Field Emission Overview: Cleanliness and processing

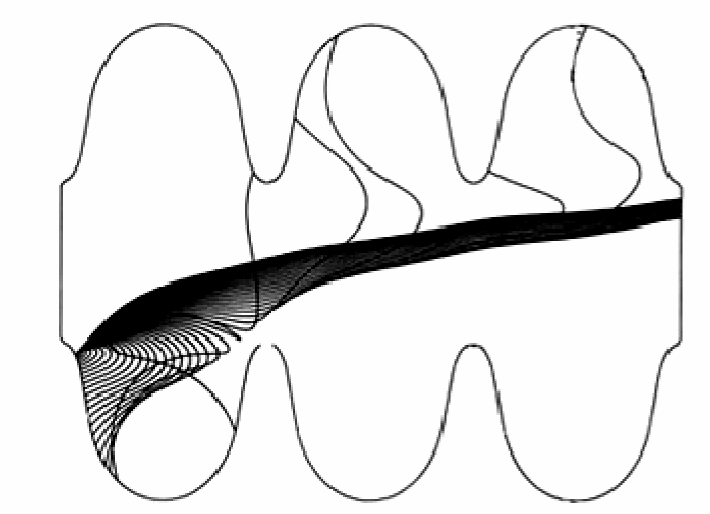
Detlef Reschke
DESY

- Introduction
- Present picture of field emission
- Standard procedures
- Practical consequences and Alternative cleaning approaches
- Processing in Accelerator Structures
- Summary

Introduction

- Major limitation of the last years in multi-cell cavities, especially in beam operation:

- **Field Emission!!**

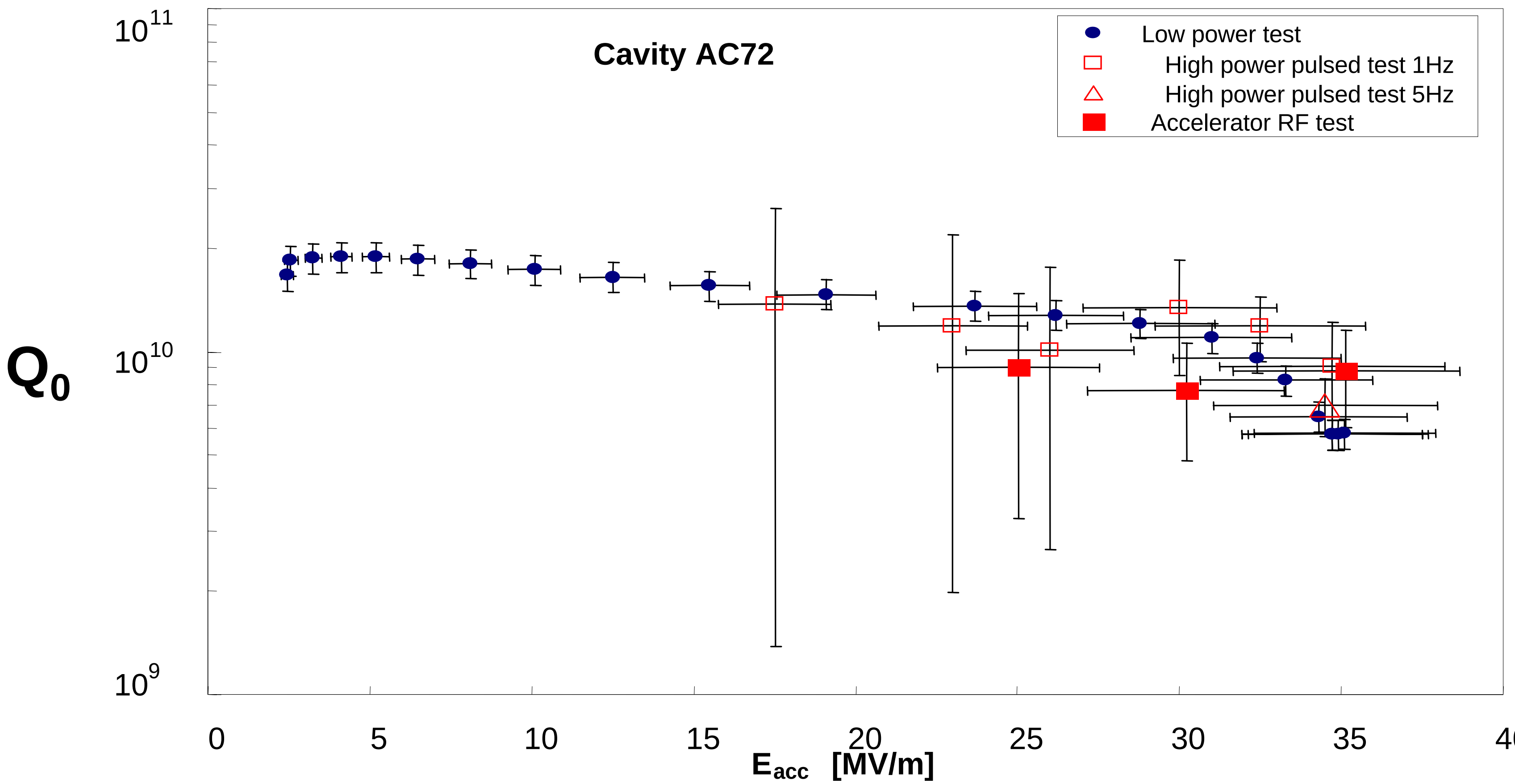


- Typical (good) onset of field emission at 1.3 GHz
  - single-cell cavities: $E_{acc,onset} > 30$ MV/m
  - multi-cell cavities (vertical + horizontal): $E_{acc,onset} \approx (20 - 25)$ MV/m

- But:

