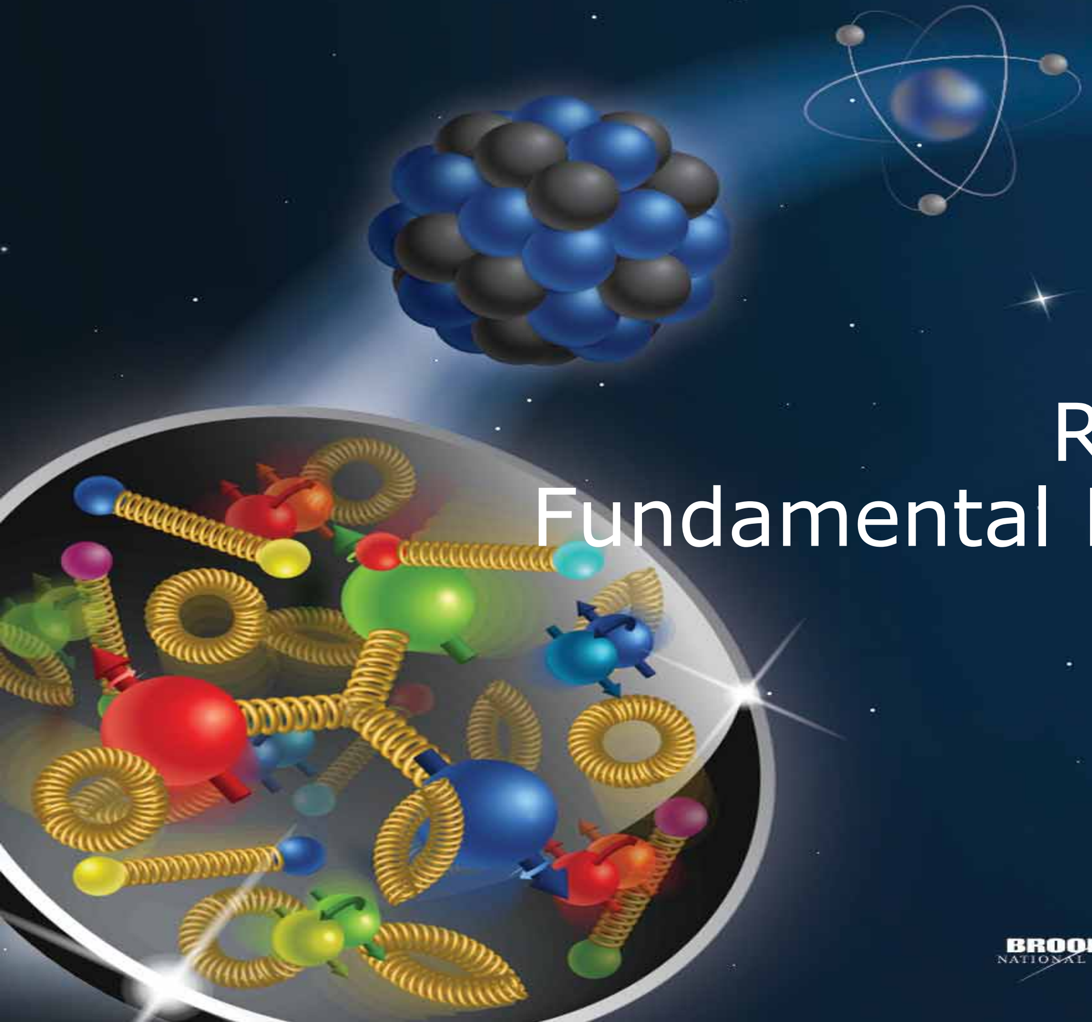

Recent Advances in Fundamental RF Power Couplers

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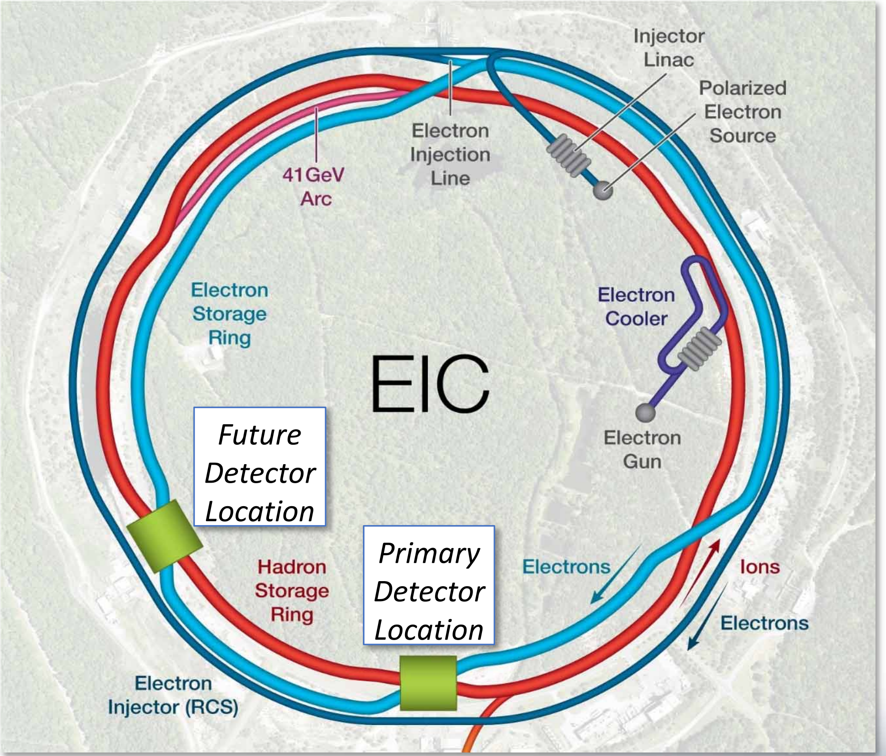
BROOKHAVEN NATIONAL LABORATORY Jefferson Lab U.S. DEPARTMENT OF ENERGY Office of Science

