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PIP-II 2nd Technical Workshop, WG#2

EP and HPR Parameter Study Including Motivation

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Fermi National Accelerator Laboratory

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A Partnership of:
- US/DOE
- India/DAE
- Italy/INFN
- UK/STFC-UKRI
- France/CEA, CNRS/IN2P3
- Poland/WUST

Introduction

- High- and low-beta 650 MHz cavities, required for prototype cryomodule and finally in PIP II accelerator, are electropolished for surface processing.
- The setup available at ANL is used for electropolishing (EP) of both types of cavities.

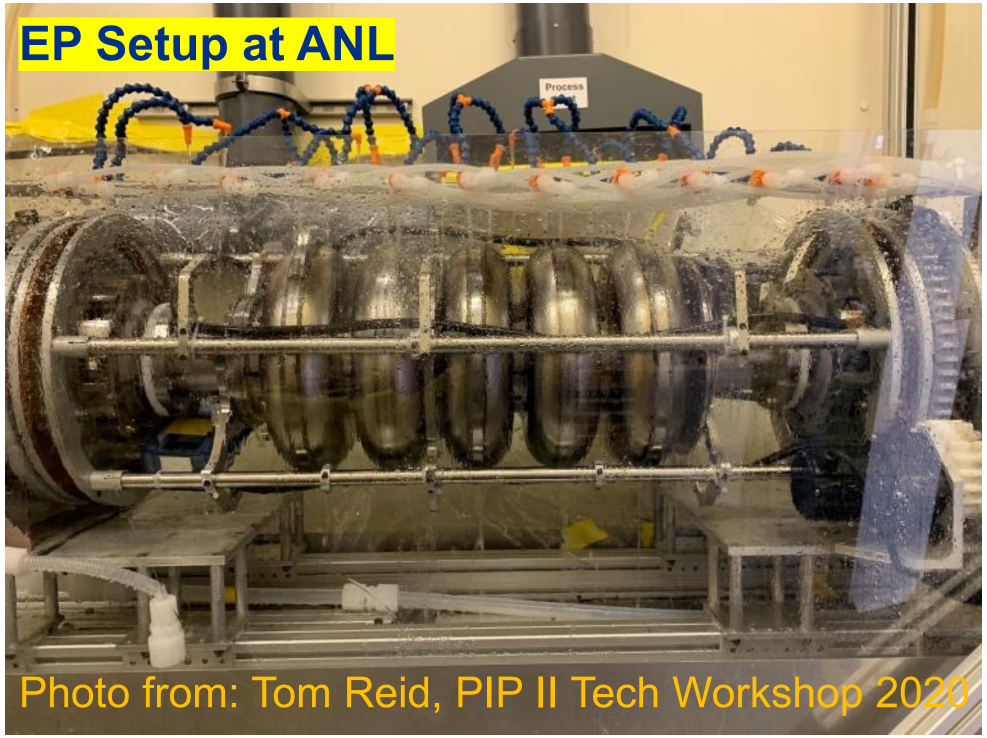
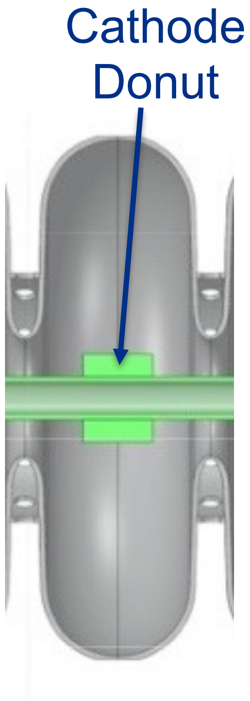


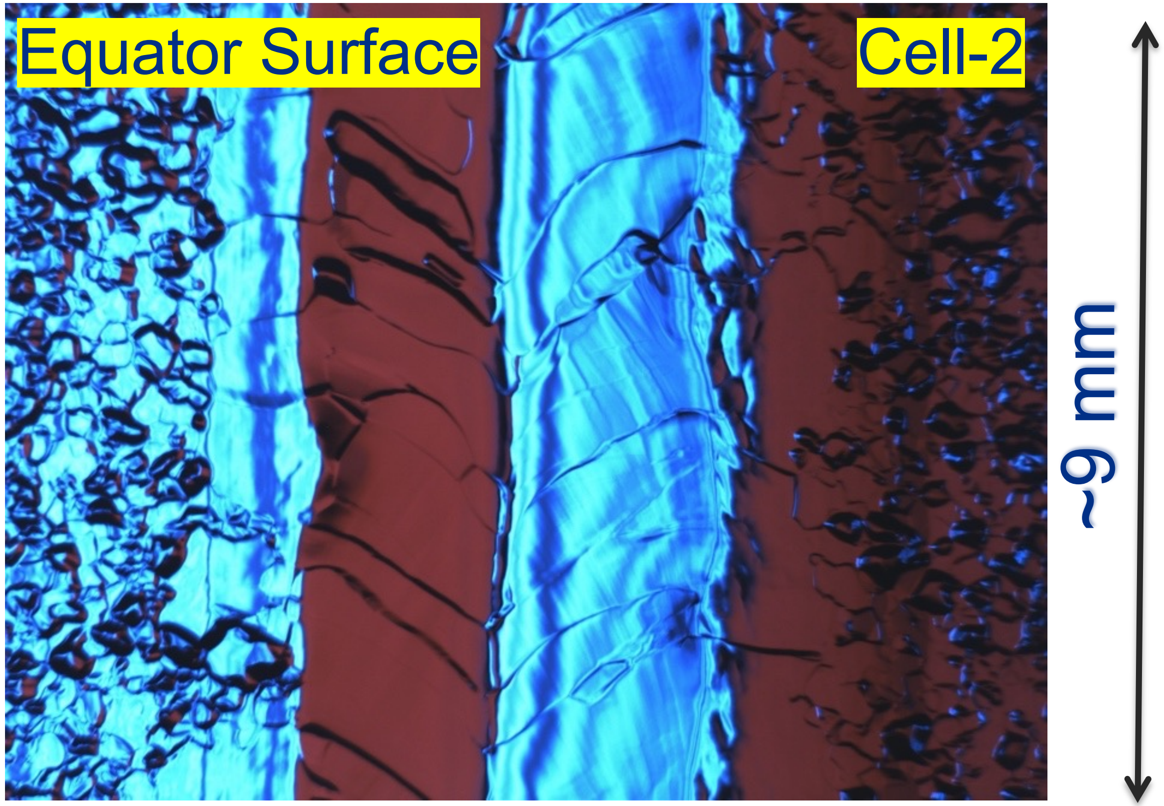
Photo from: Tom Reid, PIP II Tech Workshop 2020



Parameters	Values
Voltage	18 V
Cavity temperature	22 °C (bulk), 9-13 °C (light)
Acid flow	< 2 GPM
Cathode type	Cathode pipe + Donuts
EP rate	0.14 µm/min (bulk): 0.08 µm/min (light, cold)

Motivation of EP Study

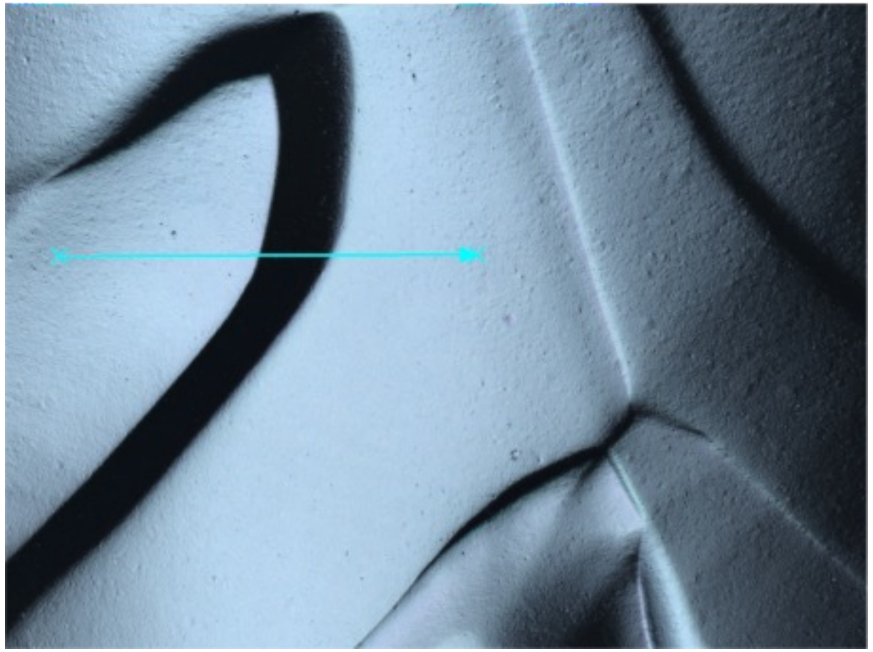
- Recent result: A low-beta 5-cell 650 MHz cavity (B61C-EZ-103) quenched at ~17 MV/m after the surface treatment (bulk EP + post N-dope EP).
- The cavity surface was inspected with an optical camera to find any surface defect that caused quench at the low field.

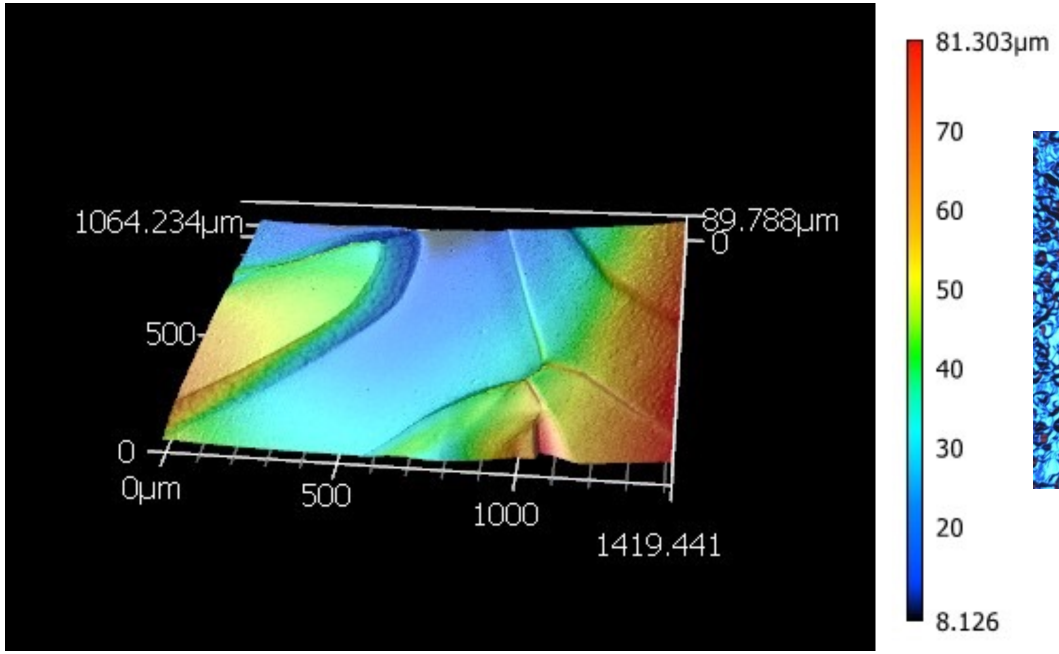


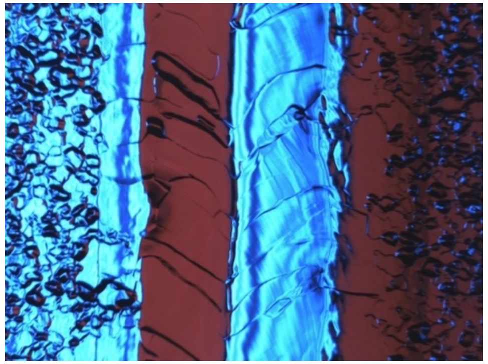
Bulk EP (~150 μm at 18V, 22 °C)
10 μm at 18V, 12 °C
N-doping + 7 μm EP at 18V, 12 °C

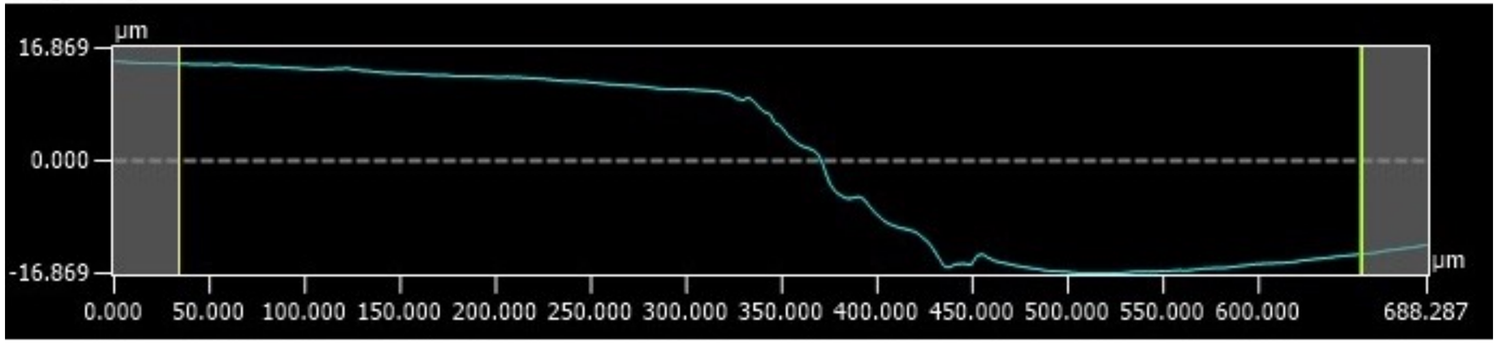
The surface appeared rough and etched like a BCP surface.