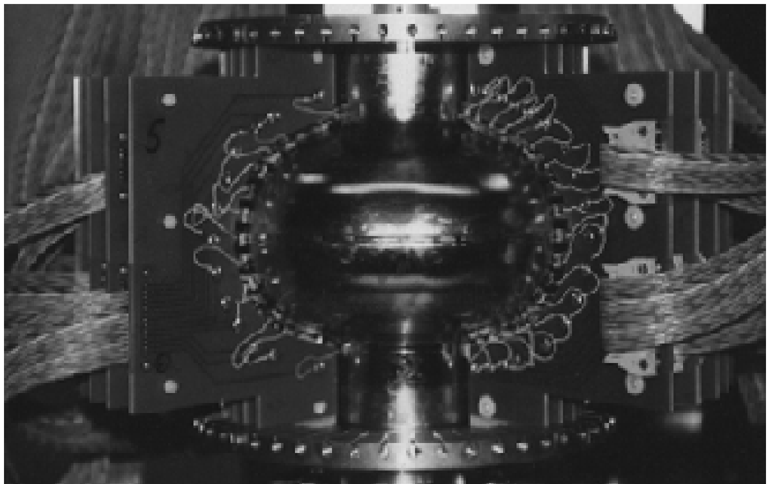
Introduction

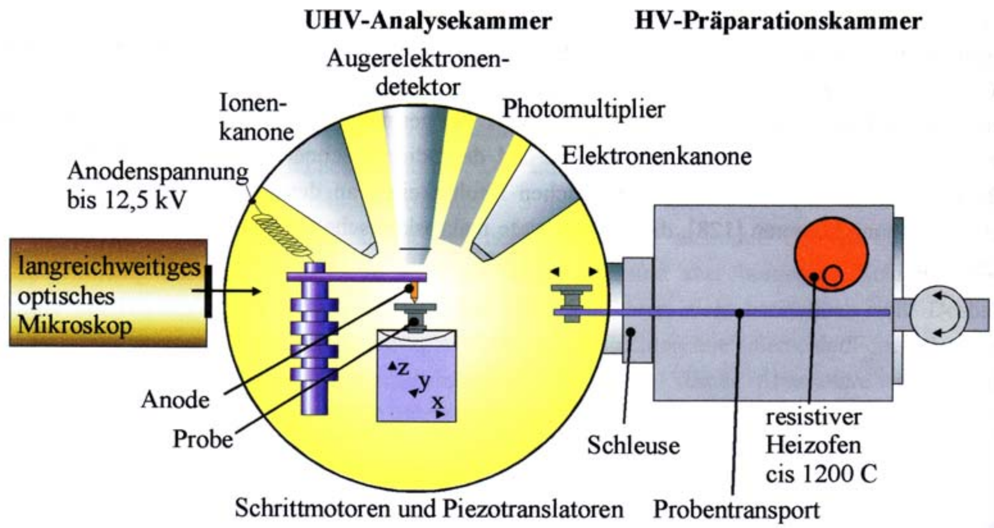
- 35 MV/m without field emission in e^- - beam operation is possible !!

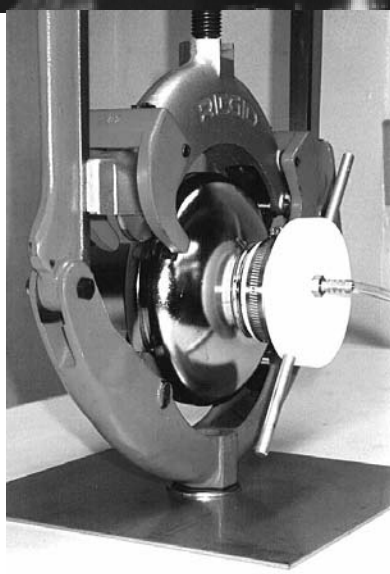


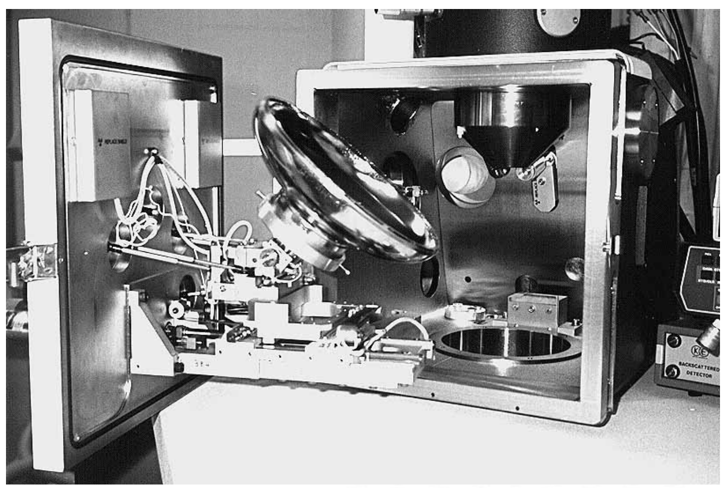
Present picture of field emission: instruments

- Some tools developed for field emission investigation



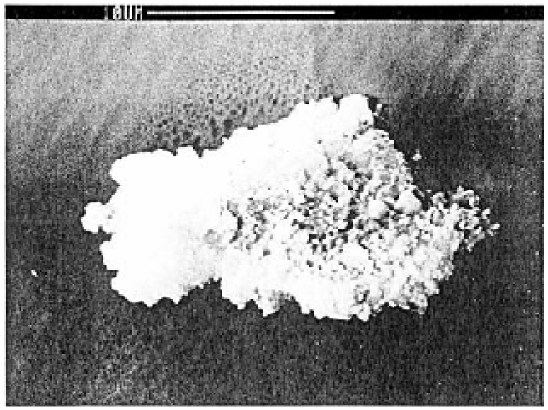






Present picture of field emission: observations

- Metallic (conducting) particles of irregular shape; typical size: 0,5 - 20 µm
- Only 5% - 10% of the particles emit
- hydrocarbon contamination of the vacuum system



- Modified Fowler-Nordheim's law :

$$I \propto A_{FN} \cdot (\beta_{FN} E)^2 / \Phi \cdot \exp\left(- \frac{C\, \Phi^{3/2}}{\beta_{FN}\, E}\right)$$

- typical β-values between 50 and 500 for srf cavities
- A_{FN} (FN emission area) not directly correlated to physical size of emitter

- No substantial difference in rf and dc behaviour

Present picture of field emission: model

- Protrusion-on-protrusion model explains the experimental observations
- Modifications of A_{FN} and β by adsorbed gases and oxide layers
- Activation of emitters between 200C and 800C by modification of the boundary layer

  → influence of 120C bake-out ??

