Update on Progress of Vertical EP at Marui and KEK

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Vijay Chouhan
Marui Galvanizing Co. Ltd/KEK

Y. Ida, K. Nii, T. Yamaguchi (Marui)
H. Hayano, S. Kato, M. Monjushiro, T. Saeki, M. Sawabe (KEK)
H. Ito (Sokendai)
H. Oikawa (Utsunomiya University)

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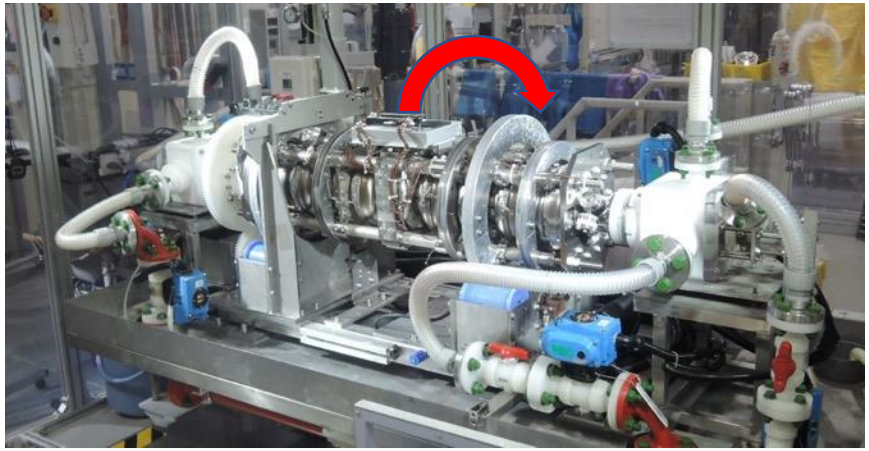
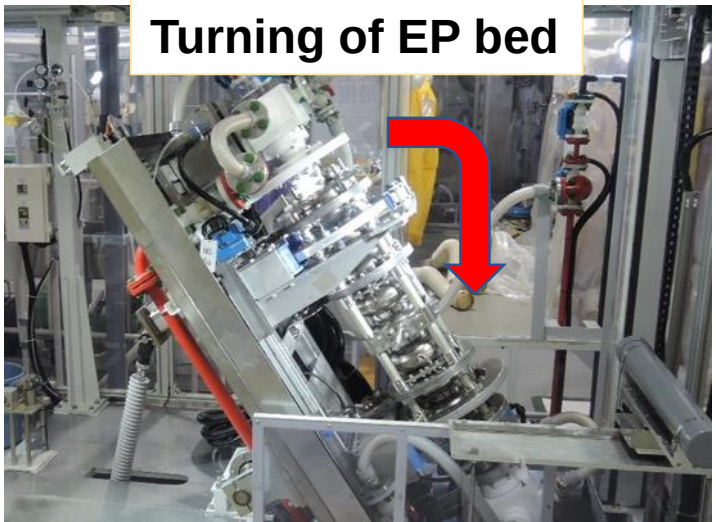
- Introduction of Horizontal and Vertical Electropolishing (EP)
- VEP Results of Single-Cell Cavity
- Parametric Study with 9-Cell Cavity
- VEP Results of 9-Cell Cavity
- Summary & Future Work

Horizontal & Vertical Electropolishing

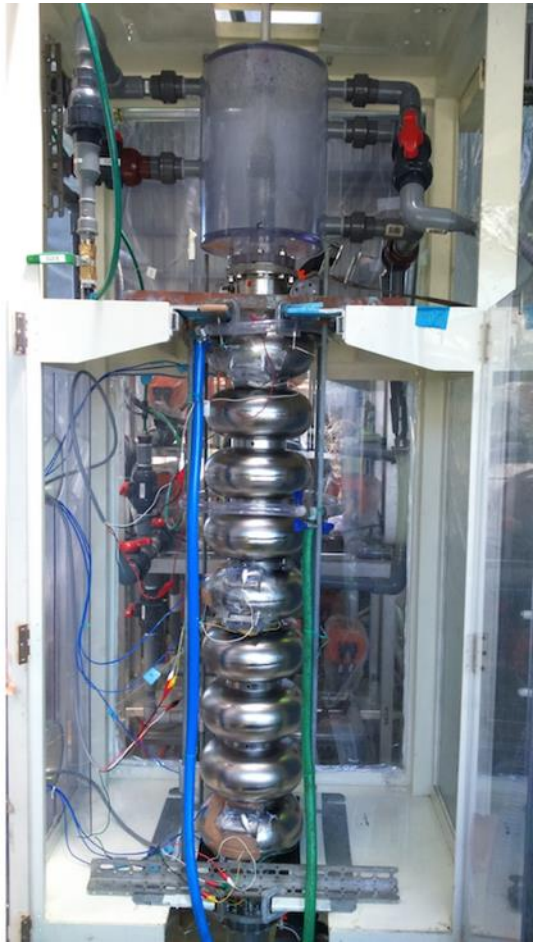
- Horizontal EP (HEP): **Cavity in horizontal position** during the EP process
- Vertical EP (VEP): **Cavity in vertical position** during the EP process

Massive Horizontal EP Setup with Rotating Cavity





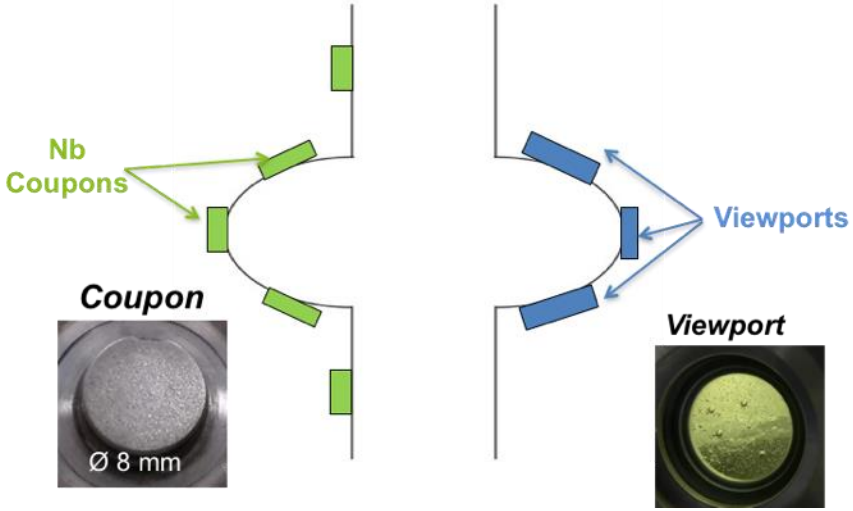
Vertical EP at Marui

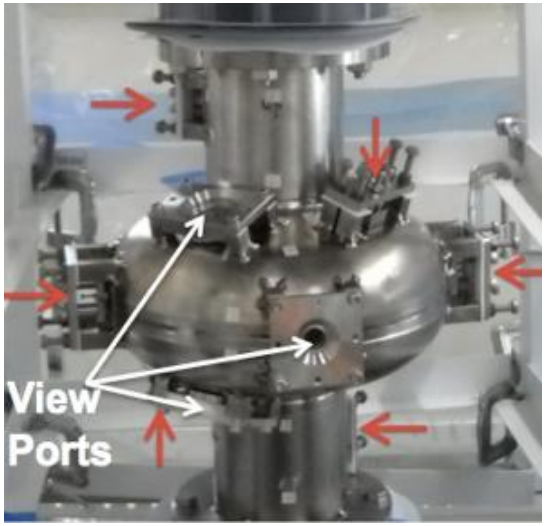


- **VEP is performed with a simple setup.**

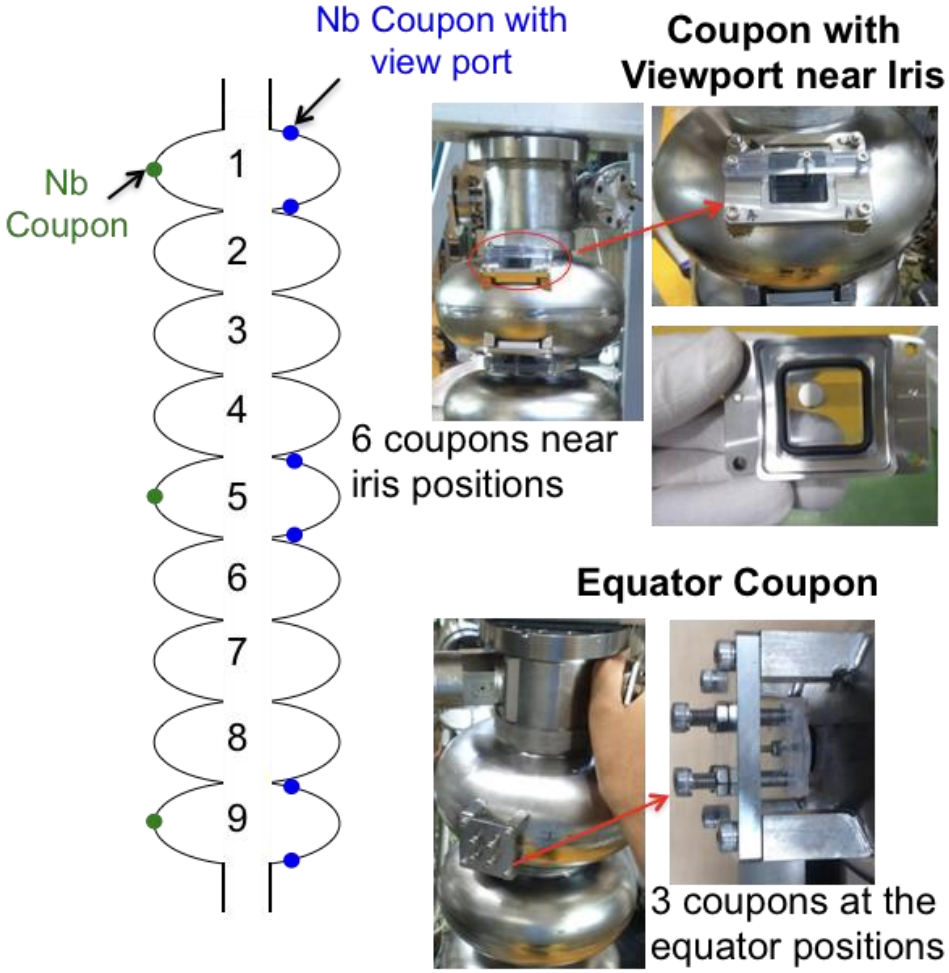
1.3 GHz Single and Nine-Cell Coupon Cavities

