Measurement Techniques

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Erice, April 27th, 2013
CAS on Superconductivity for Accelerators

Outline

- Some personal remarks
- Vertical test (Set-up + Procedure)
- Interpretation of RF signals (Part I)
- Temperature mapping
- Second Sound
- Radiation + dark current measurement
- Identification of Quench, Field emission, Multipacting (Part II)
- Processing
- Cryomodule testing

Some personal remarks

- My presentation will follow the “cavity point-of-view”.
- For more technical information + details I try to give some relevant references.
- The emphasis is on the vertical test
- Many examples will refer to the work done at DESY on 1.3GHz single- + nine-cell cavities.

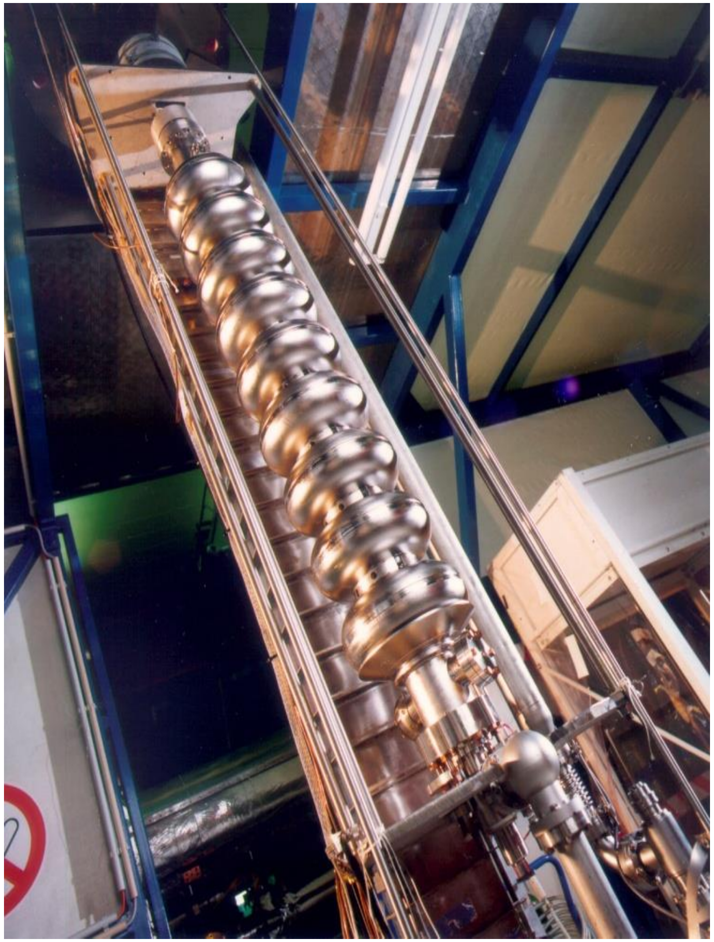
Some personal remarks

Use your common sense !!!

Vertical test of a SRF cavity

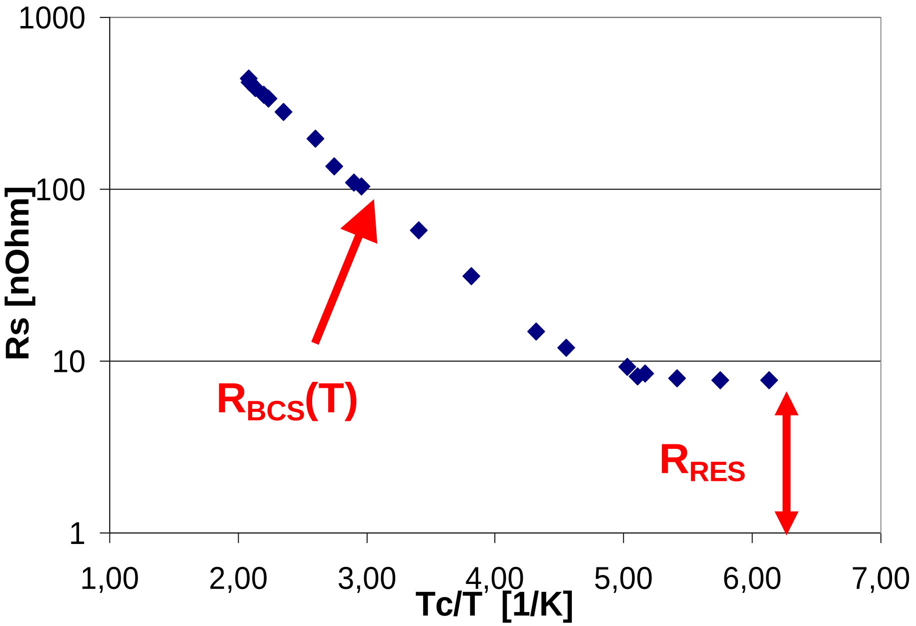
> Vertical test is

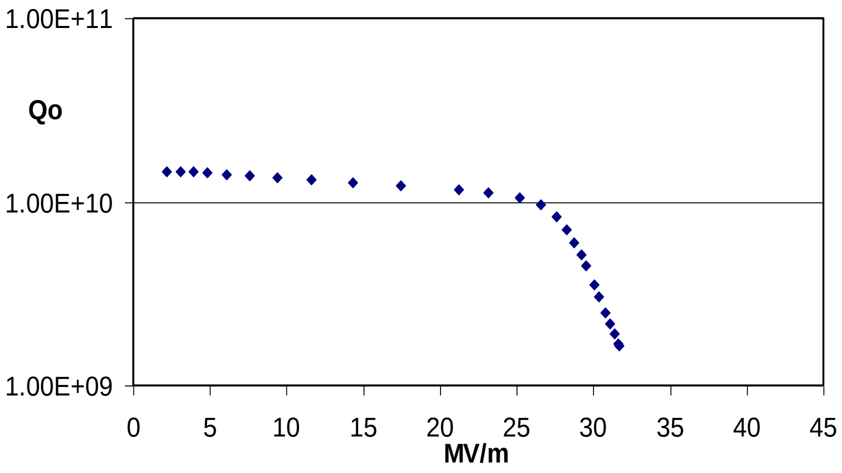
- Acceptance test of the overall cavity performance
  (e.g. XFEL series cavity production)
  => integral check of cavity fabrication
  \+ cavity surface treatment
- Check of a special treatment
  (e.g. single-cell cavities for special purposes,
  check of new techniques, etc.)
  => integral over **all** treatments / handlings
  since the vertical test before!



Vertical test of a SRF cavity II

- Goal is: Q_0 vs. E_{acc}; Q_0 vs. T
- RF measurement gives information of the average behavior => power losses are averaged over rf surface
- Operation in cw or “long” RF pulses (steady state is achieved)





Q_0 (E_{acc})

Q_0 (T) => R_s (T_c/T)

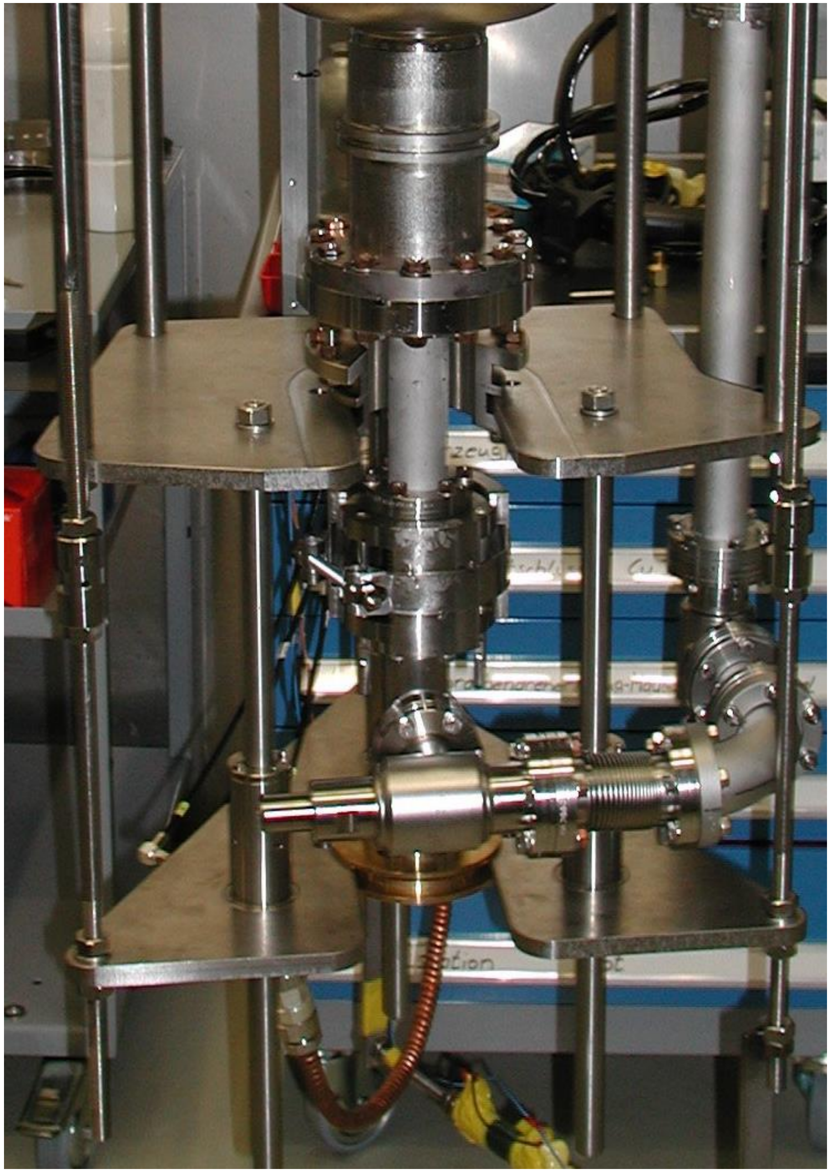
Preparation of vertical test

- Necessary preparation:
  - Cavity ready (after cleanroom work)
  - Evacuated, leak checked to < 1×10^{-10} mbar·l/sec, RGA (residual gas analysis) checked => lecture about vacuum techniques
  - Mechanical assembly to the test insert
  - Vacuum connection, pumping, leak check (+ RGA)
  - Connection of rf-cables incl. checks (short circuit, time-domain reflectometer measurement)
  - Assembly + check of diagnostics (Second Sound, temperature mapping, x-ray sensors, …)
  - Transport to vertical cryostat

Preparation of vertical test

- Preparation in vertical cryostat:
  - Mechanical assembly of insert to cryostat
  - Vacuum connection, pumping and leak check of connection
  - Connection of rf-cables, diagnostics, cryo sensors, etc. incl. check
  - Cool down to 4.2 K (maybe after holding at 100K)
  - Preparation of interlock systems
- RF test:
  - RF-cable calibration
  - *Optional:* Measurement of $Q_0(T)$ from 4.2K to ≤ 2K
  - Measurement of $Q_0(E_{acc})$
  - *Optional:* $Q_0(E_{acc})$ at various temperatures
    $Q_0(E_{acc})$ in passband modes
    Diagnostics: T-mapping, Second Sound, x-ray analysis

Vertical test insert



Vertical test insert II

Reminder: Basic Relations

- Quality factor Q_0:

$$Q_0 = \frac{\omega W}{P_{diss}}$$

W: stored energy

P_{diss}: dissipated power

$$Q_0 = \frac{G}{R_s}$$

G: geometry factor

- Accelerating gradient E_{acc}:

$$E_{acc} = \frac{\sqrt{{}^{R}/_{Q} \cdot Q_0 \cdot P_{diss}}}{l \cdot n}$$

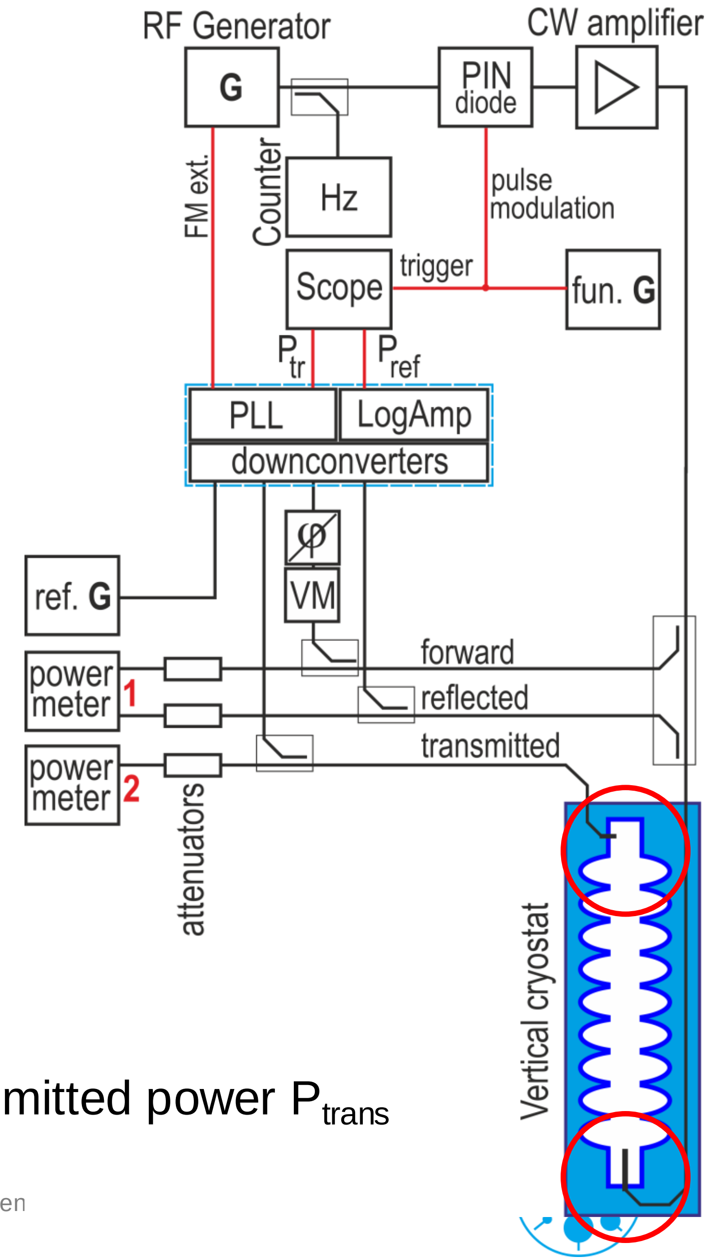
${}^{R}/_{Q}$: shunt impedance

l: active electric length

n: number of cells

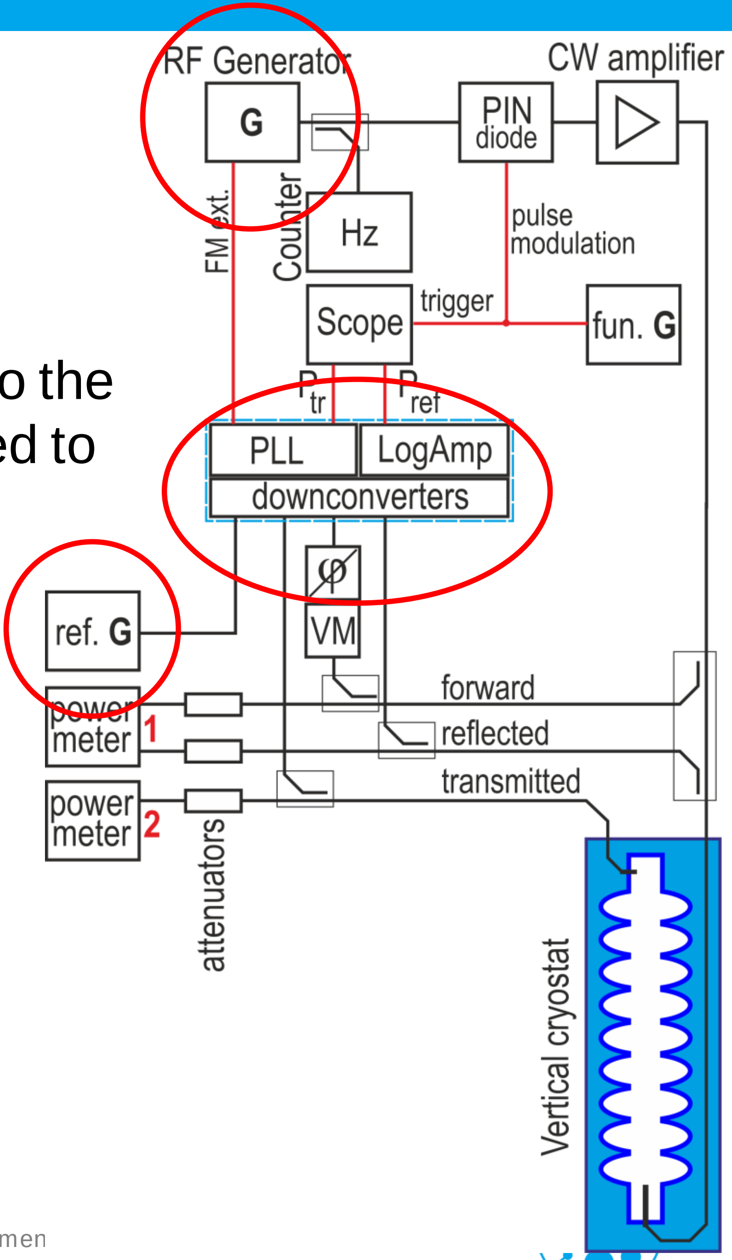
RF set-up for vertical test: Introduction

- Goal is: Q_0 vs. E_{acc}; Q_0 vs. T
- Operation in cw or “long” RF pulses
  (steady state is achieved)
- Cavity is coupled to RF with
  - Input antenna: matched or adjustable to the expected Q_0 for low (zero) reflected power
  - Pick-up probe for transmitted power:
    “weak” coupling (typically $Q_{trans} \approx 10^2$-10^3 Q_0)
  - For simplification we ignore further coupling ports for HOM damping
- Direct quantities to be measured:
  - Frequency f_0
  - Decay time τ
  - Forward power P_{for}, reflected power P_{ref}, transmitted power P_{trans}



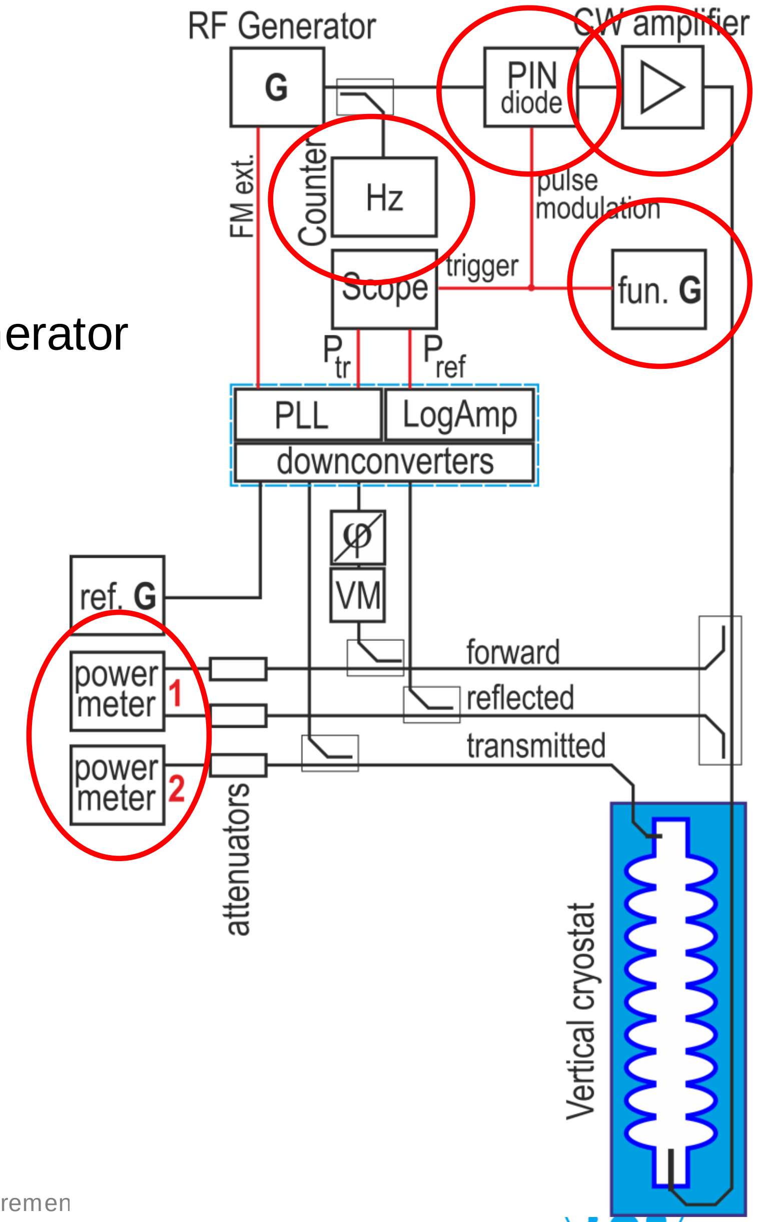
RF set-up for vertical test

- Sharp resonance (HWFM can be < 1Hz) requires “phase locked loop” (PLL)
- PLL:
  fraction of P_{trans} and P_f are fed in a rf mixer, downconverted and a voltage proportional to the phase difference between the signals is used to control the frequency of the RF generator.
  Phase shifter for one of the signals is necessary:
  Phase = 0 => Cavity on resonance
- RF generator:
  - Analog VCO (voltage controlled oscillator)
  - “modern” RF generator



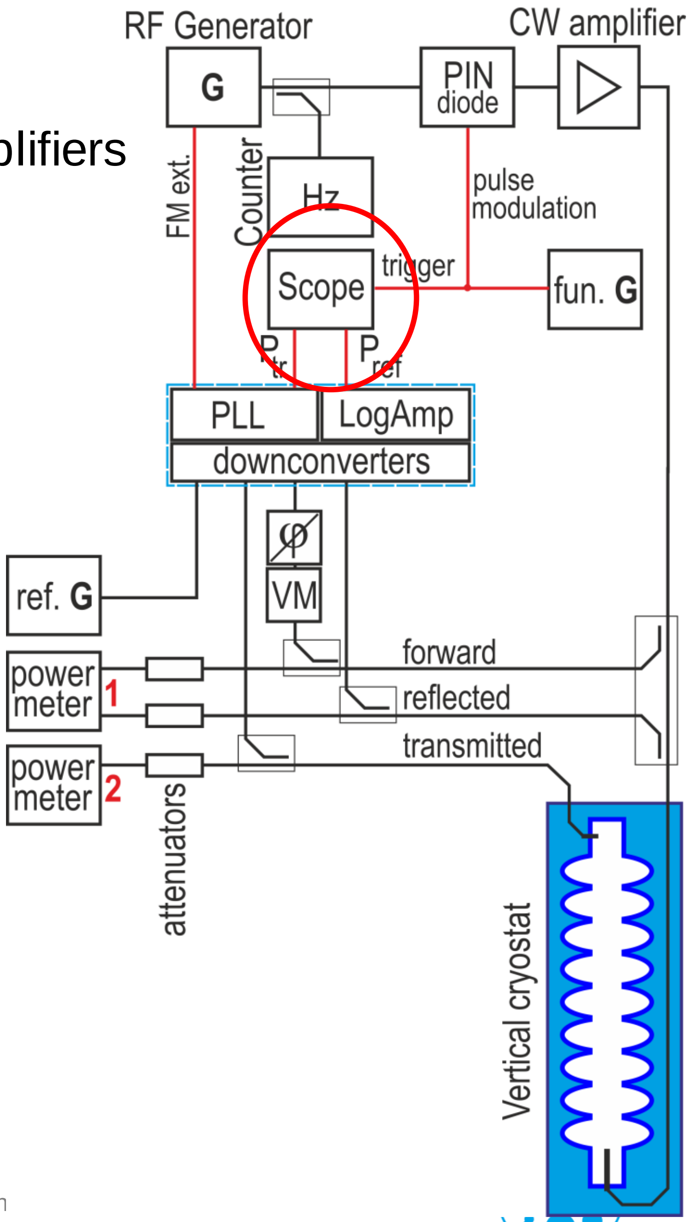
RF set-up for vertical test II

- Frequency counter
- PIN diode + function generator:
  - fast switching of the rf signal
  - typically a rectangular pulse by function generator
- CW amplifier
  - typically up to 1 kW
  - Solid-state is state-of-the-art
  - Water or air cooled
  - Important: Circulator
- Power measurement in steady state
  - Power meter



RF set-up for vertical test III

- Power measurement for pulses
  - Scope with crystal detectors or logarithmic amplifiers
  - ADC’s with logarithmic amplifiers
- Passive components:
  - Directional couplers
  - Attenuators
  - Cables



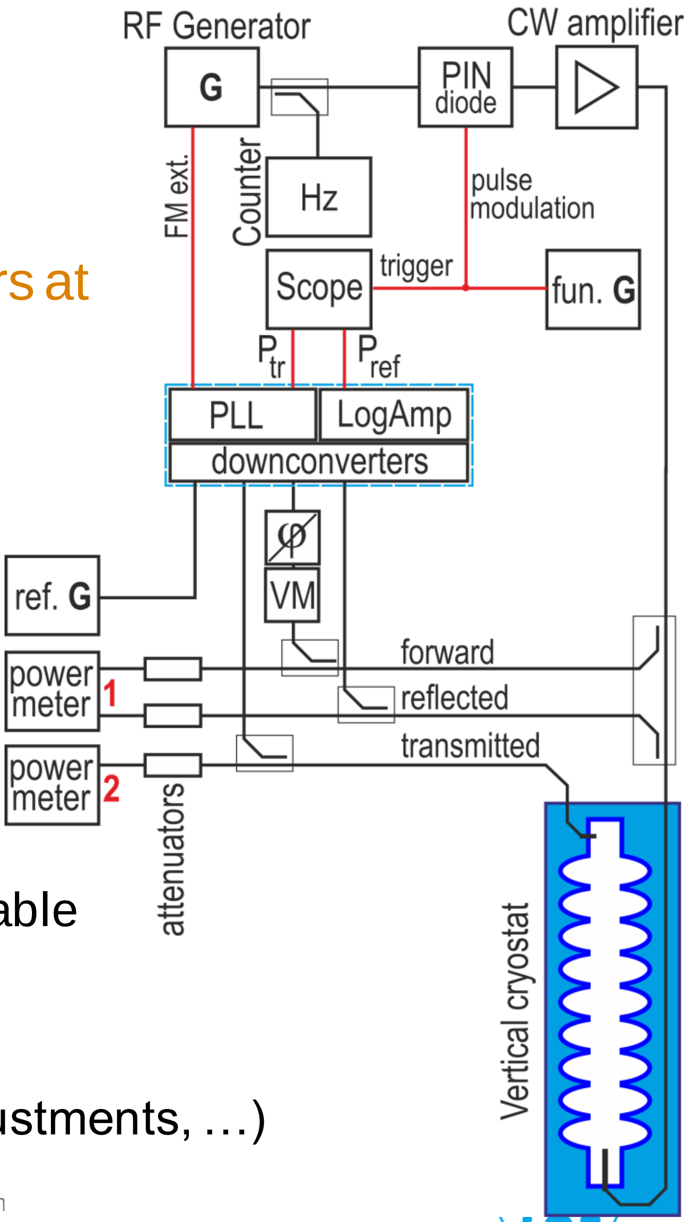
RF set-ups

AMTF DESY 1.3GHz for XFEL cavities

2005: JLab 0.5-3GHz VCO PLL system for R&D

Cable calibration

- You need the RF power levels at the cavity, but you measure in your test rack.
- Accurate knowledge of cable attenuation, attenuation of directional coupler + attenuators at test frequency mandatory!
- Cable calibration:
  - outside of the cryostat:
    1-way calibration for all cables
    => easy and low error
  - Inside of the cryostat:
    i) 2-way calibration (reflection measurement)
    ii) indirect 1-way calibration
    => use an identical (type + length) reference cable inside the cryostat
- Several sources of errors possible !!!
  (directional coupler, “bad” connections, wrong adjustments, …)



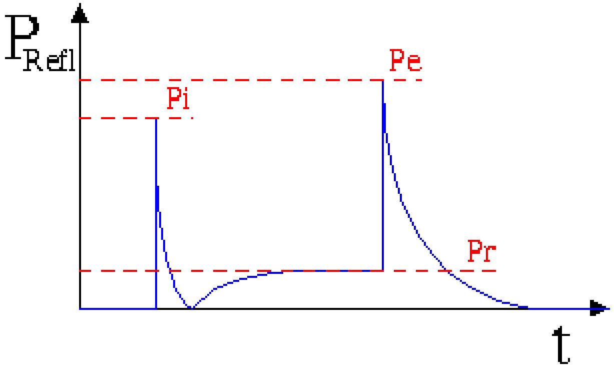
Interlock

- SRF cavities can “produce” significant and hazardous x-rays with comparatively low RF power
- RF measurements direct at the cryostat require exact rules and limits depending on your local test situation
- For high gradient measurements an appropriate shielding and operational interlock system is mandatory

The path to Q_0 and E_{acc}

- Remark: **What follows is a simplified view!**
  The full picture and set of equations can be found in the references.