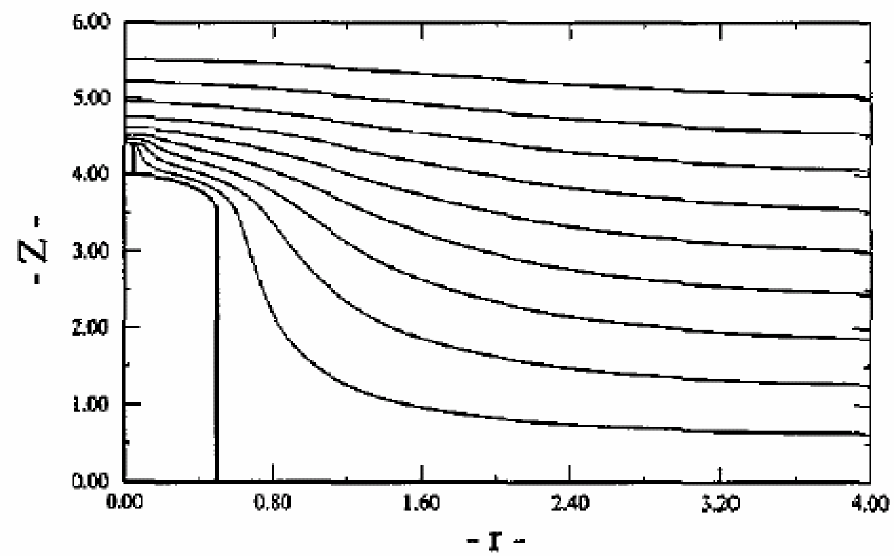
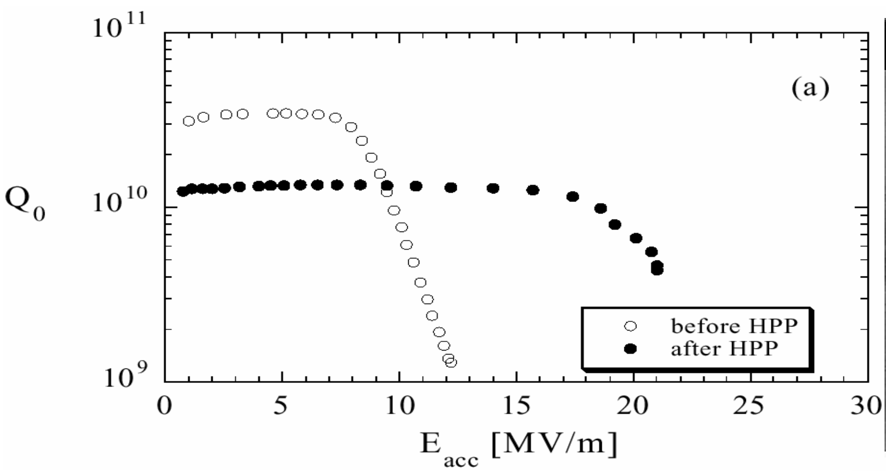
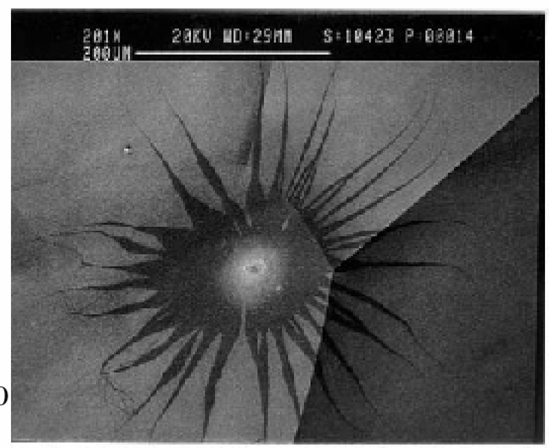


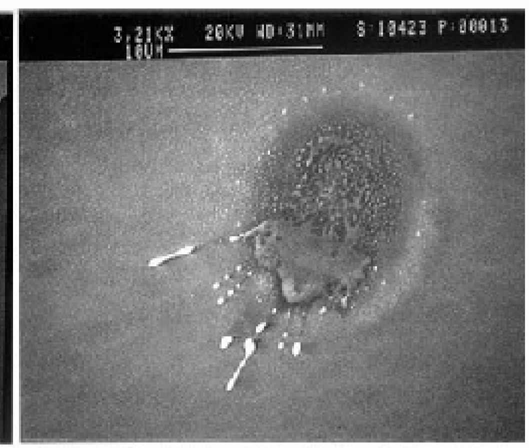
Figure 12. Calculated equipotentials for two superposed hemispherically capped cylindrical projections.

Present picture of field emission: processing

- Processing of emitters ("conditioning") possible
  - i) rf and helium proc. with moderate rf power and cw-like operation
  - ii) high peak power processing with high rf power and short pulses
- Helium processing: i) modification of the adsorbed gases (≈ seconds)
  ii) explosive destruction (≈ subseconds; rare)
- High peak power processing (HPP): 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







Present picture of field emission: summary

- Quality of final cleaning & dustfree assembly is crucial for field emission free cavities
  $\rightarrow$ perfect cleaning of cavity + all auxiliaries
  $\rightarrow$ dustfree assembly
  $\rightarrow$ pumping & venting without recontamination (particles, hydrocarbons)
  $\rightarrow$ documentation

- surface conditions are poorly known compared to semi-conductor industry:
  - No investigations of the sensitive inner cavity surface possible !
  - samples $\rightarrow$ very valuable, but bad statistics
  - cutting of cavities $\rightarrow$ continue Cornell experiments
  - imprint technique $\rightarrow$ surface morphology

- no review of contamination and cleaning mechanisms
  see P. Kneisel, B. Lewis, SRF workshop 1995

Standard procedures

- Very rough summary of final treatment !

