Recent Progress of Vertical EP R&D

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Contents

- Vertical electropolishing facility
  - Setup
  - Coupon cavities
  - Ninja cathodes
- VEP of single cell cavities and RF tests
- VEP of nine cell cavities and RF tests
- Summary

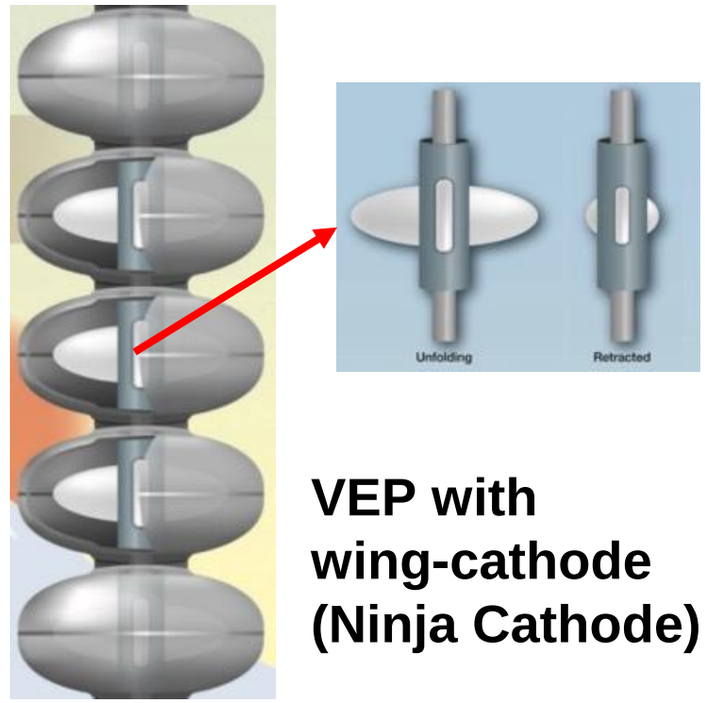
Vertical Electropolishing

VEP:

- **Performed in vertical posture**
- **Cost effective setup**
- **Small space for the setup**

Automated EP acid control valves (VEP Iwate collaboration)

VEP Stand for Single Cell Cavity

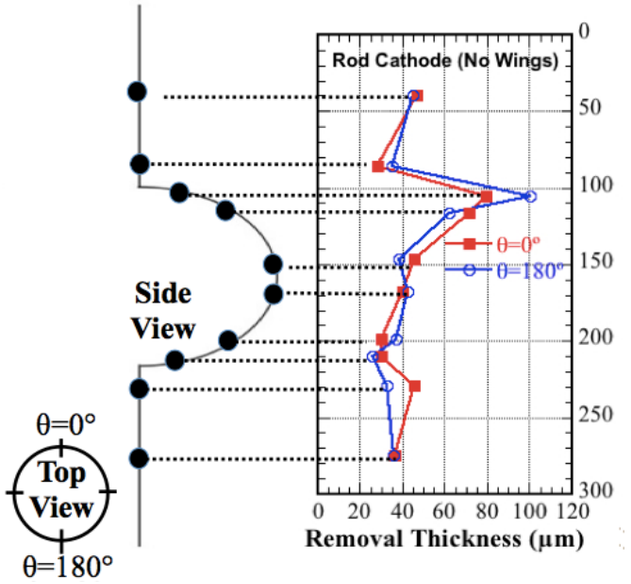


VEP with wing-cathode (Ninja Cathode)

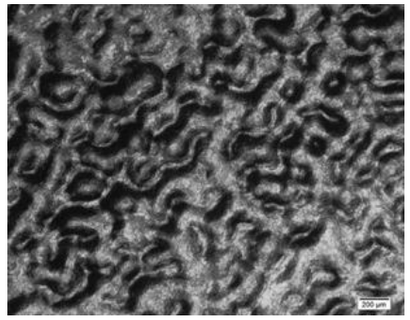
Core Issues in VEP:

- **Asymmetric removal (degrades field flatness in multi cell cavities)**
- **Rough surface/Bubble traces (leads field emission sites or quench)**

Typical Removal Asymmetry in VEP

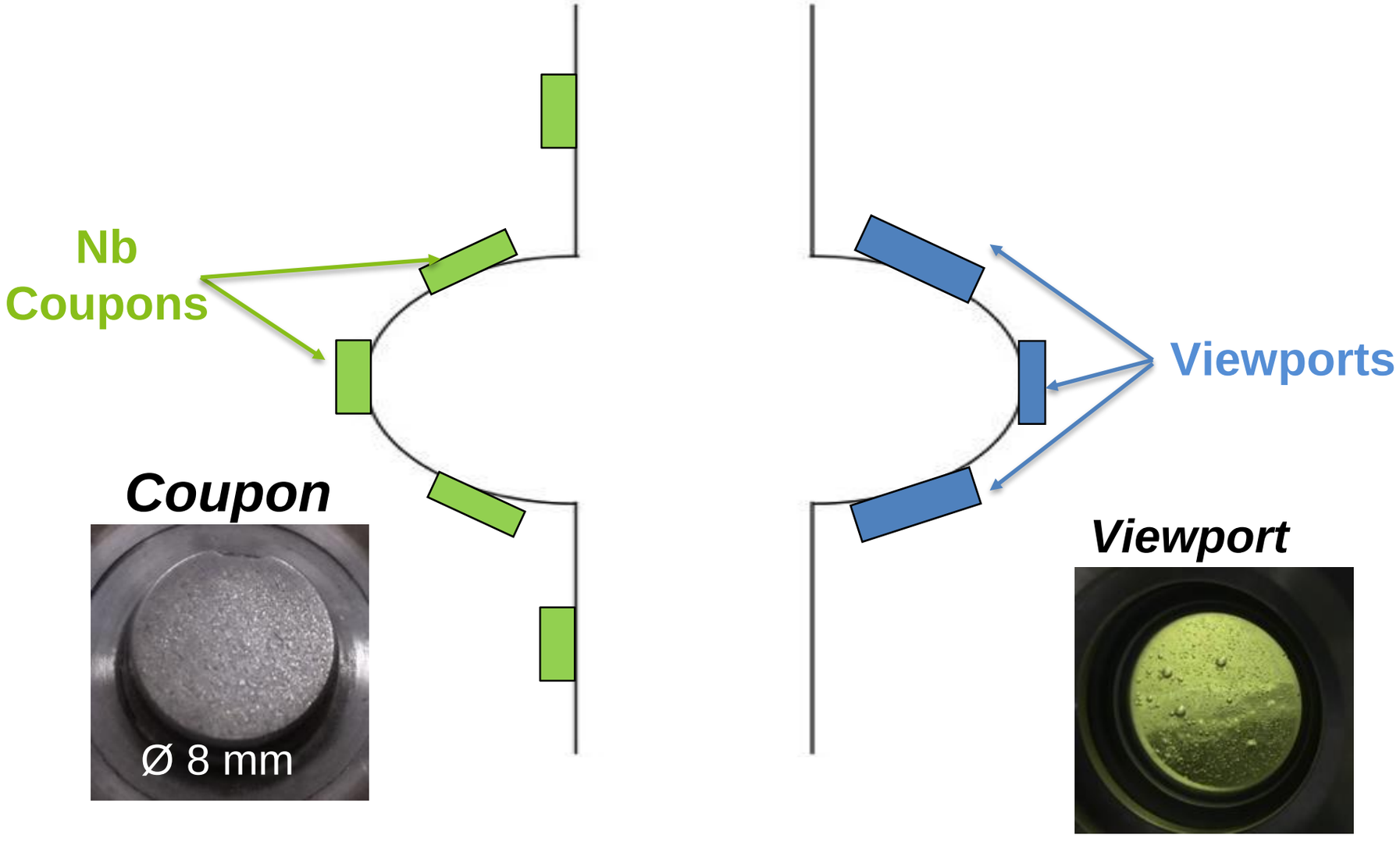


Bubble Footprints at Upper Iris

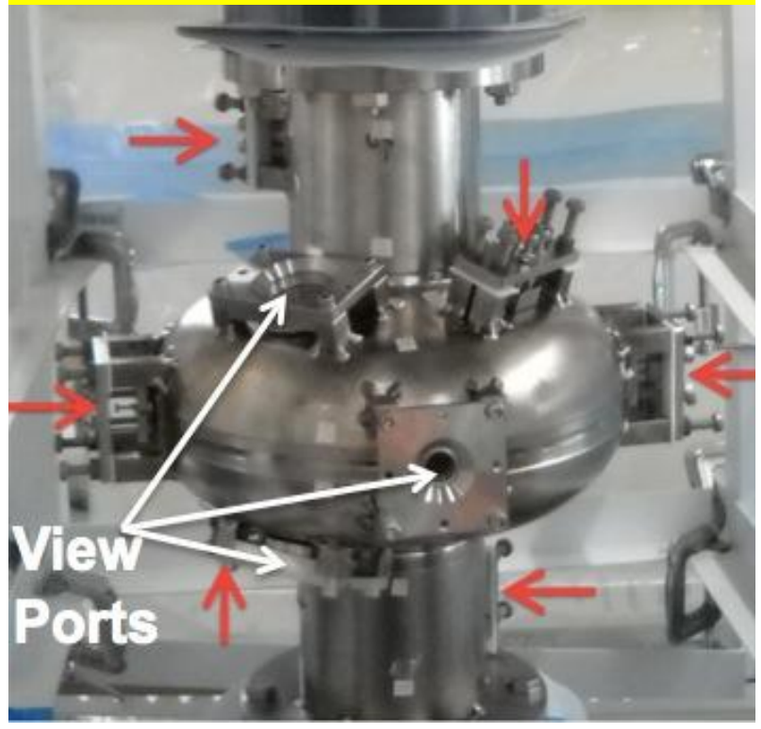


500 μm

Single Cell Coupon Cavity



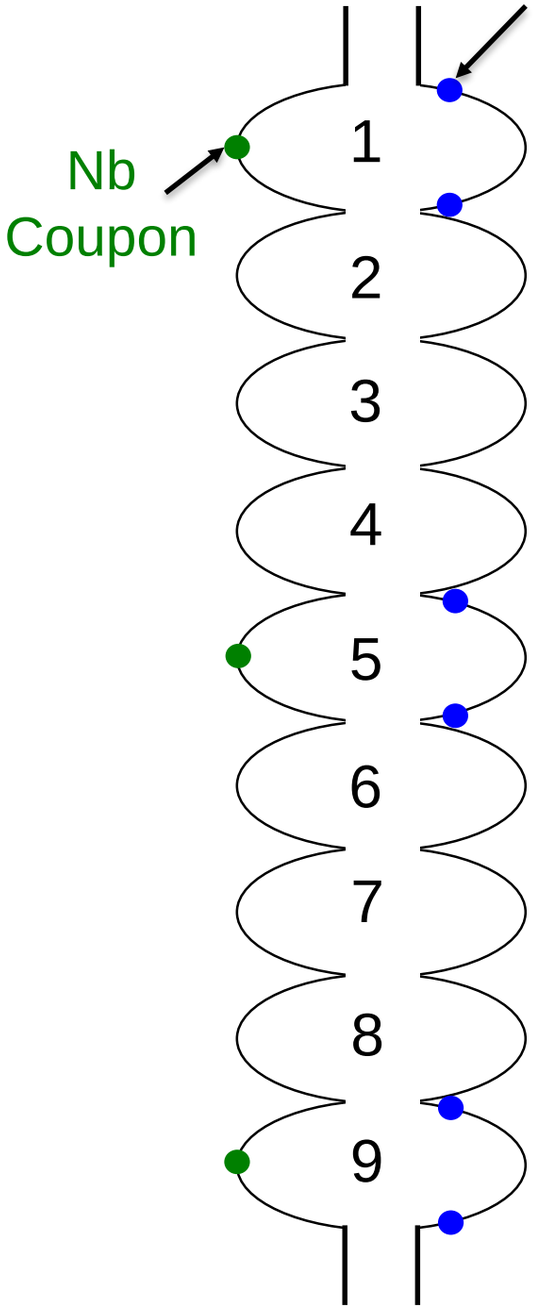
1–Cell Coupon Cavity for Parameter Study



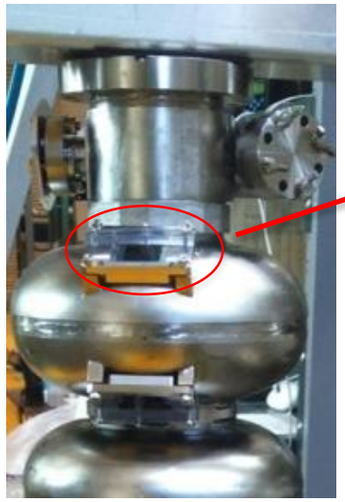
- Totally 6 coupons at the beam pipes, irises, and equator
- 4 viewports for in-situ observation
- Measurable EP current from individual coupon
- Surface analysis of the coupons

9-Cell Coupon Cavity

- The world's first 9-cell coupon cavity was fabricated to optimize VEP parameters.

