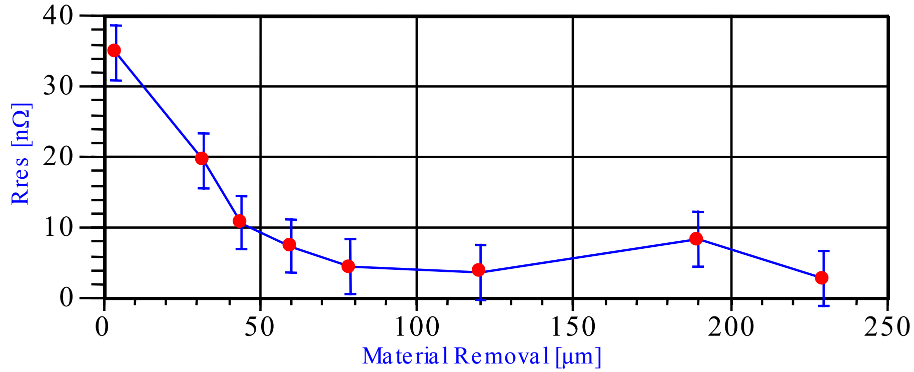
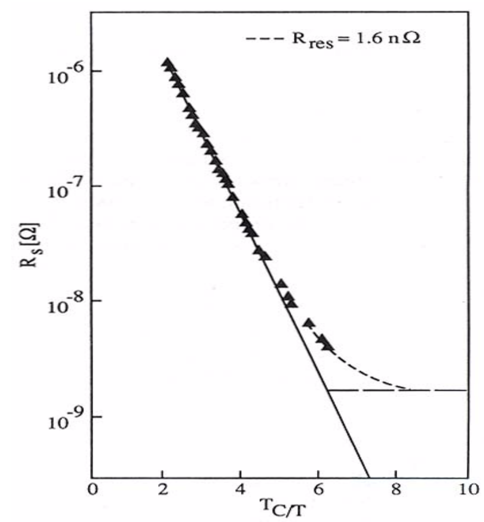
Cavity Preparation/Assembly Techniques and Impact on Q Realistic Q-factors in a Module, Review of Modules

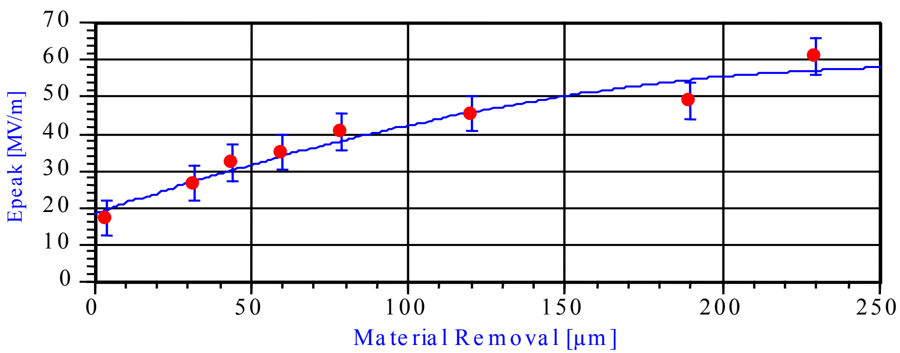
P. Kneisel
Jefferson Lab

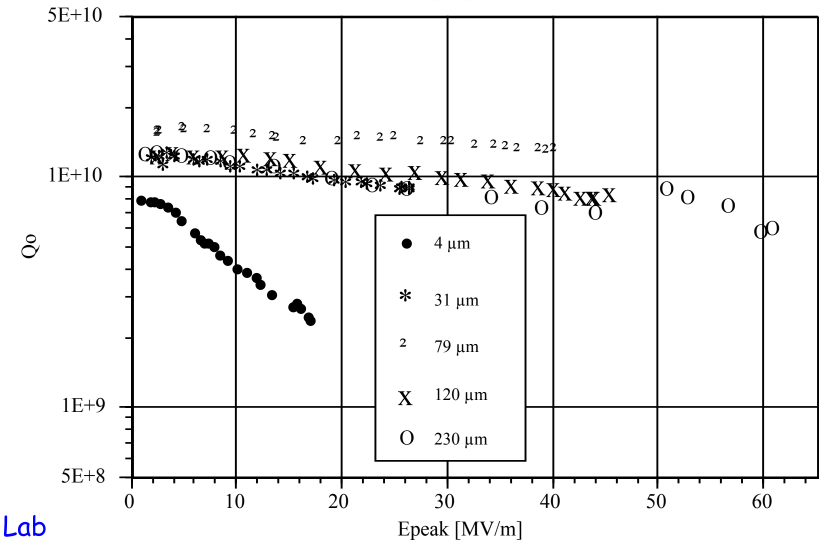
Why Surface Treatment?

Damage layer influences cavity Performance



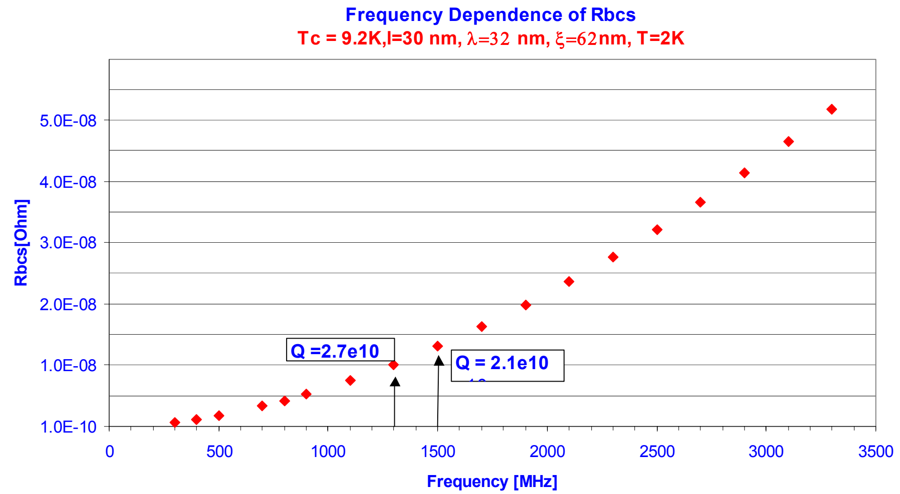






What is the goal of the surface treatment?

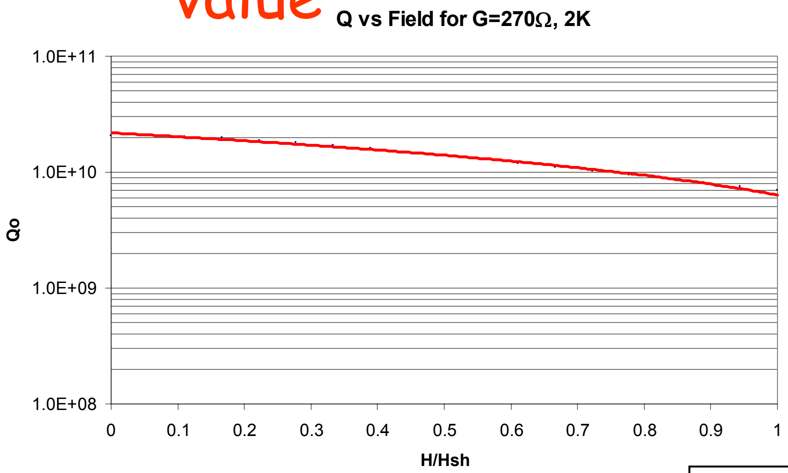
Get as close as possible to an ideal surface, achieve fundamental limits of the material: very low R_{res}, H_{crit} ~ 185 mT



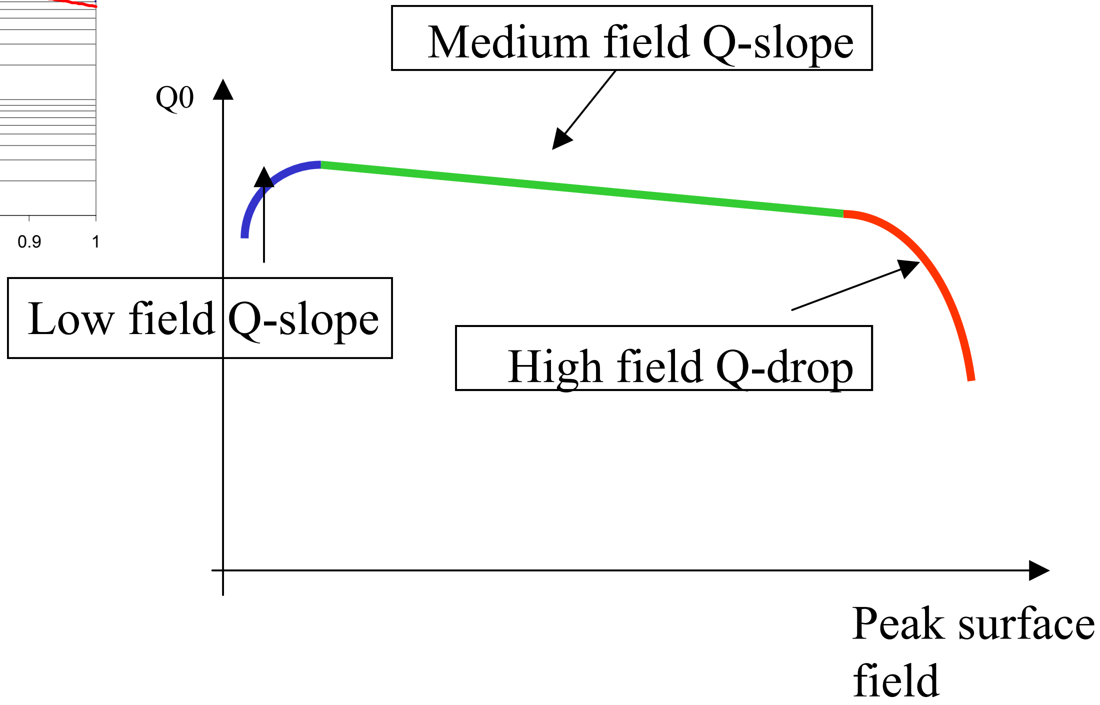
- Remove the surface damage layer (> 100 μm)
- Defect-free surface
- Contamination-free to avoid FE
- Smooth for better cleaning, avoid field enhancements…

Obstacles

Even if the low field Q is high (residual resistance low), there is typically a field dependence of the Q-value



Theoretical Dependence



Q vs E_{acc} , "Q-drop"

- For high RRR niobium often a degradation of the Q value is observed at gradients (magnetic surface fields) above ~ 20 MV/m (>90 mT)
- "In situ" baking of the cavities at 120C for long periods of time (~48 hrs) improves the Q-values

  at lower power and in the Q-drop regime
- The improvement is often more pronounced for EP cavities, but is also observed for BCP'd cavities
- The physics of the Q-drop is still not understood

  explanations range from field enhancements at grain boundaries to effects in the metal-oxide interface or weak links at grain boundaries
- It is clear that oxygen diffusion from the surface into the material plays a role; the depth of the affected zone is several hundred nm

Q vs E_{acc} , "Q-drop"

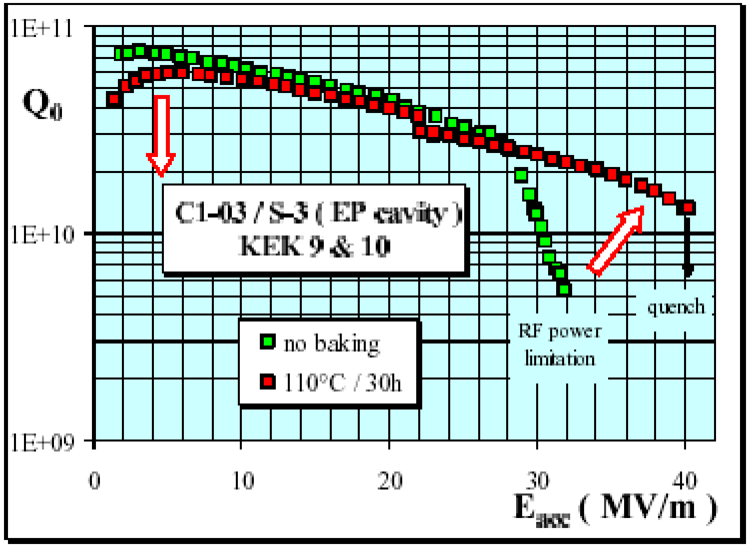
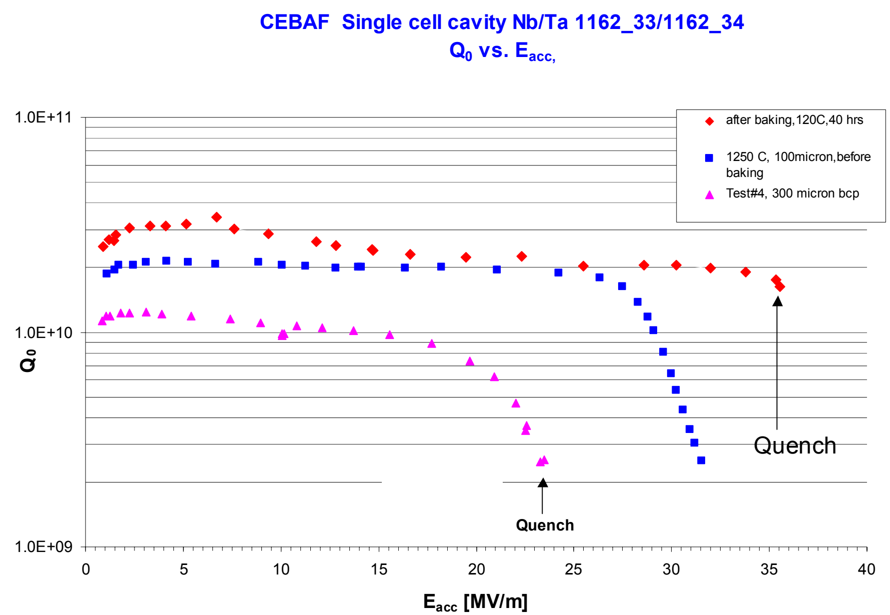


Figure 4: Baking effect on C1-03 Saclay cavity (electropolished and tested at KEK) [9].

[B.Visentin,SRF2003]

electropilished

Buffered Chemical Polished(1:1:1)



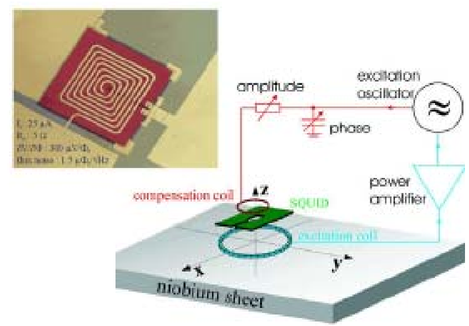
Surface Treatment Procedures

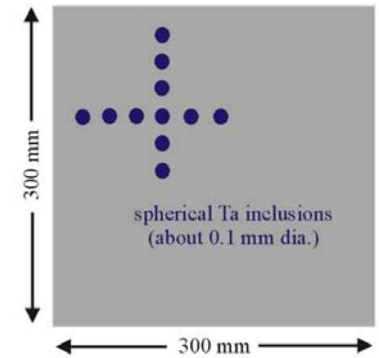
- Eddy CurrentScanning, Squid Scanning
  (successfully used at DESY on TTF cavities)
- Degreasing (ultrasound + soap+water, solvents)
- BCP (HF:HNO_3 :H_3PO_4 as 1:1:1, 1:1:2,1:1:4)
  (room temperature or below to avoid excessive hydrogen pick-up)
- Electropolishing (HF/H_2SO_4 Siemens-KEK-Recipes)
- Barrel Polishing
- High pressure Ultrapure Water Rinsing
- High Temperature Heat Treatment (600C to 1400C for Hydrogen degassing, Post Purification)
- "In-situ" baking (typically 120C for> 24 hrs)
- Alternative Cleaning:CO_2 Snow, Megasonic, UV Ozon..