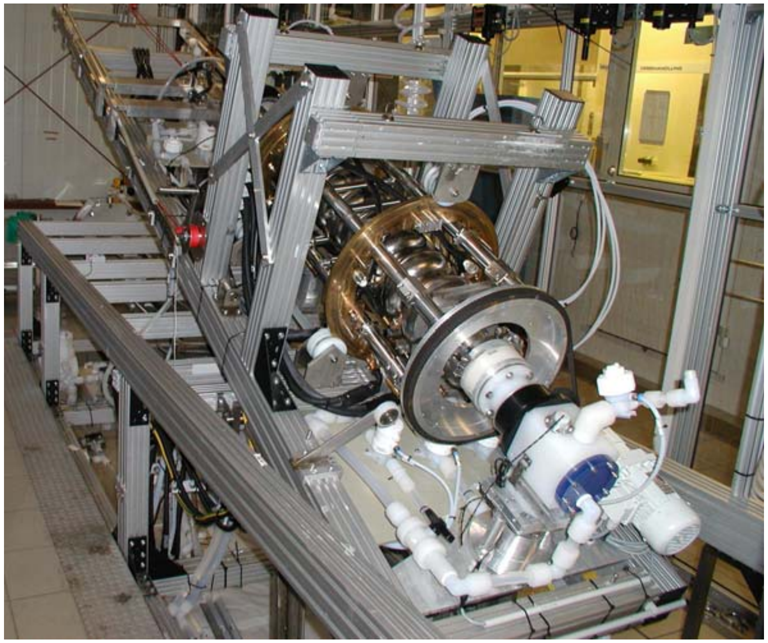
- Final chemical etching or electropolishing

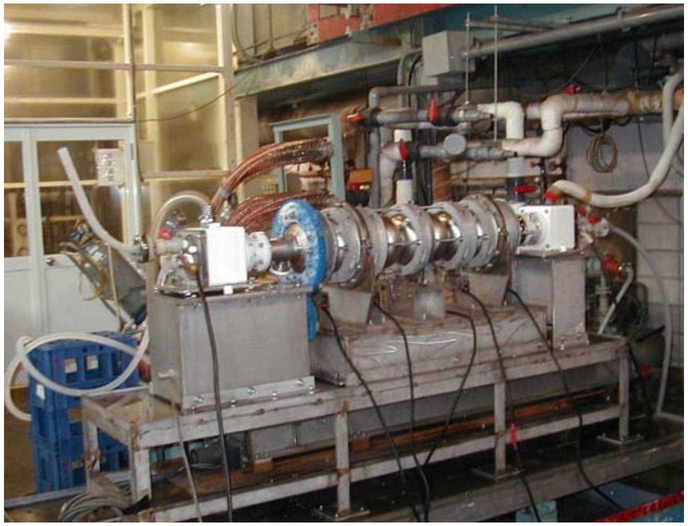
  ↓ BCP 1:1:2 ↓ HF : H_2SO_4 with volume ratio 1:9

  - typical final 10 - 40 µm removal of inner surface
  - closed system with integrated DI-/pure water rinsing
  - acid quality: “pro analysi” or better

- Questions:
  - Which level of acid quality and particle filtration necessary?
  - Which “clean” environment necessary?
  - Alternative acid mixtures? Comparison of BCP 1:1:1 vs. 1:1:2 ?

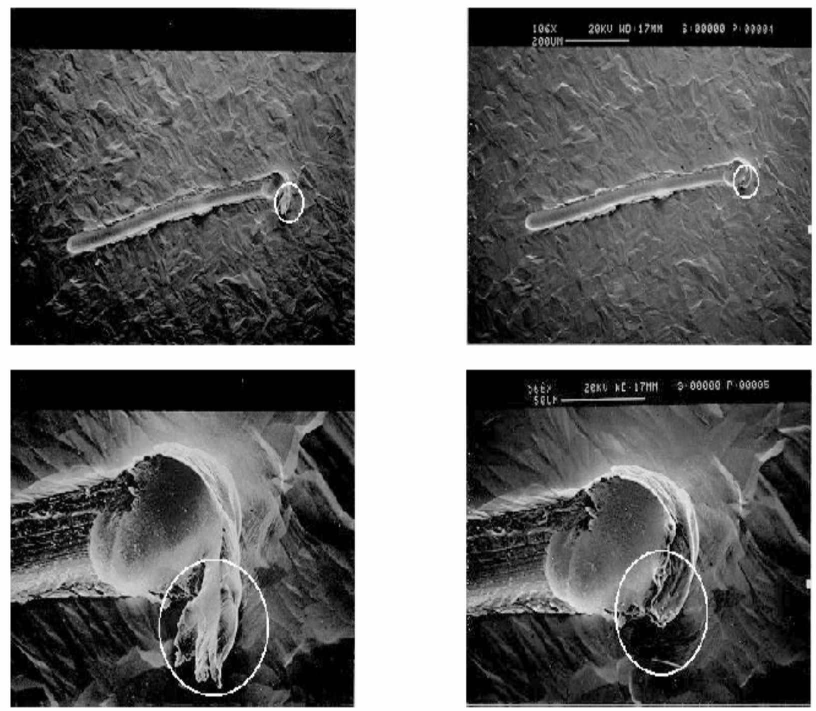
BCP and EP facilities





Standard procedures (ctd.)