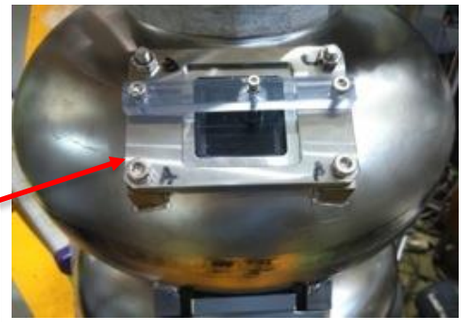


Nb Coupon with view port



6 coupons near iris positions

Coupon with Viewport near Iris



Equator Coupon

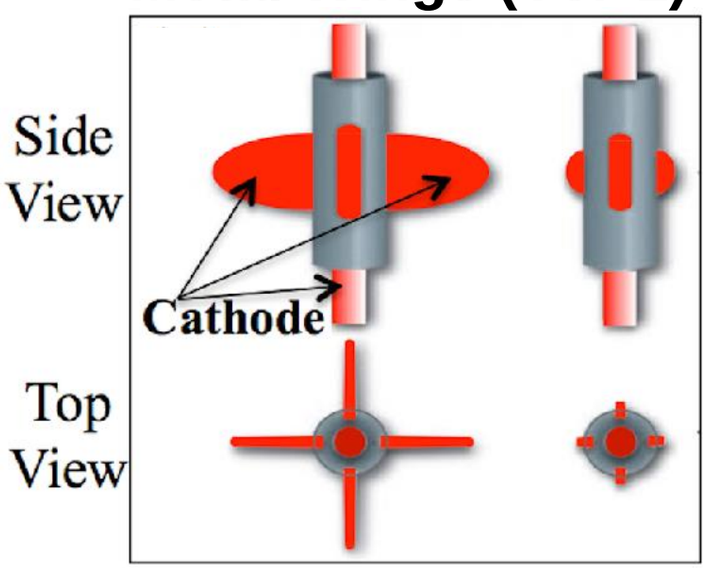
3 coupons at the equator positions

Coupon Cavity at VEP Stand

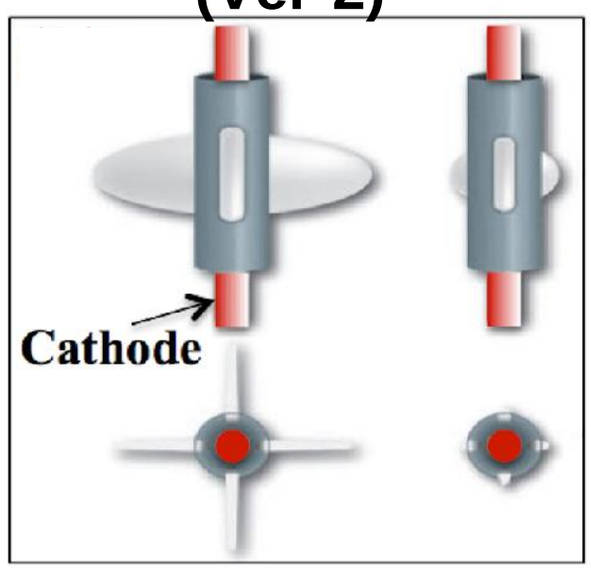
Ninja Cathodes

- We have applied several models of Ninja cathodes to find an optimized structure and VEP parameters.

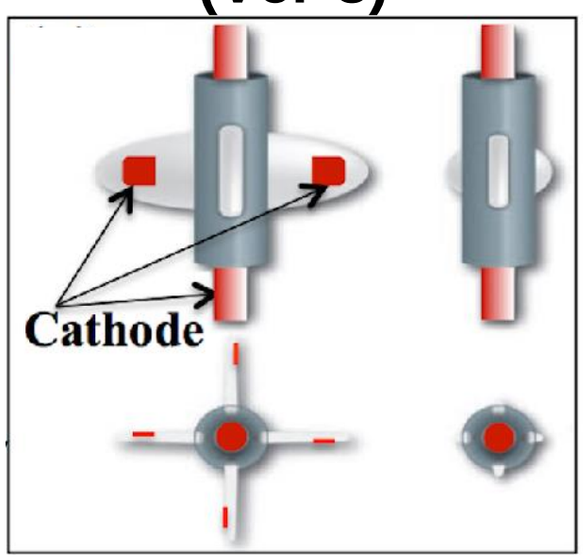
Metal Wings (Ver-1)



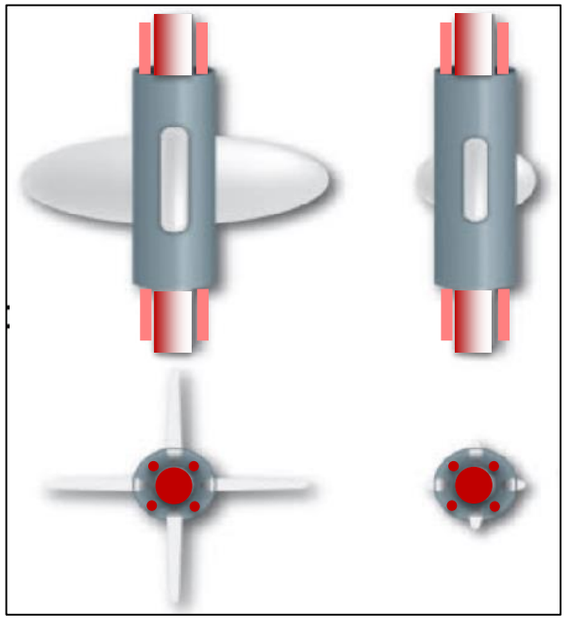
Insulating Wings (Ver-2)



Partial Metal Wings (Ver-3)



Insulating Wings + Large Cathode Surface Area + Meshed Cover (Ver-5)

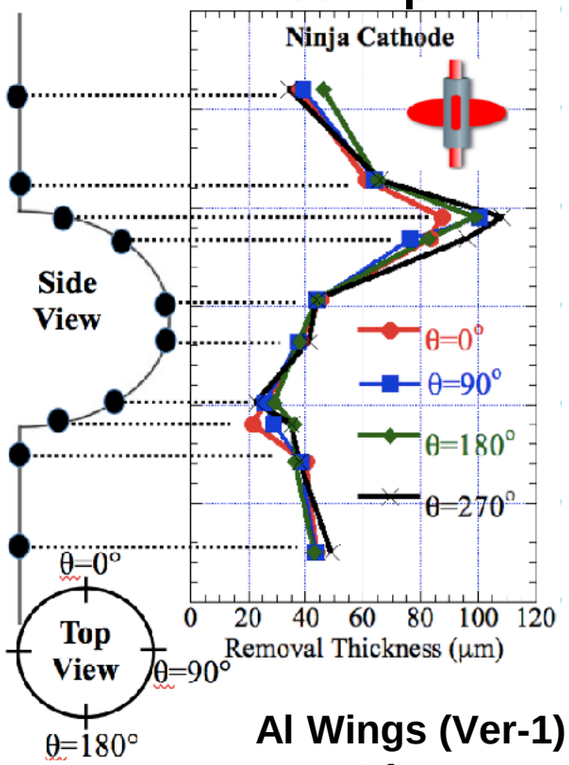


VEP tests for the coupon cavity were performed with the Ninja cathodes.

