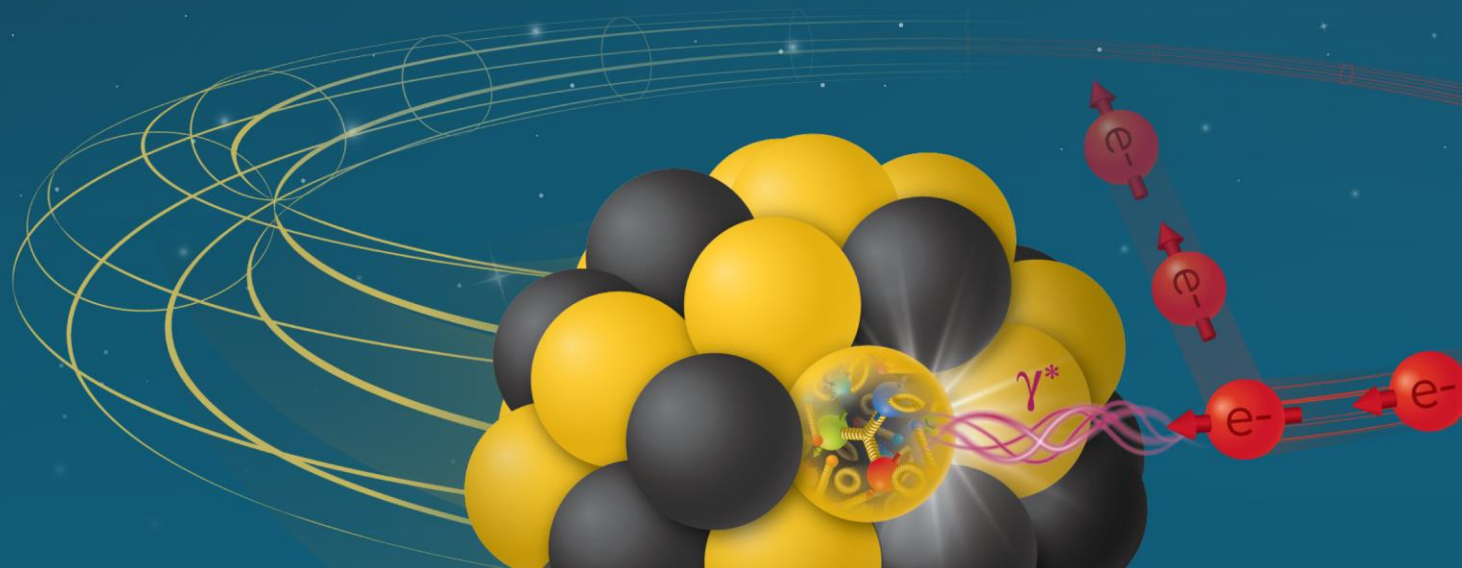
High power FPCs development for EIC

Wencan Xu

Brookhaven National Lab

WWFPC workshop July 2-3 2024

Electron-Ion Collider



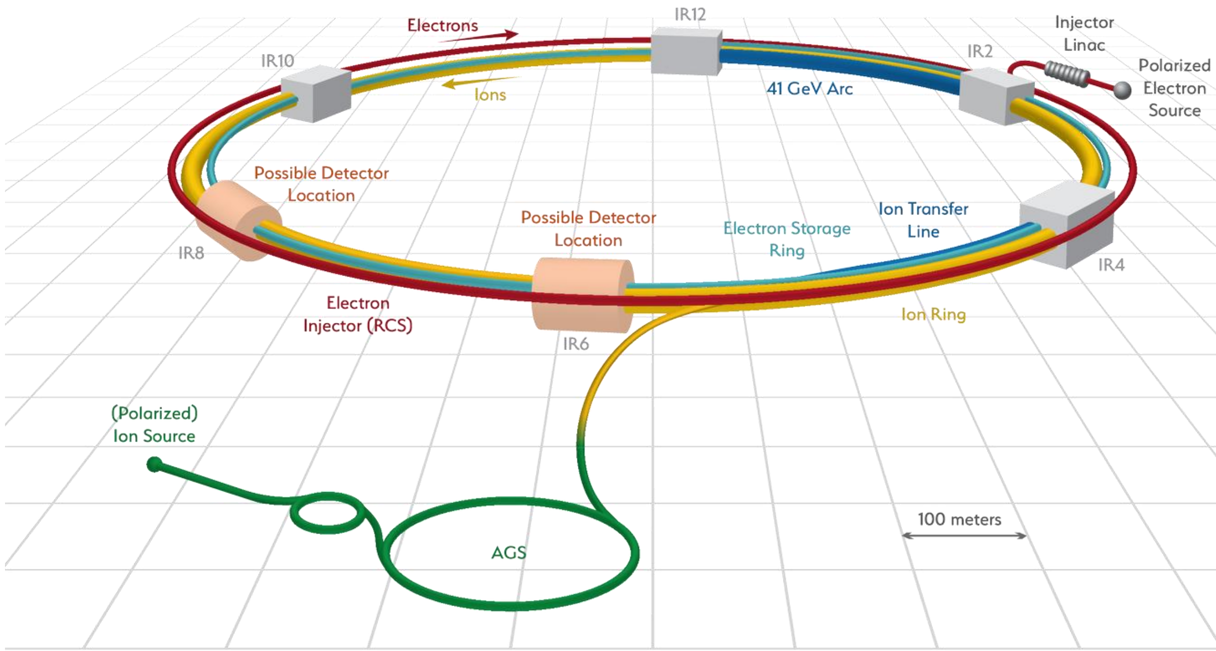
Outline

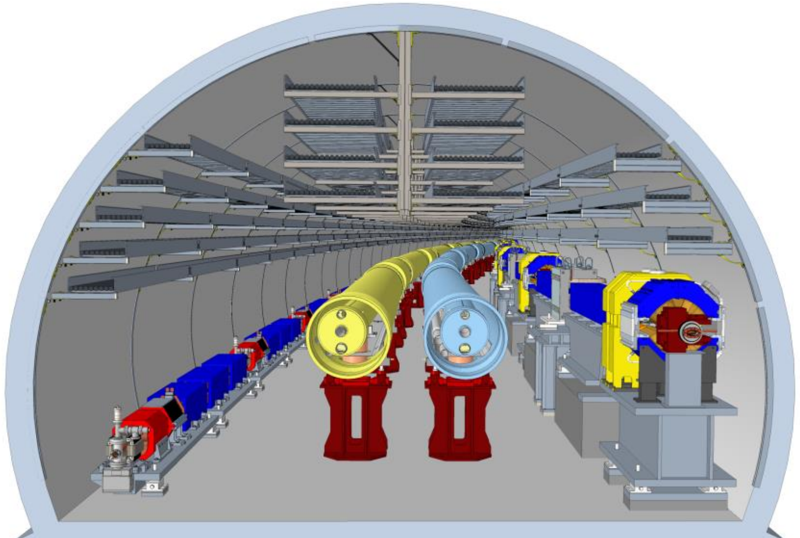
- Brief introduction of EIC RF systems and FPC counts
- High power FPC design for ESR SRF cavity
  - Requirements
  - Components design
    - Window assembly
    - Vacuum side
    - Air side
- Prototype FPC manufacture progress
  - RF window brazing recipe development
  - TiN coating sample measurement
  - Brazing and EB welding
- Summary and Future Plan

EIC

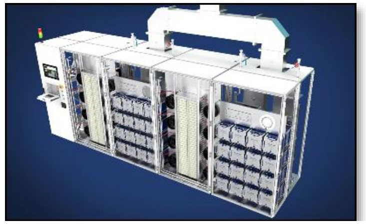
- The EIC is a unique high-energy, high-luminosity, polarized electron-proton/ion collider.
  - High luminosity: L = 1E33 to 1E34 cm-2sec-1
  - Large range of center-of-mass energies Ecm= 29 to 140 GeV
  - High flexible polarization: > 60 %

- EIC is based on the RHIC complex
  - Same RHIC tunnel (space limit)
  - HSR ring: upgraded RHIC ring.
  - New electron facility
    - ESR in RHIC tunnel
    - RCS in RHIC tunnel
    - Electron injection
- Jlab is the EIC partner lab

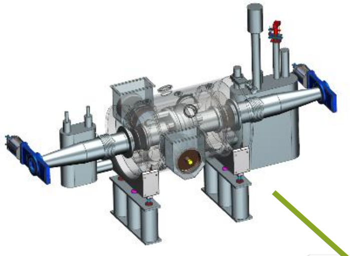




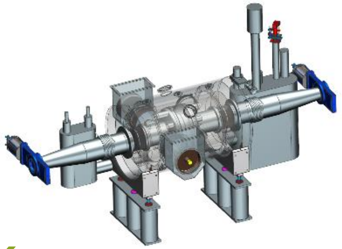
EIC RF Systems



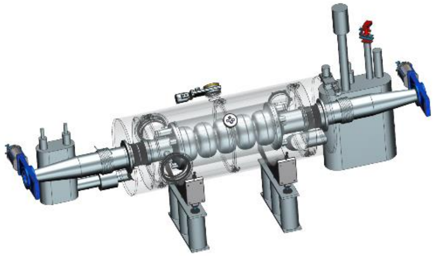
RF power and distribution 400kW×34 new SSAs for ESR 591MHz cavities, various power level for other cavities



Electron - 591 MHz electron storage cavity
17 CMs, IR10

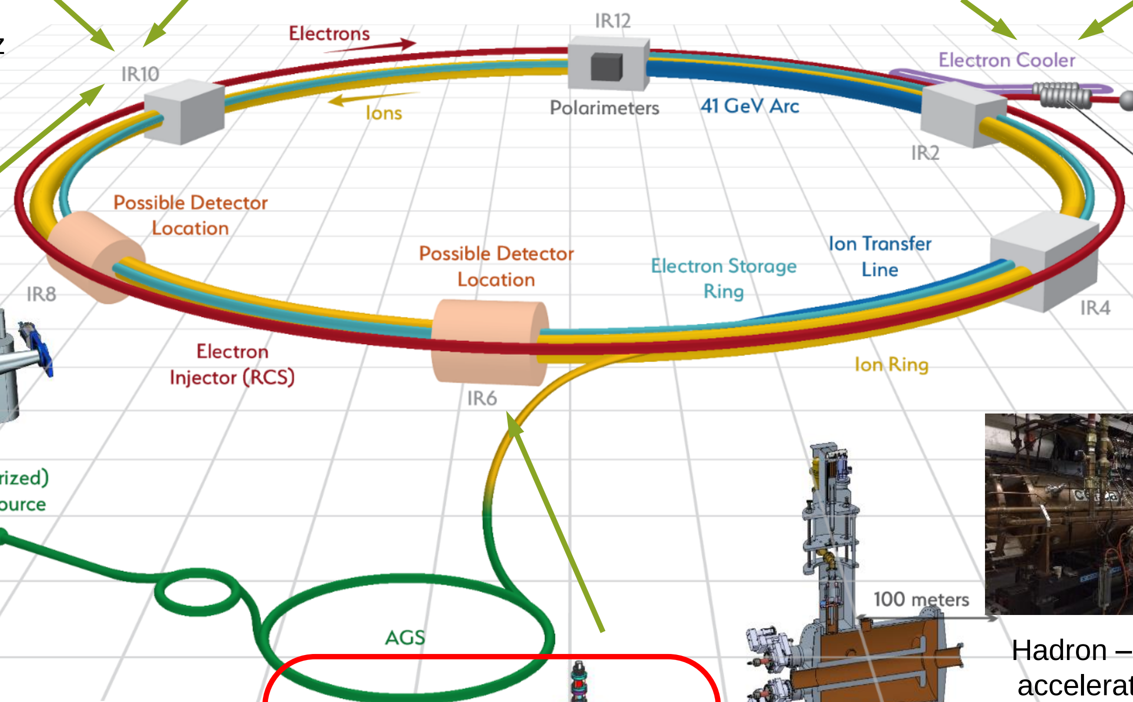


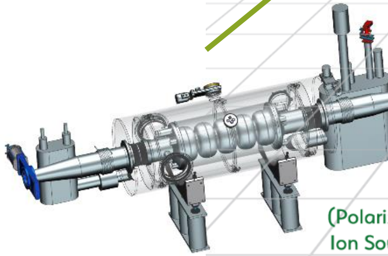
Hadron - 591 MHz bunch compression cavity
5 CMs, IR10



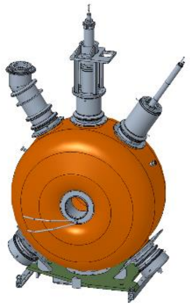
Hadron Cooling - 591 MHz acceleration cavity
10 CMs, Electron Cooler

1773 MHz 3rd Harmonic (4) Cavities (Not shown)
1 CM, Electron Cooler



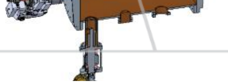


Rapid Cycling Synchrotron - 591 MHz acceleration cavity
3 CMs, IR10



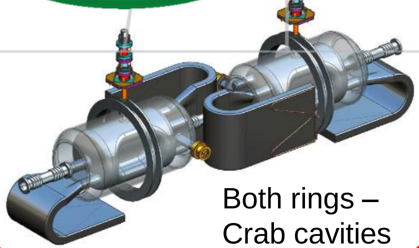
Hadron - 197 MHz bunch compression cavity

Hadron – 24.5 MHz acceleration cavity

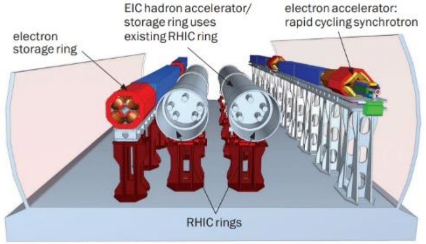


Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

Crab Cavities (per IR)	HSR (Cavities/CMs)	ESR (Cavities/CMs)
197 MHz	8/4	–
394 MHz	4/4	2/2



Both rings – Crab cavities



Electron-Ion Collider

FPC list for ERIC RF/SRF cavities

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities	# FPC/cavity	FPC power (kW)
Electron Storage Ring	Accel / Store	591	SRF, 1-cell	IR-10	17	2	380
Rapid Cycling Synchrotron (RCS)	Accel / Store	591	SRF, 5-cell	IR-10	3	1	70
	Harmonic Kickers	591	NCRF, QWR, 1-mode NCRF, QWR, 2-mode	IR-2 or IR-12	1 1	1	
	Bunch Merge Type 1	295	NCRF, Reentrant	IR-4	2	1	70
	Bunch Merge Type 2	148	NCRF, Reentrant	IR-4	1	1	70
Hadron Storage Ring	Capture / Accel	24.6	NCRF, QWR	IR-4	4	1	100
	Bunch Split 1	49.2	NCRF, QWR	IR-4	2	1	200
	Bunch Split 2	98.5	NCRF, QWR	IR-4	2	1	200
	Store 1	197	NCRF, Reentrant	IR-4	7	1	100
	Store 2	591	SRF, 1-cell	IR-10	5	1	60
Strong Hadron Cooling	ERL Injector	197 591	SRF, QWR SRF, 1-cell	IR-2	2 1	2 1	200 10
	ERL Low Energy Linac	197 591	SRF, QWR SRF, 1-cell	IR-2	4 2	2 1	200 10
	ERL Fundamental	591	SRF, 5-cell	IR-2	10	1	60
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	4 (1 CM)	1	5
Crab Cavities	Hadron	197	SRF, RFD	IR-6	8 (4 CM)	1	70
	Hadron/Electron	394	SRF, RFD	IR-6	6	1	50

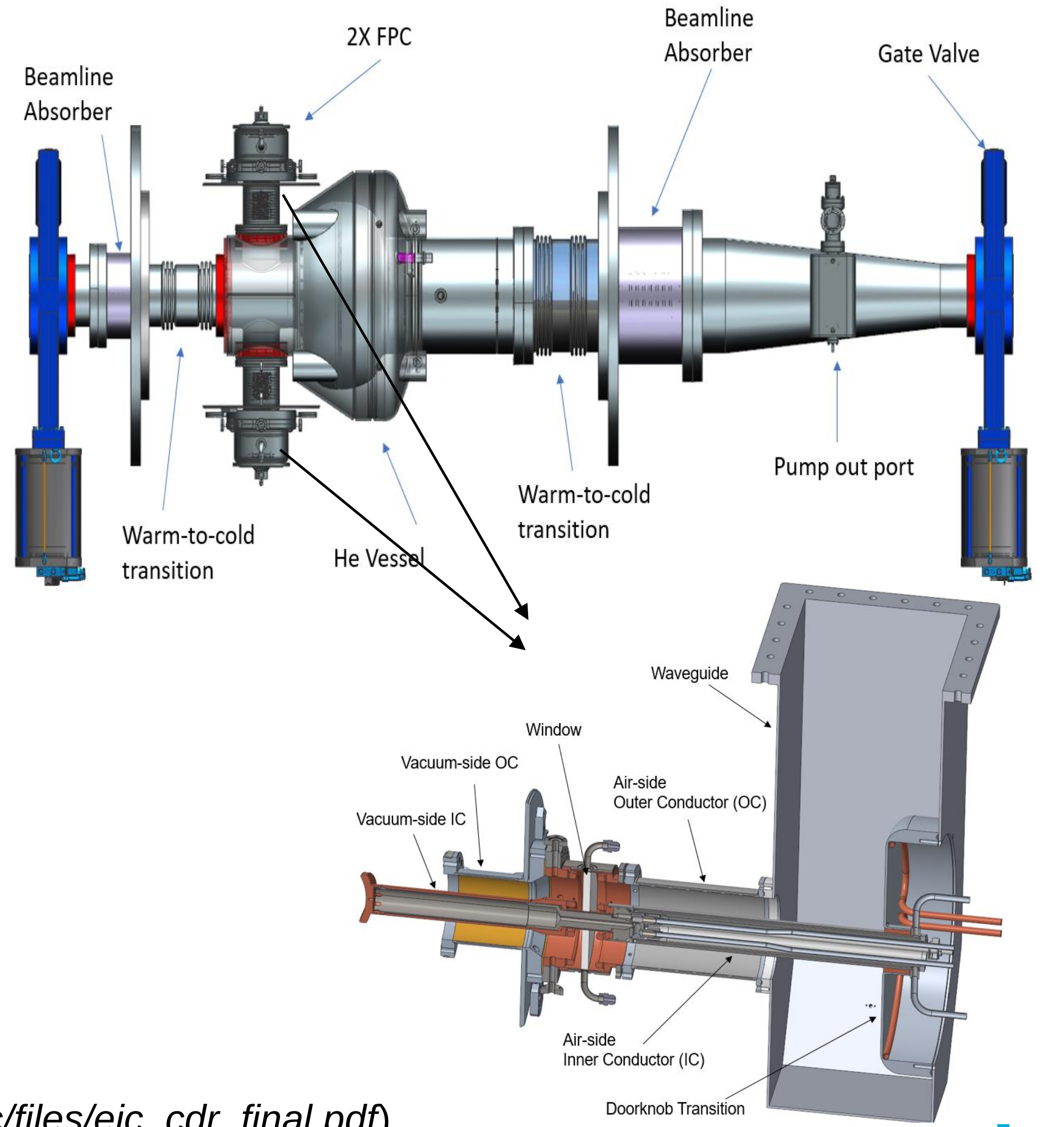
FPC list for ERIC RF/SRF cavities

RF System	Sub System	Freq [MHz]	Type	Location	# Cavities	# FPC/cavity	FPC power (kW)
Electron Storage Ring	Accel / Store	591	SRF, 1-cell	IR-10	17	2	370
Rapid Cycling Synchrotron (RCS)	Accel / Store	591	SRF, 5-cell	IR-10	3	1	70
H							
S							
	Linac	591	SRF, 1-cell		2	1	10
	ERL Fundamental	591	SRF, 5-cell	IR-2	10	1	60
	ERL Third Harmonic	1773	SRF, 5-cell	IR-2	4 (1 CM)	1	5
Crab Cavities	Hadron	197	SRF, RFD	IR-6	8 (4 CM)	1	70
	Hadron/Electron	394	SRF, RFD	IR-6	6	1	50