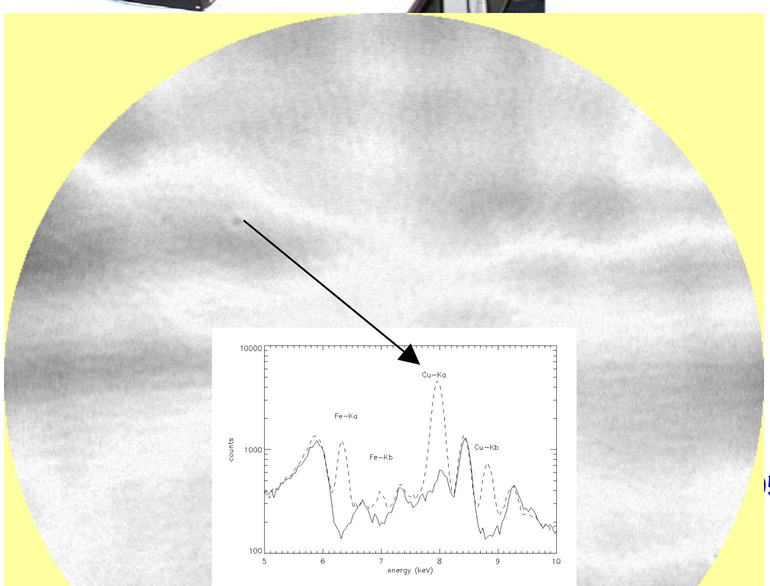
Scanning of Niobium Sheets

Successfully developed at DESY to pre-screen Nb Sheets for defects: eddy current, resolution ~ 100 μm

squid, resolution < 50 μm

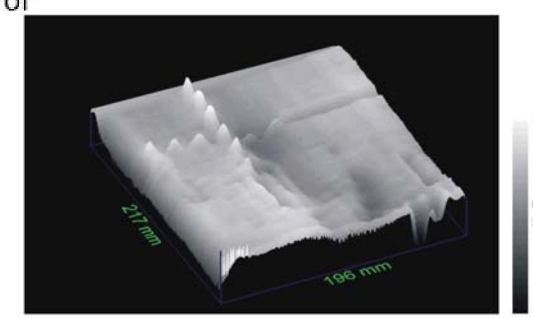






Low Tc superconducting SQUID system for eddy current testing of niobium sheets is in developn

(W.Singer, X.Singer)



Two-dimensional distribution of eddy-current field above the niobium test sample, measured from the back side of the sample. The excitation coil had 30 turns and a diamter of 3 mm; the excitation frequency was 10 kHz. The reference phase of the lock-in amplifier was chosen such that the lift-off effect was minimized.

Talk by K.Saito in JLAB on Oct. 2003

Electropolishing of Niobium

Current oscillation control: innovated by H.Diepers et al. in 1971

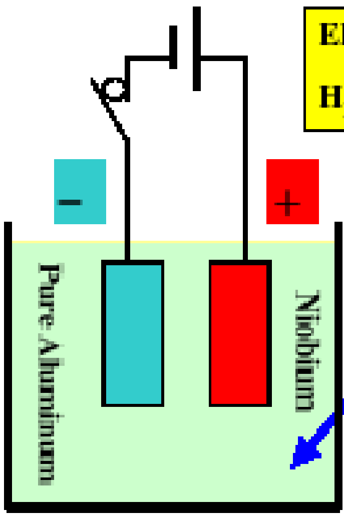
$2Nb + 10HF \rightarrow 2H_2NbOF_5 + 5H_2 \uparrow$

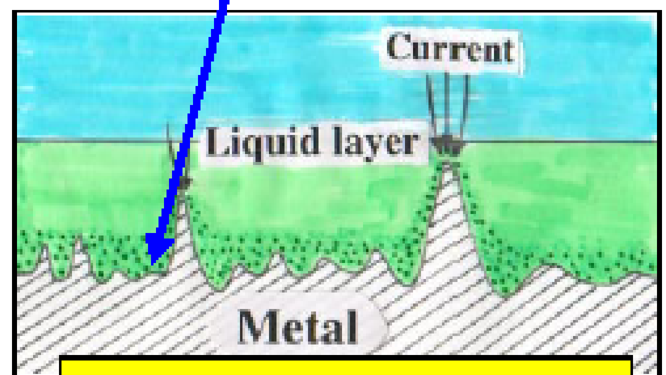
Metal complex salt

EP acid

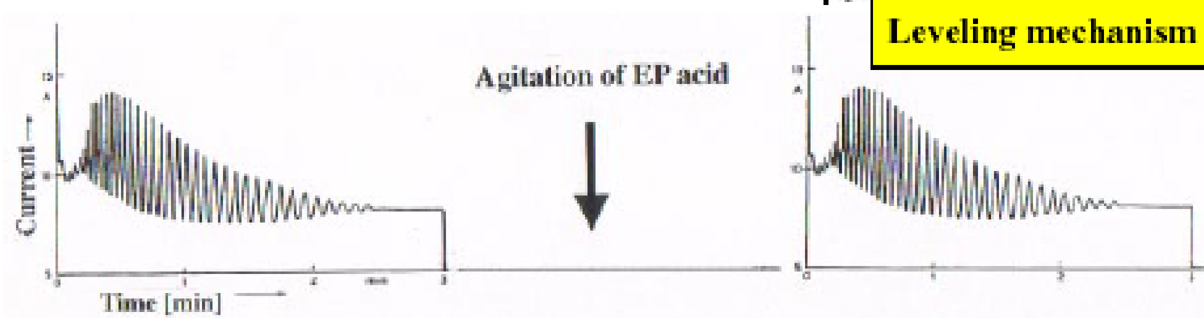
H_2SO_4(>95%) : HF(46%) = 10 : 1 V/V

Very hazardous Acid



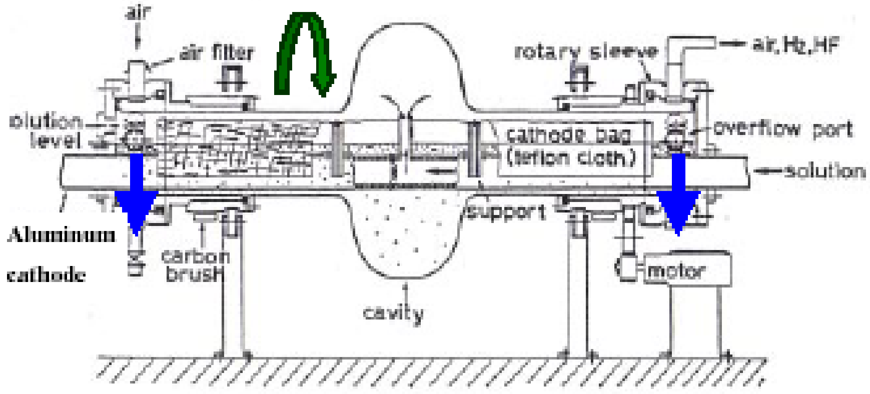


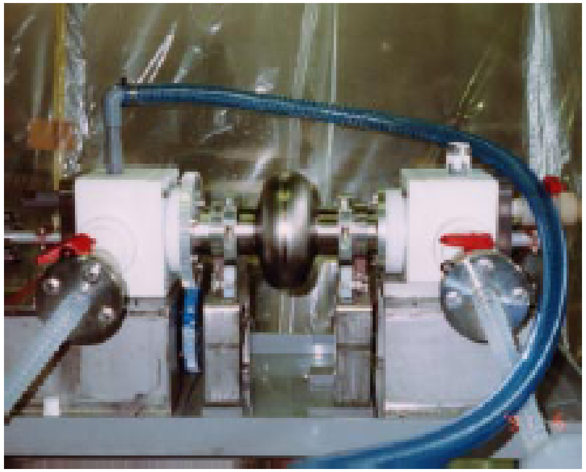
Leveling mechanism by P.A.Jaquet



Talk by K.Saito in JLAB on Oct. 2003

Horizontally Rotated Continuous EP (HRC-EP)





Advantages

1) Larger Cathode Surface Area ⇨ Smooth surface in the whole area
2) Easy Hydrogen exhaustion ⇨ Elimination of the hydrogen problem
3) Inside EP ⇨ Prolongation of the EP acid life
4) Closed system ⇨ Safe System against the hazardous EP acid
5) Easy control

"Very Suitable System for Mass Production"

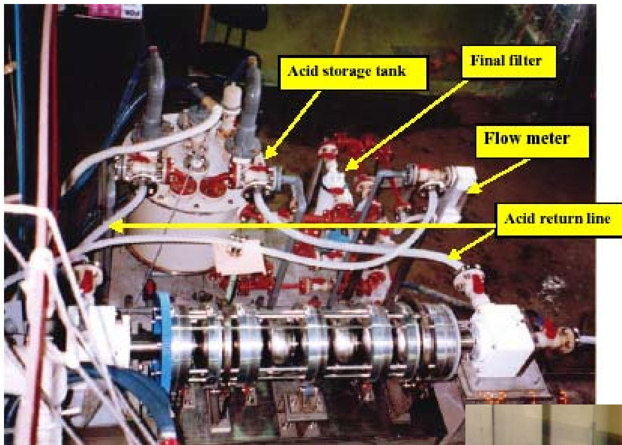
Electropolishing, cont'd

Activities

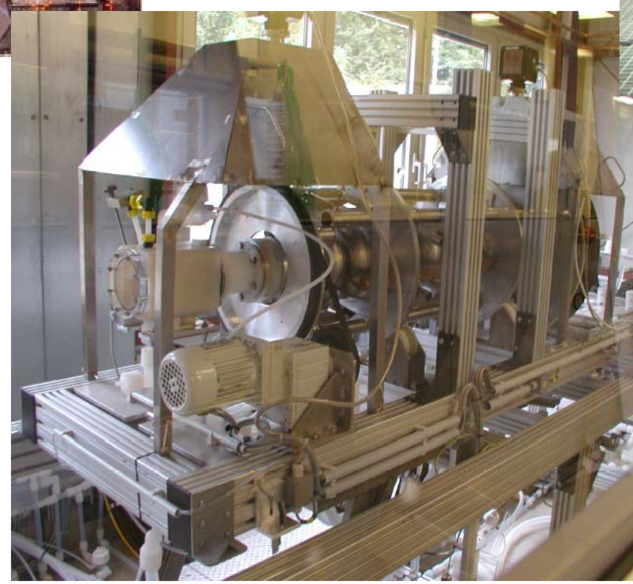
Lab	What has been done/is being done?	Reference
KEK/ Nomura Plating	Developed EP based on Siemens Recipe Successfully applied to Tristan & B-factory cavities Developed Hydrogen –free EP: HNO_3 add	K.Saito(1991) T.Higuchi,K.Saito (2003)
DESY/ TTF	Implemented,commissioned and uses system for multi-cell EP CARE: optimizing parameter (Saclay) industrializing/automating (INFN)	CARE 2004-Meeting
Jlab	Implemented and commissioned system in 2003/2004, starting to develop parameters	
Cornell	Vertical system for single cells	R.Geng(2004)

EP- Systems

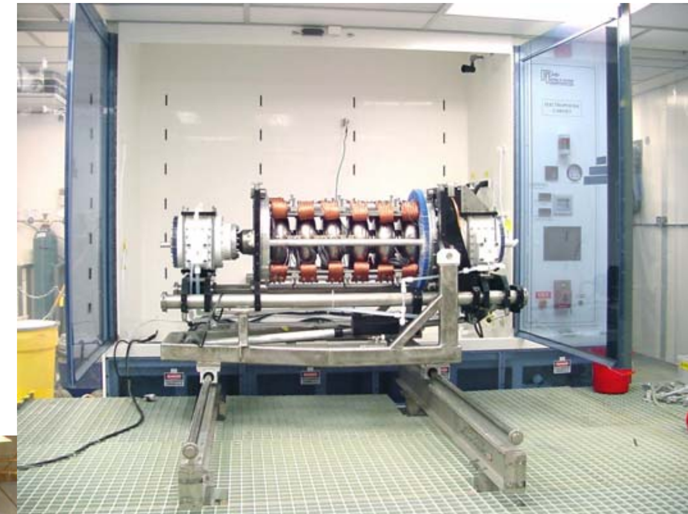
KEK/Nomura Plating



DESY

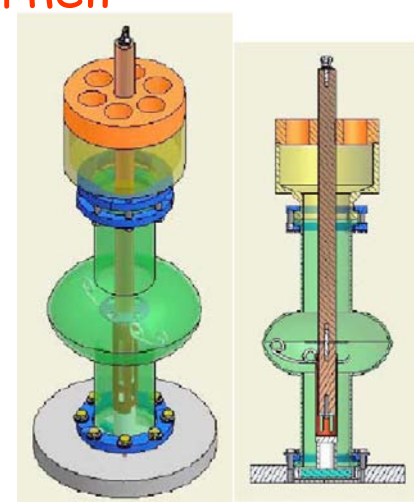


JLab



INFN

Cornell



High Pressure Water Rinsing

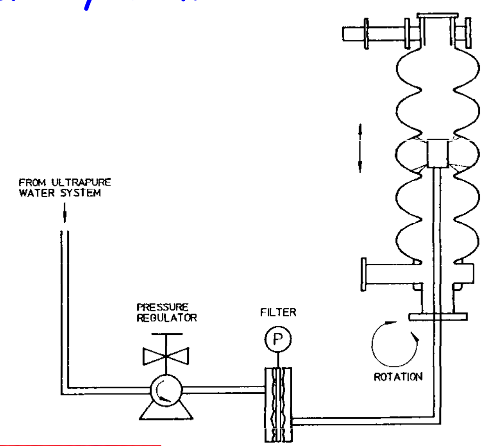
- Universally used as last step in surface preparation
- Water: ultrapure, resistivity > 18 MΩcm
- Pressure: ~ 100 bar (1200 psi)
- Nozzle configuration: varying, SS or sapphire
- "Scanning": single or multiple sweeps,
  continuous rotation + up/down
- Add. HPR after attachment of auxiliary components

High Pressure Rinse Systems

DESY-System

Jlab HPR Cabinet

KEK-System

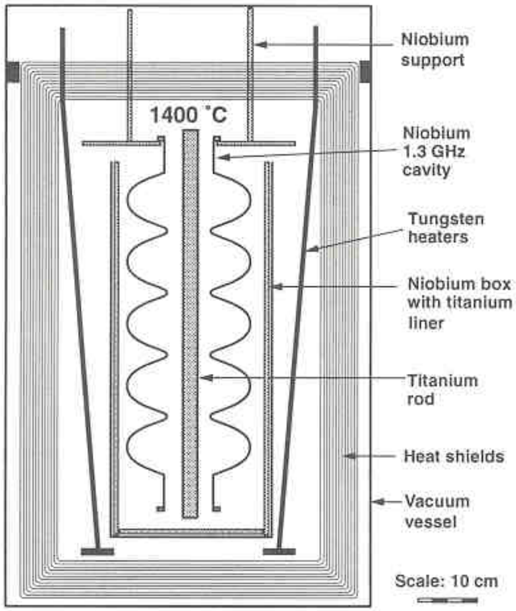


High Temperature Heat Treatment

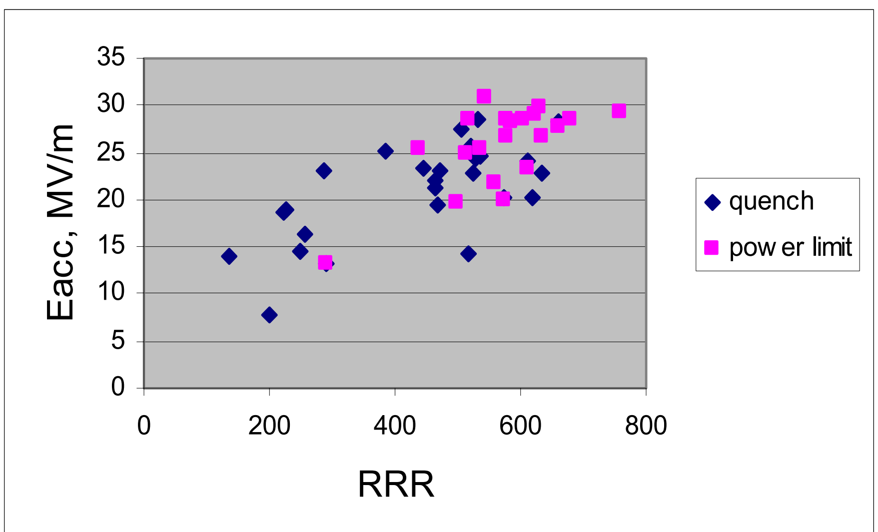
UHV Heat Treatment of Niobium used since the "beginning of times"; nowadays :

