SURFACE PREPARATION

Gianluigi Ciovati

Thomas Jefferson National Accelerator Facility

Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 µm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 µm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in cleanroom (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

If cavity meets specs after cryo-RF test…

Additional Steps for Cavity String

- Final mechanical tuning
- He-vessel welding
- Degreasing
- Final material removal (10-20 μm)
- Final HPR
- Horizontal assembly into cavity-string
- Evacuation of cavity string

Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in cleanroom (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

Degreasing with Ultrasonic Agitation

Why is degreasing needed

- To remove grease, oil and finger prints from cavity surfaces
- To remove surface contamination due to handling, RF measurements and QA inspection

Implementation:

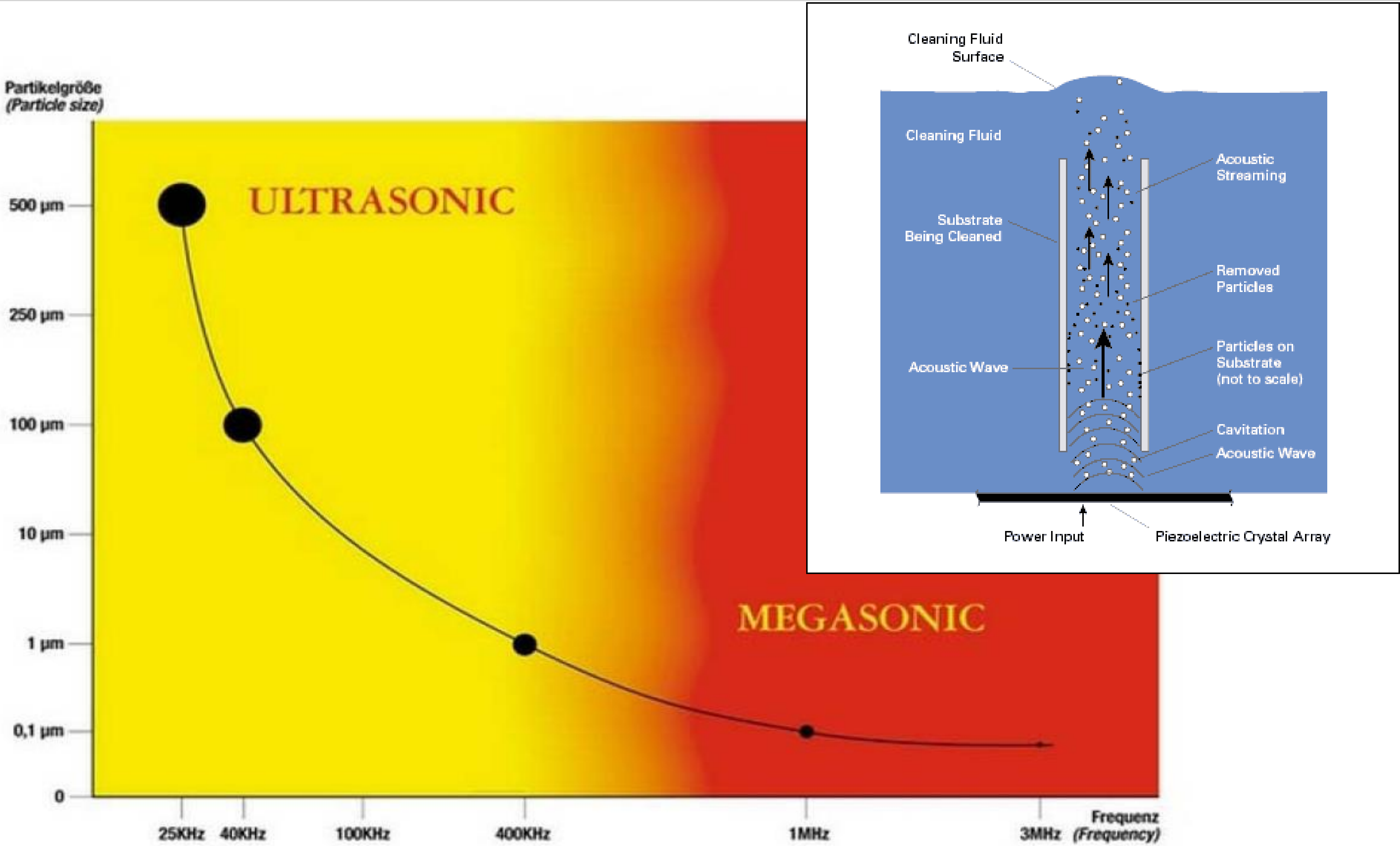
- Ultrasonic degreasing with detergent (Micro-90®, Liqui-Nox®), 1%-2% concentration, and ultra pure water
- Usually performed in Hepa filtered air
- Water quality is good, 18 MΩ cm, Filtration > 0.2μm
- Manually or semi-automated processes available
- Problem: Parts are wet and vulnerable to particulate contamination

Ultrasonic Cleaning

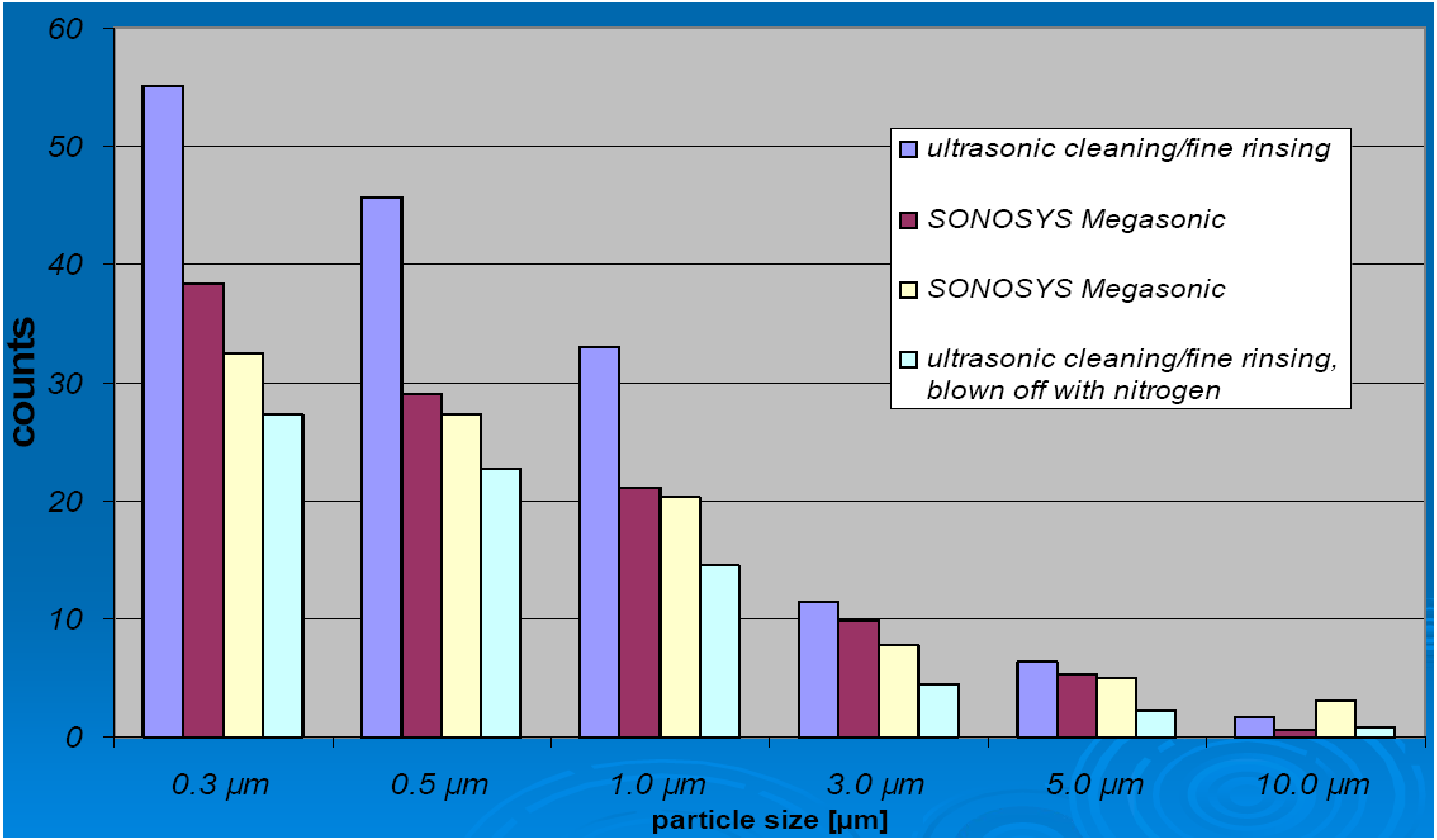
- Immersion of components in DI water and detergent medium
- Wave energy forms microscopic bubbles on component surfaces. Bubbles collapse (cavitation) on surface loosening particulate matter.
- Transducer provides high intensity ultrasonic fields that set up standing waves. Higher frequencies lowers 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.

Cavities and all hardware components (Flanges, nuts & bolts…) have to be degreased with ultrasonic cleaning

Megasonic Cleaning



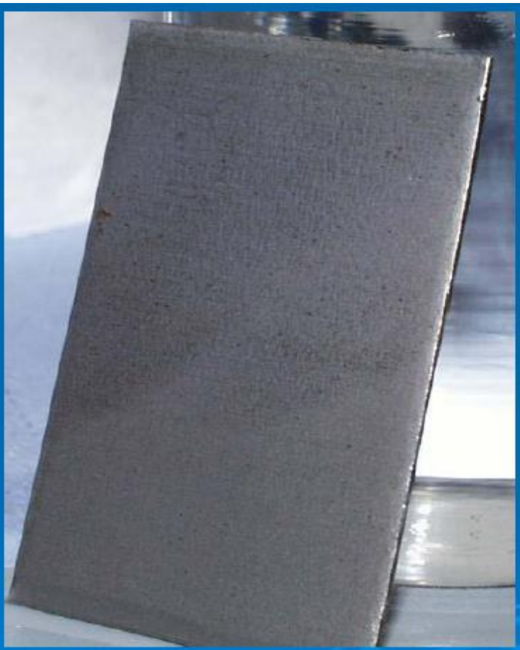
Studies on Efficient Cleaning Methods



Example on Nb Sample

Test on cleaning procedure/detergent: Nb sample polluted with grease and oil

Not efficient cleaning



After Ultrasonic cleaning with sufficient detergent and procedure

Ultrasonic Tanks for Cavity Cleaning

Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 µm)
- Removal of hydrogen from bulk Nb
- M
- Ch surface for
  - ectropolishing
- Hi to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in clean room (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation

Chemical:

- Buffered Chemical Polishing (BCP)
- Electropolishing (EP)

Mechanical

Centrifugal Barrel Polishing (CBP)

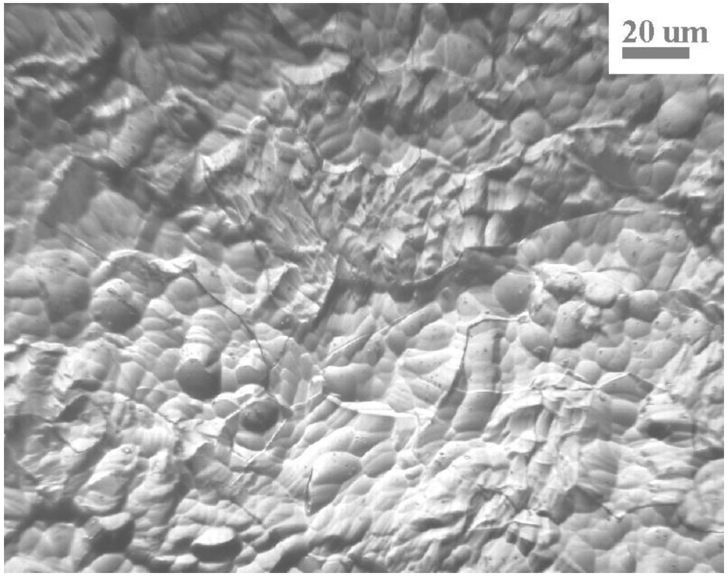
Acid Etching of Sub-components & Cavities:

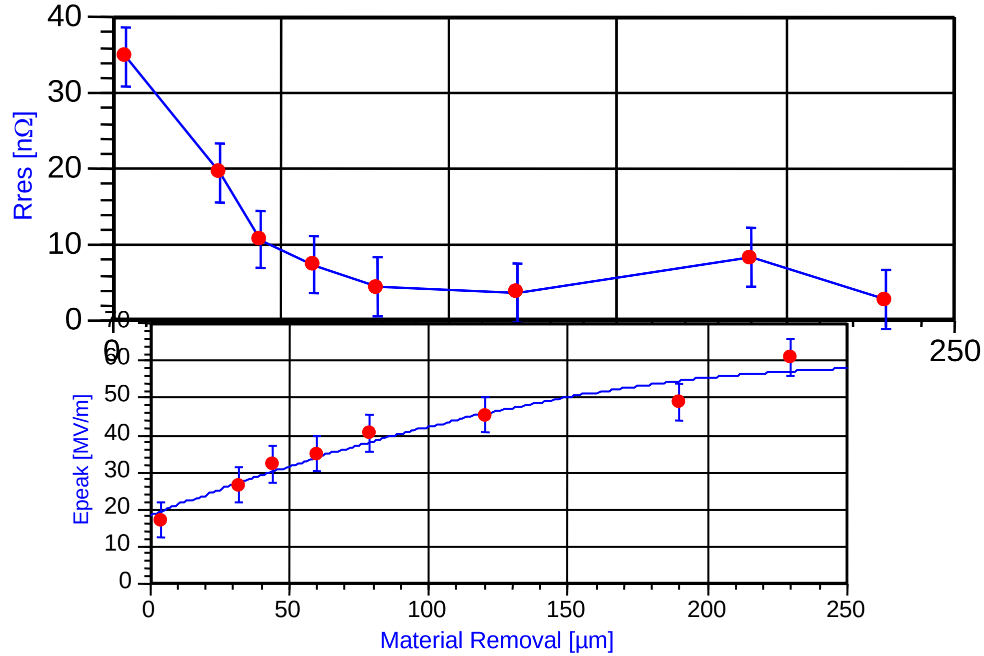
- Sub-components require
  - Removal of oxides which come from fabrication steps → lower losses and improve sealing
- Cavities require:
  - Interior chemistry to remove damaged surface layer incurred in welding and deep drawing (100-200μm)
  - Exterior chemistry to remove surface oxides that occurred in welding (10-30μm)

Implementation: (BCP or EP)

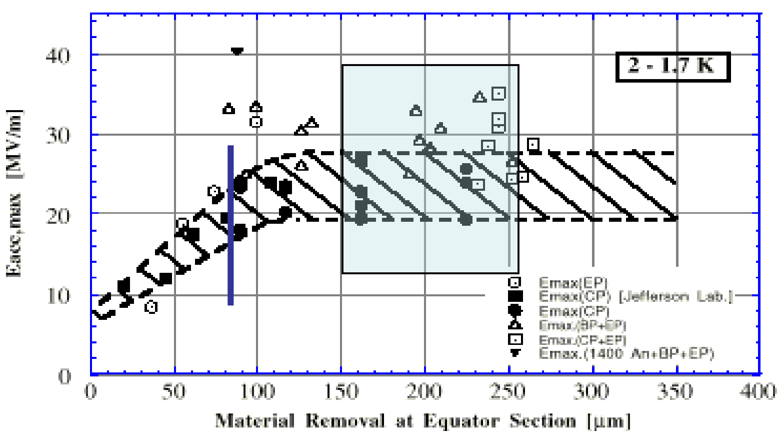
- Subcomponents usually processed by hand in wet bench
- Acid quality usually electronic grade or better, low in contaminants
- Acid temperature control required to prevent additional absorption of hydrogen (Q-disease)
- Acid mixture difficult to QA

The Need For Material Removal



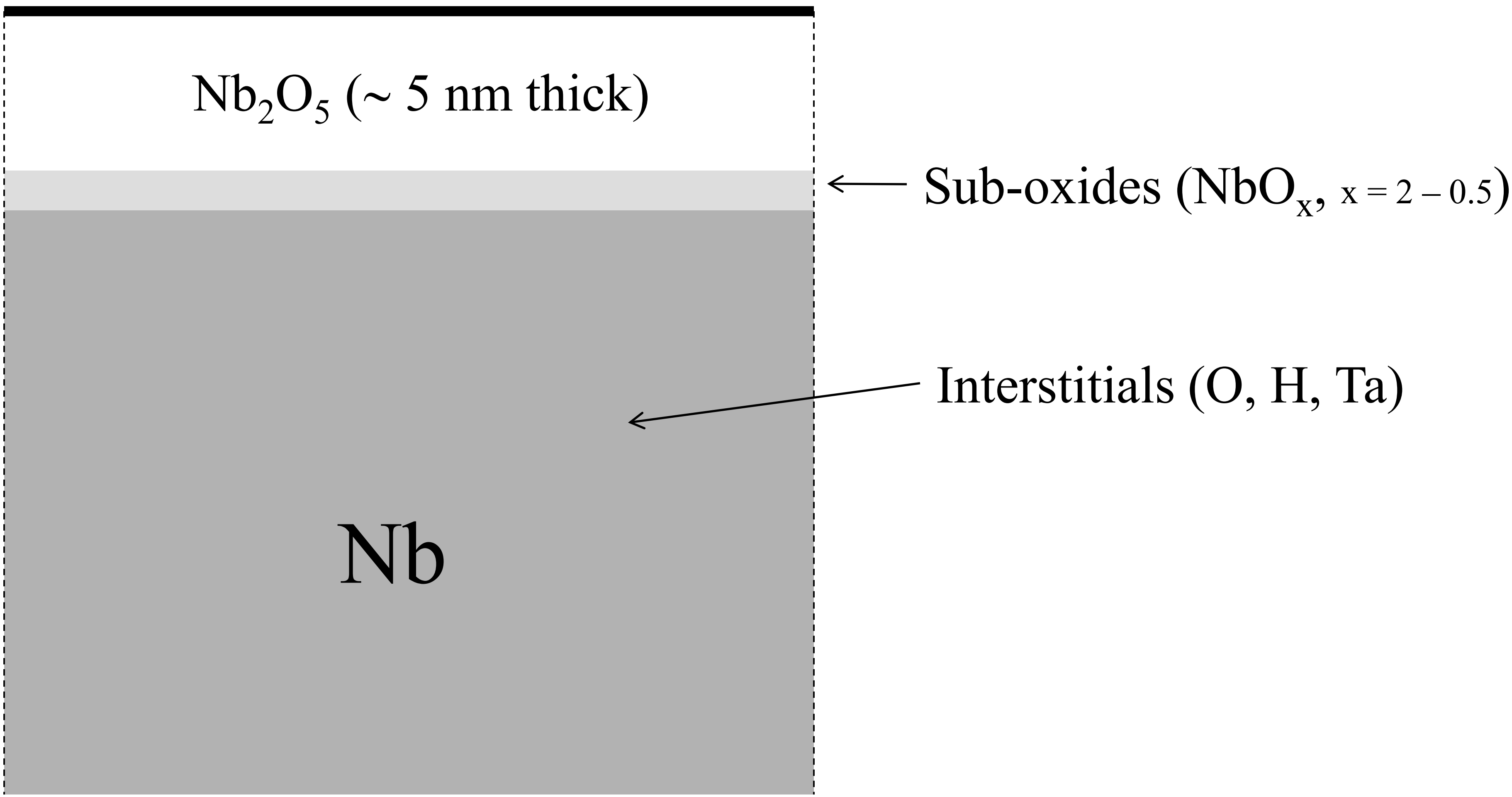


P. Kneisel



K. Saito

Nb Surface



Buffered Chemical Polish (BCP)

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

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

Oxidation

$2Nb + 5HNO_3 \rightarrow Nb_2O_5 + 5NO_2$ → Brown gas

Reduction

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

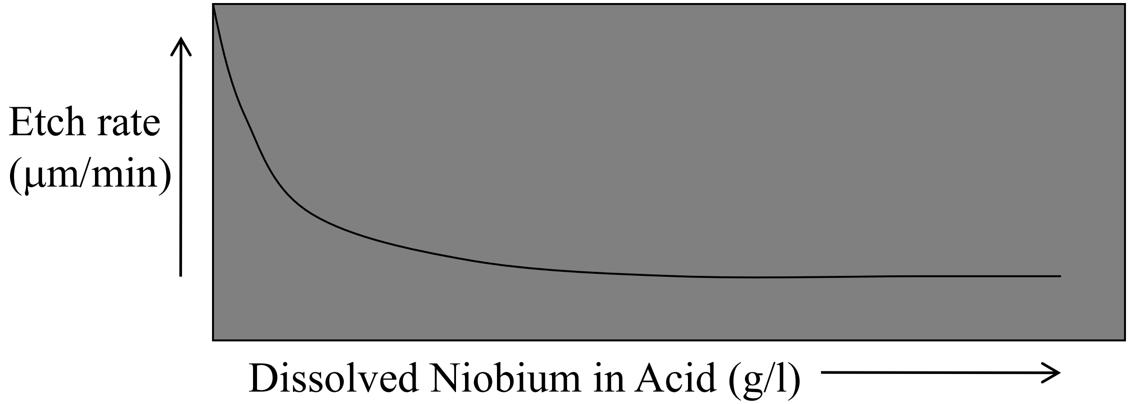
$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$

Reaction exothermic! Use H_3PO_4 as "buffer" to slow reaction rate

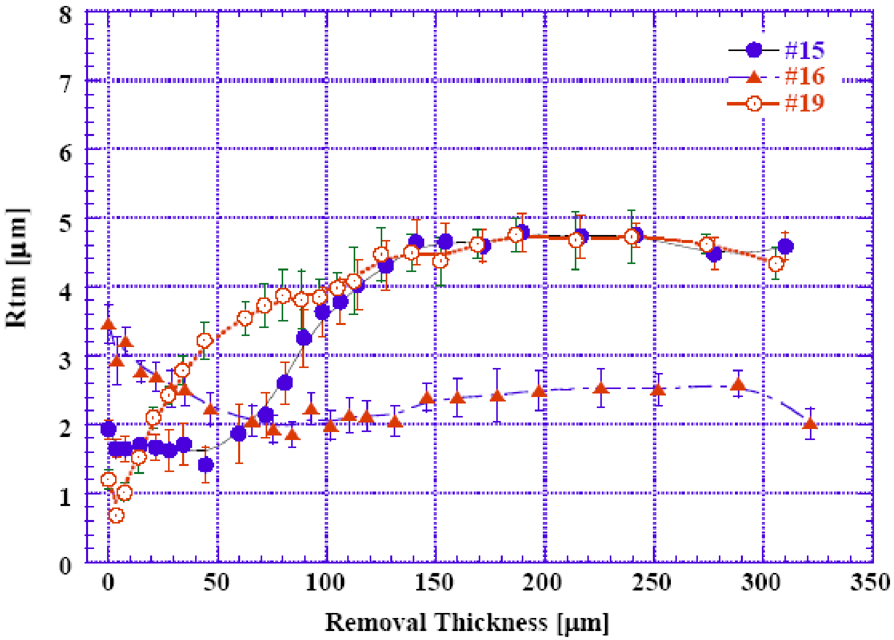
Use of BCP:

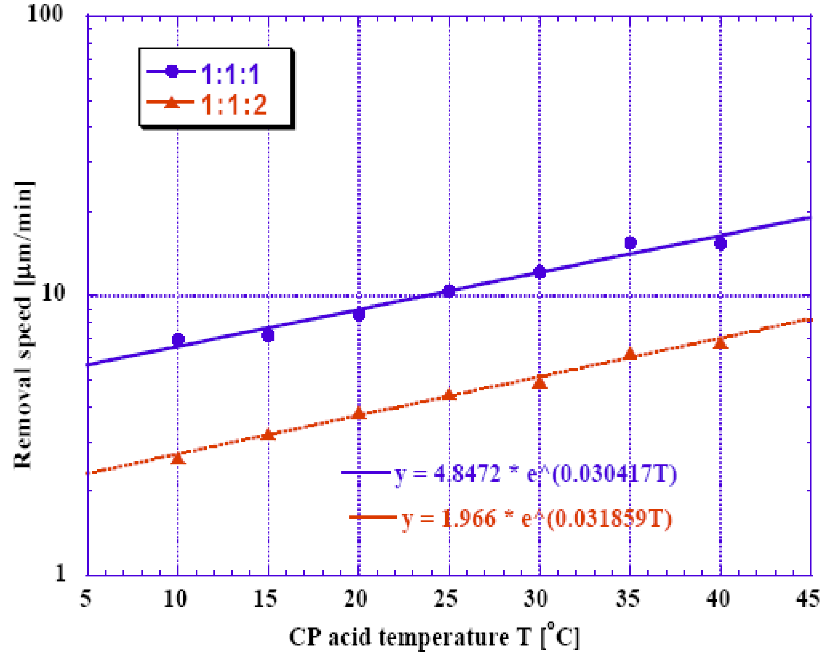
- 1:1:1 still used for etching of subcomponents (etch rates of ~ 8 μm/min)
- 1:1:2 used for most cavity treatments (etch rates of ~ 3 μm/min)
  - Agitation necessary → reaction products at surface
  - Acid is usually cooled to 10-15 °C (1-3 μm/min) to control the reaction rate and Nb surface temperatures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

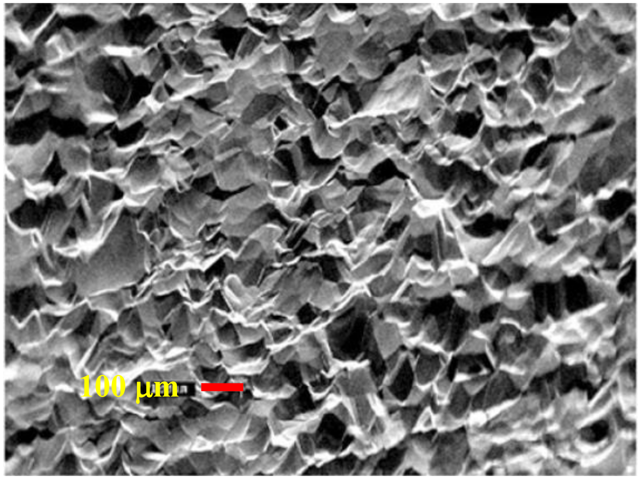
Acid wasted after 15 g/l Nb



BCP: Surface Roughness and Etching Rate







- “Simple” process
- Roughness of 2 -5 μm (100 x 100 μm² scale) after 100 μm etching
- High etching rate