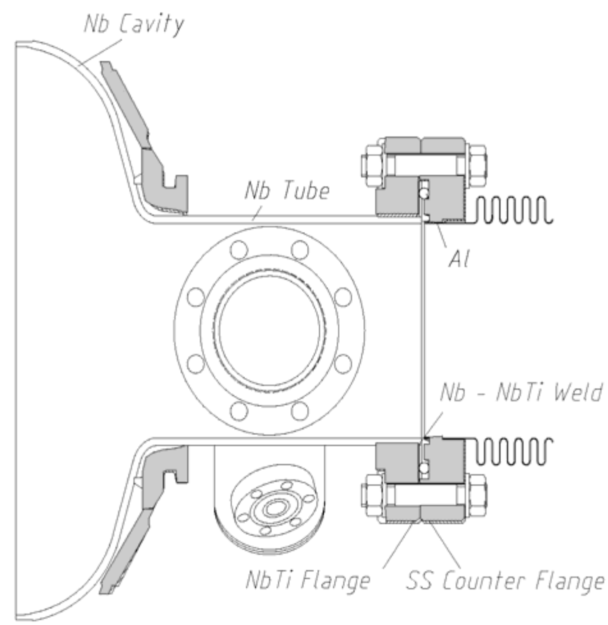
- (ultra) pure water rinsing
  - cold DI-Water > 12 MΩcm; particle filtered
- 1. High pressure rinsing (cleanroom cl.10 - 100)
  - inside rinsing of open or plastic flanged cavity
  - ultra pure water with p = (80 - 150) bar



Before HPWR After HPWR

Standard procedures (ctd.)

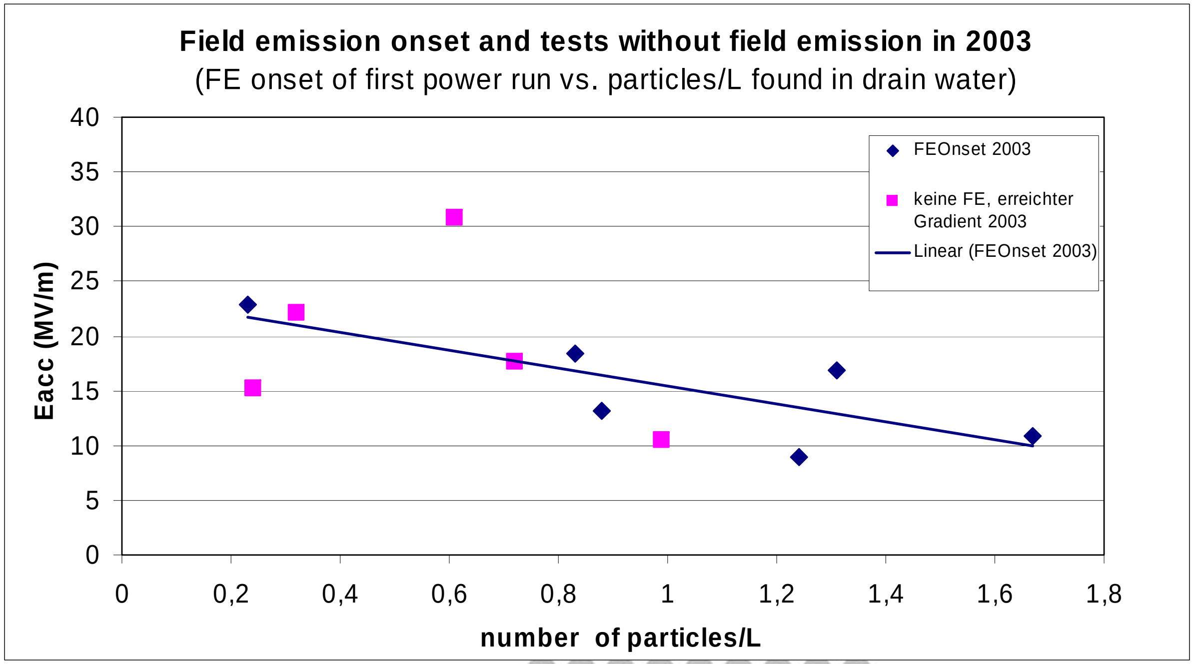
- Drying
  - e.g. open in class 10
- assembly (cleanroom cl.10)
  - well cleaned components (flanges, power coupler, bolts, nuts)
  - well-trained and motivated personal
  - keep duration of actions at open cavity short
  - simple flange & gasket design e.g. NbTi-flange with Al-gasket
  - check of cleanliness?



TESLA

Standard procedures (ctd.)

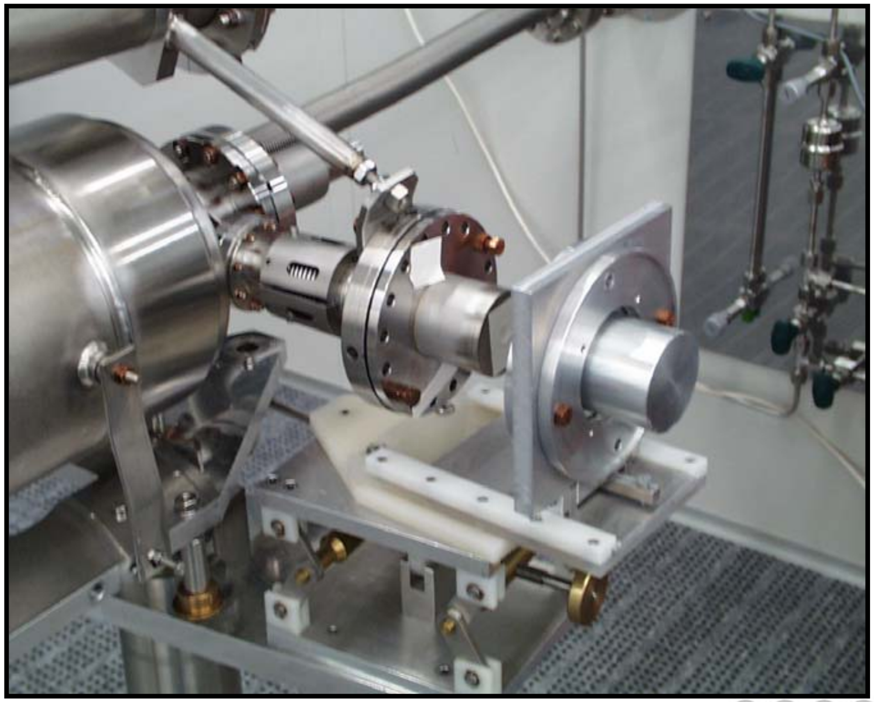
- leak check + venting (cleanroom cl.10)
  - oil-free pumping system
  - laminar venting with pure, particle filtered N_2 or Ar
- N-times high pressure rinsing (cleanroom cl.10 - 100)
  - check of particles (+ TOC) of HPR water
  - check of drain water as quality control of rinsing effect

