Recent Experience with Testing and Operating RF Couplers at SNS

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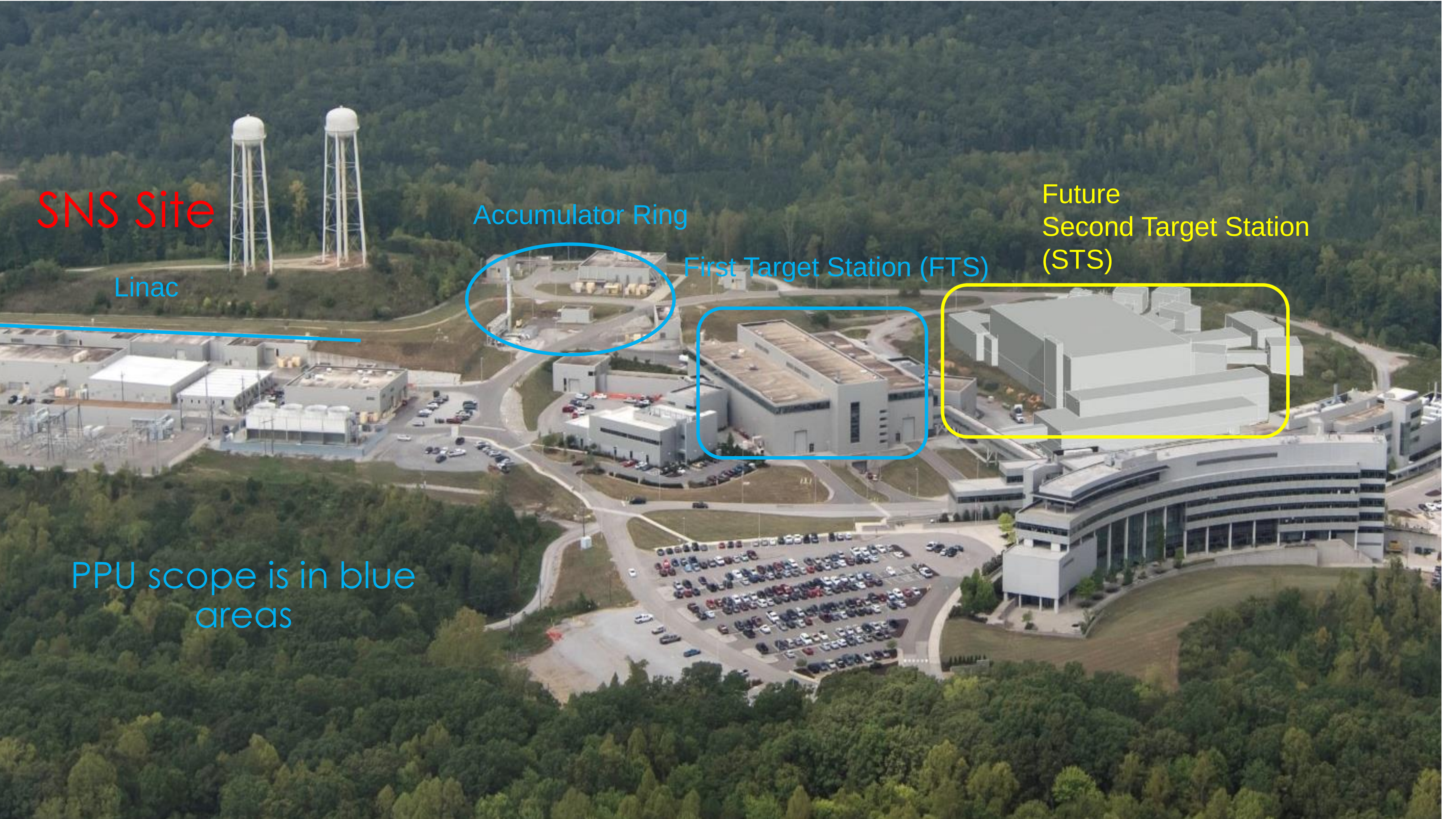
On behalf of the SCL Group

July 2nd, 2024

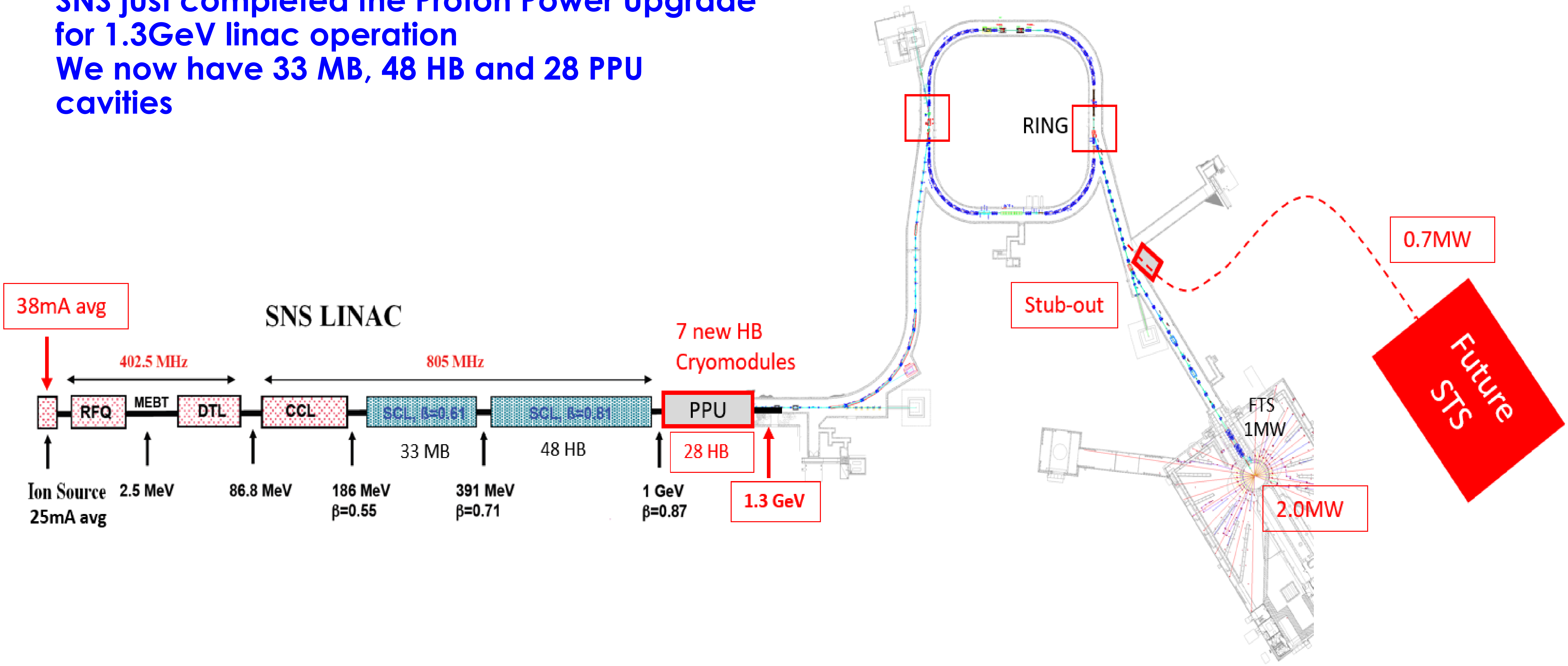
Outline

- SNS and the accelerator linac
- SCL RF coupler history
- SCL RF coupler failures and recovery in operations
- Proton Power Upgrade (PPU) RF couplers design changes and performance
- Experience from RF conditioning of PPU couplers
- PPU cryomodule testing
- Operational performance of PPU cryomodules


SNS Site
Accumulator Ring
Linac
First Target Station (FTS)
Future
Second Target Station
(STS)
PPU scope is in blue
areas

SNS Layout

SNS just completed the Proton Power Upgrade for 1.3GeV linac operation
We now have 33 MB, 48 HB and 28 PPU cavities



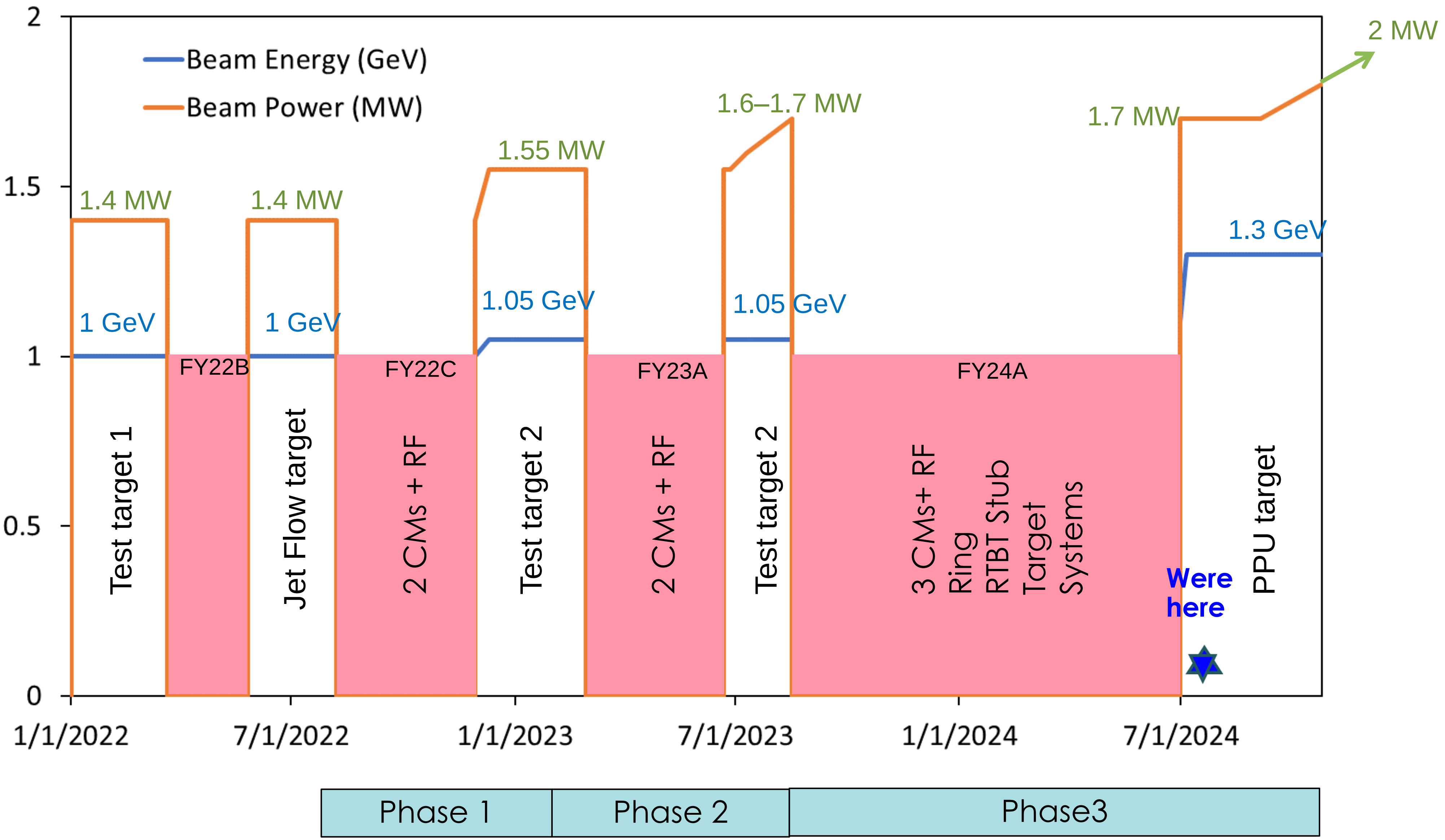
PPU specifications & KPPs

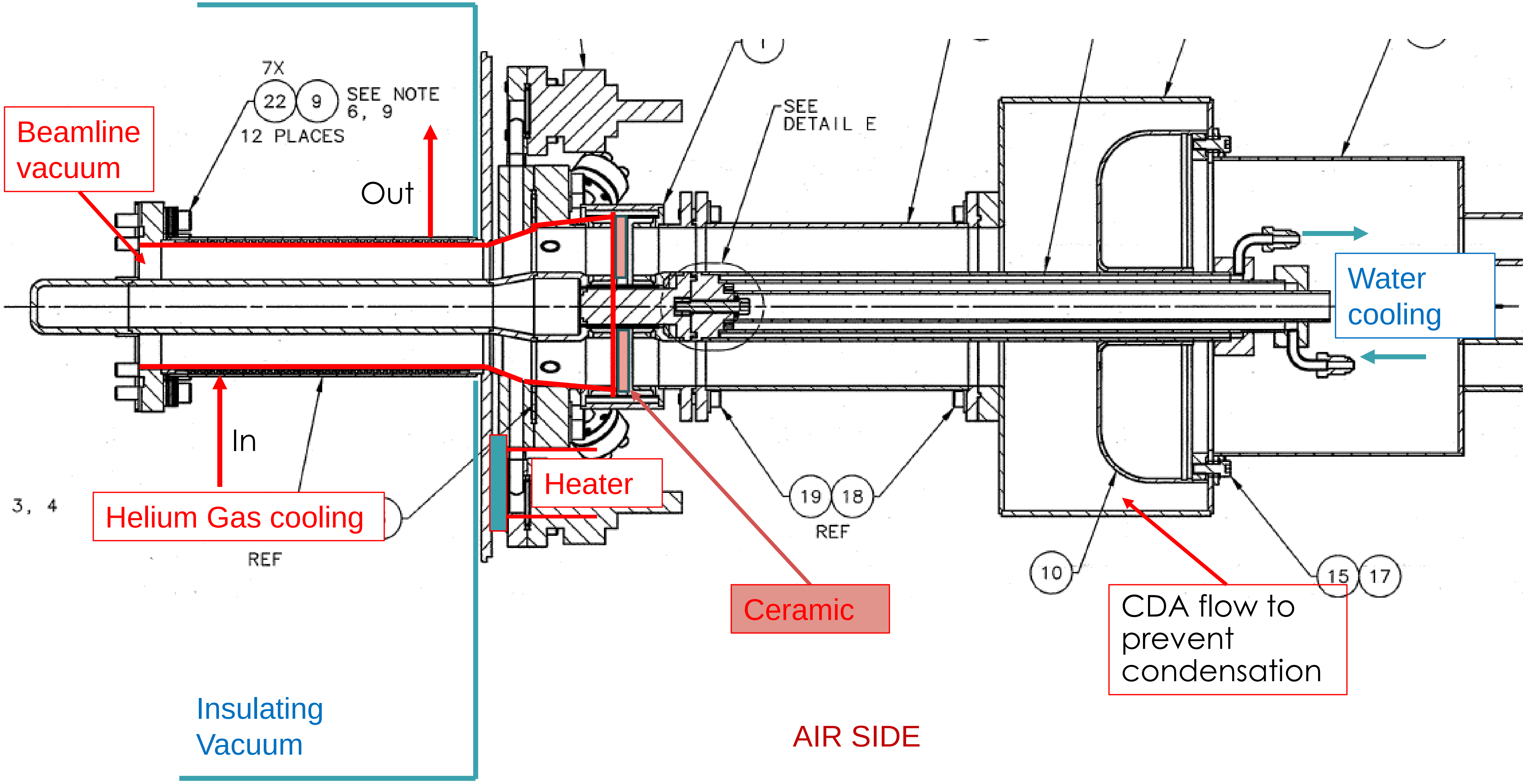
Major Specification	Current operation	Post PPU operation
Beam power (MW)	1.4	2.0
Beam energy (GeV)	1.0	1.3
Beam current, macro-pulse average (mA)	25	27
Macro-pulse length (ms)	1	1
Peak and Average power (kW)	550,50	700, 65
Energy per pulse (kJ)	24	33
Repetition rate (Hz)	60	60

