Experience with 175MHz, 200kW, CW couplers for LIPAc's RFQ

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on behalf of the IFMIF/EVEDA Integrated Project Team

6th WWFPC; 2nd - 3rd July 2024 - CERN

Linear IFMIF Prototype Accelerator (LIPAc)

Rokkasho Fusion Institute (BA Site)

Outline

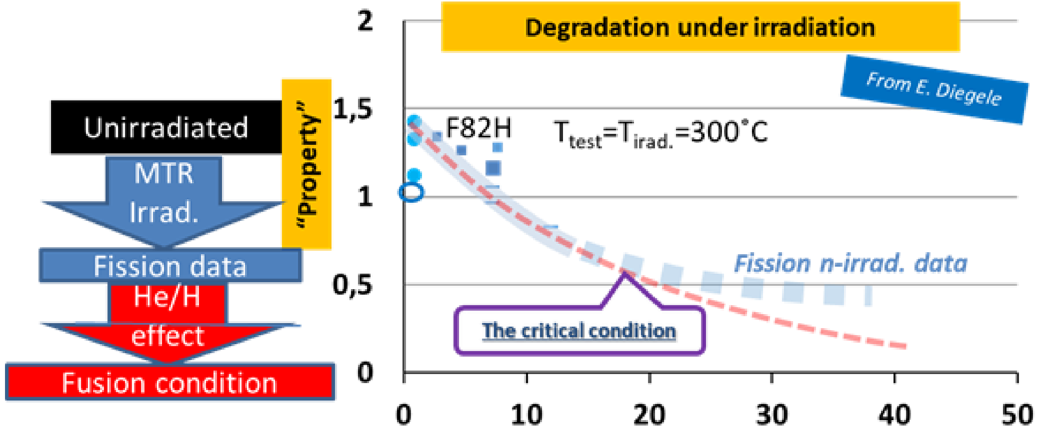
- LIPAc & its RFQ
- “O-Ring” couplers
- “Brazed couplers”

Material n-irradiation for fusion reactors

Fission irradiations

- **Intensive and broad use of MTR (Material Test Reactors) fission irradiation:** EU plans for 50M€ in the next decade
- **Complementary irradiation modelling and verification (multi-ion beams)**

To establish 1st step "best estimate" to perform engineering design



Fusion-like irradiations

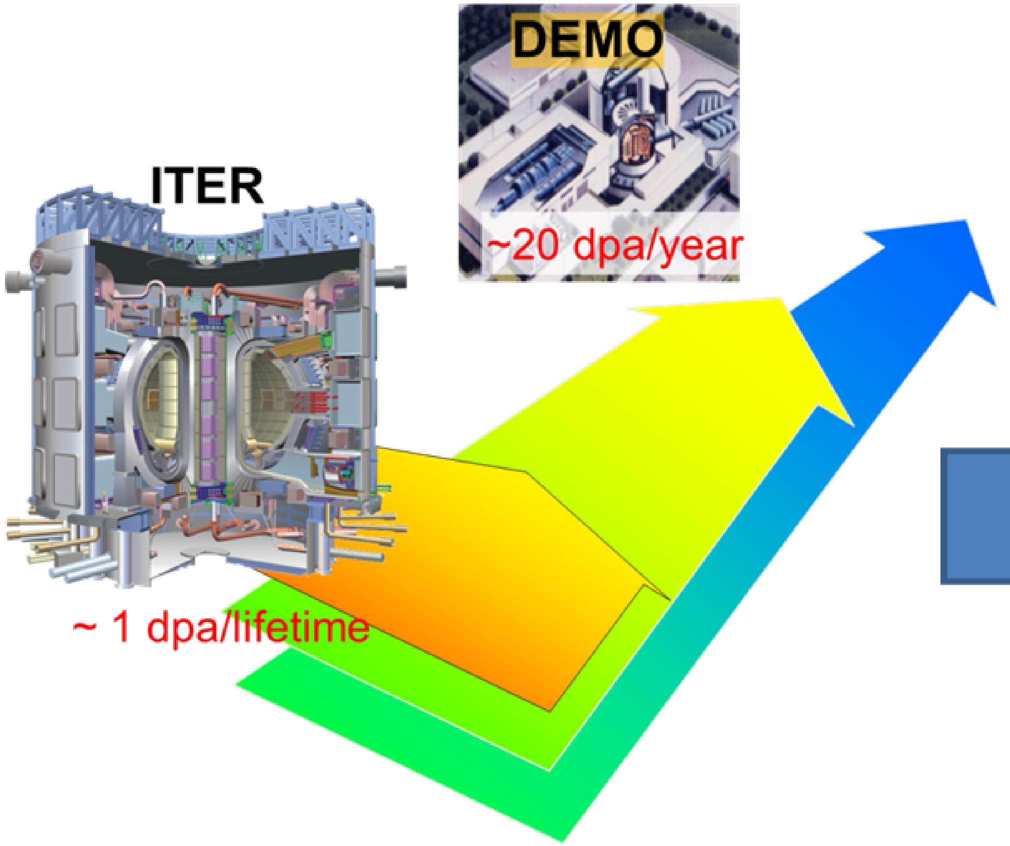
- Mandatory: a dedicated facility for material qualification that best mimics 14Mev neutrons with reasonable irradiation volume, fluence, and optimized homogeneity in T with the objective to (finally) validate in-vessel materials

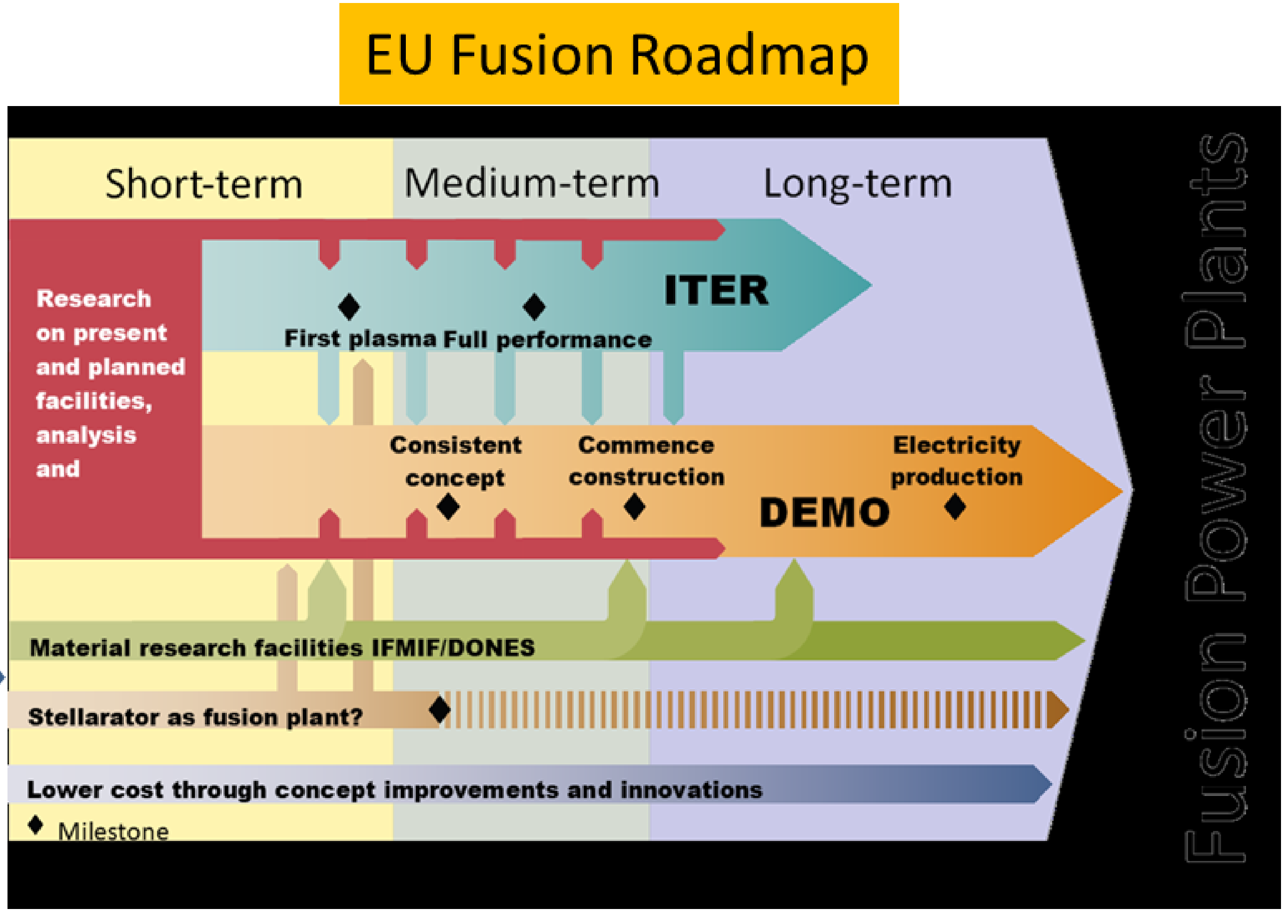
Based on the assumption that fusion-related effects will appear only at high dose (>10-20 dpa)

Also needed: develop todays "quasi-standards" of SSTT towards accepted standards and norms

Why IFMIF accelerator?

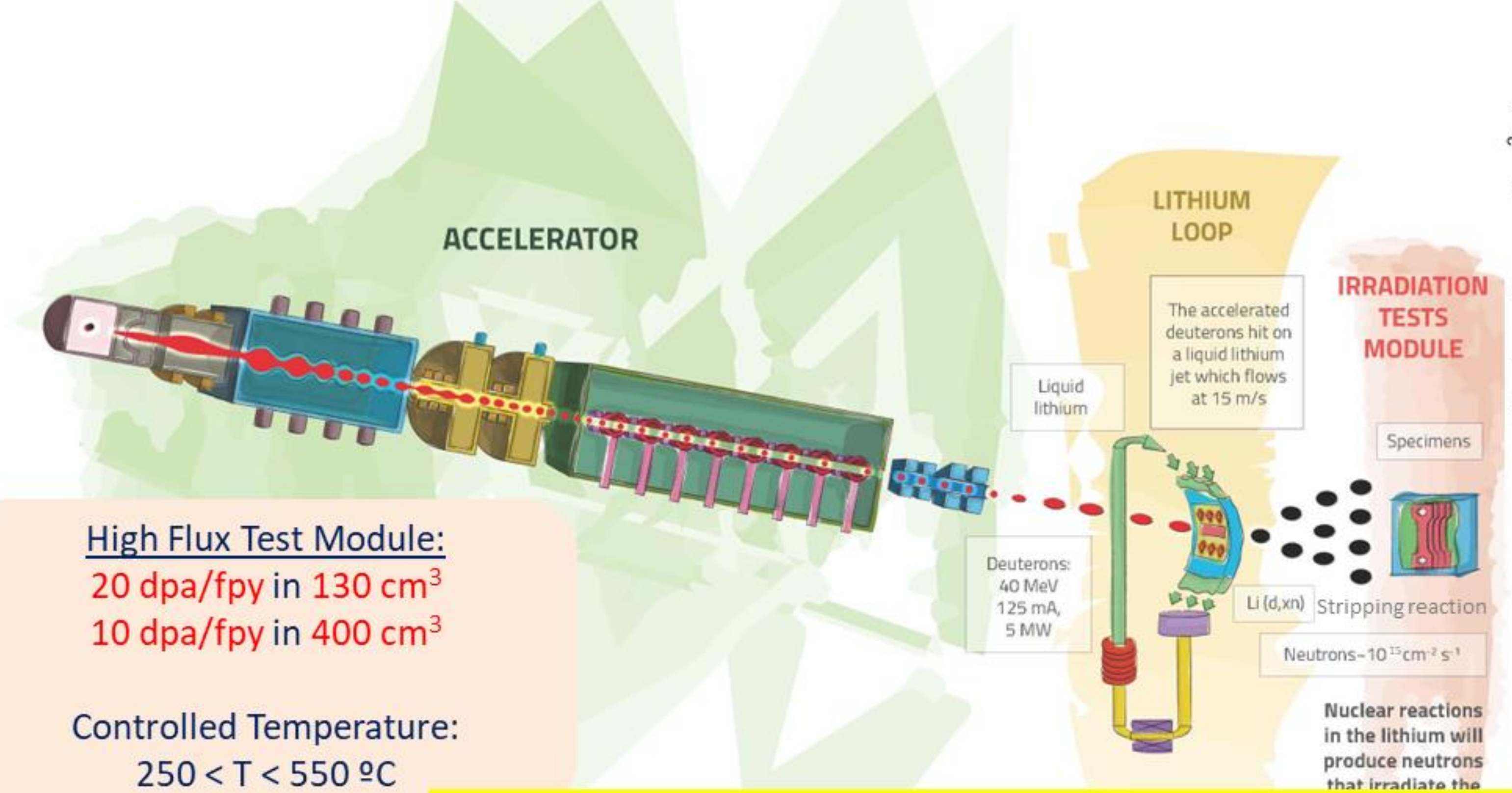
One of the main differences between ITER and DEMO is the radiation dose: at DEMO more that two orders of magnitude higher

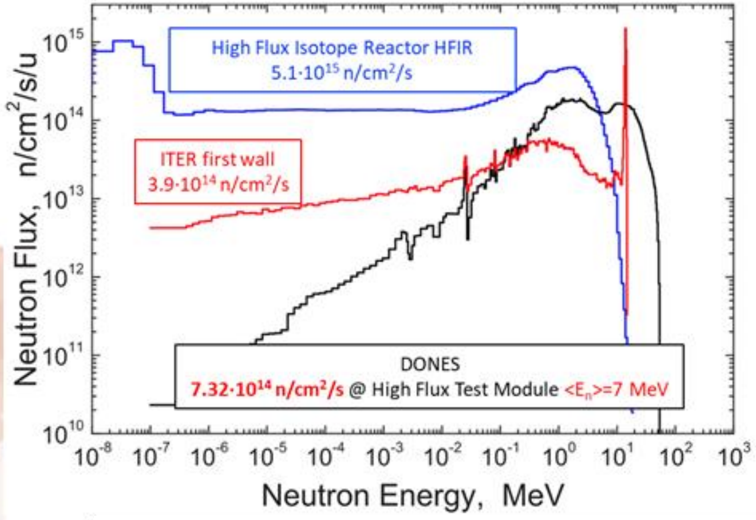




Why IFMIF accelerator?

A fusion-like neutron source required for the qualification of the materials to be used in the EU DEMO





High Flux Test Module:
20 dpa/fpy in 130 cm^3
10 dpa/fpy in 400 cm^3

Controlled Temperature:
250 < T < 550 ºC

A neutron flux of ~ 10^{15} $n/cm^2/s$ is generated with a neutron spectrum up to 55 MeV energy

Identified as high priority in the EU Fusion Roadmap
Included in the ESFRI Roadmap as a EU strategic facility

Why IFMIF accelerator?