- ***EIC FPC summary:***
  - ***About 100 new FPCs are required for EIC RF/SRF systems.***
  - ***Most EIC cavities' frequencies are below ESR SRF cavity's frequency, i.e., 591 MHz.***
  - ***The only cavities with frequency above ESR cavity's frequency are the third harmonic cavity for ERL SHC, i.e., 1773 MHz.***
  - ***The most challenging FPC is for ESR SRF cavity: CW 400 kW.***
- ***EIC FPC strategy:***
  - ***One type of window (new design) for SRF cavities with frequency < 591 MHz***
  - ***One type of window for 1773 MHz: using CEBAF FPC window***
  - ***One type of window for NCRF cavities (loop coupling)***

FPC design requirement for ESR SRF cavity

Parameters	Nominal maximum*	Ultimate maximum #
Frequency	591 MHz	591 MHz
Synchrotron radiation	8.8 MW	10 MW
HOM power per cavity	56.2 kW	72.7 kW
Total power requirement per cavity	574 kW	661 kW
Operational Overhead	15%	15%
Max. RF power per cavity	660 kW	760 kW
Couplers per cavity	2	2
Max. RF power per coupler	330 kW	380 kW



* Nominal operation parameters: Table 6.63 in CDR (*https://www.bnl.gov/ec/files/eic_cdr_final.pdf*)
# Machine design parameters

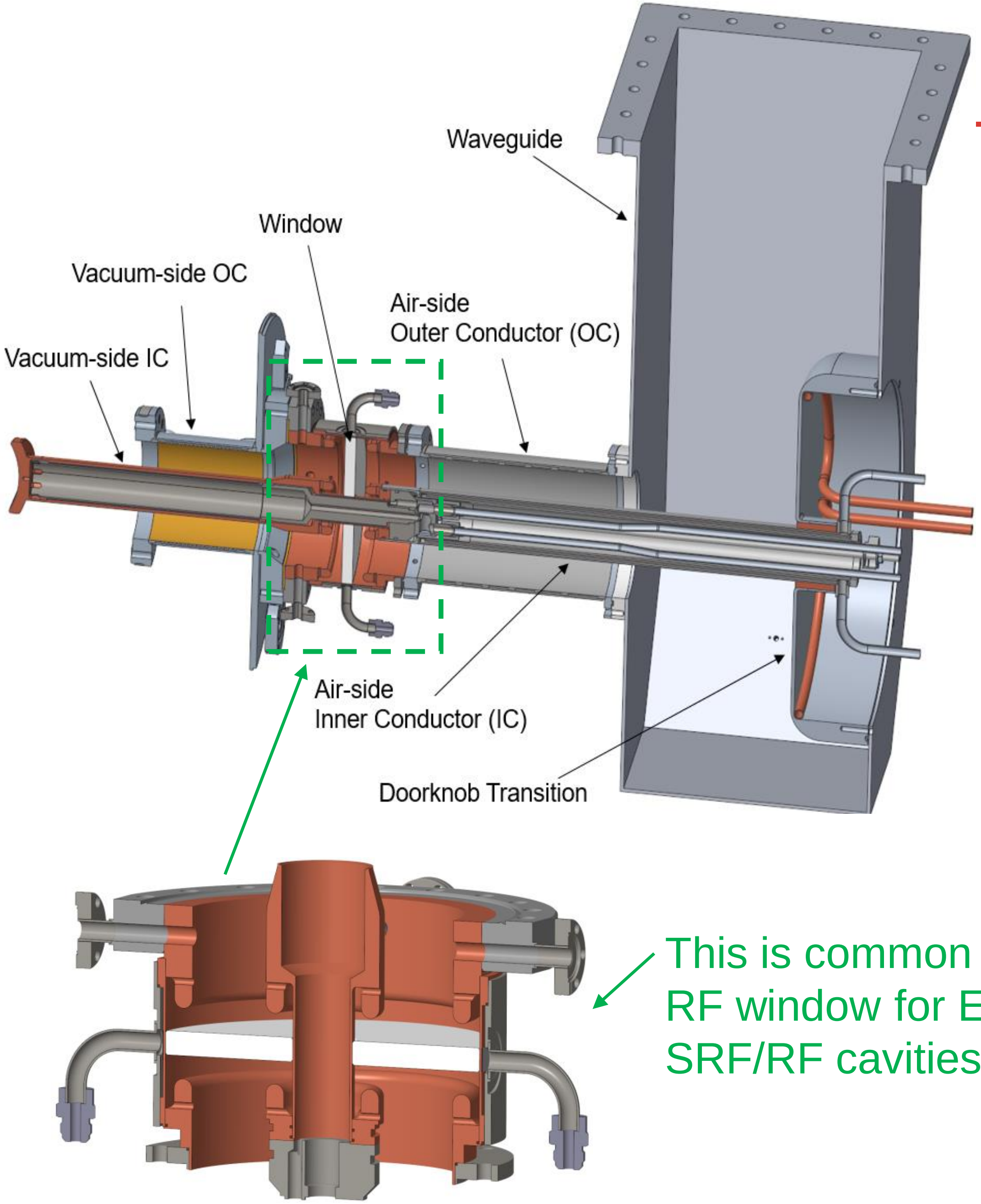
FPC design achieve vs criteria

	Requirement	FPC Design Criteria
Average RF power	380 kW *	1 MW, traveling wave 500 kW, full reflection
Peak Power (during full reflection)	1.5 MW, equivalent	2 MW, equivalent
Frequency	591 MHz	Broadband window design, good for EIC cavities below 591 MHz
Acceleration load	5g, In any orientation	5g, In any orientation
Mechanical Modal frequency	> 60 Hz	> 100 Hz
Q_{ext} of each coupler	2.5E5	Fixed coupler#, Tuning Q_{ext} with waveguide junction, a factor of 20

*The beam abort gap is RHIC is 8% of 12.8 us.
Fixed coupling is set at 4E5, and a waveguide junction was tested up to 500 kW CW standing wave(@704 MHz). However, recent evolution of EIC design demonstrated a fixed coupling is feasible for EIC operation, with RF FODO operation mode.

FPC for EIC ESR SRF Cavity

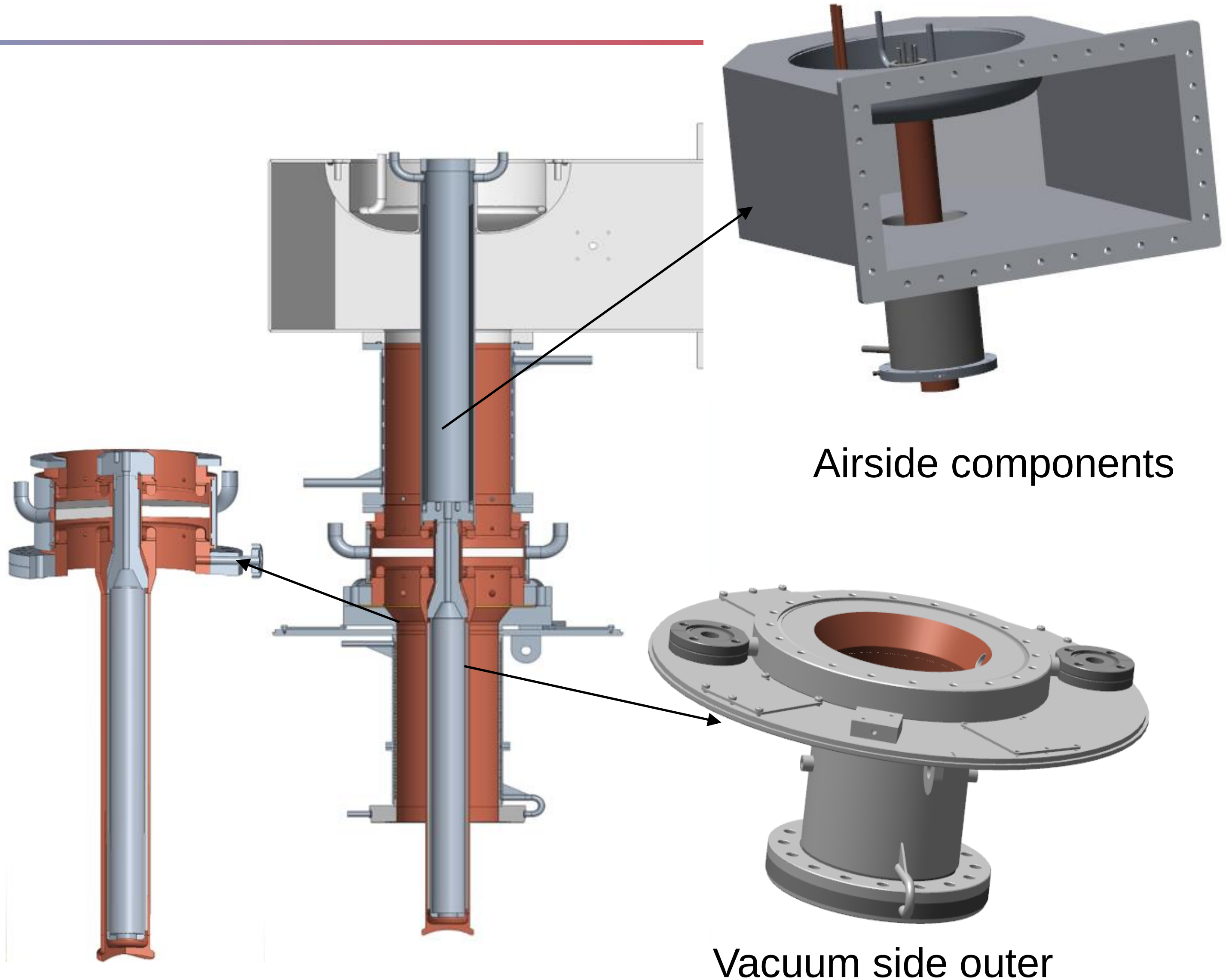
- EIC eSR FPC design is a variation of KEKB/ Tristan/SNS/BNL BeO high power window.
- Particularly, this Al2O3 window FPC improved various aspects based on lesson and learn from design and operating experiences of BNL BeO window, so that it can satisfy the EIC requirements.
  - Replace BeO window with 99.5% Al2O3 for safety and maintenance considerations.
  - Increase choke to window distance for better TiN coating and inspection.
  - Optimized coaxial line to increase power handling and coupling with cavity.
  - Larger ceramic ID to survive 5 g acceleration load in any direction.
  - Improve cooling channel design.
  - Improve instrumentations on FPC.
  - 4.5 kV bias will be ready to apply.



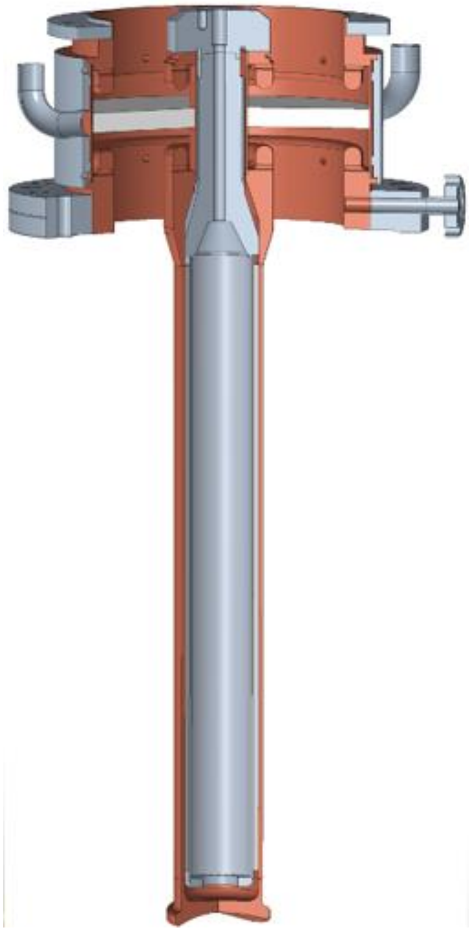
This is common RF window for EIC SRF/RF cavities.

EIC ESR FPC design

- FPC window assembly
- FPC vacuum side outer conductor
- FPC airside components
- The pre-project plan for window development
  - Fabricate 8 RF window assembly, and 4 full FPCs.
  - High power RF condition up to 500 kW standing wave, all phases.
  - Deliver two FPCs for First Article Cryomodule.

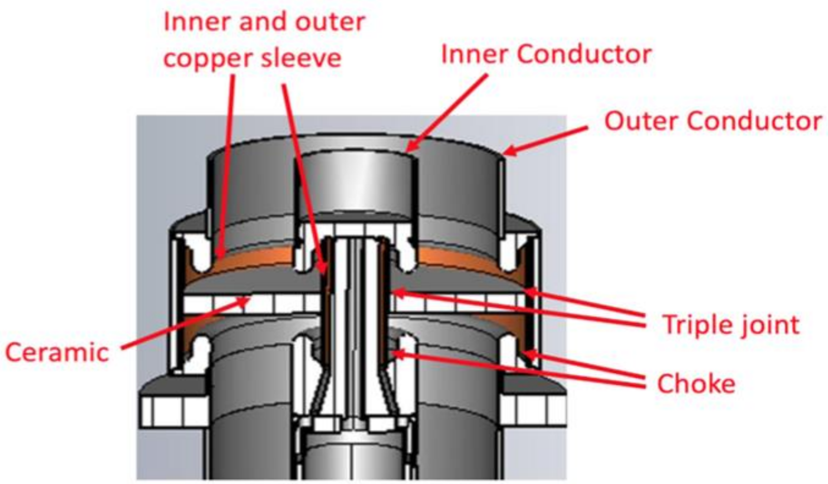


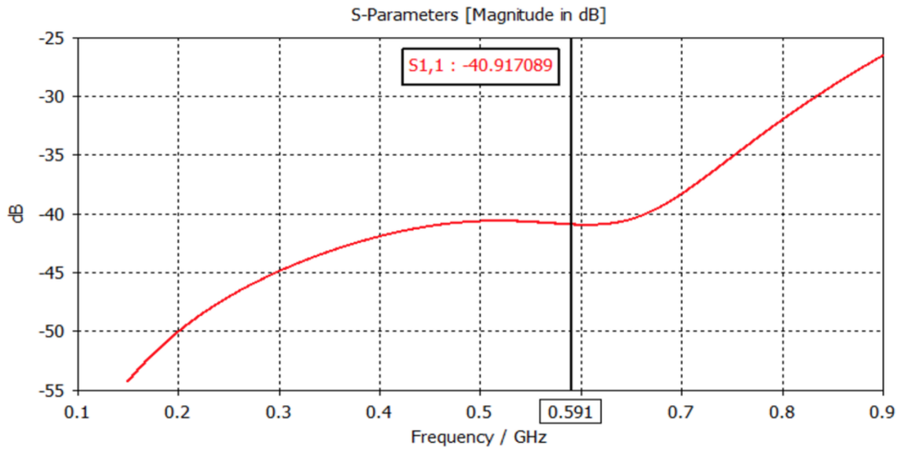
RF window assembly

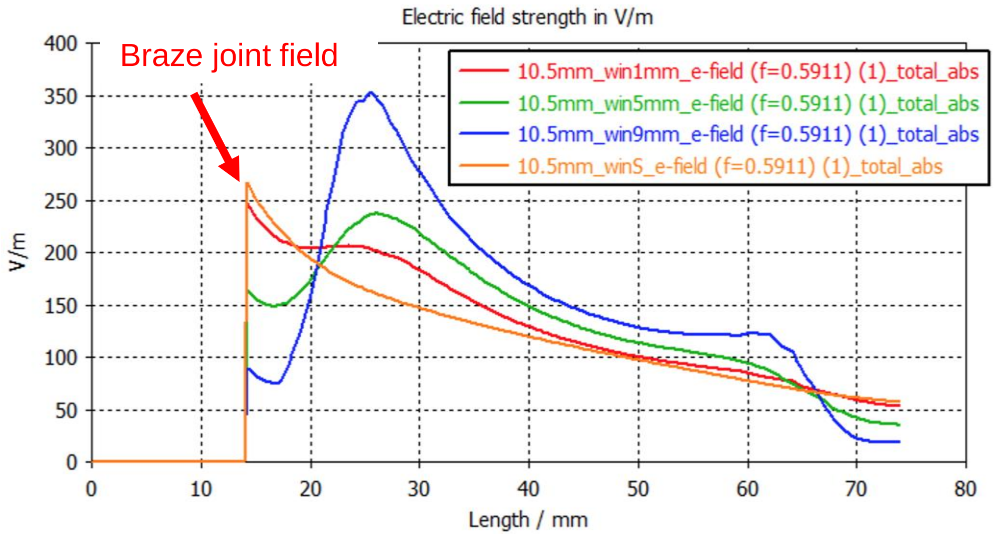


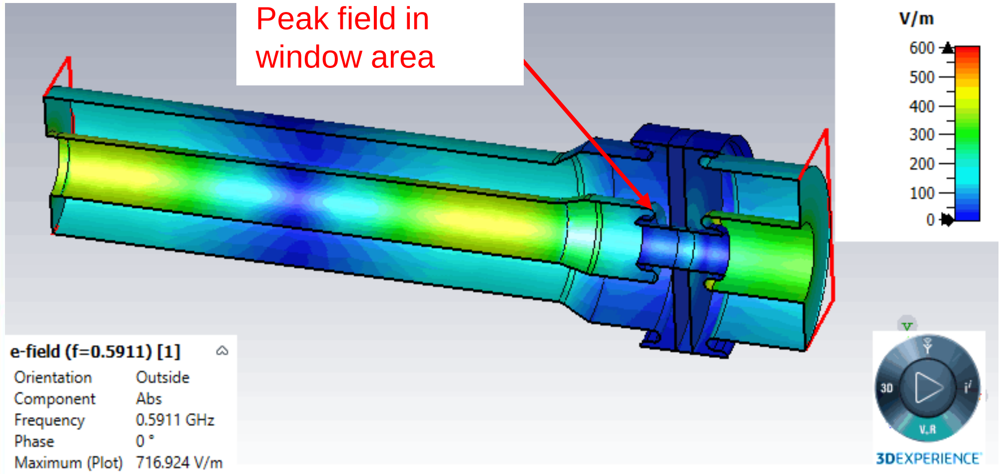
High power broadband window for EIC Cavities

- A high power, broadband window has been designed for EIC RF/SRF cavities.
  - Broadband: < -40 dB for frequency below 591 MHz.
  - The peak field at the braze-joint is 367 kV/m.