PPU Key Performance Parameter	Threshold	Objective
Beam power on target (MW)	1.7	2.0
Beam energy (GeV)	1.25	1.3
Target operation without failure (hours)	1250 at 1.7 MW	1250 at 2.0 MW
Stored bam intensity in ring (protons per pulse, ppp)	1.60×10^{14} ppp[1]	2.24×10^{14} ppp[2]

[1] corresponds to 1.92 MW at 1.25 GeV and 60 pps
[2] corresponds to 2.80 MW at 1.30 GeV and 60 pps

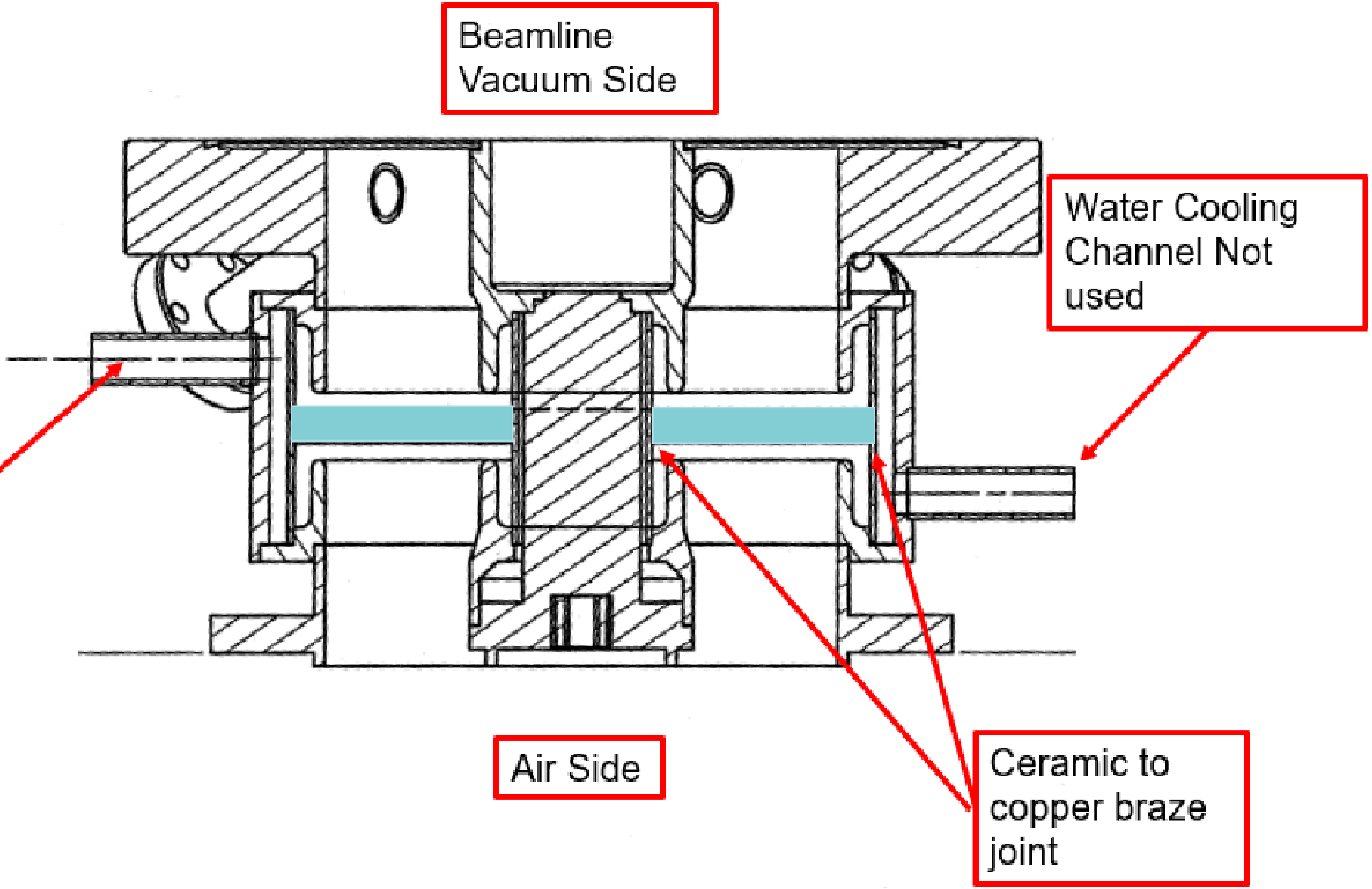
Power Ramp-up Plan





SNS Coupler Design and Cooling Scheme

RF Coupler Window

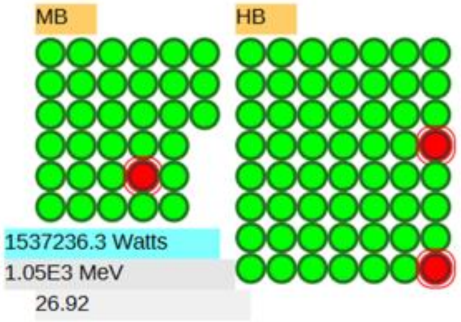


SCL RF Couplers

Type	Qty	Antenna Length (mm) flange to tip	Antenna wall thickness (mm)	Design Q-value	Conditioning Travelling wave	Conditioning Standing Wave
MB	33	309	3.95	7e5	600kW,1ms, 60Hz	500kW,0.5ms, 60Hz 300kW, 1ms, 60Hz
HB	48	304	3.95	7e5	600kW,1ms, 60Hz	500kW,0.5ms, 60Hz 300kW, 1ms, 60Hz
PPU	28	302.5	7.52	8e5	700kW,1ms, 60Hz	600kW, 0.5ms, 60Hz 400kW, 1ms, 60Hz

RF Coupler Forward Power

CM	Total PFwd	Total Pr	% Pref	Cav A	Cav B	CavC	CavD			Ia	Ib	Ic	Id
CM01	516	49	10	156	206	153				11.11 A	11.13 A	10.94 A	
CM02	555	42	8	186	167	203		78	Mod 01	11.31 A	11.05 A	10.97 A	
CM03	893	106	12	311	244	335				11.03 A	10.97 A	11.08 A	
CM04	896	119	13	276	261	358				11.01 A	11.10 A	10.73 A	
CM05	704	75	11	221	290	193				10.70 A	10.75 A	10.80 A	
CM06	857	78	9	269	327	260		78	Mod 05	11.05 A	10.98 A	11.05 A	
CM07	890	77	9	280	298	312				9.54 A	10.84 A	10.88 A	
CM08	478	42	9	207	0	271				11.26 A	10.81 A	10.79 A	
CM09	728	50	7	288	184	256				10.78 A	10.83 A	10.76 A	
CM10	569	68	12	167	133	269		78	Mod 09	10.91 A	10.78 A	10.92 A	
CM11	559	41	7	167	191	201				10.80 A	10.92 A	11.21 A	
CM12	881	83	9	241	249	192	199	82	Mod 12	11.41 A	11.39 A	11.10 A	11.53 A
CM13	1200	152	13	352	271	394	182			11.27 A	11.49 A	11.48 A	11.38 A
CM14	1609	204	13	400	325	465	419	81	Mod 14	11.44 A	11.22 A	11.32 A	11.34 A
CM15	1486	96	6	448	357	334	348			11.08 A	11.23 A	11.15 A	11.40 A
CM16	1588	124	8	419	379	406	384			11.34 A	11.27 A	11.34 A	11.26 A
CM17	1144	12	1	258	324	305	257			11.24 A	11.10 A	11.16 A	11.21 A
CM18	1303	67	5	434	312	327	230	83	Mod 18	11.24 A	11.14 A	11.20 A	11.22 A
CM19	1346	87	6	248	379	364	354			11.42 A	11.50 A	11.59 A	11.57 A
CM20	1624	187	11	462	481	417	263			11.44 A	11.52 A	0.00 A	11.53 A
CM21	1691	117	7	477	320	414	479	81	Mod 21	11.59 A	11.55 A	11.81 A	11.90 A
CM22	1393	52	4	497	239	228	428			11.16 A	11.68 A	11.24 A	11.85 A
CM23	1725	182	11	394	497	403	432			11.76 A	11.85 A	11.88 A	11.91 A
CM29													
CM30													
CM31	1094	55	5	323	354	417	0	80	Mod 30	12.25 A	12.38 A	11.87 A	-0.00 A
CM32	785	412	52	244	241	300	0			12.32 A	11.94 A	12.50 A	11.94 A



% reflected at 1.5MW beam power

Coupler Replaced in Support of Operations

- Couplers Replaced
  - CM01 A and C
  - CM05 A
  - CM06 C
  - CM12 D
  - CM17 B and C
  - CM18 B
  - CM19 D
  - CM21 B and C

CM01c removed due to its excessive corrosion, no leak

CM05a removed due to airside arcing damage, coupler ok

A total of 11 RF couplers have been replaced due to performance since 2006

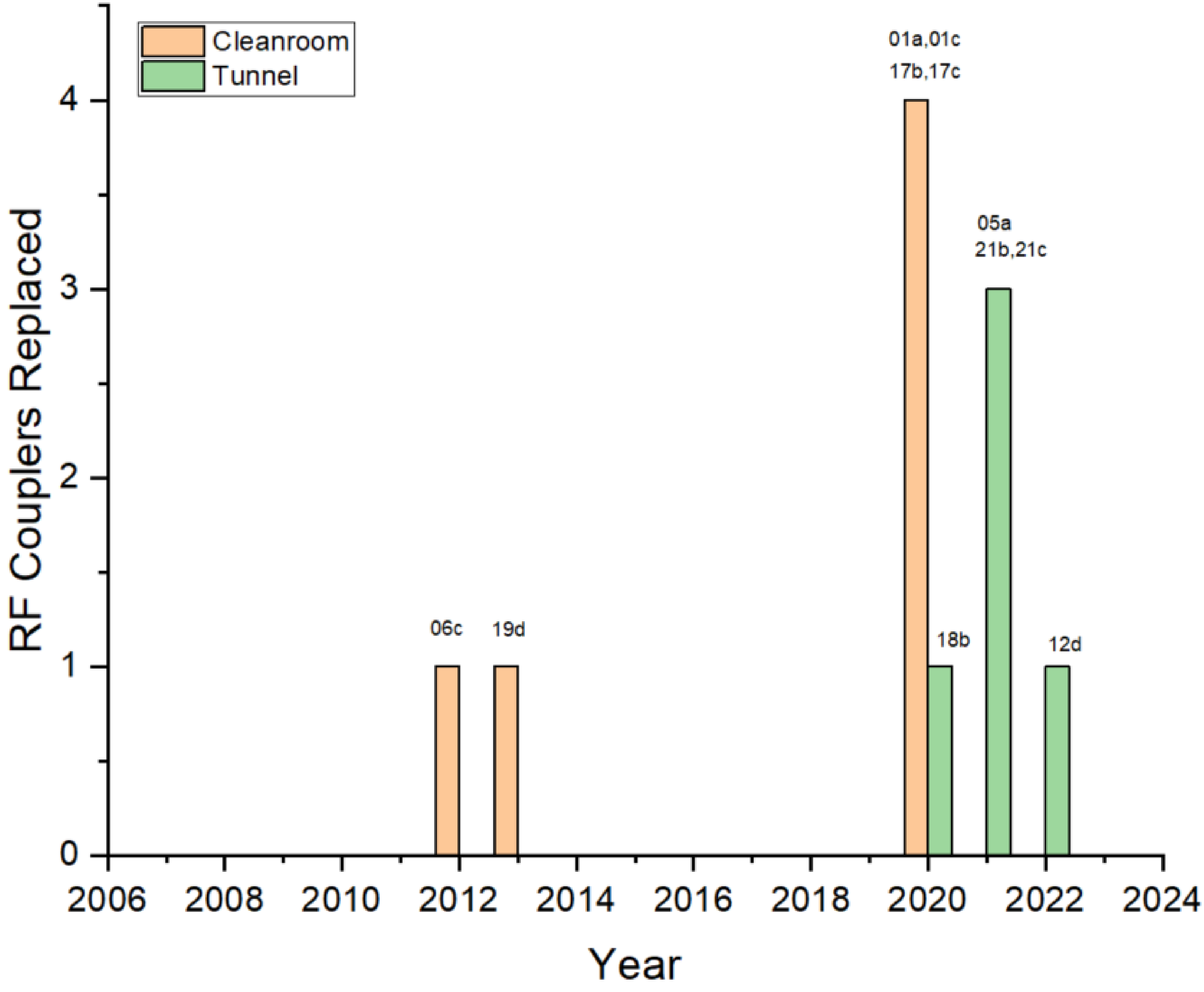
4 –MB
7-HB

Symptom: In most cases ceramic window vacuum leak occurs which leads to repetitive RF tripping which increases in frequency over time

After removal most had ~e-7 Torr L/s

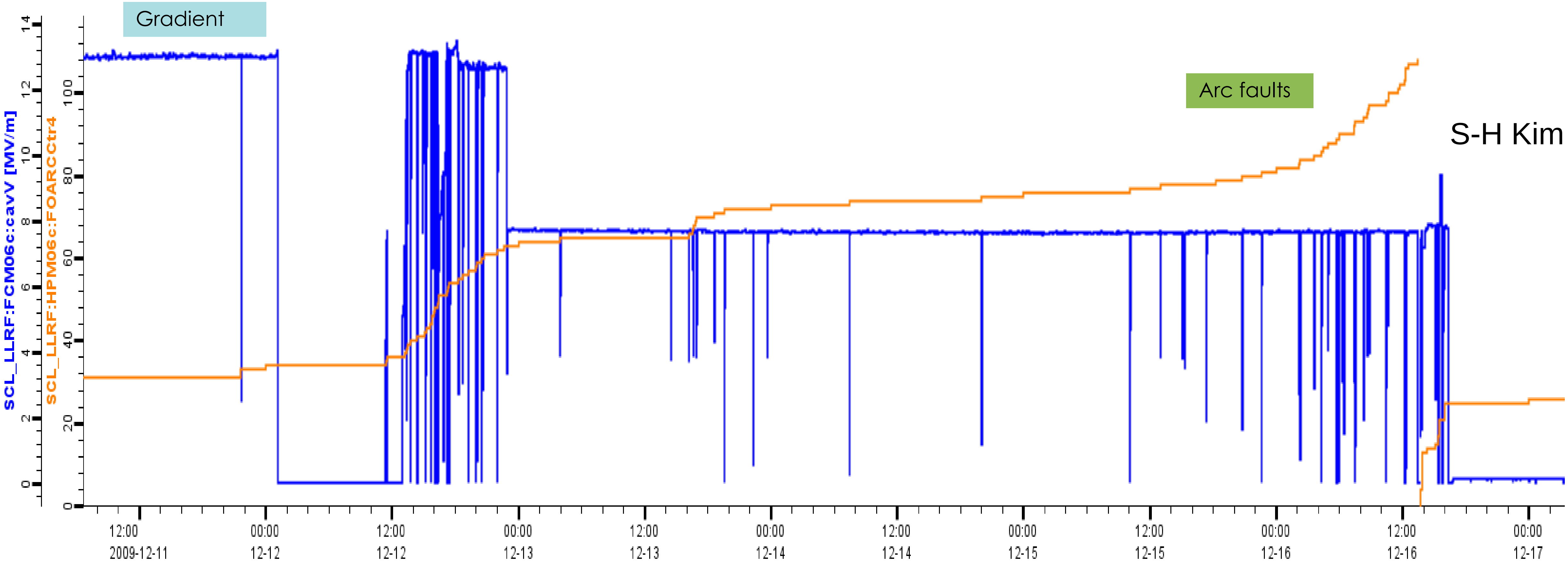
8 had Leak locations identified, all were under outer diameter choke joint at or near the braze joint