A fusion-like neutron source required for the qualification of the materials to be used in the EU DEMO

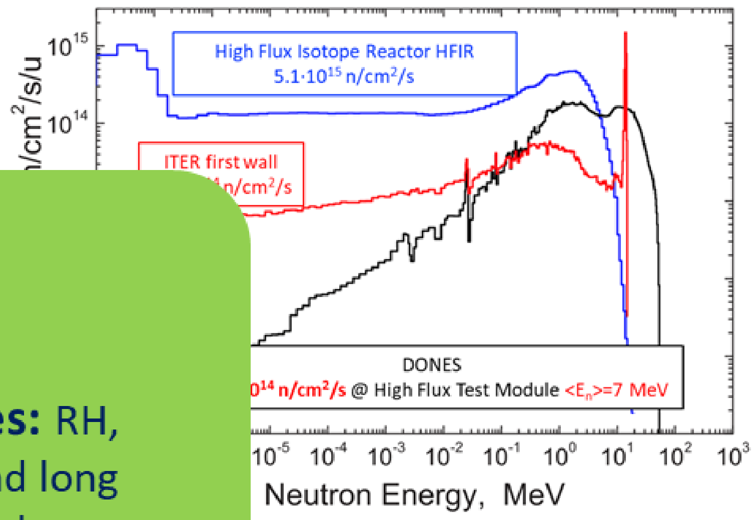
One of the more powerful accelerators in the world

Challenges: high power, high space charge, cw wave operation, high reability, longest RFQ,...

Biggest Li loop in the world

Challenges: Biggest Li loop in the world, power management, impurities management – corrosion risks-, reability, lifetime,...

Challenges: RH, reability and long term control,...



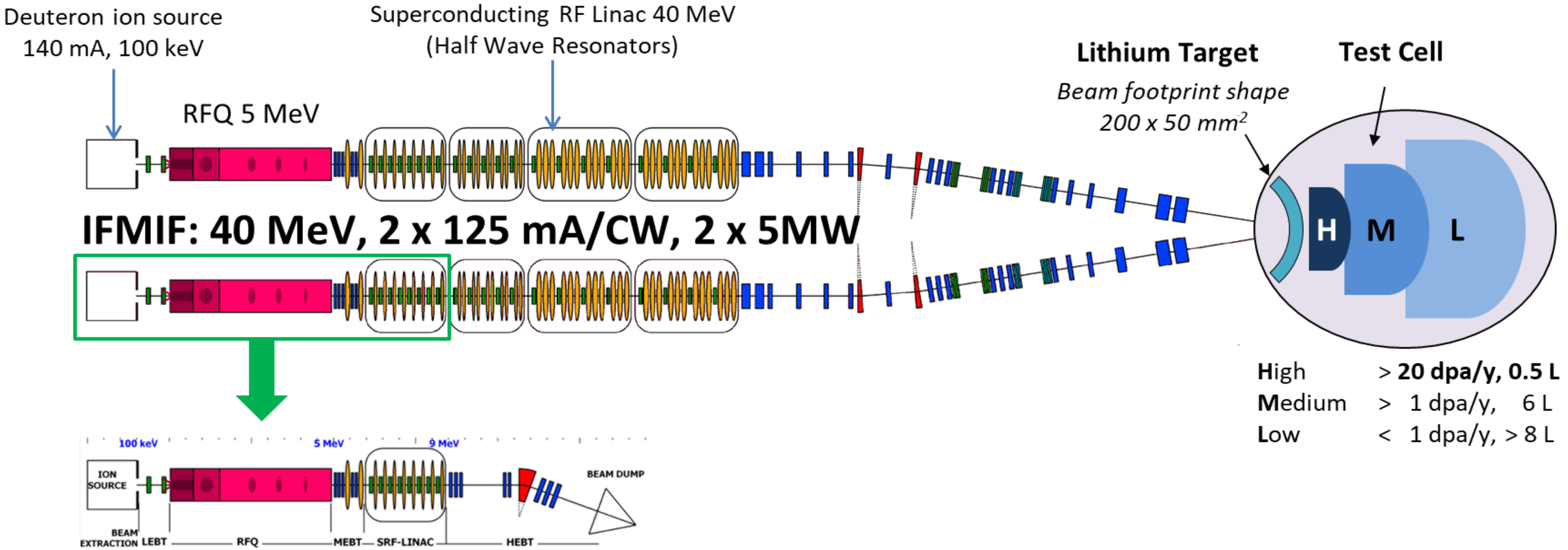
flux of ~ 10^{15} n/cm^2/s is generated with a neutron spectrum up to 55 MeV energy

Nuclear reactions in the lithium will produce neutrons that irradiate the

Identified as high priority in the EU Fusion Roadmap
Included in the ESFRI Roadmap as a EU strategic facility

Linear IFMIF Prototype Accelerator

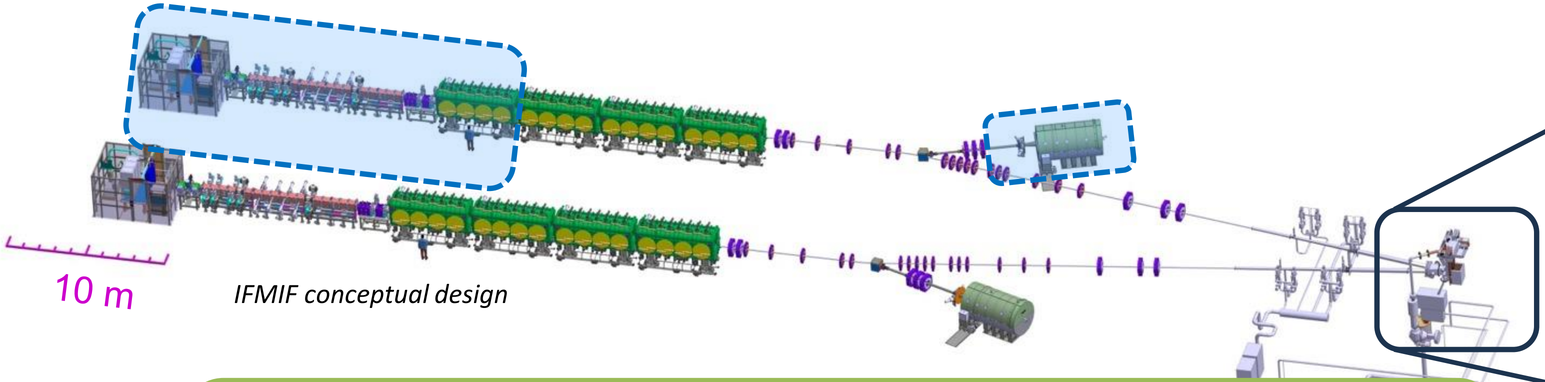
- **International Fusion Materials Irradiation Facility (IFMIF)**
  - Accelerator-based intense neutron source (**D-Li, 40 MeV, 250 mA**)
  - Subjecting candidate materials for fusion reactors to **similar conditions (14.1MeV neutrons)** expected to be experienced by a future fusion power plant (DEMO)



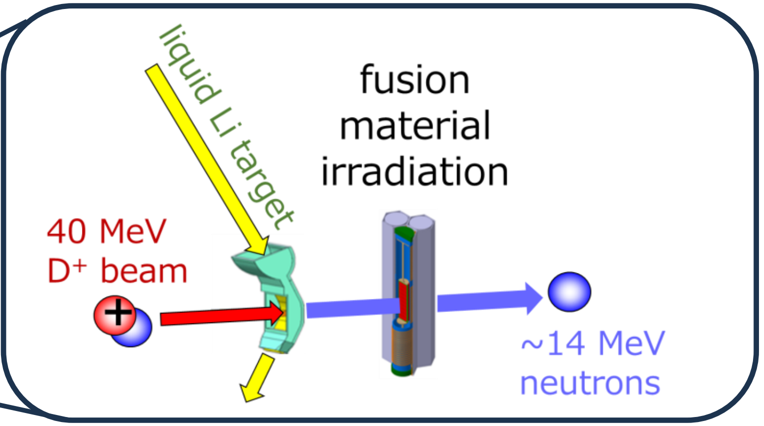
Linear IFMIF Prototype Accelerator (LIPAc): 9 MeV 125 mA Continuous Wave

Linear IFMIF Prototype Accelerator

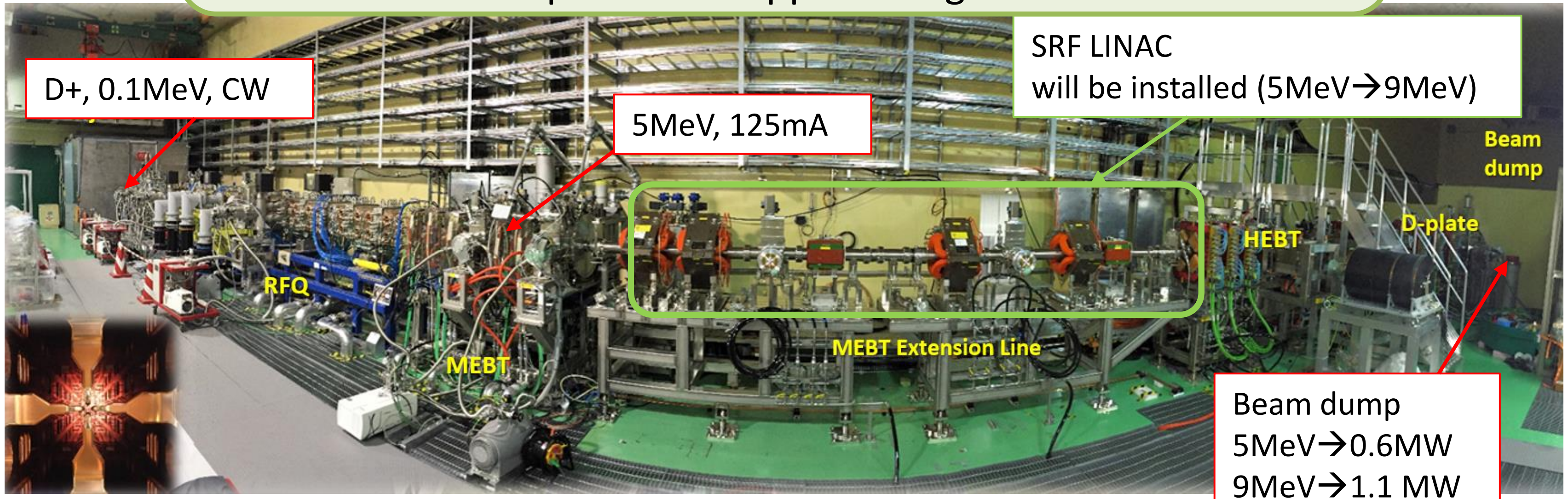
International Fusion Materials Irradiation Facility (IFMIF) will address the need of a neutron source for material tests toward future Fusion Power Plant



IFMIF conceptual design



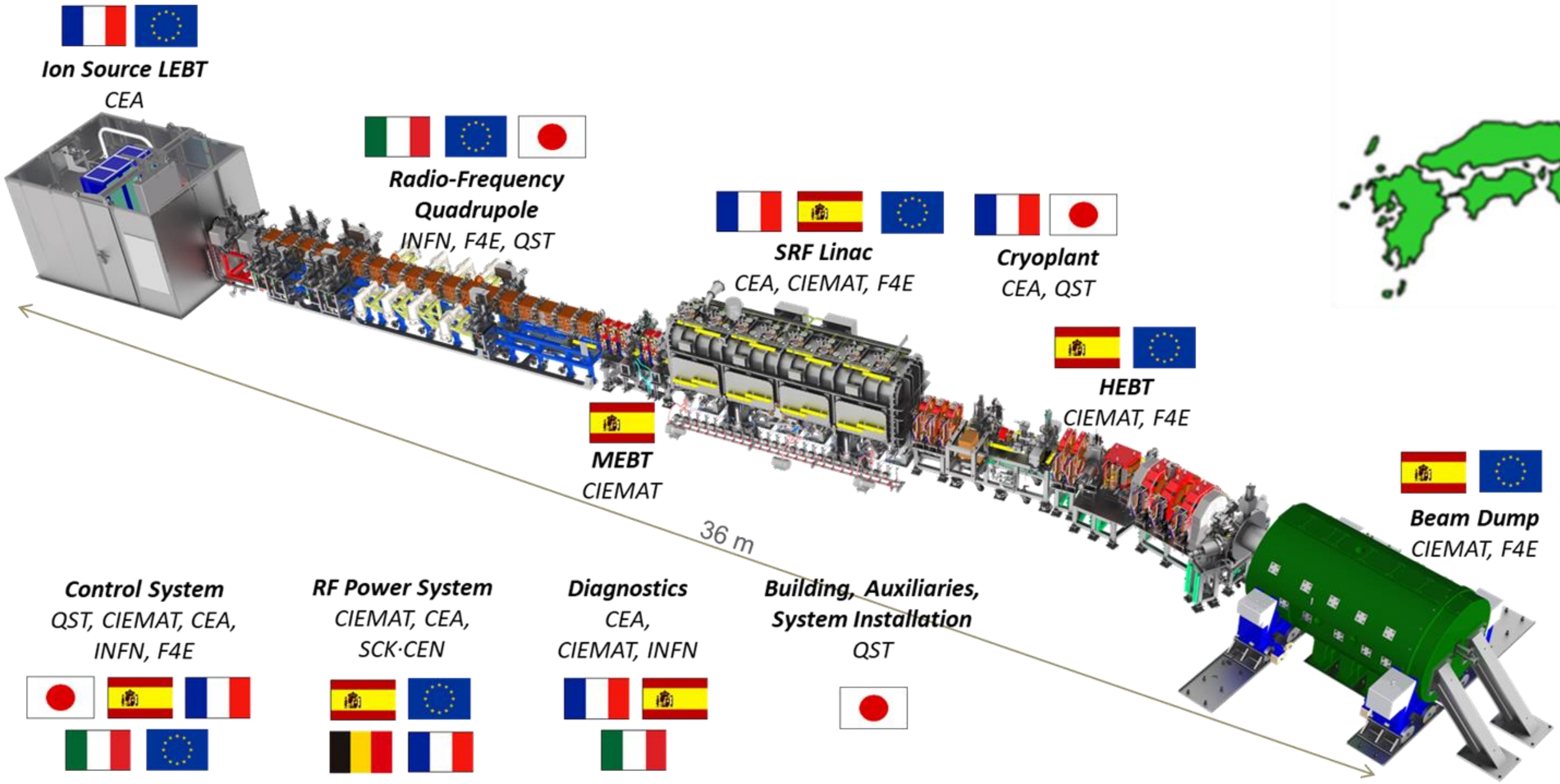
Linear IFMIF Prototype Accelerator (LIPAc)
@QST in Rokkasho, Aomori, Japan
EU-Japan Broad Approach agreement