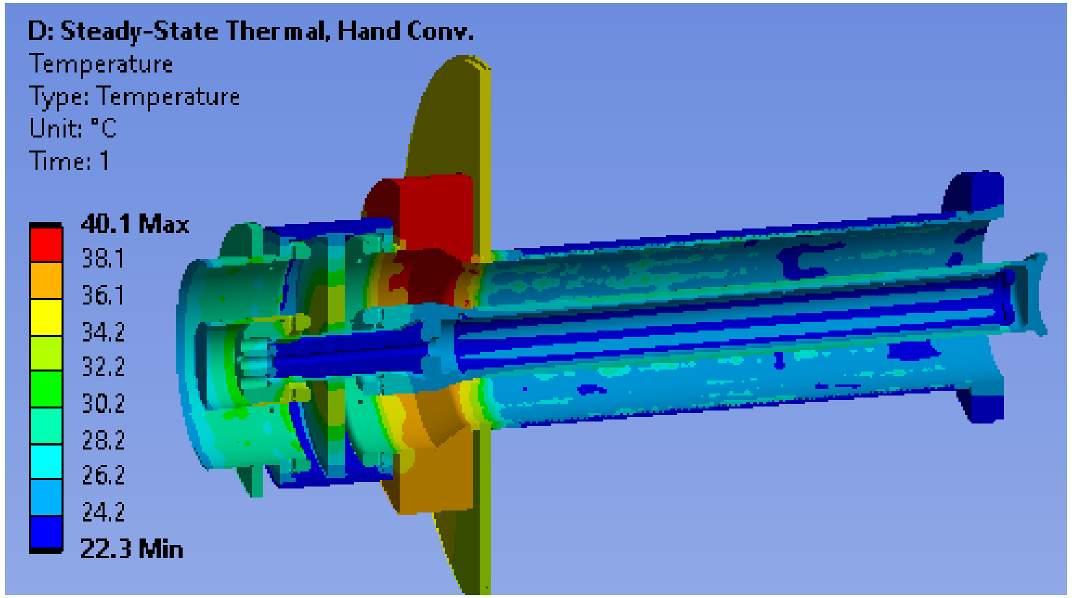




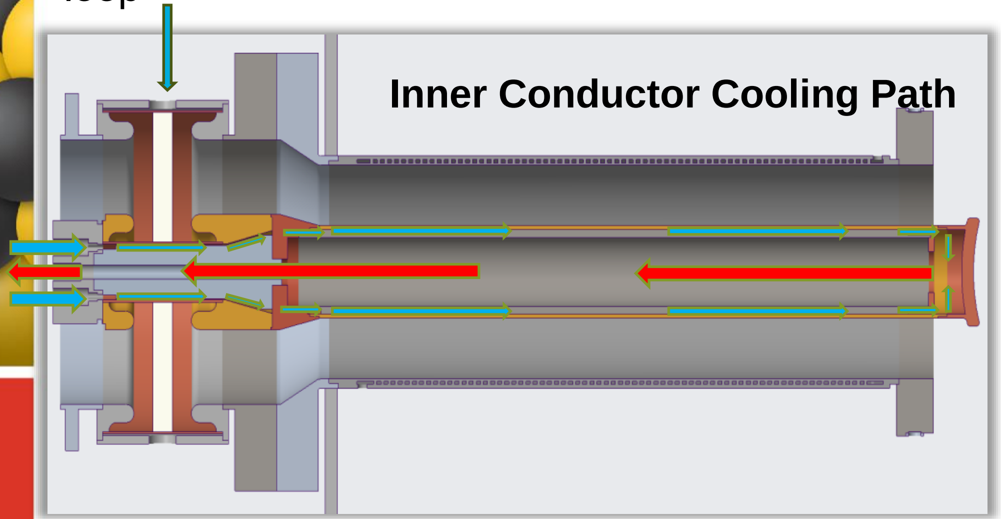


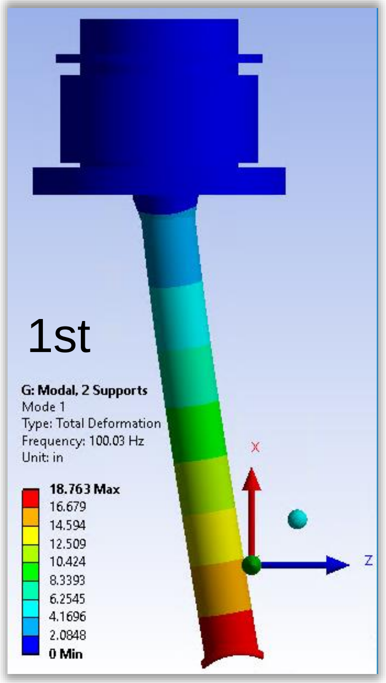
Thermal and mechanical design

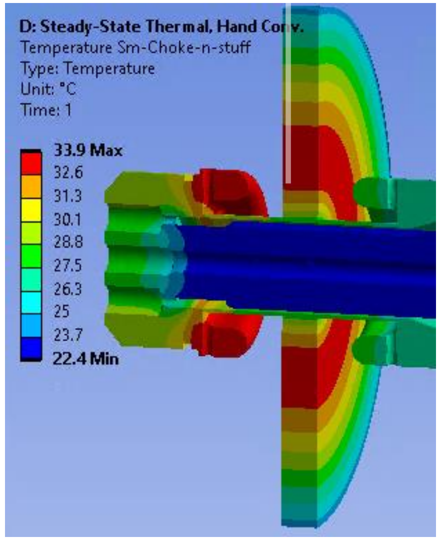
- Water cooling for inner conductor and window.
- RF thermal simulation
  - 1 MW power input
  - Conservative thermal film coefficient
- Temperature difference in the ceramic is 10 degree.
- Highest temperature of 40 C is at uncooled flanges.
- Choke tip highest temperature is 34 C.
- Al_2O_3 temperature ranges from 24 C to 34 C
- 1st mechanical modal frequency is 100 Hz



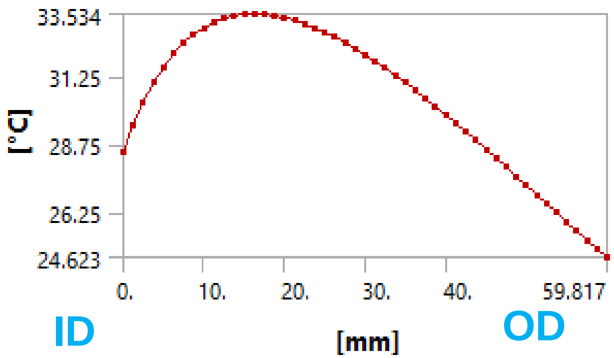
Water cooling loop



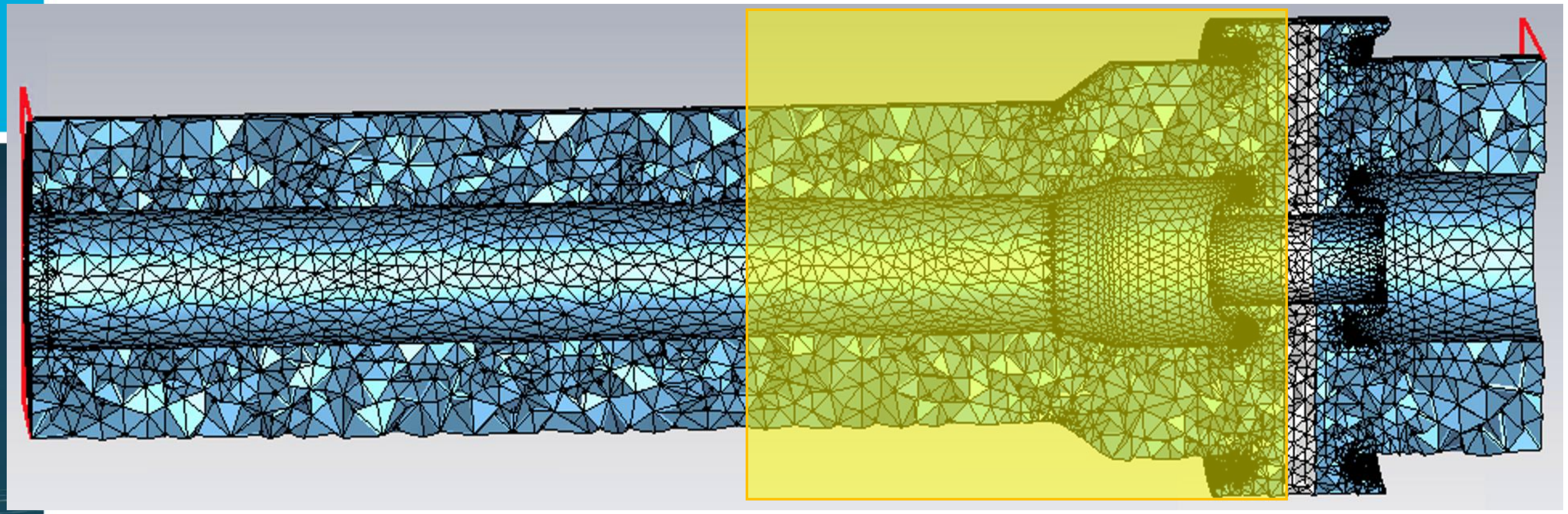




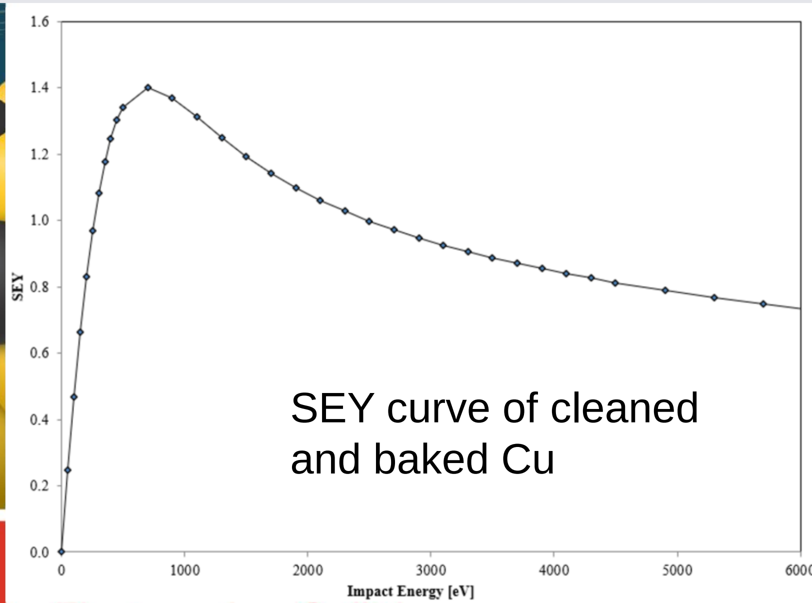
Centerline temp of Al2O3

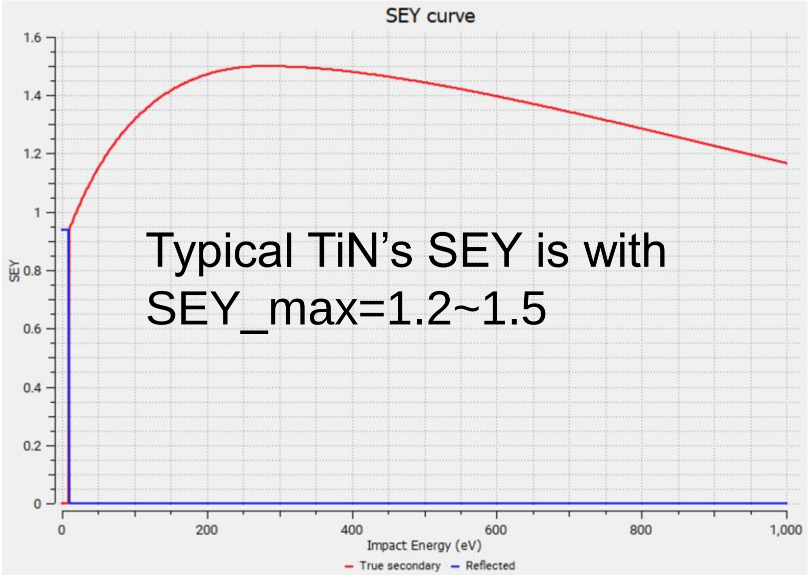


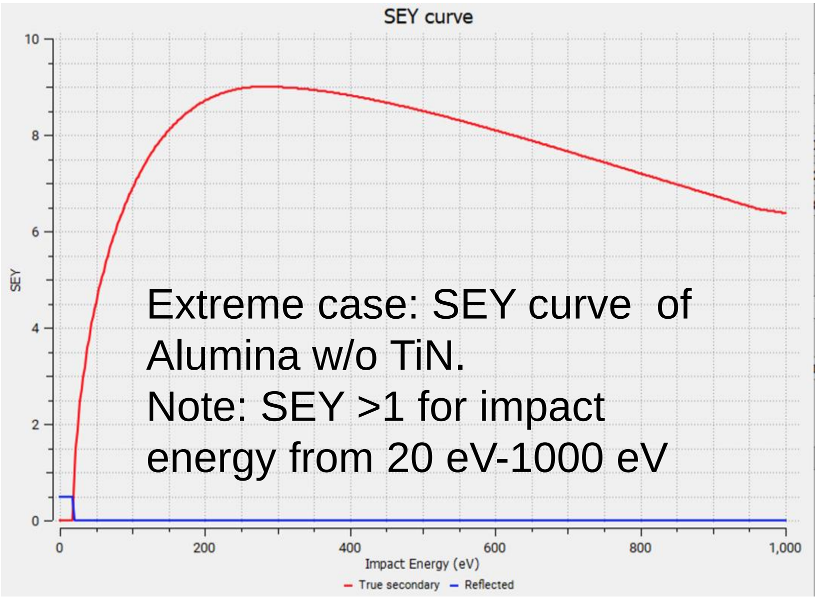
Multipacting Simulation with SPARK3D



- Mulitpacting simulation in two regions: vacuum side
- Multipacting simulation was carried out with and w/o DC bias.
- In reality, a DC bias will provision for application if we need.