RF Couplers Replaced



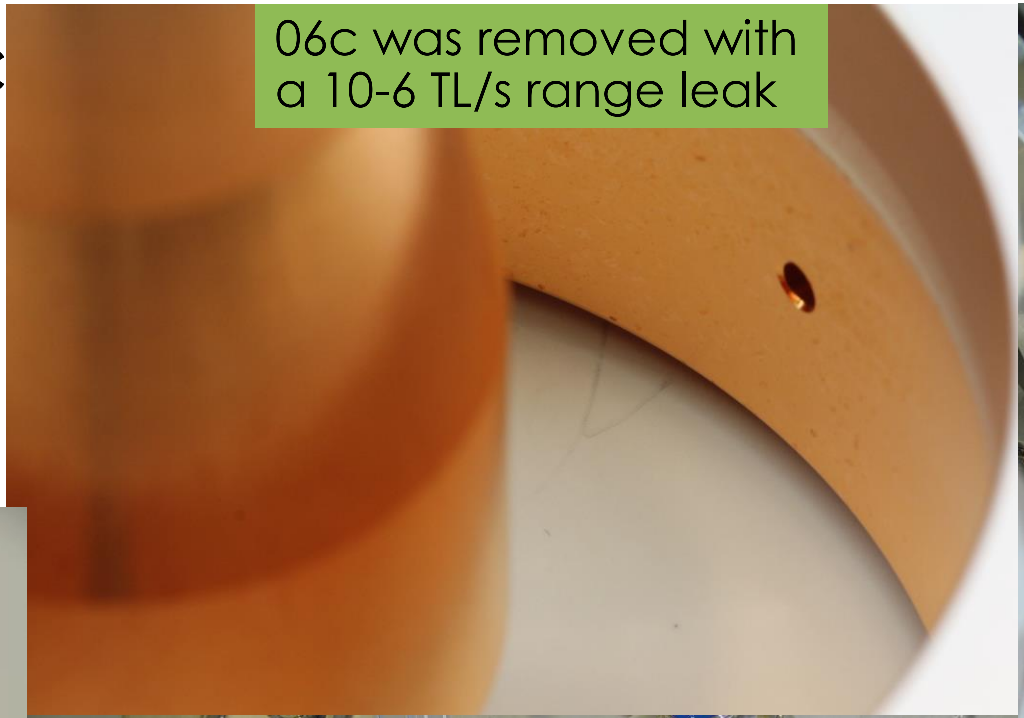
It all started in 2009 with 06c performance degrading

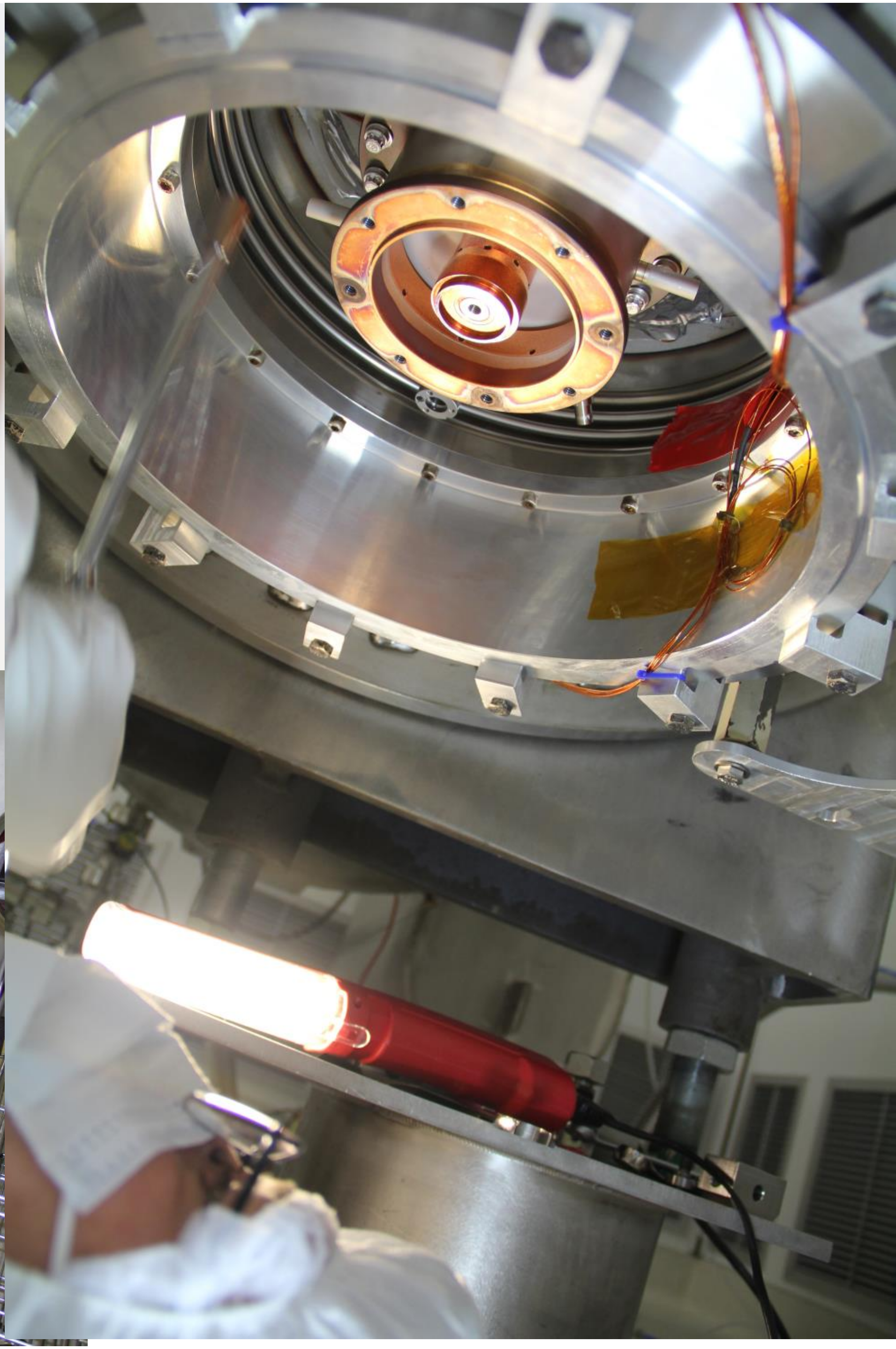
- 06c showed clear signs of Window vacuum arcs
- Gradient was significantly lowered but arcing continued