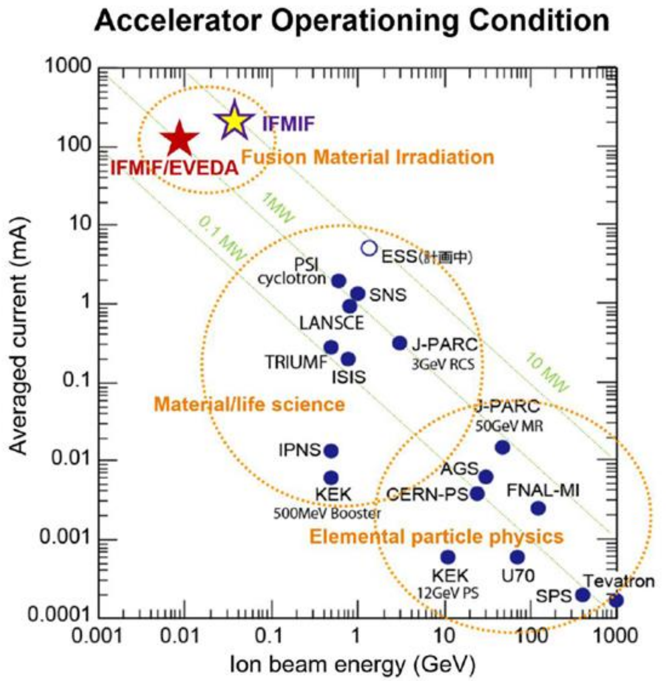


Fisheye view of LIPAc

LIPAc Status

Japan-Europe scientific collaboration based on in-kind contributions under the Broader Approach framework





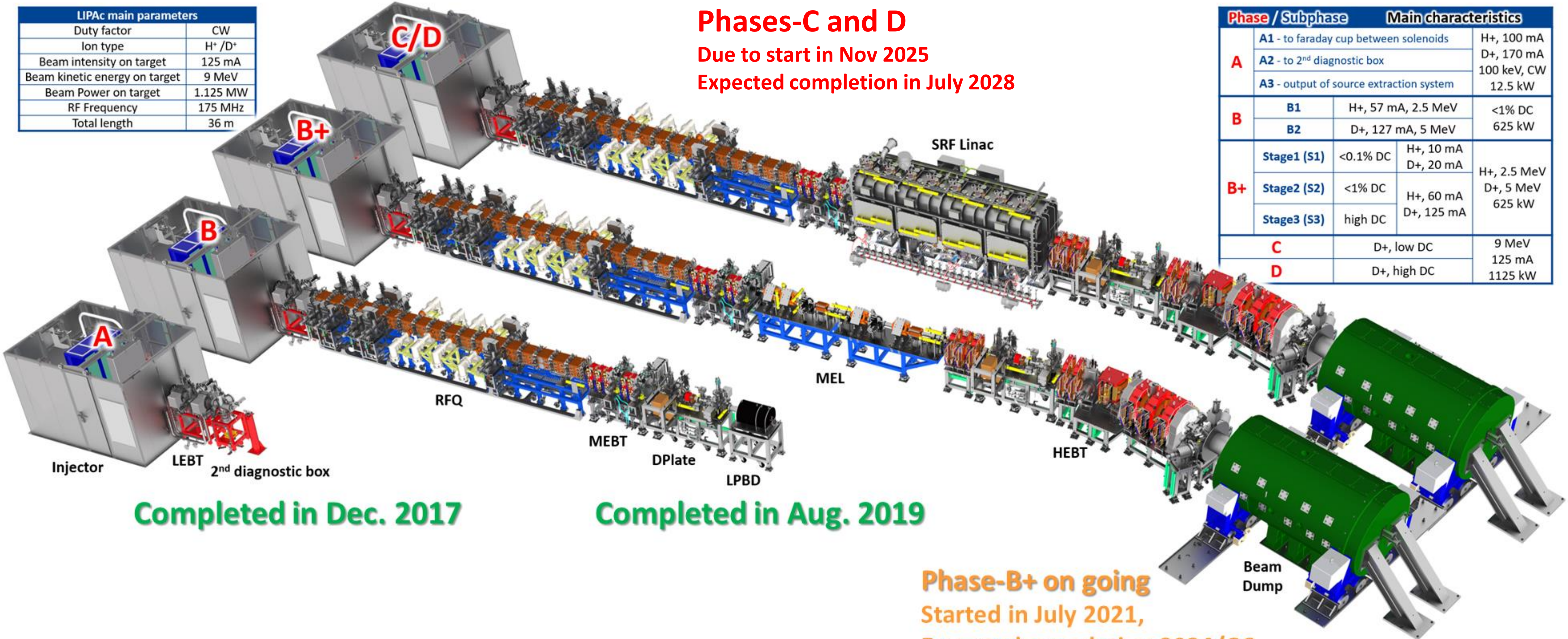
LIPAc Status

5 Phases and 4 configurations

LIPAc main parameters	
Duty factor	CW
Ion type	H^+ / D^+
Beam intensity on target	125 mA
Beam kinetic energy on target	9 MeV
Beam Power on target	1.125 MW
RF Frequency	175 MHz
Total length	36 m

Phases-C and D
Due to start in Nov 2025
Expected completion in July 2028

Phase	Subphase			Main characteristics
A	A1 - to faraday cup between solenoids			H+, 100 mA D+, 170 mA 100 keV, CW 12.5 kW
	A2 - to 2nd diagnostic box			
	A3 - output of source extraction system			
B	B1	H+, 57 mA, 2.5 MeV		<1% DC 625 kW
	B2	D+, 127 mA, 5 MeV		
B+	Stage1 (S1)	<0.1% DC	H+, 10 mA D+, 20 mA	H+, 2.5 MeV D+, 5 MeV 625 kW
	Stage2 (S2)	<1% DC	H+, 60 mA D+, 125 mA	
	Stage3 (S3)	high DC		
C		D+, low DC		9 MeV 125 mA 1125 kW
D		D+, high DC		



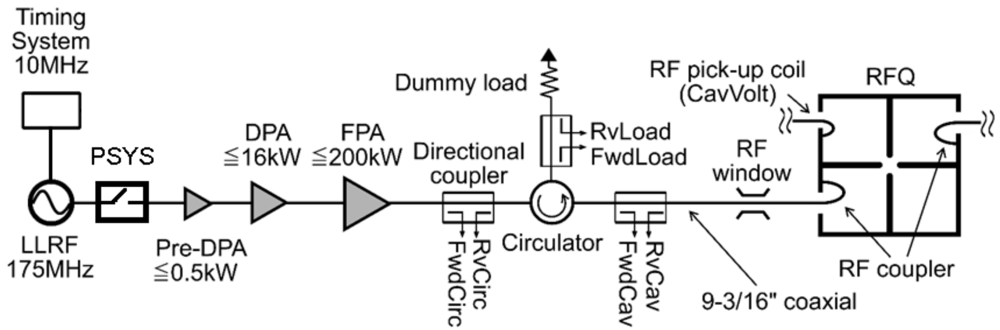
Completed in Dec. 2017

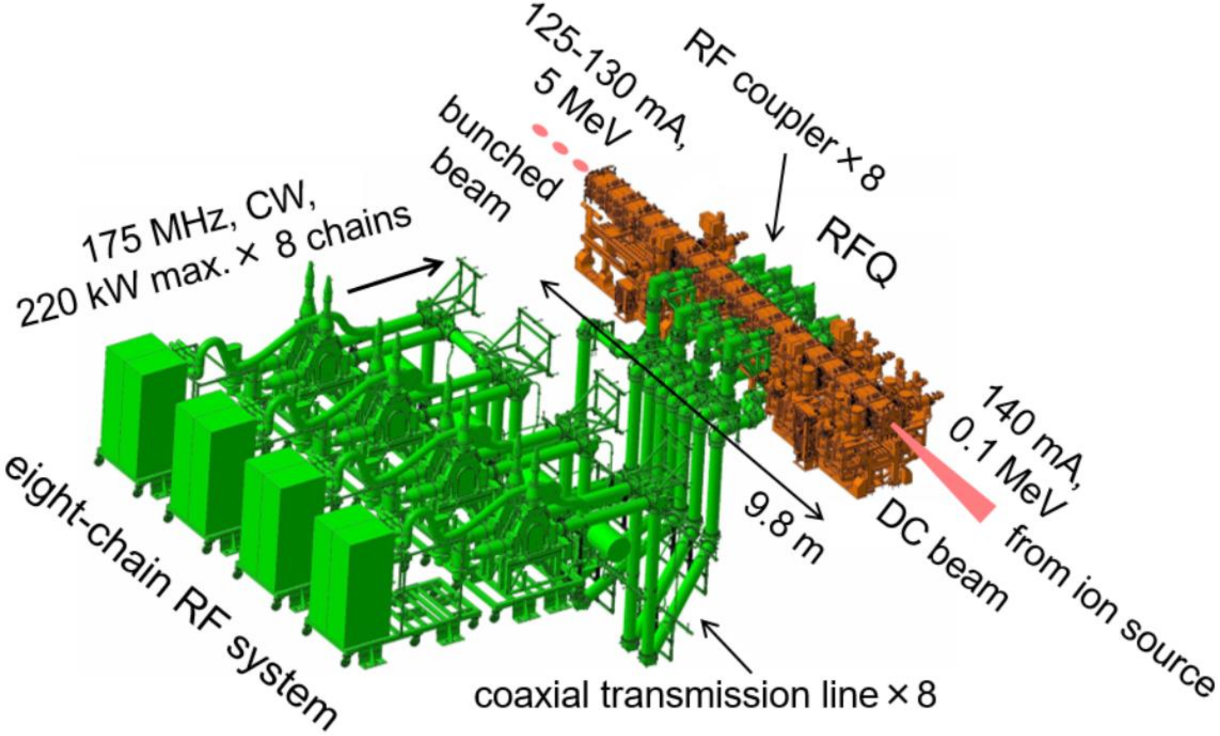
Completed in Aug. 2019

Phase-B+ on going
Started in July 2021,
Expected completion 2024/Q2

LIPAc RFQ – RF Power System

RF power from 8 RF chains synchronized with White Rabbit.

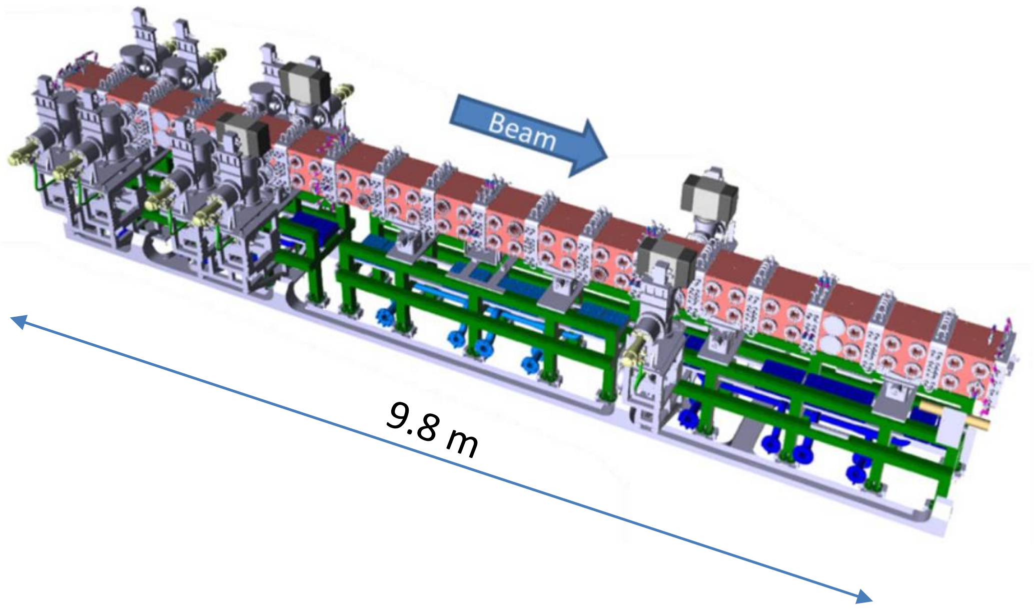


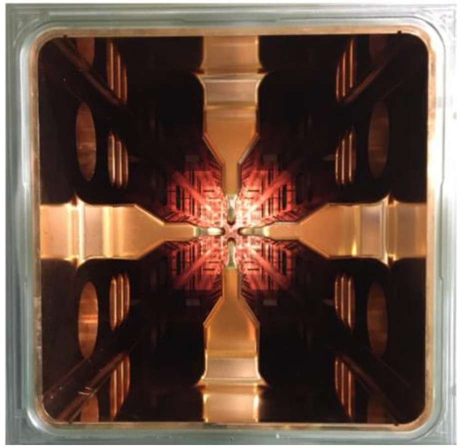


Shinya T. et. Al., FEC 2020

Weber M. et. Al., IEEE Tr. Plasma Sc. 2021

LIPAc RFQ





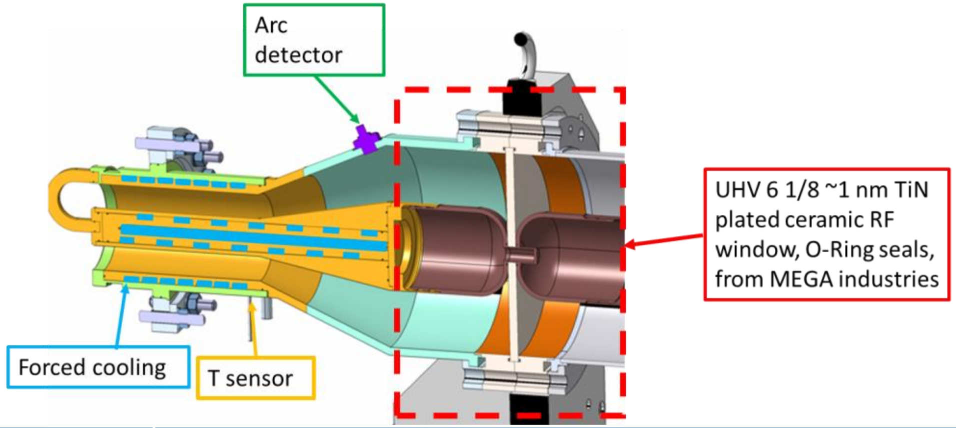
8 RF couplers (200kW; CW)