Replica Images and Surface Profile (Weld position)

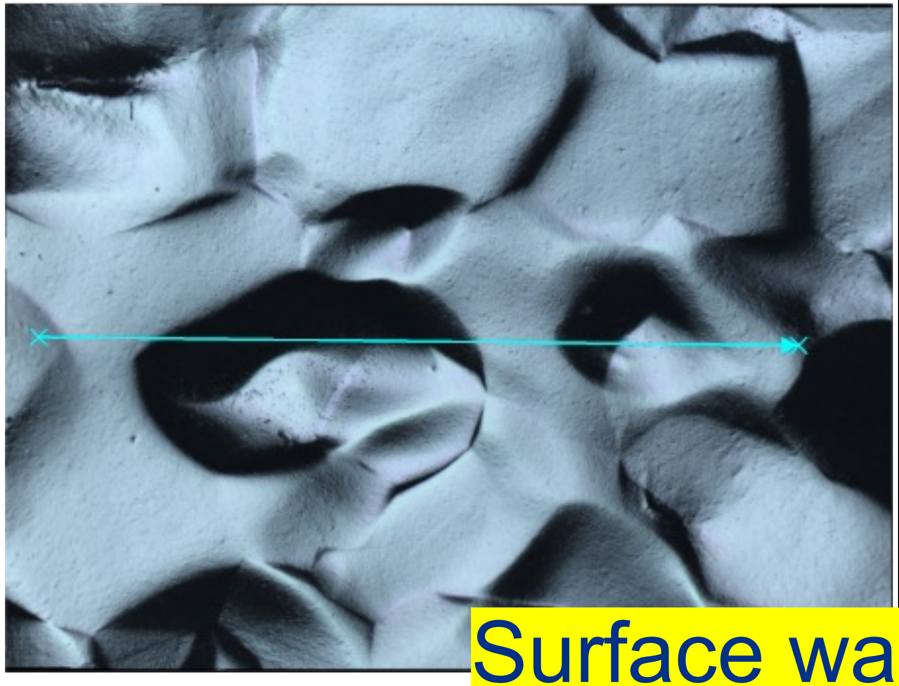


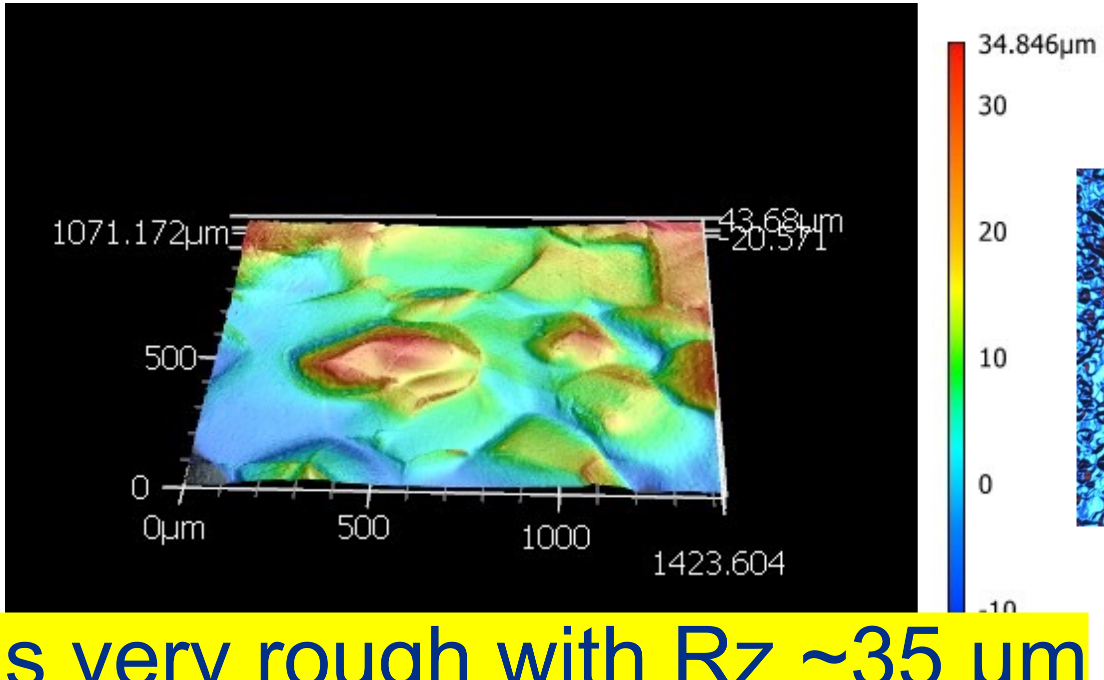


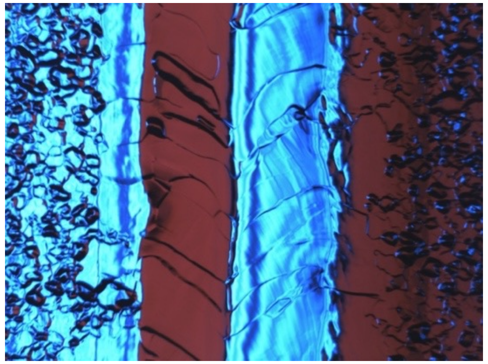




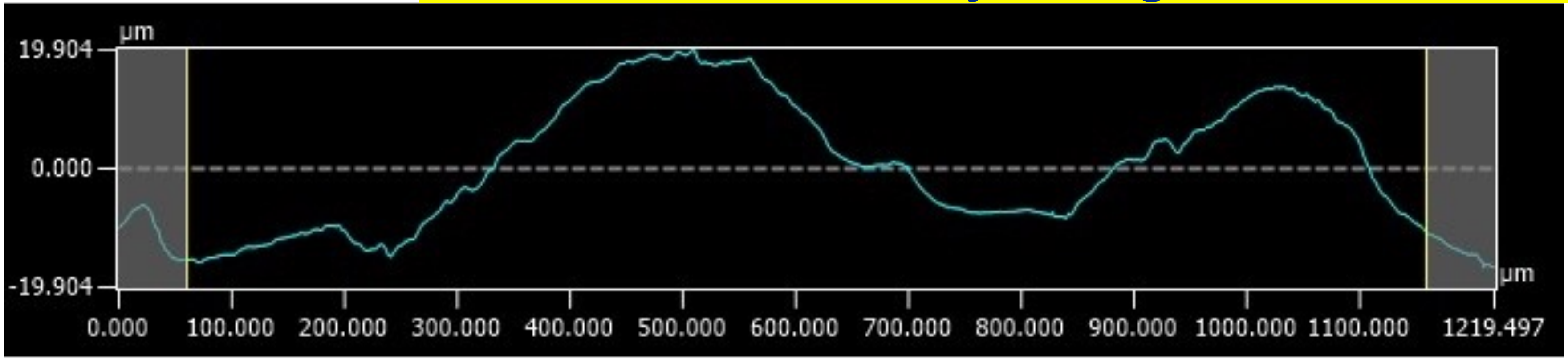
Replica Images and Surface Profile (Near-weld position)



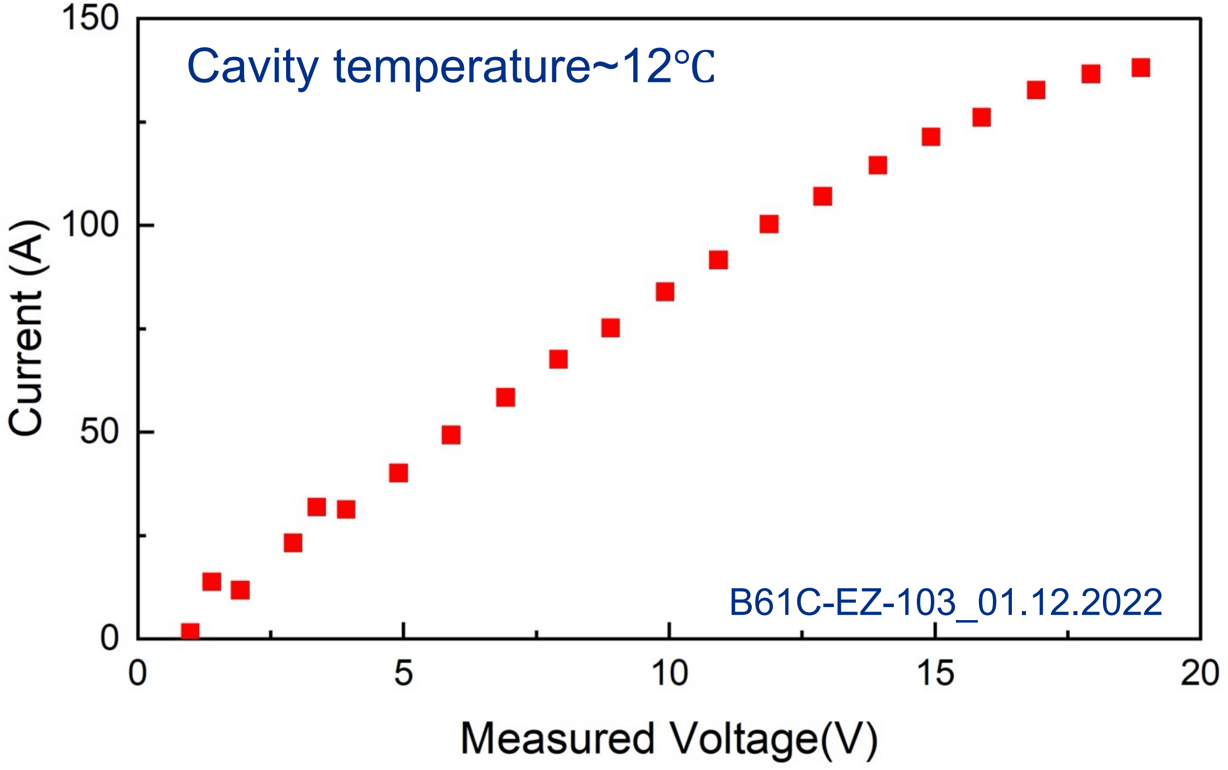




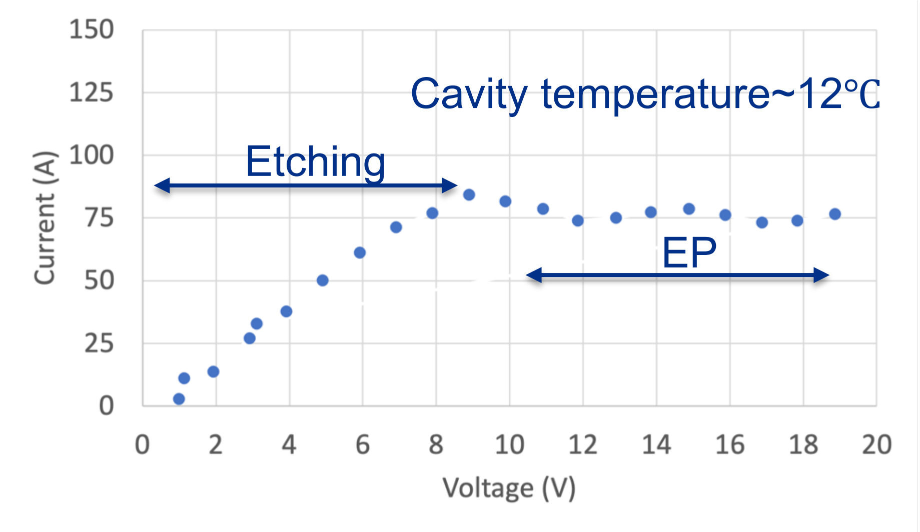
Surface was very rough with Rz ~35 µm



I-V Curve (B61C-EZ-103)