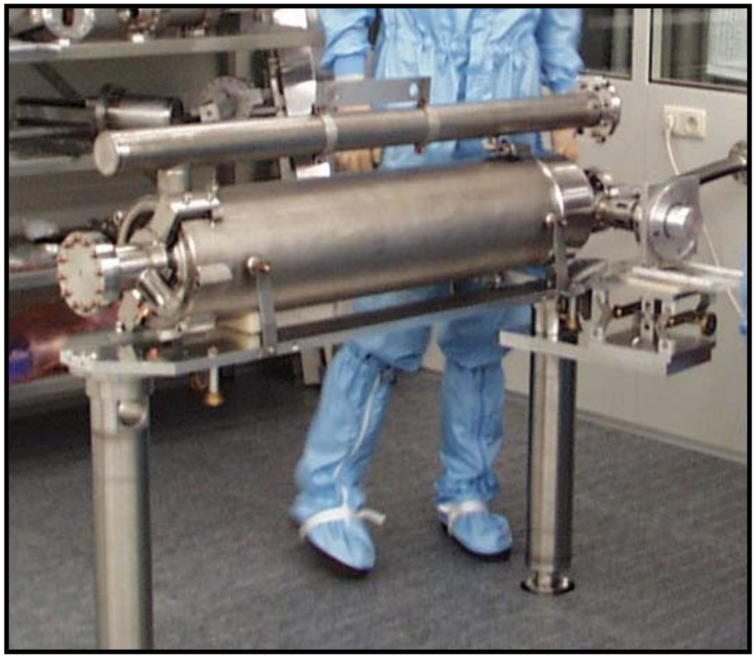


particles > 6 µm

Standard procedures (ctd.)

- assembly of final flange after open pre-drying (cleanroom cl.10)
- final drying by pumping + leak check + venting (opt.: heating < 100C)
  - analysis of residual gas composition
- assembly of power coupler (cleanroom cl.10)
  - pre-conditioning effect gets lost by water rinsing



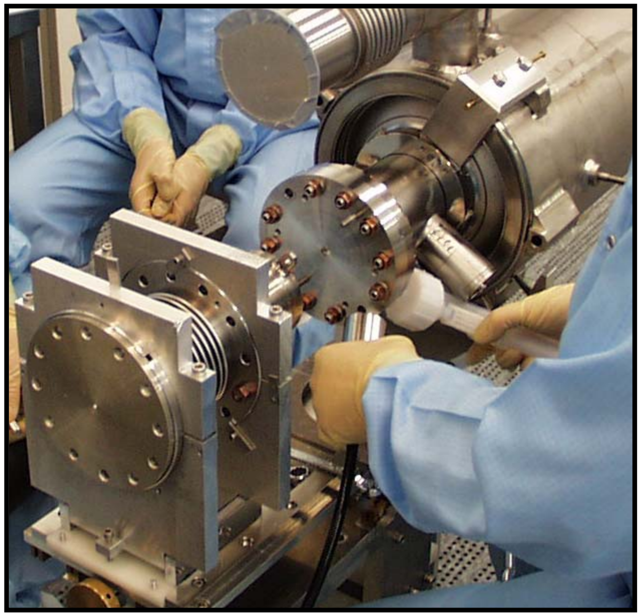


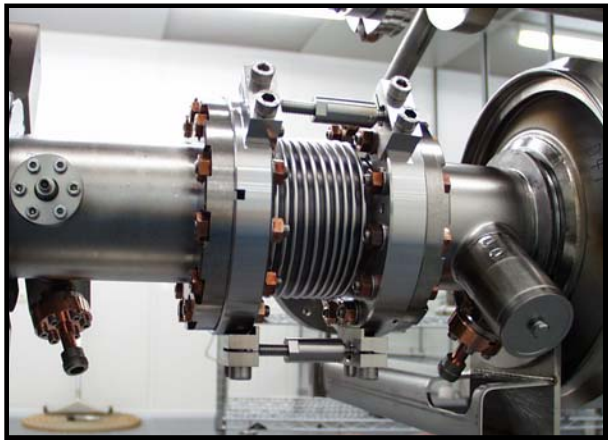
Standard procedures (ctd.)

- horizontal test (“dirty” experimental hall)
- cleaning for string assembly (“dirty” $\rightarrow$ cl. 10000 $\rightarrow$ cl.10)
- Venting (cleanroom cl.10)

Standard procedures (ctd.)

- assembly of cavity string (cleanroom cl.10)
  - includes gate valves + magnets
  - on the job cleaning of bolted beam pipe flanges necessary
- final leak check + venting for transportation (cl.10 → “dirty”)
  - maybe repeated in “dirty” surrounding





Standard procedures: risk analysis

- Assembly:
  - TTF: 3 of 10 assemblies + 3 of 4 disassemblies after final HPR
  ☠ risk of contamination with particles
  reminder: most particles are created during opening bolt-nut connections!

- String assembly:
  ☠ no further cleaning of inner cavity surface possible
  ☠ risk of improper cleaning due to complex structure

- Venting:
  - TTF: 3 - 5 times vented between final BCP/EP and beam operation
  ☠ risk of contamination with particles? => no negative experience

Practical Consequences: personal view

- Personal view of open questions and “to do”-list:
  - check of particles and water quality of HPR supply water
  - practical approach, how to judge about the quality of final cleaning

    (e.g. Is particle counting of drain water useful?

    New clever ideas for sample experiments?)
  - simplify procedure and components with respect to cleanroom work
  - cavity cleaning option before module assembly
  - optimal surface treatment with respect of field emission

    (BCP; EP; mixture)
  - influence of “120C bake-out” on field emission??
  - ????

Practical Consequences: improvements

- Improvements of present procedures
  - hot water rinsing (better solubility, better drying)

  - improved high pressure rinsing systems
    (no moving parts inside cavity; higher pressure; different jet shape; rinsing of longer units possible?)