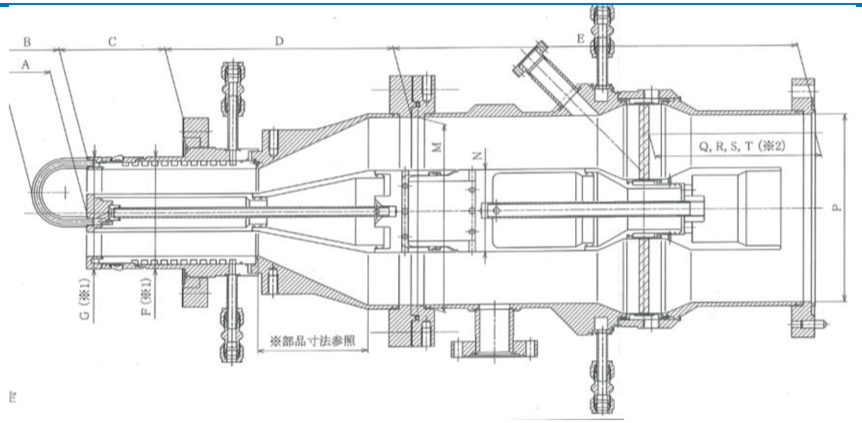
4 of the 8 coaxial lines supplying RF to RFQ

Particles	*D+*
Operation frequency	175 MHz
Input-output current	135–125 mA
Energy in-out	0.1 - 5 MeV
Voltage min-max	79 –132 kV
RF dissipated power with no beam	640 kW
Total RF power for beam acceleration	1.2 MW

Scantamburlo F. et. Al., Fus. Eng. Des 2024

Brazed couplers and O-Ring couplers





	“O-Ring” couplers	“Brazed” couplers
Materials	Cu (except ext flange of RF window SS+ Cu plated)	Mostly SS + 50 um Cu plated
RF window vacuum sealing	FKM O-Rings	Brazing – TIG -metal gasket
Vacuum gauge	Yes	Yes
e- pick up	No	No
Arc sensor	Optical fiber + PD	APD
Antenna depth	34.86 mm	45 mm
Water forced convection cooling	Loop + inner conductor + last part of ext. coax	Loop + inner conductor + last part of ext. coax + window + coax. inner conductor
Inner conductor near window	Round	Perpendicular to ceramic

Background – History Summary

Year	Brazed couplers	O-ring couplers
’13-’14	Brazed coupler are default choice for LIPAc. Prototype fail VNA test . (TiN 100nm → 30% loss)	
‘15	New couplers produced (9units) with TiN 5 nm	Designed, produced, tested in CW with 200kW (9units). Window procured from MEGA industries.
‘16	Pass VNA tests No RF chain with 200kW CW is available. Pass standing wave high Q load test.	Installed in RFQ
‘18	Set to storage (poor conditions)	1A ceramic broke during RF without interlocks. Additional T sensors.
‘19		>80 °C during CW low power test. Add water jacket.
‘21		RFQ conditioning reaches CW at 80% vane voltage. 5 couplers are hot.
‘22	High power test of 2 couplers. 1st coupler OK, but not conclusive due to MP in bridge cavity.	Vacuum leak. O-rings are damaged and black O-rings on 5 hot ones. Design upgrade with improved cooling and install in RFQ.
‘23	Bridge cavity design upgrade.	Same 5 couplers hot again, light detected proportional to combination of FWD and REV power. Small vacuum leaks appear at 25% duty cycle.
‘24	Restart high power tests.	Install external fans to further improve cooling. Beam until end of June up to 10% DC.
‘25	Install in RFQ if tests passed.	

Outline

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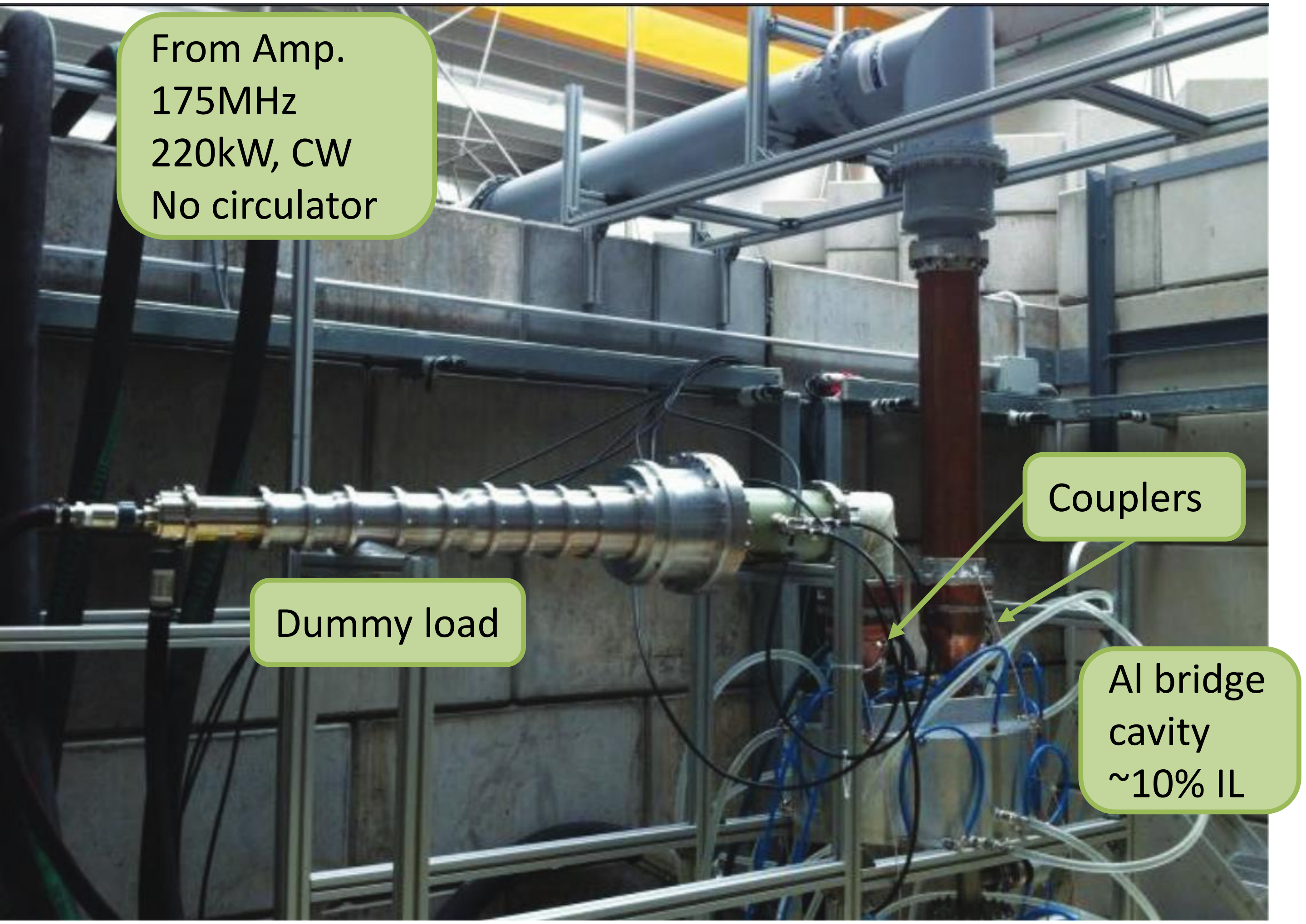
O-ring couplers – High Power Test Bench



Fagotti E. et al., LINAC14

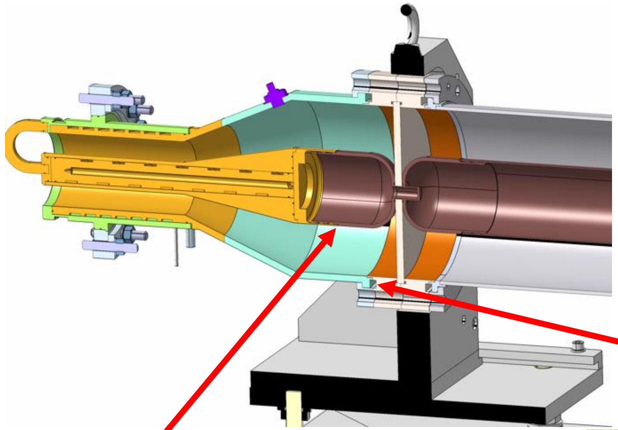
8 couplers withstood:
>72hrs at >200kW Fwd in CW

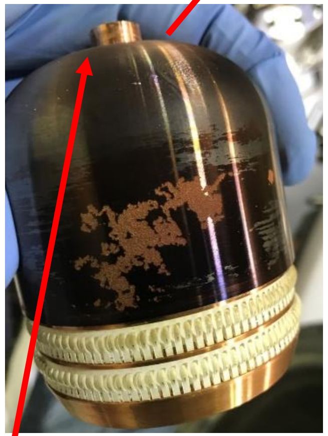
Frequency: 175MHz + 0.22 MHz
Vacuum pressure: 10^{-7} - 10^{-6} mBar

Installed in RFQ in 2016!