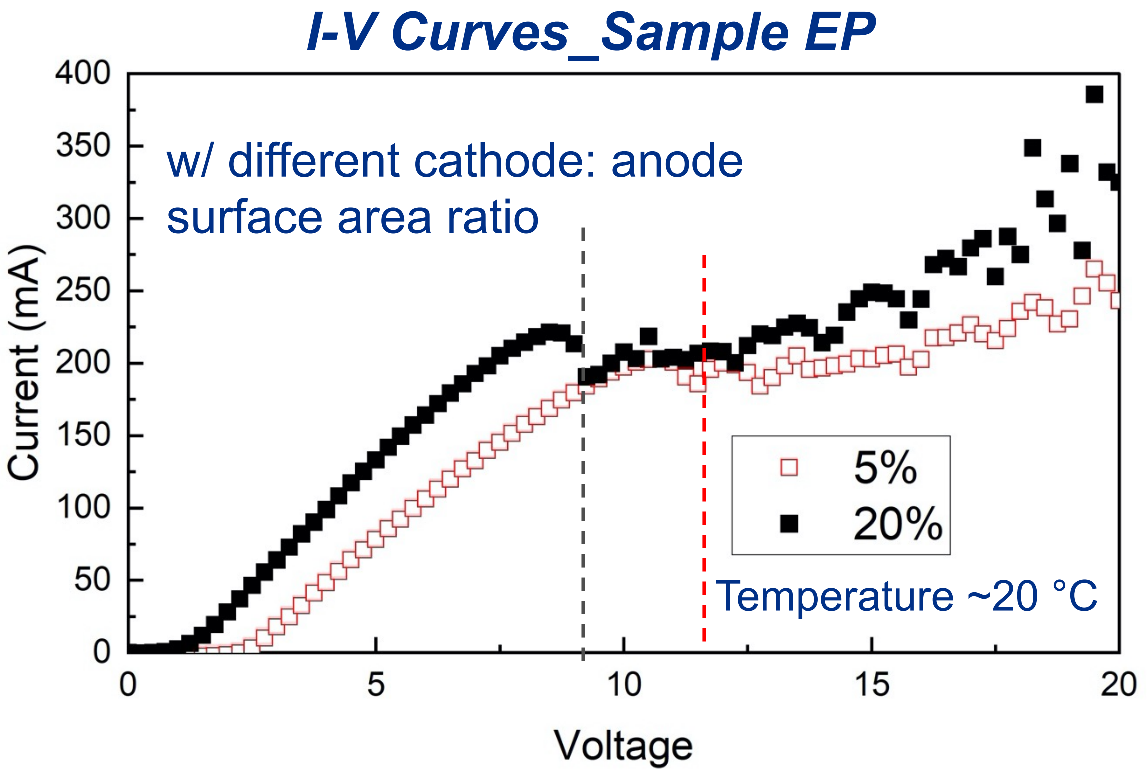


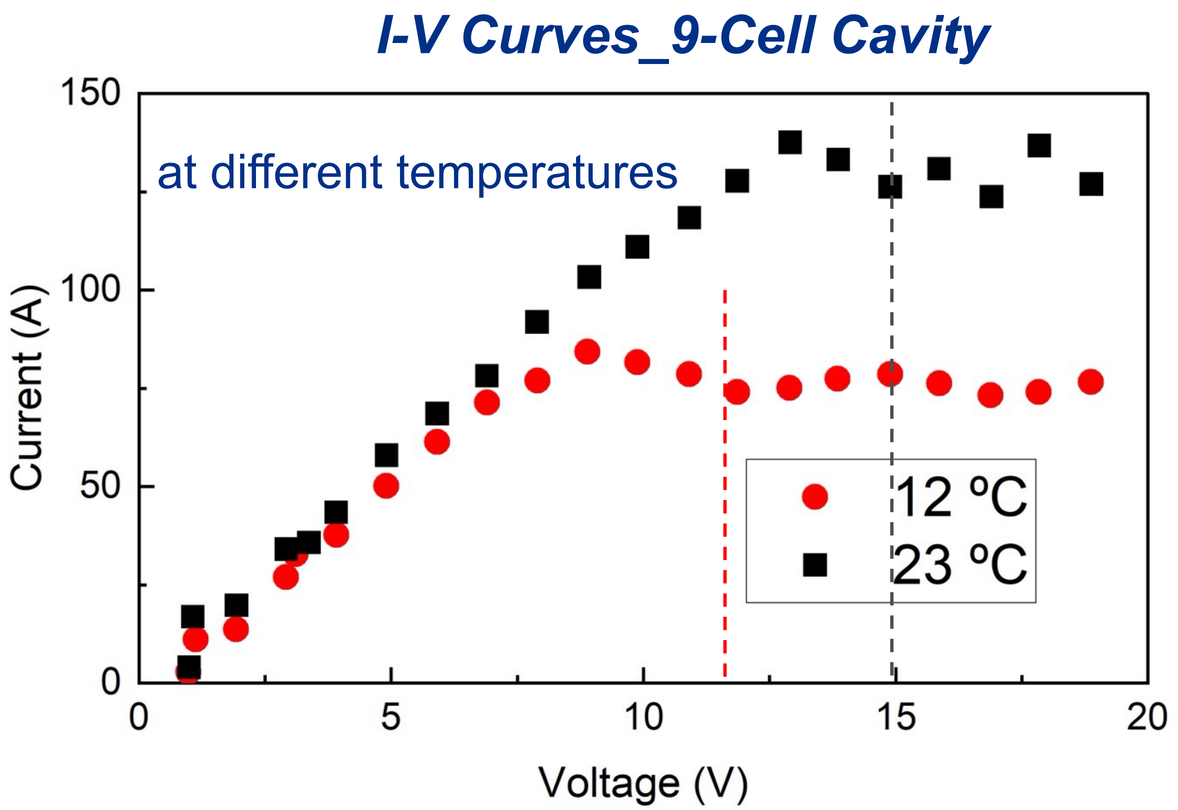
Typical I-V curve (1.3 GHz 9-cell Cavity)



- The I-V curve was linear with no plateau region which is necessary for the EP process. The removal in linear region yields a rough surface.
- The linear I-V trend was observed for both LB650 and HB650 cavities under the standard EP parameters.

Lesson from EP Results of Samples and 1.3 GHz 9-Cell Cavity

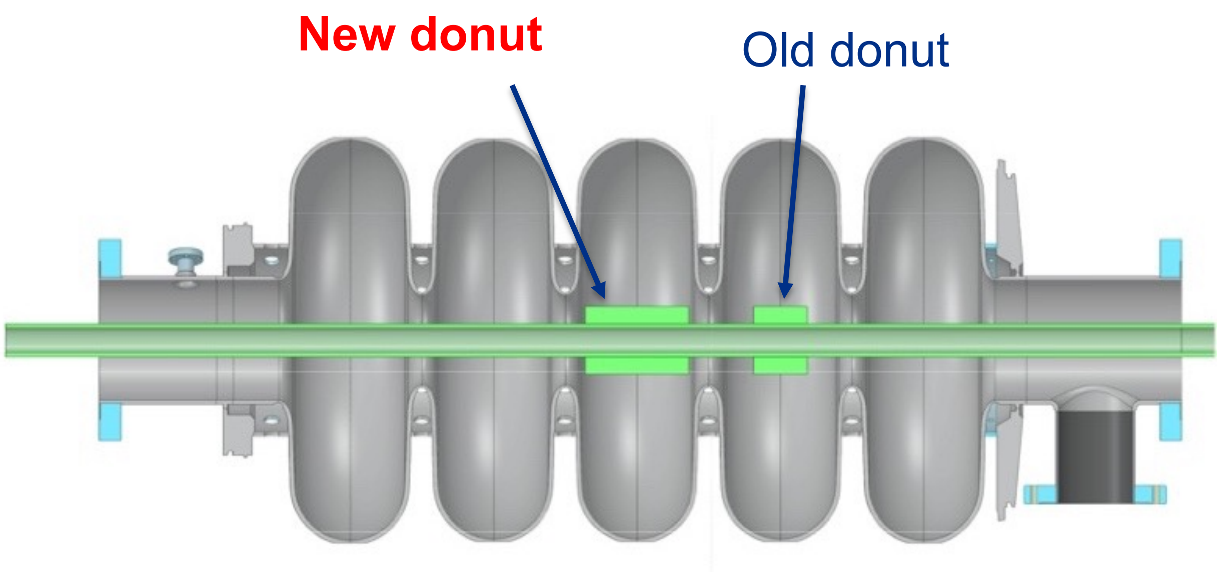




- **Cathode surface area**:
- **Cavity temperature**:

} Both affect the onset voltage for EP.

Improvement on Hardware

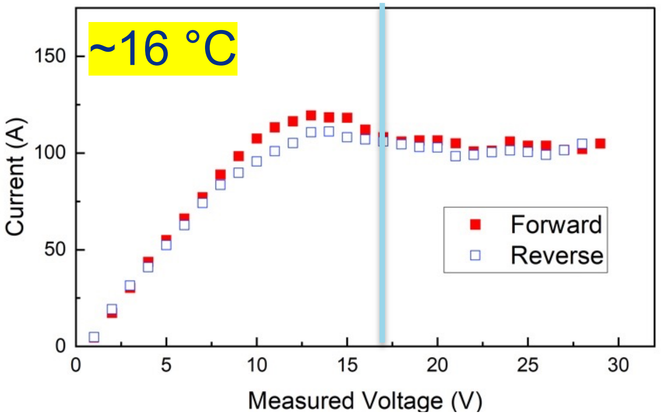


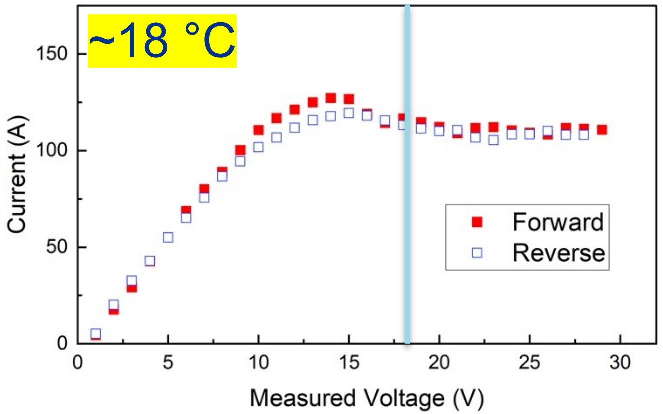
- The cathode surface area was enhanced by making the donut longer.

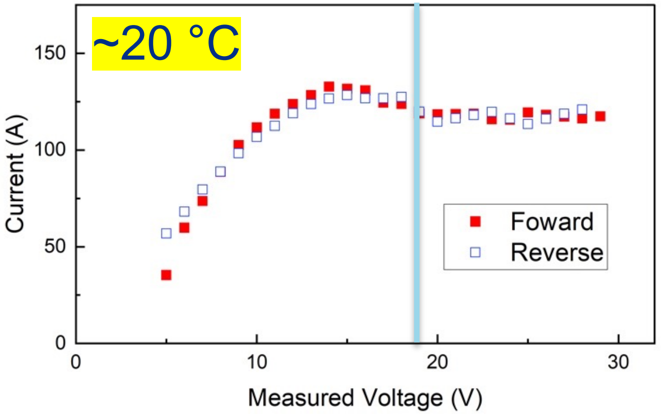
- A higher voltage power supply (30V x 210A) was used.
- Cavity cooling control was improved: 10 kW chiller was replaced with 15 kW.

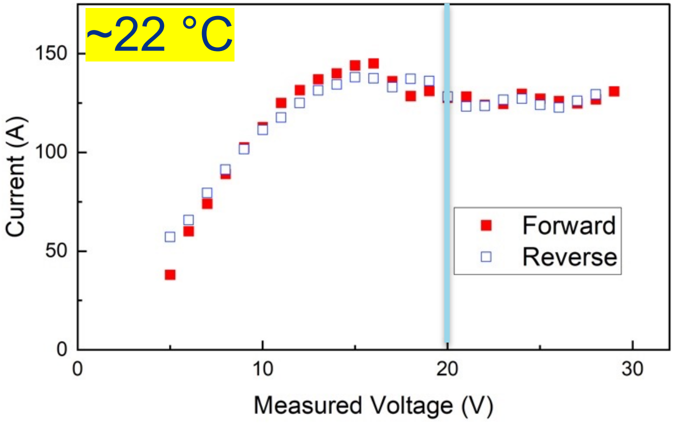
I-V Curves with New Cathode (Cavity: B61C-EZ-104)

12 data points (12 sec) /volt, average of the last 4 points

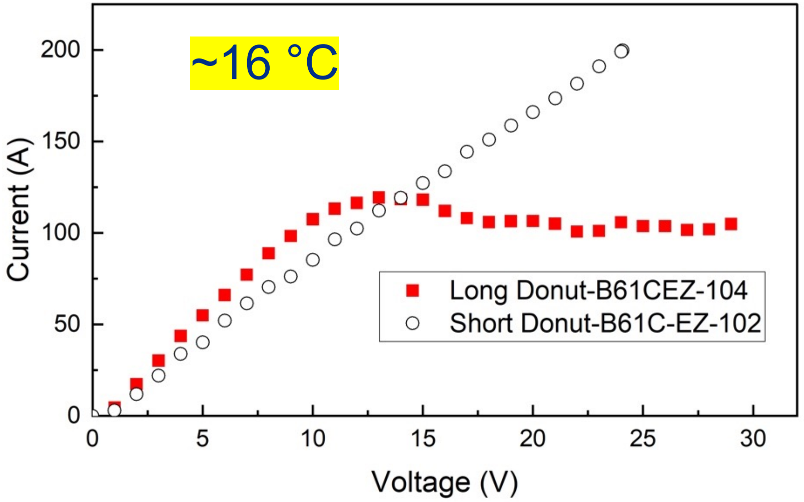






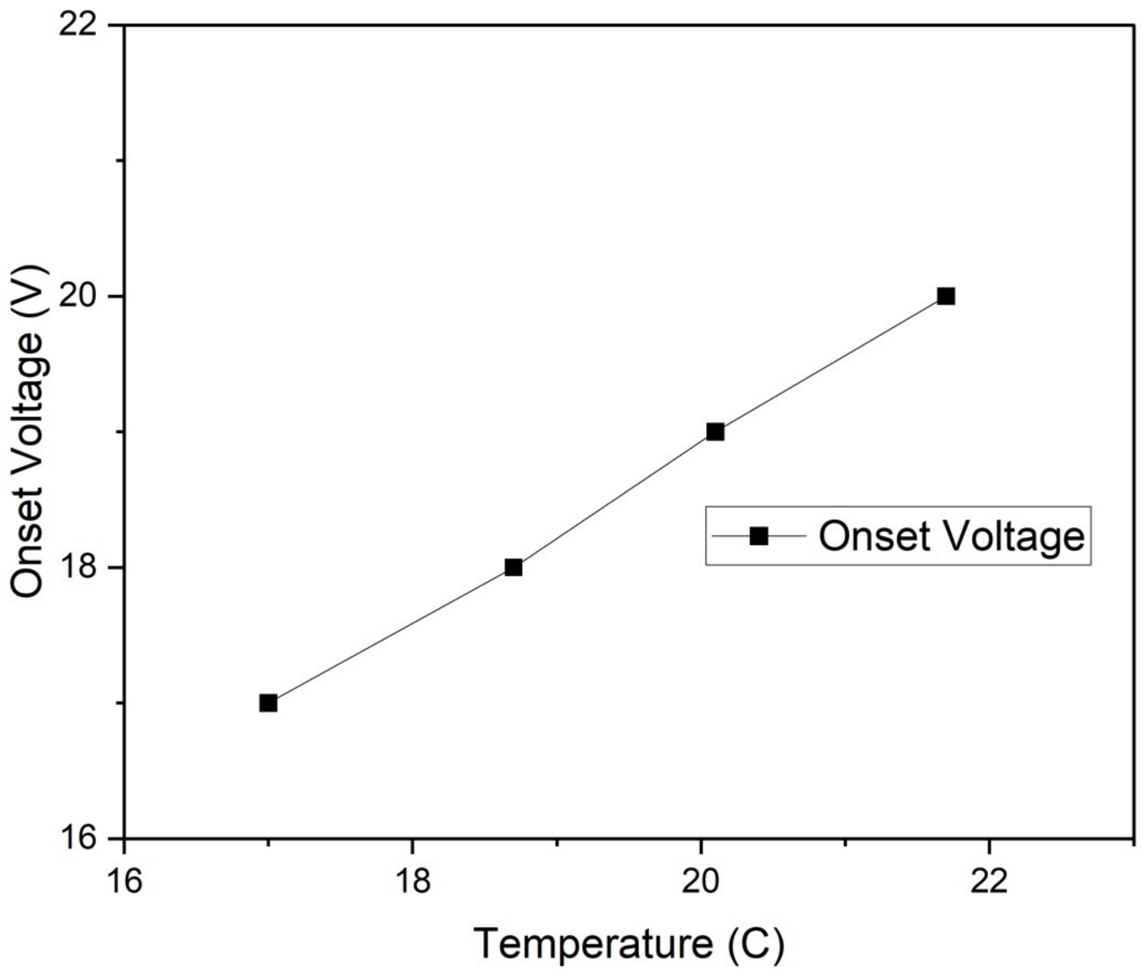


Comparison with Old Cathode



No hysteresis in forward and reverse I-V curves: Suggests 12 seconds per volt was enough to make the chemistry stable on the surface.

