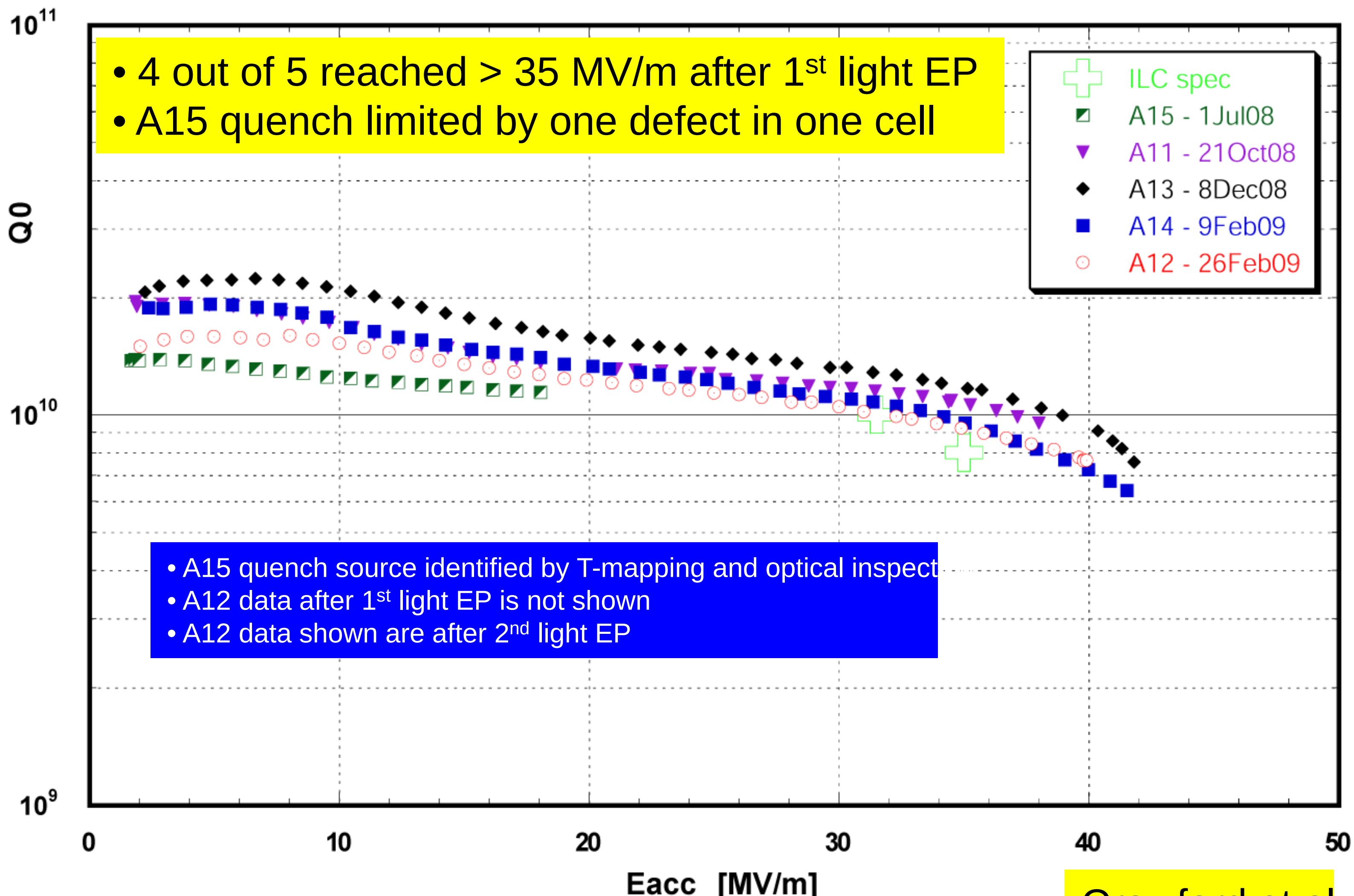
SRF Cavity Preparation and Limitations

J. Mammosser (ORNL)

Outline:

- Cavity Qualifying Test Limitations (Vertical Test)
  - Vertical Test Results
  - Main Limitations (Field emission, Thermal breakdown, Multipacting)
  - Not Covered - (Q-disease, Trapped Magnetic Field, High Field Q-Drop)
  - Performance History
- Today's Standard Processing Procedures
  - Standard Processing Sequence (30-40 MV/m)
  - Surface cleaning, Chemistry, HPR, Heat treatment, Baking, Helium Processing
- Future Process Improvements
  - Vertical EP, Plasma Cleaning, Integrated Process Automation

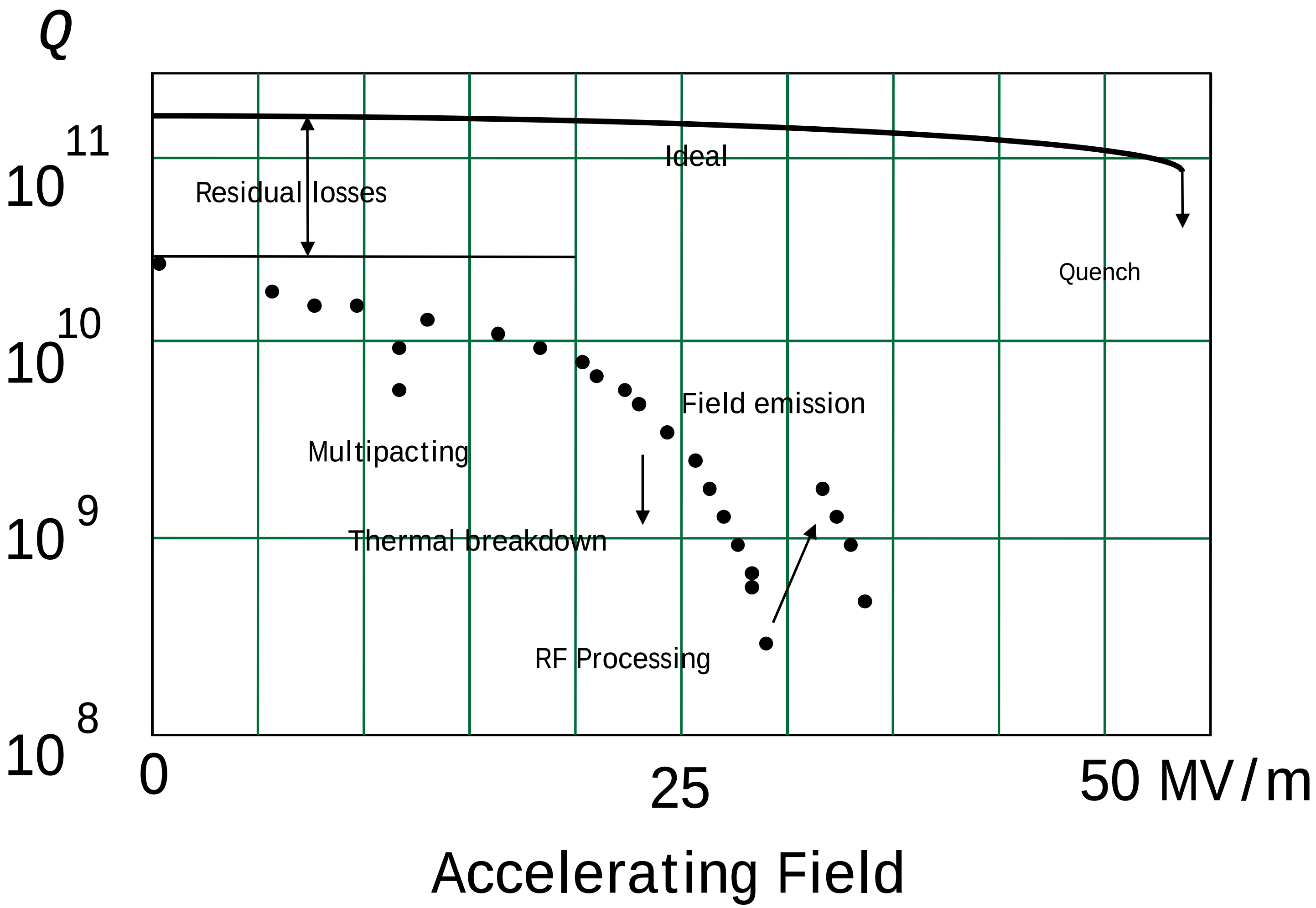
When Proper Procedure and Attention to Detail Occur –



Crawford et al

Rongli Geng

However performances are not always ideal



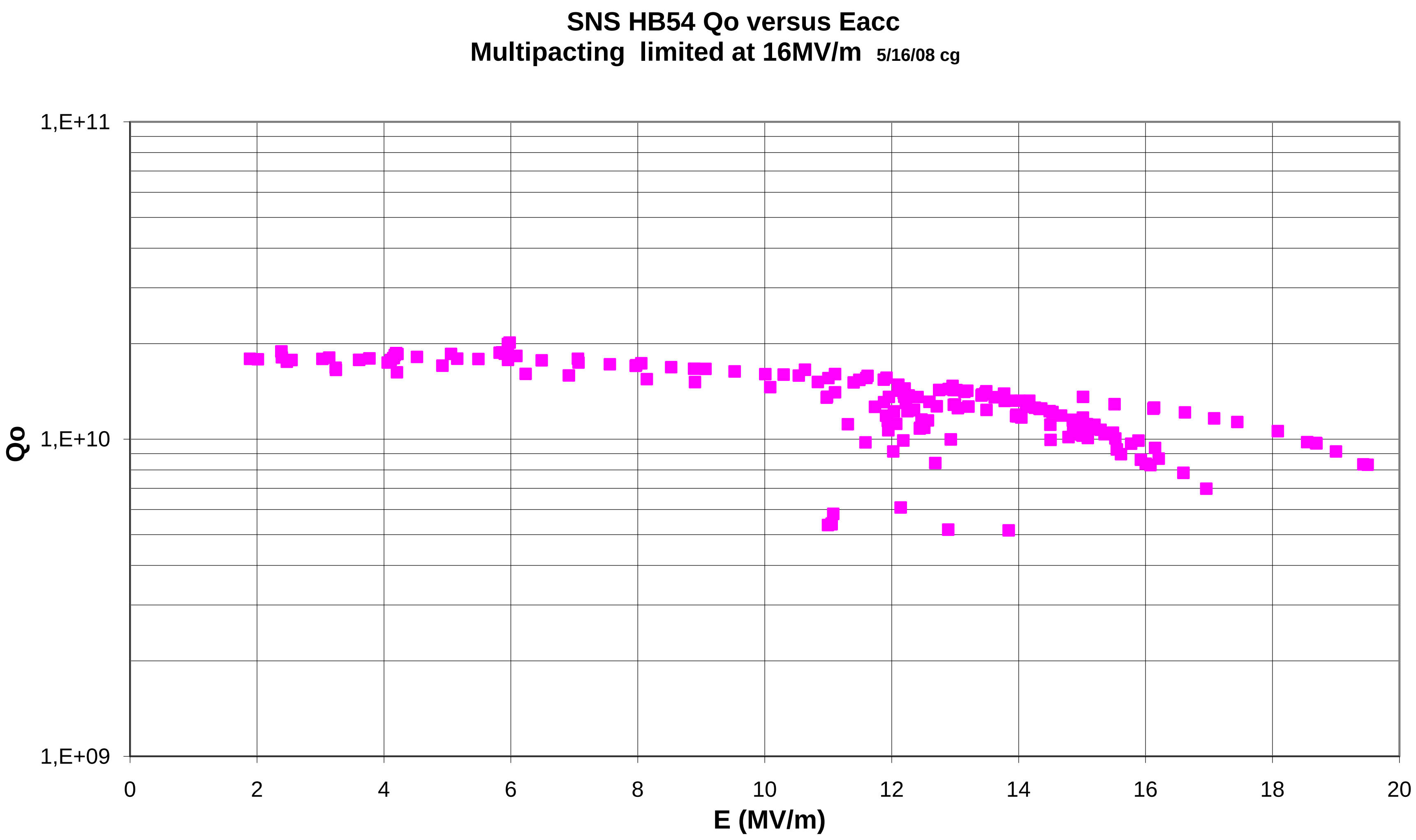
Field Emission

Characterized by an exponential drop of the Q-value

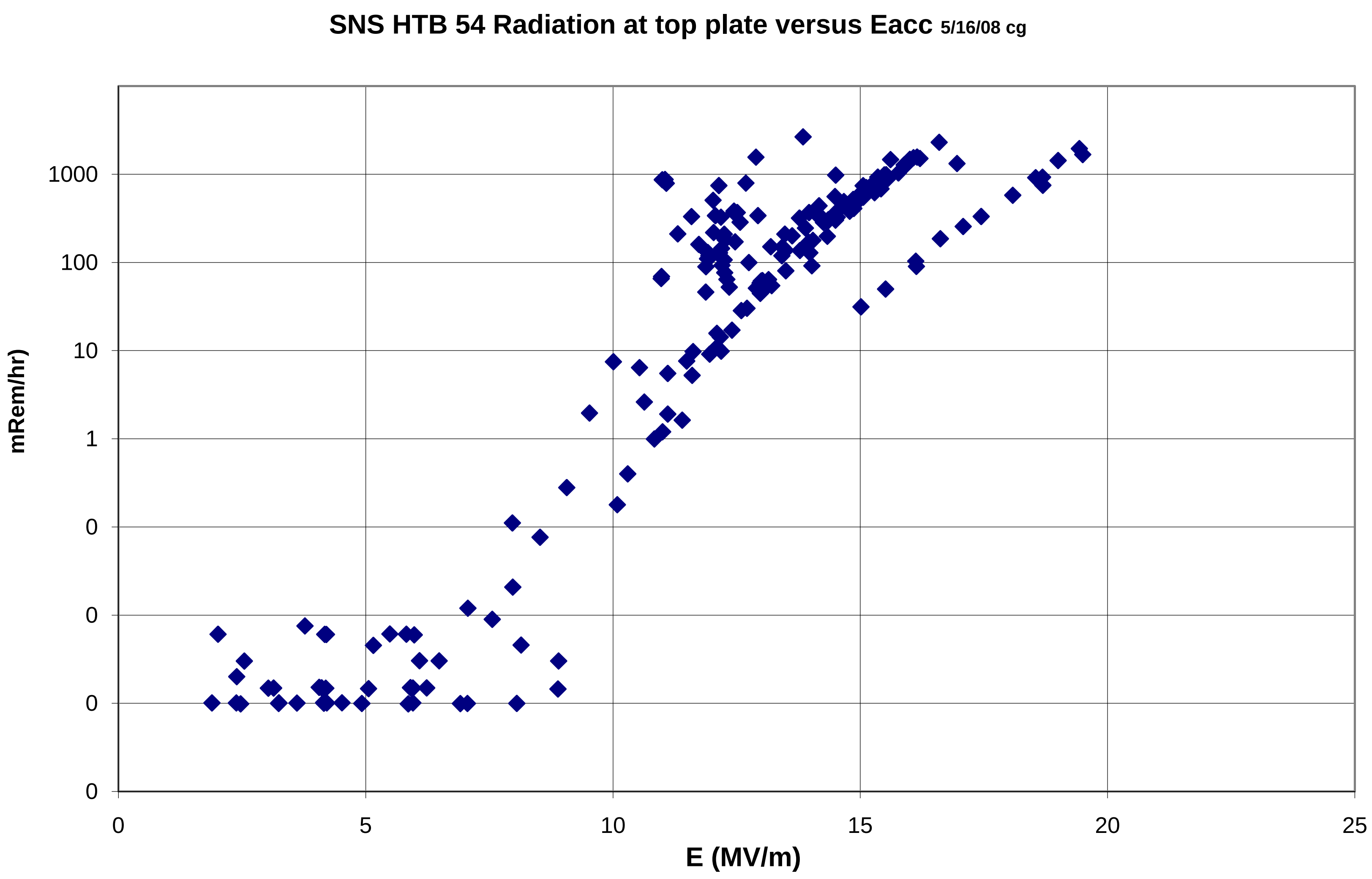
Associated with production of x-rays and emission of dark current

Today good processes and procedures can minimize or eliminate this issue but its always there at some level

Field Emission

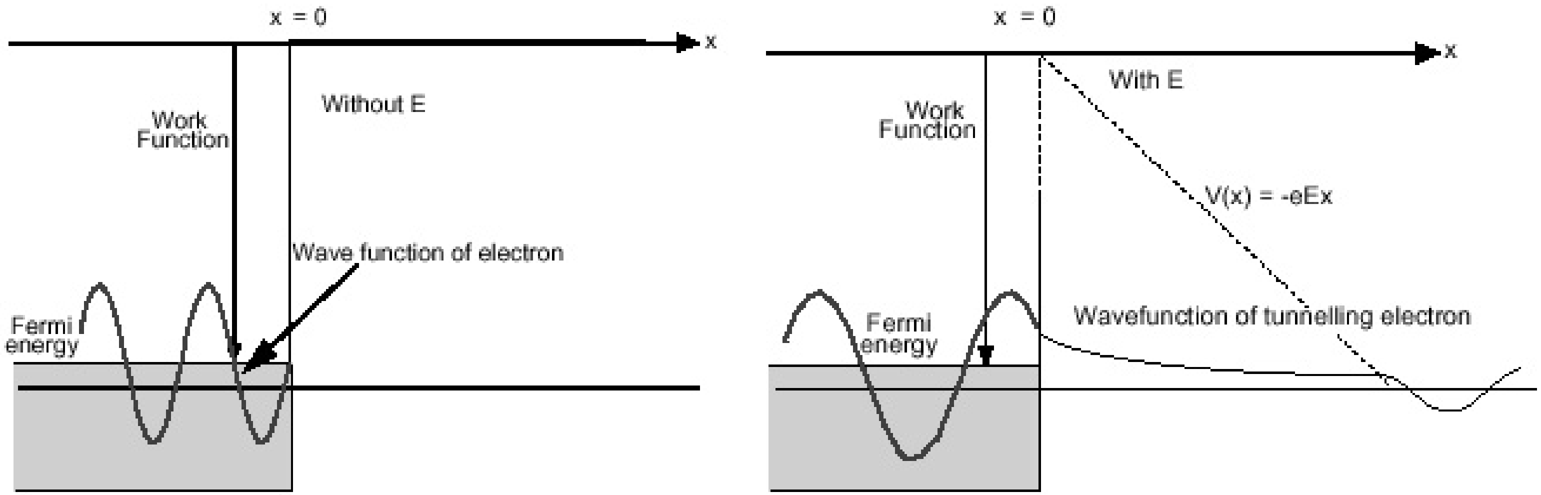


Field Emission



Field Emission from Ideal Surface

Fowler-Nordheim model



$$I(E) = \frac{1.54\times10^{6}\, Ae\,(\beta_{FN}E)^{2}}{\phi}\exp\left[-\frac{6.83\times10^{3}\,\phi^{\frac{3}{2}}}{\beta_{FN}\,E}\right]$$

$\phi = work\ function$

$A_e = Effective\ Emitter\ Surface\ Area$

$E = Electric\ Field$

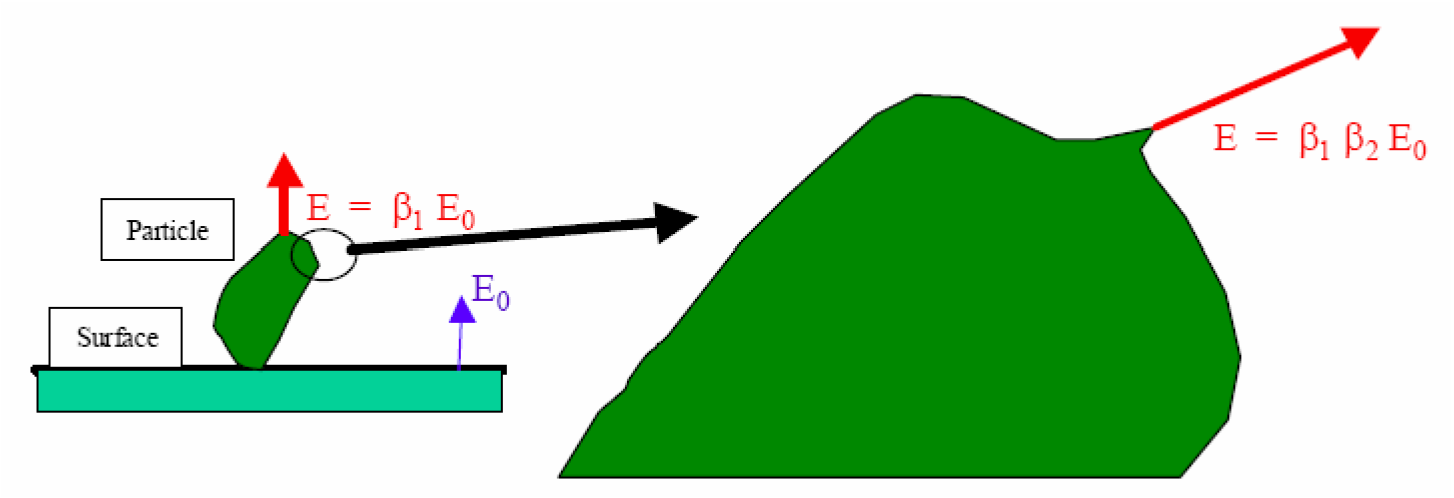
$\beta_{FN} = Field\ Enhancement\ Factor$

Geometrical Origin of Field Enhancement

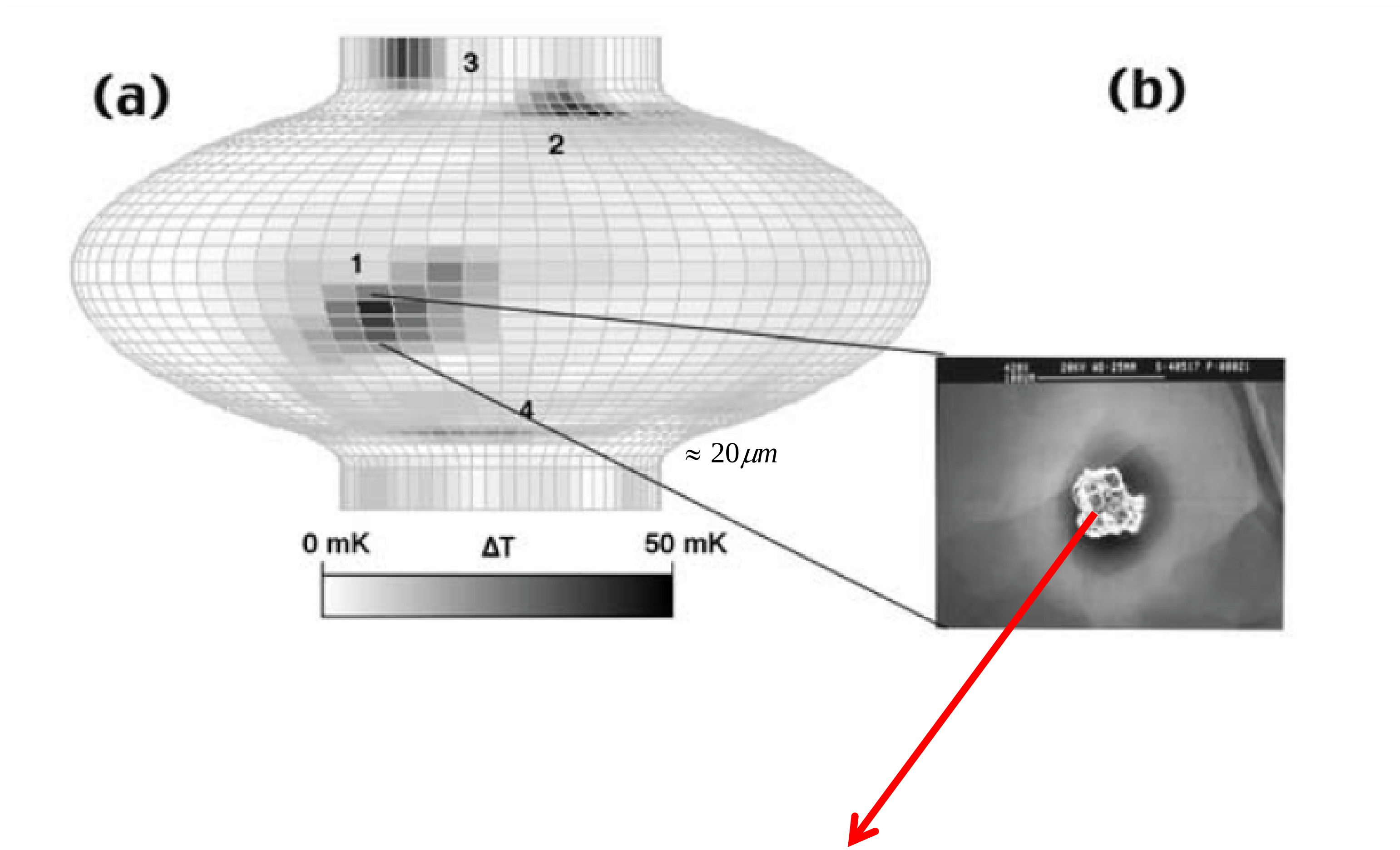
Smooth particles show little field emission

Simple protrusions are not sufficient to explain the measured enhancement factors

Possible explanation: tip on tip (compounded enhancement)

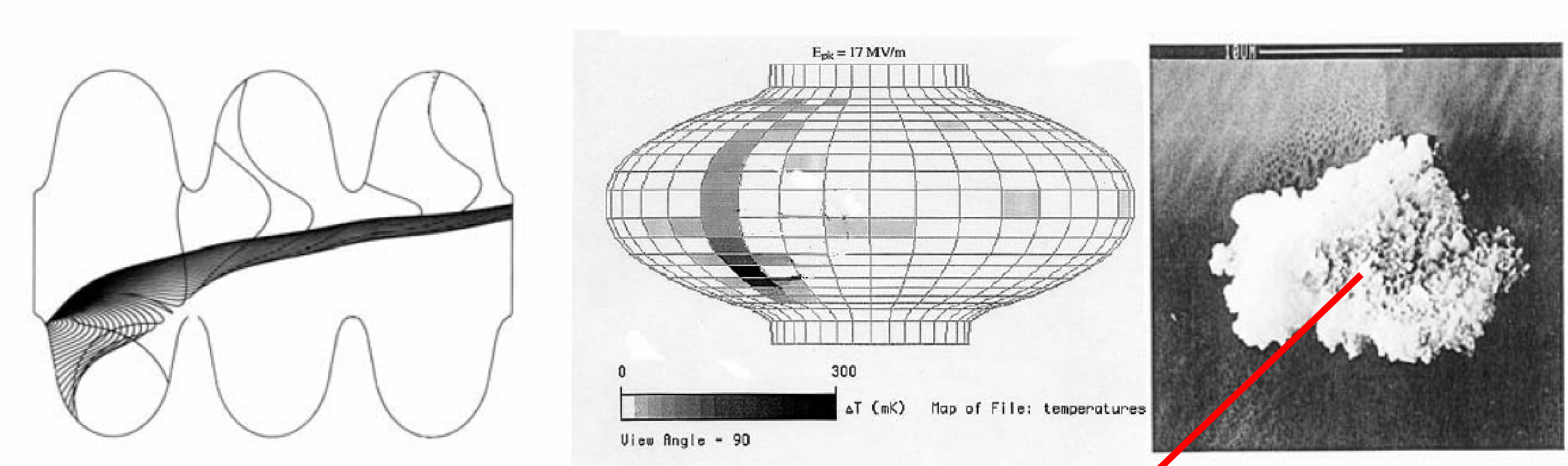


Localized Defects



$$\approx 20\mu m$$

Field Emission

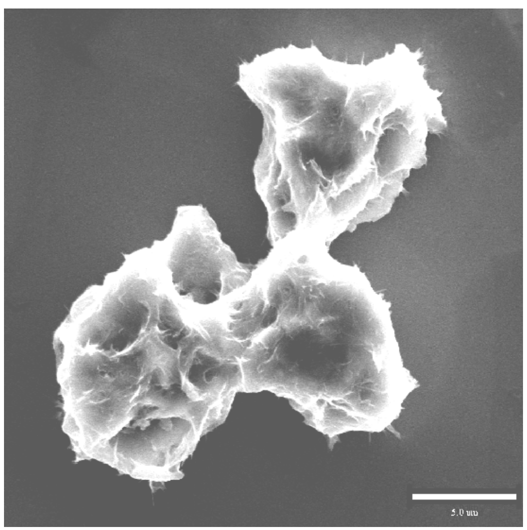


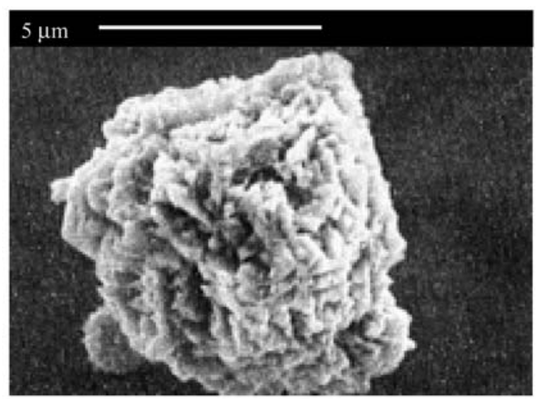
$$\approx 15\times10\,\mu m$$

Example of Field Emittors

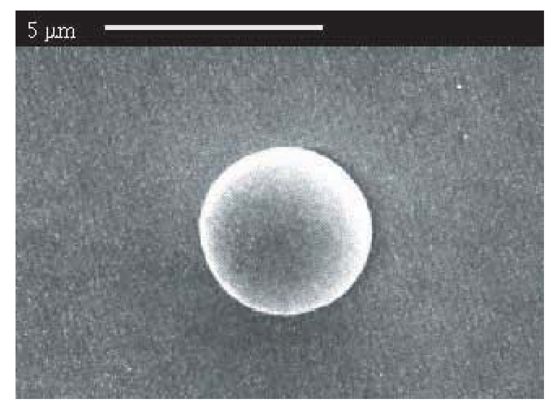
Fig. 11 Example of a scratch and a particle on a niobium surface.