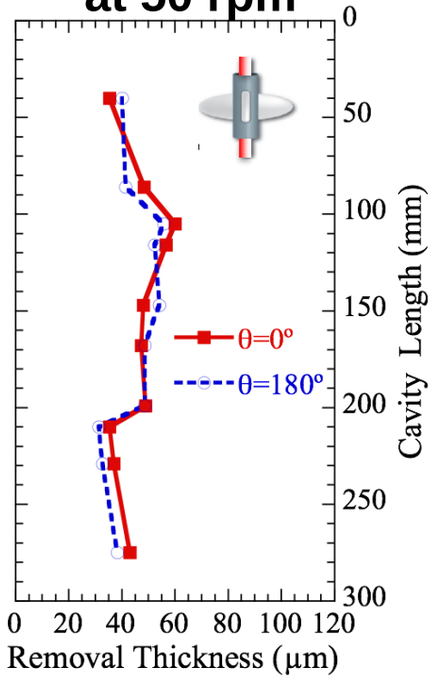
VEP for Single Cell Cavities

VEP Results with Different Cathodes

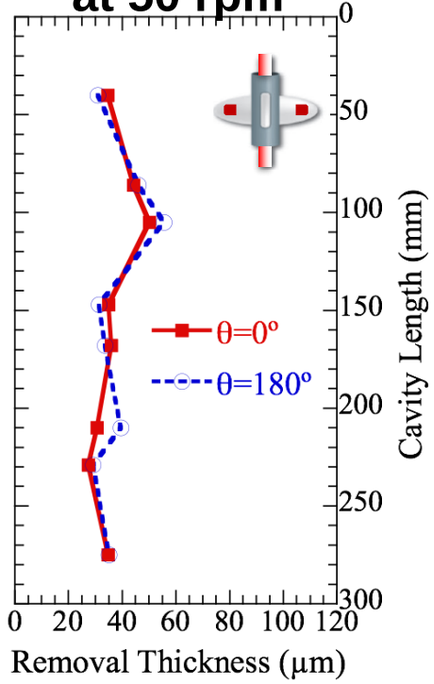
Al Wings (Ver-1) at 1 rpm

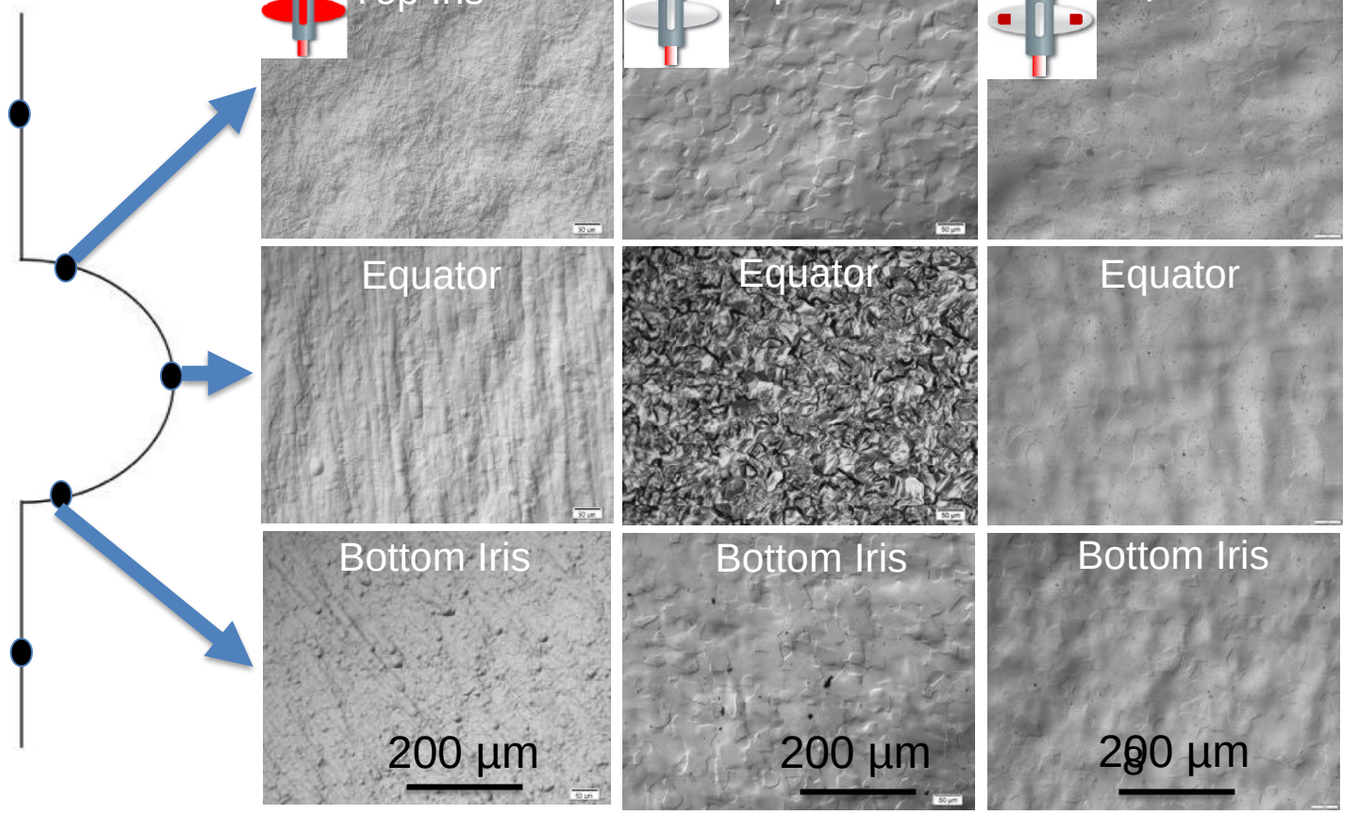


Insulating Wings (Ver-2) at 50 rpm



Partial Metal Wings (Ver-4) at 50 rpm

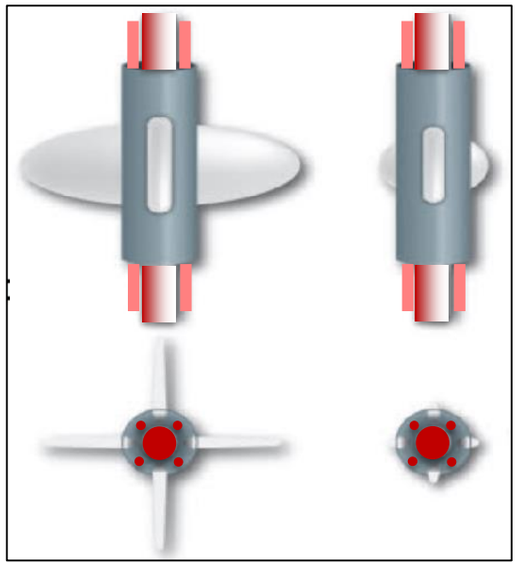




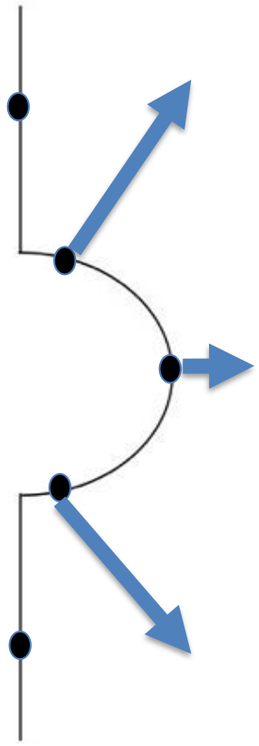
- **Removal asymmetry reduced and smooth surface obtained with Ninja cathode ver-4.**

Symmetric Removal With Ninja Cathode

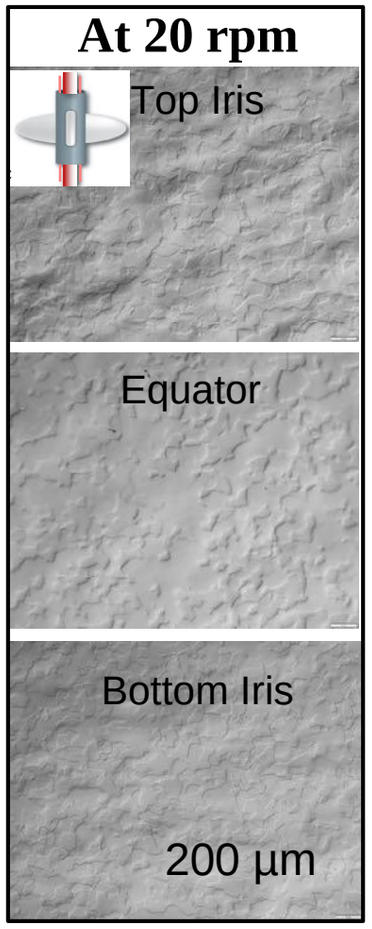
- Ninja cathode v5: Enhanced cathode surface area, cathode housing covered with meshed sheet, insulating wings



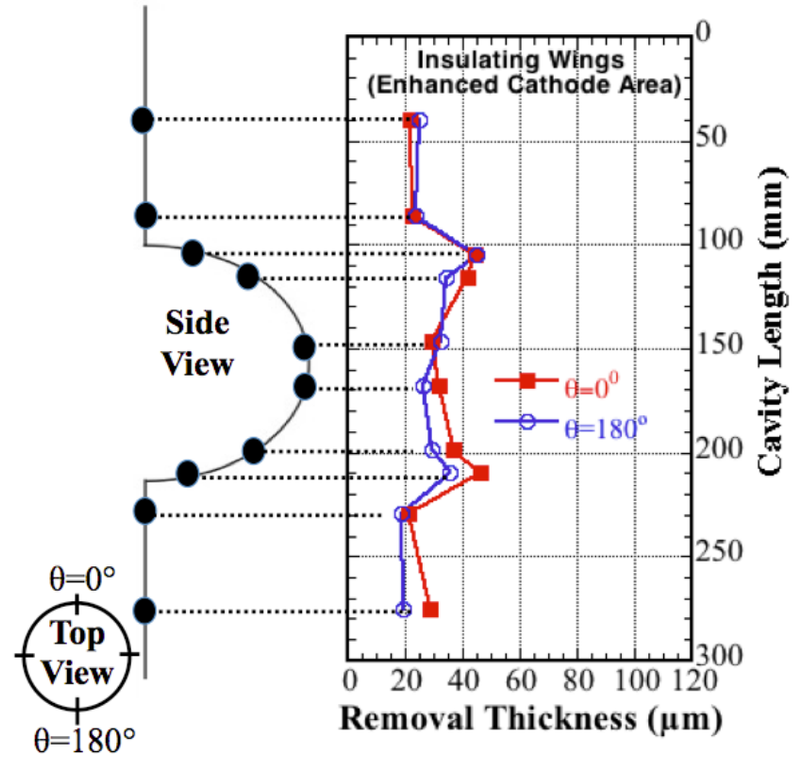
- Meshed housing: guides hydrogen bubbles along the cathode and stops bubble accumulation in the cavity cell
- Larger cathode surface: reduces cathode screening by bubbles



Optical Images



Removal Thickness



Voltage: ~13 V, Acid flow rate: ~5 L/min, Cathode rotation: 20 rpm, Temperature < 20 °C, Cavity cooling by water spray

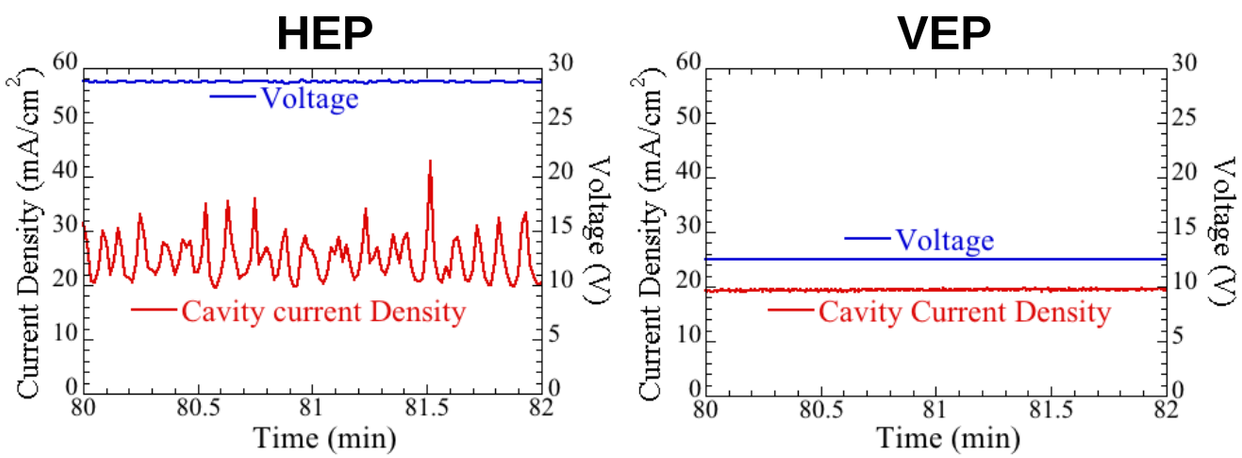
- **The cathode yielded smooth surface and symmetric removal.**
- **Hence, the cathode was opted for further VEP and RF tests.**

Comparison with HEP using Coupon Cavity

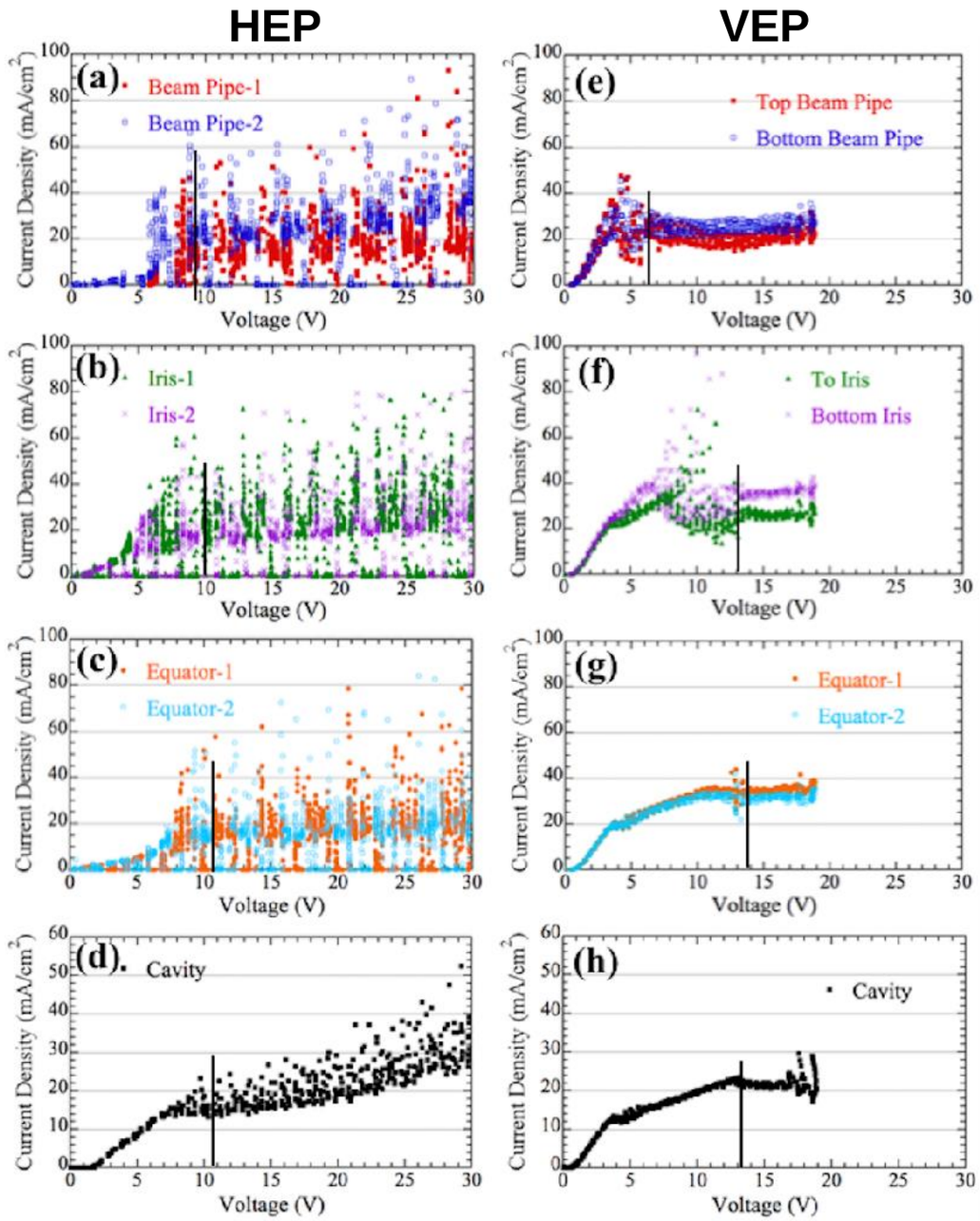
- **HEP: with standard EP parameters at STF, KEK**
- **VEP: with Ninja cathode at Marui**