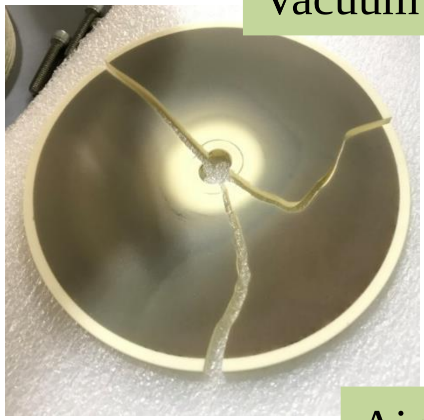
Challenges: Ceramic broke

1 ceramic broke during test while interlock were disabled

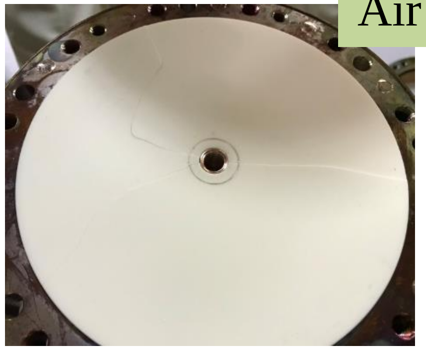


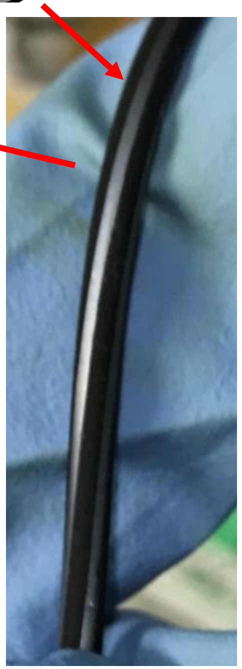


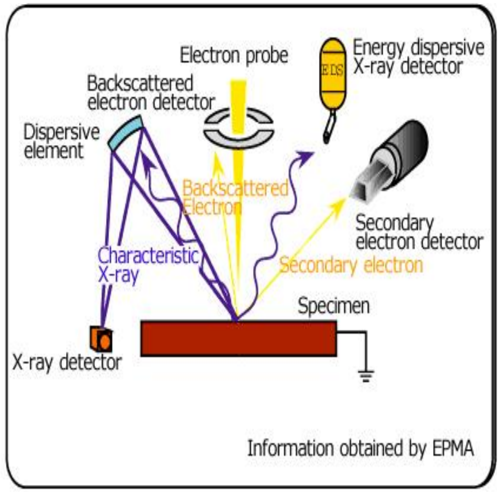
Vacuum



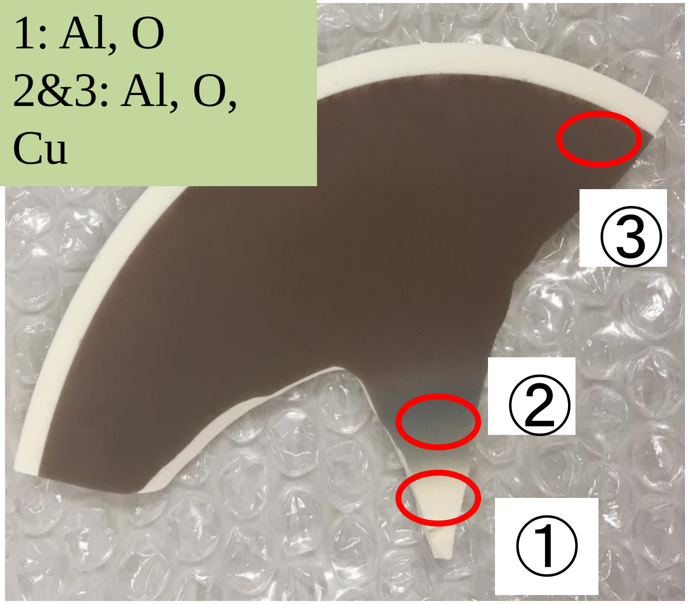
Air





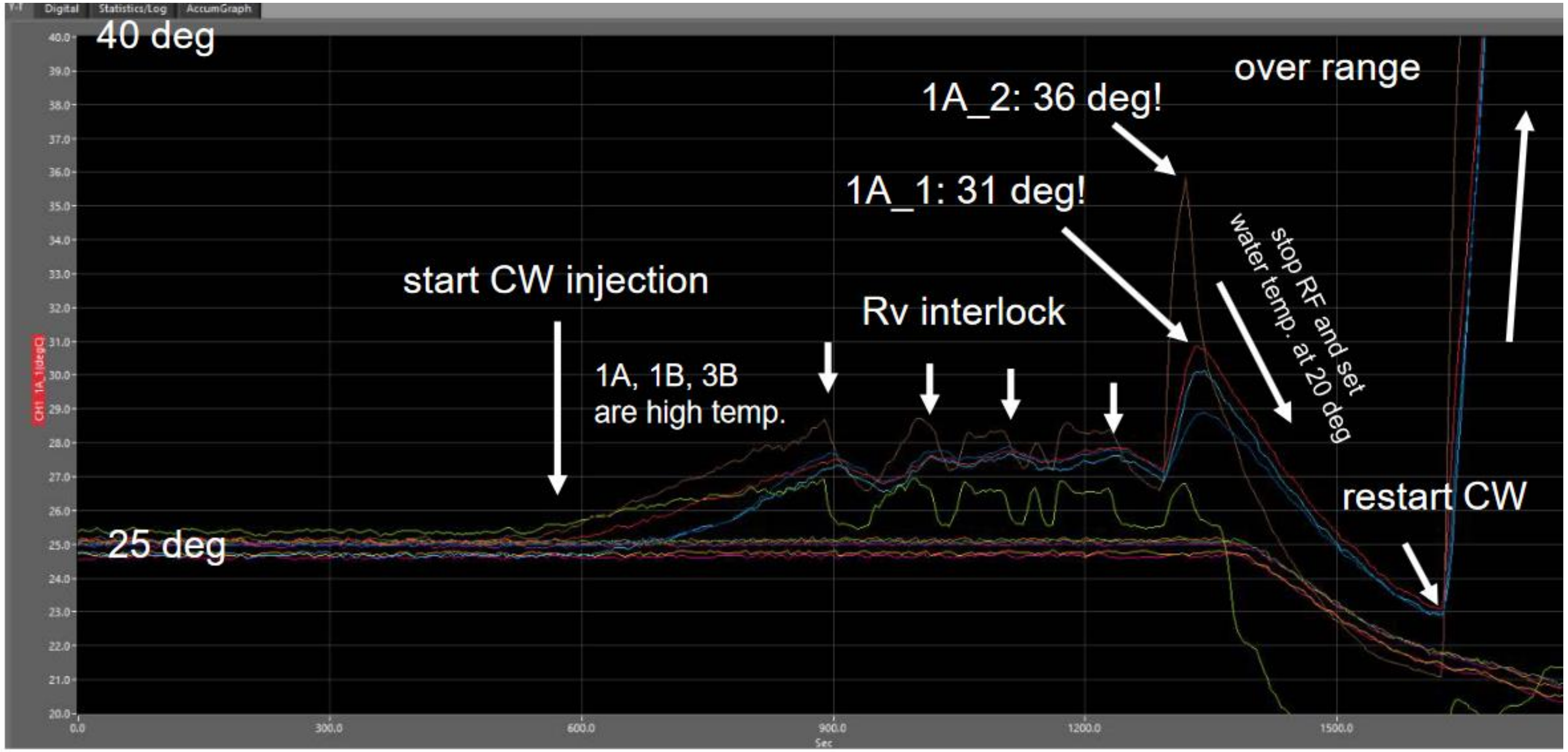


1: Al, O
2&3: Al, O, Cu



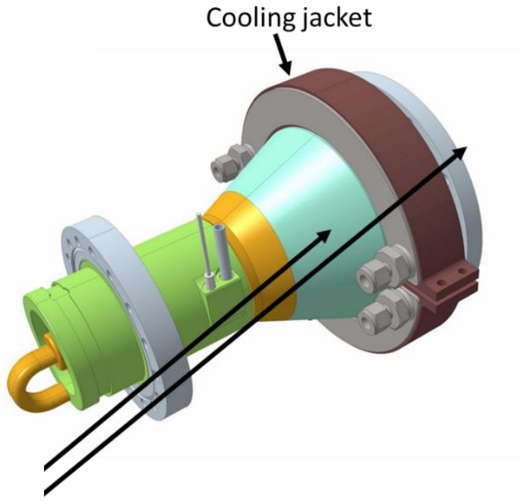
→ Additional surface temperature sensors attached to coupler.

Challenges: hot couplers



CW conditioning with ~7kW Fwd in each coupler.
3 couplers are hot.

CH(ALL)	Level	Unit
CH1 1A_1	+76.64	degC
CH2 1B	+82.28	degC
CH3 2A	+20.80	degC
CH4 2B	+20.71	degC
CH5 3A	+20.71	degC
CH6 3B	+83.05	degC
CH7 4A	+20.32	degC
CH8 4B	+20.30	degC

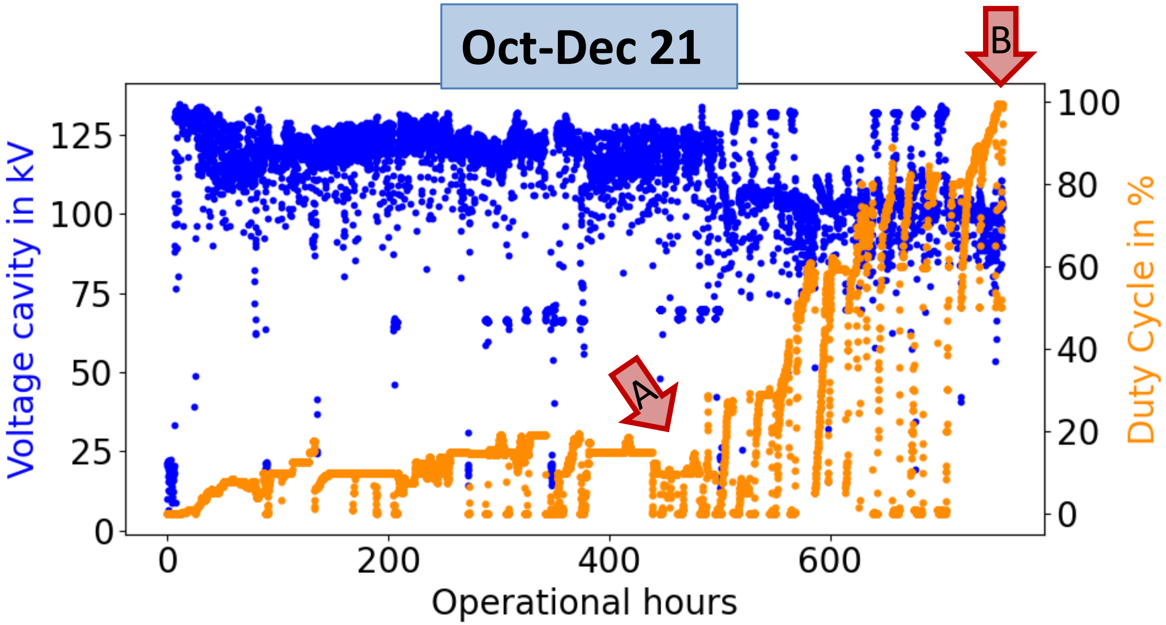


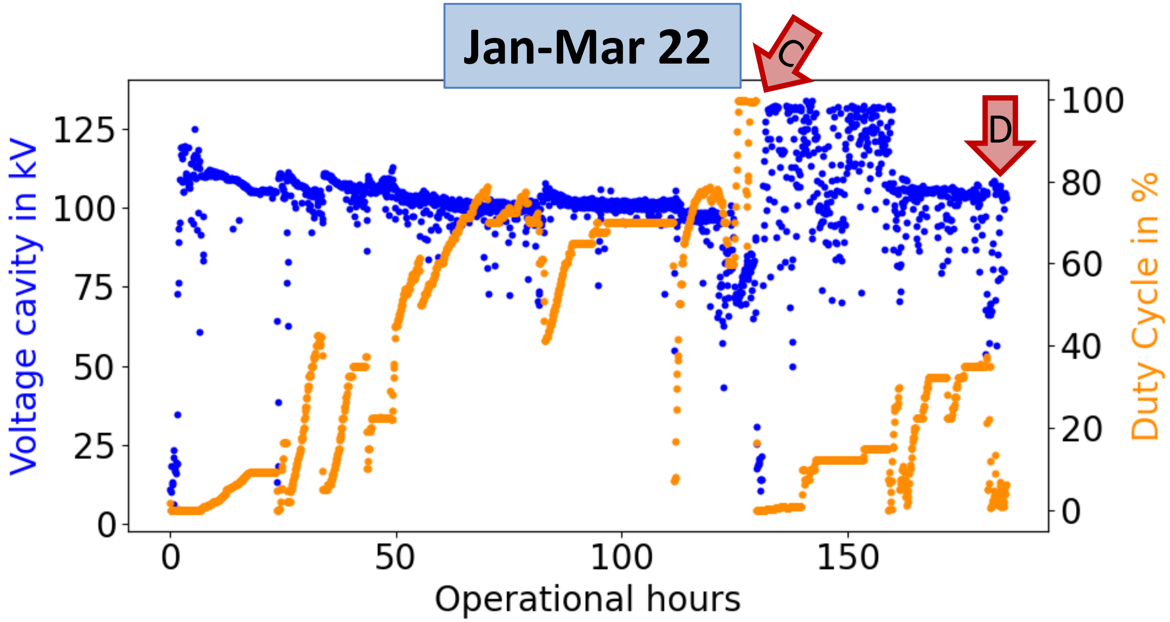
→ Install water cooling external jacket & interlock from T sensors

Conditioning towards CW – vacuum leak

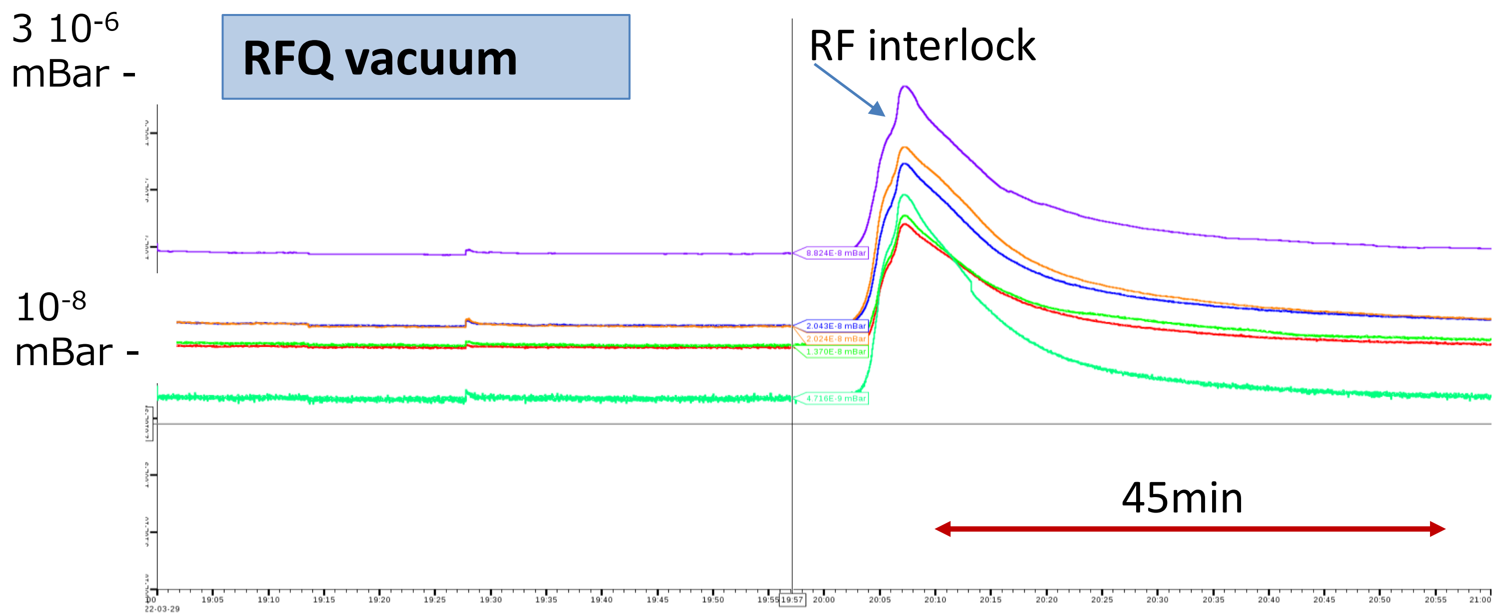
CW conditioning campaign @ nominal voltage of 132 kV started in second half of 2021.

A) Nov21 - Unable to increase duty cycle >25% (too frequent Rev peaks). Reduced power.
B) Dec21 - Successfully reached CW @ 110 kV.
C) Jan22 - Failure of Circulator of chain 1B. Operation restarted after one month with 7-chains.
D) Mar22 - RFQ vacuum leak.



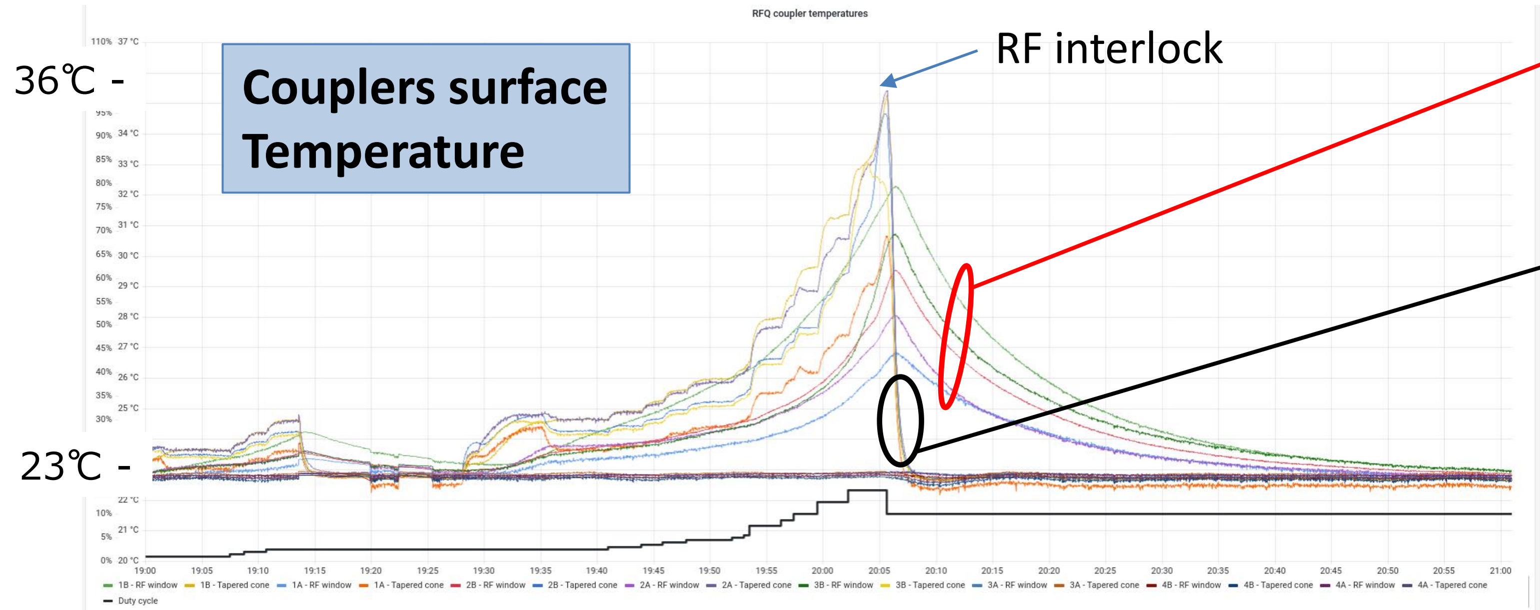


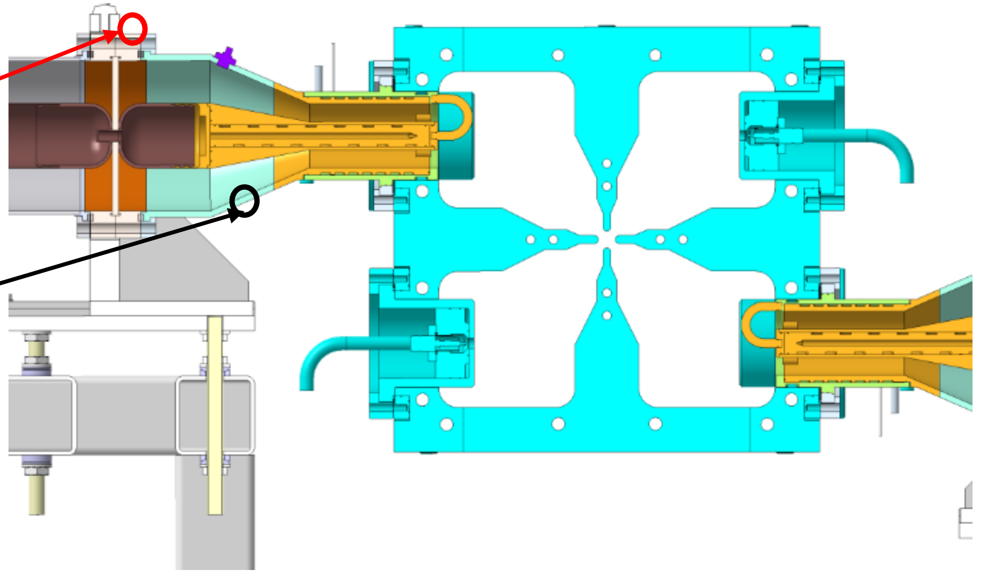
Vacuum leak detected



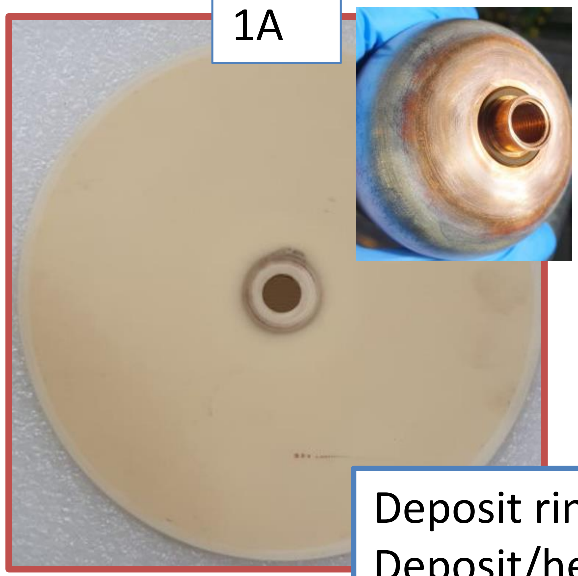
Vacuum leak time constant very slow & correlated with couplers temperature.
→ Suspect o-ring melt in RF window