- Hydrogen degassing: 600C for 10 hrs at Jlab
  750 C for 3 hrs at KEK
- Annealing: 800 C, several hrs
- Post- Purification: 1200C to 1400C in presence of a solid state getter, e.g.Ti
  Improvement of RRR
  Loss of mechanical properties
  grain growth

Post purification of Nb [W.Singer, 2003]

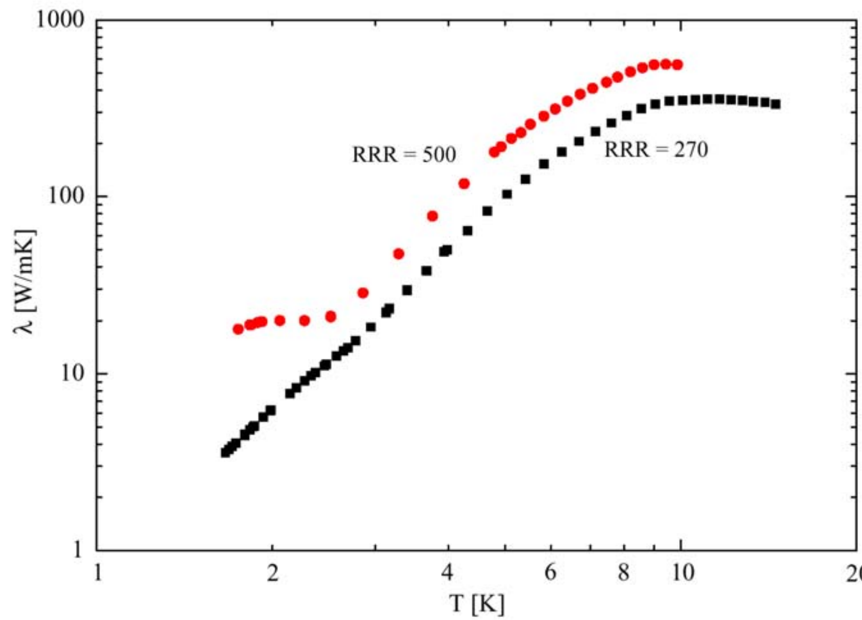


Cavity post purification (solid state gettering)



Eacc versus RRR of TTF cavities

Thermal conductivity of samples from the niobium sheets used in the TESLA cavities: before and after the 1400 ºC heat treatment (RRR = 270 and RRR = 500 respectively)



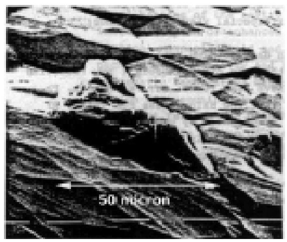
The heat treatment also homogenize the Nb (reduction of magnetic flux pinning centers shown by magnetization measurement)

Centrifugal Barrel Polishing(CBP)(1)

- Barrel Polishing ("tumbling") developed at KEK for smoothening of surfaces/welds
  plastic stones, water + abrasive
- Process very slow, by adding motion, removal rate increased 10fold: ~ 44 mm in 8 hrs
- During the process, hydrogen is dissolved in the niobium("Q-disease") and needs to be removed by furnace treatment
- Hydrogen-free CBP accomplished by using a different (hydrogen-free) agent: **FC-77 (C8F18,C8F16 O)** [T.Higuchi,K. Saito SRF 2003]

Centrifugal Barrel Polishing(2)

Purpose of mechanical grinding



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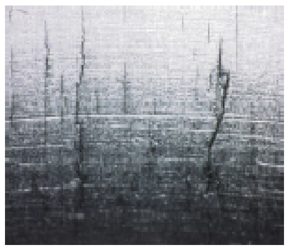
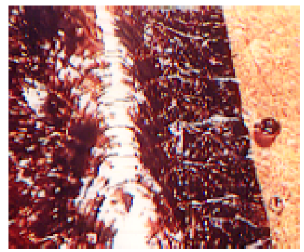
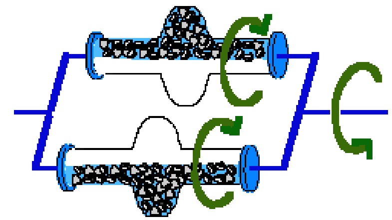

Cracks


Sputter balls

Mechanical grinding is a powerful method to remove surface defects

Centrifugal Barrel Polishing (CBP)



[T.Higuchi, K. Saito, SRF 2003]

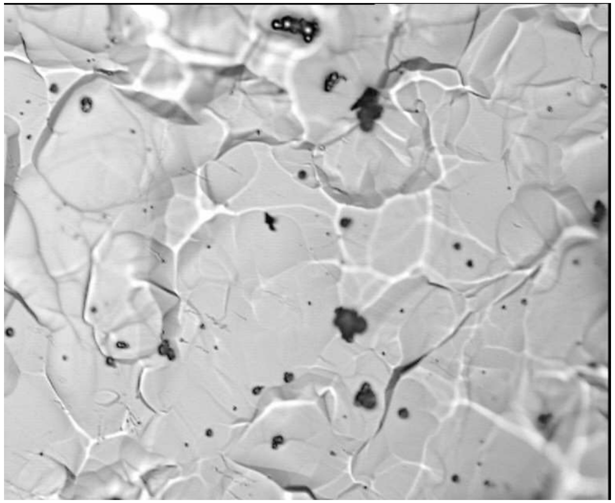
CO_2 Snow Cleaning

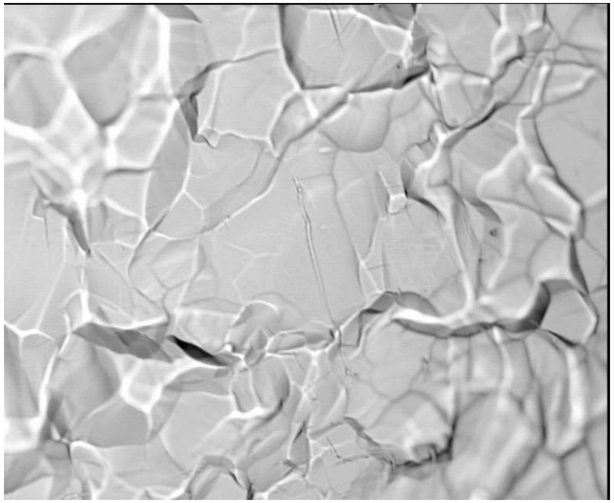
Developed at DESY (D.Reschke) as an alternative to HPR or “in situ” cleaning for modules

- A prototpye system has been fabricated and initial tests have been made on samples and on single cell cavities
- optimization of process necessary (cleaning effect; avoidance of condensation, mass flow)
- A production system is under construction and will be completed some time in the autumn of 2005

Preliminary Tests

- successful cleaning of Nb samples
  => investigation of field emission properties + reduction of particles
  collaboration with G. Müller, University of Wuppertal, Germany; see SRF Workshop 2001



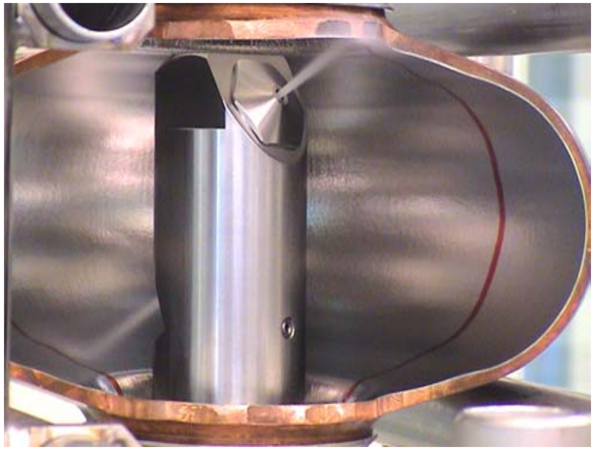


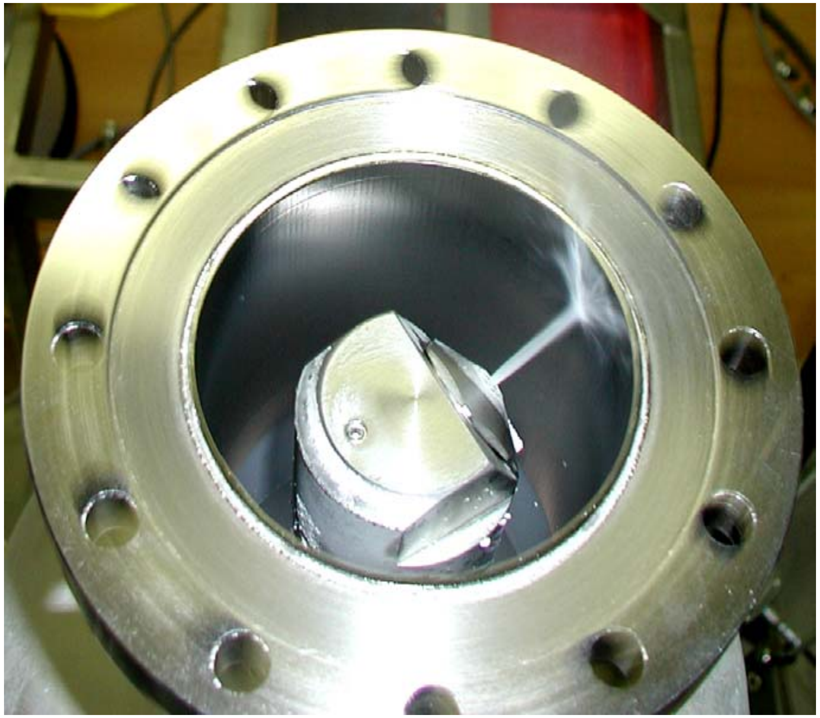
Optical microscope images before (left) and after (right) dry-ice cleaning of an sample intentionally contaminated with Fe and Cu particles (500x mag)

[L.Lilje, CARE Meeting Nov. 2004, DESY]

Cavity Tests on Mono-cells

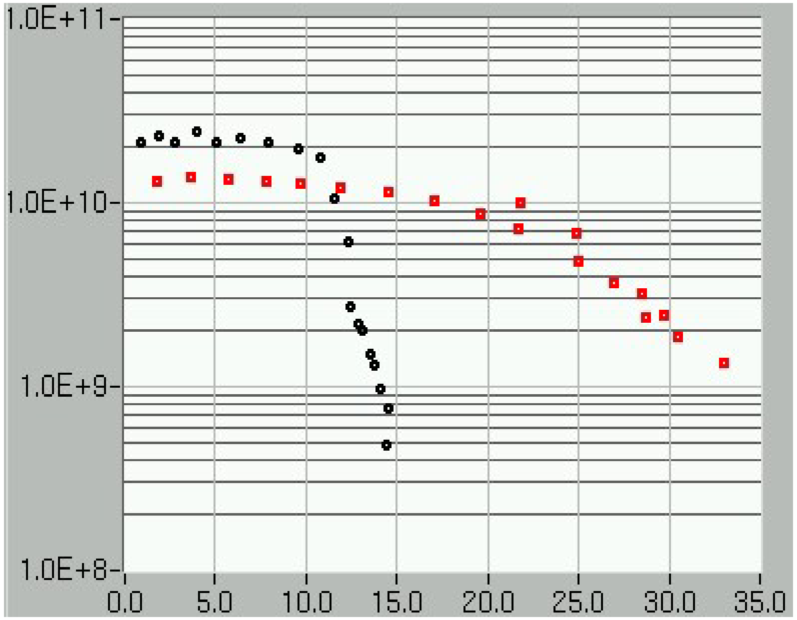
- dedicated nozzle system for cavity cleaning developed [L.Lilje, CARE Meeting Nov. 2004, DESY]

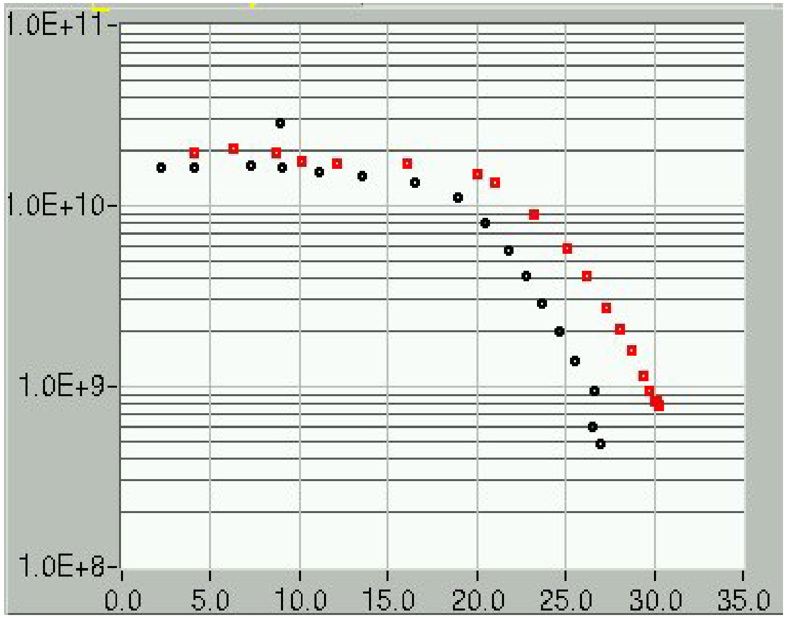




First Results of Cavity Tests

- Q-values up to $4{,}0 \cdot 10^{10}$ at 1.8 K => no surface contamination
- gradients up to 33 MV/m => field emission is limiting effect



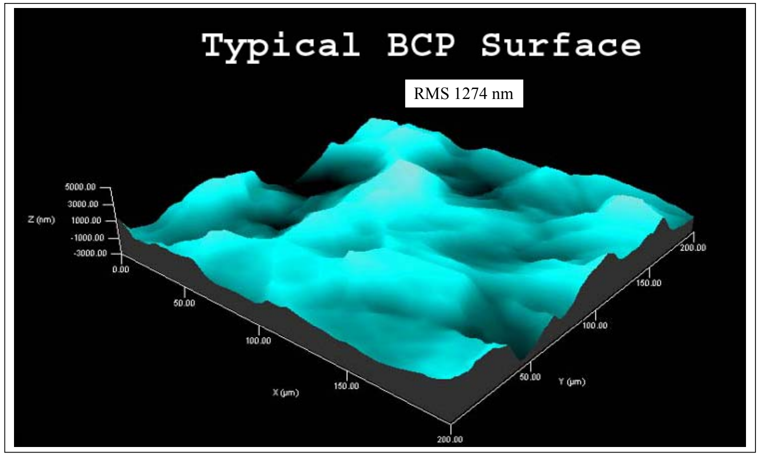


Q(E)-performance of two monocells before (black) and after (red) dry-ice cleaning

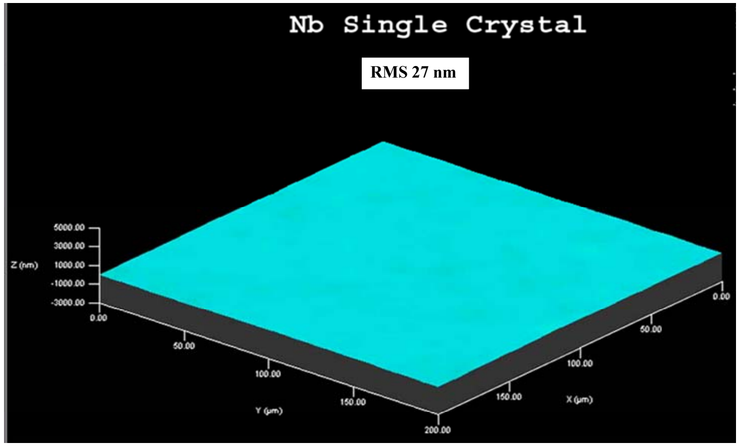
[L.Lilje, CARE Meeting Nov. 2004, DESY]