- Direct quantities to be measured:
  - Frequency $f_{0,}$ decay time τ
  - Steady state: P_{for} , P_{ref} , P_{trans}
  - Pulse measurement: P_{for} , P_{ref} , P_{e} , P_{trans} (next slides)



- Definition of coupling strength β: $\beta_x = \frac{Q_0}{Q_x} = \frac{P_x}{P_{Diss}}$
  - **high β**: strong interaction of the coupler with the cavity
    => power extracted by the coupler is large compared to the power dissipated in the cavity walls

- Definition of loaded Q_L: $Q_L = 2\pi f_0 \tau = \frac{\omega}{2 \cdot \Delta\omega} = \frac{\omega W}{P_{tot}}$

The path to Q_0 and E_{acc} II

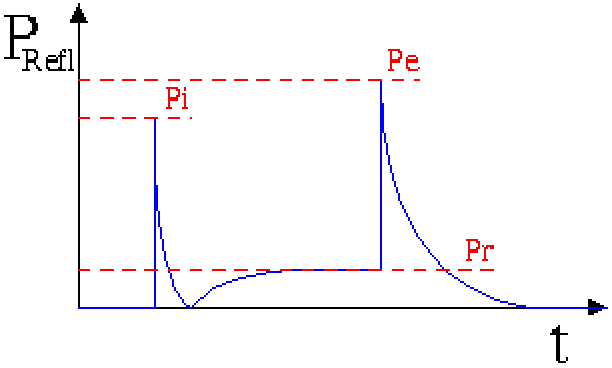
- Step 1:

  Calculation of β in steady state: $$\beta = \frac{1-\sqrt{\frac{P_{refl}}{P_{forw}}}}{1+\sqrt{\frac{P_{refl}}{P_{forw}}}}$$ for undercoupling or
  β = 1/ β for overcoupling

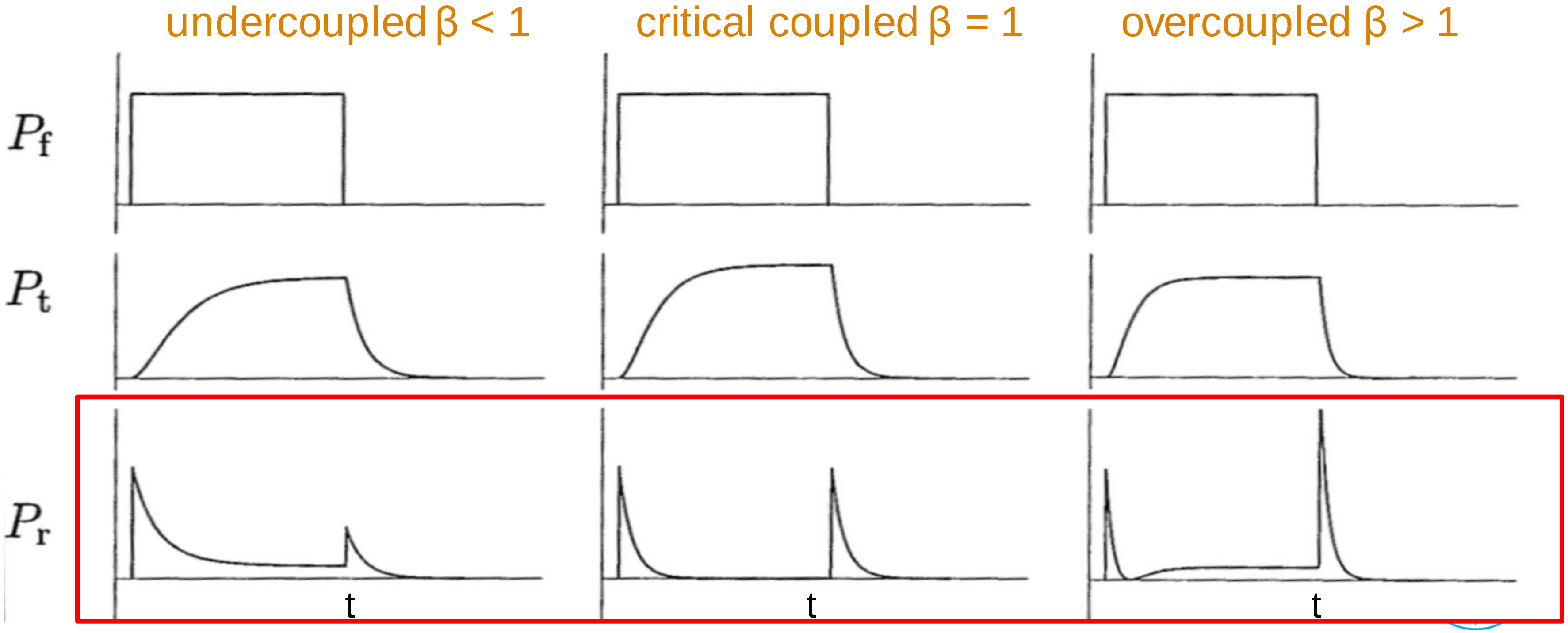
  Note: Steady state measurement is not unique
  => pulse measurement is necessary!

The path to Q_0 and E_{acc} III

- Step 2: Response of the cavity to a rectangular RF pulse
  - independent calculation of β from P_{for} , P_{ref} , P_e
=> 3 more equations for β



  - decision about coupling of the cavity:



The path to Q_0 and E_{acc} IV

- Step 3: Calculation of dissipated power:

$$P_{diss} = \frac{4 \cdot \beta \cdot P_{for}}{(1+\beta)^2} - P_{trans}$$

- Step 4: Measurement of τ and calculation of Q_L (pulse measurement)
- Step 5: Calculation of Q_0:

$$Q_0 = Q_L \cdot \left[1 + \beta \cdot \left(1 + \frac{P_{trans}}{P_{diss}}\right) + \frac{P_{trans}}{P_{diss}}\right]$$

- Step 6: Calculation of E_{acc}:

$$E_{acc} = \frac{\sqrt{R/Q \cdot Q_0 \cdot P_{diss}}}{l \cdot n}$$

- Step 7: Calculation of Q_{trans} and Q_{in} ($Q_i = \frac{Q_0 \cdot P_{diss}}{P_i}$)

The path to Q_0 and E_{acc} V

- This procedure can be repeated for each point of Q_0 (E_{acc}) + Q_0 (T)
- **Simplified sequence for Q_0 (E_{acc}) after one "full" point**:

  Next points of Q_0 (E_{acc}) can be simplified, if the Pick-up antenna is fix (assuming Q_{trans}= const.)

  => Definition of factor k_t (calibration constant):

$$k_t = \frac{E_{acc}}{\sqrt{P_{trans}}}$$

  => E_{acc} is given by

$$E_{acc} = k_t \cdot \sqrt{P_{trans}}$$

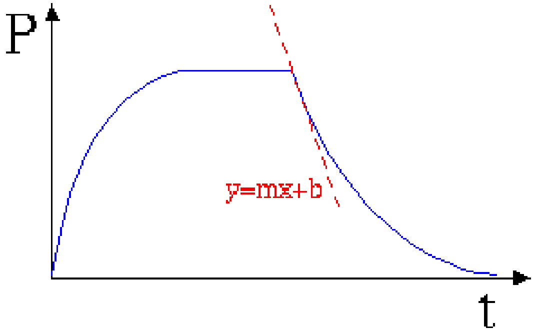
  => Q_0 is calculated by

$$Q_0 = \frac{(E_{acc} \cdot l \cdot n)^2}{R/Q \cdot P_{diss}}$$

- Remark: You still need to decide about the over/undercoupling!

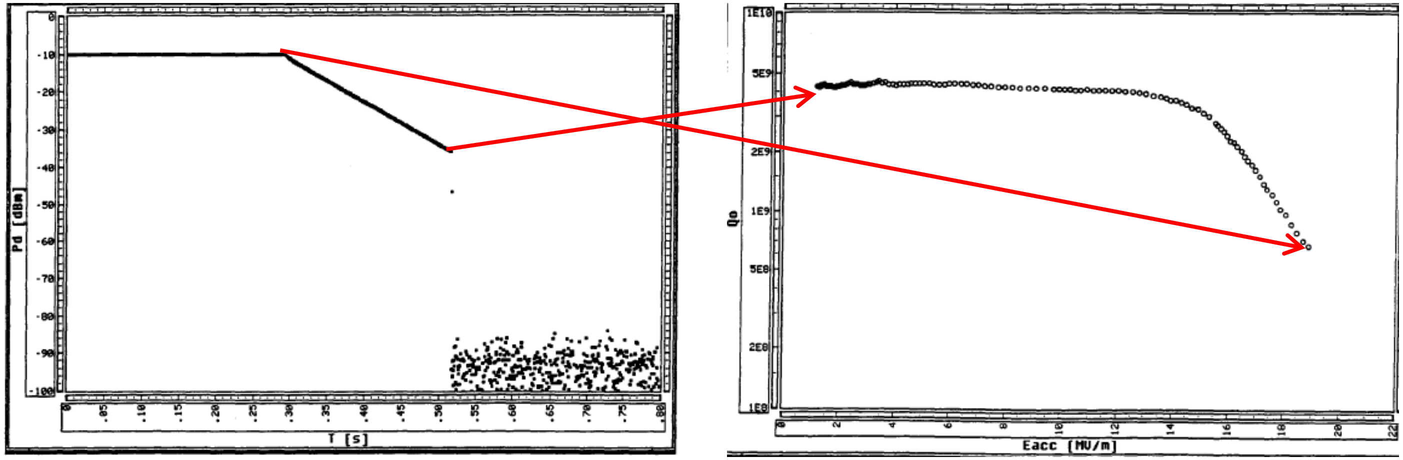
The path to Q_0 and E_{acc} VI

- An alternative approach to determine a $Q_0(E_{acc})$-curve **later** in the test is the analysis of the P_{trans} (t) measurement
  - not for the first $Q_0(E_{acc})$-curve!



- Assuming the coupling factors β_i are determined, then
  - P_{trans} gives you E_{acc}
  - the time derivative $\frac{dP_{trans}}{dt}(t)$ gives you the loaded Q_L => Q_0

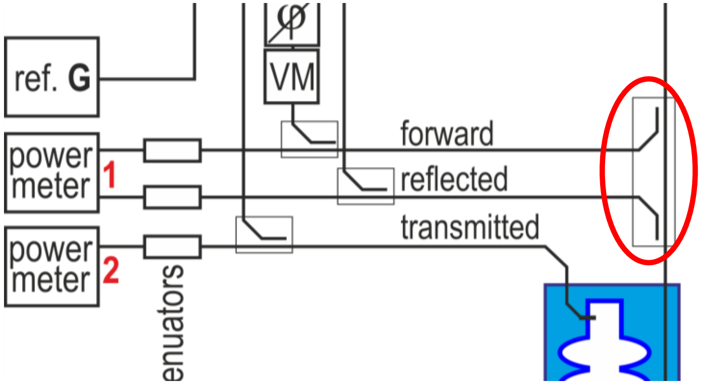
$P_{trans}(t)$



$Q_0(E_{acc})$

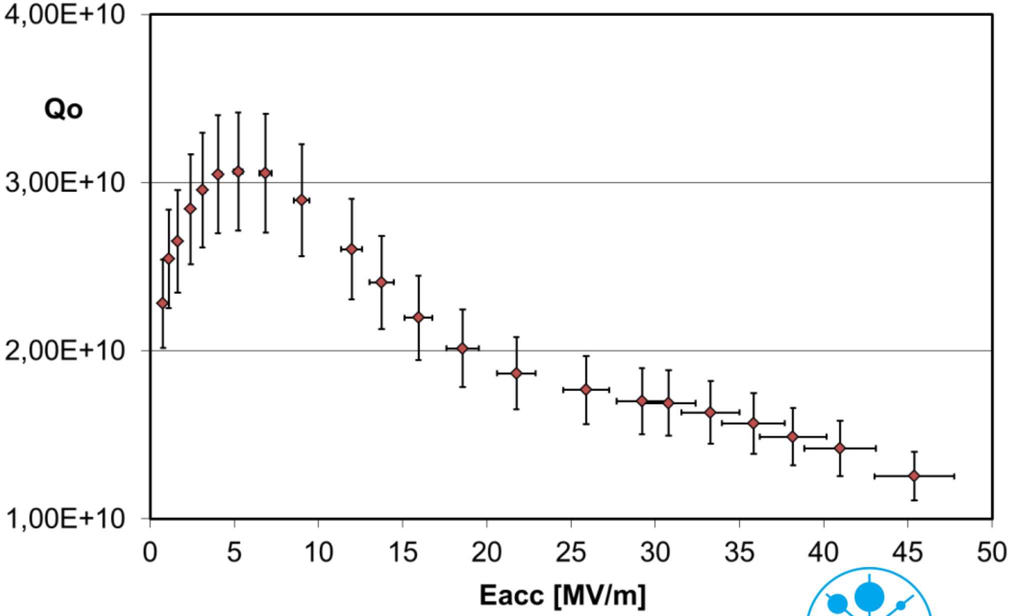
Measurement errors

- Main sources of the “typical” measurement error:
  - Directivity (≈ 30 db) of best commercial double directional coupler in the input line
  - Interference of the forward and reflected wave => affects β
  - Reproducibility of cable connections



- Critical coupling (β ≈ 1) minimizes the error => no reflected wave on the input line

- $\delta Q/Q \approx \pm(10-20)\%$
- $\delta E_{acc}/E_{acc} \approx \pm(5-10)\%$



Interpretation of RF signals

- Cavity limiting phenomena show typical RF signals ("Diagnostics Methods of Superconducting Cavities and Identification of Phenomena", H. Piel, SRF work shop1980)
- **Quench**, **Field Emission** and **Multipacting** after the diagnostics chapter

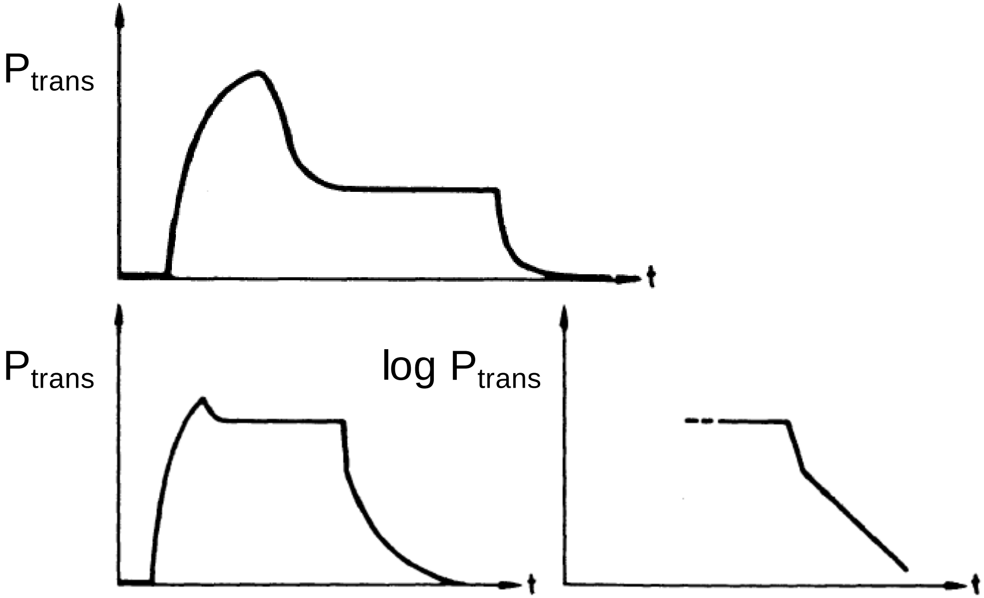
- 1) Response without any limiting / degrading / "special" effect:

Interpretation of RF signals II

> 2) Additional losses appear during the built-up time of the field

=> **something is warming up!**

- Weak-spot in the cavity
- Heating in couplers, antennas

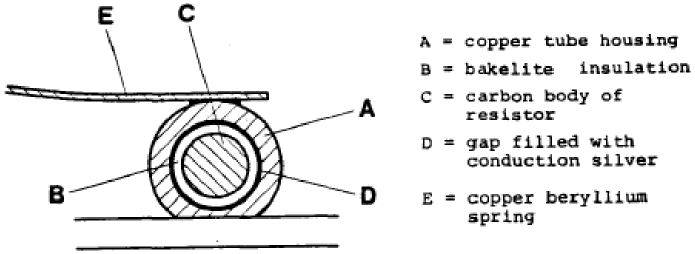


> 3) Sudden changes in the power relation appearing like a Q-switch (within one rf point or increasing the power to the next point)

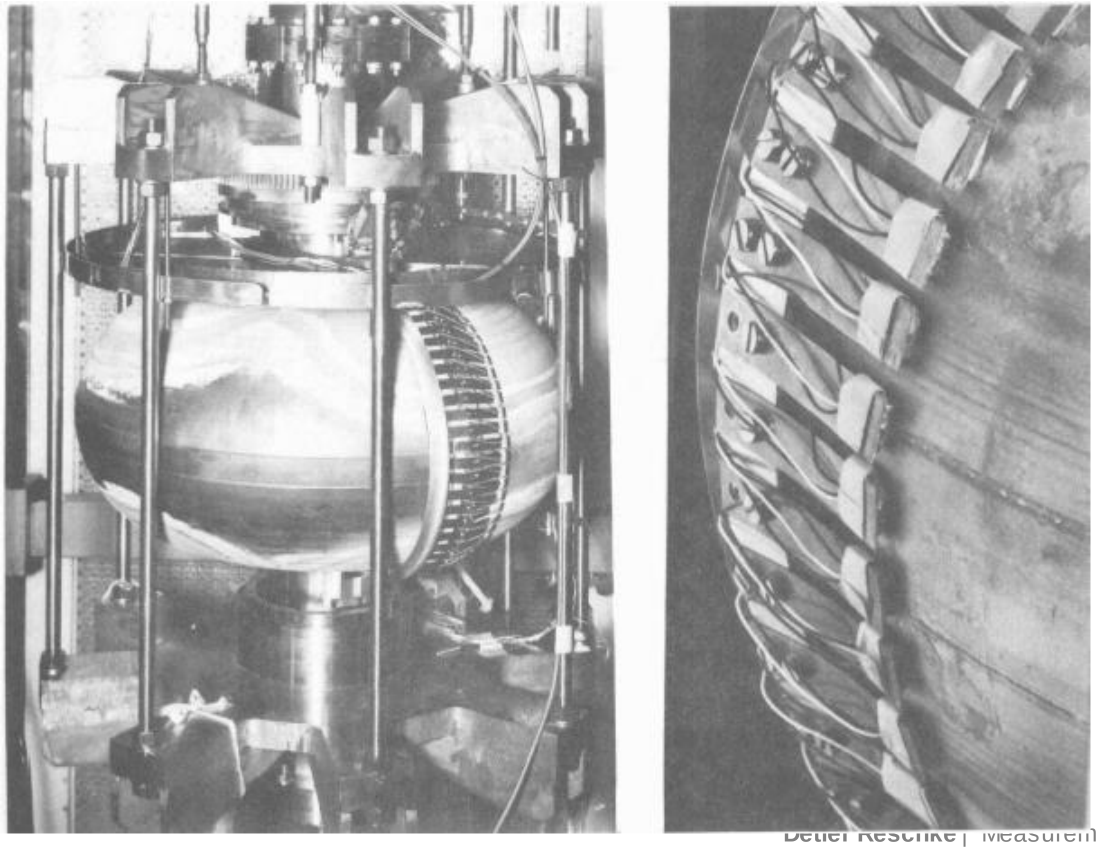
=> Maybe a breakdown in your power cable /connector by gas discharge in the low pressure helium (Paschen minimum is close)!

Temperature Mapping

- **Measure the temperature on the He-side to detect losses on the RF-side**
- Developed in the 1970es at Stanford + CERN for normal-fluid / sub-cooled helium



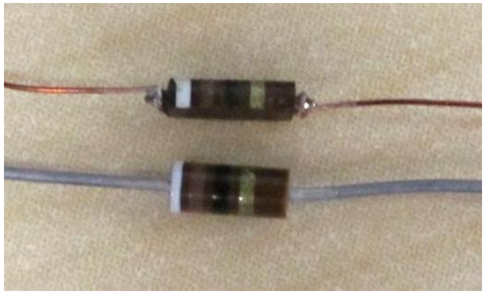
Cross section of the carbon thermometer



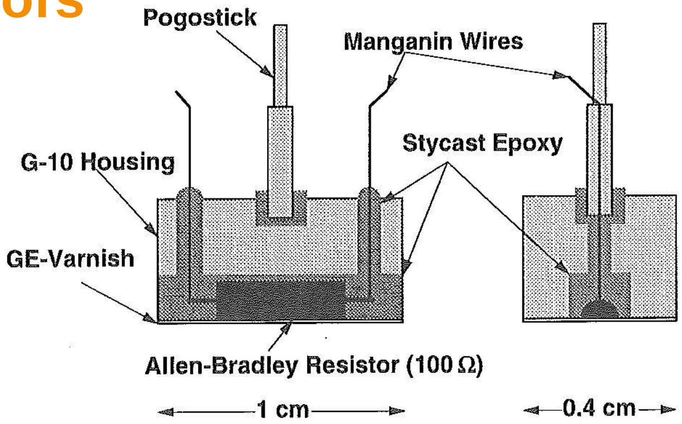
Rotating thermometry system used at CERN for 350 MHz

Temperature Mapping in superfluid He

- In superfluid He (necessary for high gradients + $f_0 > 1$ GHz):
  - + BCS losses are suppressed
  - + spatial resolution is increased
  - - “efficiency” of thermometers is reduced due to extremely good cooling
    for fixed thermometers: 20-40% with strong variations
    for movable thermometers: < 3%
- Basic component is a heat sensitive element with a strong characteristic line at low temperatures:
  mostly carbon resistors



Allen-Bradley carbon resistor 100 Ω, 1/8 W
4.2K: ≈ 1 kΩ
1.8K: > 10 kΩ

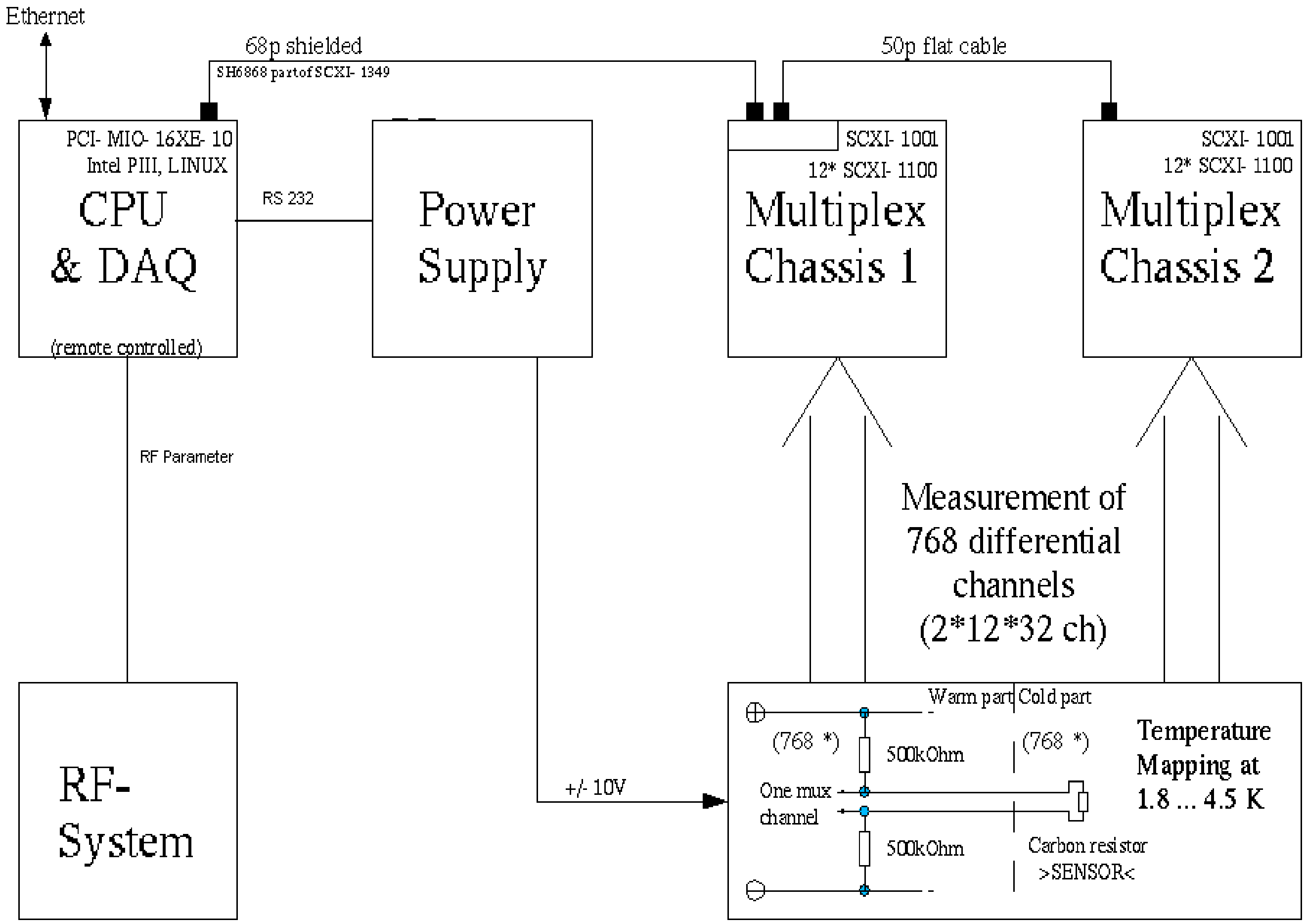


“Pogostick” Thermometer (Cornell)

Cernox® resistors

Temperature Mapping: Layout

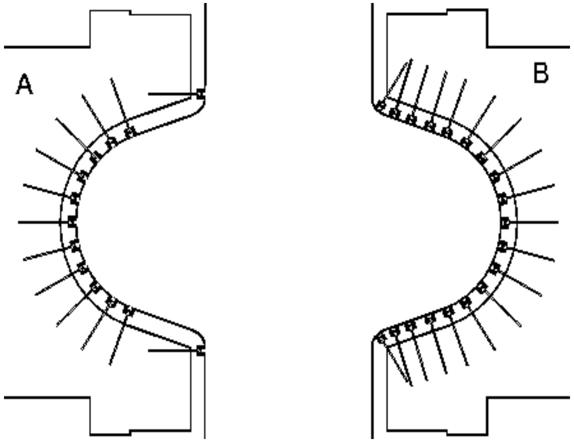
- General layout of T-mapping system (DESY):

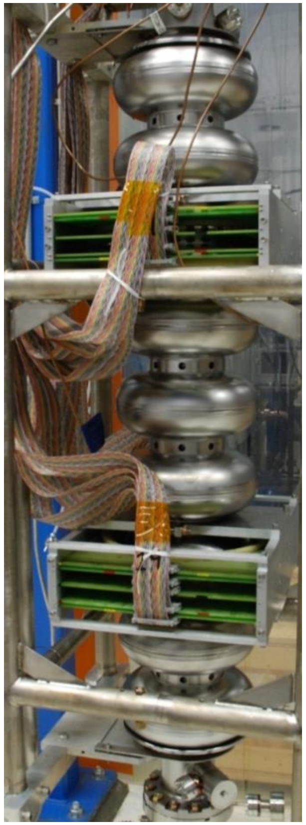


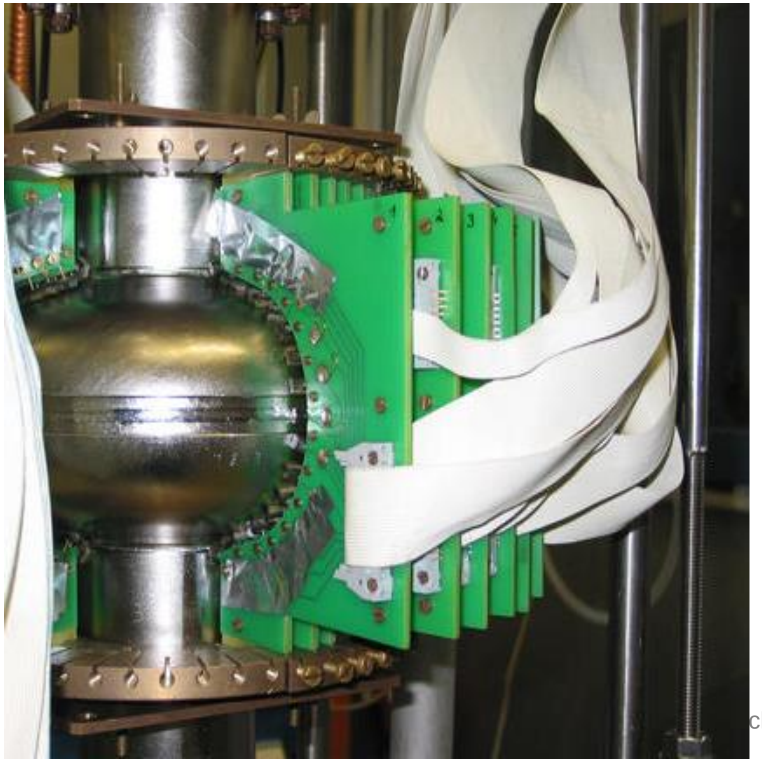
- Calibration of resistors for individual R_i (T_{bath}) between 4.2K and 1.8K

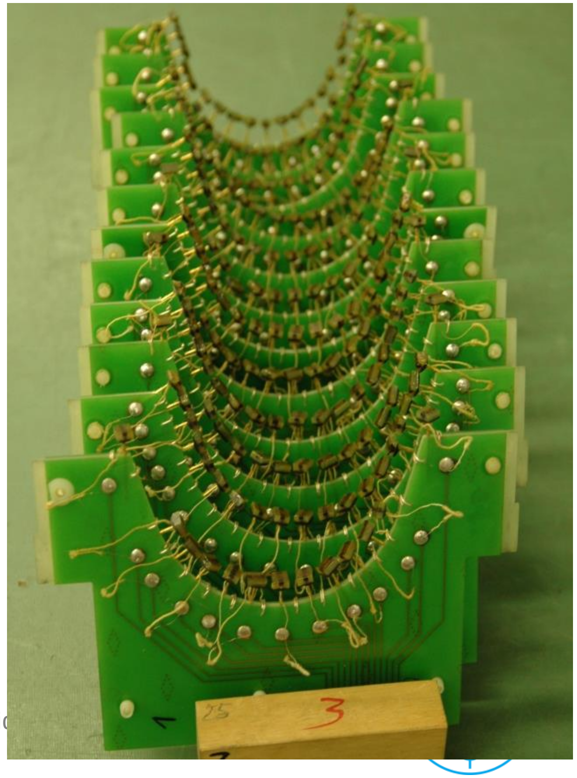
Temperature Mapping: Fixed Systems I

- Fixed systems with several hundreds of resistors
  - + Fast read-out (≈ sec)
  - + Sensitive: ΔT ≈ 0,1 mK can be detected
  - - Sensitive cabling
  - - Intensive maintenance necessary