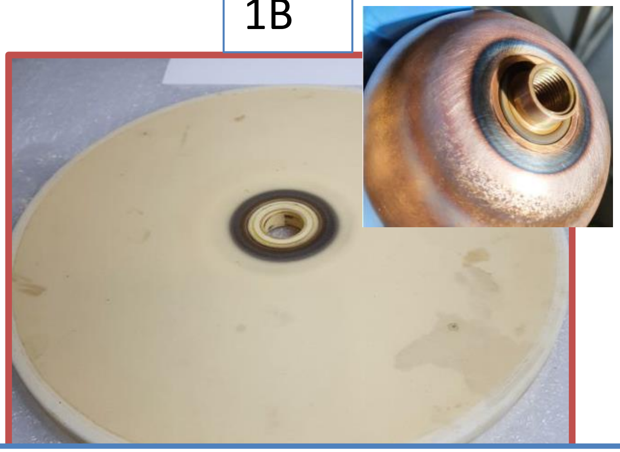
Could not clearly identify which coupler
→ Dismount all 8 for inspection

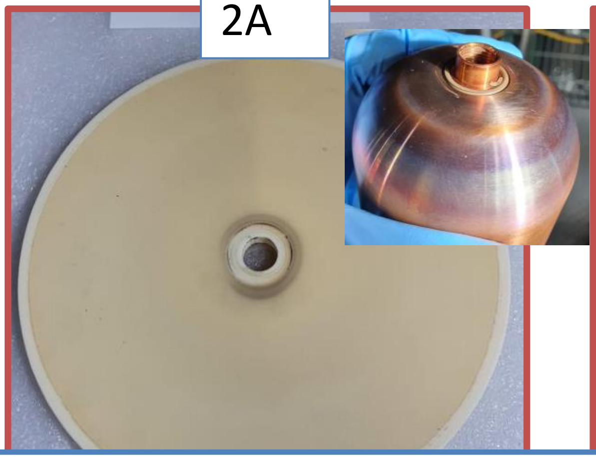


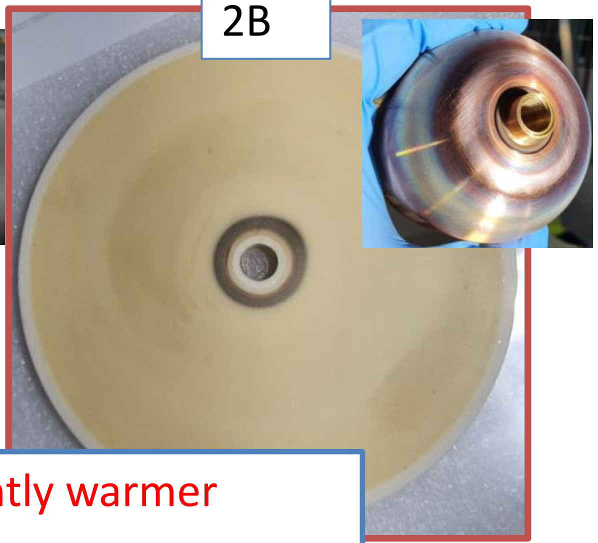


Inspection of the couplers after the leak


1A


1B

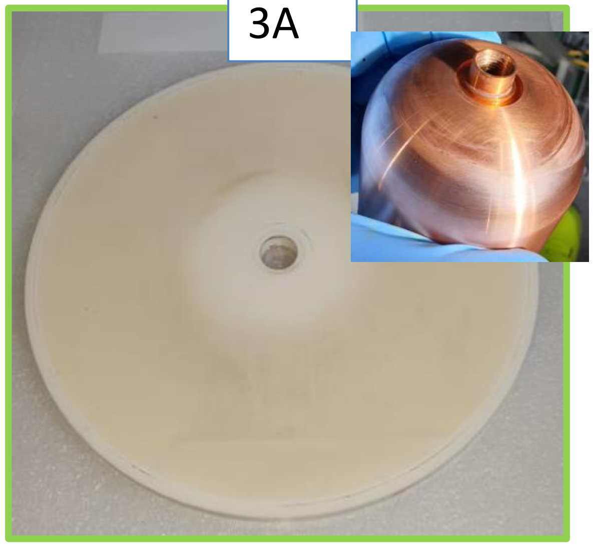

2A

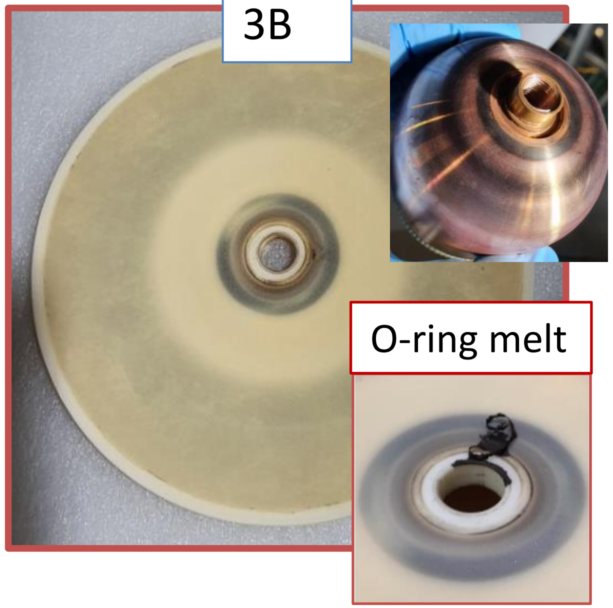

2B

Deposit ring on ceramic near inner conductor
Deposit/heat ring on anchor

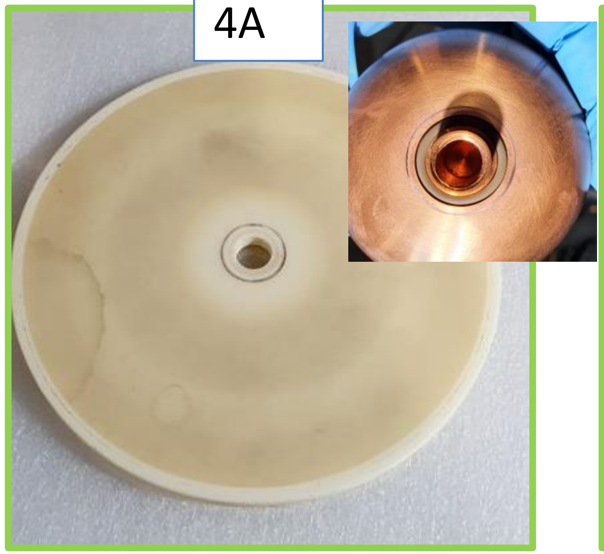
⇔

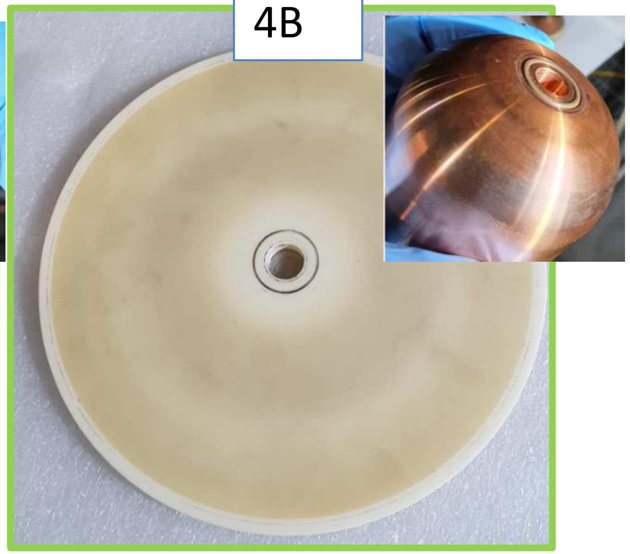
Couplers consistently warmer than others in red