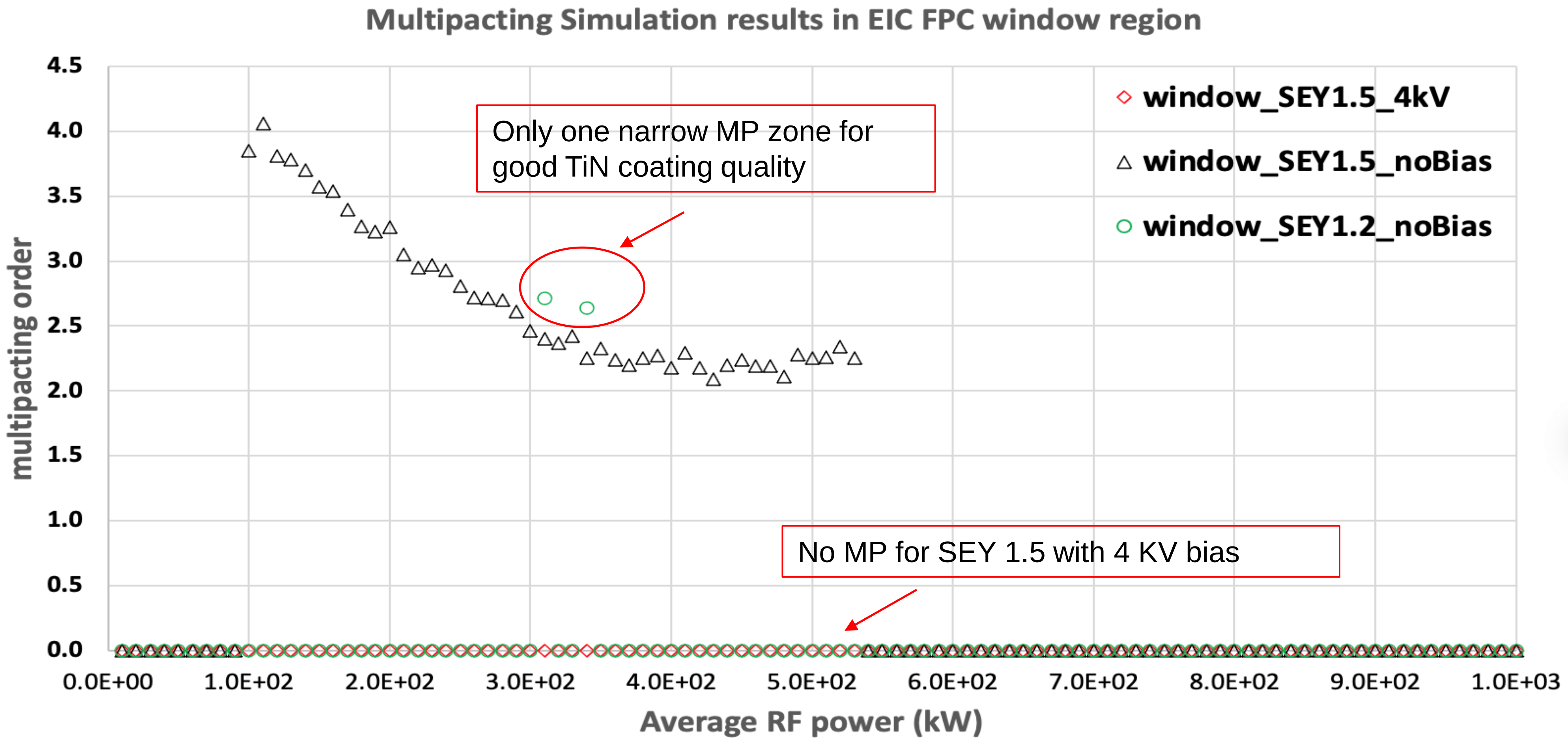






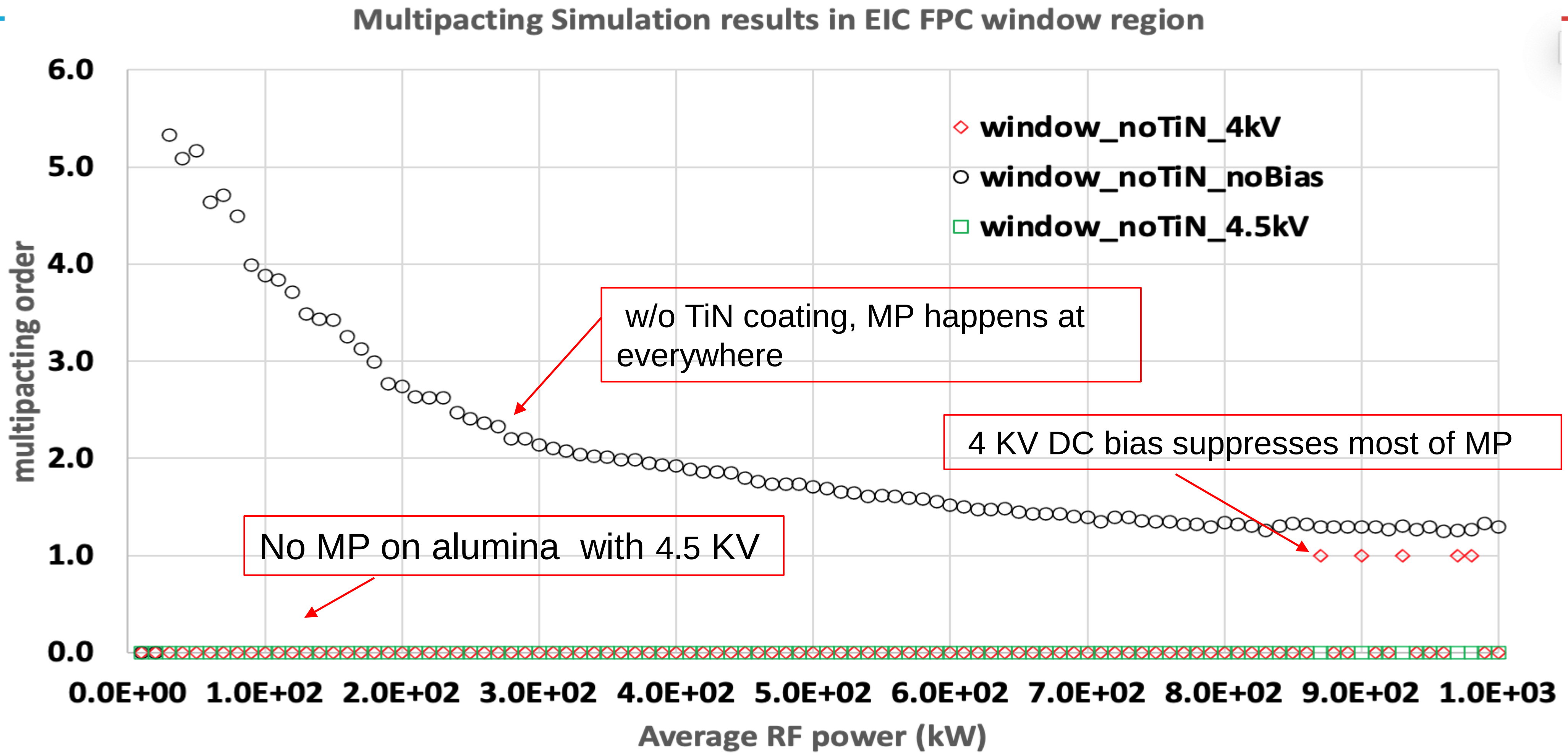
- There will be SEY measurement results on the samples in the later slide

Multipacting in Window Region: Typical TiN SEY



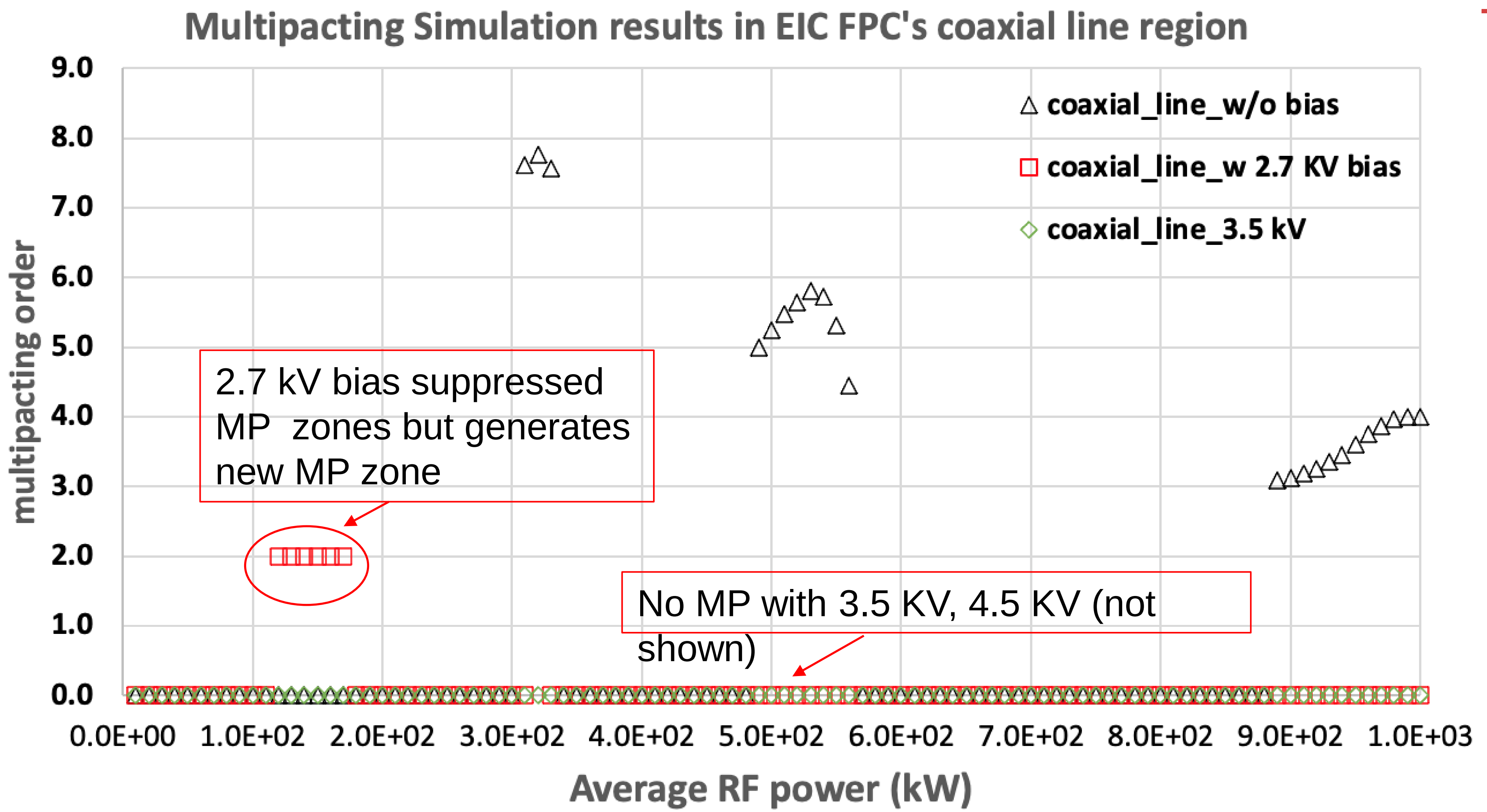
- With SEY_max=1.2, only one narrow MP zone at 310, 330 kW, no bias is needed.
- With SEY_max=1.5, a wide MP zone spans from 100-520 kW. However, when 4 kV bias is applied, there is not MP.

Multipacting in Window Region: No TiN Coating (SEY_max=9)



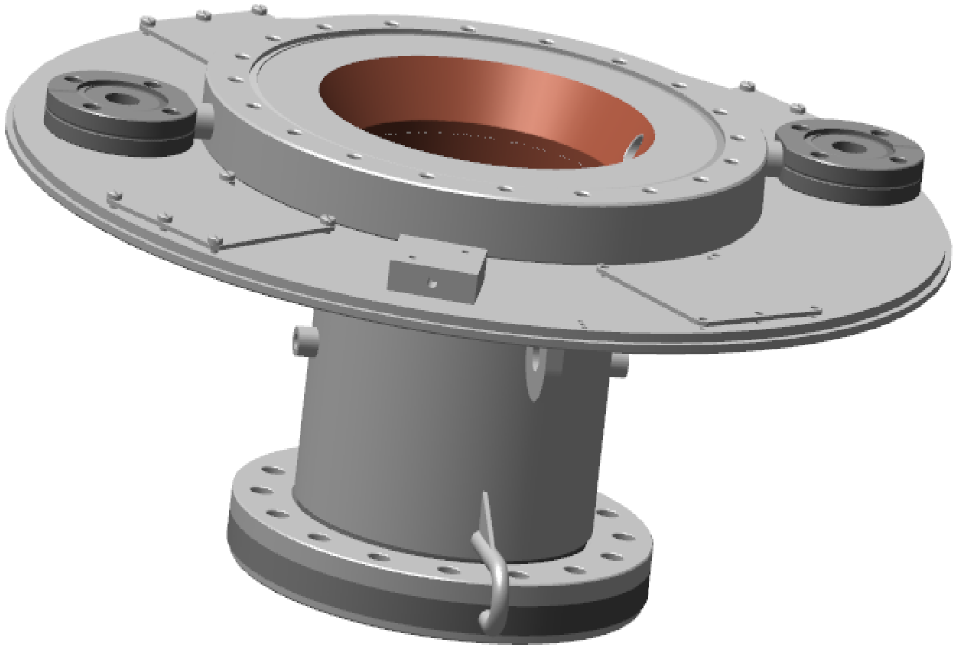
- Without TiN coating, multipacting happens everywhere, due to broad SEY>1 for all impact energy.
- With 4.5 kV DC bias, MP in the window area will be suppressed.

Multipacting in Coaxial Line Region



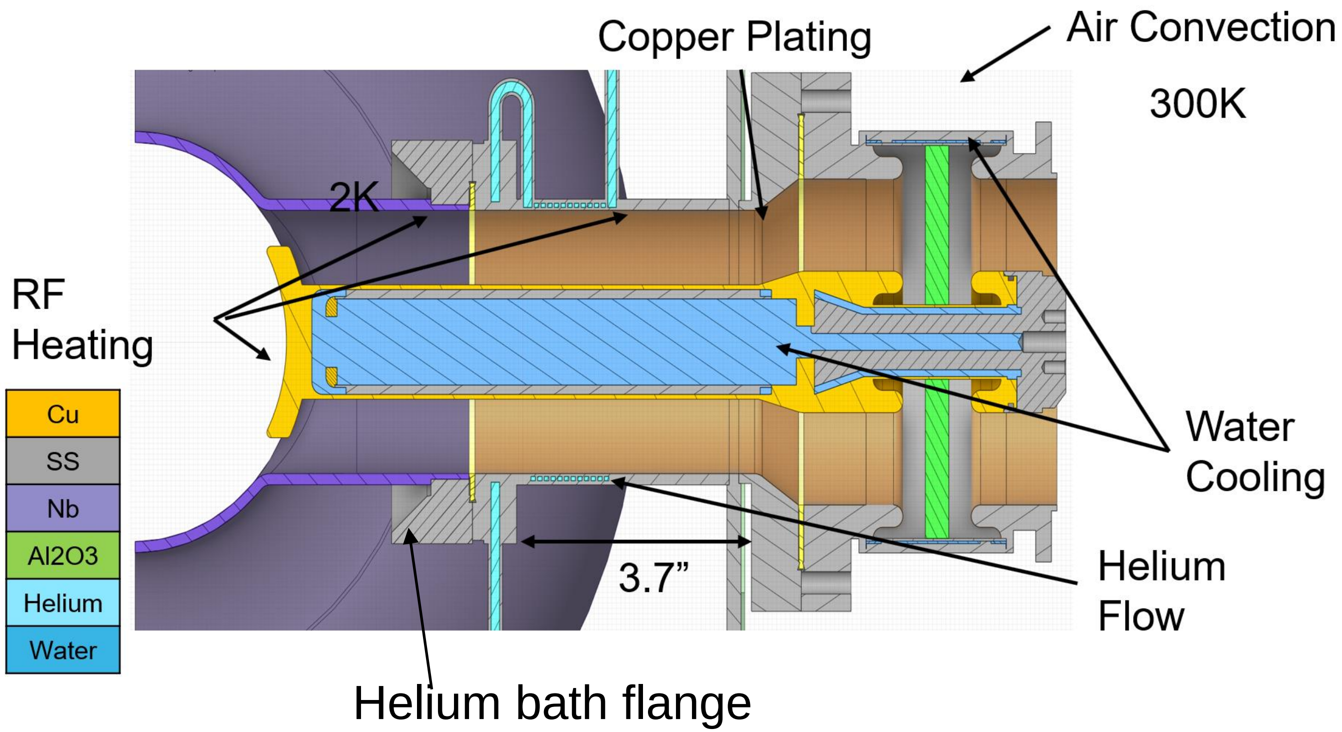
- When above 3.5 ~4.5 kV DC bias is applied, there is no MP in coaxial line region.
- So a 4.5 kV DC bias will be ready to be applied, if needed, to suppress all multipacting.

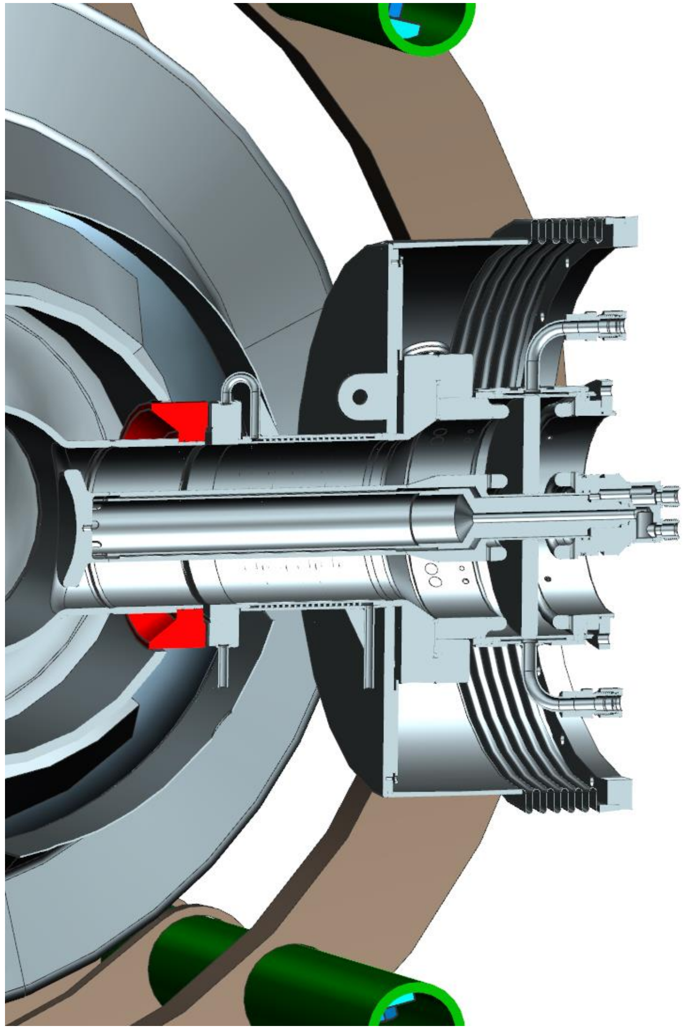
Vacuum side outer conductor



Vacuum side outer conductor

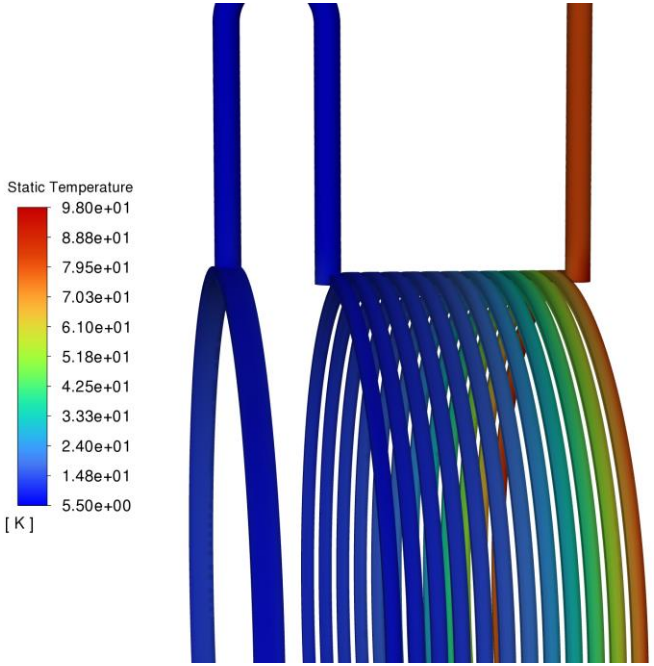
- Challenge:
  - Compact space: Short distance between 2 K to 300 K
  - Large RF heating (especially in some operation scenarios)
  - FPC flange is the LHe boundary, i.e, the FPC tube on the cavity is immersed in the LHe.





