Recent SRF R&D achievements at Peking University

LU Xiangyang

Out line

---Cavity R&D

ILC cavity

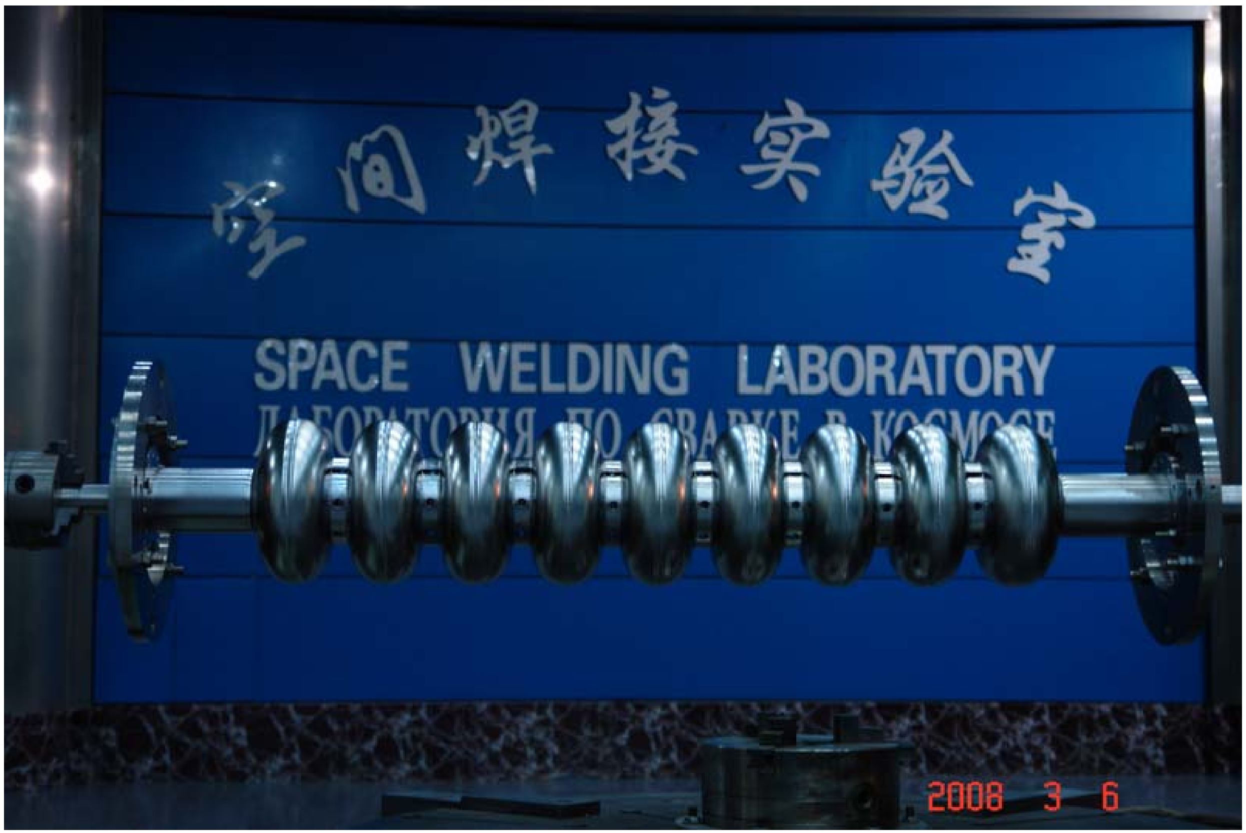
Spoke cavity

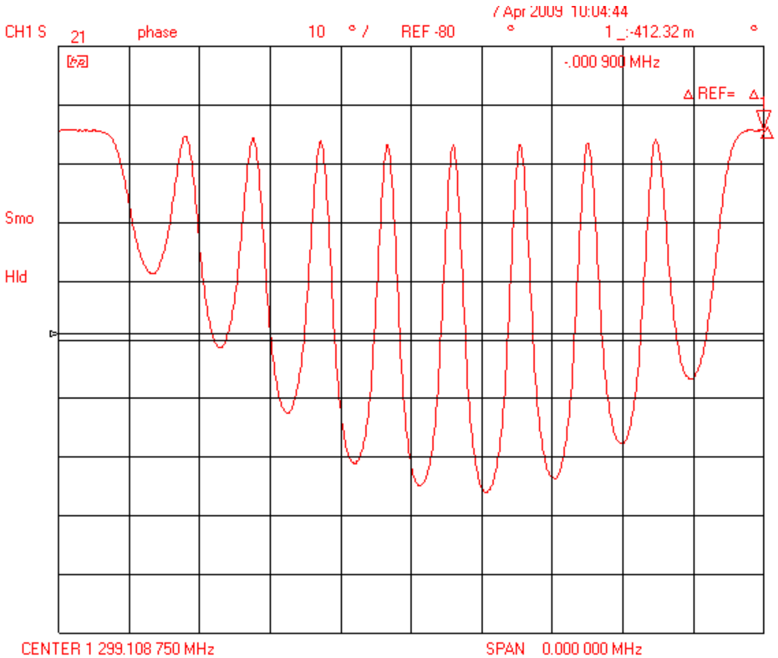
---Cavity post process R&D

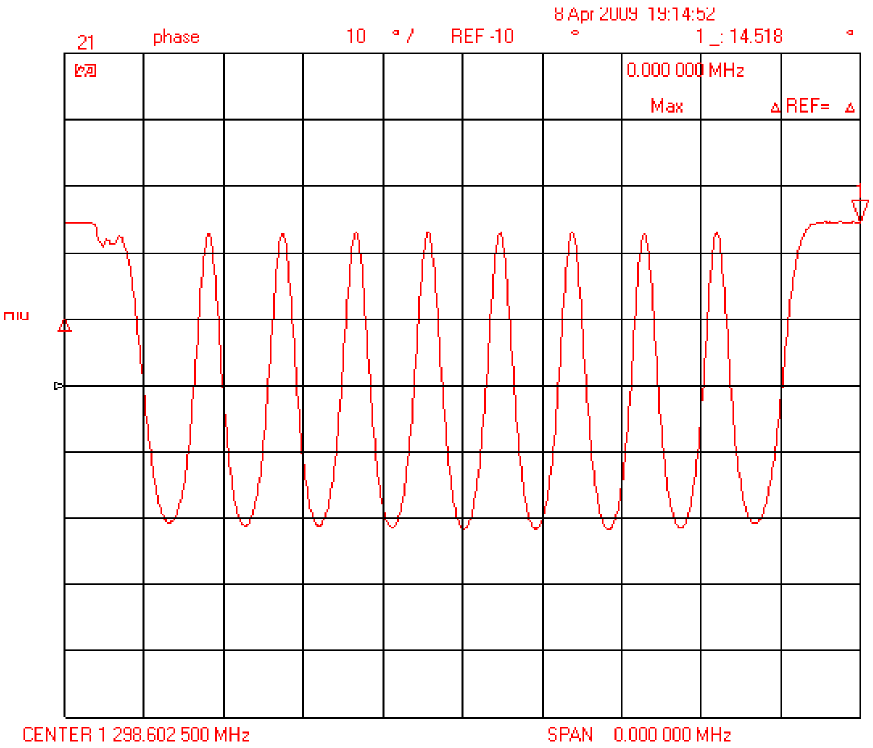
BEP and EP

Cavity R&D

2008.03.06, First 9-cell bare cavity was welded



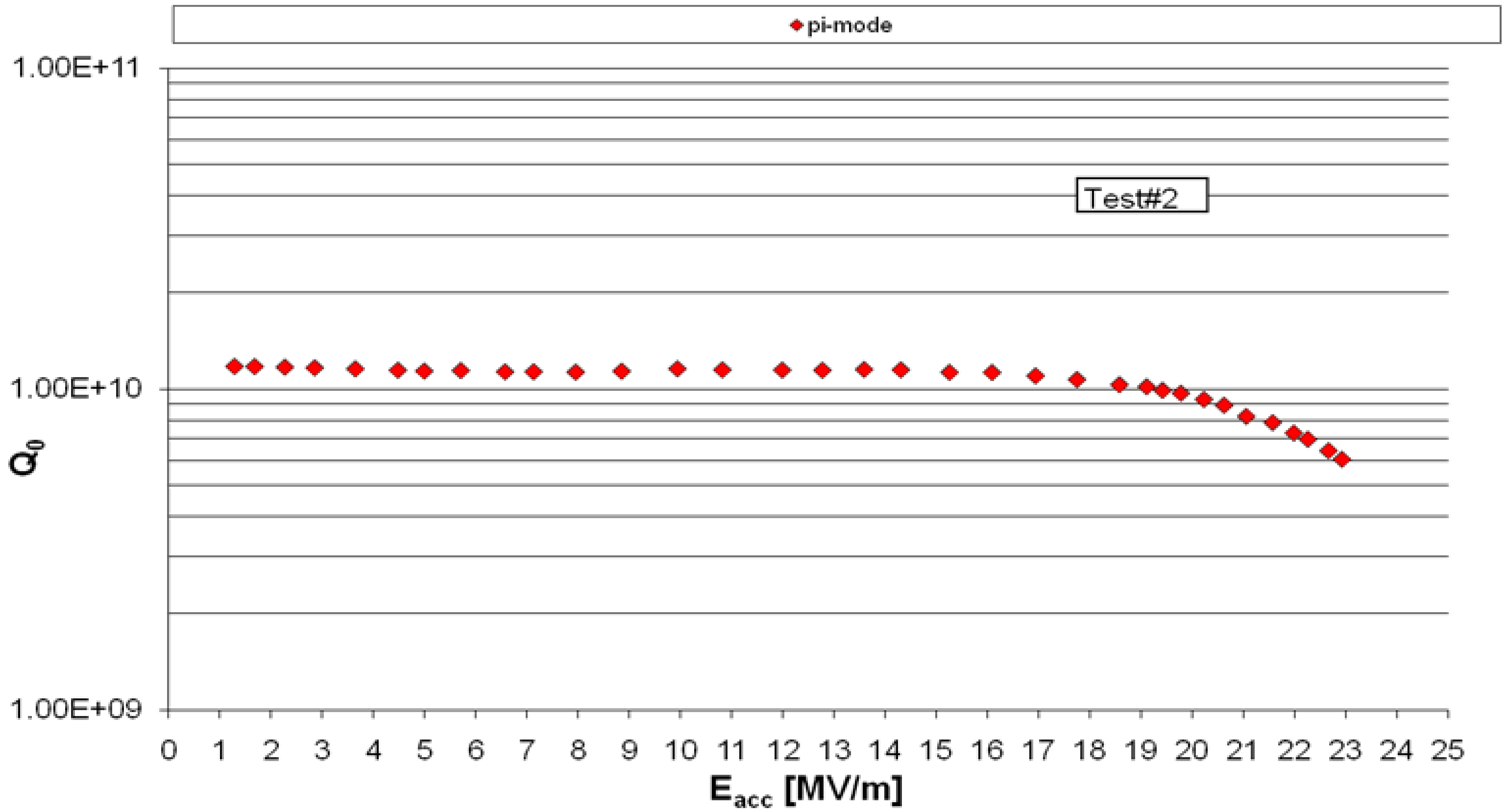




Field flatness tuning

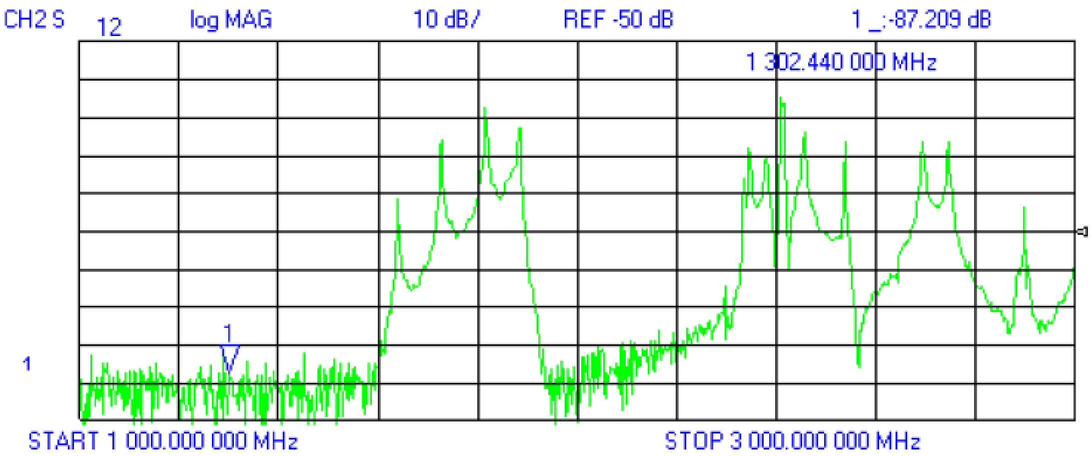
The final “flatness” is better than 95%.

Fine Grain ILC 9-cell Cavity- PKU



Measured by P. Kneisel, et.al, JLab

HOM Coupler


CH2 S 12
log MAG
10 dB/
REF -50 dB
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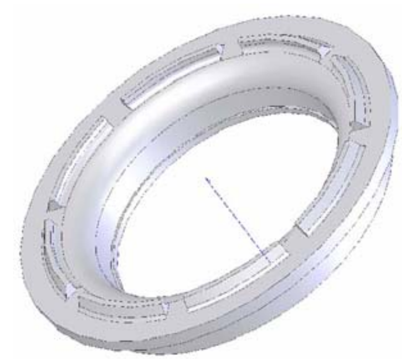
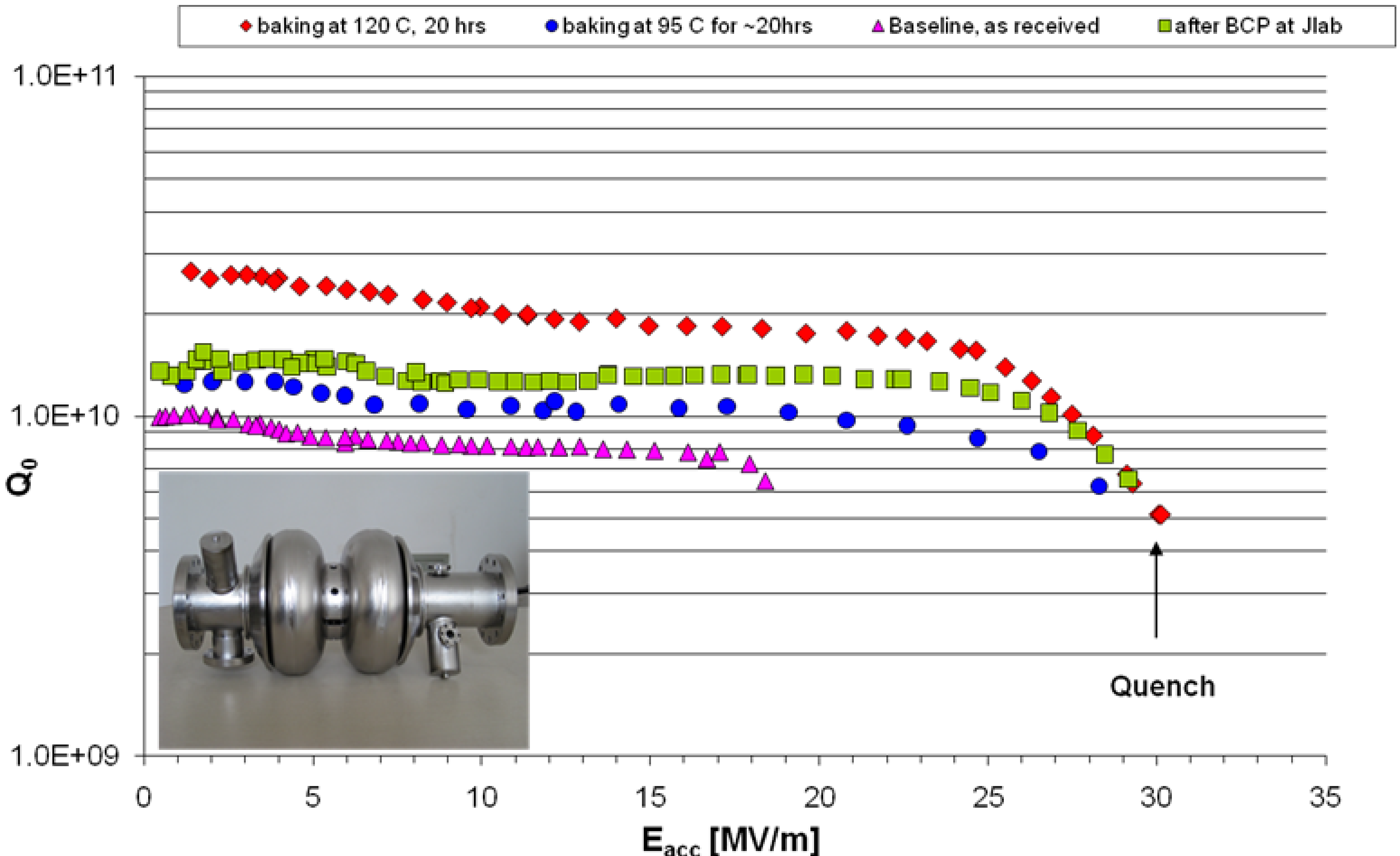
1 302.440 000 MHz
1
START 1 000.000 000 MHz
STOP 3 000.000 000 MHz

Fabrication arts studies of end-group



A 2-cell TESLA type cavity with end-groups was made

2-Cell PKU Cavity, Ningxia Niobium

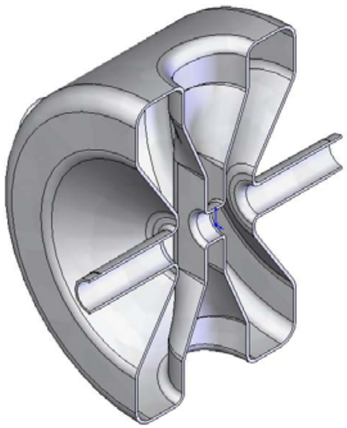


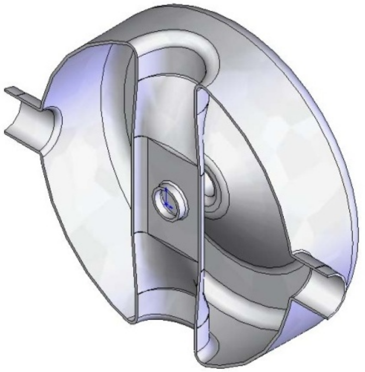
Measured by P. Kneisel, et.al, JLab

The 3+1/2cell cavity for DC-SC injector made of large grain Nb sheet.

The bare 9-cell cavity is modified. End-groups are added.

450MHz β=0.2 Single Spoke Cavity



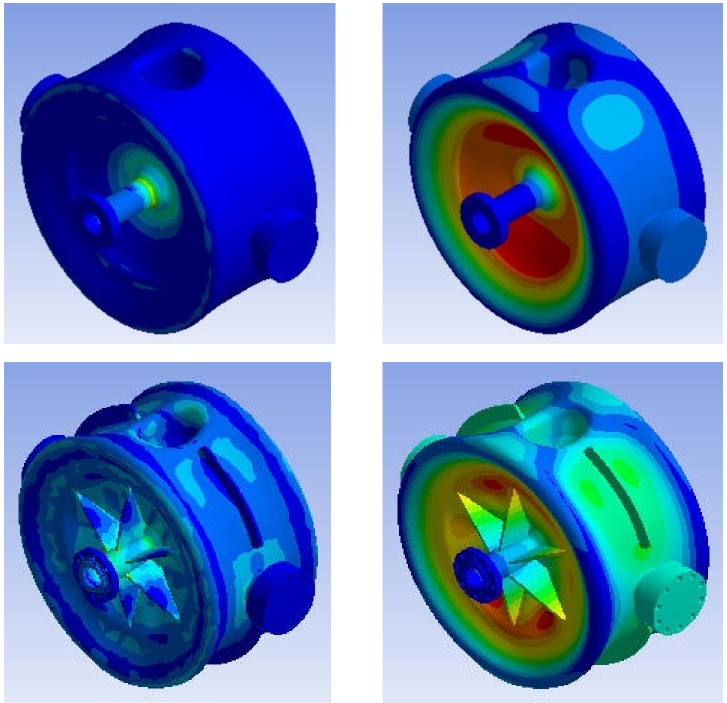


Guiding ideology— lower B_{peak}/E_{acc} to get higher quench threshold.