Outline

- Brief Introduction of EIC and EIC RF/SRF systems
- EIC FPC development
  - High power, broadband window design
  - Recent TiN coating results
  - Prototype status
  - RF window prequalification
- High normalized power FPCs
- Summary

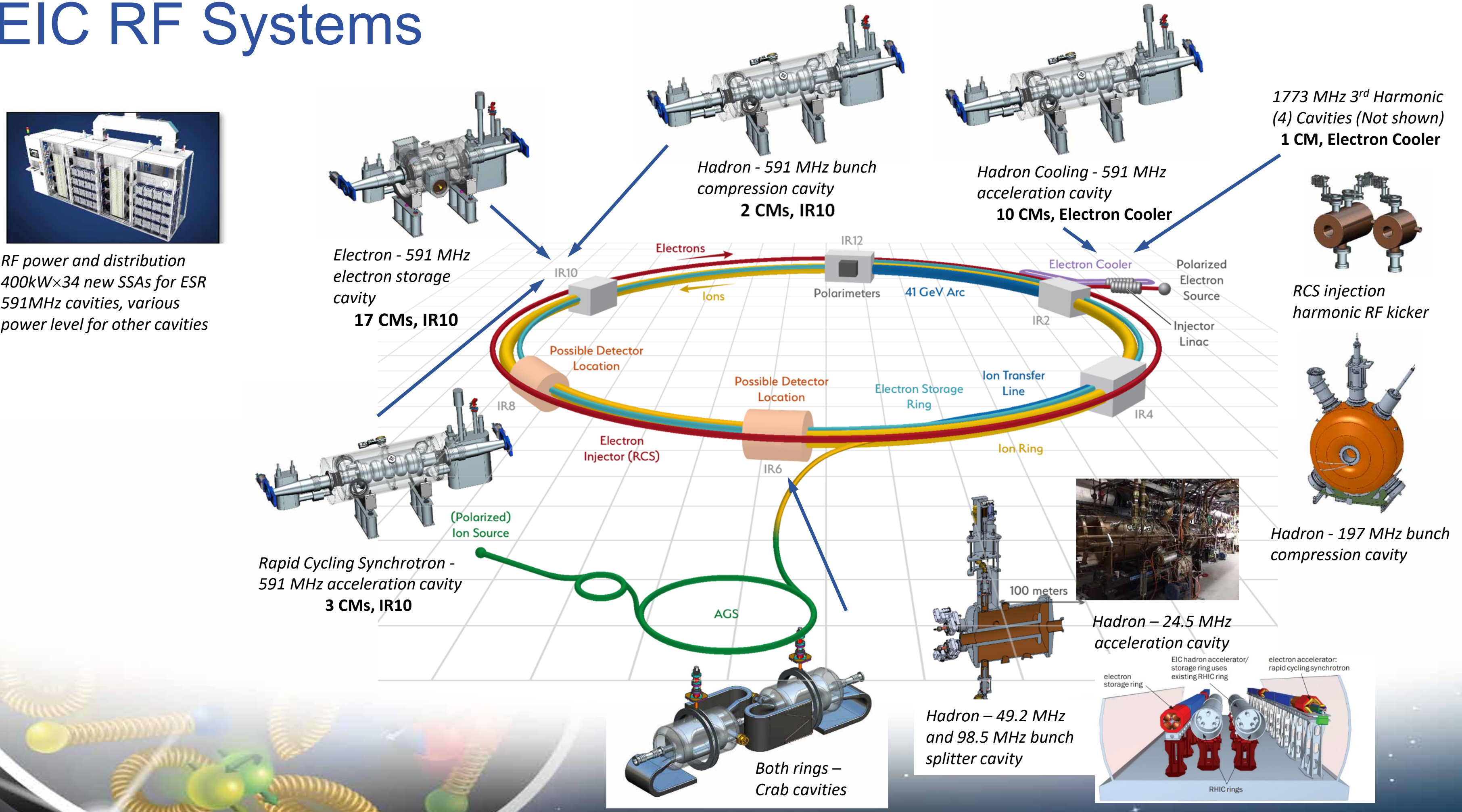
About EIC

- *EIC is an Electron-Ion Collider, to be built at BNL in a partnership between BNL and TJNAF.*
  - High Luminosity: L= 10^{33} – 10^{34}cm^{-2}sec^{-1}
  - Highly Polarized Beams: 70%
  - Large Center of Mass Energy Range: E_{cm} = 20 – 140 GeV
  - Large Ion Species Range: protons – Uranium
  - Accommodate a Second Interaction Region (IR)
- *Hadron Storage Ring (HSR) provides ion beams, which is to upgrade the existing RHIC accelerator.*
- *Electron Storage Ring (ESR) provides 5-18 GeV of high current electron beam, which is a new accelerator, including pre-injector, RCS and ESR.*
- *The EIC will be a game-changing resource for the international nuclear physics community, but it is very challenge to archive all goals.*