Single-Cell Coupon Cavity





Nine-Cell Coupon Cavity

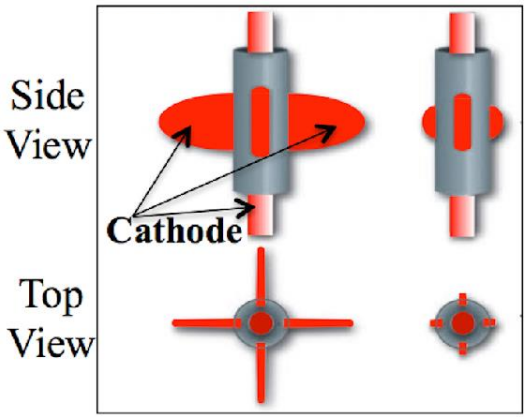


Measurable coupon current, in-situ observation, post VEP surface analysis

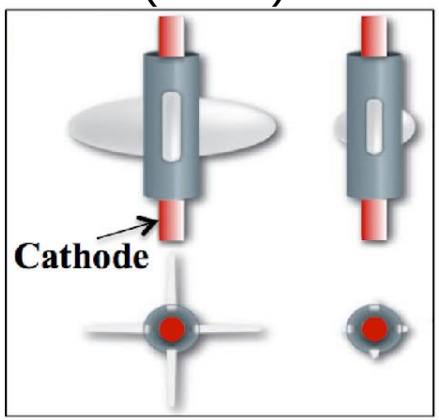
Optimized Design of Unique Ninja Cathode

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

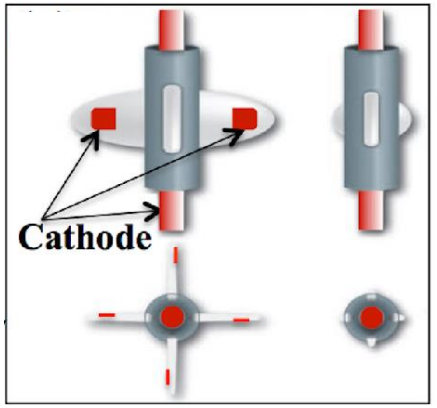
Metal Wings (Ver-1)



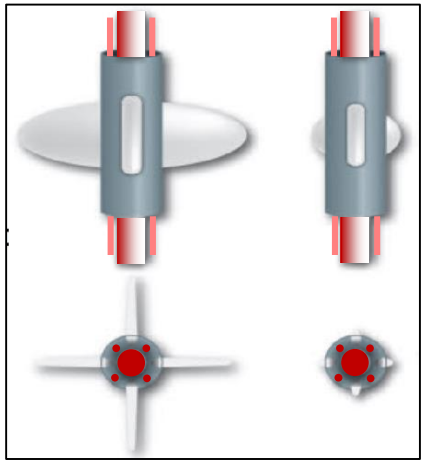
Insulating Wings (Ver-2)



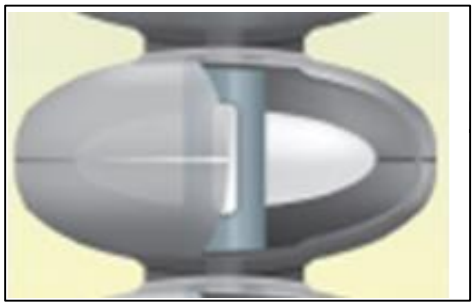
Partial Metal Wings (Ver-3)



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



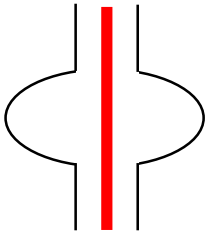
- Ninja cathode v5: Enhanced cathode surface area, cathode housing covered with meshed sheet, insulating wings



The cathode is rotated during the VEP process.

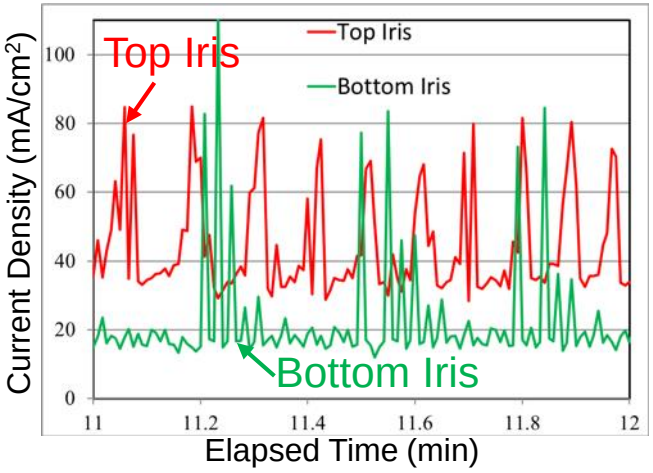
Ninja cathode is inserted in the cavity and then its blades are expanded.

VEP with Conventional Rod Cathode



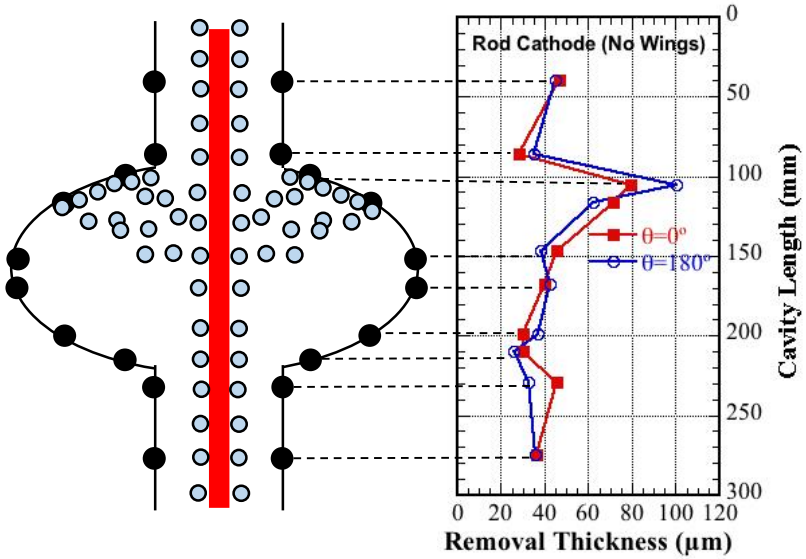
- Acid flow rate ~ 5L/min
- Voltage ~9 V

Coupon Currents

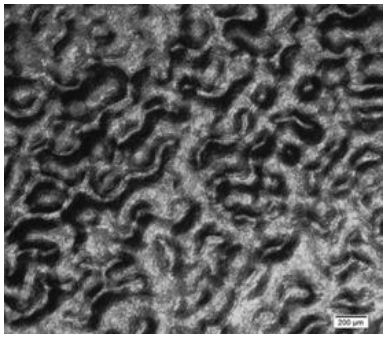


- Higher EP current at the upper half cell

Removal Trend



Bubble Footprints at Upper Iris



500 µm

Top Iris Viewport

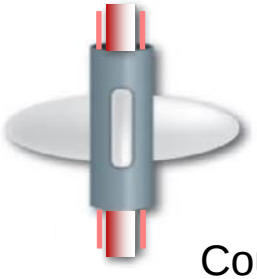
Major Issues in VEP:

- Non-uniform removal
- Rough surface/Bubble traces

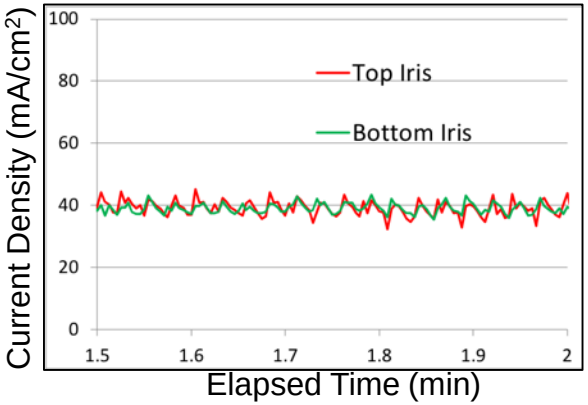
- The higher removal at the top iris is due to accumulation of H_2 gas bubble on the surface.
- It was confirmed with lab EP experiments.

V. Chouhan *et al., Phys. Rev. Accel. Beams* **20**, (2017) 083502

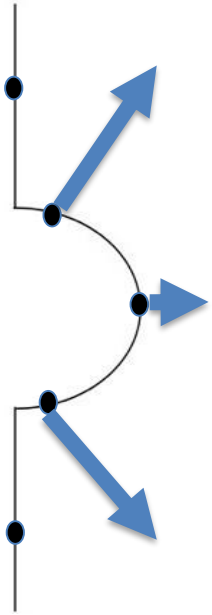
VEP with Ninja Cathode

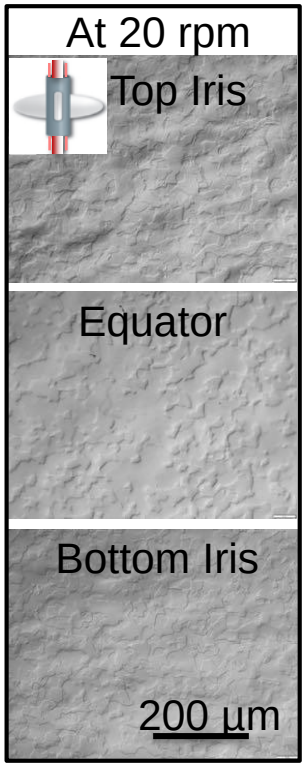


Coupon Currents

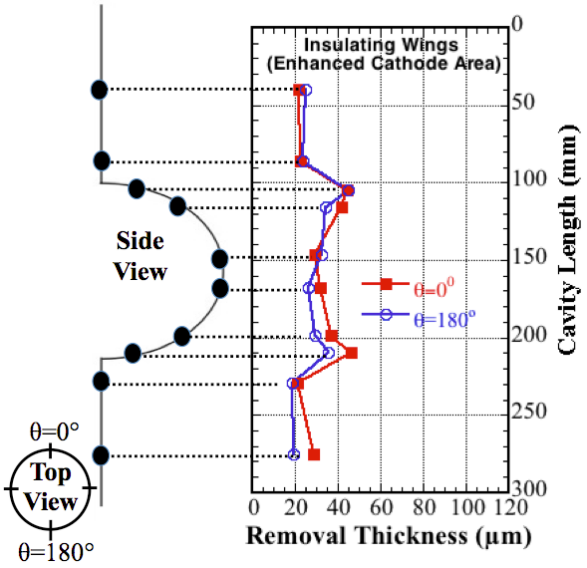


Optical Images





Removal Thickness



- **Meshed housing** guides hydrogen bubbles along the cathode and reduces bubble accumulation in the cavity cell
- **Cathode rotation** might make uniform flow on the surface
- **Larger cathode surface** reduces cathode screening by bubbles

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

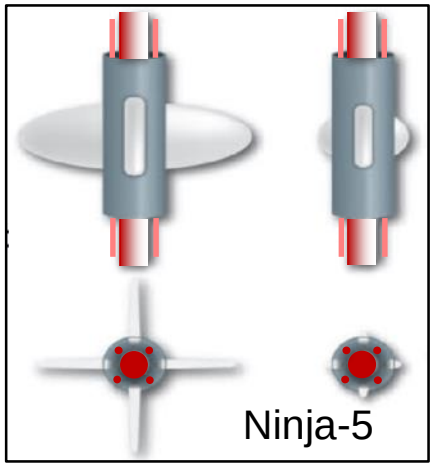
- The cathode and optimized parameters yield smooth surface and symmetric removal.
- Hence, the cathode was opted for further VEP and RF tests.