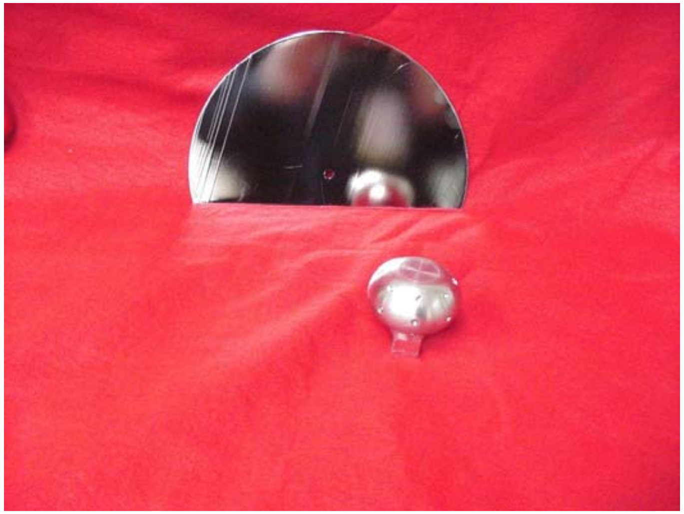
Single Crystal BCP

Provides very smooth surfaces as measured by A.Wu, Jlab



RMS: 1274 nm fine grain bcp
27 nm single crystal bcp
251 nm fine grain ep





Procedures: general remarks

- "Enemies" of good cavity performance are: insufficient material removal, defects and contamination (field emission)
- All procedures need to deal with these problems and the most difficult is control of contamination
- Level of contamination is different in different labs and depends on facilities, design, auxiliary parts, hardware (e.g. bolts, gaskets..) and people
- Optimum procedures have to be developed for each lab and project

“Standard” Treatment Procedures(1)

BCP , TTF Module 1-5, SNS

- Outside bcp(> 20 μm), inside bcp (80-100μm), clean water rinsing
- Hydrogen degassing (600C-SNS, 800C TTF)
- Rinsing in UPW, post-purification with Ti, 1400C
- BCP to remove Ti surface layer: 80 μm inside, 40 μm outside, UPW rinse
- Re-tuning

20 μm inside bcp, UHP water rinse

HPR, drying in class 10, open, 12 hrs

Assembly of auxiliary parts

Vacuum leak check of flange connections

Venting, dismount pumping flange

1. + 2. HPR(check of particle#, TOC…)

Installation of antenna for VTA test

No VTA test of bare cavity for SNS

"Standard" Treatment Procedures(2)

- Helium vessel welding with inert gas inside cavity(TIG or EBW)
- Preparation for

Horizontal test (Chechia)

Inside bcp 20 μm, HPR

Drying in class 10

Assembly of auxiliary parts

Leak check

1. + 2. HPR, drying in class 10

Assembly of final flange

Evacuating, leak check, venting

Assembly of power coupler

(avoids losing conditioning effect)

Horizontal test

Vertical test

~ 50 μm bcp, UPW rinsing

2 passes HPR, drying in class10,12 hrs

Assembly of auxiliary parts

2 passes HPR, drying in class 10

Final flange/pump-out port assembly

Evacuation, leak check

Hermetically sealed on test stand

Test at 2K

"Standard" Treatment Procedures(3)

After qualification of cavity with He-vessel

Cleaning for string assembly

("dirty" → class 10000⇨class 10)

Venting of cavity in class 10

Assembly of gate valves, magnets..

"on the job" cleaning of bolted beam pipe flanges necessary

Final leak check

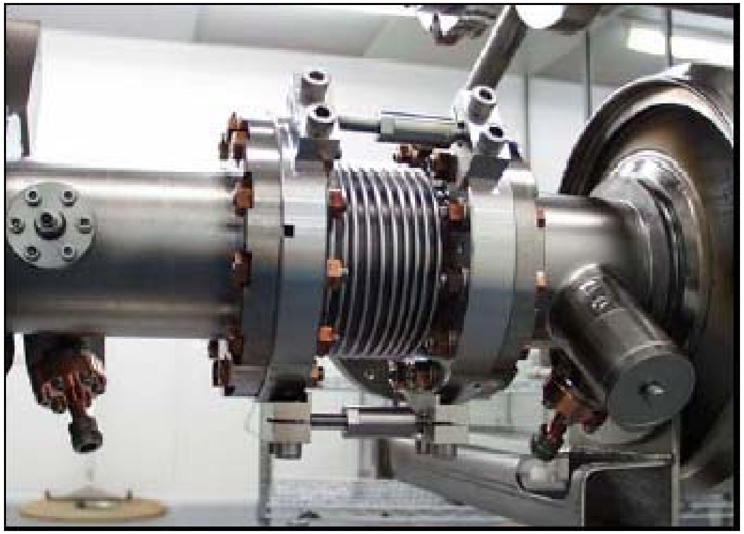
Venting for transportation to installation in cryostat

assembly

After VTA Test(without HOM probes and FPC):

- Add. 10 –20 μm bcp, HPR for 4 hrs, drying in class 10 clean room over night
- Attachment of HOM probes
- Add. 4 hrs of HPR, drying in class 10
- Assembly on assembly rail with FPC, bellows, gate valves, beam pipe opening closed with Nb plate
- Assembly of string takes several days
- Final completion with beam pipe bellows,
- Evacuation with turbo pump, leak checking

String Assembly

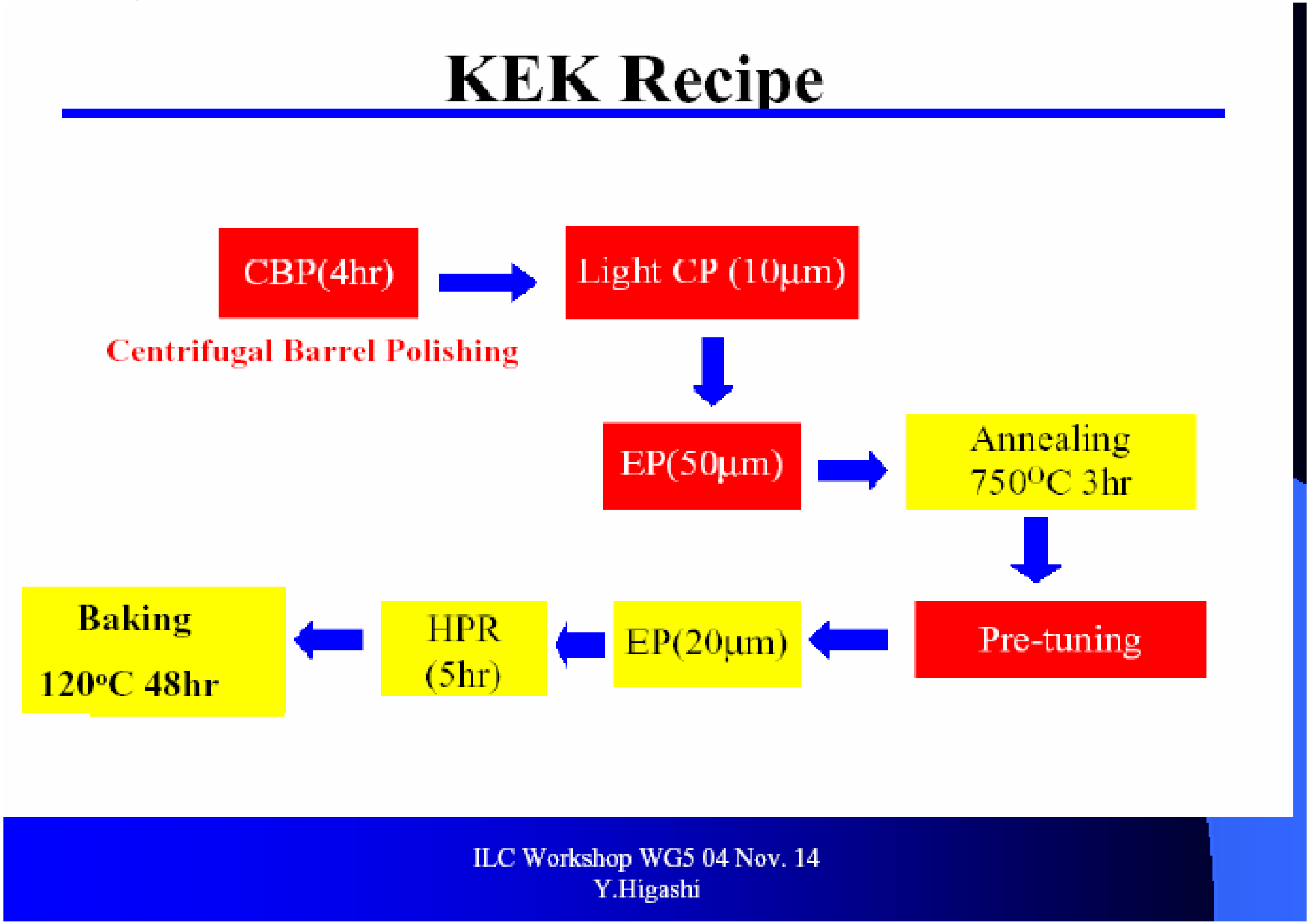


The inter-cavity connection is done in class 10 cleanrooms

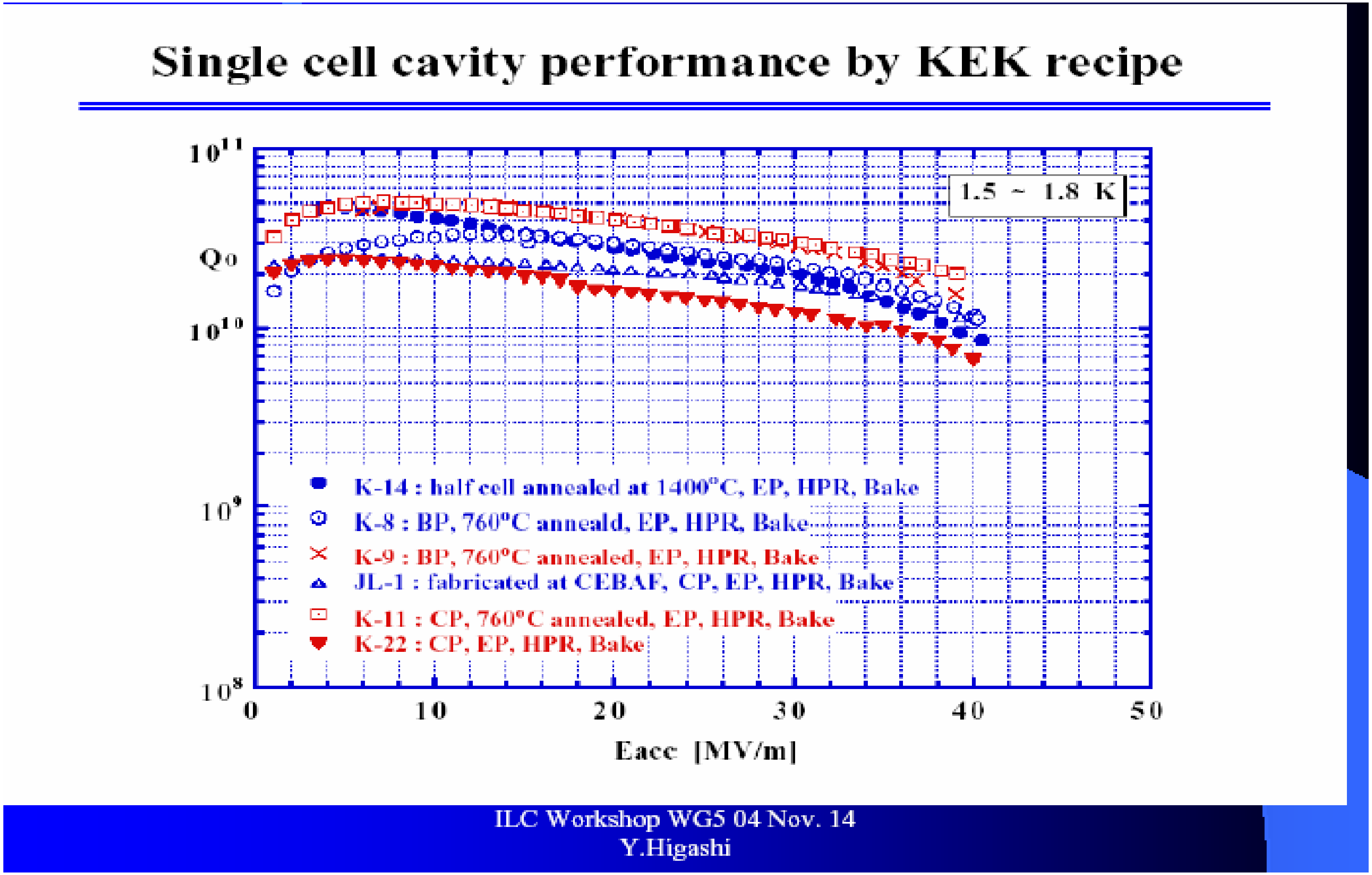
Modules

SNS Medium Beta Cavity String

Recipes


KEK Recipe
CBP(4hr)
Light CP (10µm)
Centrifugal Barrel Polishing
EP(50µm)
Annealing
750^{O}C 3hr
Baking
120^{o}C 48hr
HPR
(5hr)
EP(20µm)
Pre-tuning
ILC Workshop WG5 04 Nov. 14
Y.Higashi