EIC CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

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
2 CMs, IR10

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

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

RCS injection harmonic RF kicker

Hadron - 197 MHz bunch compression cavity

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

Hadron – 24.5 MHz acceleration cavity

Hadron – 49.2 MHz and 98.5 MHz bunch splitter cavity

Both rings – Crab cavities

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*	*379*
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*	*1.2* *3.8*
	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- or 2-cell**	*IR-10*	*5 or 3*	*1*	*60*
Strong Hadron Cooling *ERL Design remains very fluid*	*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)
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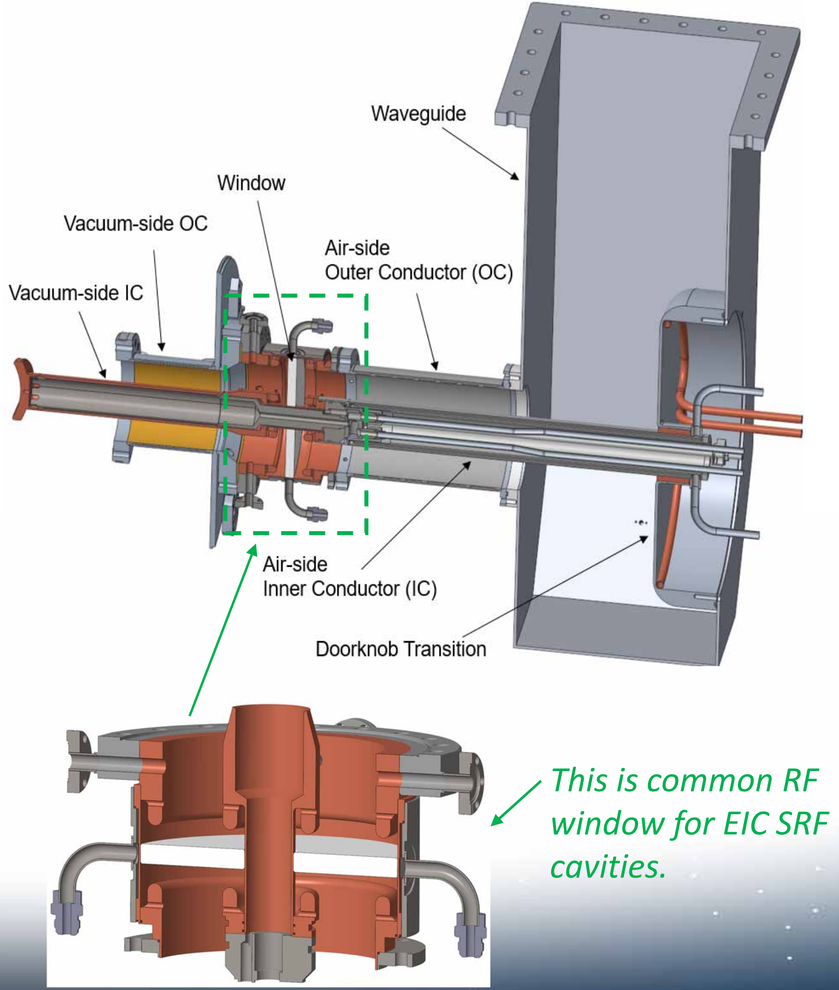
Rapid Cycling Synchrotron (RCS)	*Accel / Store*	*591*	**SRF, 5-cell**	*IR-10*	*3*	*1*	*70*
	ERL Fundamental	*591*	**SRF, 5-cell**	*IR-2*	*10*	*1*	*60*
	ERL Third Harmonic	*1773*	**SRF, 5-cell**	*IR-2*	*4 (1 CM)*	*1*	*5*
Crab Cavities	*Hadron*	*197*	**SRF, RFD**	*IR-6*	*8 (4 CM)*	*1*	*70*
	Hadron/Electron	*394*	**SRF, RFD**	*IR-6*	*6*	*1*	*50*

- ***EIC FPC summary:***
  - ***More than 90 new FPCs are required for EIC RF/SRF systems.***
  - ***Most EIC cavities' frequencies are below ESR SRF cavity's frequency, 591 MHz.***
  - ***Only the SHC ERL 3rd harmonic cavity has higher frequency, 1773 MHz.***
  - ***The most challenging FPC is for ESR SRF cavity coupler: CW 400 kW.***
- ***EIC FPC strategy:***
  - ***Develop a single broadband window for SRF cavities with frequency < 591 MHz***
    - ***New design presented here***
  - ***Adopt CEBAR window for 1773 MHz***
  - ***Use a single RF window for NCRF cavities (loop coupling)***

FPC for EIC ESR SRF Cavity

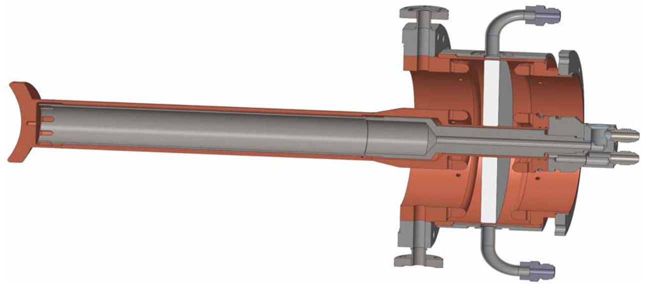
- EIC eSR FPC design is the next generation evolving KEKB/ Tristan/SNS/BNL BeO high power window design

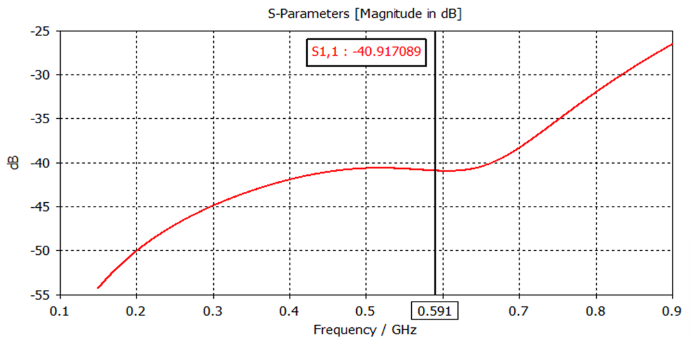
- Al_2O_3 window FPC based on lesson learned from in-house experiences on BeO window FPC.
  - Replace BeO window with 99.5% Al_2O_3 for safety and maintenance considerations.
  - 99.5% Al_2O_3 has similar dielectric losses and thermal conductivity to BeO but has better mechanical strength than BeO.
  - 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 shock load in any direction.
  - Improve FPC cooling channel design.
  - Improve instrumentations on FPC.
  - 4.5 kV bias will be ready to apply.