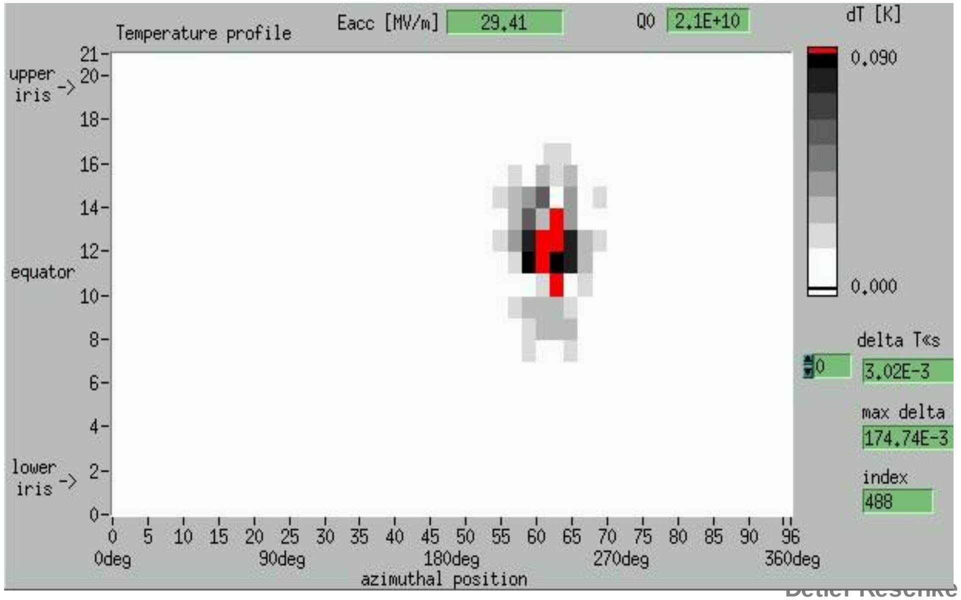






Temperature Mapping: Fixed Systems II

- Fixed systems are most complex, but most powerful:
  - 1) Qualitative analysis => quench location (easy)
  - 2) Semi-quantitative analysis => ΔT vs. E_{acc}
  - 3) Quantitative analysis => $R_{s,calc}$ from ΔT (requires additional calibration)
  - 4) time resolved measurements => temperature (quench) evolution
- Example 1: Locating the quench and the temperature distribution (2D- or 3D-view)



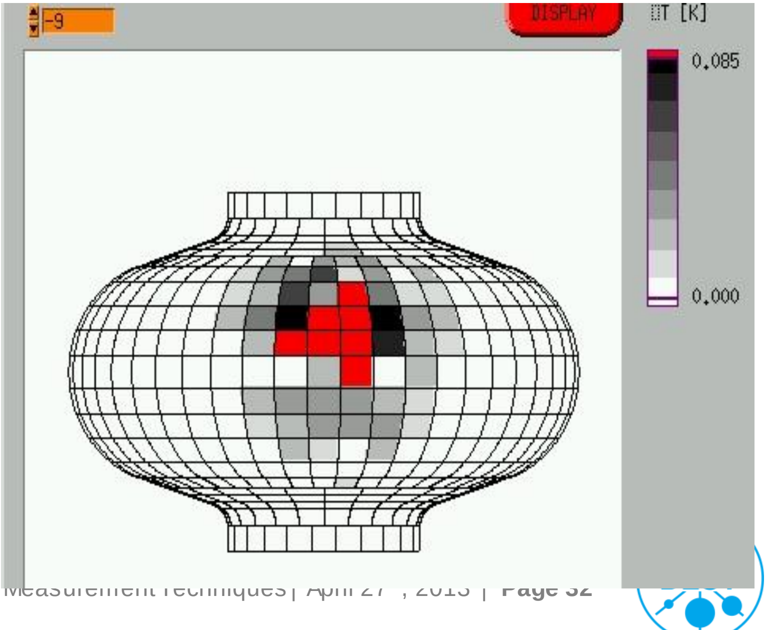
Eacc [MV/m] 29.41

Q0 2.1E+10

delta T«s 0 3.02E-3

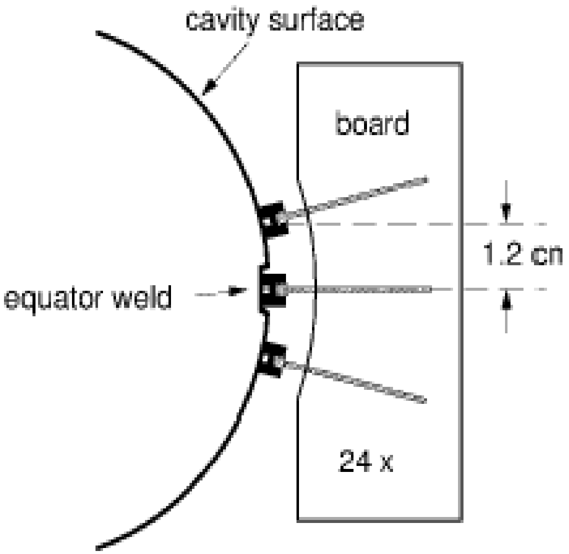
max delta 174.74E-3

index 488



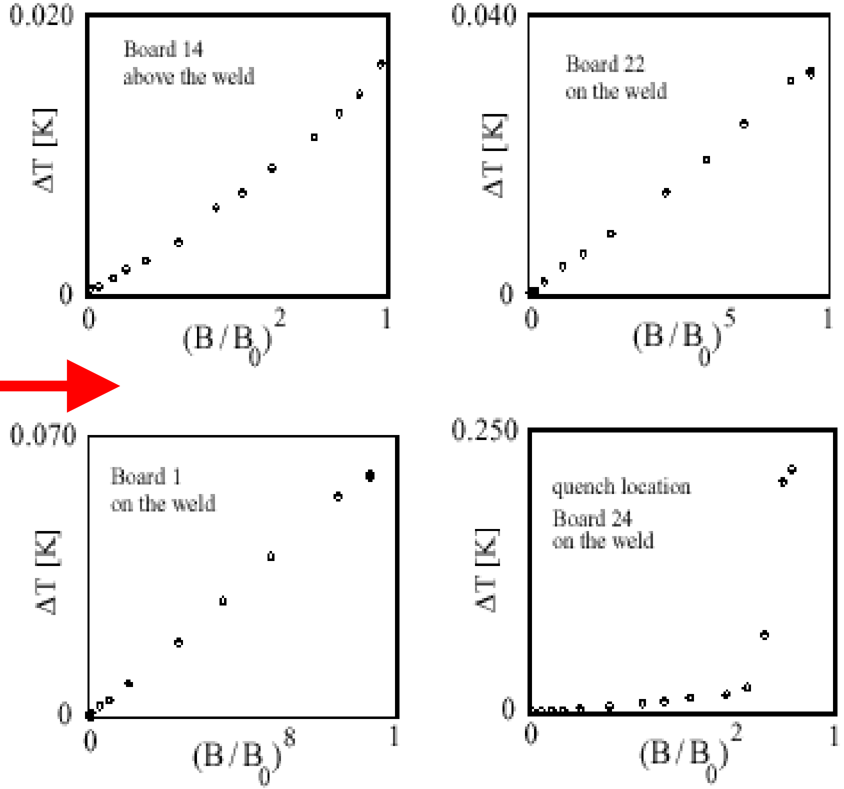
Example 2: Check of ΔT vs. B^n

Temperature mapping of the equator region

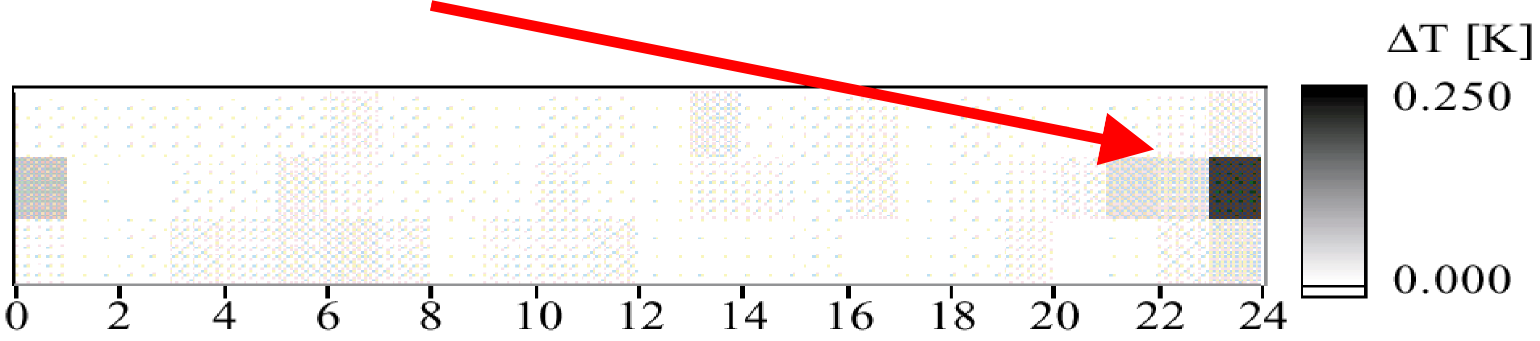


Thermometer response:

$\Delta T \sim B^2 - B^8$

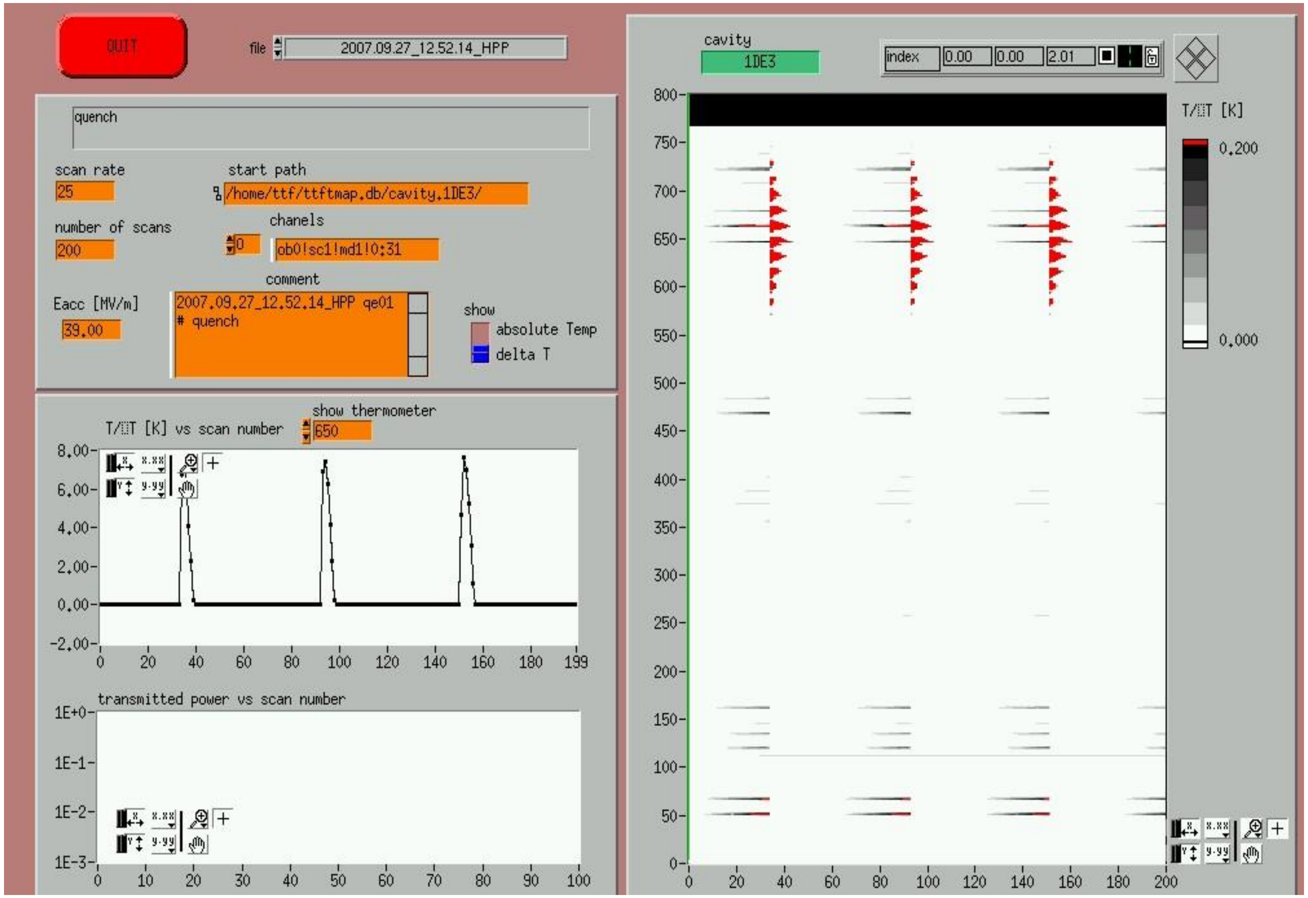


Heating on the equator



Temperature Mapping: Fixed Systems IV

- Example for time resolved T-Mapping
- Individual response of each thermometer



QUIT

file 2007.09.27_12.52.14_HPP

quench

scan rate 25

start path /home/ttf/ttfmap.db/cavity.1DE3/

number of scans 200

chanels 0 ob0!sc1!md1!0:31

comment 2007.09.27_12.52.14_HPP qe01
quench

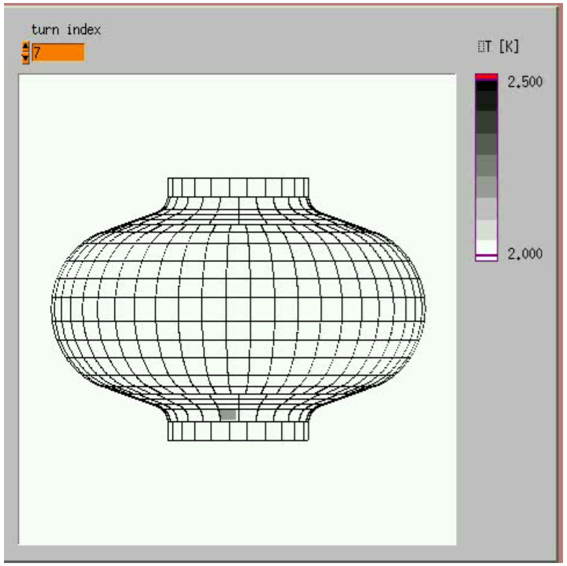
Eacc [MV/m] 39.00

show
absolute Temp
delta T

show thermometer 650

cavity 1DE3

index 0.00 0.00 2.01



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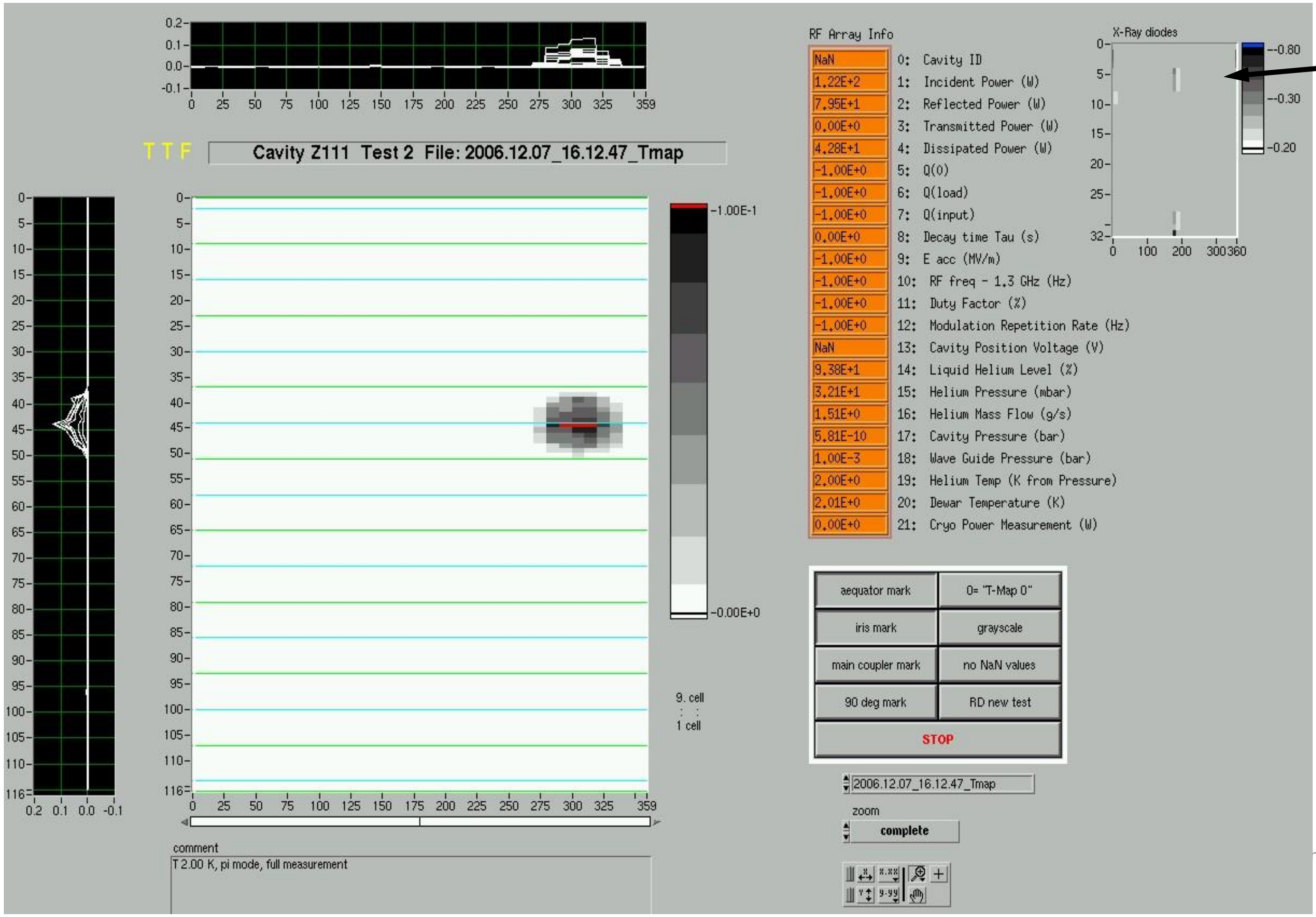
Temperature Mapping: Rotating systems I

- Quench detection + time resolved measurements possible
- Time consuming (0,5h – 1h)
- Less thermometers for multi-cell cavities



Cavity Z111 Test 2 File: 2006.12.07_16.12.47_Tmap

RF Array Info

NaN	0: Cavity ID
1.22E+2	1: Incident Power (W)
7.95E+1	2: Reflected Power (W)
0.00E+0	3: Transmitted Power (W)
4.28E+1	4: Dissipated Power (W)
-1.00E+0	5: Q(0)
-1.00E+0	6: Q(load)
-1.00E+0	7: Q(input)
0.00E+0	8: Decay time Tau (s)
-1.00E+0	9: E acc (MV/m)
-1.00E+0	10: RF freq - 1.3 GHz (Hz)
-1.00E+0	11: Duty Factor (%)
-1.00E+0	12: Modulation Repetition Rate (Hz)
NaN	13: Cavity Position Voltage (V)
9.38E+1	14: Liquid Helium Level (%)
3.21E+1	15: Helium Pressure (mbar)
1.51E+0	16: Helium Mass Flow (g/s)
5.81E-10	17: Cavity Pressure (bar)
1.00E-3	18: Wave Guide Pressure (bar)
2.00E+0	19: Helium Temp (K from Pressure)
2.01E+0	20: Dewar Temperature (K)
0.00E+0	21: Cryo Power Measurement (W)

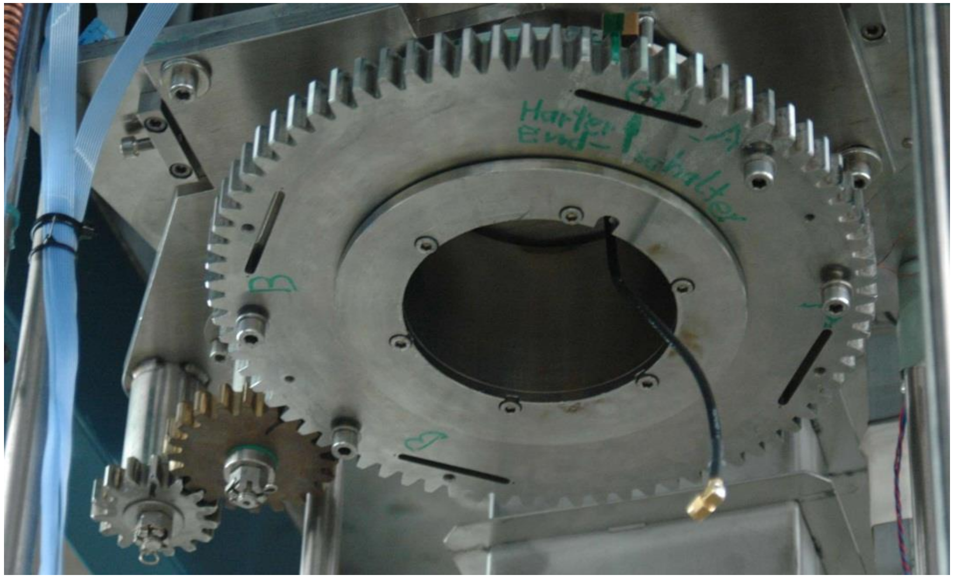
2006.12.07_16.12.47_Tmap

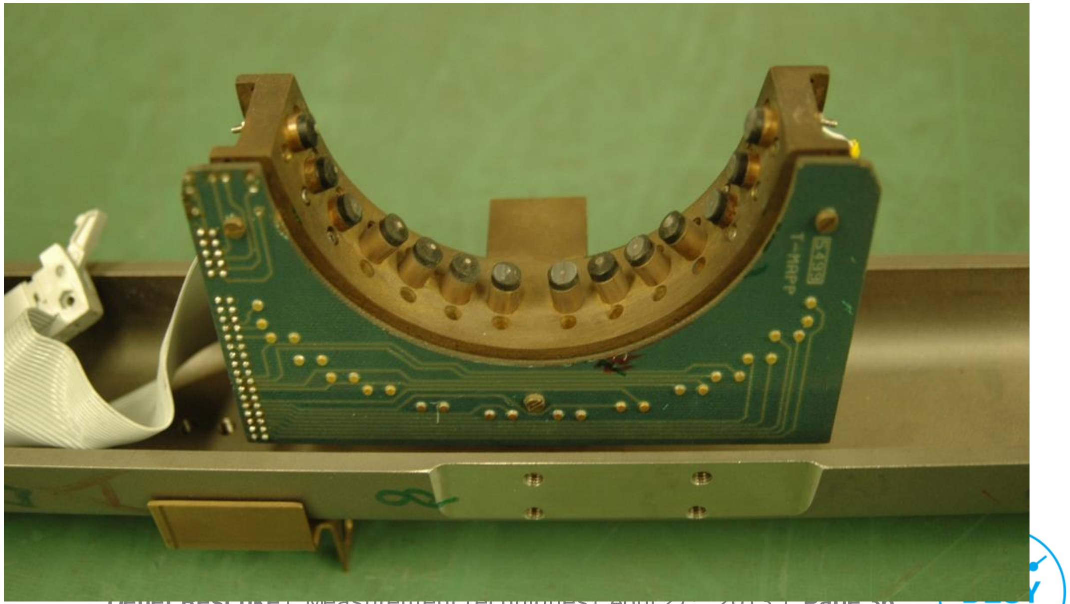
comment

T 2.00 K, pi mode, full measurement

X-ray diodes not existing !!

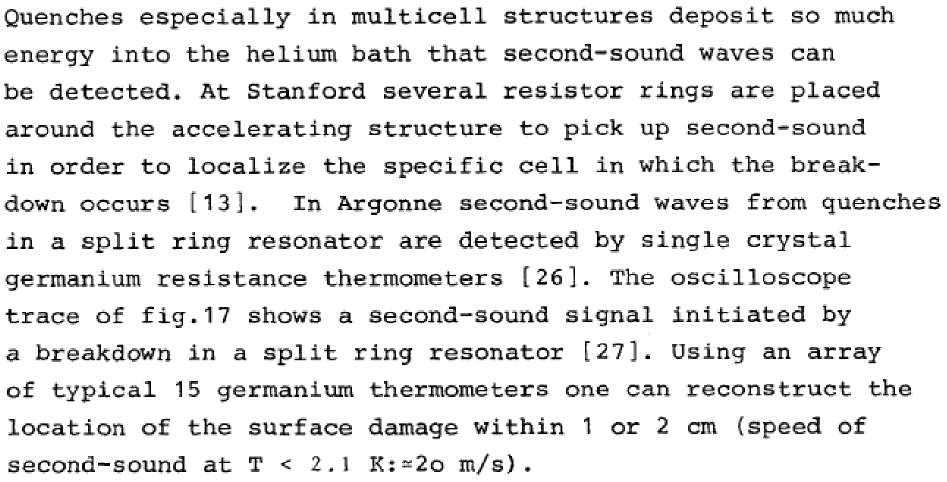
Temperature Mapping: Rotating systems II





Second Sound

- “New” technique?



Quenches especially in multicell structures deposit so much energy into the helium bath that second-sound waves can be detected. At Stanford several resistor rings are placed around the accelerating structure to pick up second-sound in order to localize the specific cell in which the break-down occurs [13]. In Argonne second-sound waves from quenches in a split ring resonator are detected by single crystal germanium resistance thermometers [26]. The oscilloscope trace of fig.17 shows a second-sound signal initiated by a breakdown in a split ring resonator [27]. Using an array of typical 15 germanium thermometers one can reconstruct the location of the surface damage within 1 or 2 cm (speed of second-sound at T < 2.1 K:≈20 m/s).

