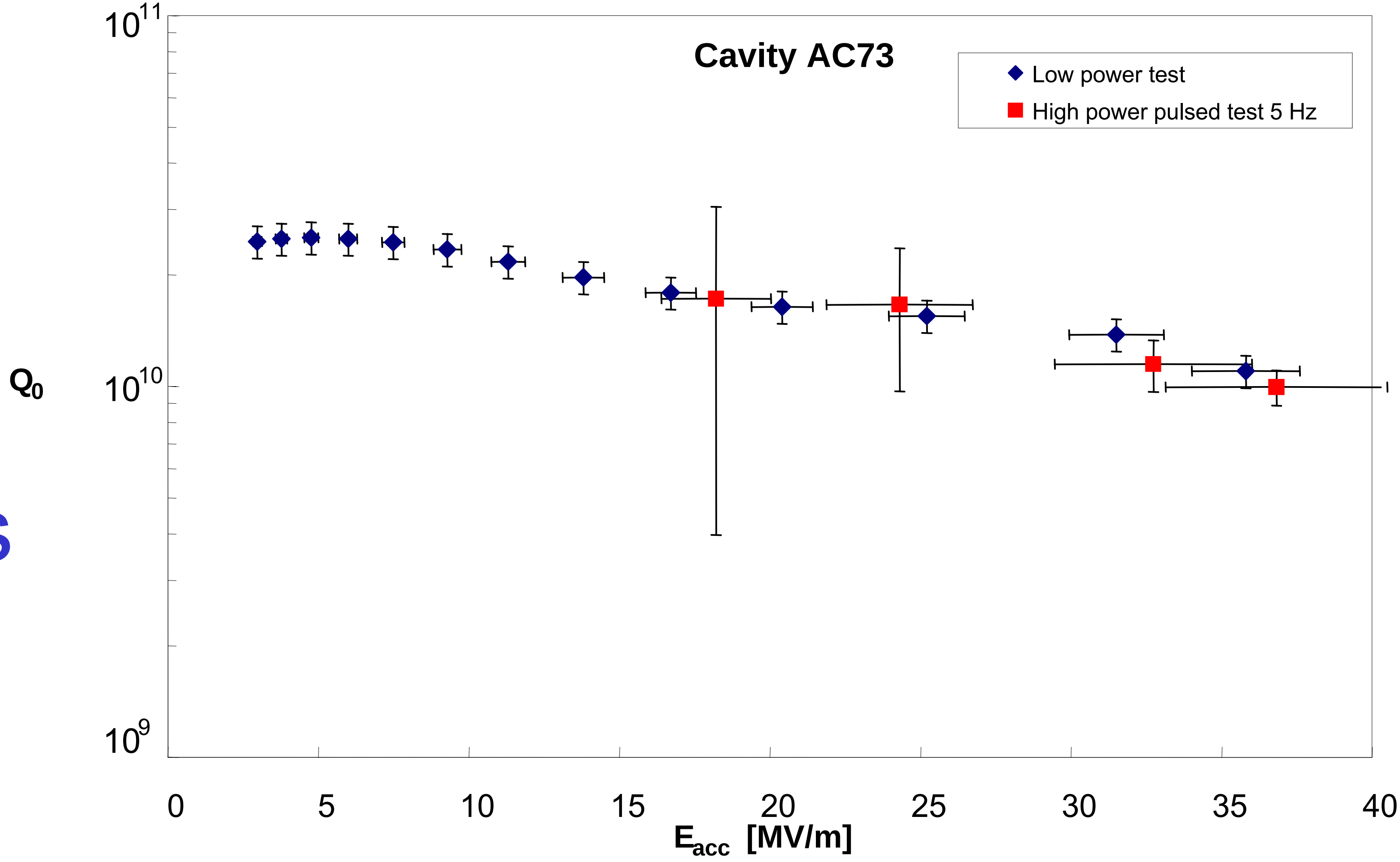
Figure 4.31: The Cryoperm shield around the helium vessel.