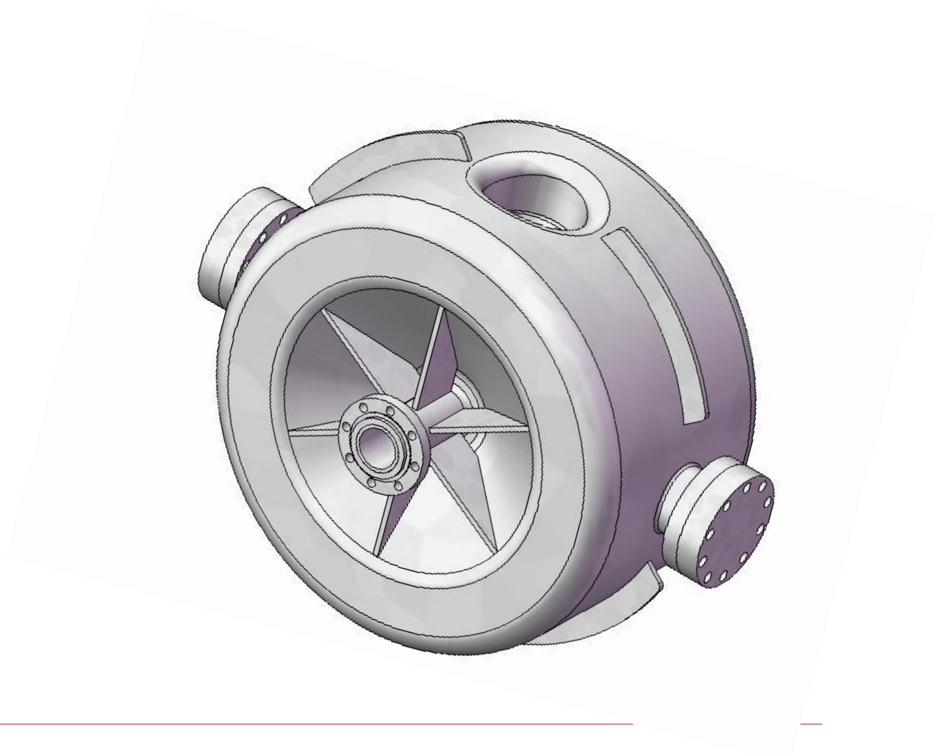
Design Parameters

Q_0 (4 K)	7.3×10^8	for 100nΩ
T (β)	0.8015	**β**=0.2
T_{max}(β)	0.8079	**β**=0.217
G	73.0 Ω	
R/Q_0	178.7Ω	
E_{peak}/E_{acc}	**2.65**	
B_{peak}/E_{acc}	**5.22 mT/(MV/m)**	

Stiffening & Strength analysis

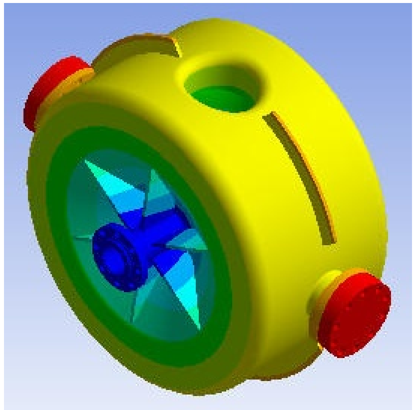


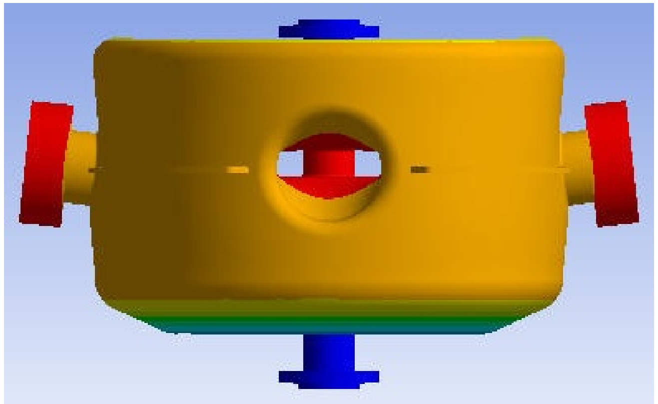
Forced by 2 atms	Peak Von Mises Stress (MPa)	Peak Displacement (mm)
No stiffened	308.2	0.221
Stiffened	55.3	0.060

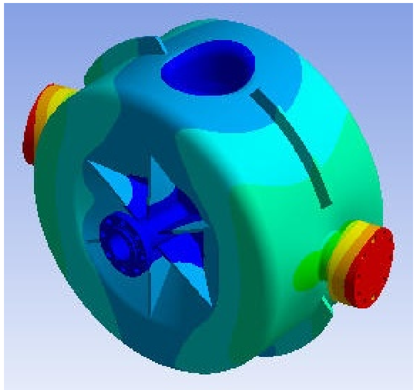


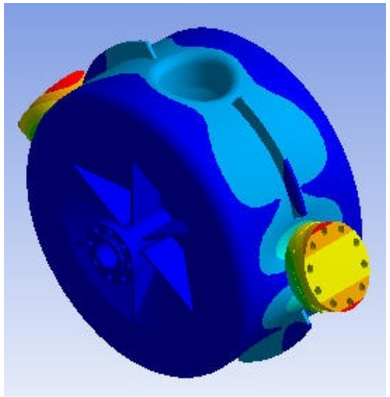
Mechanic vibration modes / Microphonics

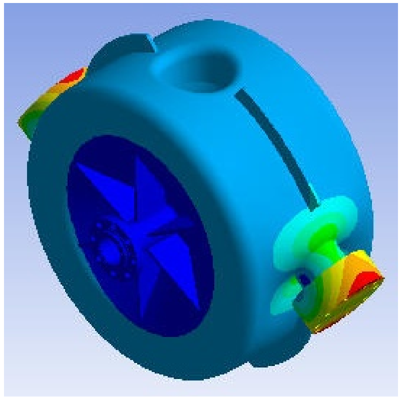
Mode	Frequency (Hz)
1	92
2	213
3	335
4	375
5	452
6	483

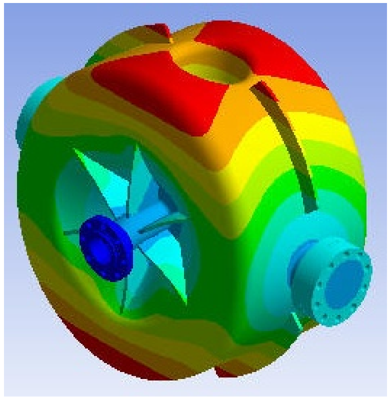

mode 1


mode 2

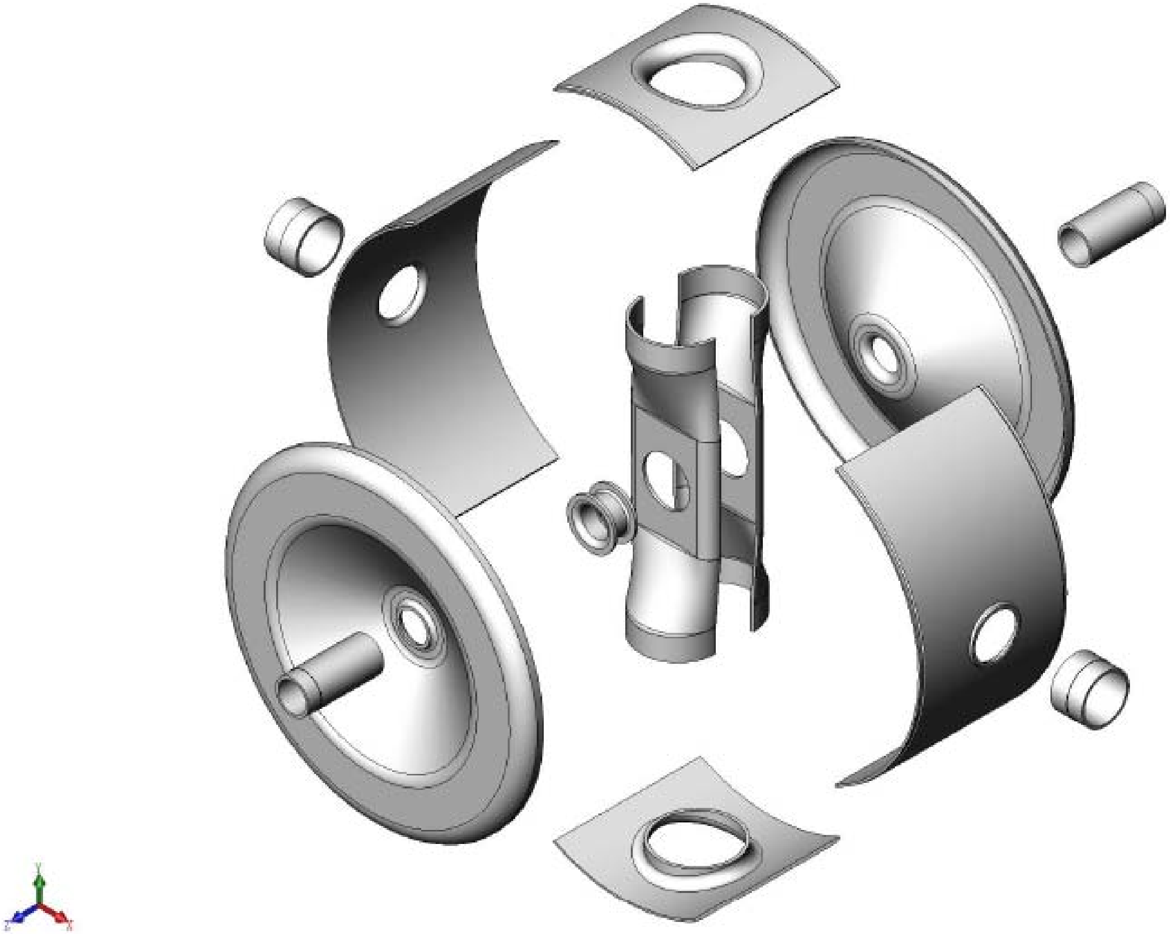

mode 3


mode 4


mode 5


mode 6

The main parts and fabrication art.



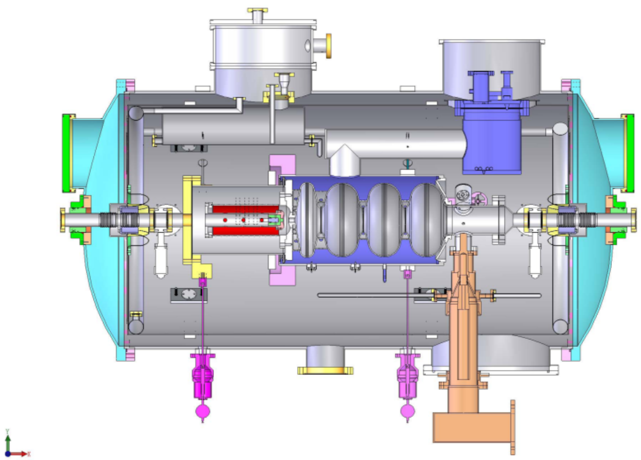
The next R&D steps in coming:

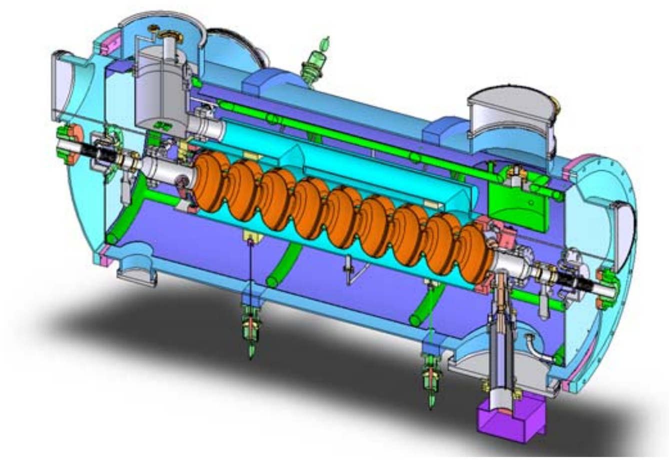
--The DC-SC photo-injector with 3.5 cell cavity.

--The LINAC module of a single 9-cell cavity.

--A LG 9-cell TESLA type bare cavity is making.

--A 4-cell TESLA type cavity with End-group is making.





Cavity post process studies

--- Study background

--- Fine grain small Nb sample BEP

Fast BEP

The optimum BEP condition

--- From sample to cavity

--- Conclusions and Discussions

The study background of our BEP

Cavity Performance Requirements

"For the vertical test, each cavity must achieve 35MV/m gradient with a Q-value of 0.8×10^{10} or greater."

---ILC-RDR, 2007

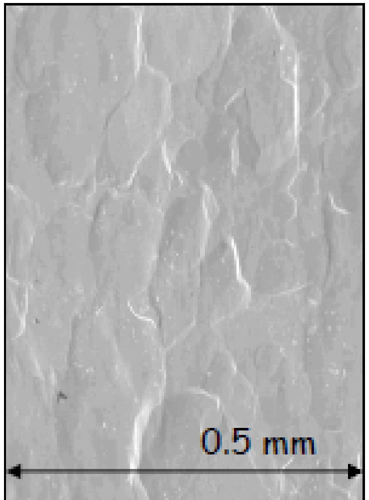
To make a good cavity is dependant on:

----High quality mechanical fabrication,

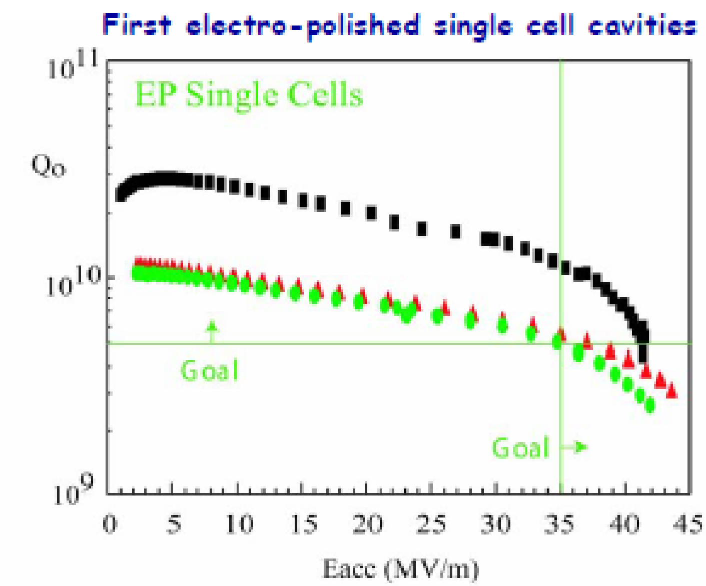
----High quality surface process.

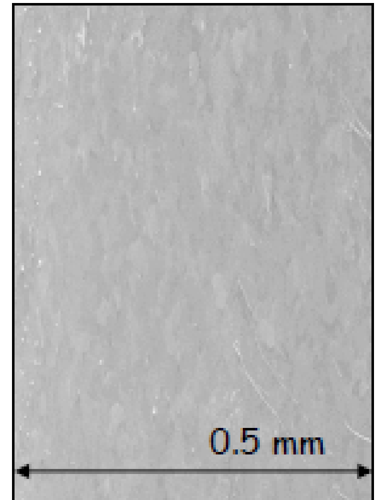
Note that top ~100 nm material determines SRF properties!

- EP developed at KEK by K. Saito (originally by Siemens)
- **Coordinated R&D effort: DESY, KEK, CERN and Saclay**



BCP Surface
(1μm roughness)





EP Surface
(0.1μm roughness)

Electro-polishing (EP) instead of the Buffered Chemical Polishing (BCP)

- Much smuther surface, less local field enhancement
- Cleaning by High Pressure Rinsing more effective
  - Field Emission onset at higher field

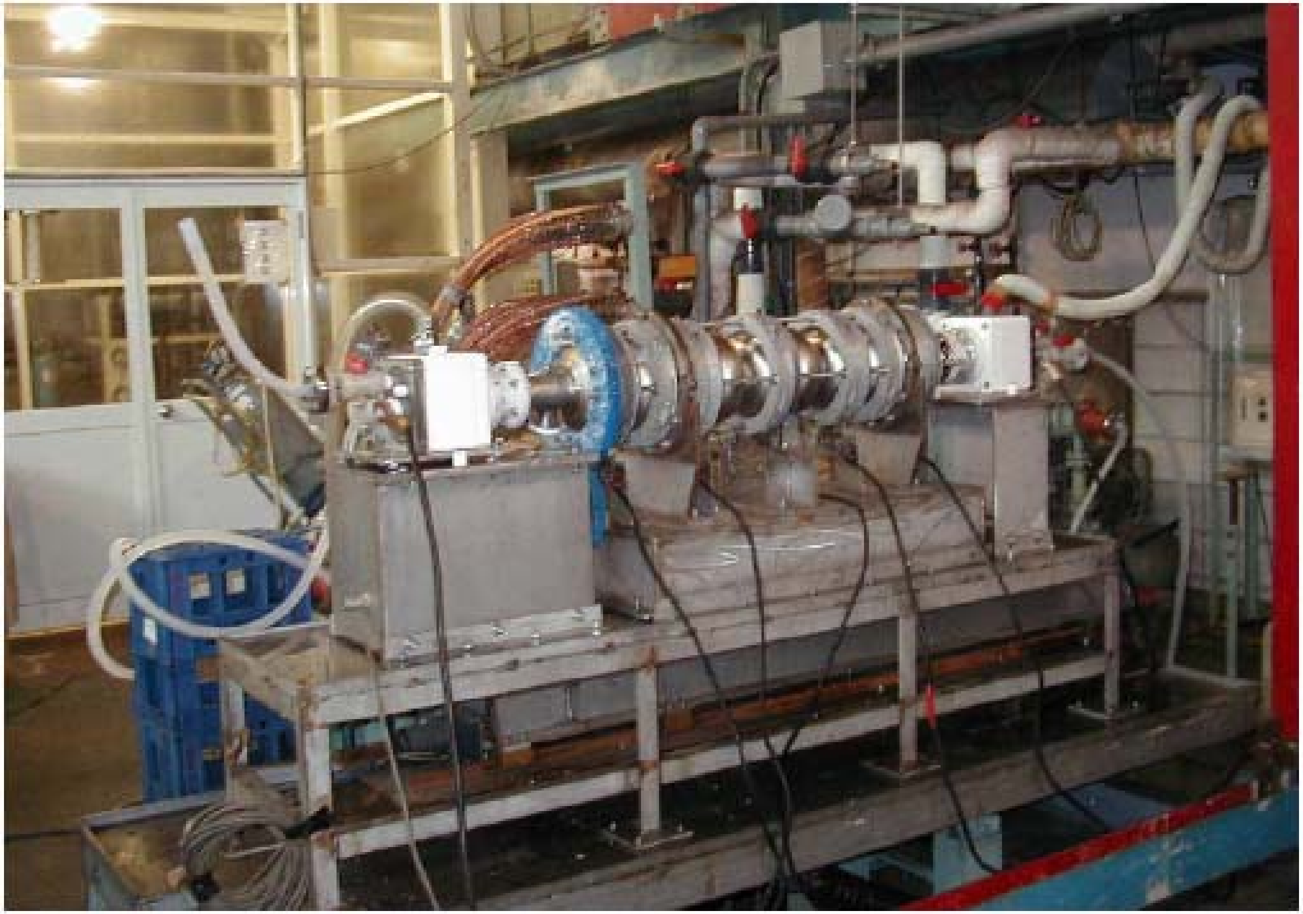
2005 ILC School - Lecture 3

Conventional post process methods: CP, BCP and EP.

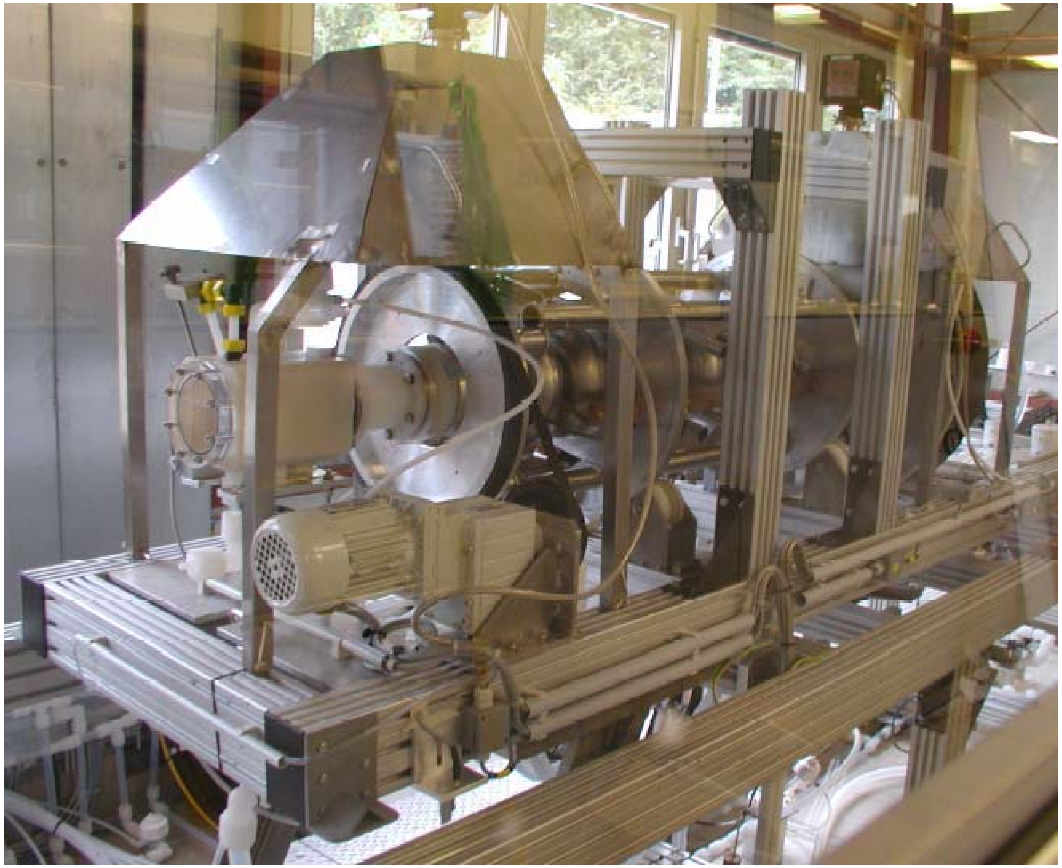
EP as a necessary cavity processing step was wrote in ILC RDR.

Current EP systems are complex and expensive!

H-EP system at KEK, Japan



EP system at DESY



PKU SRF status

~10 teachers, 20 graduated students,
~1000 m^2 area include offices.
~to set up a SC linac.
~study multi-SC structures.

Are there some new methods to make the cavity inner surface more smooth higher efficiency and low cost?

Is EP good enough?

Available online at www.sciencedirect.com

ScienceDirect

Applied Surface Science 253 (2007) 3041–3052

applied surface science

www.elsevier.com/locate/apsusc

Smooth Nb surfaces fabricated by buffered electropolishing

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The primary study shows that buffered electropolishing (BEP) could provide faster mass removal rate and smoother Nb surface.

BEP:0.646 μm / min

EP: 0.381 μm / min

Measured parameter	Treatment method		
	BCP	EP	BEP
TIR (nm)	7081	1561	290
RMS (nm)	1274	251	35
AMD (nm)	1019	198	25

In principle, BEP is as the same as EP.

We start from EP study and then repeat Dr. Andy T. Wu's experiment .

The basic concept of Electropolishing

"The Electrolytic Polishing of metals--Application to Copper and Niobium"
—*V. Palmieri*,

An **anode** is an electrode on which
an oxidation reaction is occurring,
A **cathode** is an electrode on which
a reduction reaction is occurring.

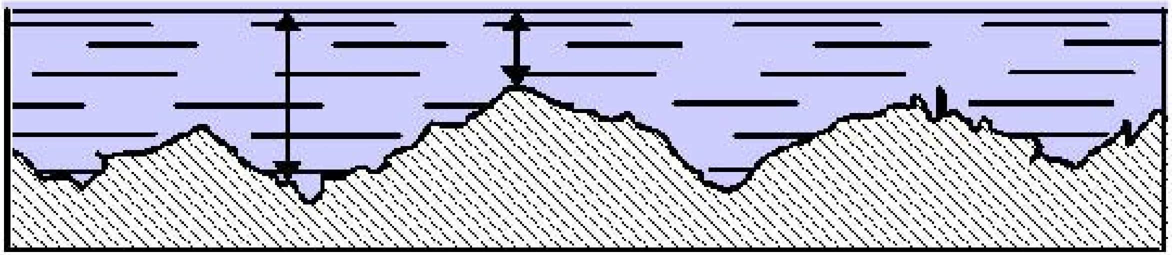
In Niobium case , the current oxidizes the Nb surface , Hydrofluoric acid solutes the oxides.