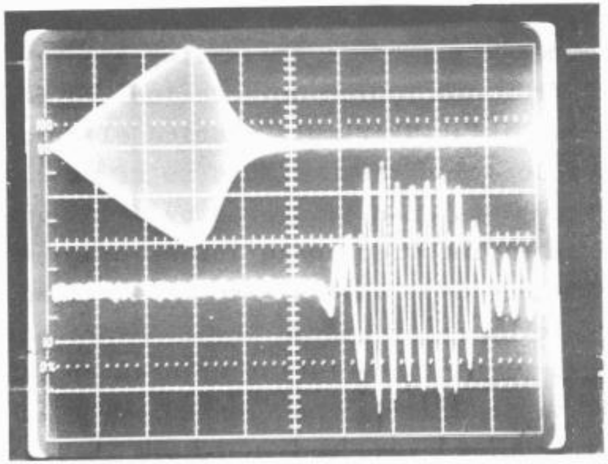
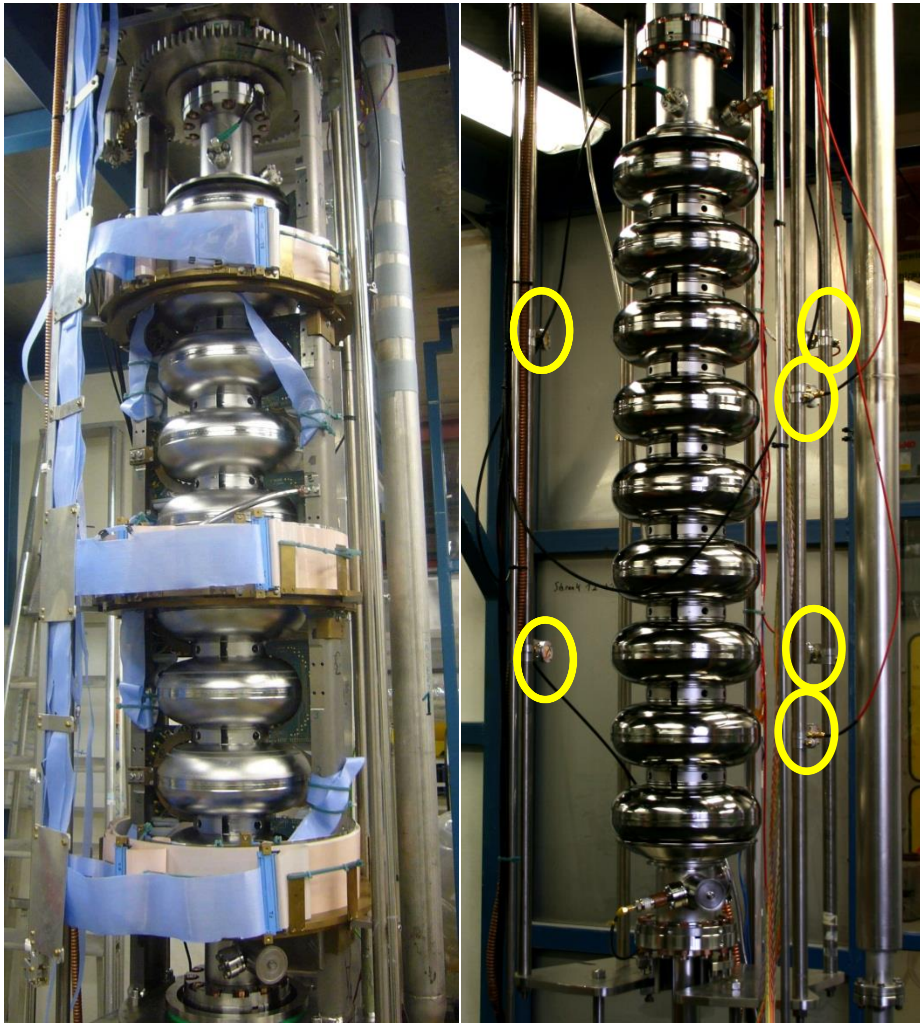


Fig. 17: "Oscilloscope display of the second-sound pulse associated with thermal breakdown of a resonator. The upper trace displays the rf field in the resonator, which is driven to E_a = 3 mV/m at which point the resonator becomes thermally unstable and the field collapses. The lower trace displays the temperature of a sensor which shows a second-sound pulse arriving 13 msec after breakdown." [27]

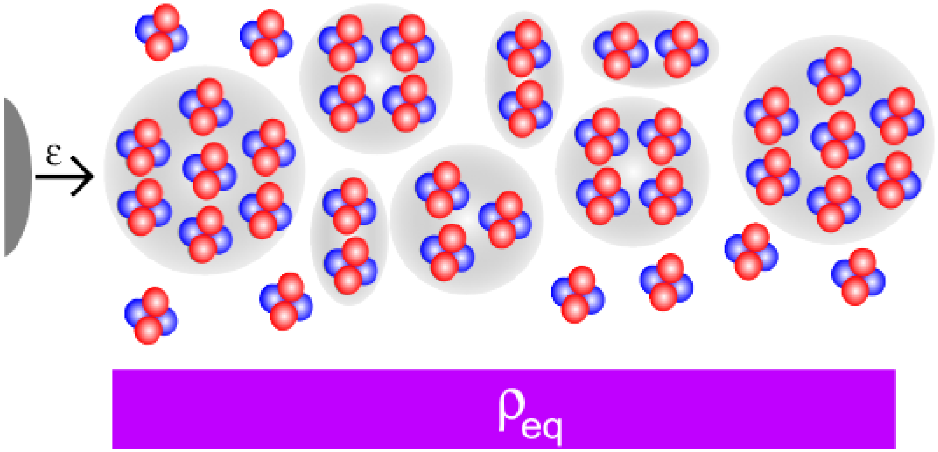
H. Piel, “Diagnostics Methods of Superconducting Cavities and Identification of Phenomena“, SRF workshop 1980

Comparison of Second Sound and Temperature Mapping

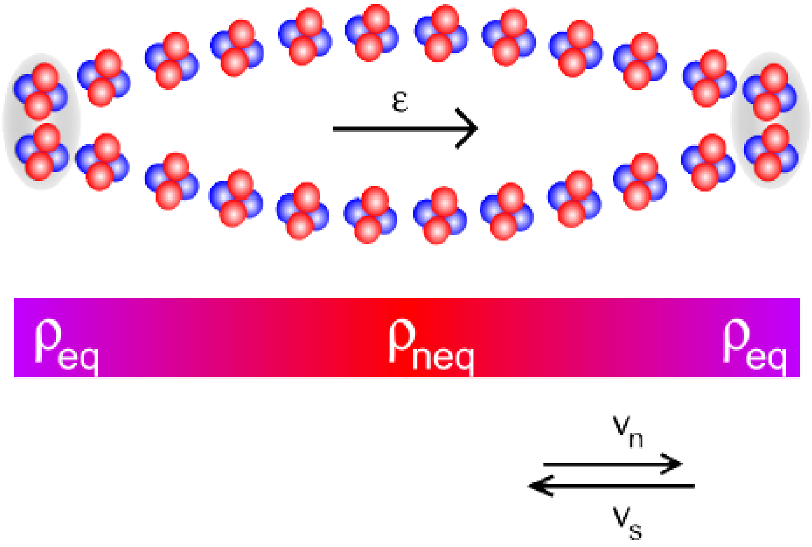
- Temperature mapping (left)
  - Complex assembly for each test required
- Second Sound (right)
  - Simple and one-time assembly at the cryostat insert
  - Fast measurement
  - 8 (16) sensors only



Second sound – mechanism (by F. Schlander)



- Two fluids
  - He I: density ϱ_n, viscosity η_n
  - He II: density ϱ_s, viscosity $\eta_s = 0$
  - Total density: $\varrho_{eq} = \varrho_n + \varrho_s$
  - Flow: $\vec{j} = \varrho_n \vec{v}_n + \varrho_s \vec{v}_s = 0$



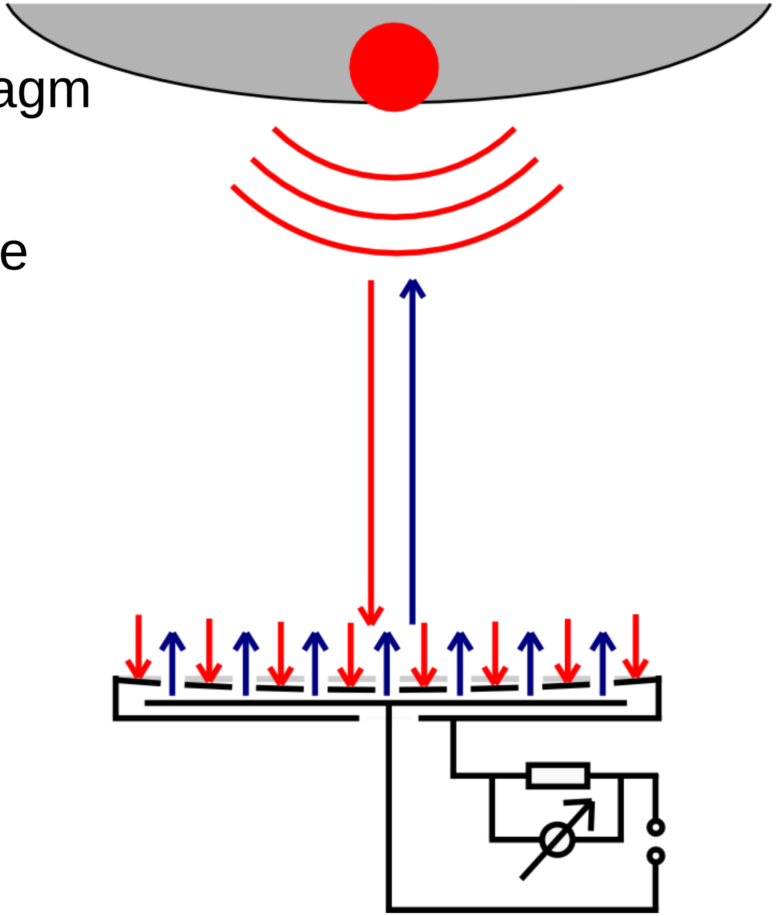
- Quench generates temperature wave
  - Absorption
  - ϱ_n increases & ϱ_s decreases → ϱ_{eq} changes locally to ϱ_{neq}

- Equilibrium required

$$\vec{v}_n = -c \vec{v}_s$$

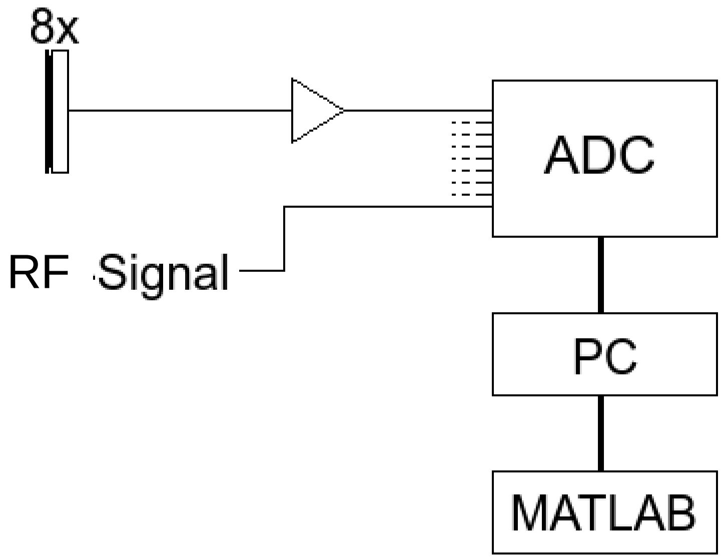
Second sound - detection

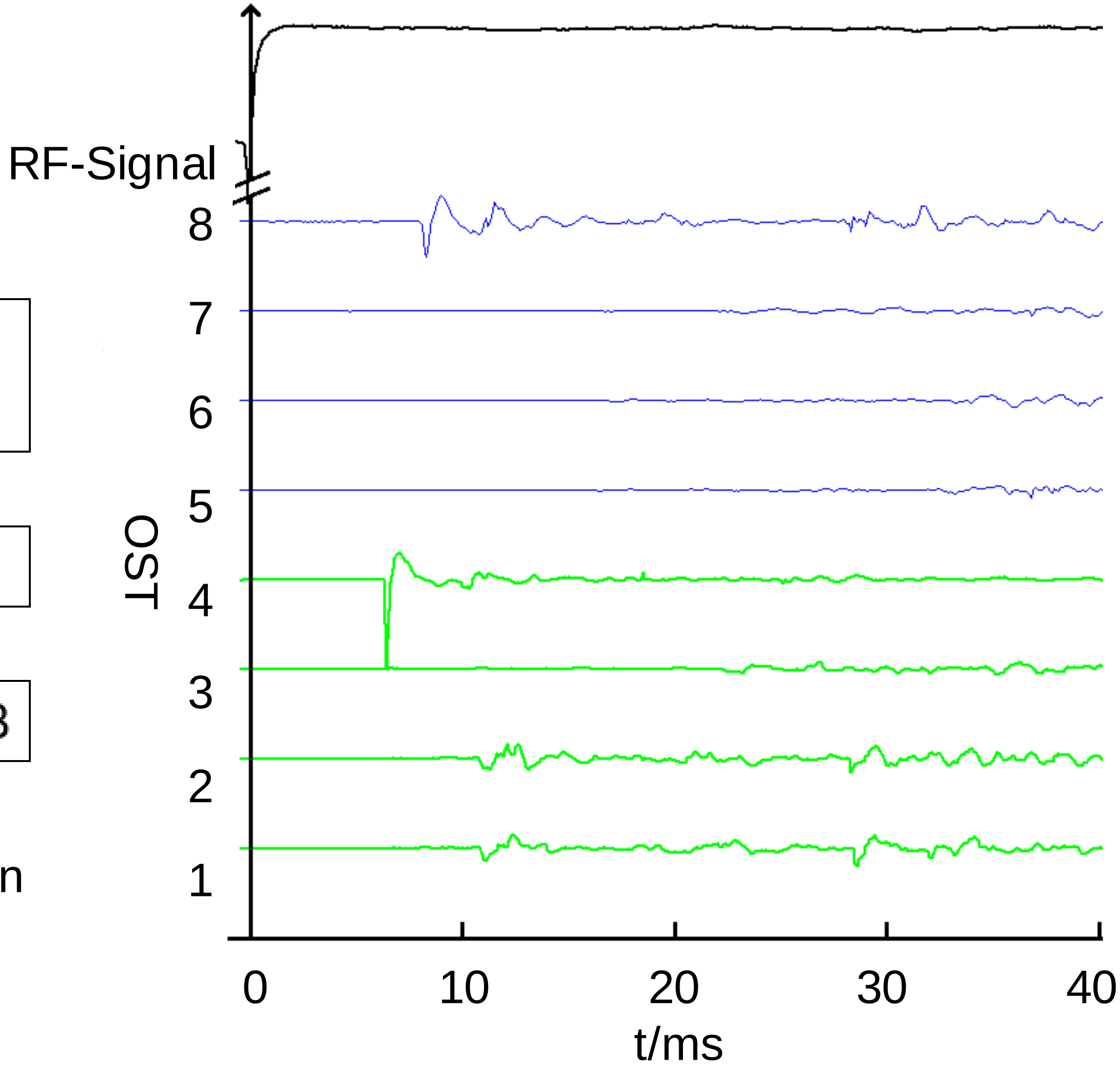
- OST (Oscillating Superleak Transducer) consisting of metal plate and thin diaphragm coated with gold → capacitor
- Second sound actuates oscillations of the diaphragm
- Measure voltage change



OST (Oscillating Superleak Transducer) of Cornell Design

Quench localisation

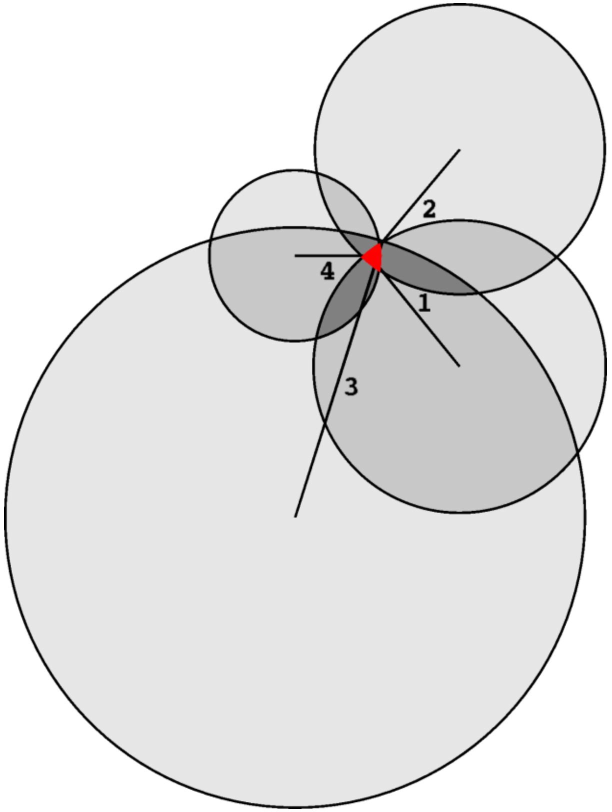


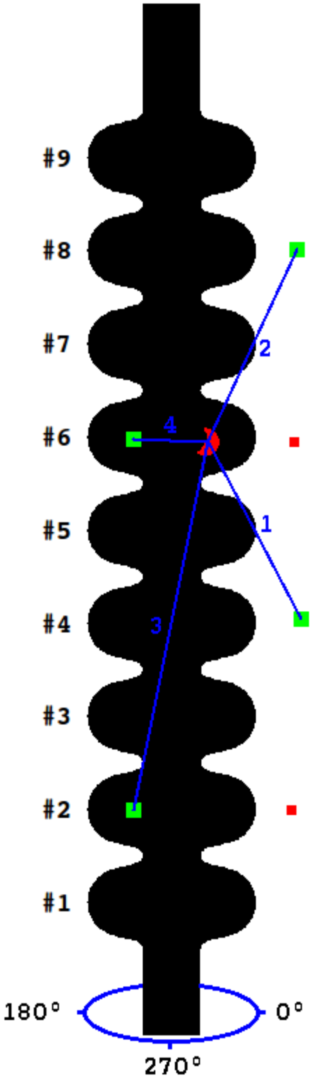


Quench localization depending on Second Sound velocity
=> some uncertainties

Quench localisation

Sketch of intersecting volume

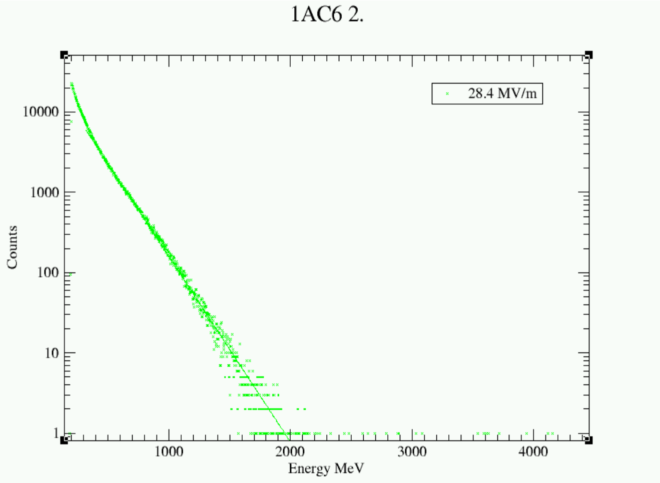




- Uncertainties:
  - Size of the OSTs
  - Heat distribution
  - Signal analysis
- Measurement uncertainty: ~ cm
- Comparison with T-Map: Agreement with uncertainty of 1-2 cm
  - Boundary condition (DESY):
    Quench on the cavity surface

X-ray (+neutron) detection

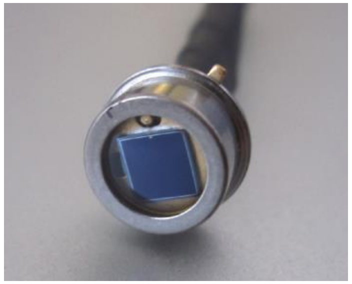
- Detect x-rays + neutrons either outside of cryostat or localization inside the cryostat
- Radiation detectors (outside of cryostat):
  - Ionization chamber
    => also relevant for personal safety!
  - Neutron detectors
    => for personal safety outside of shielding
  - Scintillator with Multi-Channel Analyzer
    => energy spectrum



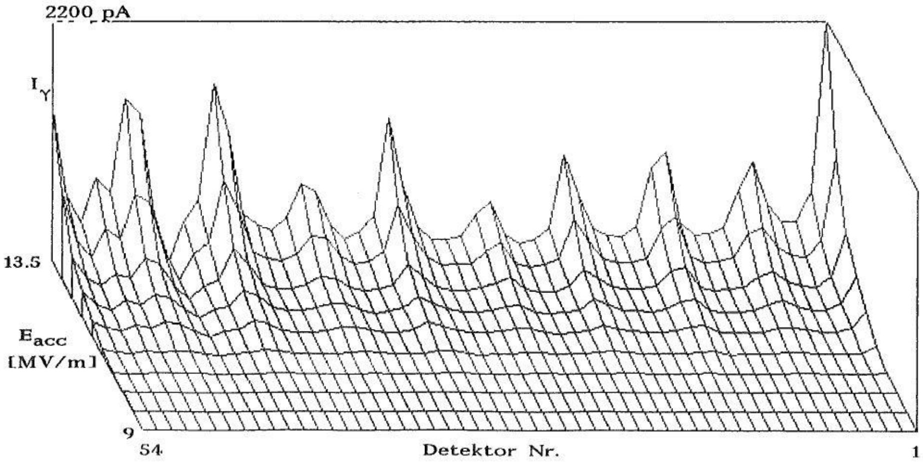
+

X-ray detection inside the cryostat

- Radiation detectors (inside of cryostat):
  - Photo Diode usable for x-rays (Hamamatsu) used in liquid He; typically in the T-mapping set-up at and close to the irises (example later)



Current vs. gradient for 54 photo diodes of a 3 GHz nine-cell set-up

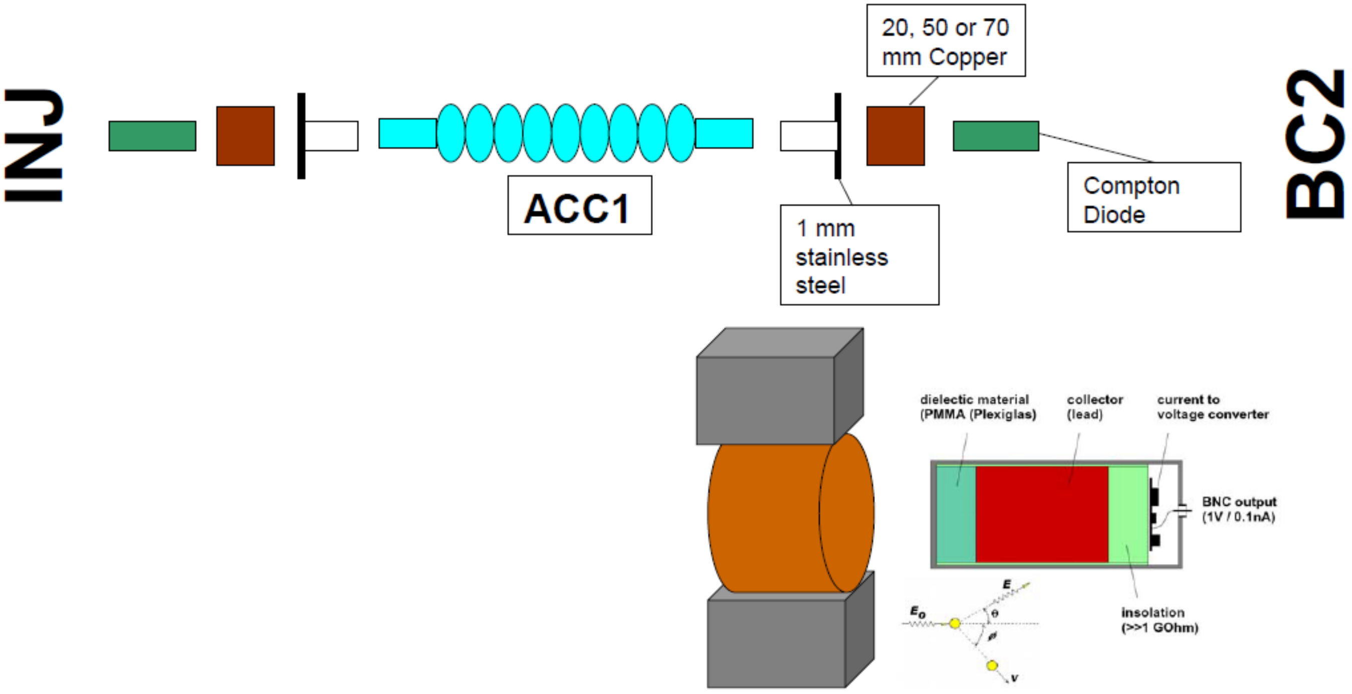


  - X-ray (medical) films

Electron / dark current detection (only 2 examples)

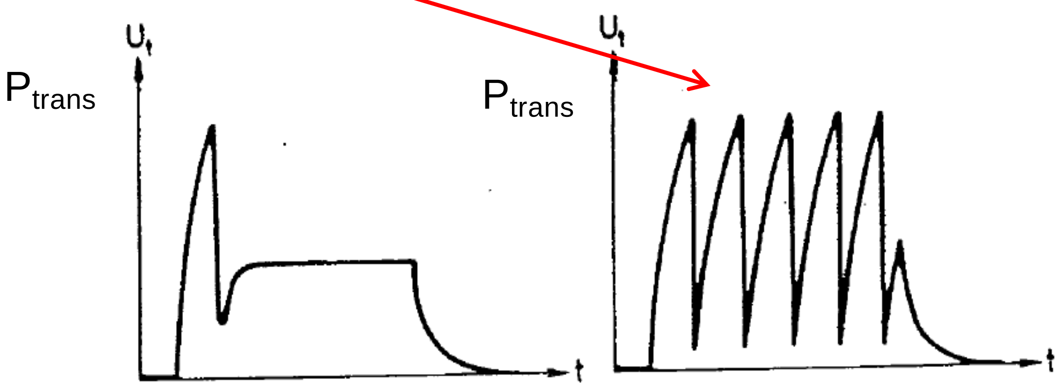
- Vertical test:
  - => Pick-up antenna can be used for e^- - detection
  - => Separation of RF – and DC signal
  - => Direct current measurement with electrometer
- Compton diode:

dark current measurements at ACC1 - setup



RF-Signals + Symptoms of Quench

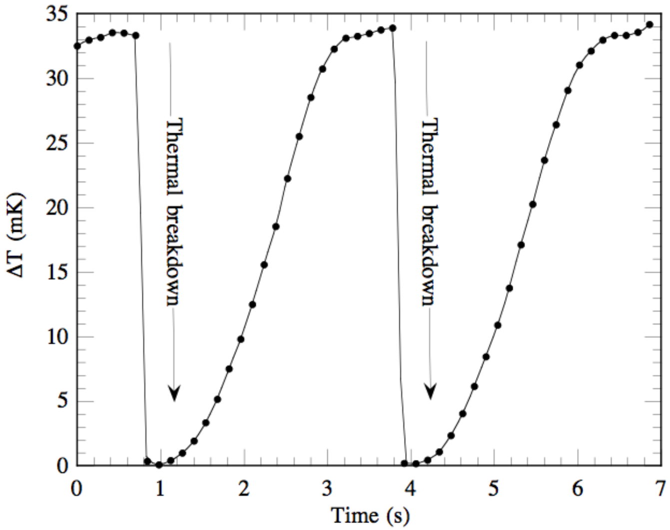
- **Quench**
- RF-signal:
  - breakdown of transmitted power within ≈ms (thermal time constant)
  - often self-pulsing

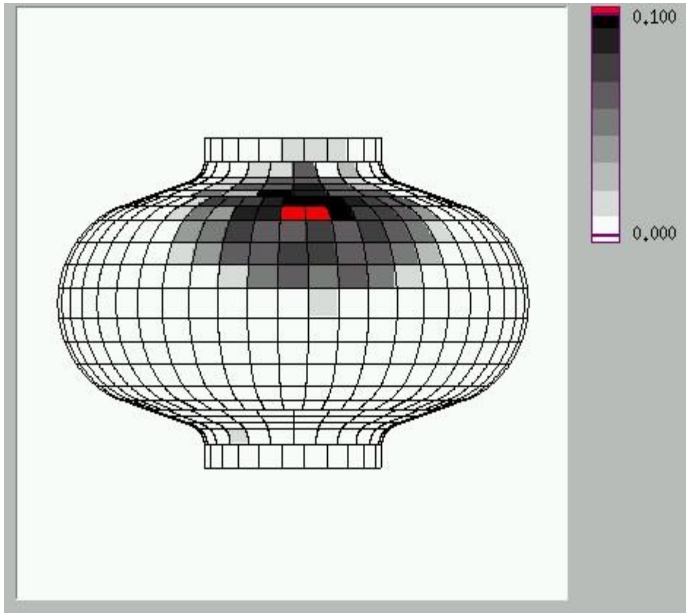


- **No X-rays !!!**
  => with x-rays life becomes more complicated (quench with FE present, FE induced quench, multipacting, …)

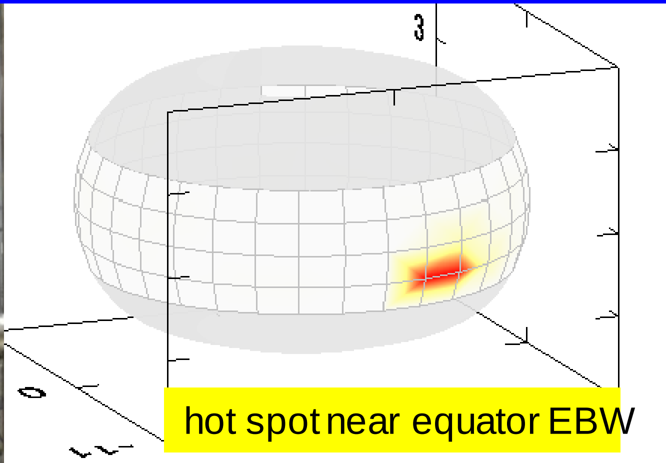
RF-Signals + Symptoms of Quench II

- T-Mapping:
  - Detection of temperature rise at cavity wall near quench location
  - ΔT during quench up to few K
  - precursor just below the quench ??

