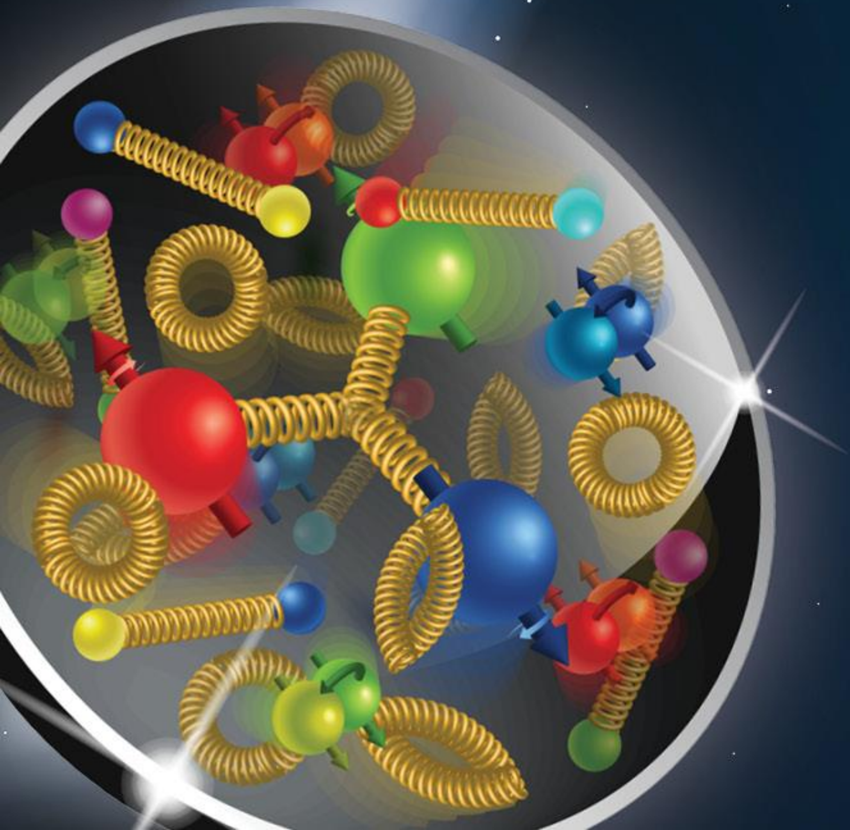
WWFPC workshop 2019

High power FPC at BNL



Wencan Xu
on behalf of eRHIC RF team
June 22, 2019

Electron Ion Collider – eRHIC

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

Outline

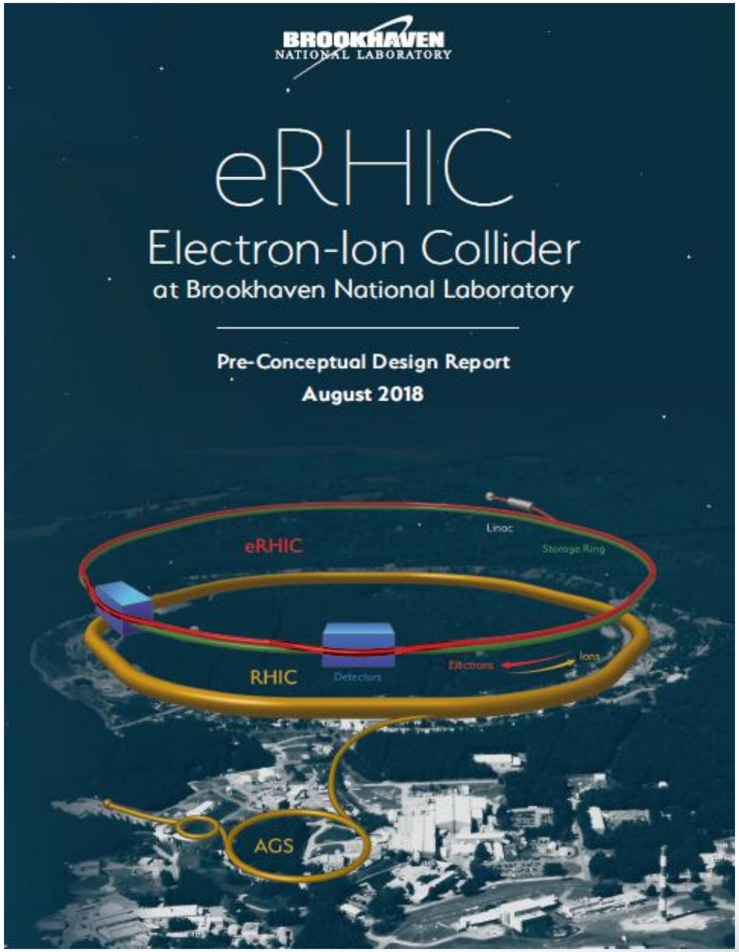
I. FPC requirements for eRHIC RF systems

II. Design, fabrication and test of adjustable Qext high power FPCs

III. Summary

I. eRHIC RF systems

- **Hadron Ring RF systems**
  - Hadron will be produced by existing RHIC.
  - RF systems will be reused for eRHIC.
  - New system: Hadron storage,Hadron cooling ERL, crab cavity
- **Electron RF Systems (All new)**
  - Pre-injector normal RF .
  - Rapid Cycling Synchrotron (RCS) SRF.
  - Electron storage ring (eSR) RF (Fundamental and third harmonic SRF).
  - Crab RF system.



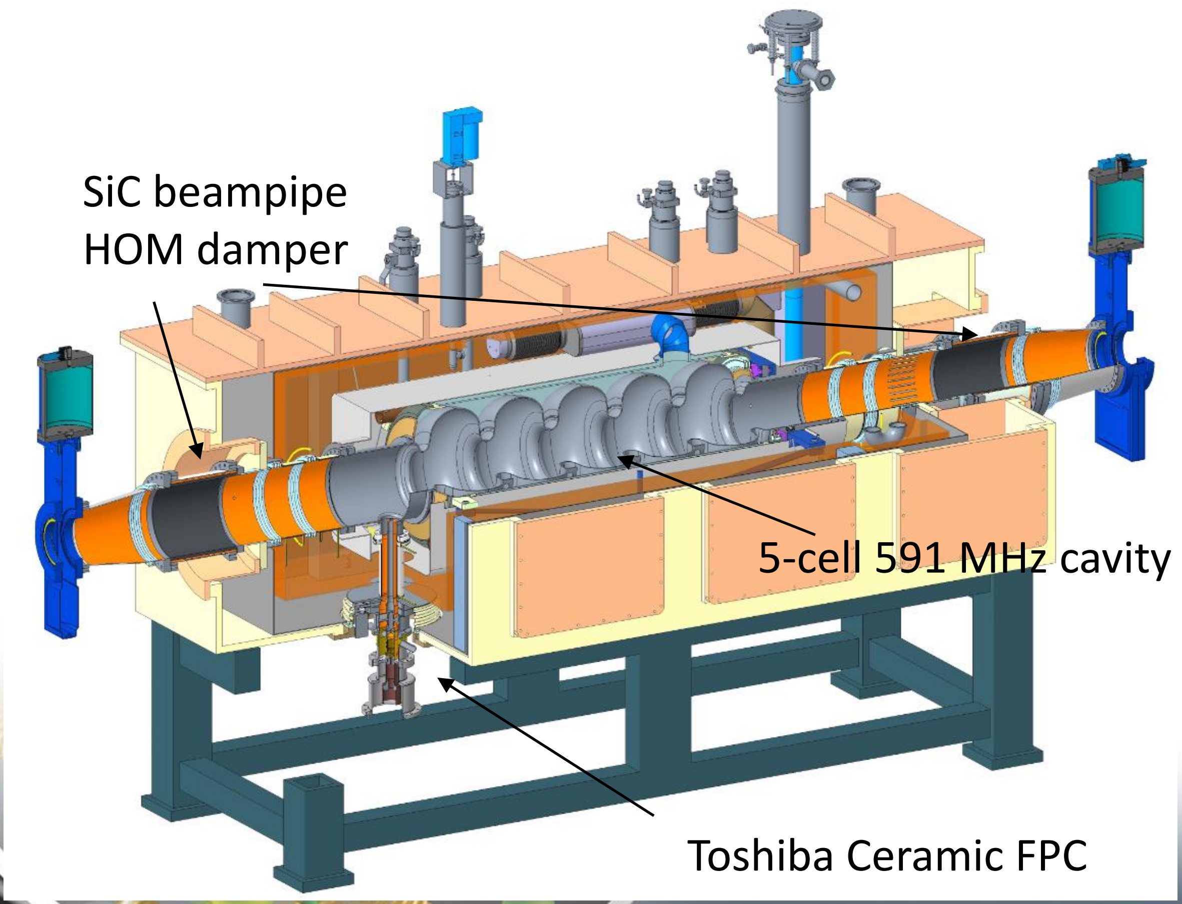
High power FPCs at eRHIC

systems	Cavity and FPC	FPC power	Qext	FPC option	No. of FPCs
RCS	5-cell 591 MHz cavity; 1 FPC/cavity	35 kW, pulse 20% duty cycle	6.6e6	Toshiba/SNS-type FPC (Ceramic window)	3X1
eSR Fundamental SRF system	2-cell 591 MHz; 2 FPCs/cavity	2 X 500 kW, CW	4E4 – 3E5	Fix BeO coupler, plus waveguide junction for Qext adjusting	14X2
eSR 3rd harmonic SRF system	1-cell 1773 MHz; 2 FPCs /cavity	2 X 120 kW, CW	5.5e5 – 5.3E5	Fix FPC; no design yet	5X2
Hadron storage	5-cell 591 MHz cavity; 1FPC/cavity	61 kW, CW	1.23E6	Toshiba/SNS-type FPC (Ceramic window)	2X1
Hadron cooling ERL	5-cell 591 MHz cavity; 1 FPC/cavity	34 kW, CW	6.6e6	Toshiba/SNS-type FPC (Ceramic window)	8X1
Crab cavity	394 MHz cavity; 1 FPC /cavity	32 kW, CW	1.17e6	Toshiba/SNS-type FPC (Ceramic window)	12X1

- Total couplers: 63 couplers (on table), plus Toshiba couplers for pre-injector and hadron ERL bunchers. ➔ over 60 new couplers for eRHIC.