V



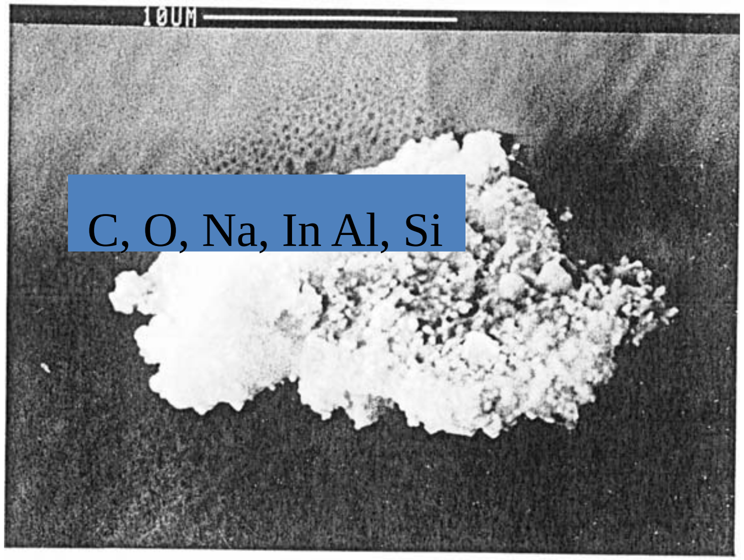


Ni

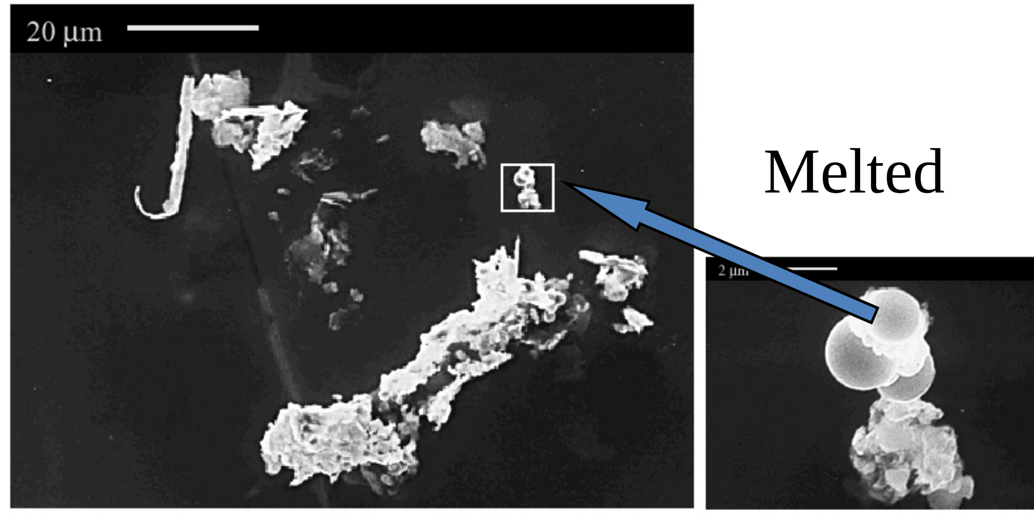


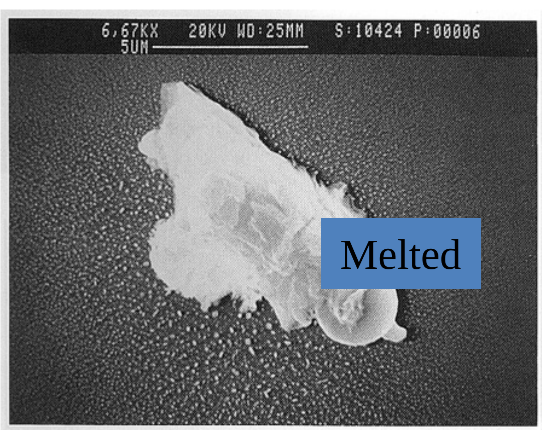
Ni

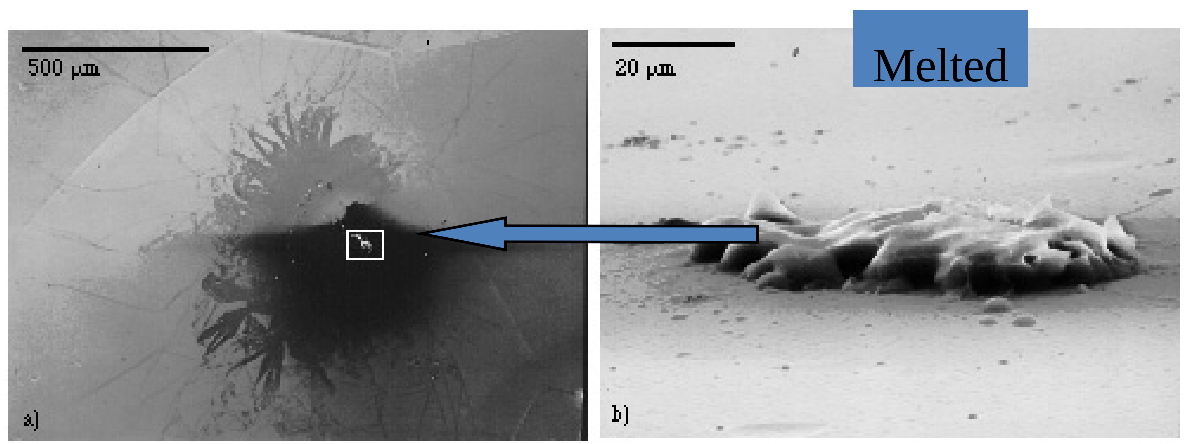
Example of Field Emitters



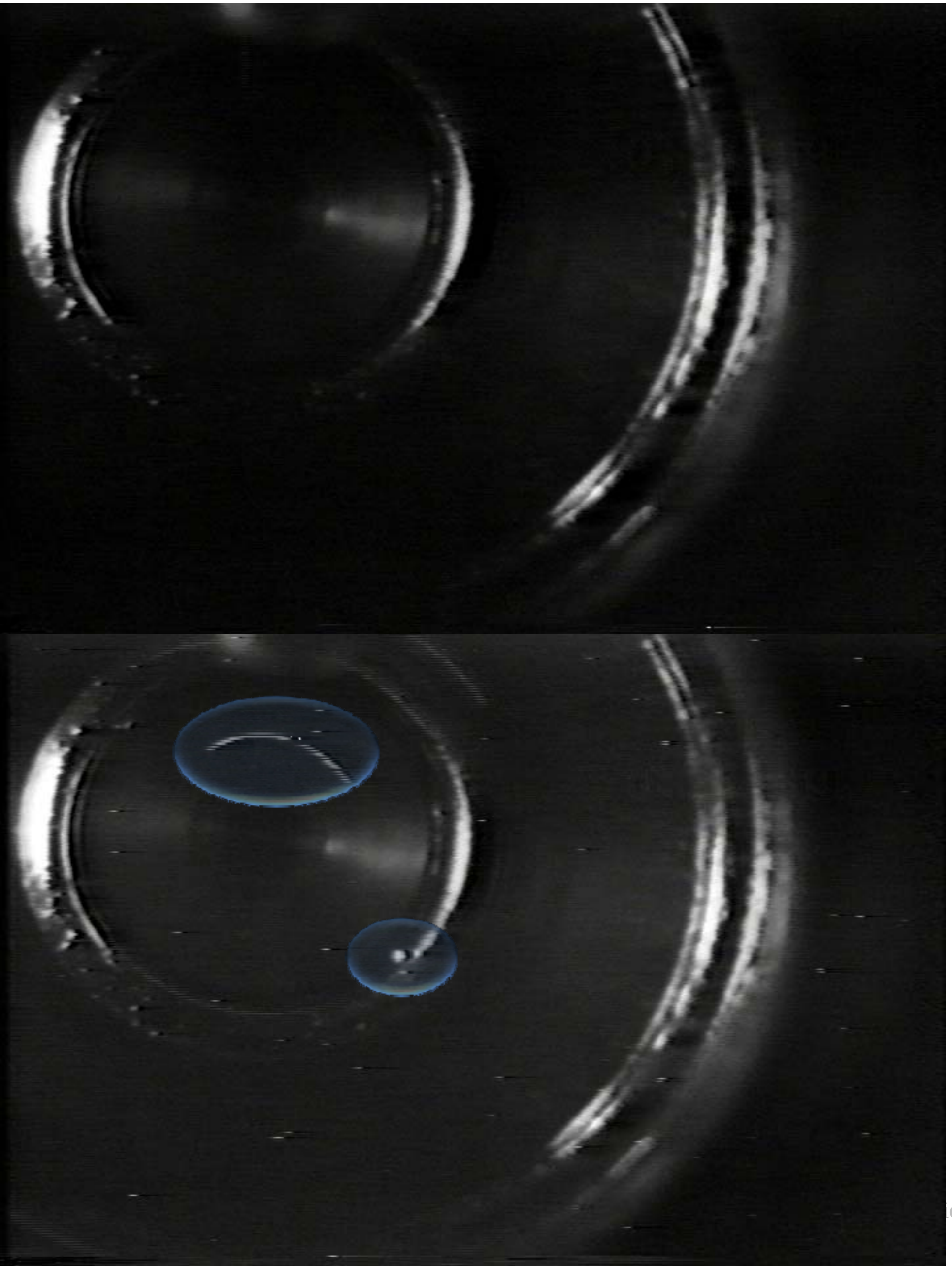
Stainless steel







Looking Inside the Cavity During Testing

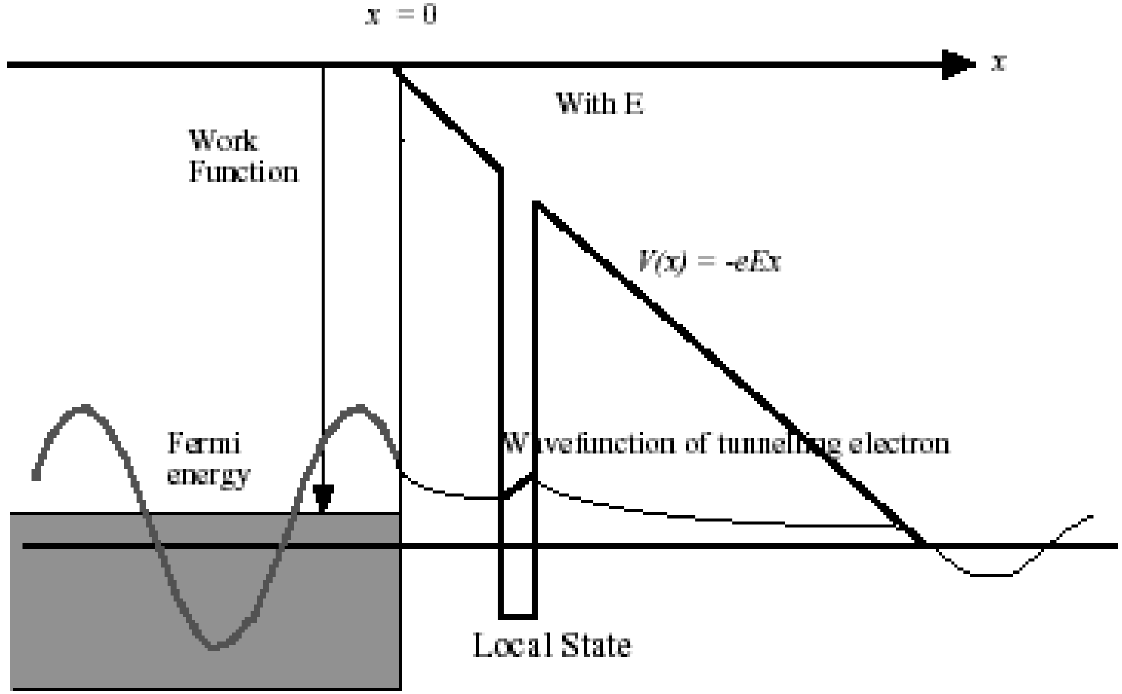


- Before onset of Radiation outside dewar

- Radiation present on detector and in CCD image

Enhancement by Absorbates

Adsorbed atoms on the surface can enhance the tunneling of electrons from the metal and increase field emission



Beta Enhancement Factors
1 - tip on tip
2 - absorbed gas
3 – insulator enhancement (field distortion)

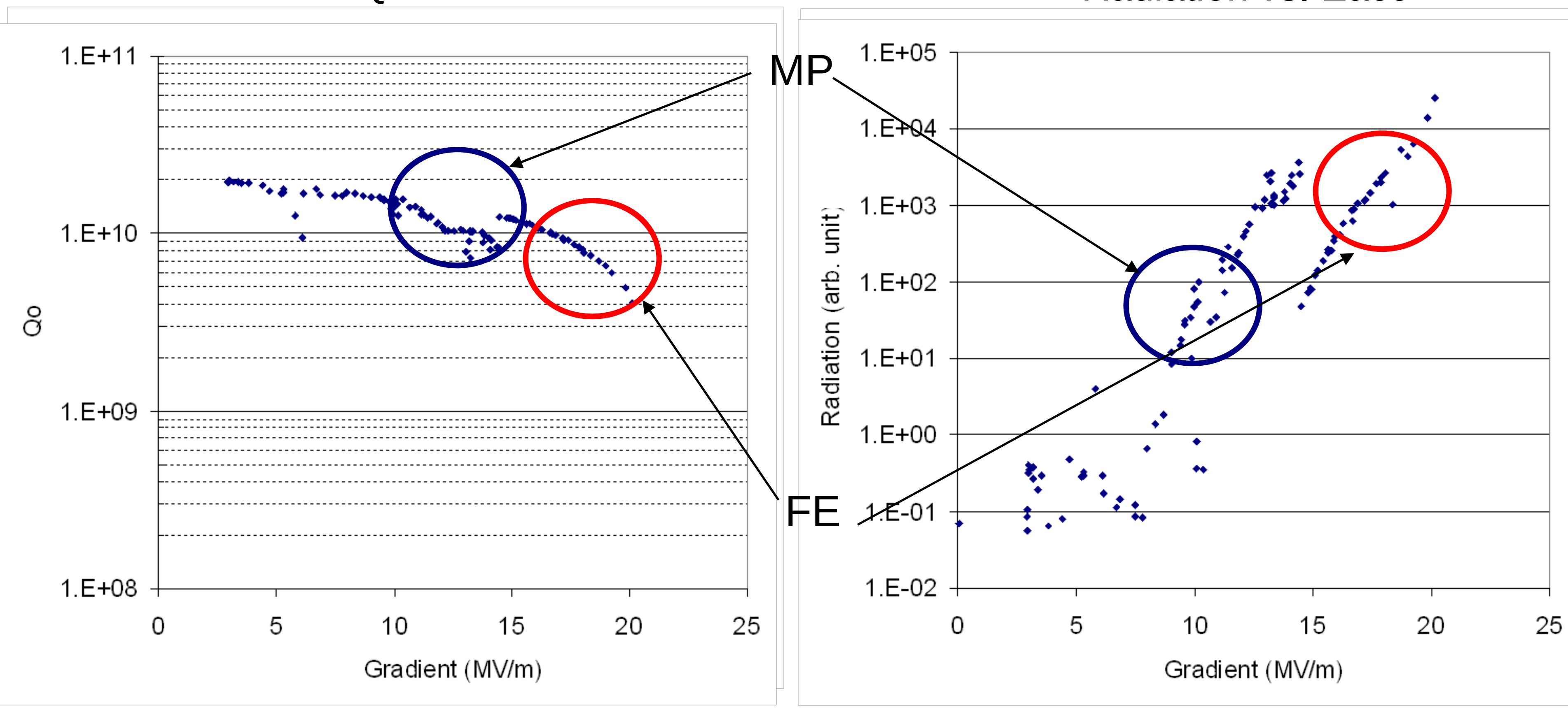
Field Emission ?

MP! And then later on Field Emission !

VTA

Qo vs. Eacc

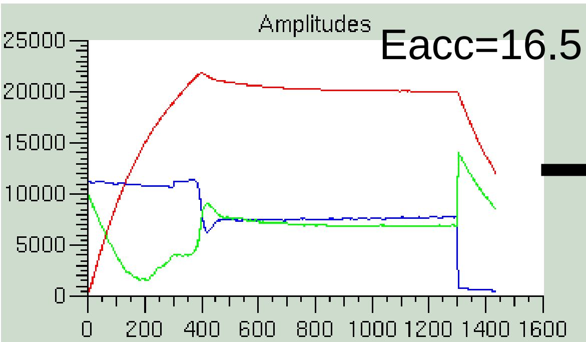
Radiation vs. Eacc



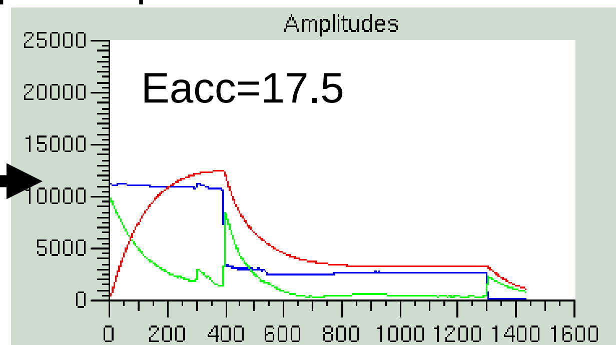
If this cavity is limited at this condition, what is the limiting factor? Field emission?

Field emission

17b in open loop

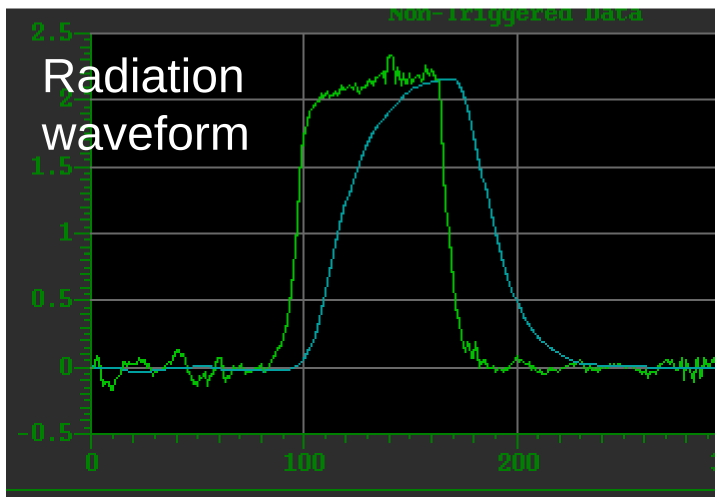


Time (us)



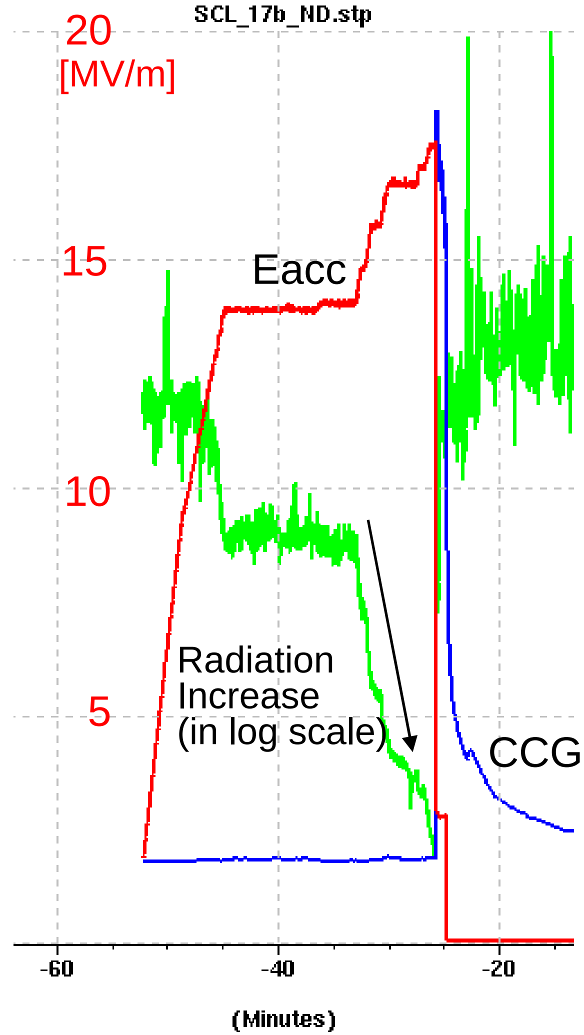
Time (us)

Pulsed operation
→Waveform tells us what is happening inside



17b
Radiation at Eacc=16.5
(Elim=17.5 MV/m due to FE!)