BCP Systems for Cavity Etching

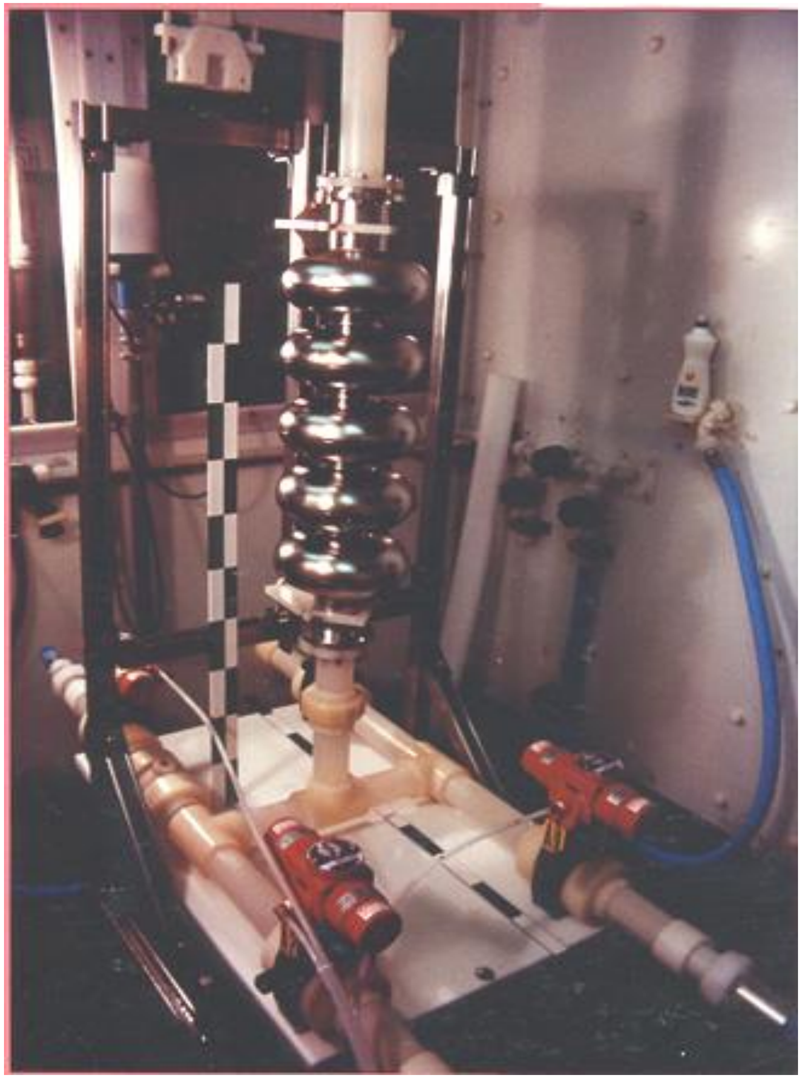
- Bulk & Final chemistry
  - Bulk removal of (100-200 μm)
  - Final removal of (5-20 μm) to remove any additional damage from QA steps and produce a fresh surface

BCP Cabinet JLab

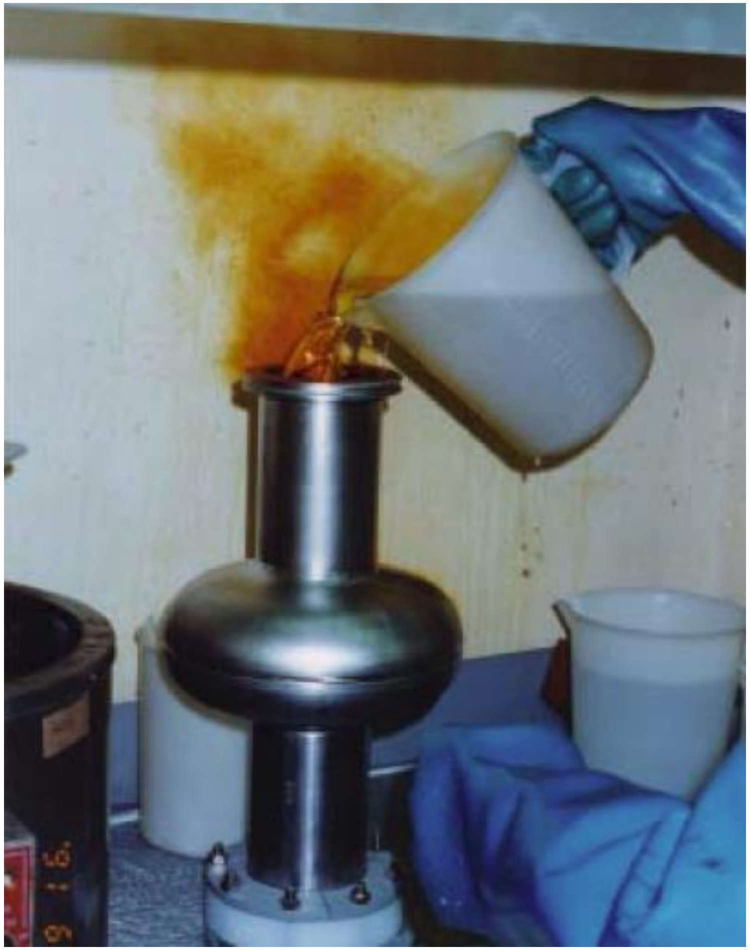
Implementation:

- Cavity held vertically
- Closed loop flow through style process, some gravity fed system designs
- Etch rate 2x on iris then equator, if no stirring mechanism
- Temperature gradient causes increased etching from one end to the other
- Manually connected to the cavity but process usually automated

Chemical Etching Setups



Old system for CEBAF cavities



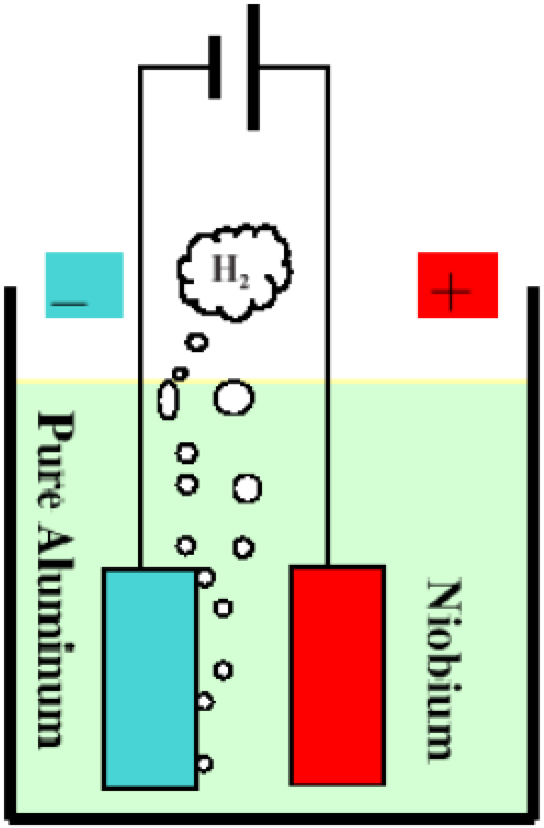
BCP of single cell cavity under chemical flow hood

Chemical Etching of Outer Surface

- ~ 20 um are removed from the outer surface of the cavity by BCP to remove "dirty" layer after fabrication in order to improve the heat transfer at the Nb/LHe interface (Kapitza resistance)

- Some labs do this as part of cavity preparation procedure (DESY), some don't (JLab)
- No clear influence on cavity performance

Electropolishing



Acid:
H_2SO_4 (>93%): HF(46%)=10:1 V/V

9:1

Electropolishing (EP) of Niobium:

- Both electrodes are immersed in electrolyte
- A voltage is applied between Nb (anode) and counter electrode (cathode, Al)

Basic reactions:

Oxidation

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

Reduction

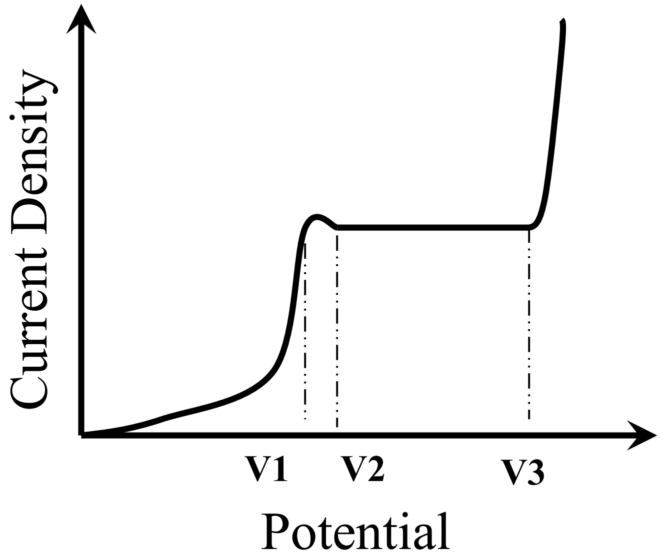
$$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F\ 0.5H_2O + 1.5H_2O$$

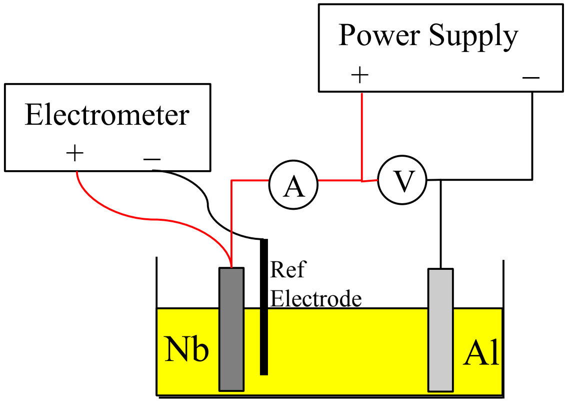
$$NbO_2F\ 0.5H_2O + 4HF \rightarrow H_2NbOF_5 + 1.5H_2O$$

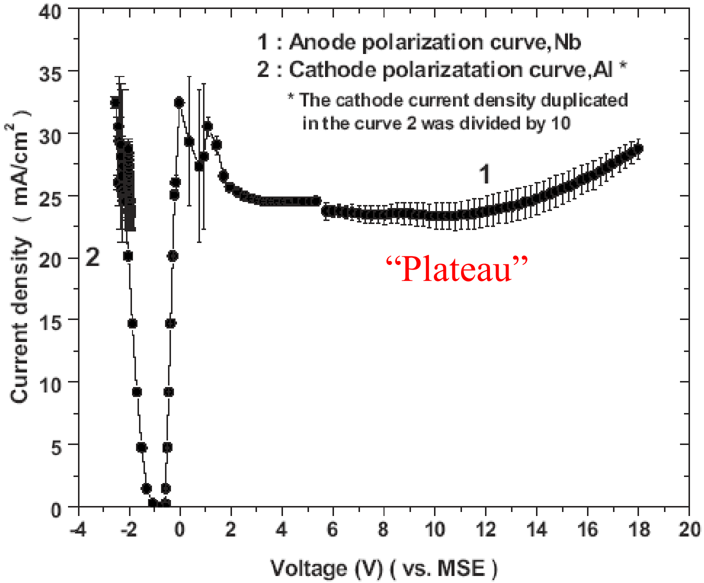
$$10H^+ + 10e^- \rightarrow 5H_2$$

Hydrogen gas produced at cathode

I-V Curve







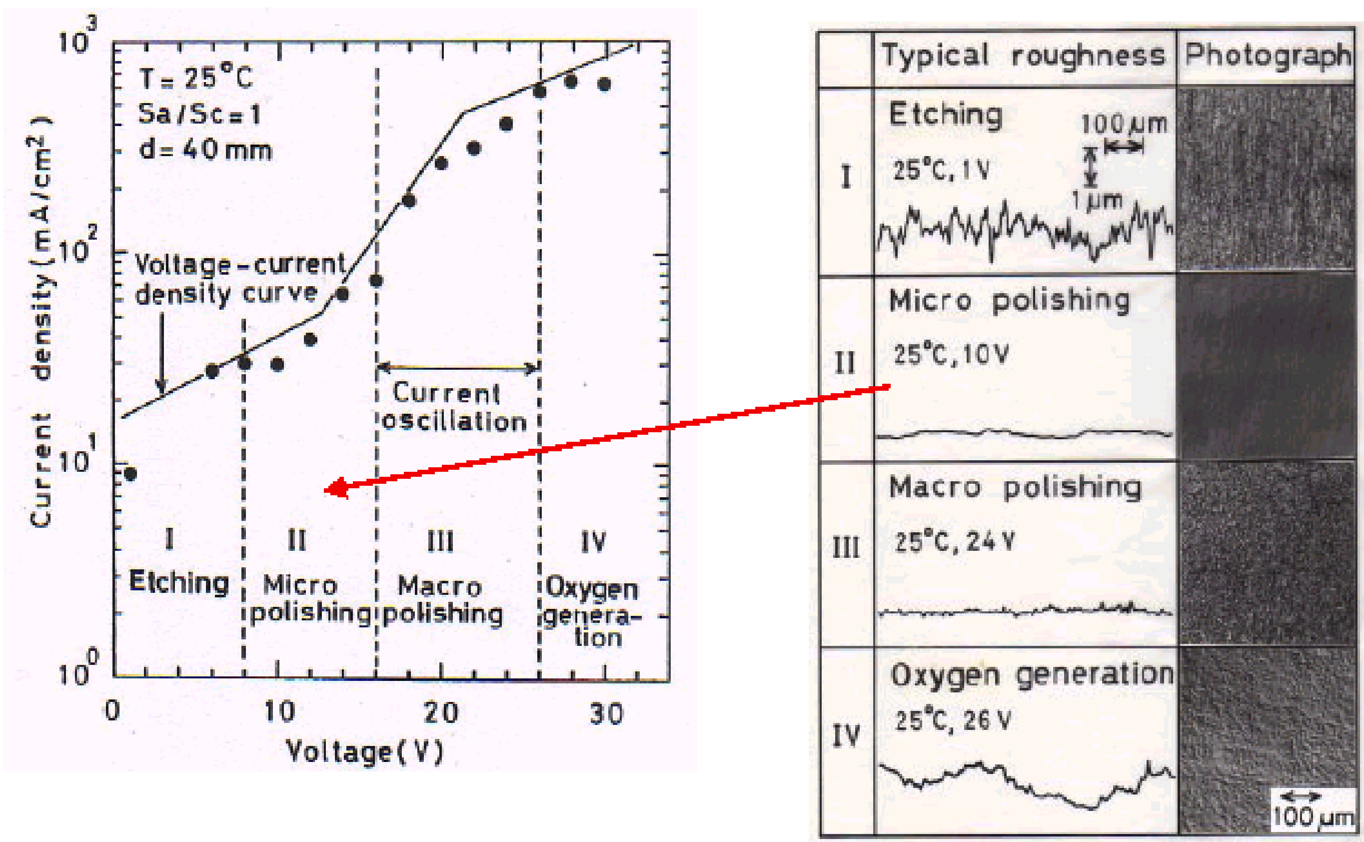
- 0-V2: Concentration Polarization occurs, active dilution of niobium
- V2-V3: Limiting Current Density, viscous layer on niobium surface
- >V3: Additional Cathodic Processes Occur, oxygen gas generated

Electrode potentials should be measured wrt a Reference Electrode!

Good surface finish when in right I(V)

Talk by K.Saito in JLAB on Oct. 2003

Micro and macro electropolishing in niobium EP

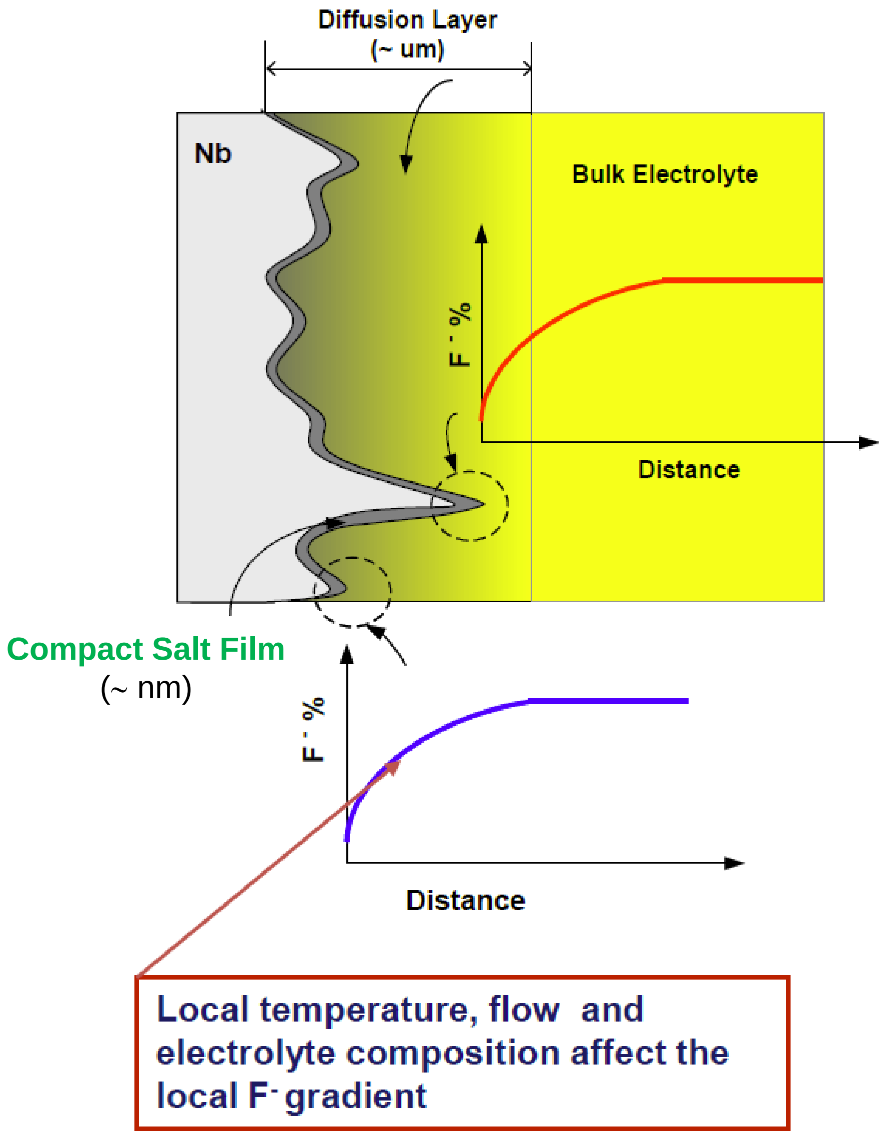


Kenji Saito, KEK, 1989

Basic Mechanism for EP

- Anodization of Nb in H_2SO_4 forces growth of Nb_2O_5
- F^- dissolves Nb_2O_5
- These competing processes result in current flow and material removal

- Above a certain anodization potential, the reaction rate plateaus, limited by how fast fresh F^- can arrive at the surface (*diffusion-limited*)
- The diffusion coefficient sets a scale for optimum leveling effects



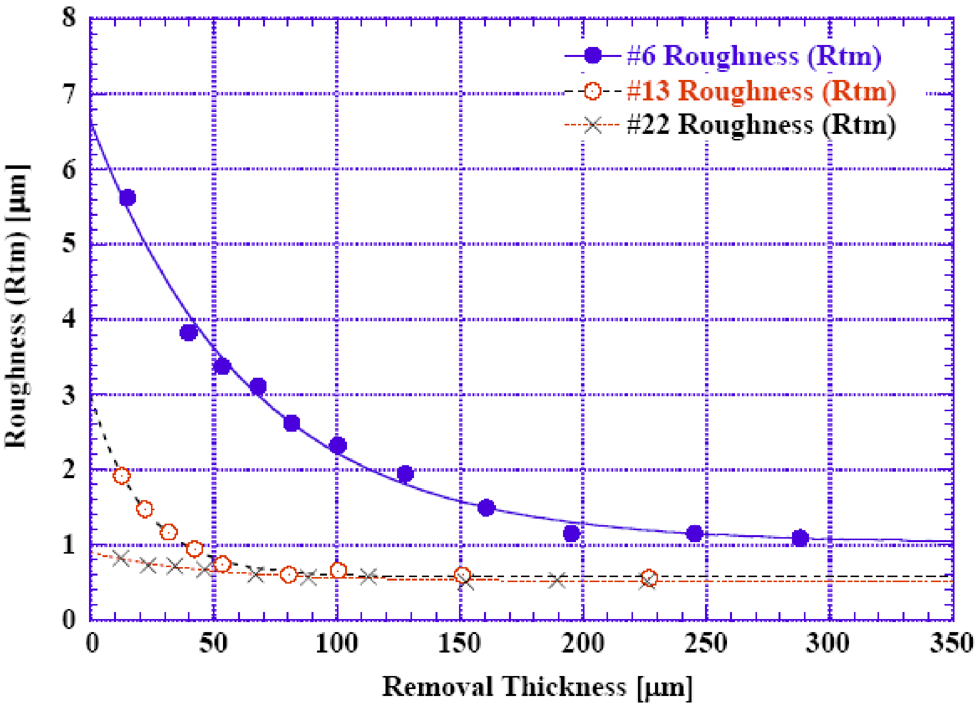
EP: tricky process

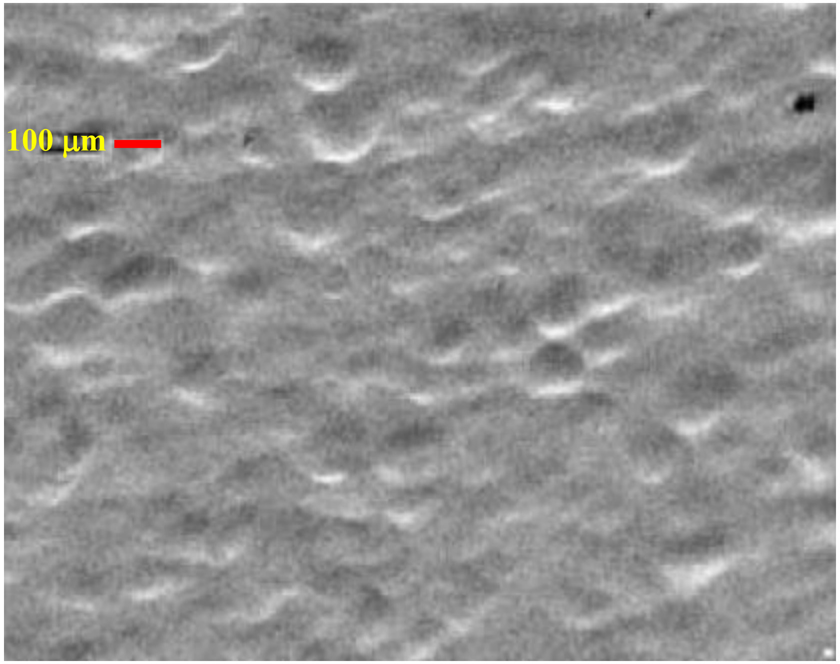
- The current density (30-100 mA/cm^2) in the plateau region:
  - decreases linearly with lower HF/H_2SO_4 ratio
  - increases with increasing temperature
- Temperature during the process is maintained between 25 – 35 °C
- Current oscillations often observed during polishing (dynamic balance between oxide formation and dissolution). It's not a necessary condition for good surface finishing but indication of good processing parameters (temperature, voltage, agitation, HF concentration)

Finding the right balance among the processing parameters becomes complicated when polishing multi-cell cavities!

EP: Smooth Surface

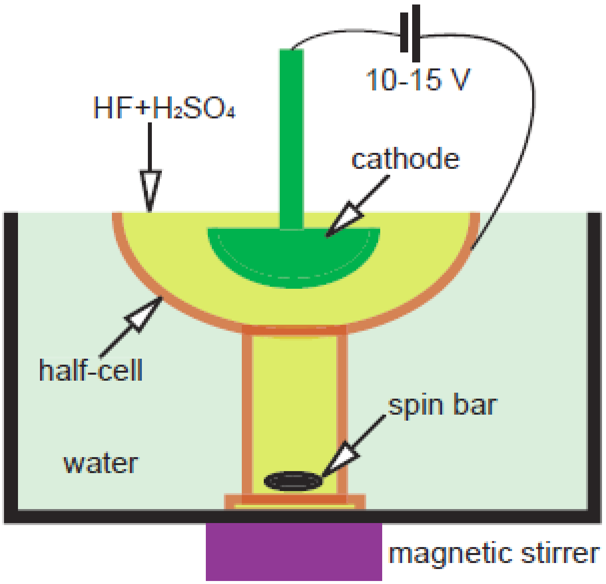
Surface roughness with EP





Typical roughness of ~ 1 μm (100 x 100 μm^2 scale)

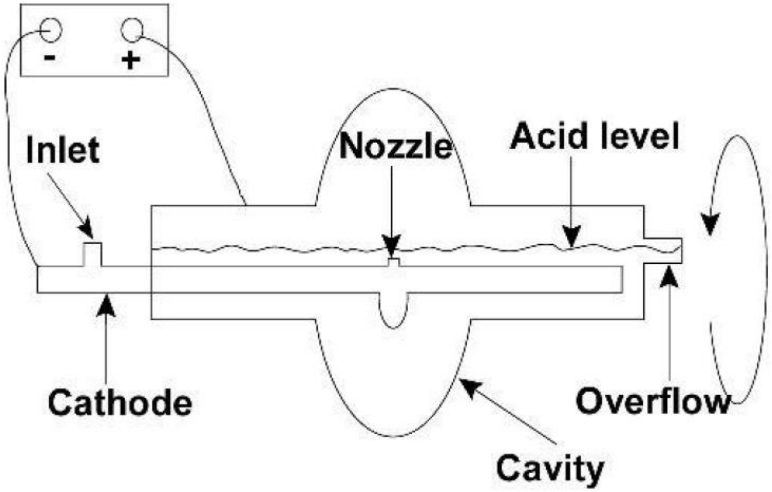
EP Setups: Half-Cells

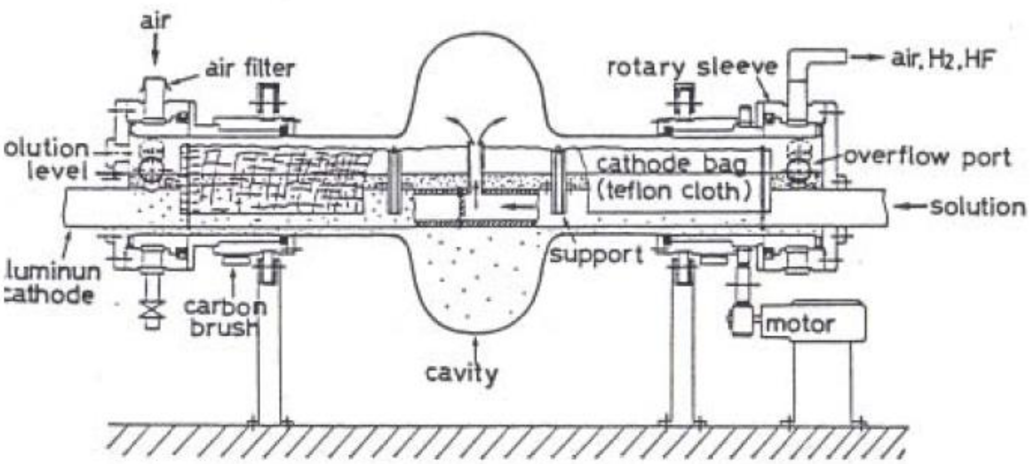


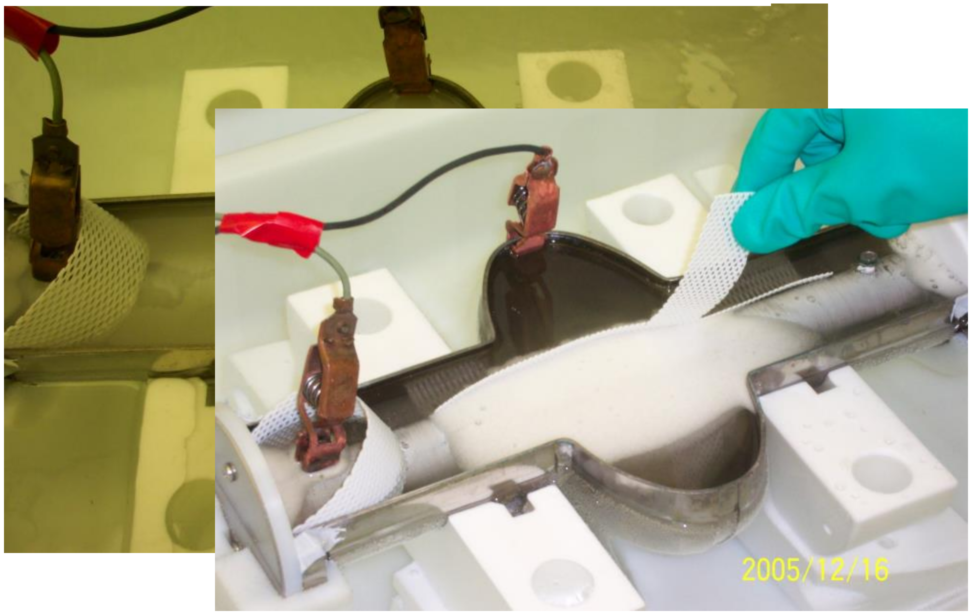
R.L. Geng, Cornell Univ.