FPC for 5-cell 591 MHz cavity cryomodule

- 5-cell 591 MHz cavities are used hadron cooling ERL, hadron storage and RCS.
- Toshiba/SNS-type window is used for FPC
- The FPC window is cooled by water, and inner conductor is conductive cooling only. The maximum power is up to 70 kW CW.
- This is not a challenge.



II. Electron storage ring RF: Why adjustable coupling?

Parameter	Unit	5 GeV (Beam-beam limit)		10 GeV (Maximum lumi)		18 GeV (SR Power Limited)
		Med Lumi	High Lumi	Med Lumi	High Lumi	
Peak Luminosity	$10^{34}cm^2s^{-1}$	0.056	0.307	0.44	1.05	0.145
# Bunches		660	1320	660	1320	330
Bunch Charge	nC	48	24	48	24	10
Bunch length	**rms mm**	23	23	19	19	17
Average Current	**A**	2.48	2.48	2.48	2.48	0.26
Synchronous Voltage	**MV/turn**	1.29		3.67		38.5
Cavity voltage	**MV**	11.1		23.7		68.10
Sync phase	**rad**	3.010		2.966		2.541
Sync Rad Power	**MW**	3.2		9.2		10.0

- Can we use fixed coupler? No! Because for a fixed coupler (β,Q_L), Pg *directly proportional to* voltage. 30 MW for 18 GeV is needed, if the same coupler for 10 GeV is used.

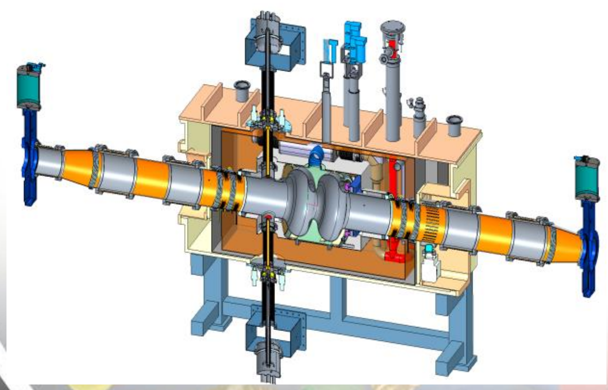
$$P_g = \frac{1+\beta}{4\beta}\frac{V_{acc}^2}{\frac{R_{sh}}{Q}Q_L}\left\{\left(1+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\cos\phi_b\right)^2+\left(2Q_L\frac{\omega-\omega_0}{\omega_0}+\frac{R_{sh}}{Q}Q_L\frac{I_b}{V_{acc}}\sin\phi_b\right)^2\right\}$$

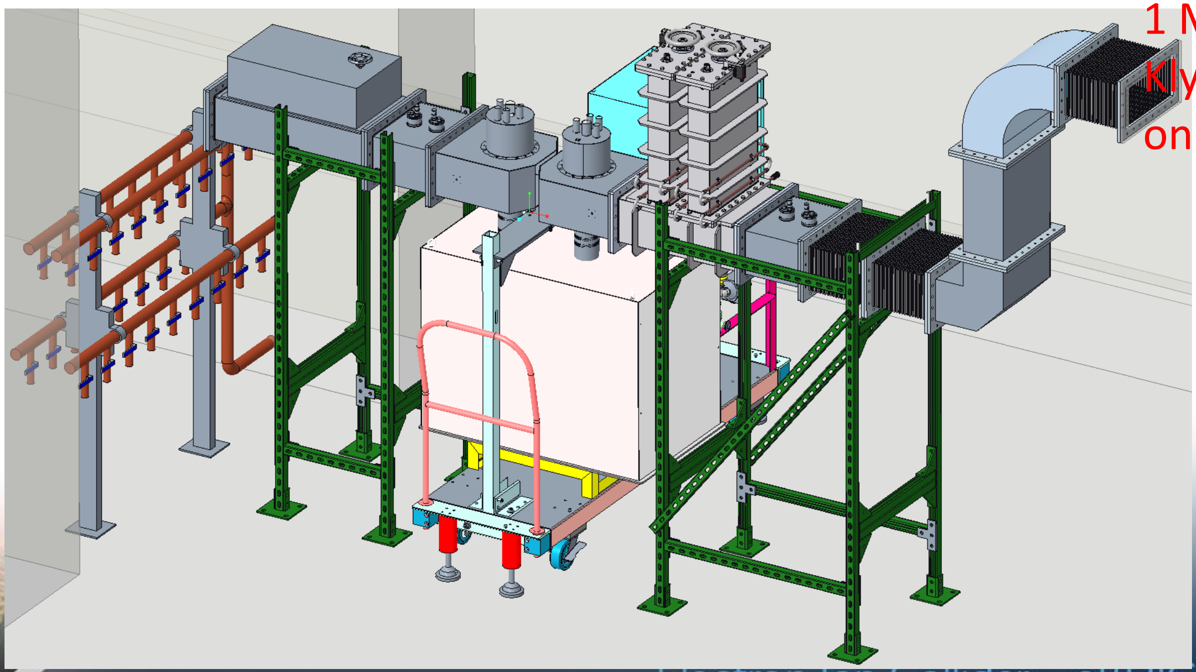
∝ Va*Va

∝ 1/Va

High power adjustable FPC for storage ring

- With two couplers, up to 1 MW (per cavity) RF power has to be coupled into 591 MHz storage ring SRF cavity, in order to compensate synchrotron radiation loss in electron beams.
- Due to wide range of operational scenarios, the Q_{ext} of the couplers has to be able to adjust by a factor of 10.
- This is a challenge. And a LDRD program is funded to demonstrate a high power coupler with Qext adjusting scheme.

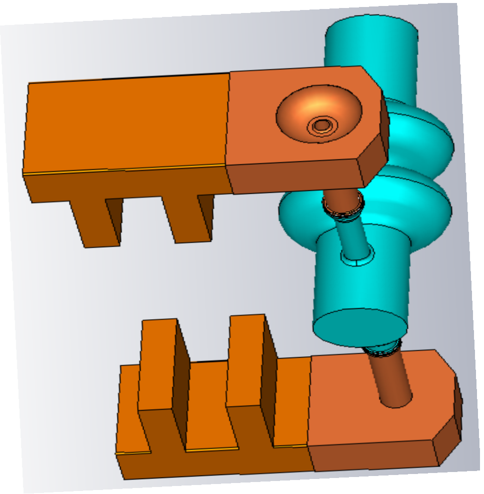


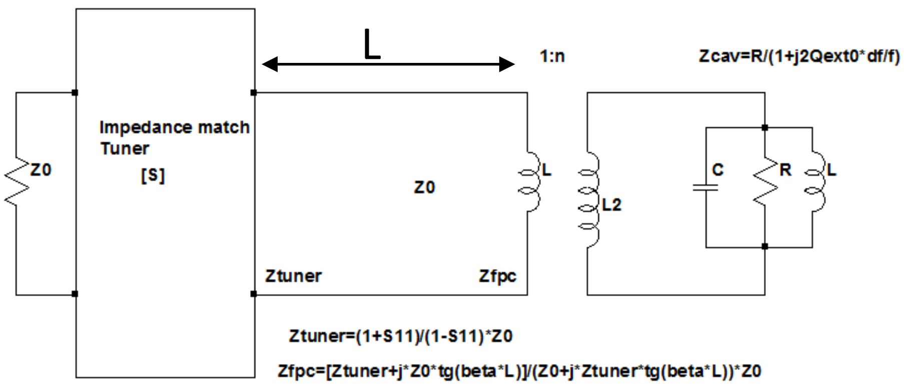


1 MW Klystron

To adjust the Qext

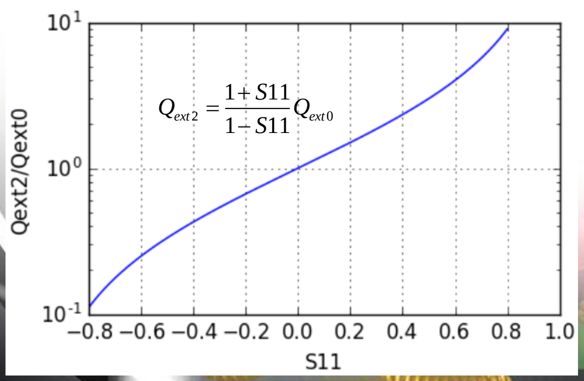
- There are two ways to adjust external Q:
  - Varying FPC's position/insertion in cavity
  - Varying impedance seen by the cavity, through a impedance transformer
- We intend to demonstrate Qext adjusting on a 500 KW with a waveguide tuner.