Parameters	HEP	VEP
Electrolyte (H_2SO_4:HF)	9:1	9:1
Acid Flow Rate	~5 L/min	~5 L/min
Cavity Surface Temperature (max)	40 °C	16 °C
Cathode	Al Pipe	Ninja-v5
Rotation	Cavity (1 rpm)	Cathode (20 rpm)
Applied Voltage	~29 V	~13 V
EP Rate	~0.26 µm/min	~0.28 µm/min
Removal Thickness	41 µm	33 µm

Current Profiles



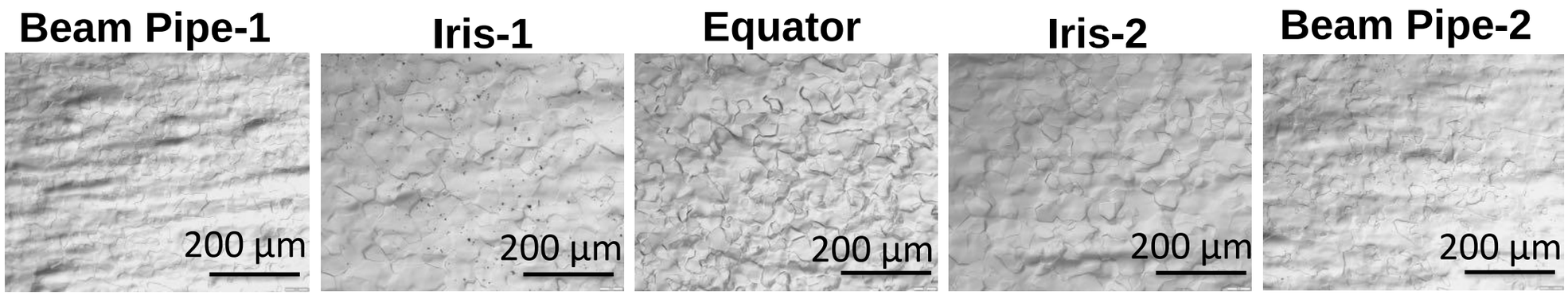
Coupon Currents



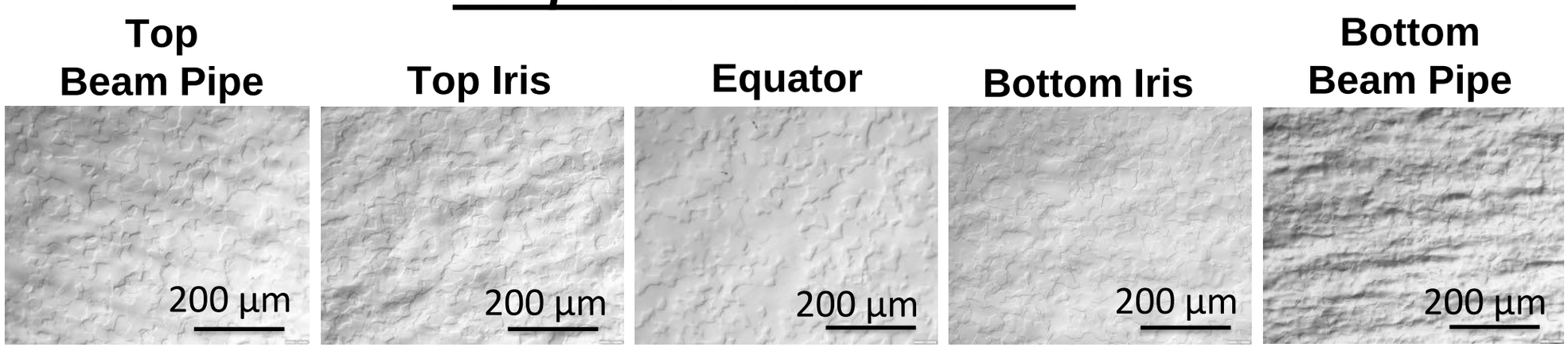
Apparent polishing plateaus in both the EP techniques.

Comparison with HEP using Coupon Cavity

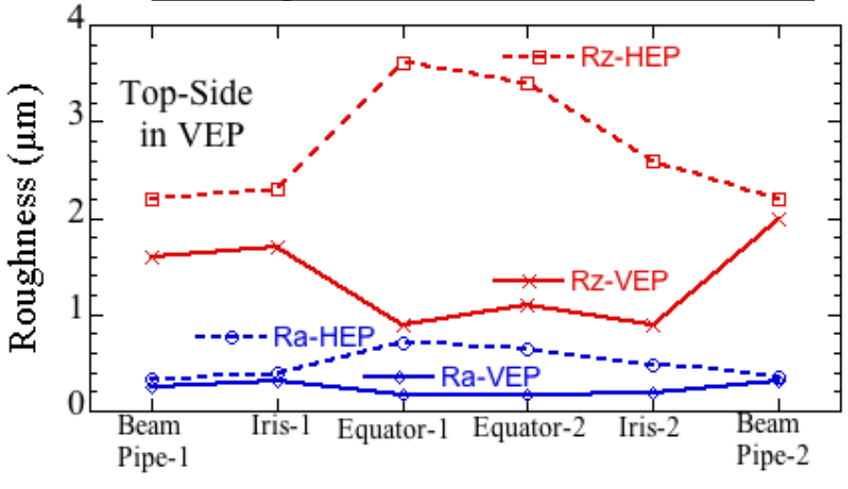
Coupon Surface after HEP



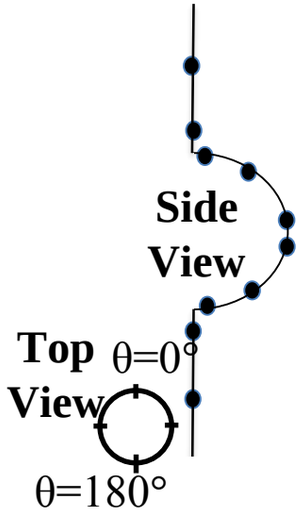
Coupon Surface after VEP



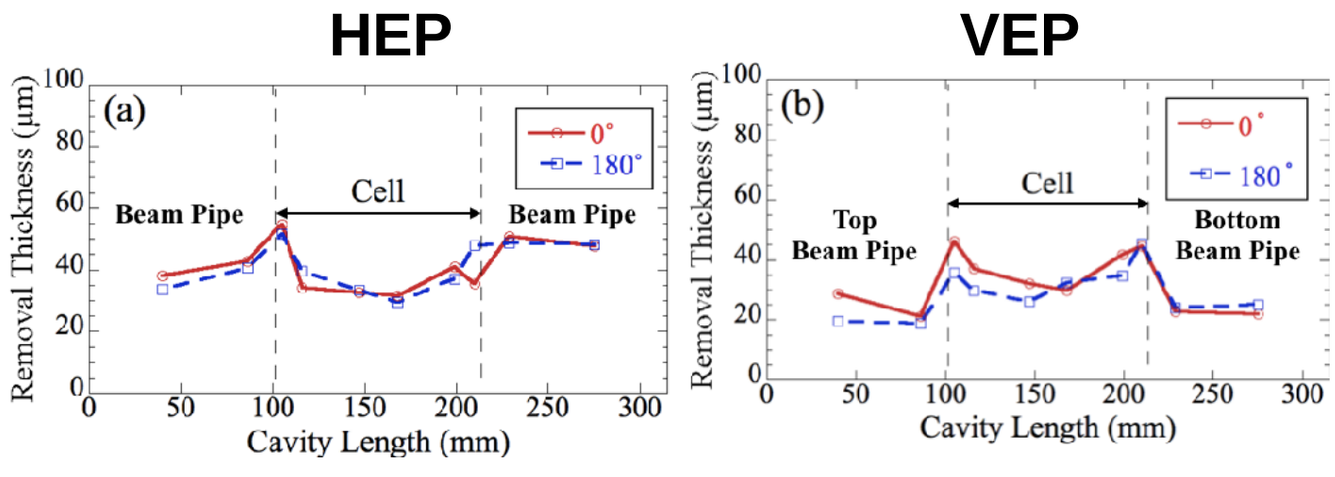
Roughness Ra and Rz



Smooth surface after VEP



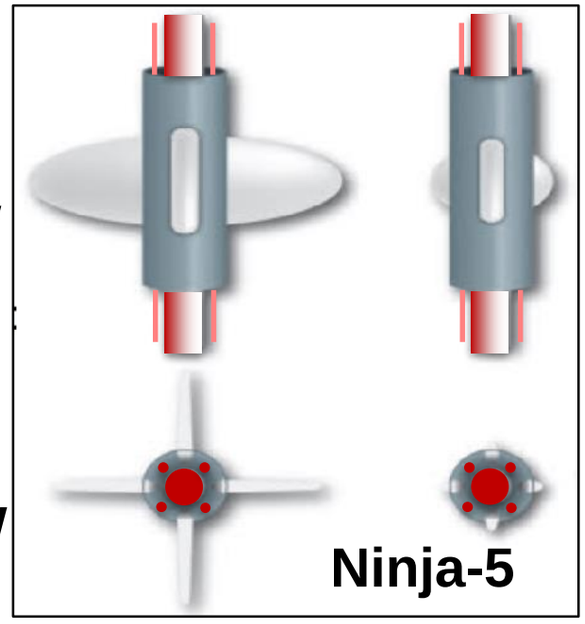
Removal Thickness along the Cavity Length



Symmetric removal in both HEP and VEP

VEP for RF Test Comparison

Ninja Cathode-v5



single-cell cavity with support-jig

Automated EP acid control valves (VEP Iwate collaboration)