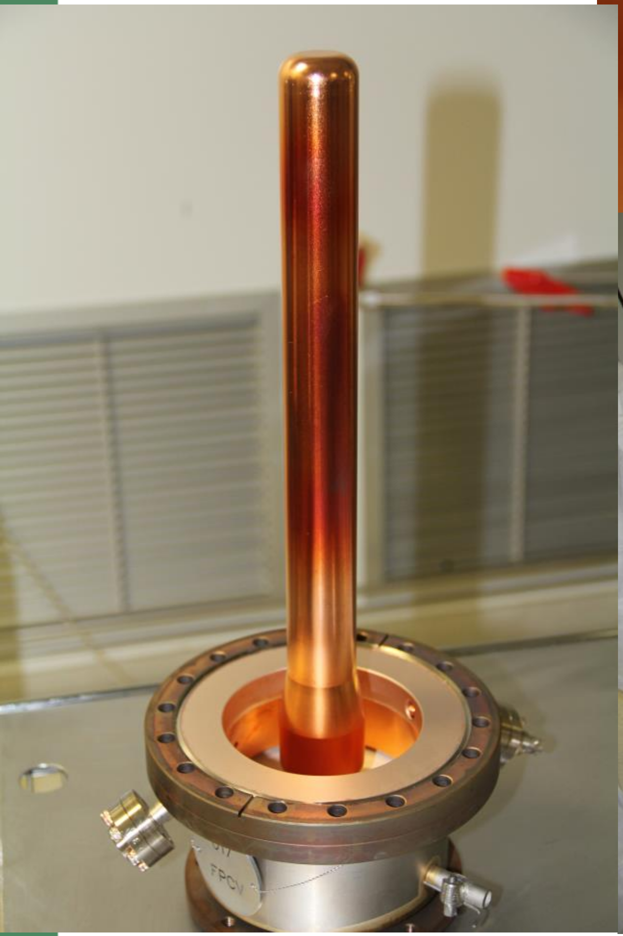


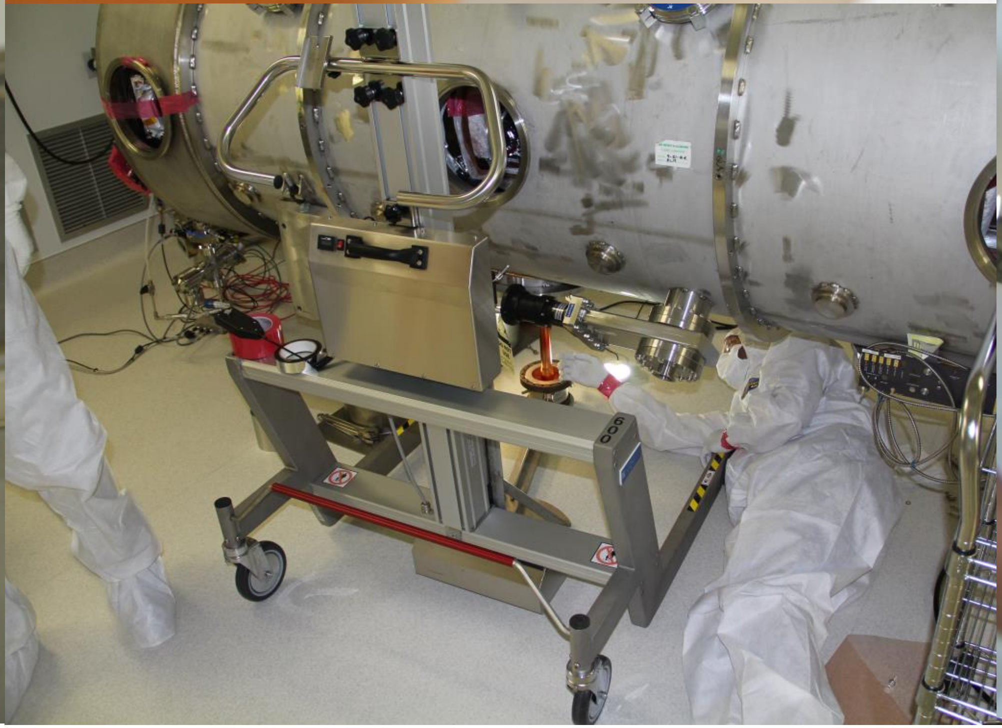
06c ceramic failure

06c was removed with a 10-6 TL/s range leak





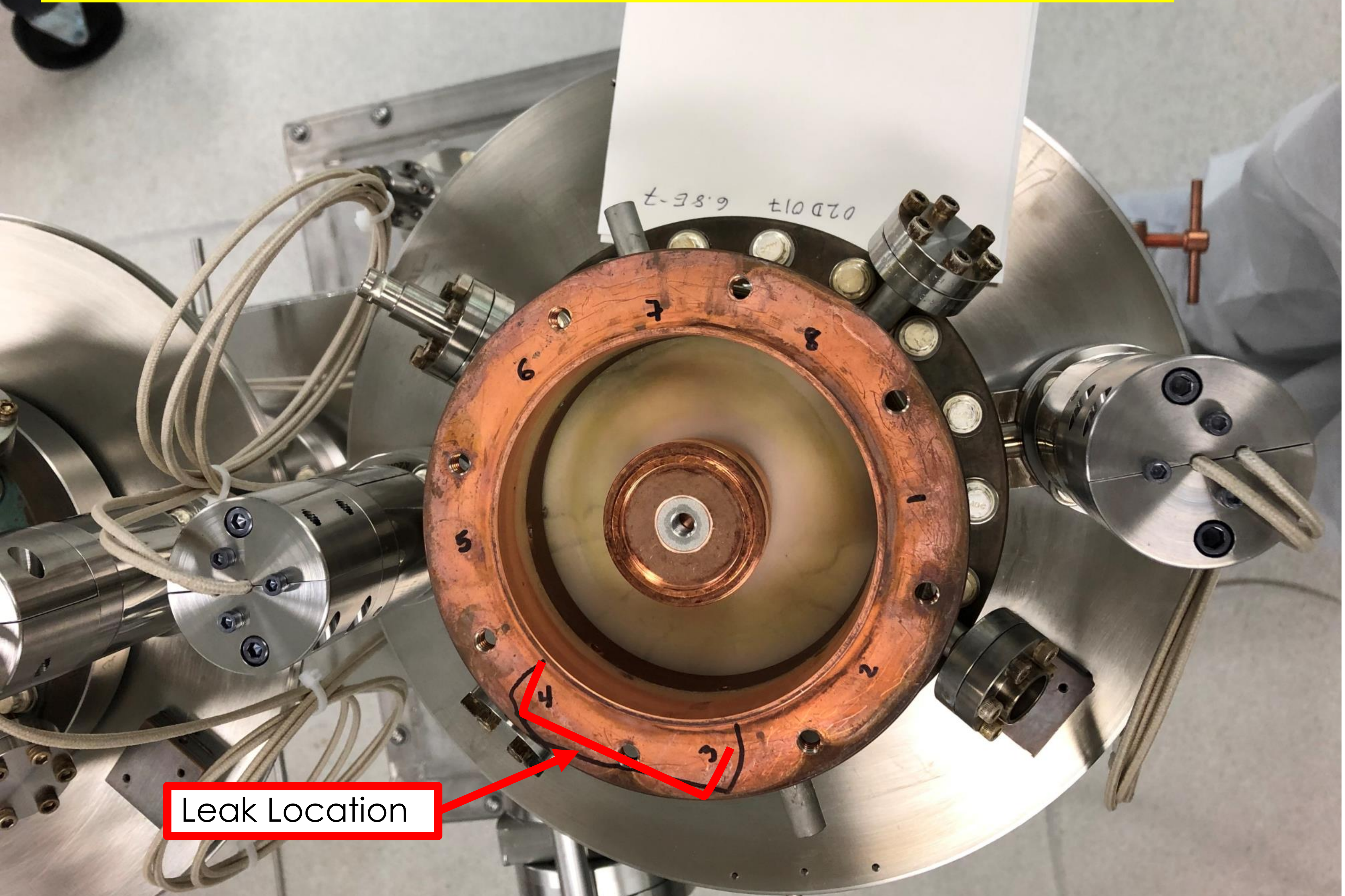




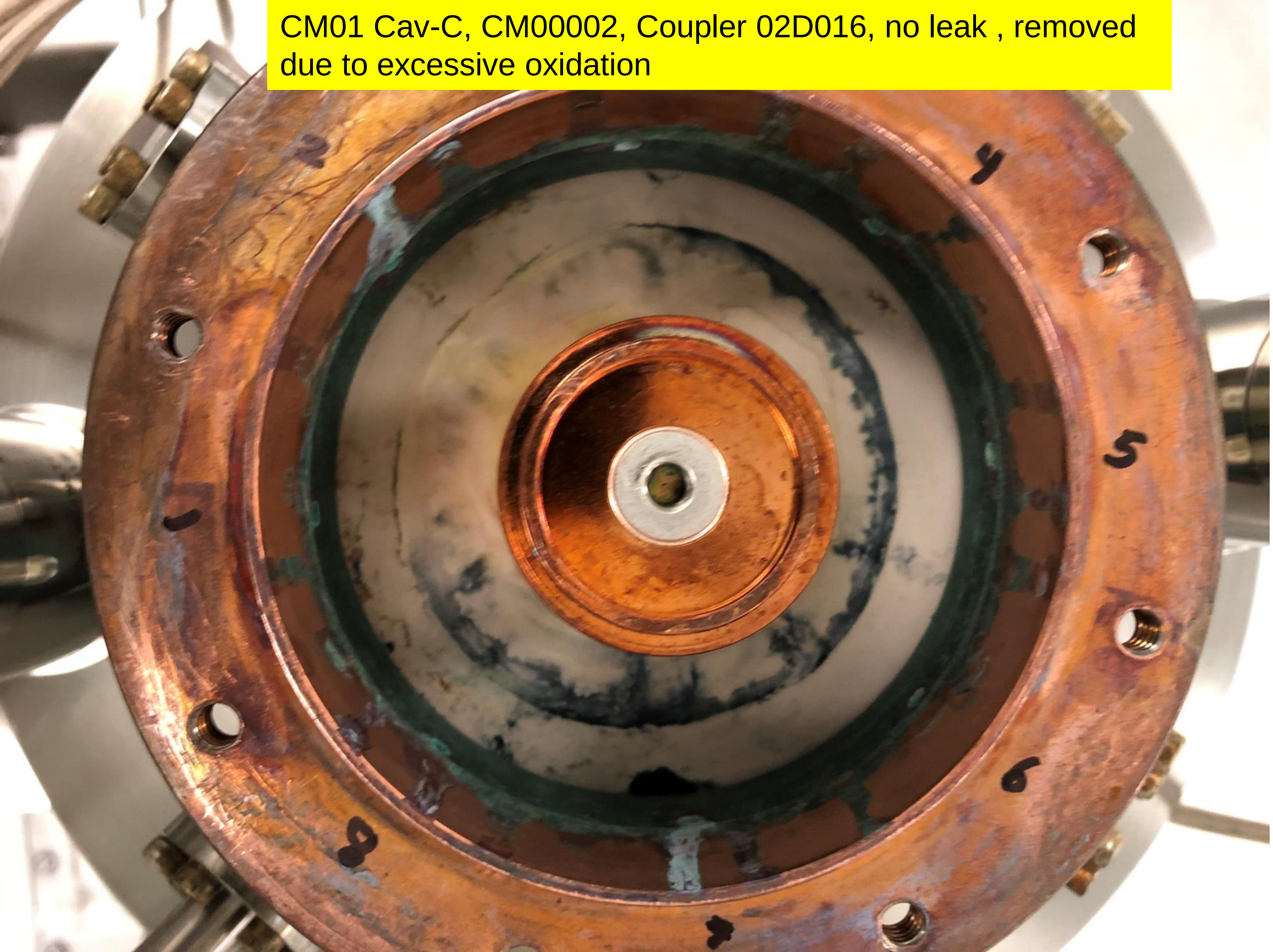
Removal of RF couplers

- Before and after coupler removal each was leak checked, most leaked
- Typical leak rate was sized off the cryomodule at 10^{-6} -10^{-7} TL/s
  - To Date only two ceramics were fractured 06c in operation, and 19J029 during conditioning
  - Remainder leaked under choke joint with no visible fracture
- We did not cut apart failed assemblies due to activation
- One coupler was removed due to severe oxidation due to condensation, 01c
- One coupler was removed due to damaged Air side, 05a

CM01 Cav-A, CM00002, Coupler 02D017, leak rate 6.8e-7 TL/s location outer conductor

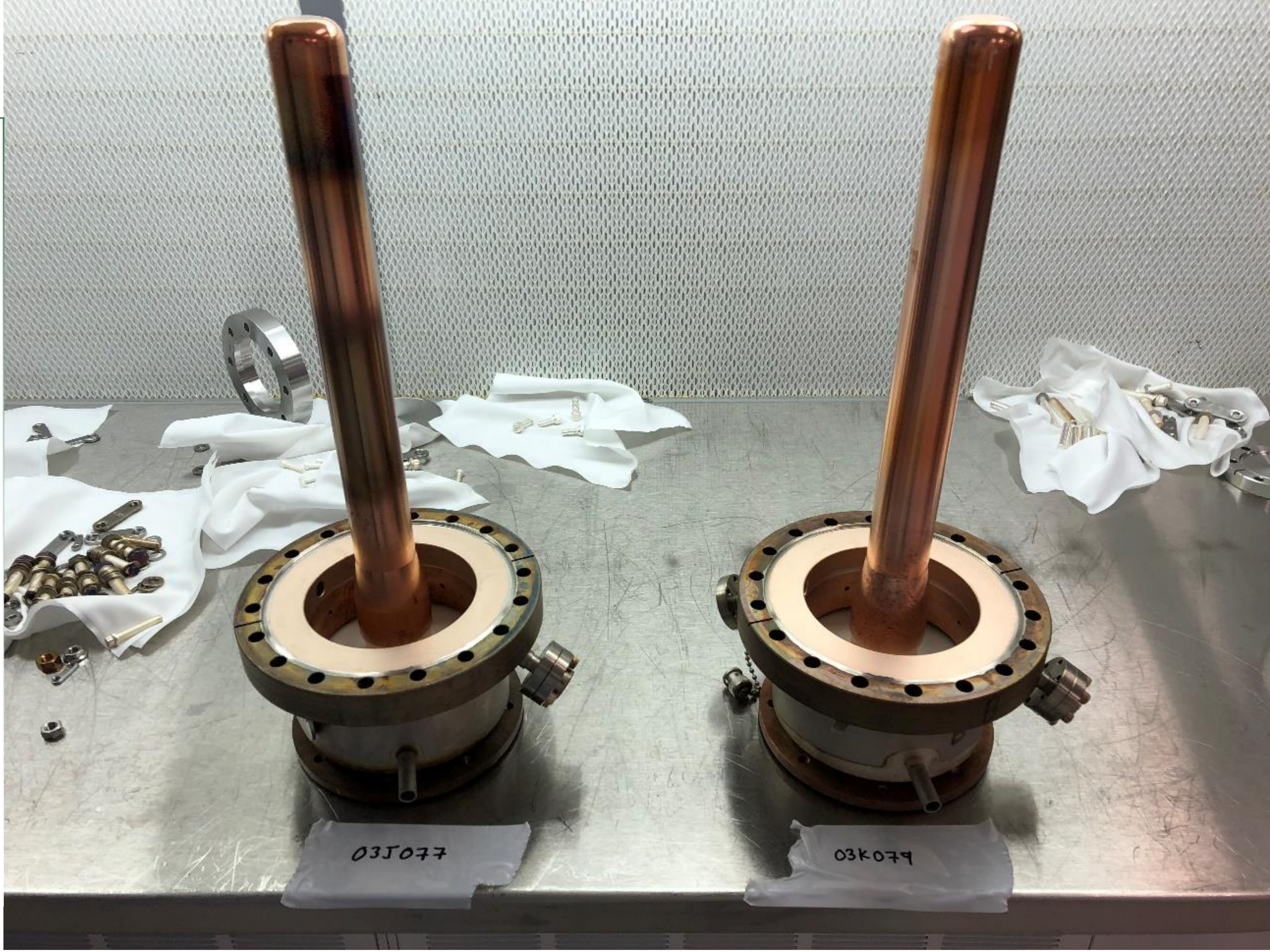


CM01 Cav-C, CM00002, Coupler 02D016, no leak , removed due to excessive oxidation

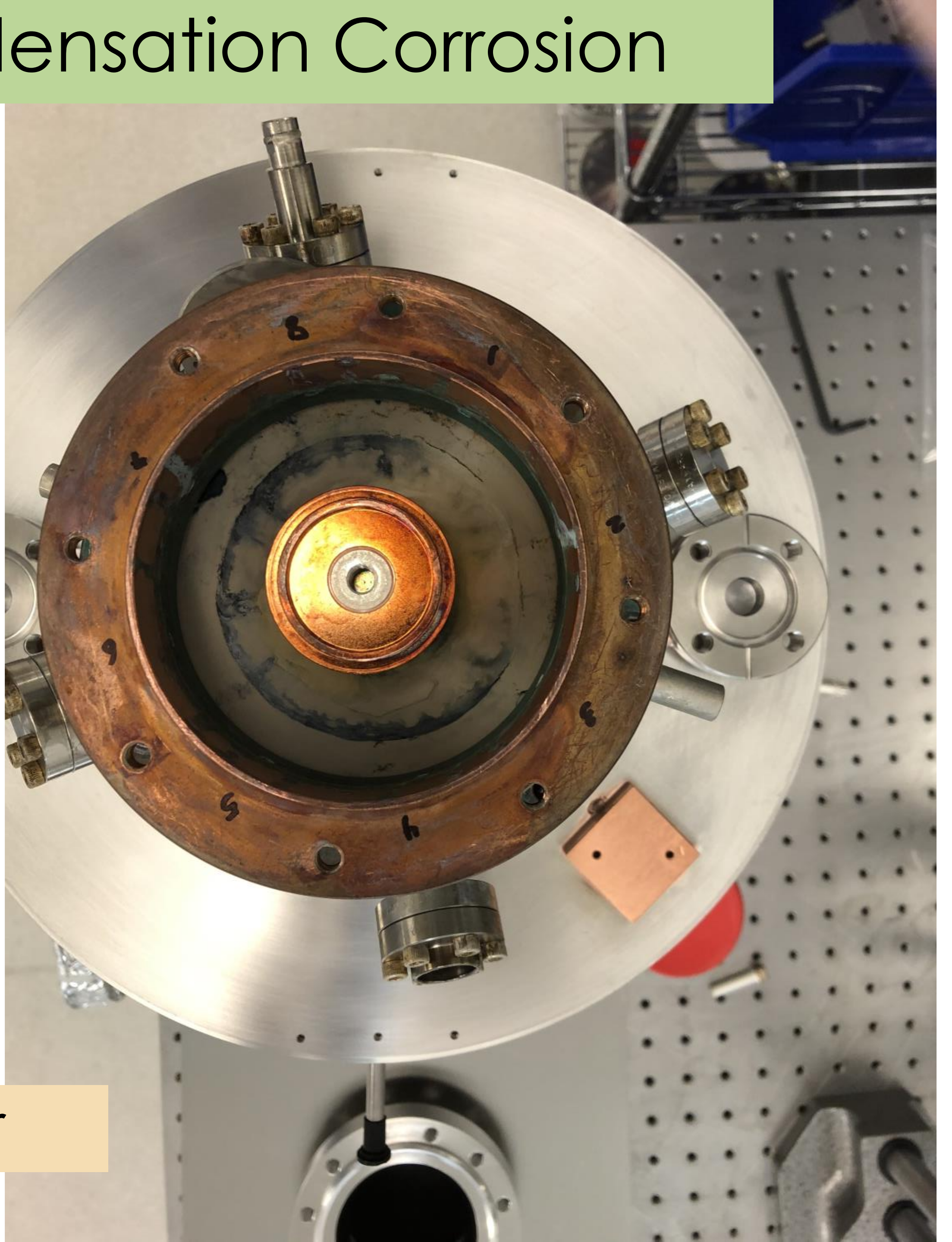


Coupler Failures

- CM17 removed from linac 1/18/2018
- Cleanroom repairs
  - 20b leak rate 1.7e-7 TL/s
  - 20d leak rate 2.2e-7 TL/s
- Removed couplers in cleanroom from 20d (left) and 20b (right)



Evidence of Arcing and Condensation Corrosion

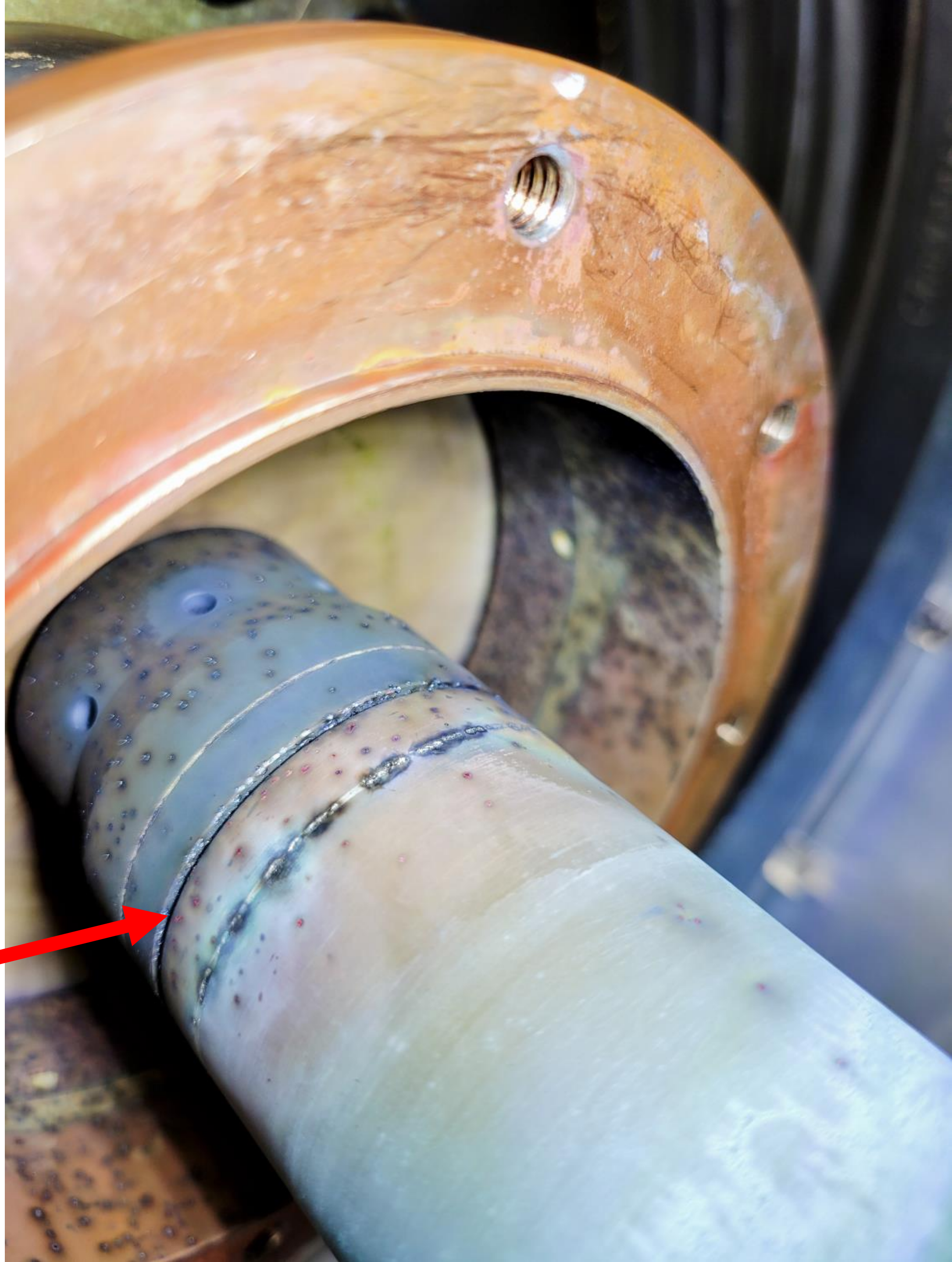


MB RF Coupler

Airside Arcing CM05a

- On 11/2021 we decided to investigate 05a airside and replace it
- What we found was the inner conductor extension was arc welded to the RF coupler
- This had been running like this for a long time