$$Z_{total} = \frac{\frac{R}{Q} \cdot Q_{ext2}}{1 + j \cdot 2 \cdot Q_{ext2} \cdot \frac{\Delta f}{f}}$$

$$Zin = Z_{fpc} \cdot n^2$$

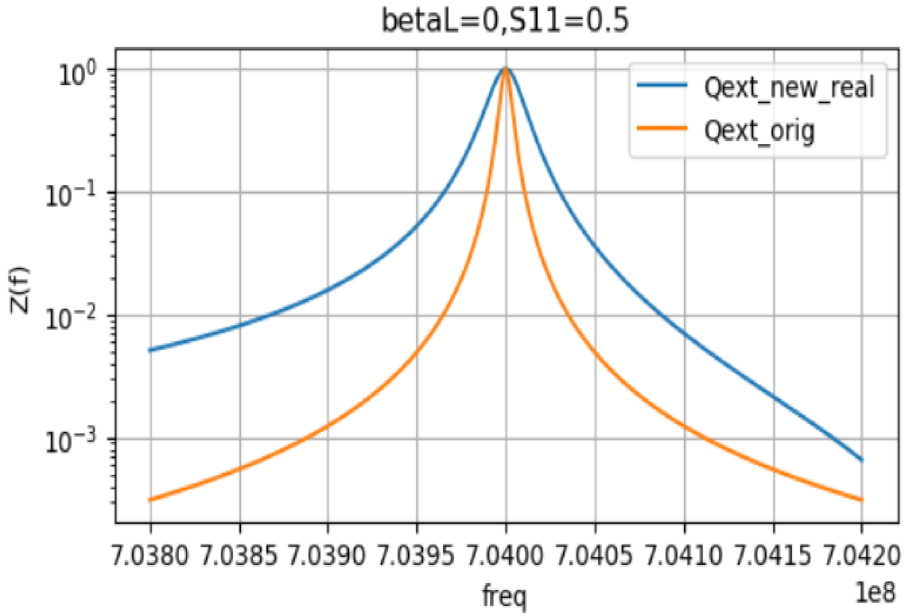


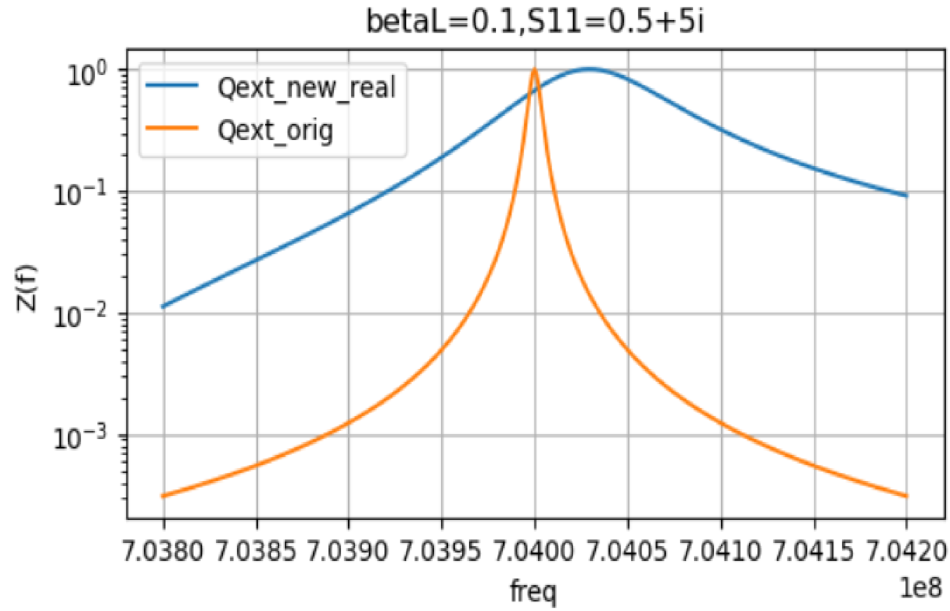
$$Q_{ext2} = Z_{fpc}/Z_0 \cdot Q_{ext0}$$

$$Z_{fpc} = Z_0 \frac{\frac{1+S11}{1-S11} - j \cdot tg(\beta l)}{1 + j \cdot \frac{1+S11}{1-S11} \cdot tg(\beta l)}$$

- If $\beta l = n\pi$ Then, $Q_{ext2} = \frac{1+S11}{1-S11} Q_{ext0}$

To adjust the Qext

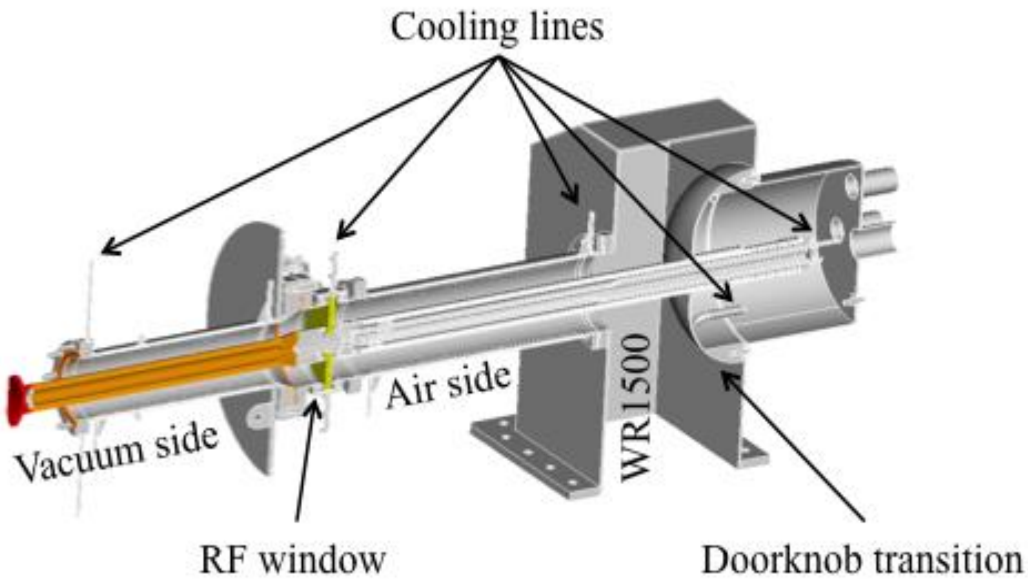




$$Z_{fpc} = Z_0 \frac{\frac{1+S11}{1-S11} - j \cdot tg(\beta l)}{1 + j \cdot \frac{1+S11}{1-S11} \cdot tg(\beta l)}$$

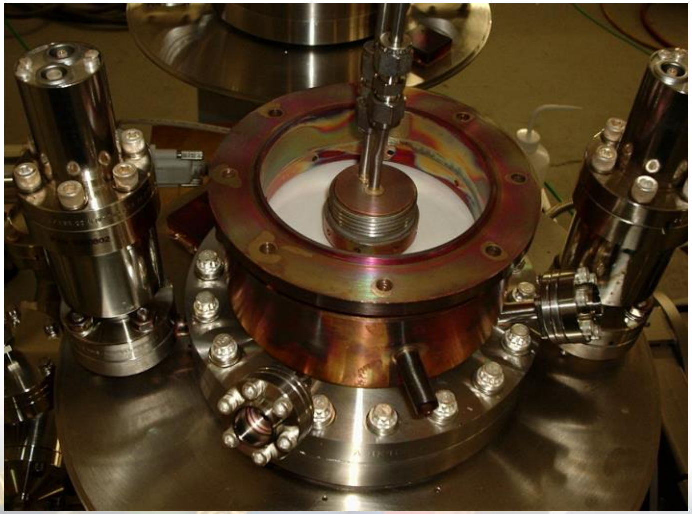
- It is easy to tune if phase advance (βL=nπ) , thus S11 is real
- However, we can adjust S11 (real and imaginary part) to make the imaginary part zero.

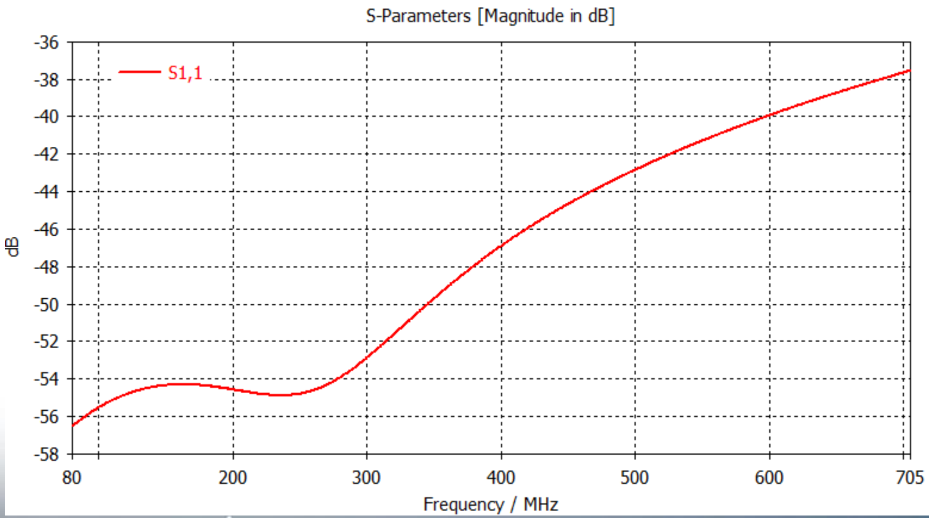
Main features of the 500 kW FPC design



Main features:

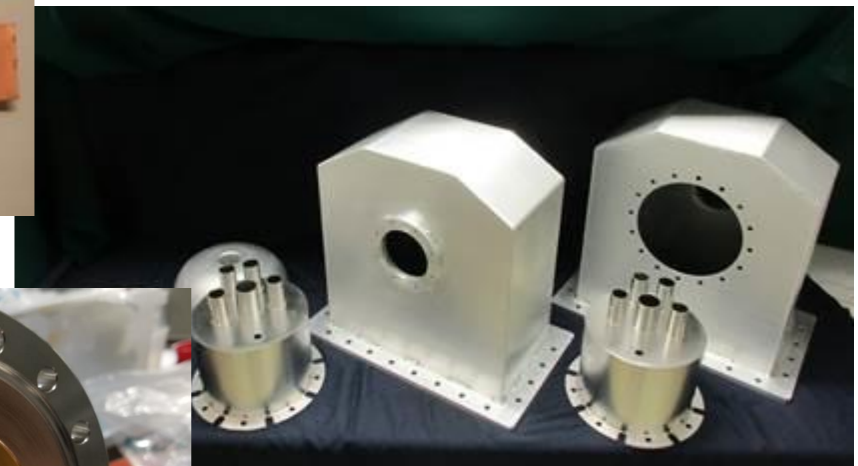
- BeO Window at room temperature.
- Pressurized helium cooling on vacuum side outer conductor.
- Water cooling in the inner conductors (both vacuum and air side), airside outer conductor and doorknob.
- Stainless steel with Cu coating.
- Very broadband window, but doorknob design need to match operating frequency.