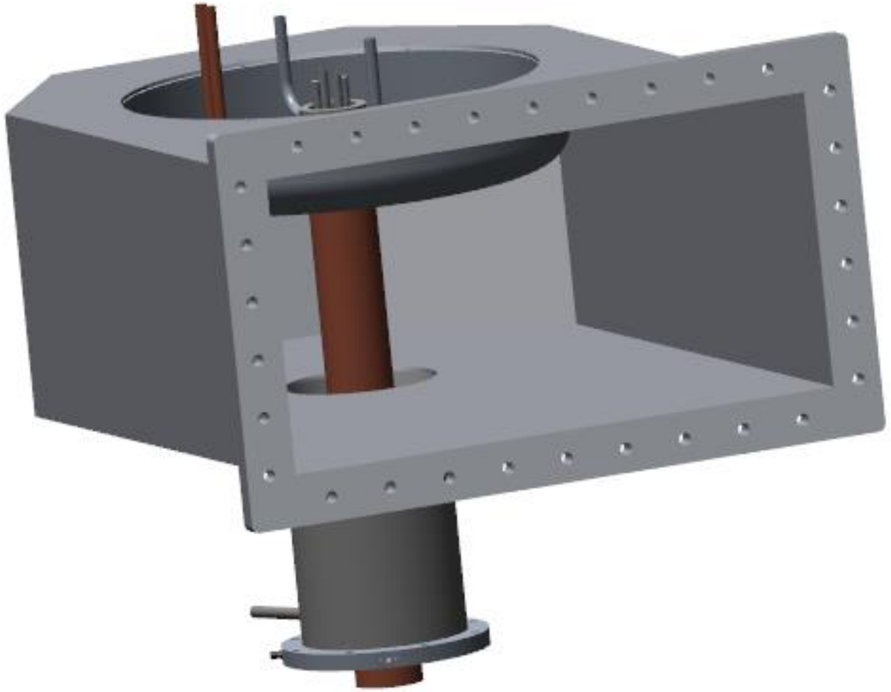
Thermal design results

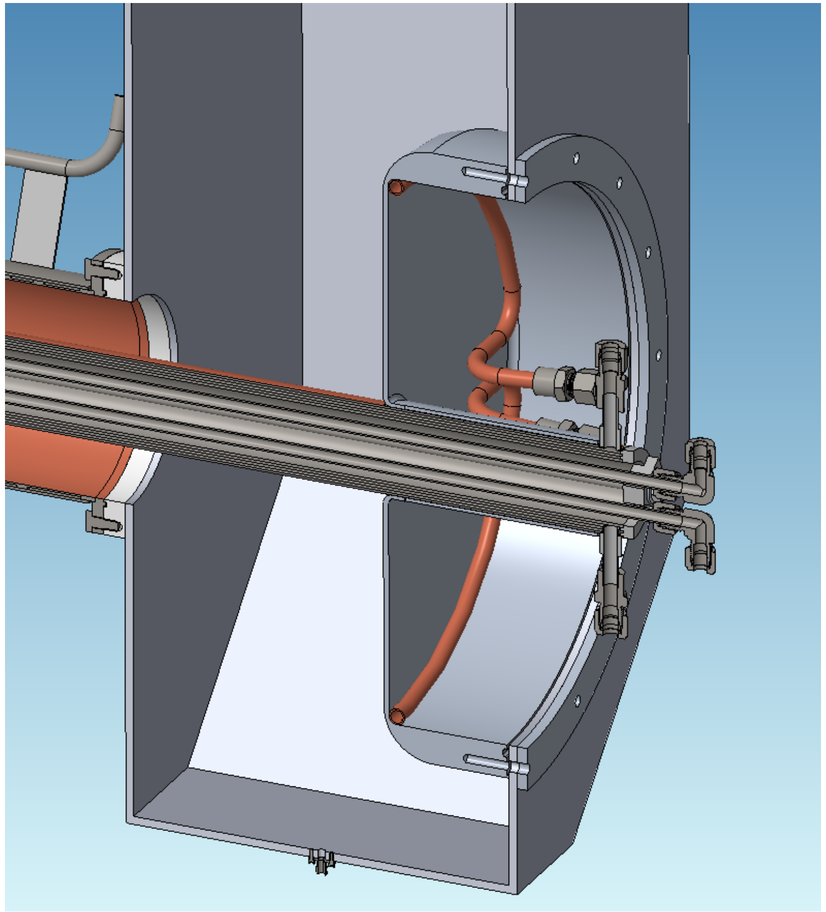
- 5.5K helium, 3.3atm, 300mg/s inlet flow
- 400kW RF power (10GeV operation voltage and 2.5A average beam current)
- 4W radiation load, 20W heaters
- Shielded seal provides direct path between warmer flange and niobium
- Assuming perfect contact for both knife edge and RF shield. No contact between flanges



- All results meet the requirements
- 6.1K niobium temperature @300mg/s trace flow
- Lowest temperature at bellows flange: 298 K
- 8.2W heat flow to 2K
- 80K outlet temperature, 287kPa pressure
- 61m/s max velocity in the channel

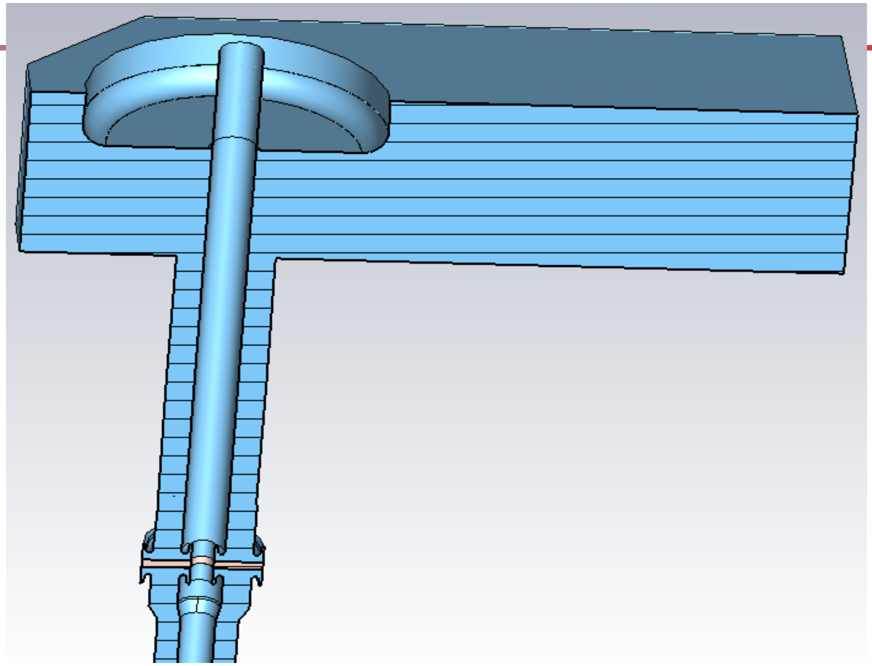
Airside components

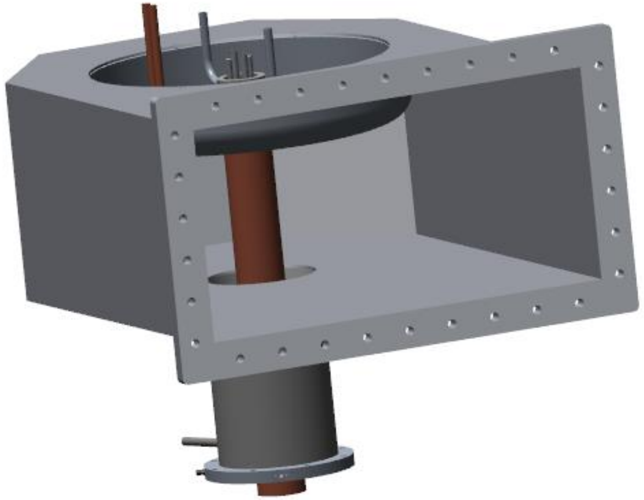




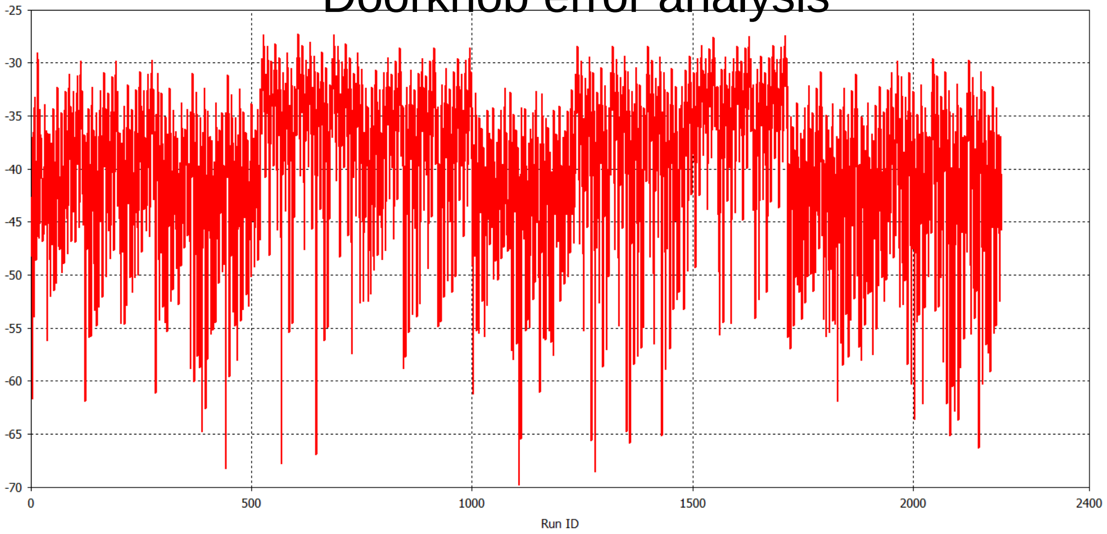
FPC air side components

- FPC Airside Components:
  - FPC airside length needs to cooperate the limit space in the tunnel
  - Doorknob is optimized for RF transmission, and we are working on engineering design based on error analysis results.

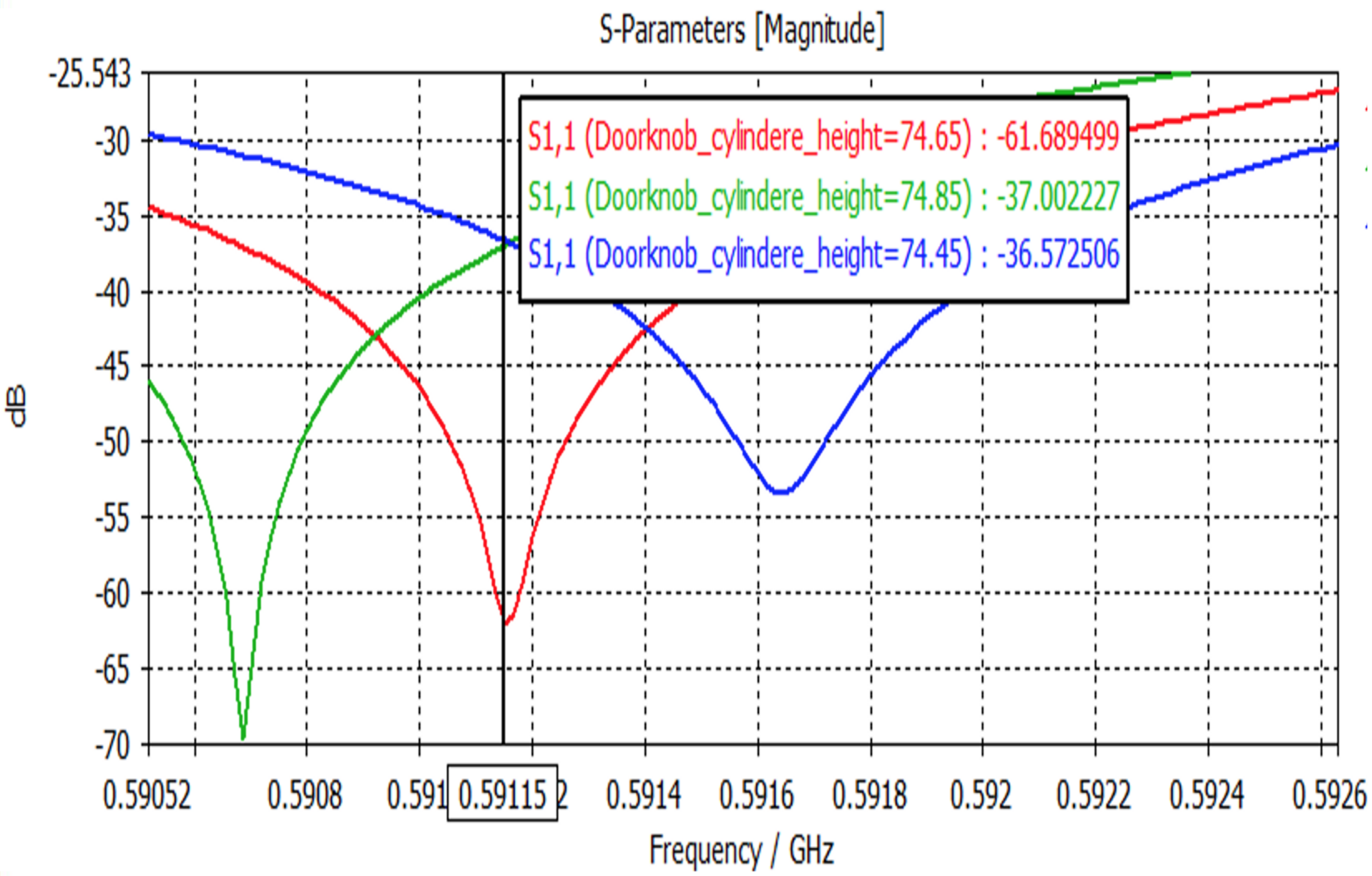




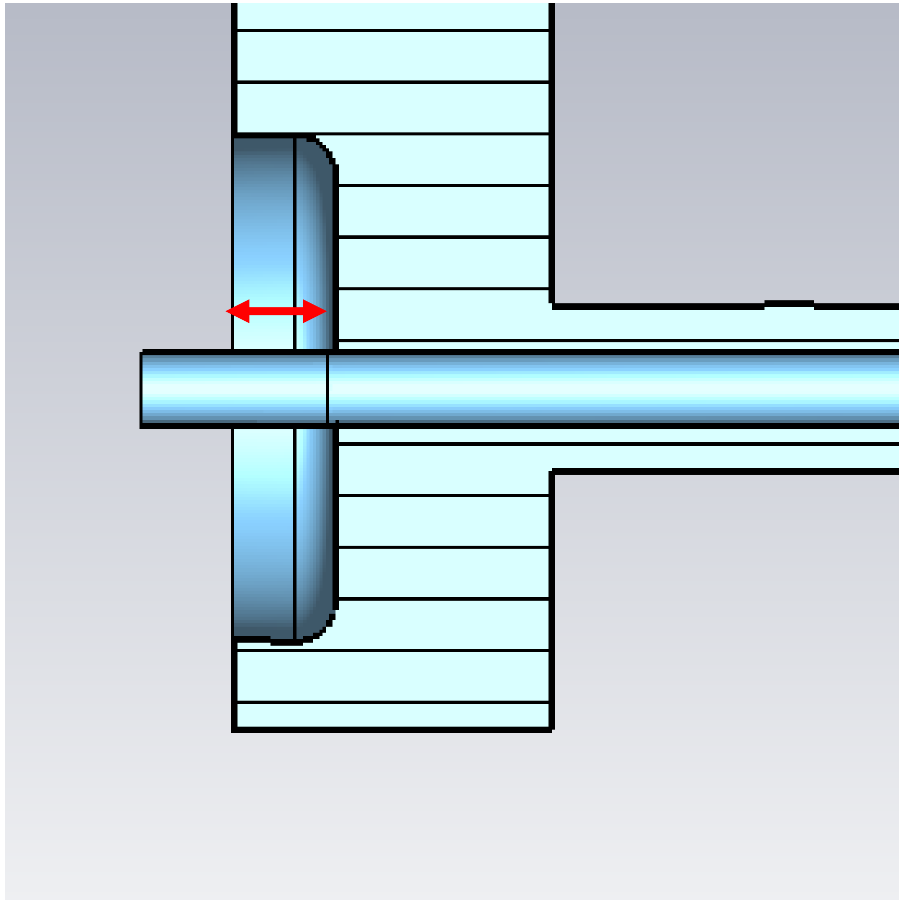
Doorknob error analysis



Doorknob tuning mechanism

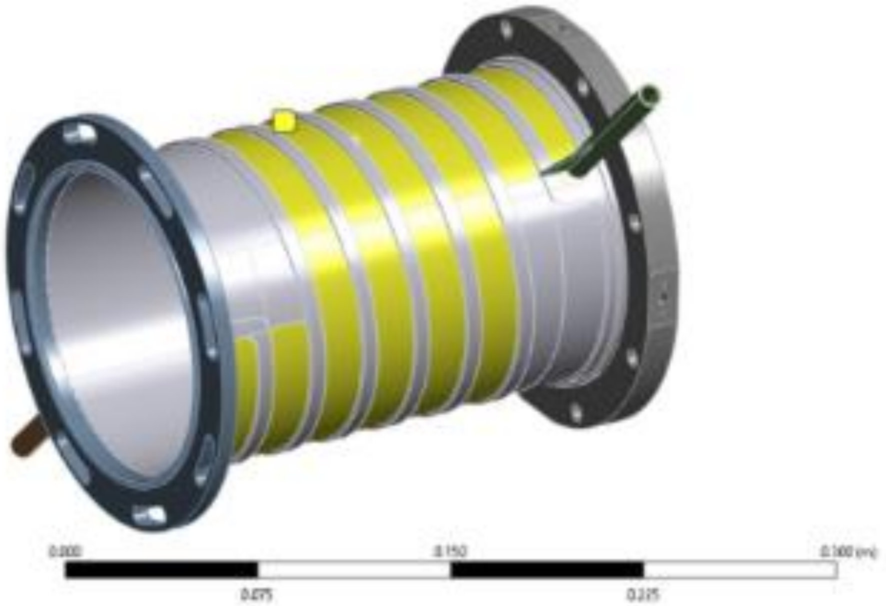


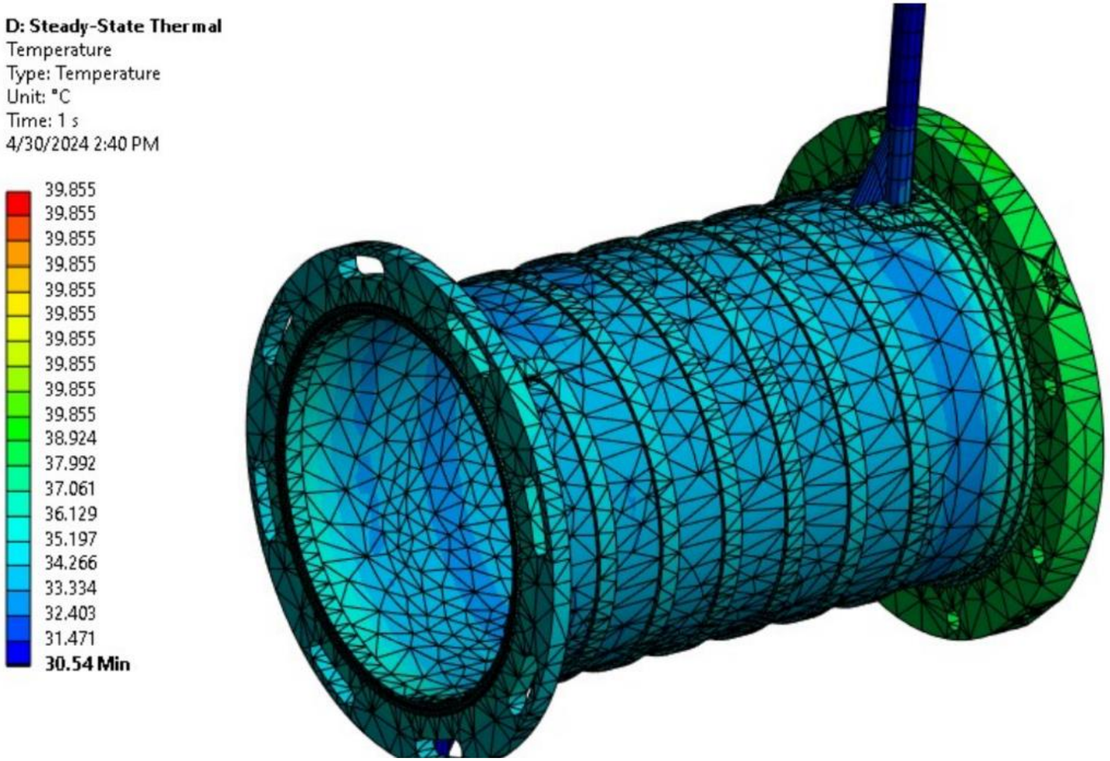
- Doorknob cylinder height
  - Red: 74.65
  - Green 74.65+ 0.2 (mm)
  - Blue: 74.65-0.2