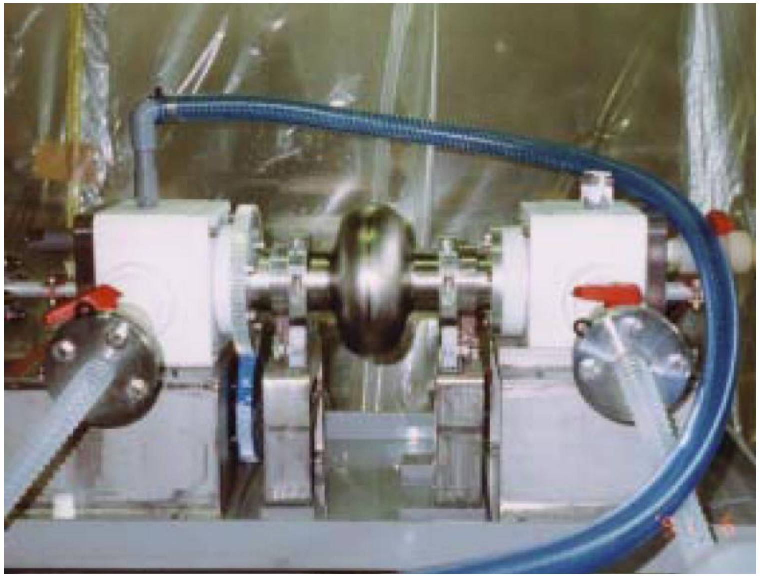
Material removal prior to final equatorial EBW

EP Systems: Single-Cell

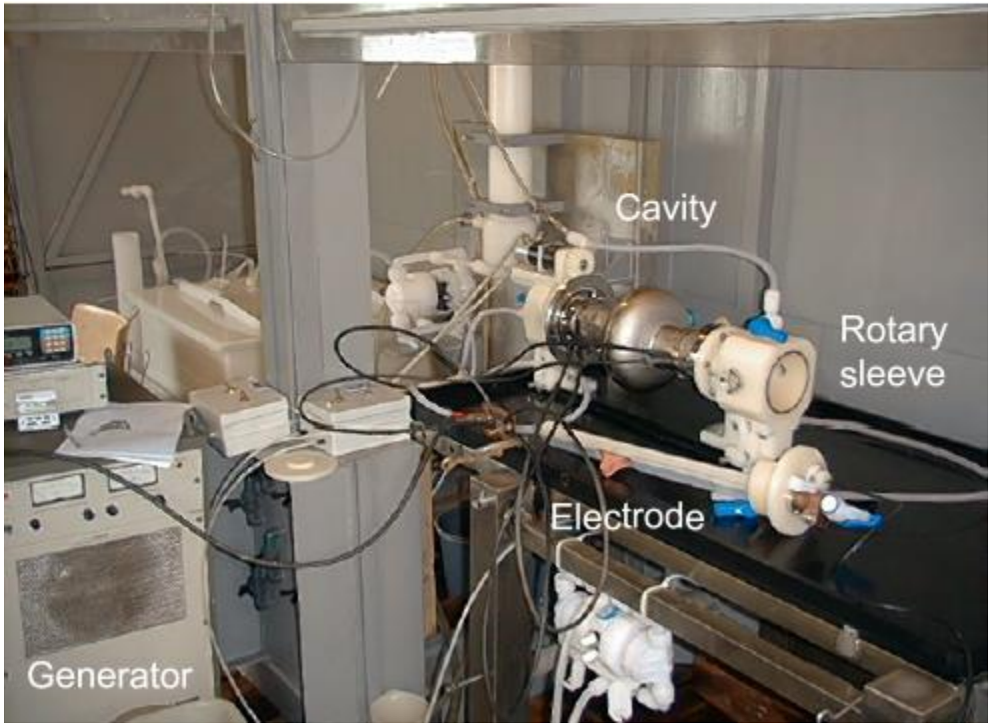


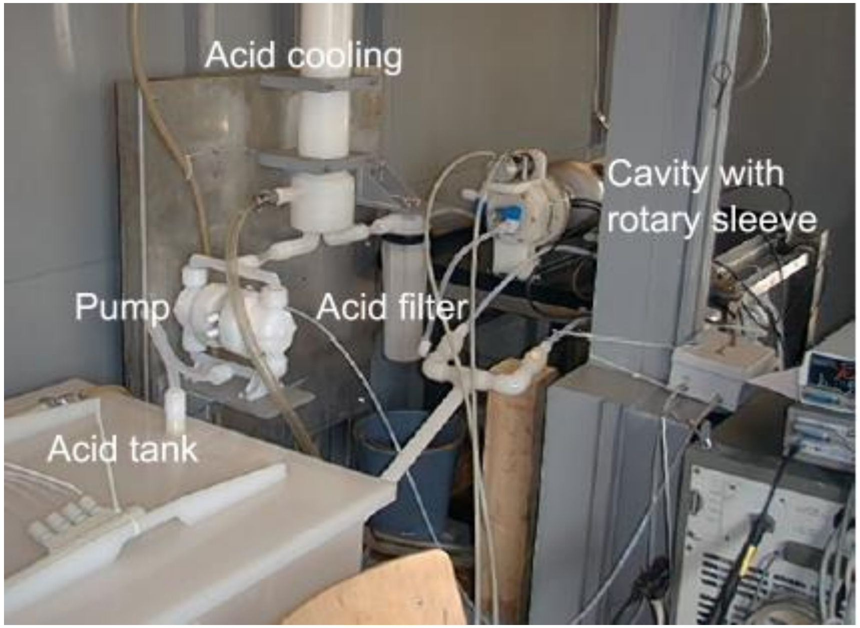






EP Systems: Single-Cell



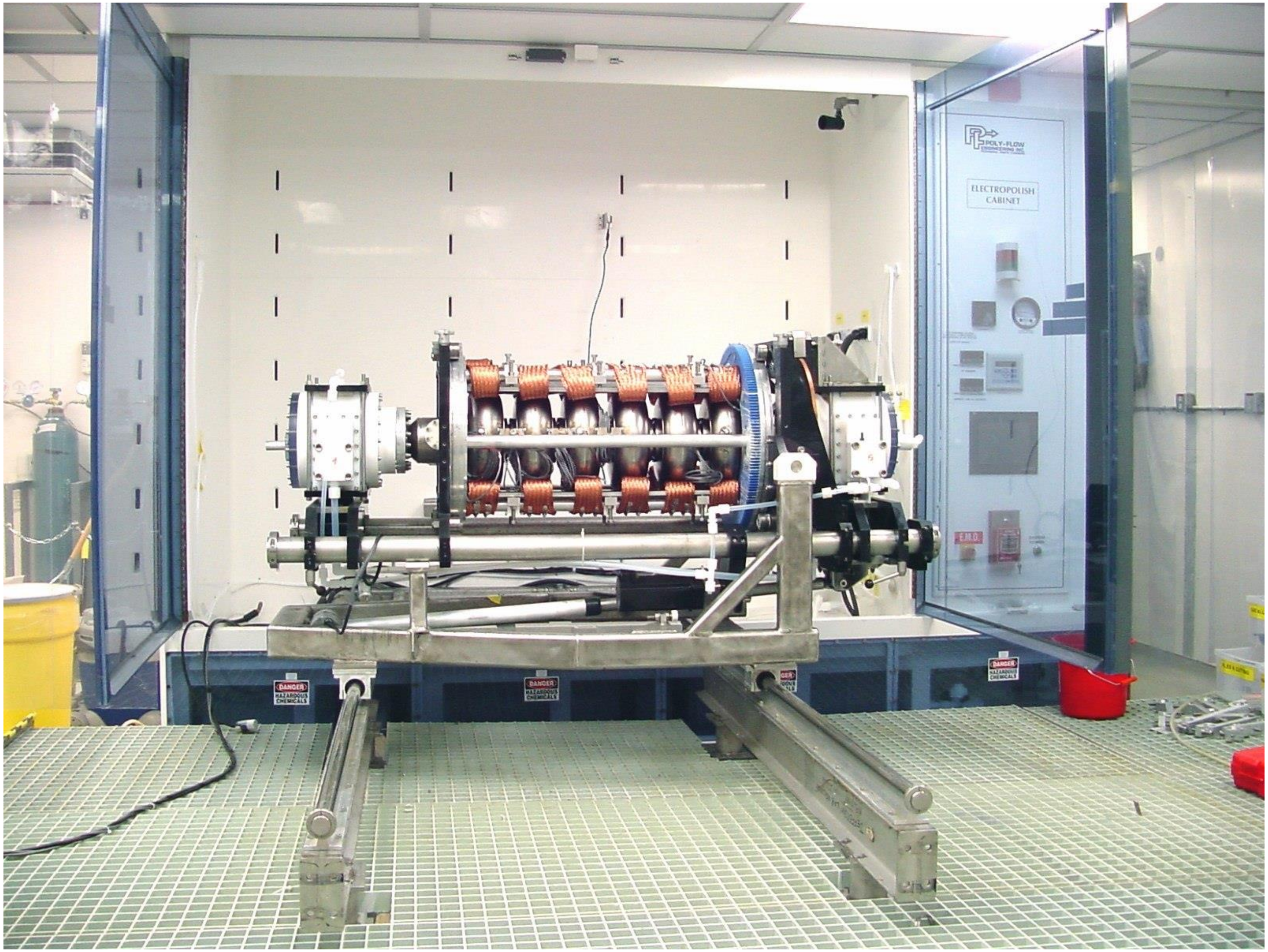


Single-Cell setup at CERN
Horizontal continuous electropolishing, polishing rate ~ 0.3 μm/min

EP Systems: Multi-cells

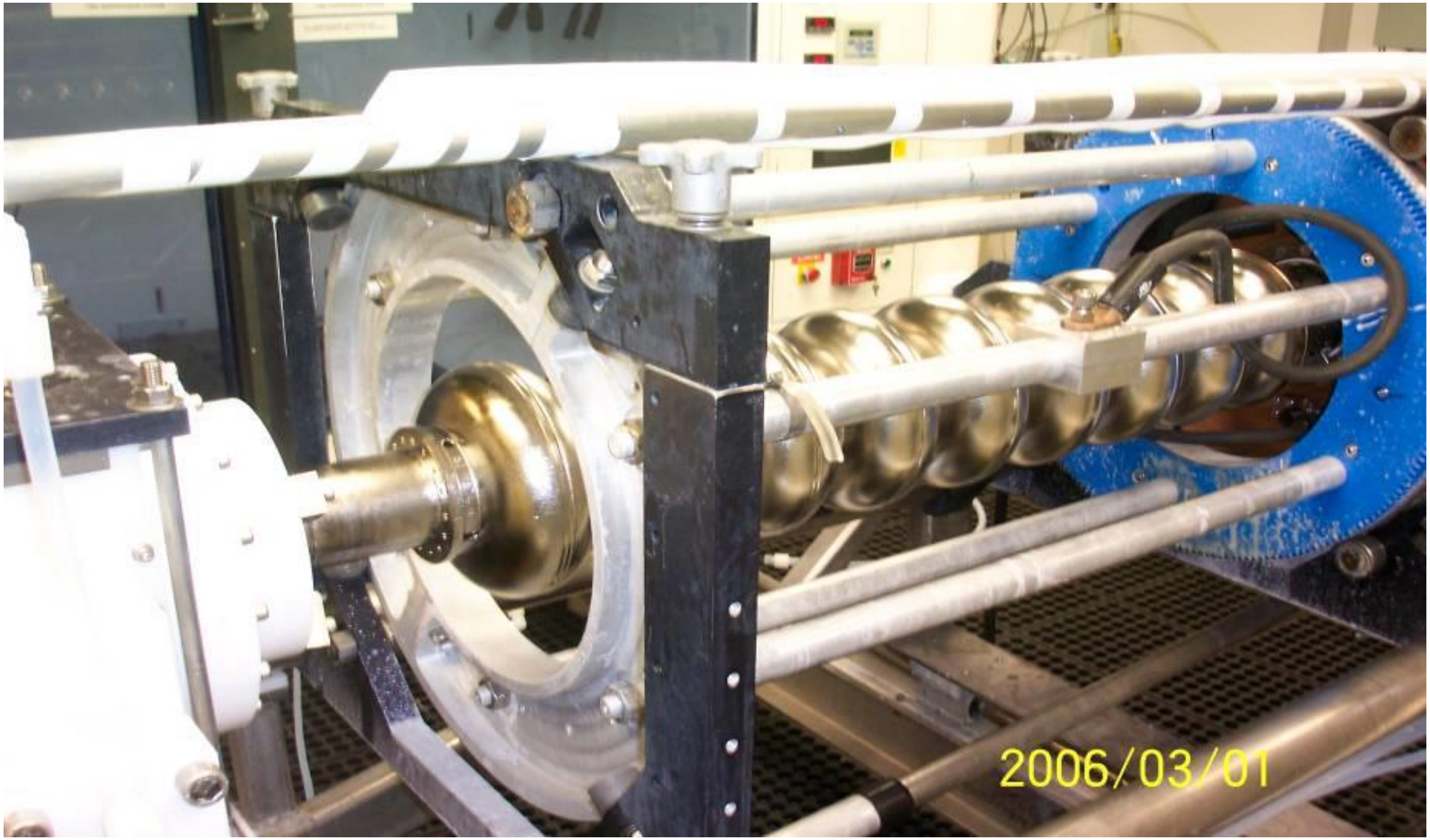
DESY

EP Systems: Multi-cells



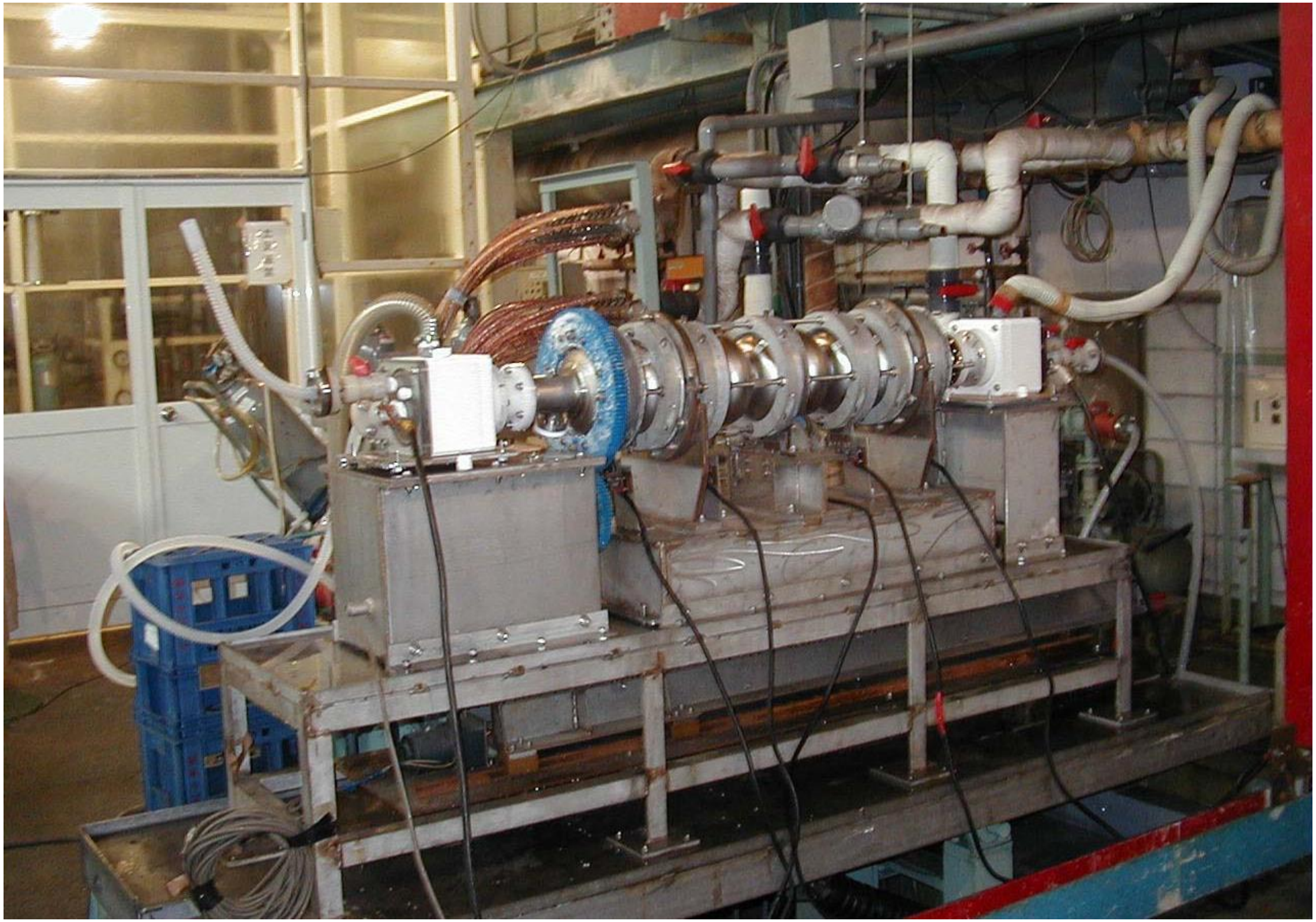
JLAB

EP Systems: Multi-cells



JLAB

EP Systems: Multi-cells



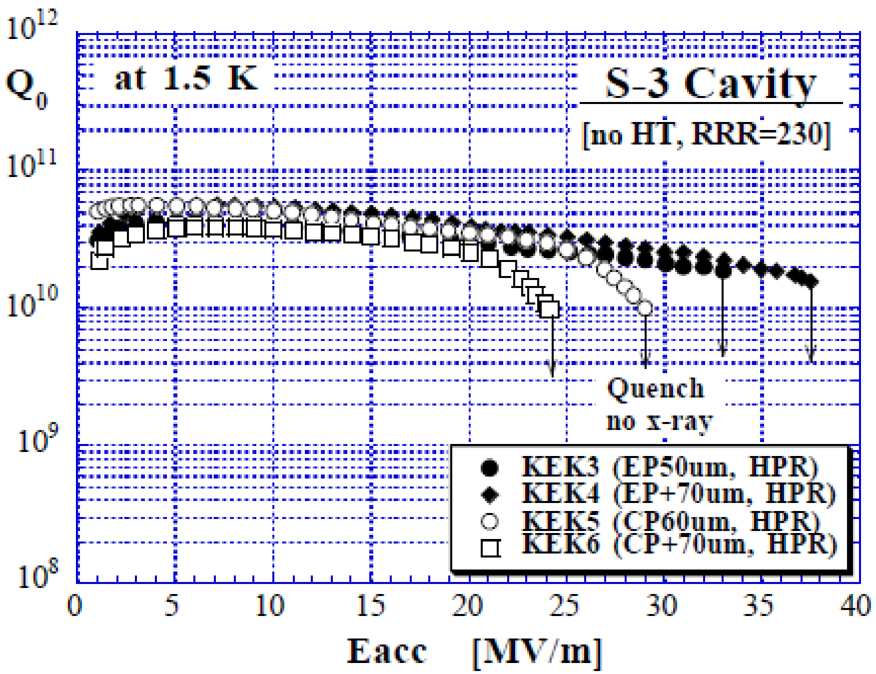
Nomura Plating and KEK

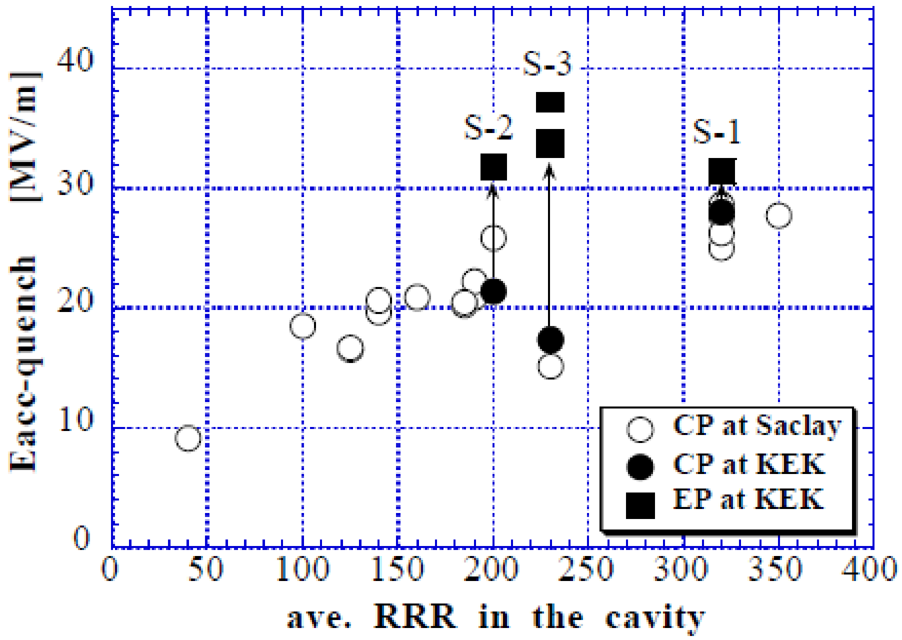
EP Issues

- HF disappears quickly from electrolyte due to surface temperature and evaporation and must be added routinely
- Difficult to add HF to the Sulfuric, reaction looses HF plus adds water to electrolyte which causes matt finishes
- Sulfur precipitates found on niobium surfaces (insoluble) and in system piping (monoclinic), impossible to add meaningful filtration
- Removal of sulfuric from surfaces difficult and requires significant amounts of DI water, hydrogen peroxide or alcohol rinses
- Typically cavity processed horizontally, slowly rotated
- Etch rate 2x on iris then equator

Why bother with EP?