  - drying procedures?

  - welding of flanges
    (connecting cavities to a “super-structure”; e^- beam or Laser welding)

  - ????

Alternative Cleaning Approaches

- Megasonic Rinsing
  - effective cleaning of sub-micron particles
  - development necessary:
    better transmission of power ⇒ (small) oscillator inside cavity
    transportation of particles ⇒ high flow rate
- Dry-Ice Cleaning
  - effective cleaning of sub-micron particles and film contamination
- Others:
  Laser, Plasma, UV light,
  hot steam, etc.
  ⇒ no activities ??!

Processing in accelerator structures: LEP II

- successful rf-processing of LEP II structures => <E_{acc}> = 7,2 MV/m in NbCu-cavities
- He-processing: “ success was limited” and high operational risk

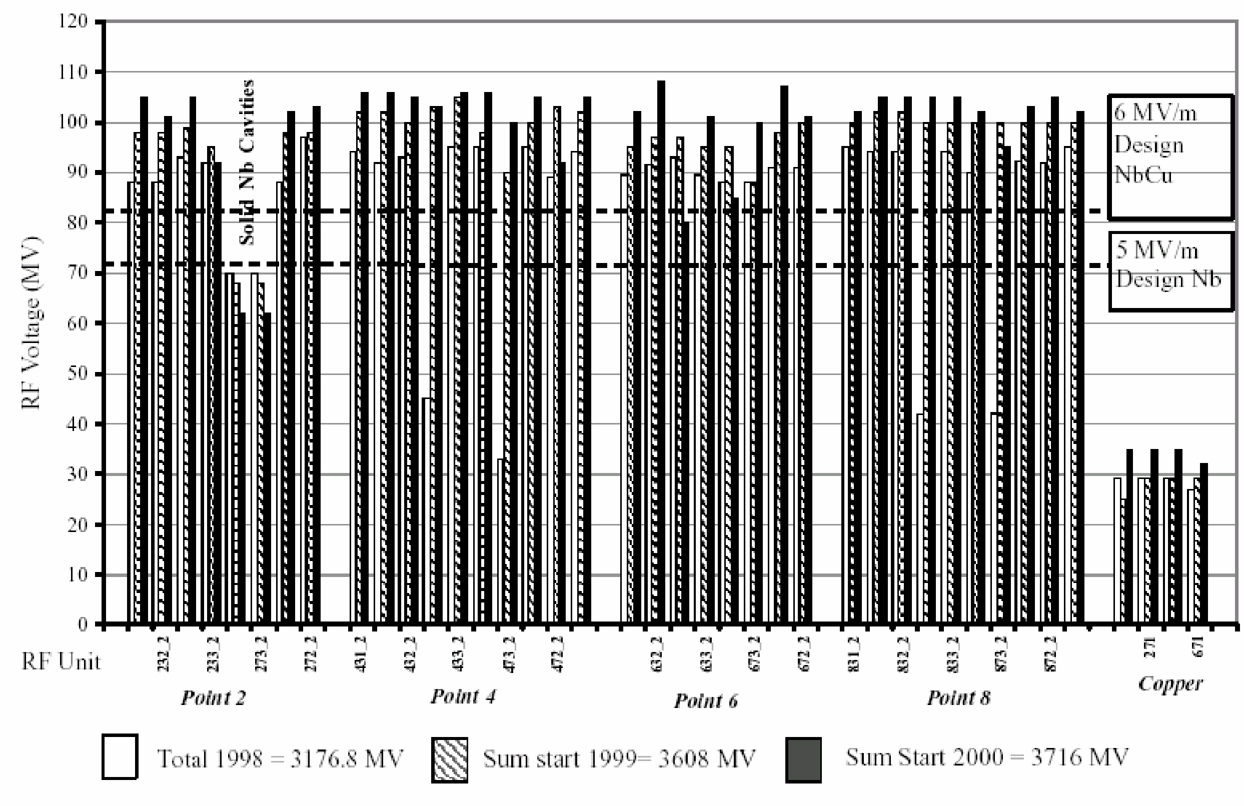


Figure 3: RF unit voltages after conditioning in 1998, 1999 and 2000

Processing in accelerator structures: TTF

- HPP on 5- and 9-cell structures in vertical tests:
  improvement from (10-15) MV/m to (20-28) MV/m
- Typically E_{acc}(pulsed) ≈ 2x E_{acc}(processed)