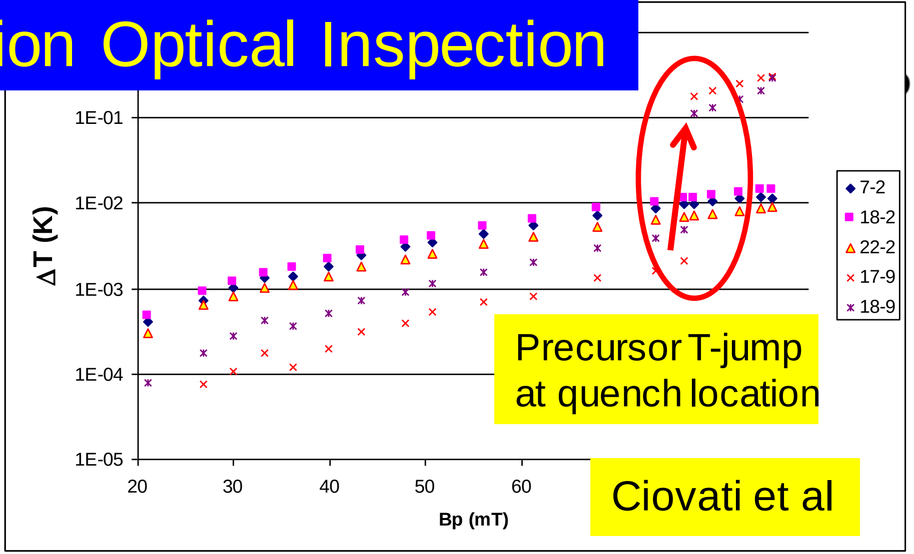




JLab T-mapping and High-Resolution Optical Inspection

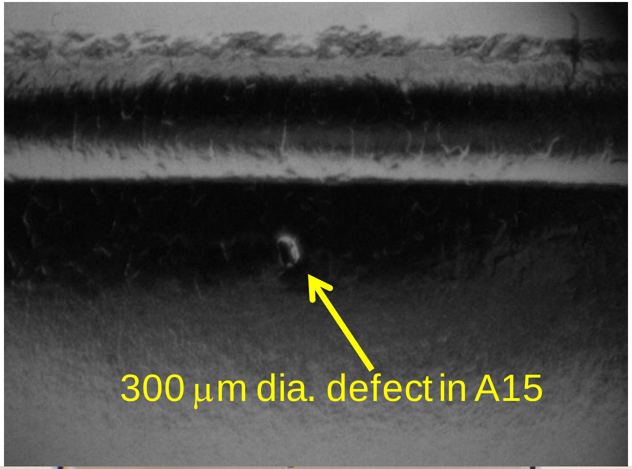


hot spot near equator EBW

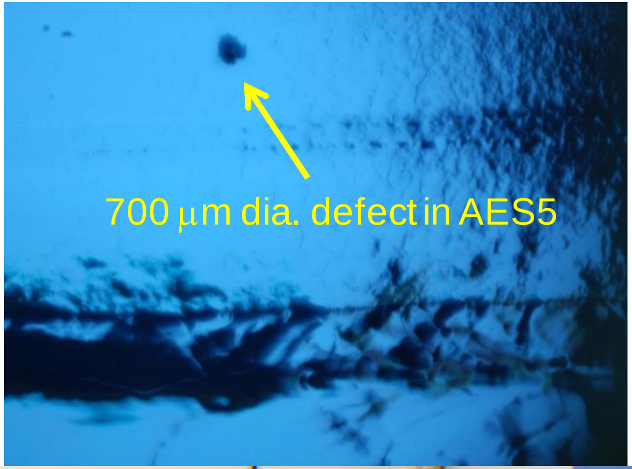


Precursor T-jump at quench location

Ciovati et al



300 μm dia. defect in A15



700 μm dia. defect in AES5

RF-Signals + Symptoms of Field Emission

- **Field emission:**

- RF-signal:
  - Change of decay slope for P_{trans}

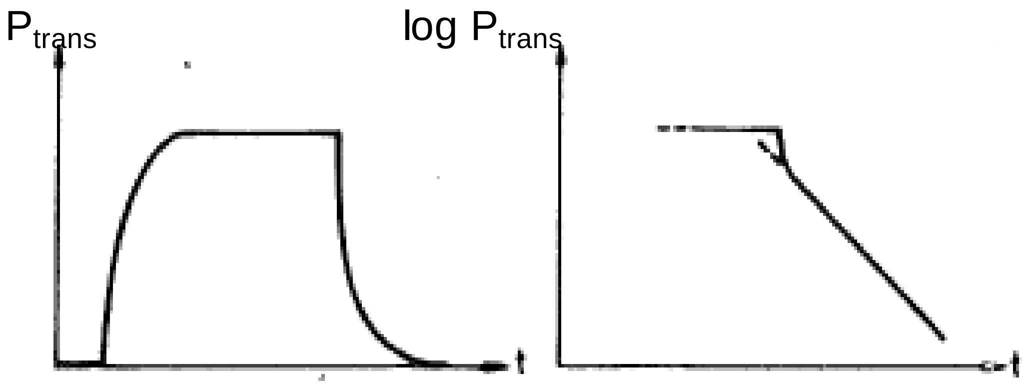


Fig. 5a

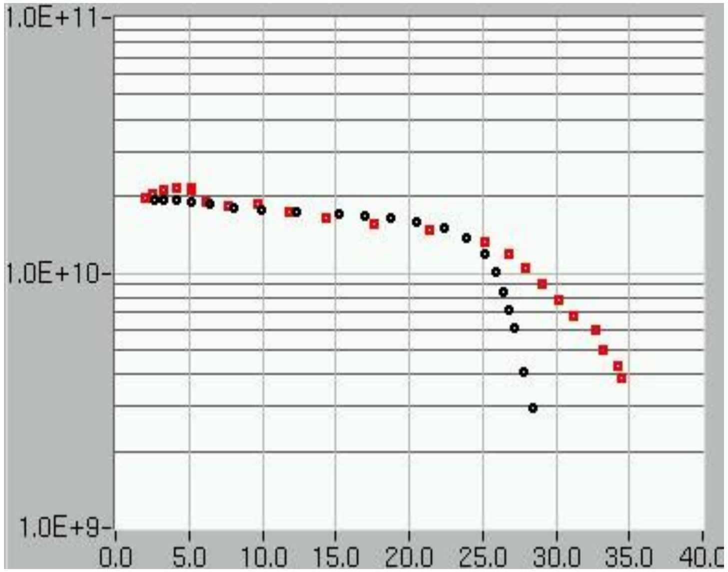
Fig 5b

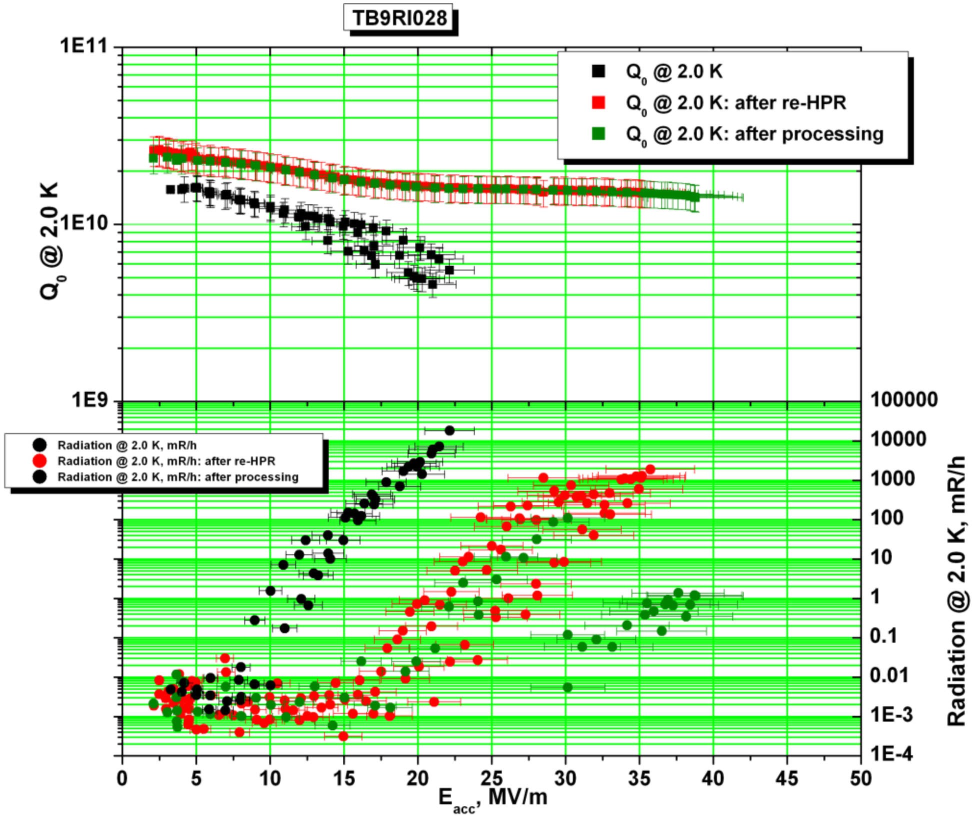
$U_t(t)$ and $\log U_t(t)$ from a cavity with field emission loading

- In multi-cell cavities:
  Excitation of other passband modes by energy transfer

RF-Signals + Symptoms of Field Emission II

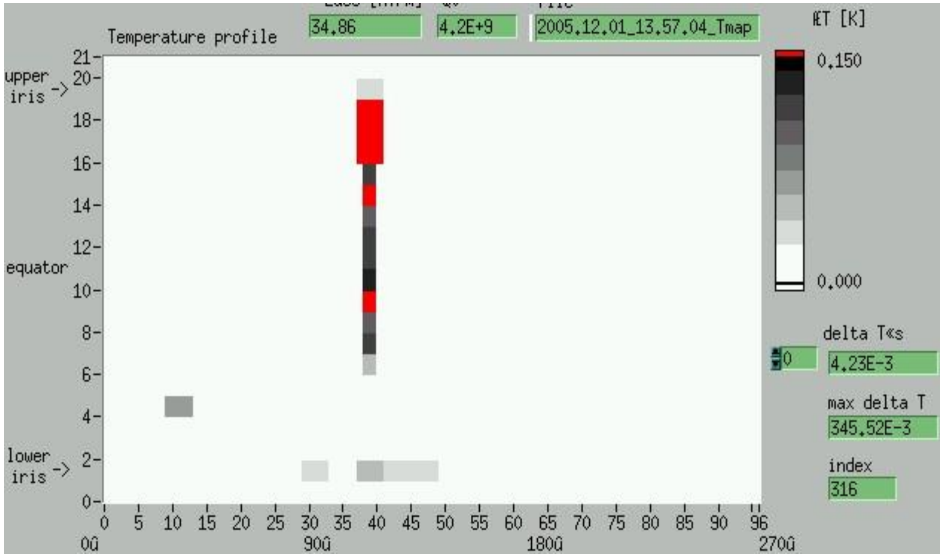
- Typical decrease of Q_0-value
  - sometimes not so obvious
- Drop of Q_0 accompanied by **exponential X-ray increase** according to Fowler Nordheim’s law
- Field emission electrons can cause a “field emission induced quench”





RF-Signals + Symptoms of Field Emission III

- T-Mapping:
  field emission gives a “hot trace” on one azimuthal position
- T-Mapping necessary to decide between “Quench with FE” and “Field Emission induced Quench”



delta T«s 4.23E-3

max delta T 345.52E-3

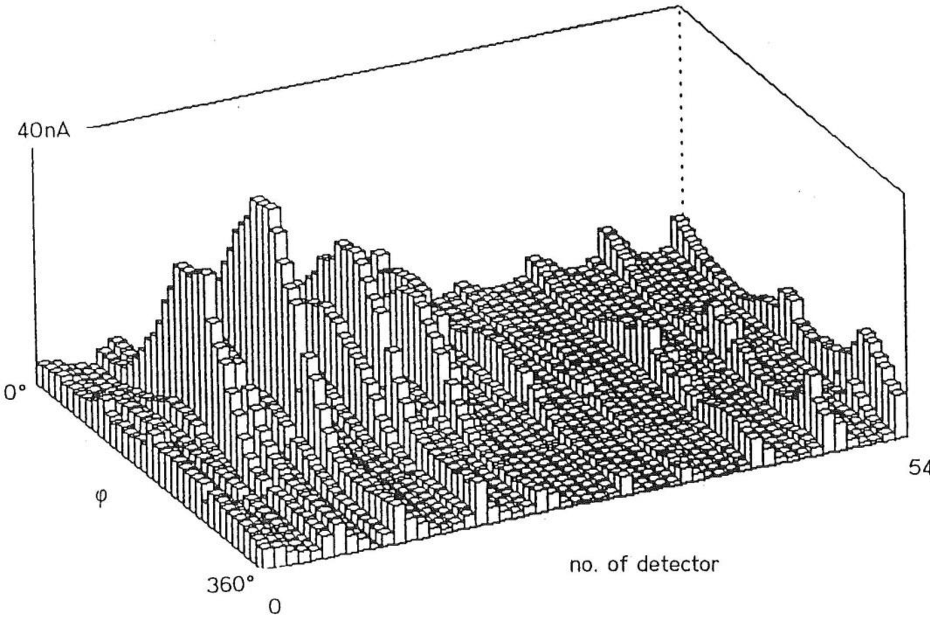
index 316

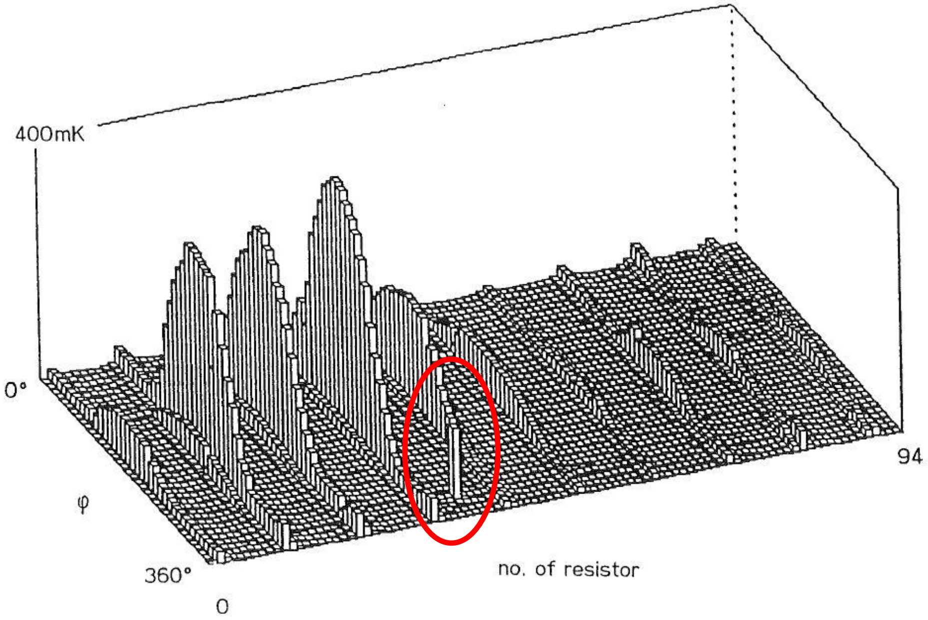
2-D T-map of a field emission loaded cavity

- Electron probe: Exponential increase of current (Fowler Nordheim’s law)

RF-Signals + Symptoms of Field Emission IV

- X-ray mapping (+ respective T-Map)





- Application of X-ray films + X-ray spectroscopy (see above)
- Remark:
  FE can be caused by strong hydrocarbon contaminations of your vacuum system
  => “Clean” pumping station + RGA at the test insert necessary

Field emission: Processing and Switch-on

- One or several “breakdowns” of the RF signal – often accompanied by loosing the lock for the PLL - resulting in

  - drop in radiation
  - higher Q_0 , higher E_{acc}

  => **Processing event**

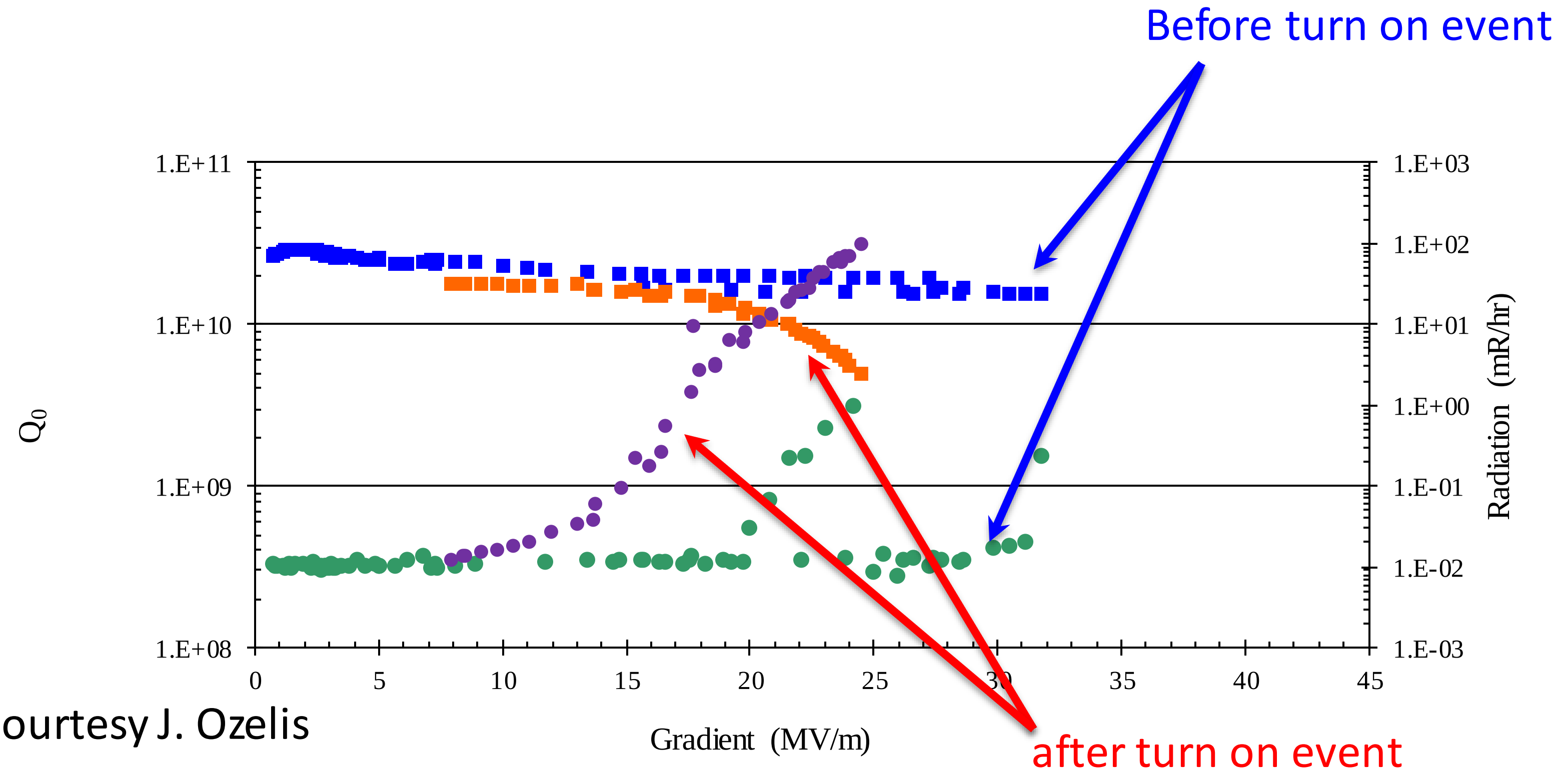
  - Sometimes slow improvement (degradation) with some instable behavior

- Sudden Q_0 and gradient degradation with accompanied sudden increase in radiation

  => **“Field emission switch on” event**

Field emission: Switch-on

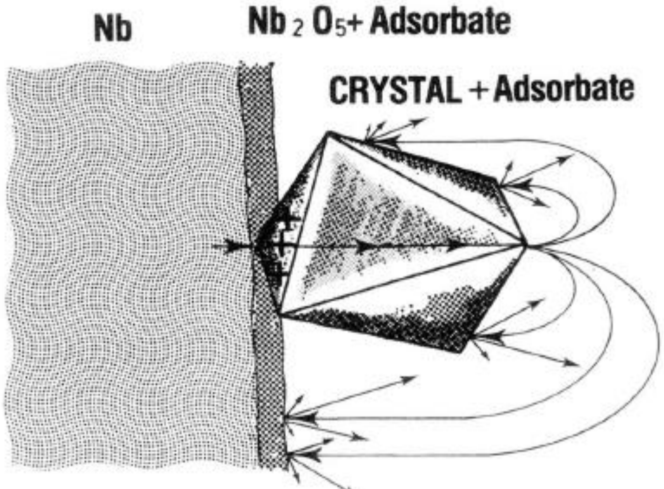
- Activation of a field emitter:



Courtesy J. Ozelis

Field emission: Processing

- Processing of emitters (“conditioning”) possible
  - **RF** and **helium proc.** with moderate rf power and cw-like operation
  - **high peak power processing (HPP)** with high rf power and short pulses
- Some **RF processing** you cannot avoid during the first $Q_0(E_{acc})$-curve in case of field emission (if you like it or not)
- **Helium processing**:

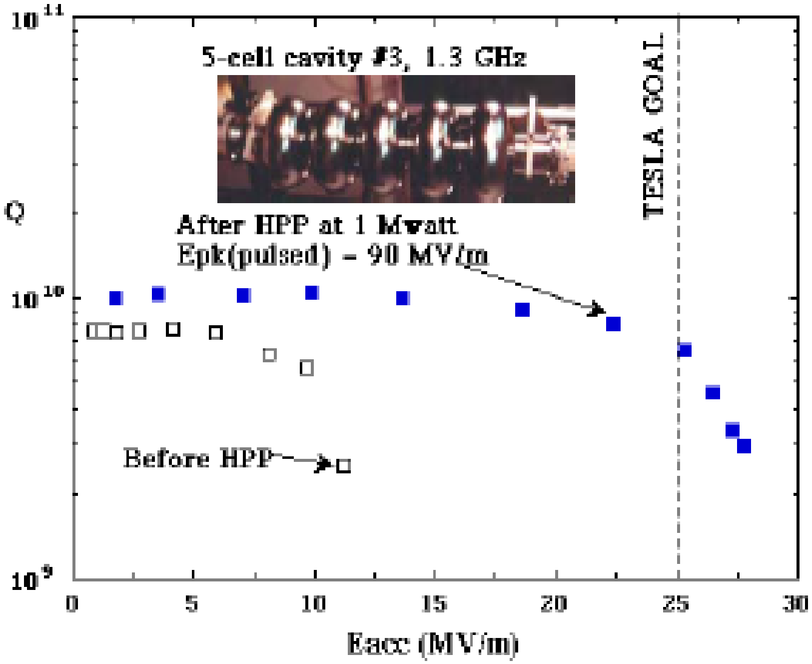


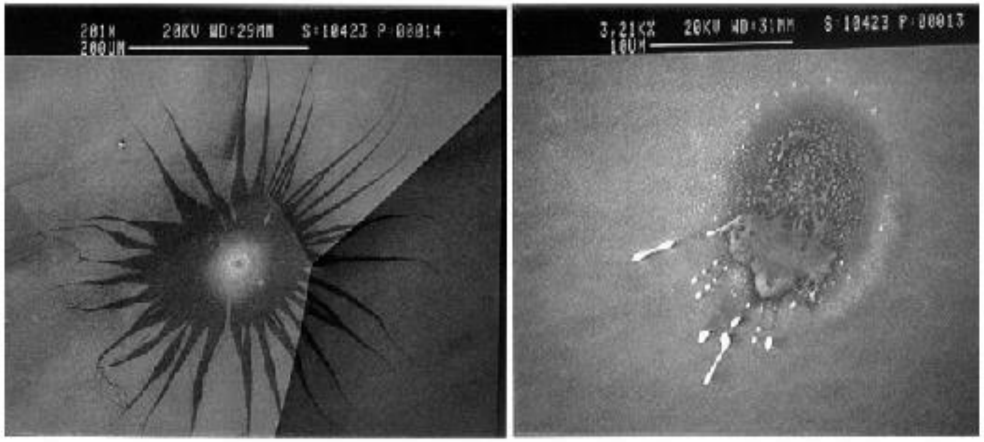
- **Variation of RF processing**
- **Keep pressure below discharge condition**
- **Run cavity in the field emission regime**
- **Push the gradient as high as the system allows**
- **The process in details is unknown**
  - **Electron spraying from FE → bombard surface → ionization of helium at around surface → destroy field emitter???**
  - **Controlled processing is difficult**

Courtesy J. Mammosser

Field emission: HPP

- **High Peak Power processing**
- Local melting leads to formation of a plasma and finally to the explosion of the emitter (model by J. Knobloch)
- “star bursts” (Lichtenberg figures) caused by the plasma





Field emission: HPP II

- **HPP in multi-cell cavities:**
- HPP on 5- and 9-cell structures in vertical tests: improvement from (10-15) MV/m to (20-28) MV/m, but often reduced Q-value
- Typically E_{acc}(during HPP) ≈ 2x E_{acc}(after processing)

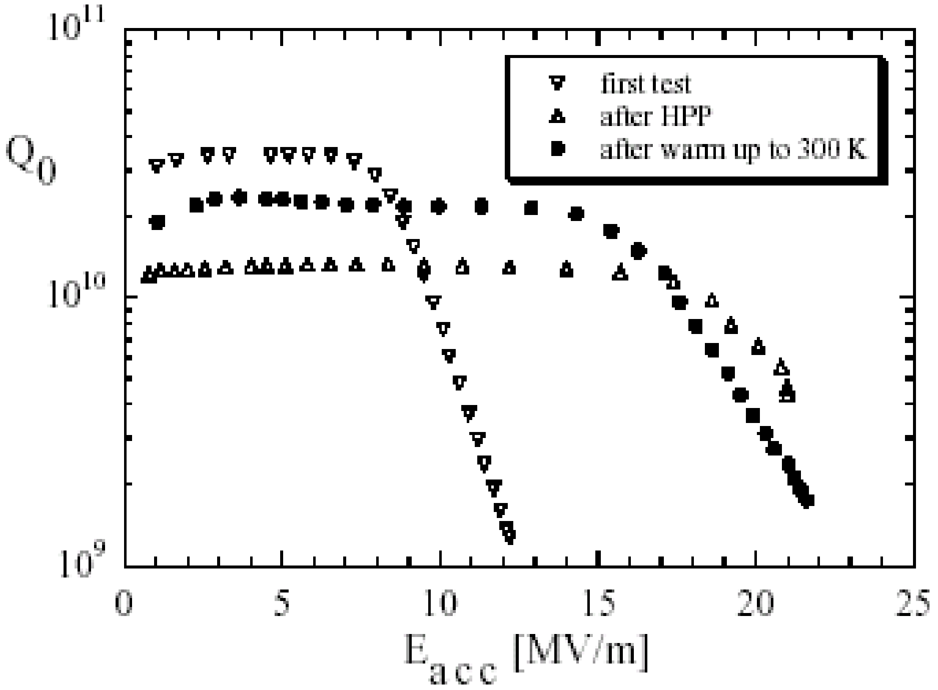
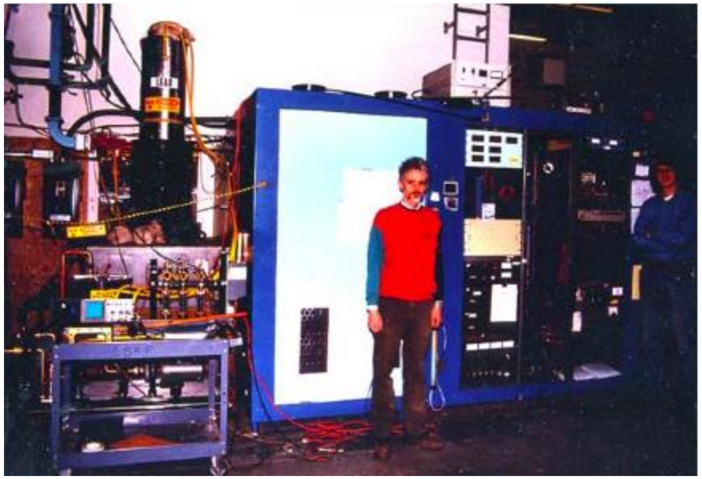


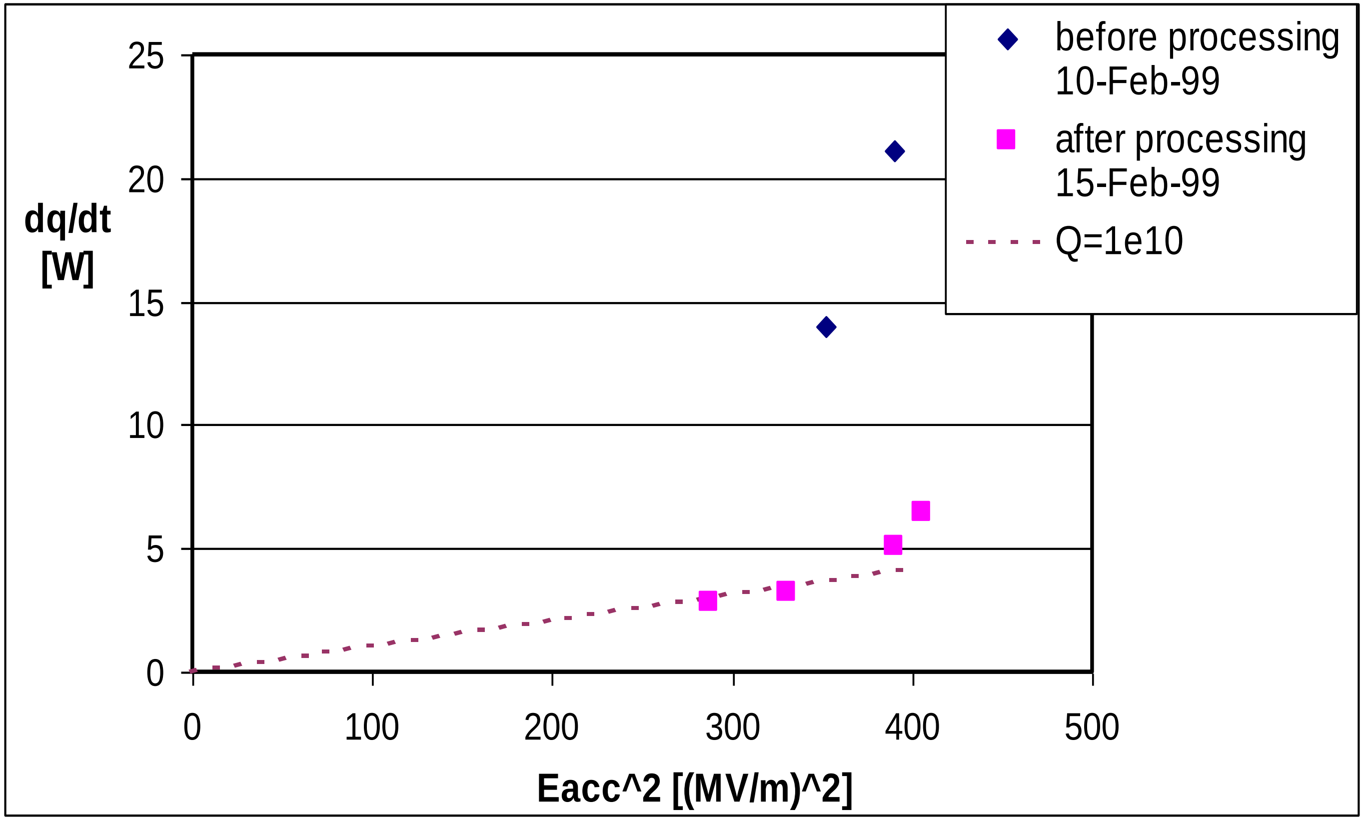
Fig. 2: Cavity C19 before and after HPP. The Q_0 recovered partially after warm up to room temperature.