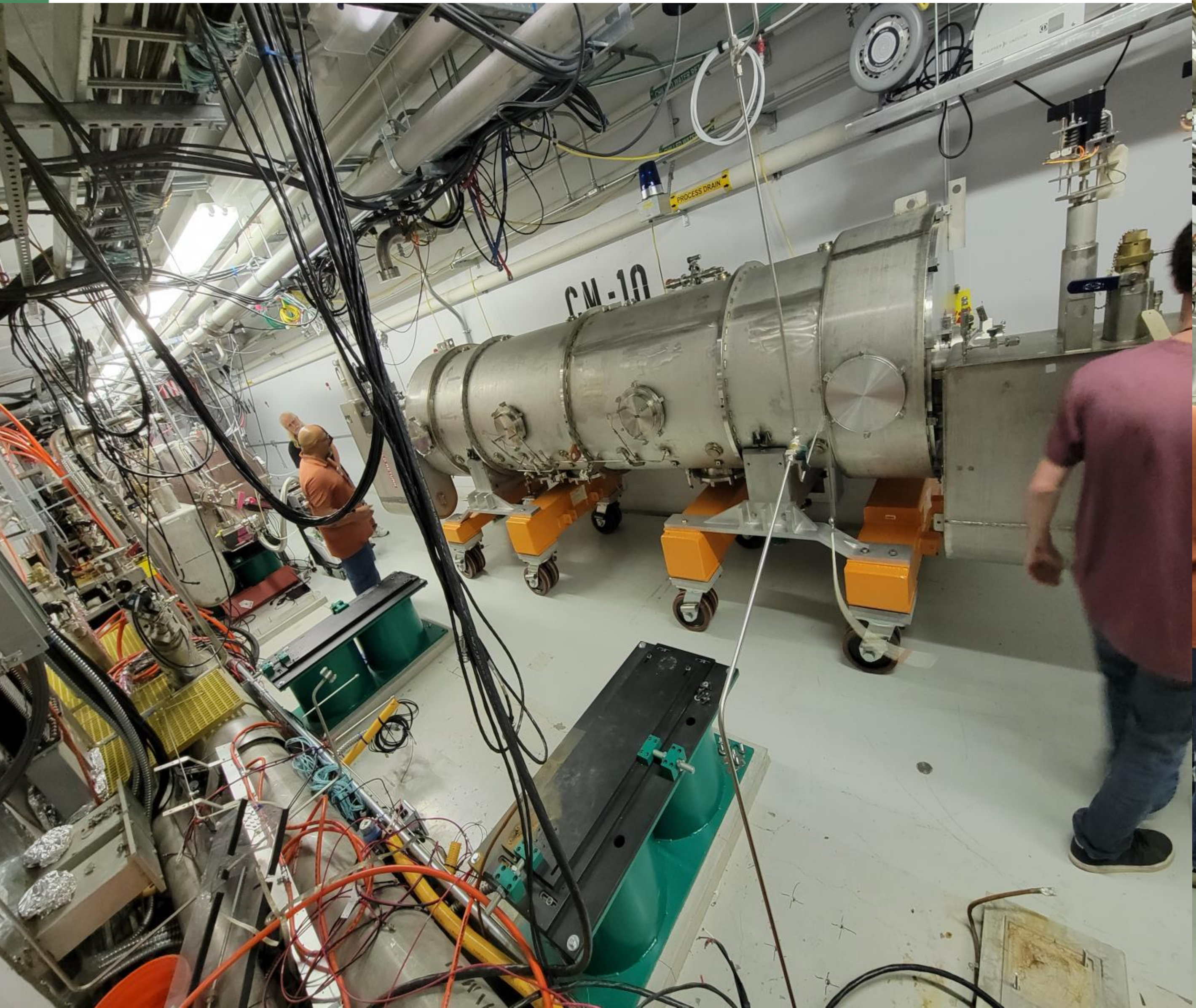
Airside inner conductor extension connection showing severe arc damage



Evolution of coupler replacement

- Up to 2020, coupler replacement required removal of the cryomodule from the linac and bringing it back to the RF Test facility cleanroom for repairs.
  - Many repairs would take place on the cryomodule including
    - RF Couplers
    - Removal of HOM antennas and detuning
    - Piezo tuner removal
    - Ion pump and coupler CCG replacements
    - Warm valves, ect.
  - Repairs did decrease performance in some cryomodules (lower field emission onset)
  - Time frame for recovery was several months and installation could only occur in a maintenance outage, 2X per year

Moving a Cryomodule In the Tunnel



Cryomodule repair in cleanroom

Development of RF coupler replacement in linac

- In 2020 we initiated coupler replacement in the tunnel
- Cleanroom was built around coupler area and procedures developed to replace in-situ
- This has been very successful, and 5 repairs took place in the tunnel
- No performance degradation has occurred so far

Cleanroom Development

- ULPA filter placed under cryomodule behind RF coupler location blowing across coupler port
- Vinyl flooring placed on tunnel concrete floor
- CM wiped down solvent and N2 cleaned
- Small gowning room on end with cleanroom supplies

Tunnel View CM18 Preparation

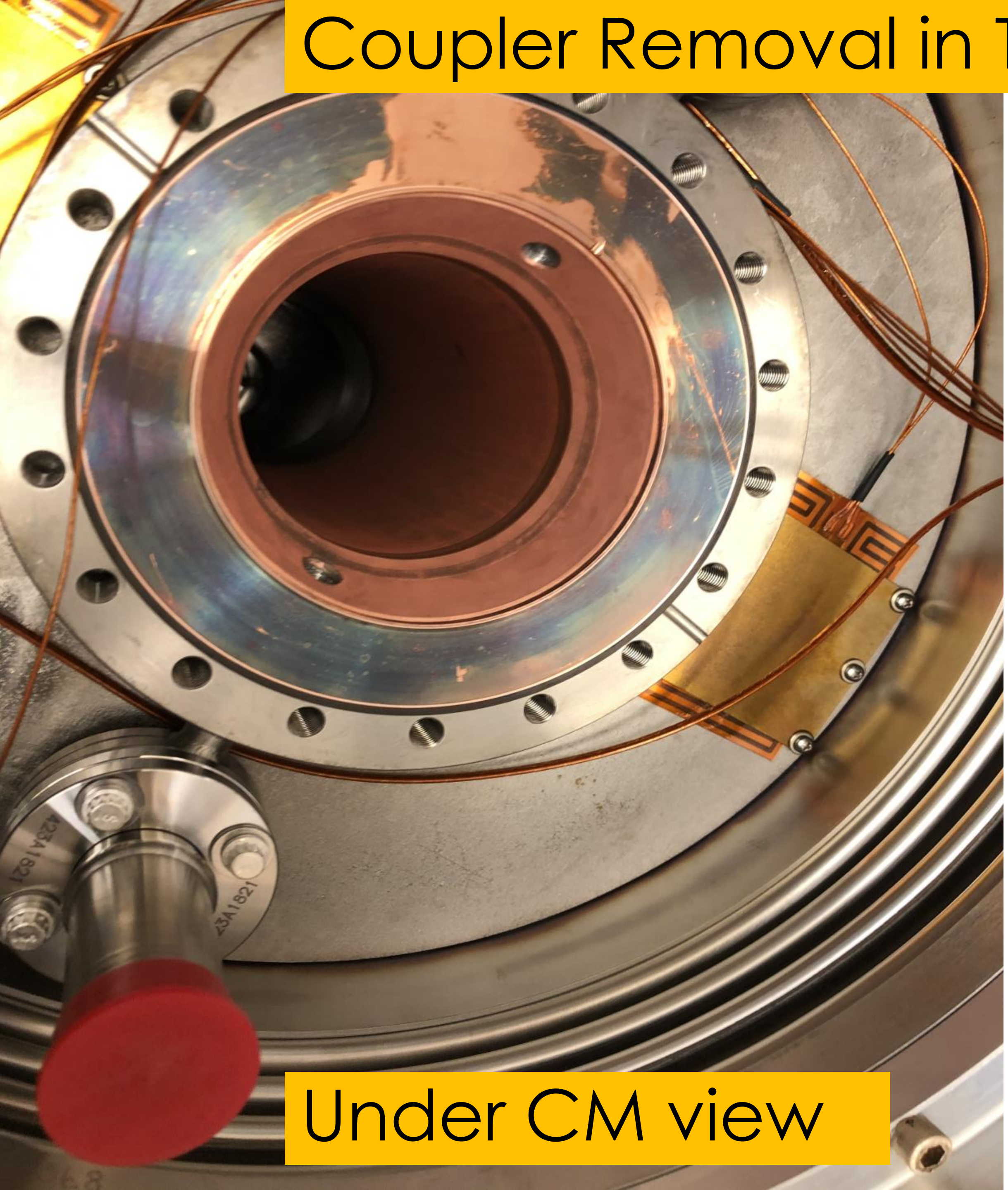
- Looking Upstream of Beamline
  - Cleanroom for RF Coupler replacement and beamline vacuum pumping seen
  - Downstream cryomodule on left also has to be warmed up for accidental venting prevention
  - Some space to get by with cart on right

Tunnel repairs

ISO 5 standards maintained at RF coupler

Replacing RF Couplers

Coupler Removal in Tunnel 21C



Under CM view

Removed Couplers

Recent Production of PPU RF Couplers

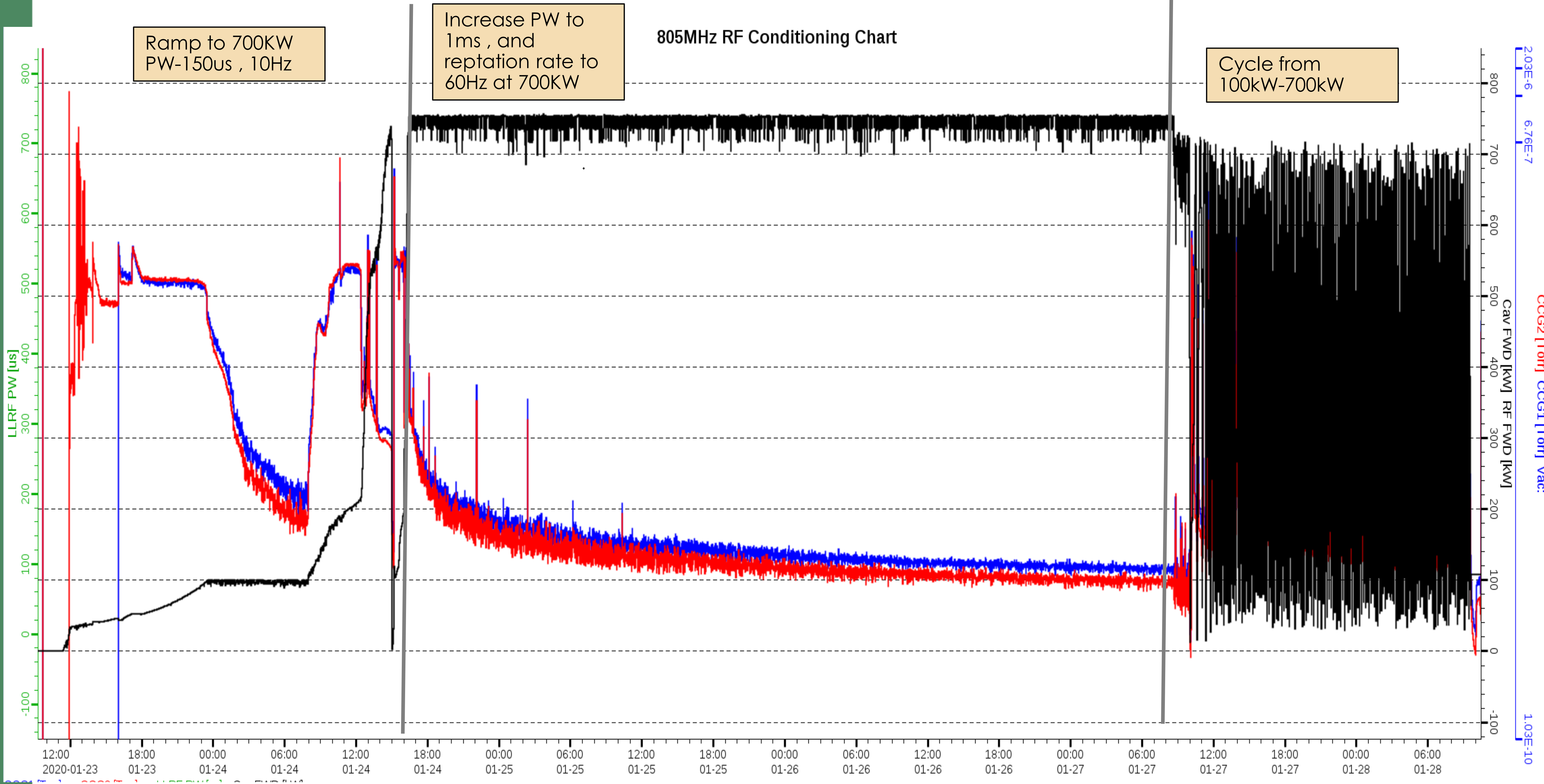
- In 2019 we procured 34 PPU style RF couplers from Sumitomo for the upgrade project
  - They delivered all for the project from 8/2019- 12/2019
- Couplers were inspected, assembled, baked and RF conditioned at SNS and then shipped to Jefferson Lab for the assembly of 8 new PPU cryomodules (32 were required)
  - What is unique here is that after inspecting the coupler they were blown clean with ionized nitrogen and no additional cleaning step were used
  - Two RF couplers then were assembled to a bridge waveguide
  - Leak checked and baked out at 200°C for 24 hours
  - Tests were performed on the HPRF test-stand