Onset Voltage and Cavity Temperature



- The onset voltage increases linearly with the cavity temperature.
- To conduct bulk EP at a temperature of ~22 °C, a voltage higher than 20 V is required.

The standard 18 V is not enough to electropolish the equator surface.

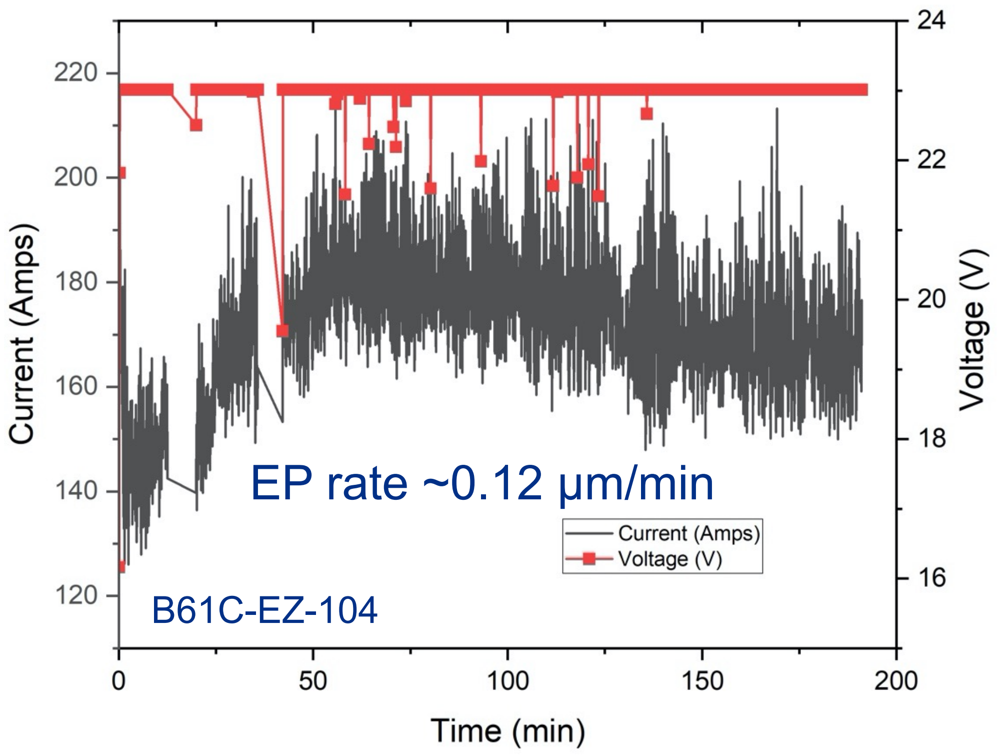
Modified Conditions for EP

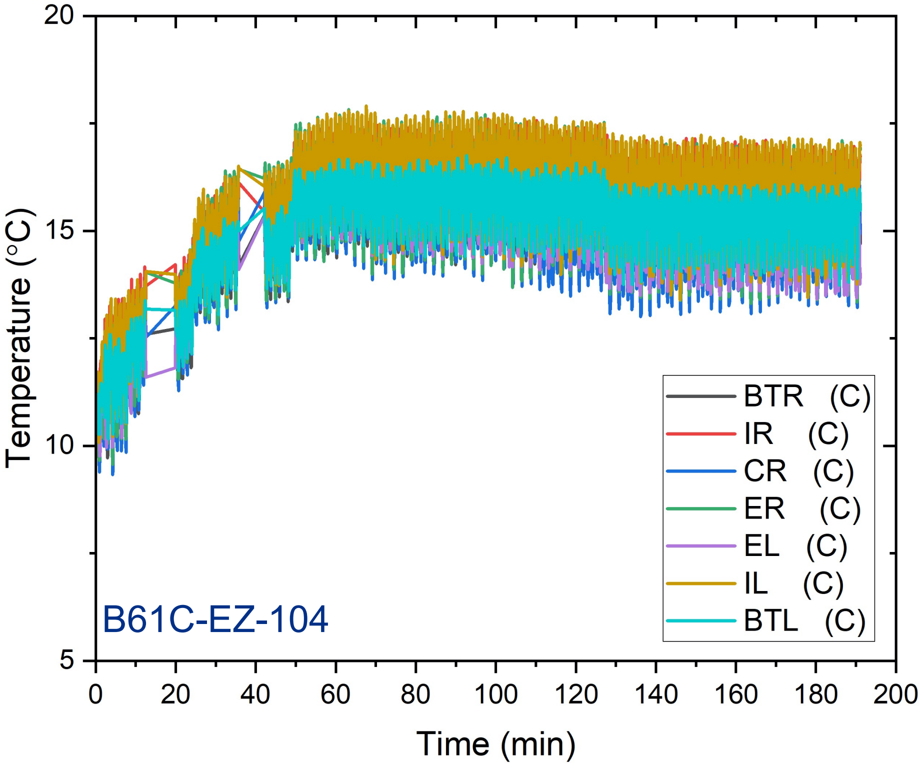
Standard and modified EP Parameters

Parameters	Standard Values	Modified Values
Voltage	18 V	**23 V**
Cavity temperature	22 °C (bulk), ~13 °C (light)	Target~22 °C
Acid flow	< 2 GPM	< 2 GPM
Cathode type	Cathode pipe + donuts	**Cathode pipe + longer donuts**

- The cavity B61C-EZ-104 was electropolished with the modified conditions.

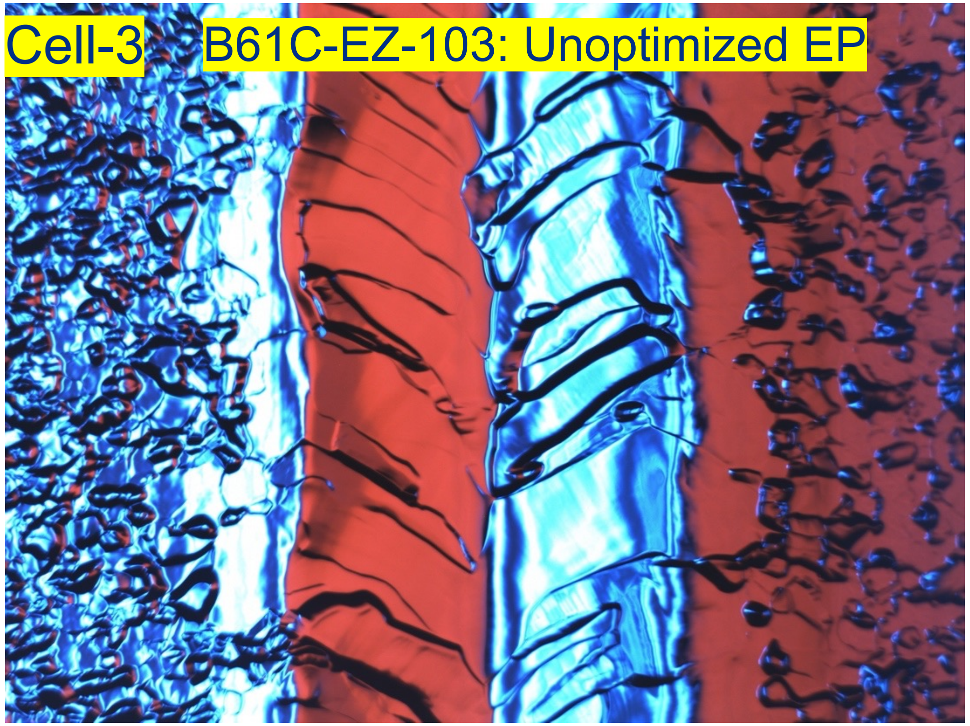
Current and Temperature Profiles

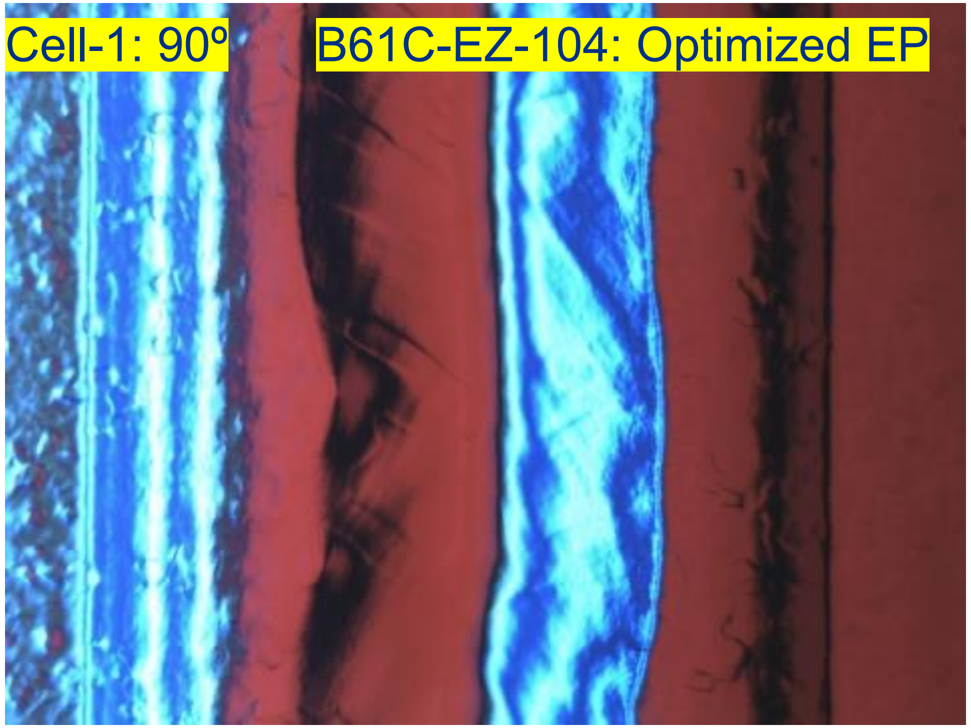




- Current oscillations were seen with fresh acid and optimized EP conditions. No current oscillation was observed in the unoptimized-EP case.
- The cavity temperature was intentionally kept ~17 °C (lower than standard temperature for bulk EP) to maintain the current lower than 210 A (the rated current of the temporary power supply).

Surface after Optimized EP





Bulk EP (~140 µm at 18V, 22 °C + 10 µm at 18V, 12 °C)
N-doping + 7 µm EP at 18V, 12 °C

Bulk EP (~120 µm at 23 V, 16–22 °C)

Surface is smooth like 1.3 GHz cavity surface, no pits on iris, mirror finish on beam tube

Motivation/Goal of HPR Study

- We are consistently observing field emission from 650 MHz cavities.
- The goal of this study is to understand the effect of HPR parameters on surface cleaning/removal of particles from the surface.
- Since 650 MHz cavities are larger in size and surface area than the 1.3 GHz cavities, optimization of HPR parameters is necessary.
- HPR parameters includes
  - Type of nozzle
  - Nozzle-wall distance
  - Spray-wall angle
  - Operating pressure
  - Rinsing time

Finally decides static pressure on the rinsing wall (first four parameters)

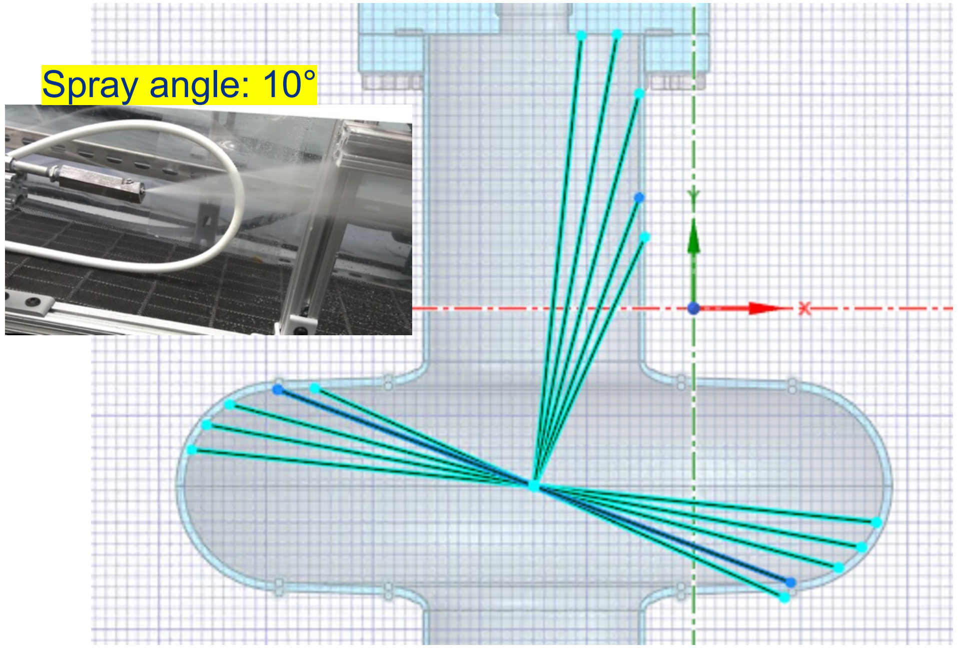
HPR Tool for 650 MHz Cavity at Fermilab

Initial Spray head w/ nozzles

This study is focused on solving field emission issue in 650 MHz cavities.