Recipes-KEK



Single cell cavity performance by KEK recipe
1.5 ~ 1.8 K
Q0
Eacc [MV/m]
K-14 : half cell annealed at 1400°C, EP, HPR, Bake
K-8 : BP, 760°C anneald, EP, HPR, Bake
K-9 : BP, 760°C annealed, EP, HPR, Bake
JL-1 : fabricated at CEBAF, CP, EP, HPR, Bake
K-11 : CP, 760°C annealed, EP, HPR, Bake
K-22 : CP, EP, HPR, Bake
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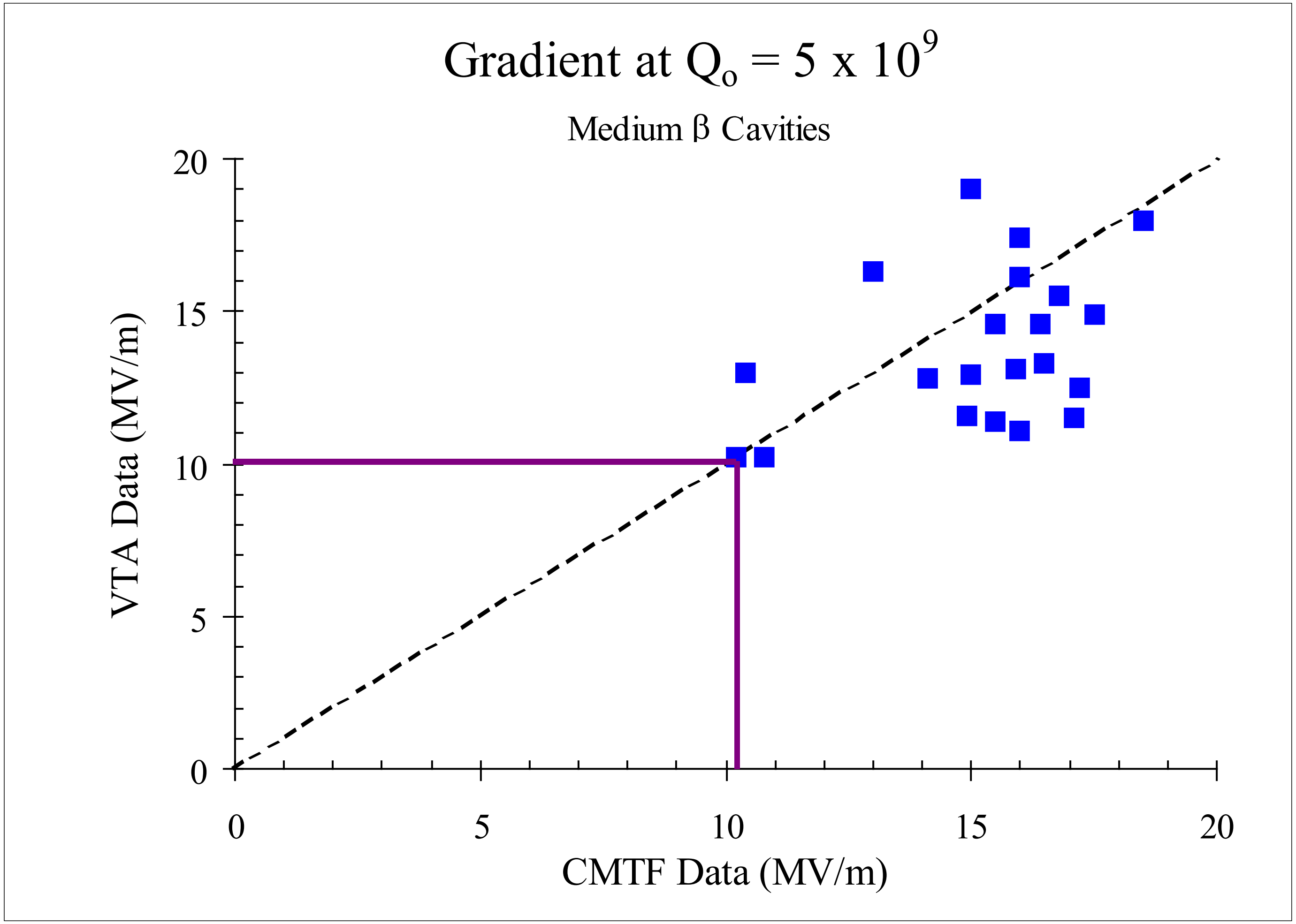
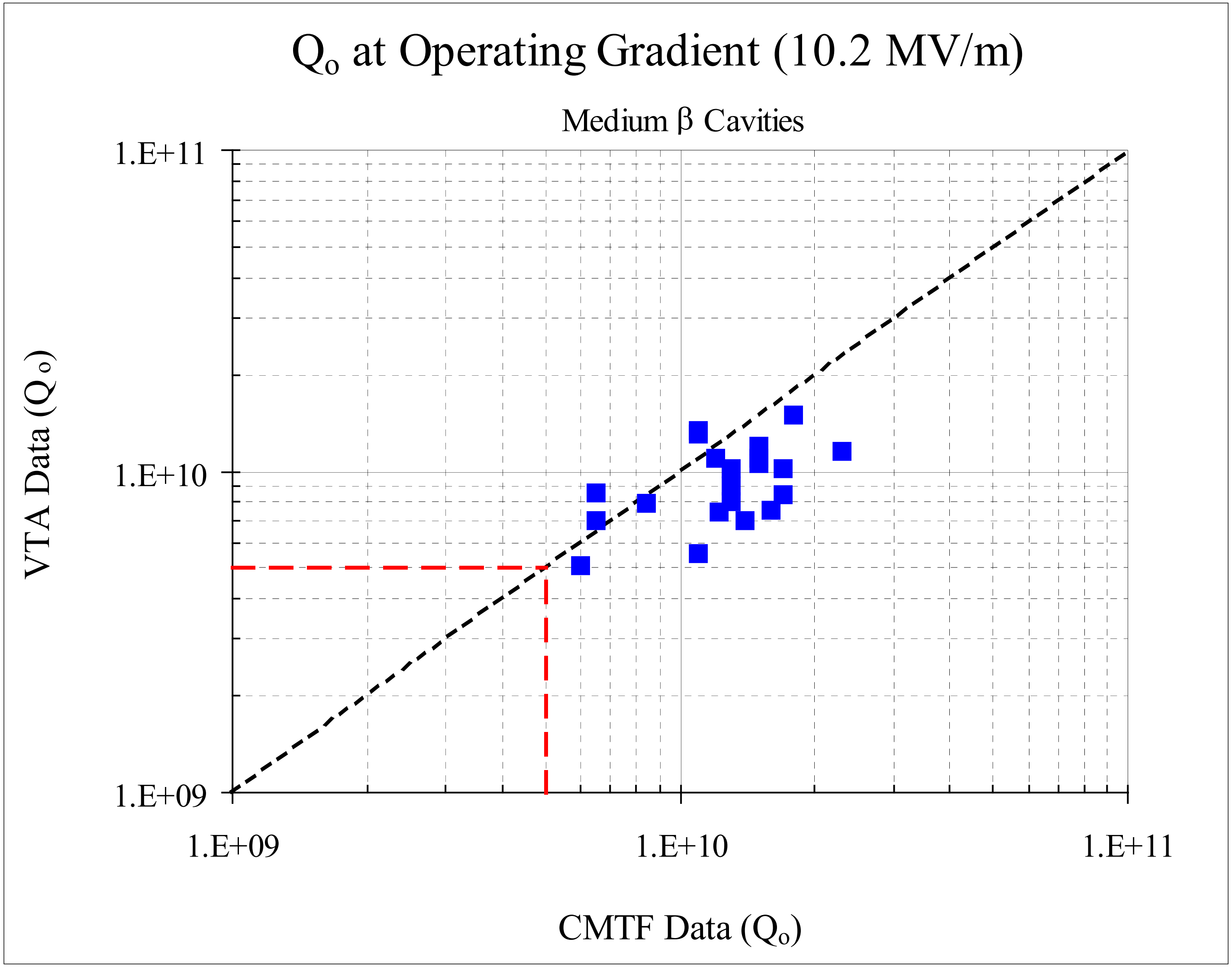
Y.Higashi

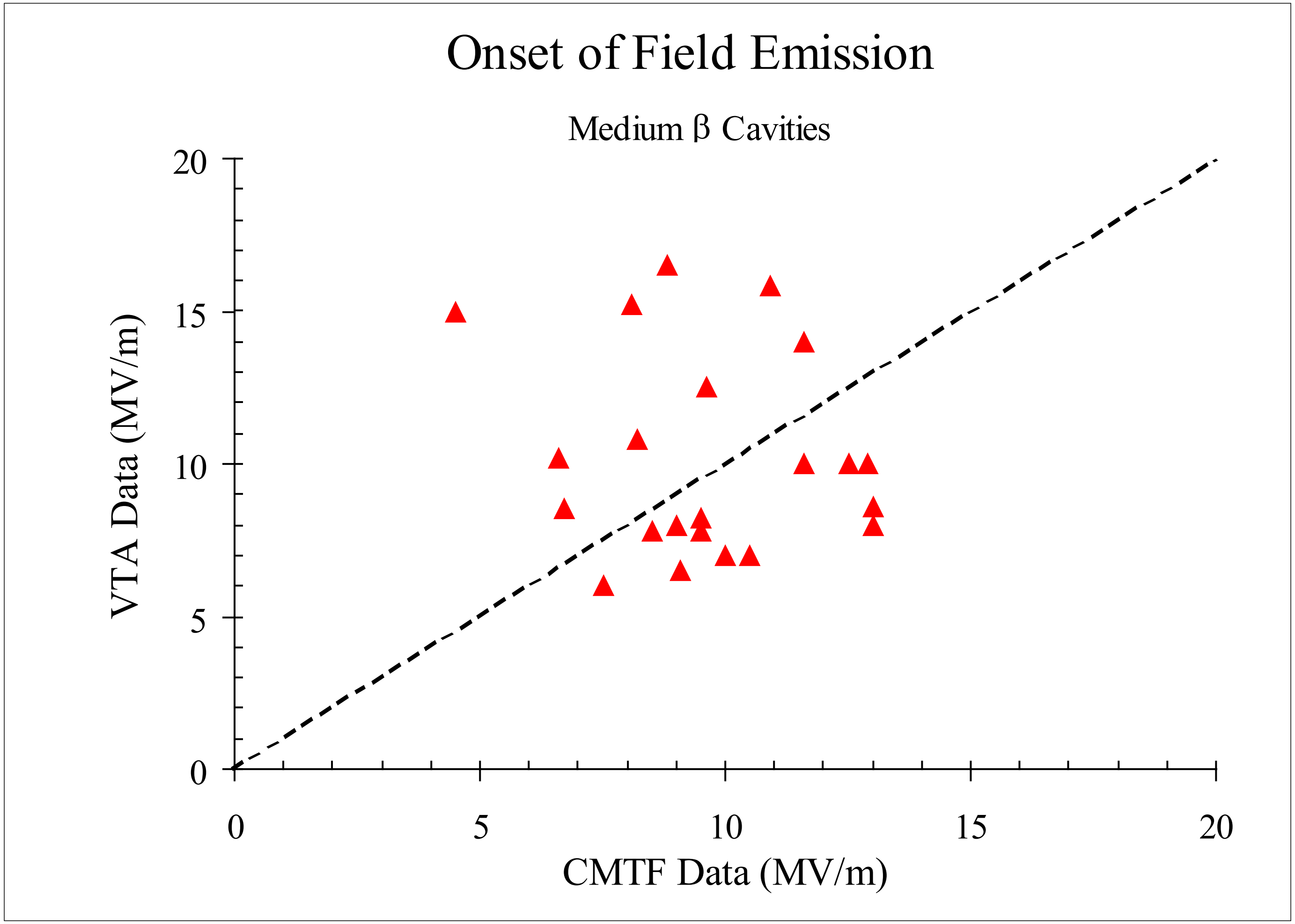
SNS- Modules

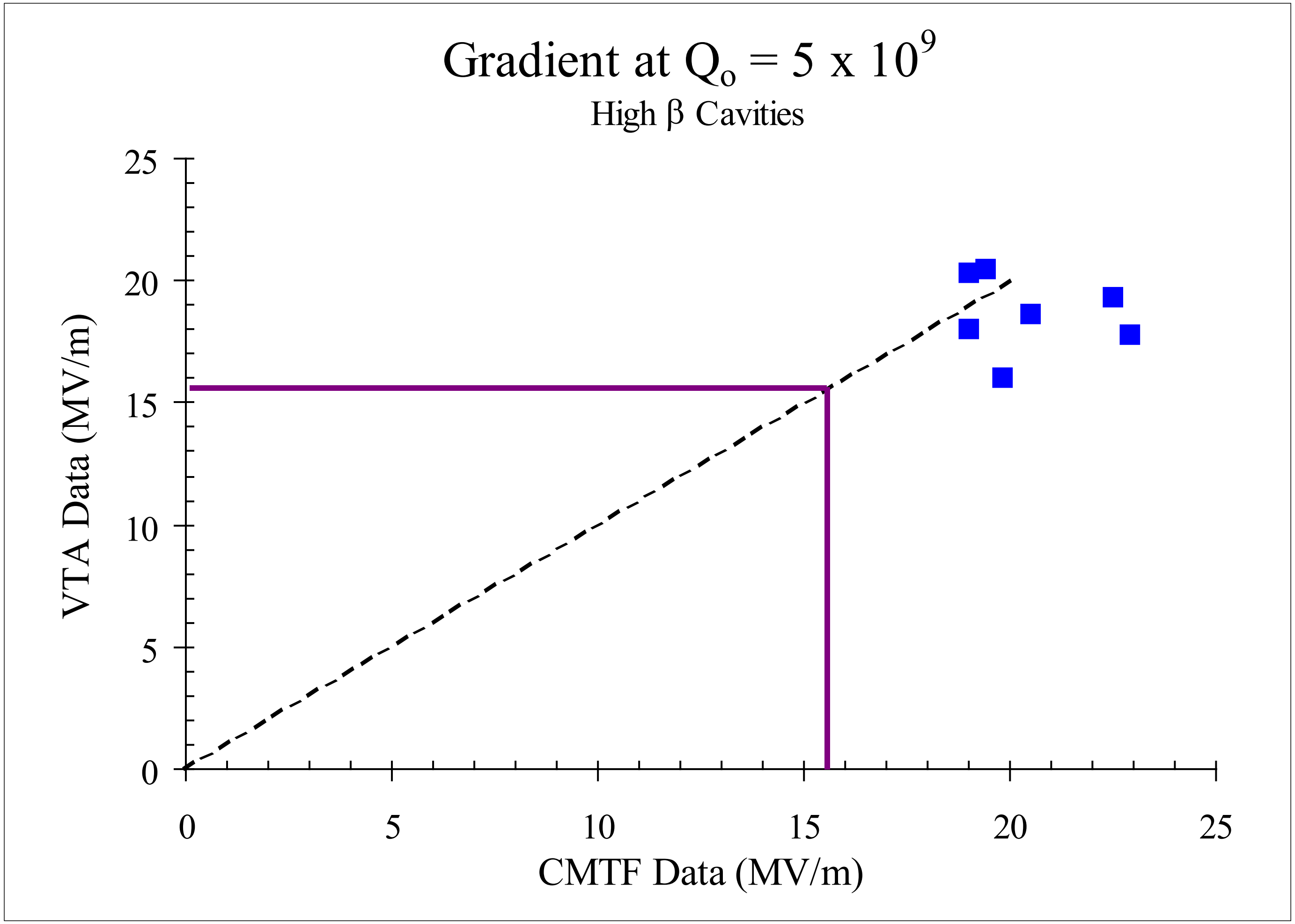


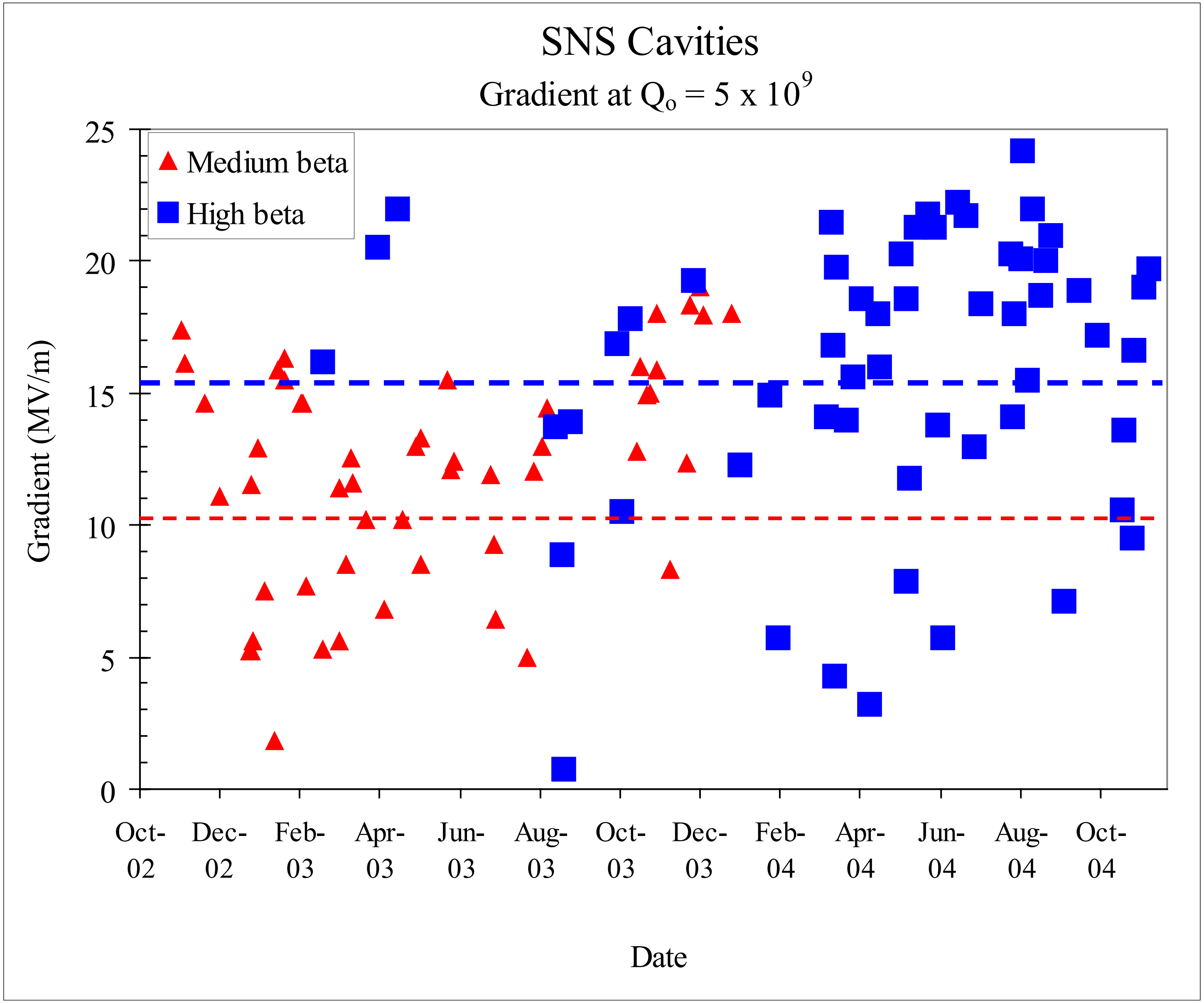
Gradient at $Q_o = 5 \times 10^9$
Medium β Cavities
VTA Data (MV/m)
CMTF Data (MV/m)
0
5
10
15
20
0
5
10
15
20