Cleanroom Assembly

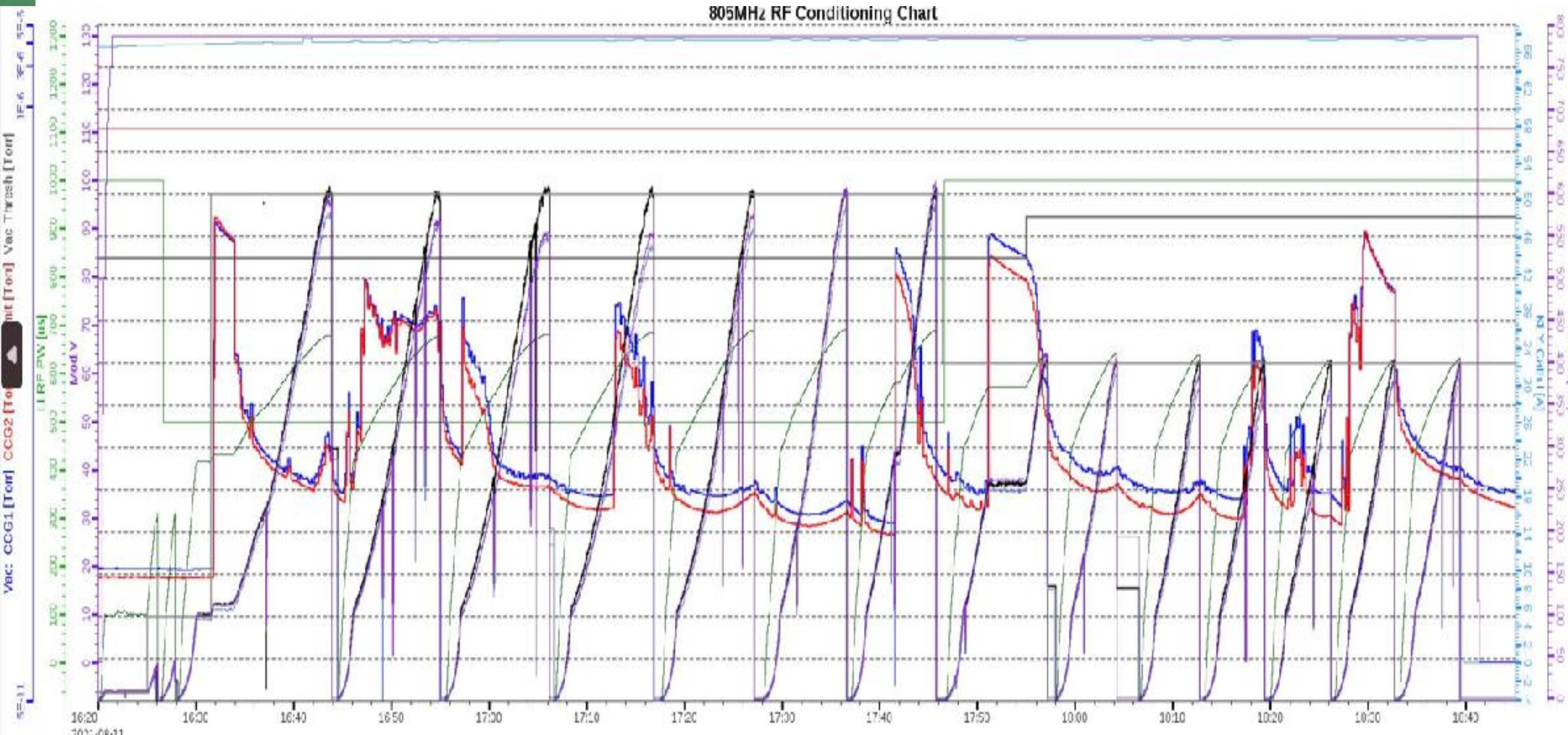
Coupler test sequence

- 2 RF Couplers assembled on the bridge waveguide
- Pumping and leak check
- RF S21 measurement
- Transfer to bake cart
- Baking
- Move to test stand and insertion
- RF Conditioning
- Removal from test stand
- Storage in cleanroom

Typical Conditioning in Travelling Wave Mode



Typical conditioning with Standing wave

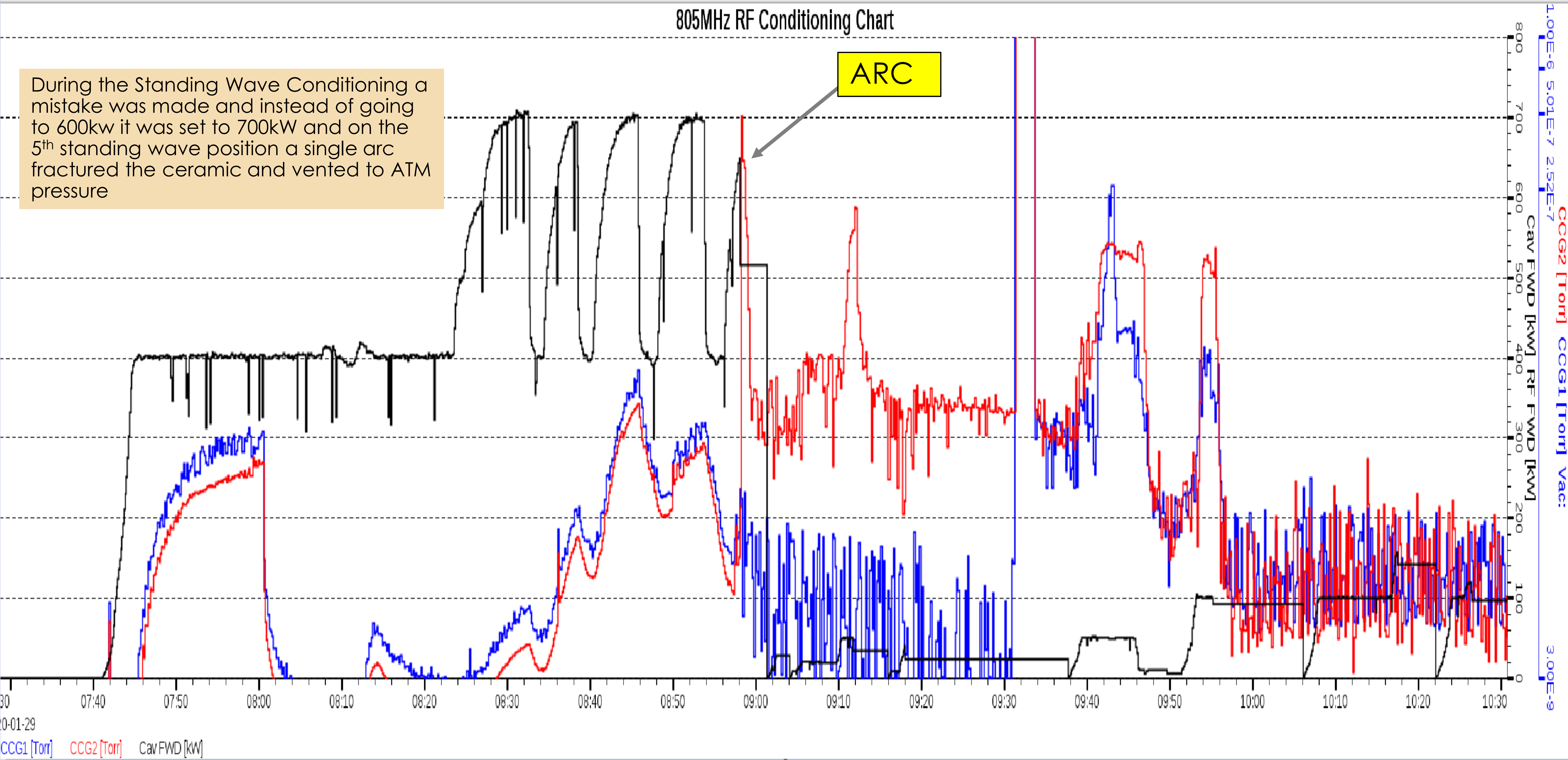


Typical Standing Wave Conditioning

- With the sliding short at one end of travel
- Ramp to 600kW, PW 0.5ms for seven positions of the sliding short
- Ramp to 400kW, PW 1.0ms for seven positions of the sliding short

Standing Wave Conditioning of 19J029

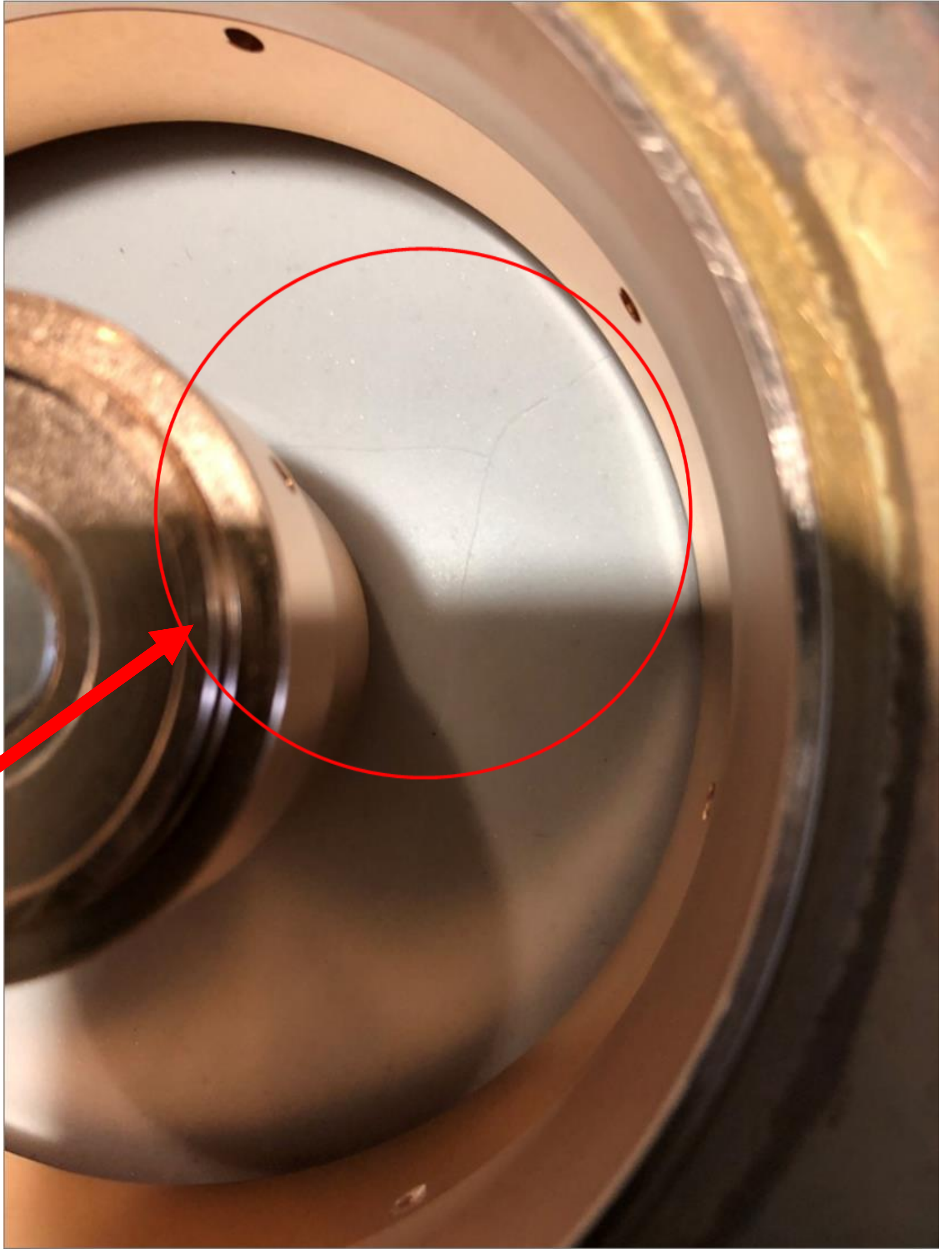
During the Standing Wave Conditioning a mistake was made and instead of going to 600kw it was set to 700kW and on the 5th standing wave position a single arc fractured the ceramic and vented to ATM pressure



Failure of 19J029 during RF conditioning

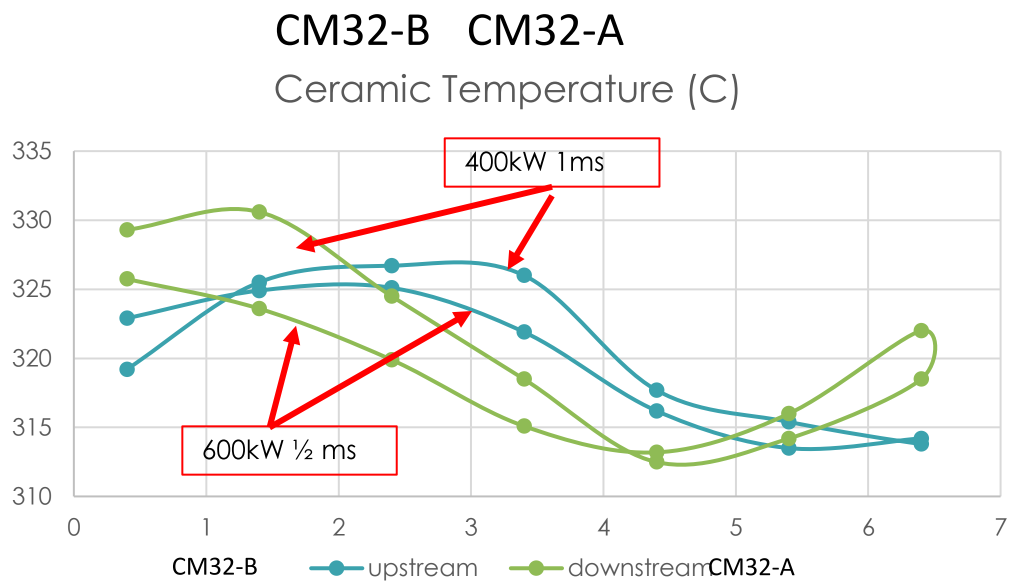
- During testing one ceramic broke by a single arc event during standing wave testing
  - Venting the waveguide, >10-4 range leak
  - This type failure only happened once 06c in operations
  - Most likely failed due to thermal shock

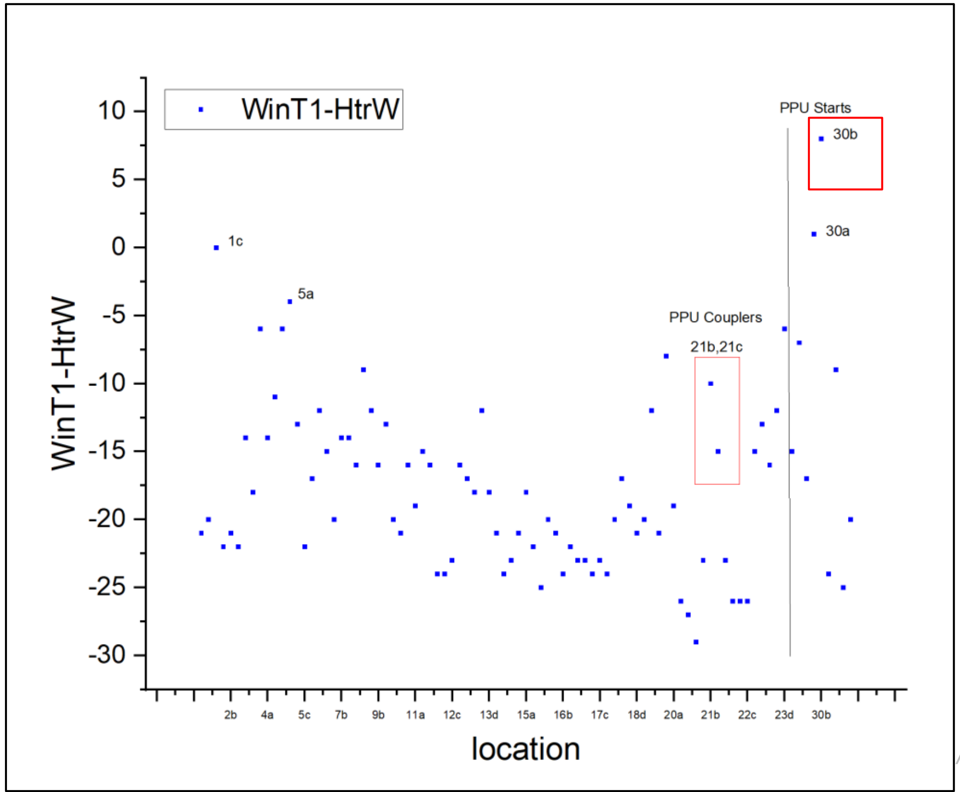
Complete fracture of the ceramic from inner to outer conductor