Ex. 17b individual



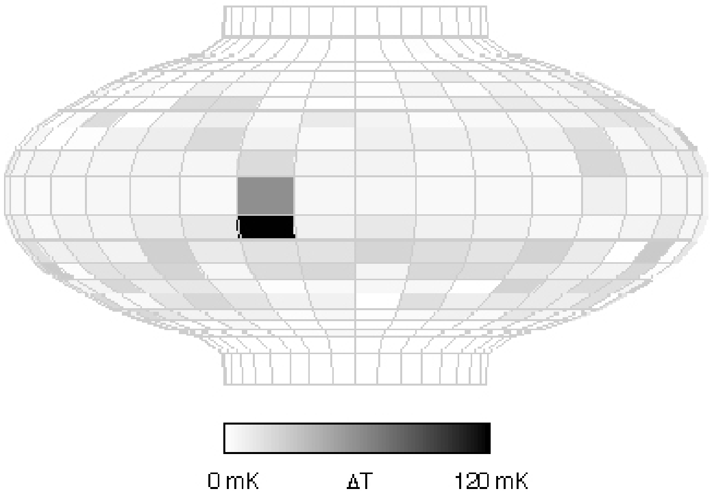
Thermal Breakdown

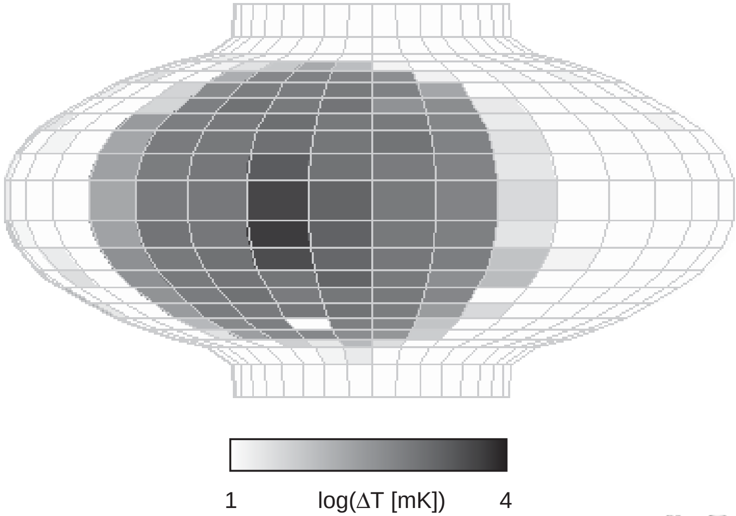
Localized heating

Hot area increases with field

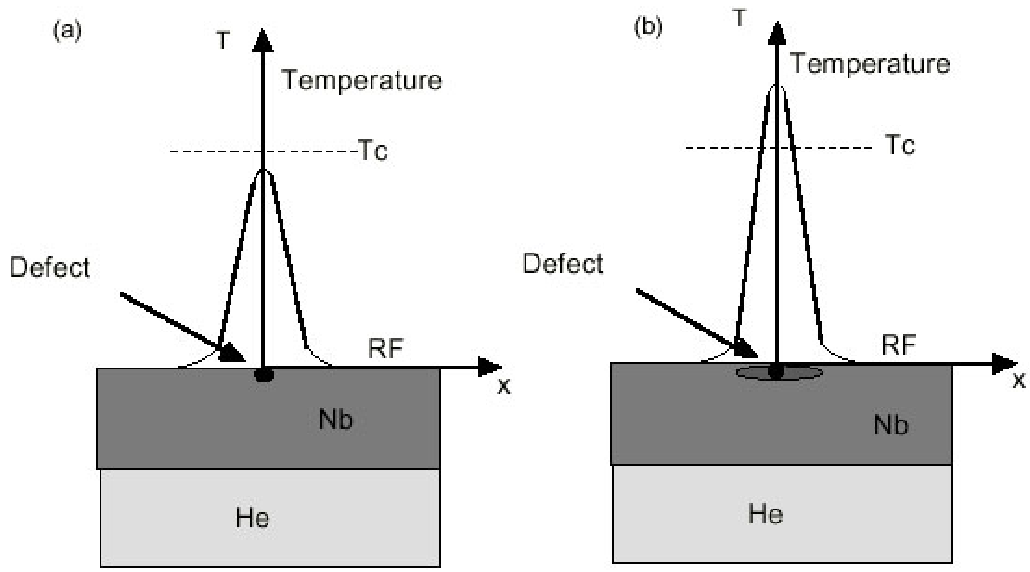
At a certain field there is a thermal runaway, the field collapses

- sometimes displays a oscillator behavior
- sometimes settles at a lower value
- sometimes displays a hysteretic behavior





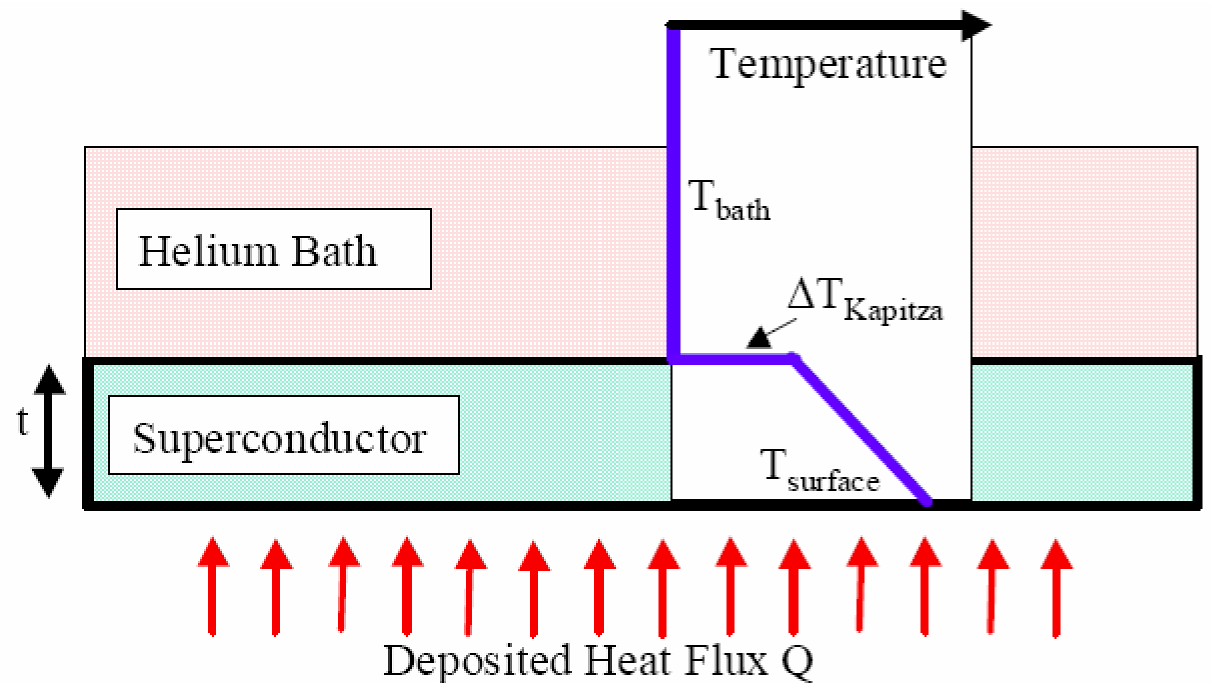
Thermal Breakdown



Thermal breakdown occurs when the heat generated at the hot spot is larger than that can be evacuated to the helium bath

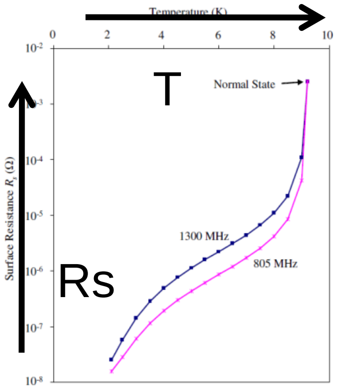
Both the thermal conductivity and the surface resistance of Nb are highly temperature dependent between 2 and 9K

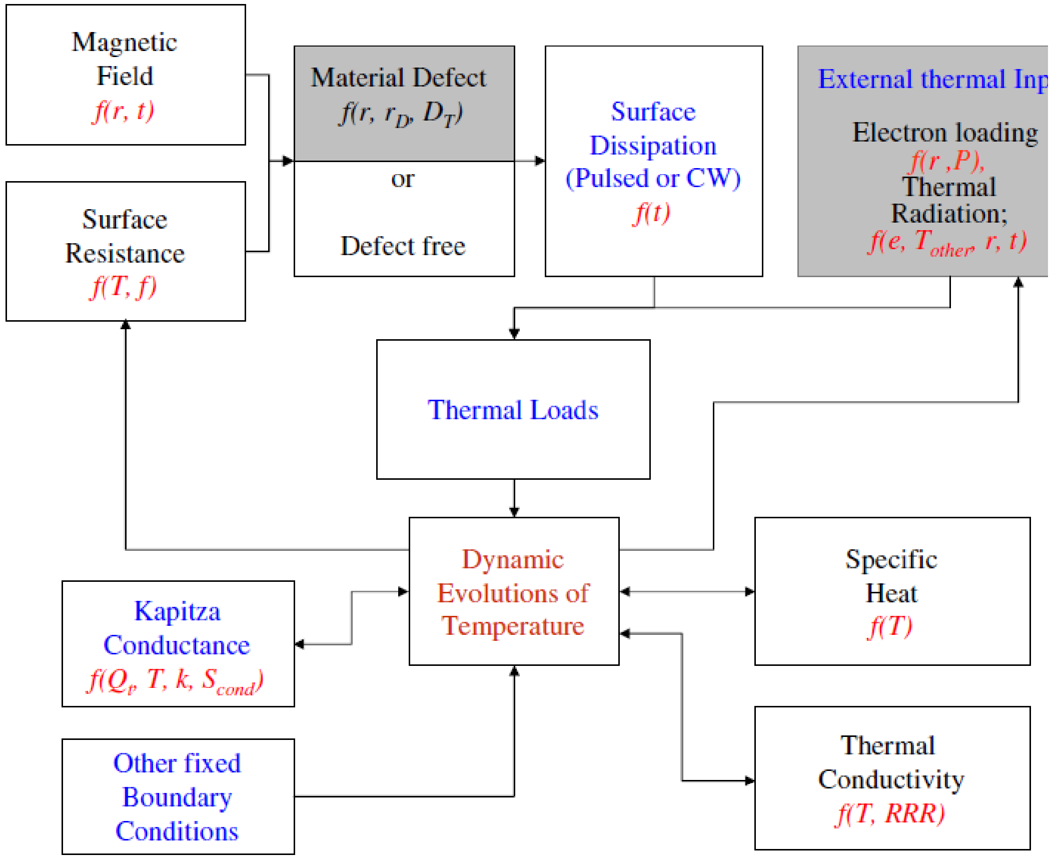
Thermal Breakdown

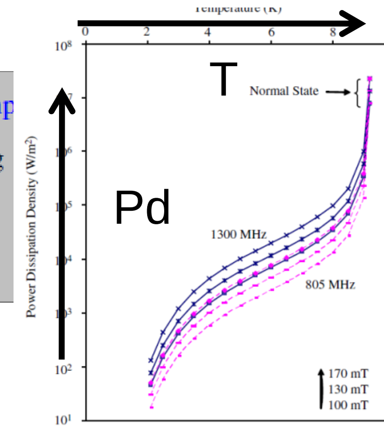


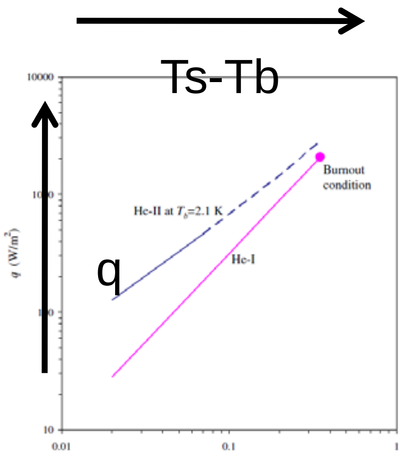
Thermal stabilities and optimal operating parameters for the Oak Ridge Spallation Neutron Source superconducting linear accelerator

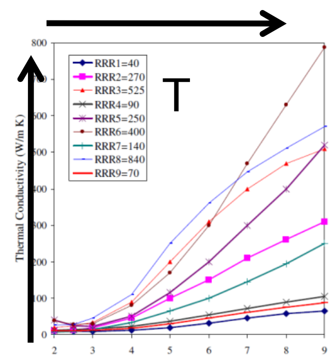
Sang-ho Kim and Isidoro E. Campisi

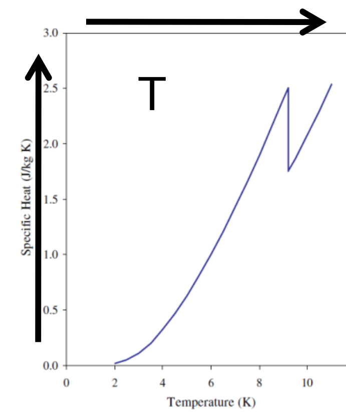




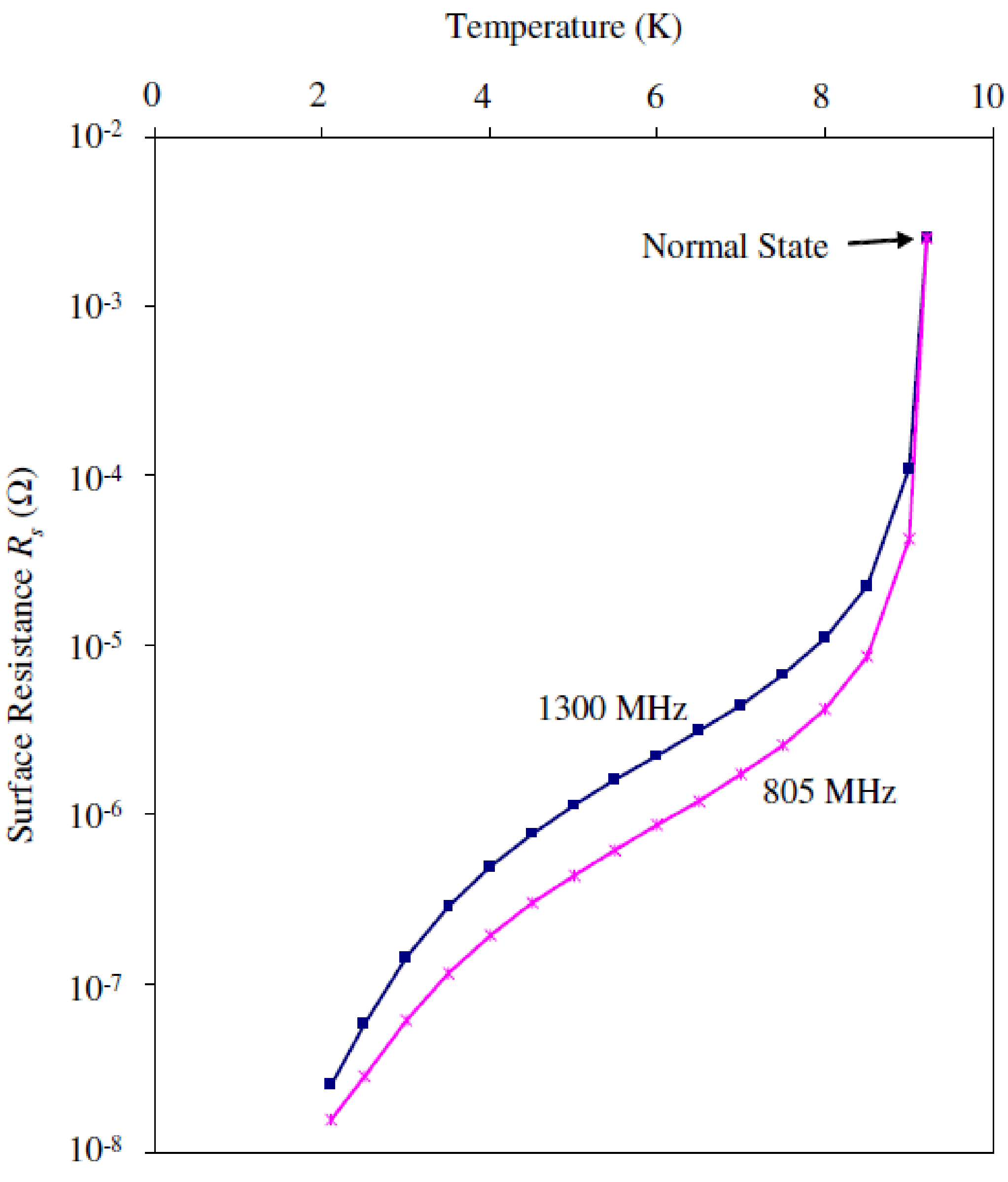




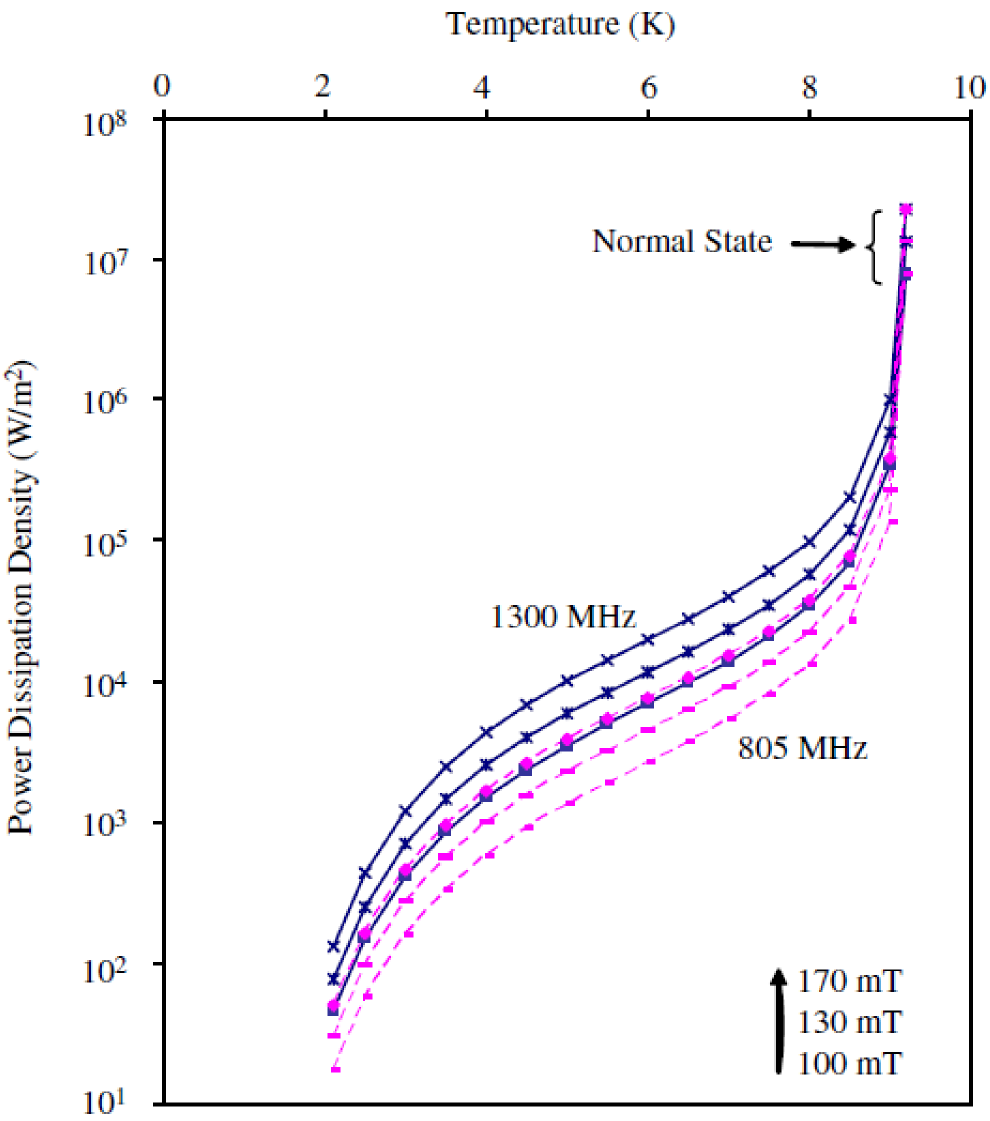




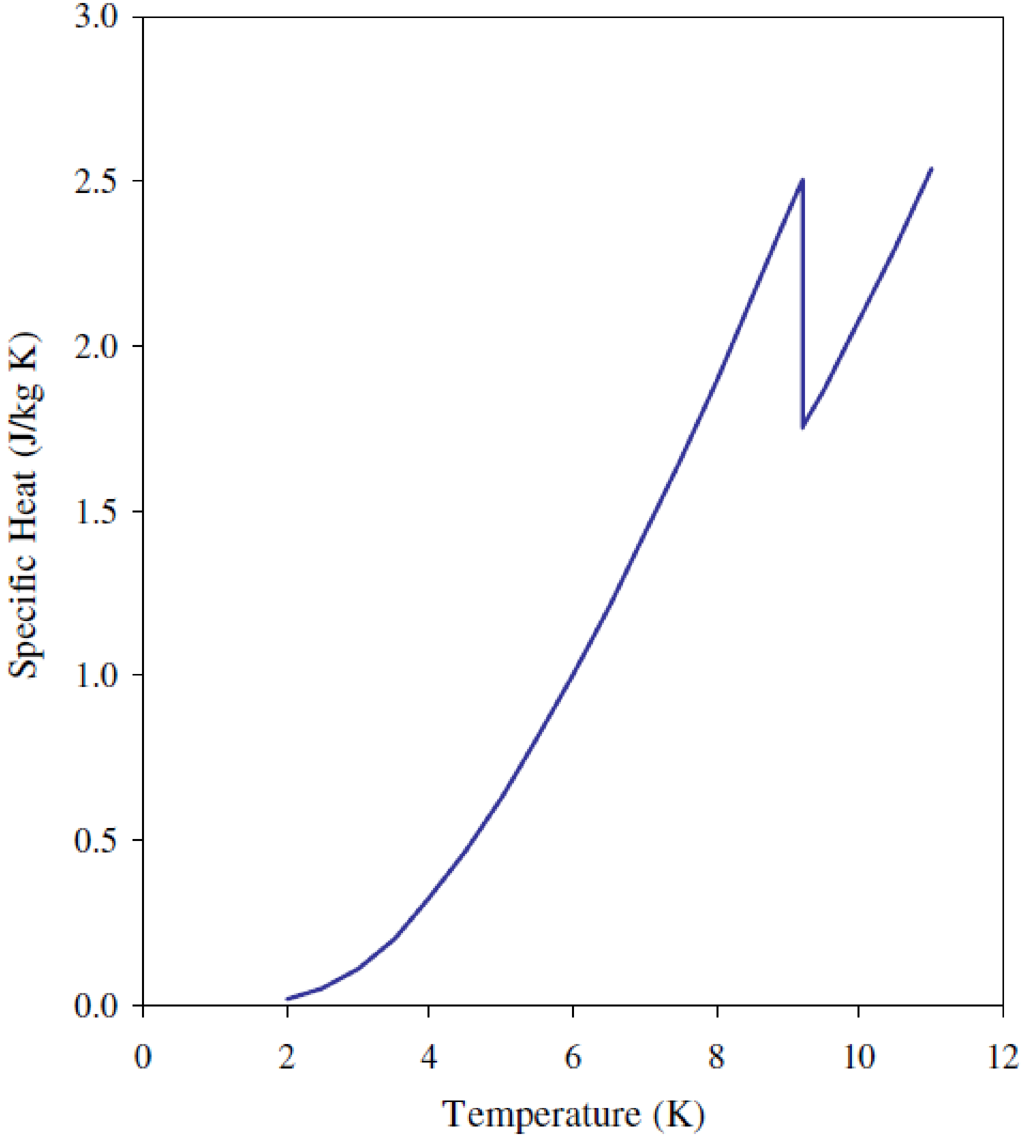
Surface Resistance vs Temperature



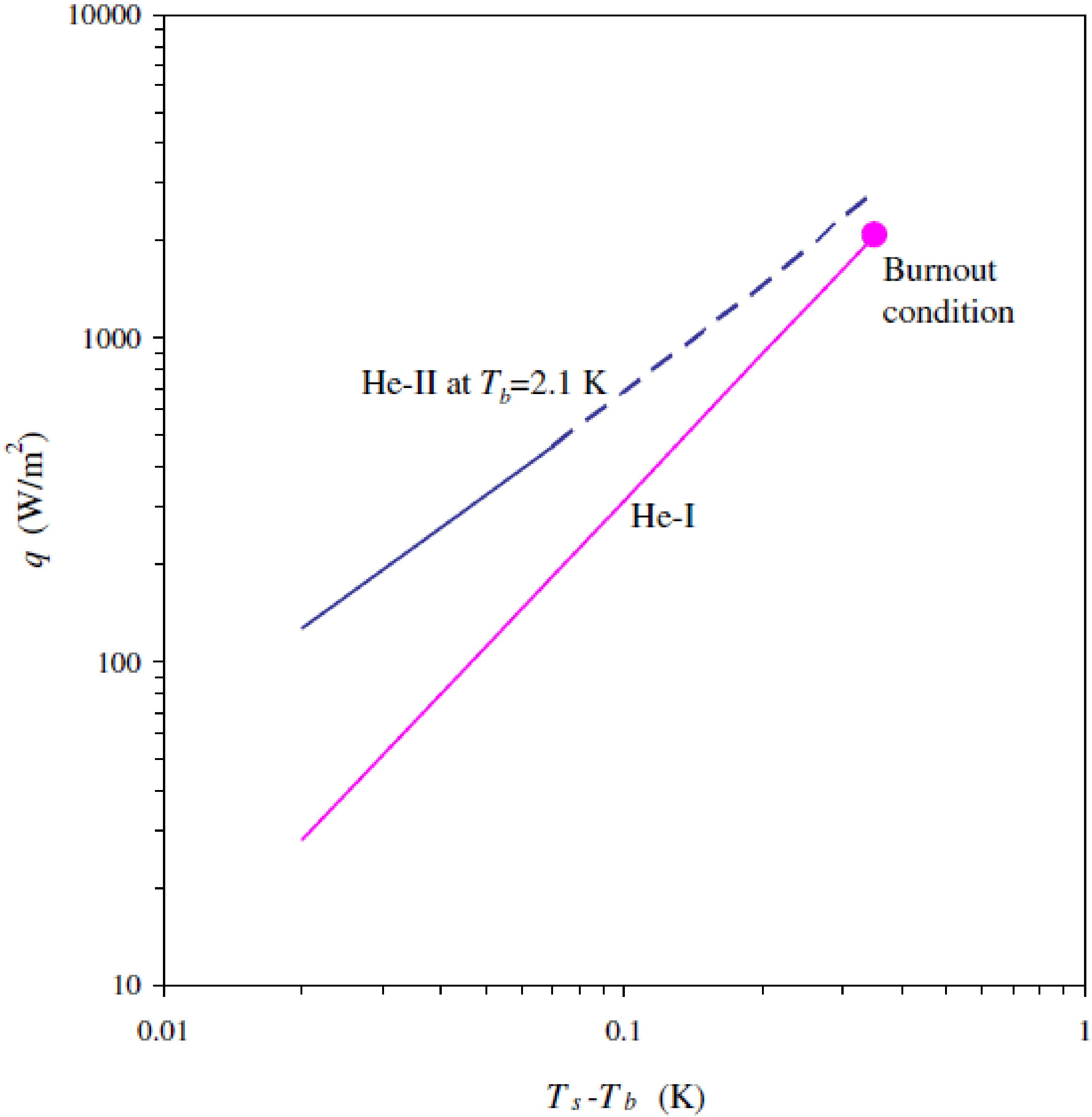
Power Dissipation vs Temperature



Niobium Specific Heat vs Temperature

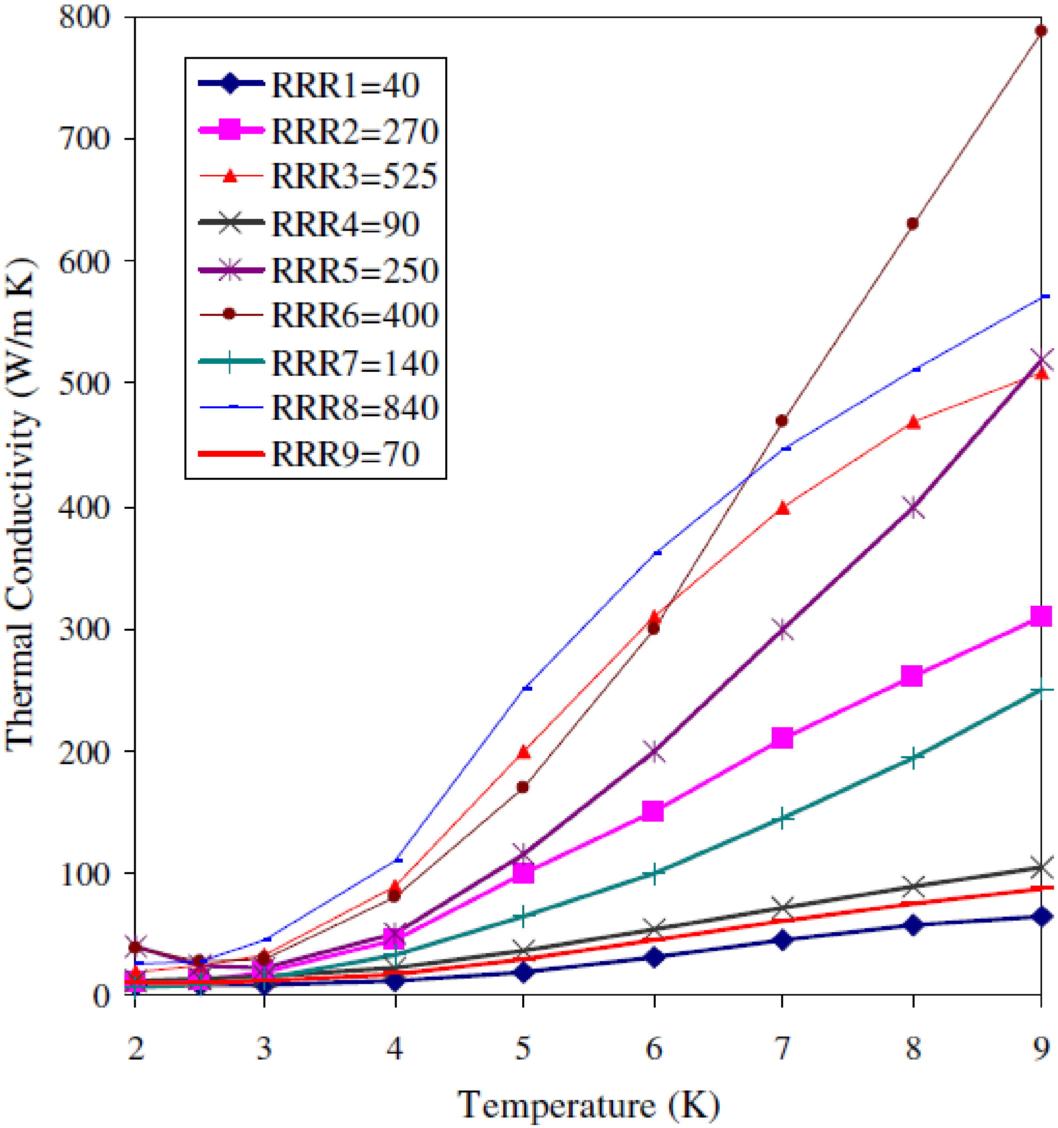


Heat Transfer Density (Bath-Niobium)