Process

VEP1（50um）

↓

HPR & 120 °C baking

↓

Annealing

↓

VEP2（10um）

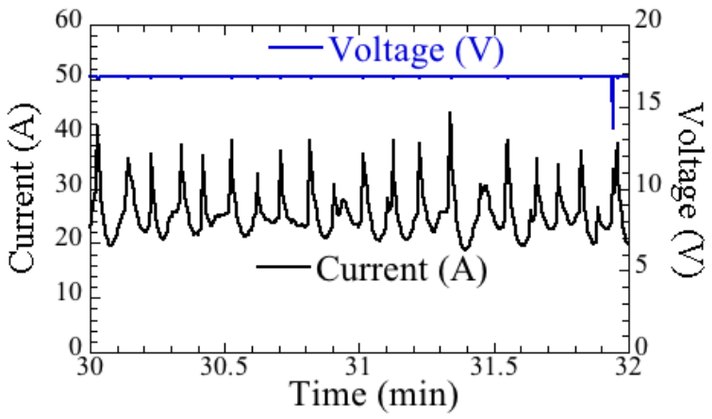
↓

HPR & 120 °C baking

↓

Vertical test

VEP Current Profile



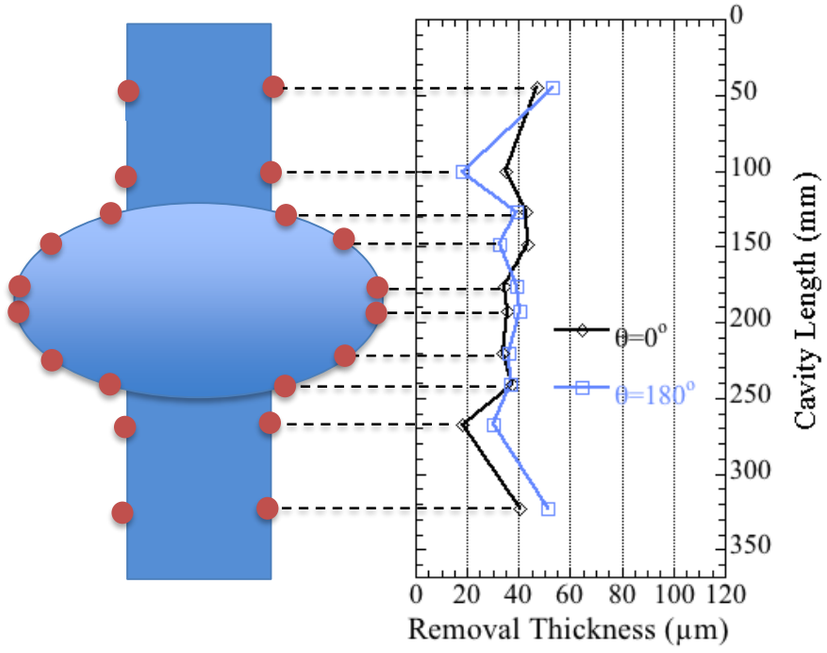
Voltage: 16-17 V

Cathode rotation: 20 rpm

Acid flow rate ~ 5 L/min

Temperature ~ 20 °C

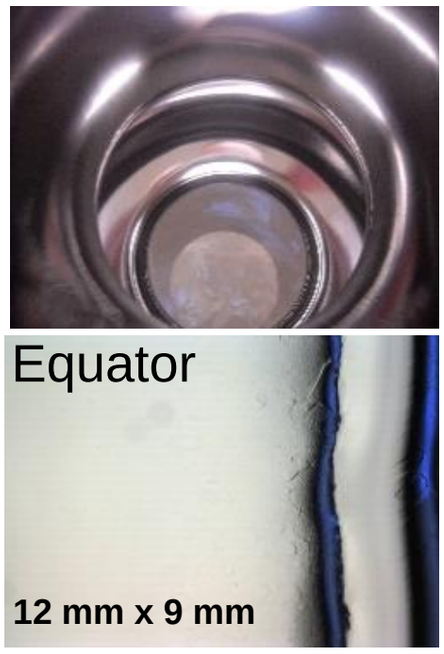
Removal Thickness in VEP-1



Uniform removal in the cell

Removal rate: 0.22 μm/min

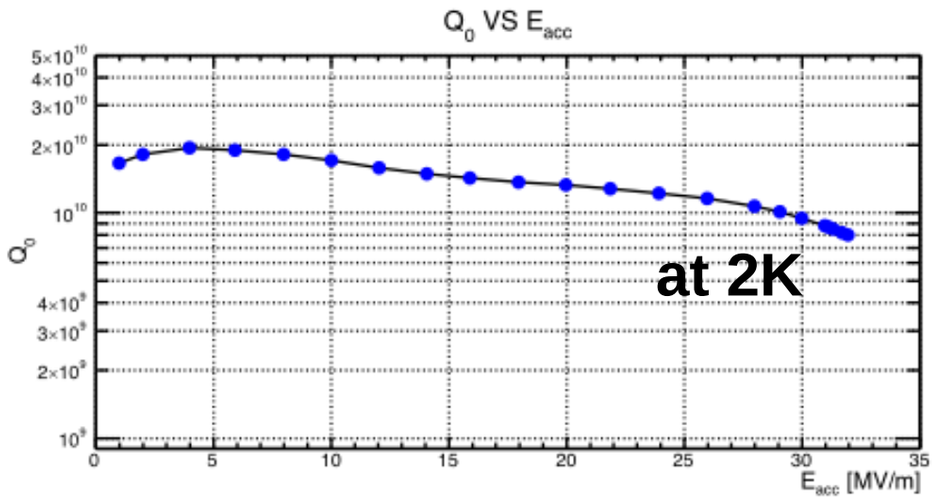
Cavity Surface after VEP-1

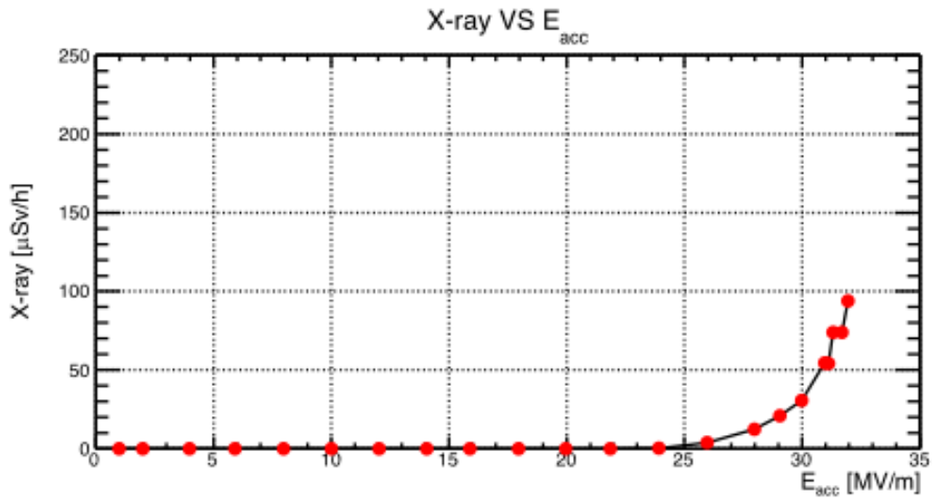


Smooth and glossy surface

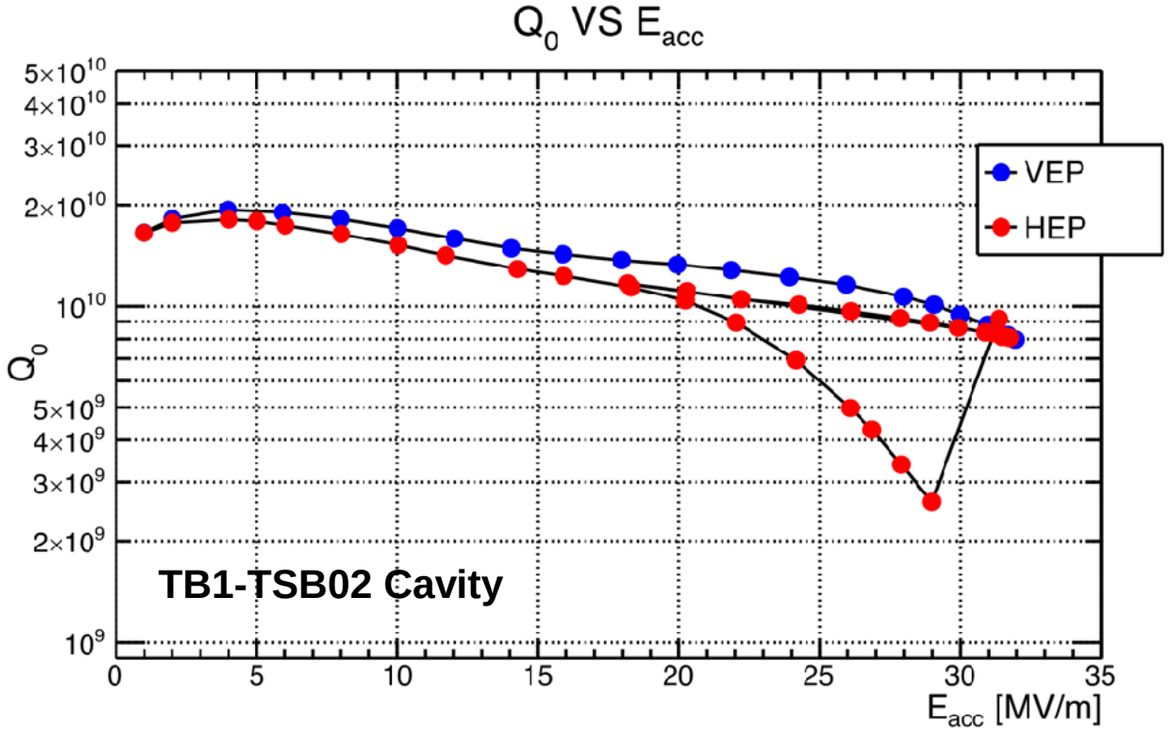
RF Test Results after HEP and VEP

Cavity Performance after VEP





Cavity Performance after HEP and VEP



- 32 MV/m (Q_0=8.0E9) was achieved after VEP.
- The accelerating gradient after VEP was similar as achieved after HEP.

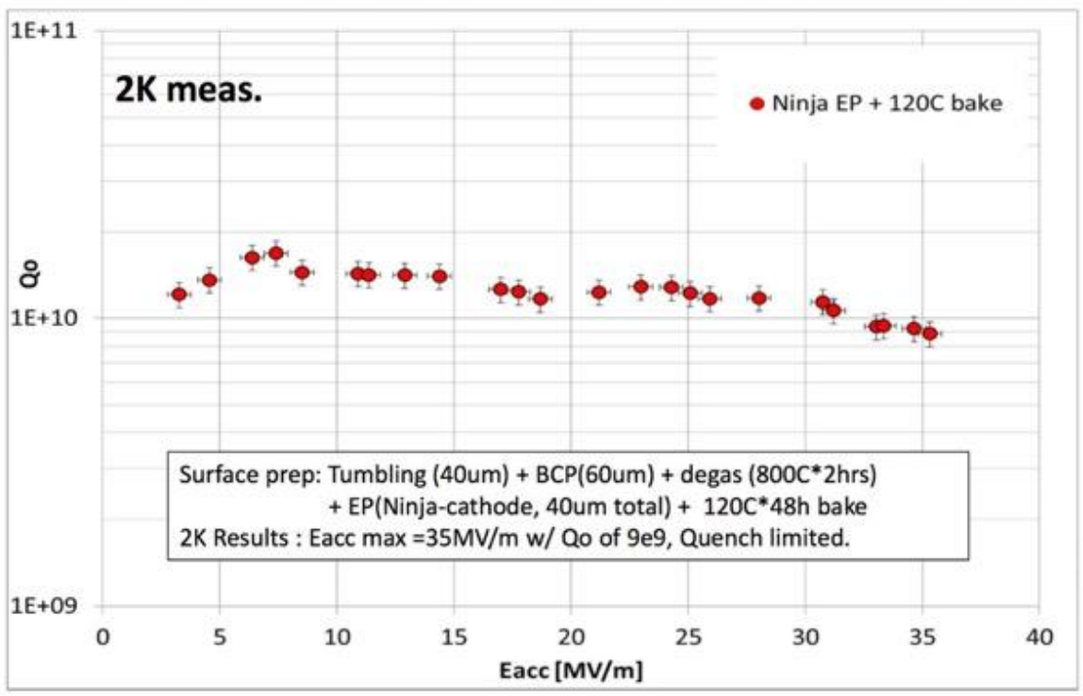
Collaborative Work with Cornell University

- Ninja cathode was tested with VEP setup at Cornell University.
- VEP for a single cell cavity was performed with Cornell's cathode and Ninja cathode for comparison.

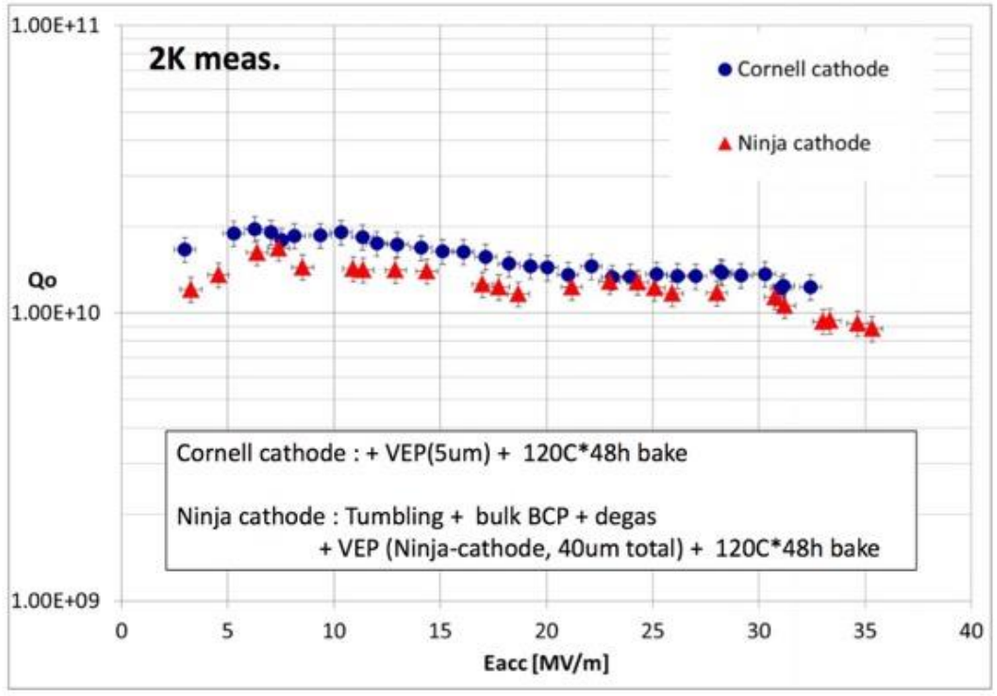
VEP conditions:
Voltage: 14 V, Cathode rotation: 50 rpm, Temperature < 20 ^{o}C