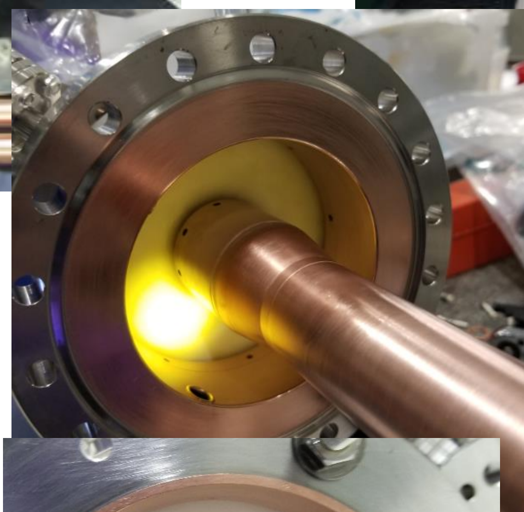


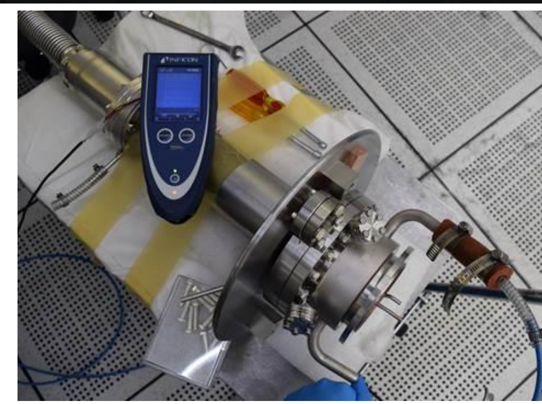


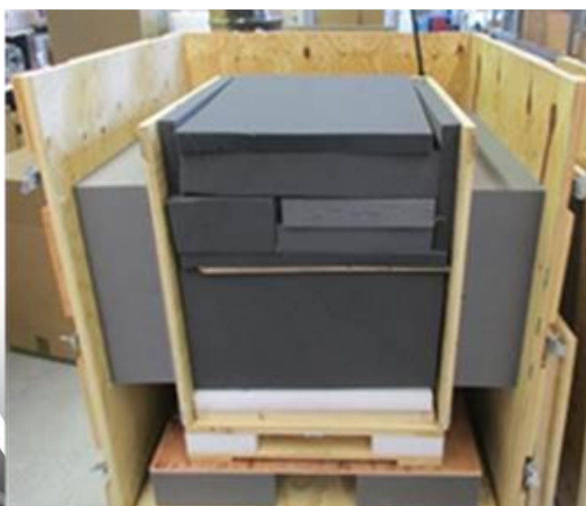
More detail info: Design, simulations, and conditioning of 500 kW fundamental power couplers for a superconducting rf gun, PRSTAB 072001, 2012