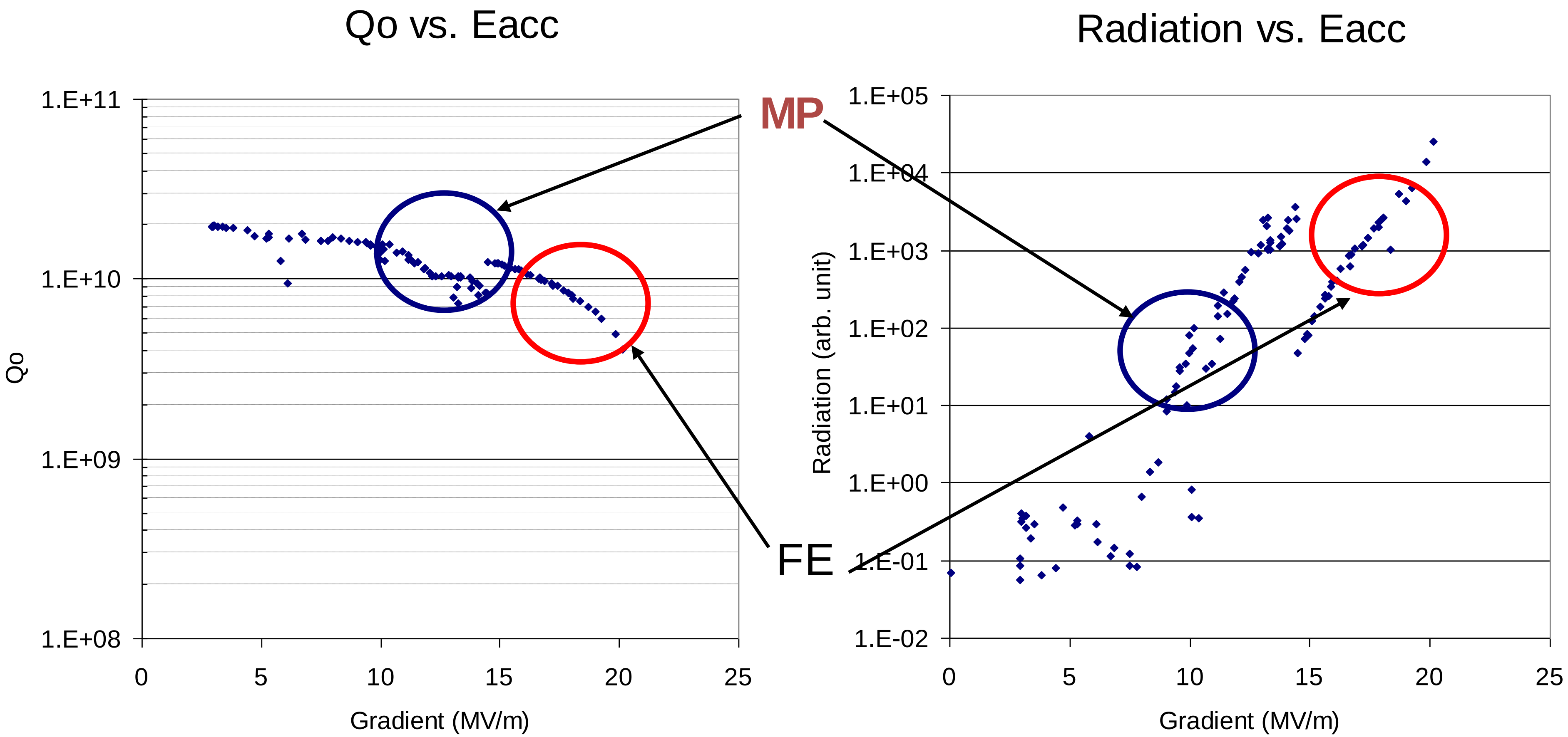
Courtesy H. Padamsee

Field emission: Processing in accelerator structures

- Processing example at TTF DESY:
- Processing of module 2 in linac successful (Feb 1999) (operation limited by power coupler above 19 MV/m)



Field Emission ?
MP! And then later on Field Emission !

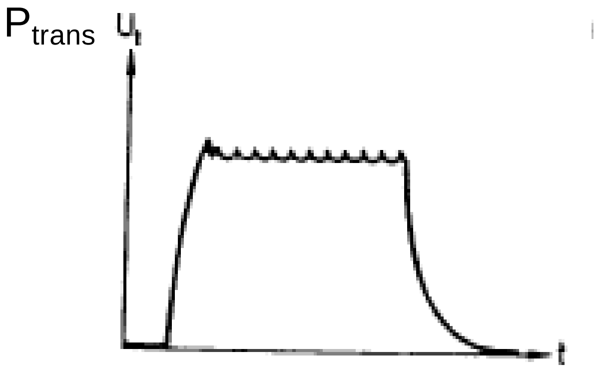


If this cavity is limited at this condition, what is the limiting factor? Field emission?

Courtesy J. Mammosser

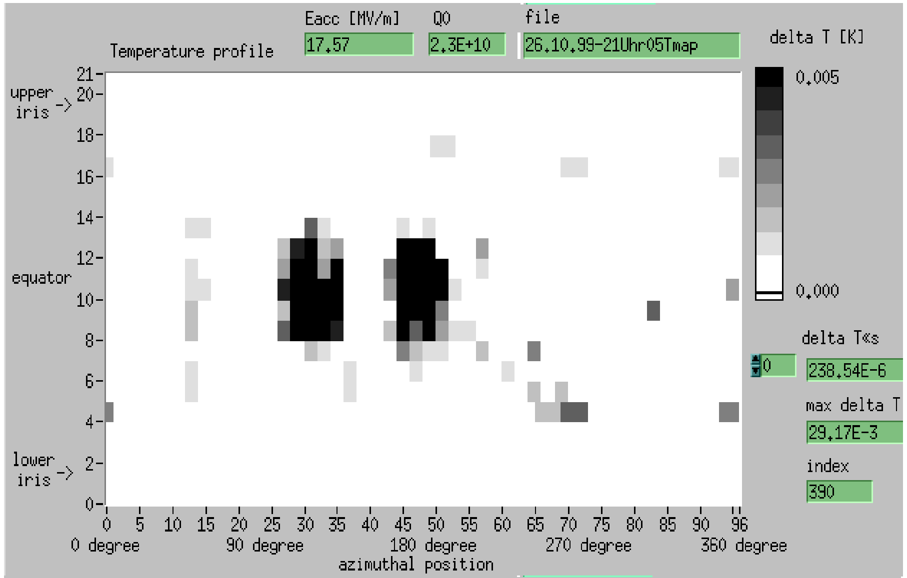
RF-signals and symptoms of Multipacting

- **Multipacting:**
- Each cavity shape has its individual MP barrier(s)
- rf-signal of transmitted power:
  - no increase of P_{trans} for enhanced forward power (barrier)



- often breakdowns of rf field (like quench) during processing
- X-ray detectors and electron pick-ups are also showing activity (in the moment of breakdown!!!)

Multipacting: Temperature mapping



Temperature profile

Eacc [MV/m] 17.57

Q0 2.3E+10

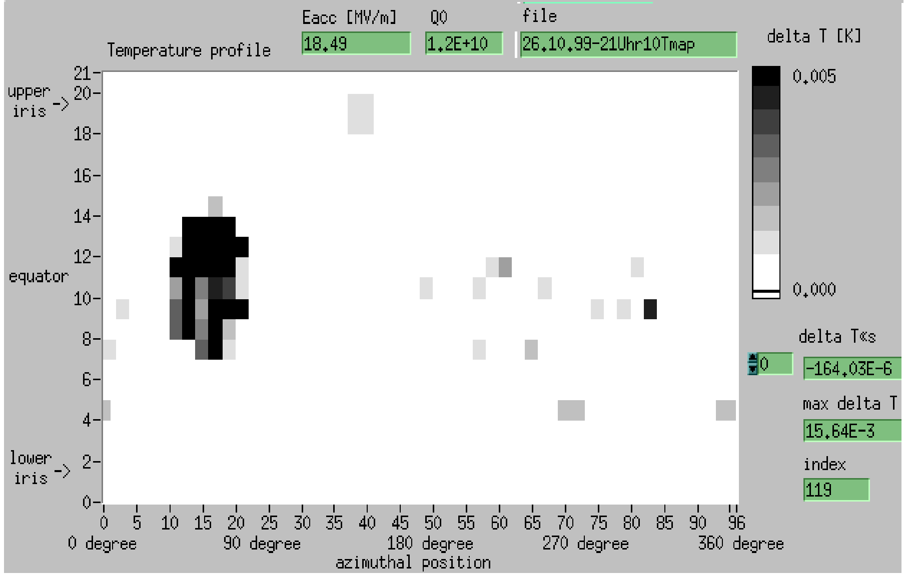
file 26.10.99-21Uhr05Tmap

delta T [K]

delta T«s 0 238.54E-6

max delta T 29.17E-3

index 390



Temperature profile

Eacc [MV/m] 18.49

Q0 1.2E+10

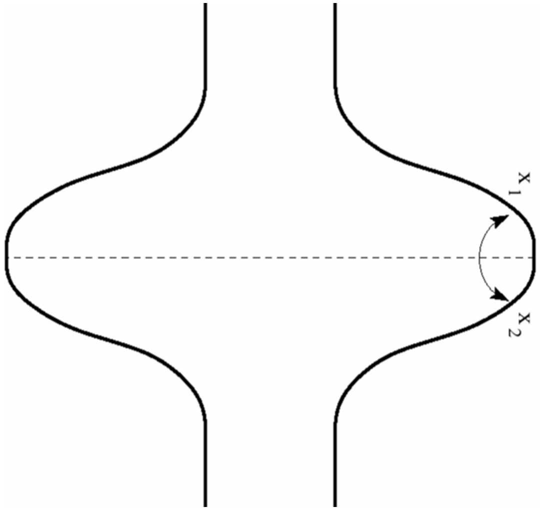
file 26.10.99-21Uhr10Tmap

delta T [K]

delta T«s 0 -164.03E-6

max delta T 15.64E-3

index 119



“Hot spot“ may move along the equator

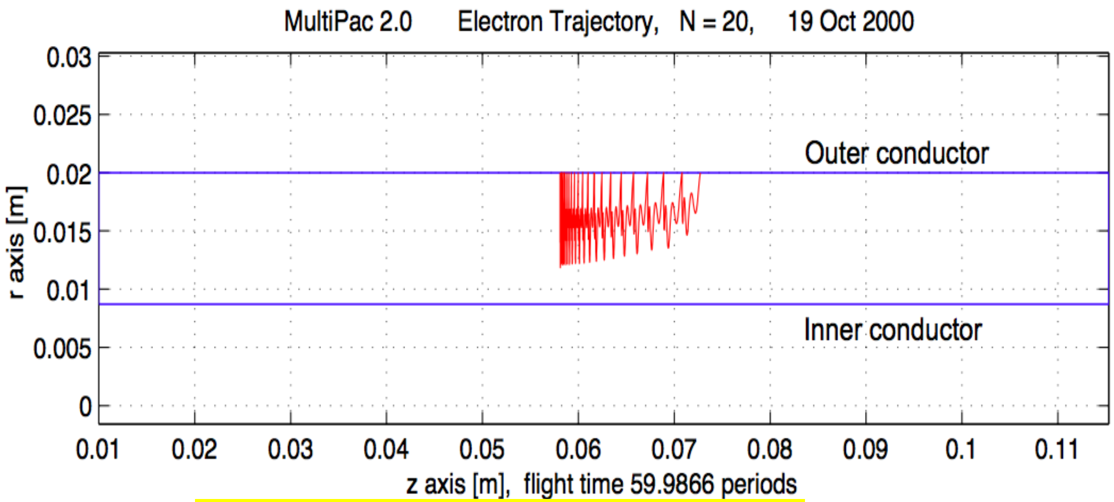
Multipacting: Processing

- Processing takes seconds to hours
  - one-point MP: hard barrier => maybe no processing success
  - two-point MP: soft barrier => fast processing (sec to min)
- After warming up to room temperature (mostly) re-processing is necessary

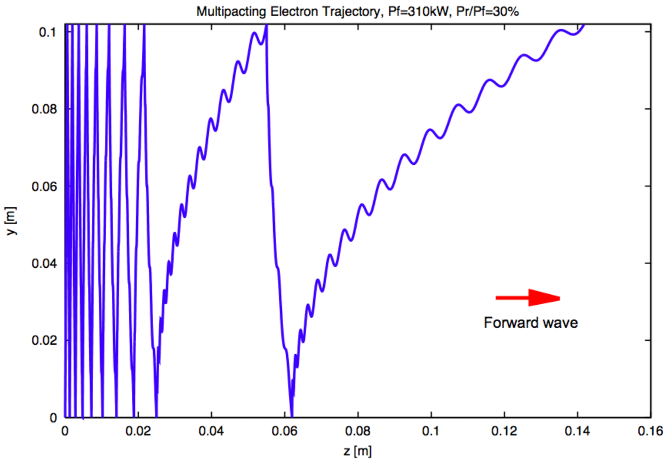
- Remark:
  MP can be caused by surface gas layers esp. hydrocarbon contaminations of your vacuum system
  => “Clean” pumping station + RGA at the test insert necessary

Multipacting in other components

- Remark: Multipacting is an issue of interest in higher order mode coupler and fundamental power coupler for cavities
  - See references
  - MP calculations using “MultiPac” for 2 coupler types



1-side 3rd order MP in coaxial coupler



2-side 5th order MP in waveguide coupler

P. Ylä-Oijala, TESLA Report, TESLA 97-21, (1997).

Horizontal Cavity Tests

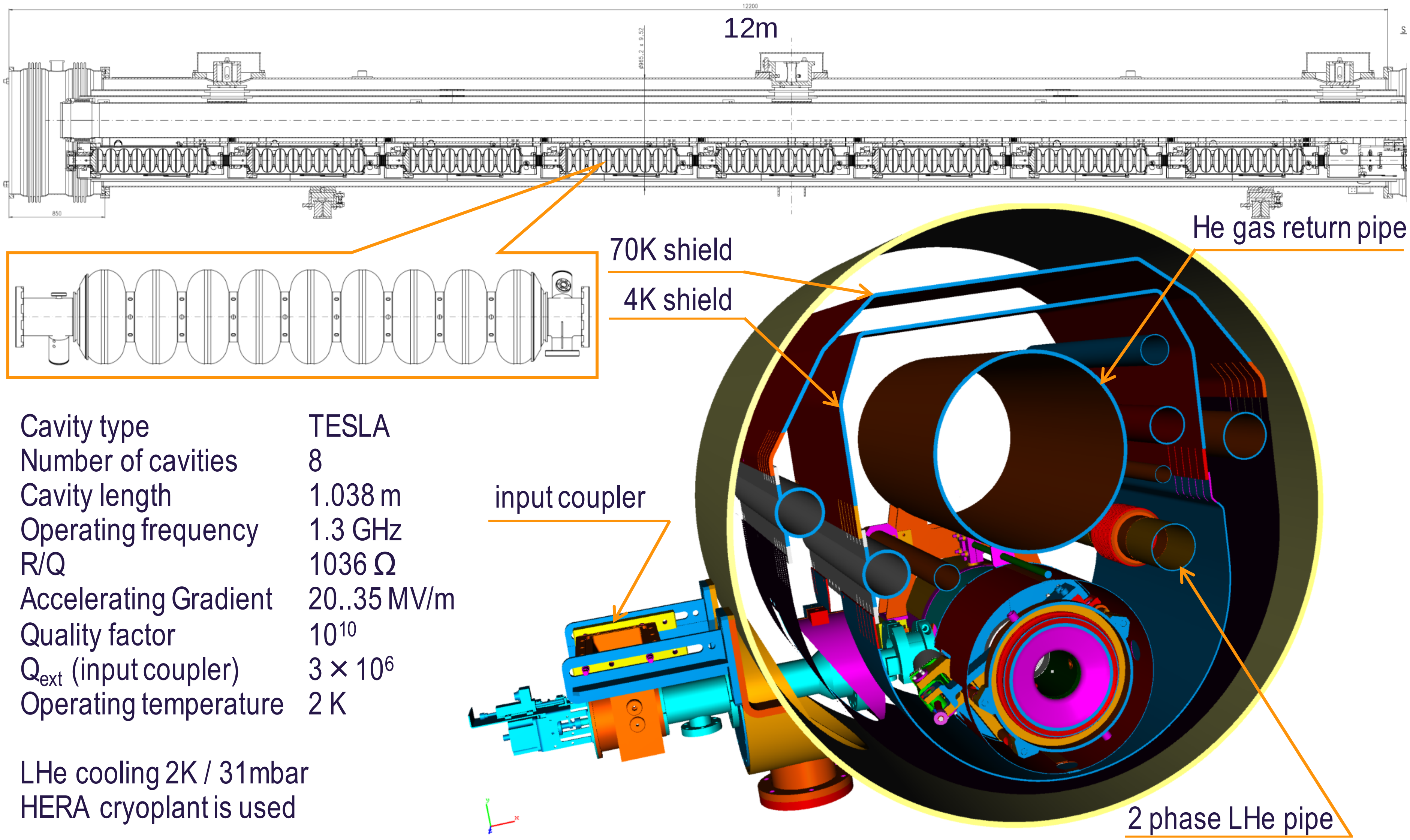
- Horizontal cavity tests are important in order to a cavity full equipped with its subsystems before a module integration
  - Power coupler
  - Tuner
  - Piezo-Tuners

- Horizontal cryostat at DESY for high power pulsed operation (without beam)

Cryomodule testing

- Closely follows a presentation by Denis Kostin (DESY)
- Cryomodule tests for FLASH + XFEL as example

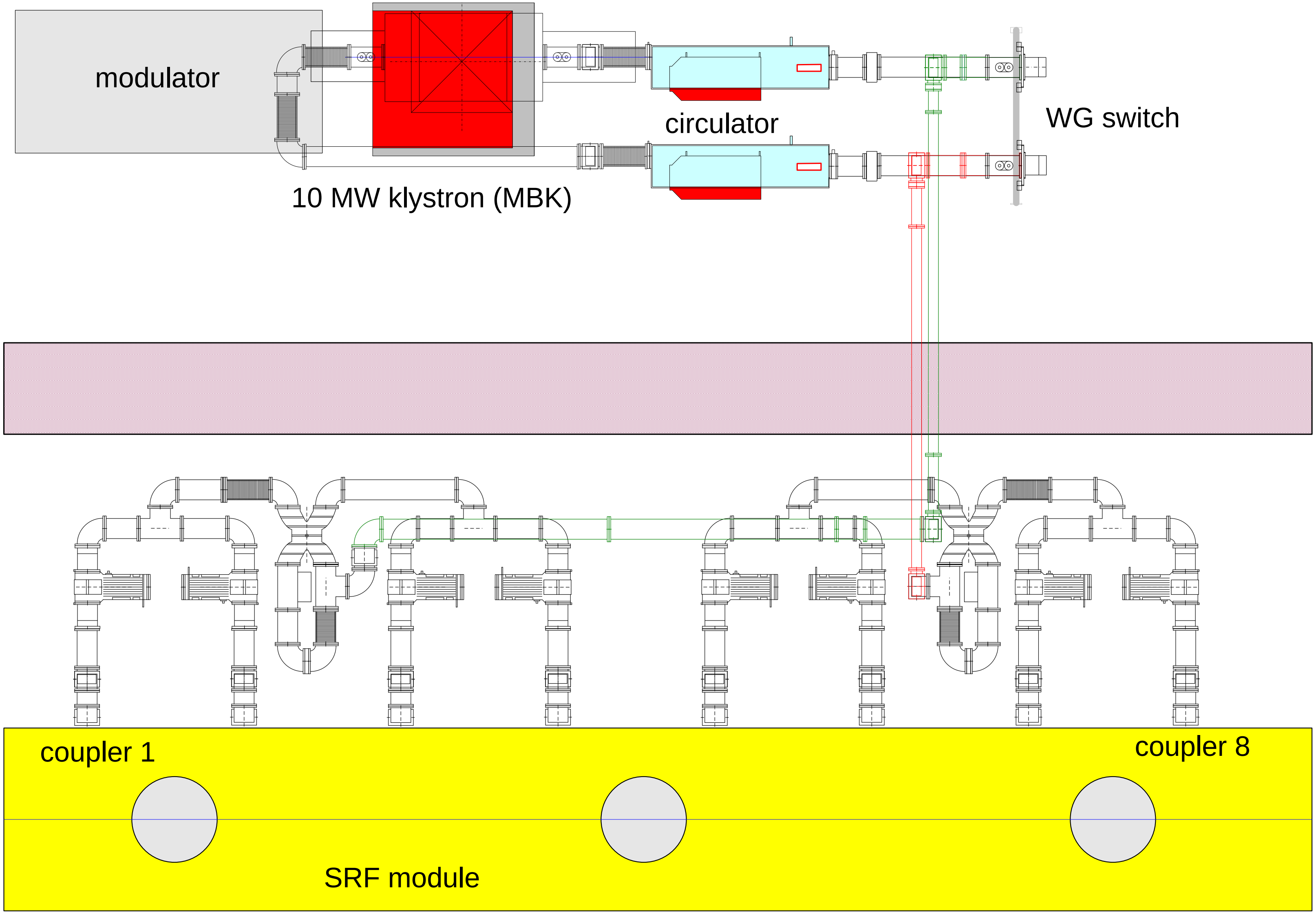
Module / Cryogenics



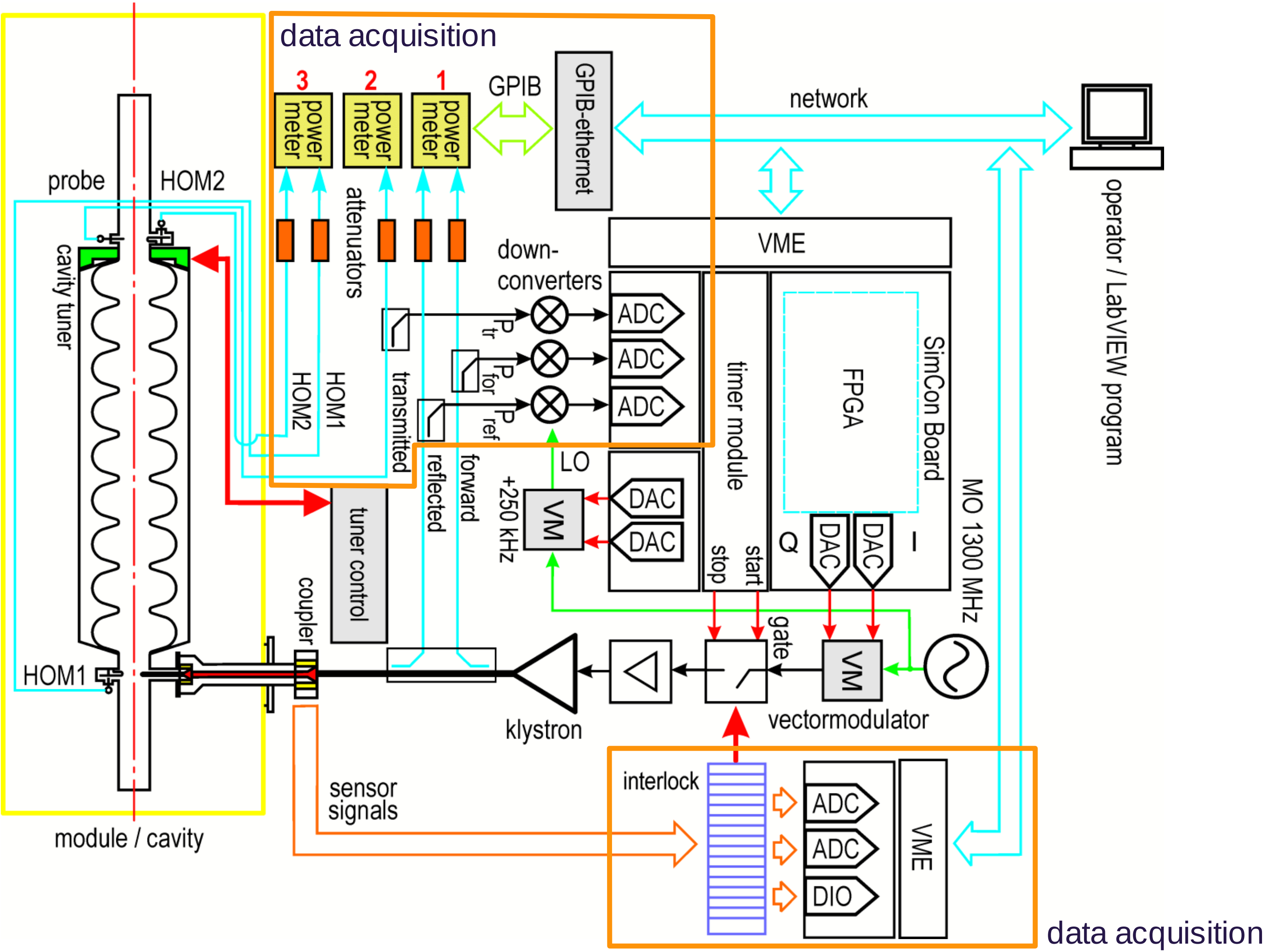
Cavity type	TESLA
Number of cavities	8
Cavity length	1.038 m
Operating frequency	1.3 GHz
R/Q	1036 Ω
Accelerating Gradient	20..35 MV/m
Quality factor	10^{10}
Q_{ext} (input coupler)	3×10^6
Operating temperature	2 K

LHe cooling 2K / 31mbar
HERA cryoplant is used

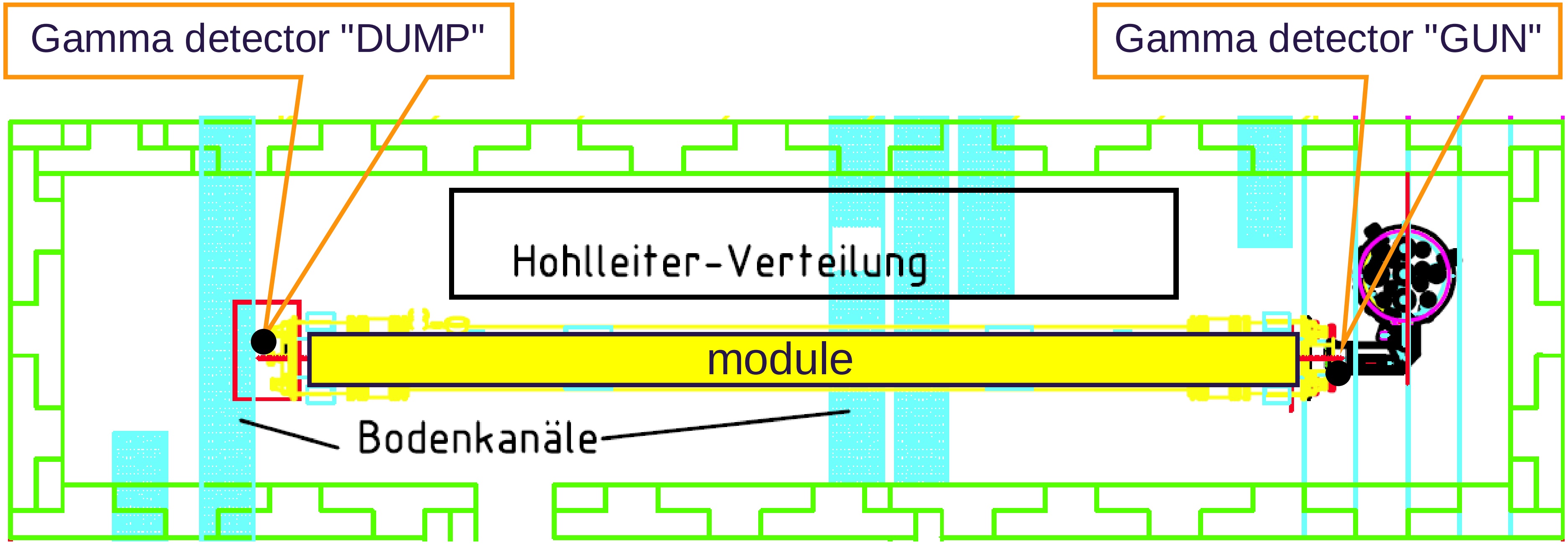
CMTB RF System



CMTB LLRF System



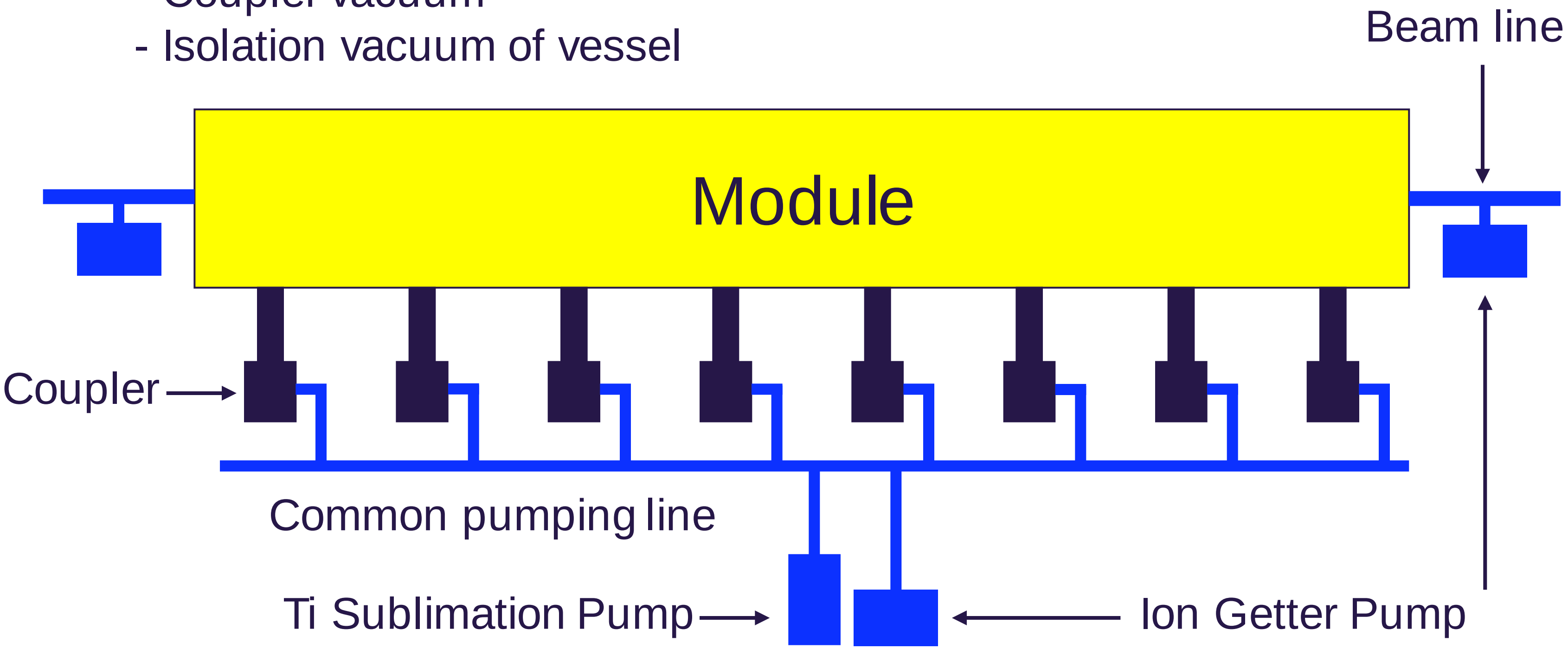
Module Gamma Radiation Measurement



Two gamma detectors are placed near the beam line on both ends of the module (by the end-caps).