NR1-2 VT results

The first breakthrough of Ninja-cathode EP with single cell cavity



Cornell VEP and Ninja cathode VEP

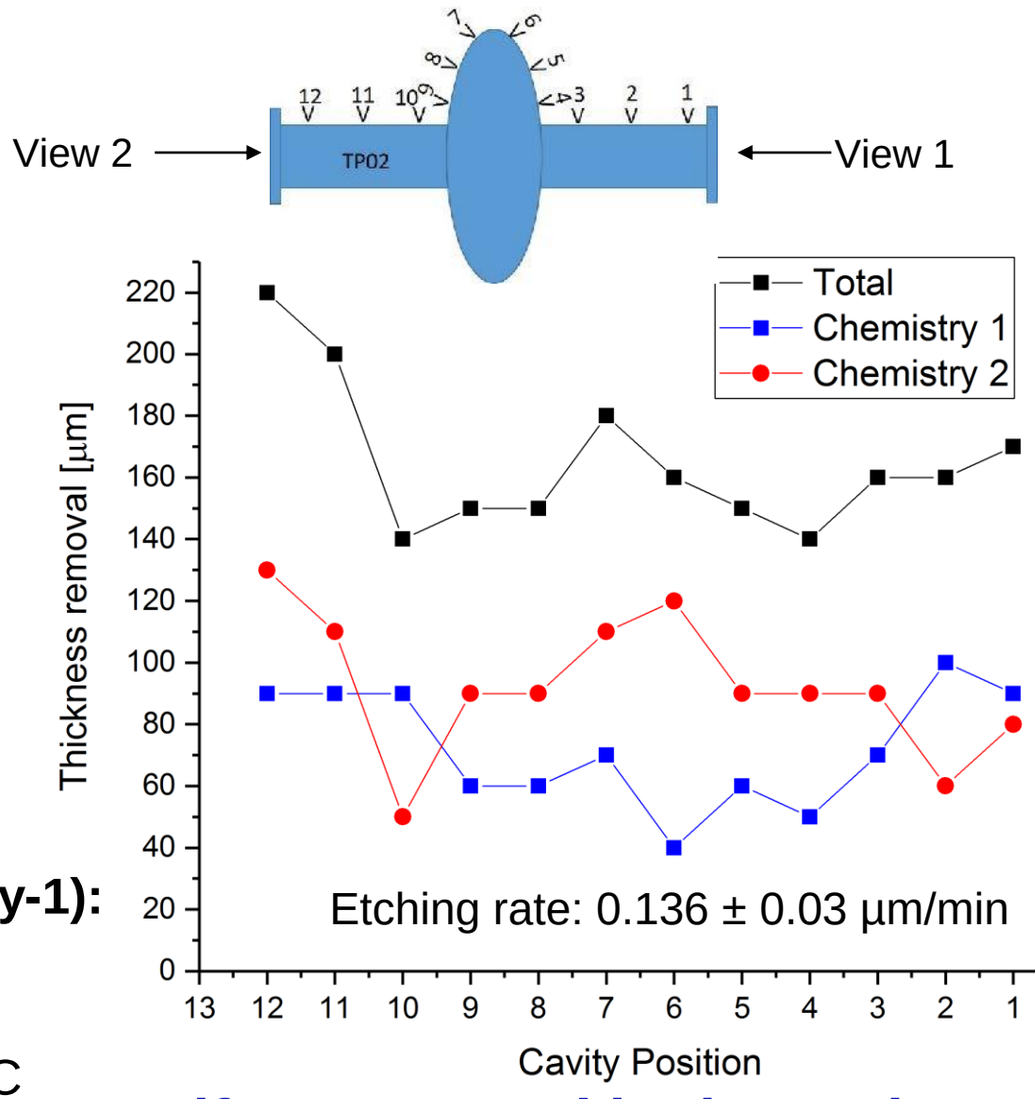


Similar cavity performance was attained with Cornell's cathode and Ninja Cathode.

Collaborative Work with CEA-Saclay

- Ninja cathode and investigated VEP parameters were applied on two cavities at Saclay.

VEP setup with Ninja cathode



After Final EP

Uniform removal in the cavity cell

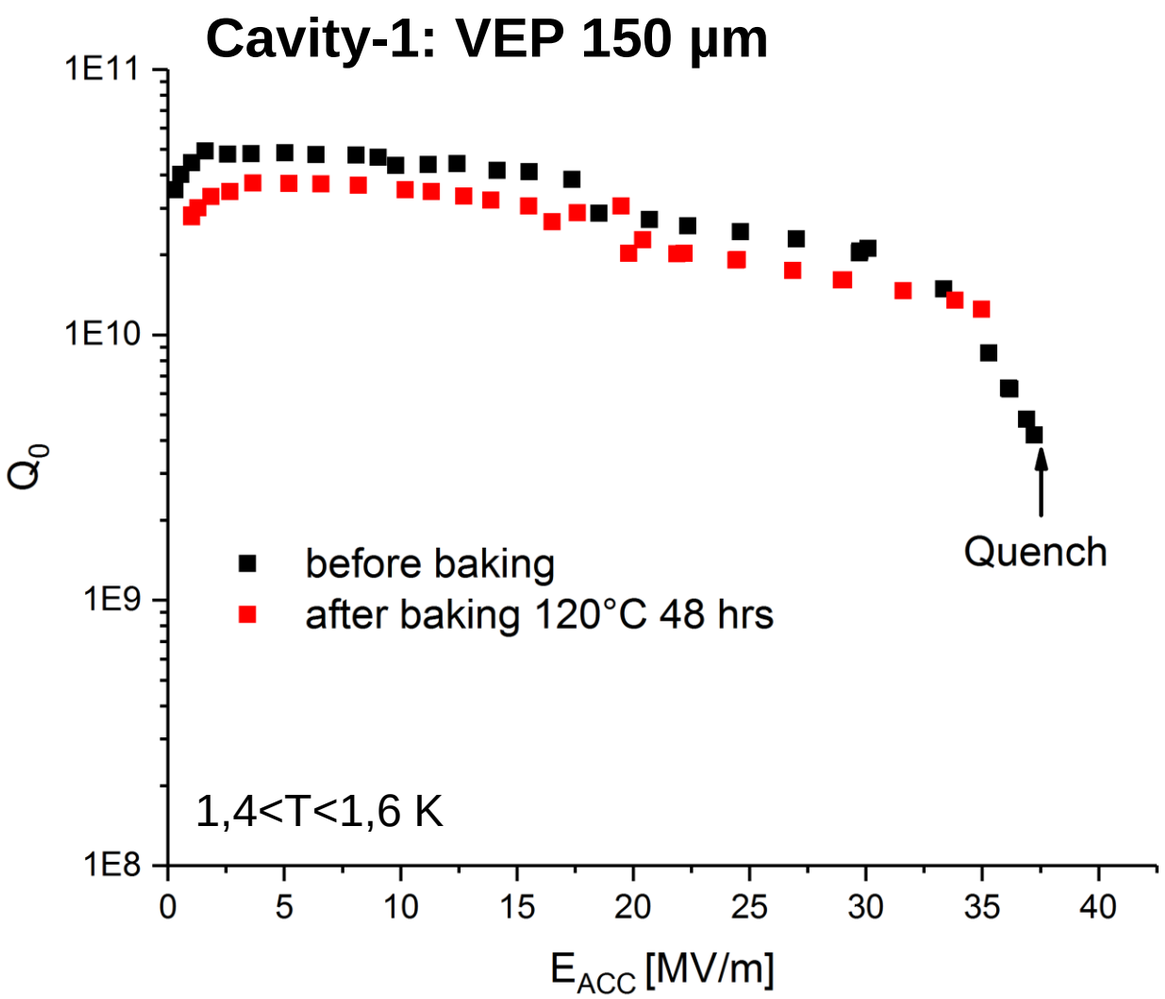
Targeted Vertical EP conditions (Cavity-1):

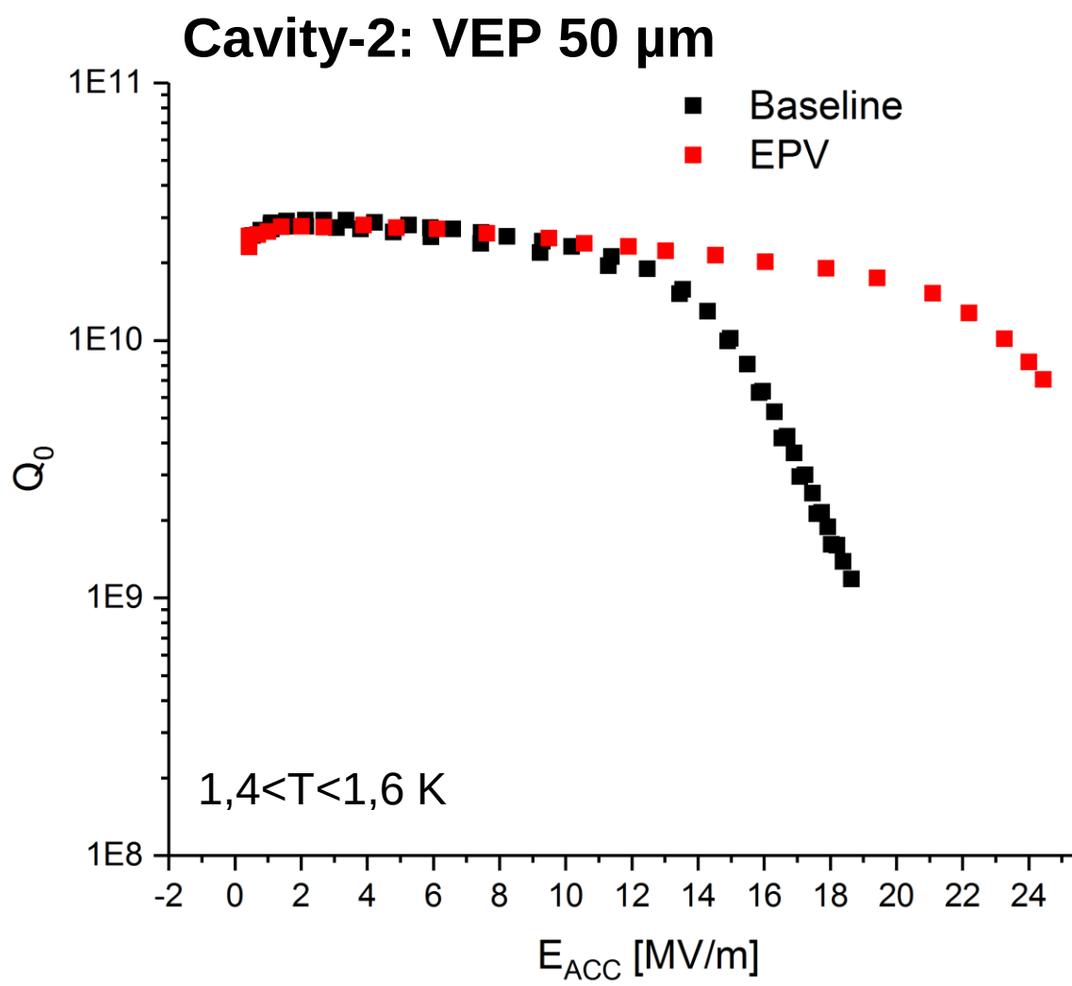
- Thickness removal 150 µm
- Acid Temperature in tank: 18°C
- External Cool down Temperature: 12°C
- Acid flow: 10L/min
- Rotation cathode: 20 rpm
- Voltage cathode: 17.3 V
- N_2 flow: 6L/min
- Cavity: TESLA design 1.3 GHz
- Volume acid Tank: 200L

VEP conditions (Cavity-2):

- VEP process: 50 µm, same conditions as for cavity-1

RF Test Results





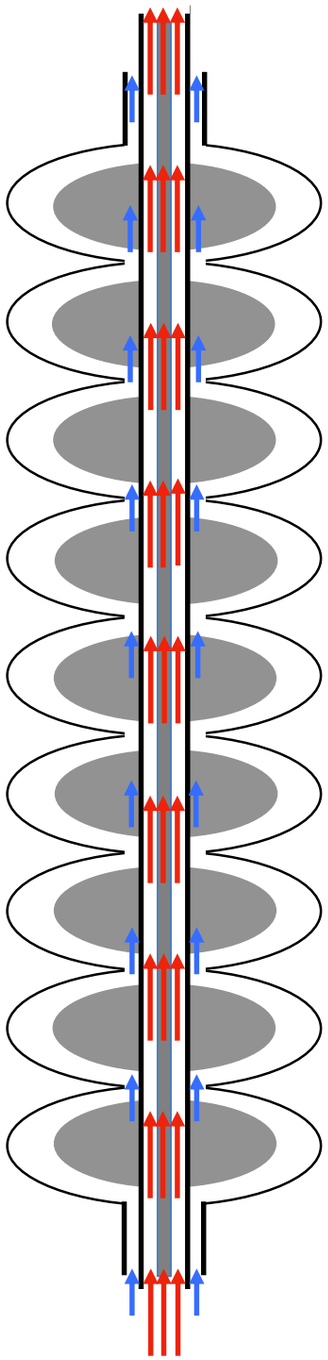
- **Quench at 37.2 MV/m and 35 MV/m with Q_0 = 1.26 x10^{10} before and after baking**
- **Future: High temperature annealing 650°C – 10 hrs with Nb caps**