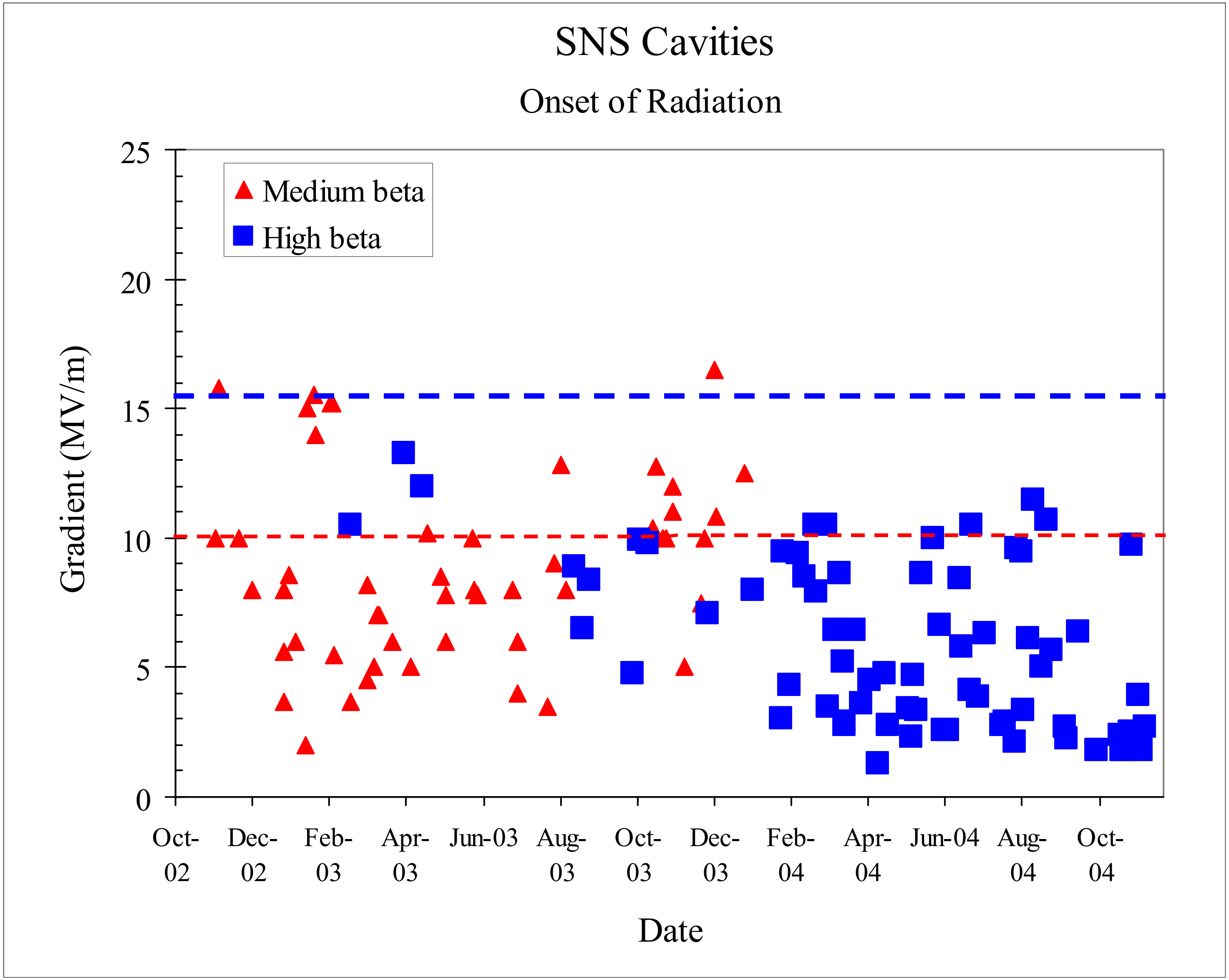


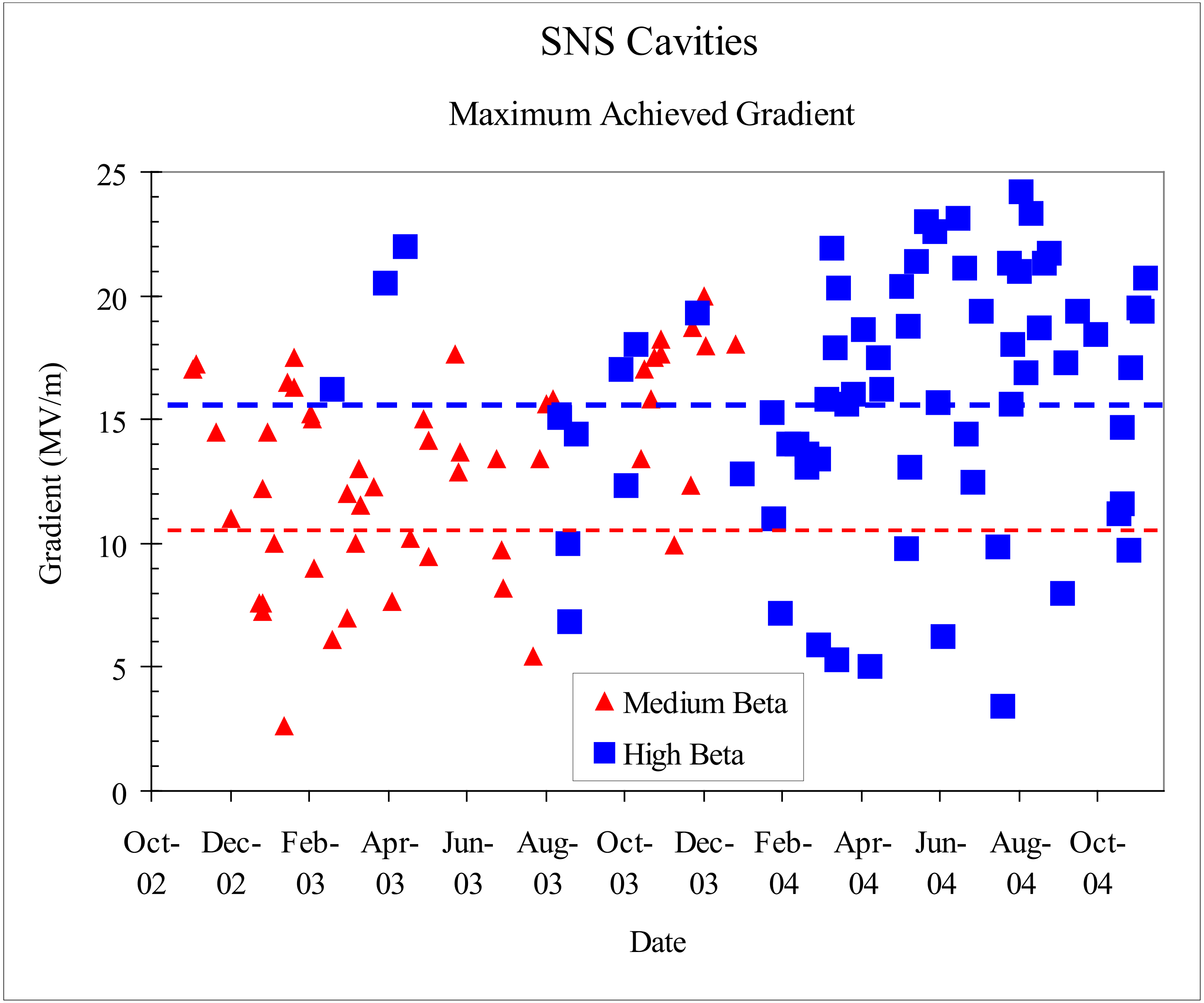
Qo at Operating Gradient (10.2 MV/m)
Medium β Cavities
1.E+11
1.E+10
1.E+09
VTA Data (Qo)
1.E+09
1.E+10
1.E+11
CMTF Data (Qo)

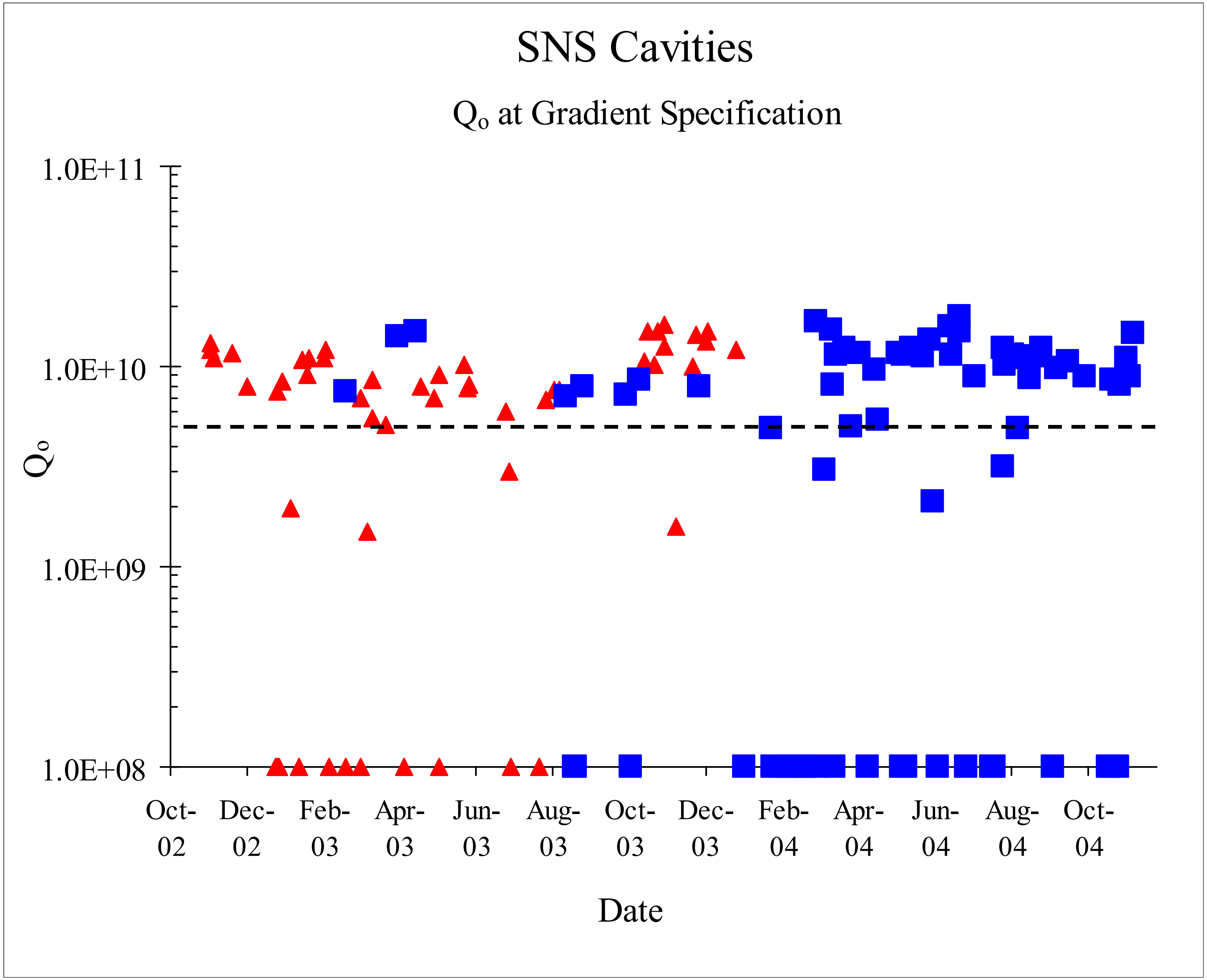

Onset of Field Emission
Medium β Cavities
VTA Data (MV/m)
CMTF Data (MV/m)
0
5
10
15
20
0
5
10
15
20


Gradient at Qo = 5 x 10^9
High β Cavities
VTA Data (MV/m)
CMTF Data (MV/m)
0
5
10
15
20
25
0
5
10
15
20
25

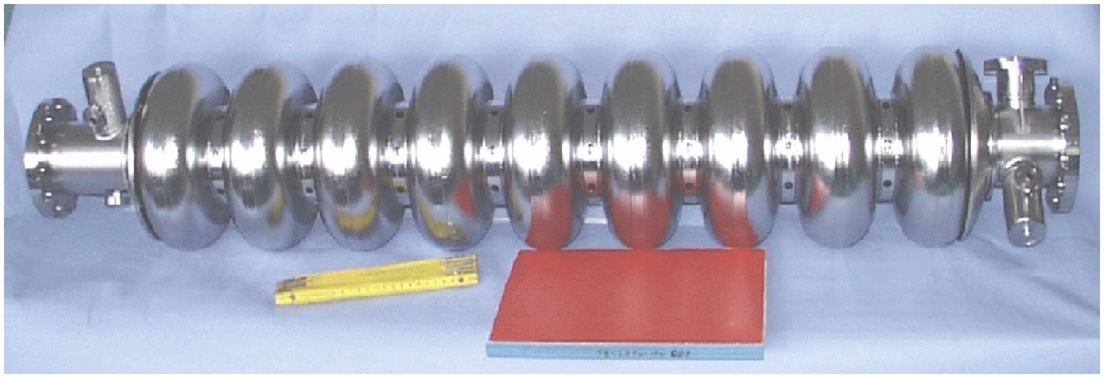

SNS Cavities
Gradient at $Q_o = 5 \times 10^9$
Medium beta
High beta
Gradient (MV/m)
25
20
15
10
5
0
Oct-02
Dec-02
Feb-03
Apr-03
Jun-03
Aug-03
Oct-03
Dec-03
Feb-04
Apr-04
Jun-04
Aug-04
Oct-04
Date


SNS Cavities
Onset of Radiation
Medium beta
High beta
Gradient (MV/m)
25
20
15
10
5
0
Oct-02
Dec-02
Feb-03
Apr-03
Jun-03
Aug-03
Oct-03
Dec-03
Feb-04
Apr-04
Jun-04
Aug-04
Oct-04
Date


SNS Cavities
Maximum Achieved Gradient
Gradient (MV/m)
25
20
15
10
5
0
Oct-02
Dec-02
Feb-03
Apr-03
Jun-03
Aug-03
Oct-03
Dec-03
Feb-04
Apr-04
Jun-04
Aug-04
Oct-04
Date
Medium Beta
High Beta


SNS Cavities
Q_o at Gradient Specification
1.0E+11
1.0E+10
1.0E+09
1.0E+08
Q_o
Oct-02
Dec-02
Feb-03
Apr-03
Jun-03
Aug-03
Oct-03
Dec-03
Feb-04
Apr-04
Jun-04
Aug-04
Oct-04
Date

The TTF Linac‘s Accelerating Cavities

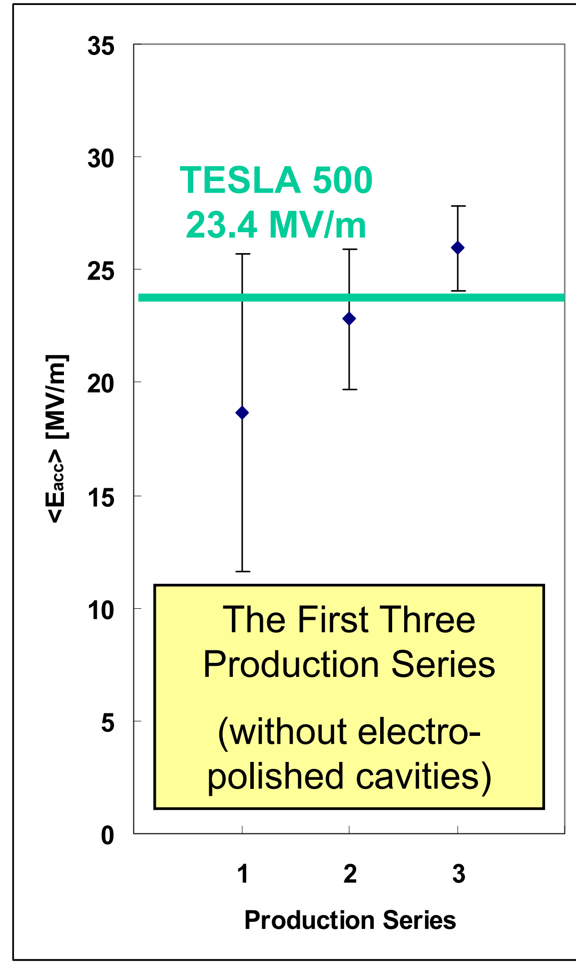


Approx. 80 cavities were produced in three production series.
Gradient and gradient spread improved a lot.