3A

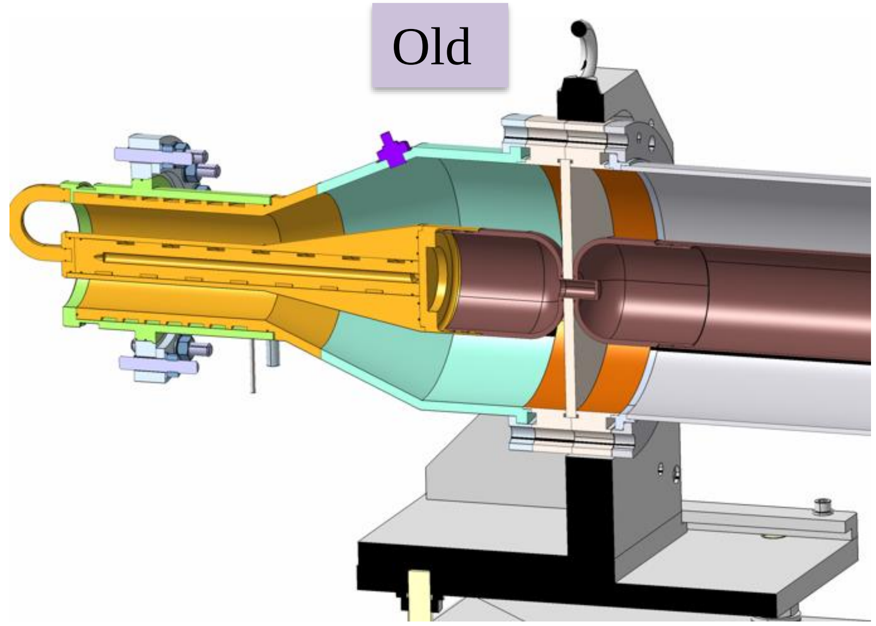

3B

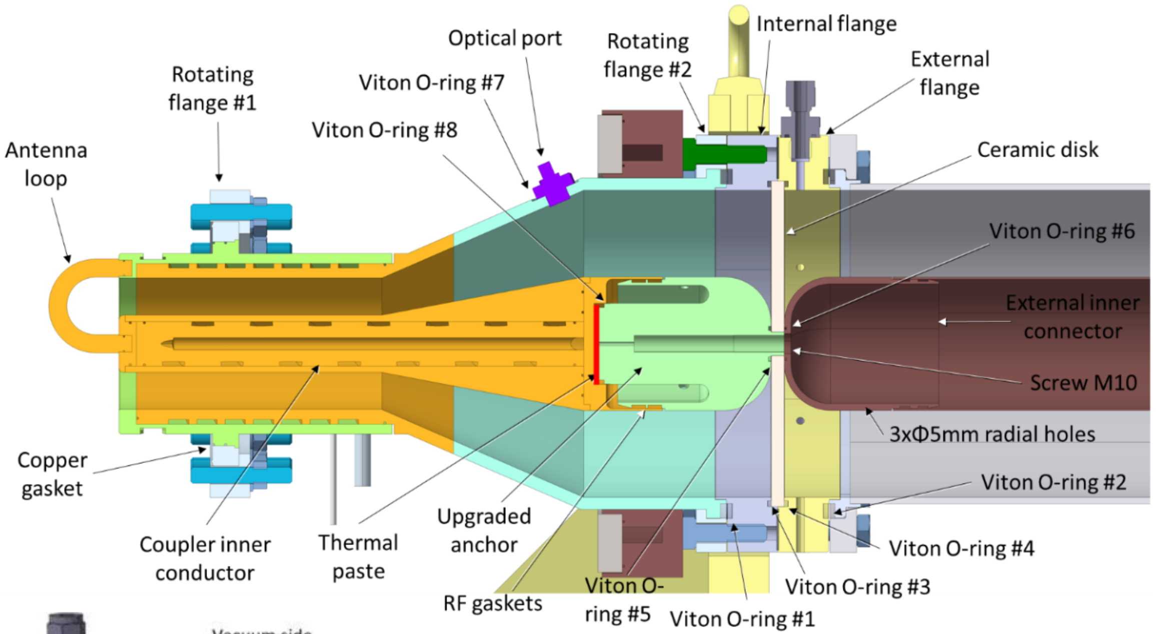
O-ring melt


4A

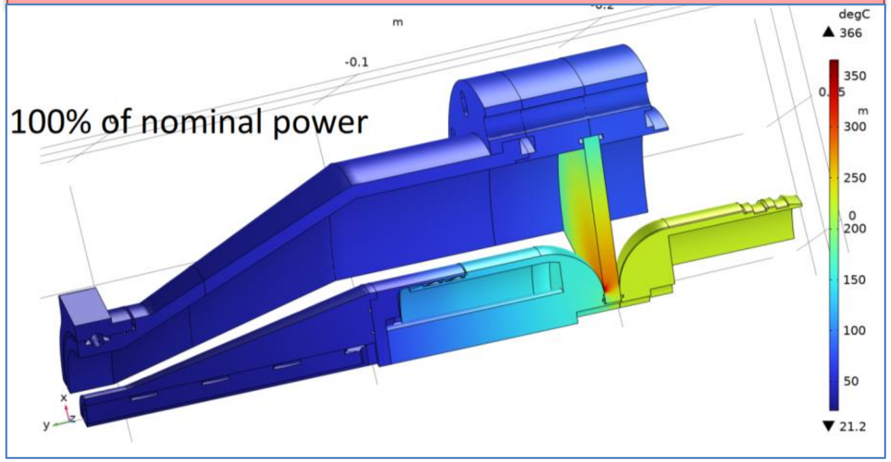

4B

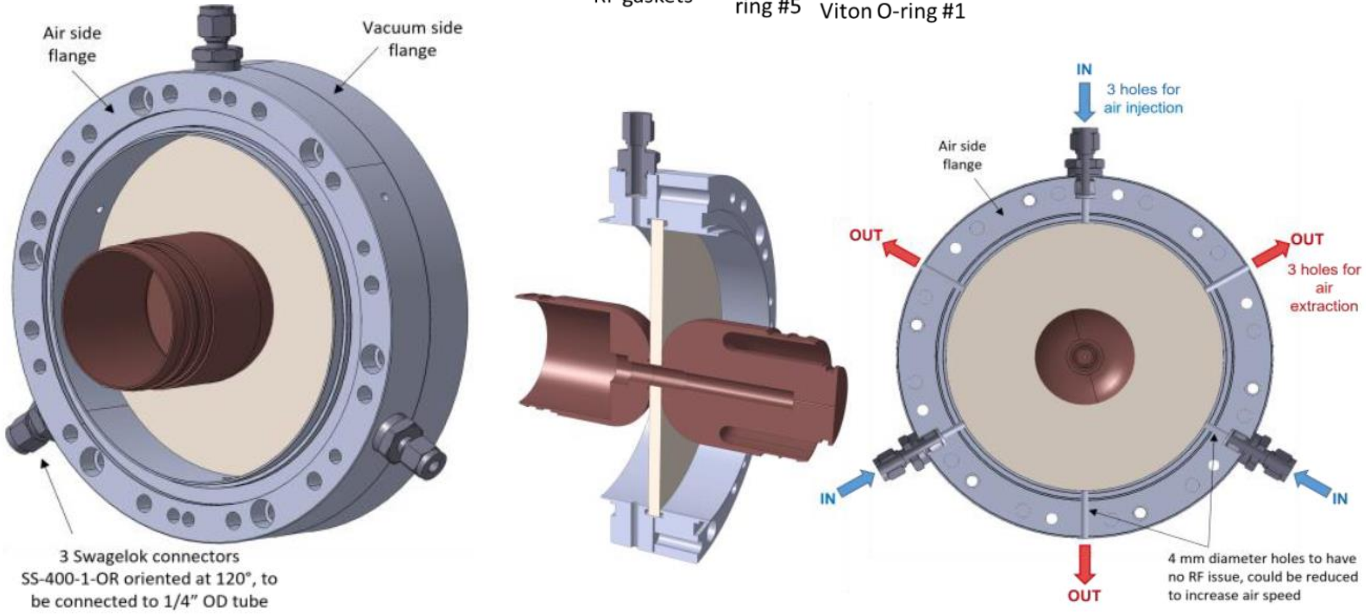
O-ring couplers cooling enhancement





Extensive simulations performed

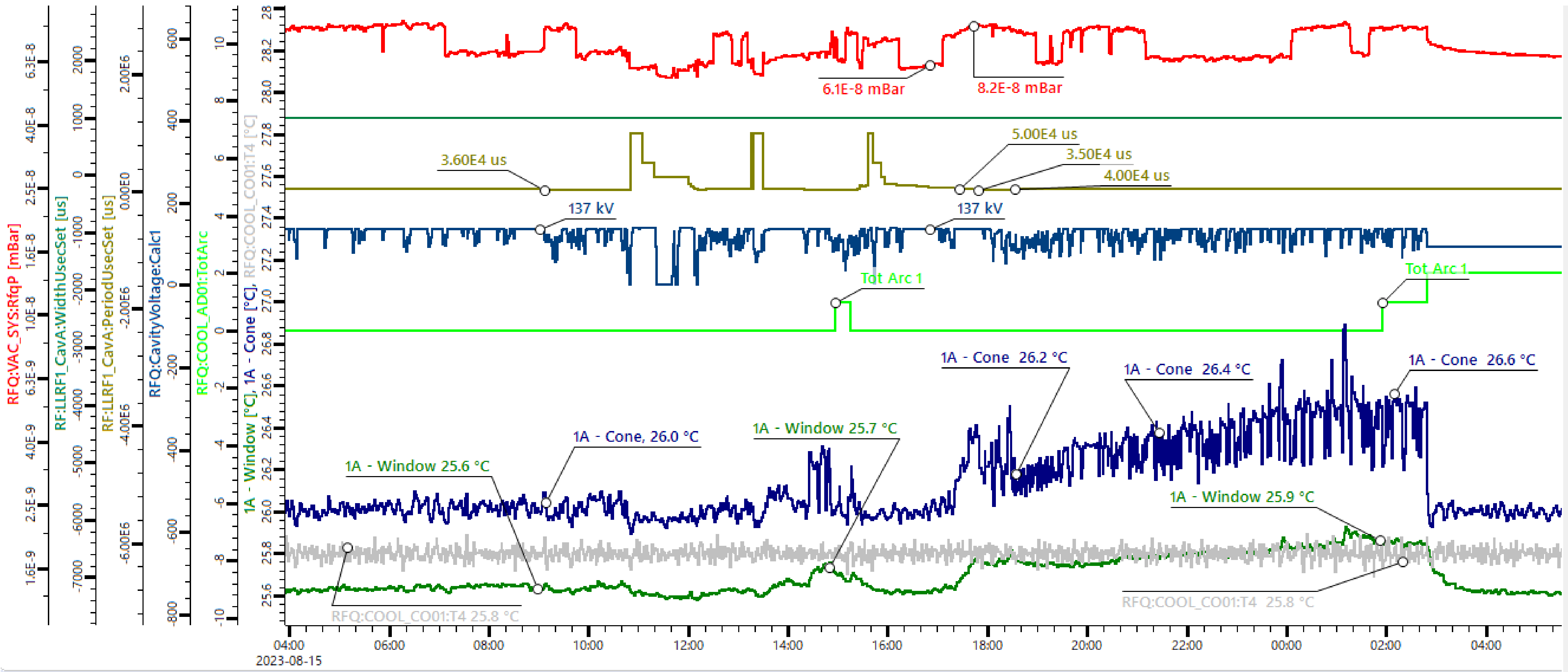




Results with improved O-ring couplers

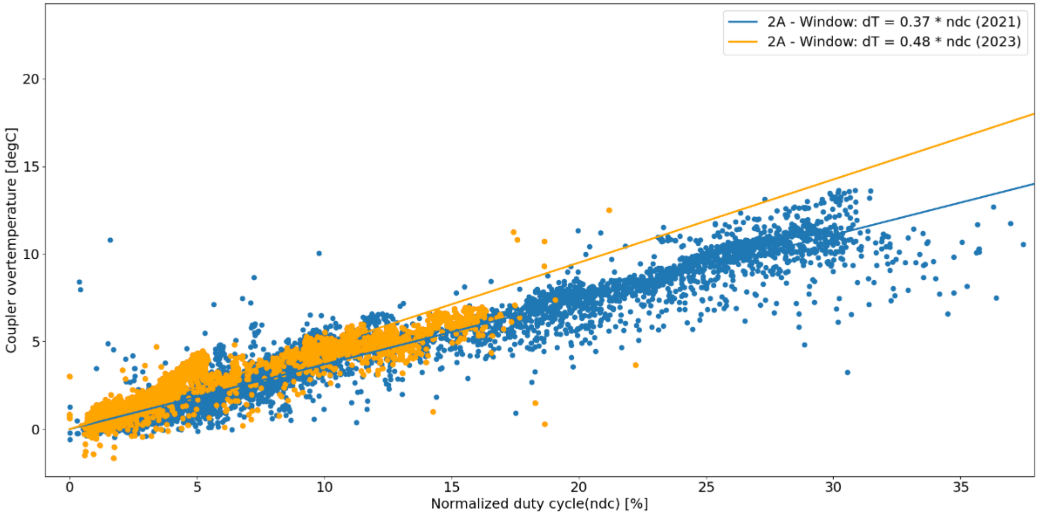
Same ceramics are installed, but vacuum/air surface is flipped. The ceramics of couplers 1A(hot) and 4A(cold) are swapped. Initially all couplers are cold, one by one the same 5 units start to become warm.

Example of 1A

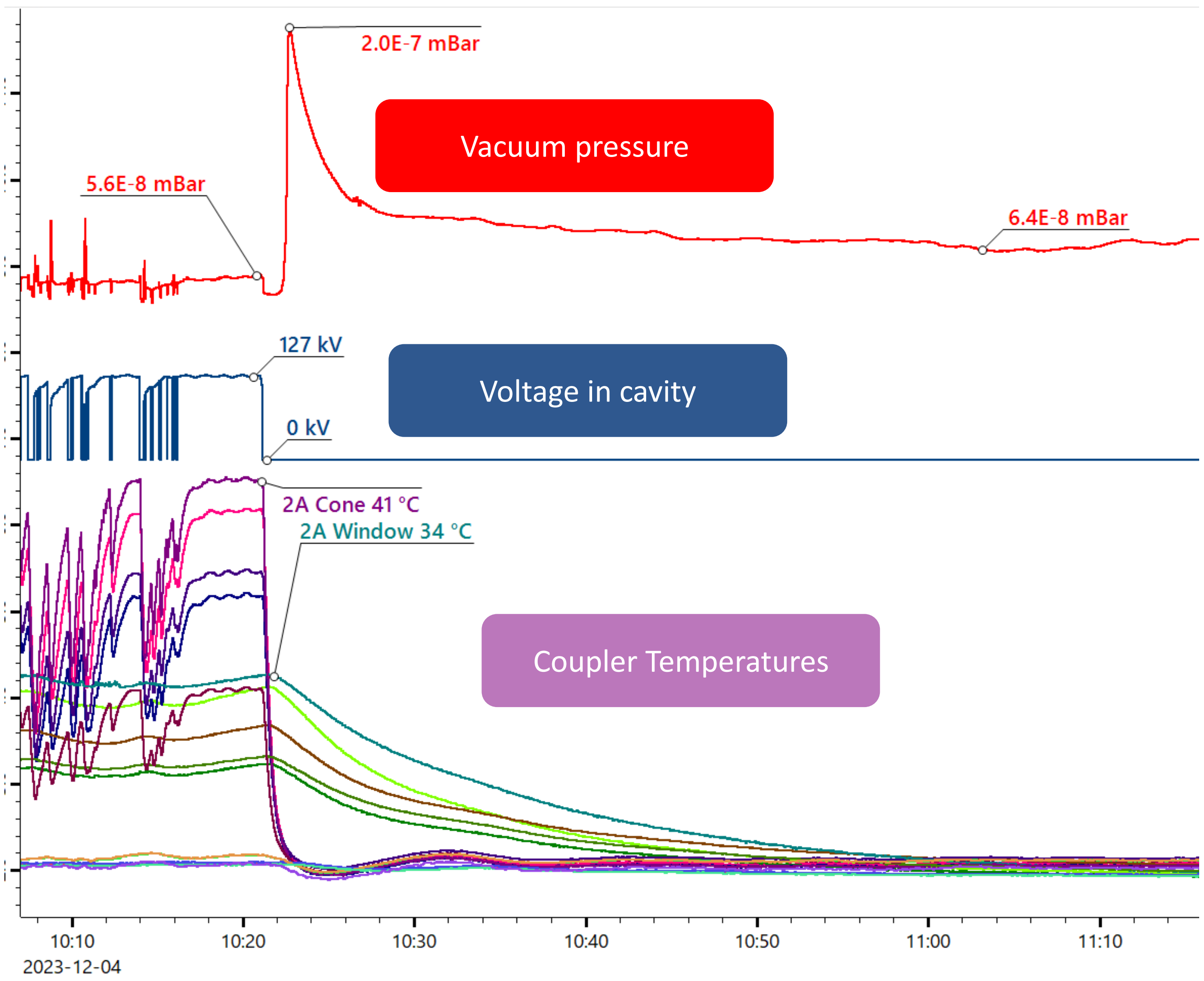


New vacuum leaks detected

Coupler external surface temperature increase per unit d.c. is comparable to previous campaigns.

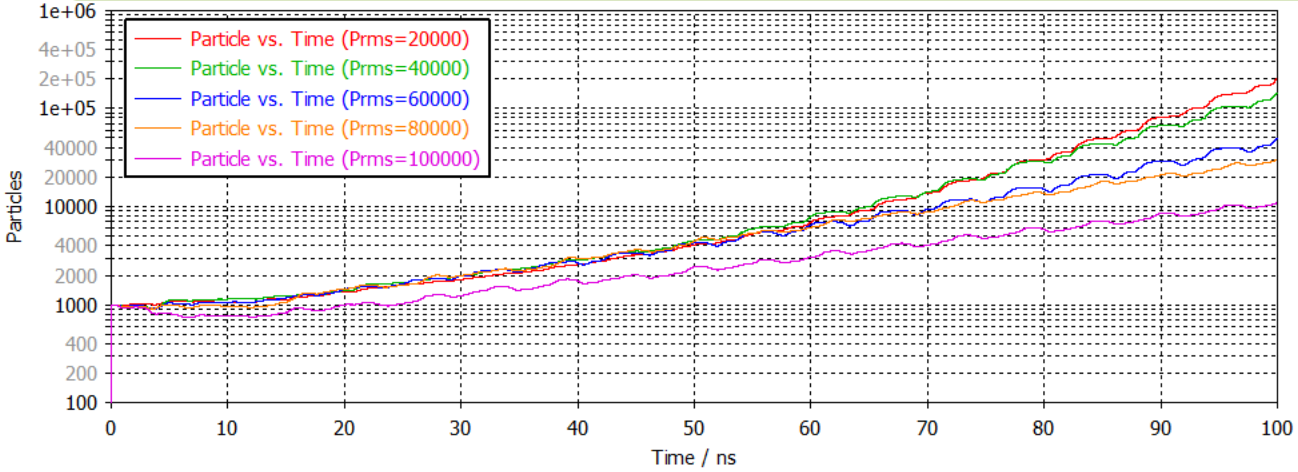


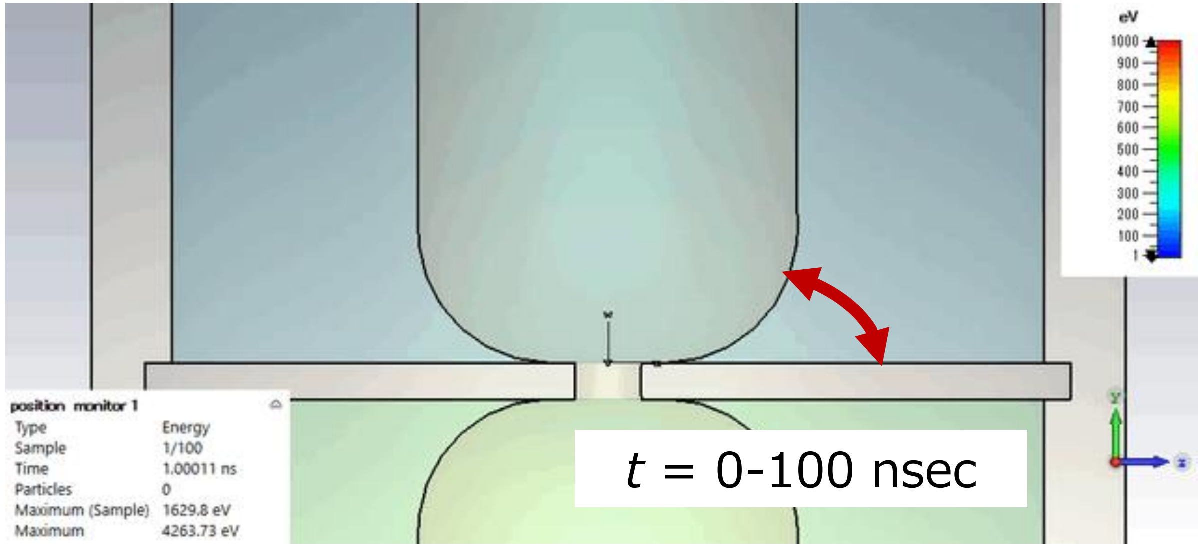
Reached 26% d.c. and small vacuum leaks are detected.
Behaviour suggests damage to O-rings.