Initial Spray Head

Spray angle: 10°



1.3 GHz Cavity

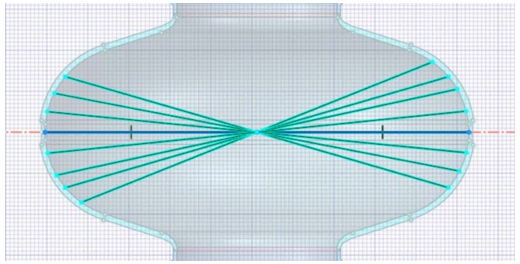
Spray head w/ big nozzles

Spray angle: 40°

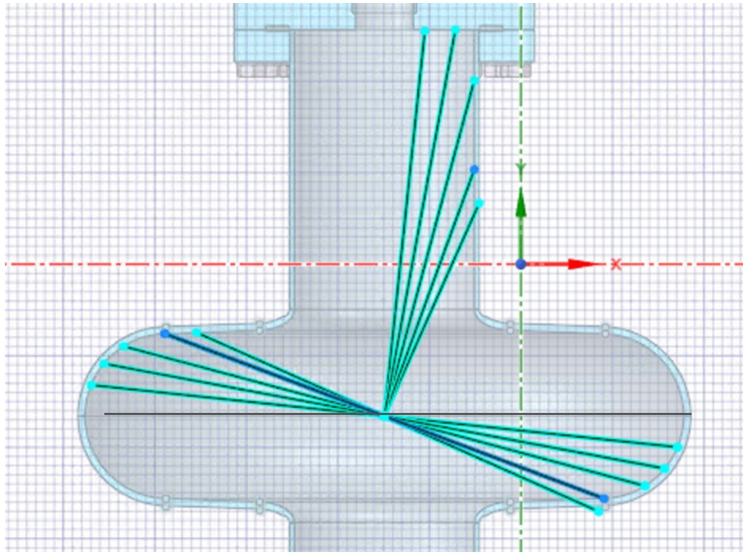
HPR Parameters

Conditions	1.3 GHz	650 MHz (Current Conditions)
Spray angle (nozzle type)	40° (big type)	10° (small type)
Nozzle inclination angle*	0°	15°
Spray-head rotation	4 rpm	4 rpm
Cavity movement	5 mm/min	5 mm/min
Number of passes	5	3+5
Estimated Spray Force	~9 N @ 1250 PSI	~9 N @ 1250 PSI

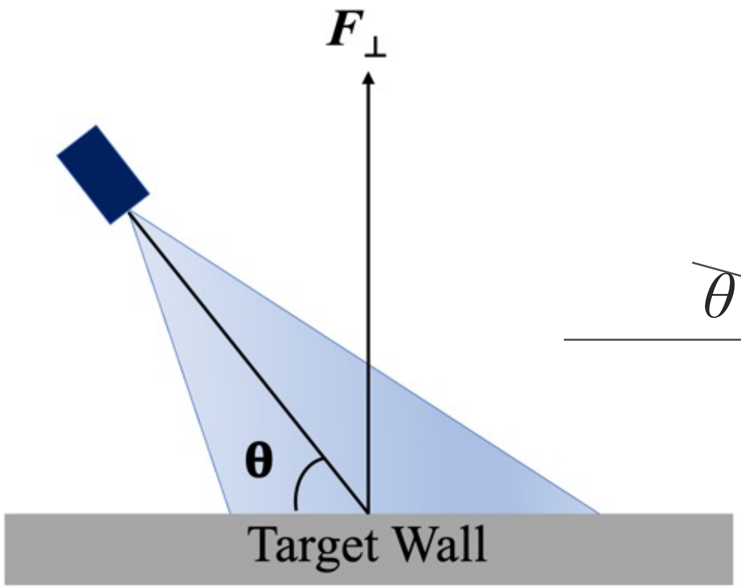
Spray on 1.3 GHz Cavity



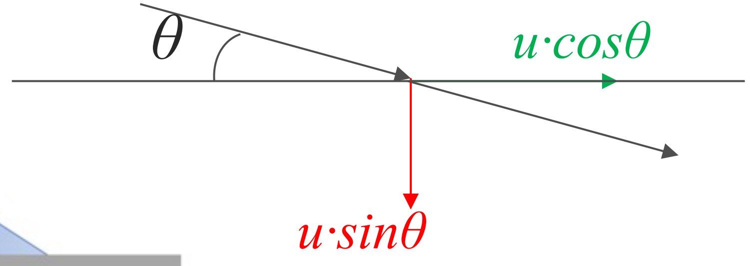
Spray on 650 MHz Cavity

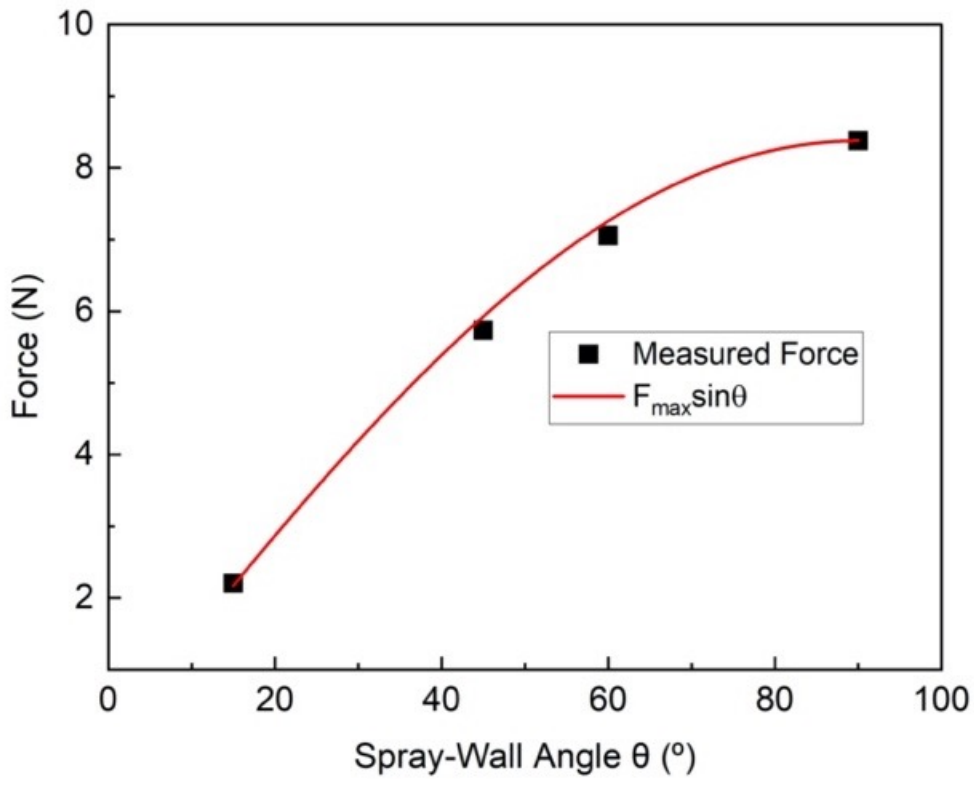


Relation of Impact Force and Spray-Wall Angle



$$F_{max} = \rho \cdot Q \cdot u$$
$$F_\perp = F_{max} \cdot \sin\theta$$



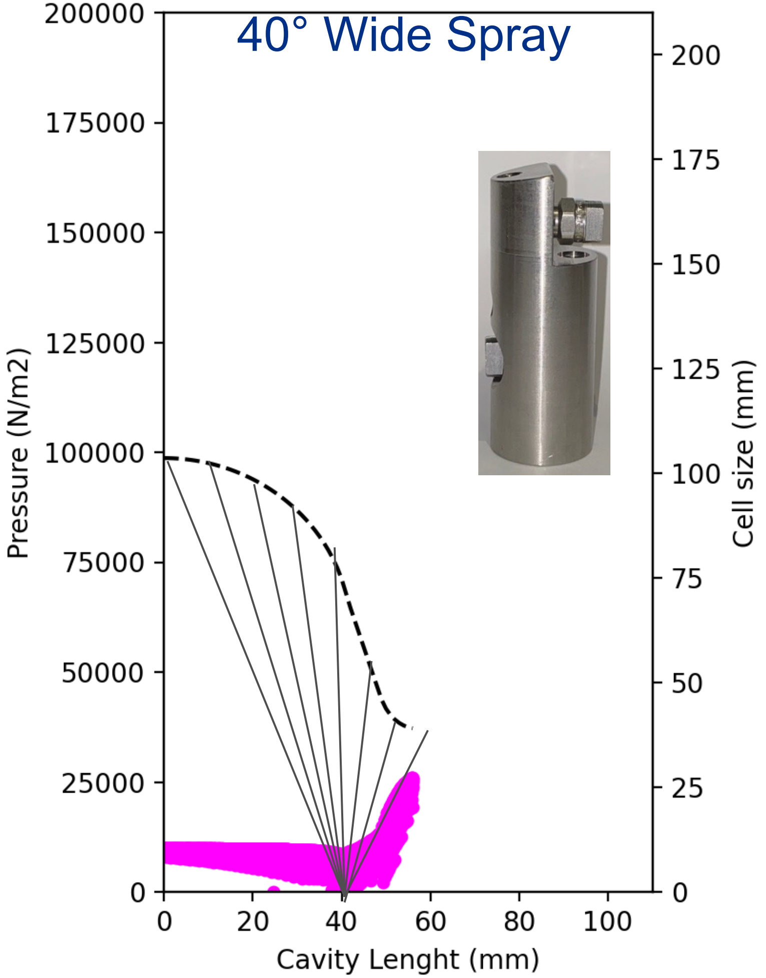


θ: average spray-wall angle
$F_\perp$: Force normal to the surface

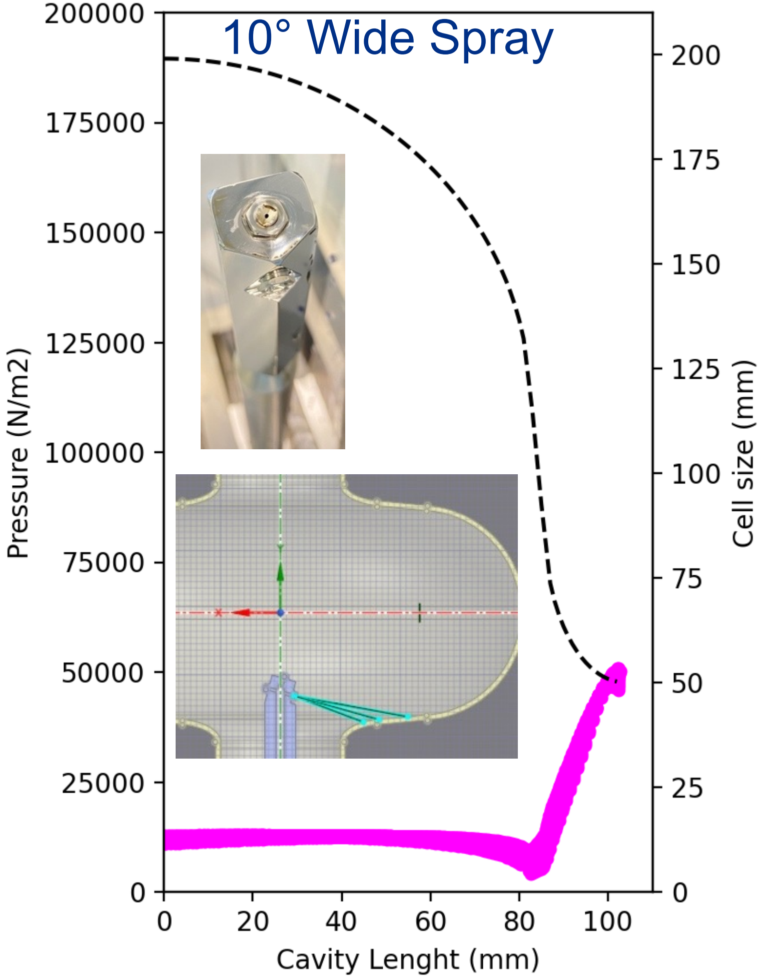
$F_\perp$ follows the sinusoidal relation with the spray-wall angle.