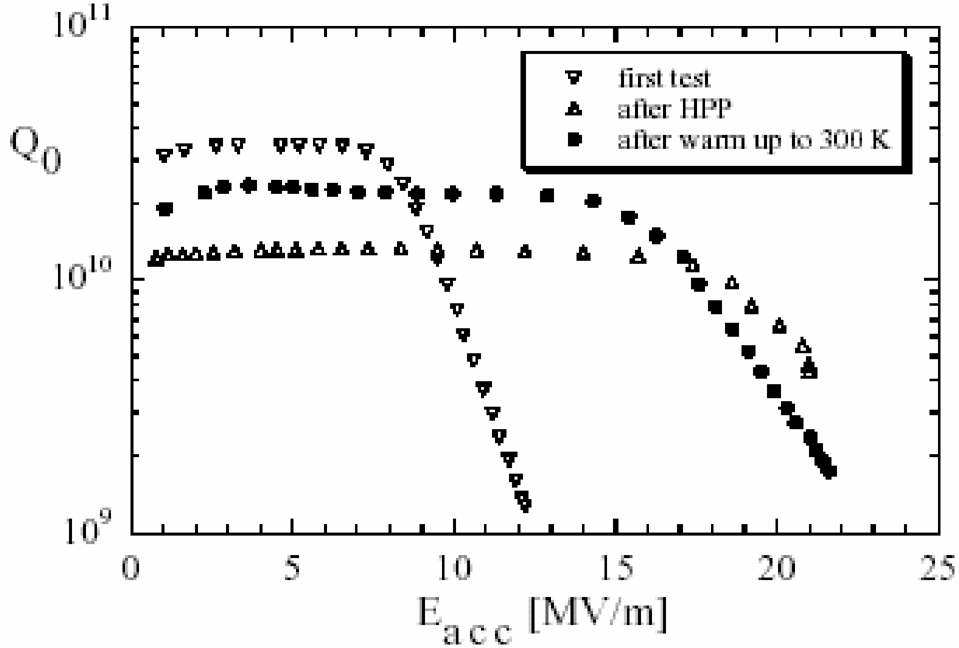
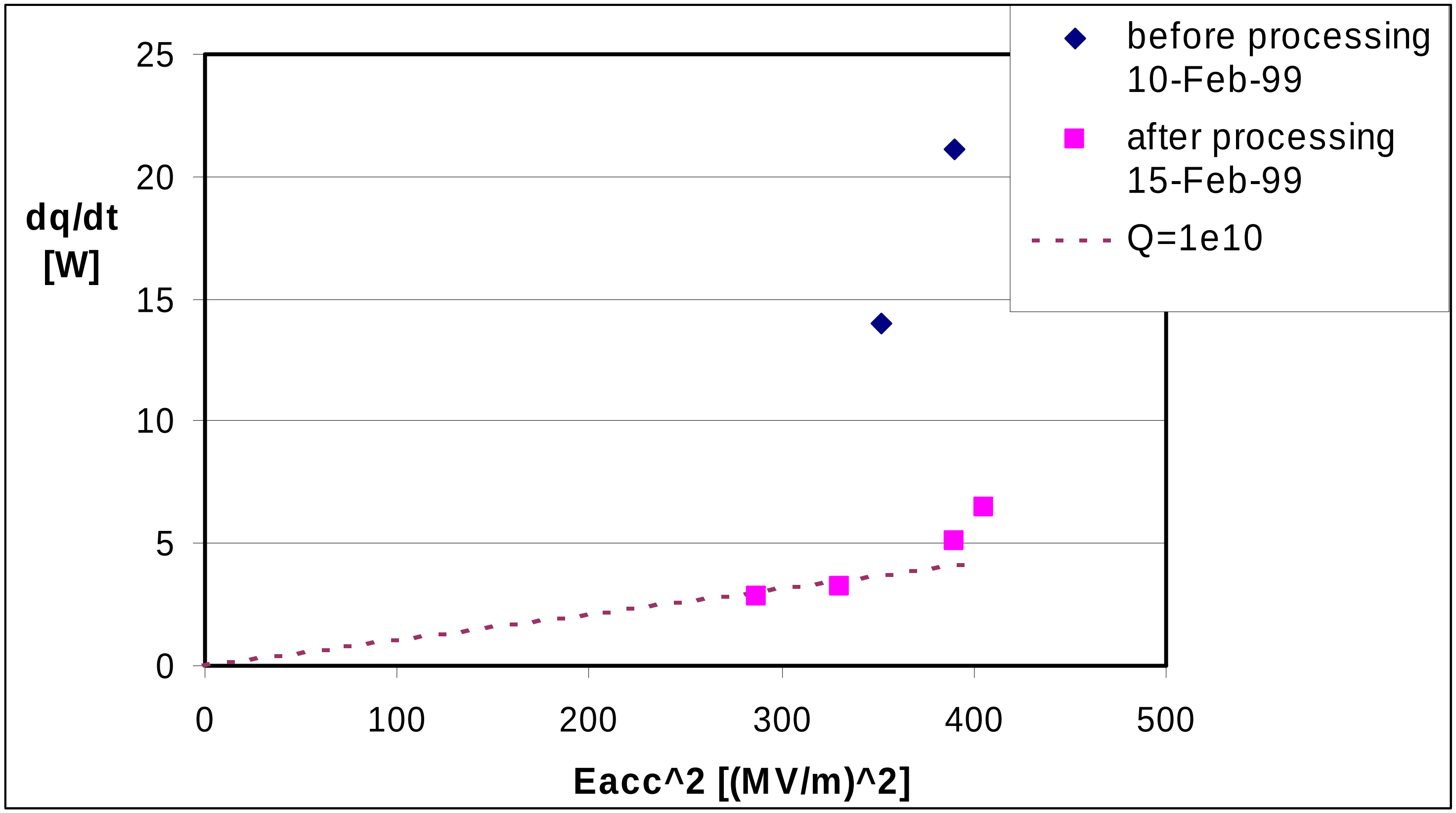


Fig. 2: Cavity C19 before and after HPP. The Q_0 recovered partially after warm up to room temperature.

Processing in accelerator structures: TTF

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



Processing at high gradients

- HPP for gradients above 30 MV/m in 1.3GHz nine-cell structures?
- → No experience?!
- → Very high power necessary (coupler performance)

	pulse length [µsec]		
Eacc [MV/m]	200	400	500
40	2,45 MW	0,79 MW	0,57 MW
60	5,5 MW	1,77 MW	1,28 MW
80	9,77 MW	3,15 MW	2,28 MW

for $Q_L = 3 \cdot 10^6$ (by D. Kostin, DESY)

Summary

- Precent picture of field emission not complete, but well substantiated
- Standard cleaning and assembly procedures allow high quality cavity performance, but:
  Field emission (= dark current) is still the main limitation, if usable gradients above 20 MV/m in multi-cell accelerator cavities are required
- Further improvements of standard techniques, quality control and development of alternative approaches necessary!

- Thanks to C. Antoine, R. Losito, L. Lilje, D. Kostin, W.-D. Moeller, H. Padamsee, B. Visentin and many other colleagues!

Literature

- Some literature:
  - E. Ciapala et al., SRF Workshop 2001
  - W. Kern ed., Handbook of Semiconductor Cleaning Technology, 1993
  - P. Kneisel,B. Lewis, SRF Workshop, 1995
  - P. Kneisel, Contamination Workshop Jlab, 1997
  - H.Padamsee, J.Knobloch, T.Hays, RF Superconductivity f. Accelerators, 1998
  - D.L. Tolliver, Handbook of Contamination Control in Microelectronics, 1988
- In general:
  Proceedings of the SRF Workshops