Airside outer conductor

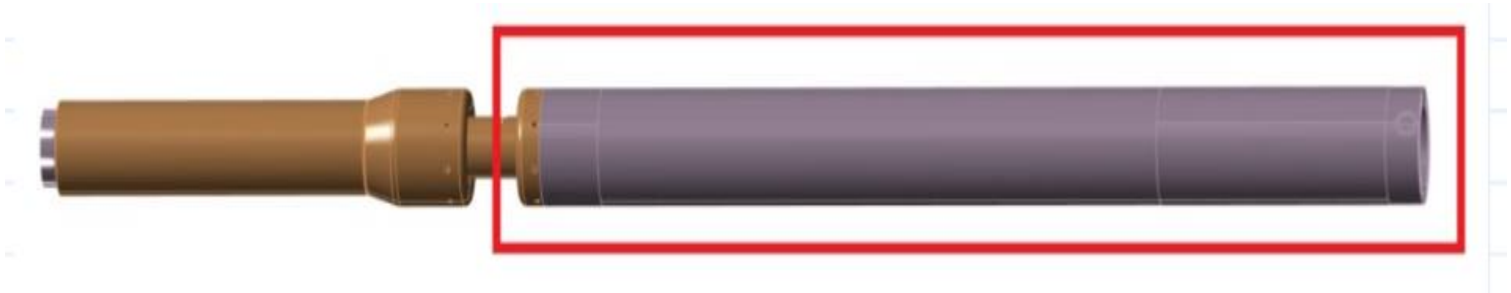
- Water cooling.
- 150 W RF power dissipation

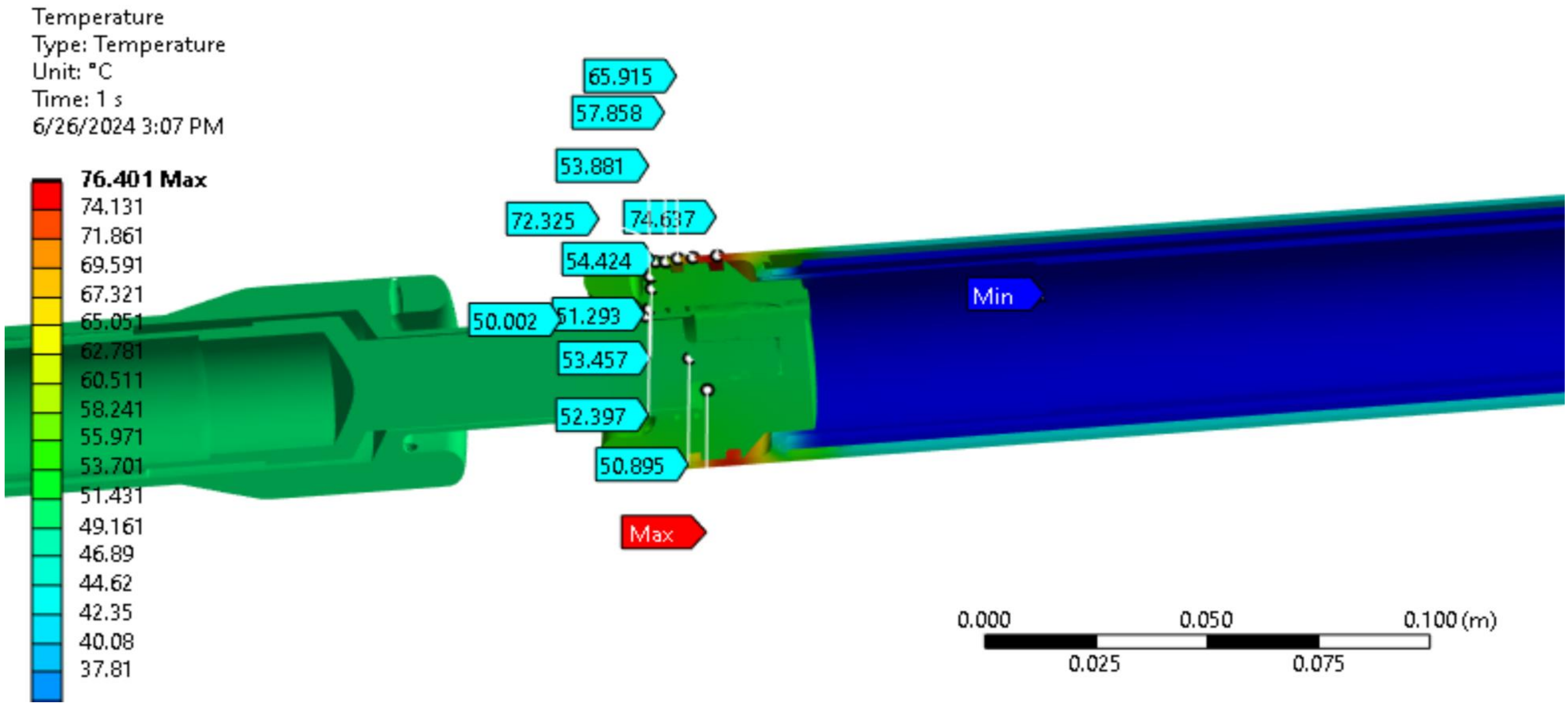




Airside inner conductor

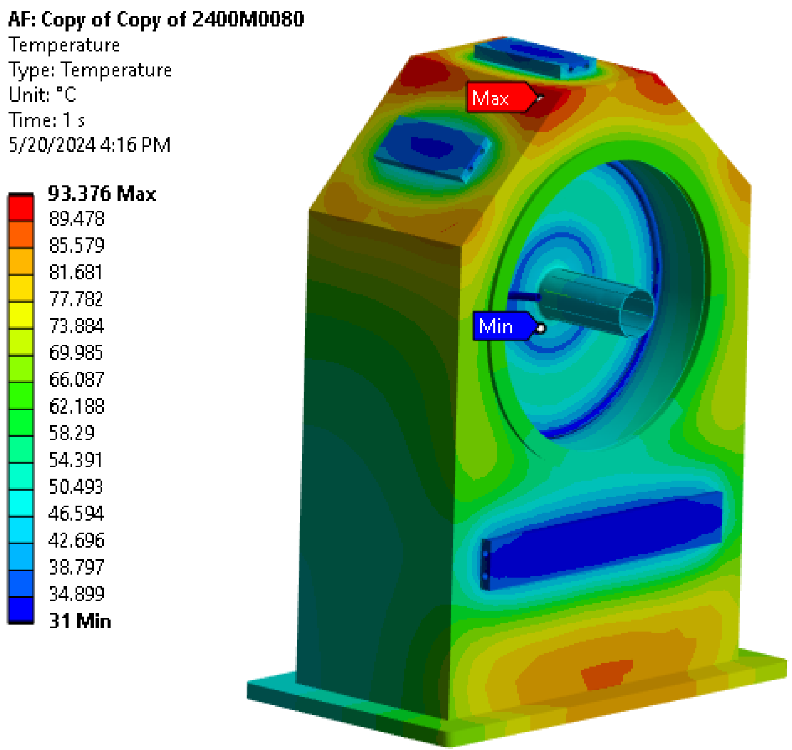
- Challenge to bring water to the end of the airside inner conductor.
- 1500 W of RF dissipation (With RF FODO operating scenarios, RF dissipation is ~10 times smaller).





Water cooling for doorknob and waveguide

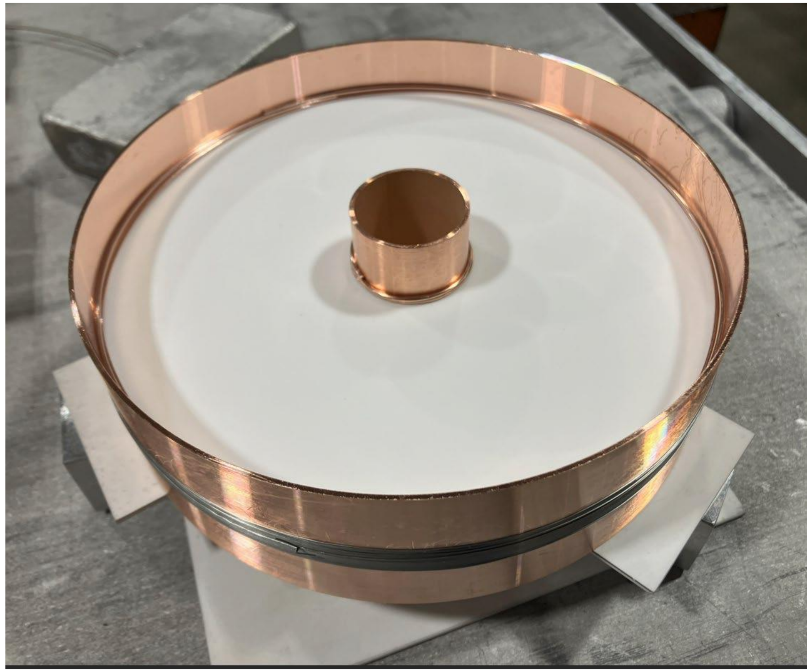
- Water cooling design is capable of up to 5.4 kW RF dissipation.
- RF dissipation will be only ~500 W, with recent determination of the operation mode (focus-defocus).

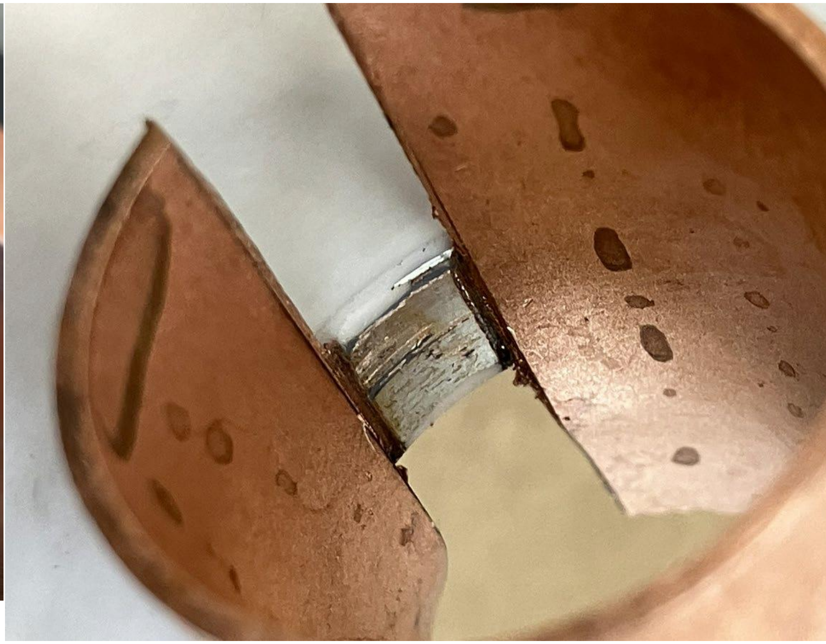
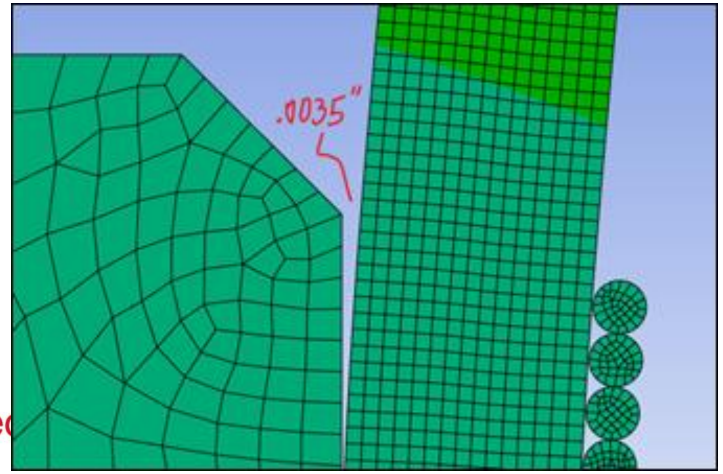


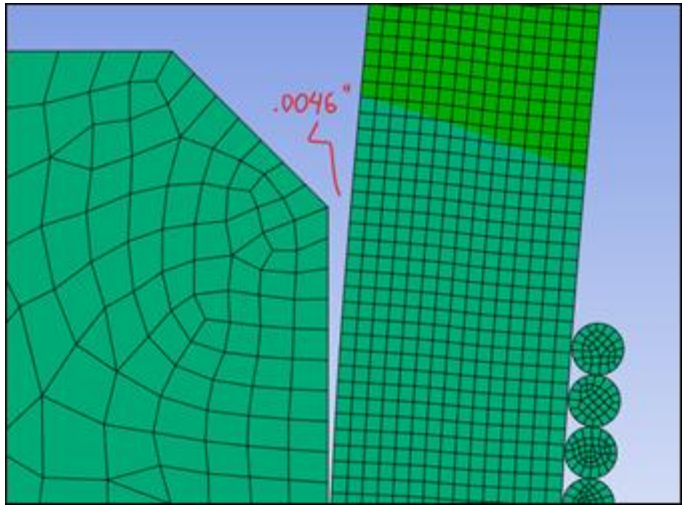
Prototype FPC manufacture progress

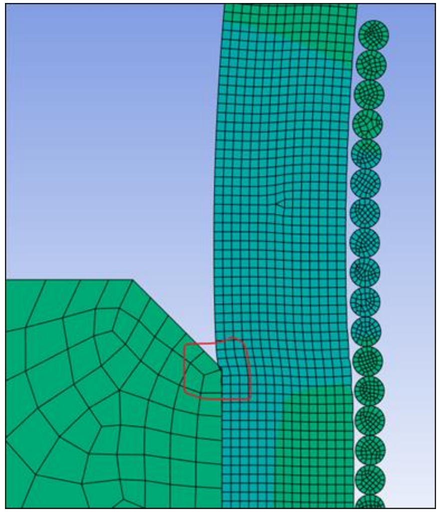
- RF window brazing recipe development
- TiN coating sample measurement
- Brazing and EB welding

RF window brazing recipe development

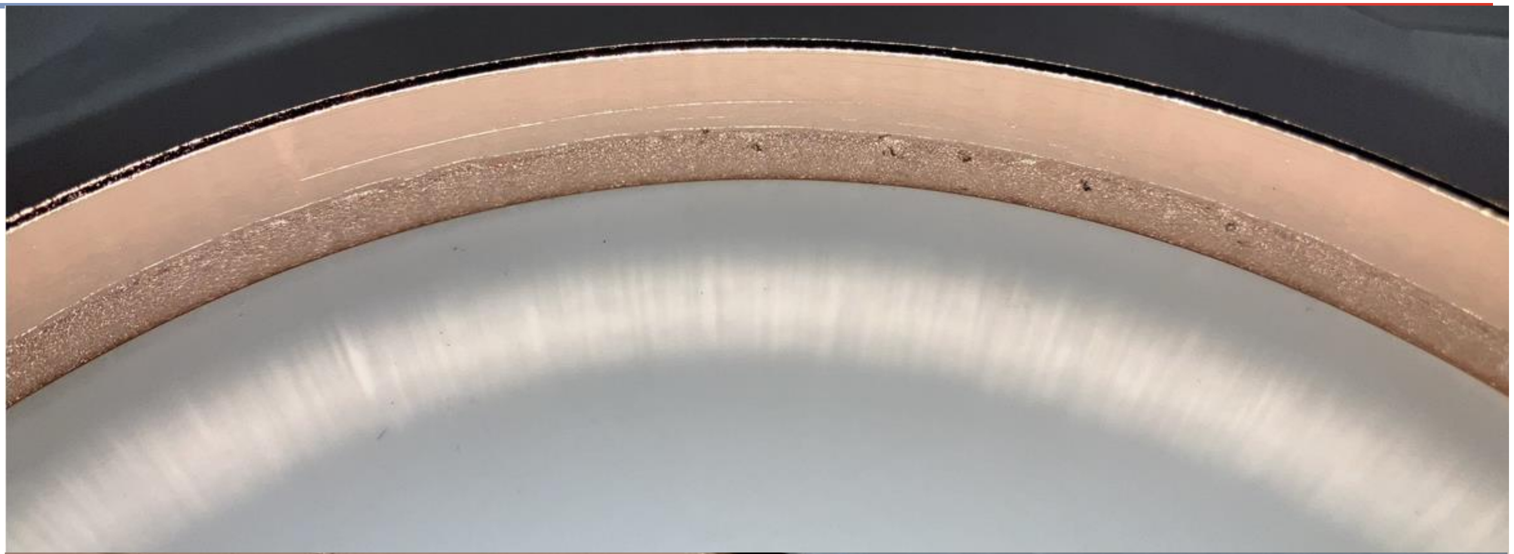






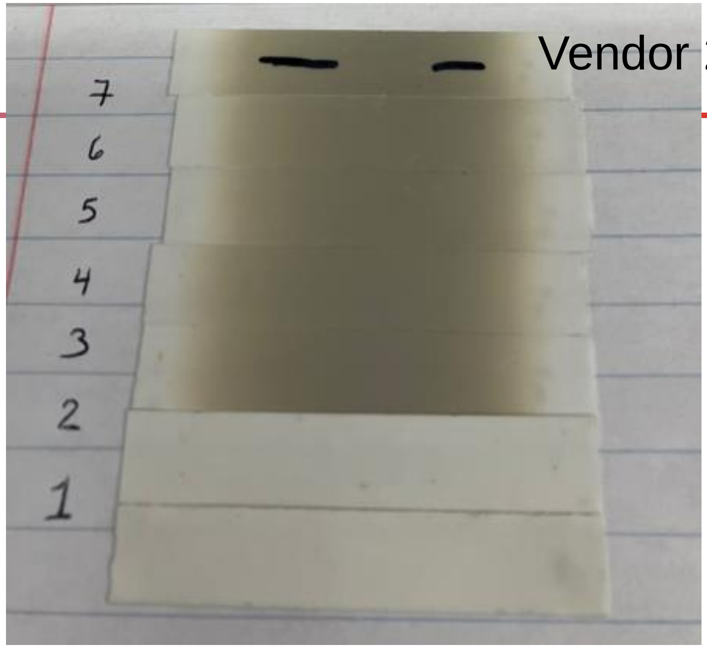
Successfully brazed RF window

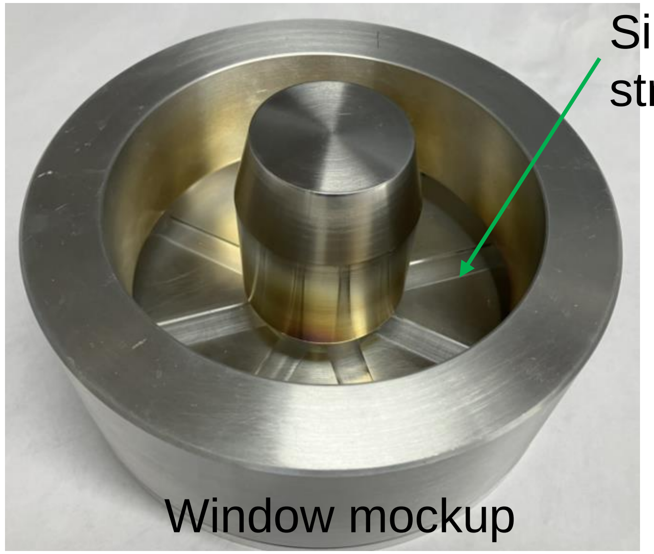


Question: which side is preferred for the vacuum side?