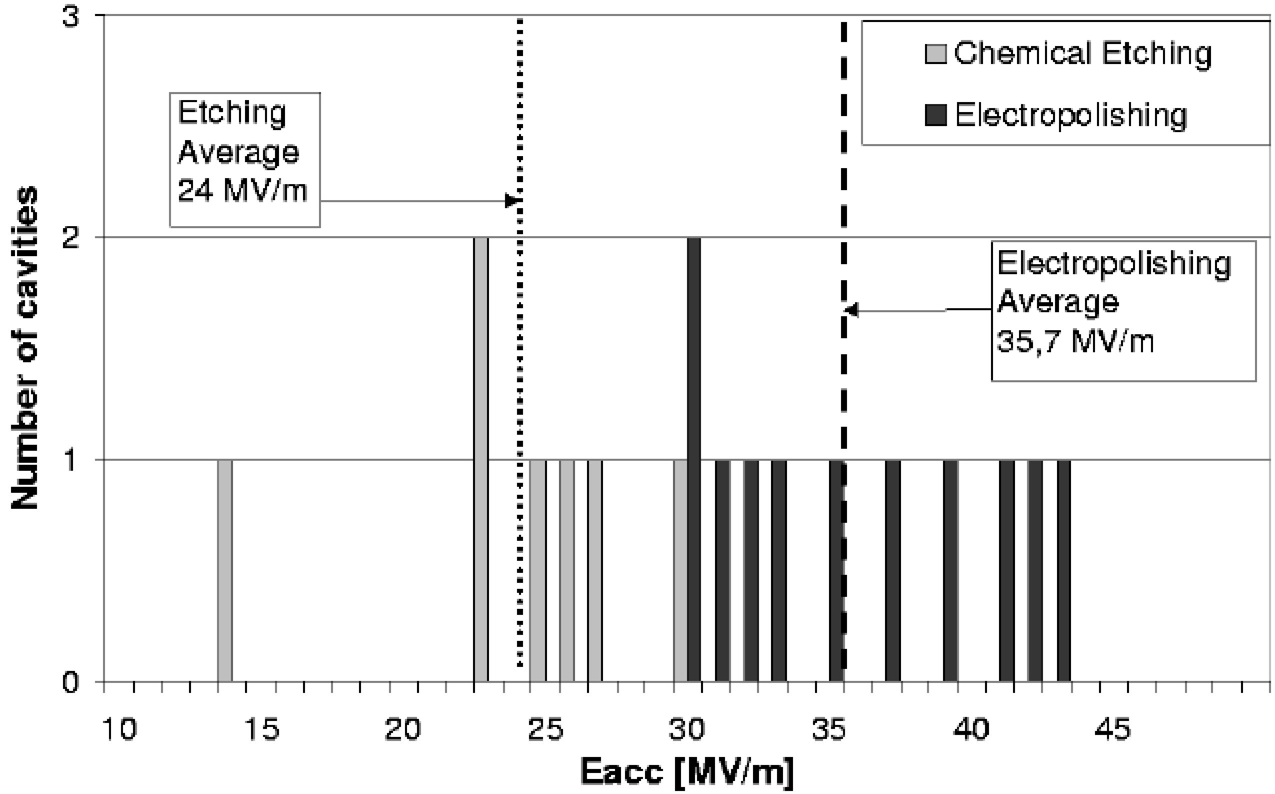
EP: achieving high accelerating field





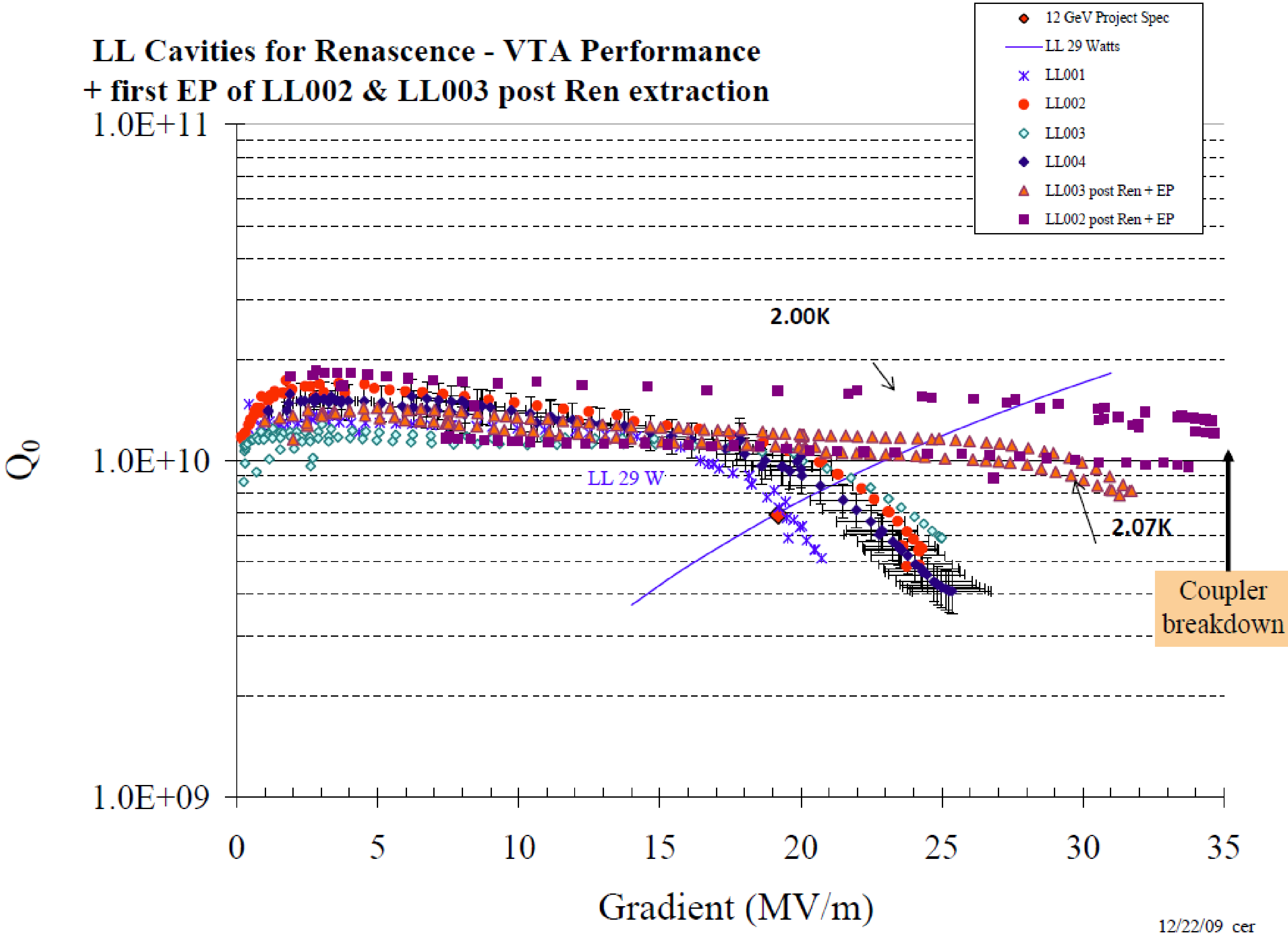
1999, KEK

EP: achieving high accelerating field



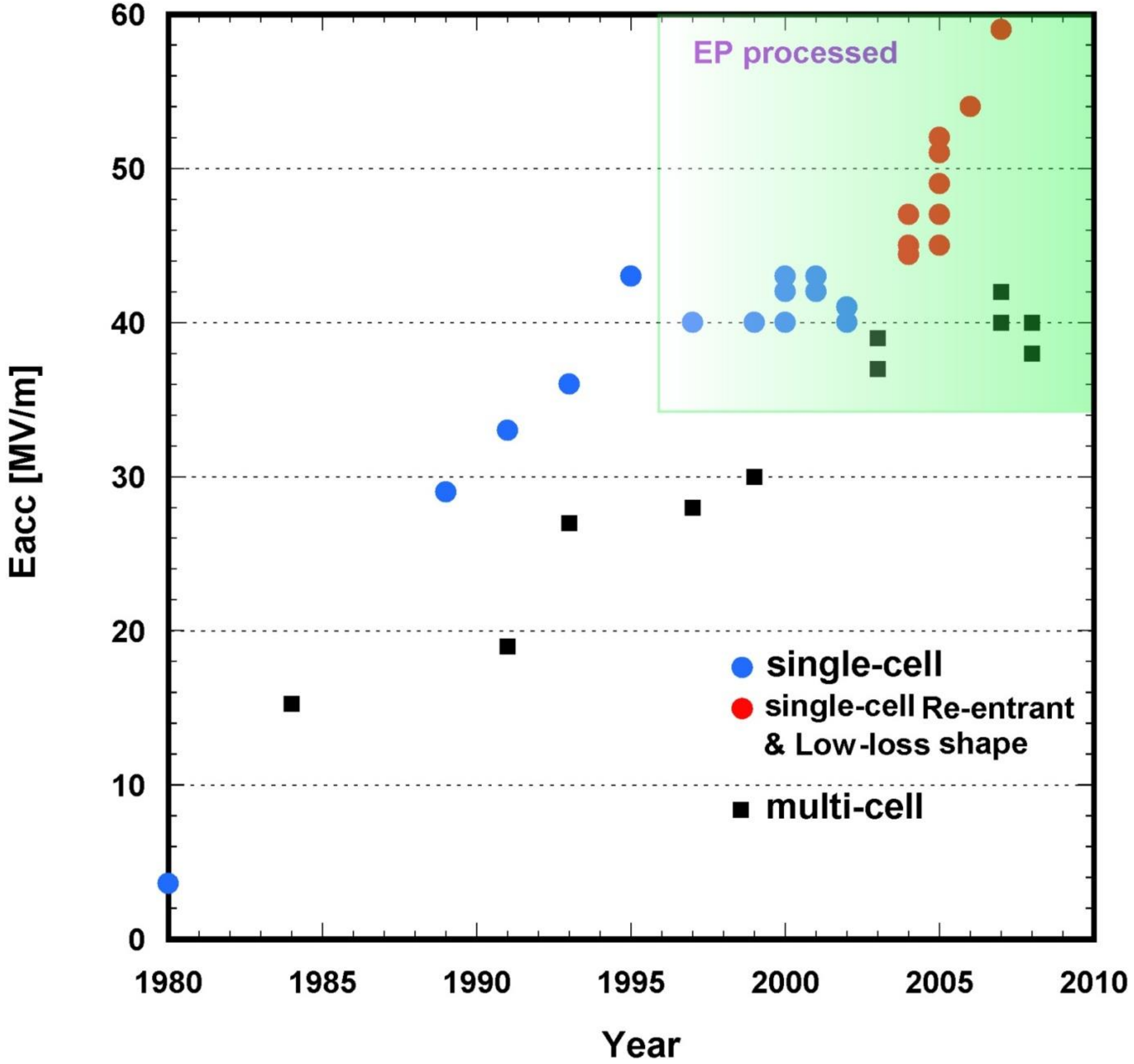
2001, CERN-CEA-DESY Collaboration

EP: achieving high accelerating field



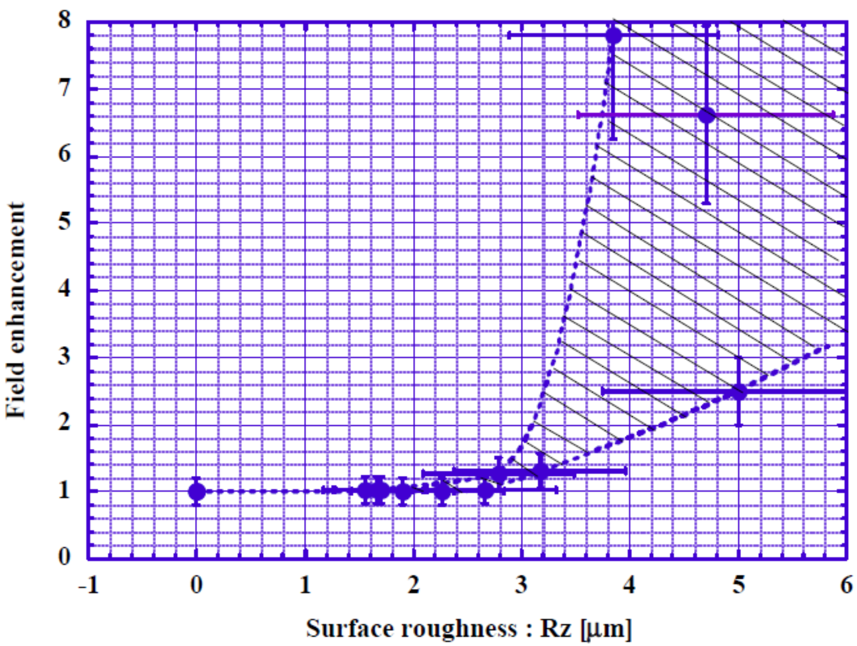
2009, JLab

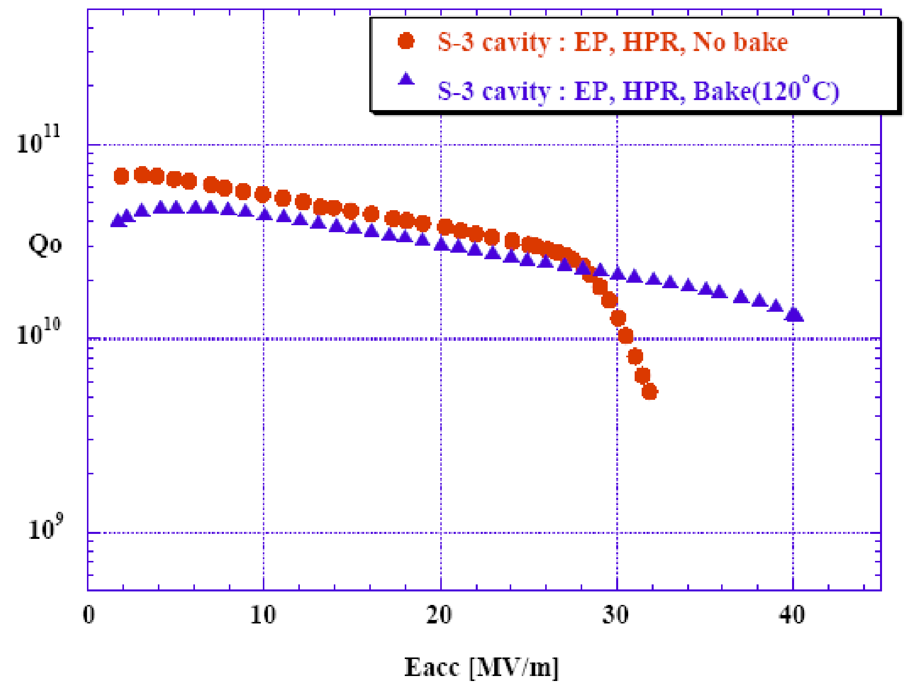
EP: achieving high accelerating field



Why Is EP Better?

- Q-drop recovers after baking
- Smoother surface



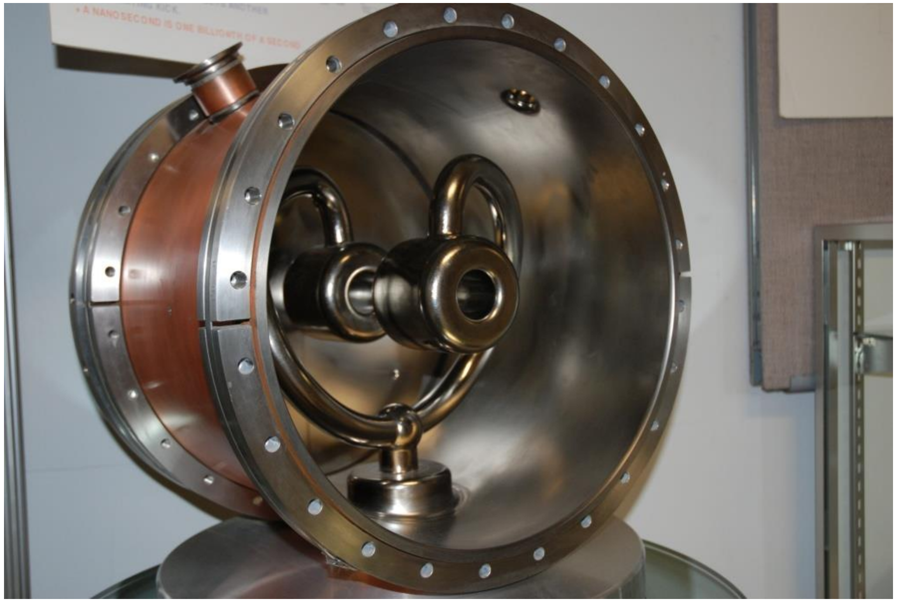


$$E_{acc,\max} \propto \frac{r\ H_{c,RF}}{\beta}$$

β = magnetic field enhancement factor

r = reduction of critical magnetic field due to “polluted” surface layer

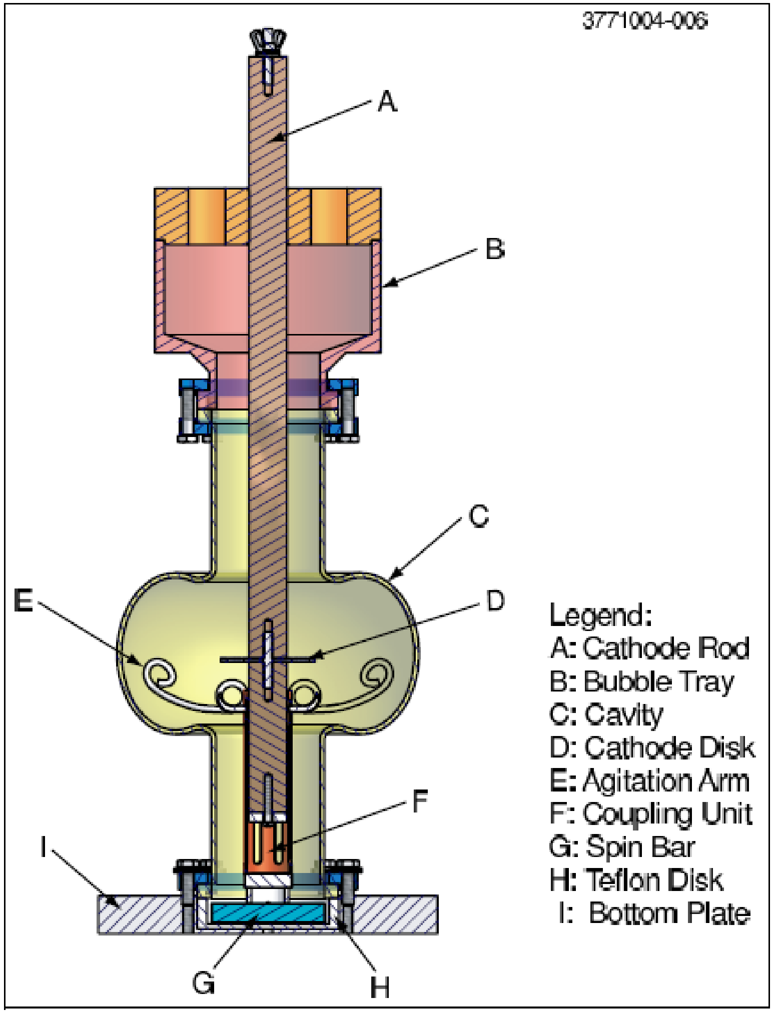
EP: used also in low-β cavities for heavy ion accelerator



SRF cavities for ATLAS and future FRIB

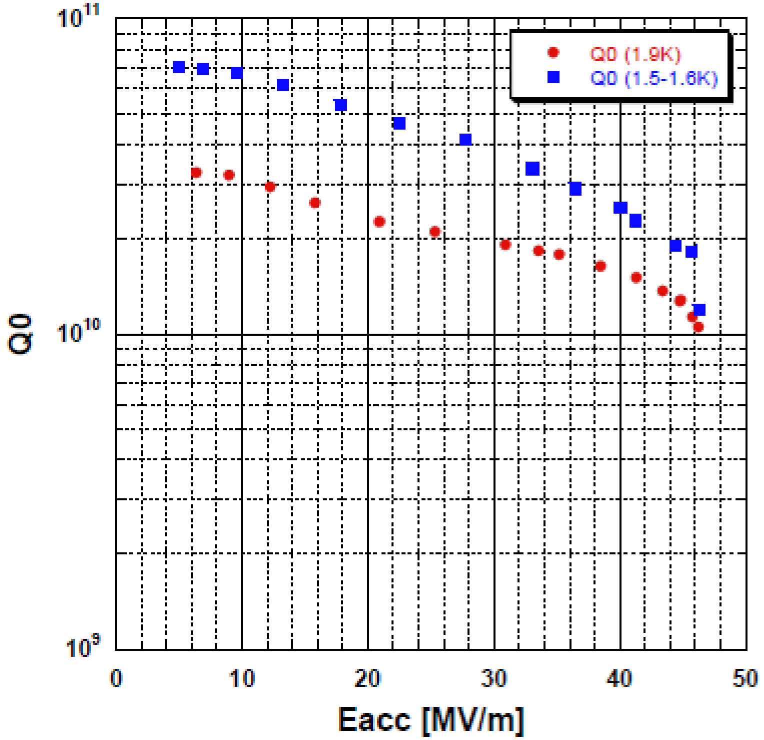
Argonne Nat'l Lab

Vertical EP

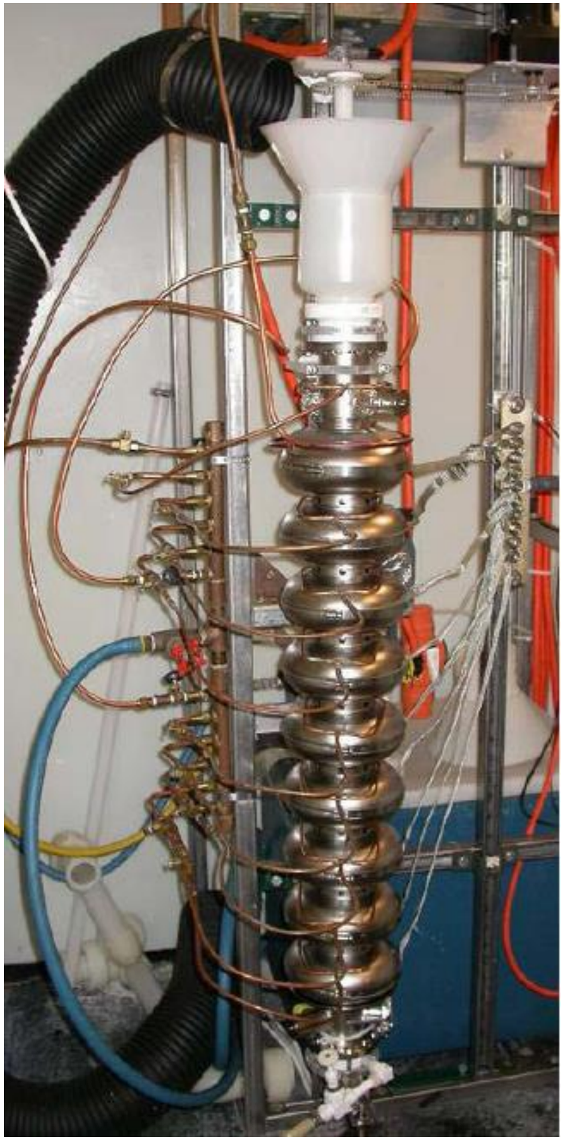


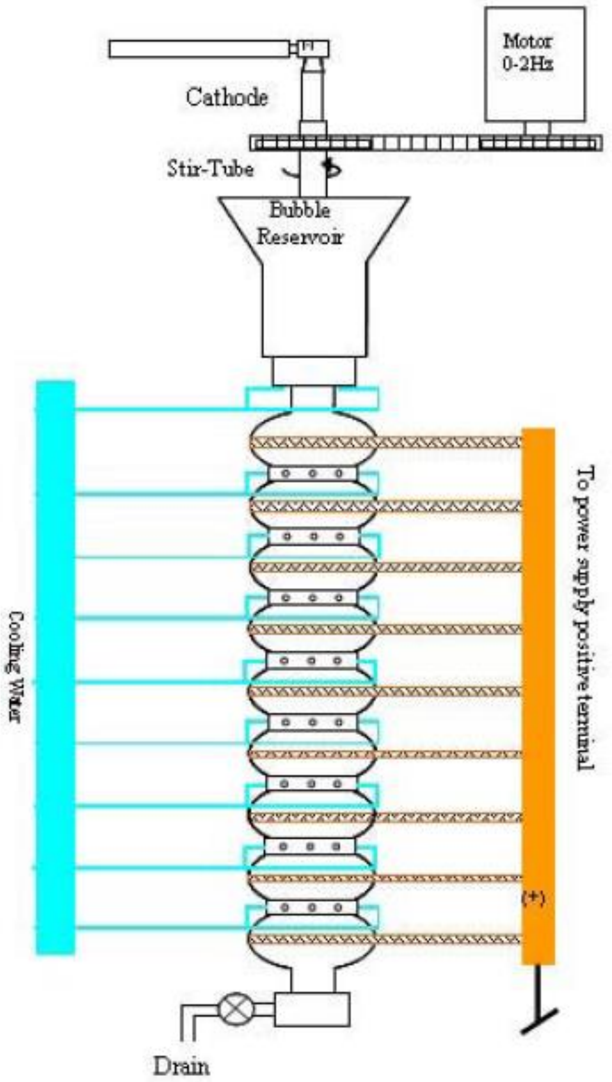
Cornell Univ.

- No rotary acid seals
- Twice removal rate than horizontally rotating EP
- No sliding electrical contacts
- No large acid reservoir and heat exchanger

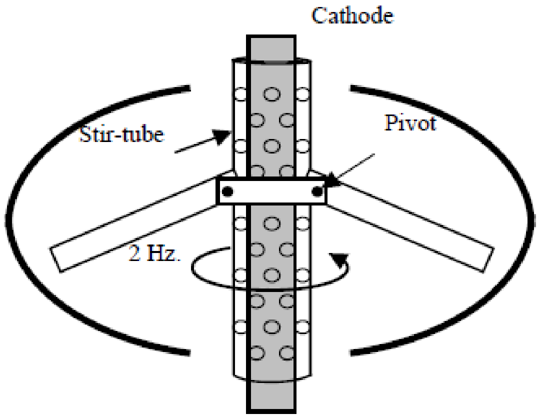


Vertical EP

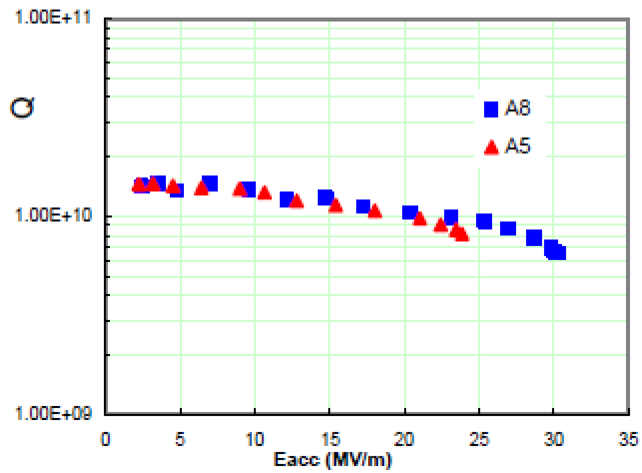




Motor
0-2Hz
Cathode
Stir-Tube
Bubble
Reservoir
Cooling Water
To power supply positive terminal
(+)
Drain

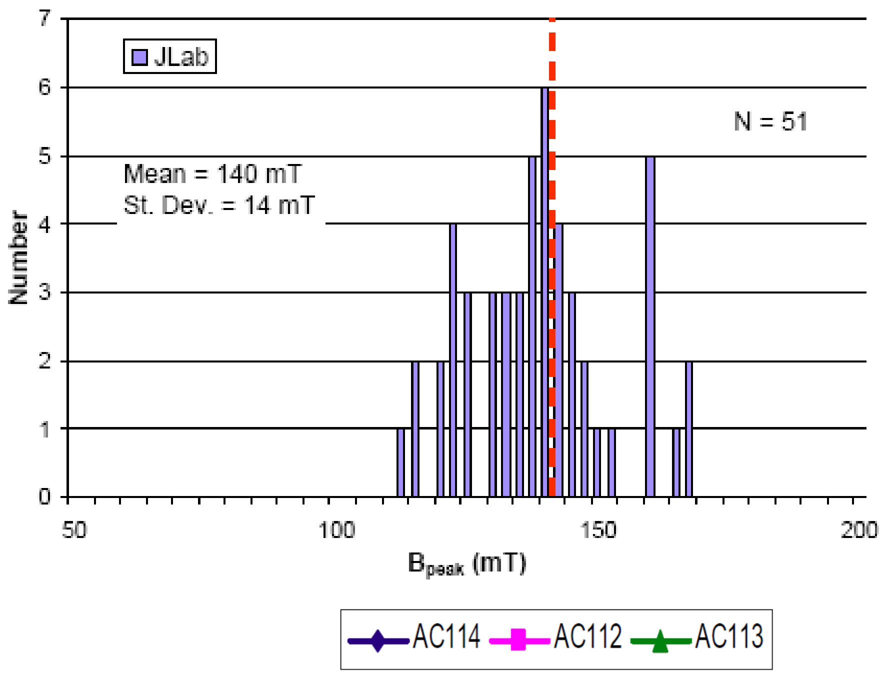


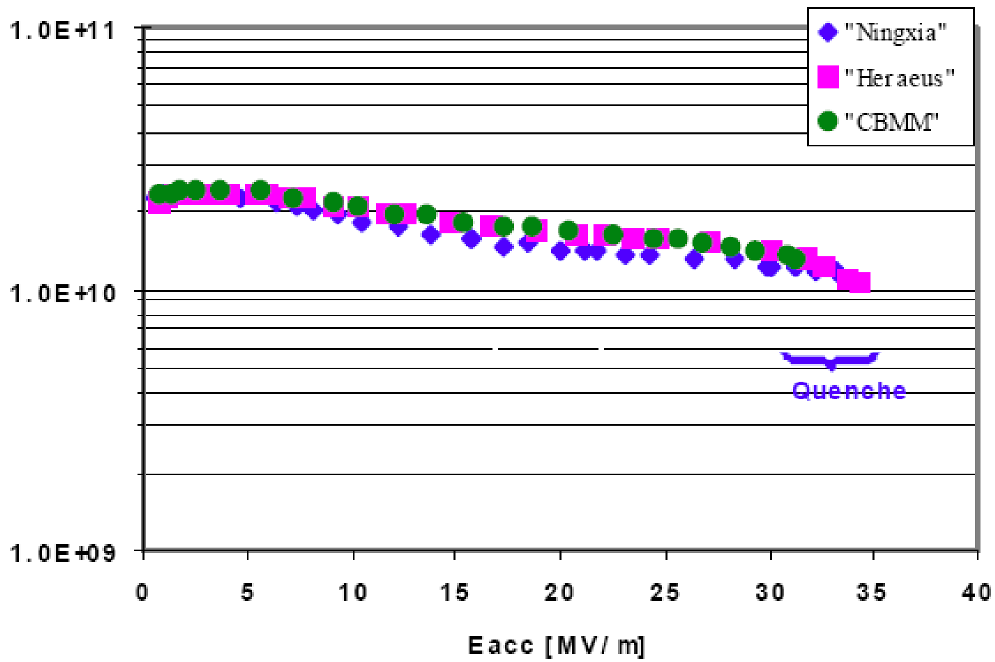
Cathode
Stir-tube
Pivot
2 Hz.