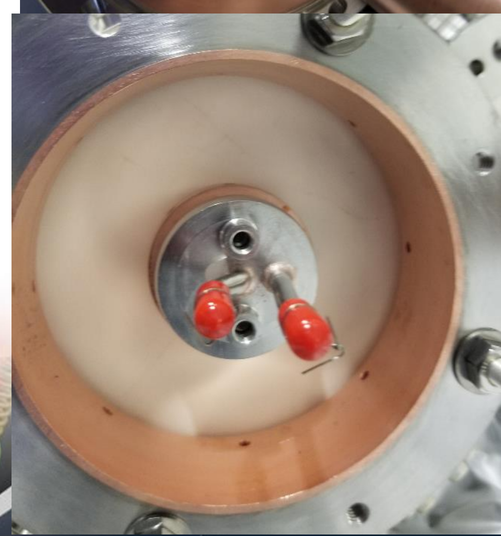
FPC fabrication and inspection

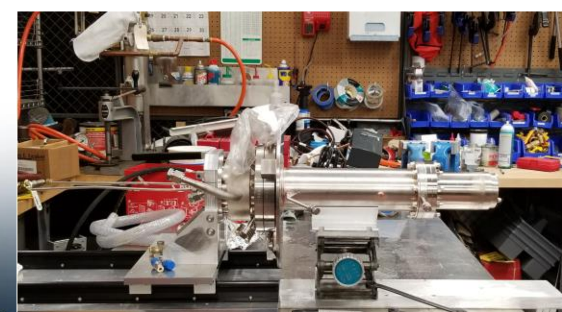




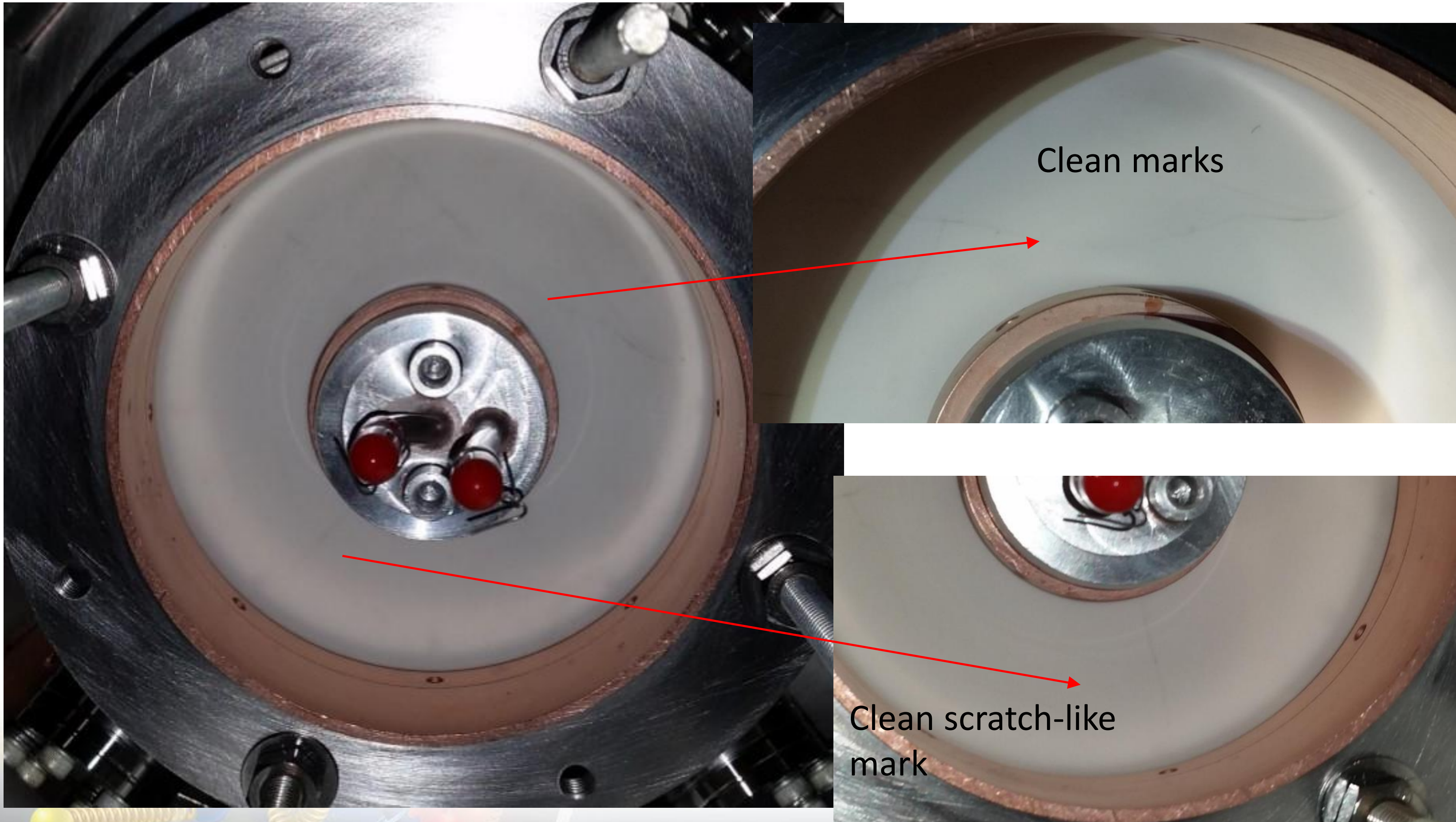




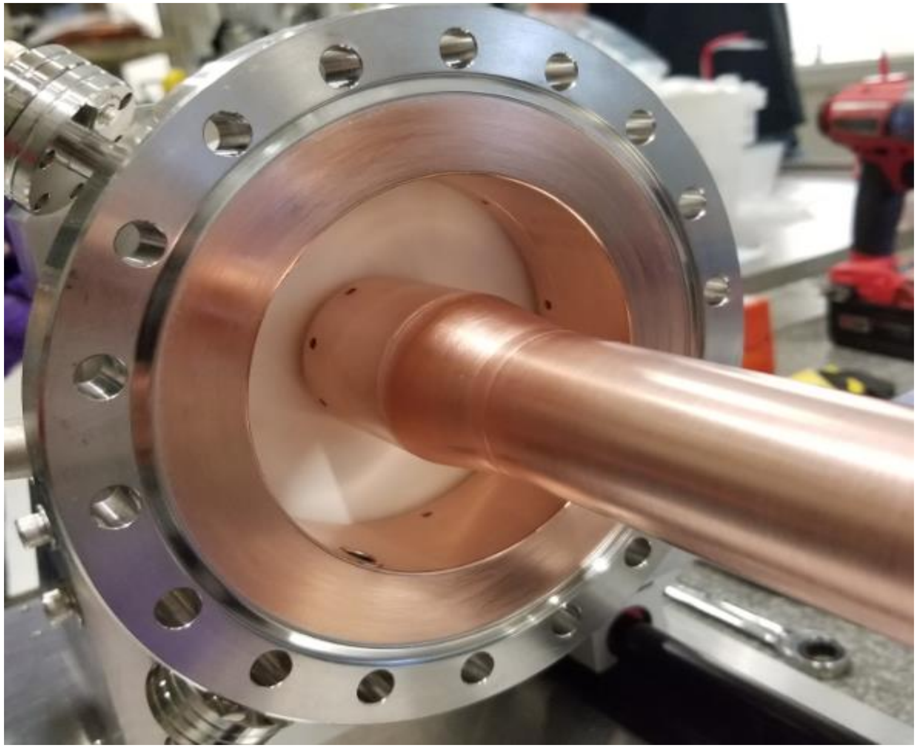


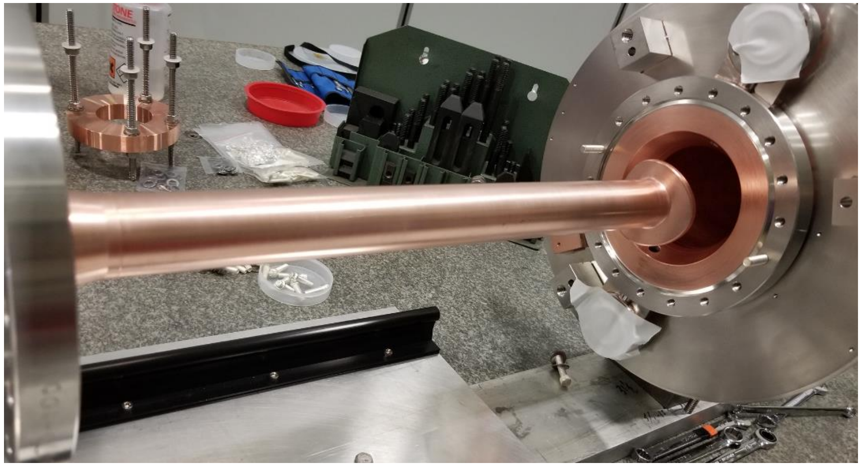


Airside BeO window-1 inspection

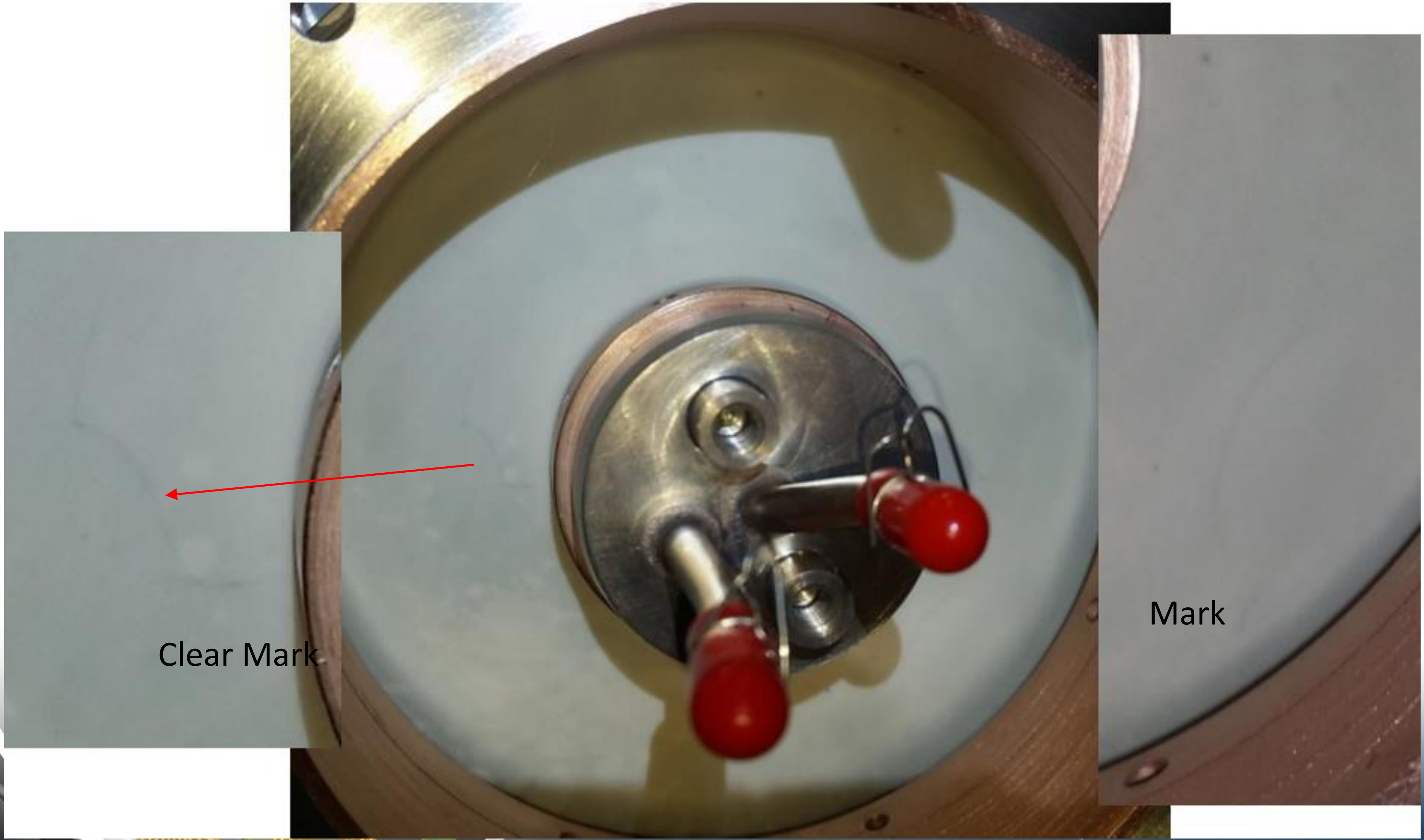


Vacuum side BeO window-1 inspection

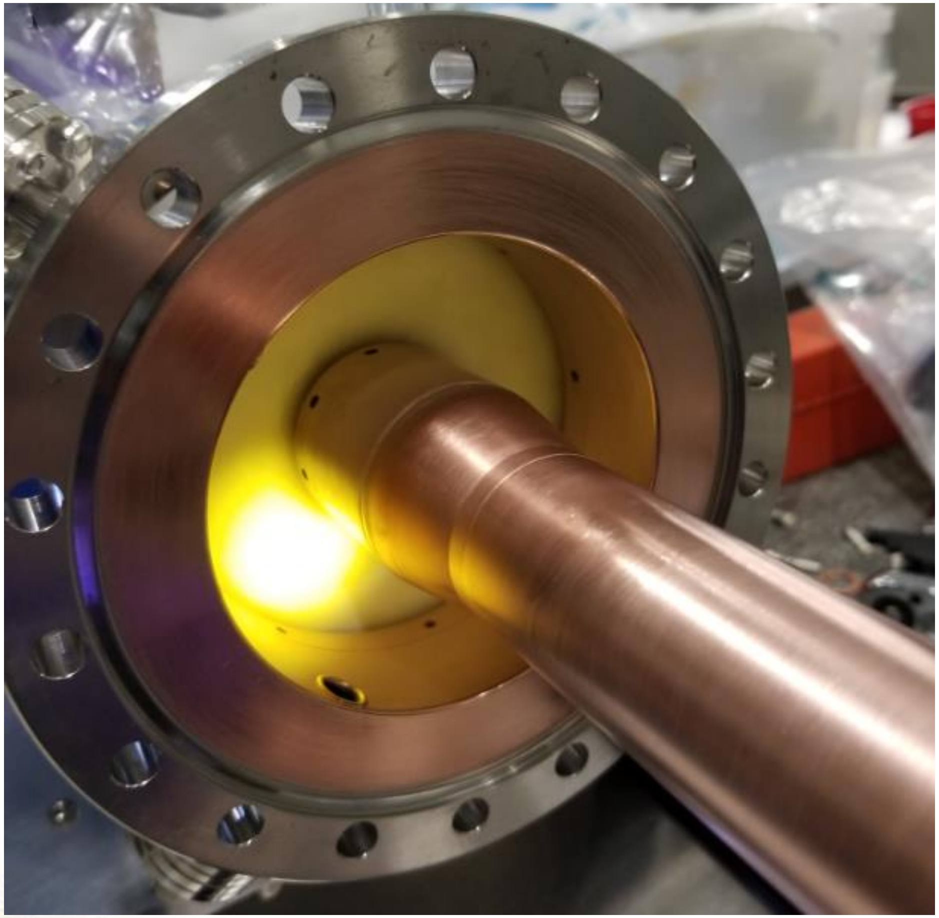


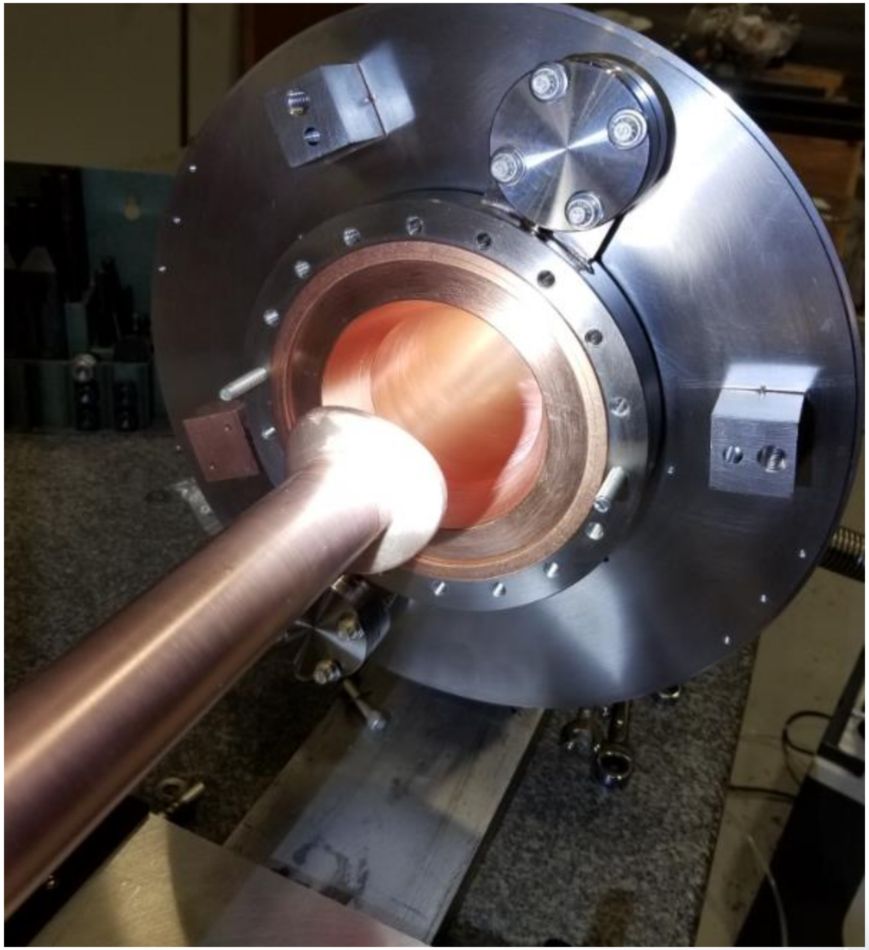