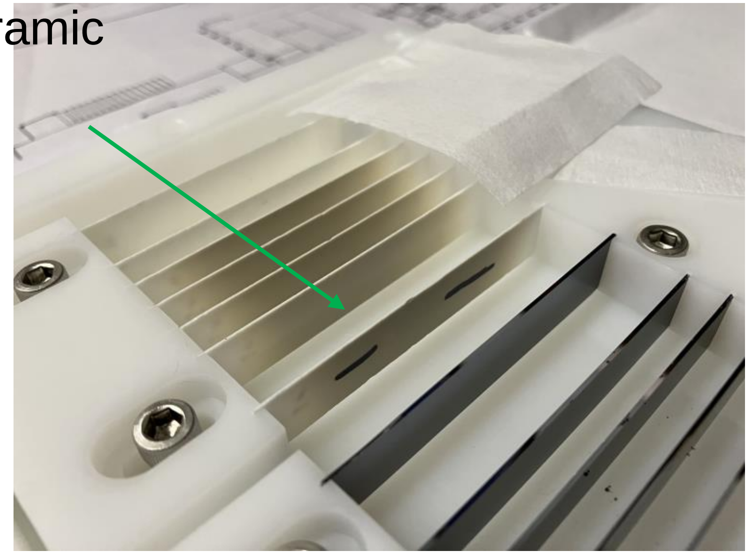
TiN coating study (1)

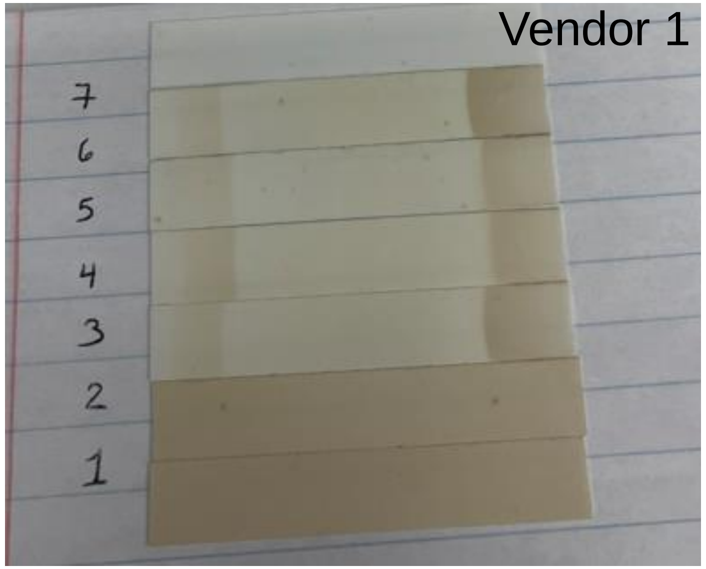
- TiN coating will be coated on ceramic vacuum side.
- TiN coating study
  - TiN coating on a window mockup structure.
  - Coated by two vendors
  - Measure SEY
  - Measure species on the TiN coating
  - Measure TiN coating thickness



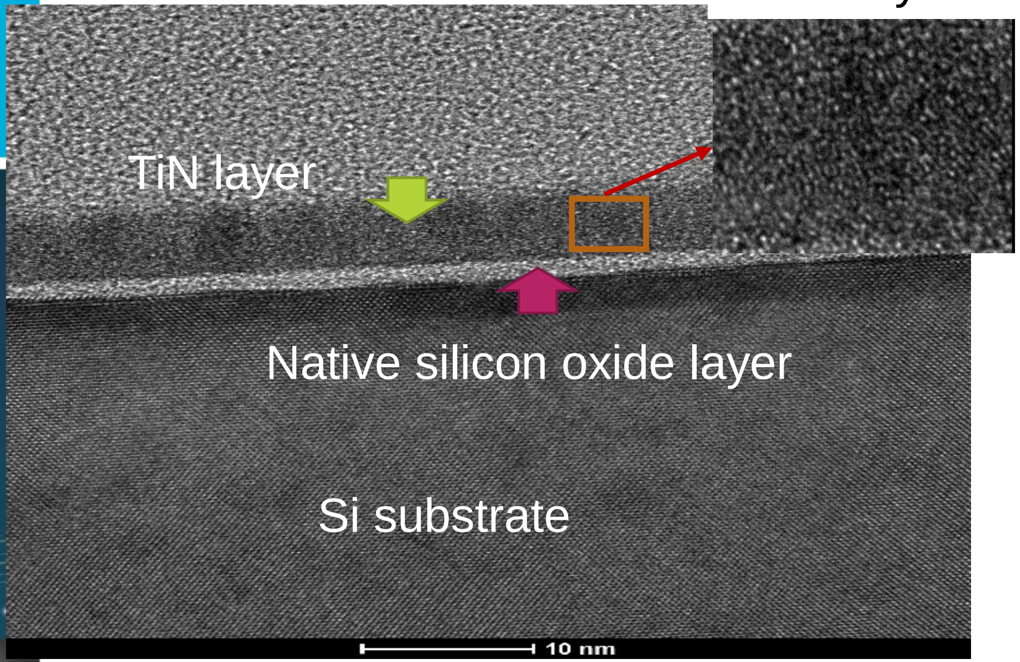


Si and Ceramic stripe



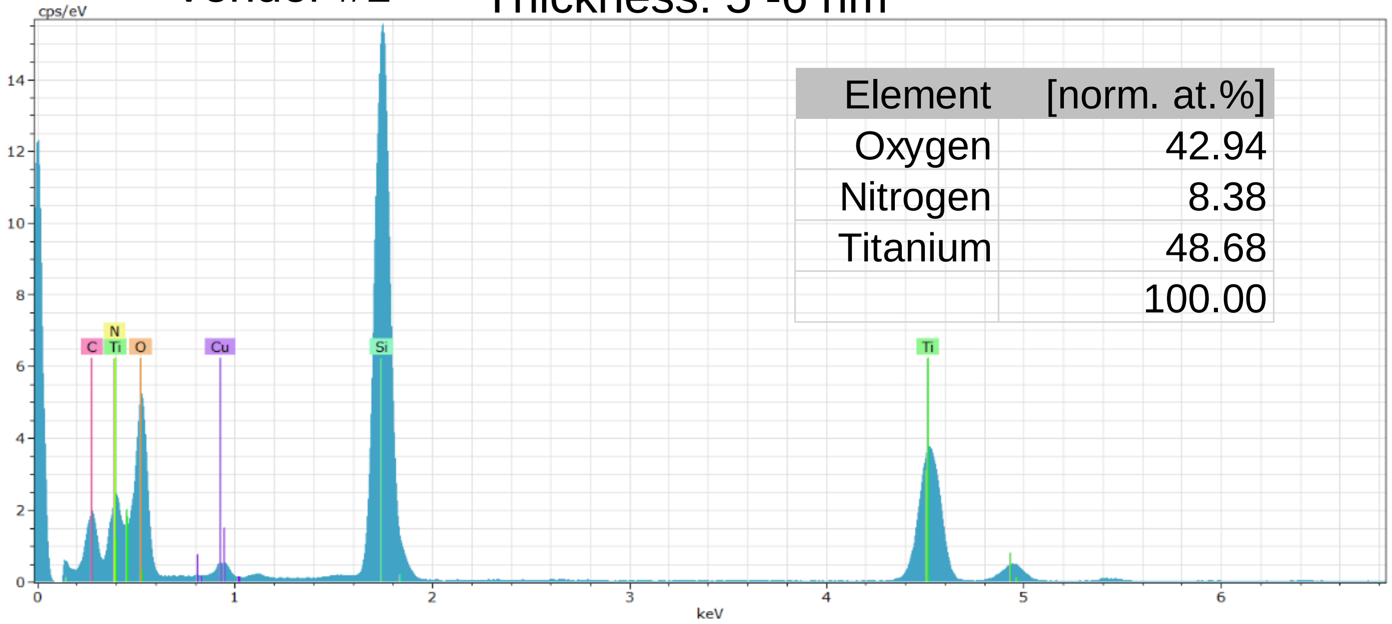


TEM analysis on TiN coating



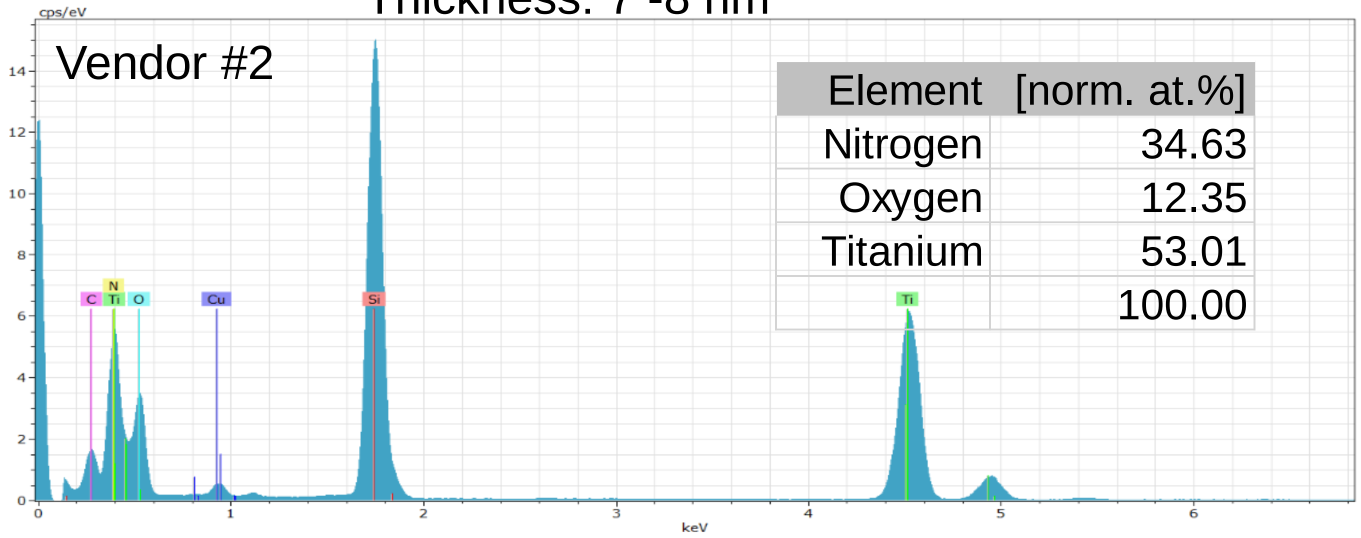
- TiN coating analysis by BNL Center for Functional Nanomaterials (CFN) with transmission electron microscopy (TEM)
- Similar TiN coating thickness from two vendors
- Both vendor got TixNiyOz, but with different composition.

Vendor #1 Thickness: 5 -6 nm



Element	[norm. at.%]
Oxygen	42.94
Nitrogen	8.38
Titanium	48.68
	100.00

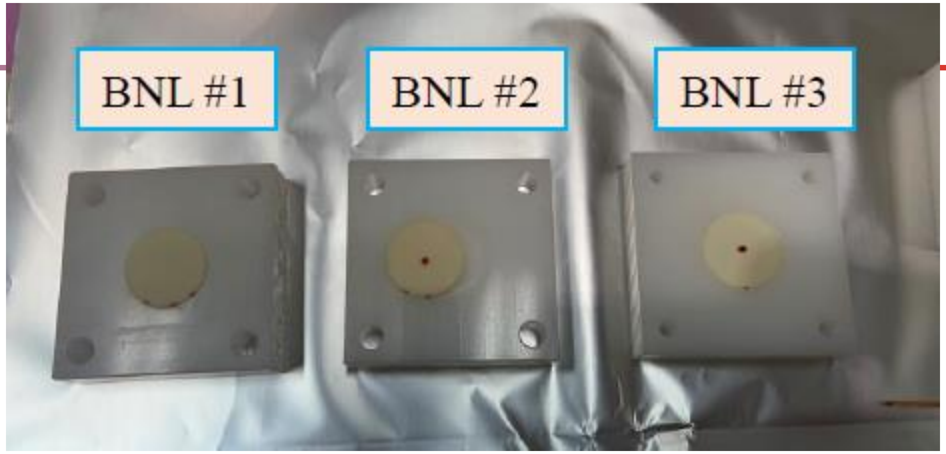
Thickness: 7 -8 nm Vendor #2

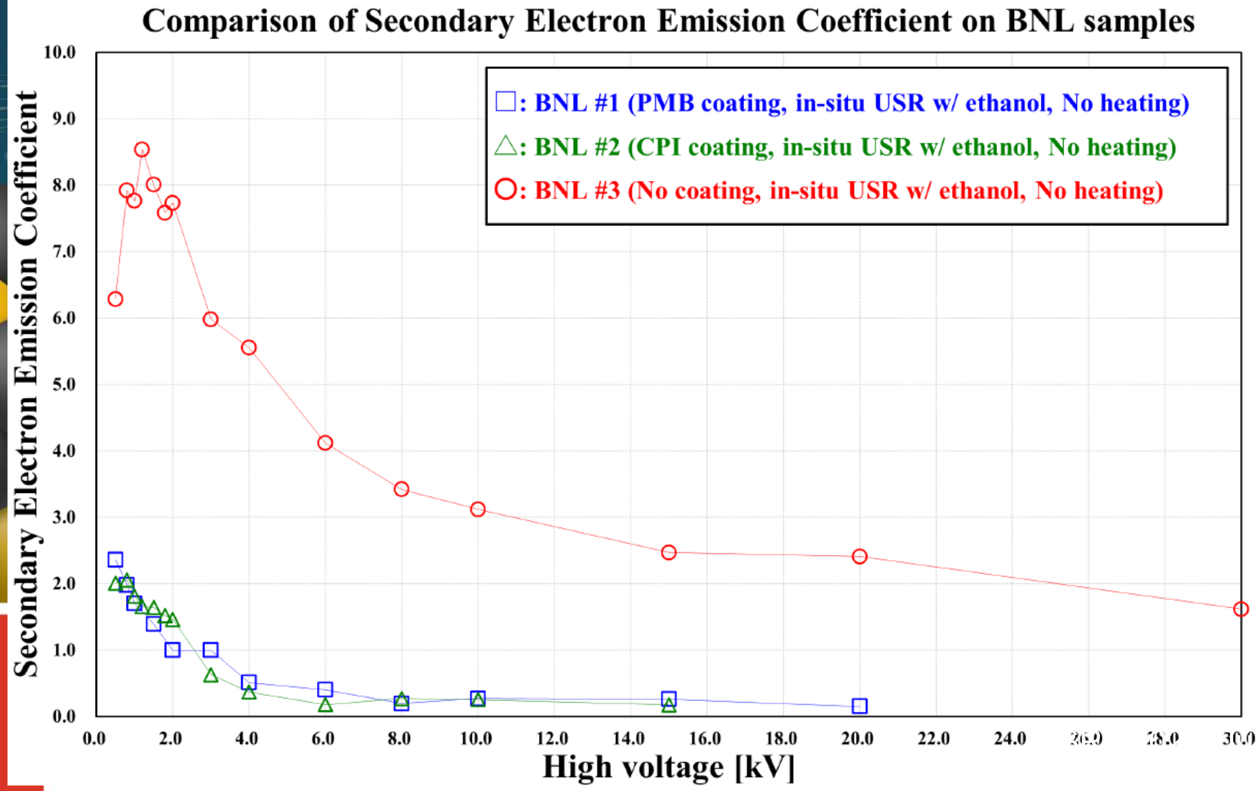


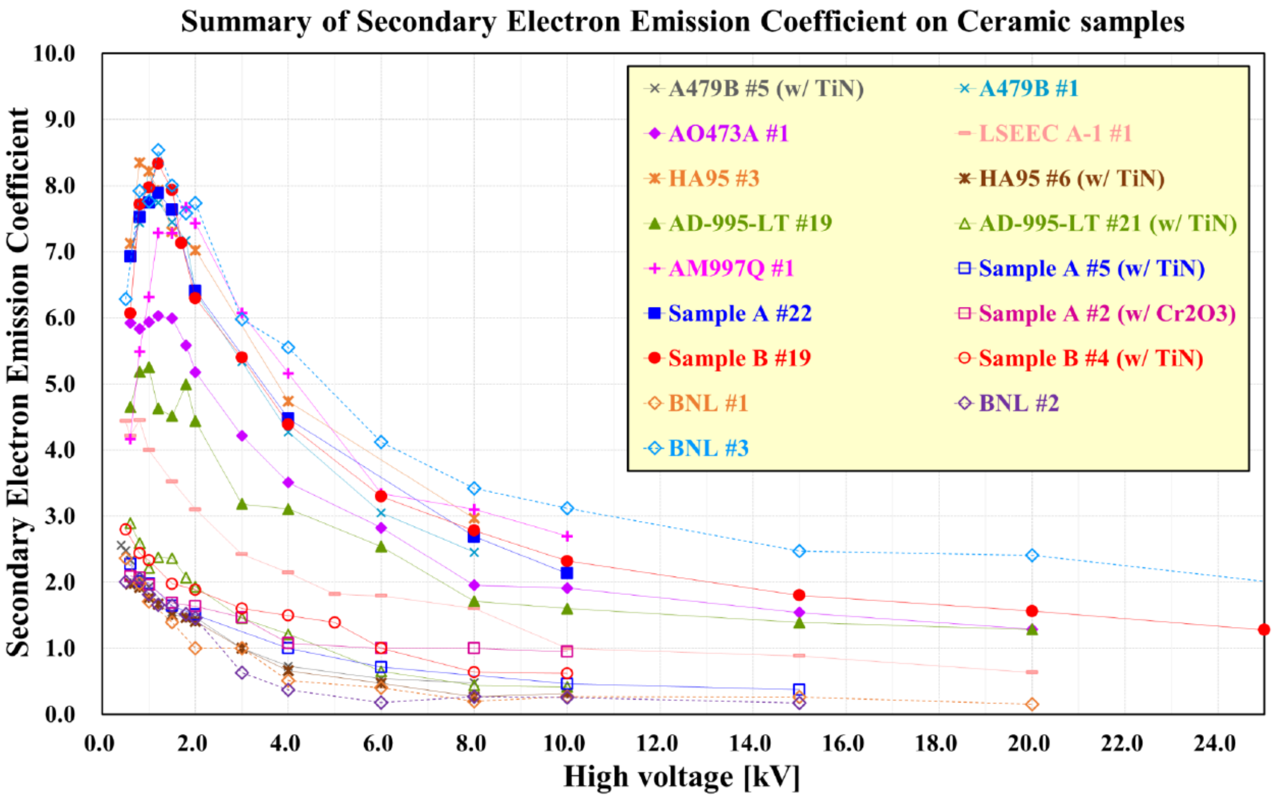
Element	[norm. at.%]
Nitrogen	34.63
Oxygen	12.35
Titanium	53.01
	100.00

TiN coating SEY measurement

- Three samples sent to KEK (Kirk Yamamoto, Thank you!) for SEY measurement
  - BNL#1 and BNL#2 were coated by vendors
  - BNL #3 was bare Al2O3
- Both vendors' SEY results are close to each other.