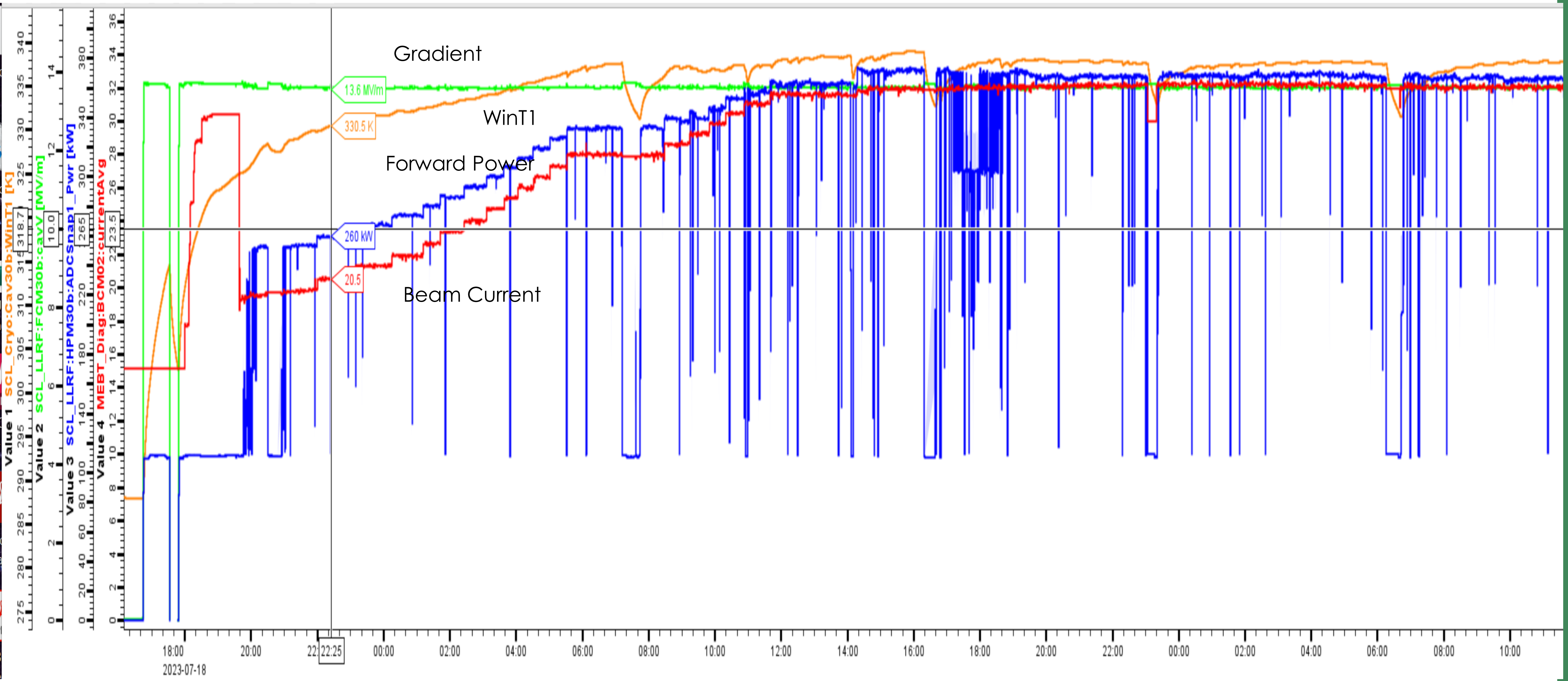
RF Coupler Heating

- During RF Conditioning of the RF couplers ceramic temperatures would depend on the position standing wave
- Once installed in the tunnel several cavities became limited by the RF coupler ceramic temperature 30b and 32b were the highest
- Since installation and two run periods CM32 was warmed up to repair a tuner and after that the RF coupler temperature has seemed to recover to a much lower value