Airside BeO window-2 inspection



Vacuum side BeO window-2 inspection





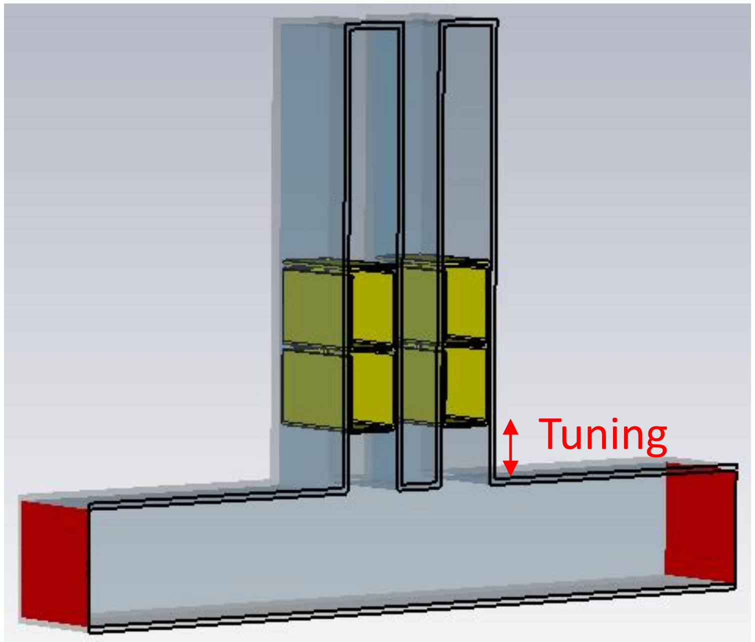
BeO Raw material

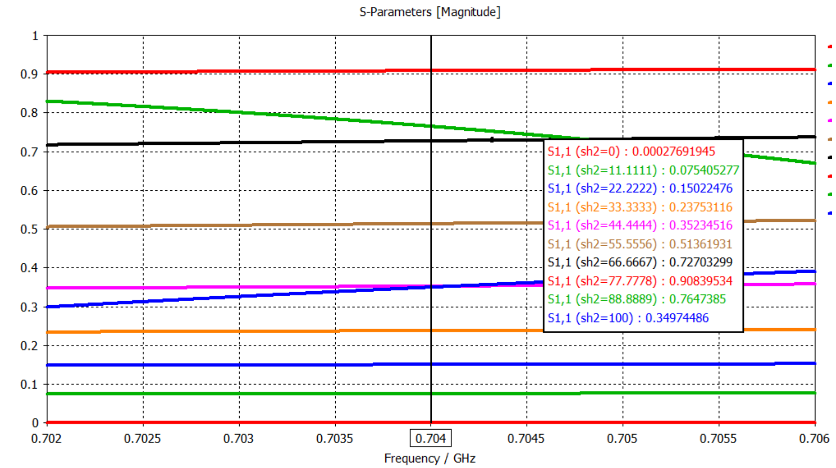
Back

Front

The raw BeO window was very clean, no marks, no scratches.

Waveguide junction design

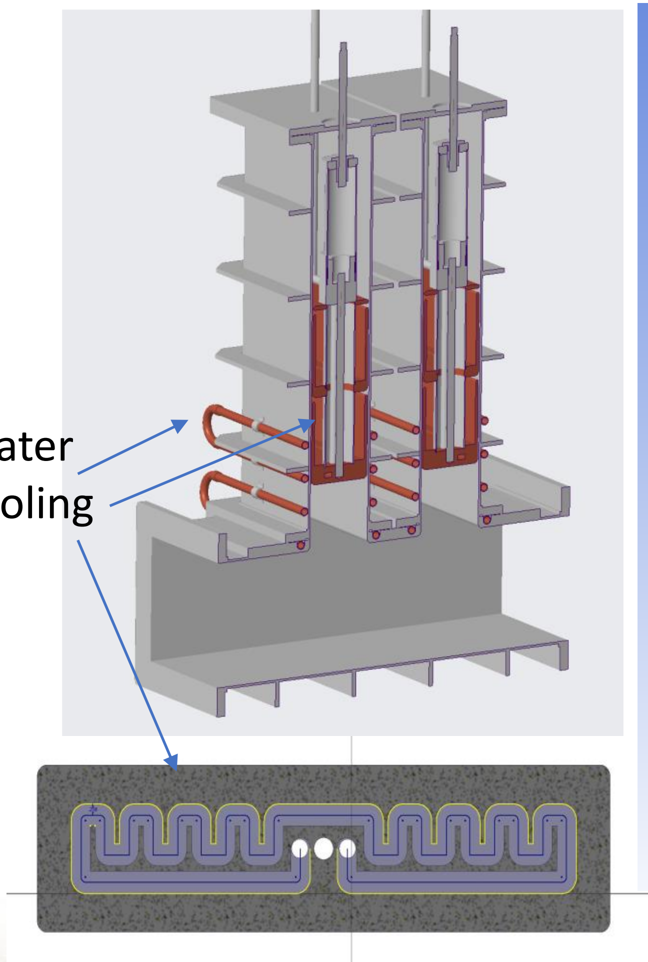


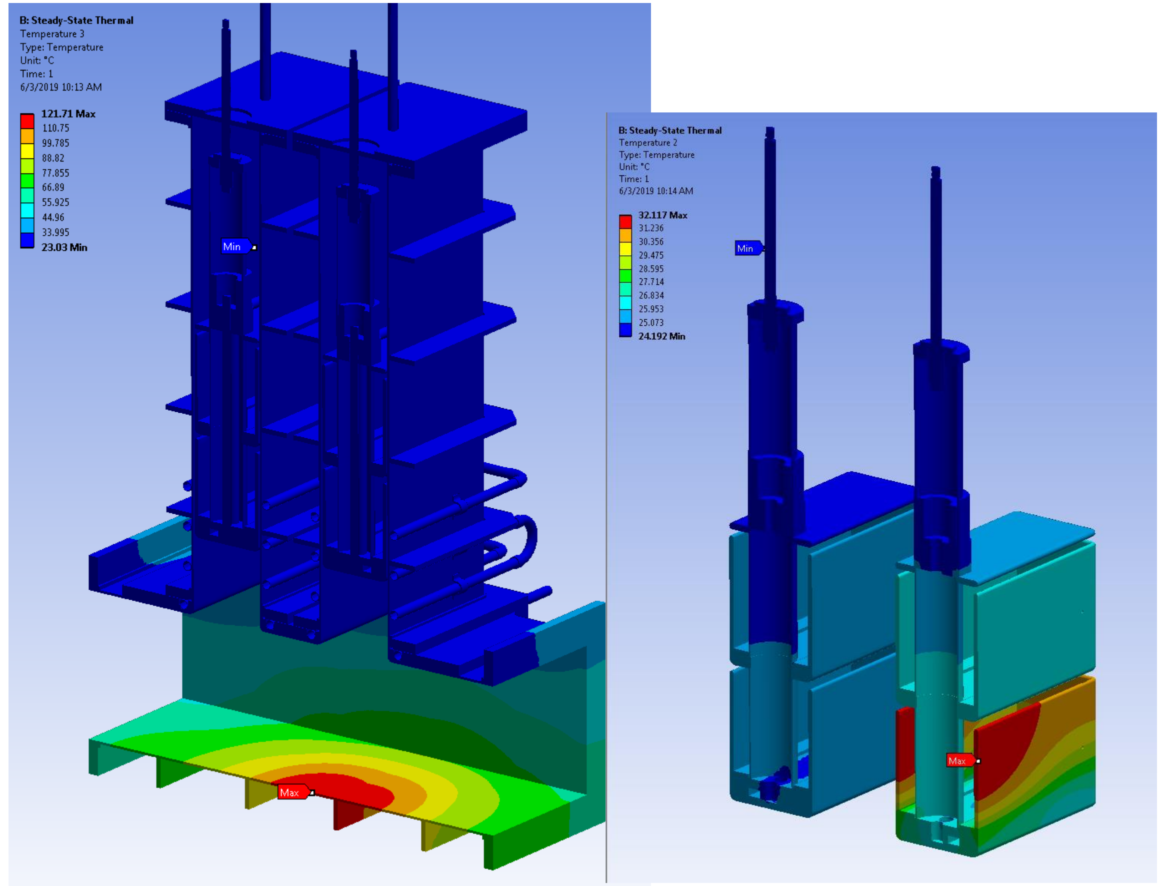


- The two short plates will be tuned at the same height from 0 to 80 mm to cover the S11 range.