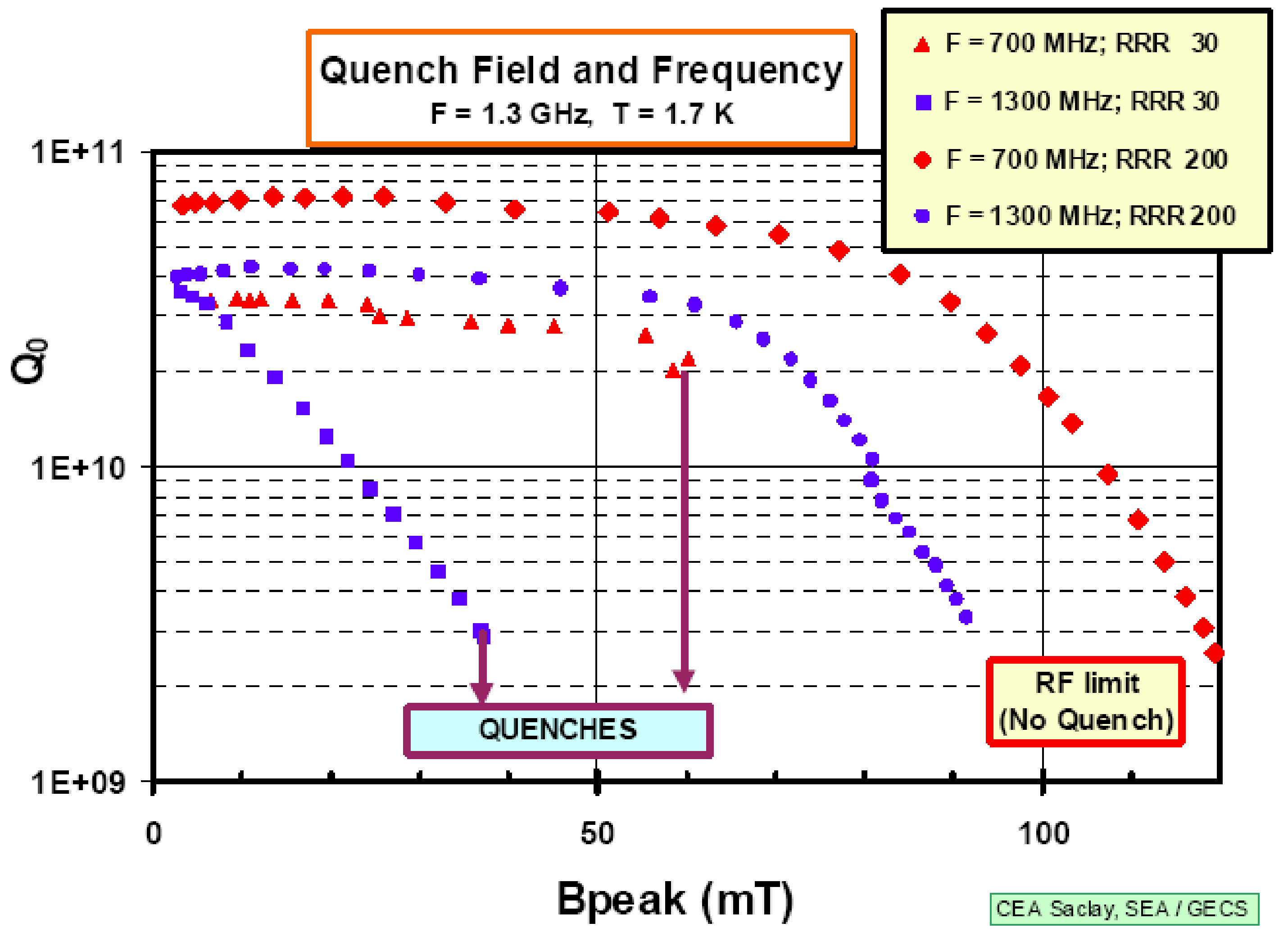


- Tb –Helium Bath
- Ts – Niobium Surface Helium side
- q- heat density

Niobium Thermal Conductivity vs Temperature



Thermal Breakdown



Thermal Conductivity of Nb

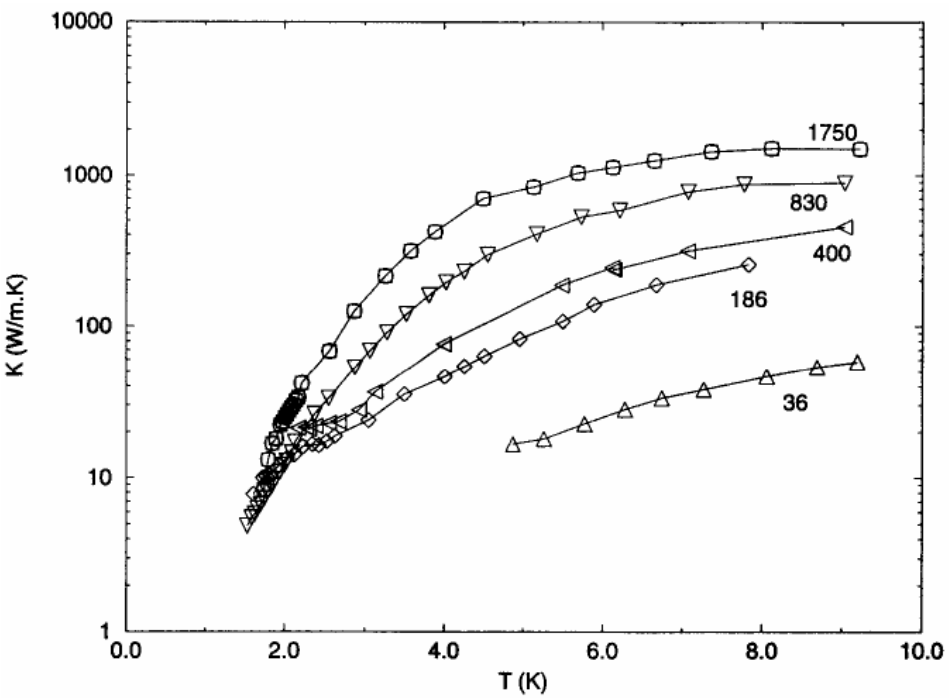
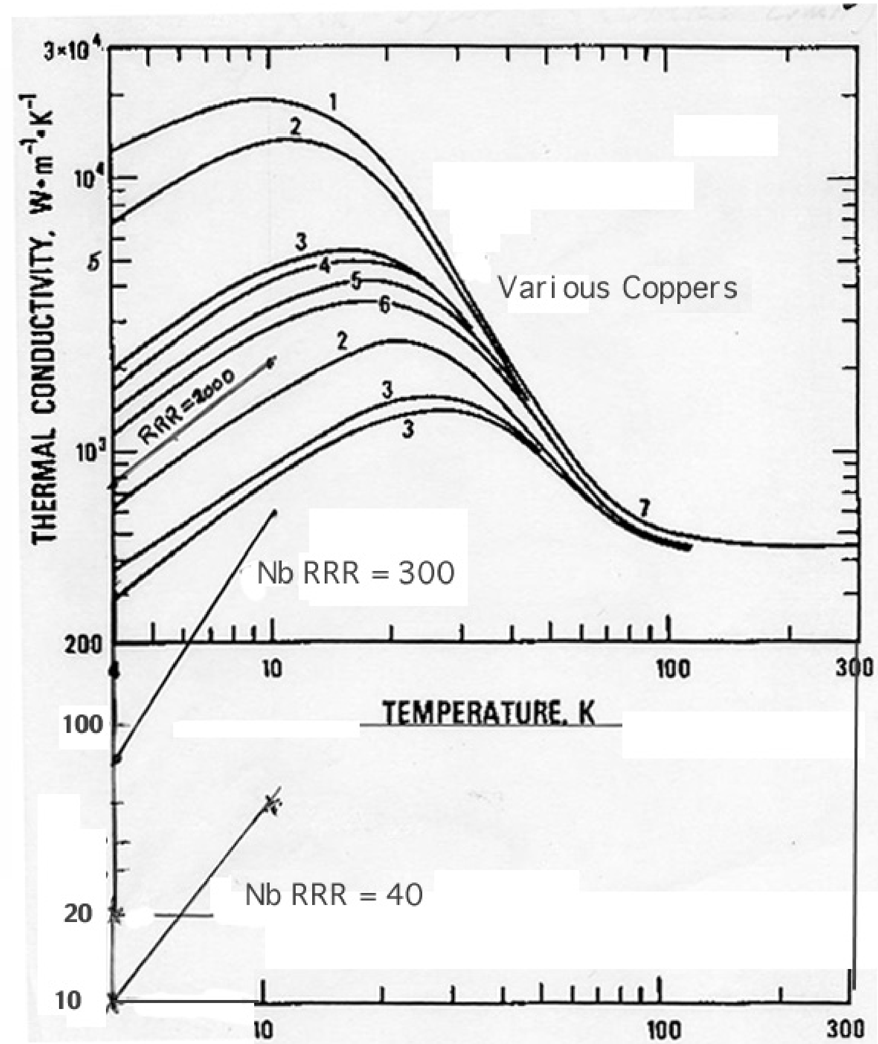


Fig. 3 The thermal conductivity of niobium as a function of temperature, for various RRR values.



Residual Resistance Ratio

RRR is the ratio of the resistivity at 300K and 4.2K

$$RRR = \frac{r\,(300K)}{r\,(4.2K)}$$

At normal conducting and cryogenic state

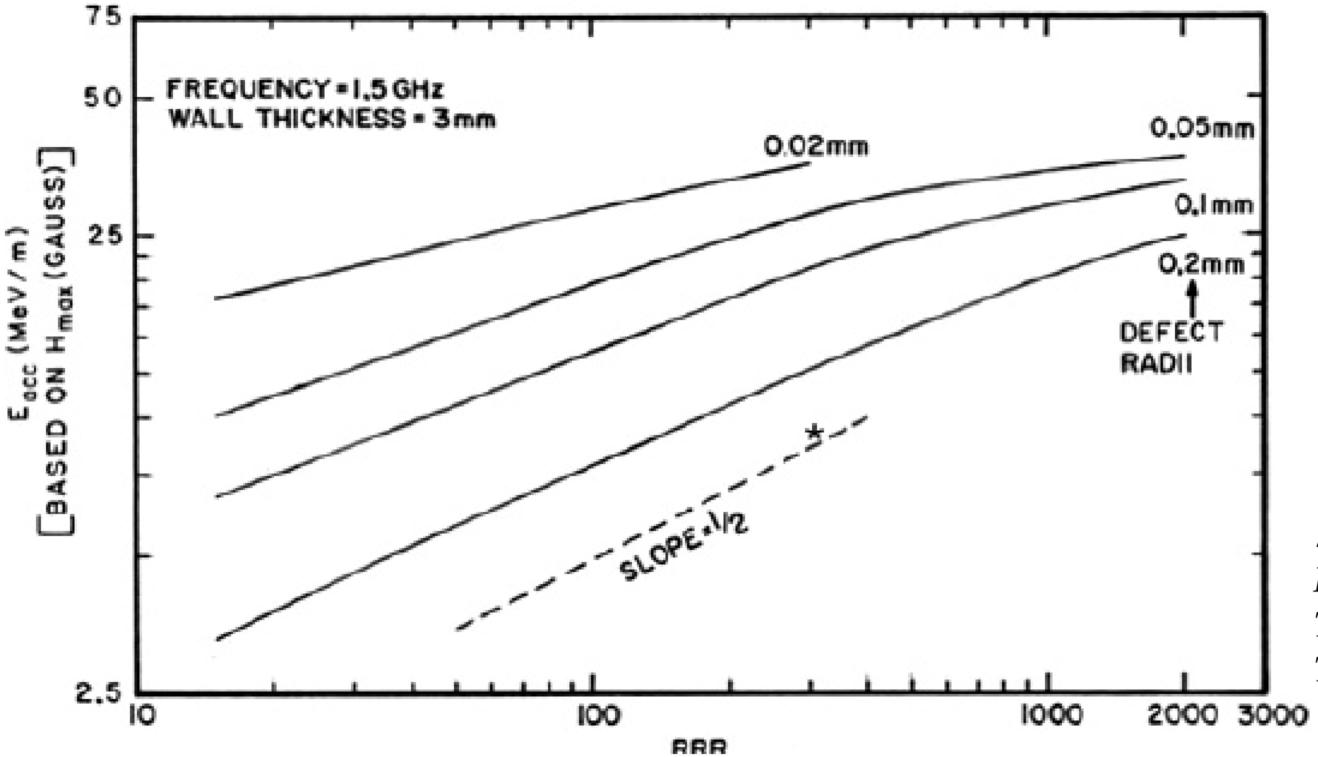
RRR is related to the mean free path.

For Nb: $l(T = 4.2K) \text{ » } 27\ RRR\ (\text{Å})$

RRR is related to the thermal conductivity

For Nb: $l\ (T = 4.2K) \text{ » } RRR/4\ (\text{W. m}^{-1}\text{. K}^{-1})$

Thermal Breakdown



Breakdown field given by (very approximately):

$$H_{tb} = \sqrt{\frac{4k_T(T_c - T_b)}{r_d R_d}}$$

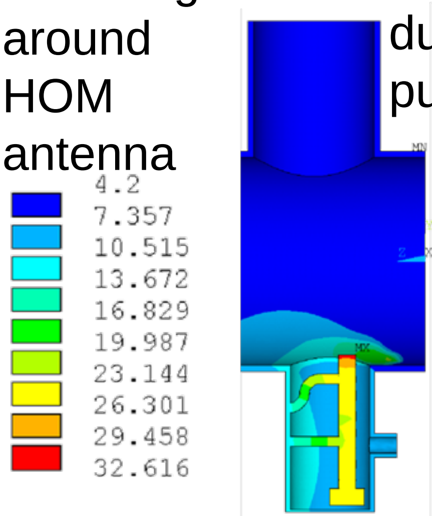
κ_T: Thermal conductivity of Nb
R_d: Defect surface resistance
T_c: Critical temperature of Nb
T_b: Bath temperature

Quenching pattern examples in the end group

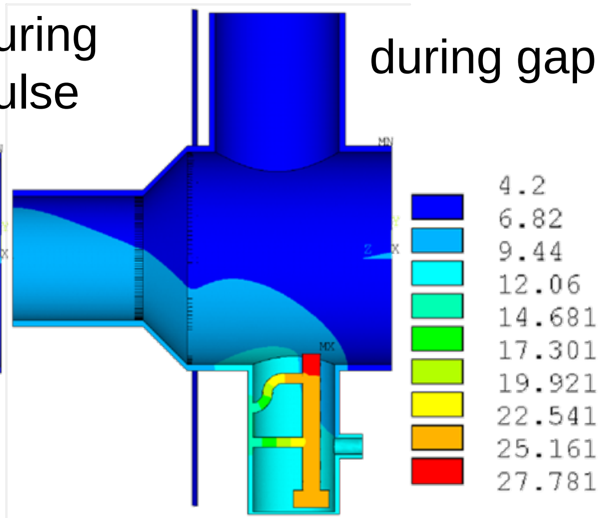
Kim ORNL

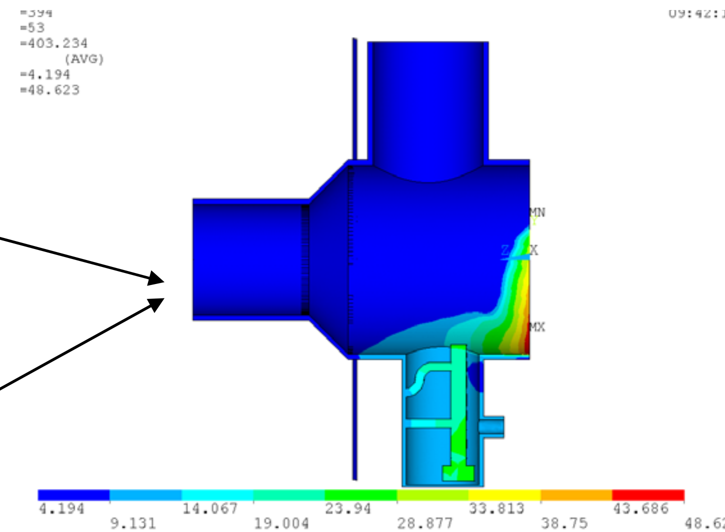
e-loadings around HOM antenna

during pulse

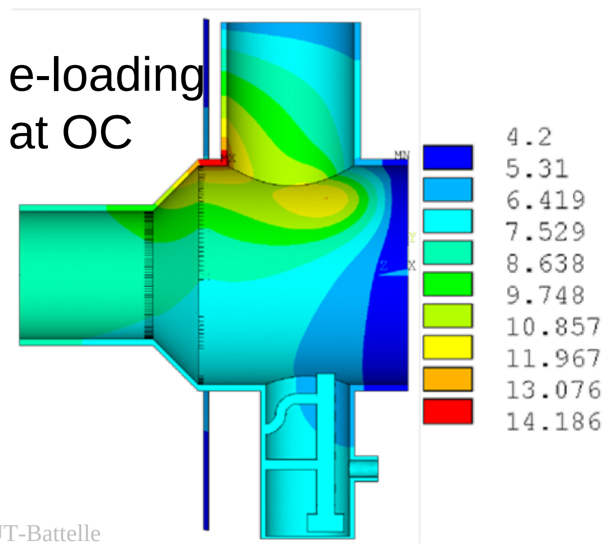


during gap



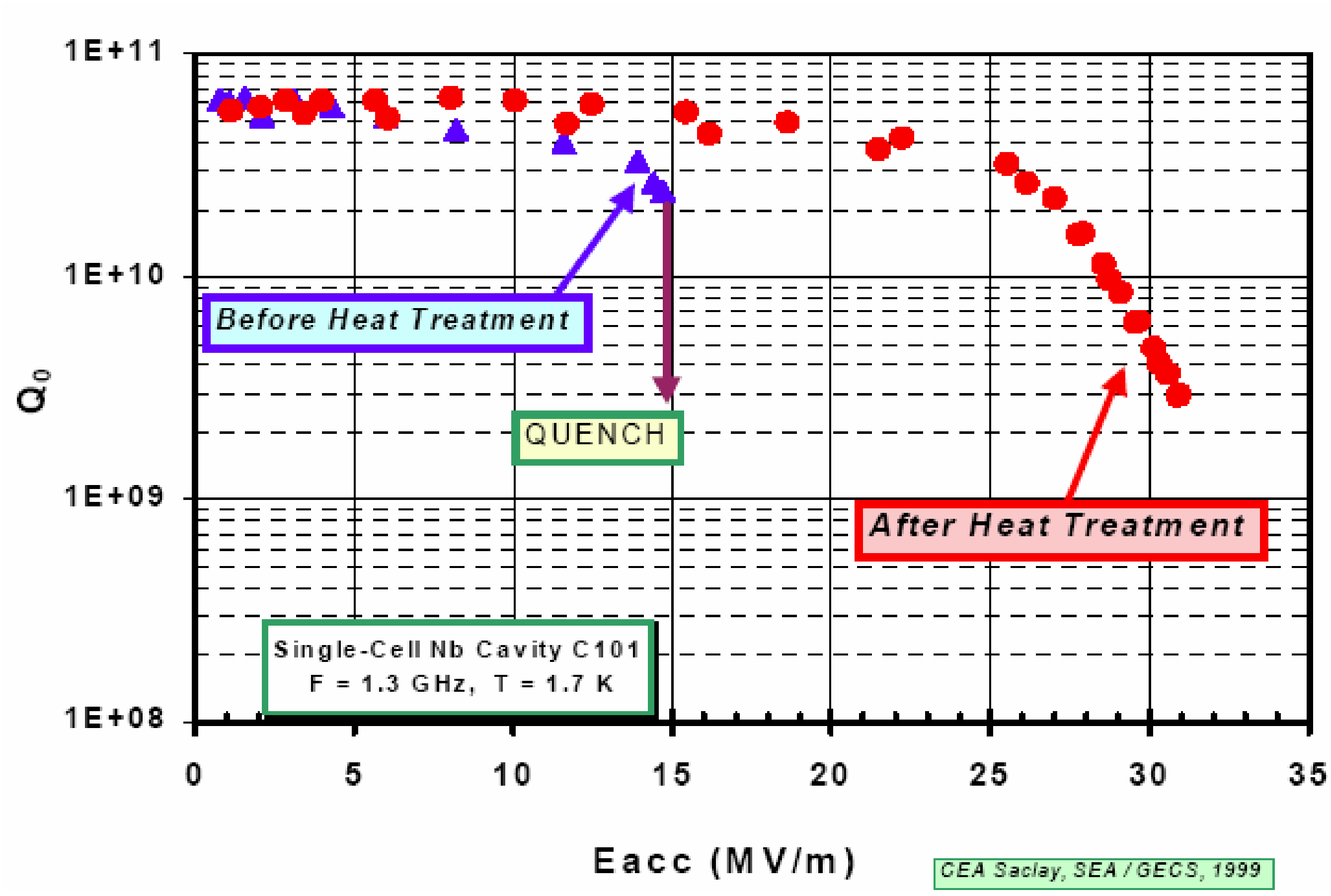


e-loading at OC

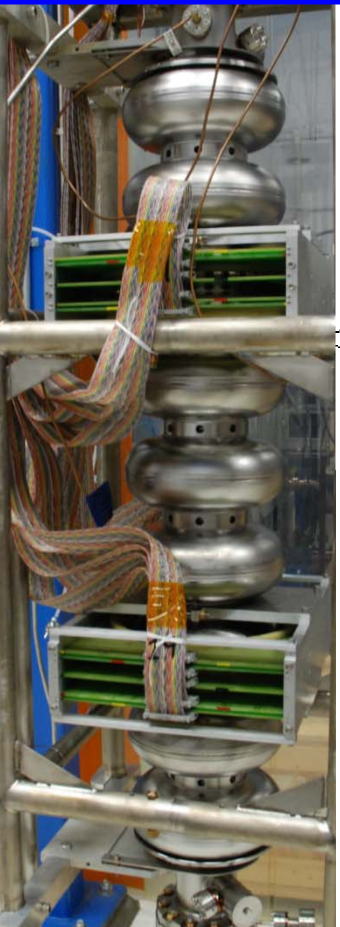


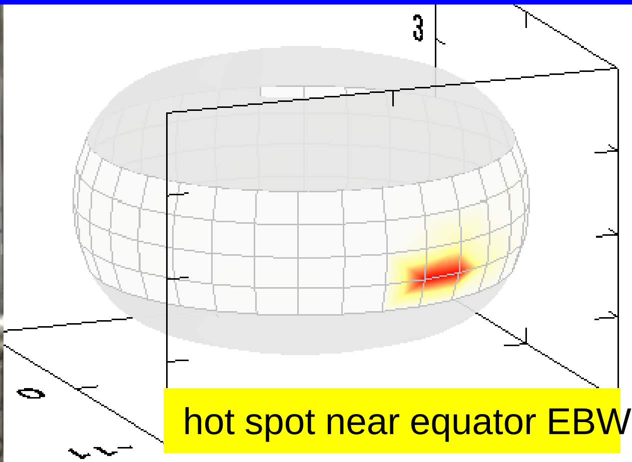
Low RRR & long path to the thermal sink
→Thermal margin is relatively small,
→Intermediate stage at the end-group
→Results in thermal quench/gas burst