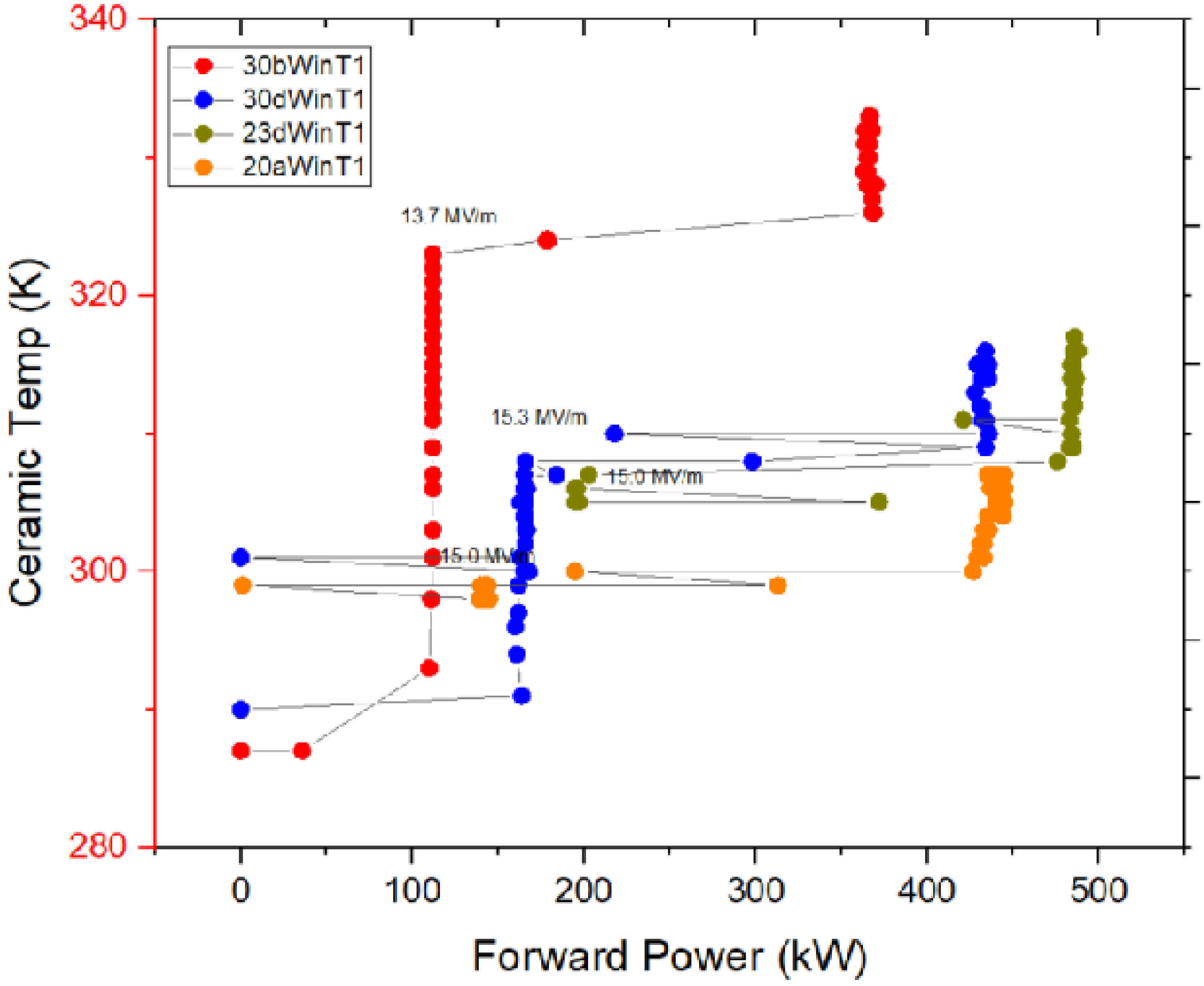




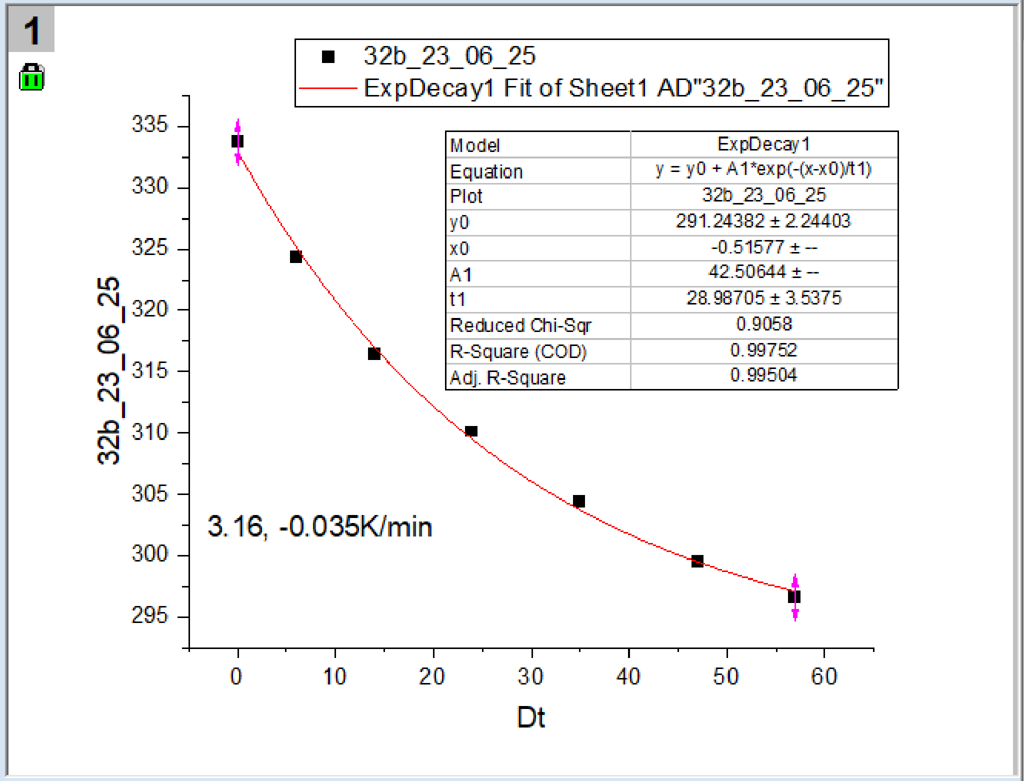
30b beam current ramp



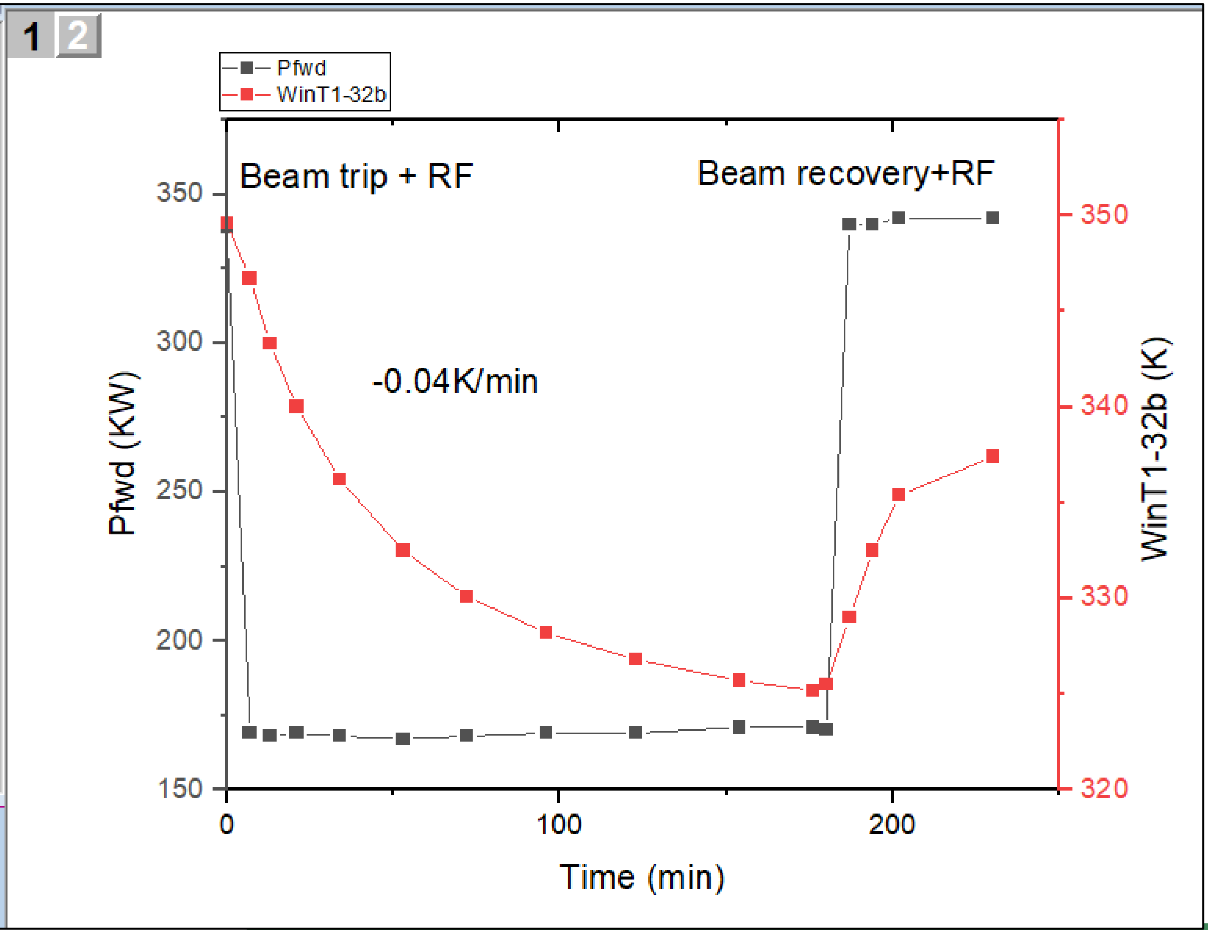
Ceramic Temperatures During Operations



Thermal decay was analyzed and very consistent for the PPU cavities

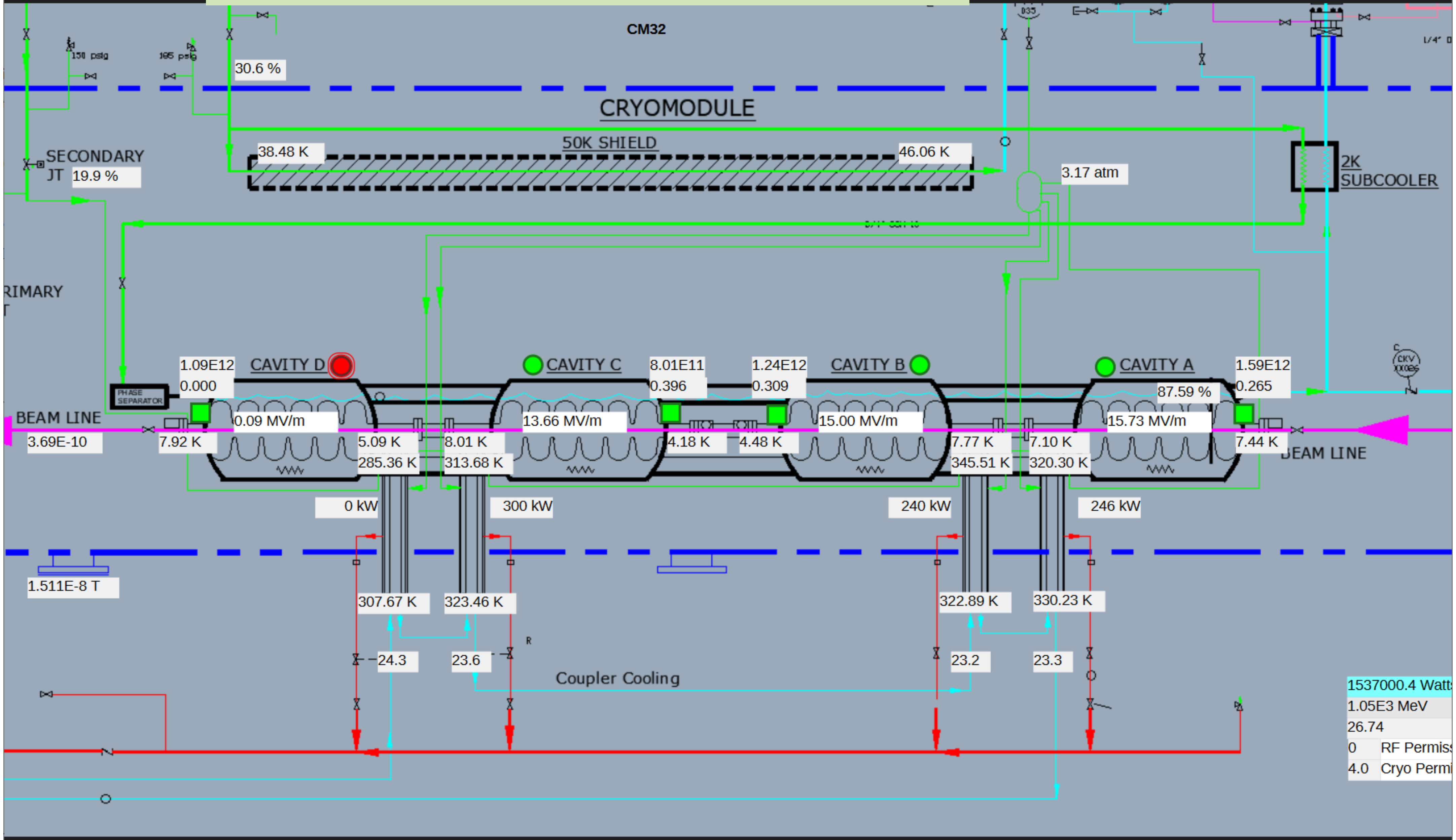


Model	ExpDecay1
Equation	y = y0 + A1*exp(-(x-x0)/t1)
Plot	32b_23_06_25
y0	291.24382 ± 2.24403
x0	-0.51577 ± --
A1	42.50644 ± --
t1	28.98705 ± 3.5375
Reduced Chi-Sqr	0.9058
R-Square (COD)	0.99752
Adj. R-Square	0.99504



CM32 Linac Performance

CM32_Data 2_27_



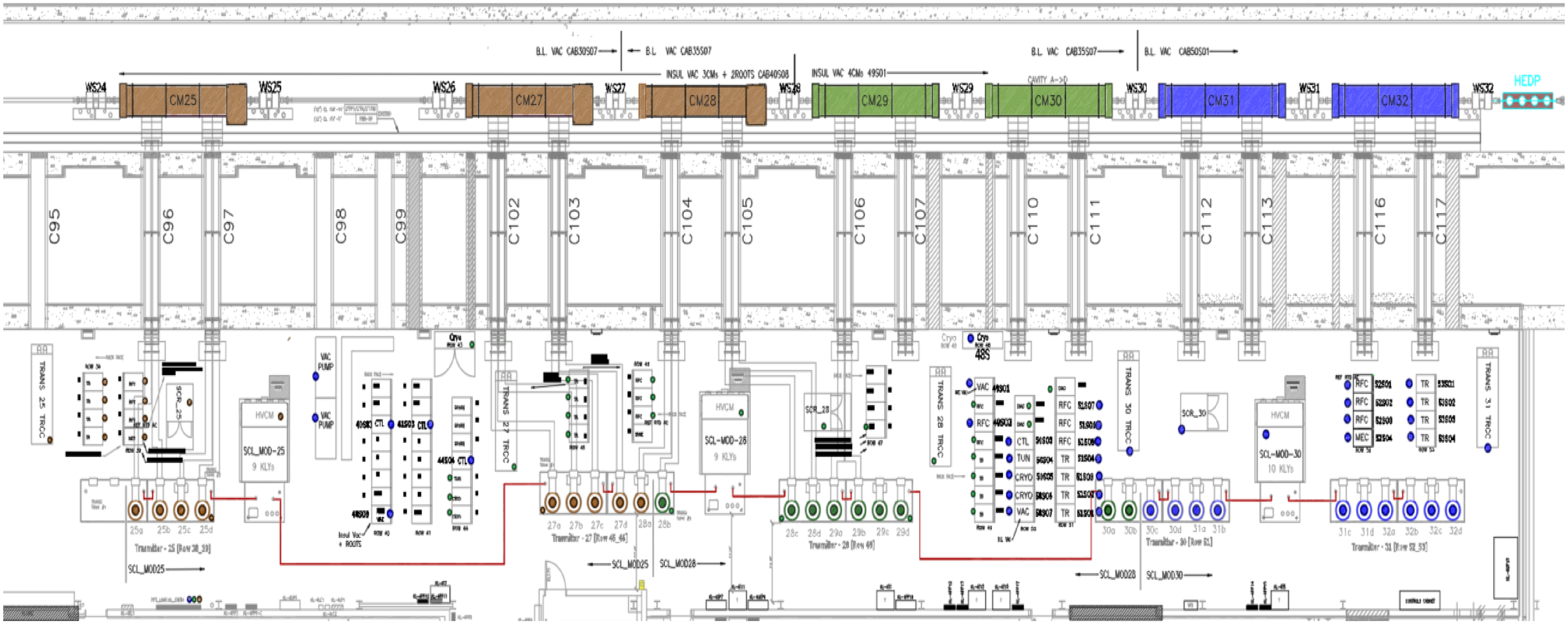
100%

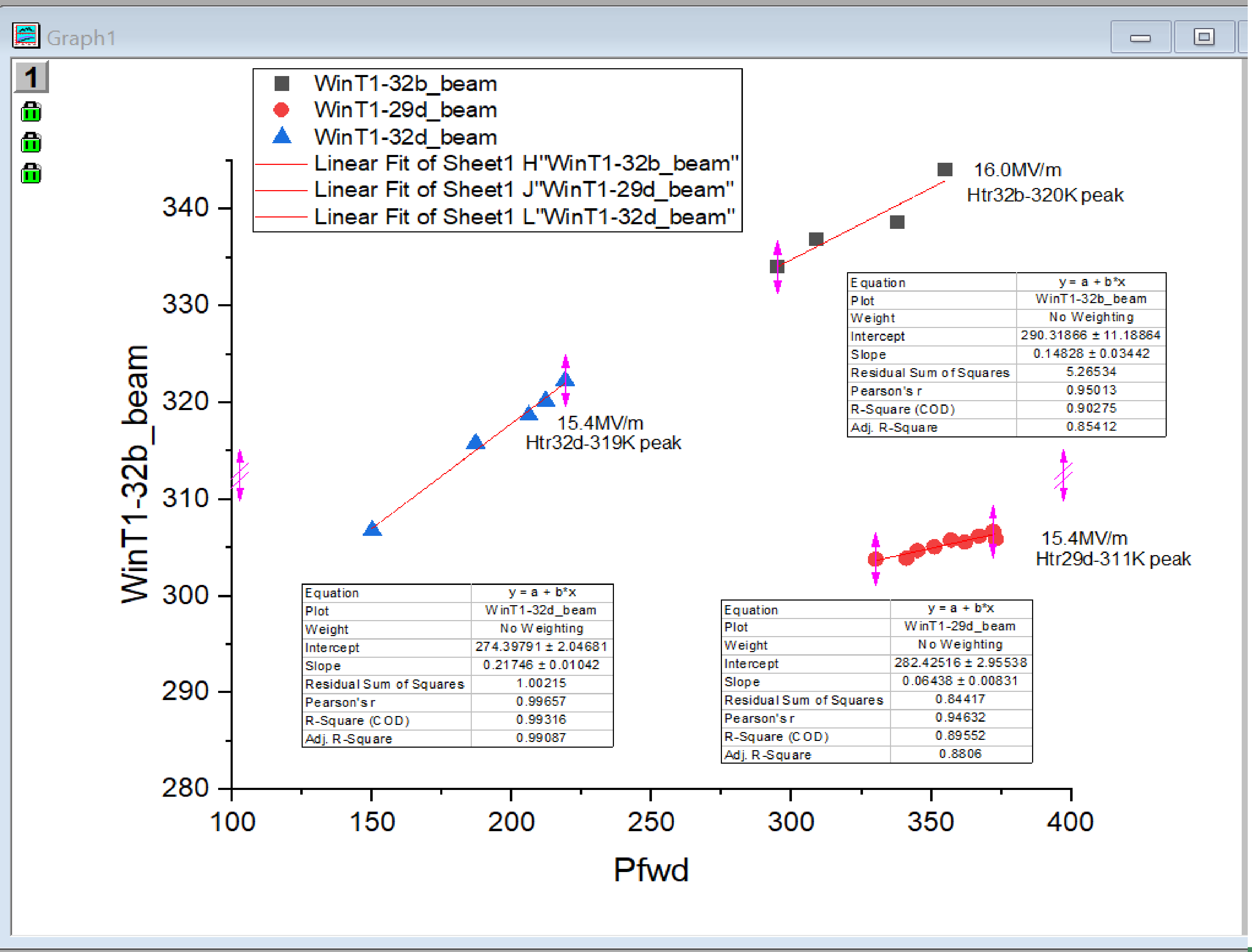
Summary

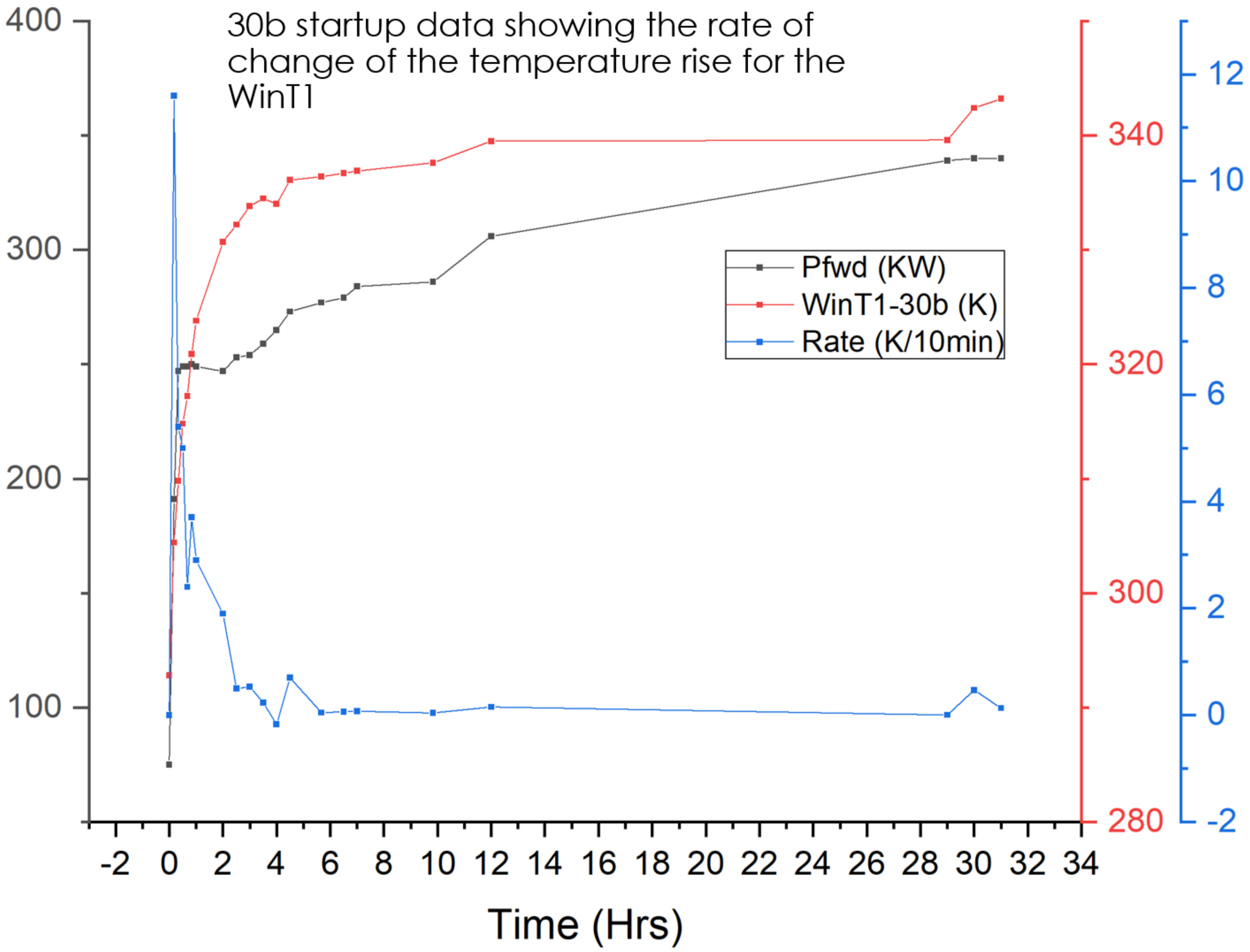
- Since 2006 SNS had 11 RF Couplers replaced
  - Most failures had 10-7 TL/s ceramic leak located under outer diameter choke joint
  - Airside Arcing required replacing one coupler and corrosion another
  - In-situ replacement of couplers was developed and performed 7 times with great success
- PPU Couplers were RF conditioned for the 8 new cryomodules
  - Cryomodules are now all installed
  - During conditioning one coupler failed due to ceramic fracture
  - Ceramic heating was observed on some couplers and is currently being investigated

Backup Slides

New PPU Cryomodules Installed at end of the linac




Graph1
WinT1-32b_beam
WinT1-29d_beam
WinT1-32d_beam
Linear Fit of Sheet1 H"WinT1-32b_beam"
Linear Fit of Sheet1 J"WinT1-29d_beam"
Linear Fit of Sheet1 L"WinT1-32d_beam"
16.0MV/m
Htr32b-320K peak
15.4MV/m
Htr32d-319K peak
15.4MV/m
Htr29d-311K peak
Equation | y = a + b*x
Plot | WinT1-32b_beam
Weight | No Weighting
Intercept | 290.31866 ± 11.18864
Slope | 0.14828 ± 0.03442
Residual Sum of Squares | 5.26534
Pearson's r | 0.95013
R-Square (COD) | 0.90275
Adj. R-Square | 0.85412
Equation | y = a + b*x
Plot | WinT1-32d_beam
Weight | No Weighting
Intercept | 274.39791 ± 2.04681
Slope | 0.21746 ± 0.01042
Residual Sum of Squares | 1.00215
Pearson's r | 0.99657
R-Square (COD) | 0.99316
Adj. R-Square | 0.99087
Equation | y = a + b*x
Plot | WinT1-29d_beam
Weight | No Weighting
Intercept | 282.42516 ± 2.95538
Slope | 0.06438 ± 0.00831
Residual Sum of Squares | 0.84417
Pearson's r | 0.94632
R-Square (COD) | 0.89552
Adj. R-Square | 0.8806
WinT1-32b_beam
Pfwd
280
290
300
310
320
330
340
100
150
200
250
300
350
400


30b startup data showing the rate of change of the temperature rise for the WinT1
Pfwd (KW)
WinT1-30b (K)
Rate (K/10min)
Time (Hrs)
400
300
200
100
340
320
300
280
12
10
8
6
4
2
0
-2
-2 0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34