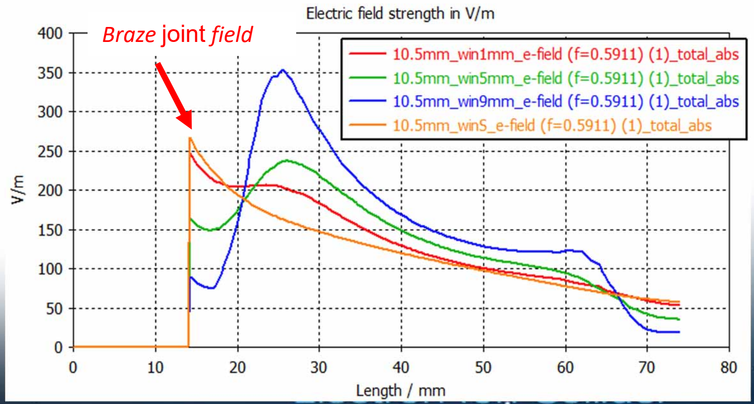


High power broadband window for EIC Cavities

- *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 (@2MW).*
- *Mechanically, the window design satisfies transportation and cryomodule requirement.*



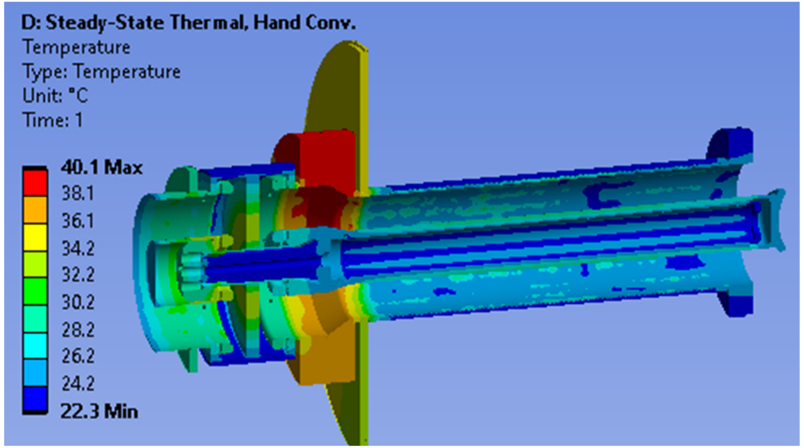




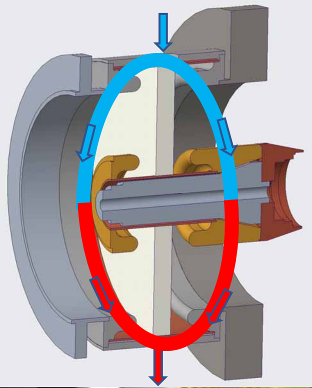
	Requirement	**FPC Design**
Average RF power	*379 kW*	*1 MW, traveling wave* *500 kW, full reflection*
Peak Power	*1.5 MW, equivalent*	*2 MW, equivalent*
Frequency	*591 MHz*	*Broadband window design,* *for EIC cavities below 591 MHz*
Shock load	*5g*	*5g,*
Modal frequency	*> 60 Hz*	*100 Hz*
IC length	*289 mm*	*425 mm*

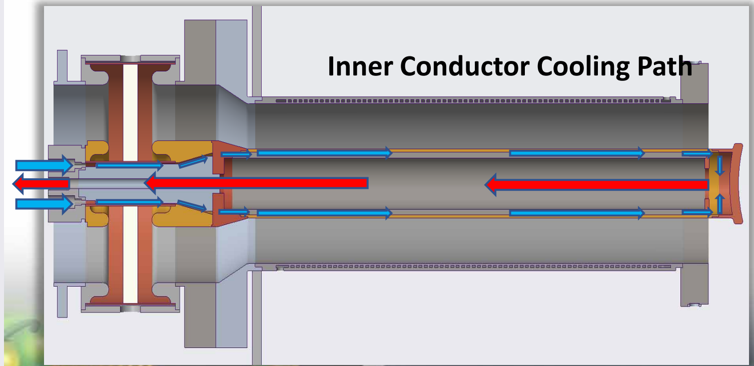
Window cooling and thermal analysis

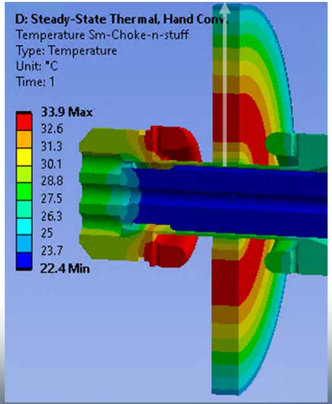
- *Water cooling for inner conductor and window.*
- *RF thermal simulation*
  - *1 MW power input*
  - *Conservative thermal film coefficient*
- *Highest temperature of 40 C is at uncooled flanges.*
- *Choke tip highest temperature is 34 C.*
- *Al_2O_3 temperature ranges from 24 C to 34 C*