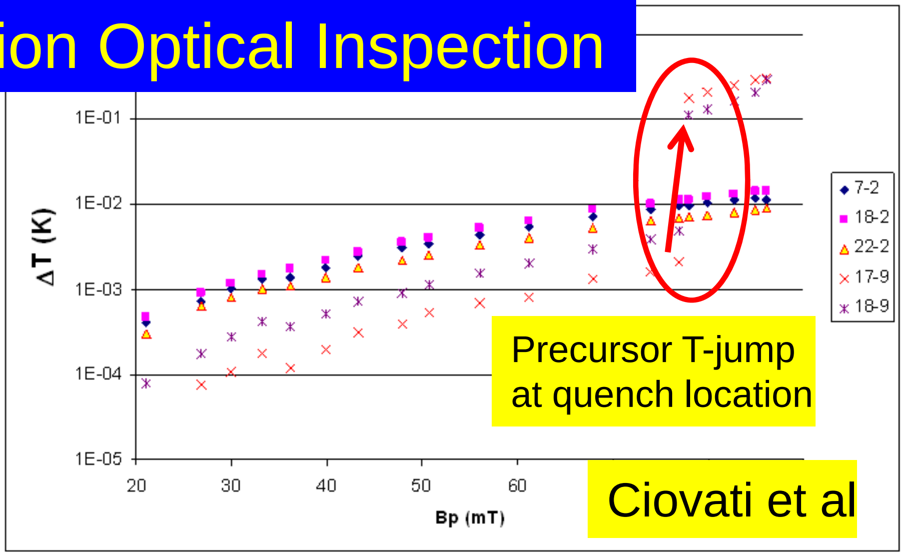
Thermal Breakdown

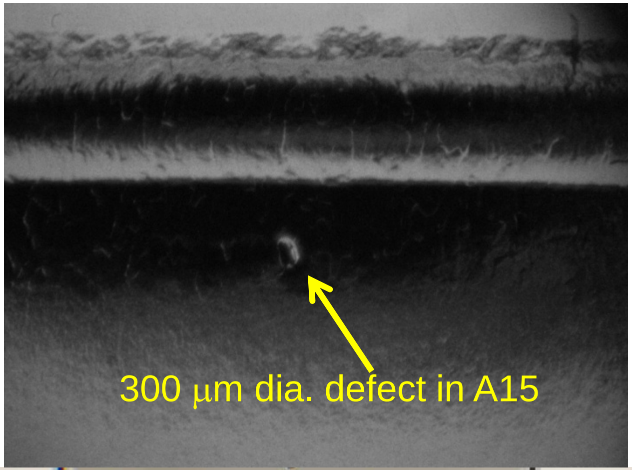


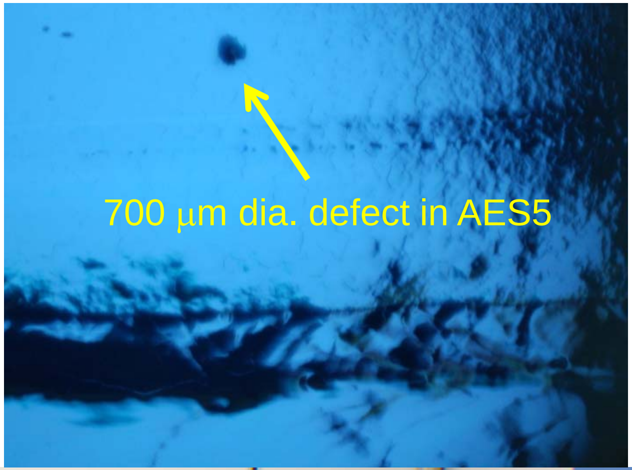
JLab T-mapping and High-Resolution Optical Inspection

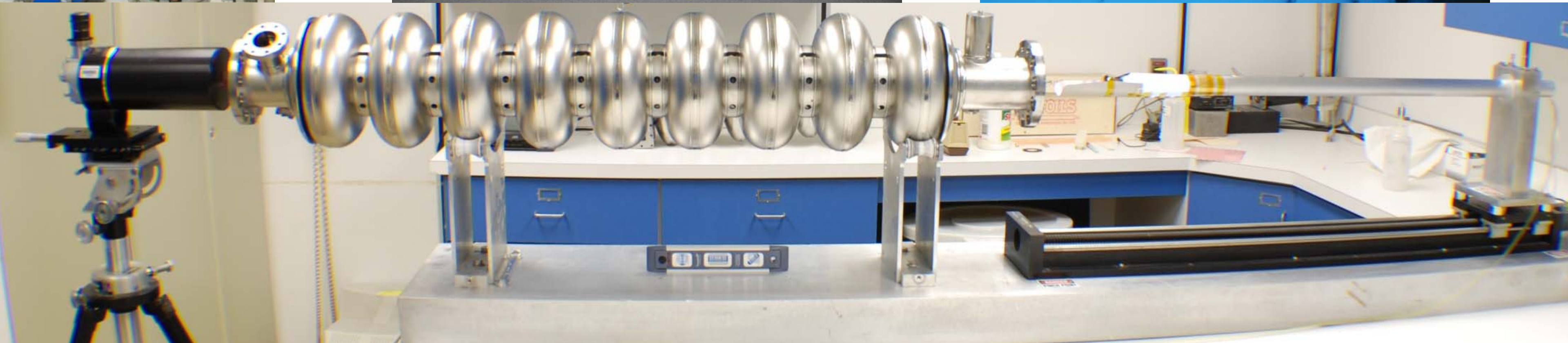




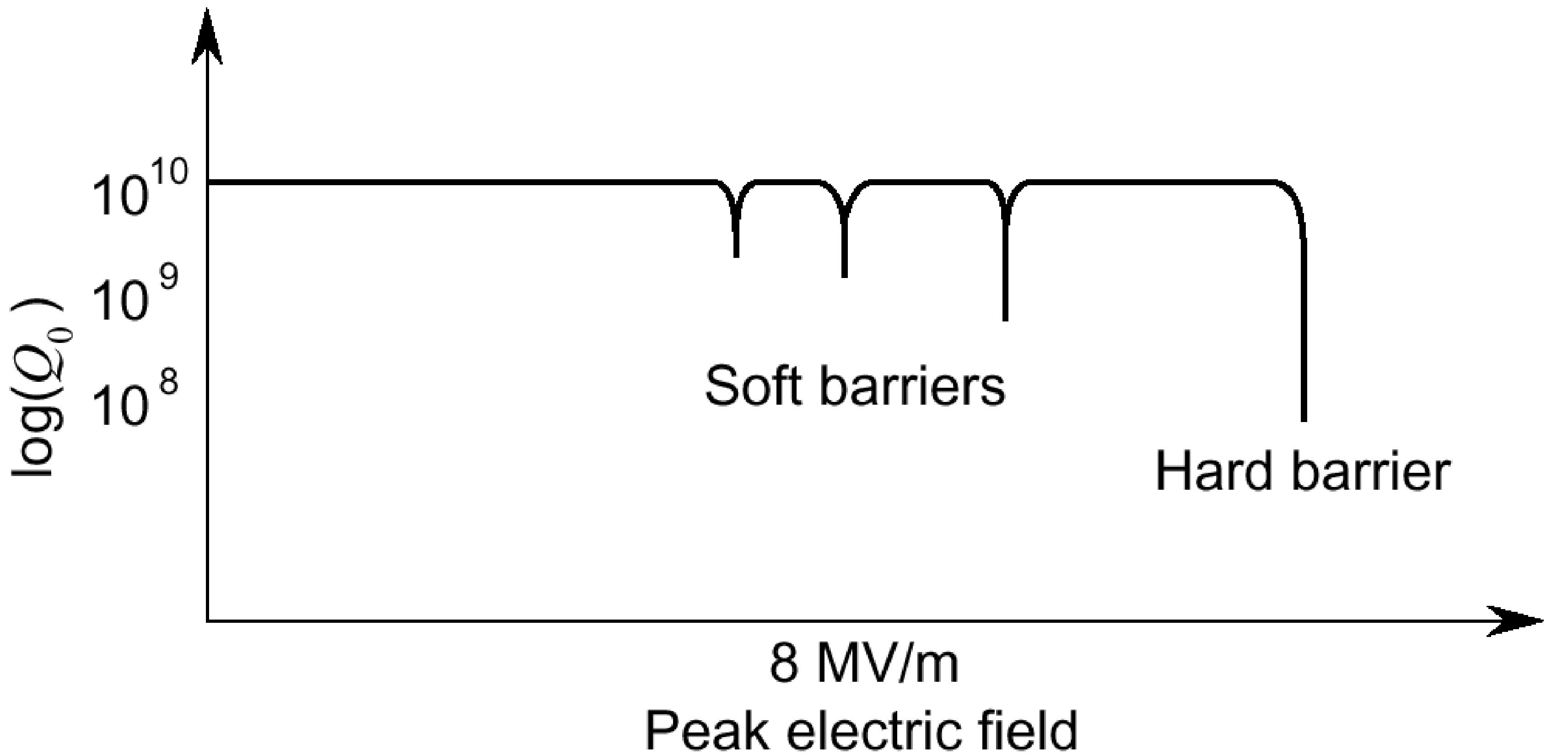




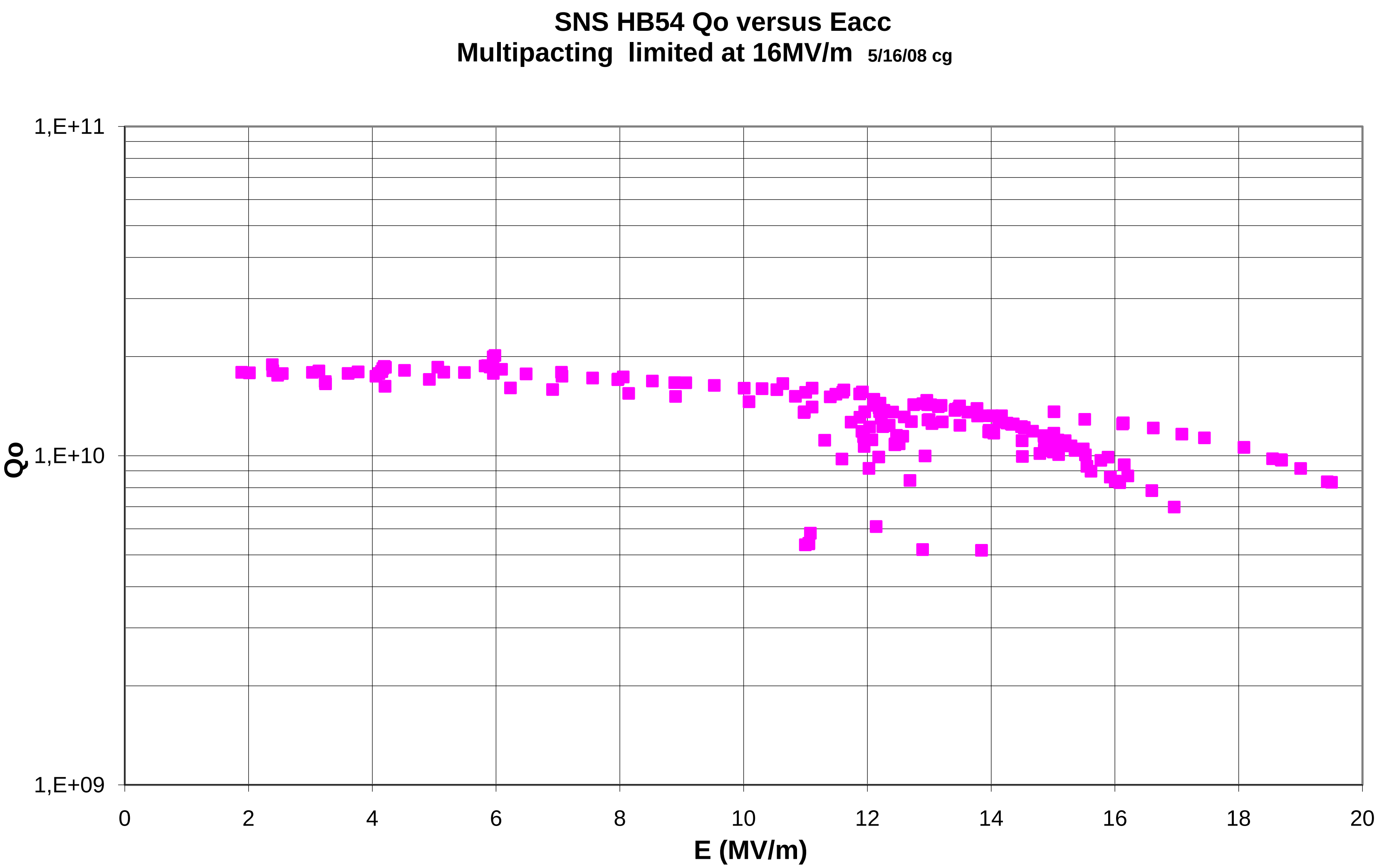




Multipacting



Multipacting

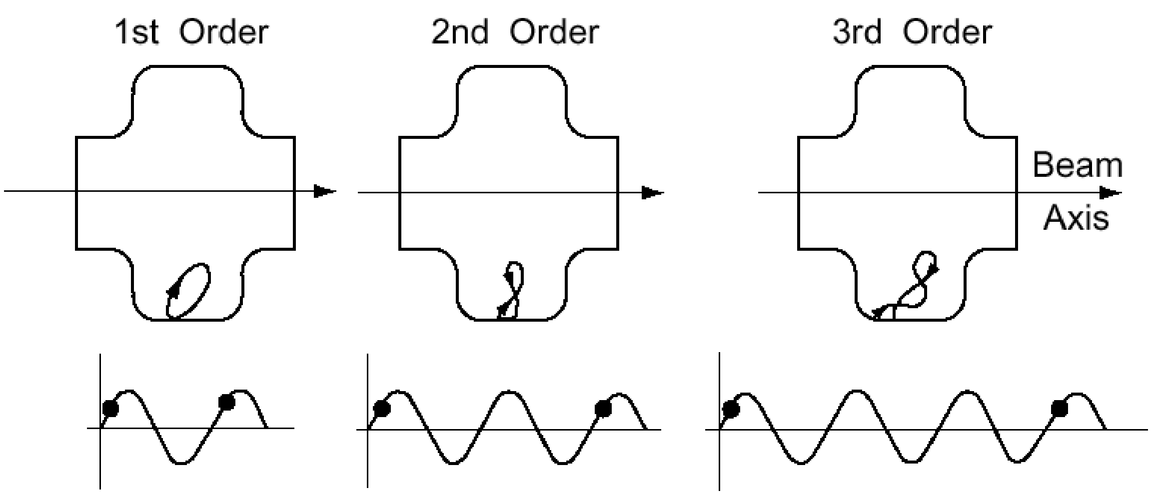


Multipacting

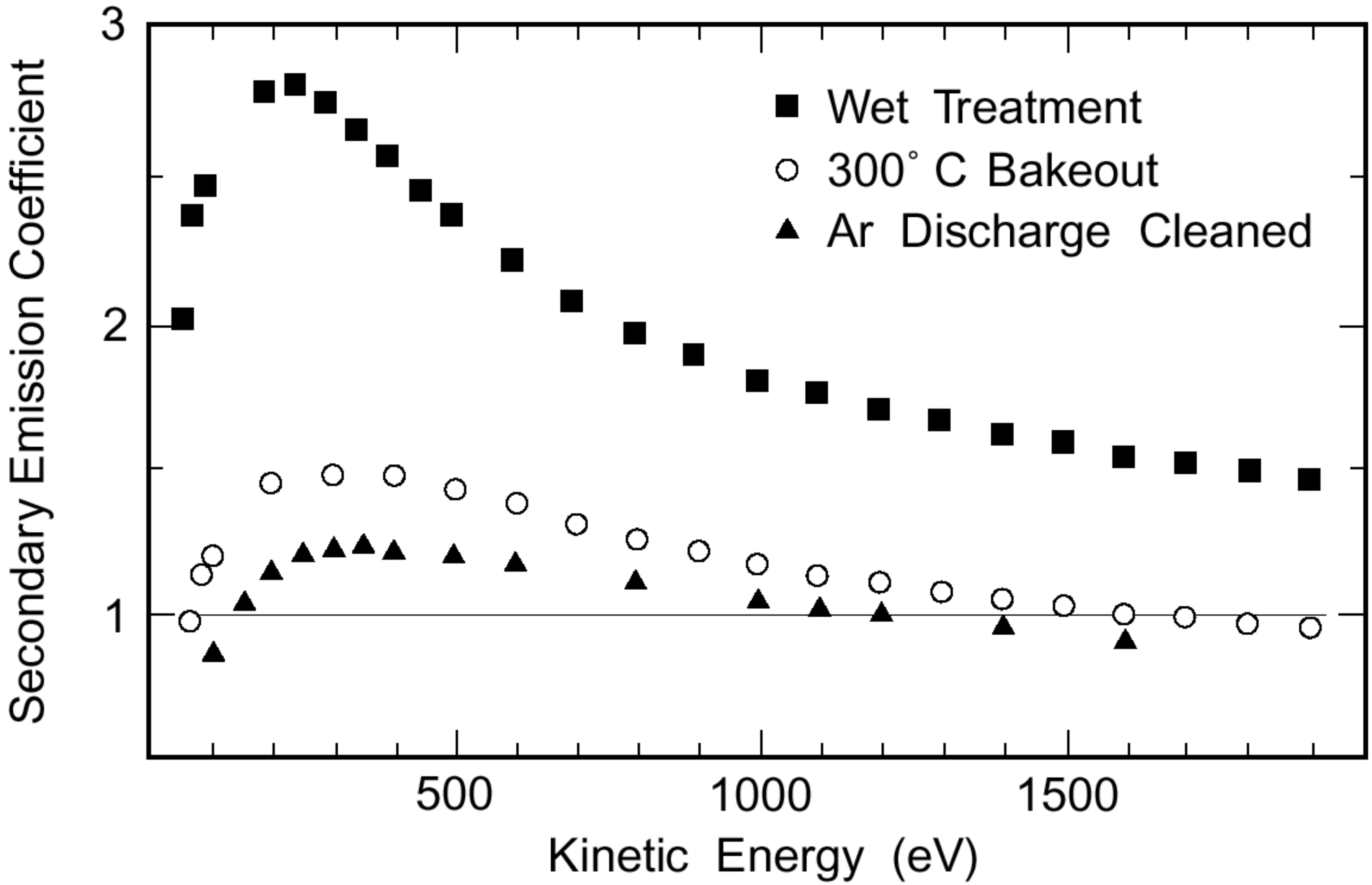
Multipacting is characterized by an exponential growth in the number of electrons in a cavity

Multipacting requires 2 conditions:

- Electron motion is periodic (resonance condition)
- Impact energy is such that secondary emission coefficient is >1



Multipacting



Secondary Emission in Niobium

STUDIES OF MULTIPACTING IN AXISYMMETRIC CAVITIES FOR MEDIUM-VELOCITY BEAMS*

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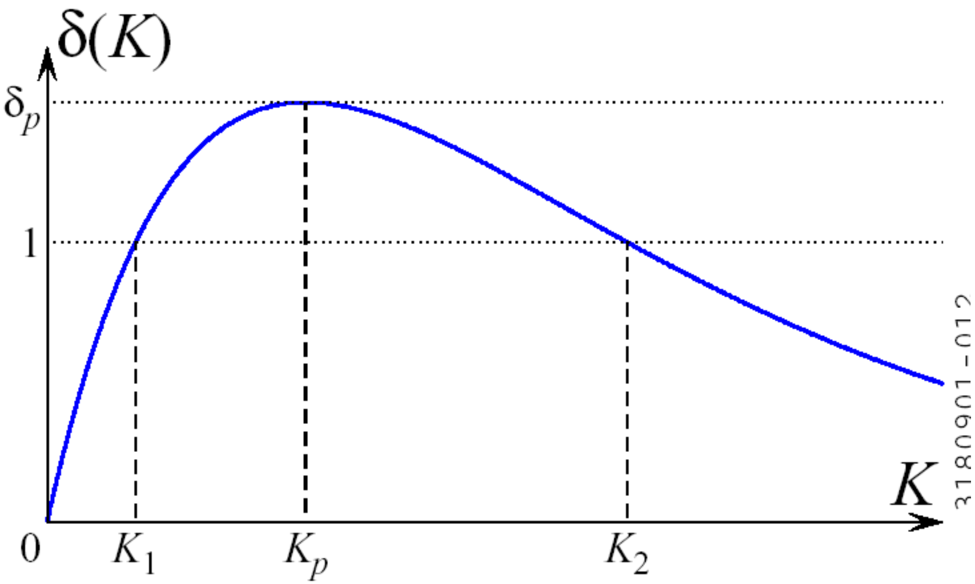
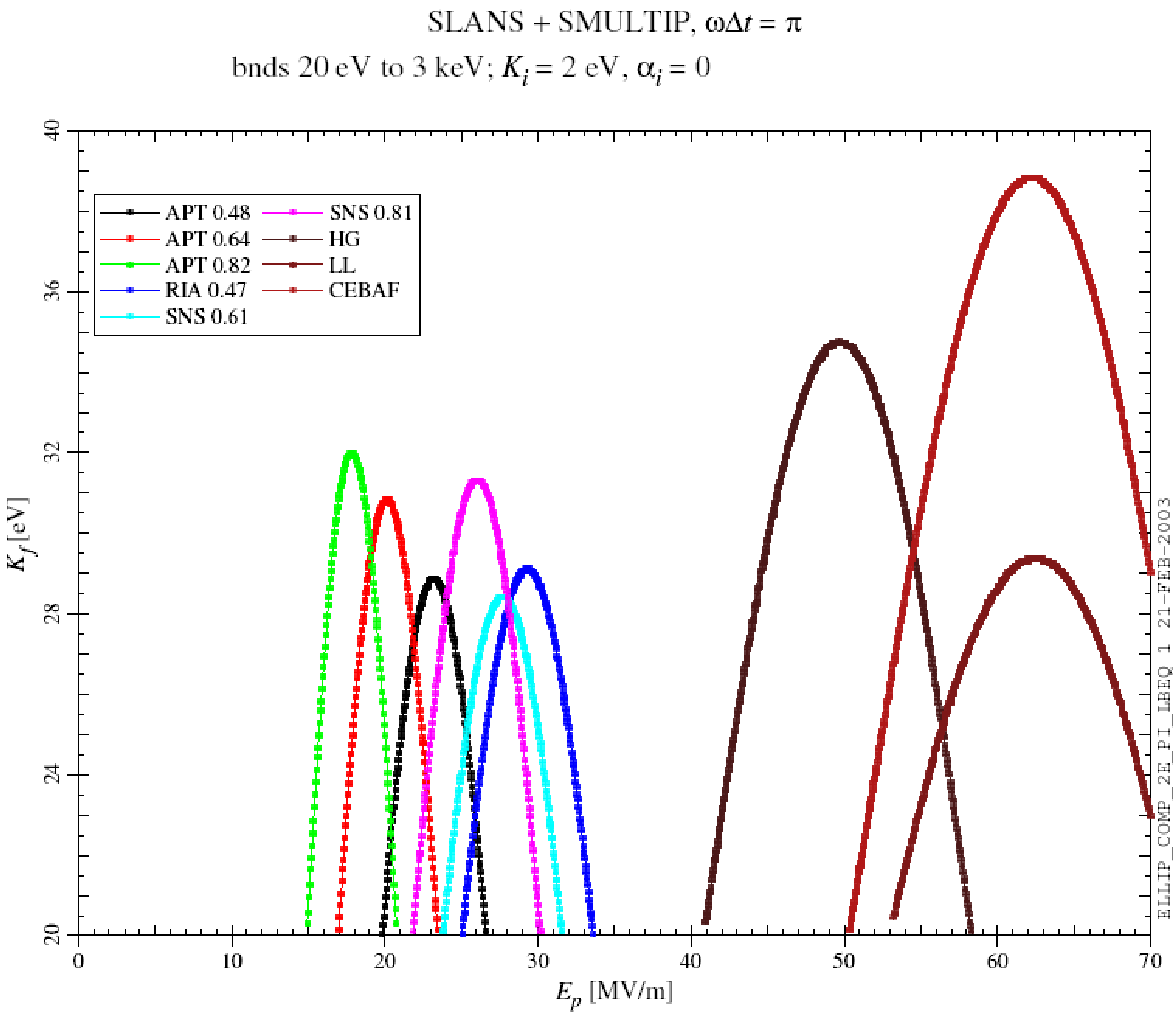
National Superconducting Cyclotron Lab, Michigan State University, East Lansing, Michigan
F. Krawczyk
Los Alamos National Laboratory, Los Alamos, New Mexico
H. Padamsee
Laboratory of Nuclear Studies, Cornell University, Ithaca, New York

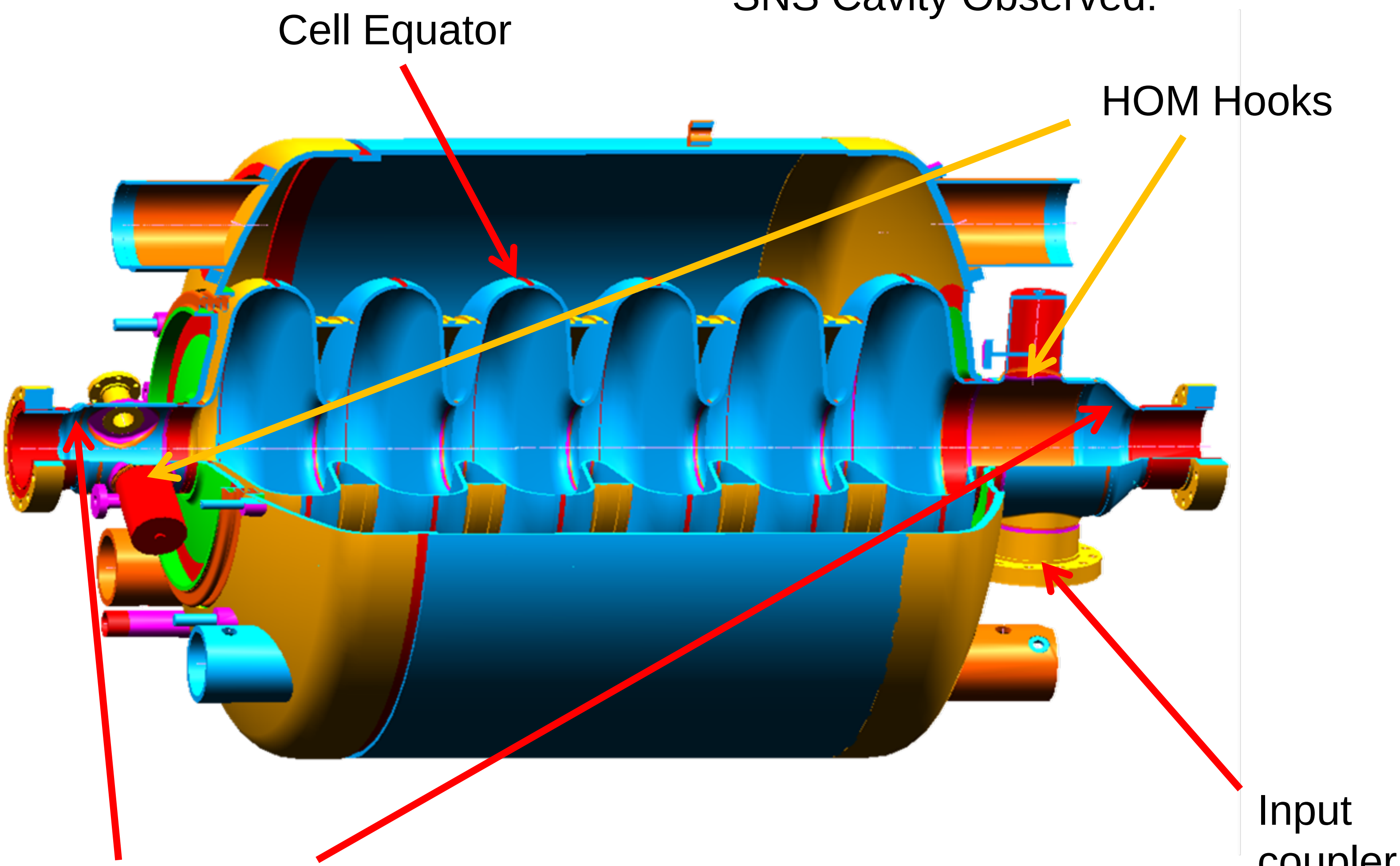


Condition	K_1	K_2
high SEY	$\sim$ 27 eV	$\gtrsim$ 2000 eV
typical SEY	$\sim$ 40 eV	$\sim$ 1000 eV
low SEY	$\sim$ 150 eV	$\sim$ 750 eV