Jacquet proposed a simple mechanism for EP:

Jacquet, P.A., Trans. Electrochem Soc, 69, 629, (1936)

A viscous layer of anodic dissolution products is formed:

Respect to the bulk of the electrolyte, this layer has **higher viscosity** and **greater electrical resistivity**



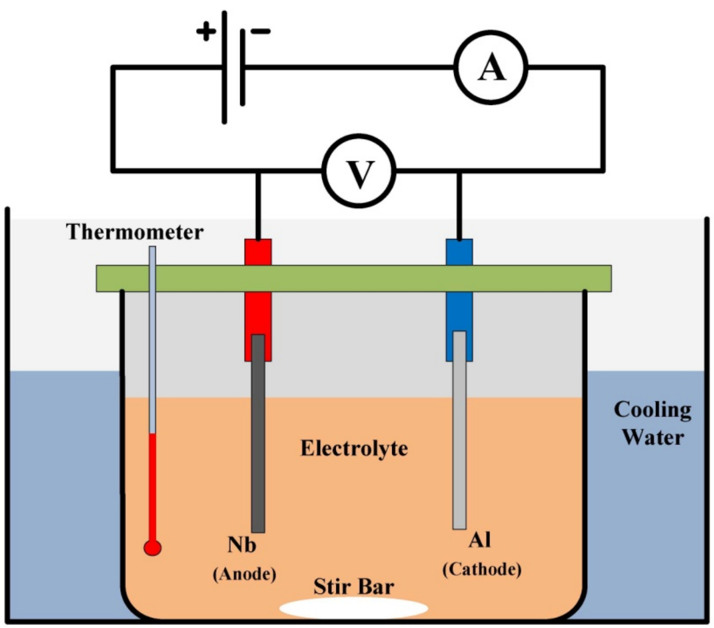
- The thickness of the liquid **insulating** layer is greater in crevices than on projections.
- The current density on projections it is higher than in crevices.
- For this reason, projections dissolve more rapidly than crevices, and this produces a surface-leveling effect.

—V. Palmieri

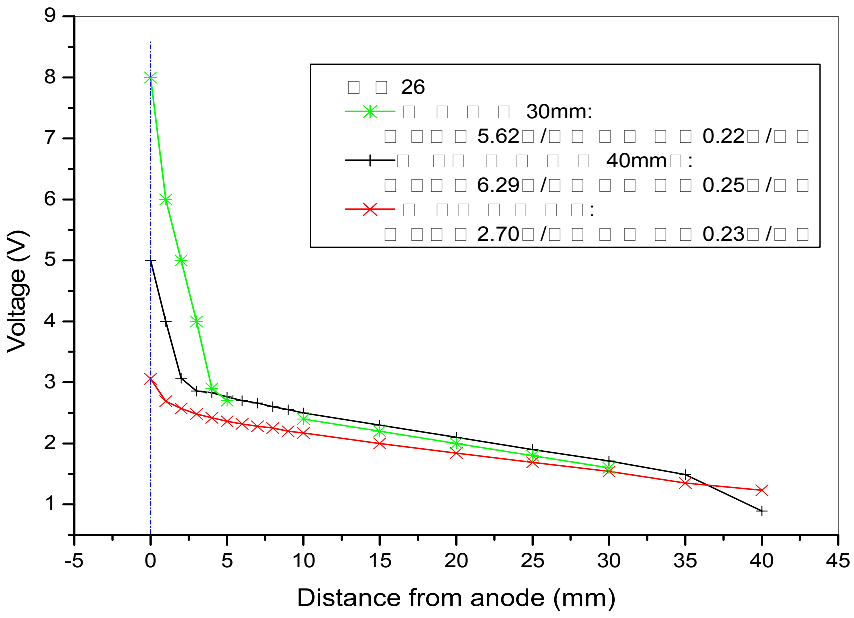
We think that the viscous layer which is formed on anode surface is the key point.

At the first, we need to prove the existence of the viscous layer.

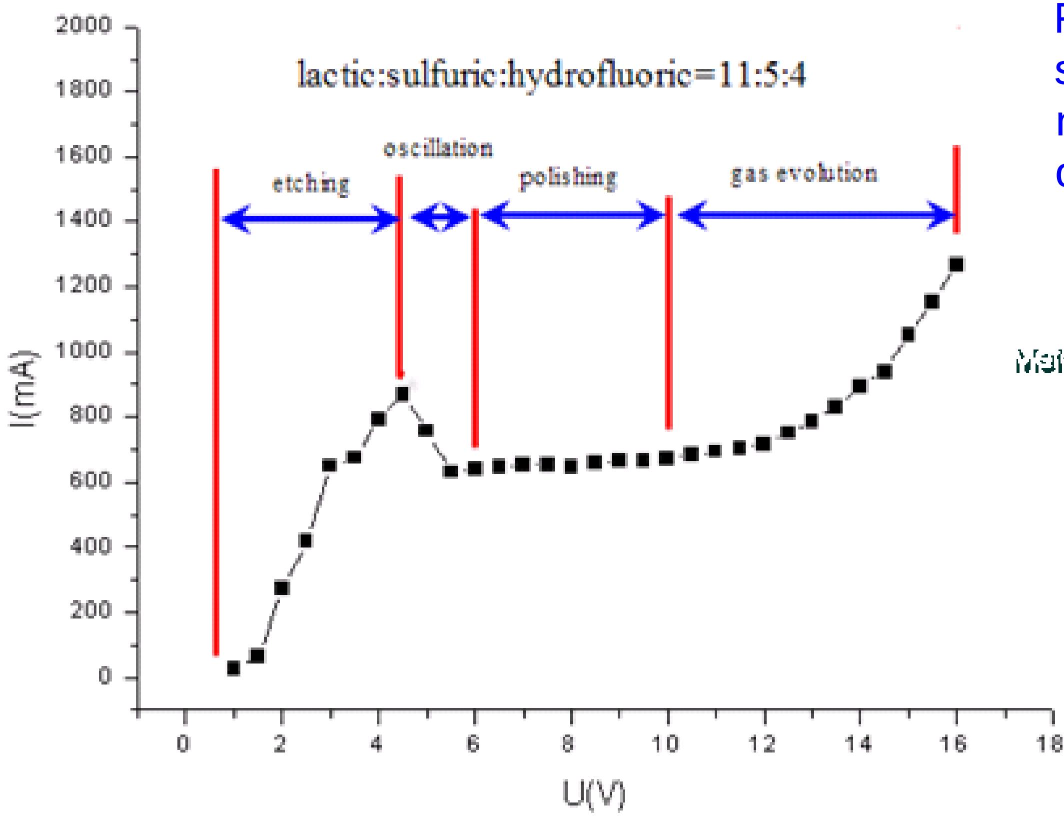
Electrolyte: HF(46%)+H_2SO_4 (> 93%) +Lactic acid(> 85%), 4 : 5 : 11



Applied voltage: 10V

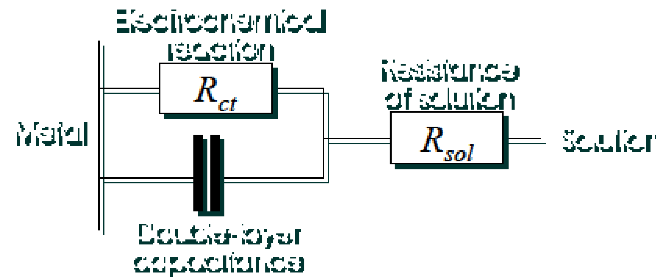


volt-ampere characteristic



Anode current measured as a function of applied for polishing Nb sample

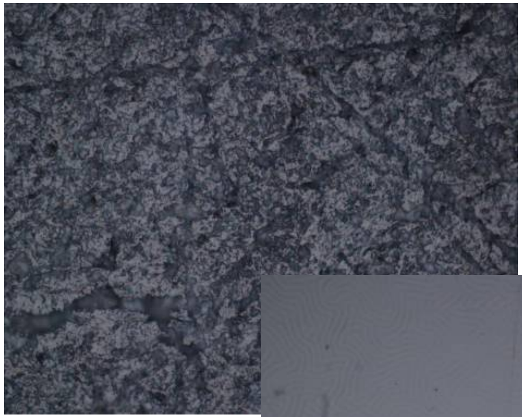
From about 4 to 6 volt, the slope of the I-V curve is negative, and oscillation is observed.



We believe that there is a layer on anode surface and it is high resistivity.

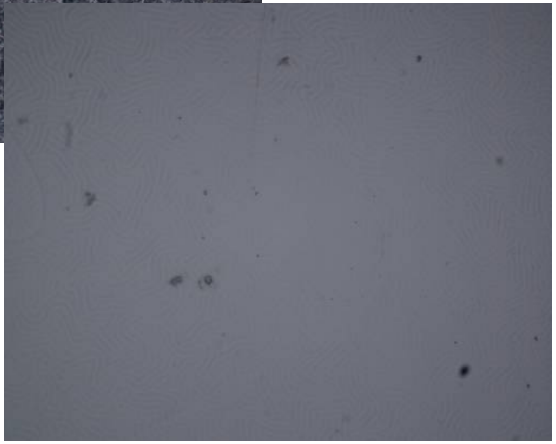
Chemical Process workshop at PKU

The primary BEP study



By MP

×1000



After BEP

×1000

Fast Nano-scale buffered electropolishing

***Agitation of solution* could accelerate chemical reaction.**

In BEP/EP case, when the solution is agitated, the ion diffusion is speed-up.

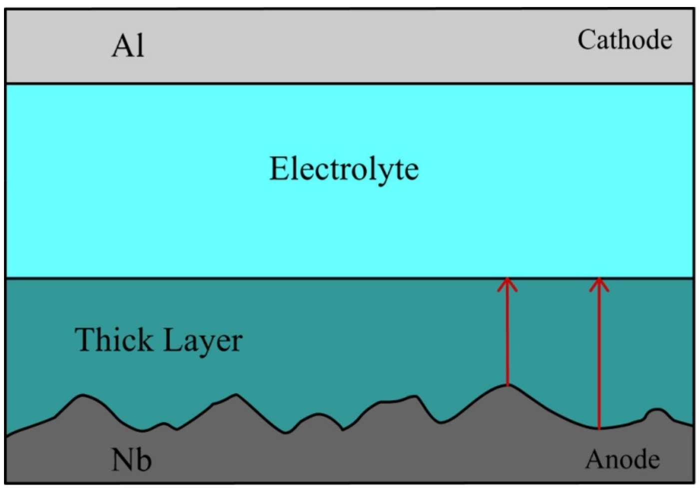
The electrolyte of BEP is quite viscous because it is mixed with lactic acid. So, the flow also could take some soft matter nearby to move together.

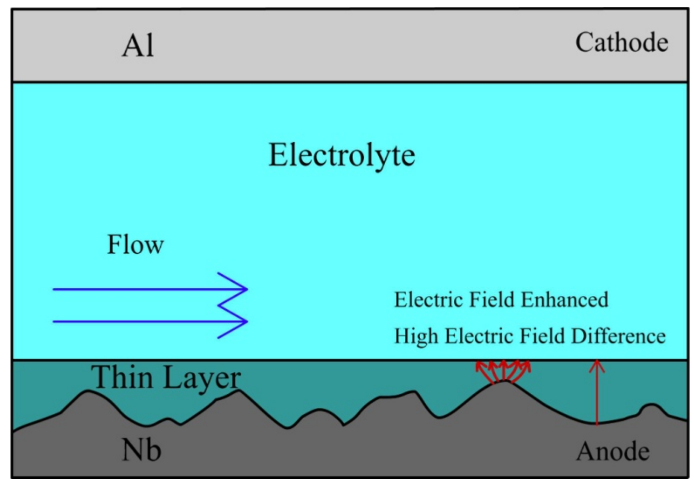
Our idea: to remove a part of Jacquet layer by the electrolyte flow and then not only to speed up the ions diffusion, but also the E-field is enhanced to get high current density.

When the layer is thinner:

——The strength of electric field in the layer is higher that positive ions are more easy left the solid surface and into solution.

——The E-field difference between peaks and hollows are enhanced.





Stirring the electrolyte could speed up the EP process and get more smooth result in the mean time.

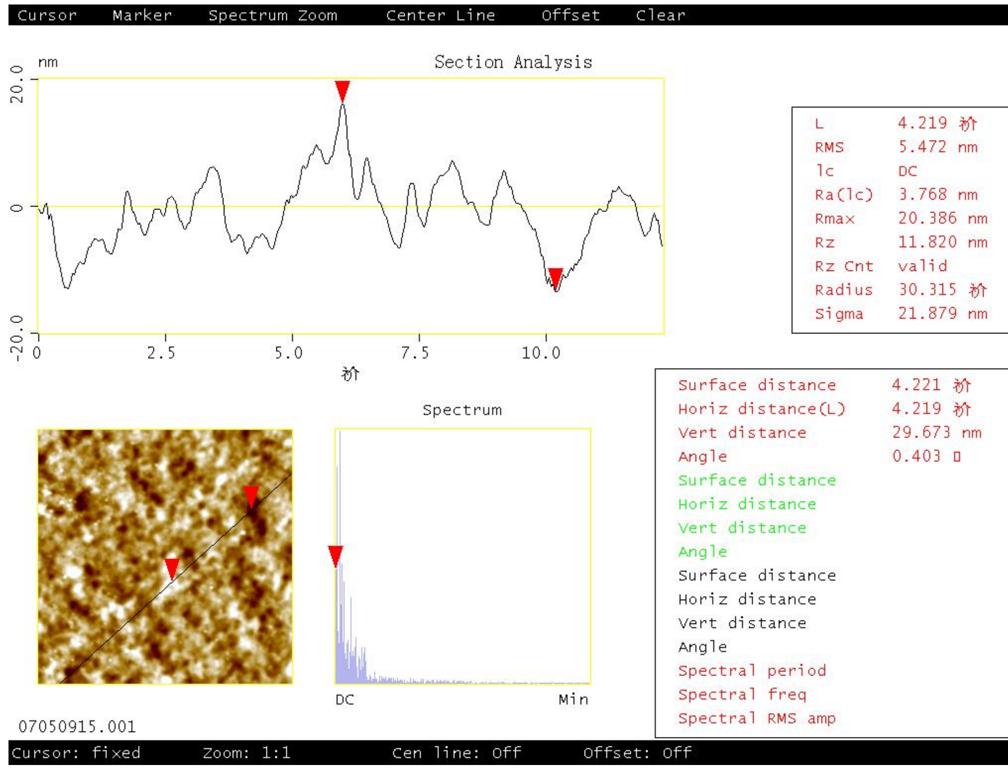
BEP experiments

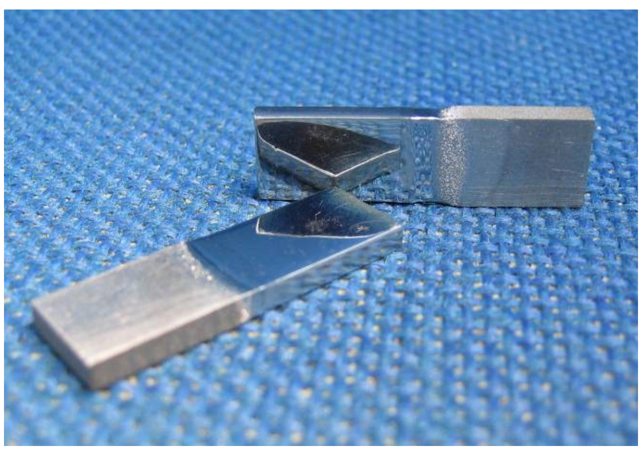
Small sample

Area ratio: ~1:1

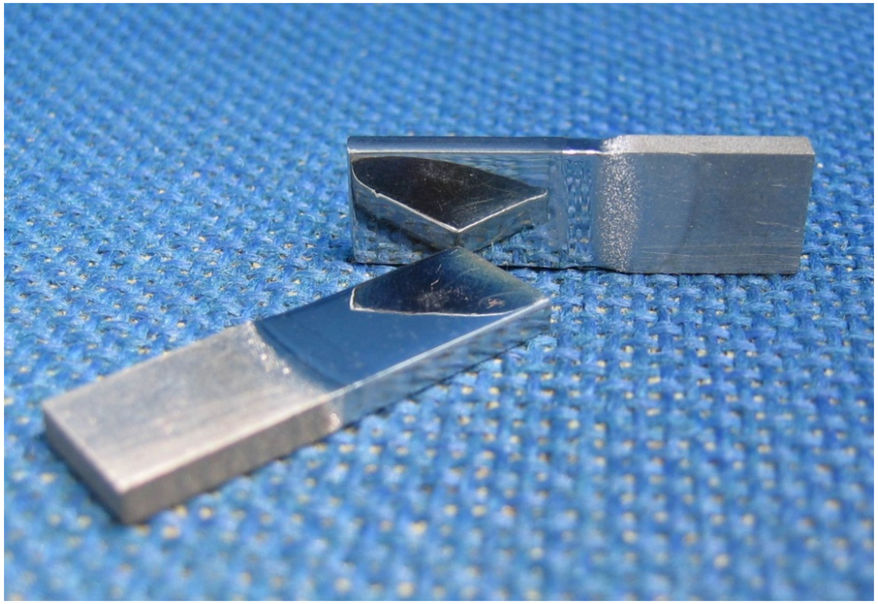
Current density:
265mA/cm2

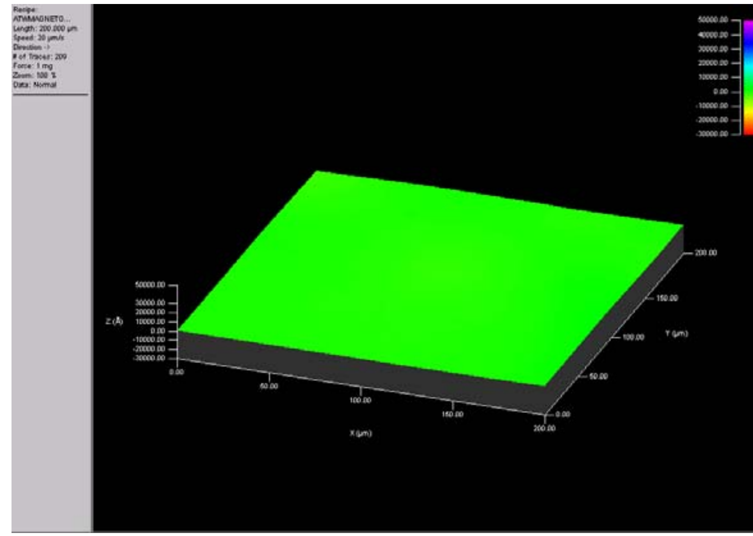
Mass removal rate:
3.79μm/min

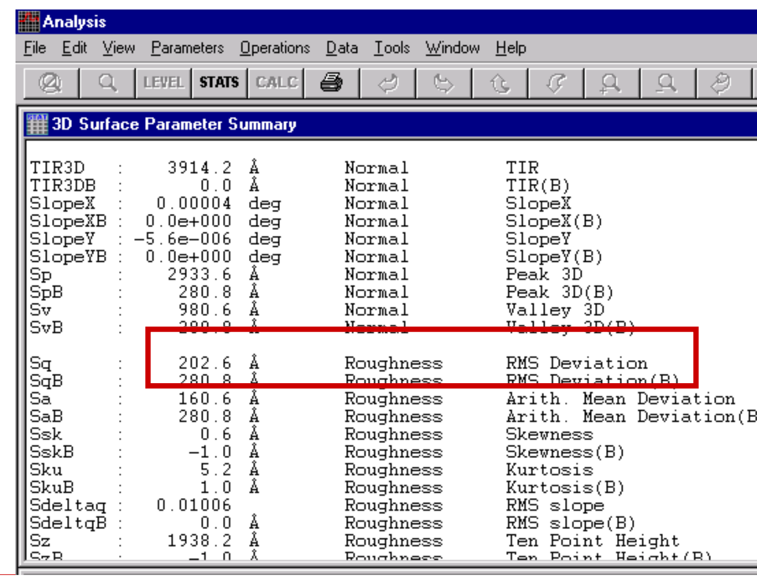




The BEP sample surface analysis by AFM, **RMS<5.5 nm**, analysis area: 10×10μm. (2006)







Roughness (RMS): **20 nm**

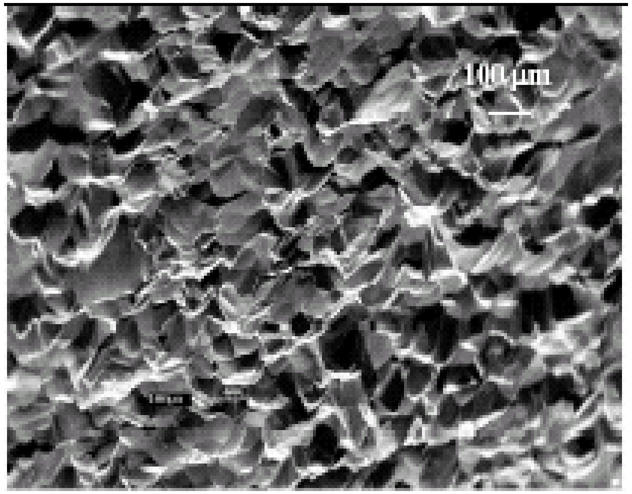
Measurement area: **200×200 μm**

(by Dr. Andy T. Wu, JLab,2008)

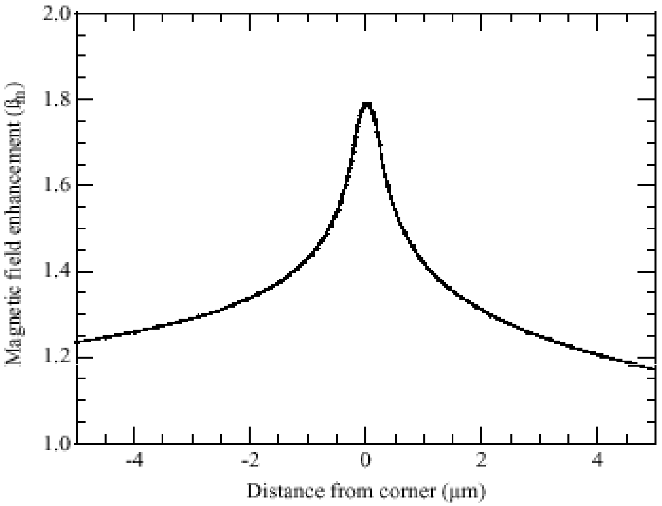
Notice:

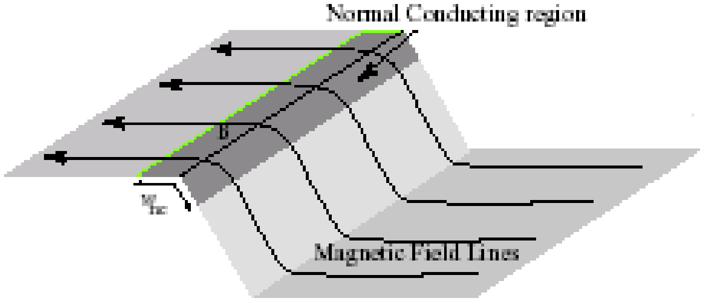
The London penetration depth is about 40 nm;
The coherence length for Niobium at 2K is about 40 nm;
The RF penetration depth of 1.3 GHz is 50 nm.