Calculated Pressure Profiles with Initial Spray-Head

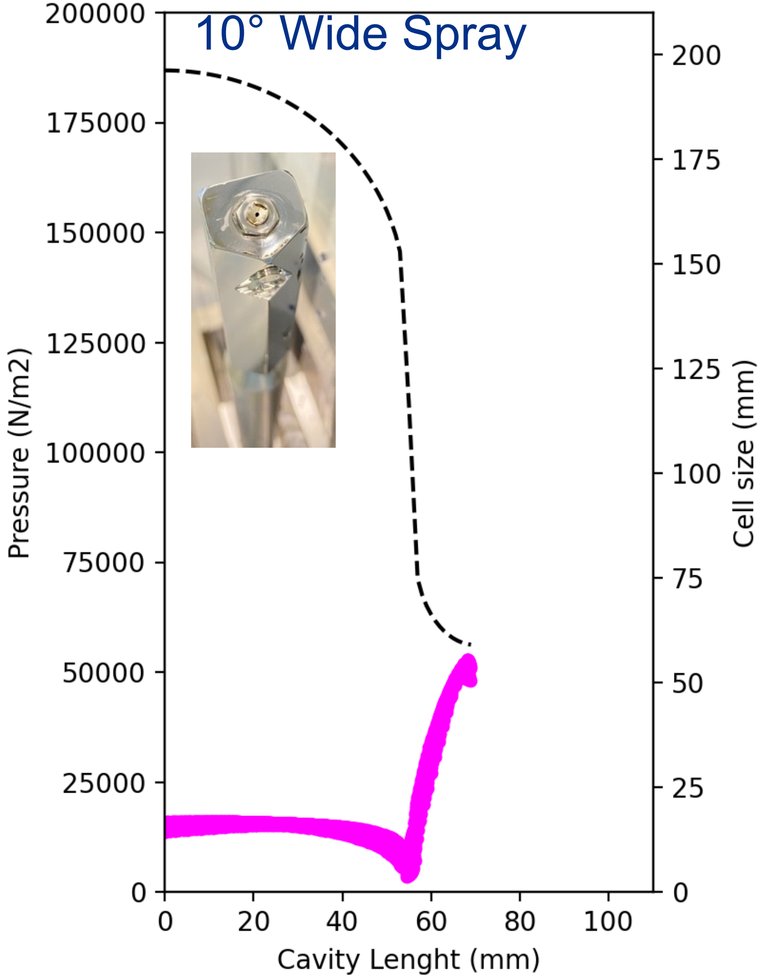
1.3 GHz Cavity



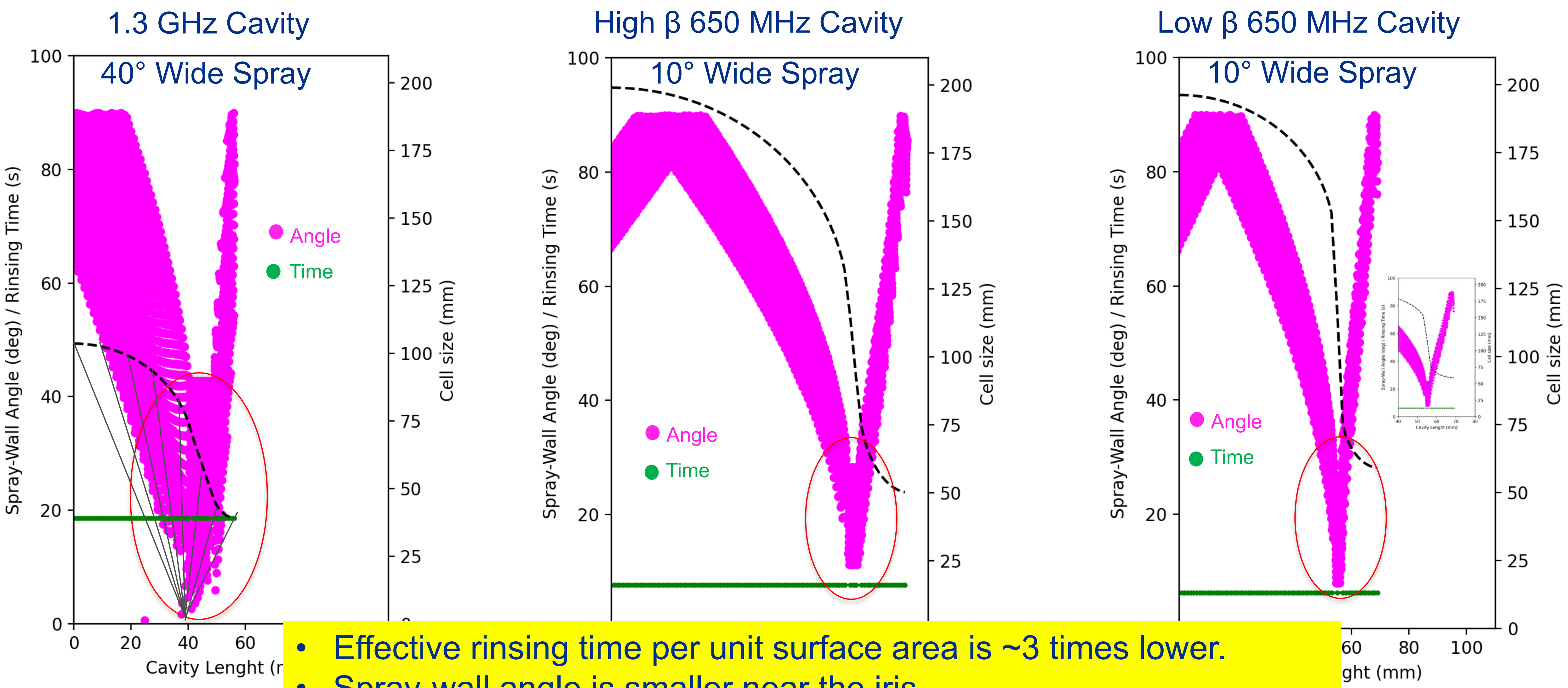
High β 650 MHz Cavity



Low β 650 MHz Cavity

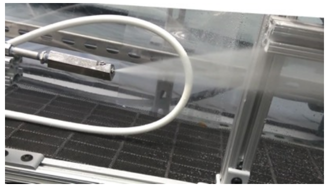


Calculated Spray-Wall Angle and Rinsing Time

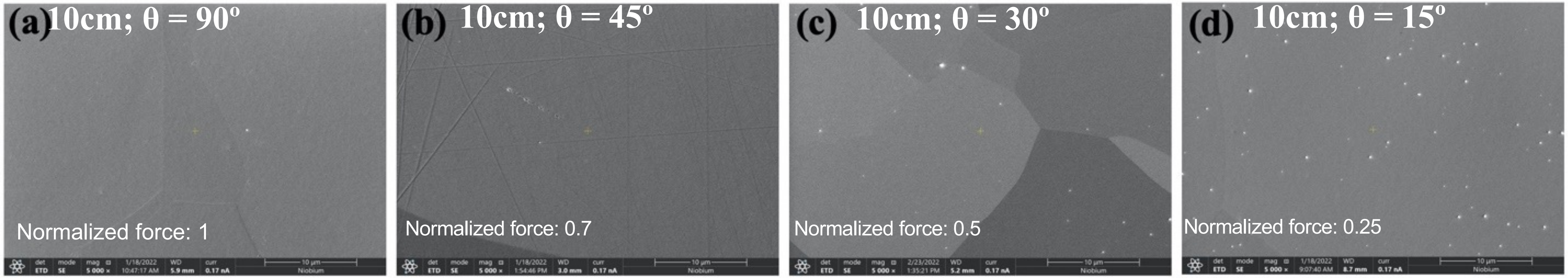


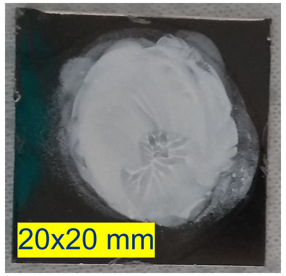
- Effective rinsing time per unit surface area is ~3 times lower.
- Spray-wall angle is smaller near the iris.

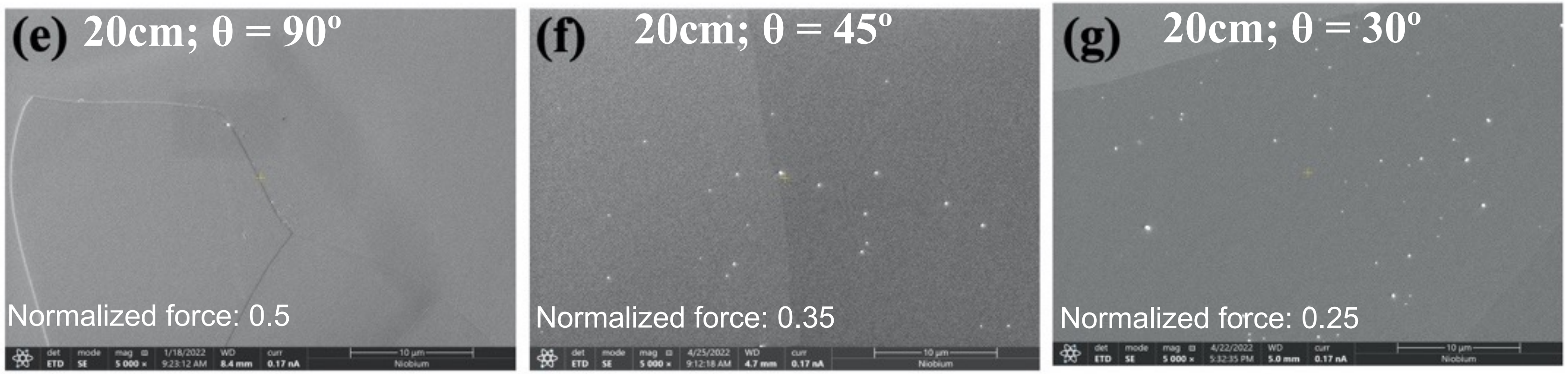
SEM Images of Rinsed Surfaces

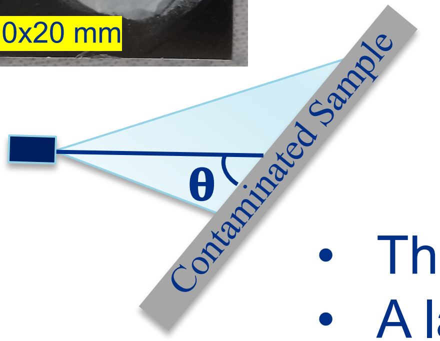


Contaminated samples were rinsed at 10 and 20 cm distance from nozzle for 5 sec.



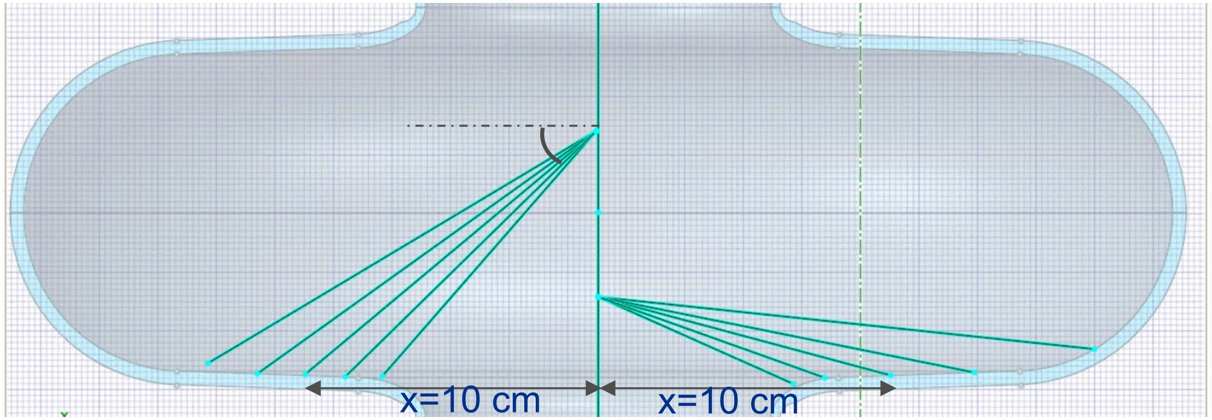




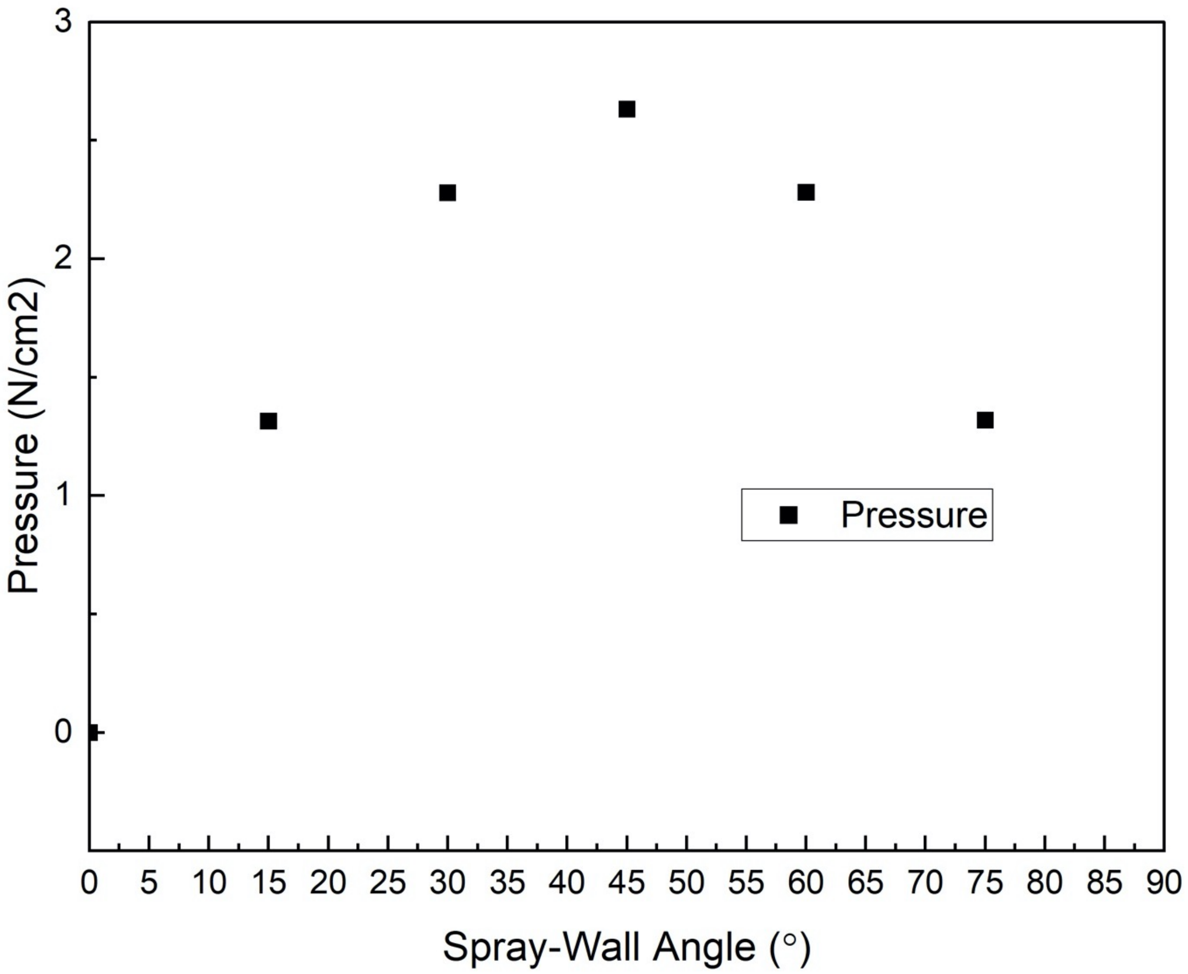


- The results suggest that a shallow spray-wall angle is not good for cleaning the surface.
- A larger nozzle-wall distance and small spray-wall angle reduce the impact force.

Optimized Angle of Nozzle Inclination



Profile at x = 10 cm



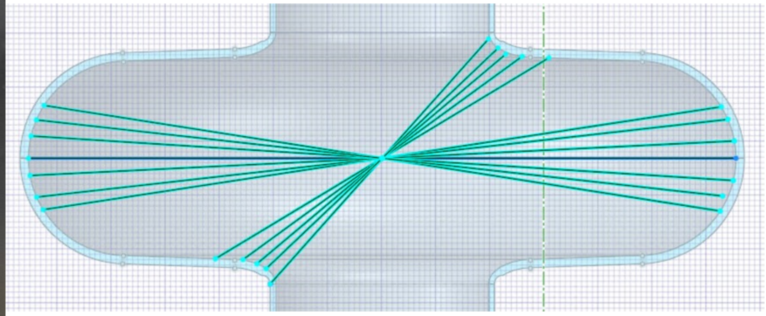
- When the nozzle inclination angle is changed, nozzle-wall distance changes. And accordingly, pressure changes on the cavity wall.
- The maximum pressure can be obtained at spray-wall angle of 45°.

Modified Spray Head

- The spray head was modified to increase the spray-wall angle and static pressure.
- Two nozzles were set with 0° inclination for cleaning of equator and iris.
- Other two nozzles were set at 40° inclination to clean the wall between iris and equator.