Waveguide junction design

Water cooling

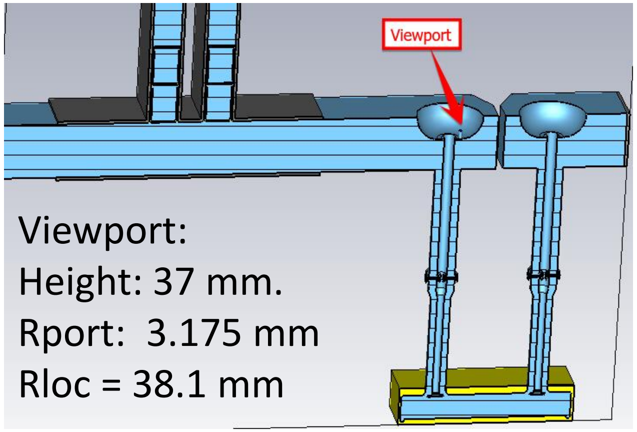


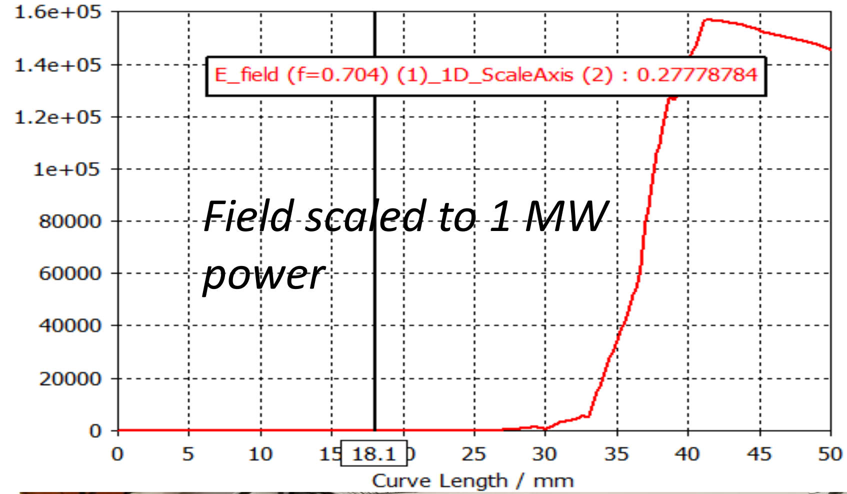


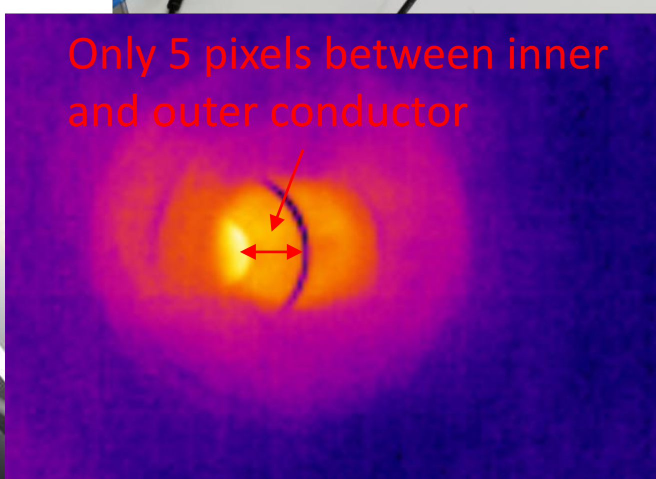
Result@P1=0,P2=90&10cm: Buckets: -447.93 W; Waveguide: -1050.9 W; Free Convection: -237.64 W

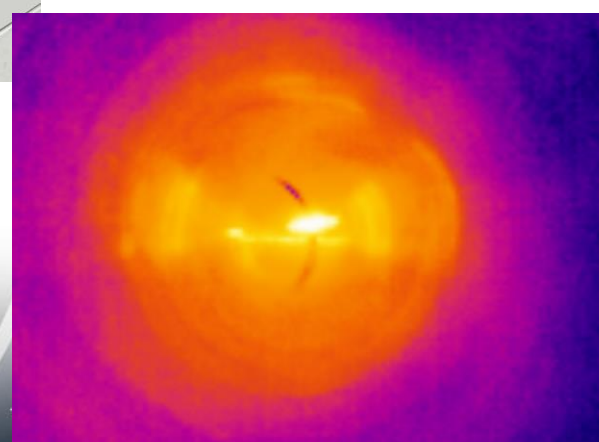
- Tremendous RF-thermal simulation was carried out.
- We believe that 3 GPM water cooling is sufficient for water bucket. However, waveguide is only cooled with slow dry air, maybe additional fan?