VEP for RF Test Comparison

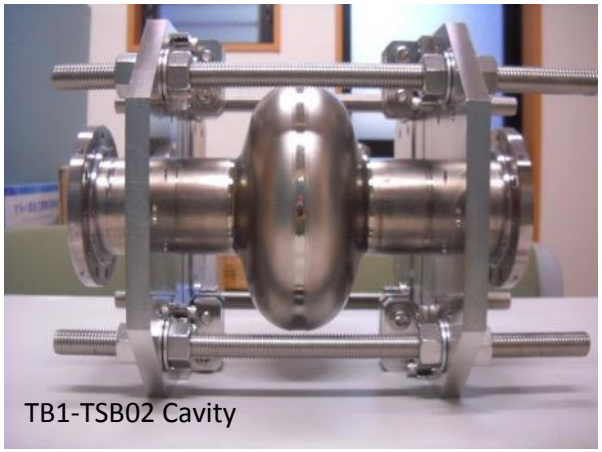
Ninja Cathode-v5

Side View

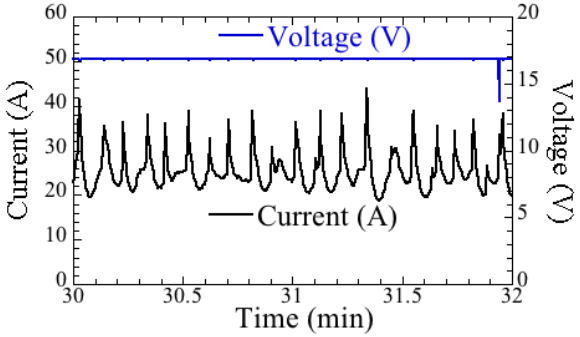
Top View



Single-Cell Cavity with Support-jig



VEP Current Profile



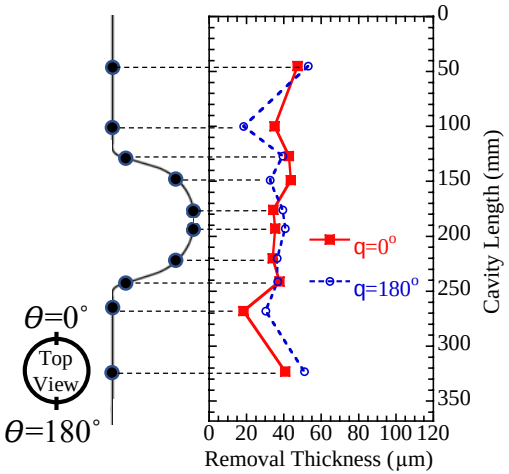
Voltage: 16-17 V

Cathode rotation: 20 rpm

Acid flow rate ~ 5 L/min

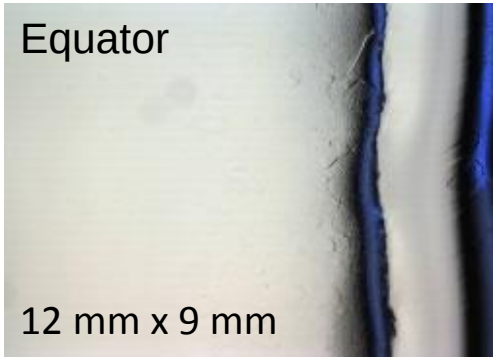
Temperature ~ 20 ºC

Removal Thickness Profile



Avg. removal: 36 μm

Cavity Surface after VEP



Uniform removal in the cell

Removal rate: 0.22 μm/min

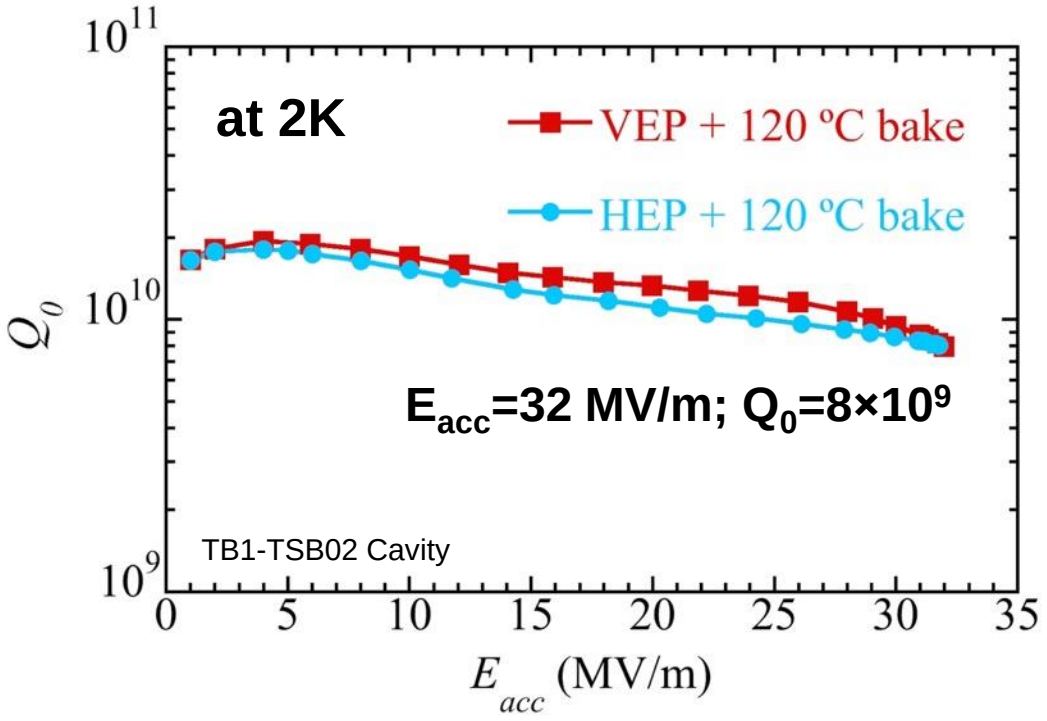
Smooth and glossy surface

SRF Performance (Single-Cell Cavity)

VEP Process

VEP1（36μm）
↓
HPR &
120ºC baking
↓
Annealing
(750ºC)
↓
VEP2（10μm）
↓
HPR &
120ºC baking
↓
Vertical test

Cavity Performance after HEP and VEP

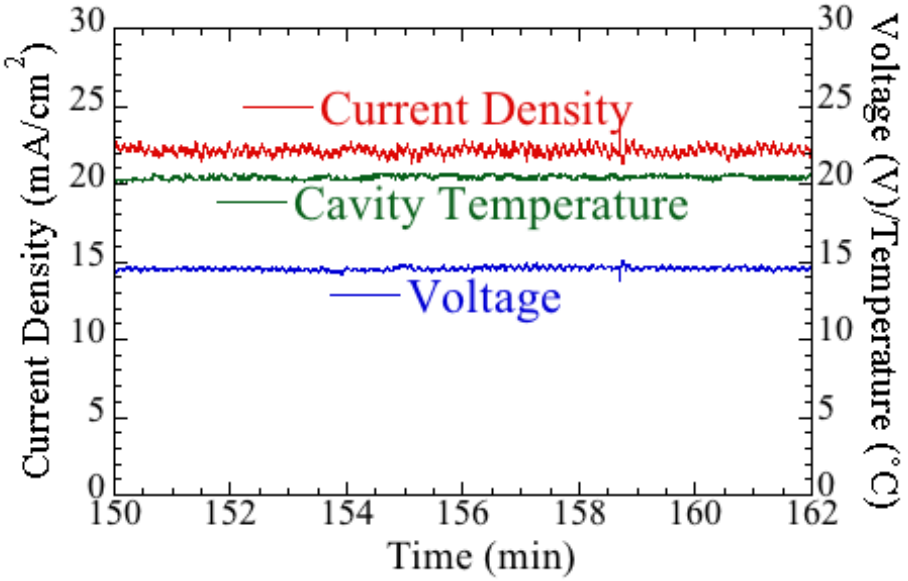


- Field gradient of 32 MV/m (Q_0=8×10^9) was achieved after VEP.
- The accelerating gradient after VEP was as good as achieved after HEP.

VEP of 9-Cell Cavity

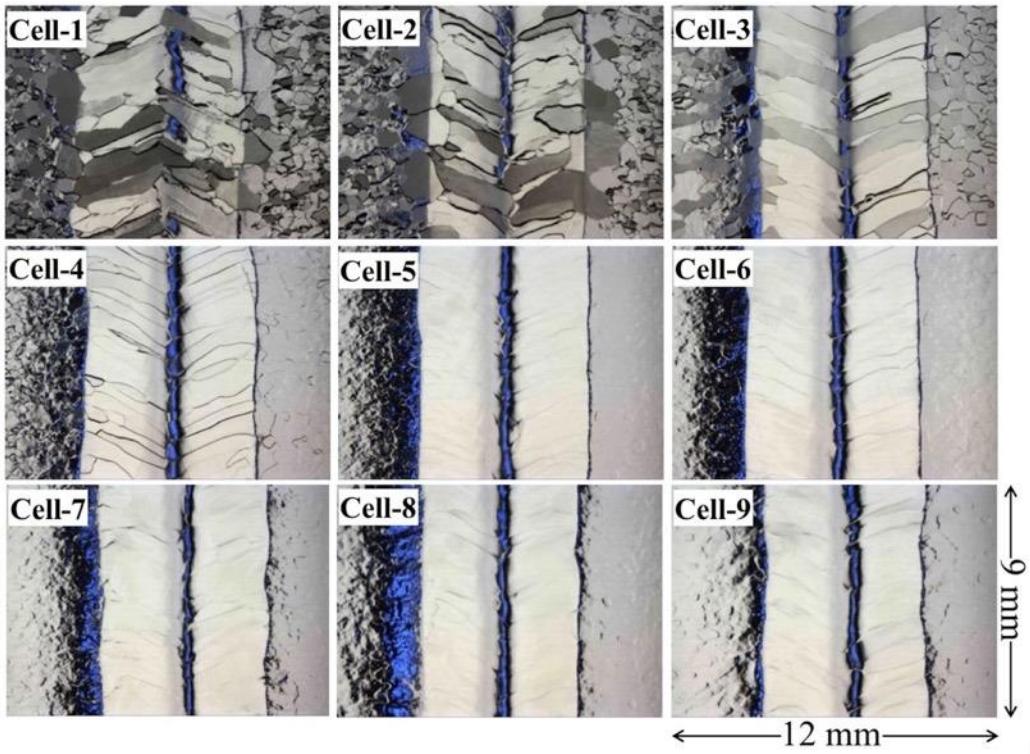
- **VEP test was conducted with similar parameters as optimized with the single-cell cavity.**

Condition	Value
Cathode Type	Ninja v-5
Cathode Rotation	20 rpm
Cavity Temperature	15–22 °C
Voltage	15 V
Acid flow rate	~5 L/min