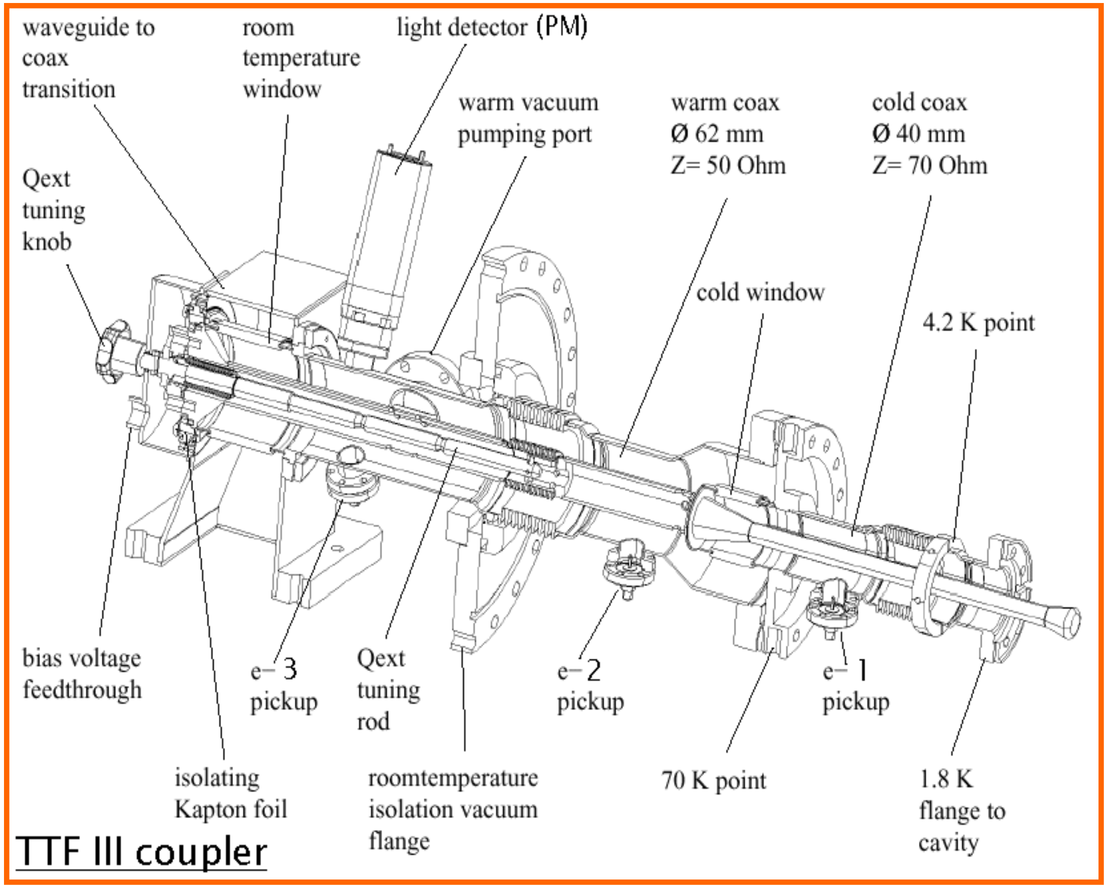
Module Vacuum System

Three vacuum systems:
- Beam vacuum
- Coupler vacuum
- Isolation vacuum of vessel



TSP/IGP connected in parallel and IGP used as a vacuum gauge.

Coupler Technical Interlock



3 times e- (charged particles)
light in coupler vacuum
light in wave guide (air side)
temperature cold ceramic
temperature warm ceramic
vacuum coupler
vacuum cavity
bias voltage
cryogenic OK

low level RF gate on klystron

all thresholds are hardware set

Module Test Procedure (1)

1. RF Cables Calibration.
   - TDR cables check
   - Dir.Couplers / Circulators: get calibration data.
   - Calibrate RF power measurement cables with attenuators at 1.3 GHz (P for/ref att. ~ 93 dB, P trans/HOM ~ 40 dB)
   - Calibrate RF power measurement cables with attenuators at 1…4 GHz (optional)
   - Make RF calibration summary table
2. Technical Interlock / Sensors.
   - Check the sensors (e-, Light, Spark, Temp.)
   - Set the hardware interlock thresholds
   - Check the interlock
3. RF source / Waveguides / LLRF.
   - Klystron / LLRF check on the load
   - WGs visual check
   - System check / RF leak check at low power (1 kW pro coupler)
4. Warm Input RF Couplers Conditioning (all / 1234 + 5678).
   - Run the standard conditioning program:
     20, 50, 100, 200, 400 μs pulse lengths up to 1MW (min. 700kW),
     800, 1300 μs pulse lengths up to 600 kW, 2 Hz rep.rate.
     (If the klystron gives not enough of RF power divide the system into the successive tests in such a way that each coupler will be conditioned up to 1MW.)

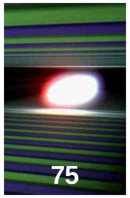
Module Test Procedure (2)

5. Cooldown to 2K.
   - Run coupler conditioning (RF power sweep) during the cooldown from 300K to 200K.
6. Cavities Spectra measurements.
   - Measure the fundamental mode spectra
   - Measure the cavities HOMs spectra and Q_{load}
   - Calibrate the cold RF cables at 2K
7. Cavities Tuners Test.
   - Test the cavities step-motor frequency tuners
   - Tune the cavities to the 1.3GHz using the Network Analyzer
8. Couplers Q_{load} measurement.
   - Measure the Q_{load} vs antennae positions,
     check $Q_{load.MIN}$ and $Q_{load.MAX}$ using the Network Analyzer
   - Set $Q_{load} = 3\times10^6$ for each coupler
9. Cavities On Resonance.
   - Cavities fine-tuning to the 1.3GHz using LLRF system
   - Q_{load}, K_t calibration ($E_{acc}=k_t\times(P_{trans})^{1/2}$)

Module Test Procedure (3)

10. Cold Input RF Couplers and Cavities Conditioning.
    - ! Short RF pulse test at 2K on resonance (100 .. 500 µs pulse lengths up to 700kW, 2 Hz rep.rate), first cavity power-up, coupler / cavity conditioning (HPP). !
11. Module Performance Measurement.
    - Module $E_{acc.MAX}$ measurement at 2 Hz rep.rate with 500 + 100 µs flat-top pulse.
    - Module accelerating gradient measurement at 10 Hz rep.rate with cryo losses (Q_o) and radiation measurements (500 + 800 µs flat-top pulse).
    - Gamma Radiation / Dark Current measurements.
    - WG power redistribution possibilities check in case of too different cavities limits ($\Delta E_{acc.MAX}$ > 5 MV/m)
12. Single Cavities Measurements.
    - Detune all cavities except the one under test
    - Flat-top pulse measurements at 10 Hz rep.rate with cryo losses (Q_o) and radiation measurements
    - Investigate the cavities limits at 10 Hz rep.rate
13. Cryo system performance test.
    - Static Cryogenic Losses measurement, temperature measurements.
    - Stretch-wire monitor module geometry deviations measurements.
    - Cool-down cycles.

Module Test Data



coupler RF power conditioning	8 couplers
coupler sensors data history	8 couplers
k_t (cavity probe calibration)	8 cavities
Q_{load} (at 1.3 GHz)	8 cavities
Q_{ext_probe}, $Q_{ext\_HOM1/2}$ (at 1.3 GHz)	8 cavities
frequency / spectra	8 cavities
$E_{acc.X.start}$ (single)	8 cavities
$E_{acc.max}$ (single, no Q_o)	8 cavities
X-rays ($E_{acc.max}$)	8 cavities
$Q_o(E_{acc})$	module
X-rays(Eacc)	module
cavity conditioning data	8 cavities
HOM couplers Q_{ext}(Freq_HOM)	8 cavities

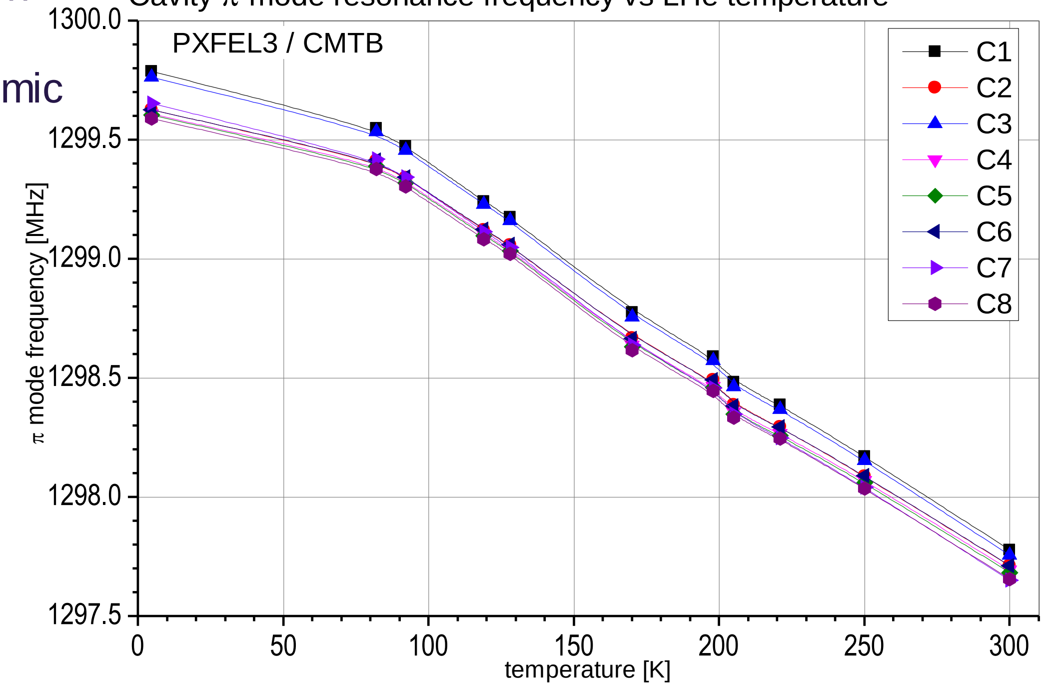
- coupler / cavity vacuum pressure
- e- probes signal (voltage)
- light (PM) signal (voltage) – not for the XFEL / AMTF
- spark detector (diode) signal (voltage)
- cold ceramics temperature (PT1000) T_{70K}
- warm ceramics temperature (IR/PT1000) T_{300K}

- coupler sensors data
- RF power / cavity gradient
- gamma radiation (X-rays)
- LHe level / pressure

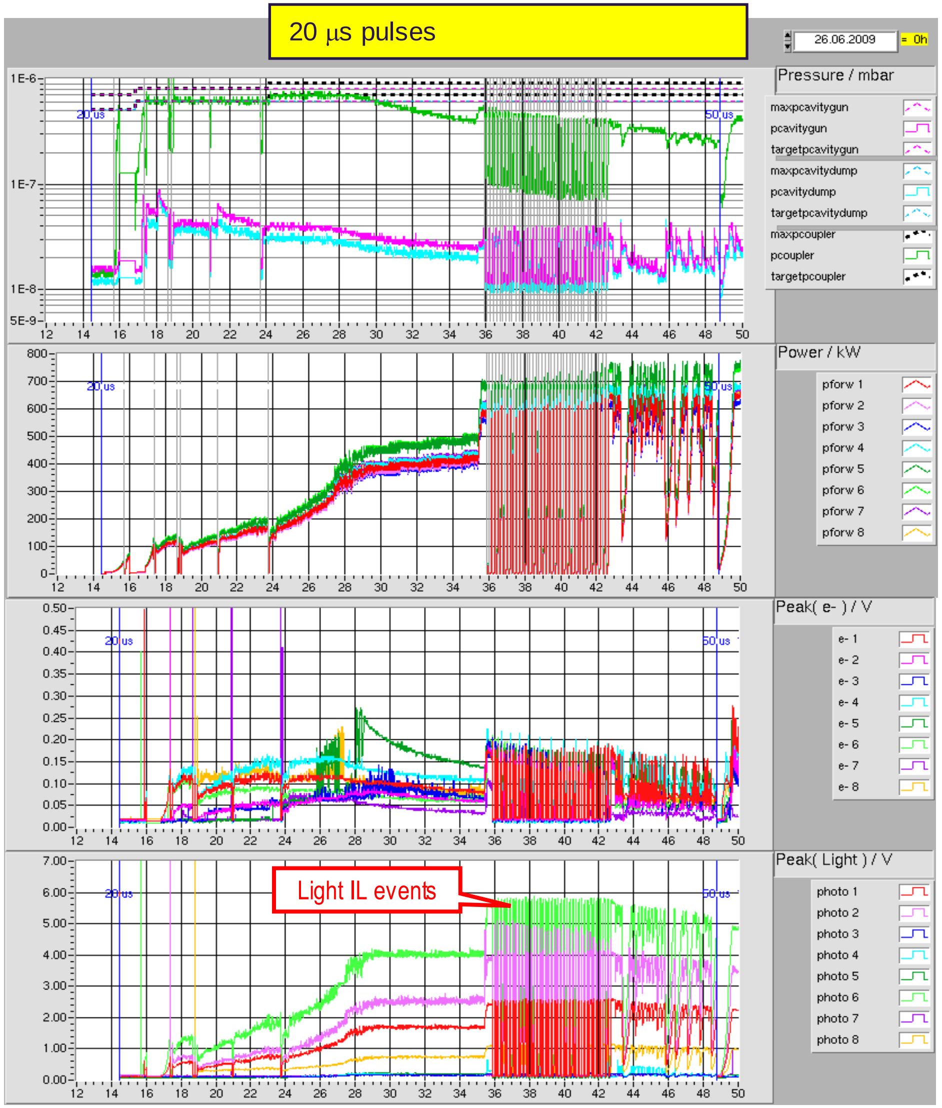
Cryosystem/Cooldown Test

- temperature measurement: temperature sensors (cavities/couplers + cryogenics) data are stored.
- multiple cooldown / warm-up test.
- cavity resonance frequency measurement during the cooldown.
- cryogenic losses measurement based on temperature and LHe flow data: 2K, 4K and 70K static (infrastructure) and dynamic (RF power) losses.
- stretch-wire based module dimensional changes measurements.

Cavity π-mode resonance frequency vs LHe temperature

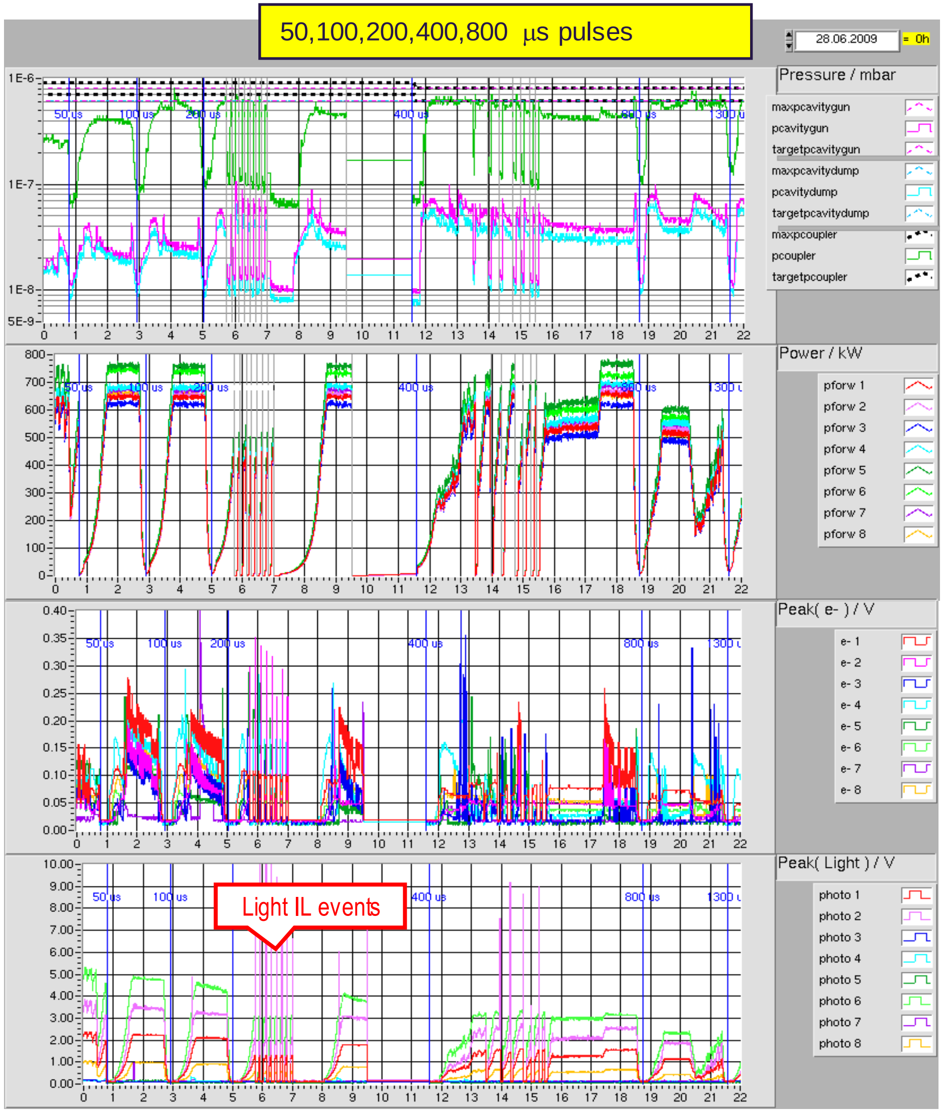


RF Couplers Conditioning History/Data (1)



20 µs pulses

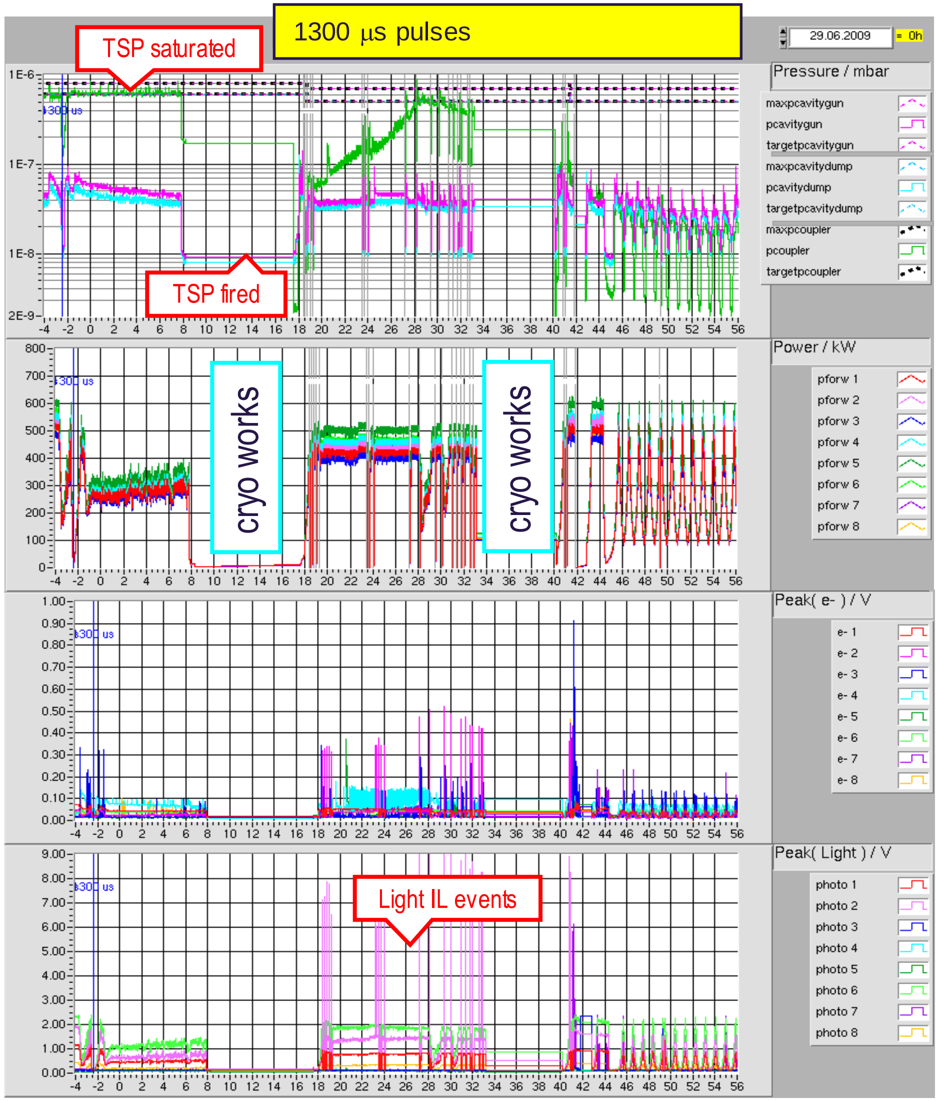
Light IL events

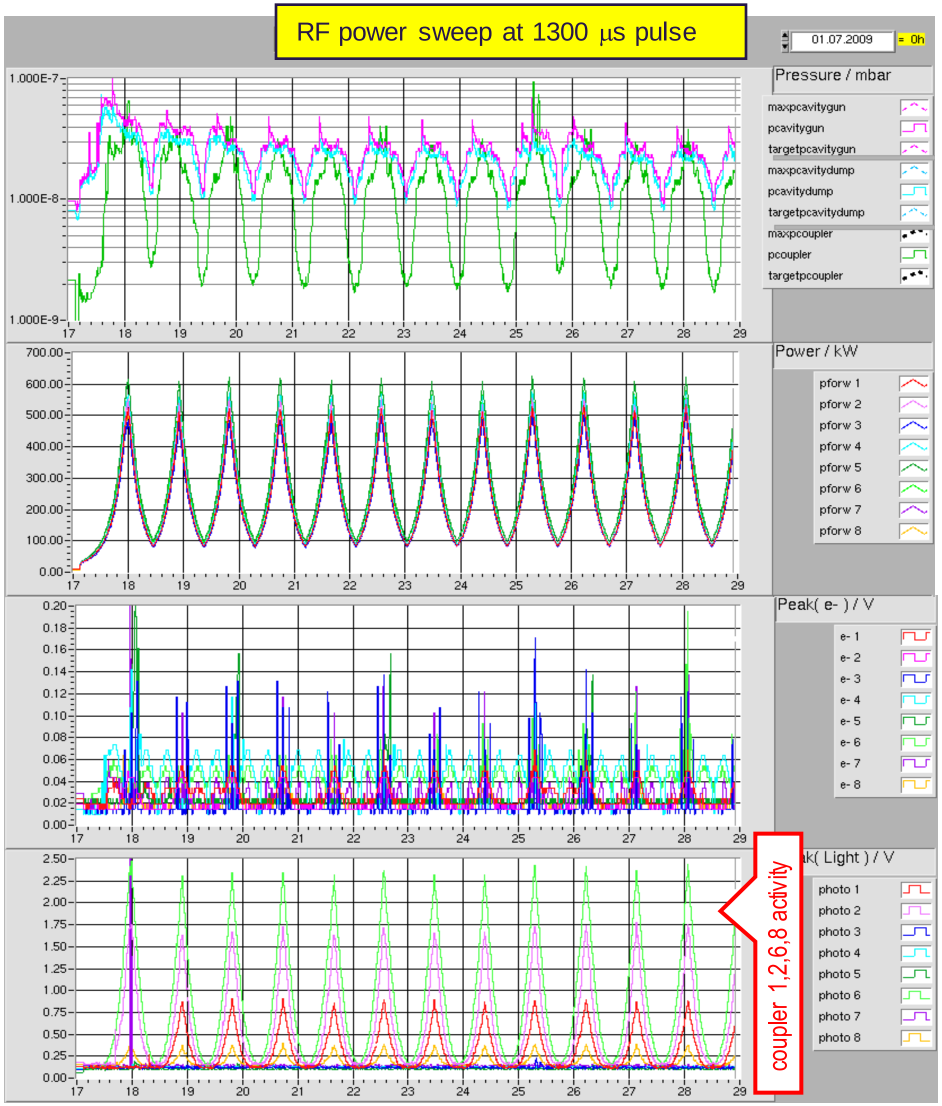


50,100,200,400,800 µs pulses

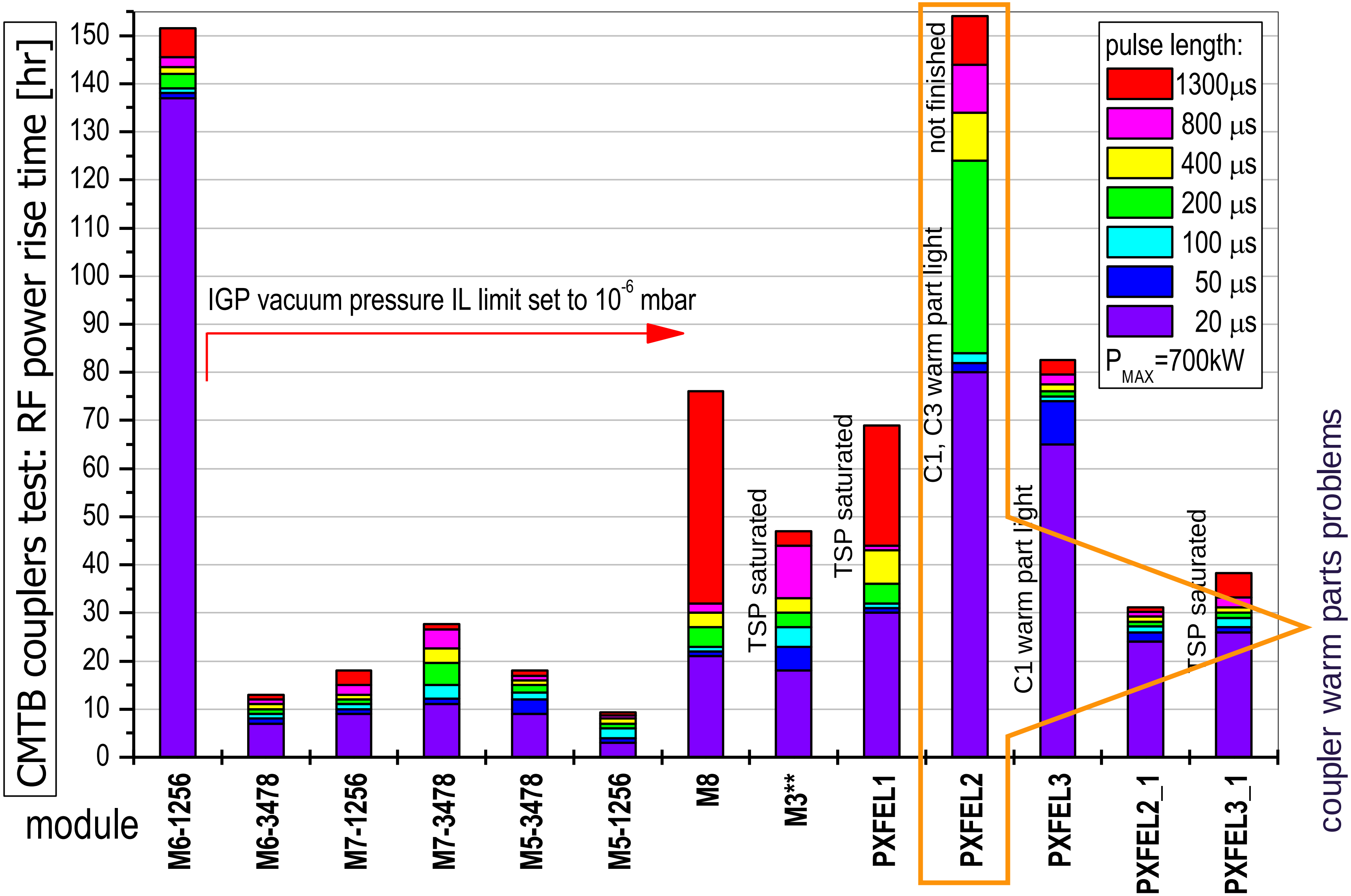
Light IL events

RF Couplers Conditioning History/Data (2)