Magnetic field enhancement (MFE)



Chemically polished surface

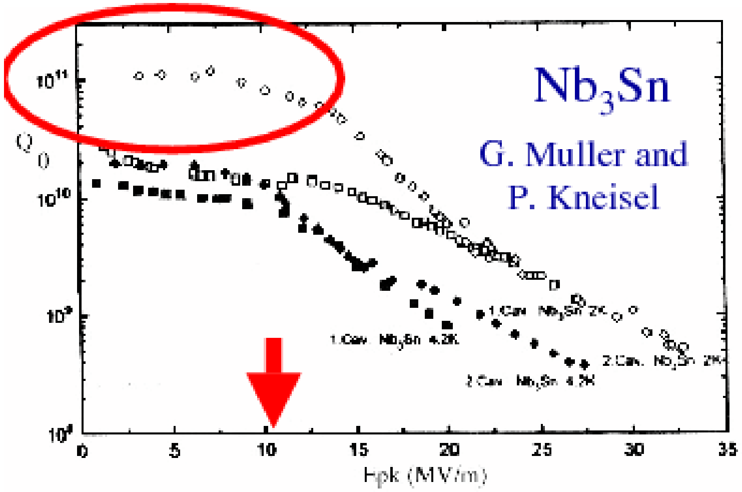


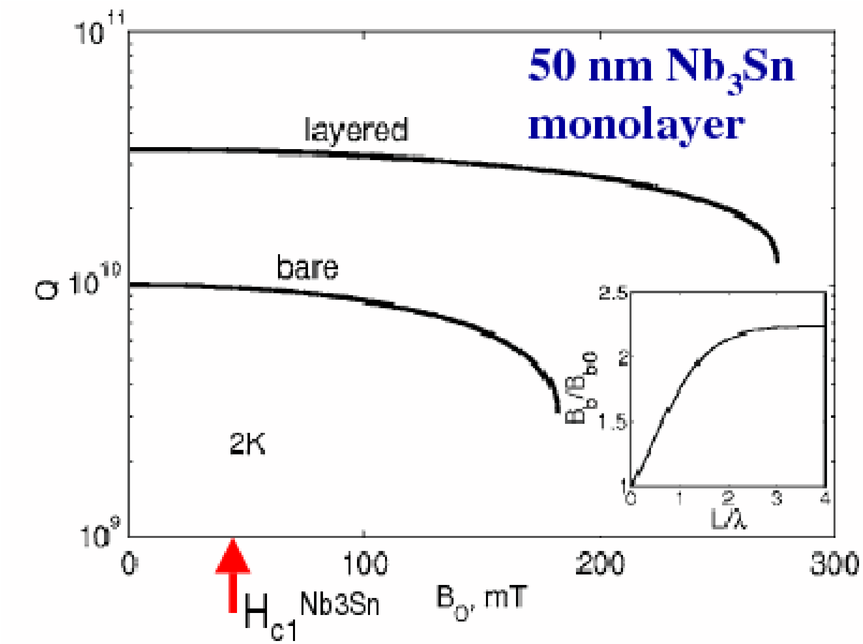


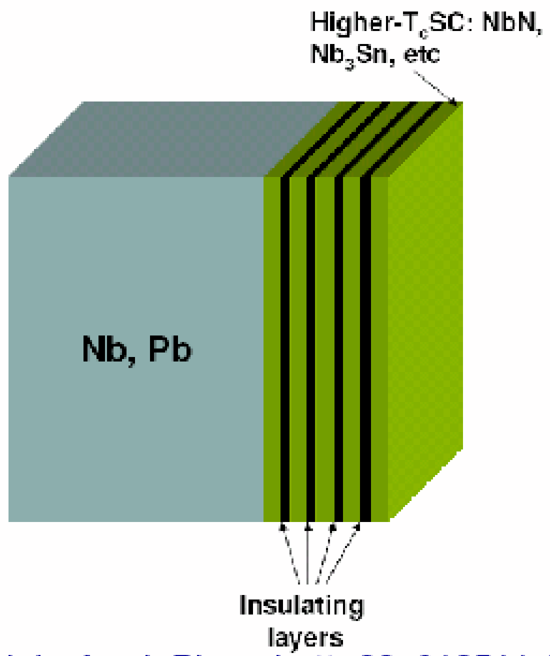
Field enhancement region with enhancement factor β, if β H > H_c the region becomes normal conducting

(J. Knobloch - SRF '99 - Santa Fe)

Beyond the Nb technology







A. Gurevich, Appl. Phys. Lett. 88, 012511 (2006)

- Thin high-H_c layers ($d < \lambda$) separated by insulating layers increase H_{c1} well above the bulk H_{c1}.

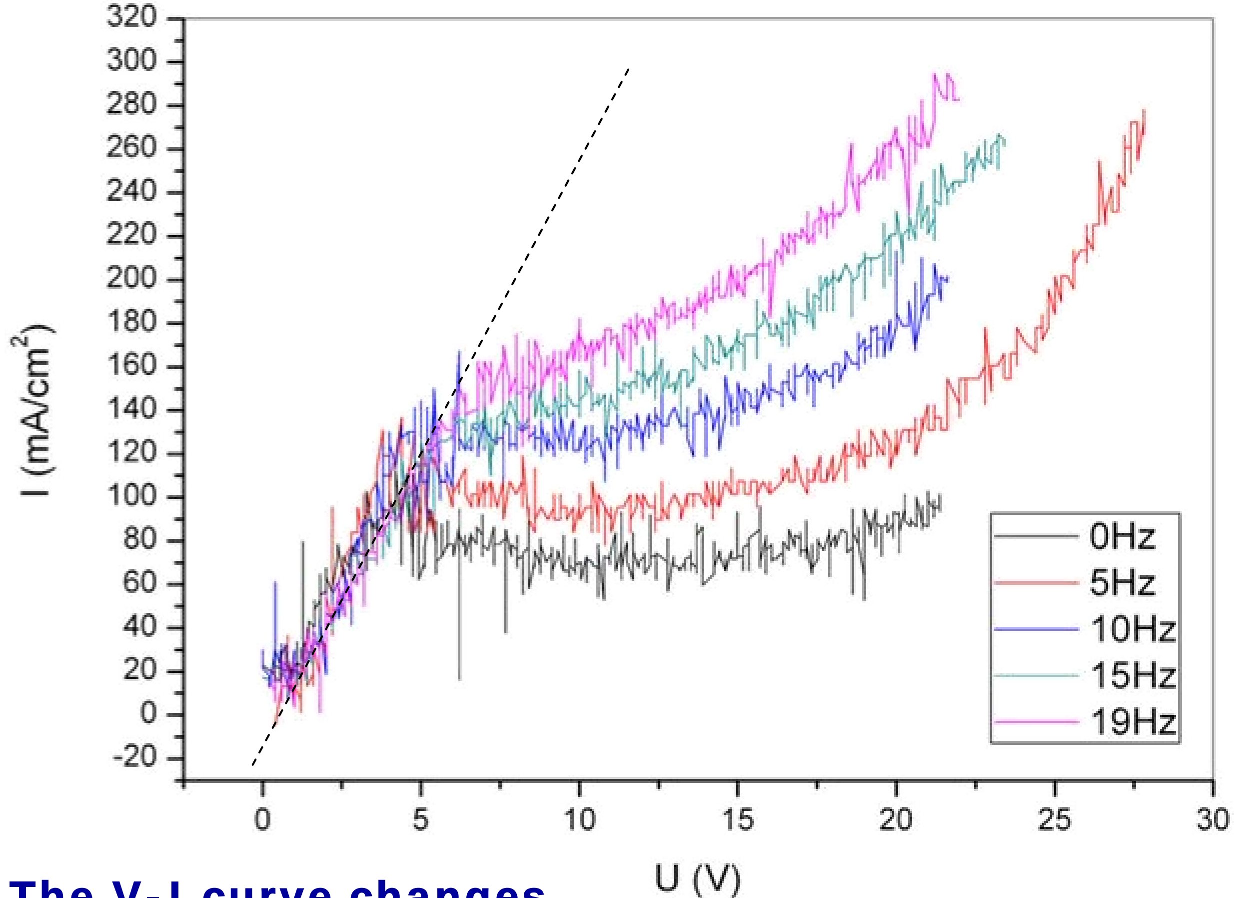
- Nb_3Sn thin film coating may triple the breakdown field of Nb and increase **$Q \sim \exp(\Delta/k_BT)$**, by 3-10 times because **$\Delta_{Nb3Sn} \approx 1.8\Delta_{Nb}$**

183μm (235mA/cm²)

111μm (210mA/cm²)

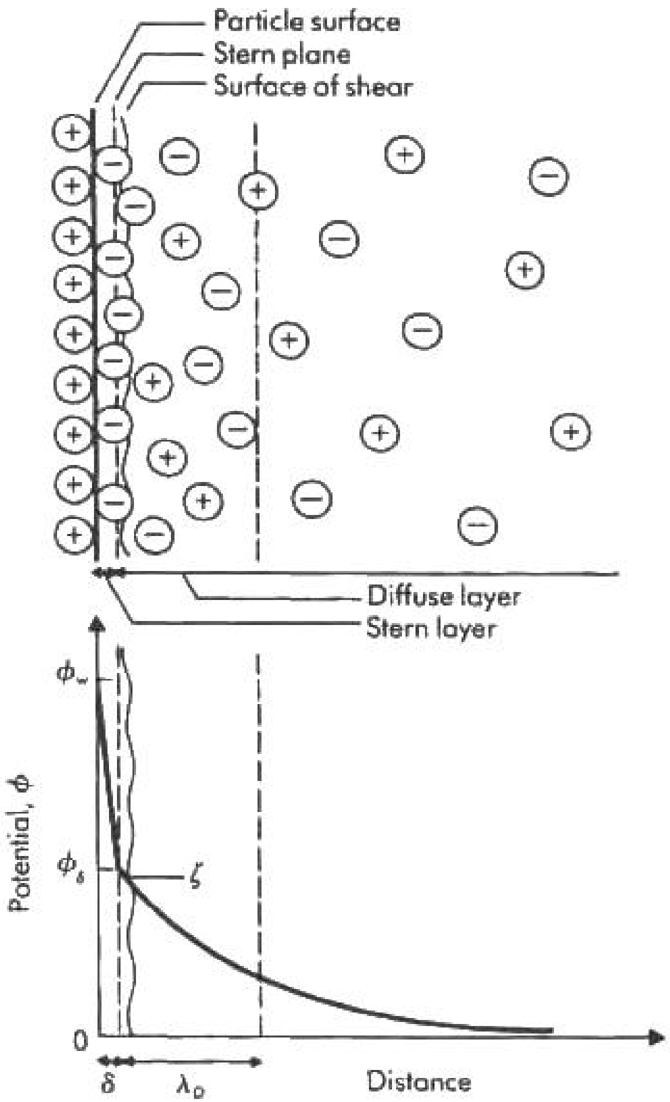
Scratches could be removed

The evolution of Volt-ampere character



The V-I curve changes with different flow rate.

1Hz --- stirrer runs 1 turn per second



* When stirring the electrolyte, the balance of the neutralization near anode surface is dissolved. The system is in the status of etching.

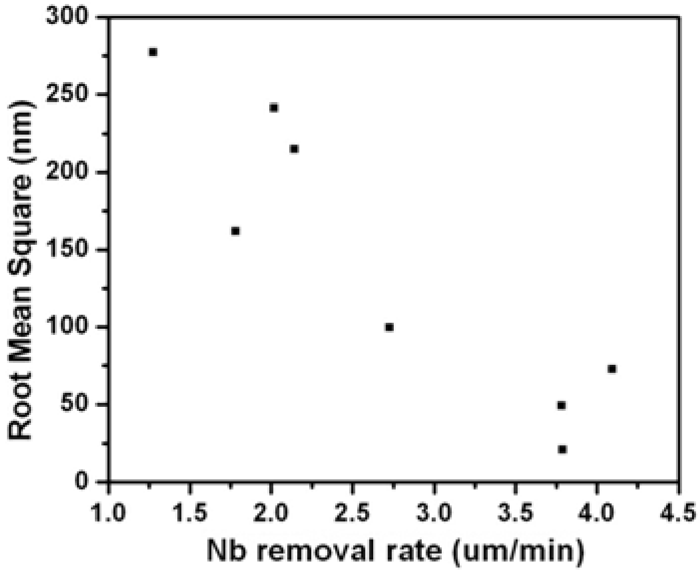
* It should apply higher voltage to produce more positive ions for set up a new balance---to get the constant current. The current density is increase.

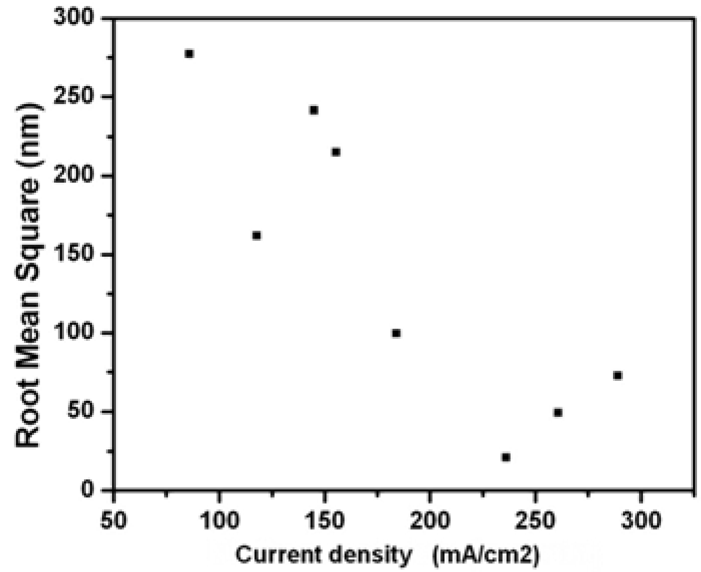
* The capacitive of the new layer is not always fit the oscillation condition. When the electrolyte flow is fast, the oscillation will not be observed.

The optimum BEP conditions

A compare experiment of a series sample has been done with different current densities/stirring speeds.

All samples are polished for 20 min, under 30□.





Dr. Andy T. Wu, JLab, joined the experiment and measured samples.

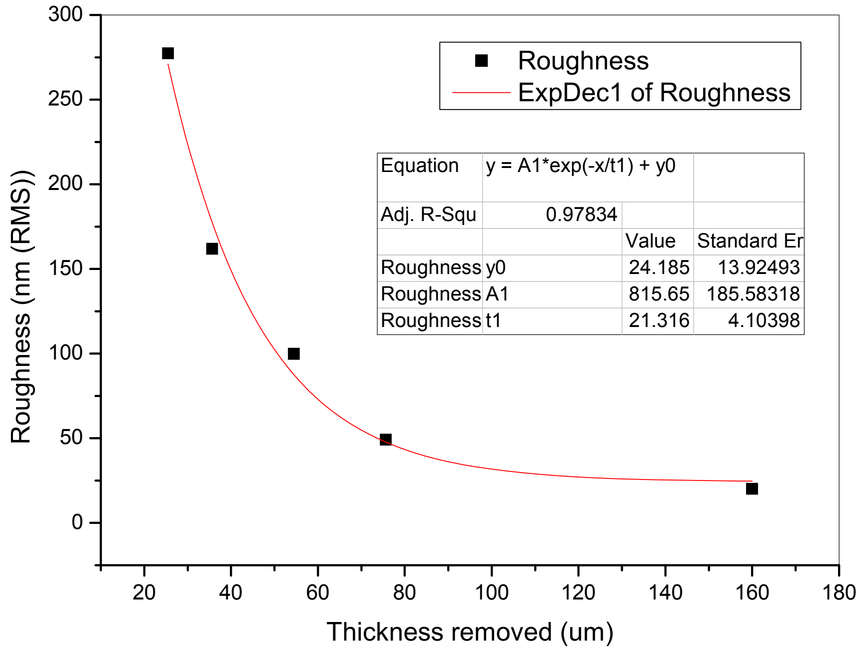
The optimum BEP conditions

Applied voltage: 10~15V

Current density: 240~260 mA

Surface flow speed: ~30-50 cm/s (estimated)

Electrolyte temperature : <50□



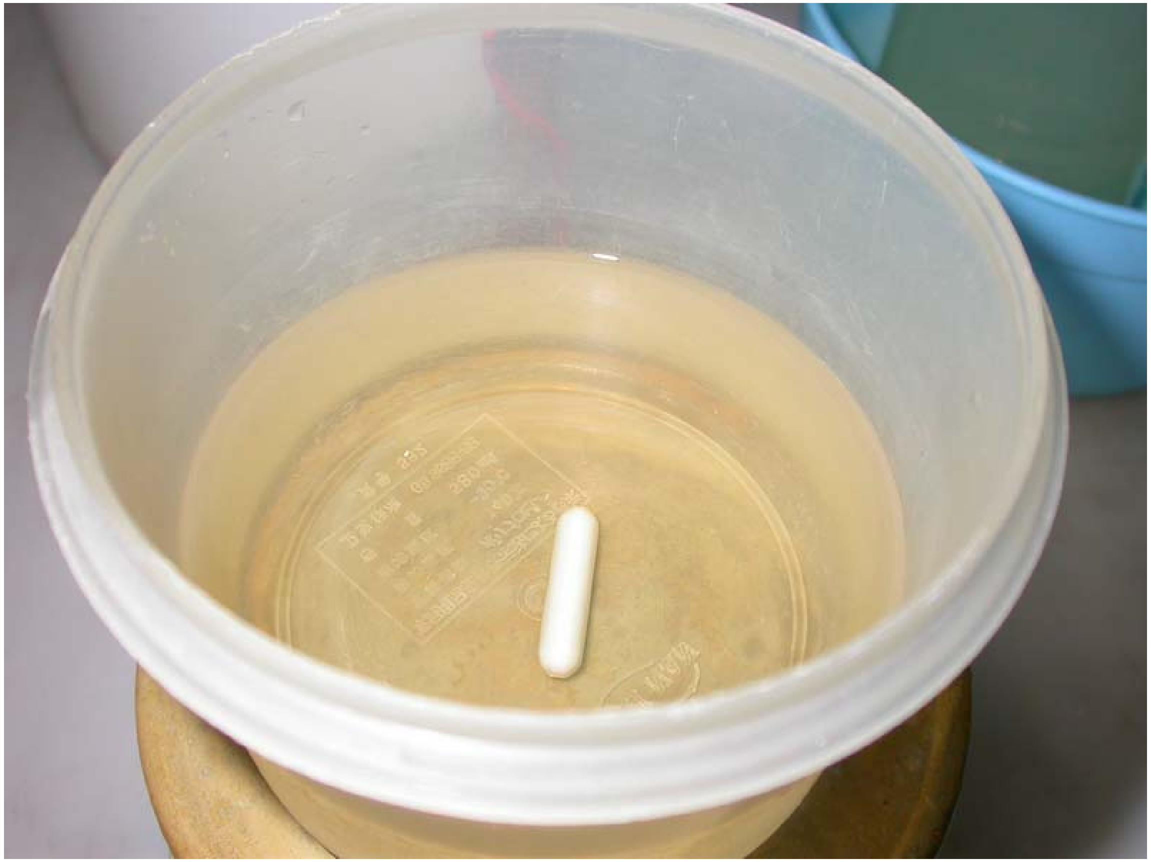
The PKU Mixing Order of BEP Electrolyte

First: Lactic acid + HF
then: mixed with H_2SO_4.

If first mix Lactic acid with H_2SO_4, the H_2SO_4 will take water from the molecular of Lactic and produce some carbide and the electrolyte shows dark color.

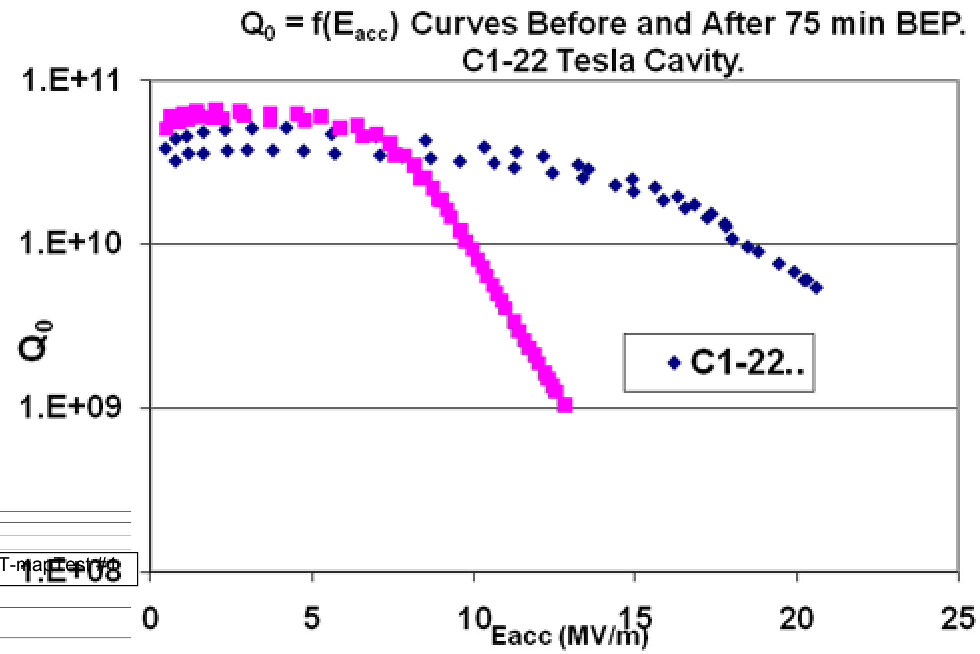
Those carbide will directly effect cavity performance if some of them left on the cavity surface.

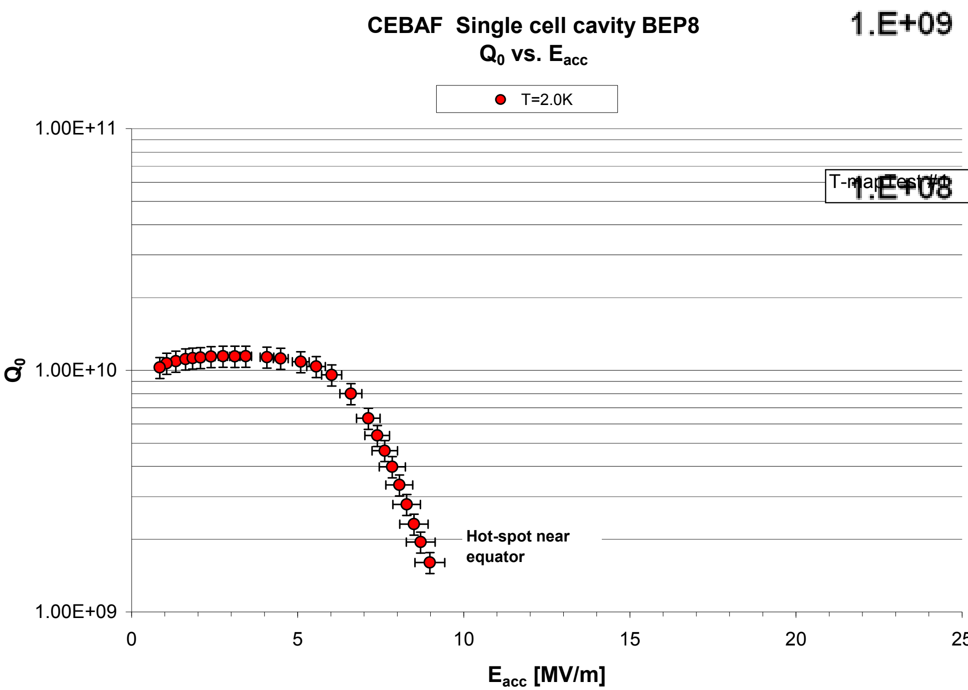
The electrolyte is pure and clean which is mixed by PKU Order.