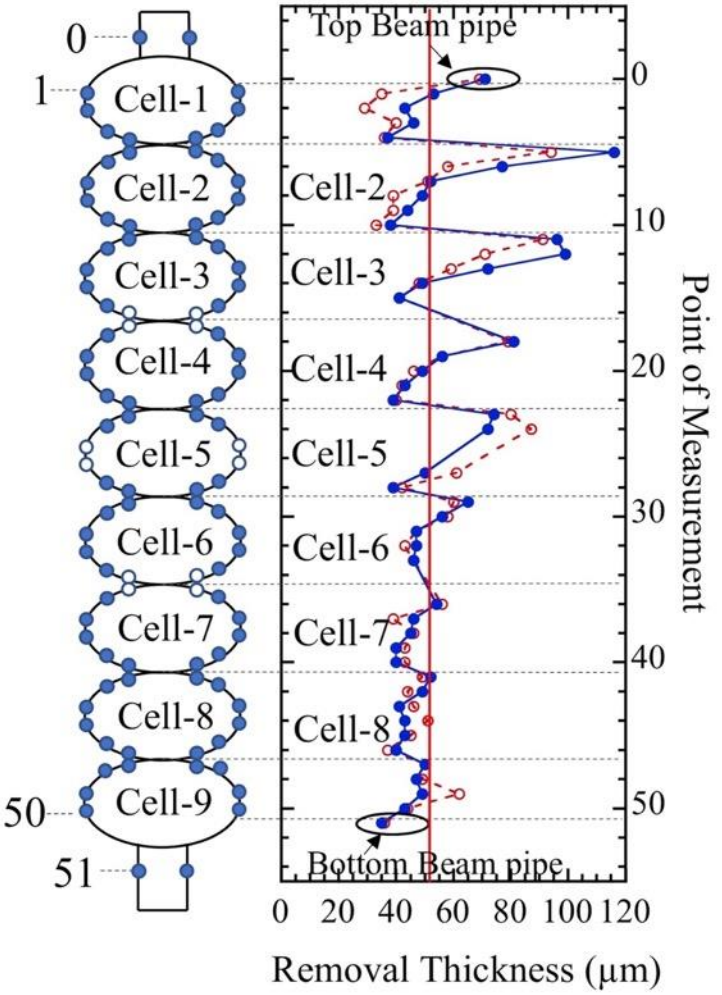


Results of VEP

Equator Surface after VEP



Removal Trend



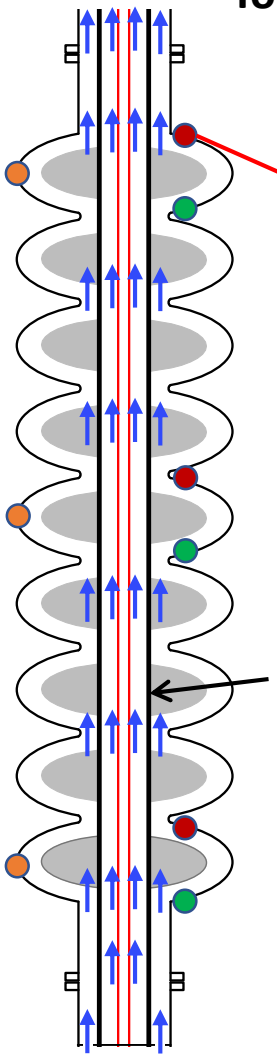
- VEP yields rough equator surface and asymmetric removal in the upper cells.
- The optimized parameters for the single cell cavity are adequate for a 4-cell-scale cavity.
- But these parameters are not adequate to apply to the 9-cell cavity.

Avg. removal: 50 μm

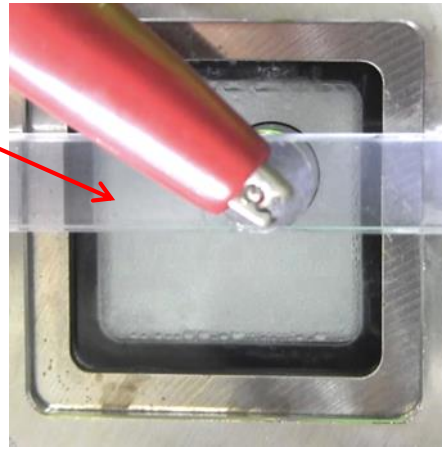
Parametric Study with 9-Cell Coupon Cavity

V Chouhan *et al.*, Phys. Rev. Accel. Beams **22**, (2019) 103101

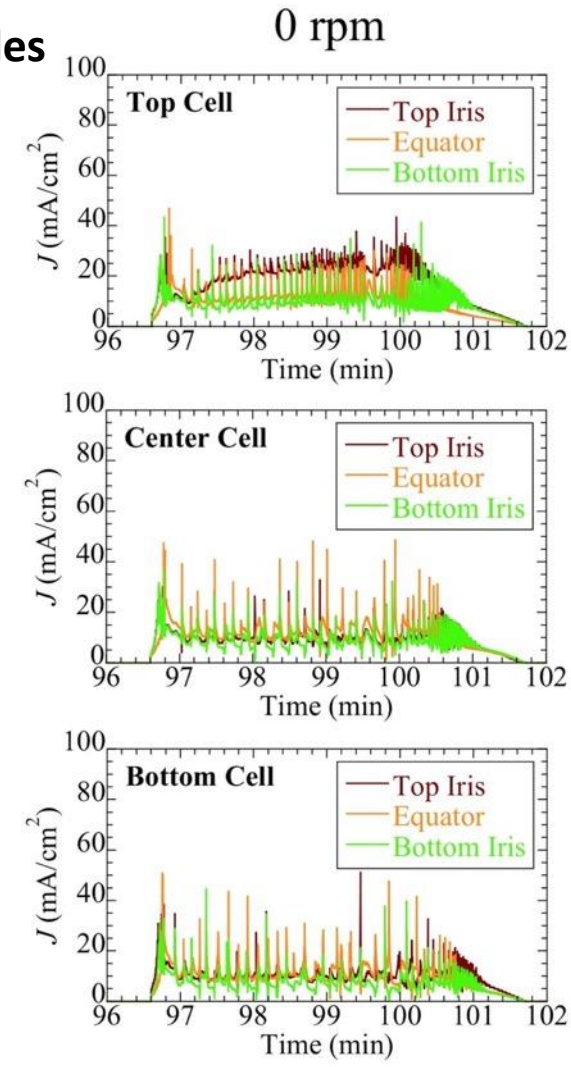
Effect of Cathode Rotation

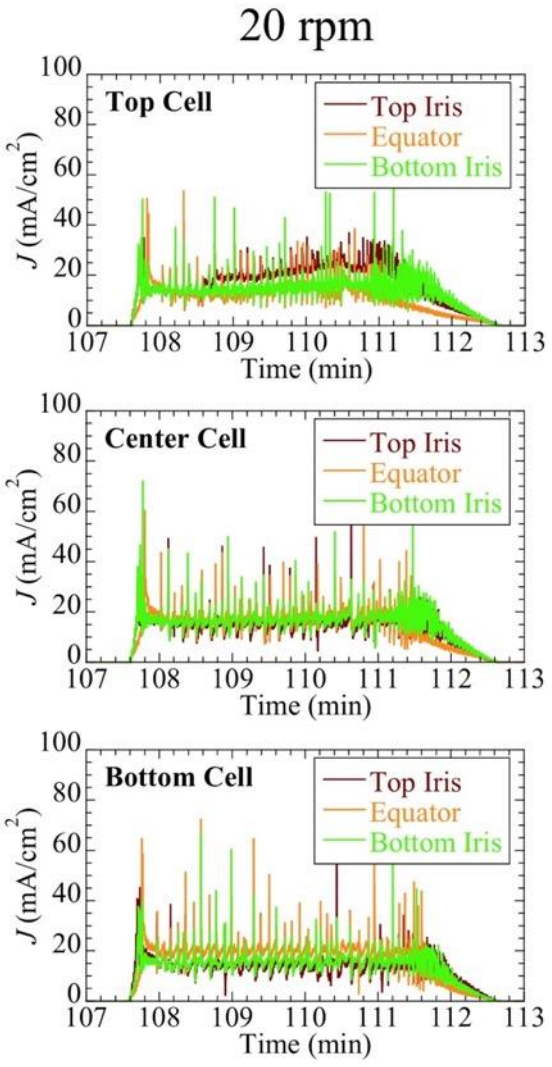


Top Cell Filled with bubbles



Cathode Housing



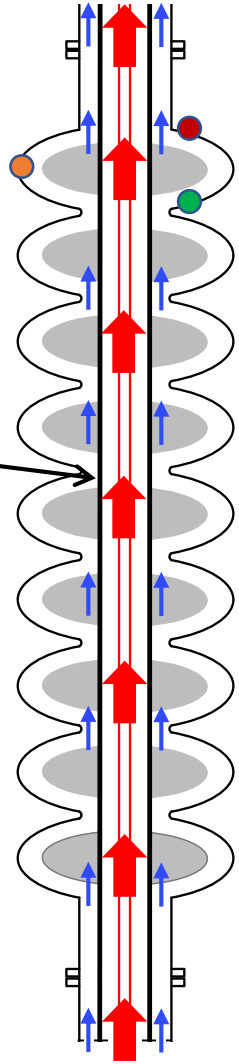


Acid Flow Rate = 5 L/min

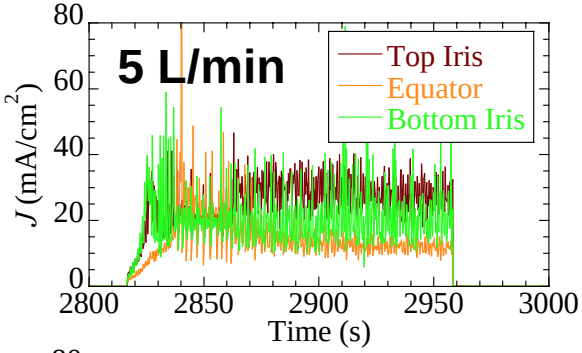
Cathode rotation of 20 rpm reduces the difference in the coupon currents in the top cell.

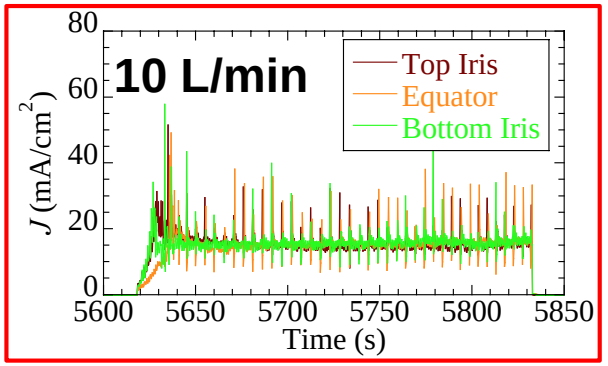
Novel Acid Flow Method (Dual Flow)

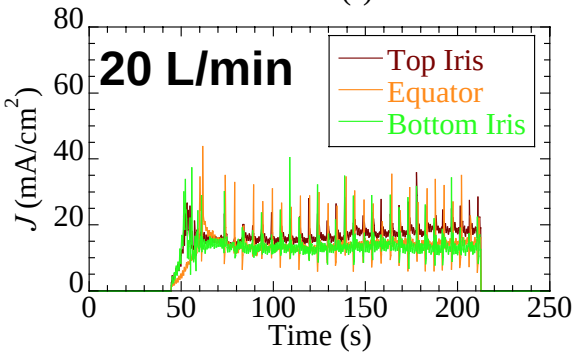
Acid was flowed separately in the cavity and cathode housing.