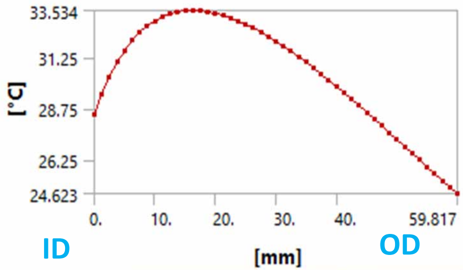
Large Copper Sleeve Cooling Loop





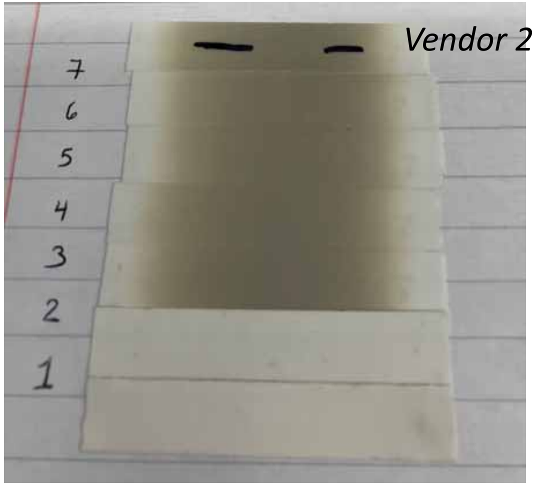


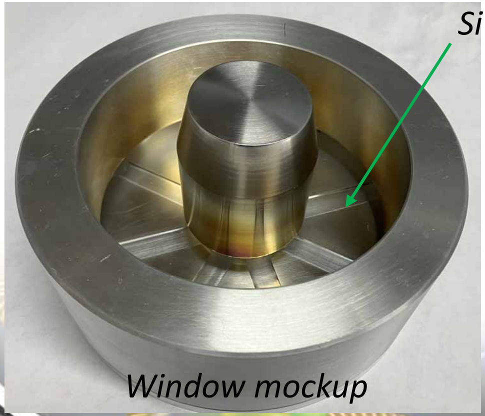
Centerline temp of Al2O3

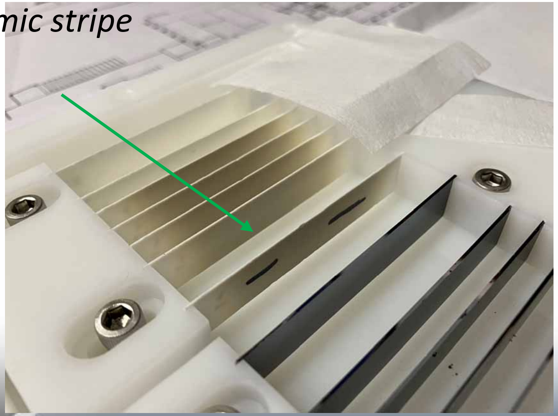


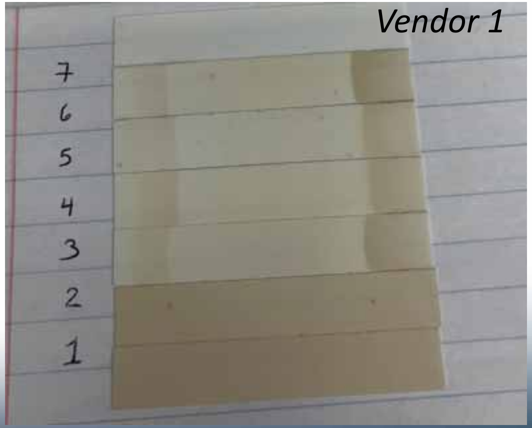
TiN coating study (1)

- TiN coating will be coated on ceramic vacuum side only.
- 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