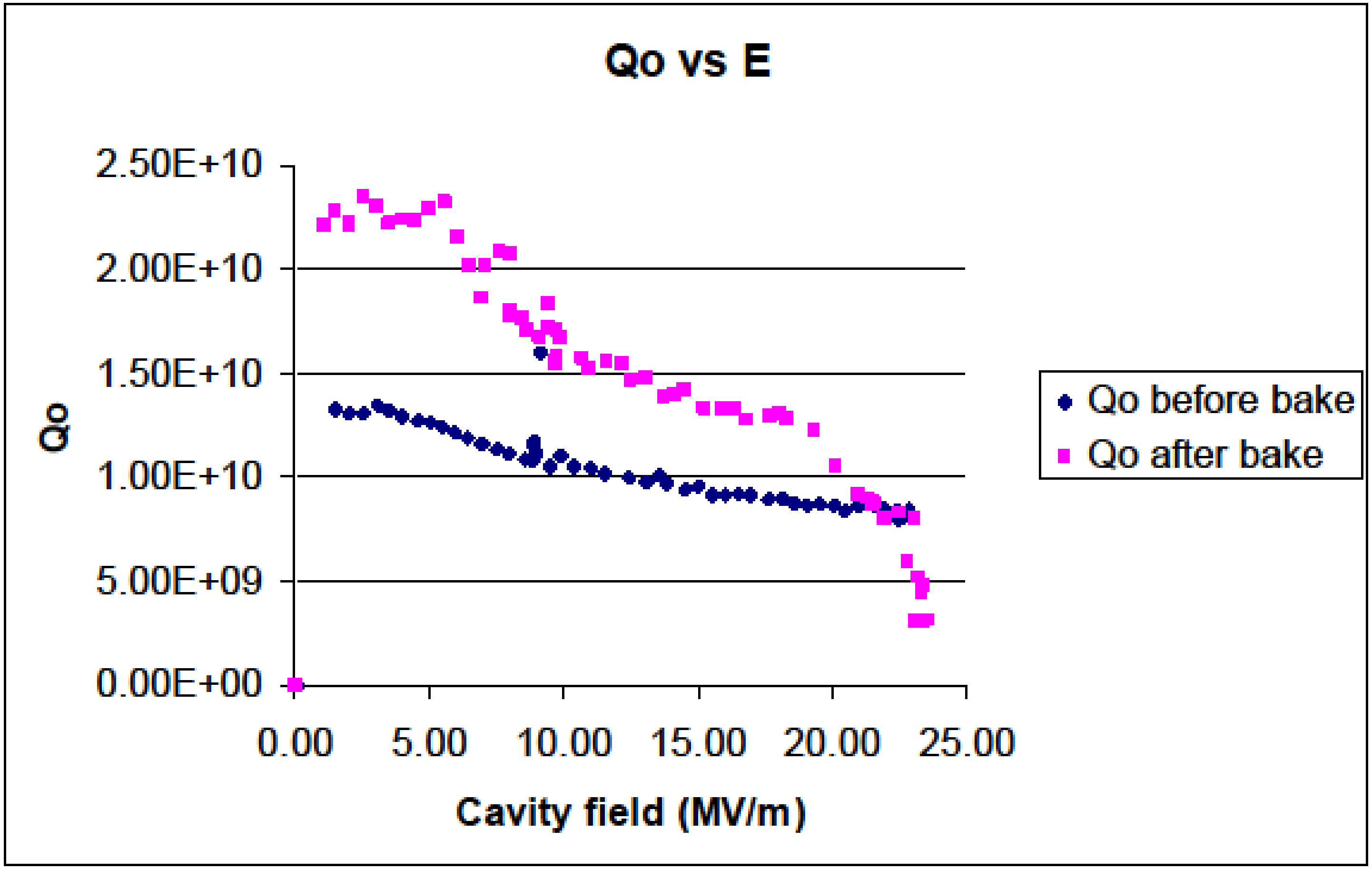
The commercial mixed. Photo is from Dr. Andy T. Wu.

BEP using the **commercial acid**, Q_0 of both CEBAF and TESLA (from CEA-Saclay) cavities are drop down extremely fast, no FE.



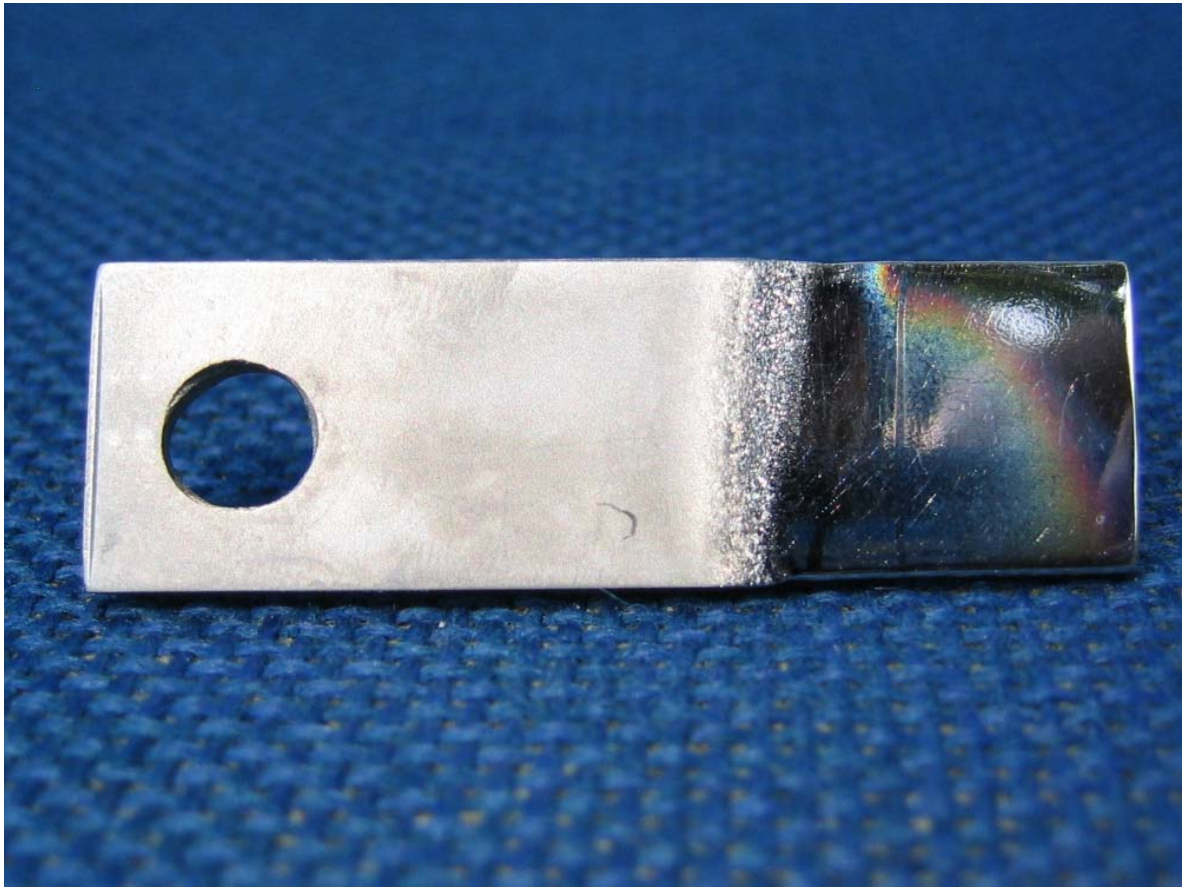


The carbide particles which residue on cavity surface cause the dissipation of RF energy.



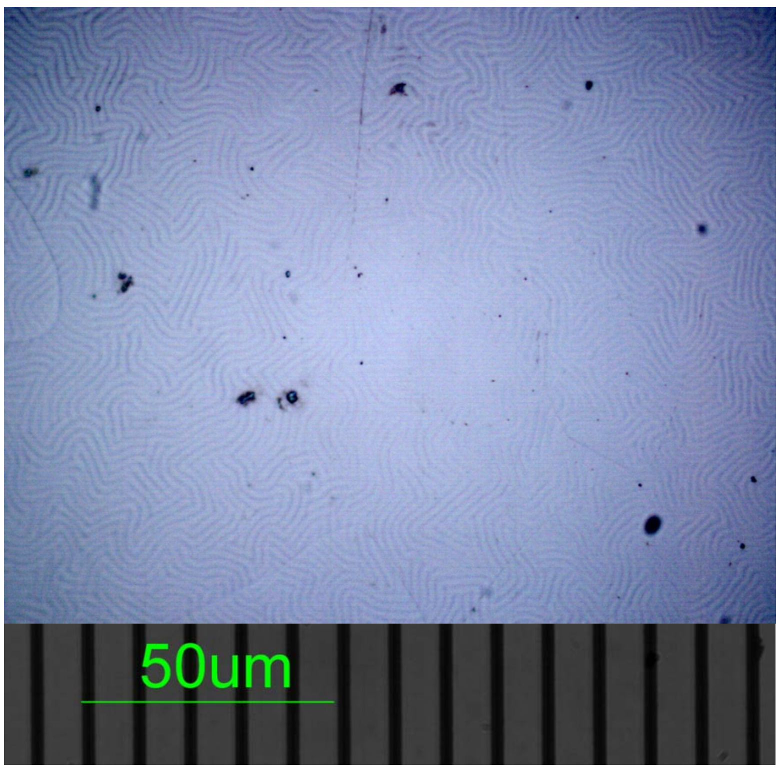
BEP with the acid which mixed in PKU order, the Eacc is about 23 MV/m. (The latest data is 26.7 MV/m).

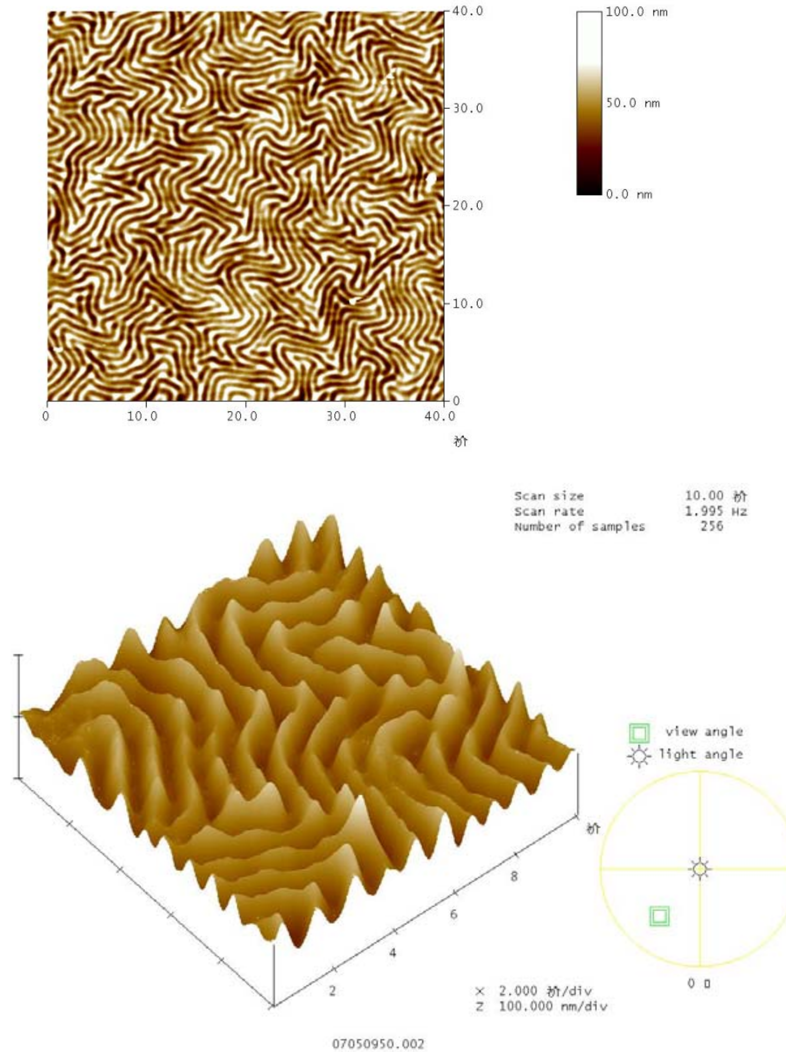
Associated phenomena---“Rainbow”



Microscope view of "rainbow"

(Optical , *down* ; AFM , *right*)





AFM measurements show the typical height of the patterns is 100~200 nm (valley to peak).

The interval between two hills is less than 1 μm.

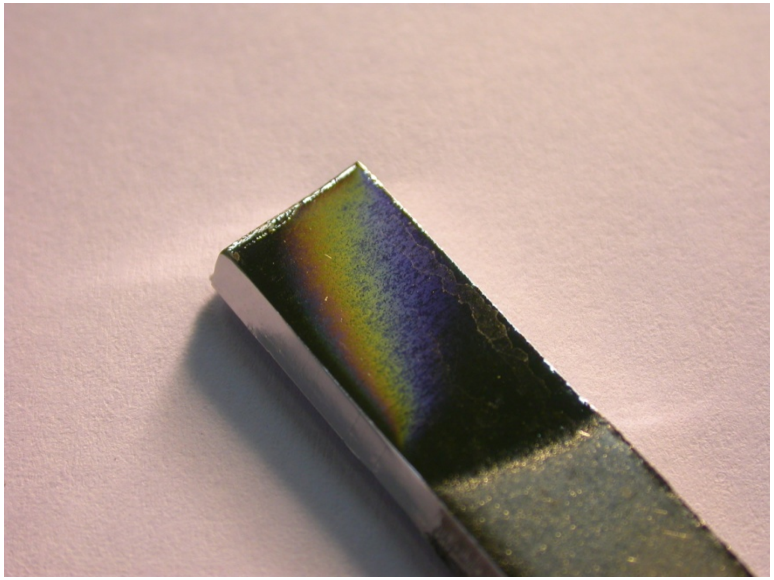
The RMS roughness of the pattern is about 10 to 25 nm. (**Nano-Engineering**)

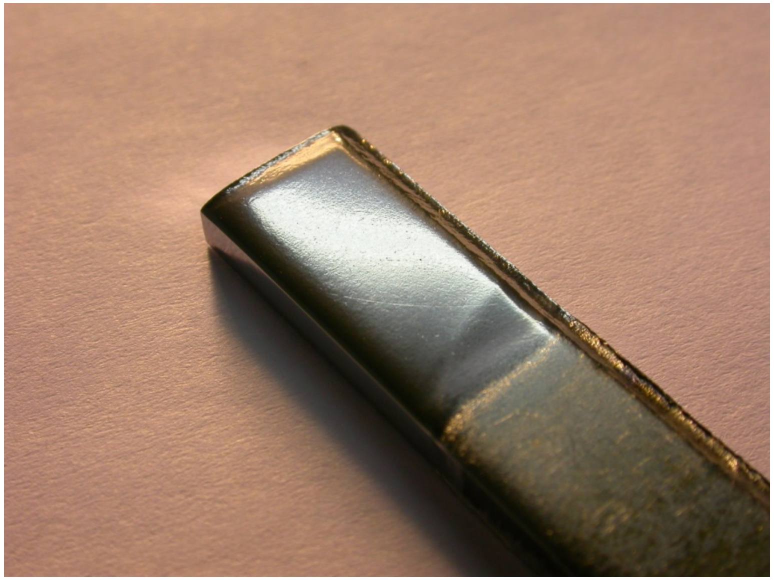
We did not analysis the pattern material yet.

We think that the "Rainbow" is the result of the disturbance of electrolyte flow on the soft, skin like film.

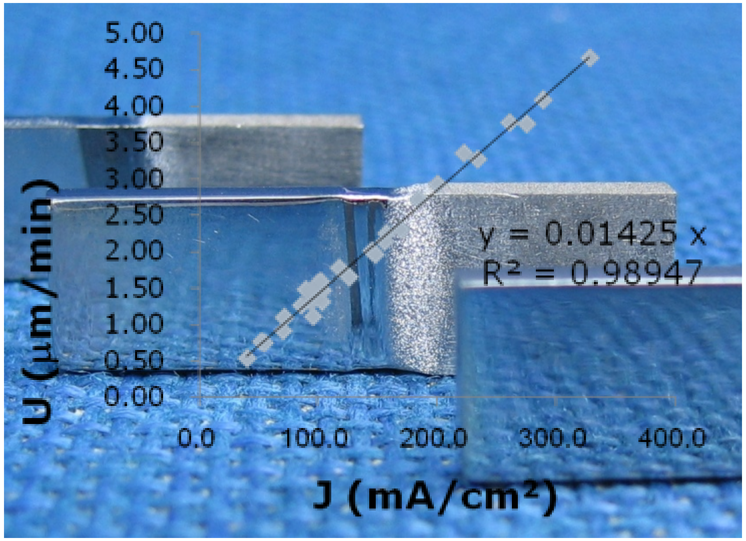
"Rainbow" could be removed

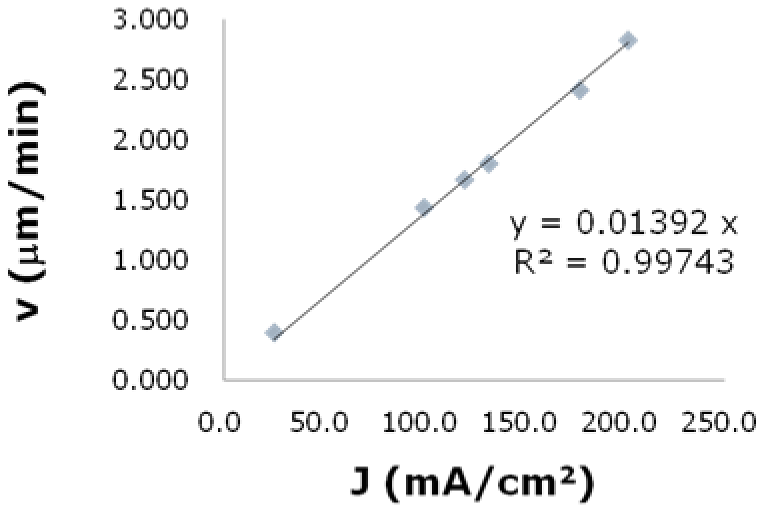
When there is electrolyte flow, under a certain condition, the "rainbow" will appear on the sample (cavity) surface. If the "rainbow" is un-wanted, it could be easily removed.





What did happened at the liquid-air interface ?



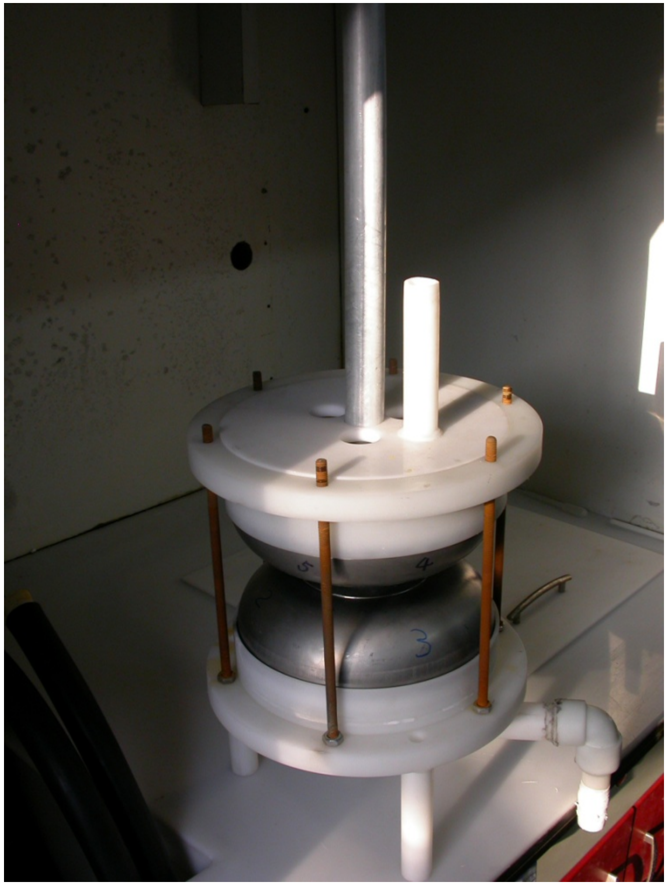


If all Nb ions are Nb^{+5}, the ratio of mass removal rate over current density should be **0.0134.**

We set our BEP device in Argon sphere , the groove disappear and the slope is smaller.

Is there a relation with the air bubbles?

BEP—from sample to cavity

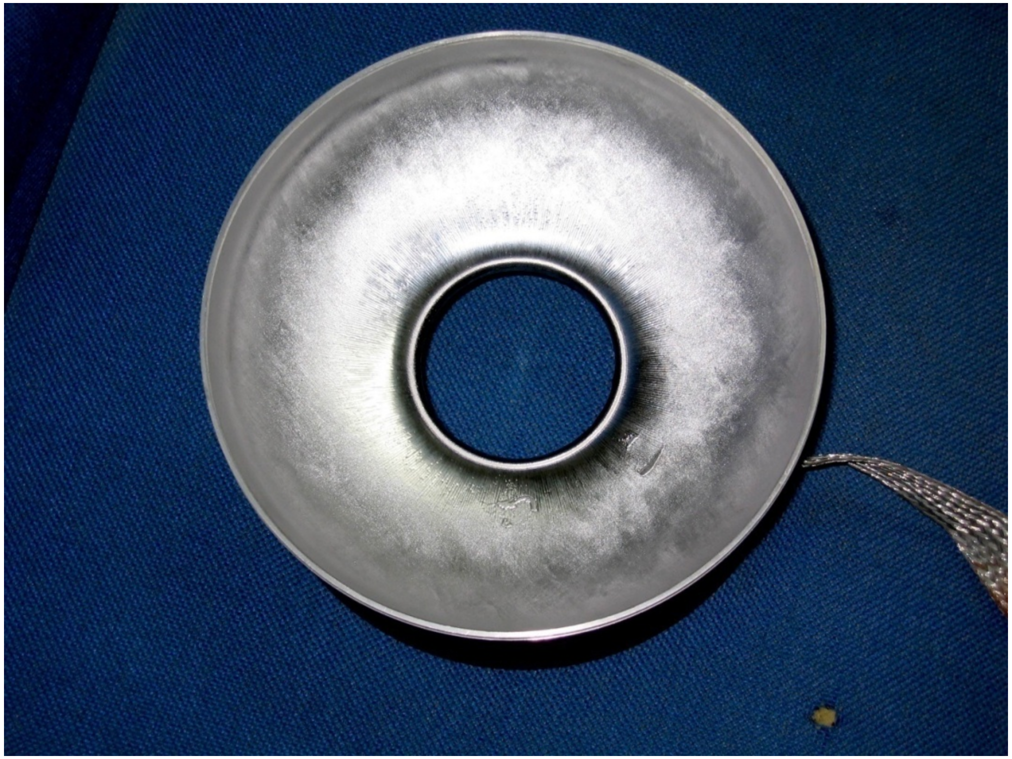


A dumb-bell as anode.