5 L/min in the cavity, and different flow rates in the cathode housing

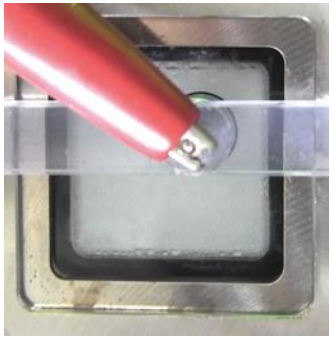




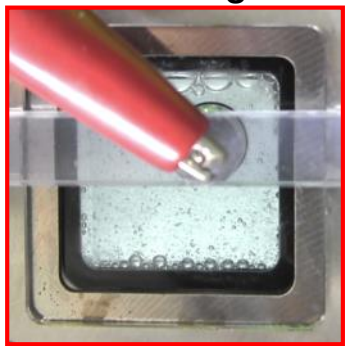


Adequate flow rates:
Cavity: 5 L/min
Cathode housing: 10 L/min

No intentional flow in cathode housing

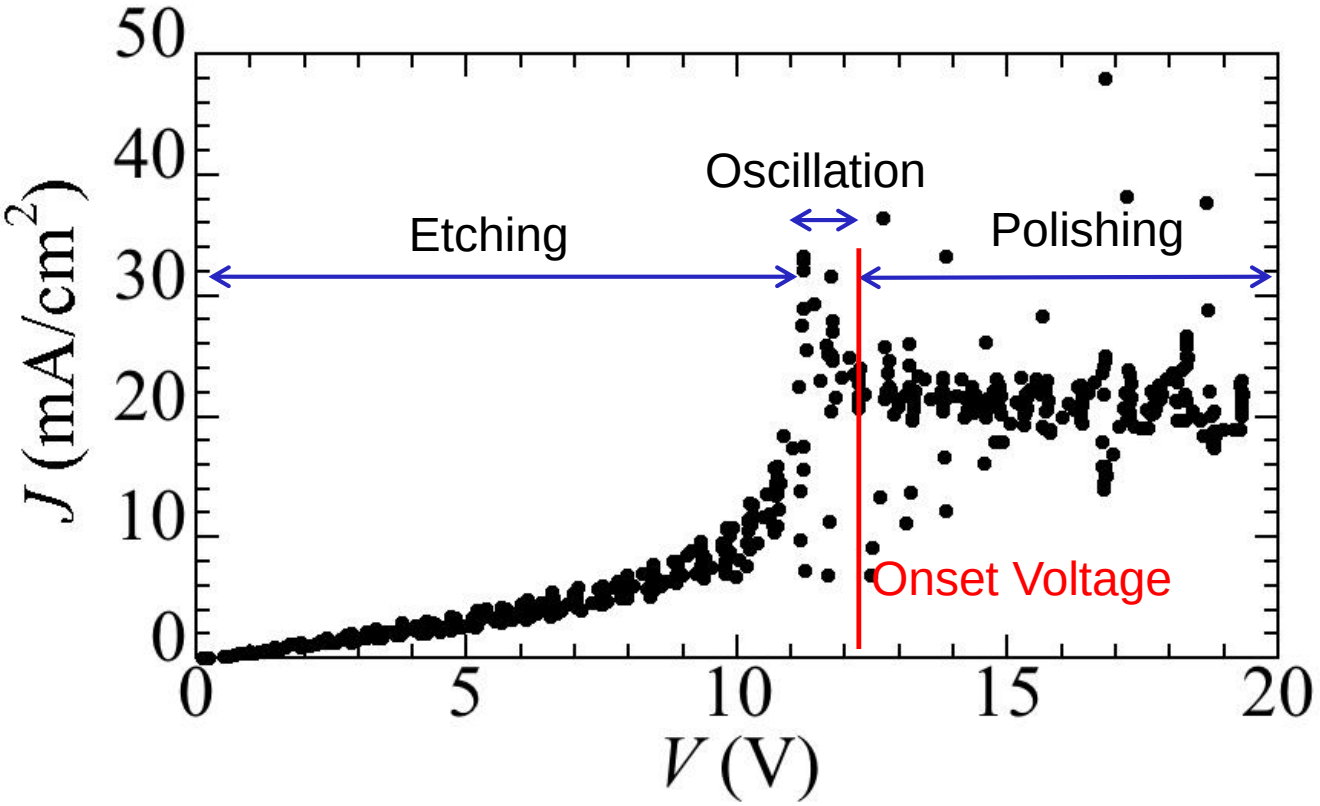


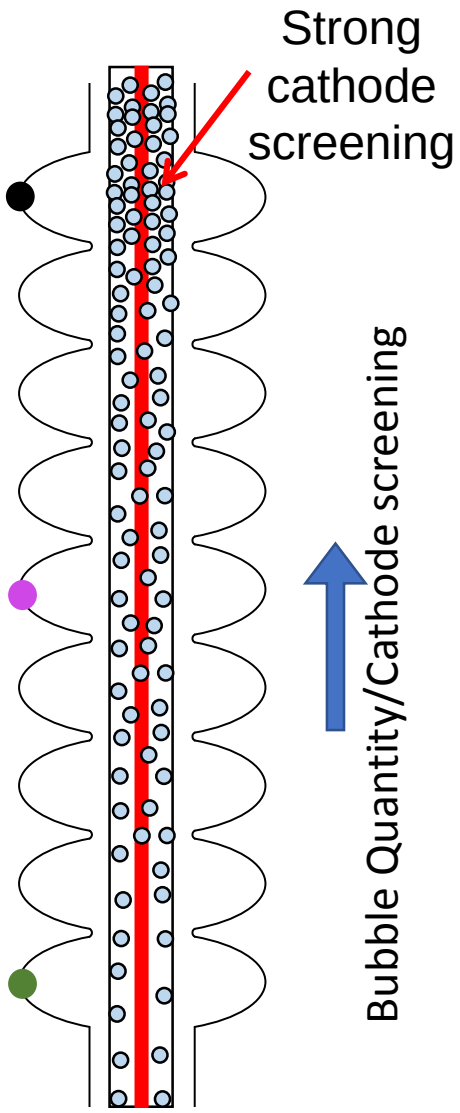
10 L/min in cathode housing



Effect of Temperature

- Polarization (*J*-*V*) curves were obtained at different temperatures of the cavity.

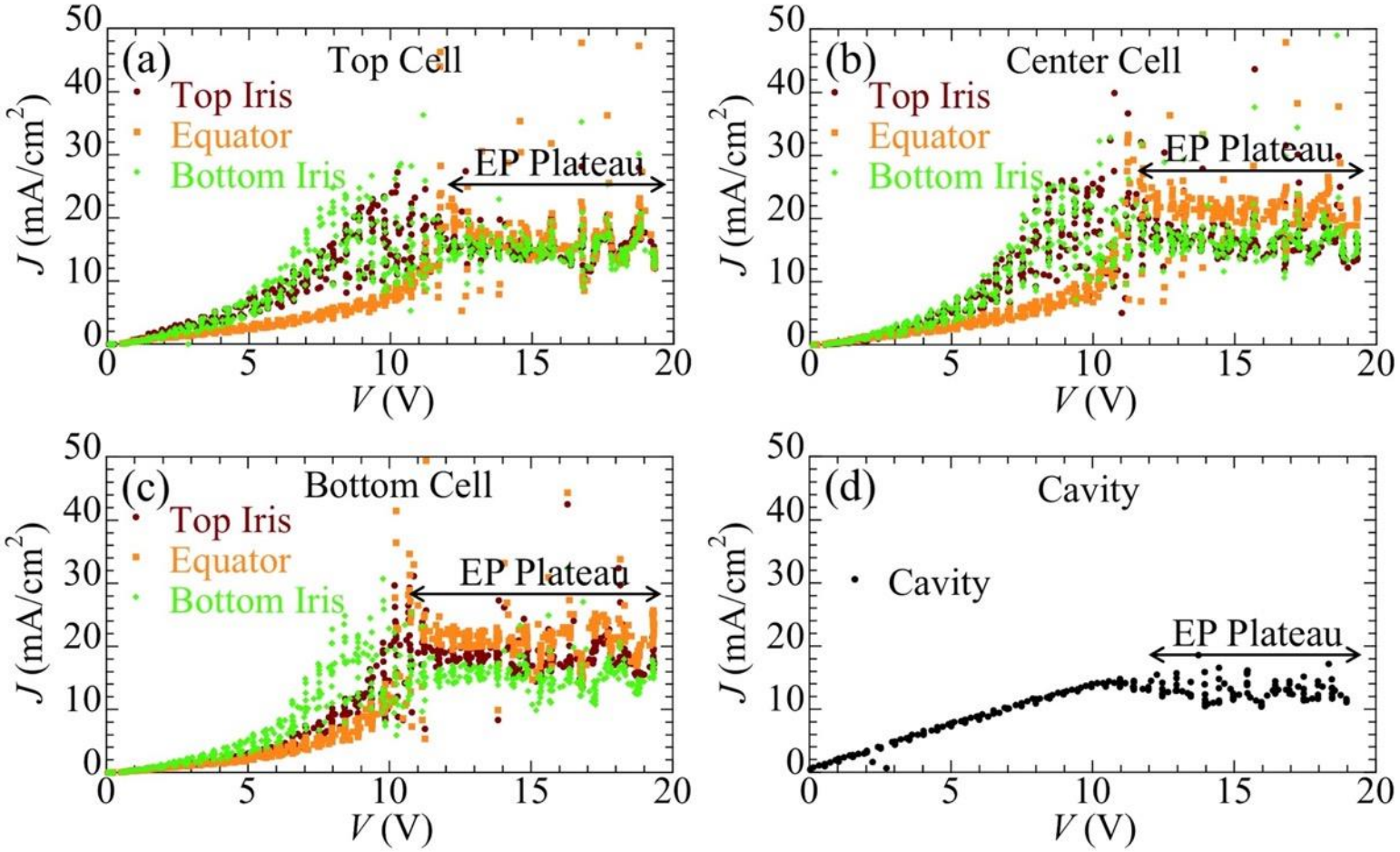




The optimized voltage can be chosen for a set cavity temperature.