- **Quench improved from 18 MV/m to 25 MV/m after VEP (50 µm)**
- **Future: Further EP for 50 µm**

VEP for 9-Cell Cavities

Parameter Study with 9-Cell Coupon Cavity

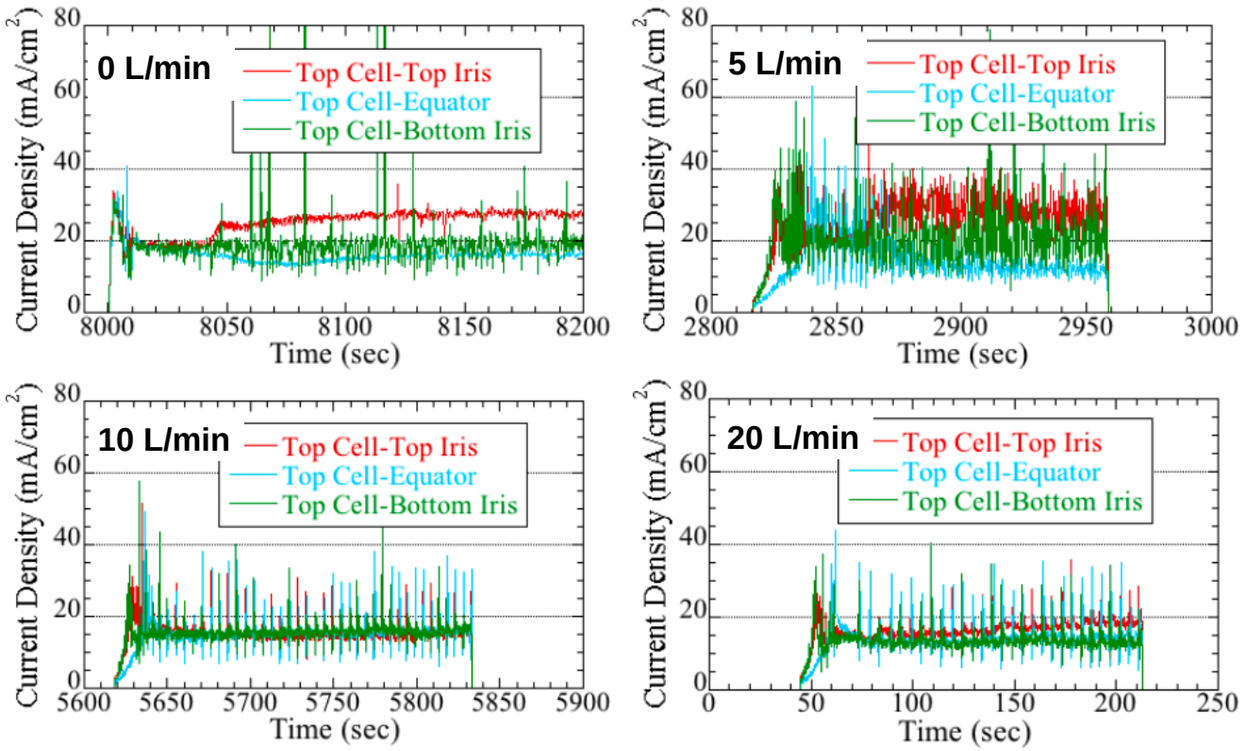
Separate Flow in Cavity and Cathode



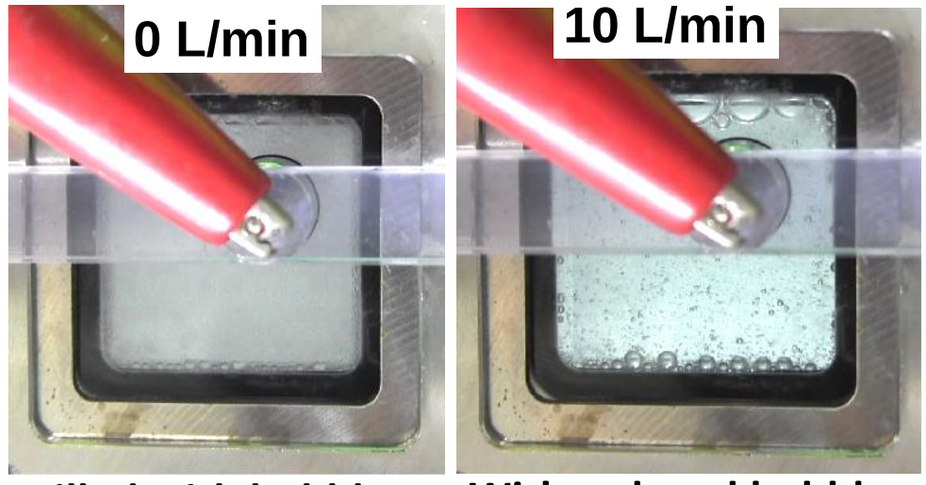
- Removal of bubbles quickly from a multi-cell cavity to stop bubble accumulation is more difficult and challenging.

Separate Acid Flow in Cathode and Cavity

Coupon currents at 5 L/min in Cavity & Different Flow Rates in Cathode Housing



Viewport (Top Cell) at 0 and 10 L/min in Cathode Housing



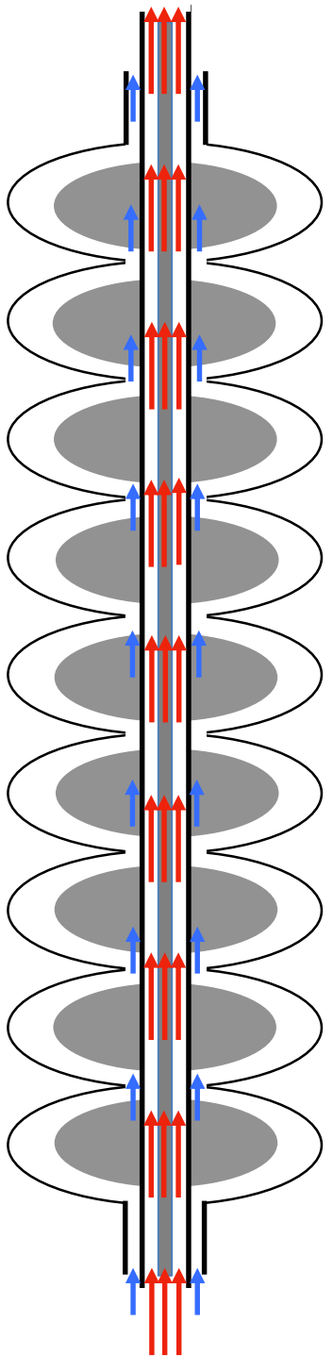
Filled with bubbles **With reduced bubbles**

Adequate acid flow:
Cathode housing ~ 10 L/min & Cavity ~ 5 L/min

Separate acid flow in the cavity and cathode housing reduced bubble accumulation in the cavity cells.

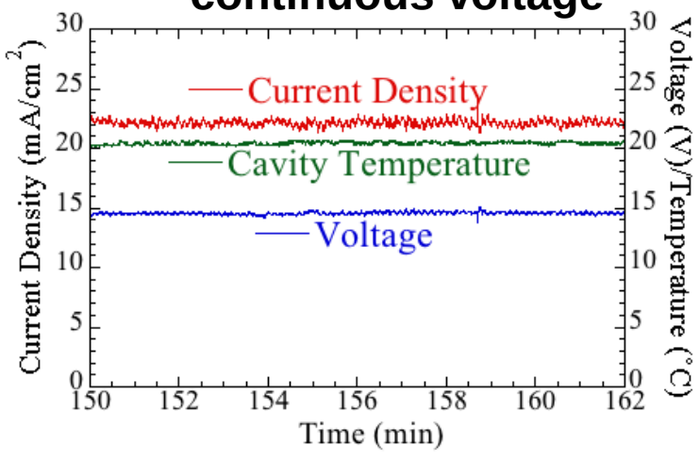
VEP of 9-Cell Cavity

Separate Flow in Cavity and Cathode

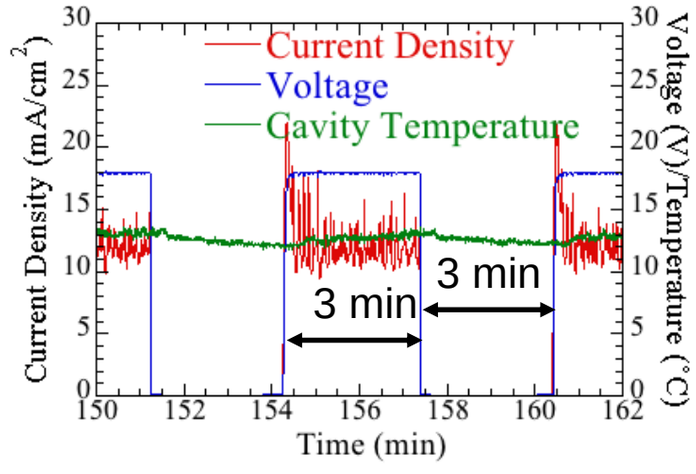


- Two VEP tests were conducted with combined and separate acid flow in the cathode housing and the cavity.

Combined acid flow and continuous voltage



Separate acid flow and on-off voltage cycles

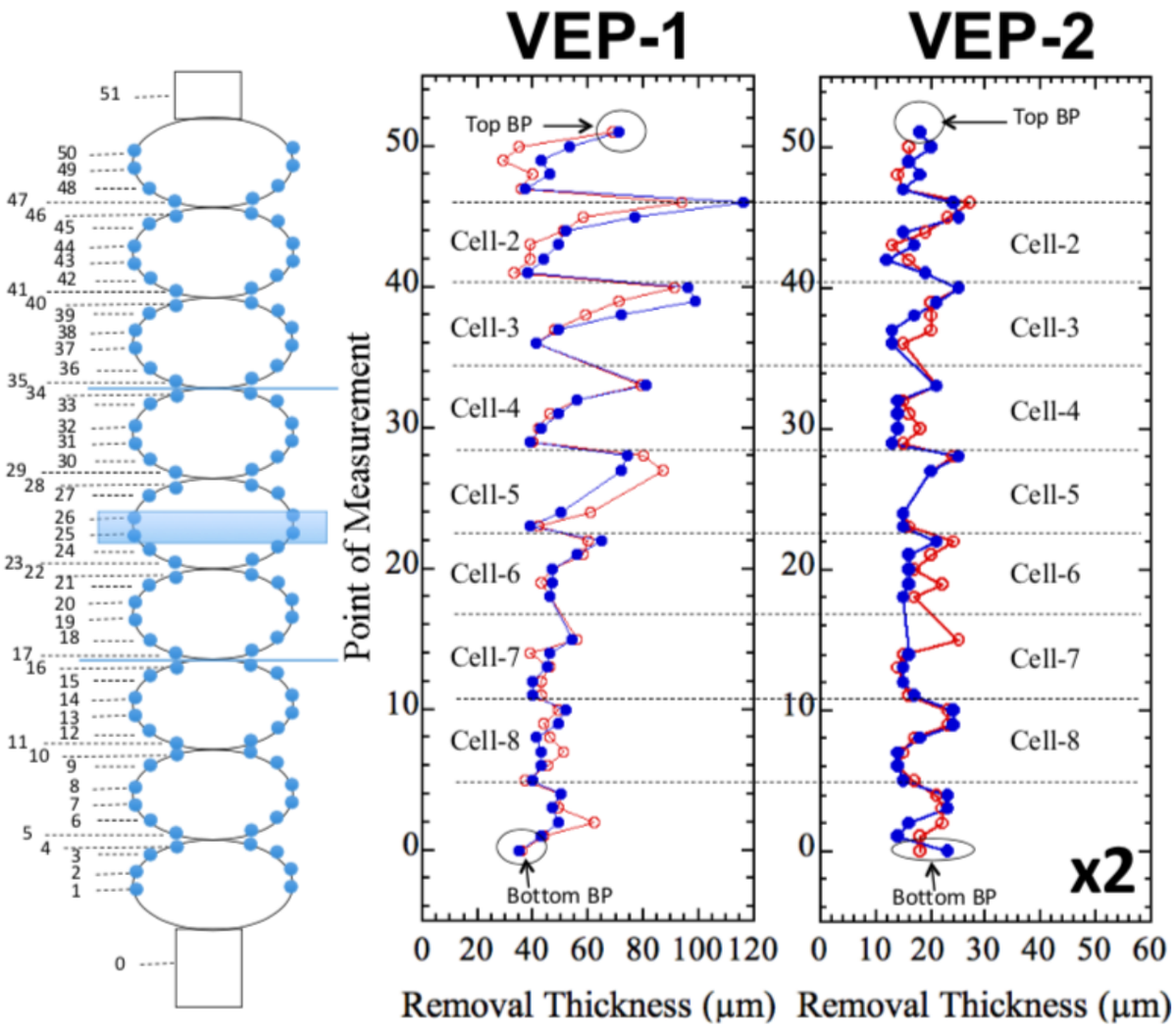


VEP parameters

Parameters	VEP-1	VEP-2
Electrolyte (H_2SO_4:HF)	9:1	9:1
Electrolyte Flow in Cavity and Ninja	Combined Flow	Separate Flow
Flow Rate	~5 L/min	~5 L/min in cavity & ~10 L/min in Ninja
Cavity Surface Temperature (Max)	20 °C	15 °C
Cathode Rotational Speed	20 rpm	20 rpm
Applied Voltage	~15 V	~18 V
Average Removal	52 µm	18 µm