Cathode is an pure Al rod.
(Diameter is 30 mm)

To take a rod shape cathode is according to the such idea that the Jacquet film is high resistive. So that, the most part of voltage would apply on the compact film and the current density should be almost the same at very where of the dumb-bell .

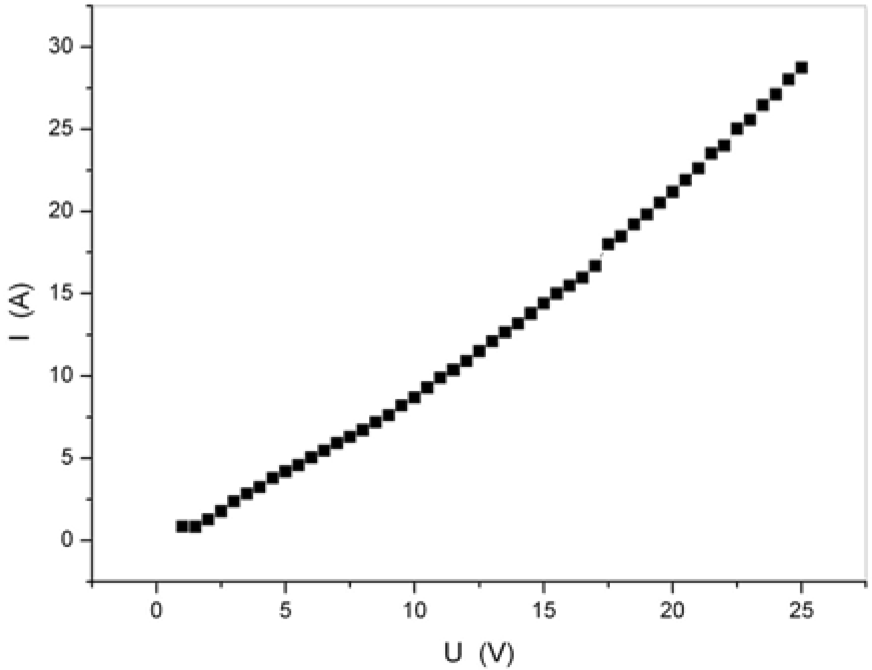
The first result shows that only the iris part was polished.

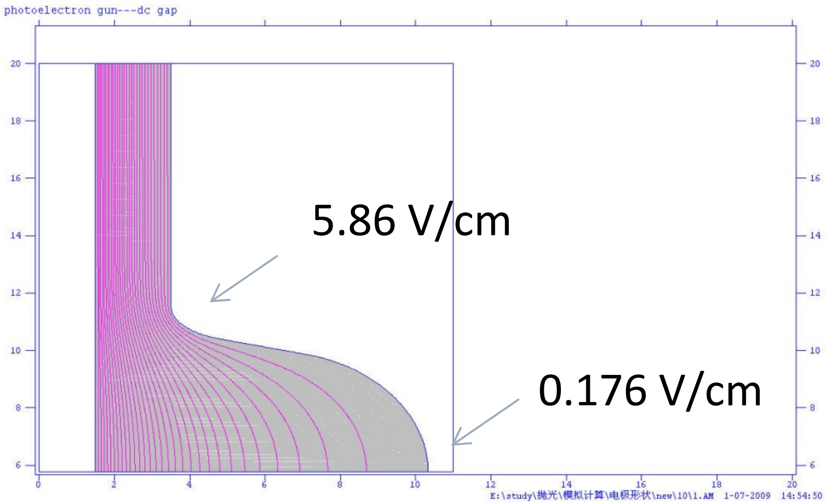


From Dr. A. T. Wu's paper, we knew that the similar situation was happened for BEP of a single cell cavity by using a rod shape cathode.

The I-V curve of Dumb-bell is different from small sample.

It is quite in linear shape and no oscillation was observed until the applied voltage up to 25V.

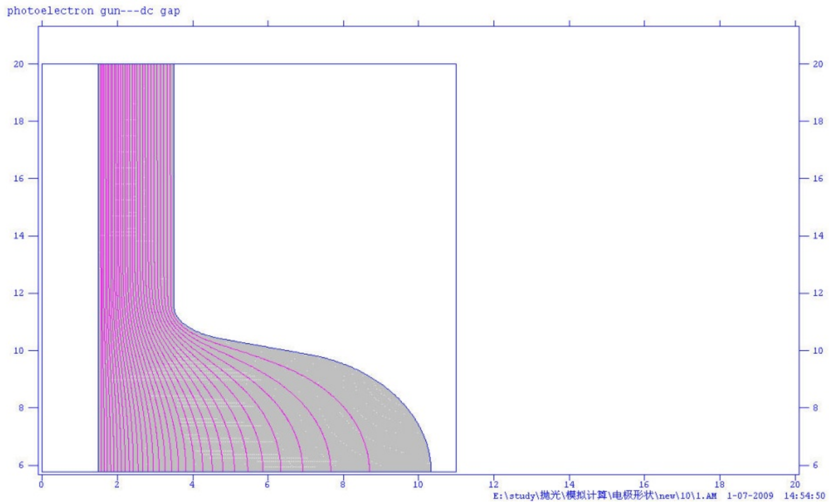




Simulation tell us that the E-field at iris is about 33 times higher than at equator.

We guess that Jacquet layer is not well formed at low-E area, in this case.

The explanation of the dumb-bell I-V curve is that the film is not formed everywhere homogeneously as our expectation.

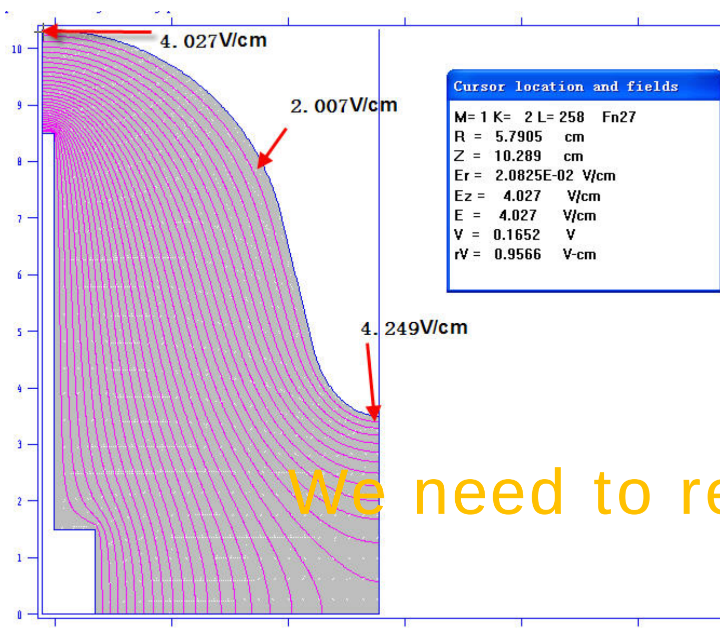


At the iris part, the film is formed well. There is no film at most other area. The system shows the low resistive integrally and we got such I-V character. Without the film, those parts of dumb-bell is etched.

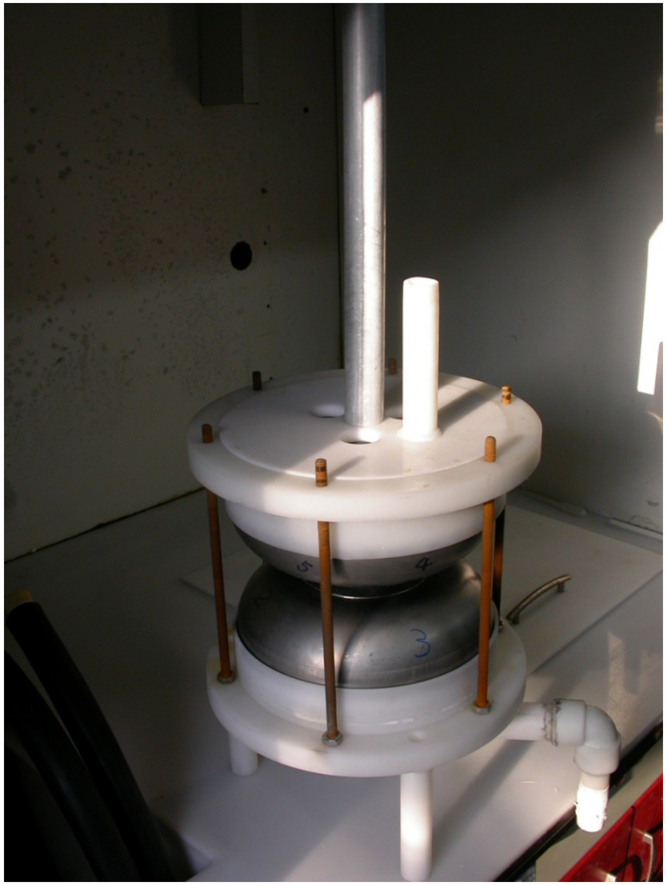
When the generation rate of ion-complex is greater than its diffusion rate, the film could be formed.

The BEP experiment of Dumb-bell

The cathode shape was changed according to the simulation result.



We need to reduce the E-field difference.



For the downward cup, cathode is an Al dish (ϕ160 × 1 mm) .

Upward cup

Downward cup

There are several questions of ECP need to study experimentally. Such as:

--- What is/are the difference(s) of ECP operation from sample to cavity?

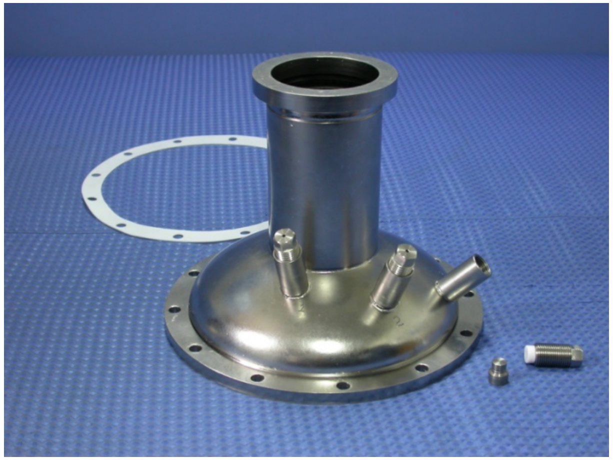
--- The removed mass amount is (or not) the same everywhere of cavity inner surface?

--- Cavity surface could be how smooth and ECP could be how fast? Is it the same everywhere?

--- Is the polishing result effected by cavity orientation for a vertical ECP system?

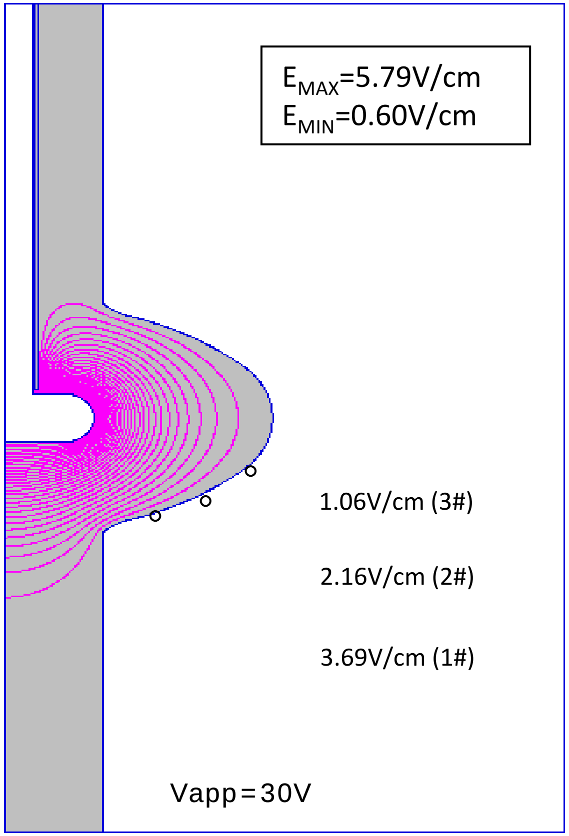
--- What is the best shape/size of cathode for cavity polishing?

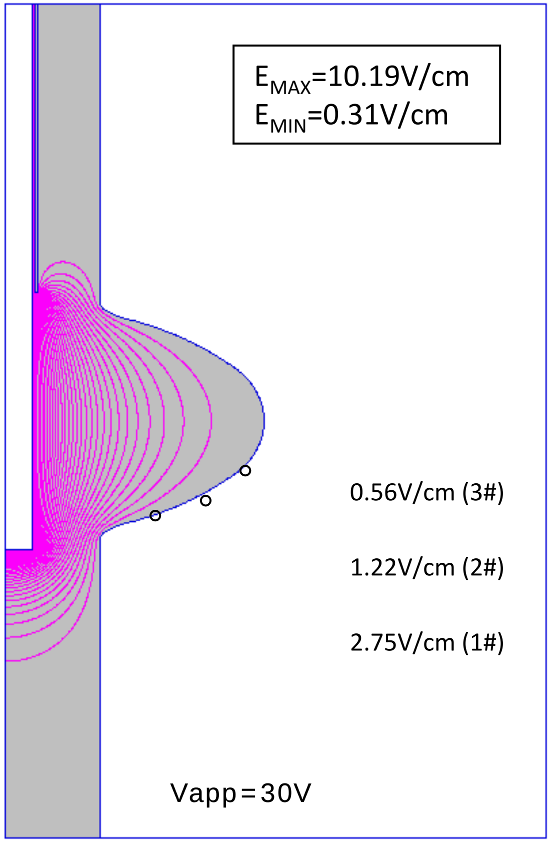
Demountable cavity-made by JLab



A new cathode is turbinate to reduce the field difference and agitate the electrolyte. When ECP, the bar is covered by Teflon.

A vertical ECP device is made. The maximum cathode rotation rate is 450 t/min. The max cathode current~200A. There is not the electrolyte recirculation at present.

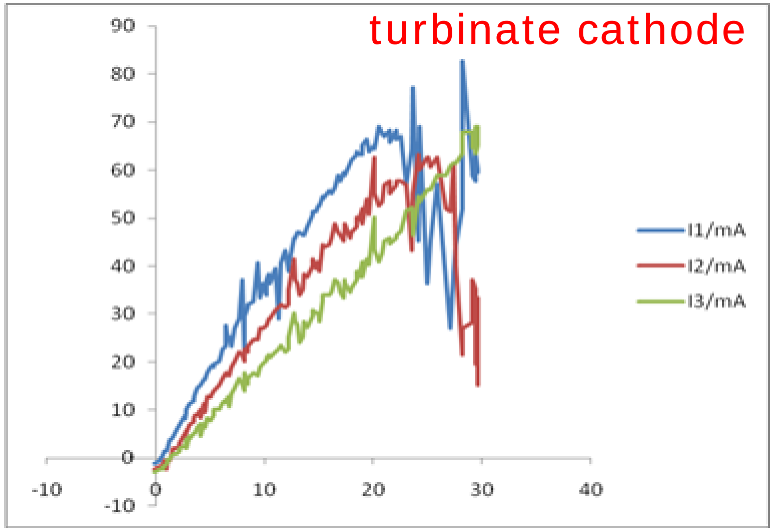


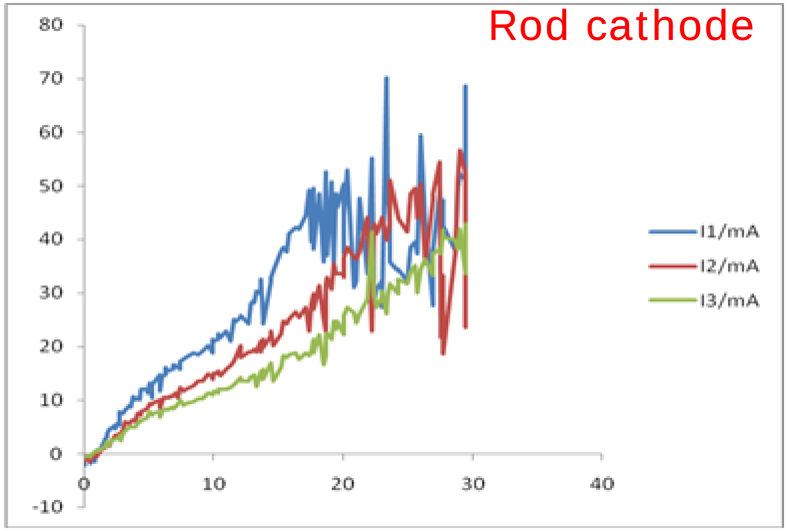


The E-field distribution of cavity surface of rod and turbinate cathode. (by SUPERFISH)

Those marked places are corresponding to 3 sampling-electrodes.

The I-V characters of sample electrodes





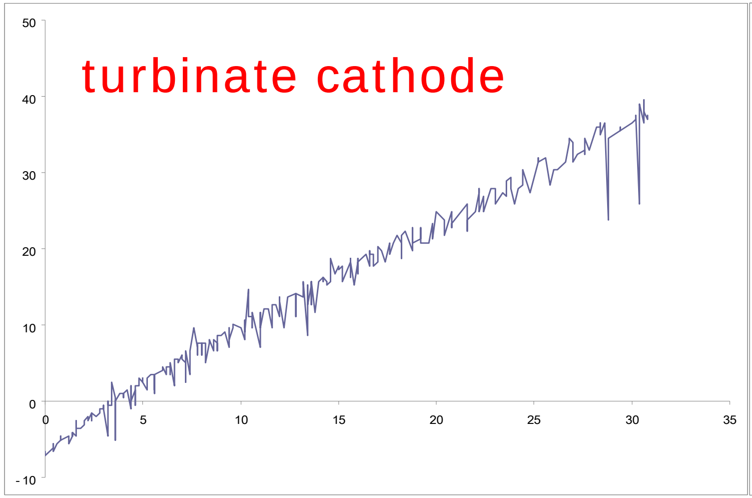
Blue: iris side　　Red: in middle　　Green: equator side

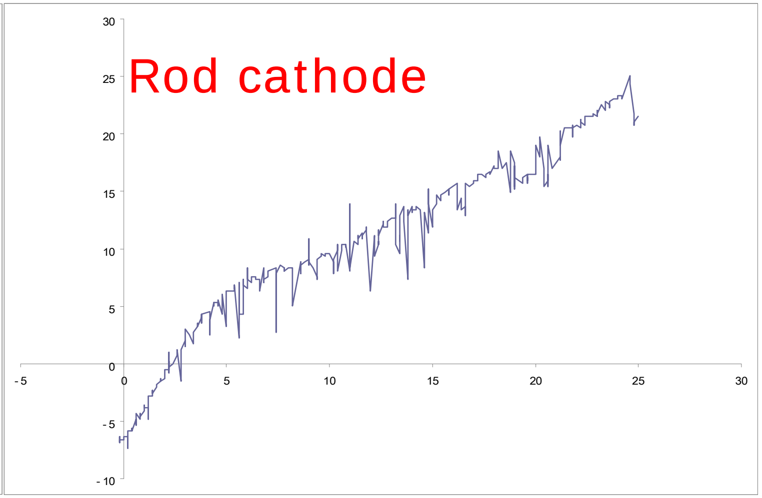
The film is formed sequentially : from higher E field to lower field area.

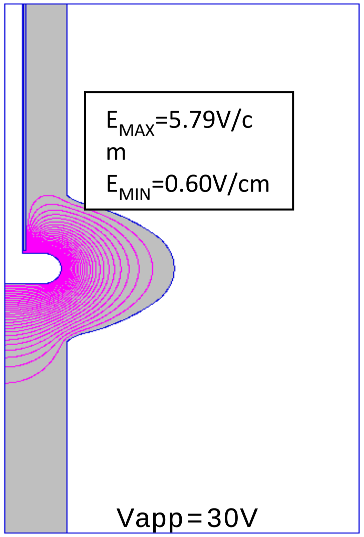
The limit of our power supply out is 30V.

The equator area is no film.

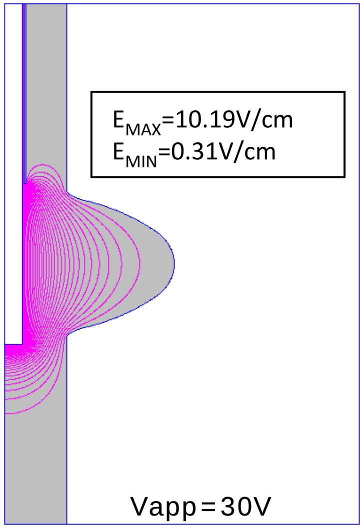
The I-V curve of total current *vs* applied voltage





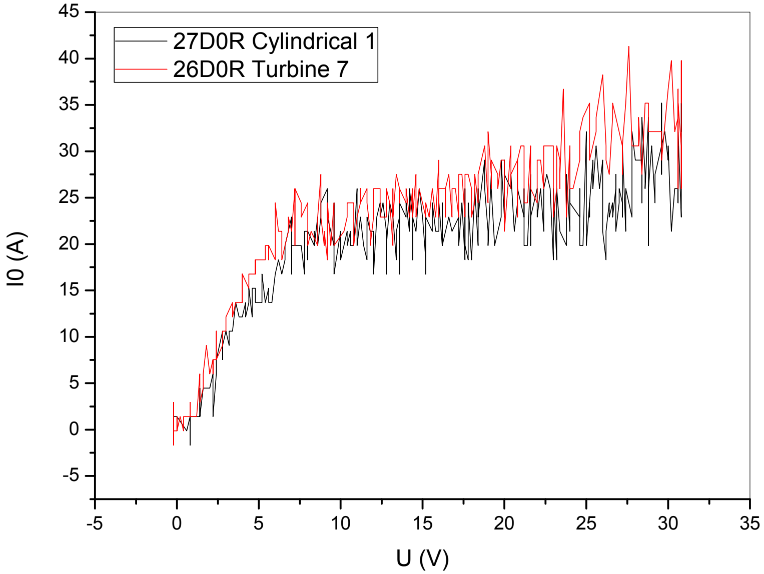


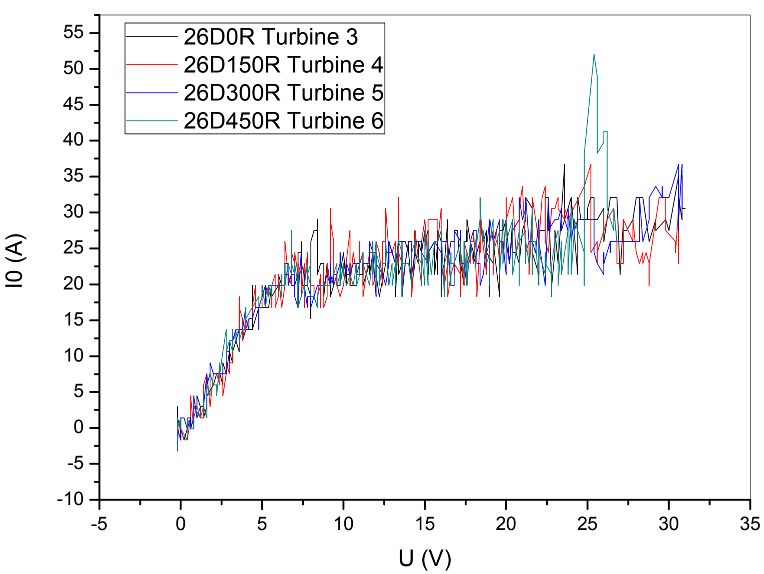
The I-V character difference caused by field distribution. For rod cathode, the film is appeared at iris part at about 5V. Then the current of this part turns to constant and there is a inflection point in the I-V curve .