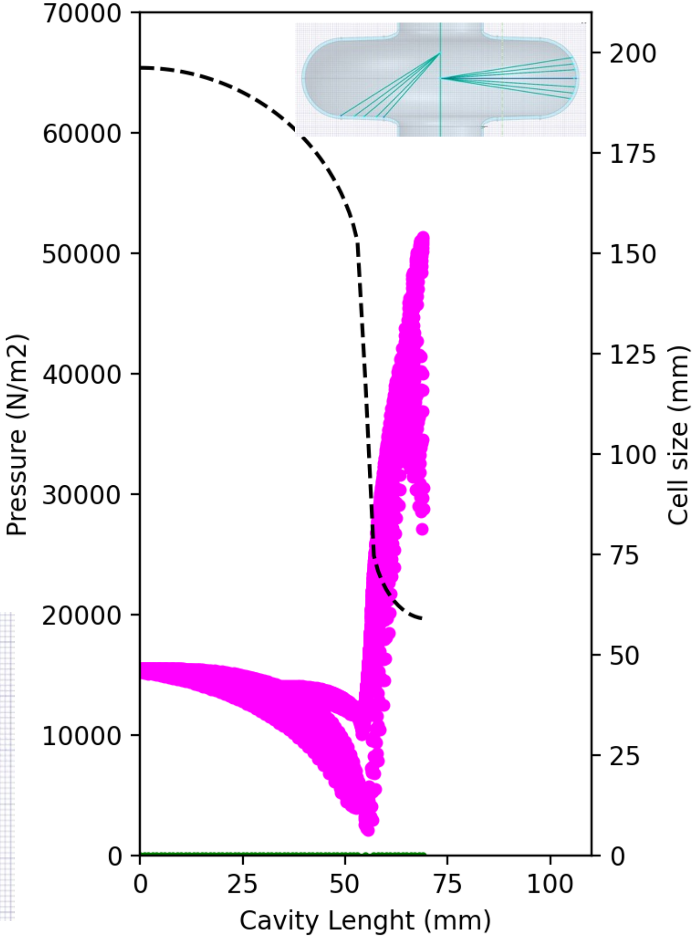
New spray head

Modified

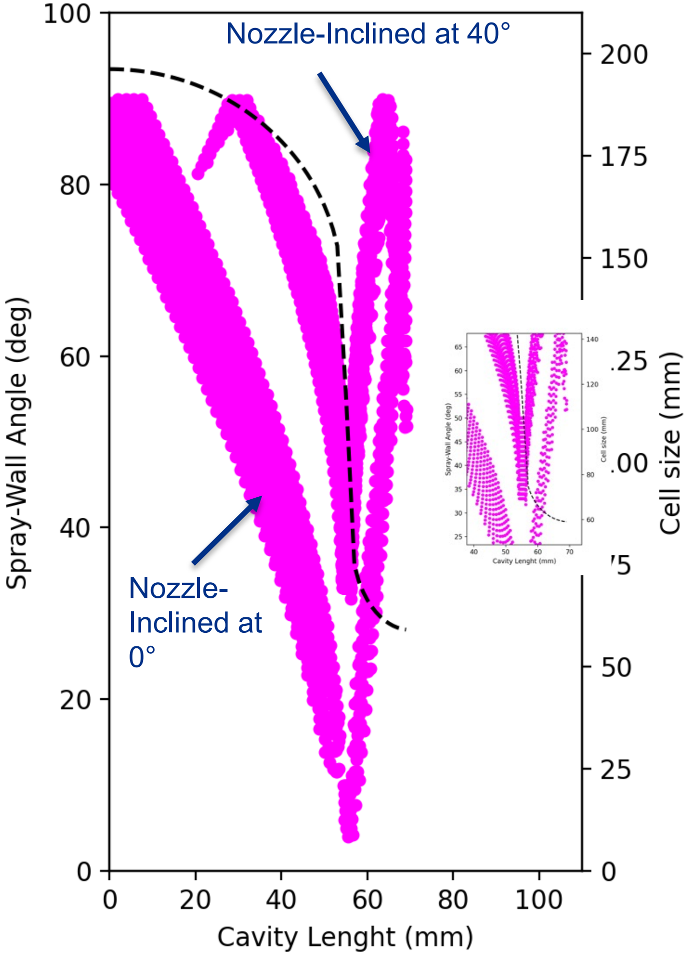


Inclination angle: 0 and 40°

Low β 650 MHz Cavity



Low β 650 MHz Cavity



A cavity was successfully rinsed with the new spray head.

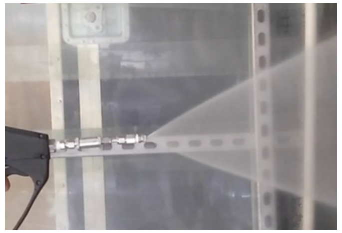
Summary

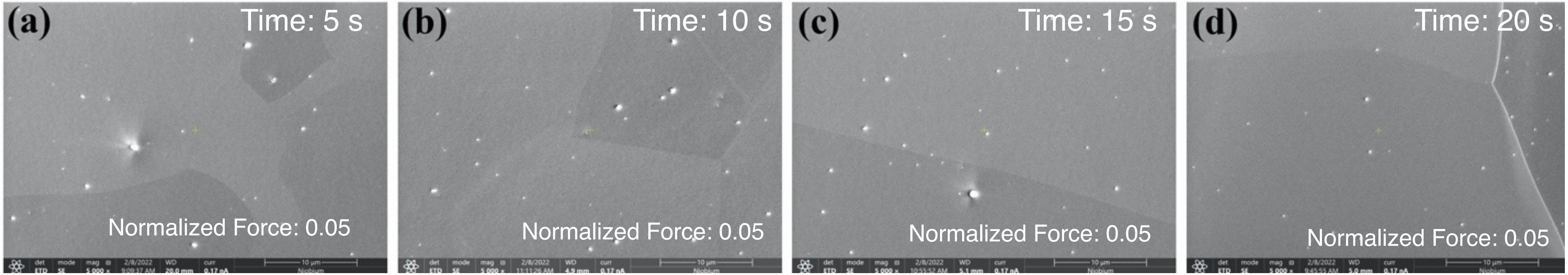
- Electropolishing parameters were studied and optimized for LB650 cavities.
- The polarization curves revealed the impact of cathode surface area, temperature, and voltage.
- The small cathode surface area (~5%) and the standard voltage (18 V) were not enough to perform EP of the equator surface of LB650 cavities.
- The modified EP conditions yielded a smooth surface of the LB650 cavity.
- HPR parameters were studied by carrying out HPR tests with contaminated samples.
- The spray-head was modified to improve the water jet pressure on the cavity wall.
- The spray-head was tested with the cavity B61C-EZ-103. No FE was observed up to the quench field (17 MV/m). More HPR tests on HB650 cavities are necessary to understand the effect of the modified spray-head.


Thank You!

Effect of Rinsing Time

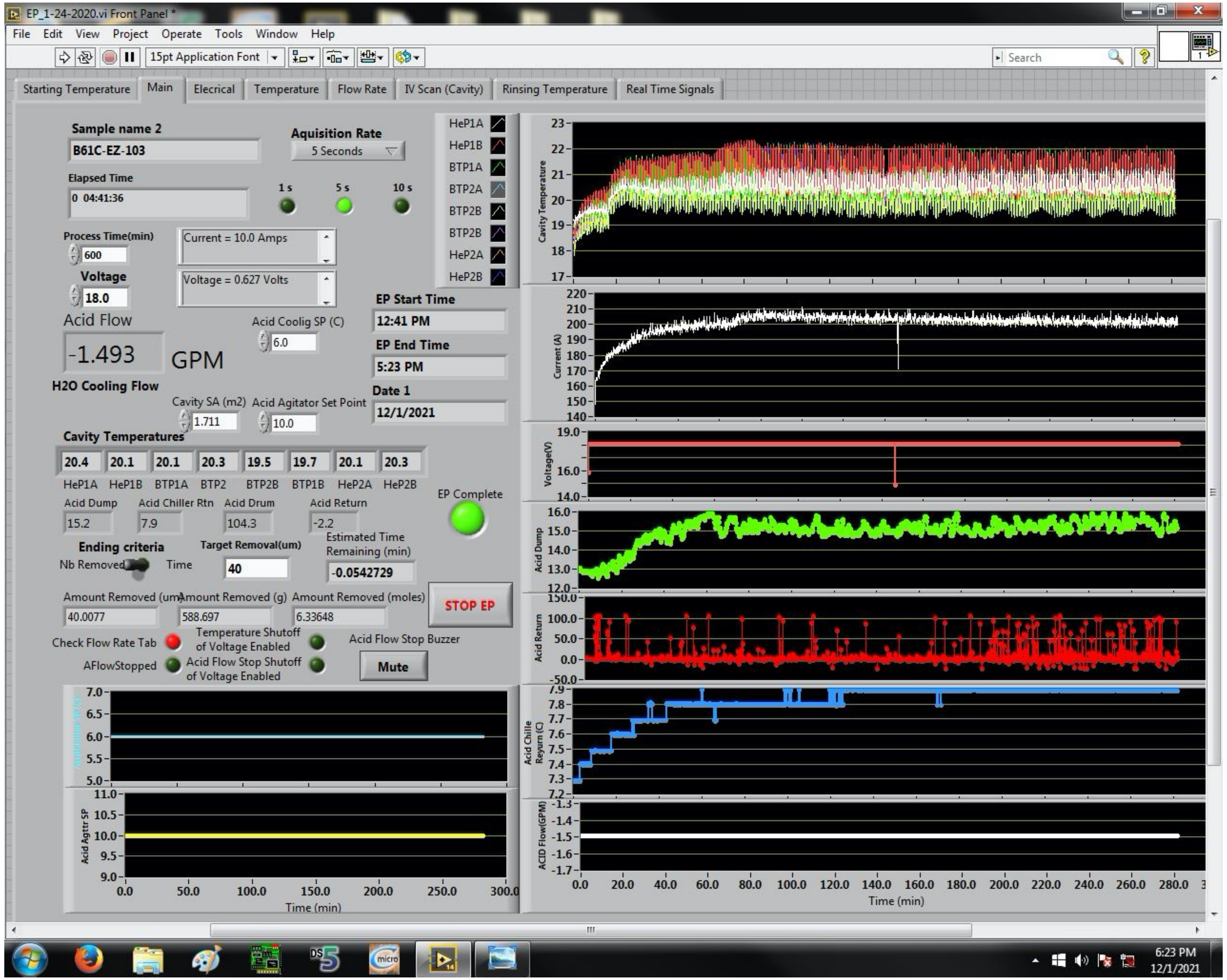
Four samples were rinsed with 40° nozzle at a nozzle-sample distance of 20 cm for different rinsing time.



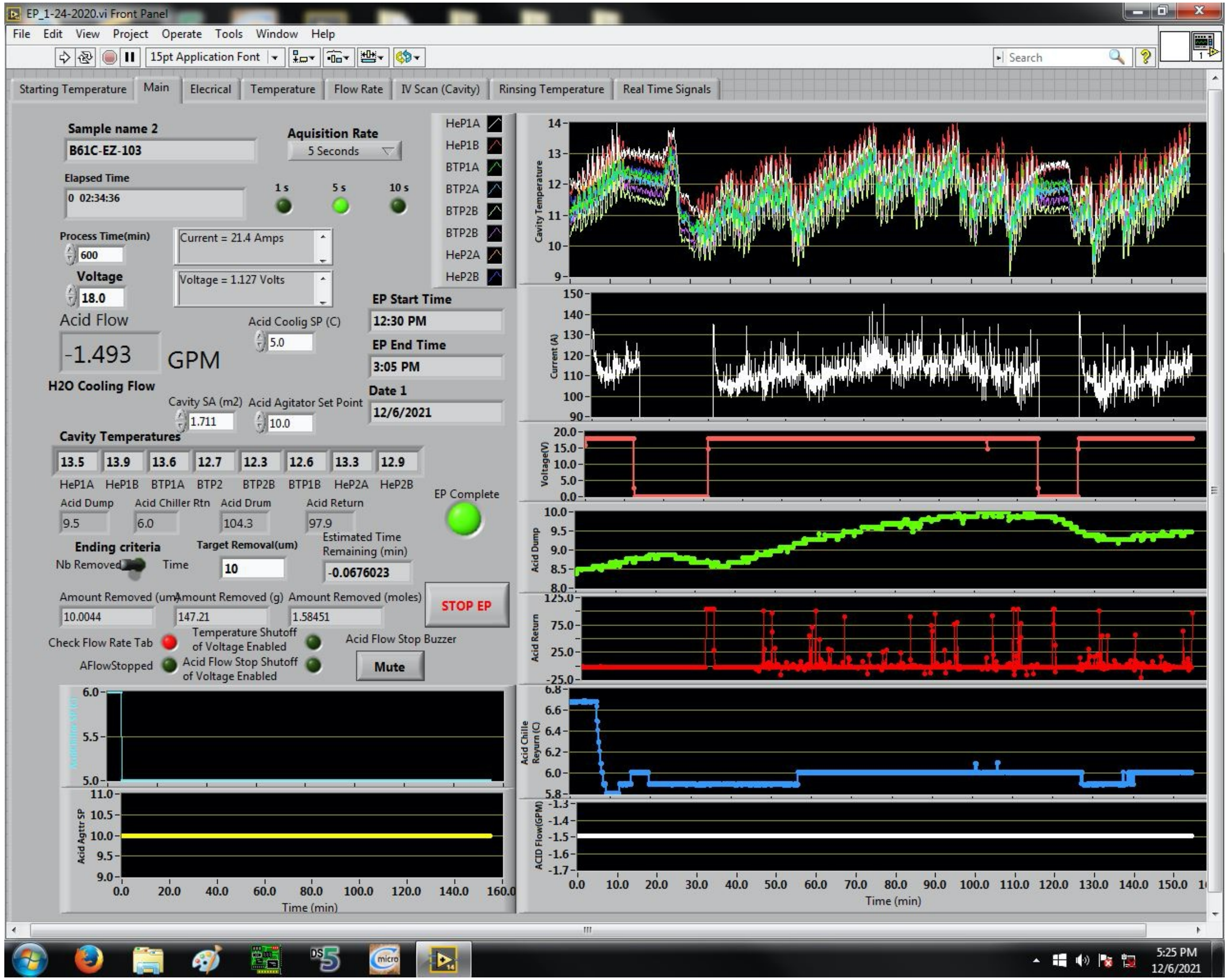


- The number density of particles were similar regardless of the rinsing time.
- If the spray pressure is lower than the adhesive force between particles and the surface, a long rinsing time/number of rinsing passes will not solve field emission problem.
- A longer rinsing time may be effective when contaminants are water-soluble or move from the rinsing position to another position on the cavity.