J-V Curves under Optimized Conditions

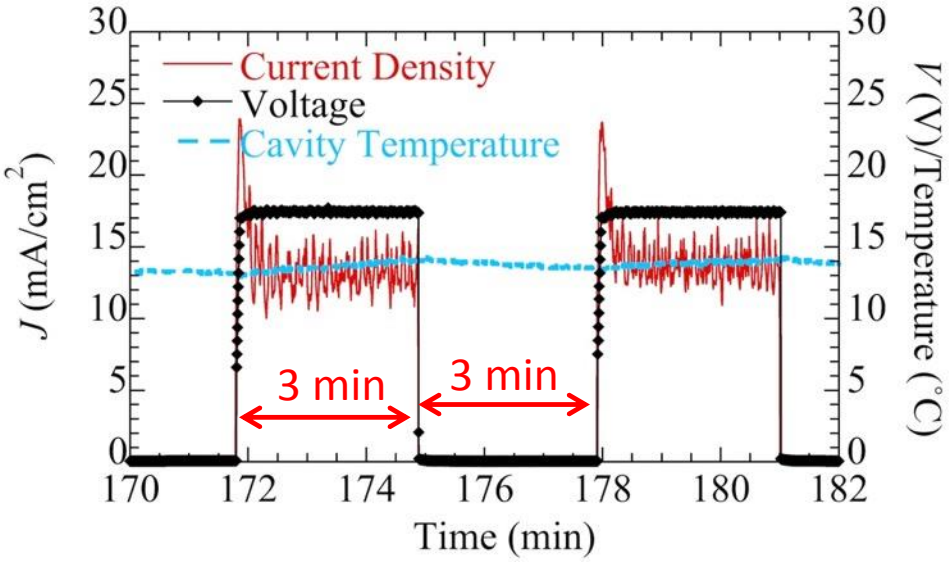
Polarization curves at ~15 ºC.



The EP plateaus are apparent for all the coupons and cavity.

VEP Conditions (Dual Flow)

Condition	Value
Acid flow type	Dual flow
Flow rate in cathode housing	10 L/min
Flow rate in cavity	5 L/min
Cathode Type	Ninja v-5
Cathode Rotation	20 rpm
Cavity Temperature	< 15 ºC
Voltage	17.5 V
Voltage-on/off period	3/3 min

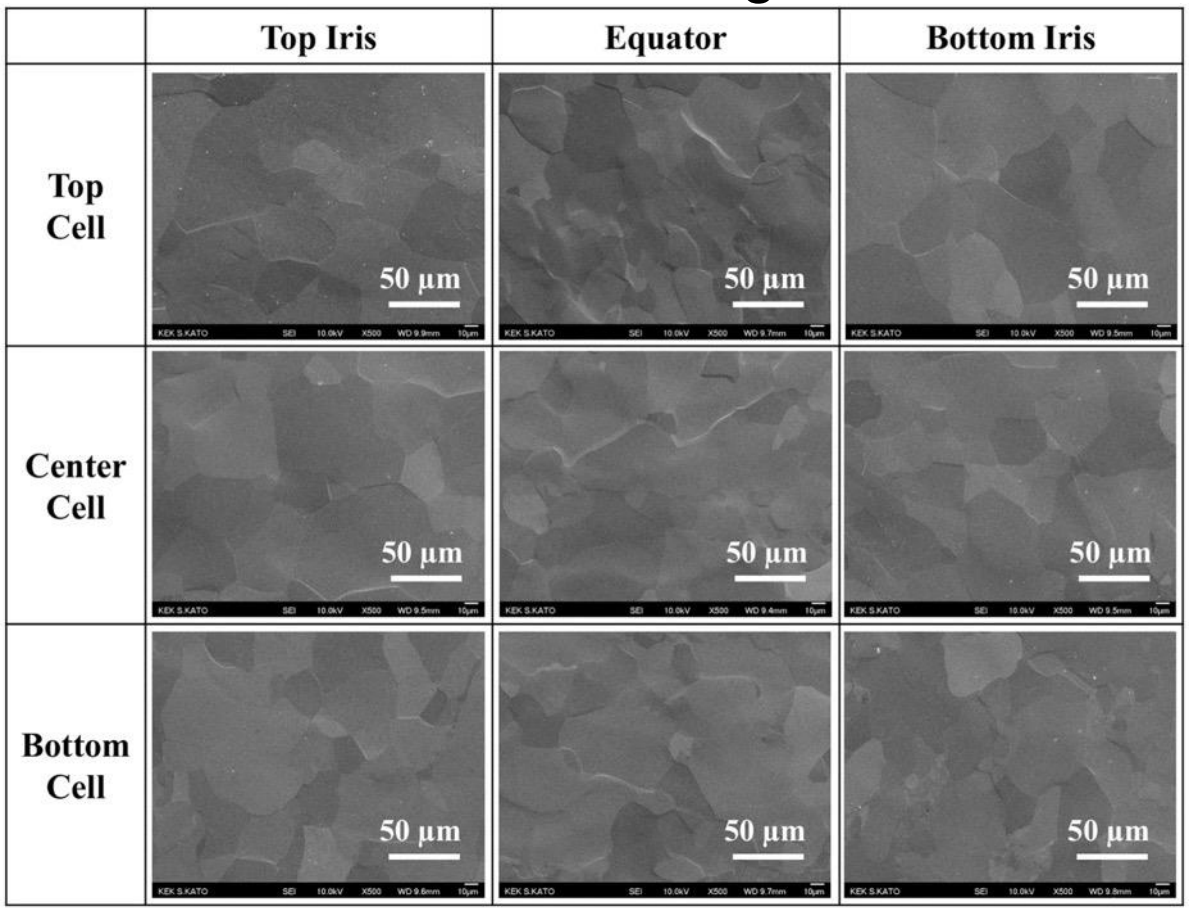


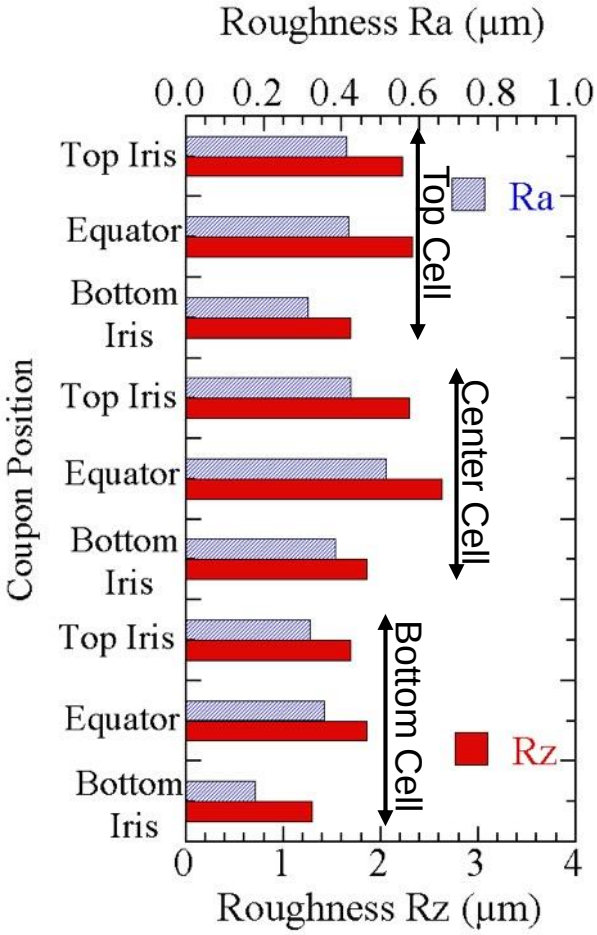
- On/Off voltage cycles were applied to reduce returning bubbles from the acid tank to the cavity.

Surface Morphologies

VEP was conducted for an average removal thickness of 25 µm.

SEM Images



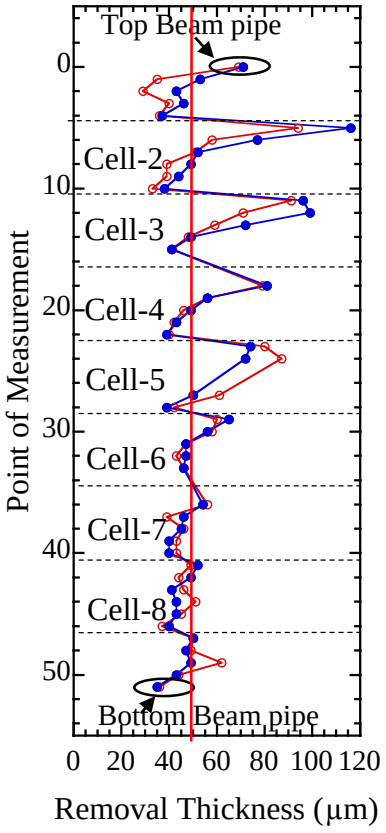


The coupon surfaces were smooth after VEP with the optimized conditions.

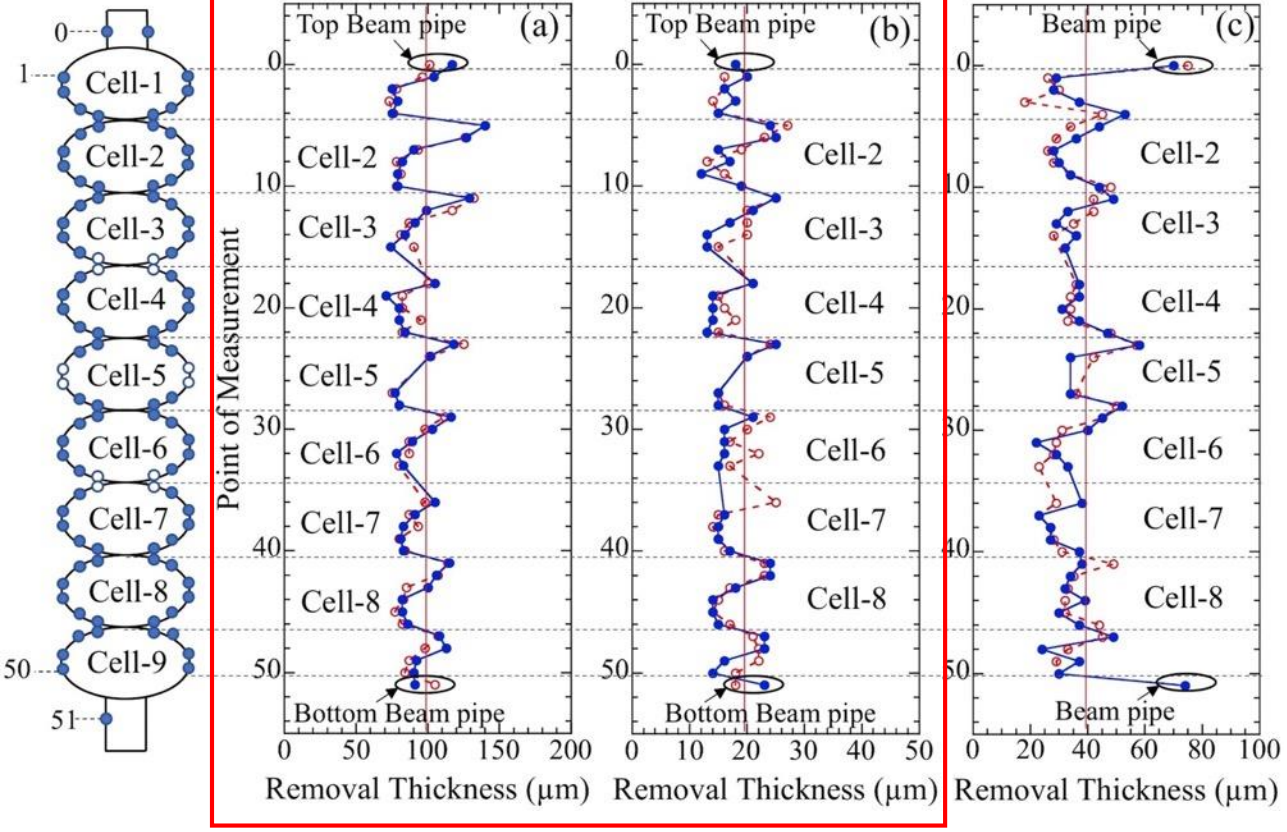
Bulk and Light Removal (Removal Trend)