EP study with demountable cavity

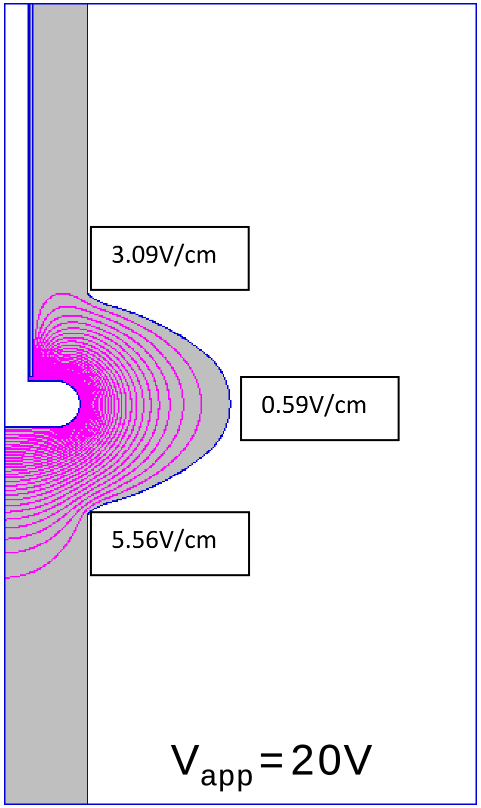
There are some common properties for both BEP and EP. Cavity EP could help us to understand cavity BEP.





There is I-V plateau (electrolyte 1:9).
Use turbinate cathode. The total current is slightly higher than the rod.
Total current is not sensitive to cathode rotation speed.
The inflection voltage is ~8V, almost the same as *T. Tajima*'s data.

EP of demountable cavity



Turbinate cathode. ϕ65×20 mm

T: 20~35°C
No agitation.
Integrated time: 60 min.
~50μm was removed.

The upward cup is polished.
The downward cup only shows the etched surface even simulation shows that its surface field is higher!

The primary BEP result

Conclusions

* Our BEP study is start from Jaquect theory.

* In our experiments, the high resistive film is formed.

* One of the significant differences between EP and BEP is the viscous of electrolyte. More viscous could get more smooth result, this is conventional EP experience. ---BEP can get more smooth surface than EP (BEP: 35nm, EP: 250nm).

* Another difference is the resistive of electrolyte. BEP is operated at higher apply voltage---higher current density. ---BEP is faster than EP (BEP:0.646 μm/min, EP: 0.381 μm/min).

* The basic concept of our fast BEP is based on reducing the thickness of the film. ---more fast and smooth.

* Small sample fast BEP can reach RMS roughness of 20 nm in large area, and in the mean time, the mass removal rate is 3.7 μm/min.

Conclusions (cnt)

* The mass removal rate at the air-liquid interface is higher than in liquid.

* The “rainbow” appears on sample surface when the electrolyte was agitated over certain flow rate. And it could be removed.

* The evolution of V-I character with different agitation rate is studied. The stronger agitation, the film is thinner and polishing current density is higher. The oscillation phenomenon is not always observed.

* In our experiments, the slope of mass removal rate *vs* current density is higher than theoretical prediction. Perhaps, it means that Nb ions are not all in valence of 5+ in the solution.

* The significant differences from sample to cavity are not only the surface ratio between anode and cathode, but also the E-field ratio.

* The simple cathode maybe not easy to get a satisfaction result.

Discussions and Questions

In our present research stage, some questions and ideas need further studies.

-What is the E-Chemical reaction of BEP?

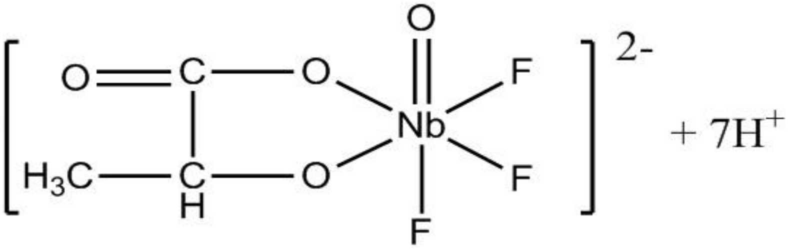
-Why present cavity-BEP result is not as good as our expected?

-Does BEP changes Niobium surface properties?

-

Possible chemical reaction of BEP:

$Nb + H_2O + 3HF + CH_3CHOHCOOH - 5e \longrightarrow$



The larger molecule makes Jacquet film more sticky.

$$2H^+ + 2e \longrightarrow H_2$$

Compare with EP reaction

1st

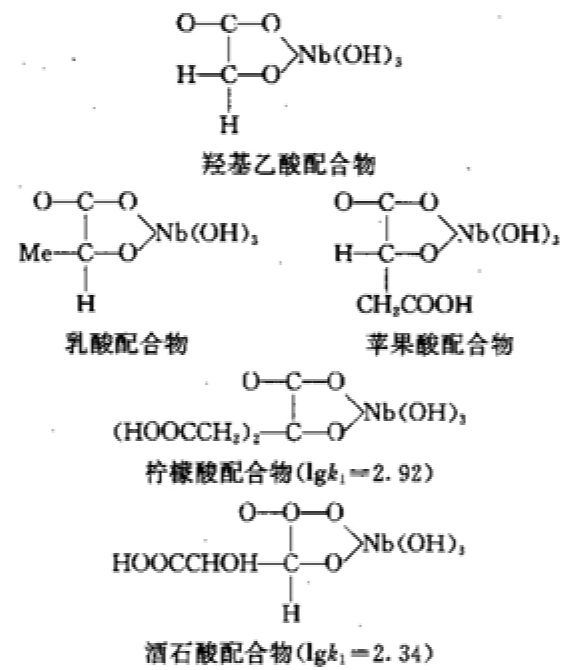
$$2Nb + 5SO_4^{2-} + 5H_2O \rightarrow Nb_2O_5 + 10H^+ + 5SO_4^{2-} + 10e^-$$

2nd

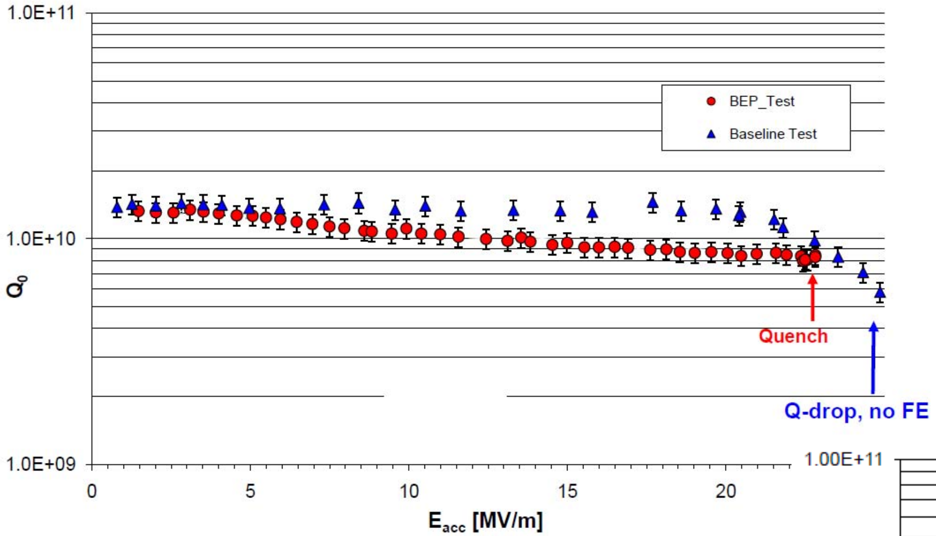
$$Nb_2O_5 + 6HF \rightarrow H_2NbOF_5 + NbO_2F \bullet 0{,}5H_2O + 1{,}5H_2O$$

3rd

$$NbO_2F \bullet 0{,}5H_2O + 4HF \rightarrow H_2NbOF_5 + 1{,}5H_2O$$



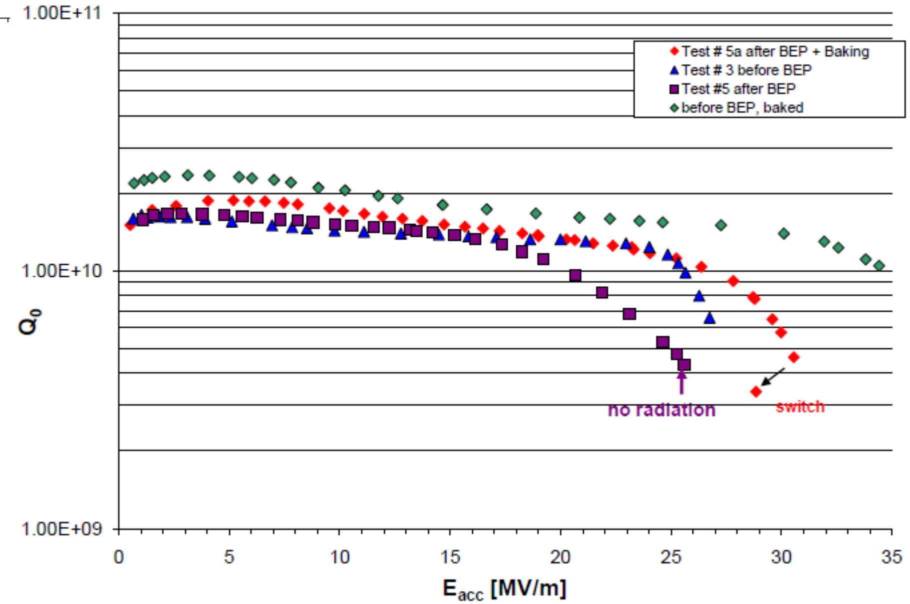
《无机化学丛书》第八卷 钒分族，罗裕基，第367页，科学出版社，1998.9（in chinese）



RF data of a fine grain Nb single cell cavity treated by BEP using home-mixed acid.

----Dr. Andy T. Wu, JLab

RF data of a large grain Nb single cell cavity



Why BEP results are worse then BCP?

BEP8 Optical Inspection

A. Crawford 3mar09

Cavity: 1.5 GHz CEBAF profile single cell.

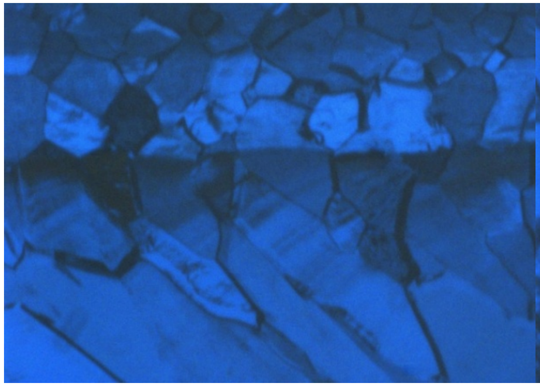


Figure 1. Equator weld

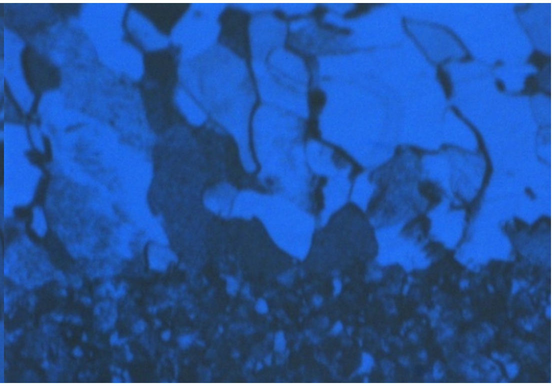


Figure 2. Edge of Equator weld heat affected zone

Surface smoothing appears to have been localized to the irises. Areas of the cell that are more than 2 centimeters away from the iris weld show sharp, well defined grain boundary edges and steps. There is no evidence for pitting or exaggerated erosion in any specific location

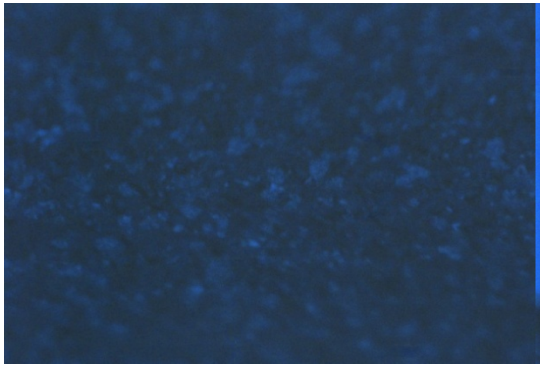


Figure 3. T-Map Location 1

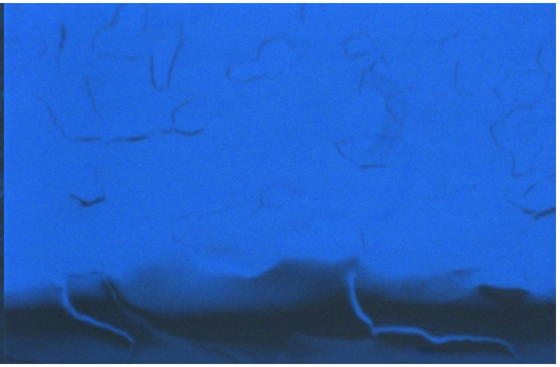


Figure 4. Iris weld

There are two locations on this cavity that have been identified as hot spots by T-Map. No outstanding or unusual features were observed at or near these locations.

The surface status is not good enough!

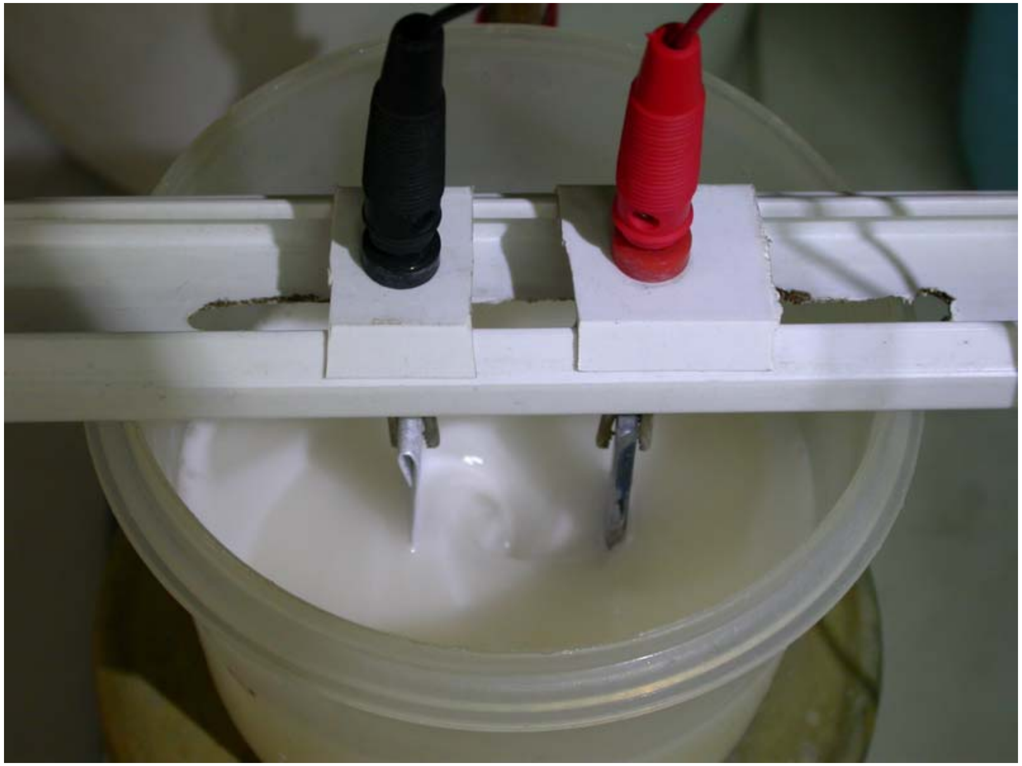
To find out the optimum operation conditions for cavity BEP. (I-V character studies.)

Our fast BEP ask high flow rate (the surface flow speed is up to 50cm/s), it is difficult for most EP polishing system setup.

To develop a post clean art for BEP.

Does BEP changes the SRF properties of Niobium?

Does “bubble bath” increase the mass removal rate?

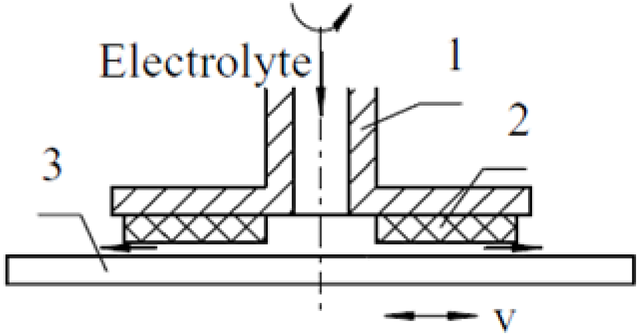


Electrochemical-mechanical polishing

Electrochemical mechanical polishing (ECMP) is a process combined by electrochemical and mechanical action.

The mechanism of ECMP is electrochemical passivation of metal and then abrasive brushing to passive film.

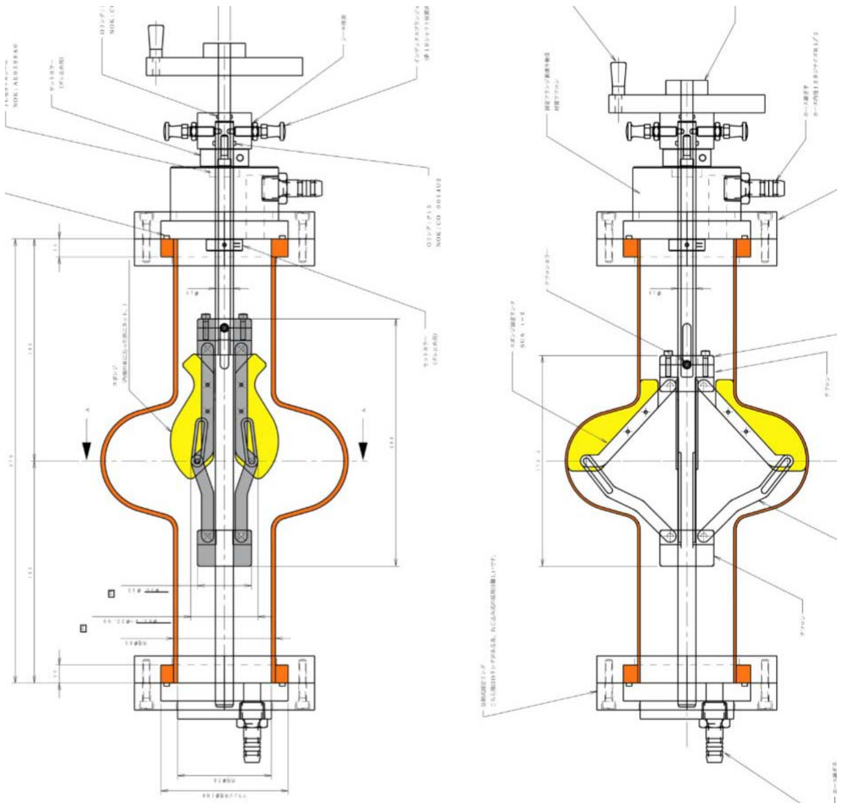
The major difference of our fast BEP and ECMP is the later using stronger tool to brush the film. It could be faster and get more clean and more homogeneous mass removal.



Plane surface ECMP

1: Cathode;
2: abrasive tool;
3: workpiece

Electrochemical-mechanical polishing

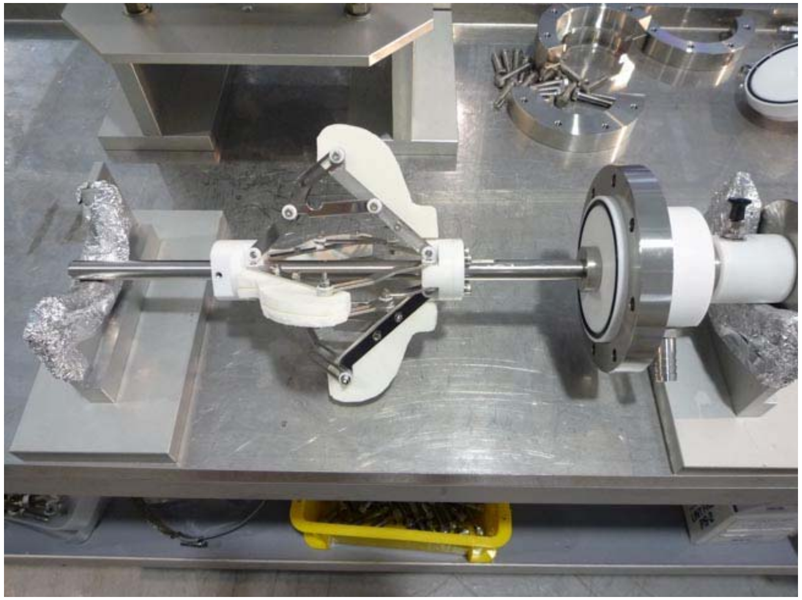


http://ilc.kek.jp/JFK□S0/

In ECMP processing, abrasive is used to brush away the film. So there is no need to use very hard and strong abrasive tools, also not very high press.

Soft and elastic abrasive tool such as sponge rubber abrasive, PVA sponge abrasive are efficient for ECMP.

Is PE sponge good enough?



We can combine KEK mechanical with ECP idea.

Redesign part of the “umbrella” bones, made of pure Al, as the cathode, to fit the shape of cavity inner surface.

The gap between cathode and anode could be 1~5 mm. Electrolyte is feed in and fast through the gap. Using sponge to brush the film. Then, we can ECMP a cavity cell by cell.

We need do some sample experiments firstly.

What do we expect for ECMP:

* More smooth surface

Compare with conventional EP, ECMP could reach the roughness of Ra<0.1μm.

For ECMP, the roughness are depend on processing time and the grain size of abrasive tool.

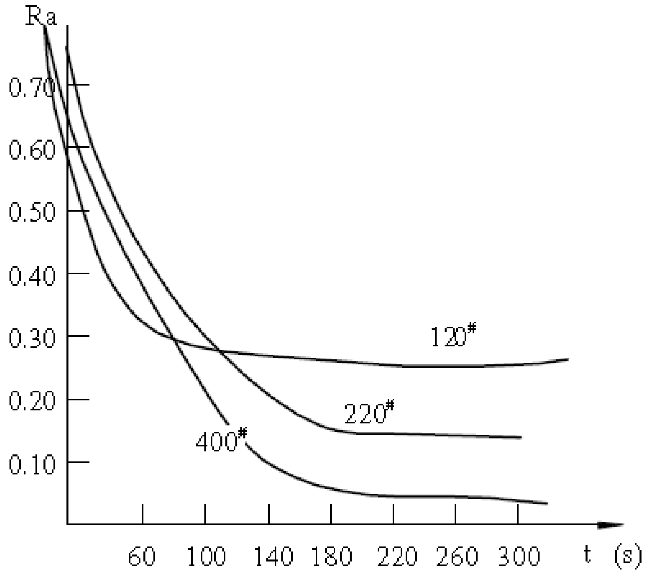


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Fig. 4. Relationship between grain and Ra.