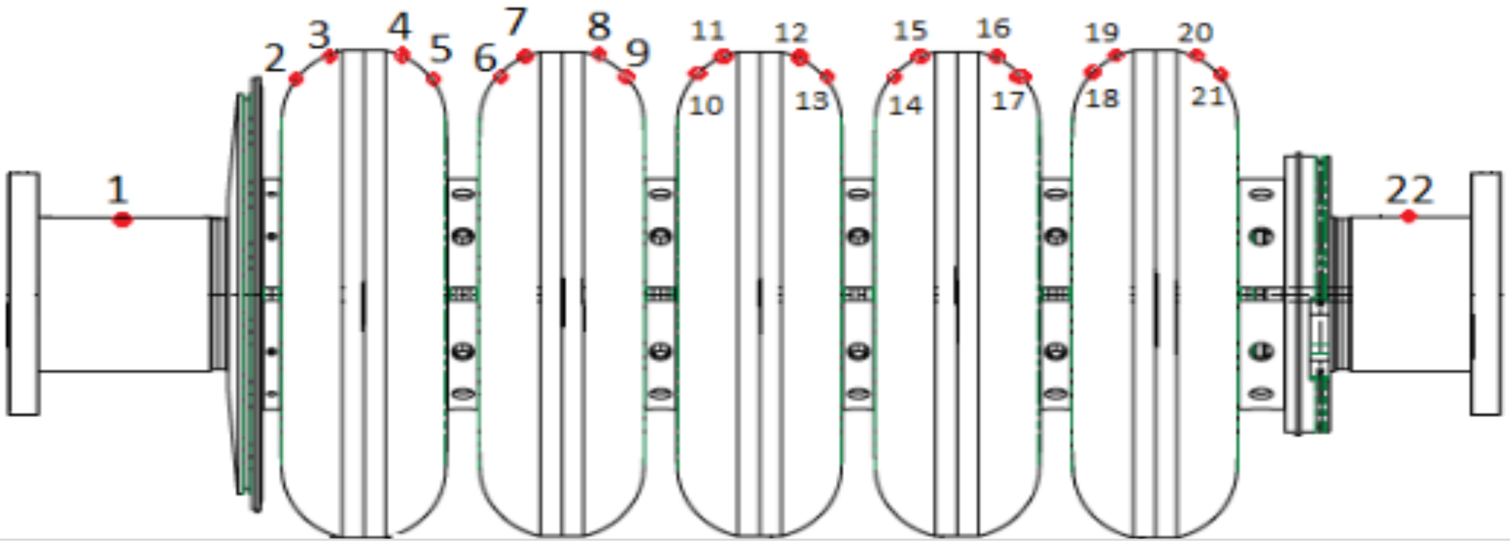
Standard Hot EP

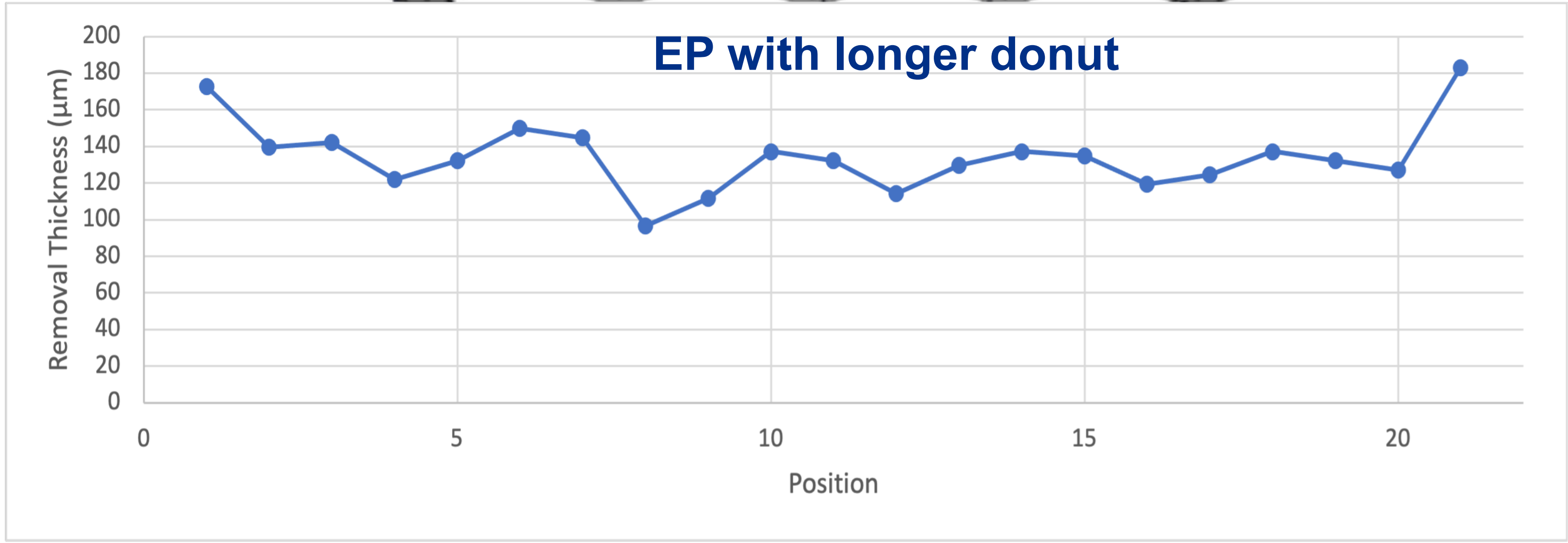


Standard Cold EP



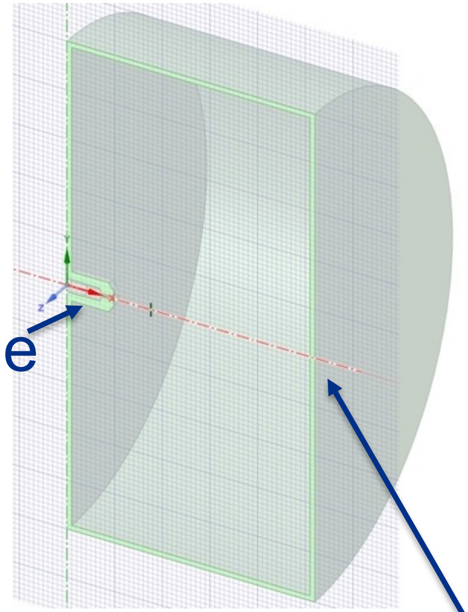
Removal Profile





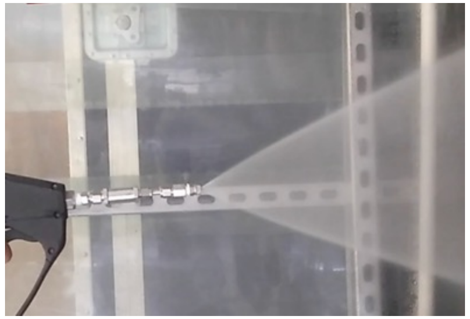
CFD Simulation

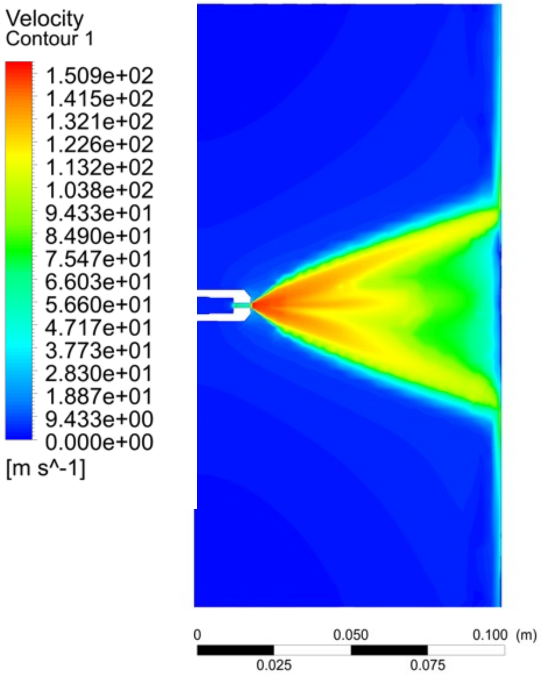
Big 40° nozzle



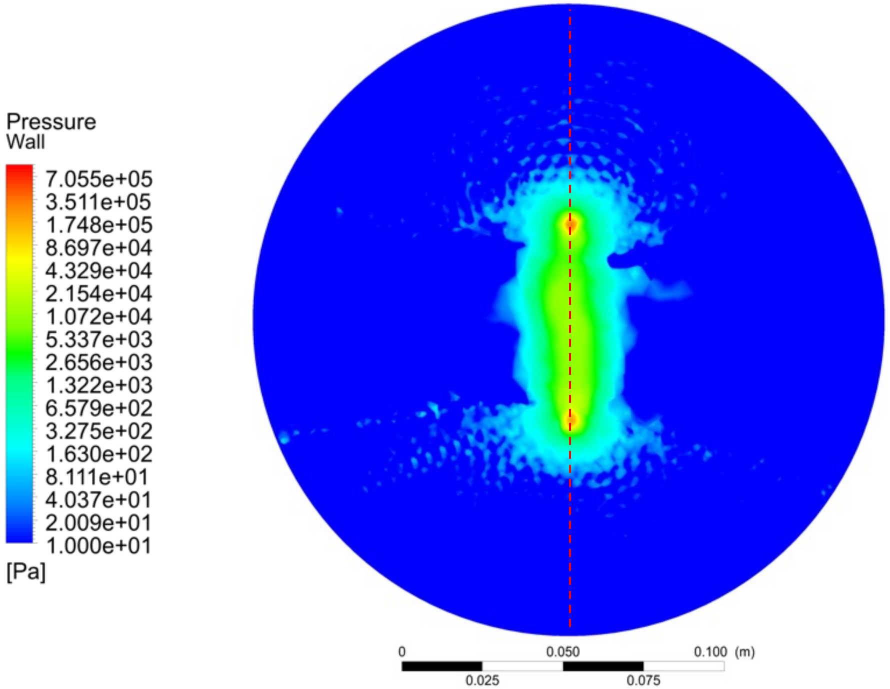
Nozzle

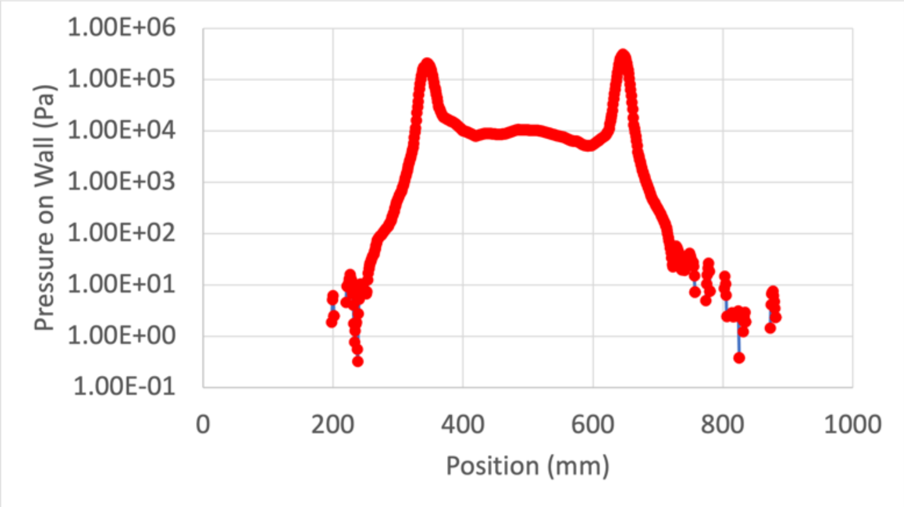
Target Wall





Target Wall





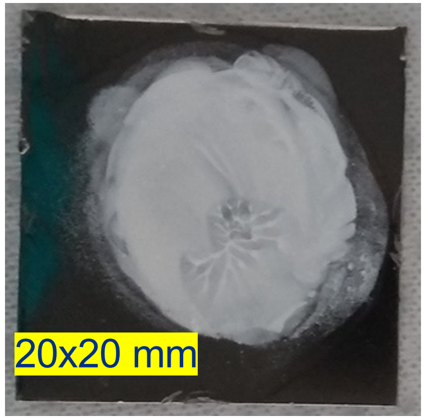
To be verified experimentally.

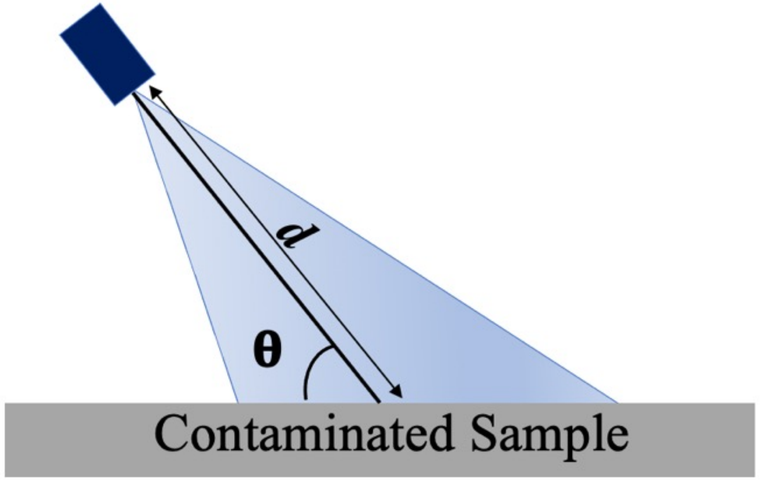
PIP-II

HPR Study on Sample

- Samples contaminated with TiO_2 powder were rinsed with **10° nozzle** at different spray-wall angles.

Contaminated Surface





Gauge for Force Measurement

Nozzle Type	Spray-Wall Angle (θ)	Nozzle-Sample Distance *d* (cm)	Pressure (N/cm^2)	Rinsing Time (s)
10° spray	90°	10	1.9	5
	45°		1.4	
	30°		0.95	
	15°		0.5	
	90°	20	1	
	45°		0.7	
	30°		0.5	

Samples were cleaned with different **θ** and *d*.