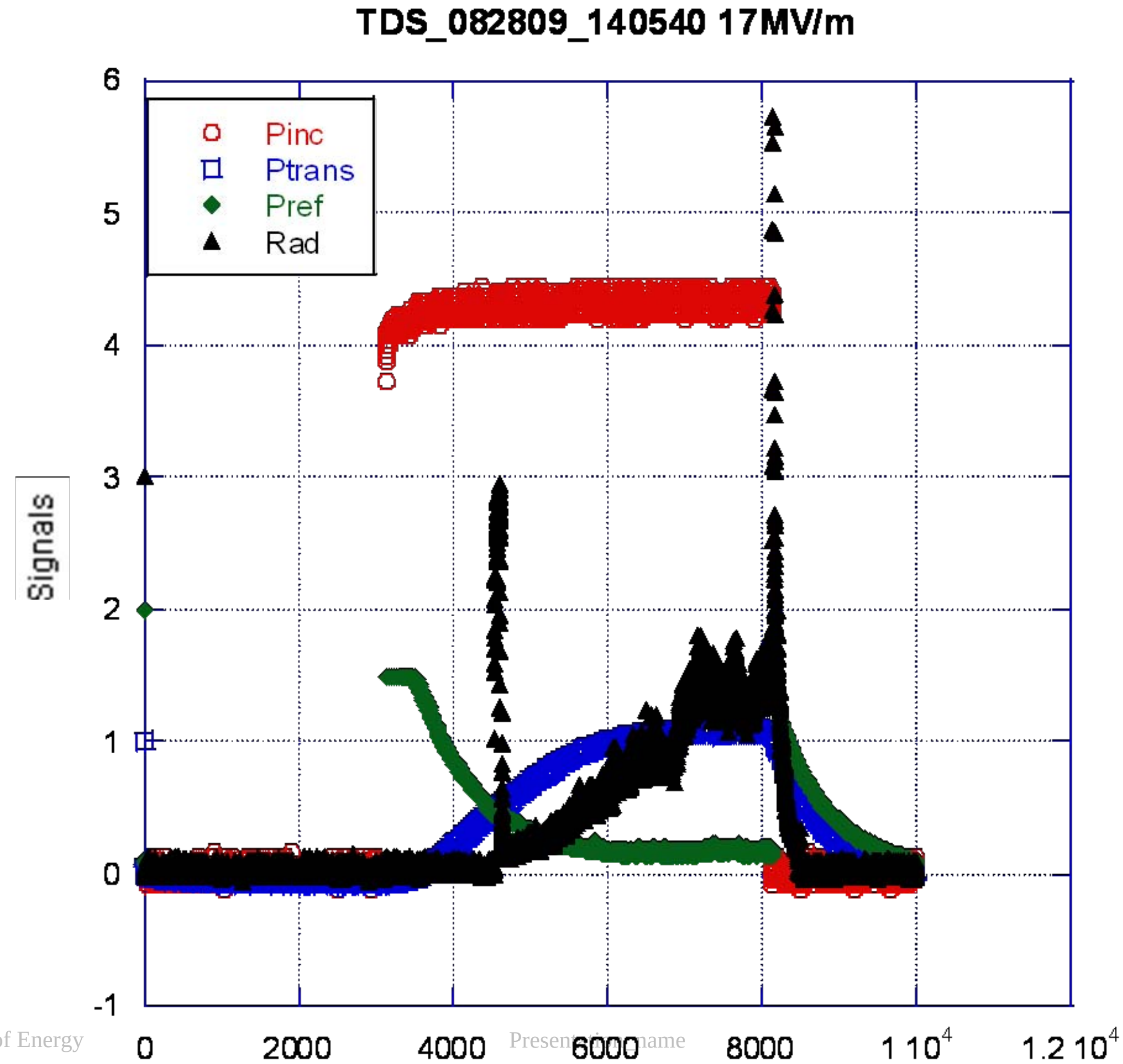

SLANS + SMULTIP, ωΔt = π
bnds 20 eV to 3 keV; K_i = 2 eV, α_i = 0
APT 0.48
APT 0.64
APT 0.82
RIA 0.47
SNS 0.61
SNS 0.81
HG
LL
CEBAF
K_f [eV]
E_p [MV/m]
20
24
28
32
36
40
0
10
20
30
40
50
60
70
ELLIP_COMP_2E_PI_LBEQ 1 21-FEB-2003

More Then Just Cell Mulitpacting

4 MP Locations in the SNS Cavity Observed:

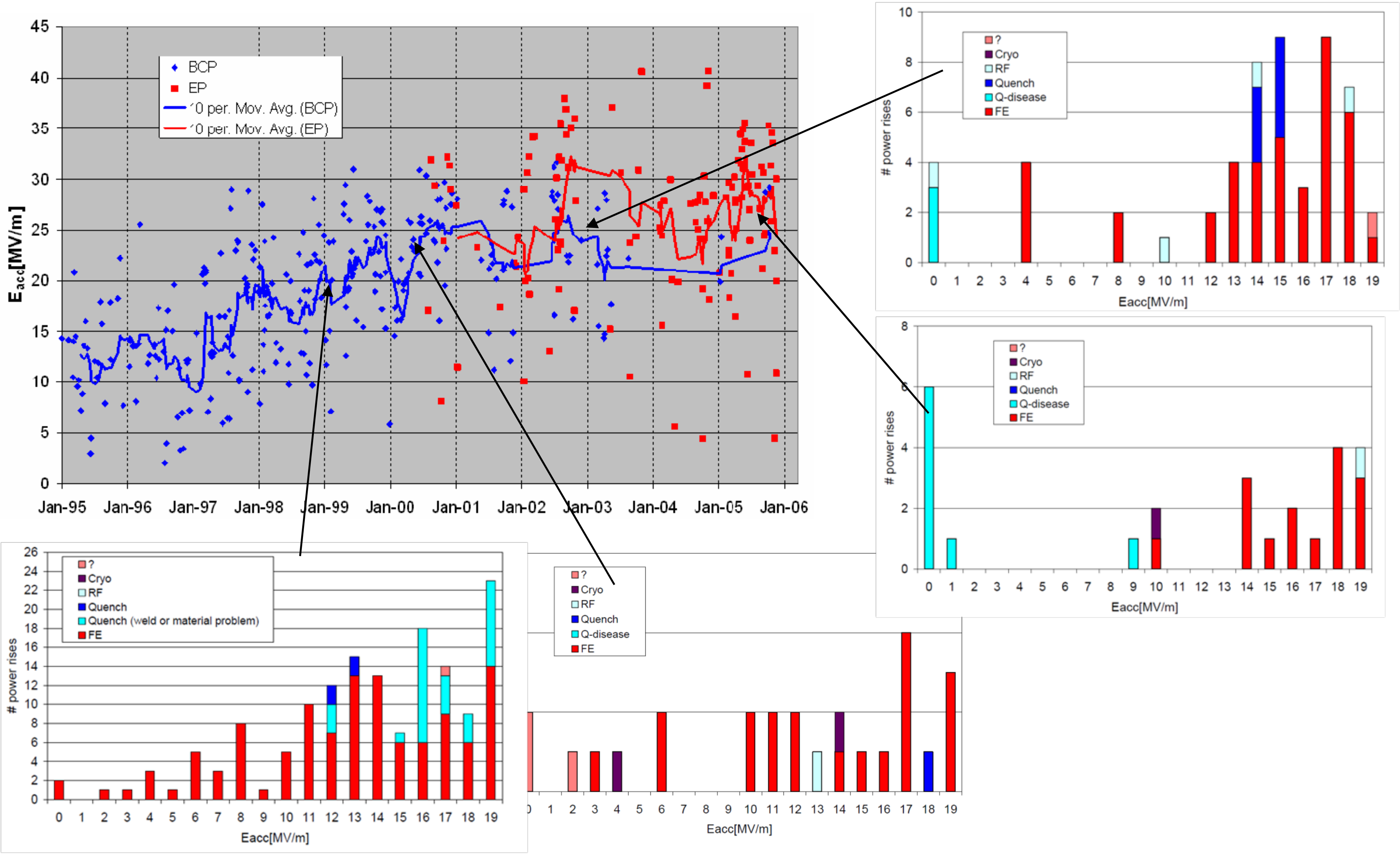


Separating MP and Field Emission Contributions to X-rays Observed



Performance History

DESY cavity experience



L. Lijie's summary of DESY cavity databank, DESY, 2006

Performance from my experience

- In the early 1990's gradients were mainly limited around15MV/m vertical test and 10MV/m in machines
  - Field emission dominated the performance
  - Preparation procedure
    - Bulk removal BCP, RF tuning, Degreasing, Final light BCP, DI water rinsing, Assembly
- By the mid 1990's high pressure rinse was established as a new cleaning method to reduce field emission
- Early 2000
  - Gradients had reached 20-25 MV/m vertical test which correlated to machine performance as well
  - Electropolish chemistry was reintroduced and showed gradients could be pushed to 30-35MV/m
- Today the focus is on reproducibility with occasional 40MV/m performances

Standard Process Generalized

- Heavy chemical etch (EP or BCP)
  - Removal of damaged surface layer (100-150um) caused by fabrication and handling
- Removal of surface contamination
  - Ultrasonic cleaning of surface with detergent and DI water, heated and or
  - Alcohol rinse of surface to remove chemical residues
- Heat treatment (600-800C in vacuum furnace)
  - Removes hydrogen from the bulk niobium to reduce the risk of Q-disease
- RF tuning and mechanical inspection
  - Last chance to prepare cavity for operational use
  - Field profile, calibration of test probes, check mechanical structure

Standard Process Generalized cont.

- Removal of surface contamination
  - Ultrasonic cleaning of surface with detergent and DI water, heated
- Light chemical etch (EP)
  - Remove any risk from damage during handling and furnace contamination
- Removal of surface contamination (chemical residues)
  - Ultrasonic cleaning
  - Alcohol rinse
- High pressure rinse (UPW) + Class 10 drying of cavity
  - Reduction of field emission sources, surface particulates
  - At least two passes over entire surface

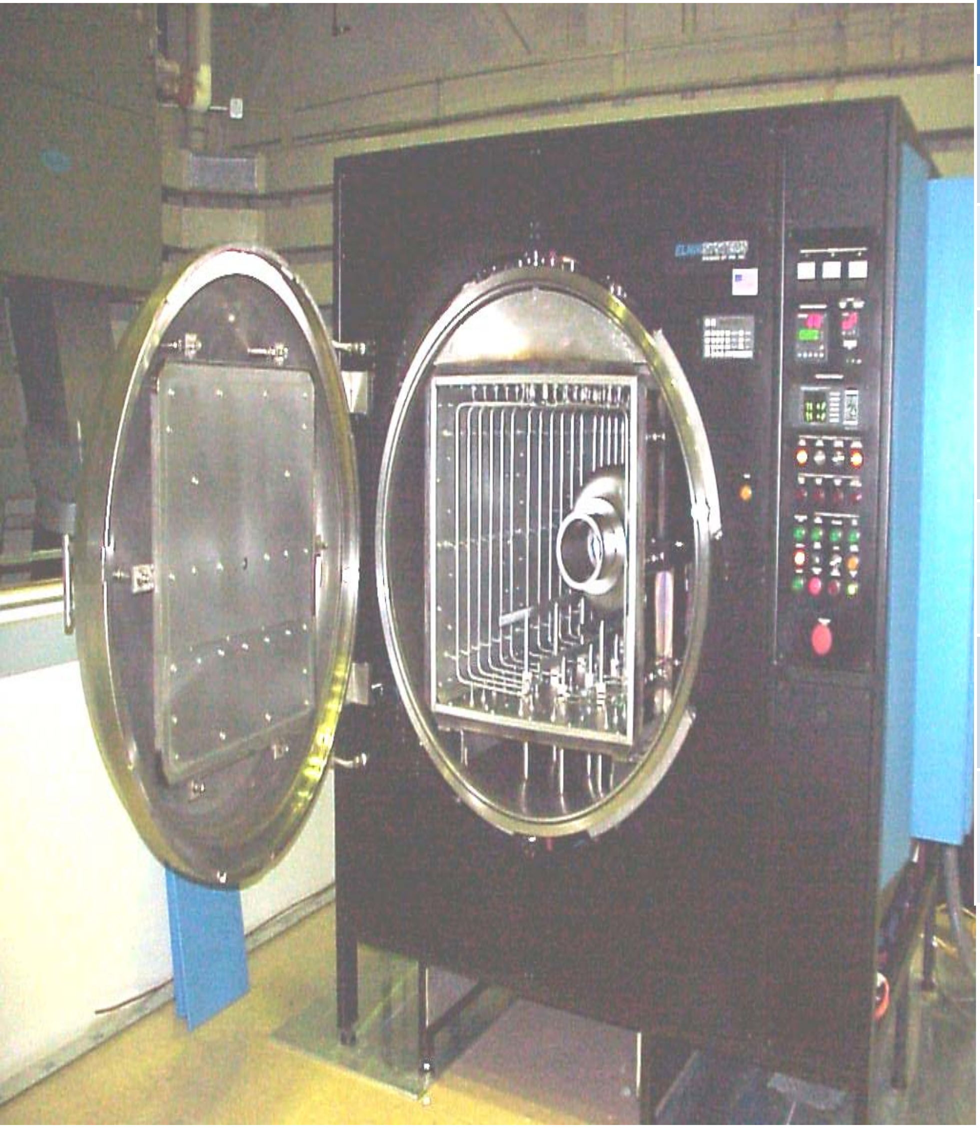
Standard Process Generalized cont.

- Assembly of subcomponents (most hardware at this step)
  - Process of connecting subcomponents to cavity openings
  - Slow and careful steps, high level of attention to detail
  - Ionized nitrogen gas blow off (cleaning) of subcomponents and hardware
  - Assembly optimized to reduce particulate contamination into cavity surface

- High pressure rinse (UPW) + Class 10 drying of cavity
  - Last chance to clean surface and remove particulates from first assembly
  - Most critical cleaning step against field emission
  - At least two passes over entire surface

- Assembly of subcomponents (final evacuation flange)
  - Most critical assembly step no follow-up cleaning

Heat treatment (600-800C)



Details		
Temperature of hot zone	Low end 600C	Typical 800C
Vacuum	Start 1e-7 Torr	End 1e-5 Torr
Cavity cleaning	Typically - degreasing	Sometimes- Chemistry and HPR
Support structure	Moly rails or rods	
Automated controls	RGA, PLC	
Process time	6-12 hrs or more	

Small Part Ultrasonic Cleaning Stations

- Rinse tank out
- Fill with DI water
- Add Liquid Detergent
  - Liquinox
  - Micro-90
  - Few percent by volume
- Ultrasonic agitation
  - 15-60 minutes
- Remove and rinse parts with DI water
- Blow dry
  - ionized nitrogen gas
  - Laminar flow hepa air

Ultrasonic cleaning

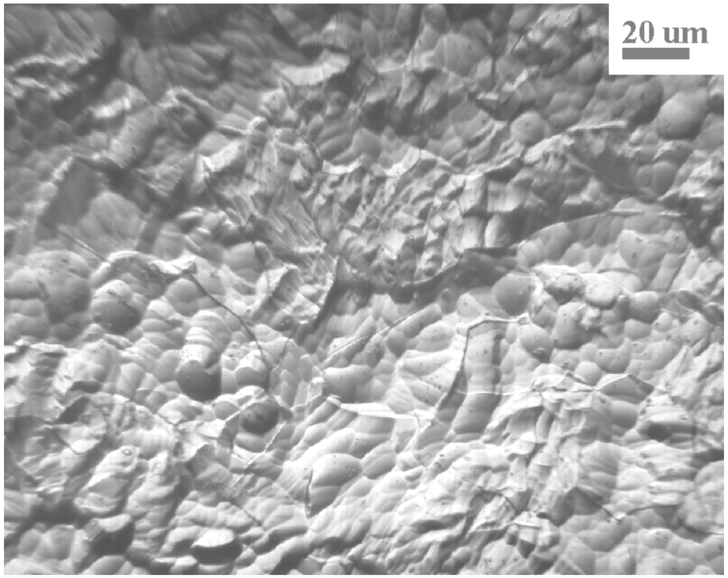
- Immersion of components in DI water and detergent medium

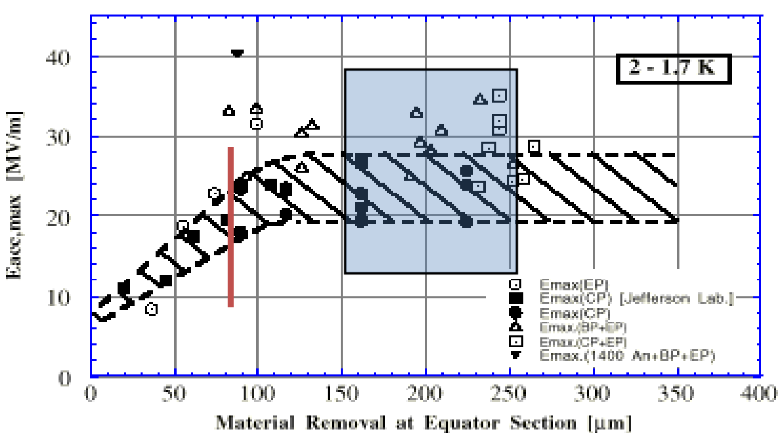
- Wave energy forms microscopic bubbles on component surfaces. Bubbles collapse (cavitation) on surface loosening particulate matter.

- Transducer provides high intensity ultrasonic fields that set up standing waves. Higher frequencies lowers the distance between nodes which produce less dead zones with no cavitation.

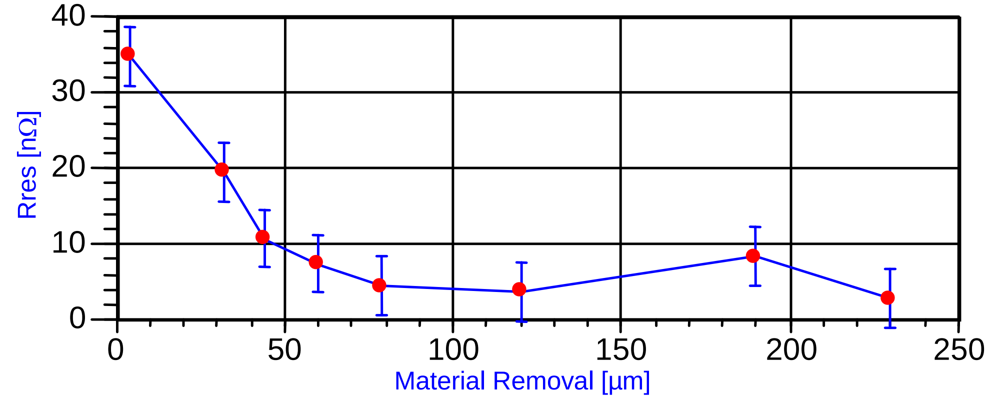
- Ultrasonic transducers are available in many different wave frequencies from 18 KHz to 120 KHz, the higher the frequency the lower the wave intensity.

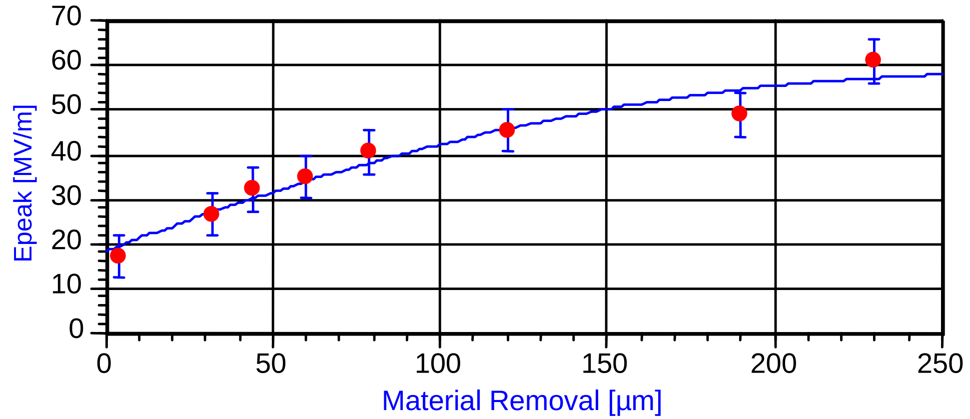
The Need For Material Removal





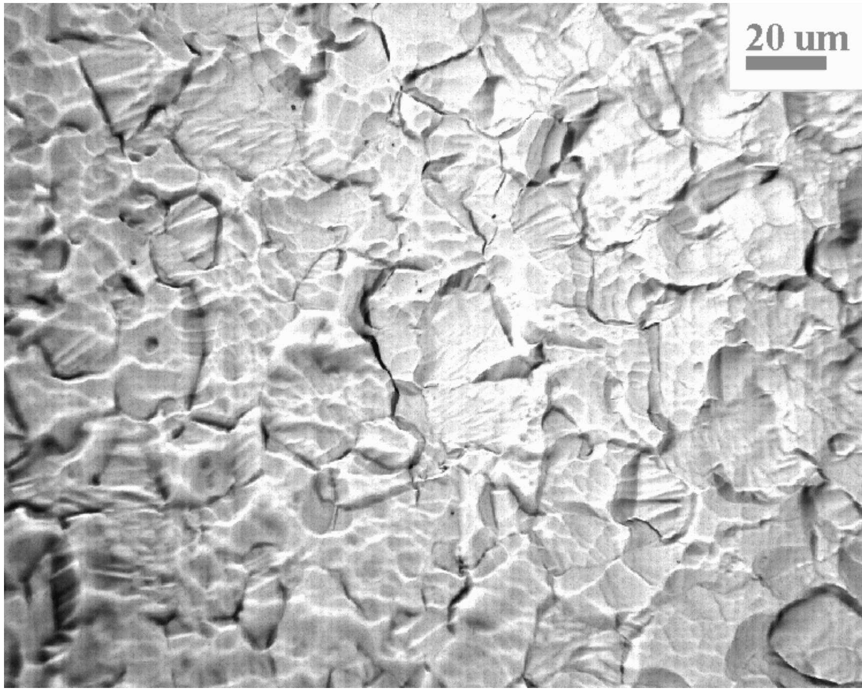
K. Saito



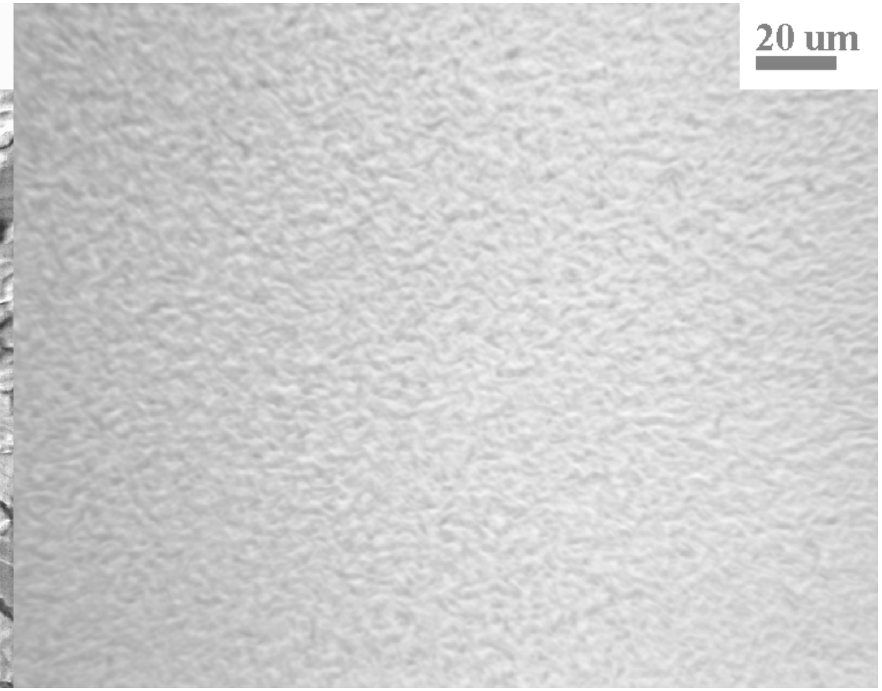


P. Kneisel

Niobium Material Removal by Chemistry



Niobium surface after BCP



Niobium surface after EP

Hydrofluoric Acid Safety

- Hydrofluoric acid is an anomaly
  - It does not react like all other acids once absorbed into the skin
  - It absorbs deeply into skin, destroys everything in the path, then slowly releases into blood stream bonding all calcium
  - Calcium is needed to control the hart → cardiac arrest can result in 8 hours after the exposure
  - Time to proper first aid (removal of and bonding of fluorine) is the most important detail and will determine the outcome
  - Large exposures always lead to death even with first aid and medical treatment

HF Safety cont.