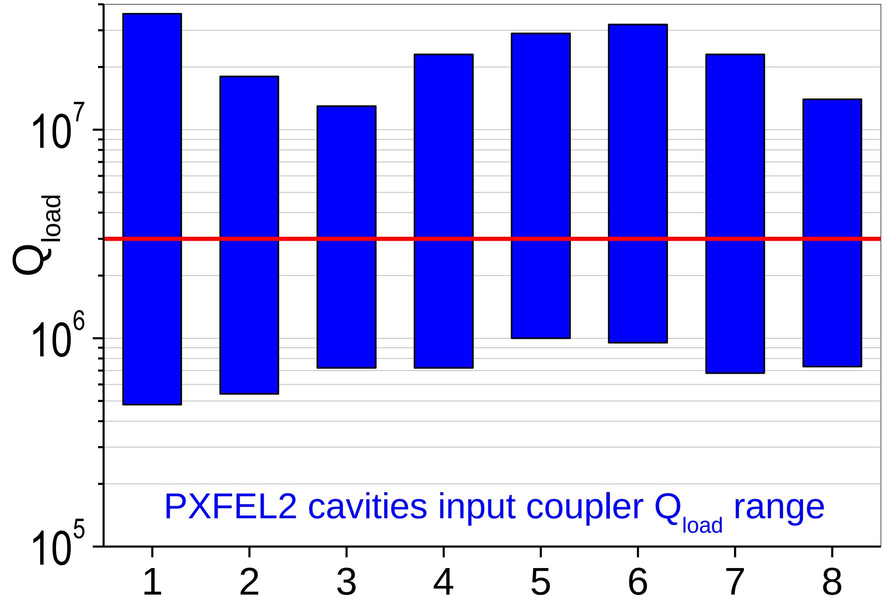


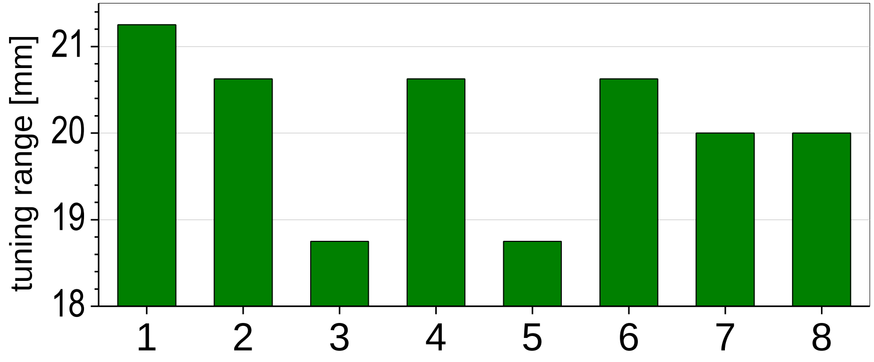
RF Couplers Conditioning Time

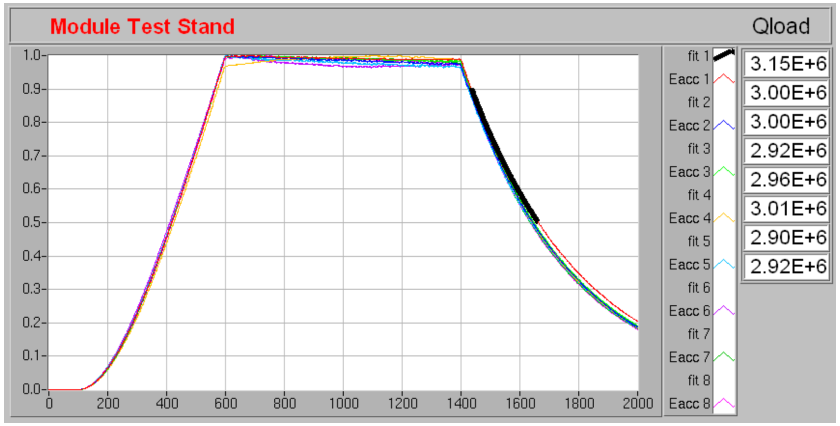


RF Couplers Q_{load} Tests

Input RF Couplers coupling tuning range measured at CMTB



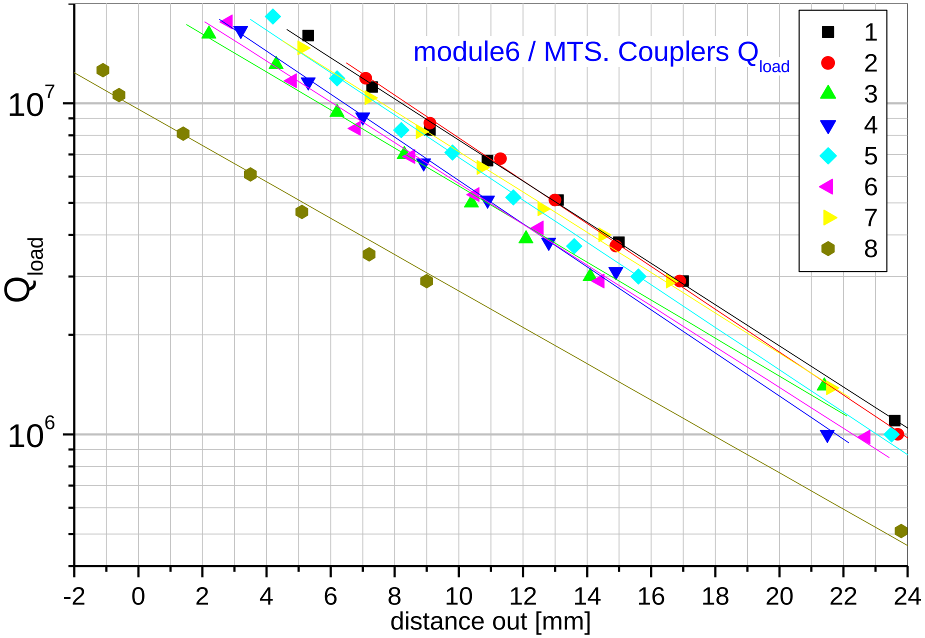



Module Test Stand

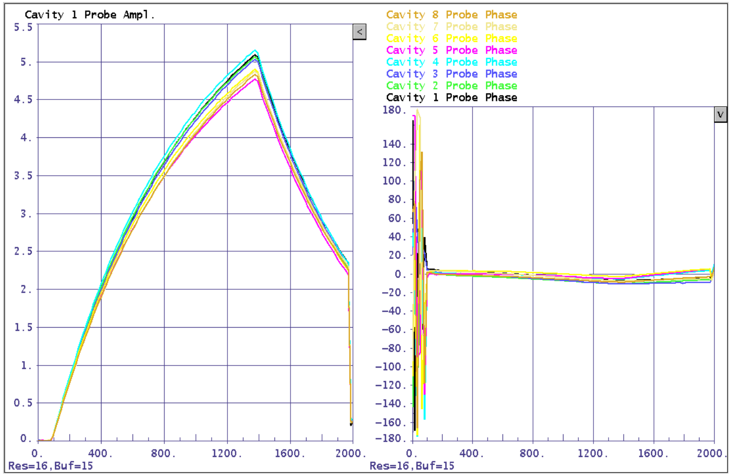
Qload

Qload
3.15E+6
3.00E+6
3.00E+6
2.92E+6
2.96E+6
3.01E+6
2.90E+6
2.92E+6

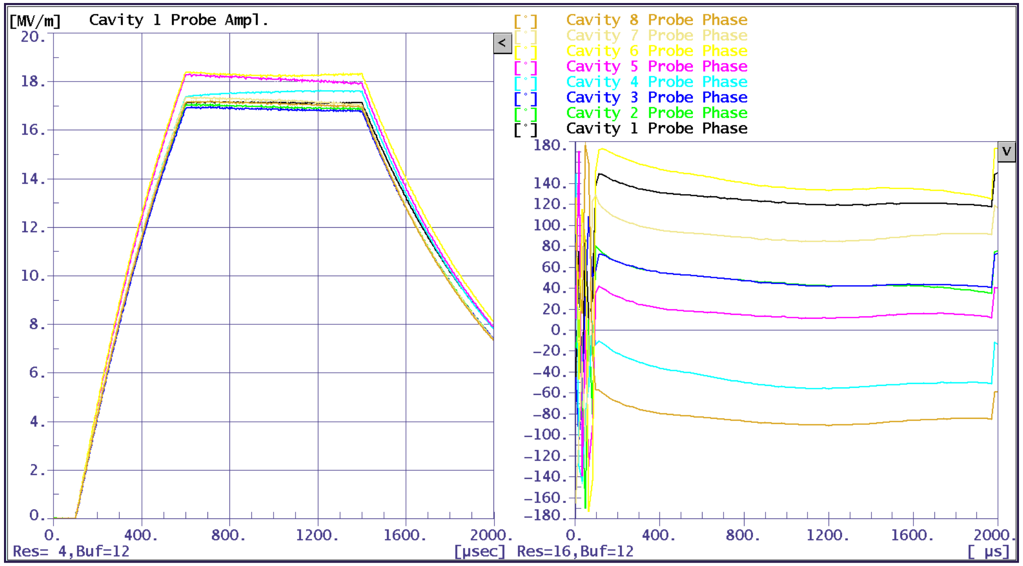
operating value $Q_{load}=3\times10^6$



RF Calibration / Cavity Test



Cavities gradients for the 1.3 ms rectangular pulse



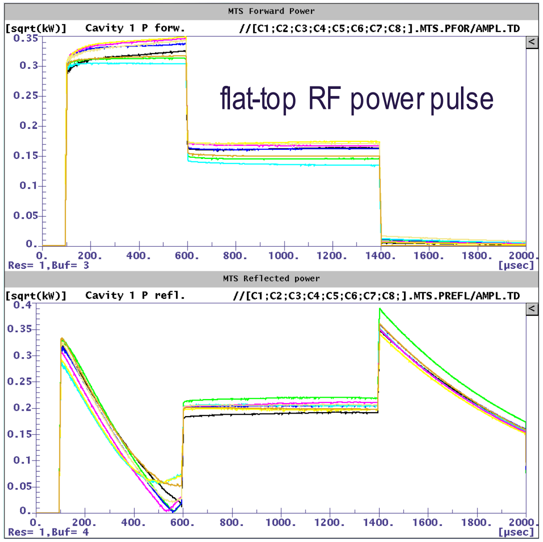
RF Power Calibration

$$E_{ACC} = \frac{\sqrt{4\frac{R_{sh}}{Q} Q_{load} P_{for}}}{L_{cavity}} \times \left[1 - e^{-\frac{\pi f_0 t_{fill}}{Q_{load}}}\right] =$$

$$= k_t \times \sqrt{P_{trans}}, [V/m]$$

evaluated error margins for accelerating gradients in this test are about ±10..16%.

$R_{sh}/Q=1030\Omega$, Lcavity=1.035m,
Qload=3×10^6, f_0=1.3GHz, Pfor≈5kW,
t_{fill}=1300μs (for calibration, 500μs for flat-top)



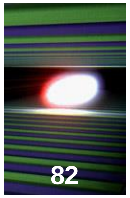
$$Q_0 = \frac{(E_{acc}L)^2}{R/Q\,P_{loss}};$$

$$P_{loss} = \frac{P_{cryo}}{t_{pulse}\,rep.rate}$$

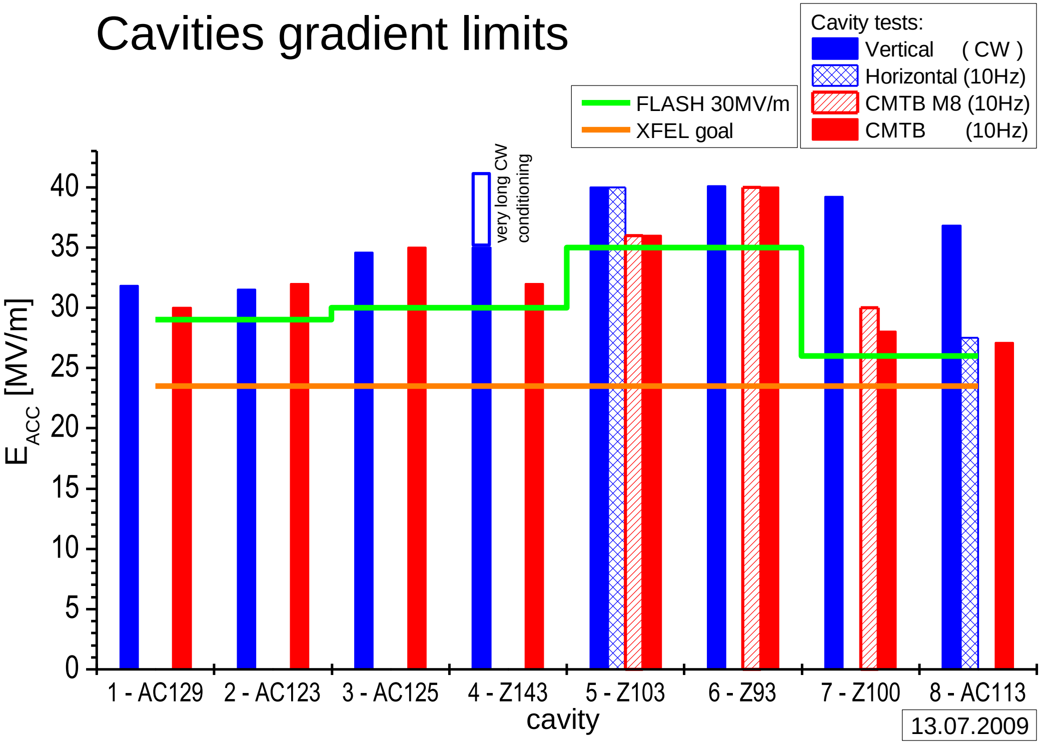
$$Q_{ext} = \frac{(E_{acc}L)^2}{R/Q\,P_{ext}};$$

$$P_{ext} \rightarrow P_{trans}, P_{HOM}$$

Example:
Test Results: PXFEL1 Data (1)

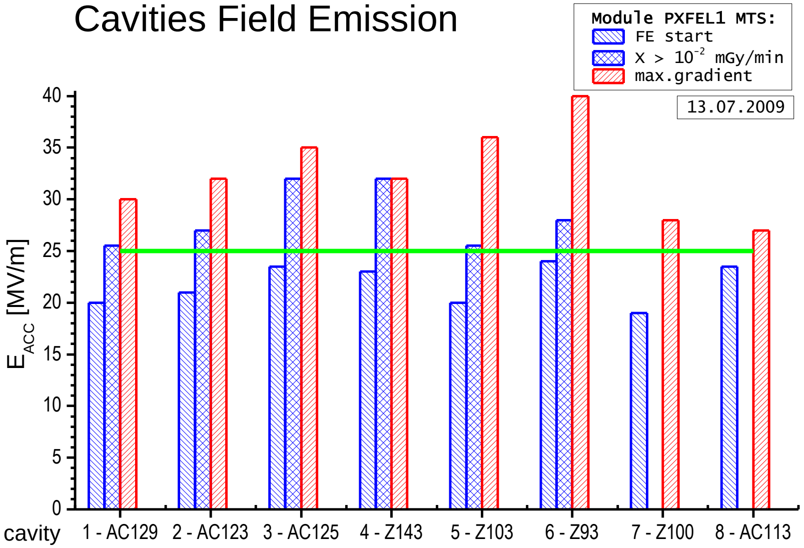


Cavities gradient limits



13.07.2009

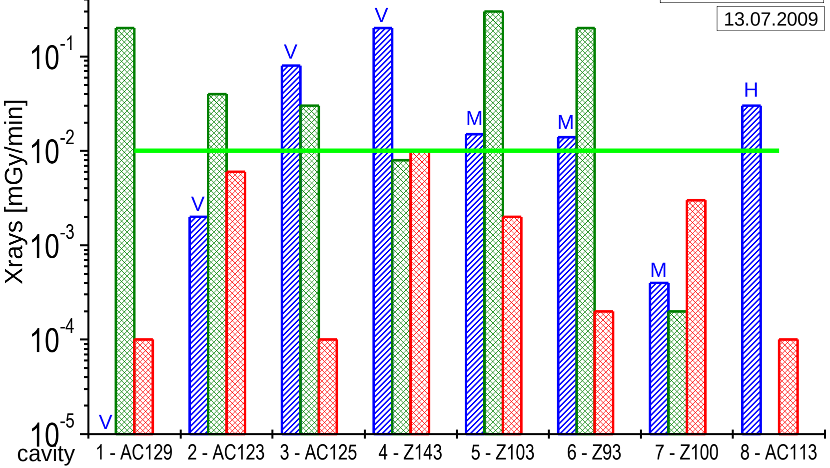
Cavities Field Emission



13.07.2009

single cavities radiation at $E_{acc.max}$

cavities 1..4 tested in vertical cryostat before module assembly (V)
cavities 5,6,7 were in the module 8 at the same positions (M)
cavity 8 tested in horizontal cryostat before module assembly (H)

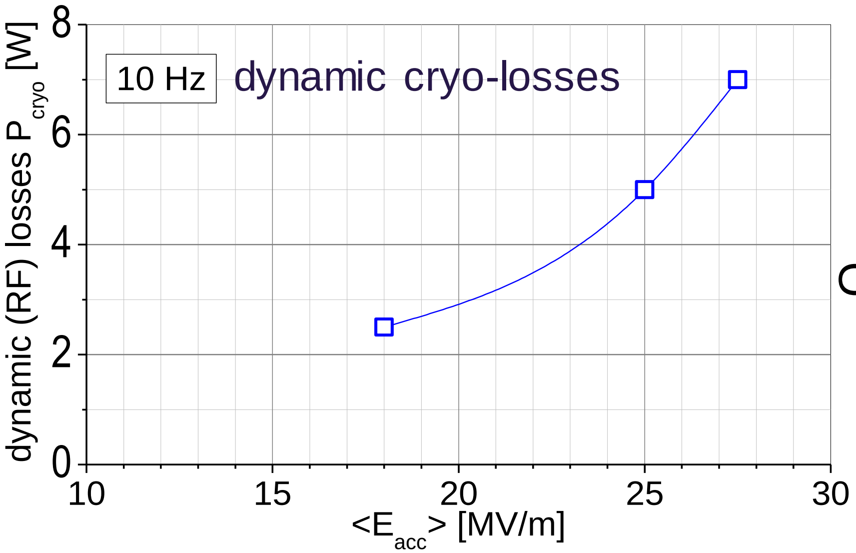


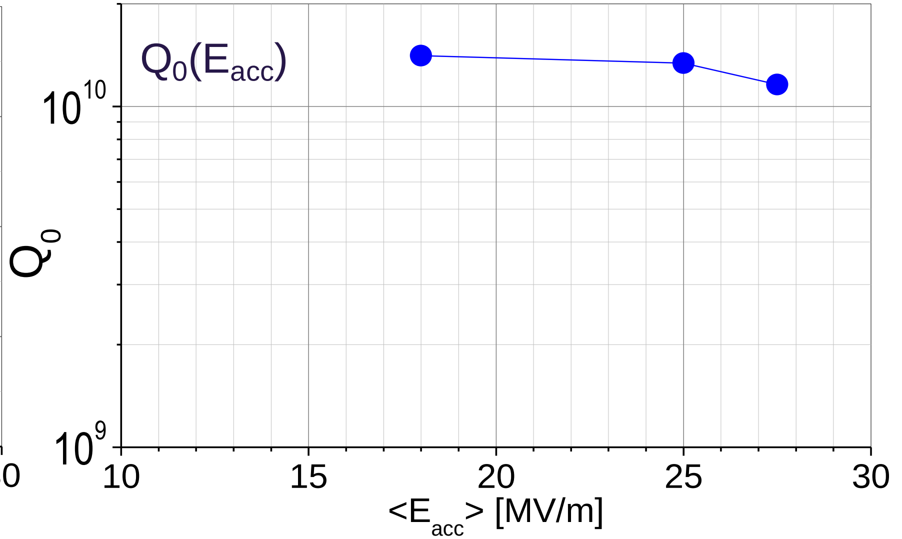
13.07.2009

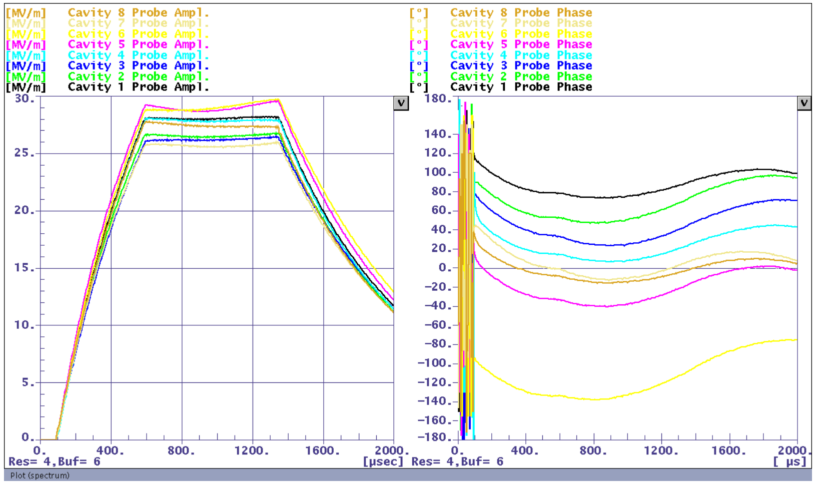
static cryo-losses:

	measured (CMTB)		XFEL specification
RF power, kW	120	230	200
4K losses, W	0.1	0.26	0.5
70K losses, W	2.5	3.75	6.0

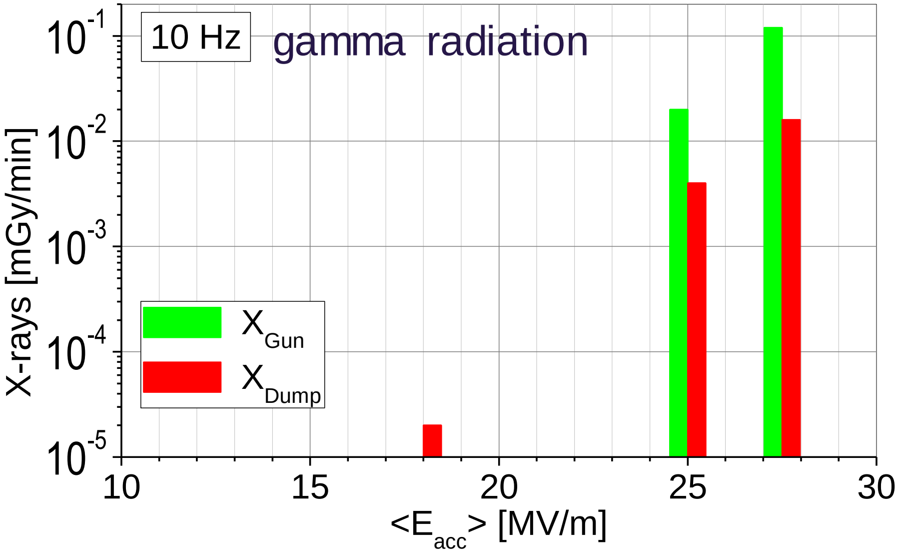
Example:
Module Test Results: PXFEL1 Data (2)



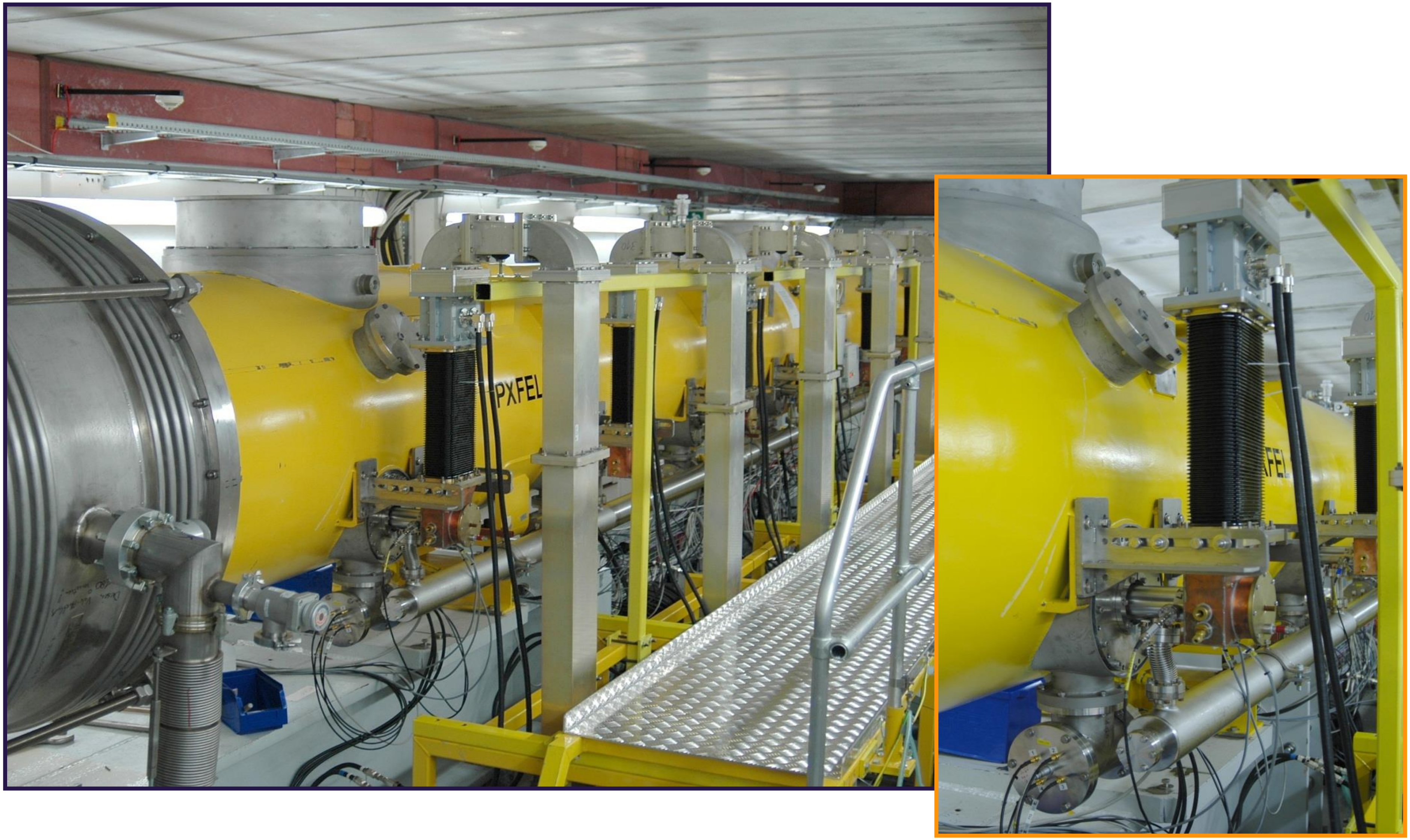




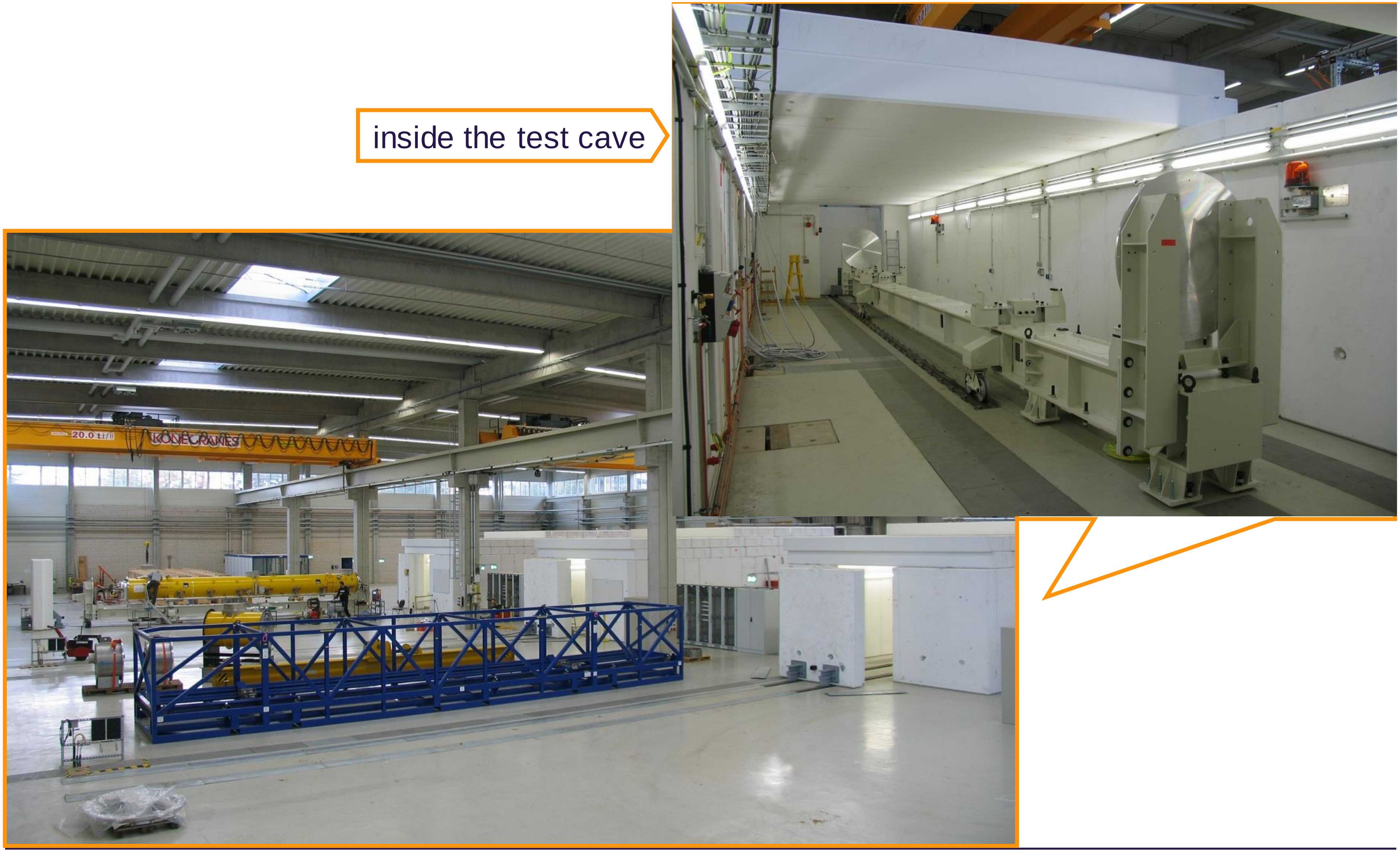
Flat-top pulse 500+800µs operation at 10 Hz



Cryo Module Test Bench



Accelerator Module Test Facility overview



inside the test cave

References

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- T. Powers, “Theory and Practice of Cavity Test Systems”, Tutorial SRF Workshop 2005
  + “Practical Aspects of SRF Cavity Testing and Operations”, Tutorial SRF Conference 2011
- W.-D. Moeller, “Design, Fabrication, and operation of High-Power and HOM- Coupler for SC Cavities”, Tutorial SRF Conference 2011
- J. Sekutowicz, “Superconducting Cavities”, CAS 2010
- R. Geng, “Limits in Cavity Performance”, Tutorial SRF Conference 2011
- H. Piel, “Diagnostics Methods of Superconducting Cavities and Identification of Phenomena”, SRF workshop 1980
- Tutorials and Contributions to SRF workshops / conferences

Thank you !

Thanks to all colleagues for their support, transparencies and "stolen" figures especially

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J. Mammosser, H. Padamsee, H. Piel, T. Powers,
F. Schlander, J. Sekutowicz, H. Weise

The end !