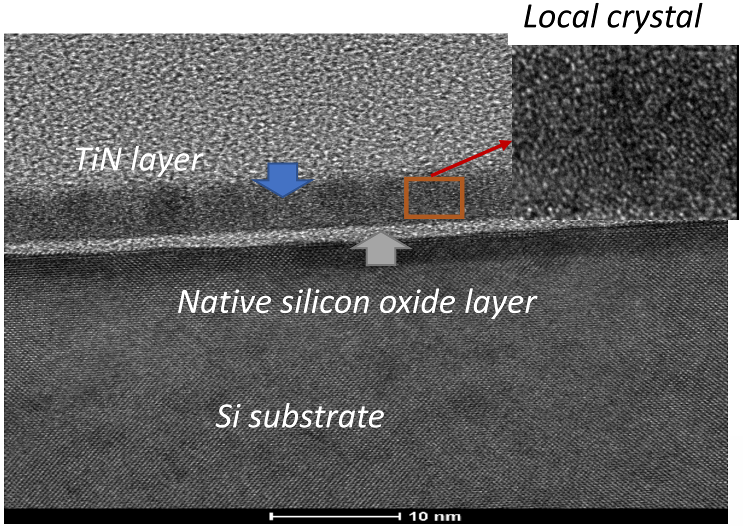


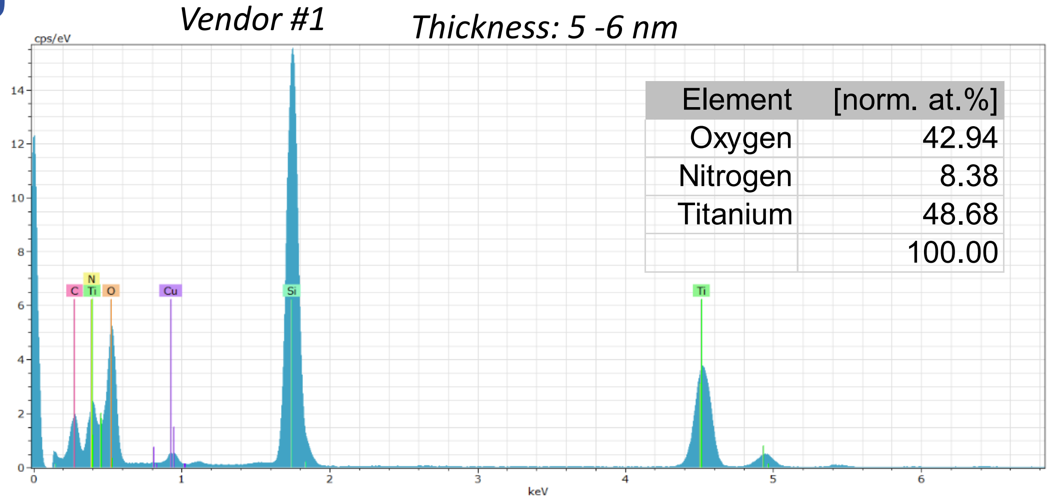




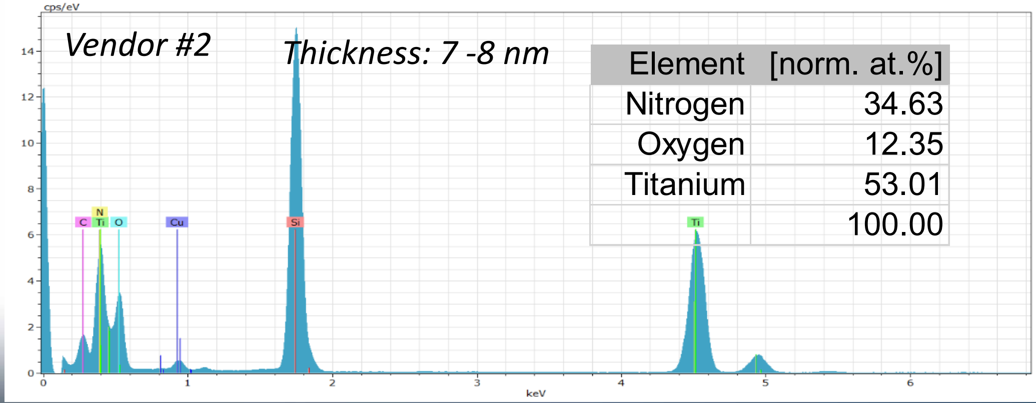


TEM analysis on TiN coating





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

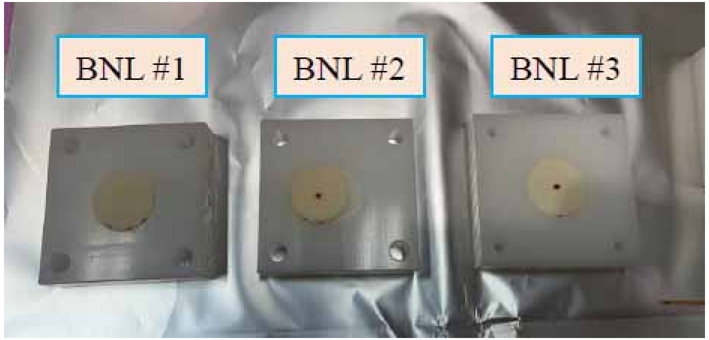


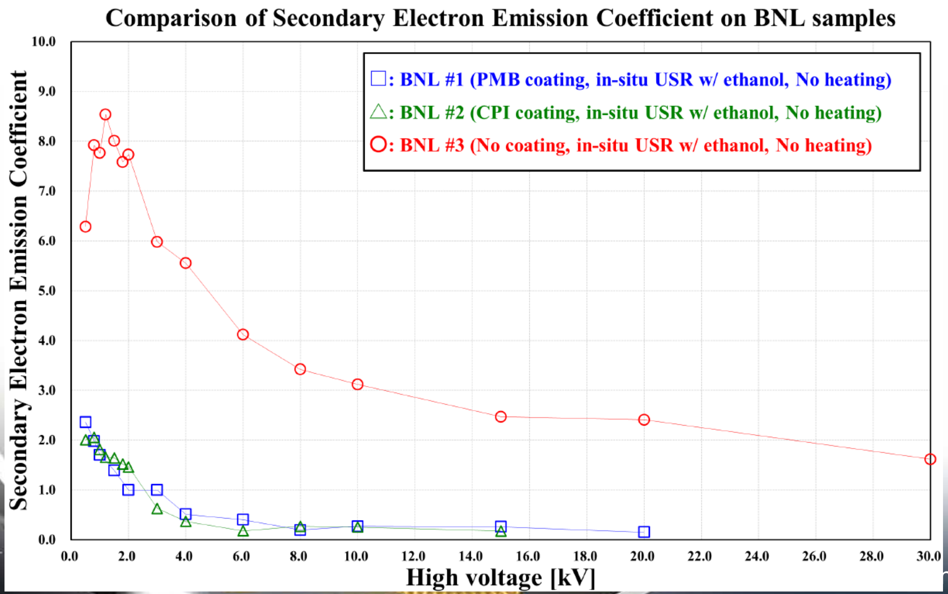
Element	[norm. at.%]
Nitrogen	34.63
Oxygen	12.35
Titanium	53.01
	100.00

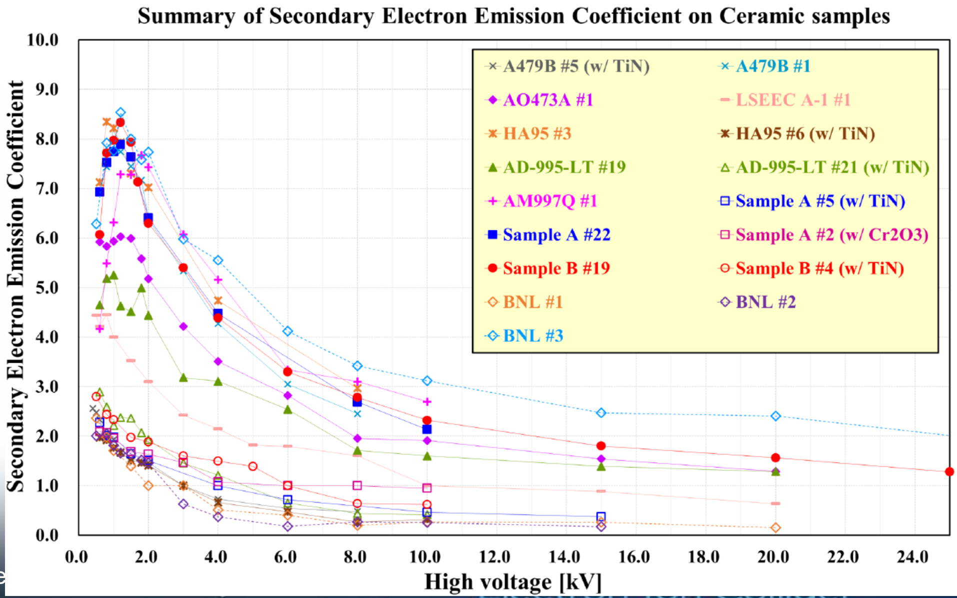
- *TiN coating analysis by BNL Center for Functional Nanomaterials (CFN) with transmission electron microscopy (TEM)*
- *Similar TiN coating thickness from two vendors*
- *Both vendor got $Ti_xNi_yO_z$, but with different composition.*

TiN coating SEY measurement

- *Three samples sent to KEK for SEY measurement*
  - *BNL#1 and BNL#2 were coated by vendors*
  - *BNL #3 was bare Al_2O_3*
- *Both vendors' SEY results are close to each other.*