- Before using HF
  - Ensure the lab has a functioning safety shower
  - Calcium gluconate cream or equivalent
  - Proper PPE to cover all exposed skin
  - Additional personnel trained in providing first aid and available

- Before using a System
  - Review and understand the hazards
  - Know what to do when an accident happens

Buffered Chemical Polish (BCP)

Acid = HF (49%), HNO_3 (65%), H_3PO_4 (85%)

Mixture 1:1:1 , or 1:1:2 by volume typical

Reaction:

Brown gas

Oxidation

$2Nb + 5HNO_3 \rightarrow Nb_20_5 + 5NO_2$

Reduction

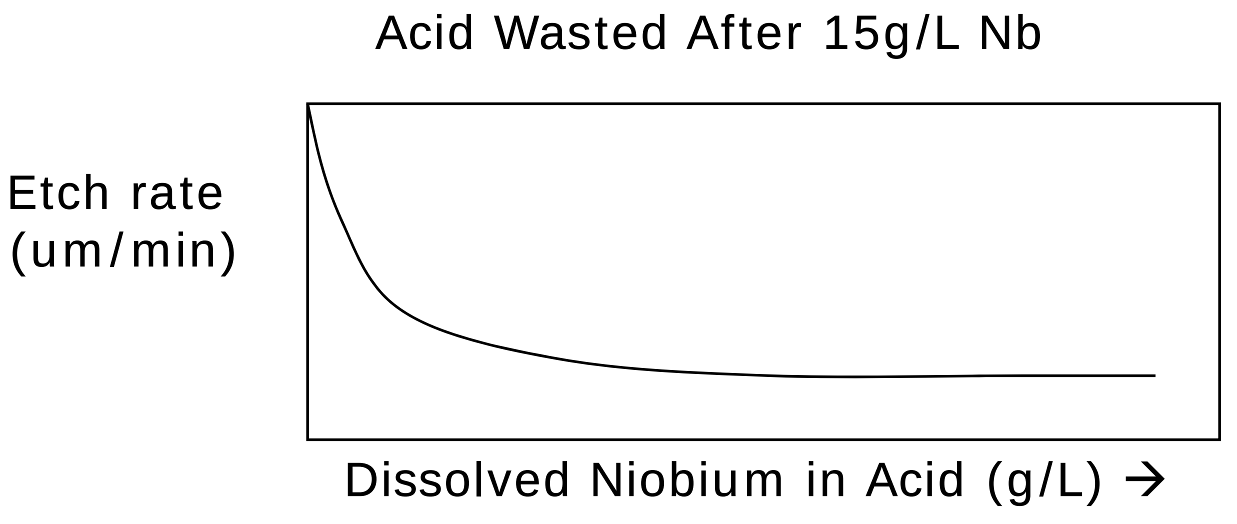
$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F\ 0.5H_2O + 1.5H_2O$

$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$

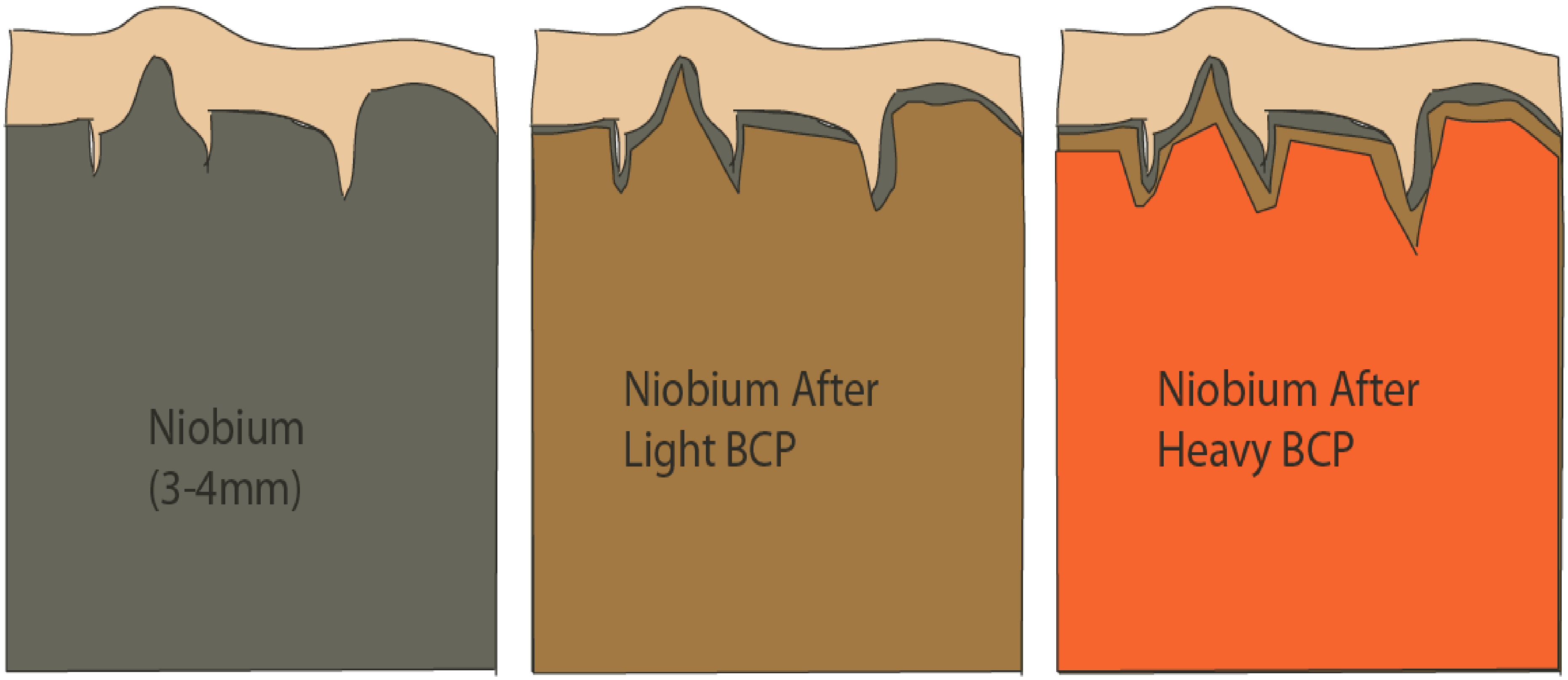
Reaction exothermic!

Use of BCP:

- 1:1:1 still used for etching of subcomponents (etch rates of 8um/min)
- 1:1:2 used for most cavity treatments
  - Mixing necessary → reaction products at surface
  - Acid is usually cooled to 10-15C (1-3um/min) to control the reaction rate and Nb surface temperatures (reduce hydrogen absorption)



Effects of BCP on The Niobium Surface



(BCP) Systems for Cavity Etching:

- Bulk & Final chemistry
  - Bulk removal of (100-200um)
  - Final removal of (5-20um) to remove any additional damage from QA steps and produce a fresh surface

BCP Cabinet JLab

Implementation:

- Cavity held vertically
- Closed loop flow through style process, some gravity fed system designs
- Etch rate 2X on iris then equator
- Temperature gradient causes increased etching from one end to the other
- Manually connected to the cavity but process usually automated

Electropolish (EP)

Electrolyte = 1 part HF(49%), 9 parts H_2SO_4 (96%)

Hydrogen Gas

Reaction:

Oxidation

$$2Nb + 5SO_4^{2-} + 5H_2O \rightarrow Nb_2O_5 + 10H^+ + 5SO_4^{2-} + 10e^-$$

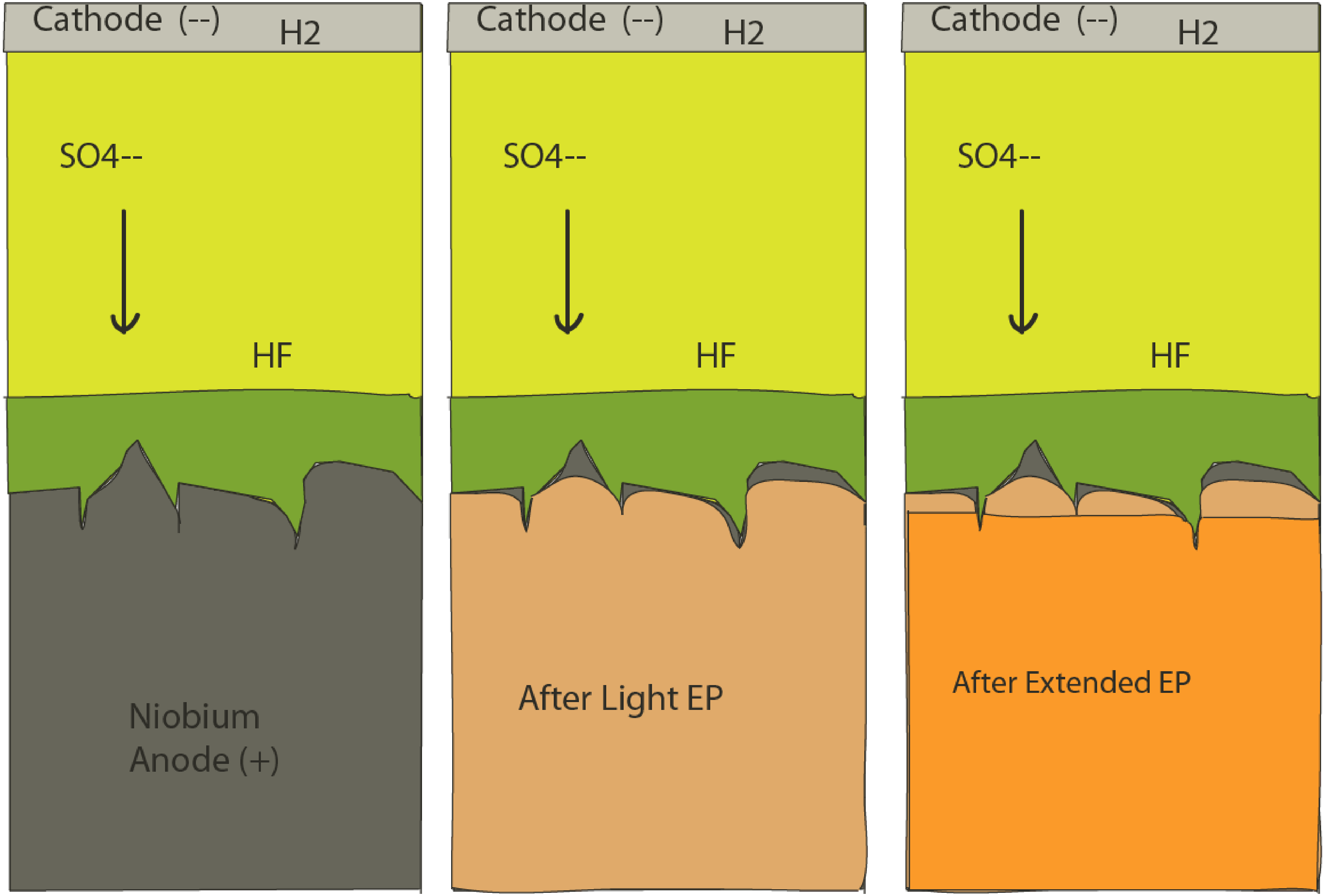
Reduction

$$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F\ 0.5H_2O + 1.5H_2O$$

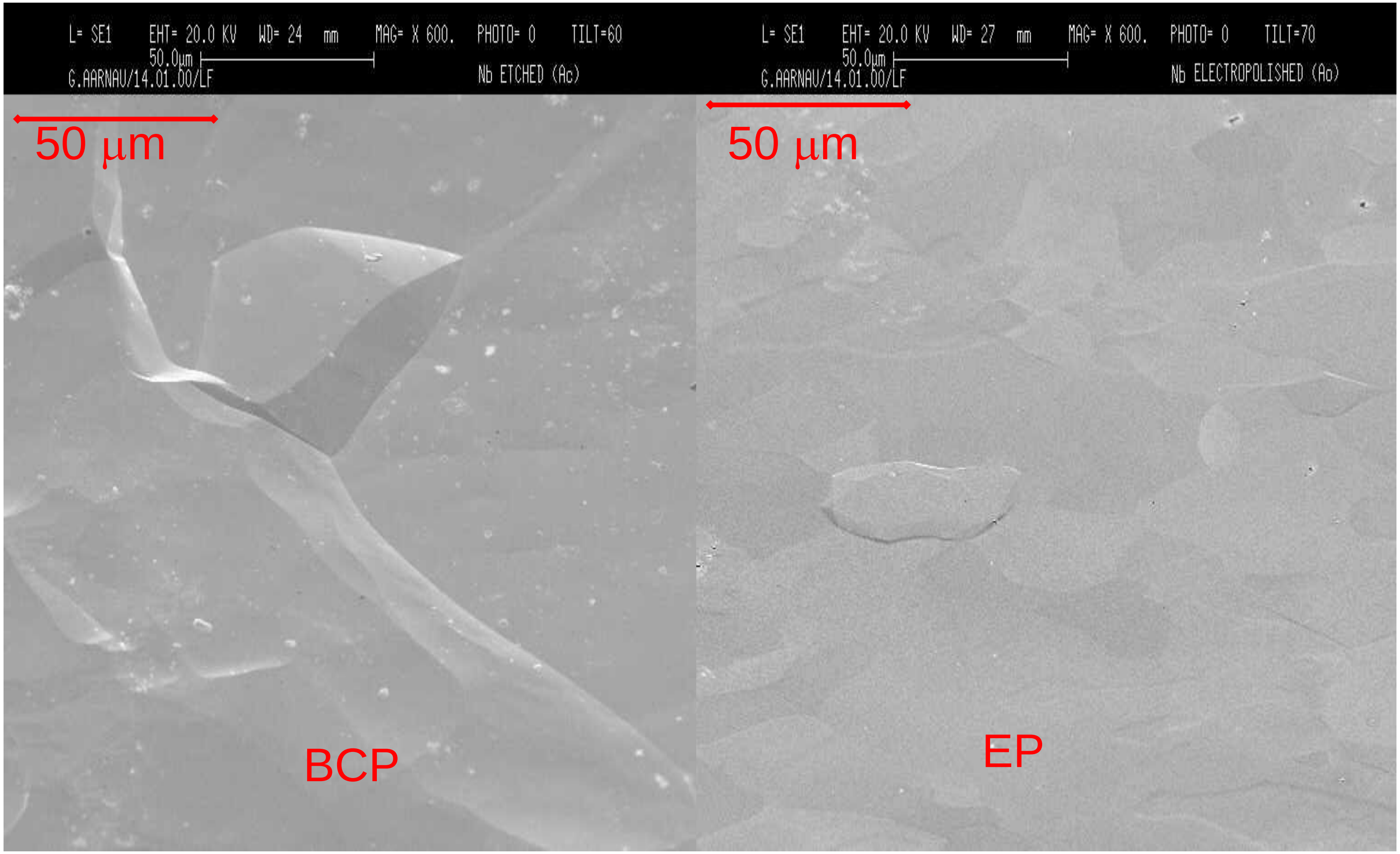
$$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$$

These are not the only reactions that take place!

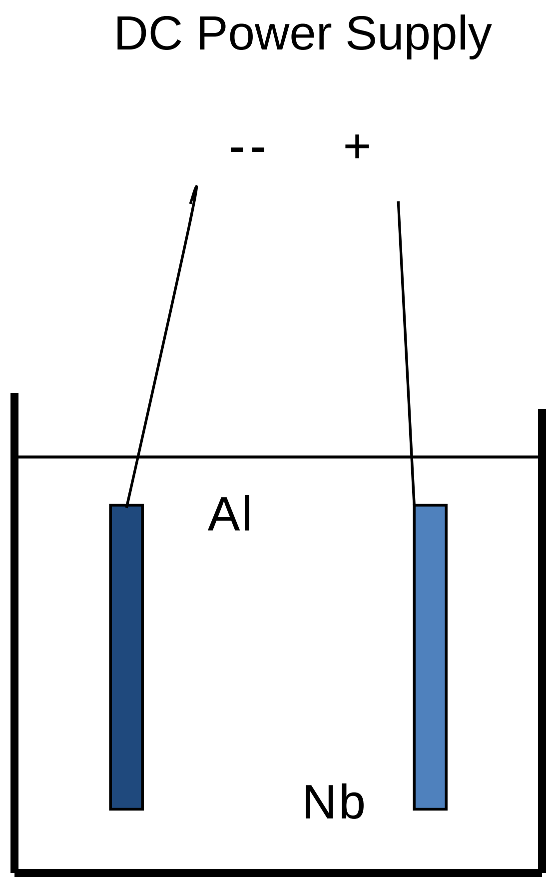
Nb Surface Effects After EP

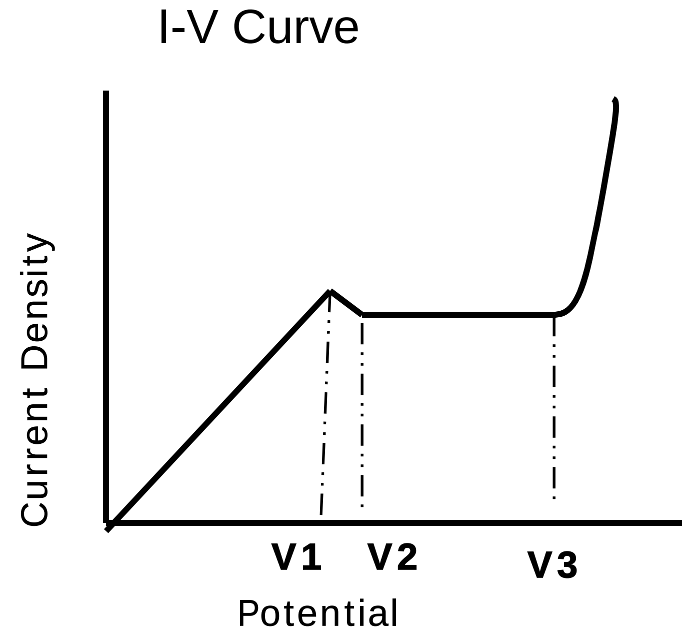


Surface Roughness of Niobium



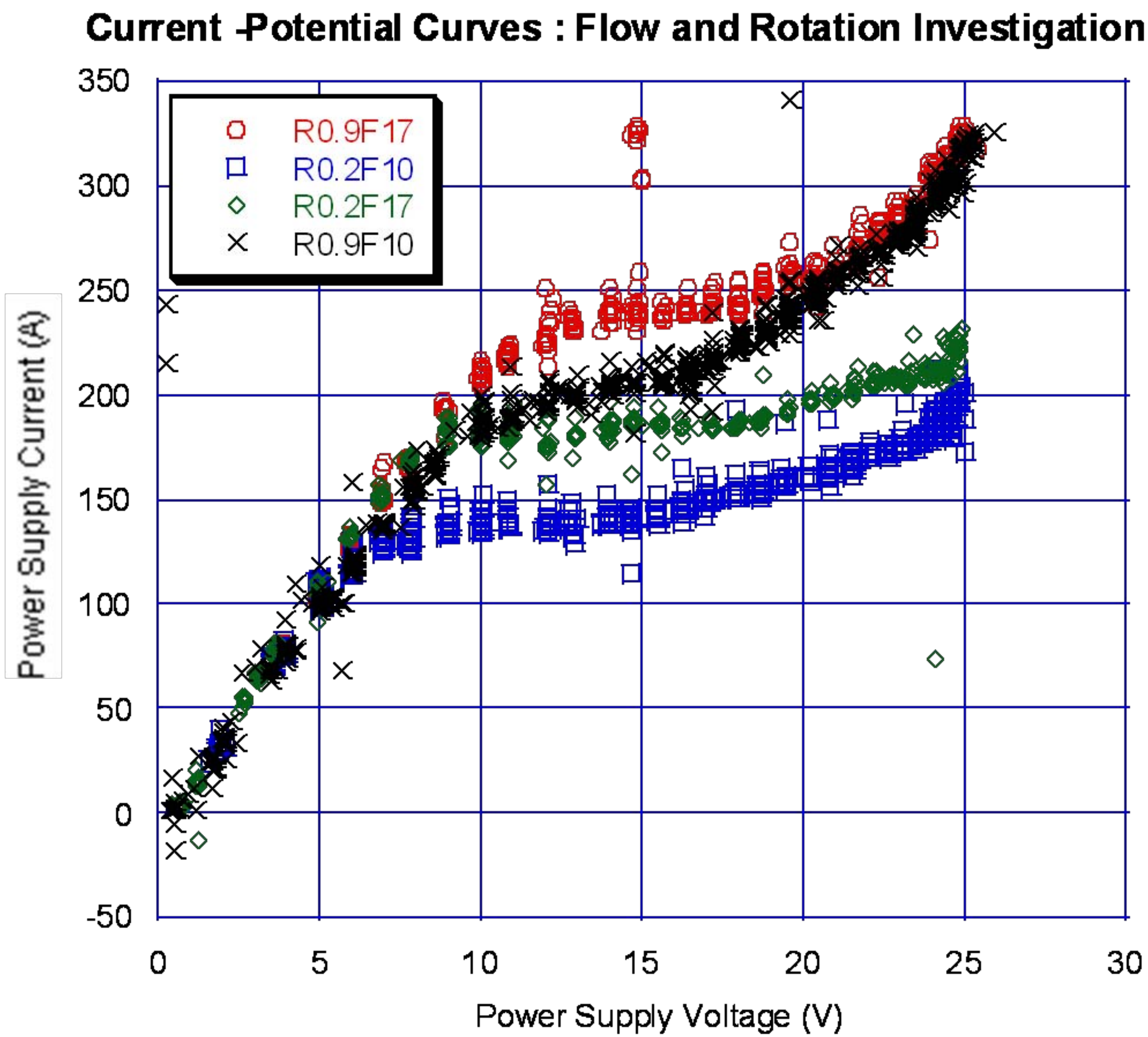
Basic Concepts of EP



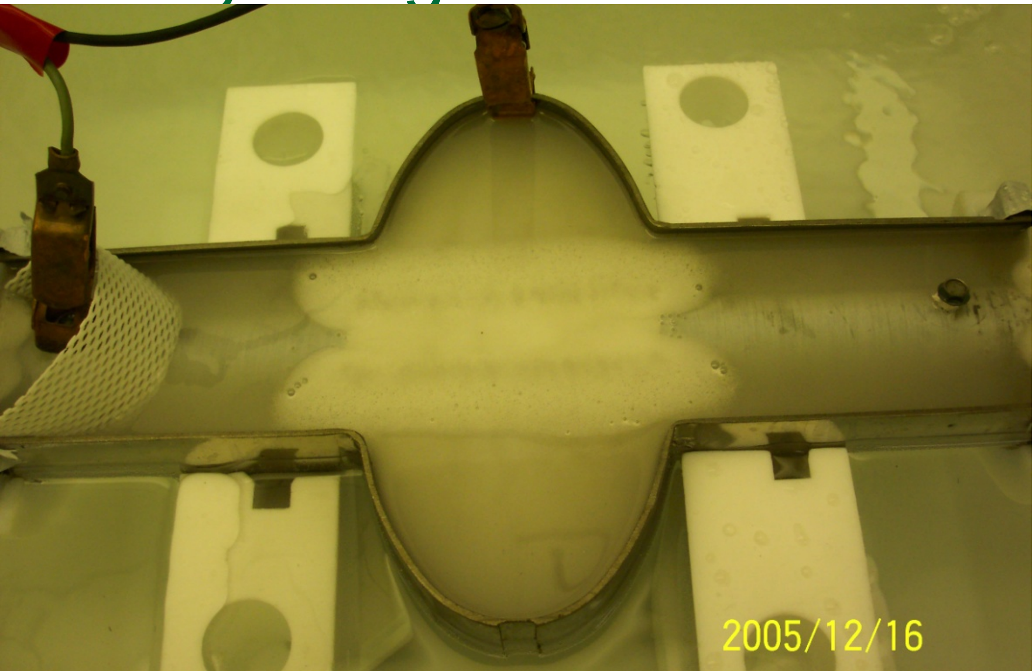


- **0-V1- Concentration Polarization occurs, active dilution of niobium, electrolyte resistance**
- **V2-V3 – Limiting Current Density, viscous layer on niobium surface**
- **>V3 Additional Cathodic Processes Occur, oxygen gas generated**

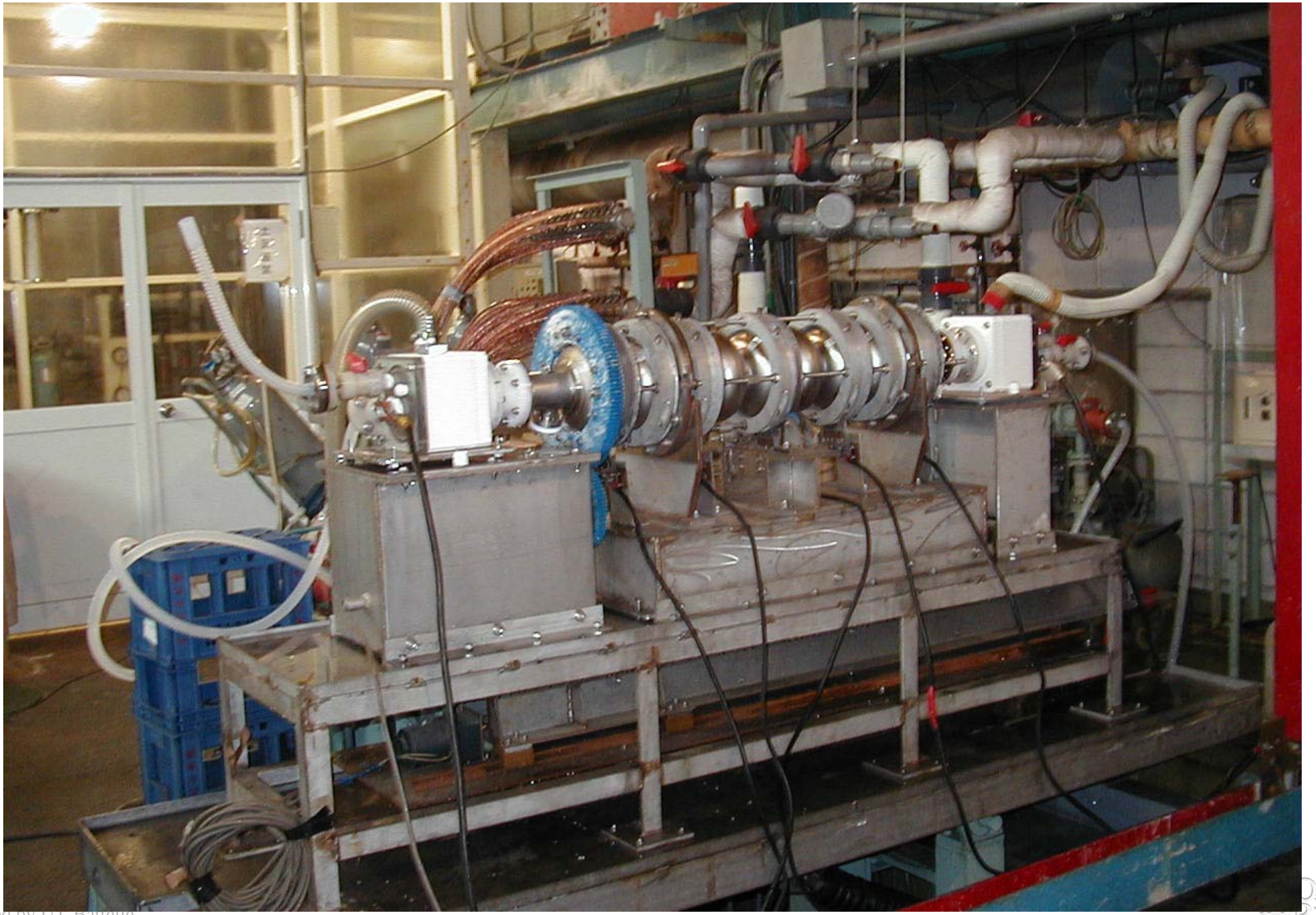
Cavity IV Curve not easy to interpret



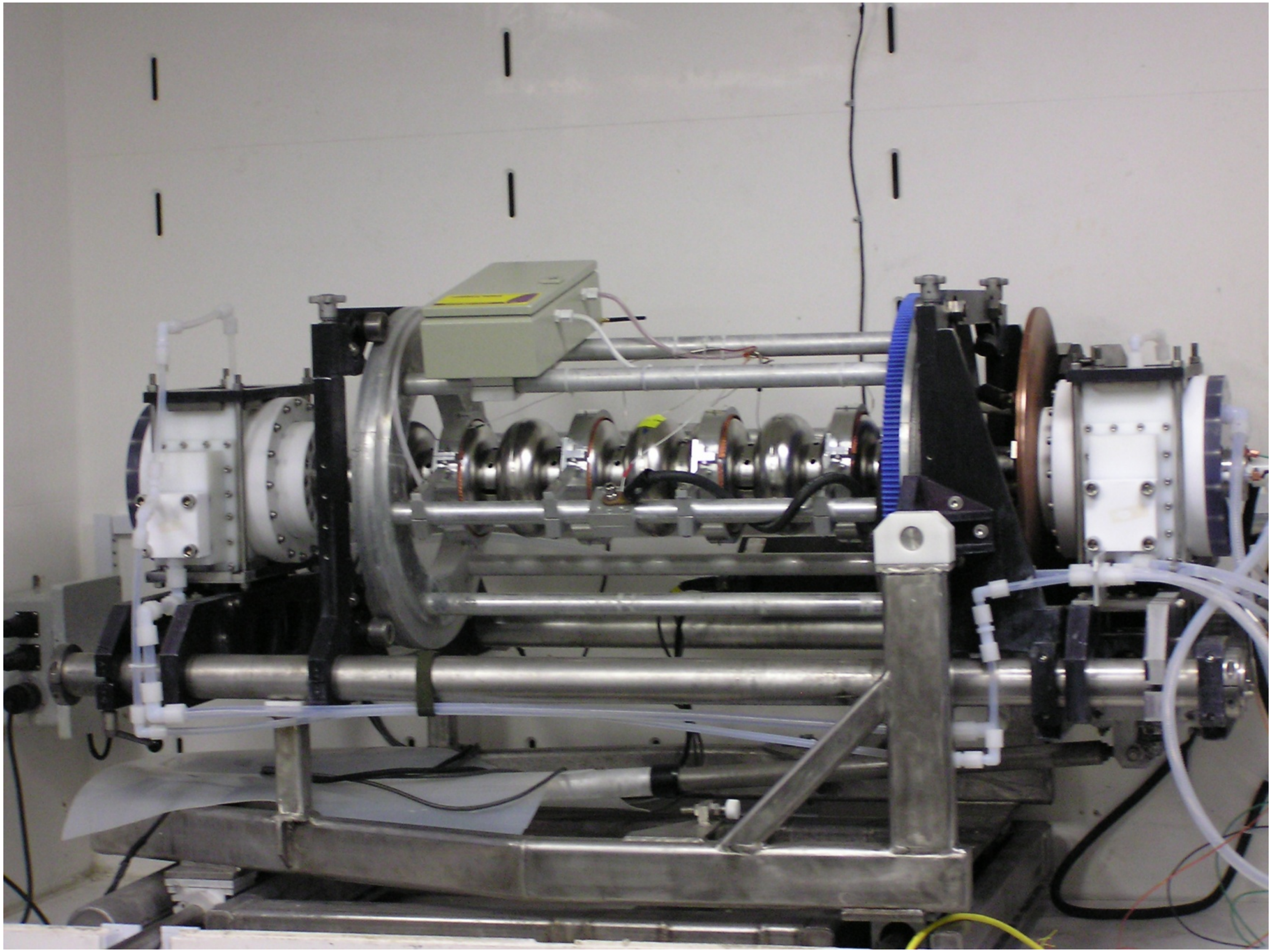
Hydrogen Gas Shielding Experiment



Electropolishing of 9-cell Resonators (Nomura Plating & KEK)