* Higher efficiency

The gap between electrodes is narrow, E-field is much strong than conventional application. It is beneficial for processing at high current density.

* Homogeneous mass removal

The applied E-field is more equality.

*High precise control for mass removal

After a certain period, the surface roughness will not change significant, the mass removal is determined by time.

a small shaft ($\phi 25 \times 200$) can be polished from R_a 3.2–0.02 within 20 min.

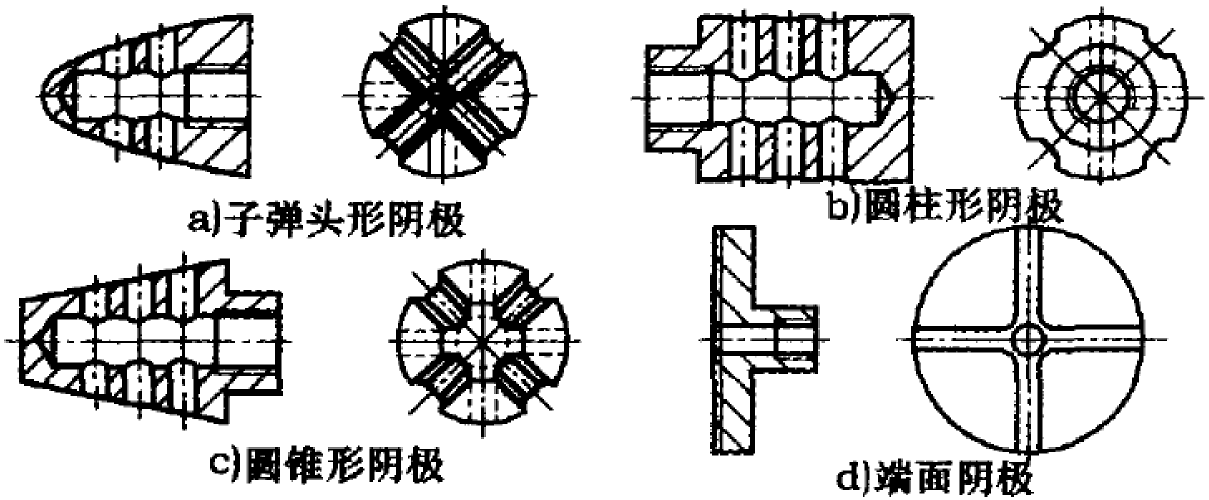


图 2　部分工具阴

ower supply
of the cavity

* Easy for industry

There are many su
in china.

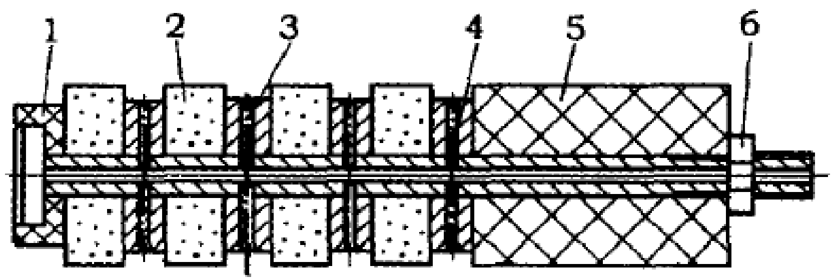


图 4　加工小孔的阴极结构

1. 橡胶垫　2. PVA 海绵砂轮　3. 铜电极片
4. 铜电极芯　5. 橡胶套　6. 螺母

现代制造工程 2005(7)

What is/are the significant parameter (s) to evaluate the cavity polishing quality?

We need to setup the ECP quality control system both for laboratory and industrial fabrication!

Acknowledgements

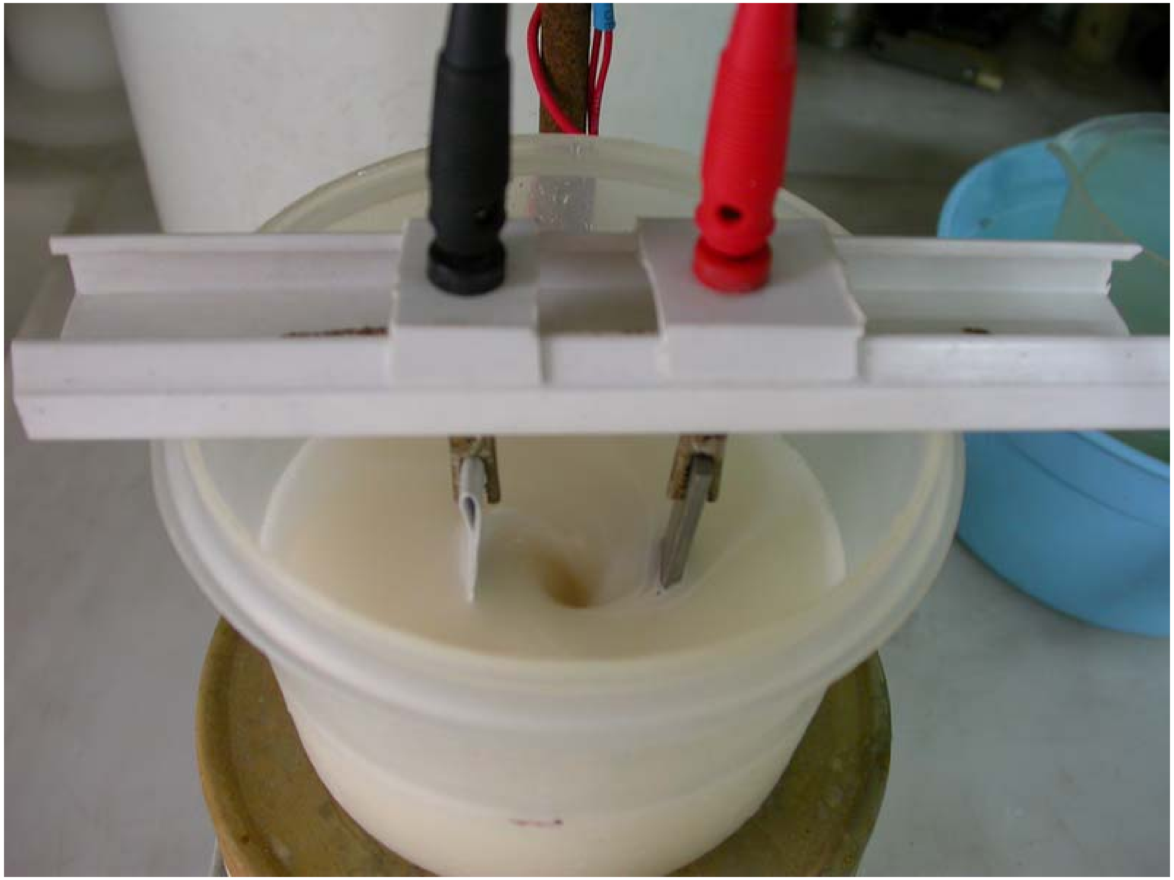
The works are supported by NSFC and other related projects, under the leadership of Prof. Chen jia-er and Prof. Zhao Kui.

Dr. A. Matheisen and Dr. P. Kneisel offered great the advices and helps for our cavity R&D.

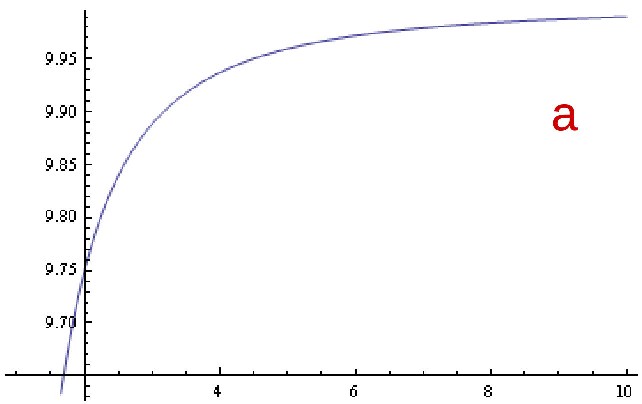
Dr. L. Phyllips had worked with us and provided very helpful references of safety operation with HF. Dr. A. T. Wu also worked with us and measured BEP samples, handout very important data.

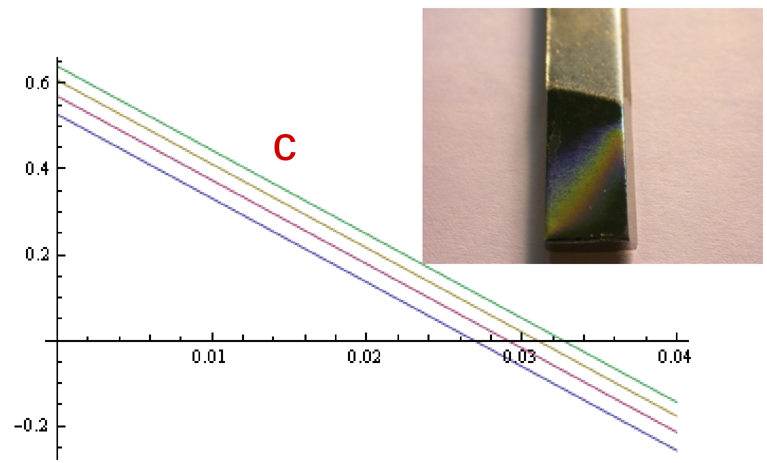
诚谢垂聆

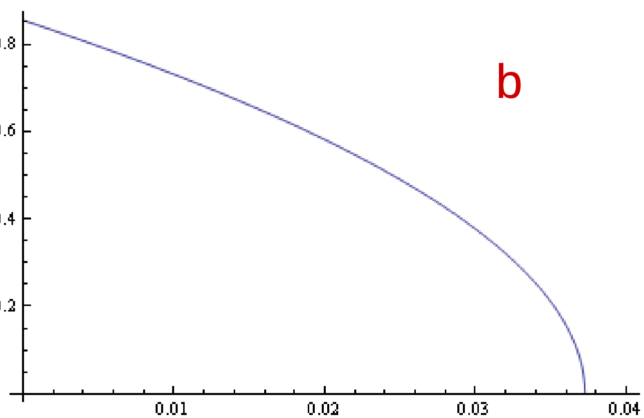
The “rainbow” is the result of the interaction between Jacquet film and electrolyte flow.



We've made a hydrodynamics simulation of our stirring system and shows good agreement.







a. The liquid surface profile (a part of whirlpool) .

b. The sample surface flow rate distribution with the depth.

c. The isometric line of the flow at sample surface.

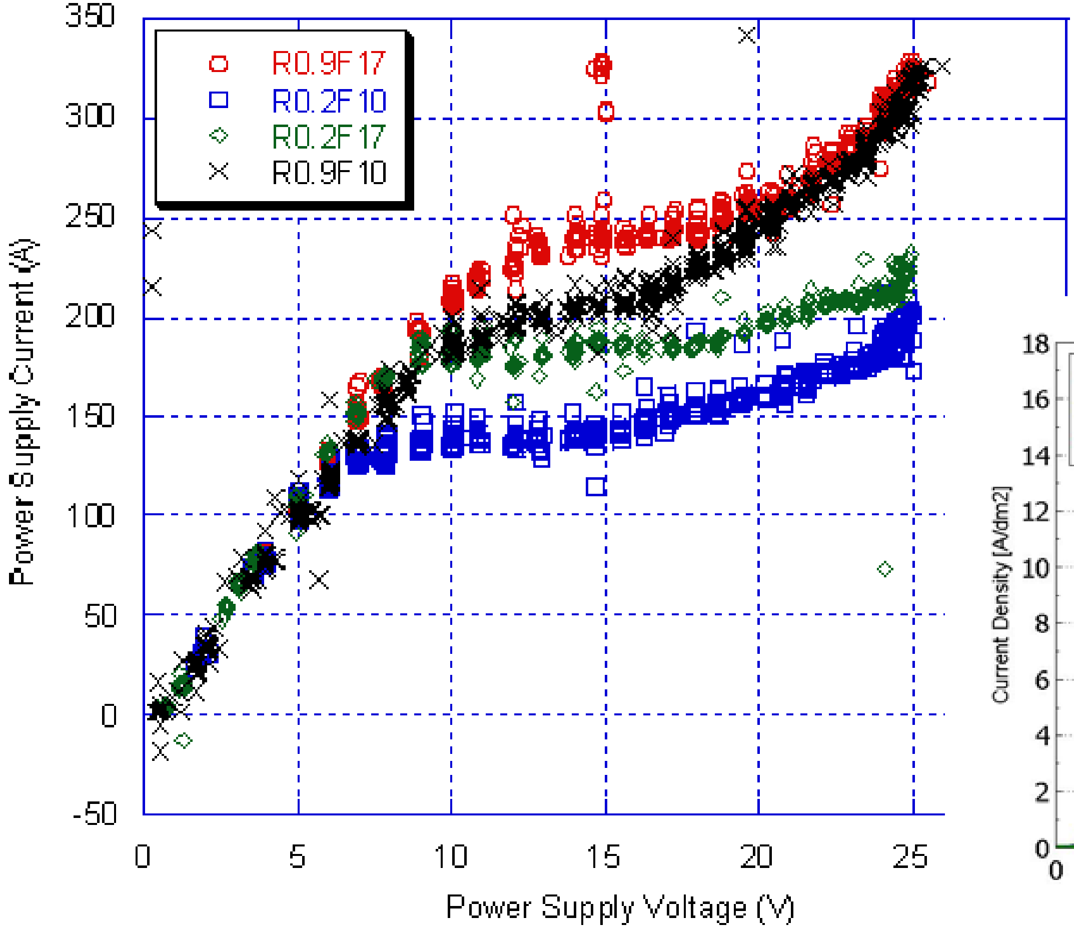
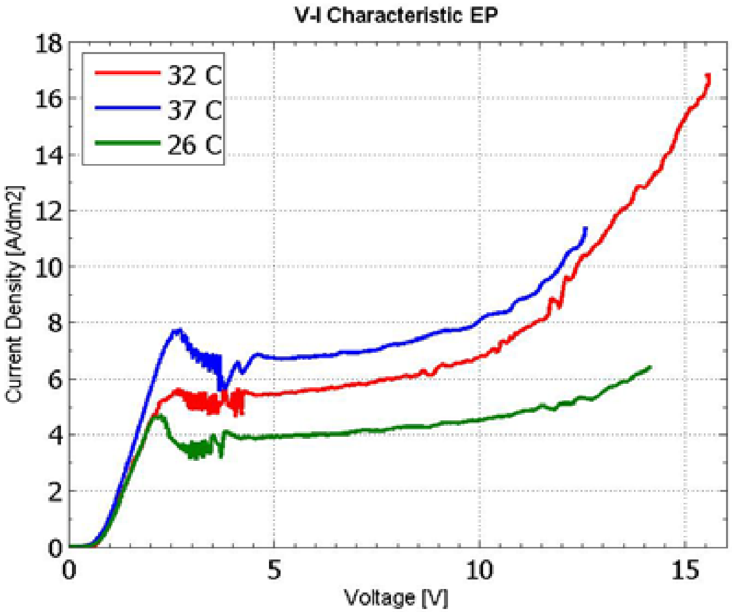


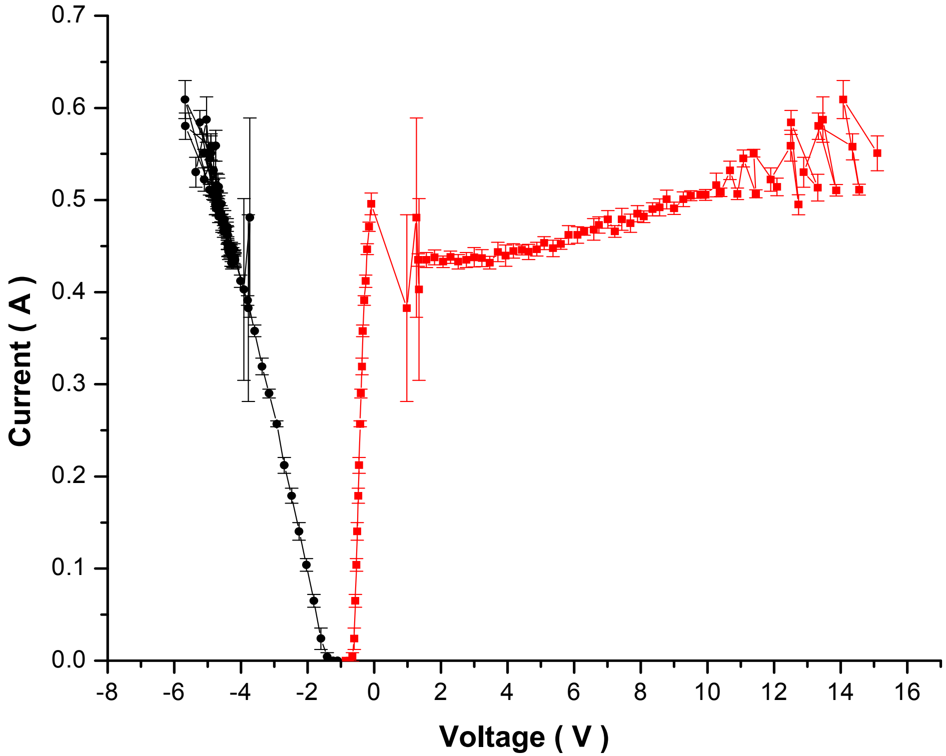
Figure 2: I-V curves for a 9-cell TESLA cavity at different rotation speeds and flow rates. “R0.9F17” denotes 0.9 rpm and 17 L/min. *---T. Tajima, LANL*

I-V character difference between 9-cell cavity and small sample.

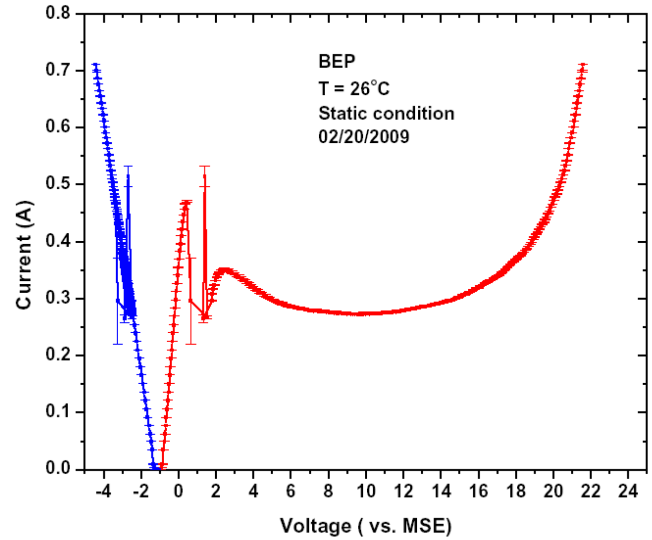


Small sample EP
---C. Boffo,FNAL

I-V curve for EP



I-V curves for BEP



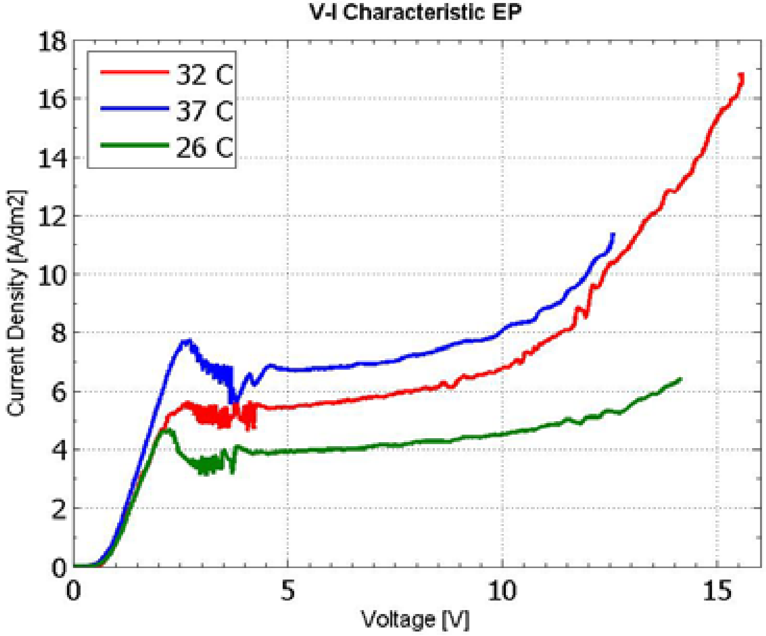
Measured by Hui Tian

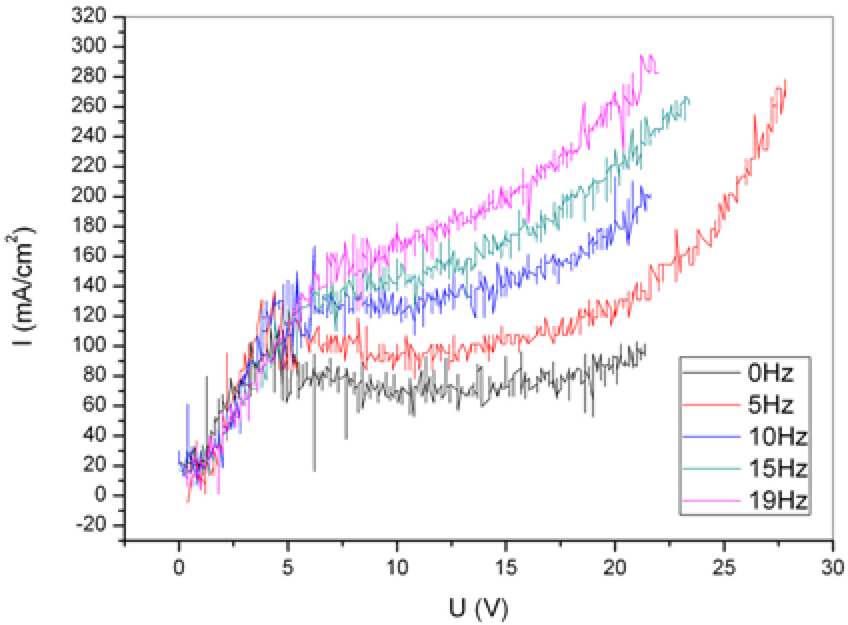
$$V_{PwrSup} = V_{cathode} + V_{electrolyte} + V_{anode}$$

$$15V = \sim 4\ V + \sim 2\ V + 9\ V$$

Cavity Processing R&D at JLab

C. Reece





Small sample EP
---C. Boffo, FNAL

Small sample BEP
--- PKU

The operation voltage of BEP is higher than EP.

The current density of BEP is more than 5 times higher.

For 9-cell cavity BEP, probably, it needs a 2000A/50V power supply.