Flow rate: Cathode housing-10L/min, Cavity-5L/min

VEP with Unoptimized Conditions



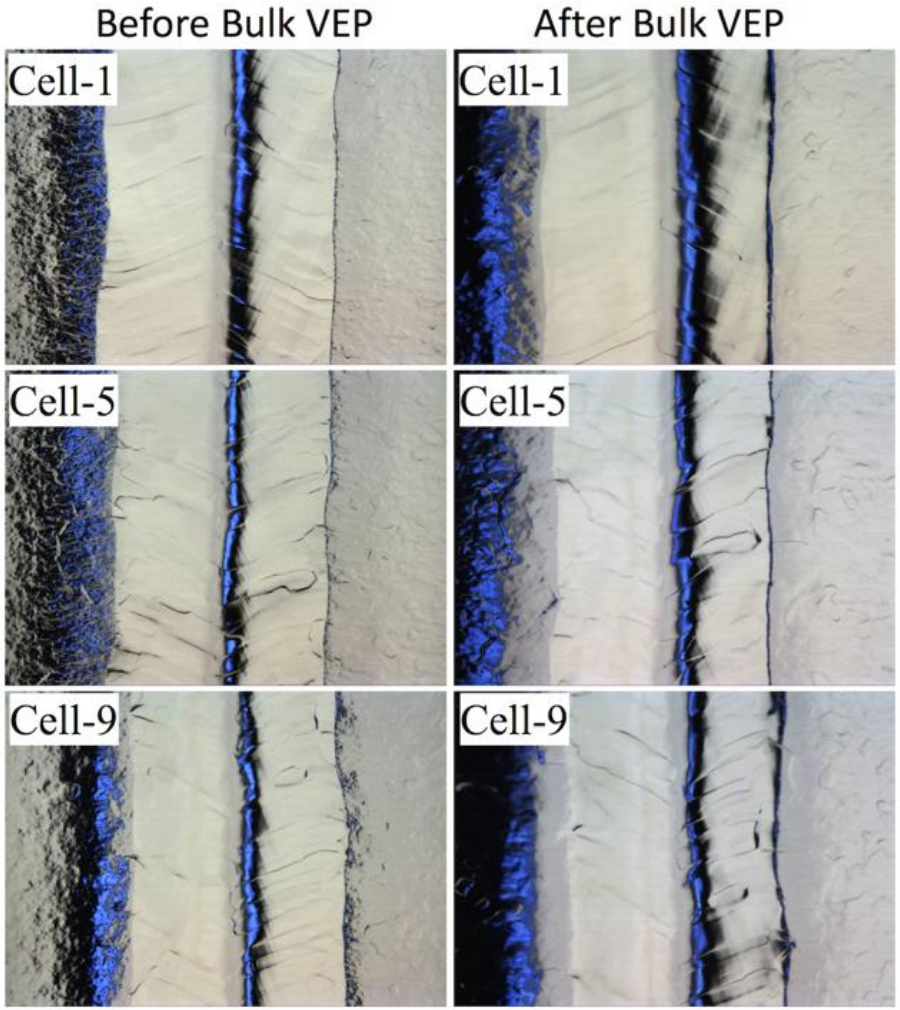
VEP with Optimized Conditions



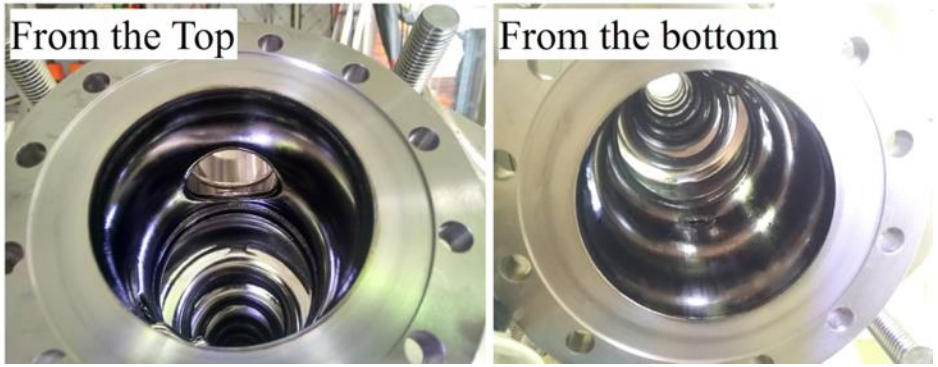
- Removal asymmetry significantly reduced.

Surface after Bulk Removal

Flow rate: Cathode housing-10L/min, Cavity-5L/min



12 mm x 9 mm



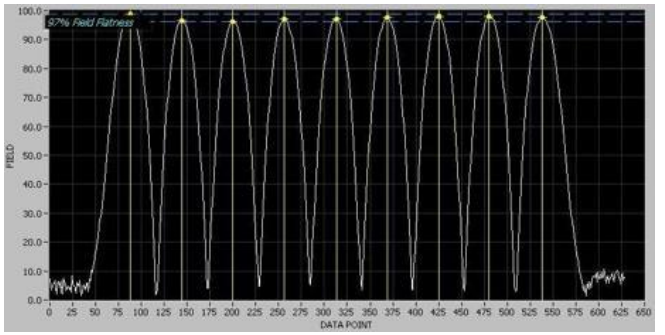
- Surface was smooth in all the cells.
- A pristine cavity can be processed with VEP.

Field Flatness

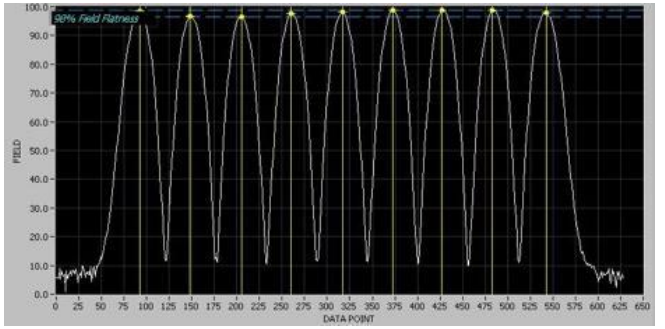
Field Flatness before and after VEP

VEP condition	Removal thickness (µm)	Field Flatness before VEP (%)	Field Flatness after VEP (%)
Unoptimized	51	91	67
Optimized	**100**	**95**	**91**
Optimized	**20**	**97**	**98**
Optimized	**10**	**99**	**99**

Field Flatness before VEP (20 µm)



Field Flatness after VEP (20 µm)



- Degradation in the field flatness after bulk removal is similar as observed after HEP.
- No degradation in the field flatness after 10 and 20 µm removal.

SRF Performance (Nine-Cell Cavity)

Horizontal EP (baseline RF test)

VEP for 100 μm

750ºC bake

VEP for 20 μm

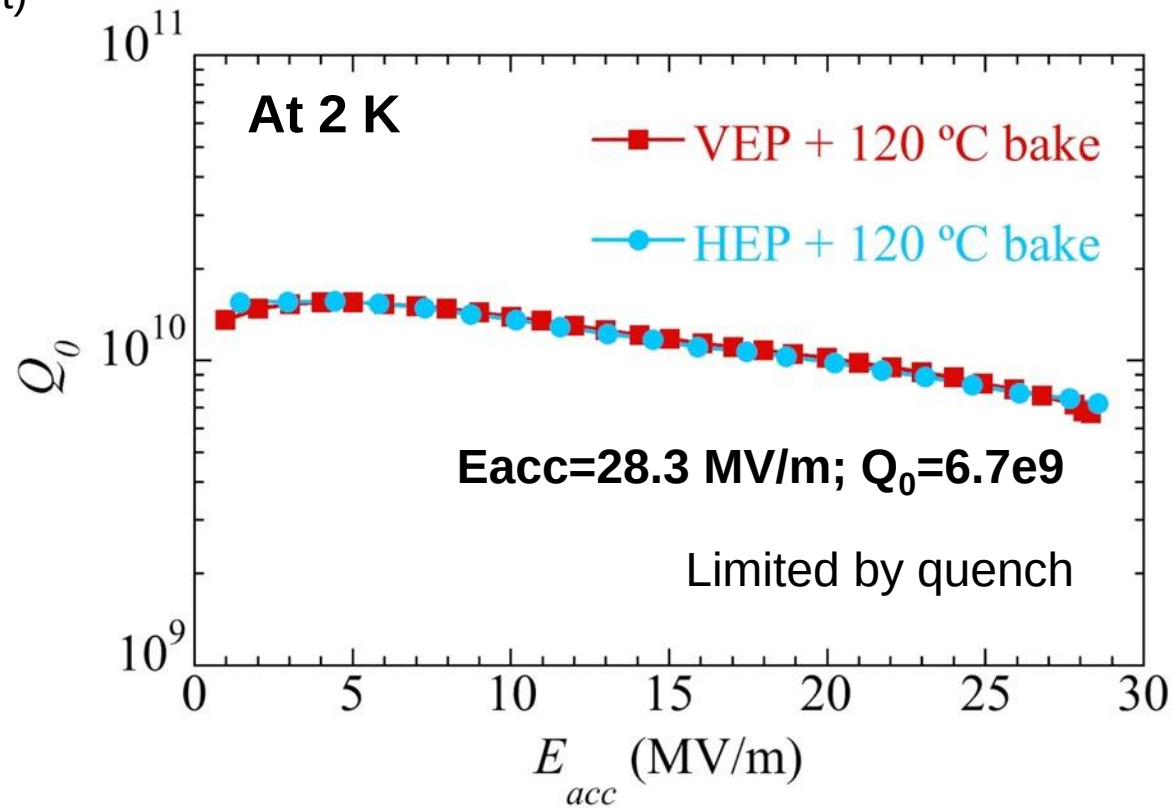
750ºC bake

Field Flatness Tuning (99%)