Electropolishing Systems JLAB



Electropolishing Systems DESY

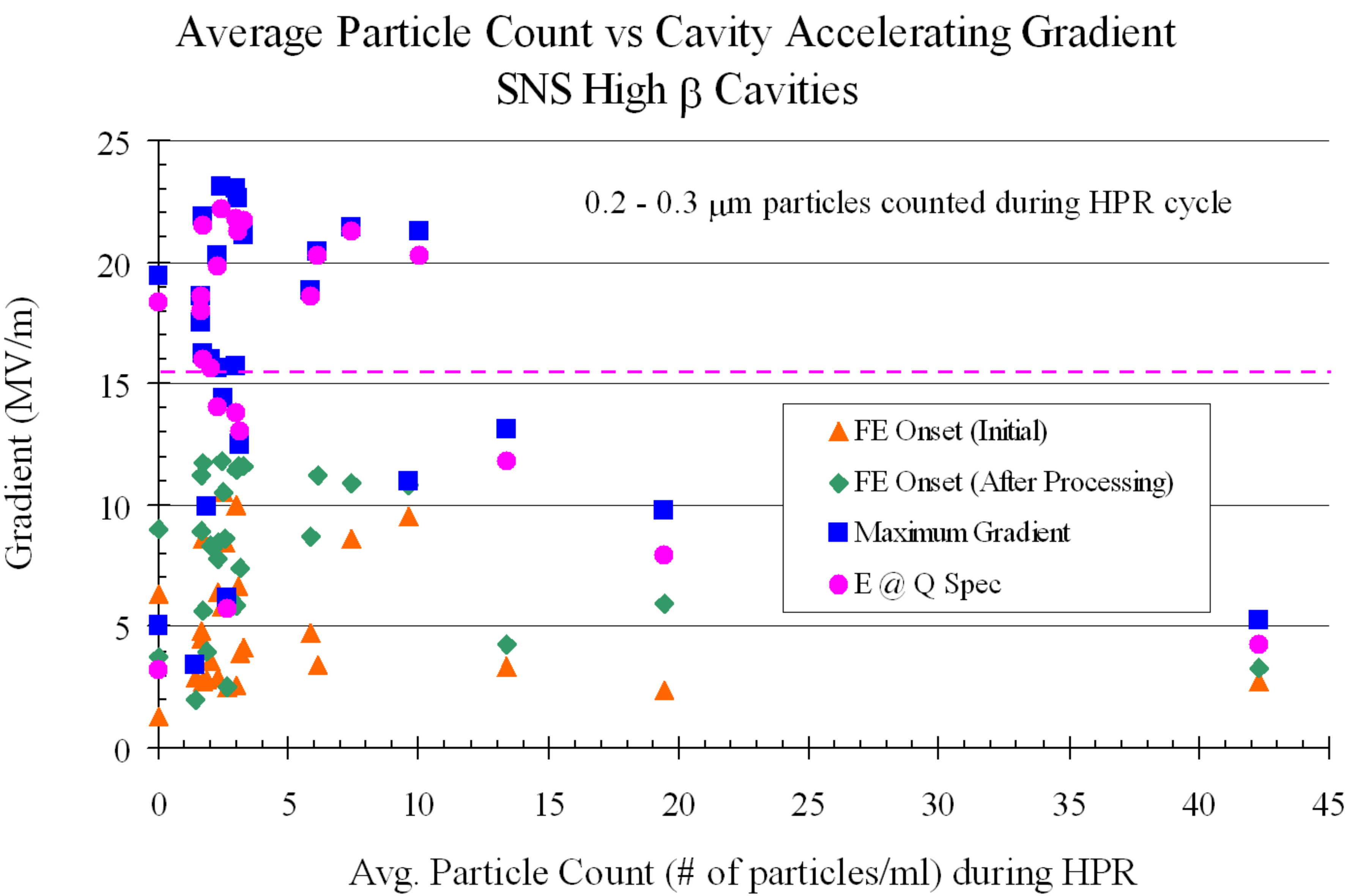
High Pressure Rinsing:

• **This is still the best cleaning method against field emission!**

- The need for HPR surface cleaning:
  - Entire surface contaminated after chemistry, early field emission will result if not performed
  - Effective at removing particulates on the surface after assembly steps

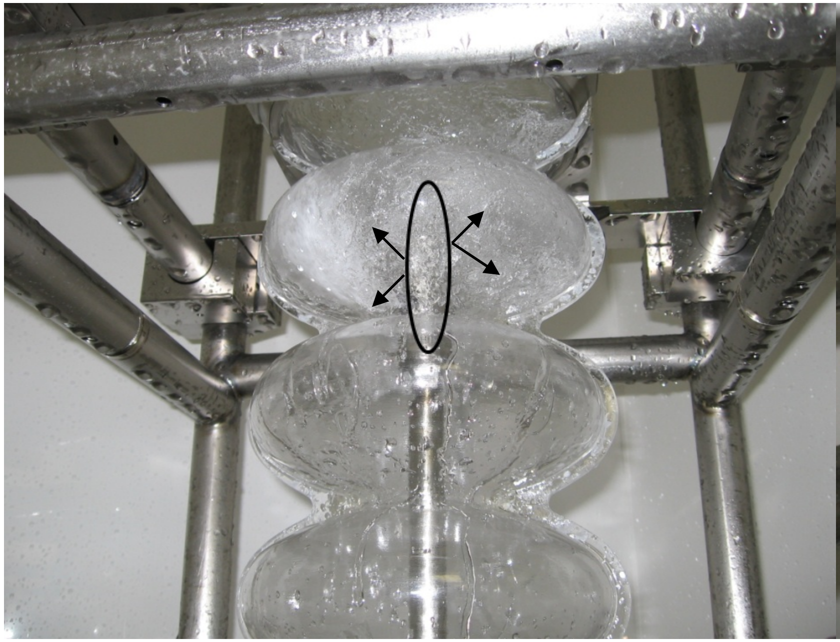
ISSUES:

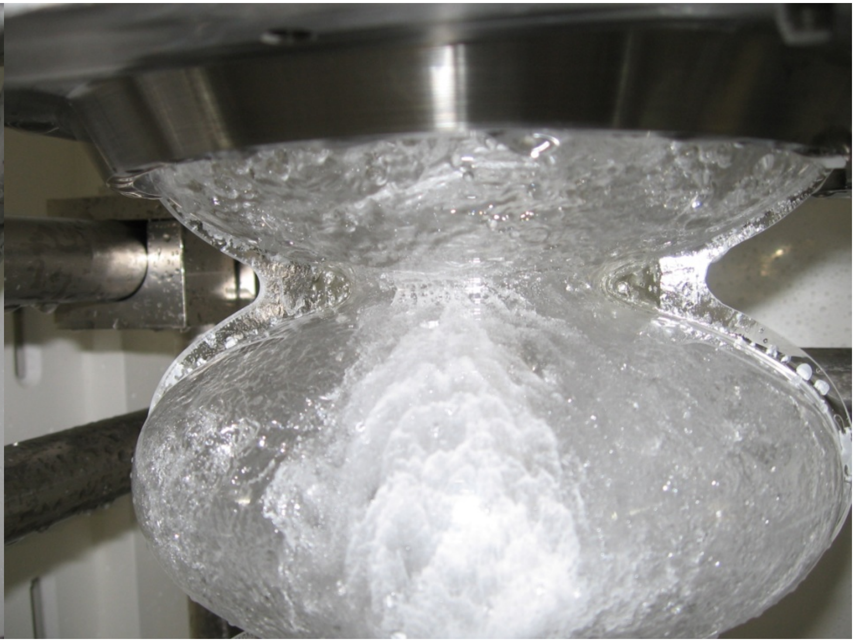
- HPR systems are still not optimized for the best surface cleaning performance
- Surface left in a vulnerable state, wet



Average Particle Count vs Cavity Accelerating Gradient
SNS High β Cavities
0.2 - 0.3 μm particles counted during HPR cycle
Gradient (MV/m)
25
20
15
10
5
0
0
5
10
15
20
25
30
35
40
45
FE Onset (Initial)
FE Onset (After Processing)
Maximum Gradient
E @ Q Spec
Avg. Particle Count (# of particles/ml) during HPR

HPR spray heads needs to be optimized for a particular geometry!



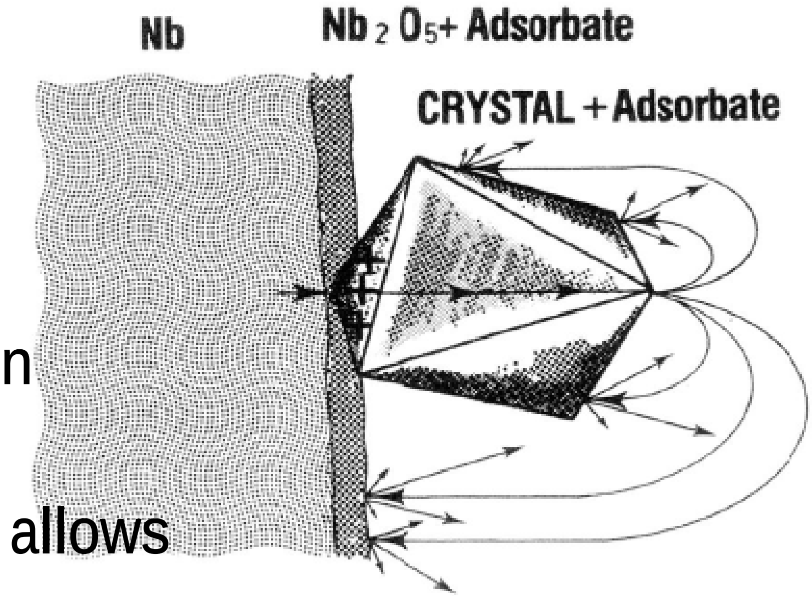


Very effective on irises

Equator fill with water → too high flow rate

For a given pump displacement the nozzle opening diameter and number of nozzles sets the system pressure and flow rate

Helium Processing

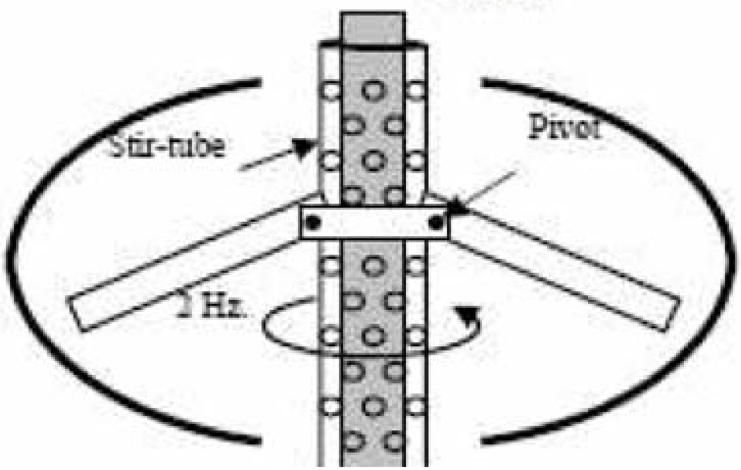


- Variation of RF processing
- Keep pressure below discharge condition
- Run cavity in the field emission regime
- Push the gradient as high as the system allows
- The process in details is unknown
  - Electron spraying from FE → bombard surface → ionization of helium at around surface → destroy field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

Cornell University
Laboratory for Elementary-Particle Physics

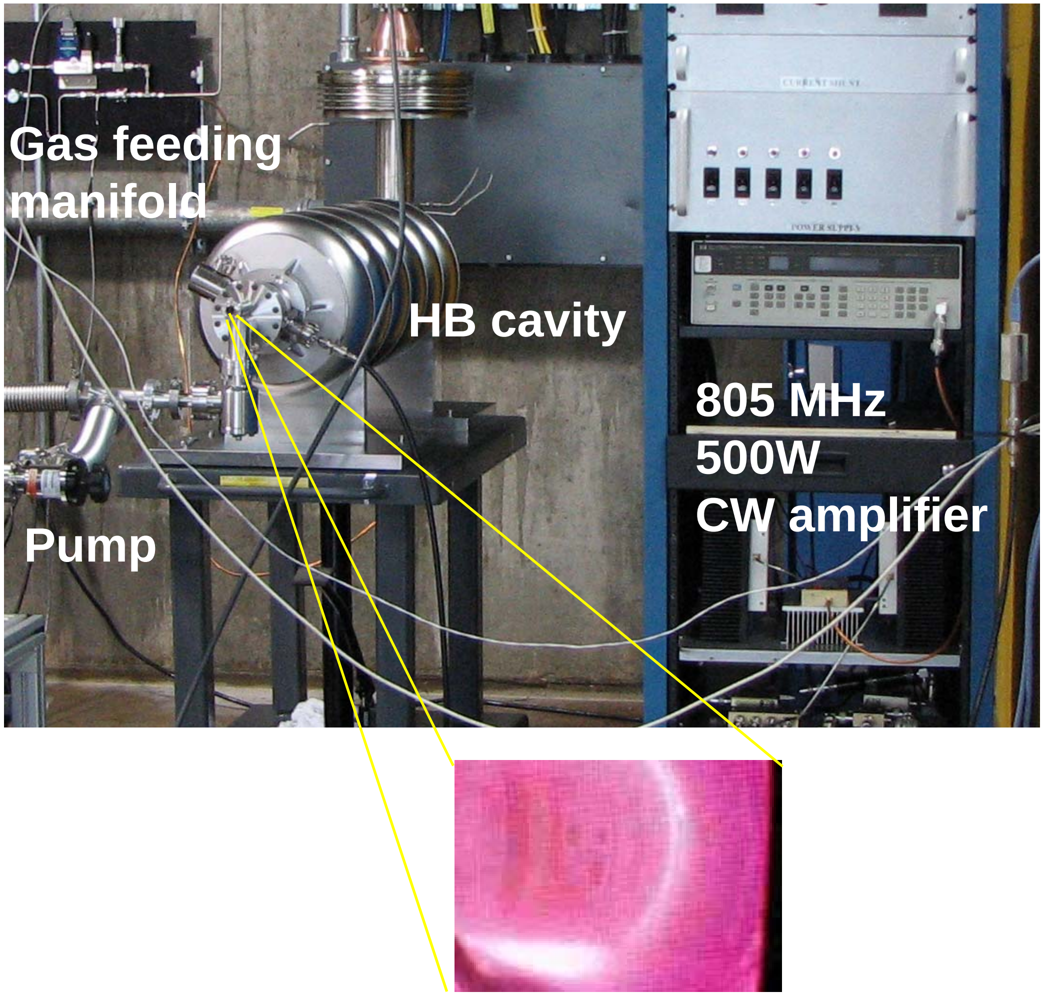
Vertical Electropolish Proven Effective

- We have demonstrated gradients >35 MV/m in individual cells of two 9-cell cavities processed with vertical EP.
- In each test the π-mode was limited by quench.



Rongli Geng

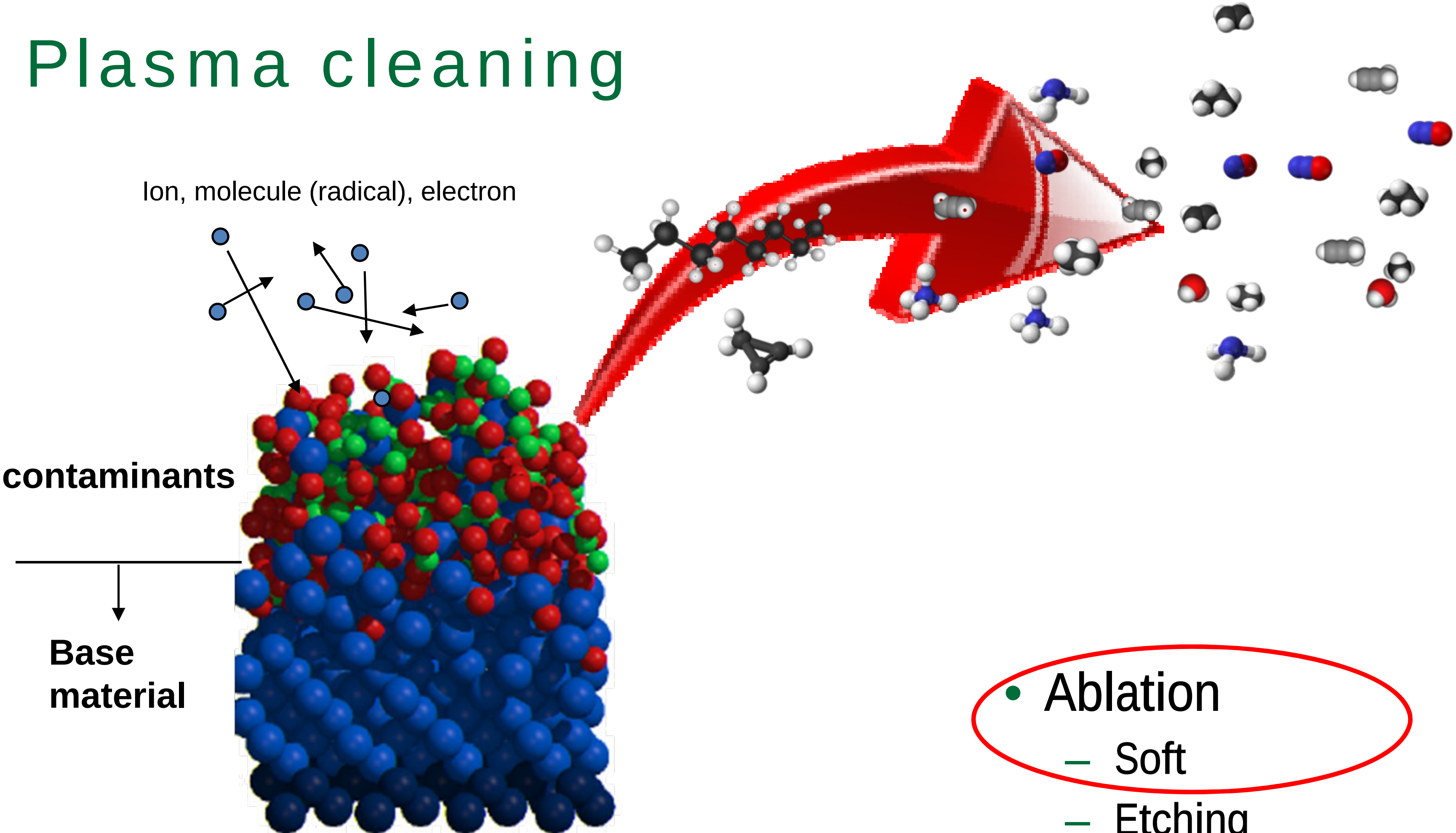
Preliminary experimental setup in RFTF



First plasma in the SNS HB cavity

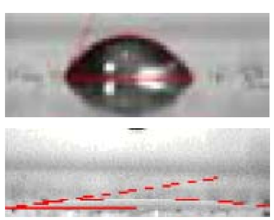
300W forward
200W reflected
1e-4 torr

Plasma cleaning



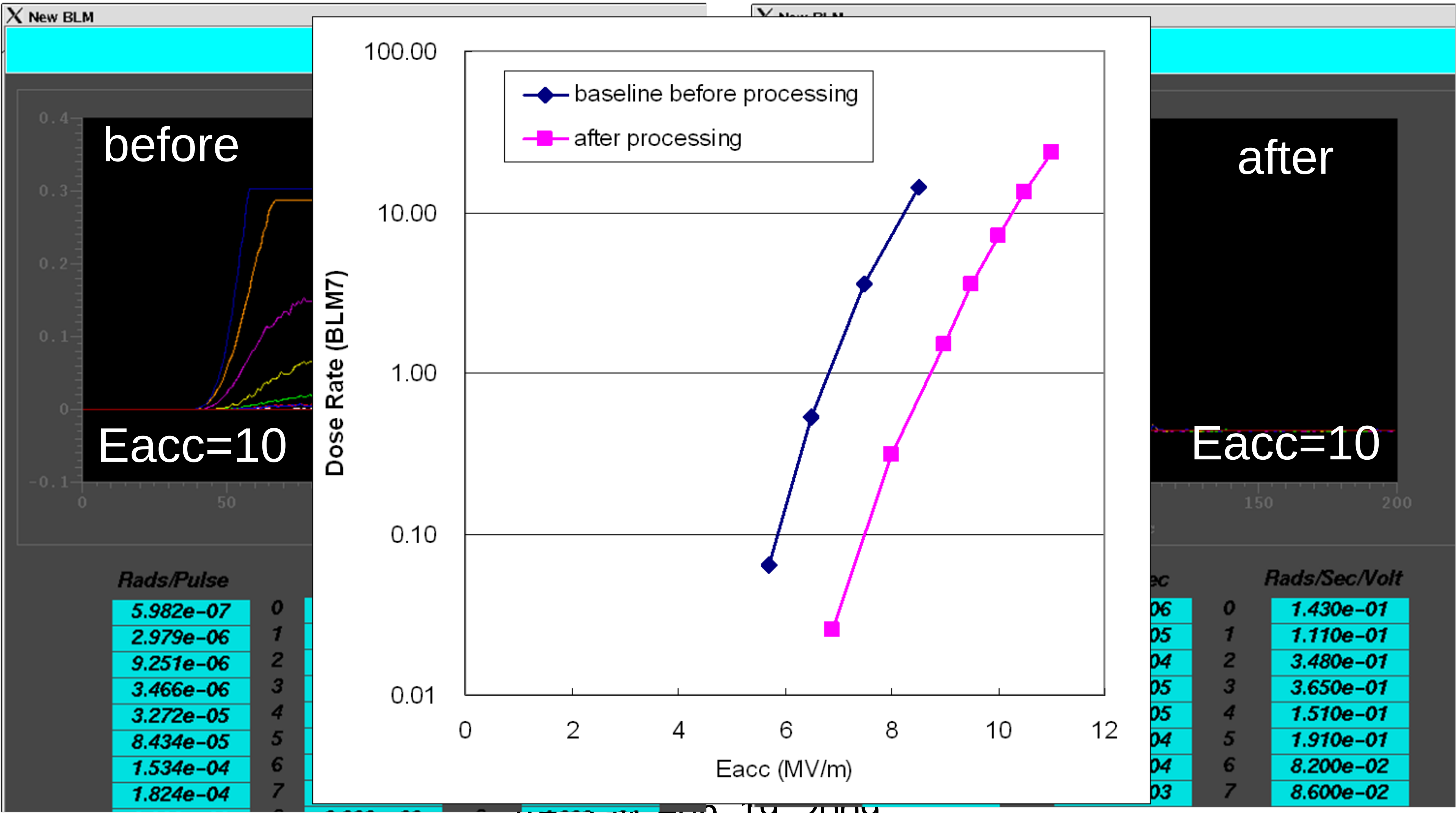
- Ablation
  - Soft
  - Etching
- Activation
- Crosslinking
- Deposition

wettability



Radiation (before and after processing)

Radiation reduced by factor of 5 to 100
Showed promising results for in-situ processing



Integrated Process Automation

The Need!

- Cryomodules are expensive ($M)
  - Amount of hands-on labor
  - Failure rates (sensitivity of performance to errors)
  - Material costs (increasing with time, complexity of design)

- Machine energies are increasing
  - Cryomodule numbers are increasing (100,s → 1000’s)

Integrated Process Automation

- There is hope however for reduction of failure rates and labor
  - In my opinion "Vertical EP" may be the breakthrough we needed

  - Now one can imagine combining many of the processes into a single process station or two
    - Example

    - Degreasing — Assembly
    - Electropolish → Evacuation
    - HPR — Leak test
    - Drying — Baking