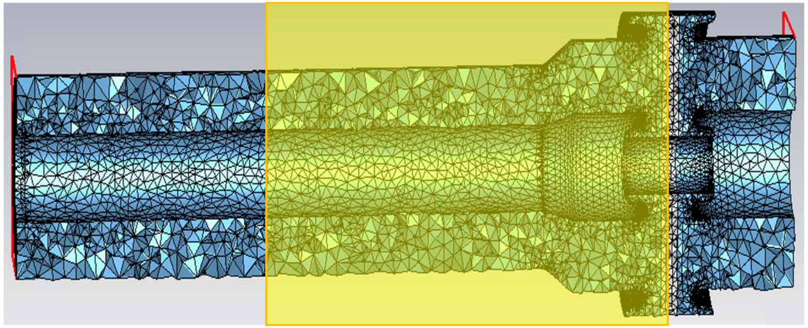


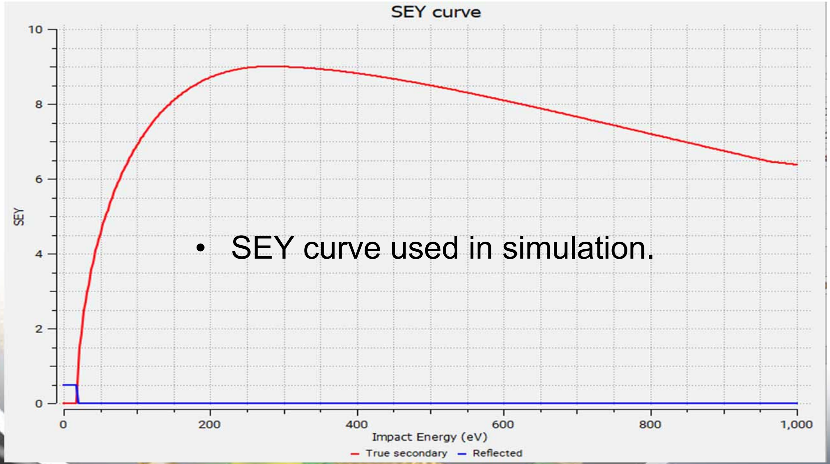




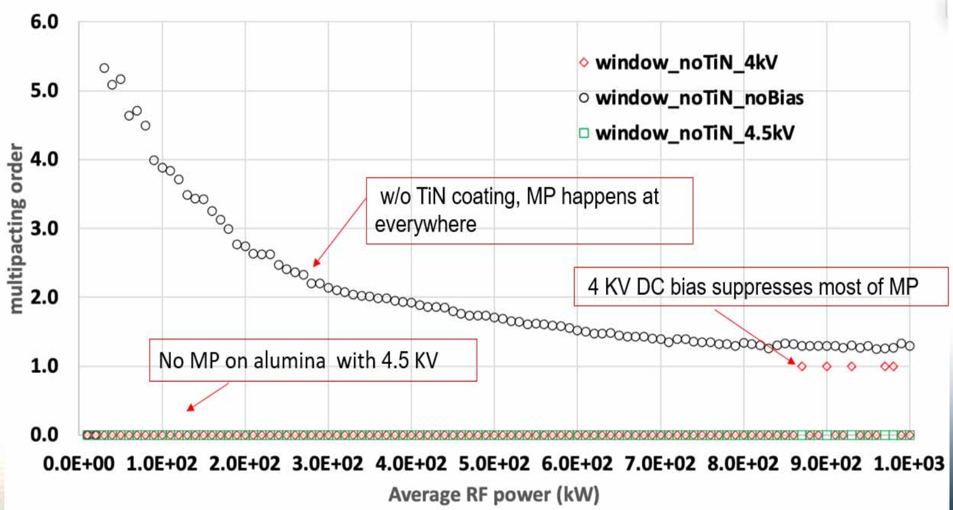
Multipacting simulation

- *Multipacting analyzed with SPARK3D*
- *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's vacuum side .*
- *FPC test will start without bias.*



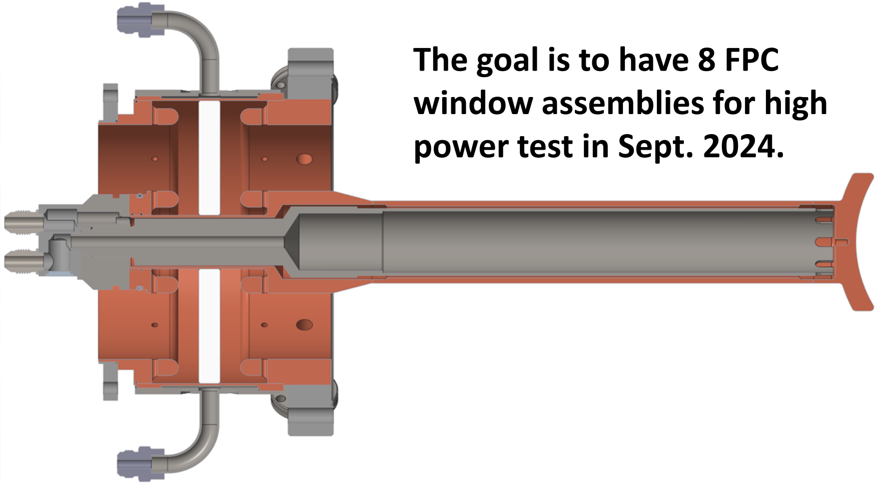


- SEY curve used in simulation.

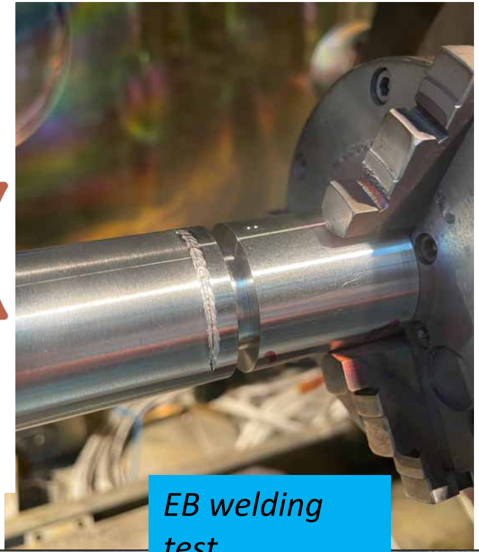


Status

First window brazing



The goal is to have 8 FPC window assemblies for high power test in Sept. 2024.