VEP for 10 μm and 120ºC

RF Test

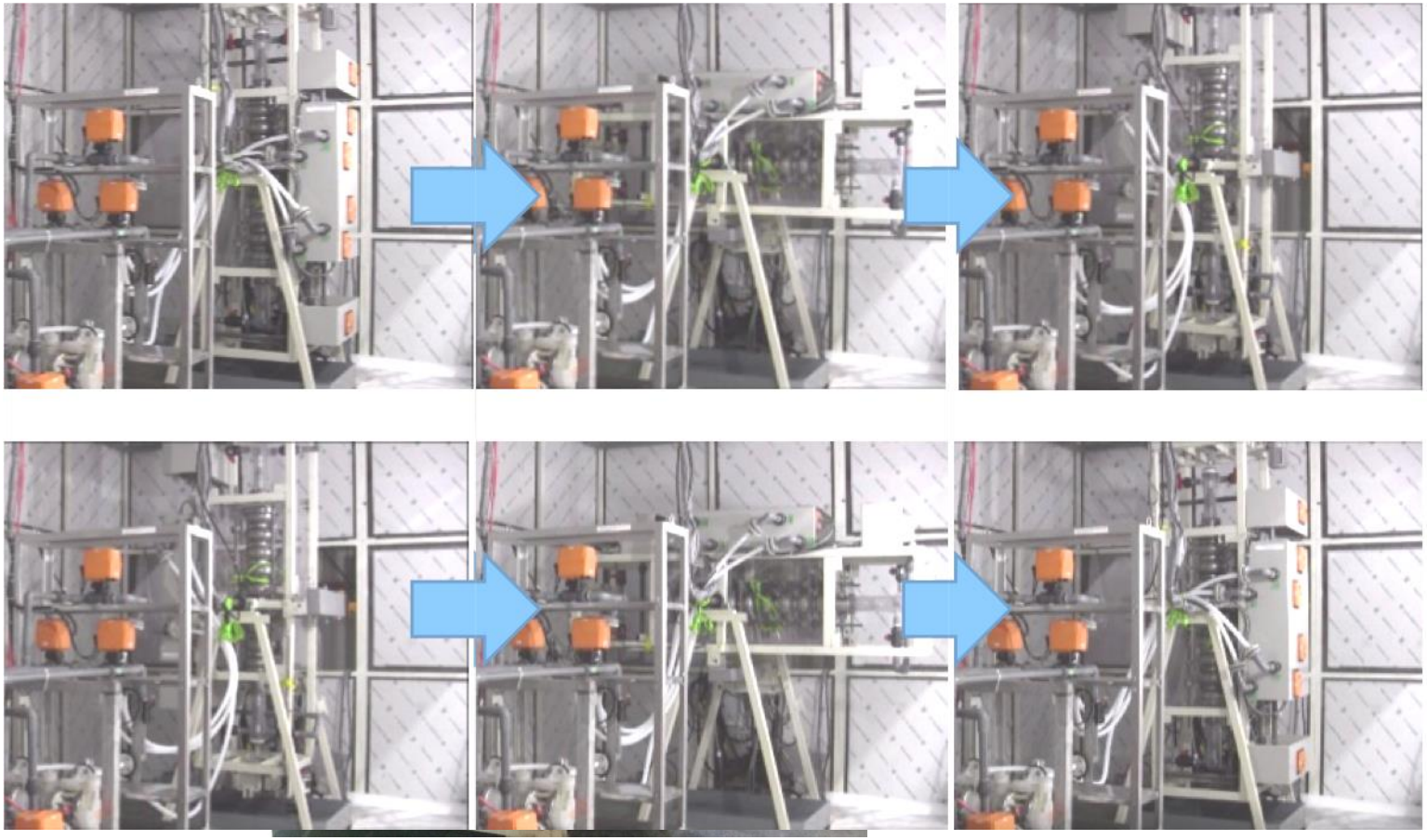
Field Flatness: 99%



The SRF performance after the HEP and VEP was the same.

Flipping System for VEP

- We are also working on another method to improve the removal uniformity.

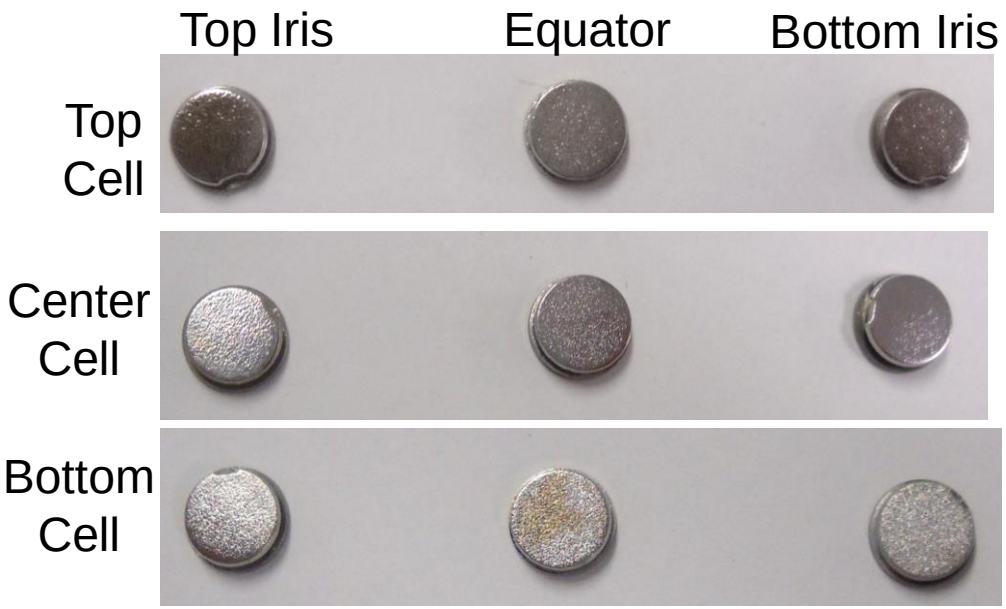


The cavity is flipped upside down periodically.

Preliminary Result of VEP with Flipping System

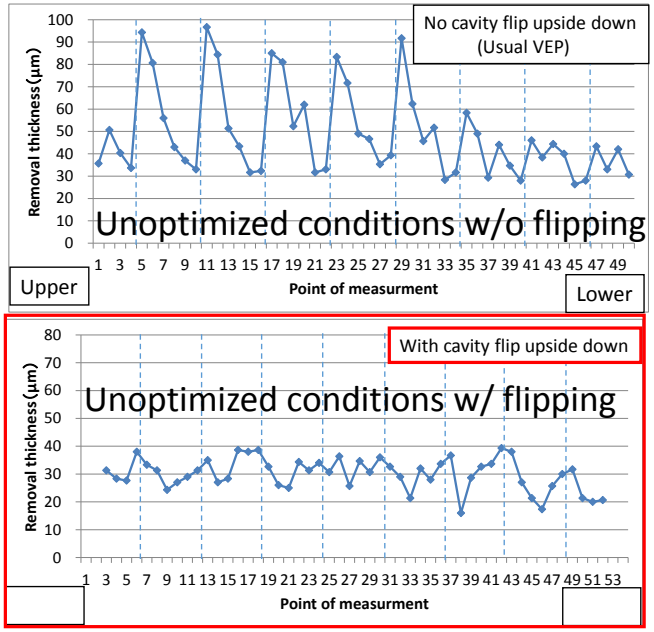
Condition	Value
Voltage	14 V
Acid flow rate	5–10 L/min
Cathode	Ninja Cathode (metal wings)
Cathode Rotation	20 rpm
Cavity Temperature	20–30 ºC
Flipping frequency	Flipped every 20 min of EP

Coupon surface



Surface is rough. Parameter optimization is necessary.

Removal Trend



Uniformity is significantly better.

Summary and Future Work

- The VEP process was successfully optimized with the single-cell coupon cavity. The optimized parameters and cathode yield desired surface and removal uniformity.
- A single-cell cavity showed good and the same SRF performance after HEP and VEP. The field gradient reached 32 MV/m at Q_0=8e9.
- A parametric study was conducted with the 9-cell coupon cavity. A novel dual flow method was developed and VEP parameters were optimized. The asymmetry was significantly reduced and smooth surface was attained for the 9-cell cavity as well.
- The 9-cell cavity after bulk removal with VEP showed a good SRF performance (E=28.3 MV/m; Q_0= 6.7e9). The performance is the same as the baseline performance.
- The VEP parameters for 9-cell cavity will be further tuned to improve removal uniformity.
- VEP is planned with a bigger acid tank that could avoid circulation of bubbles from the tank to the cavity. Parameters will be optimized for the VEP with flipping method.

Acknowledgement

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&

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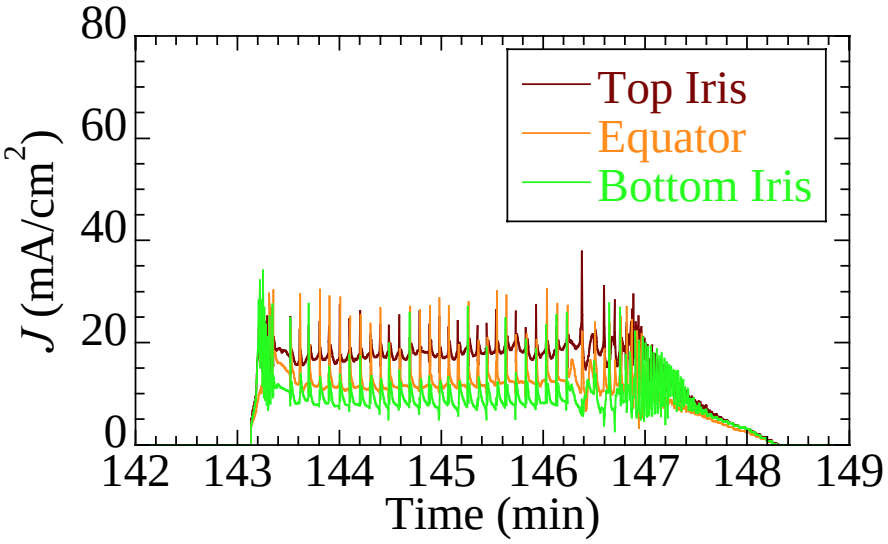
Thank You

Backup Slides

Effect of Dual-Flow Method

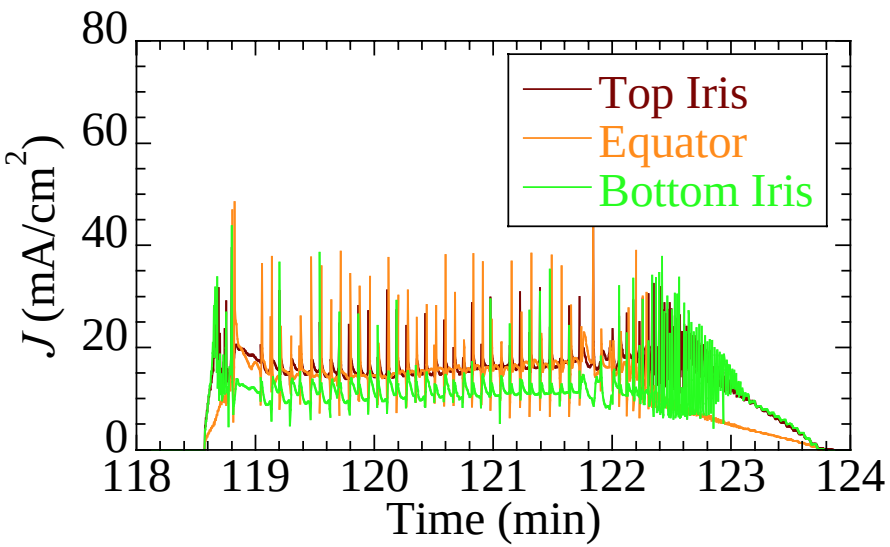
Coupon currents for the top cell with no cathode rotation

No Intentional Flow in Cathode Housing



Total Flow Rate: 15 L/min

Optimized Dual Flow



Total Flow Rate: 15 L/min (Cavity-5L/min ; Cathode Housing-10 L/min)

The difference in the current was higher when no intentional flow was applied in the cathode housing.