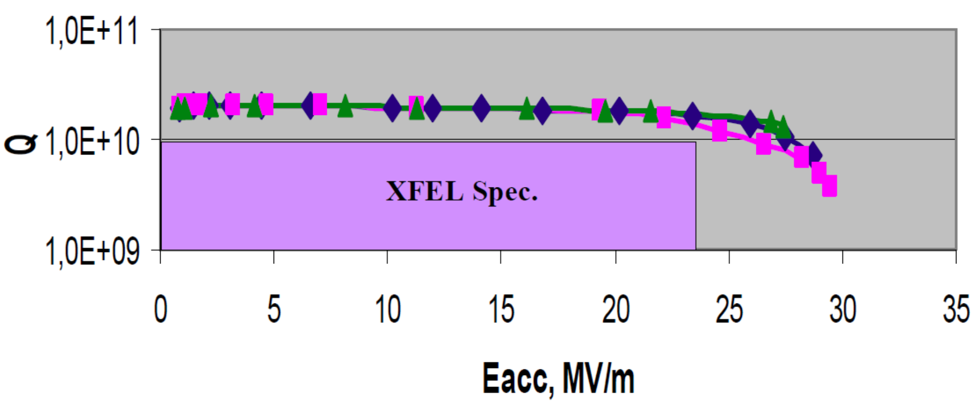


1.00E+11
1.00E+10
1.00E+09
Q
A8
A5
0
5
10
15
20
25
30
35
Eacc (MV/m)

Challenge to EP: Large Grain Nb & BCP

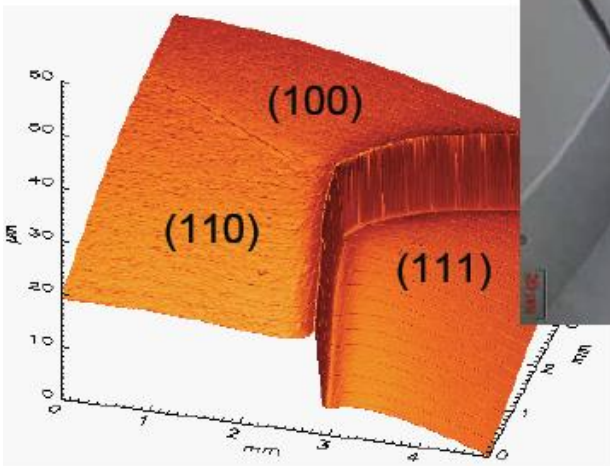


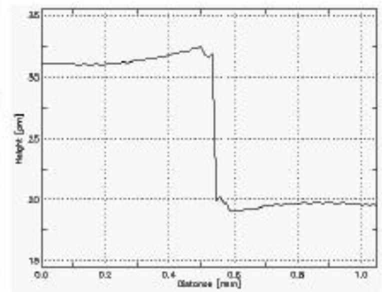


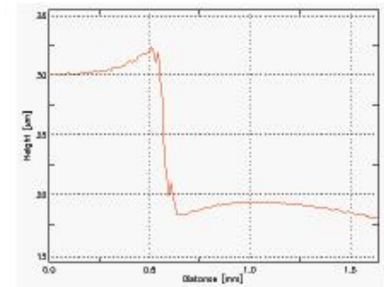


- Very reproducible performance
- $E_{acc} \geq 30$ MV/m is possible

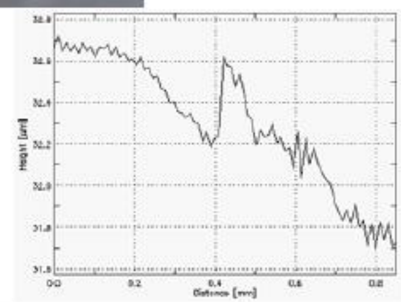
Large-Grain Nb Surface After BCP



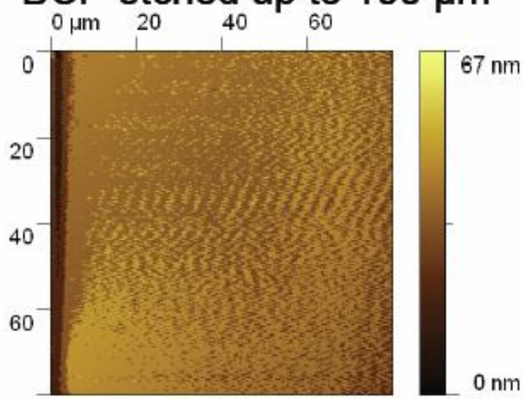


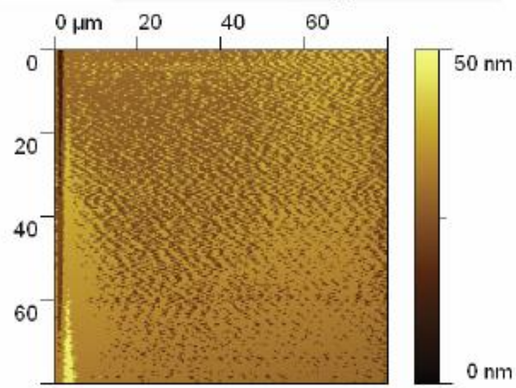


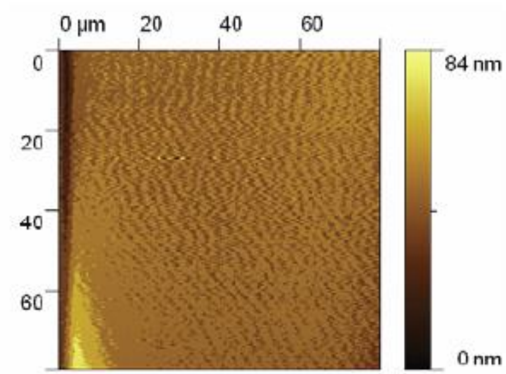
Light microscope and AFM image of LG Nb, BCP etched up to 100 µm



Profile and step heights of the three grain sample at the grain boundary intersection

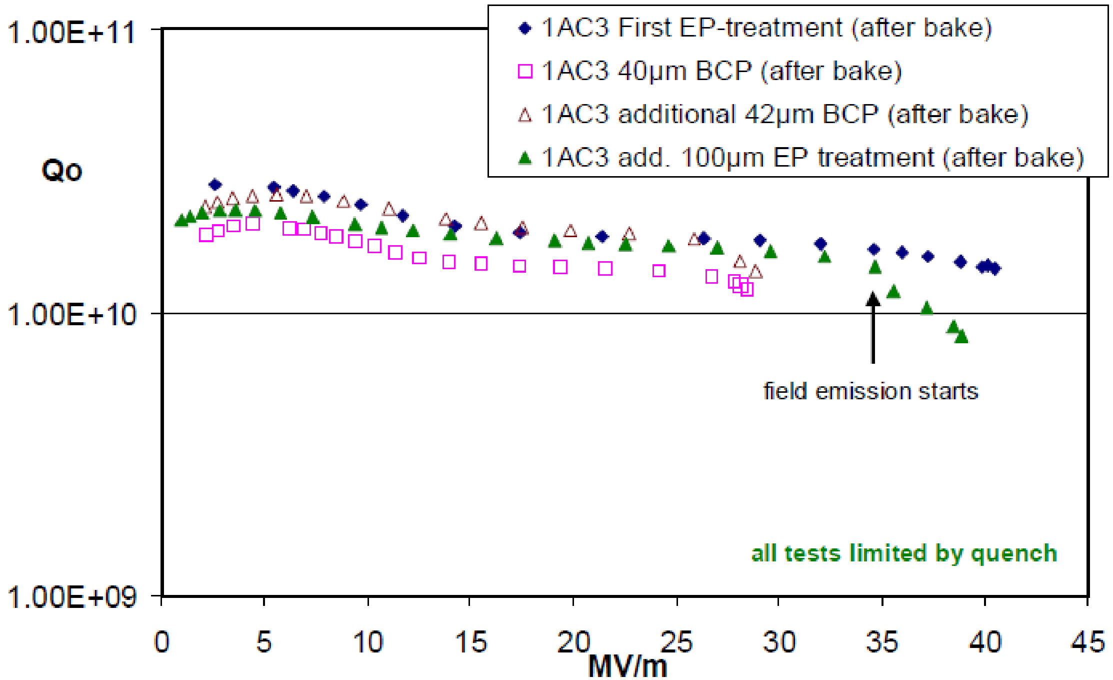






Roughness of fine-grain Nb sample treated by EP is ~ 250 nm

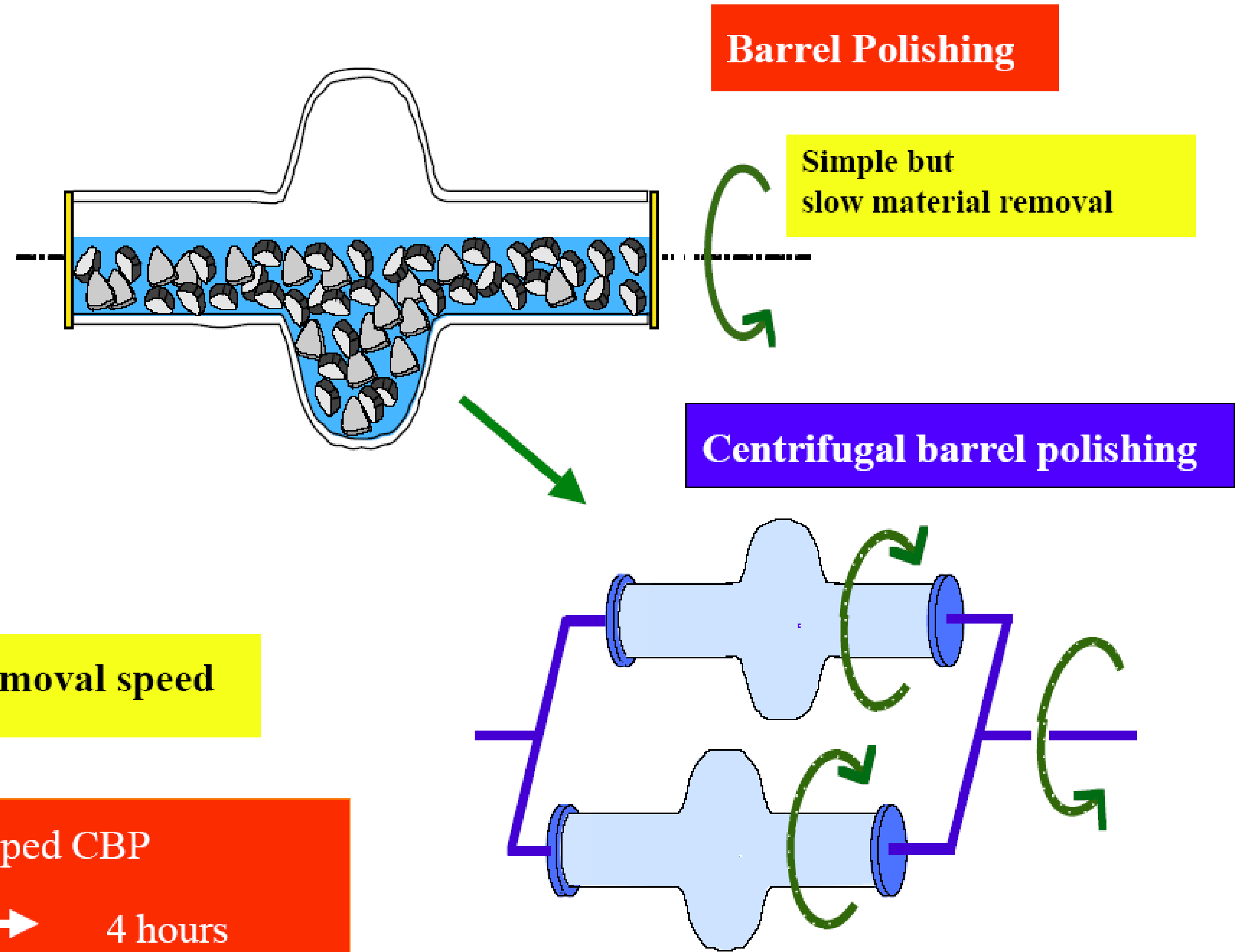
Challenge to EP: Large Grain Nb & BCP



	Quench gradient after final EP	Quench gradient after final BCP
Large grain Nb	(33 – 43) MV/m	(25 – 30) MV/m
Fine grain Nb	(36 ± 4) MV/m	Data not sufficient

- Studies at DESY show higher E_{acc} after EP even for large-grain Nb
- The typical performance of large-grain Nb cavities treated by BCP would satisfy the requirements for most accelerator projects

Centrifugal Barrel Polishing



High material removal speed

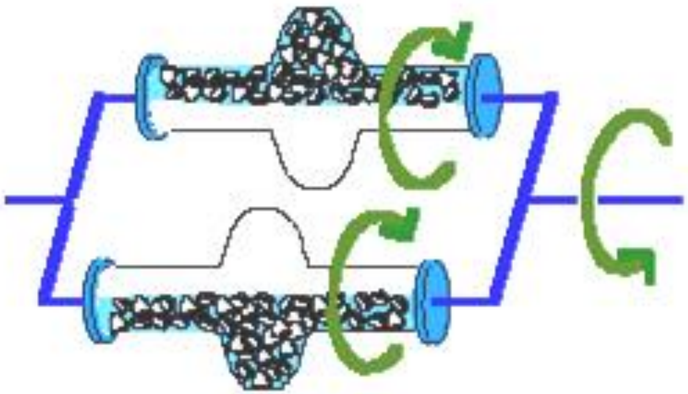
Succesufully developed CBP

One week → 4 hours

Developed in 2001 at KEK

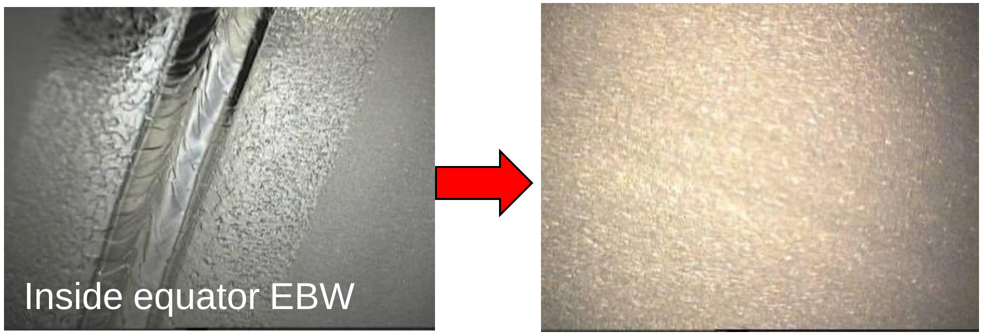
CBP Implementation

Centrifugal Barrel Polishing (CBP)



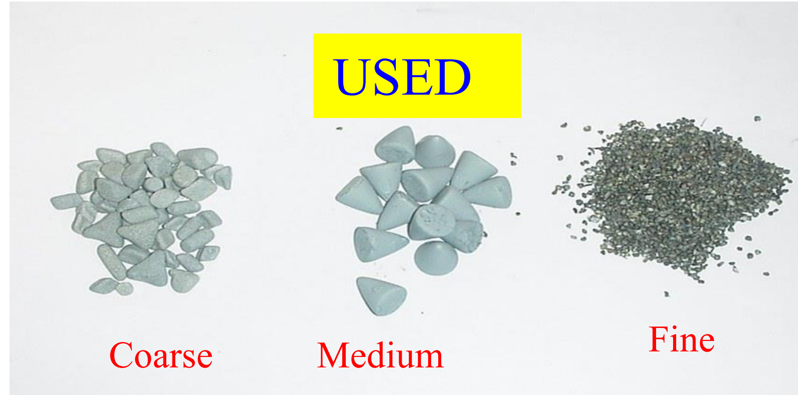
Implementation:

- Plastic stones and liquid abrasive added inside cavity and rotated
- Stones rubbing on surface removes material thus smoothing the surfaces (including weld areas)
- Benefit is less overall chemistry needed (80 µm) and smooth weld areas

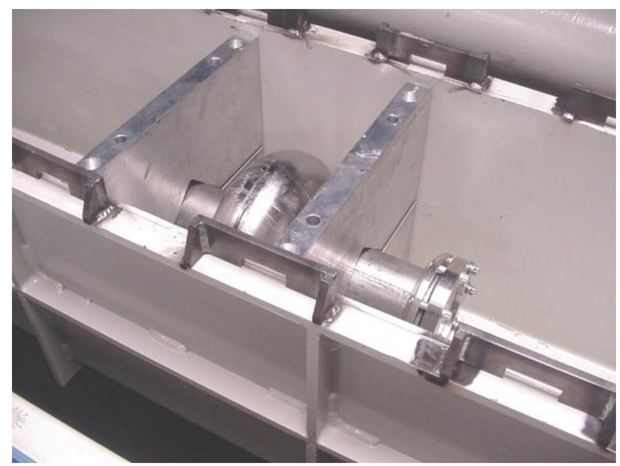


- Removal of material 2x on equators then irises. Average removal rate ~ 5 µm/h

Barrel Polishing Machine at JLab



- Removal rate ~ 3 – 4 μm/h

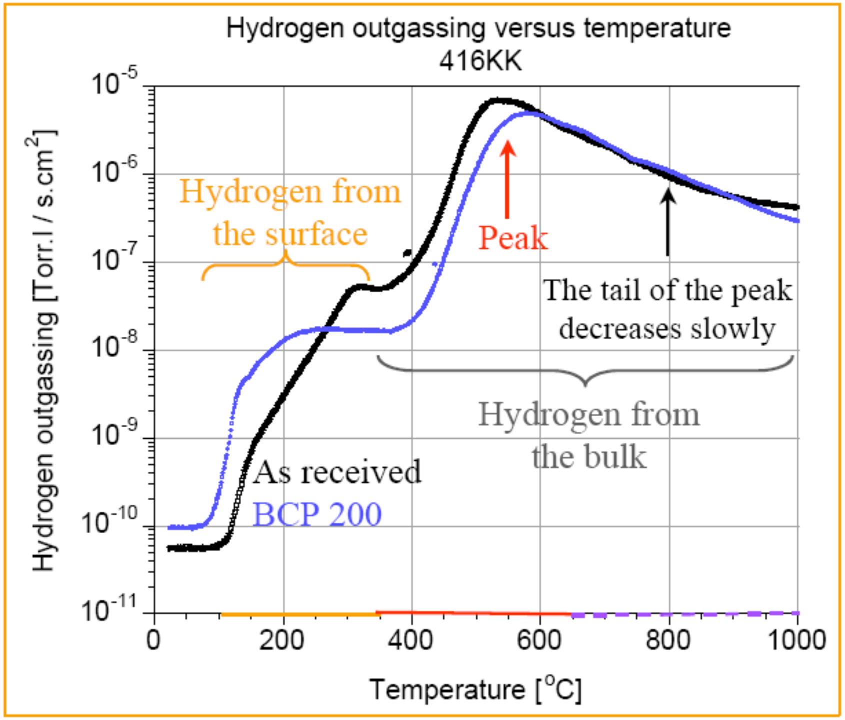


Required Procedures for Qualifying SRF Cavities

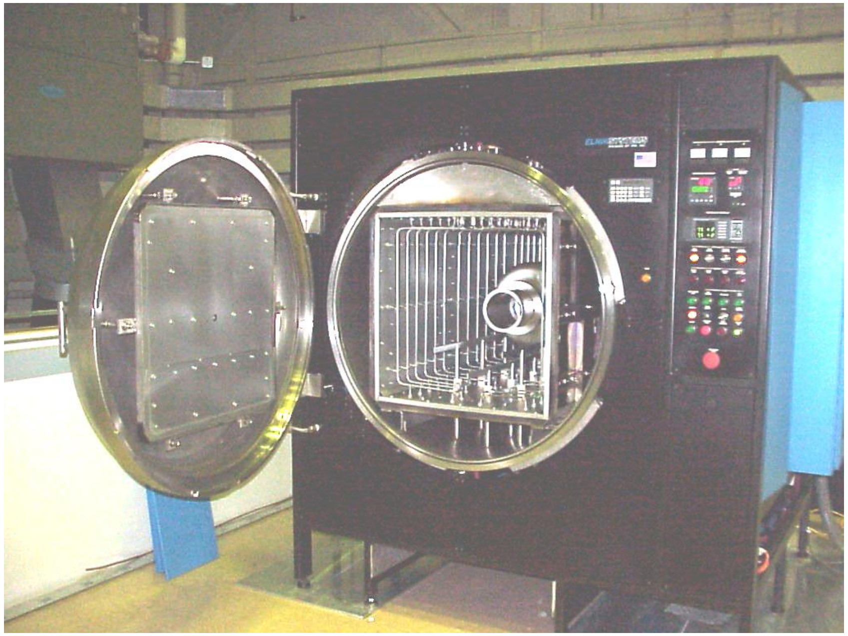
- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 µm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 µm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in clean room (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

Heat Treatment for H-degassing

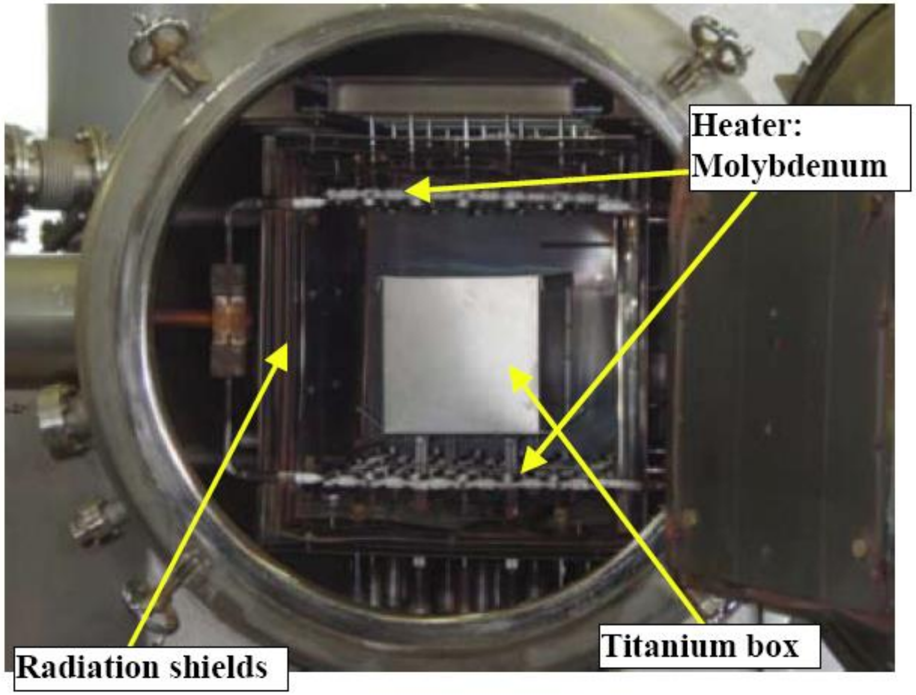
- H absorption occurs during chemical and/or mechanical material removal
- Reduce bulk H concentration in Nb to avoid Q-disease
- The heat treatment also “stress-relieves” the Nb
- Different parameters at different labs:
  - 600 °C/10 h at JLab
  - 800 °C/2 h at DESY
  - 750 °C/3 h at KEK



High Temperature Vacuum Furnace



Heat Treatment Furnace at JLab up to 1250 °C, P ≤ 10^{-6} Torr



Vacuum furnace in KEK : Temp.= 1300 ^{O}C max, Vac. = 1xE-6 torr

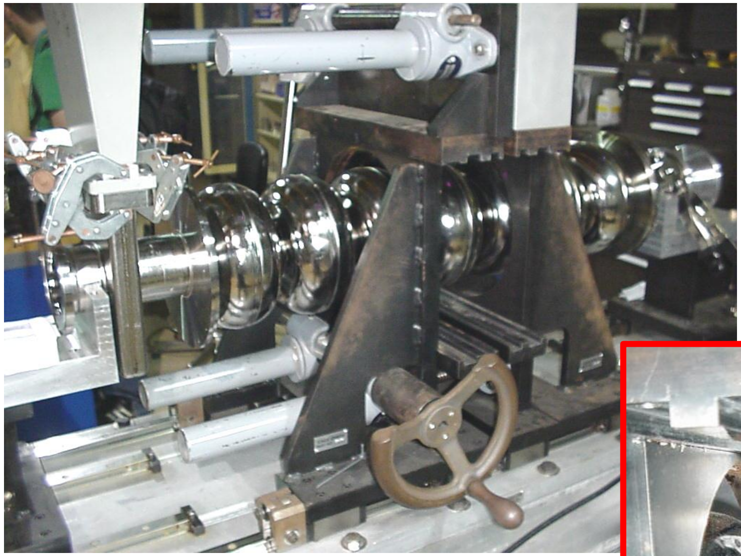
Use Residual Gas Analyzer to monitor the partial pressure of residual gases during heat treatment

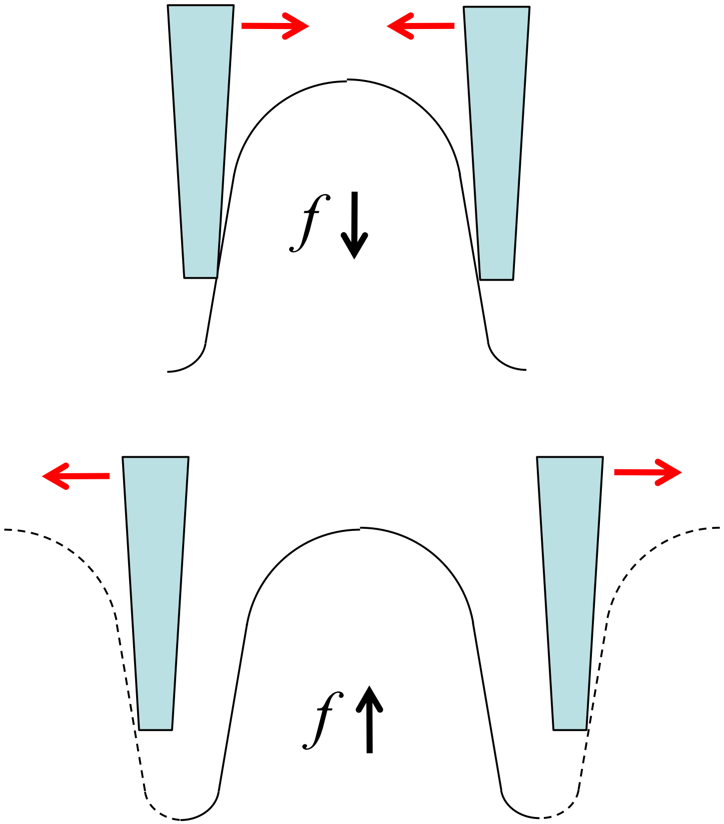
Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in clean room (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