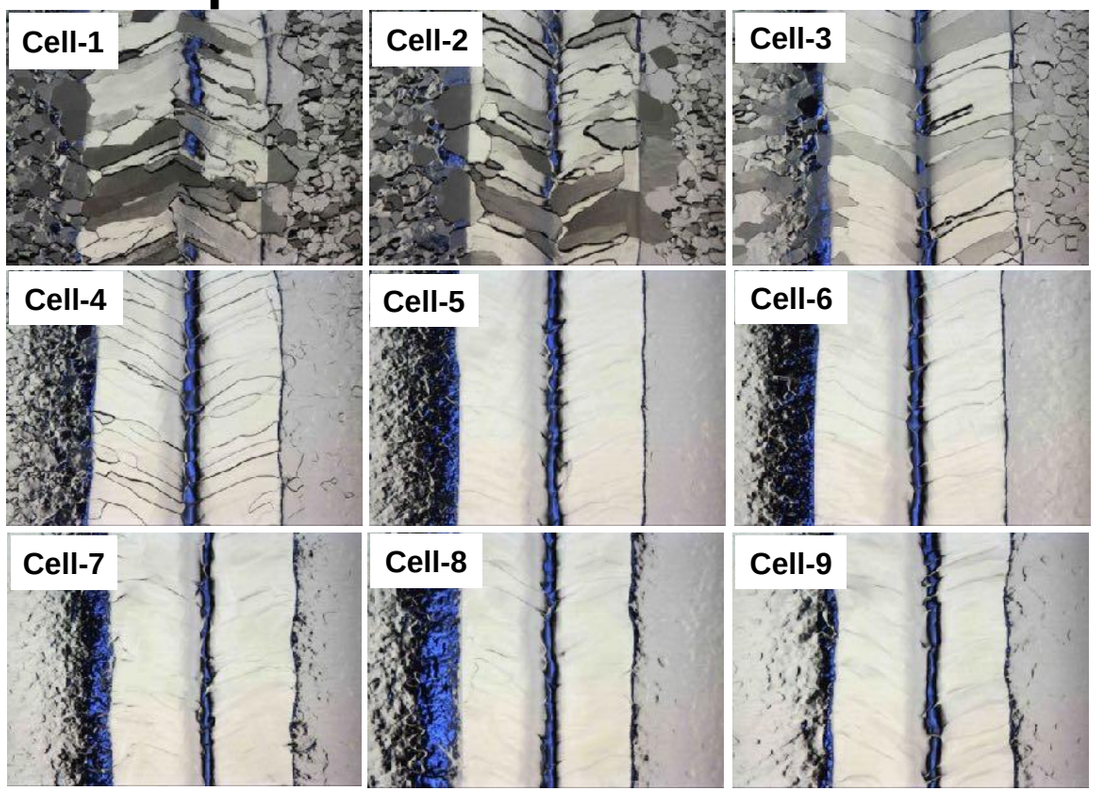
Parameters for VEP-2 were found with the 9-cell coupon cavity tests.

Removal Thickness and Surface after VEP

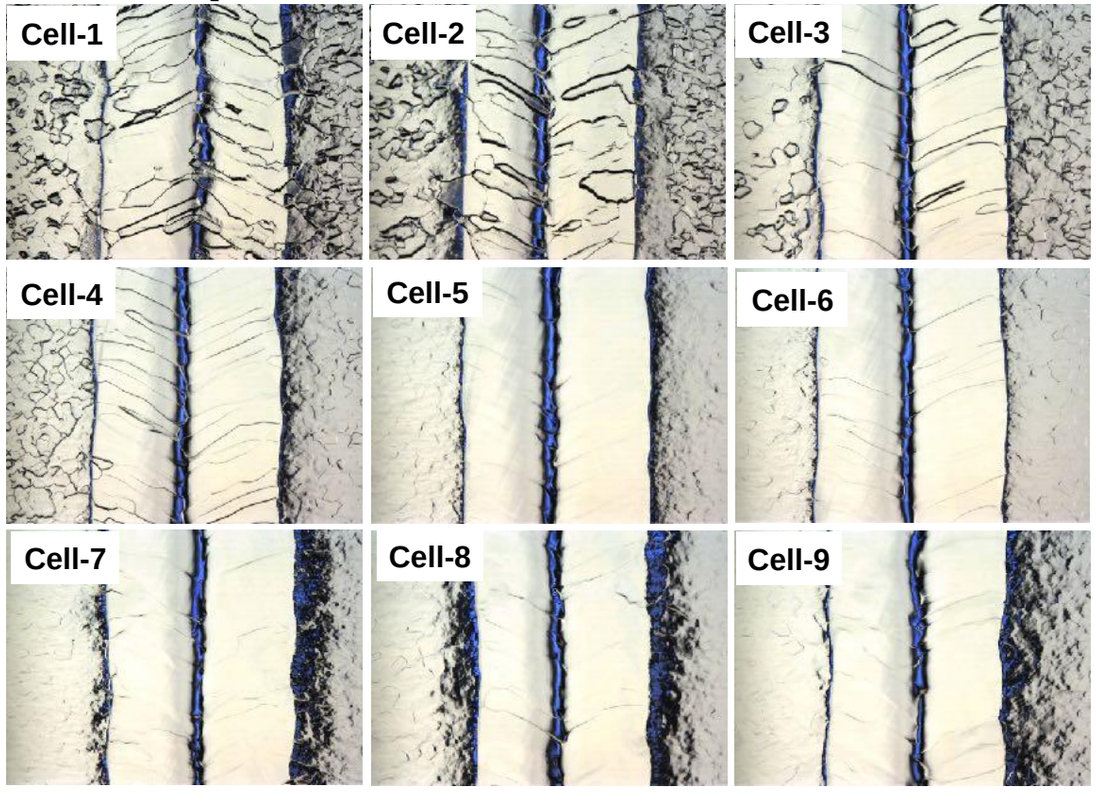


- Removal asymmetry along the cavity length significantly reduced in VEP-2 performed with separate acid flow.
- Surface roughness also reduced in VEP-2.

Equator Surface after VEP-1

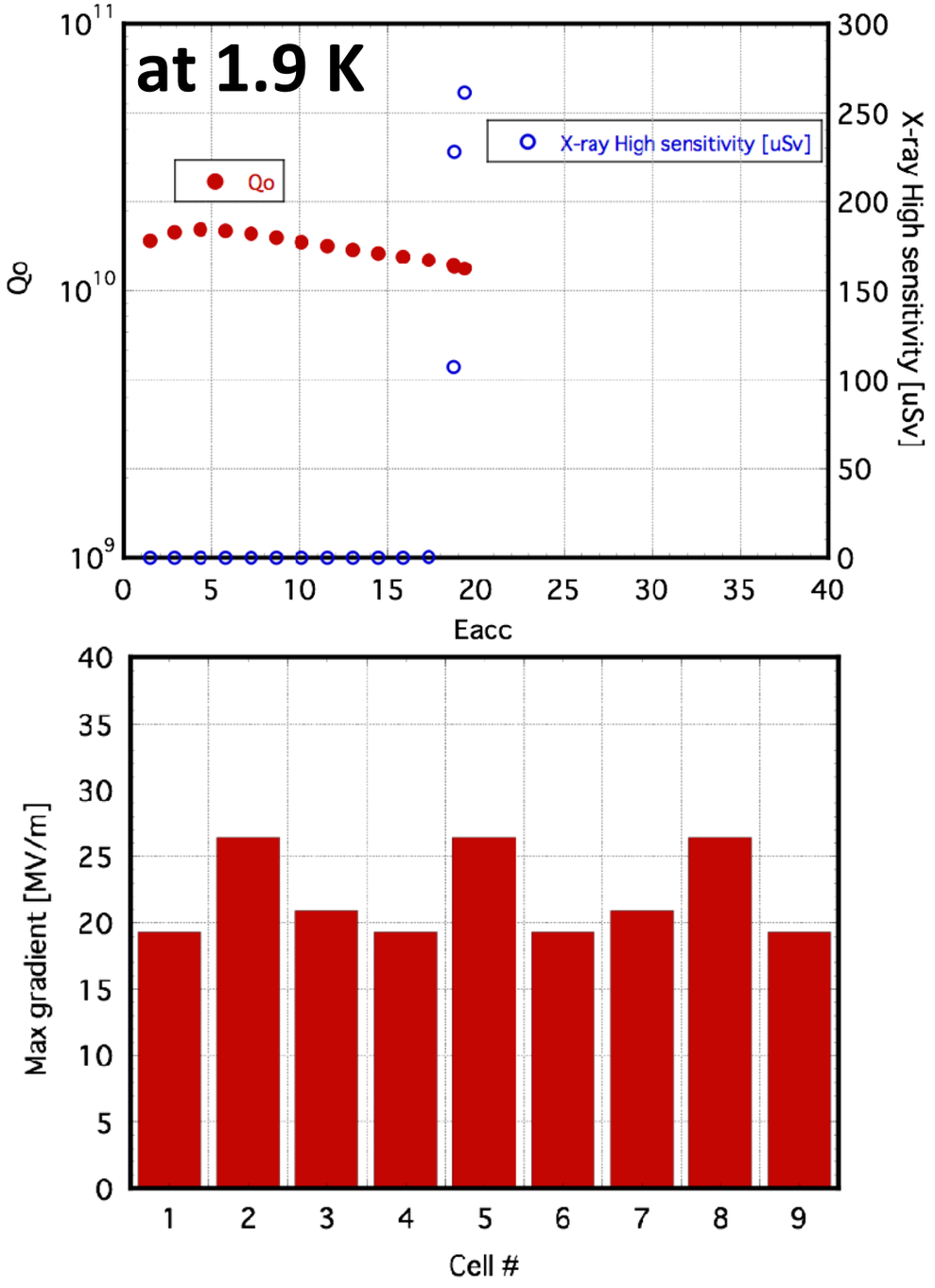


Equator Surface after VEP-2



Vertical Test Result

- Horizontal EP-1 (100 µm)
- Annealing
- Tuning (Field flatness 90%)
- VEP-1 (52 µm)
- HPR + 120 ºC baking for 48 h
- No VT due to leak
- Field Flatness 67%
- Tuning (Field flatness 97%)
- VEP-2 (18 µm)
- HPR + 120 ºC baking for 48 h
- Vertical Test
- Field flatness 98% (no change)



- Field Gradient: 19.3 MV/m, Q_0 = 1.3 x 10^{10}, limited by field emission/quench (heating spot at the slop region in the 2nd cell)
- The maximum field gradient in each cell was measured using passband-modes (8π/9, 6π/9, 5π/9, and 3π/9)

Summary

- VEP tests for single and nine cell cavities were performed.
- Different types of Ninja cathodes were tested to find an adequate design.
- Single and nine cell coupon cavities were used to optimize VEP parameters for smooth surface and uniform EP.
- A successful VEP process (parameters and cathode) for single cell cavity has been established.
- Now VEP process successfully performed with our optimized VEP parameters and Ninja cathode in three region (Asia, Europe, and USA): at KEK and Marui, CEA-Saclay, and Cornell University.
- VEP parameters for a 9-cell cavity are under study. Currently, removal asymmetry in 9-cell cavity was successfully reduced with separate acid flow system.
- Future: Bulk VEP for a 9-cell cavity and RF test, test of the Ninja cathode on 9-cell cavity at CEA-Saclay, further study of VEP parameters with coupon cavity