Nine accelerator modules with 8 cavities each were assembled.

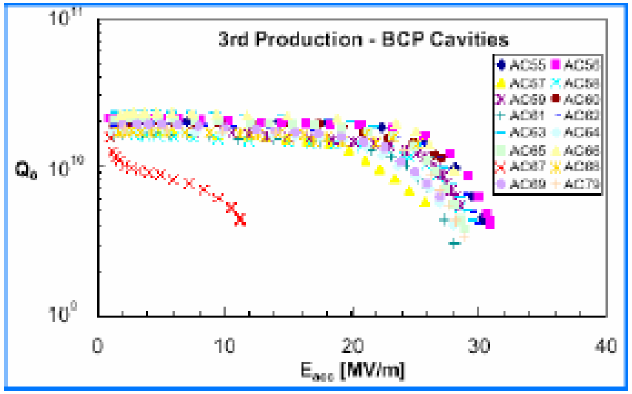
58 different cavities were used for the module assembly. Some cavities were used for a second assembly.

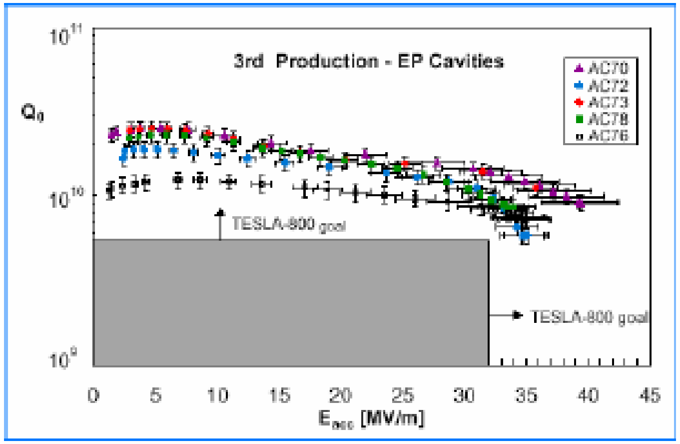
Series 1	**18.7 ± 7.0**
Series 2	**22.8 ± 3.1**
Series 3	**26.0 ± 1.9**

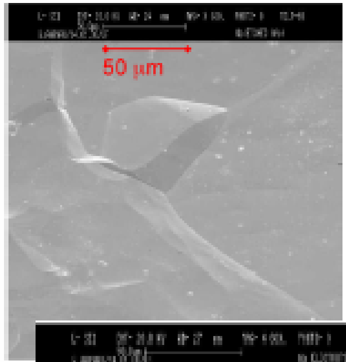


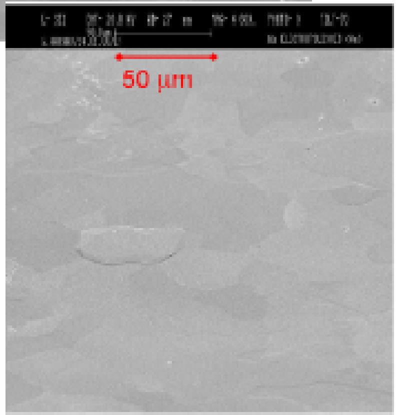
DESY/TTF

Vertical tests









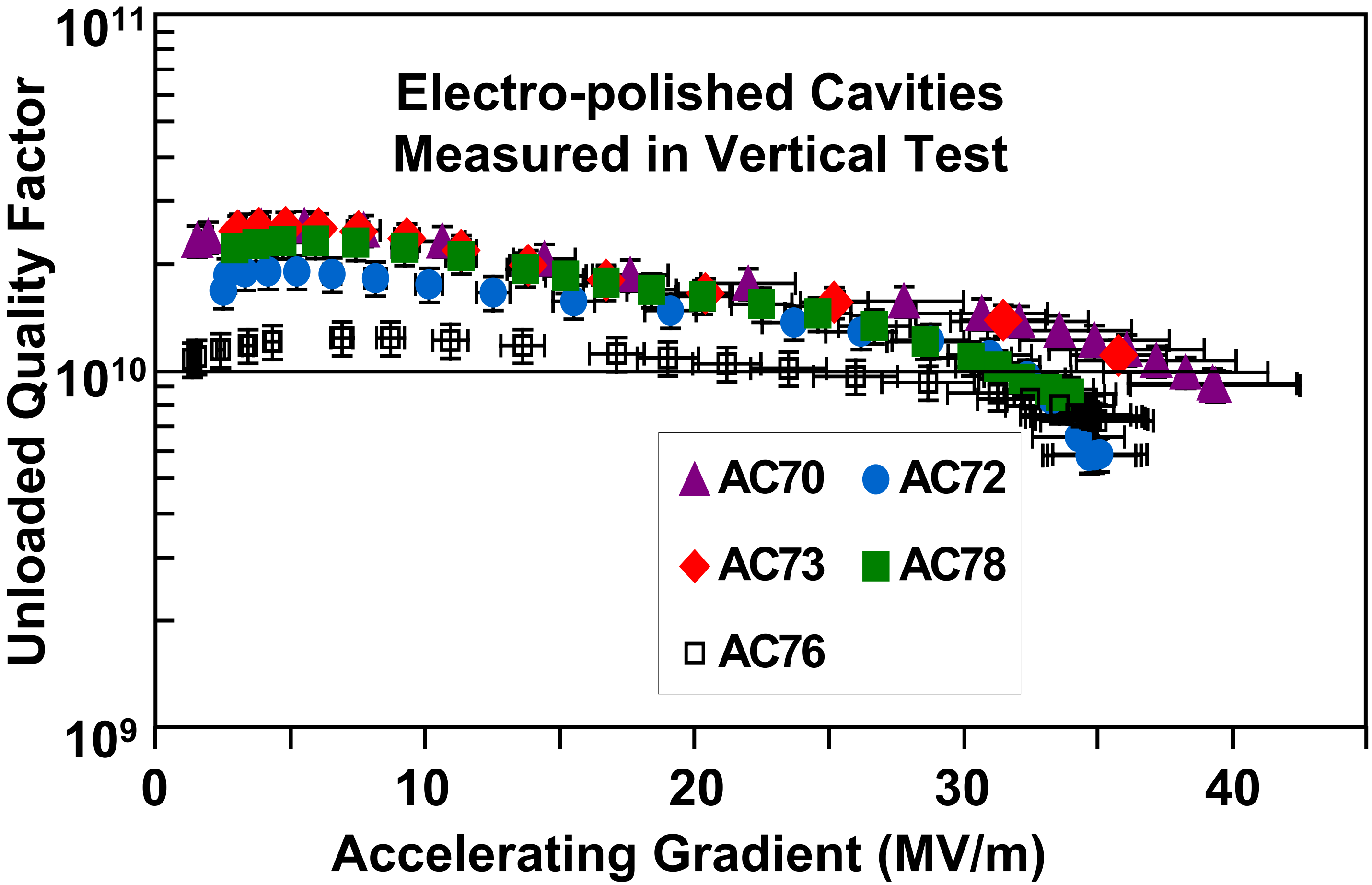
EP and Baking 5 cavities tested

Eacc = 35 - 40 MV/m

Assembly in Class 100 Clean Room

< 100 particles/cu.ft > 1 µm

Electro-Polishing becomes State-of-the-Art Surface Preparation Technique and will be used for the XFEL



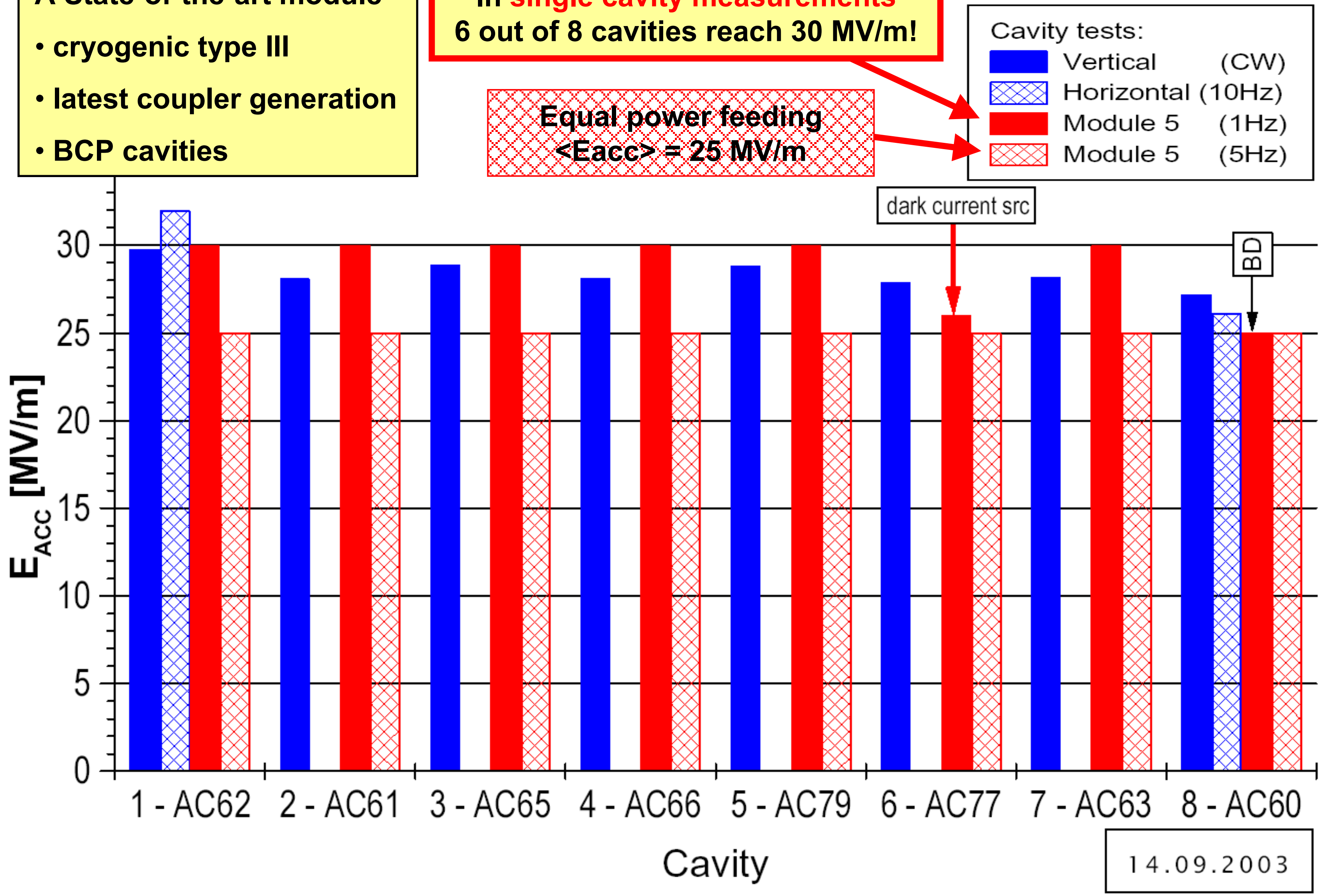
Performance of Accelerator Module 5

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



Dark Current Measurement

The on-axis dark current was measured for modules ACC4 / ACC5.

Only one cavity in module ACC5 produced a mentionable dark current.

- captured dark current could be measured at the exit of ACC5
- there was no d.c. from this cavity at the entrance of ACC4
- *the d.c. decreased as a function of time*

after module commissioning (August 2003)
100 nA at 16 MV/m increasing by a
factor 10 for each 4.4 MV/m gradient step
i.e. approx. 10 μA at 25 MV/m

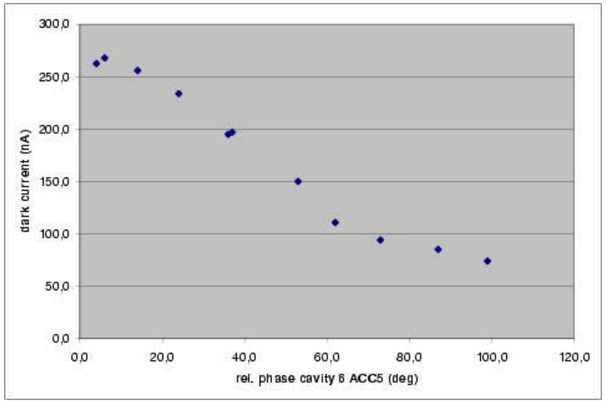
May 4th
100 nA at 20 MV/m increasing by a
factor 10 for each 3.7 MV/m gradient step,
i.e. 1.2 μA at 25 MV/m

September 22nd
after a few weeks on-time at 20 – 25 MV/m
250 nA at 25 MV/m

- detuning of cavity no. 6 left over an integrated dark current of the order of 20 to 25 nA at 25 MV/m average gradient

Dark Current vs. RF phase with respect to neighbouring cavities is just as expected

(max ➘ min) over pi/2



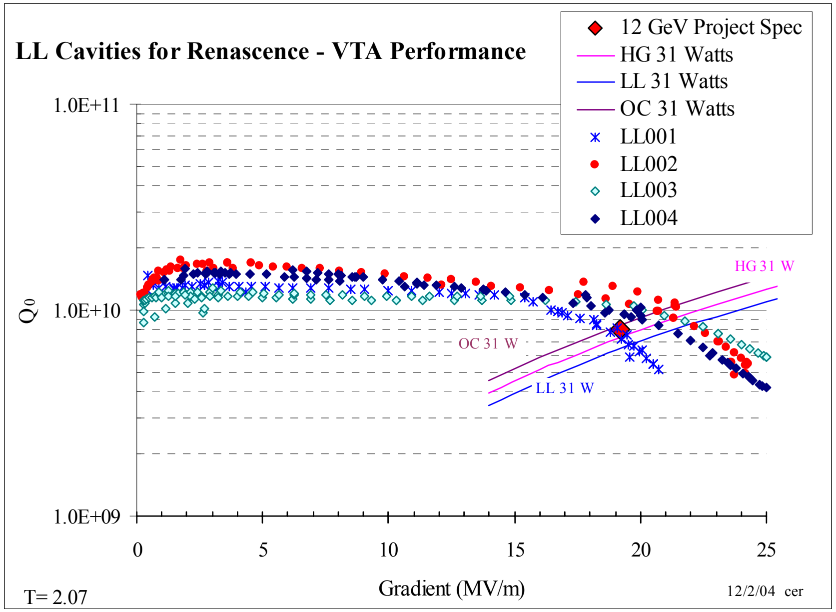
Reminder:

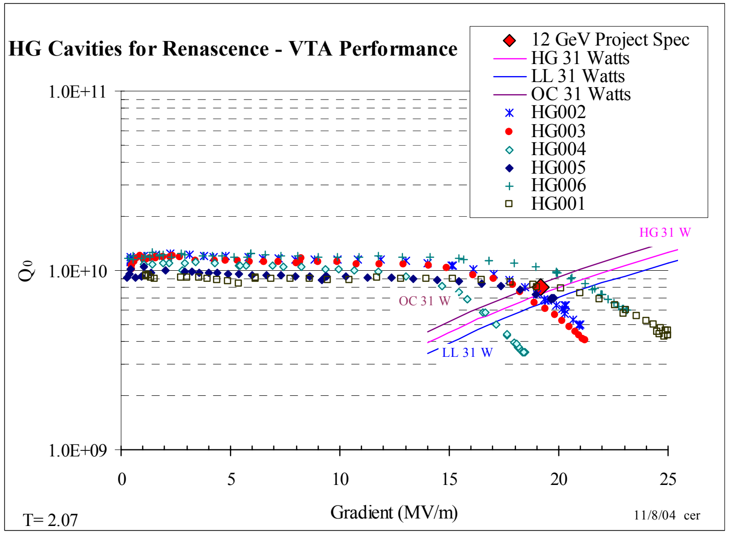
The TESLA limit is defined by additional cryogenic losses:

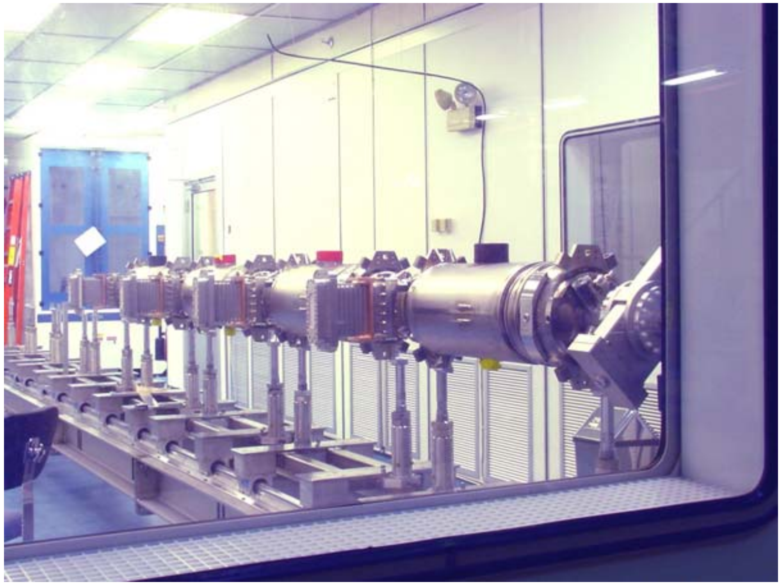
The captured d.c. has to stay below 50 nA per cavity.
(see TESLA Report 2003-10).