Example: High-Power Test of Two EP Cavities in the TTF Horizontal Cryostat

- Pulsed operation
  - TESLA-like (no beam)
- Important tool for tests on subsystems
  - Couplers
  - Tuners
  - Piezos

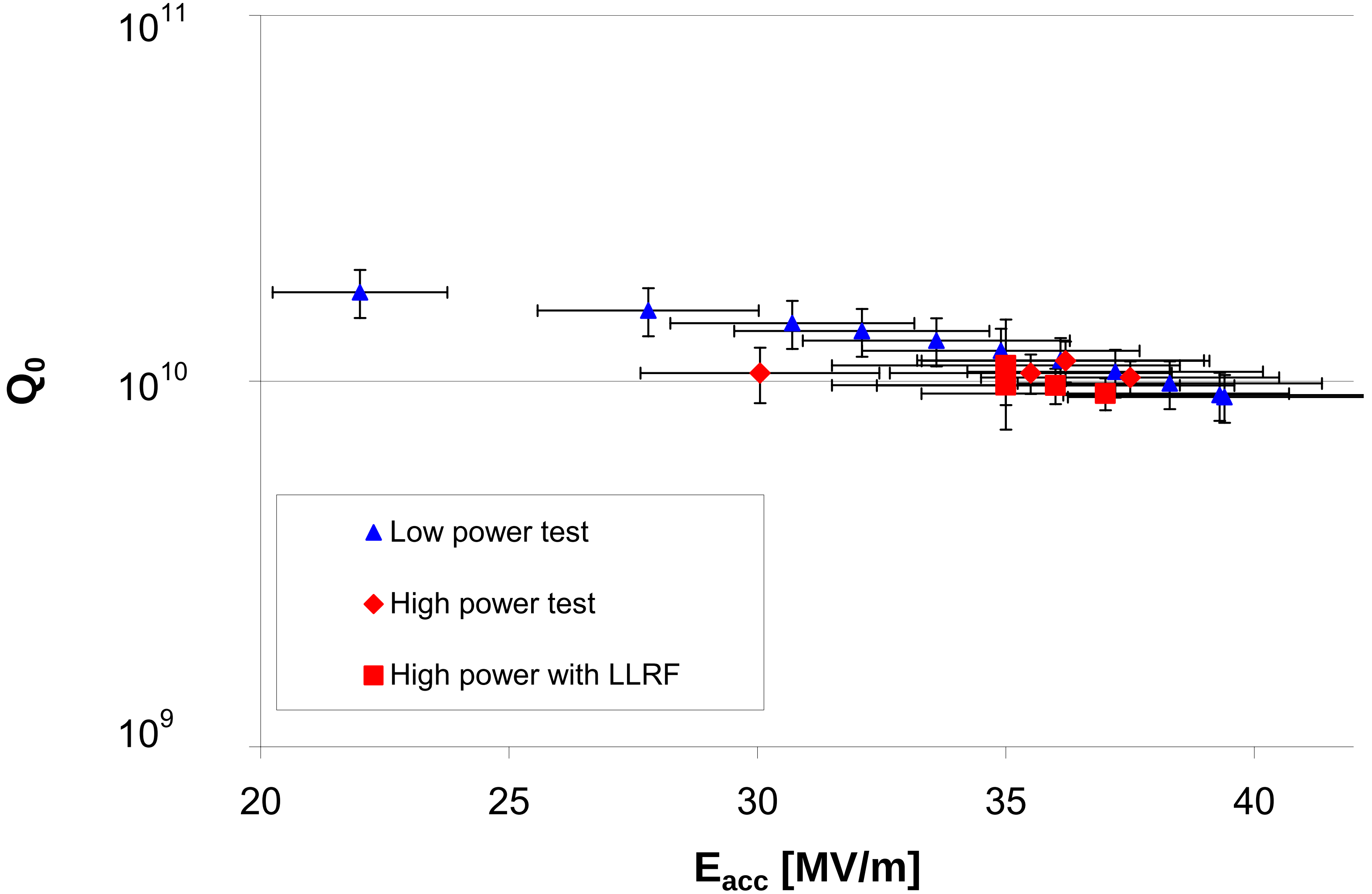
High Power Test Results

- 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.



TESLA Baseline Cavity Design Summary

- There are minor changes on components which still need to be tested (everybody believes it will be o.k., but final test needed):
- Cavity
    - Short inter-cavity spacing o.k.
        - This will NOT be done for the XFEL!
- HOM coupler
    - Mirrored upstream HOM coupler
    - Larger HOM Pickup antenna
    - The 4th production series of TTF cavities has these features

TESLA Baseline Cavity Design (ctd.)

- There are things which need a lot of detailed engineering
  - Coupler
    - Diagnostic
    - Adjustable Q_{ext} needed?
    - Repetition rate
    - Cost reduction
  - Tuner
    - Compact lateral tuner
      - Feasibility
    - Coaxial tuner
      - Integration of active elements
    - Fast tuner
      - Proof-of-principle done
      - Choice of Actuator
      - LLRF Integration
    - Beamline absorber (HOM)
      - Prototype for XFEL (see Jaceks Talk WG2)
- Work on energy upgrade needed
  - Use superstructures?
  - Couplers for superstructures
  - Superconducting bellows directly on the cavity (->Jacek)
    - Even more compact