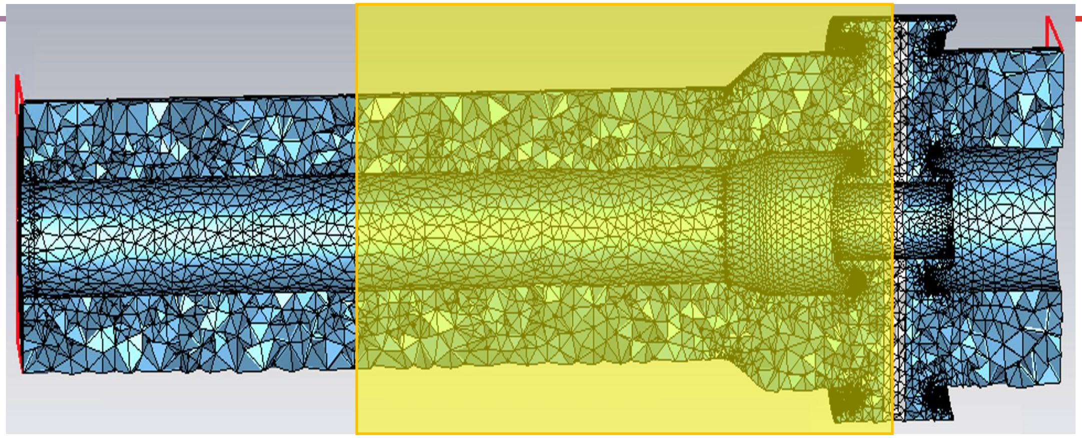


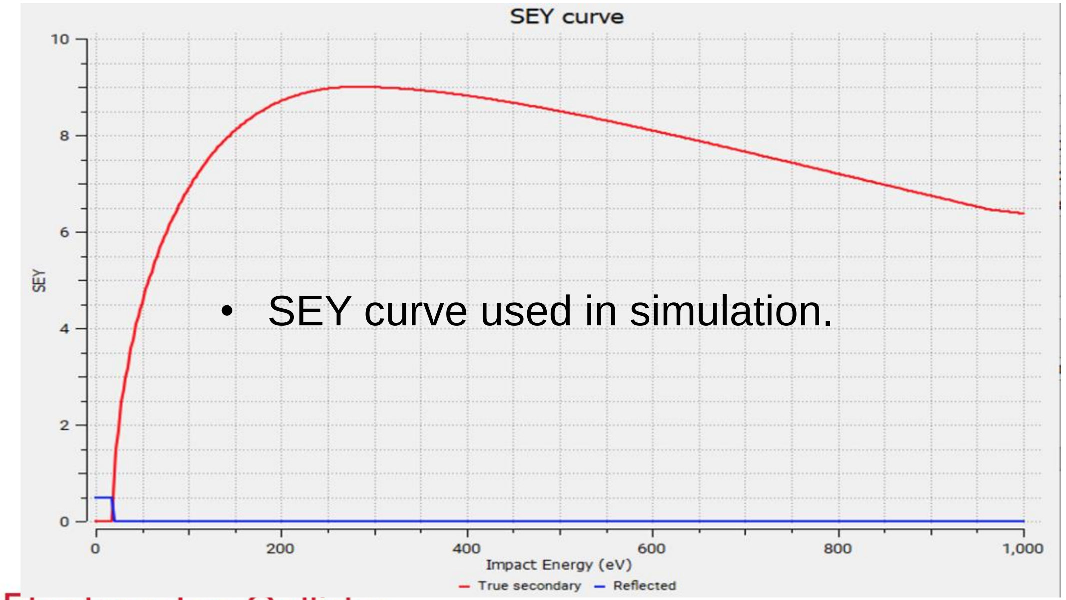




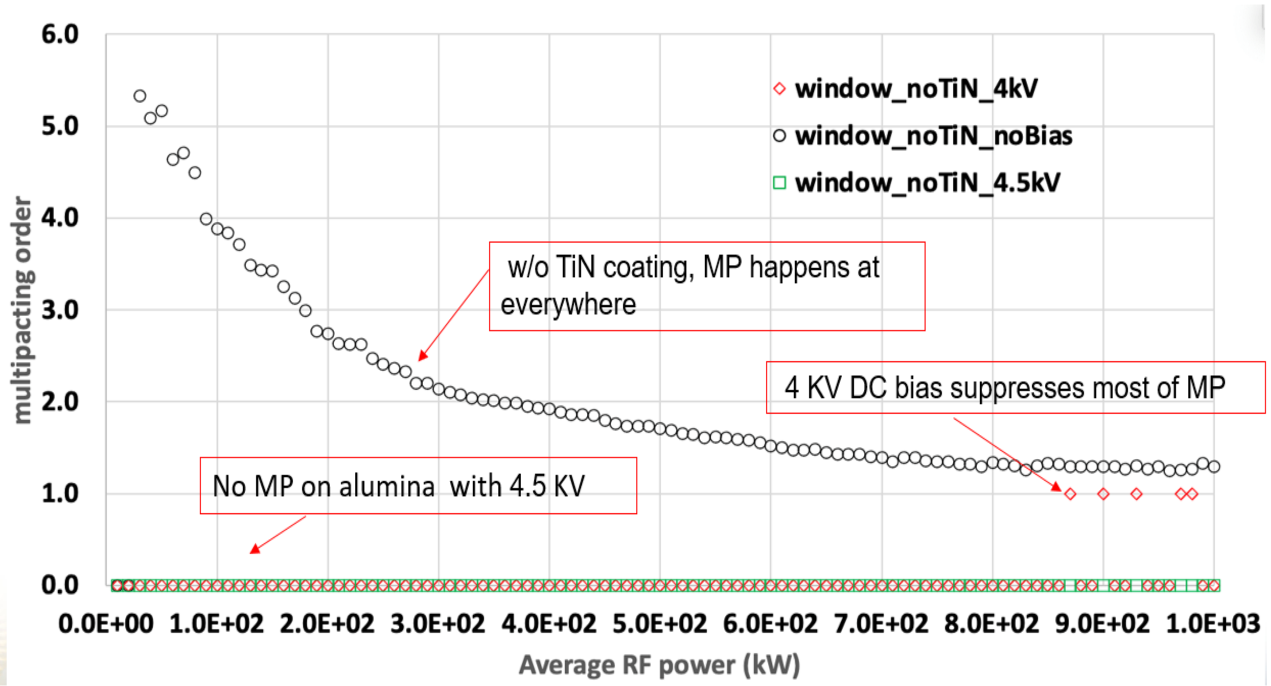
Multipacting simulation

- Conservative (worse than the measurement results) SEY curve was used for multipacting simulation.
- Multipacting simulation shows that multipacting will be fully suppressed (even no TiN coating on ceramic) with 4.5 kV DC bias applied.
- However, TiN will be coated on the ceramic.
- FPC test will start without bias.



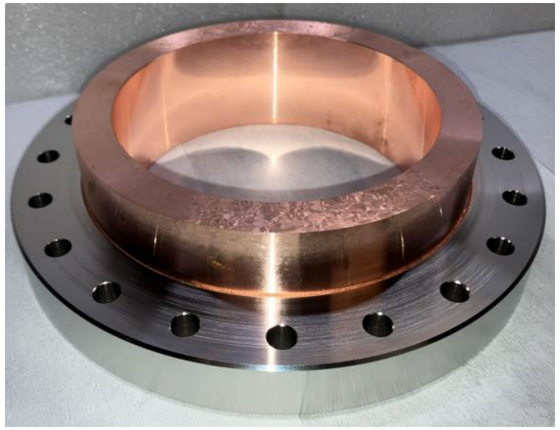
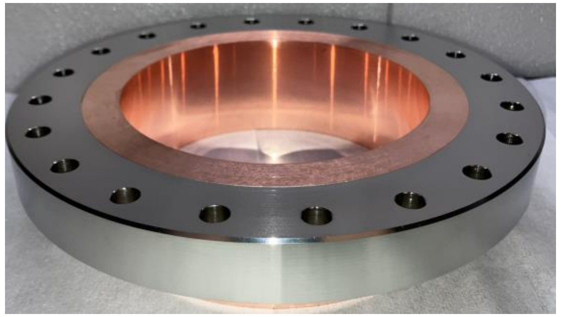


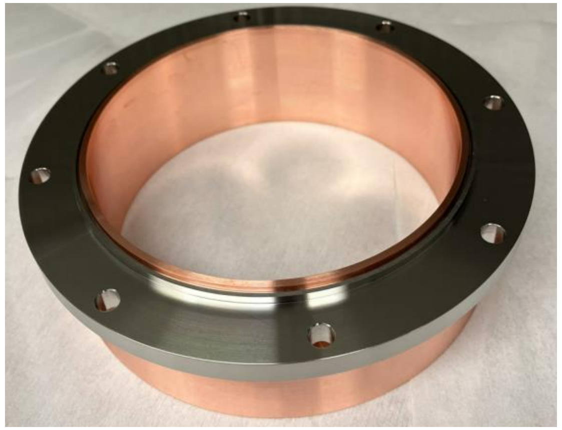
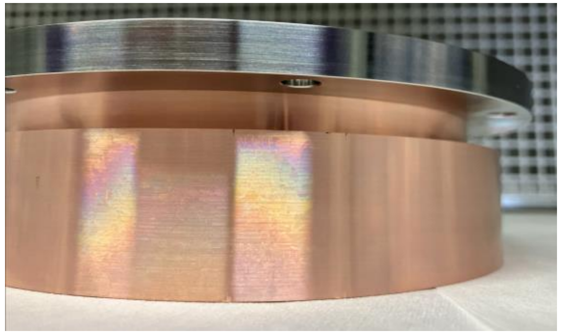
- SEY curve used in simulation.



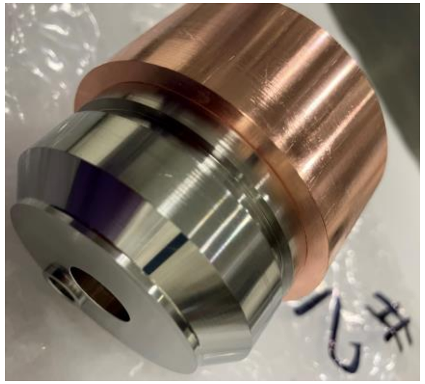
Window Manufacturing - Status


Water adapters

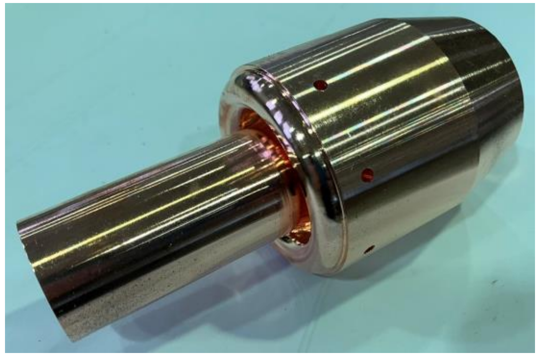
Vacuum-side Flange sub-assembly



Air-side Flange sub-assembly




Water supply/returns


Air-side Choke/Hub sub-assembly

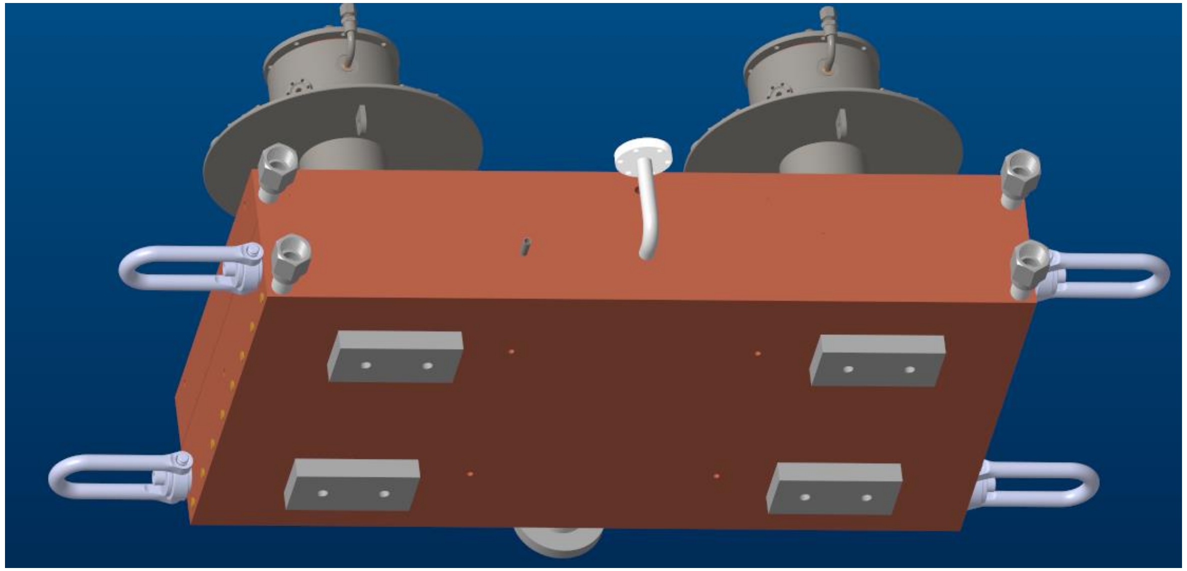

Antenna “Pringles”

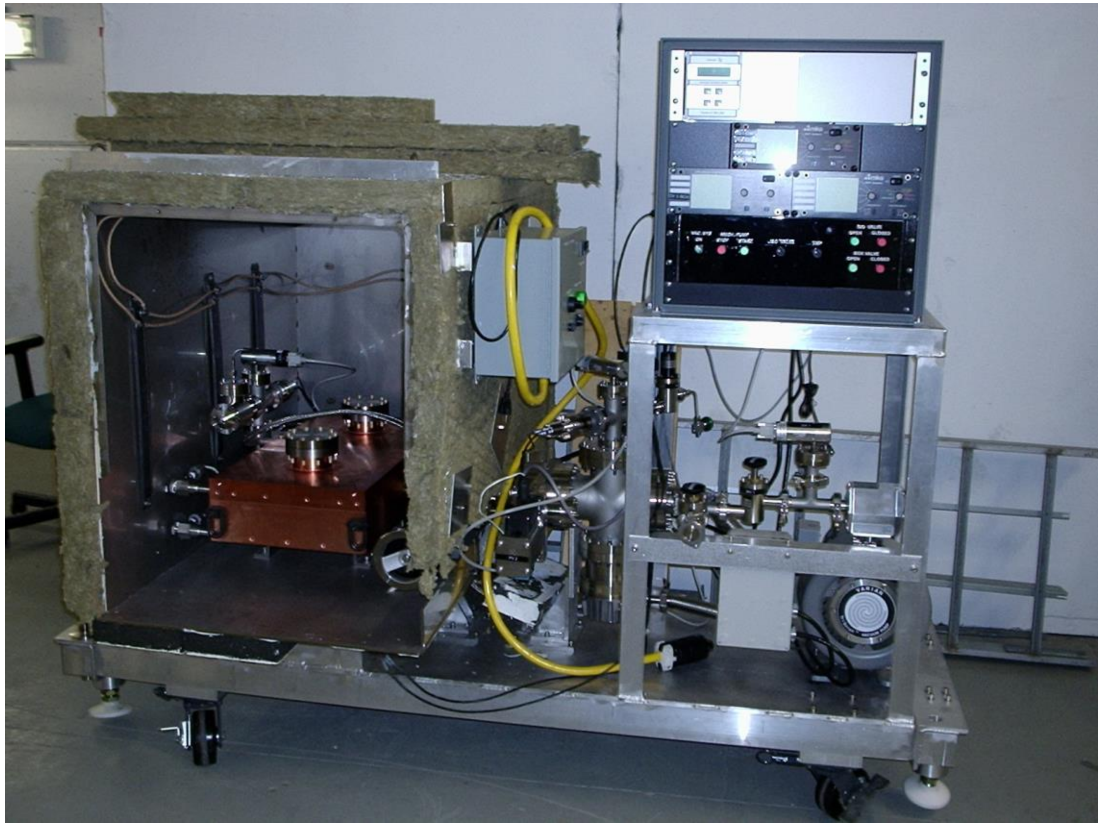

Small Sleeve / Tapered Choke

EB welding test

FPC conditioning box and cart

- Finalized FPC conditioning box drawing package.
- Started to refurbish FPC conditioning cart.
- Hopefully, we can start high power conditioning by the end of summer 2025





Summary and plan

- EIC RF needs about 100 new FPCs, which most of them will use the same RF window design.

- The most demanding FPC is the FPC for ESR SRF cavities. And a CW 500 kW high power FPC has been designed for ESR SRF cavity.

- Prototype Manufacture
  - Will make 8 window assembly and 4 full FPCs.
  - Completed sample tests (brazing, EB welding, coating).
  - Most of parts have been made for 5 full FPCs.
  - Ready to proceed full FPC manufacture.
  - Completed FPC conditioning box design and working on drawing package.
  - FPC conditioning setup is under preparation.

Acknowledge

- BNL: Jesse Fite, Doug Holmes, Eric Link, Eric Polanco, Donald Landwehrle, Alex Zatsman, Kevin Smith, and more…
- Jlab: Bob Rimmer, Zack Conway, Eduard Drachuk, Jim Henry, and more…
- CERN: Eric Montesinos
- SNS: John Mammosser
- KEK: Eiji Kako, Kirk Yamamoto
- IHEP: Tongming Huang
- FNAL: Sergey Belomestnykh
- **Everyone in this meeting !!**