Mechanical Tuning

- Small mechanical adjustments to the cavity's cells to obtain flat field profile and desired frequency

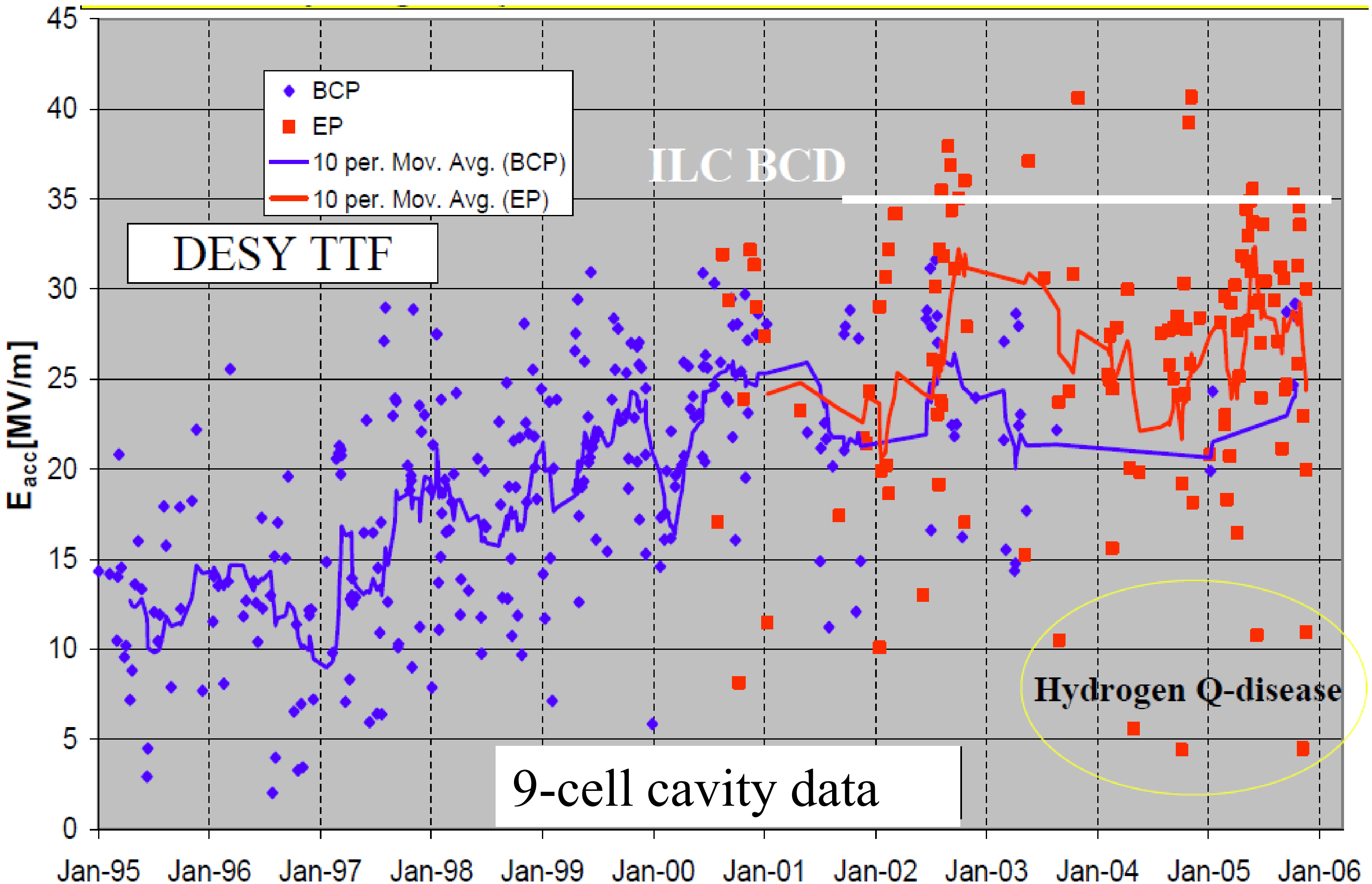




Post-EP Cleaning

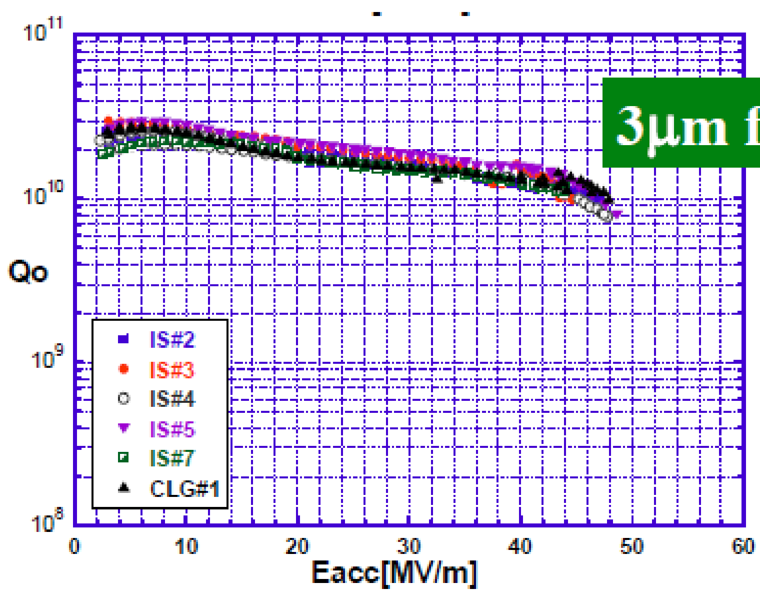
- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional “cleaning” steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in clean room (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

EP: high E_{acc} but large scattering

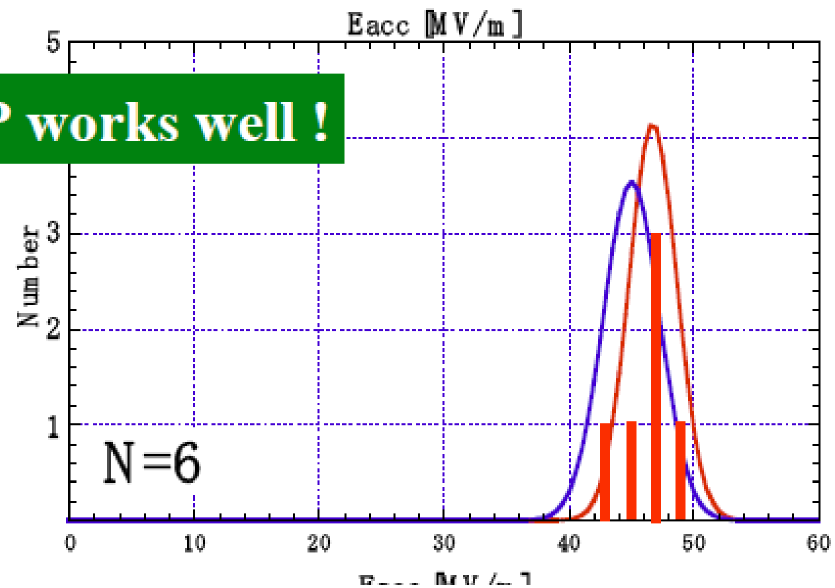


Post-EP Cleaning Processes

- Ethanol Rinse (DESY)
- "Flash" BCP (10 μm) (DESY)
- "Flash" EP (3 μm, fresh acid, no re-circulation) (KEK)
- Ultrasonic Degreasing with Micro-90 and hot water (JLab)



3μm fresh EP works well !

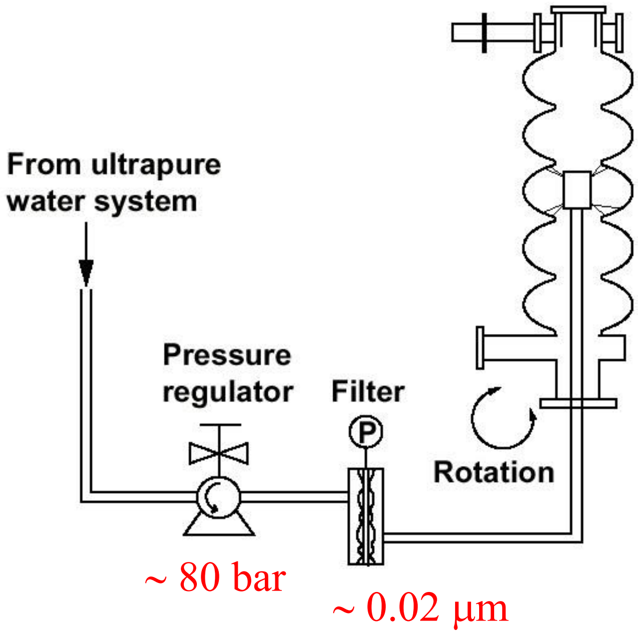


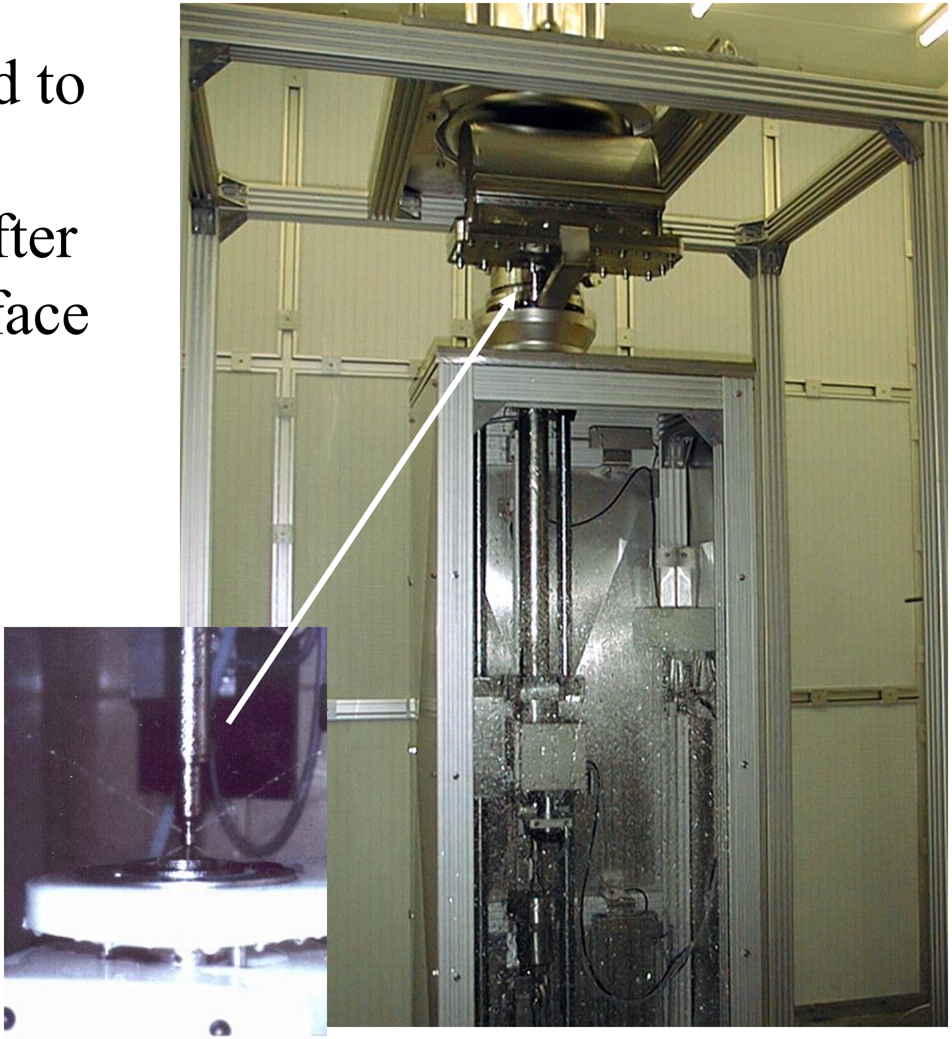
Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in clean room (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

High Pressure Rinsing (HPR)

- SRF cavities cleaning method to remove particulates from handling and contaminants after chemistry from the inner surface

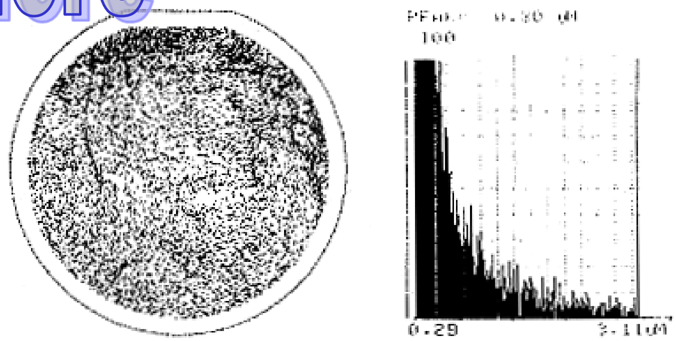




ACCEL Instruments

High Pressure Rinsing (HPR)

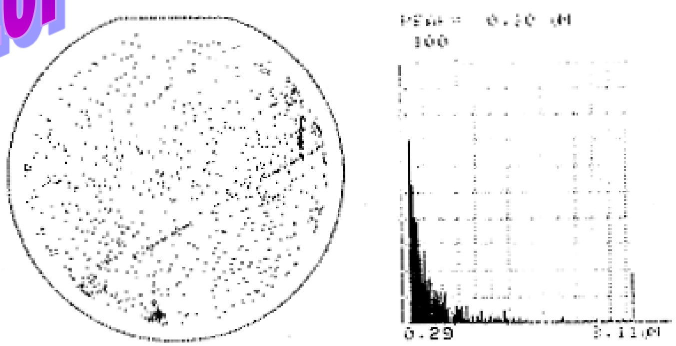
Before



Particle size	Count
0.30-1.20 µm	5825
1.20-2.01 µm	405
2.01-3.00 µm	2720
> 3.00 µm	1069
Total	10019

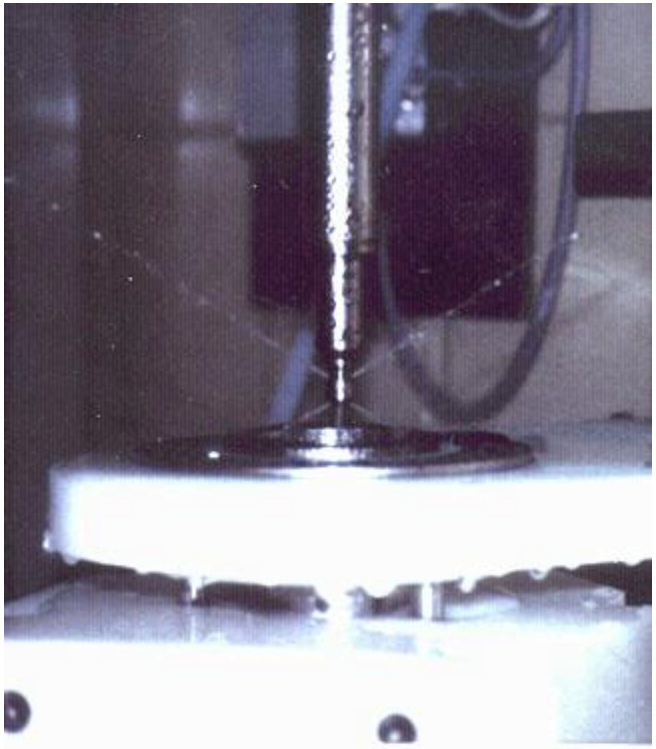
After

6 Residual particles on a wafer surface after the TRISTAN final rinsing.

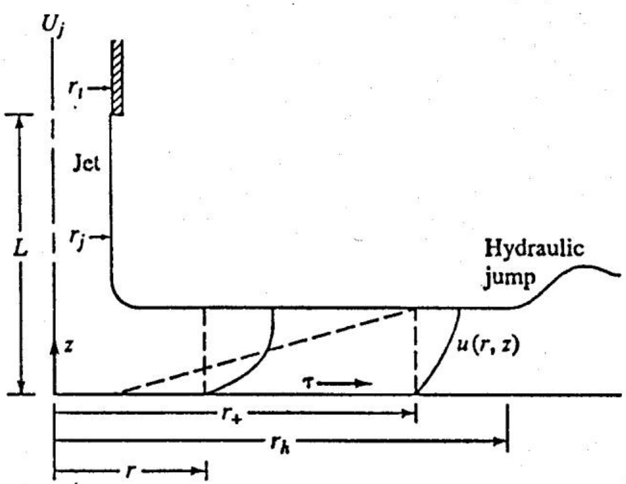


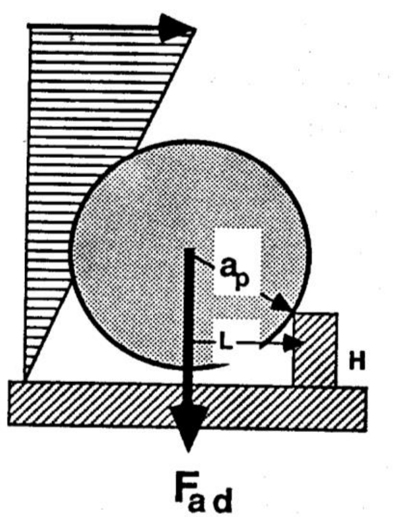
Particle size	Count
0.30-1.20 µm	646
1.20-2.01 µm	52
2.01-3.00 µm	282
> 3.00 µm	37
Total	1017

Fig. 7 Residual particle on a wafer surface after HPR.



Particle Removal Mechanism



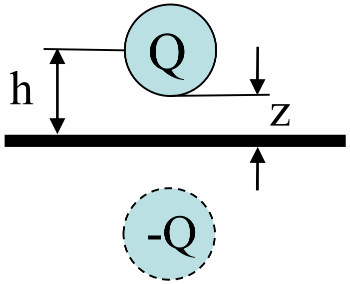


- Hydrodynamic model allows estimating the shear stress τ of the water jet, which depends on flow rate and pressure
- Particle removal by rolling if the water shear stress is greater than a critical shear stress τ_0, related to the particle size, adhesion force and surface roughness

$$\tau_0 = \frac{F_{ad}}{44a_p^2}\sqrt{2\frac{H}{a_p}+\left(\frac{H}{a_p}\right)^2}$$

Adhesion Forces

Particle of diameter *d*



Adhesion forces:

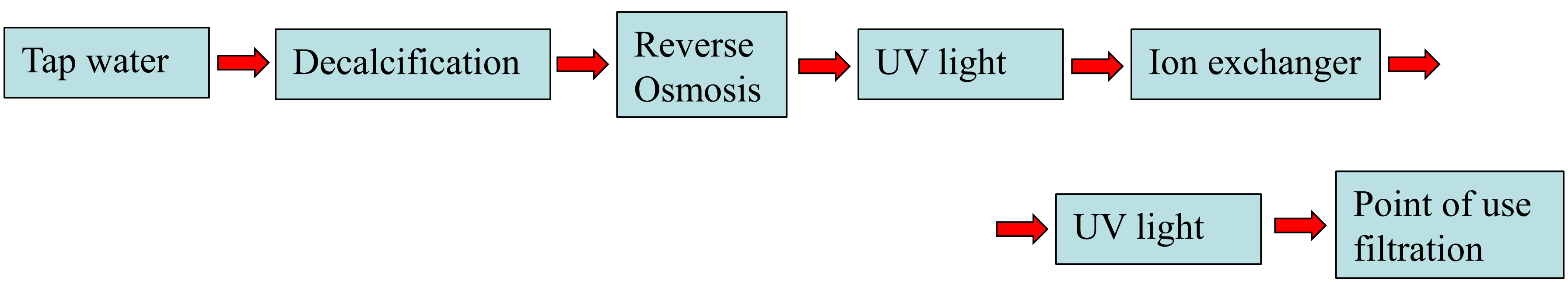
Example: 1 μm glass particle on water

- Coulomb $F = \alpha \frac{Q^2}{4\pi\varepsilon_0 d^2}$ — 1.4×10^{-7} N
- Capillary $F = 2\pi\gamma d$ γ: surface tension — 4.5×10^{-7} N
- Van der Waals $F = \frac{7.2\text{eV}}{16\pi}\frac{d}{z^2}$ — 3×10^{-8} N
- Electrical double layer $F \propto \frac{\Delta\Phi^2 d}{z}$ — 1×10^{-8} N

Ultrapure Water Quality

- Water quality of ultrapure water for SRF cavities preparation:
  - Resistivity: 18.2 MΩcm
  - Total organic carbon (TOC): < 5 ppb
  - Particulate counts (> 0.3 μm/l): < 10
  - Bacteria counts: < 0.1 CFU/100ml

Typical water purification stages:



HPR QA

- Online monitoring of TOC, resistivity and particulate counts
- Collection of water from rinsed cavity for particulate analysis

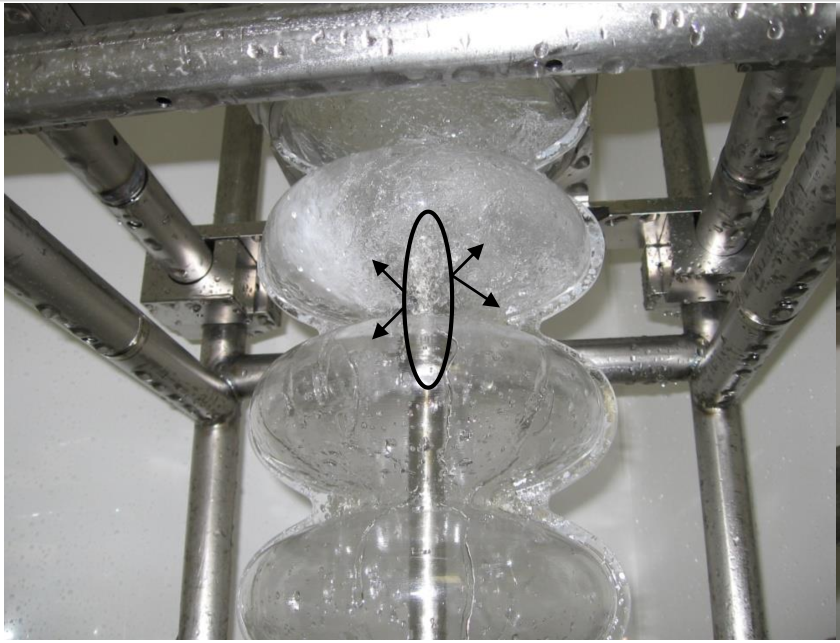
HPR Systems

HPR stand inside the clean room at JLab

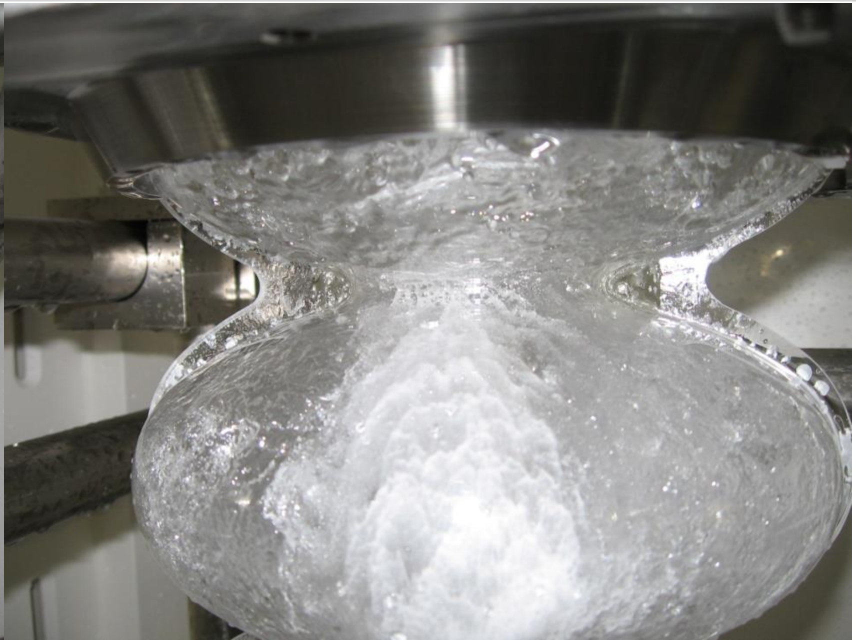
HPR Systems

HPR stand inside the clean room at DESY

HPR spray heads optimization



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

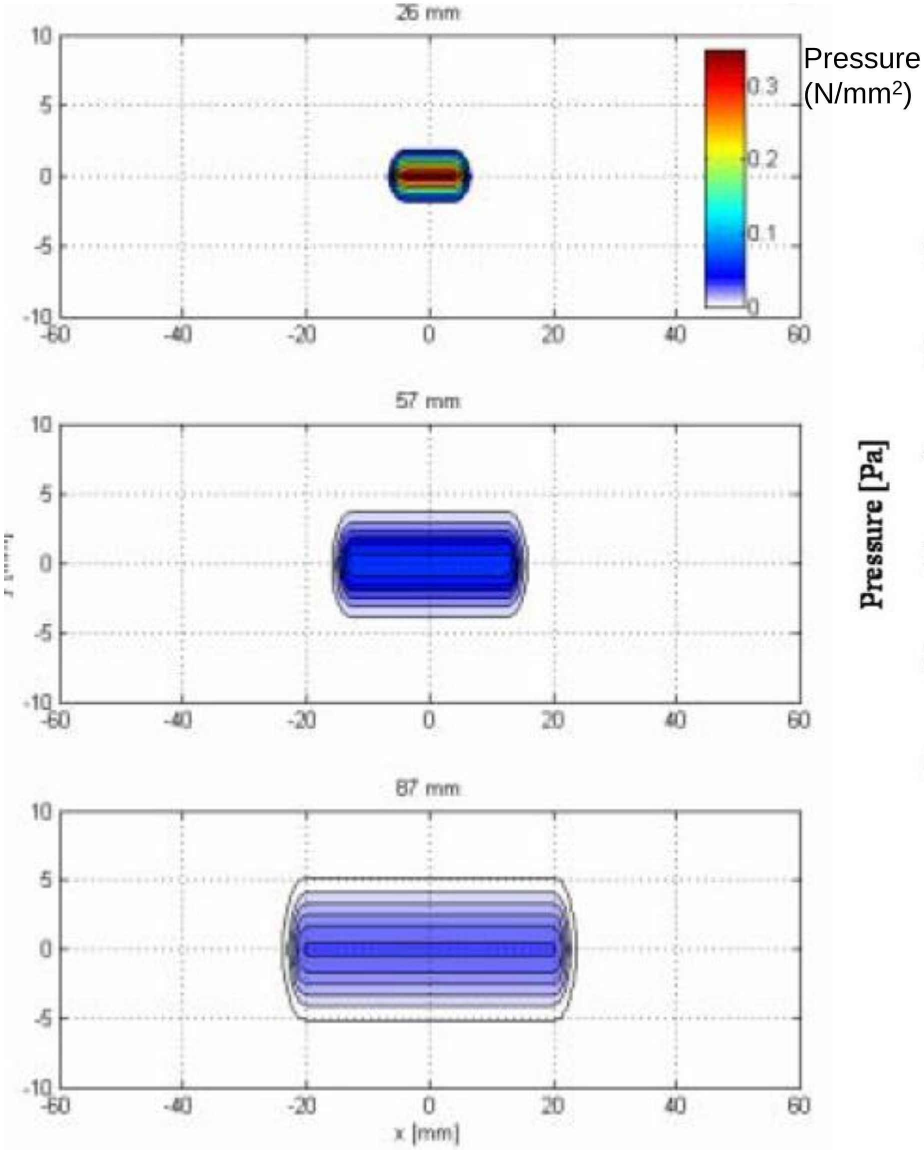
HPR Jet Characterization

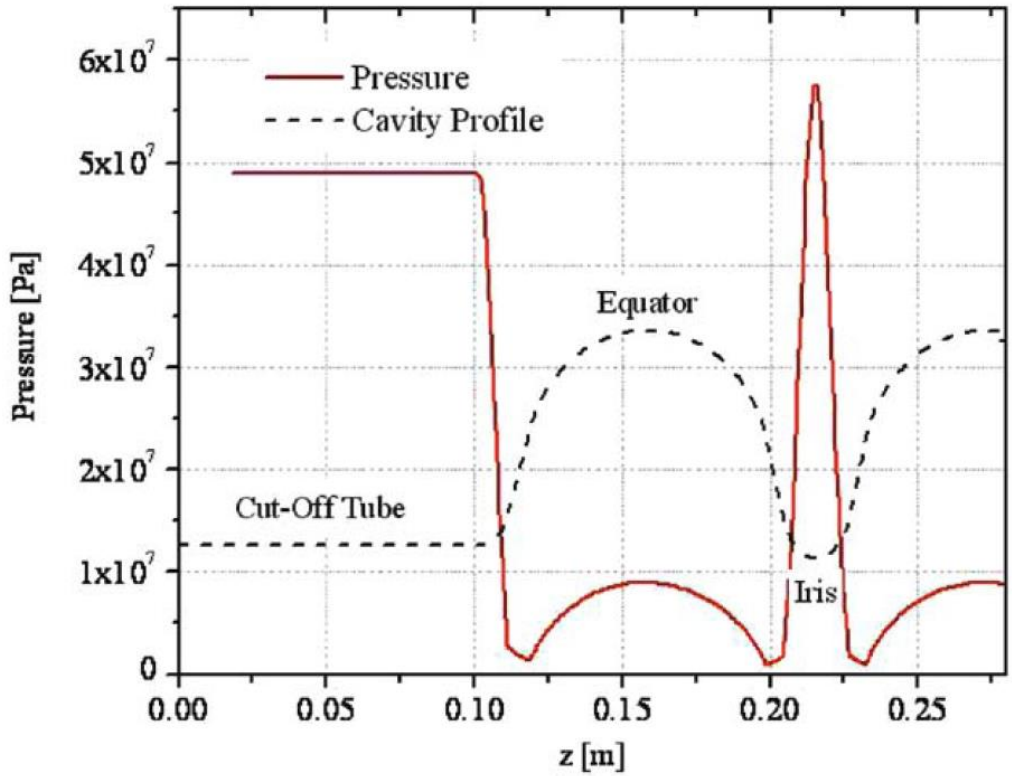
- Use a load cell to measure the force vs. distance of the water jet