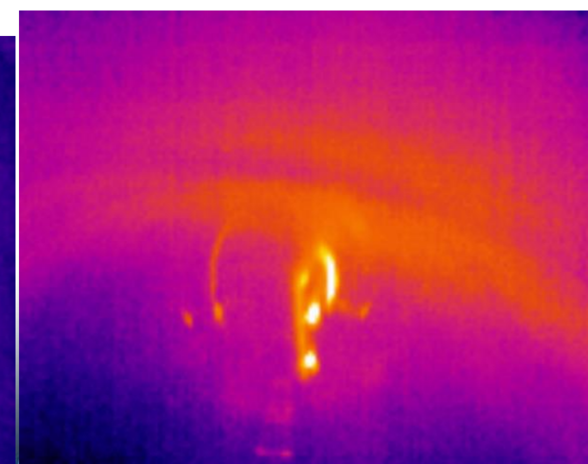
Window viewport and mockup



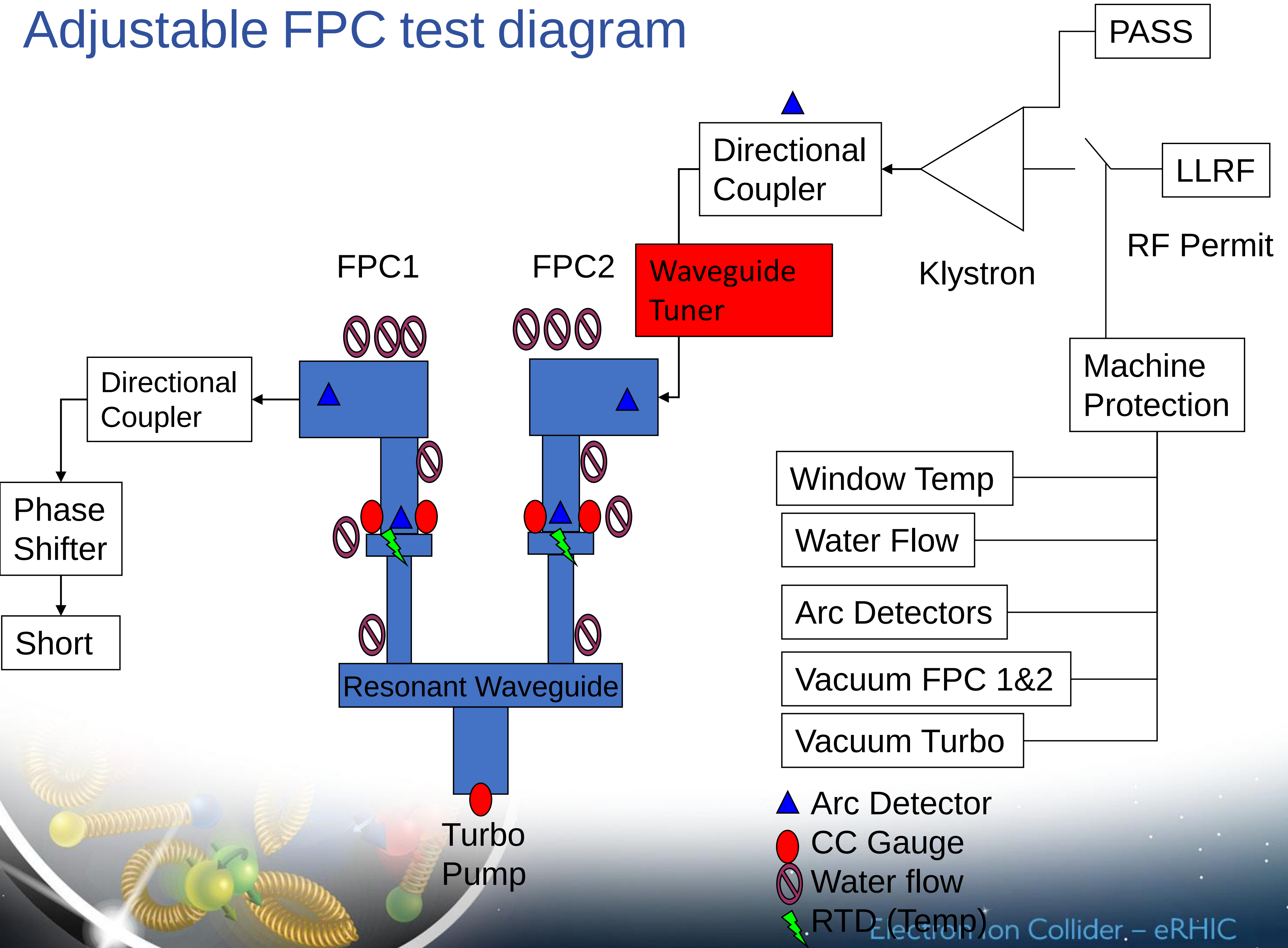




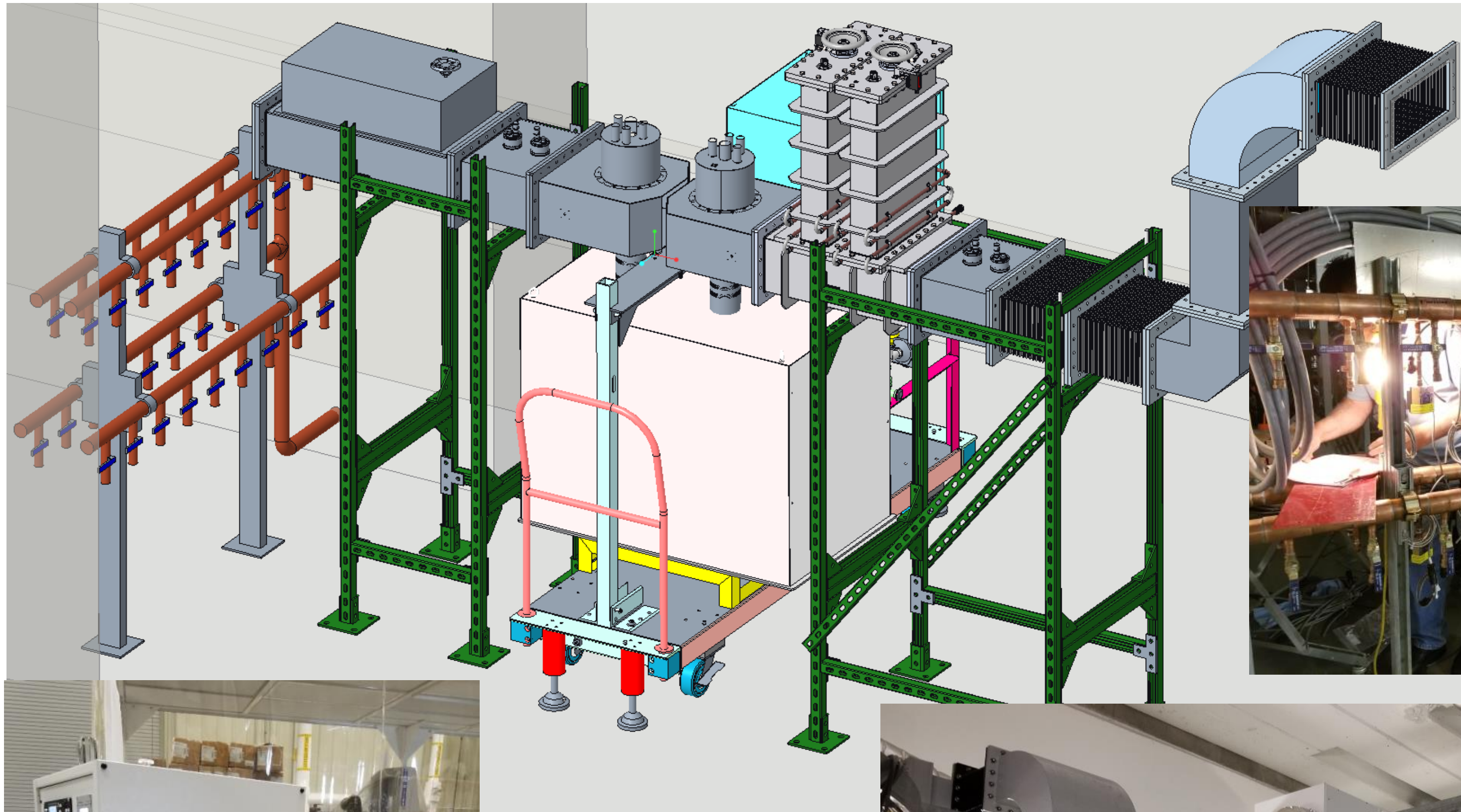


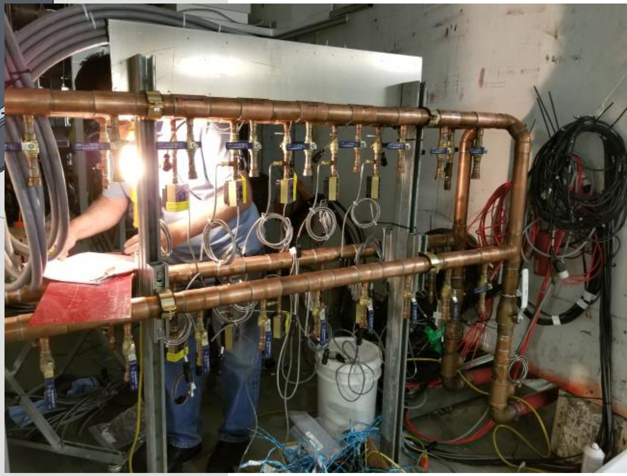


Adjustable FPC test diagram



FPC conditioning system setup





Status of the project

1. Fabricate two 500 kW fix coupler for ERL gun/booster cavity(delivered)
2. The impedance transformer will be reached by waveguide junction and/or stub tuners (delivered)
3. Refurbish FPC conditioning box and conditioning station (almost done).
4. Condition the FPC with 704 MHz klystron up to 500 kW, full reflection, all phases (starting in August).
5. Safety: ESRC review completed.

Summary

- eRHIC requires a decent amount of high power couplers, with various application conditions.
- The most challenge FPC is the adjustable coupler for electron storage ring.
- A Qext adjusting scheme with waveguide impedance tuner has been designed, simulated, and experimental test is under preparation.
- Similar scheme is able to use for other cavities and projects.

Acknowledgement (incomplete)

BNL:

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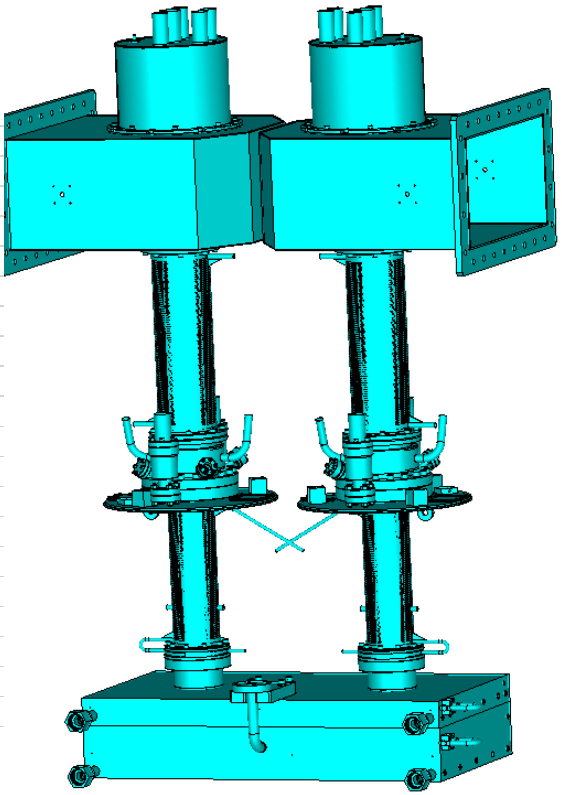
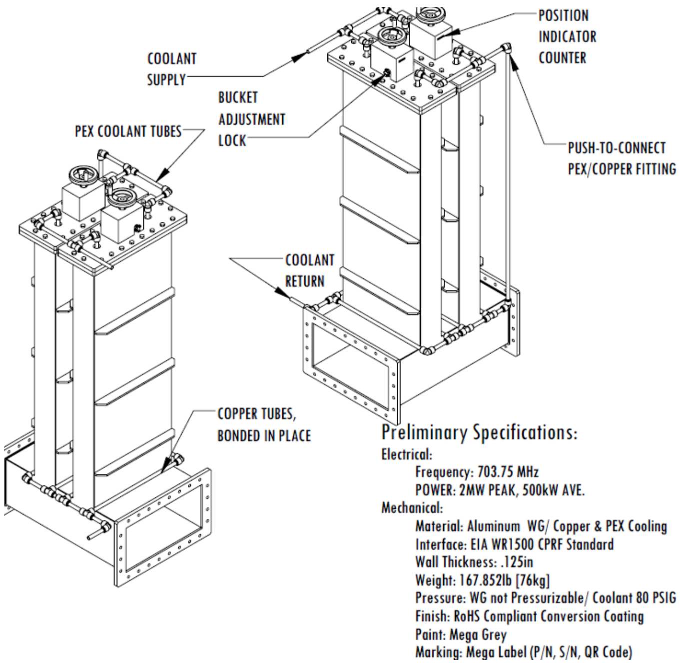
CPI: Steve Einarson

Mega: Peter Matthew, Lisa Cummings

Water cooling requirement

Component	gpm	temp sensors
FPC 1 - Vac Side Inner Cond	1.3	2
FPC 1-Vac Side Outer Cond	3	2
FPC 1 - Window OD	6.9	2
FPC 1 - Air Side Outer Cond	3	2
FPC 1 - Air Side Inner Cond	3	2
FPC 1 - Waveguide & Doorknob	1	2
FPC 2 - Vac Side Inner Cond	1.3	2
FPC 2-Vac Side Outer Cond	3	2
FPC 2 - Window OD	6.9	2
FPC 2 - Air Side Outer Cond	3	2
FPC 2 - Air Side Inner Cond	3	2
FPC 2 - Waveguide & Doorknob	1	2
Box-1	16	2
Box-2	16	2
Waveguide junction	3	2
water bucket	3	2
spare		8
total	74.4	40





- 16 water channels
- 36 temperature sensors, we can also use on common temperature sensor for input

RF-thermal simulation