Jlab Upgrade: Renasence Module

5 LL cavities, 3 HG cavities







Acknowledgements

Many colleagues provided me with informations for this talk and I used slides from presentations by several colleagues:

C. Reece,Jlab, J. Ozelis, Jlab.H. Whitehead, Jlab
A.Matheisen, DESY,L. Lilje, DESY,H. Weise, DESY,
D. Reschke, DESY

http://adweb.desy.de/~weise/:Operational Experience with the TTF Linac
Das Europäische XFEL Projekt

http://www.aps.anl.gov/conferences/RFSC-Limits/Presentations.html
D.Reschke,"Field Emission Overview ; Cleanliness and Processing"
http://lcdev.kek.jp/ILCWS/WG5.php
A.Matheisen,"Cavity fabrication and Processing"
http://www-bd.fnal.gov/niobium/program.html
W.Singer,"Material Properties of High Purity Niobium for SC Cavities"

Back-up Slides

SNS: Cavity String Assembly

After VTA Test(without HOM probes and FPC):

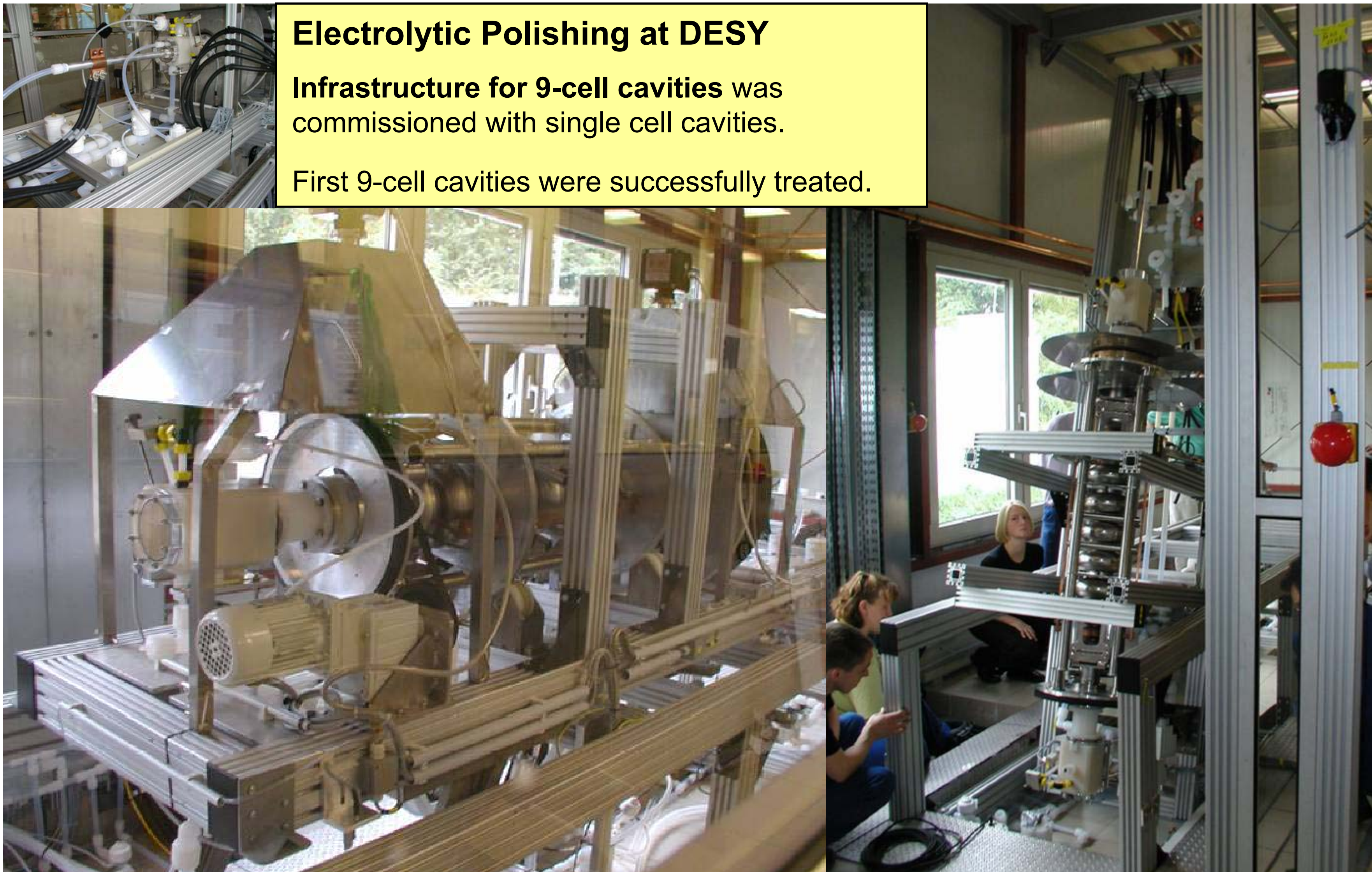
- Add. 10 –20 μm bcp, HPR for 4 hrs, drying in class 10 clean room over night
- Attachment of HOM probes
- Add. 4 hrs of HPR, drying in class 10
- Assembly on assembly rail with FPC, bellows, gate valves, beam pipe opening closed with Nb plate
- Assembly of string takes several days
- Final completion with beam pipe bellows,
- Evacuation with turbo pump, leak checking

35 MV/m for 800 GeV c.m.

Electrolytic Polishing at DESY

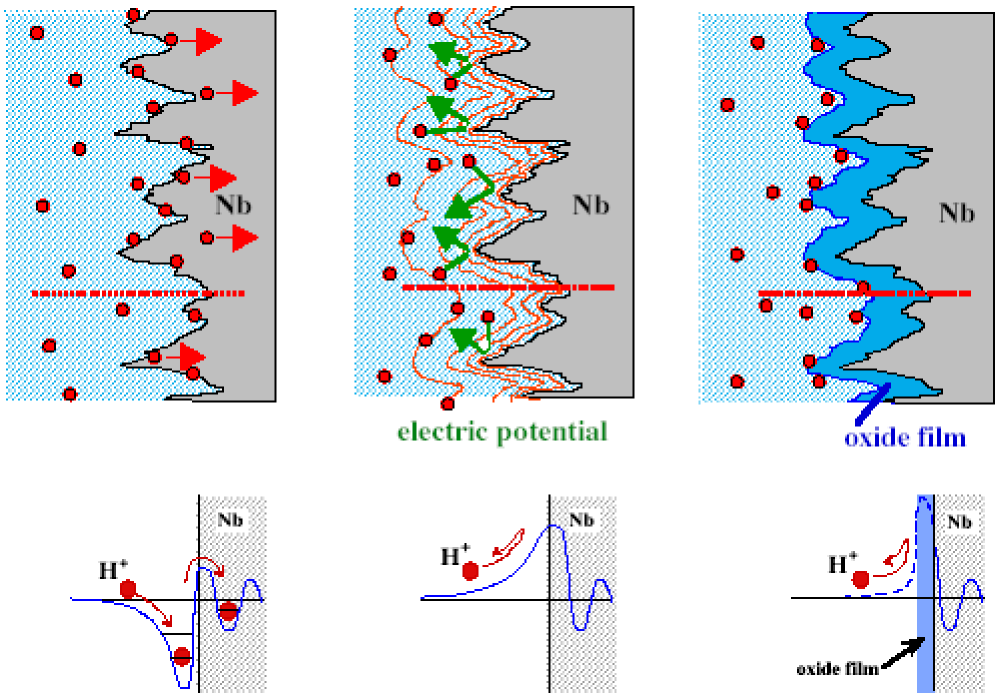
Infrastructure for 9-cell cavities was commissioned with single cell cavities.

First 9-cell cavities were successfully treated.

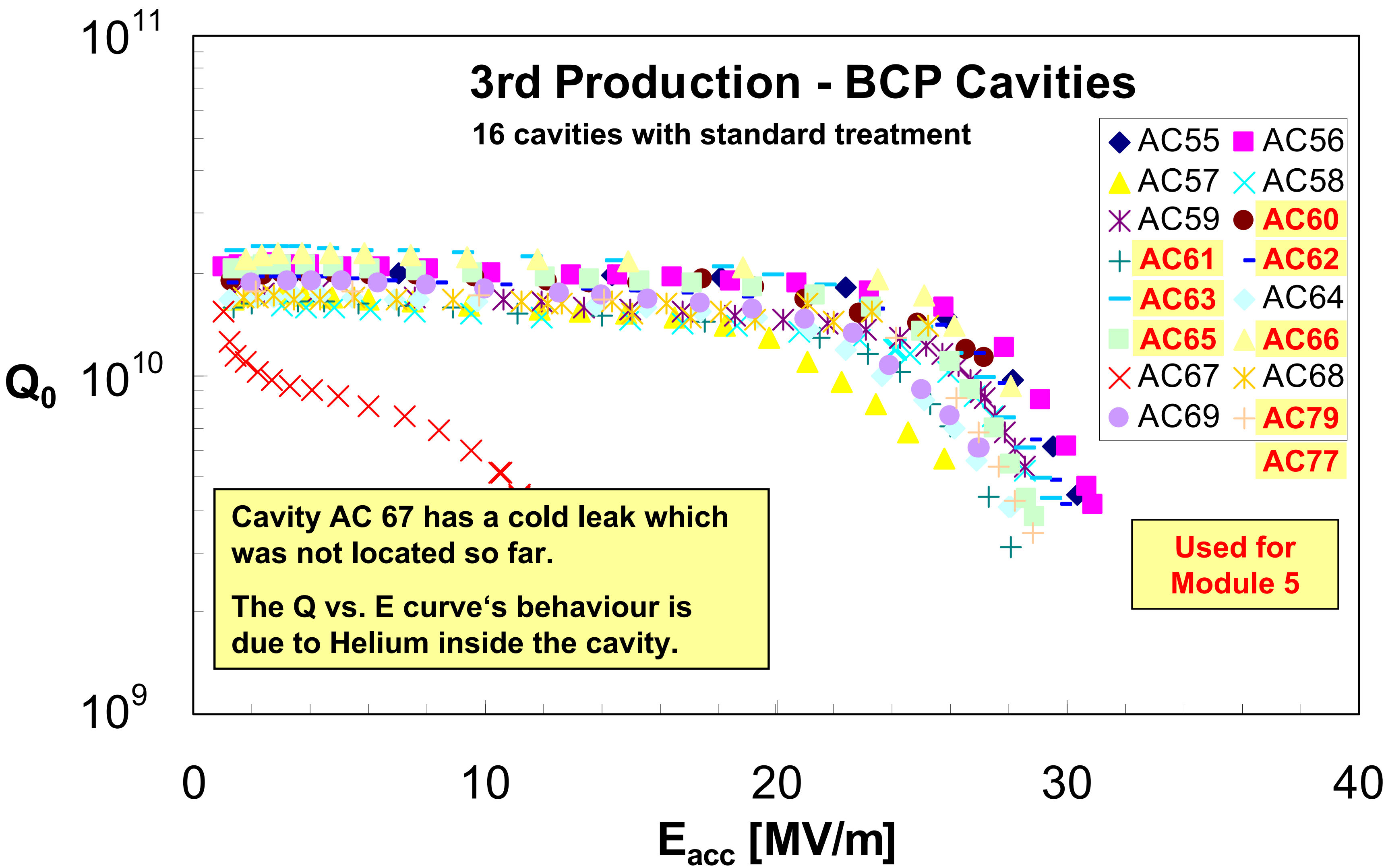


Electropolishing

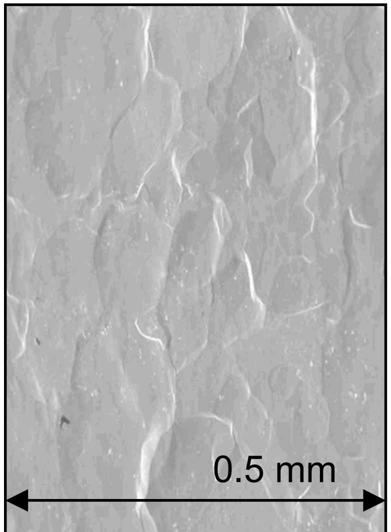
Absorption of Hydrogen avoided by applying a potential to the sample and adding an oxidizer (HNO_3) to the EP solution [S.Higuchi, K.Saito SRF2003]



High Gradient Performance

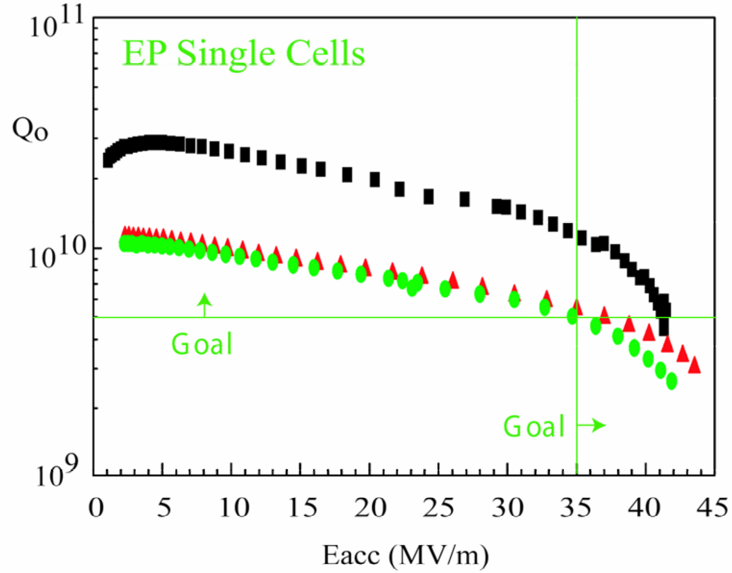


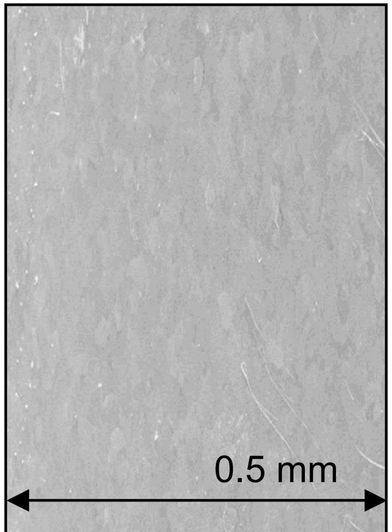
35 MV/m for 800 GeV c.m.



BCP Surface
(1μm roughness)

First electro-polished single cell cavities





EP Surface
(0.1μm roughness)

Electro-polishing (EP) instead of the standard chemical polishing (BCP) eliminates grain boundary steps. The development of this technique is strongly connected to work done by Kenji Saito (KEK).

Gradients of 40 MV/m at Q values above 10^{10} are now reliably achieved in single cells at KEK, DESY/CERN and TJNAF.

The highest gradient achieved was 42 MV/m.