$$F = \rho \cdot Q \cdot u \qquad u = \sqrt{\frac{2 \cdot p}{\rho}}$$

u = velocity
Q = flow
p = pressure
ρ = density

Water Pressure vs. Distance





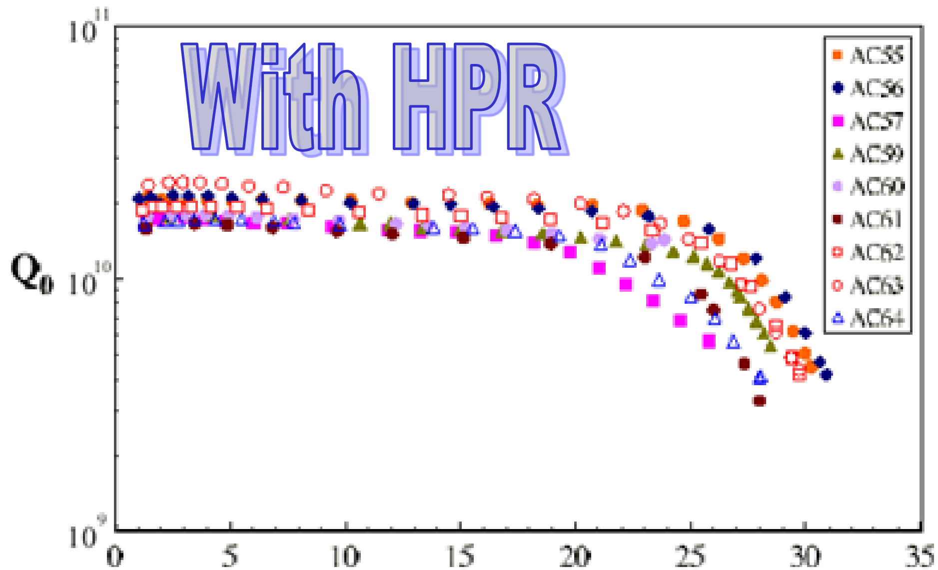
Different HPR Configurations

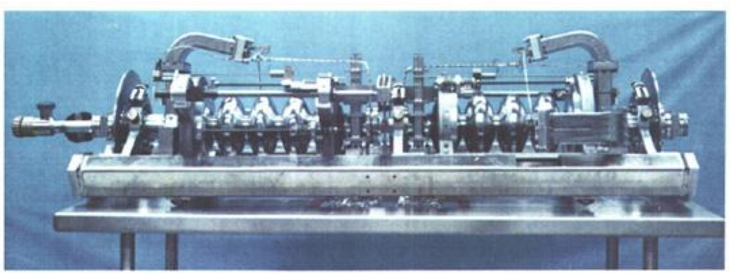
Lab.	# nozzles	Tested nozzles	Flow [l/min] (1 nozzle)	Pump Press [bar]
JLAB Prod	2	SSC-FAN: 1502 4002 40015	5@85 bar	85
JLAB R&D	2 9	SSC-FAN 1502 Φ=0.4 mm Sapphire	5@85 bar ---	85
KEK Tsukuba	8	Φ=0.6 mm SS	1.5@70 bar	70-50
KEK Nomura	8	Φ=0.6 mm SS Φ=0.6 mm SS	1.1@50 bar 0.9@40 bar	50-40
DESY	8	Φ=0.6 mm Sapphire	1.6@100 bar	90-110

- "Fan" jet allows greater surface coverage compared to a standard round jet
- HPR Duration: 3 - 12 h on 9-cell cavity
- Cavity rotation: 2 – 20 rpm
- Wand movement: 8 – 50 mm/min

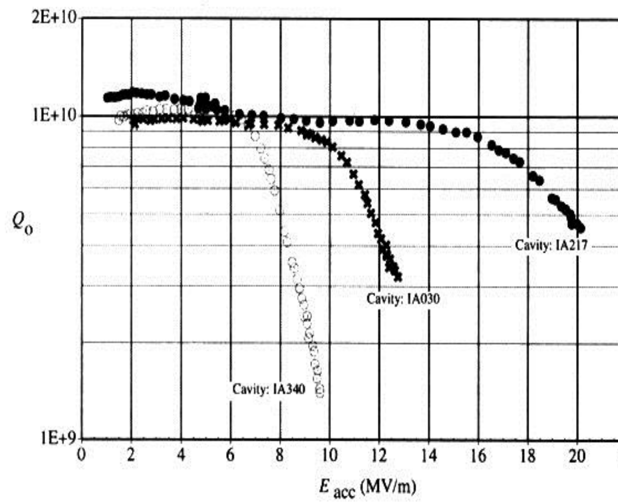
Performance Improvement After HPR

TESLA Cavities



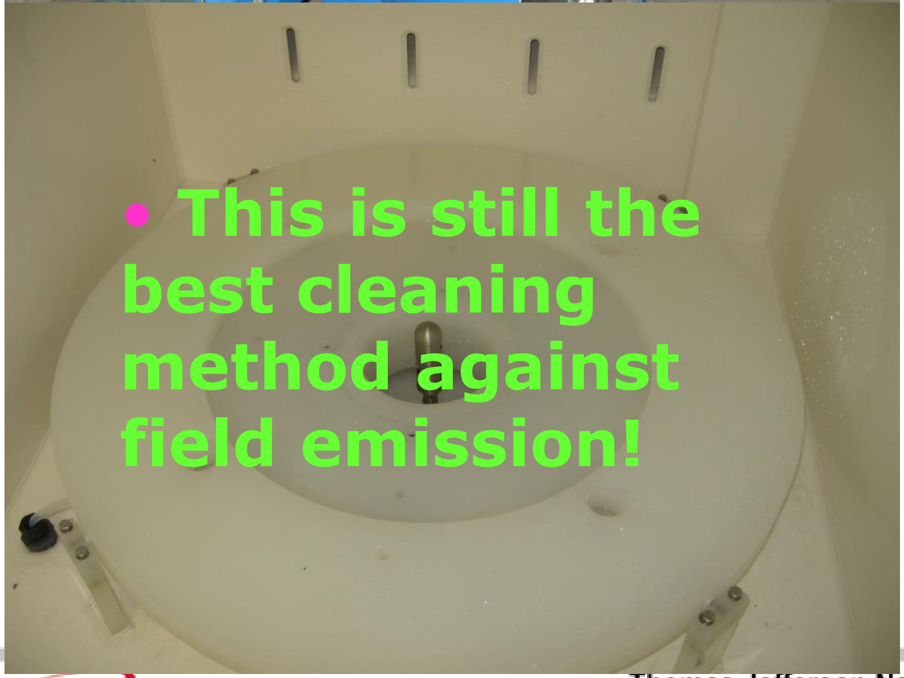


CEBAF Cavities



No HPR

HPR Issues



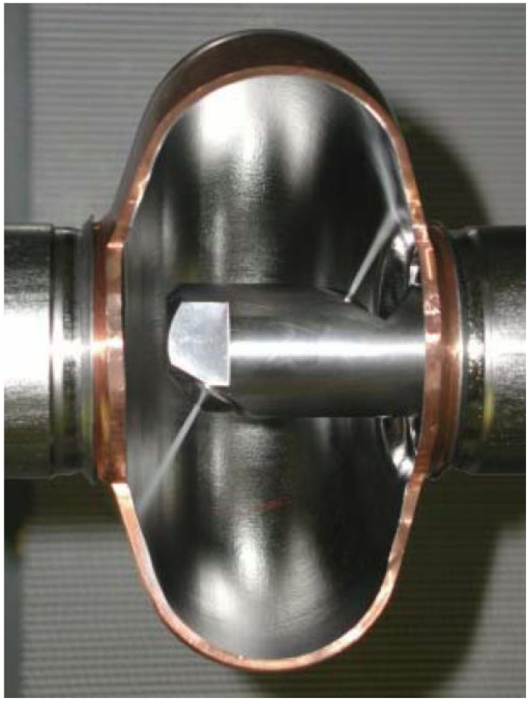
- **This is still the best cleaning method against field emission!**

ISSUES:

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

Dry Ice Cleaning

- Complementary method to HPR, developed at DESY
- Liquid CO_2 jet flowing through a nozzle and resulting in a snow/gas mixture at a temperature of 194 K
- Removal of hydrocarbons and sub-micron particles while keeping the surface dry by
  - Thermal
  - Mechanical
  - Chemical
- Could be applied to a fully assembled cavity mounted horizontally as a part of a "cavity-string"

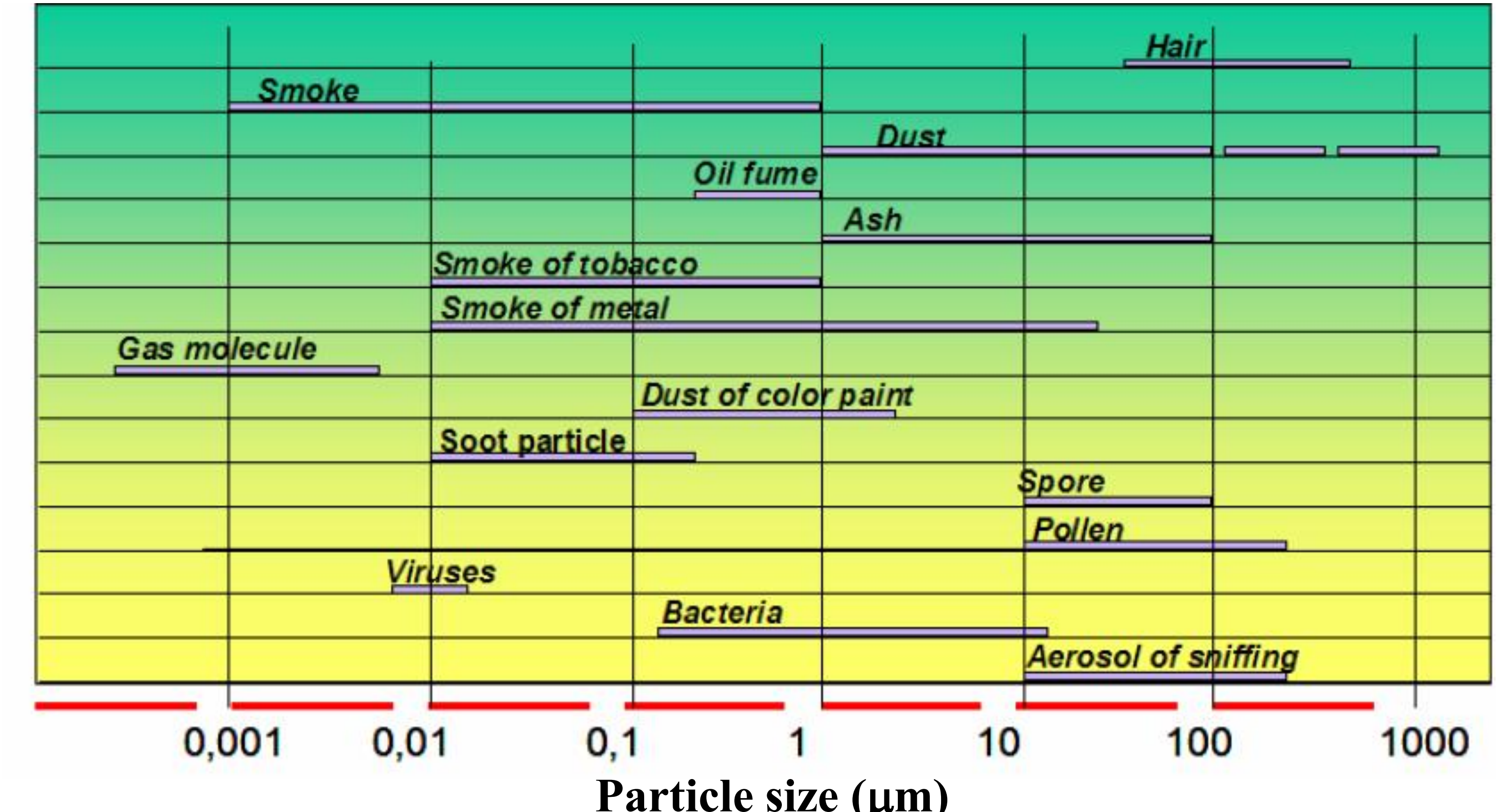


Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in cleanroom (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

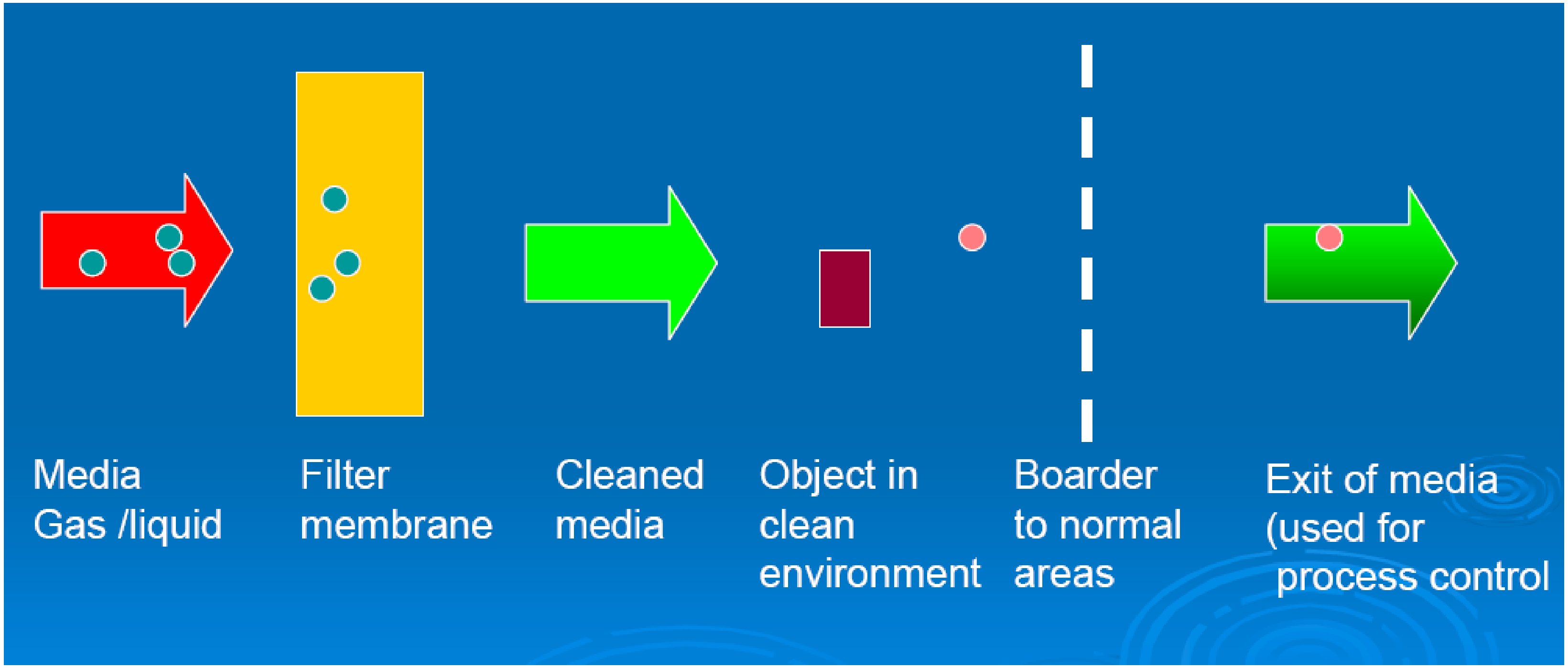
Particulates in Air

- Cleanroom technology is required to prevent airborne particulates from settling on the surface of SRF cavities

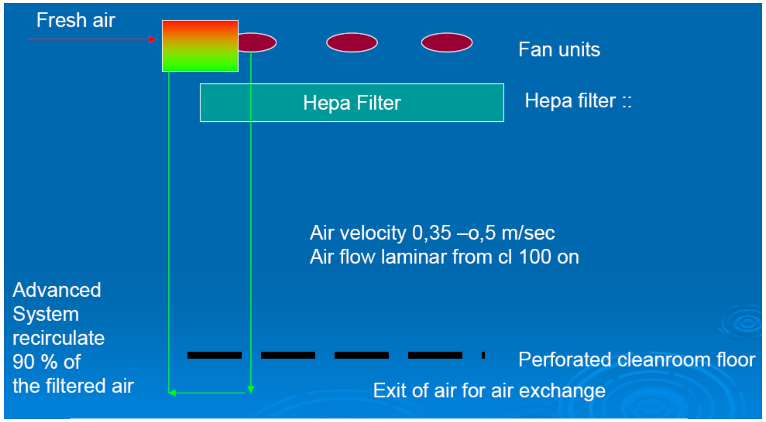


Cleanroom Technology

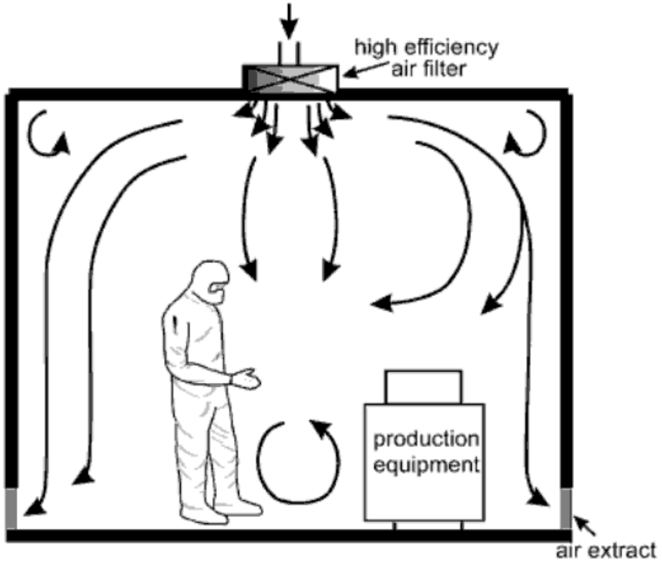
Cleanroom: a controlled environment in which all incoming air, water and chemicals are filtered to meet high standards of purity. Temperature, humidity and pressure are controlled, but the key element is air filtrations.

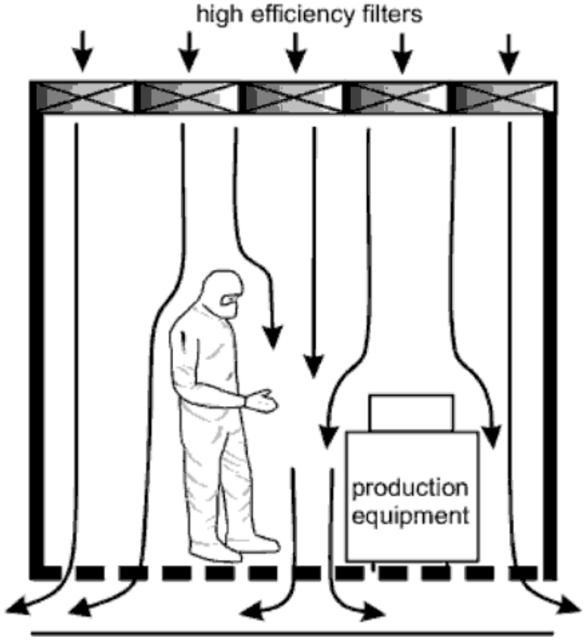


Type of Cleanrooms



Non-Unidirectional airflow type





Unidirectional airflow type

Cleanroom Classification

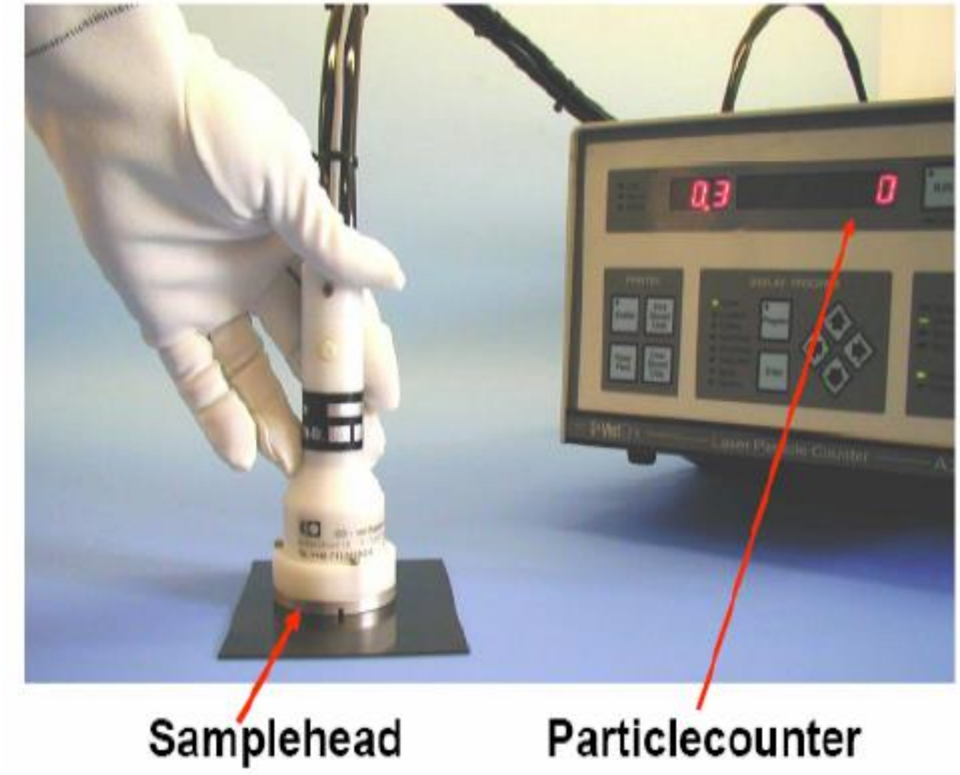
ISO Classification number	Maximum concentration limits (particles/m³ of air) for particles equal to and larger than the considered sizes shown below					
	>=0.1µm	>=0.2µm	>=0.3µm	>=0.5µm	>=1µm	>=5.0µm
ISO Class 1	10	2				
ISO Class 2	100	24	10	4		
ISO Class 3	1 000	237	102	35	8	
ISO Class 4	10 000	2 370	1 020	352	83	
ISO Class 5	100 000	23 700	10 200	3 520	832	29
ISO Class 6	1 000 000	237 000	102 000	35 200	8 320	293
ISO Class 7				352 000	83 200	2 930
ISO Class 8				3 520 000	832 000	29 300
ISO Class 9				35 200 000	8 320 000	293 000

ISO 14644-1 Classes	Class 3	Class 4	Class 5	Class 6	Class 7	Class 8
FS 209 Classes	Class1	Class 10	Class 100	Class 1000	Class 10, 000	Class 100, 000

Cavity assembly (→ Class 10)

Cleanroom for SRF (→ Class 100)

Particle Counters



People in Cleanrooms

- People are a major source of particulate contamination inside a clean room through:
  - Body Regenerative Processes - Skin flakes, oils, perspiration and hair.
  - Behavior - Rate of movement, sneezing and coughing.
  - Attitude - Work habits and communication between workers.