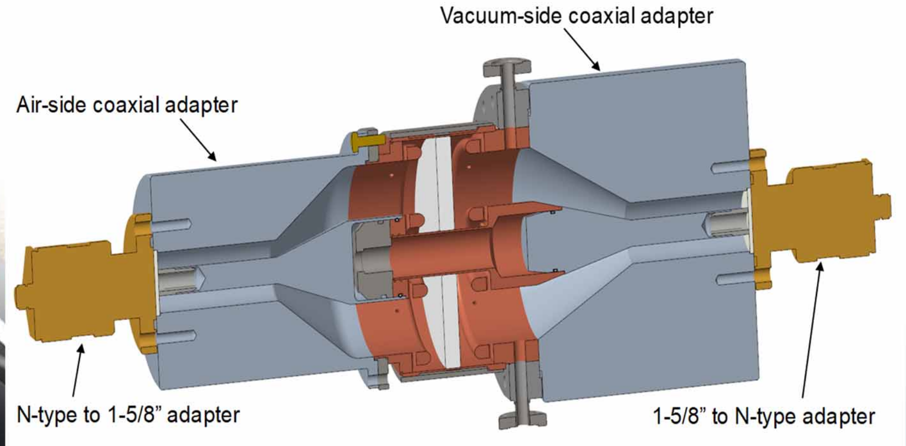
EB welding test

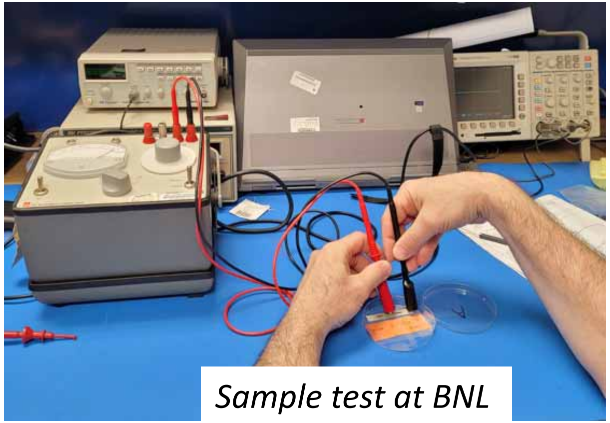
Shrink fit test

Brazing test

RF Window prequalification

- Eventually, high power RF conditioning is the necessary step to qualify a RF window, prior to installing on a cryomodule.
- However, we are working on developing a systemic testing procedure to prequalify a high-power RF window.
  - Material certification + independent coupon test
  - Visual inspection
  - Vacuum leak check
  - Water leak/pressure test
  - DC resistance measurement on TiN coating
  - RF measurement on a window





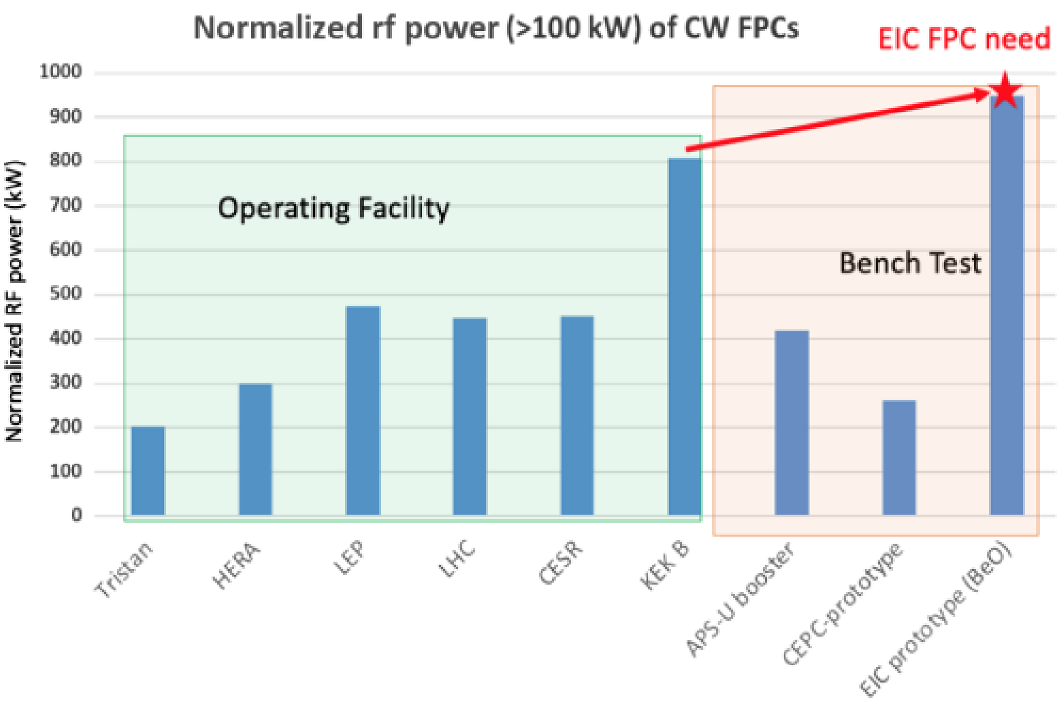
Sample test at BNL

Photo from Christian Arcambal at ESS

High normalized FPCs

- As one of the most dedicate points in the cryomodule, the FPC has its only challenge for each SRF system .
- However, from normalized power point of view, EIC eSR SRF cavity's FPC remains the most challenging FPC in the world.
  - Normalized FPC power:

$$P[kW] \times \sqrt{f[\mathrm{MHz}]/500}$$



Summary

- FPCs are one of most challenging items in EIC RF/SRF system
- Recent developments on the broadband, high power FPC window for EIC was reported.
- EIC prototype testing in Sept. 2024!

Acknowledgements

- *BNL : J. Fite, K. Smith, B. Xiao, D. Holmes, A. Zaltsman, Z. Conway, S. Andres-Verdu, Q. Wu and many others*
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- *FNAL: S. Belomestnykh*
- *SNS: J. Mammosser (ORNL)*
- *IHEP: Tongming Huang*
- *ESS: Christian Arcambal*
- *Many others….*