Assembly: Vacuum Hardware

- The cavity strings have to be vacuum tight to a leak rate of < 1 $x10^{-10}$ torr l/sec

- The sealing gaskets and hardware have to be reliable and particulate-free

- The clamping hardware should minimize the space needed for connecting the beamlines

Assembly: Vacuum Hardware

- Present choice for ILC cavities:

  diamond-shaped $AlMg_3$ –gaskets + NbTi flanges + bolts

  Also used for SNS cavities

- AlMg-Gasket

- Alternative:

  radial wedge clamp, successfully used for CEBAF upgrade cavities

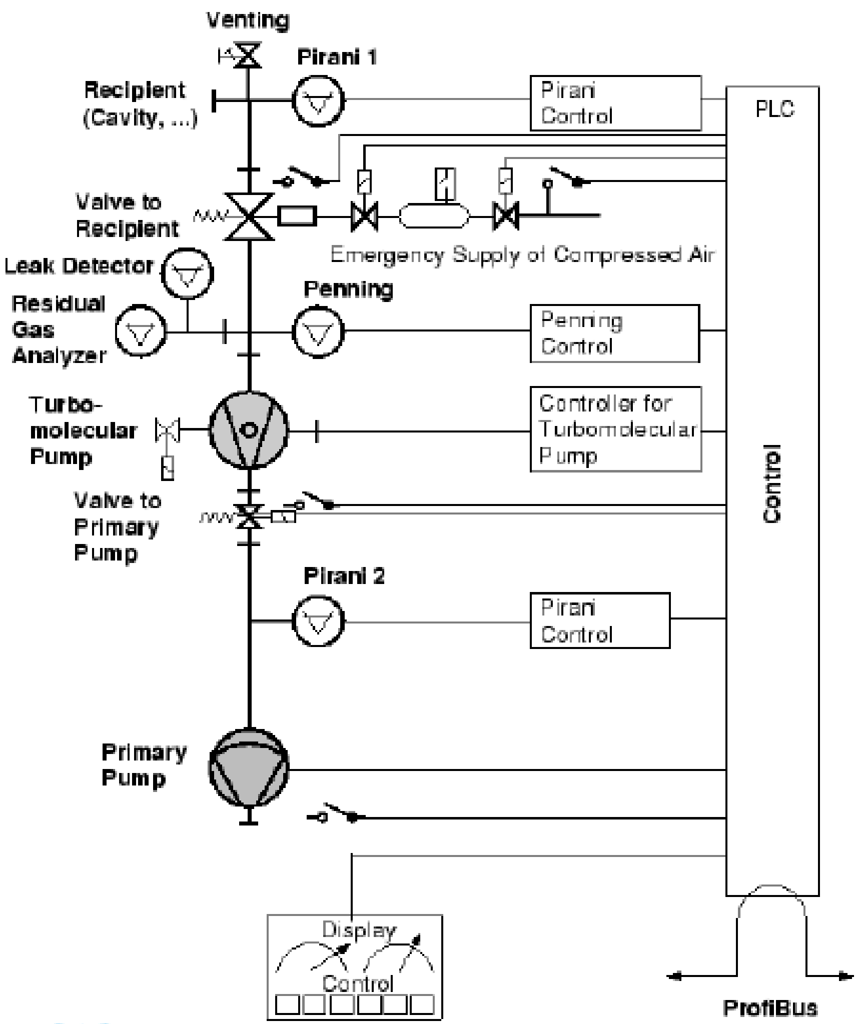
- Radial Wedge Clamp

Cavity Assembly

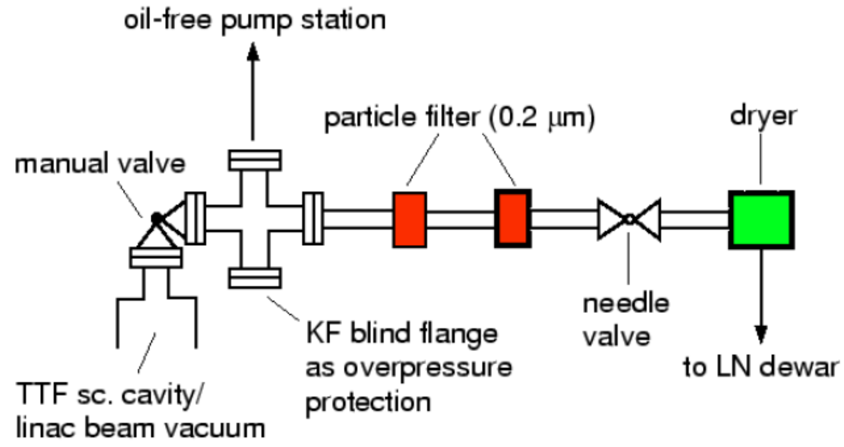
Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 µm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 µm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in cleanroom (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

Clean Evacuation



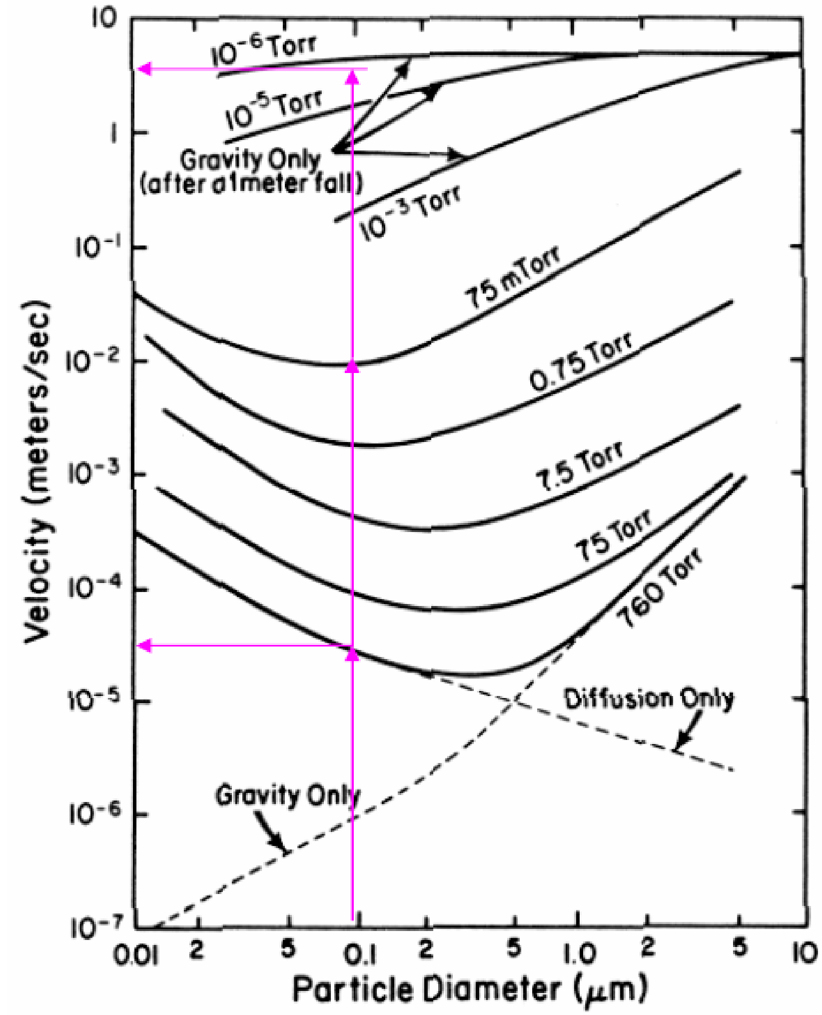
- Oil-free pump stations with leak check and residual gas analyzer
- Laminar venting with pure, particle filtered N_2 or Ar



Clean Vacuum Systems

- “Dirty” or “contaminated” (hydrocarbons, air leaks) vacuum system can re-contaminate the surface of a clean cavity!

Settling velocity for particles in air at room temperature



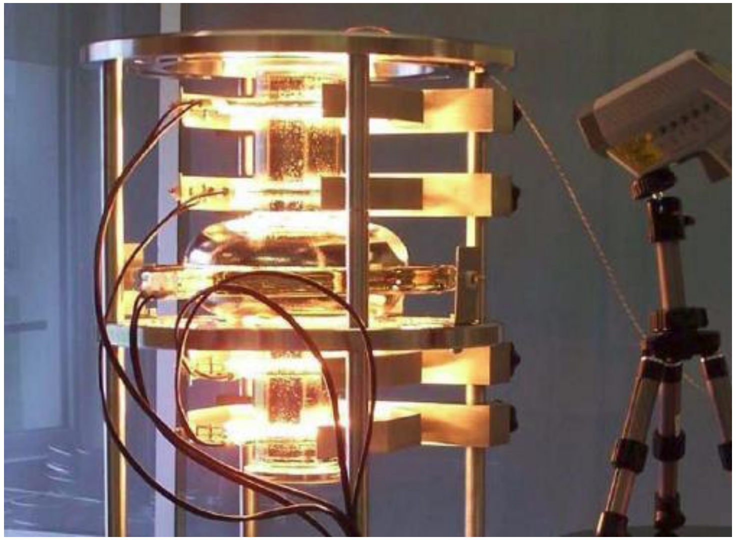
Required Procedures for Qualifying SRF Cavities

- Degreasing surfaces to remove contaminates
- Chemical removal of exterior films incurred from welding
- Removal of damage layer of niobium from fabrication (~150 μm)
- Removal of hydrogen from bulk Nb
- Mechanical tuning
- Chemical removal of internal surface for clean assembly (10-20 μm)
  - Additional "cleaning" steps if Electropolishing (EP) is used
- High Pressure Rinsing (HPR) to remove particulates from interior surfaces (incurred during chemistry and handling)
- Drying of cavity for assembly in cleanroom (reduce risk of particulate adhesion and reduce wear on vacuum systems)
- Clean assembly
- Clean evacuation
- Low-temperature baking

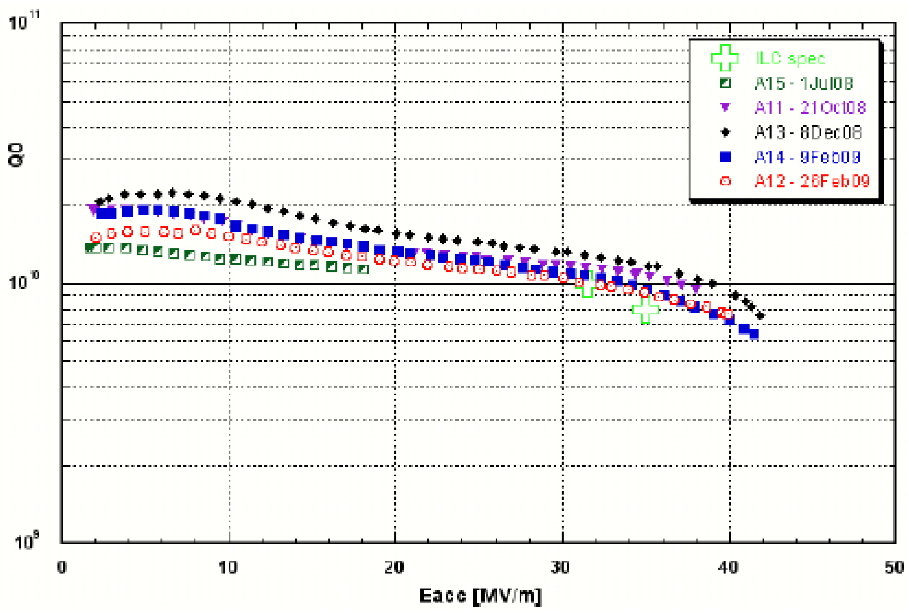
Low-Temperature Baking

Hot N_2 gas uniformly heats up the cavity (JLab)

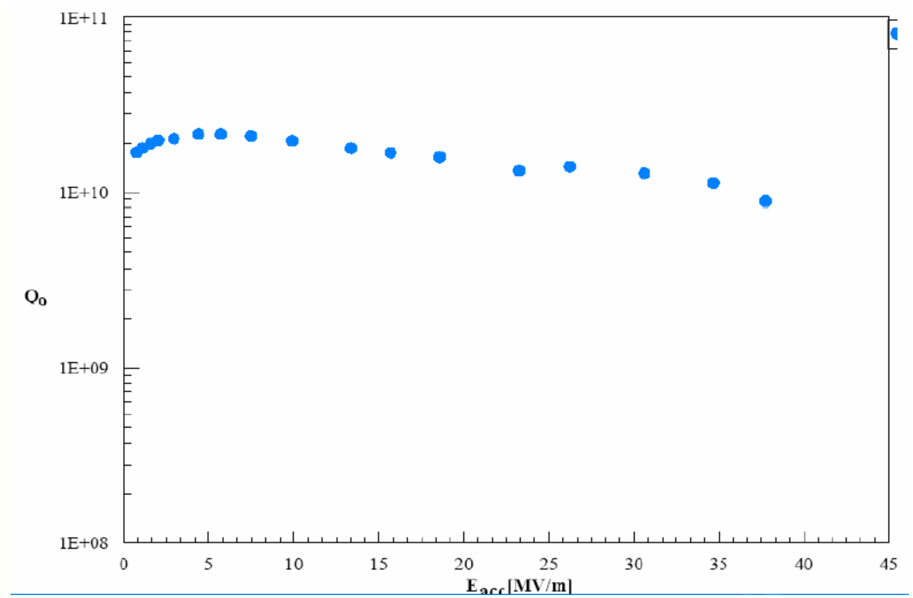
Infrared heaters heating the open cavity inside the cleanroom (Saclay)



If Everything Works Well…



JLab



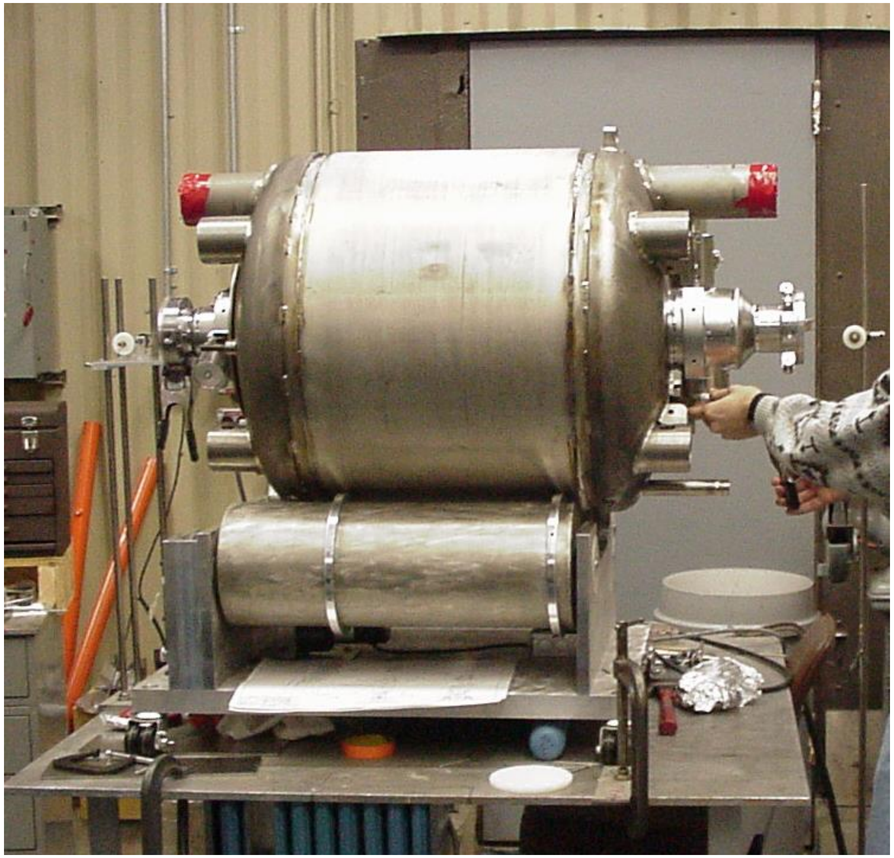
DESY

$E_p \cong 80$ MV/m, $B_p \cong 170$ mT can be achieved in the vertical test of 9-cell ILC cavities (~ 1 m^2 of Nb surface)

Additional Steps for Cavity String

- Final mechanical tuning
- He-vessel welding
- Degreasing
- Final material removal (10-20 μm)
- Final HPR
- Horizontal assembly into cavity-string
- Evacuation of cavity string

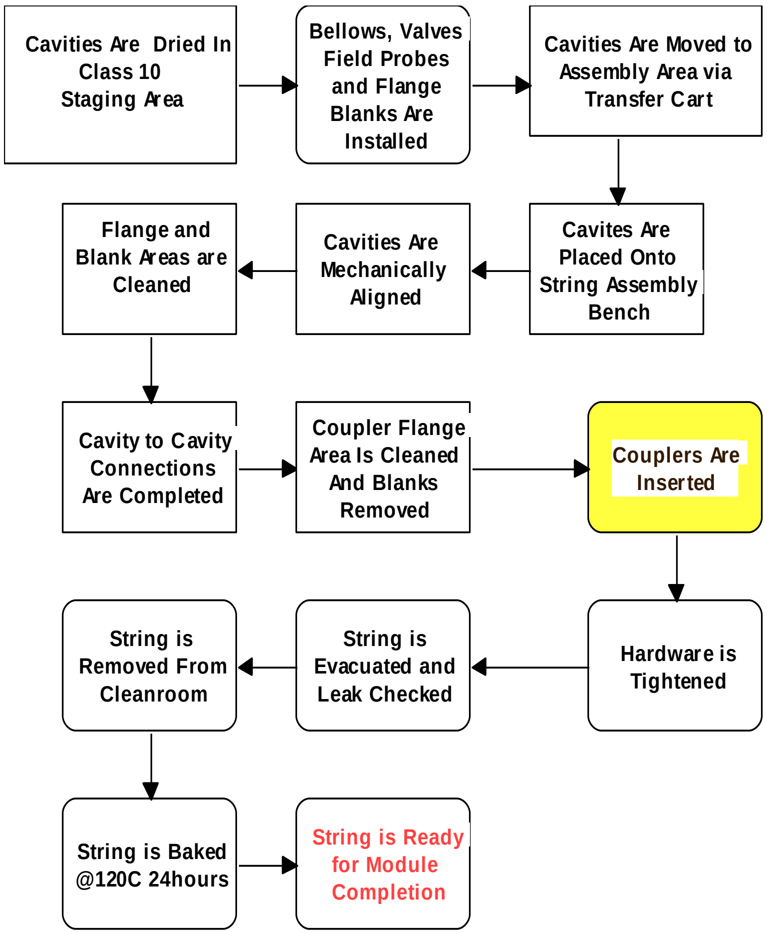
Helium Vessel Welding



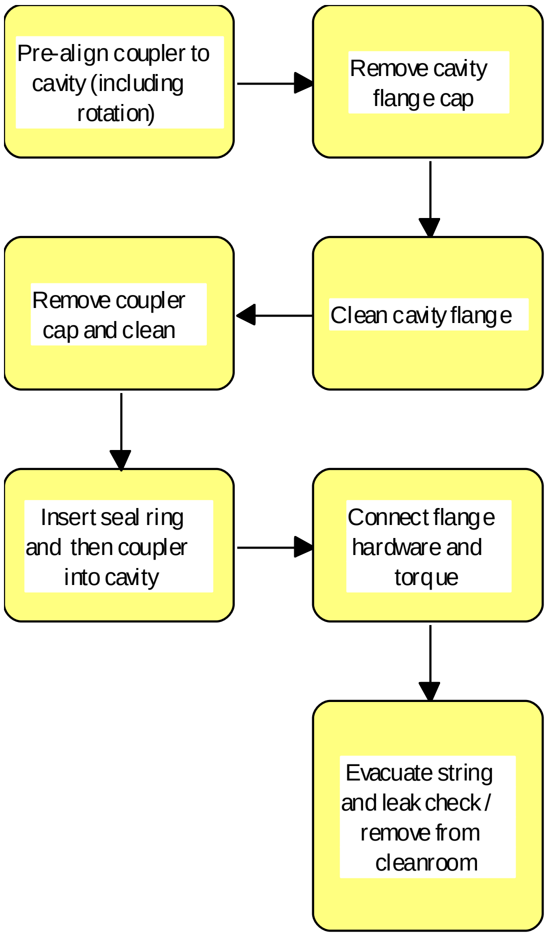
String Assembly

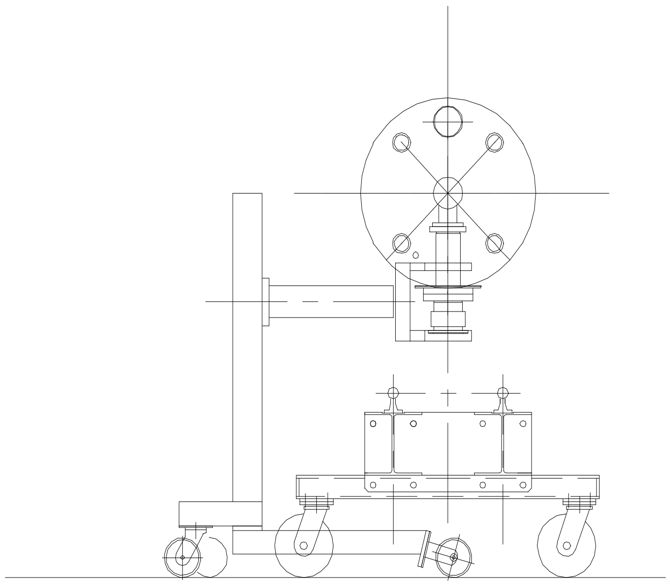
- A cavity string is assembled in a class 10 or class 100 clean room on an assembly bench over a period of several days after they have been qualified in a vertical or horizontal test.
- Prior to assembly, the cavities are high pressure rinsed for several hours, dried in a class 10 clean room, mounted onto the assembly bench and auxiliary parts are attached.
- The most critical part of the assembly is the interconnection between two cavities, monitored by particle counting

Example of Cavity Assembly Sequence



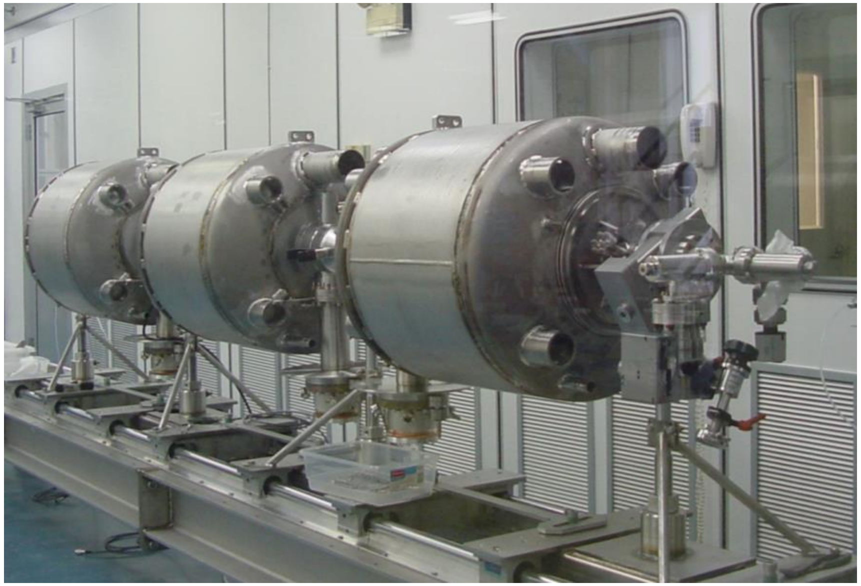
Coupler Insertion Procedure





String Assembly

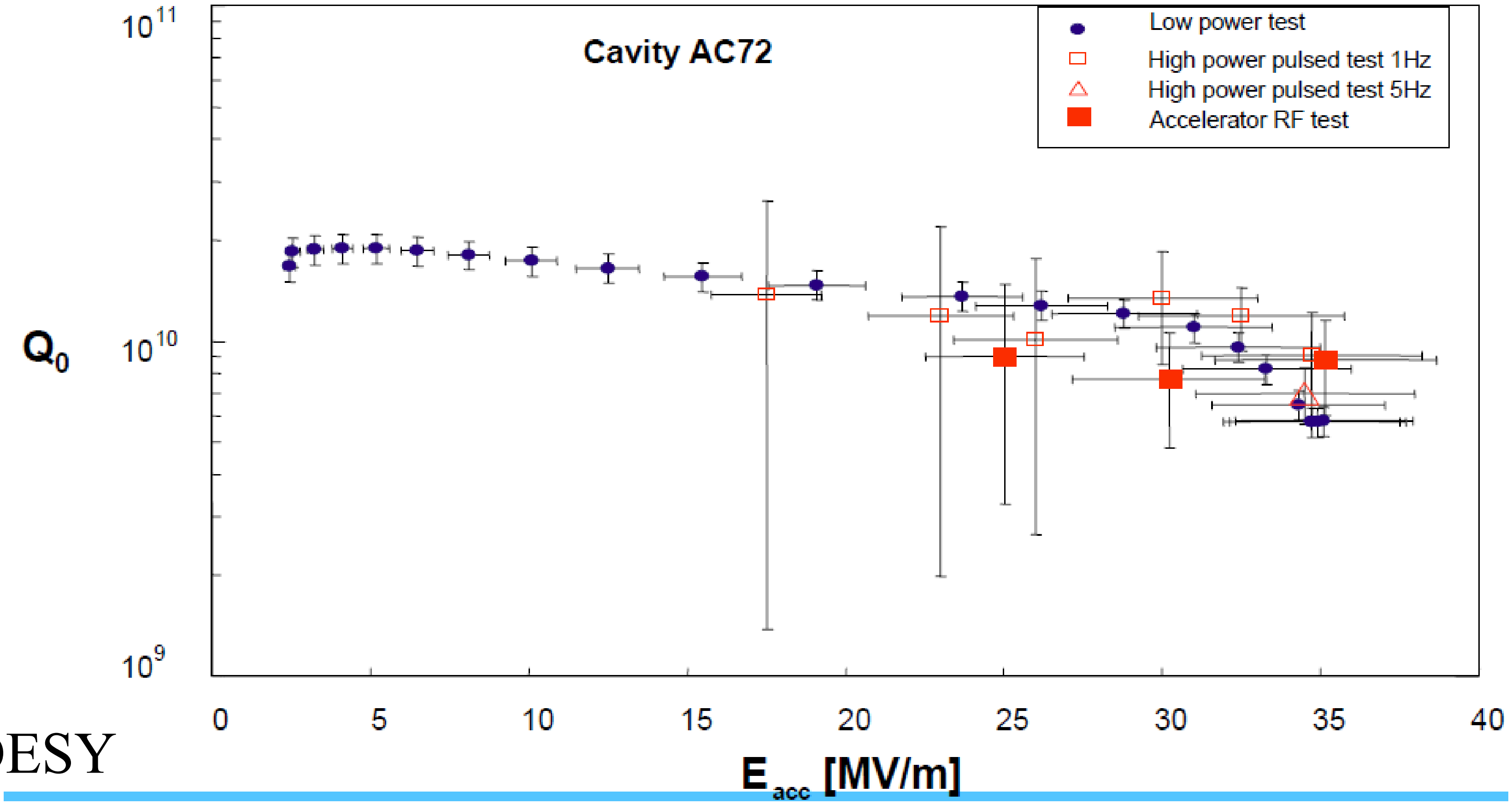
XFEL at DESY: 8 cavities per string



SNS β_g=0.61 string at JLab: 3 cavities per string

If Everything Works Well…

35 MV/m without field emission in operation with electron beam is possible!



DESY

Comments on Facilities and Process Steps

RF Cavities

- RF structures have excellent quality in materials and fabrication but flange designs require significant hardware for assembly and extensive manual labor → lots of room for errors

Facilities

- Cleanroom environments are typically excellent, easy to monitor
- DI water quality excellent in most cases, easy to monitor
- Sub-component cleaning not at same level with cleaning quality for cavities
- Many system failures reported, leading to large recovery times
- No two process system designs the same

Process Steps

- Assembly steps present the most interaction and largest source of particulate contamination, very difficult to monitor
- Subcomponent cleaning insufficient but easy to monitor
- BCP Chemistry in good control easy to monitor
- EP currently has less process control and more process variables

History Plot of High Gradient