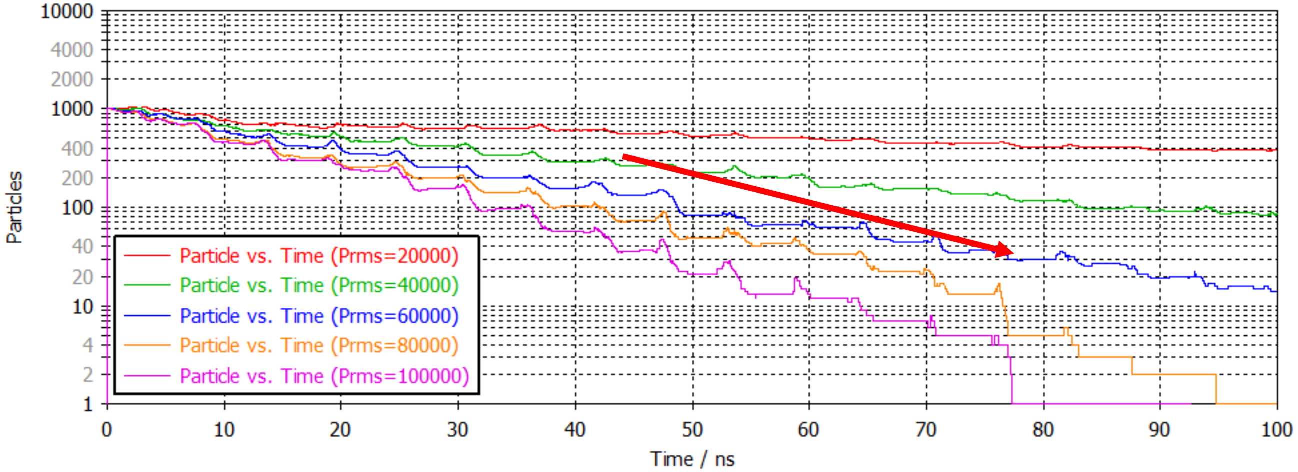
Multipacting simulations and B field bias

Number of electrons with time for different Fwd power [W].
No B field bias.

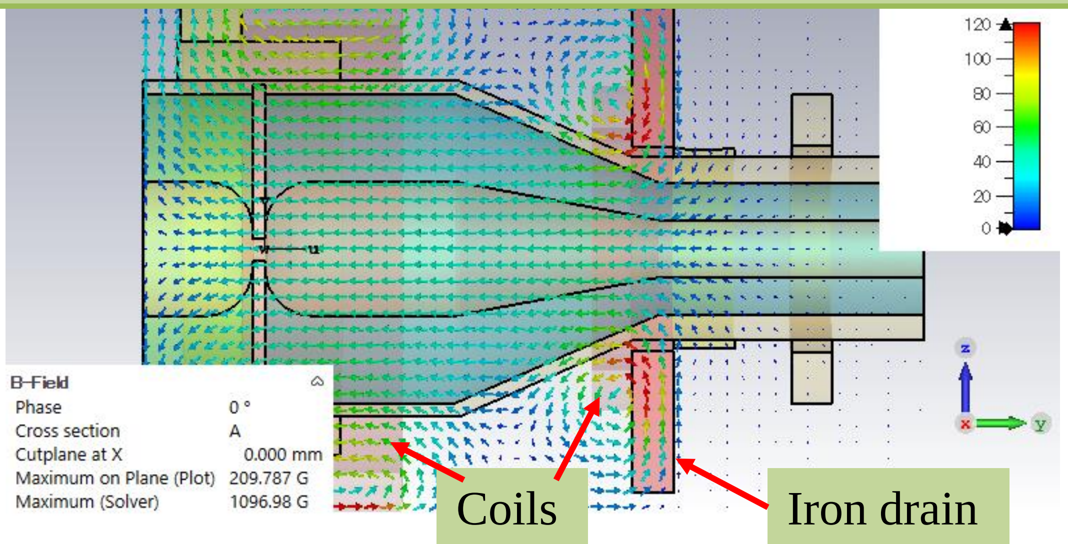




With B field bias.



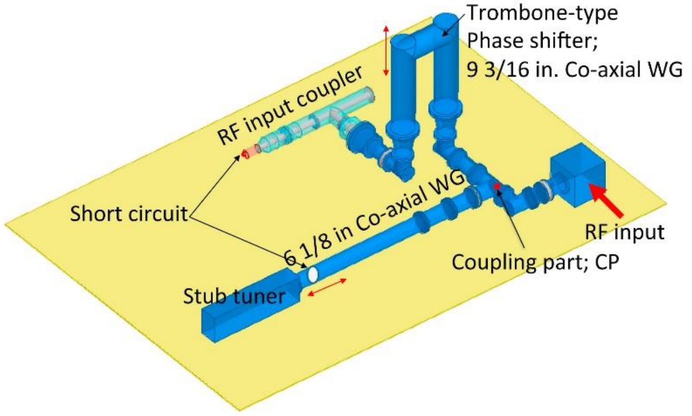
Designing a test with one unit in autumn 2024.



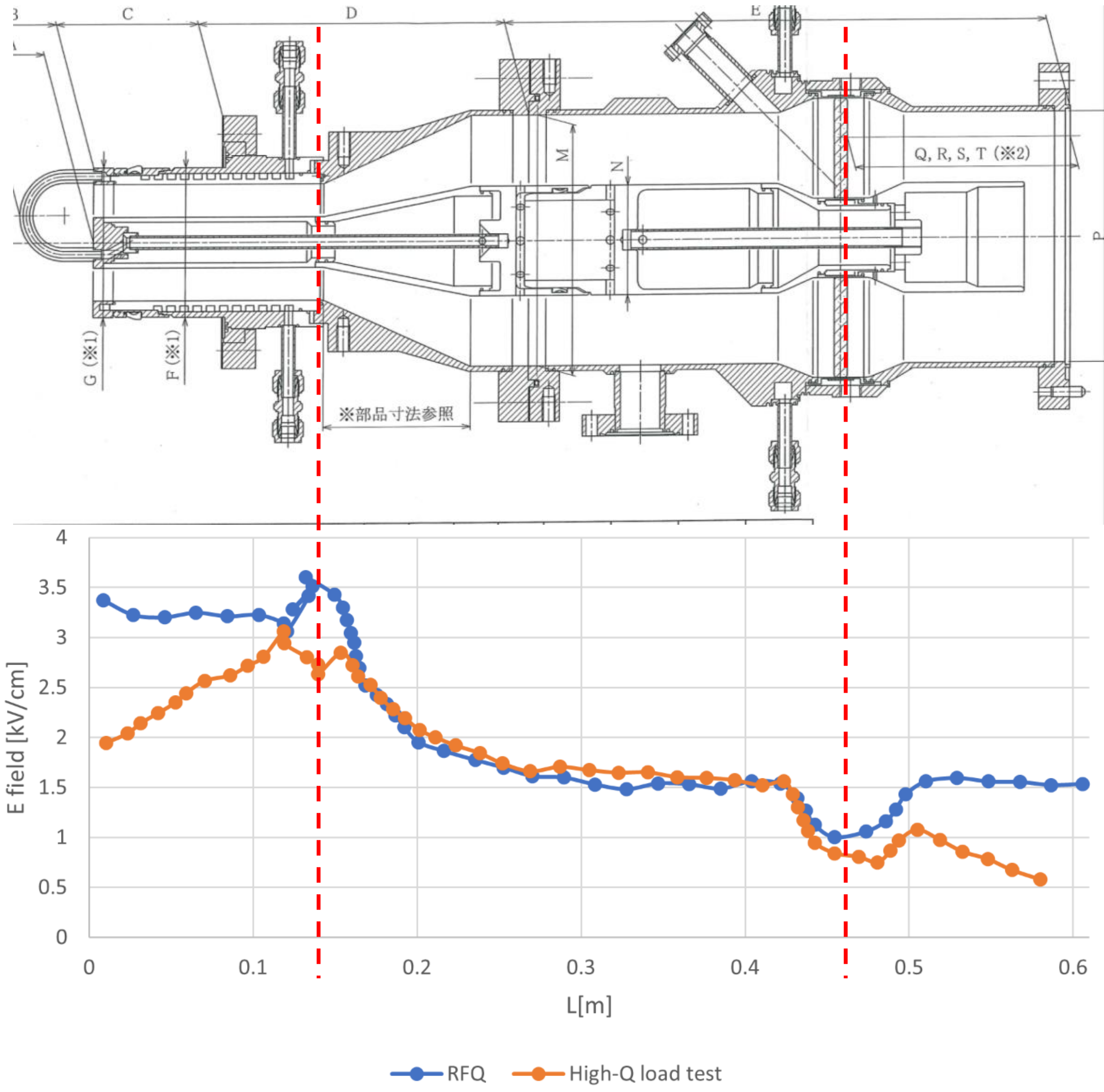
Outline

- LIPAc & its RFQ
- “O-Ring” couplers
- “Brazed couplers”

High Q load test



Maebara S. et al., Fus. Eng. Des. 2017



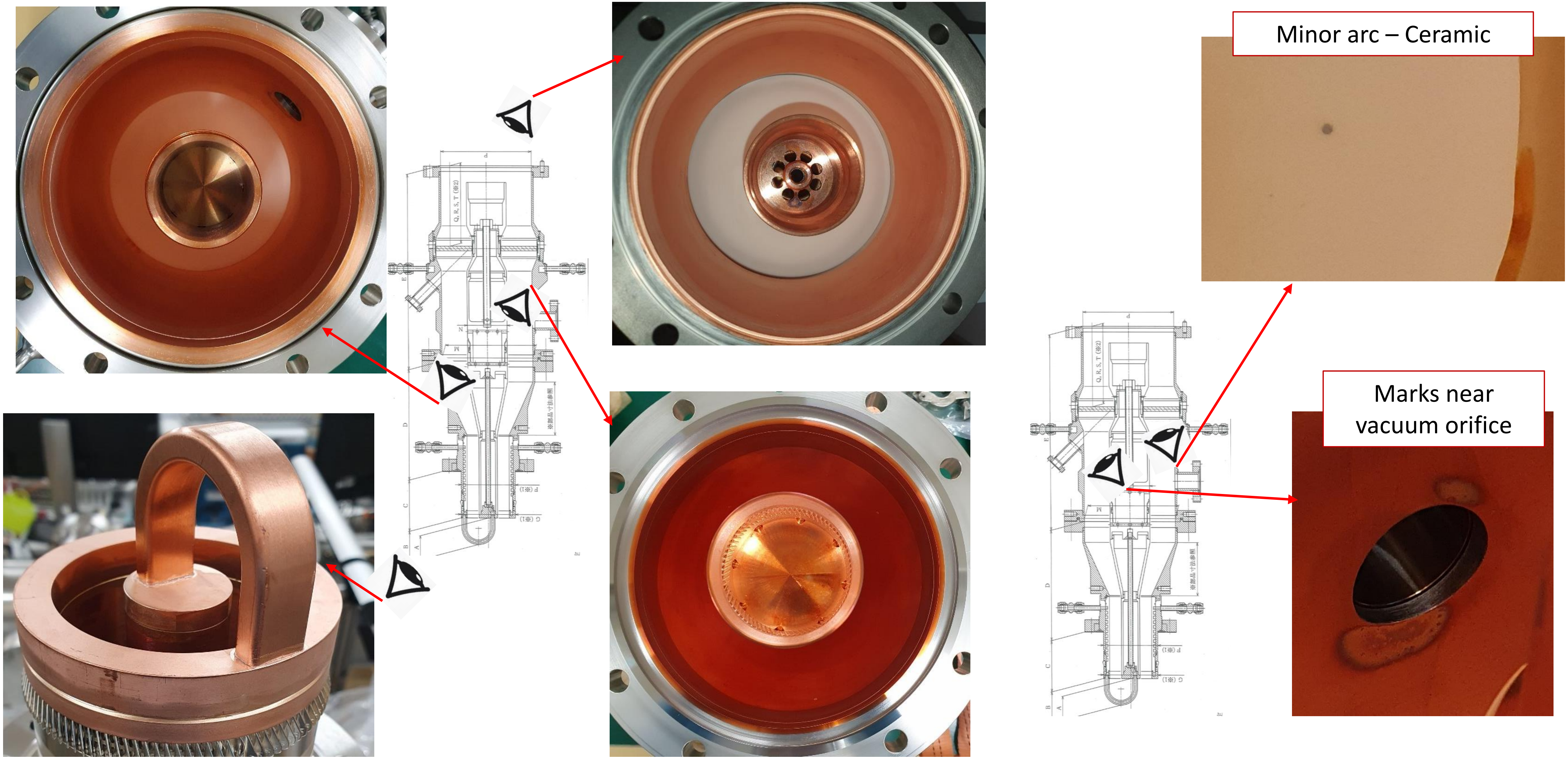
Comparison of E field in high Q load and RFQ

9 units withstood 200kW eq. standing wave in CW

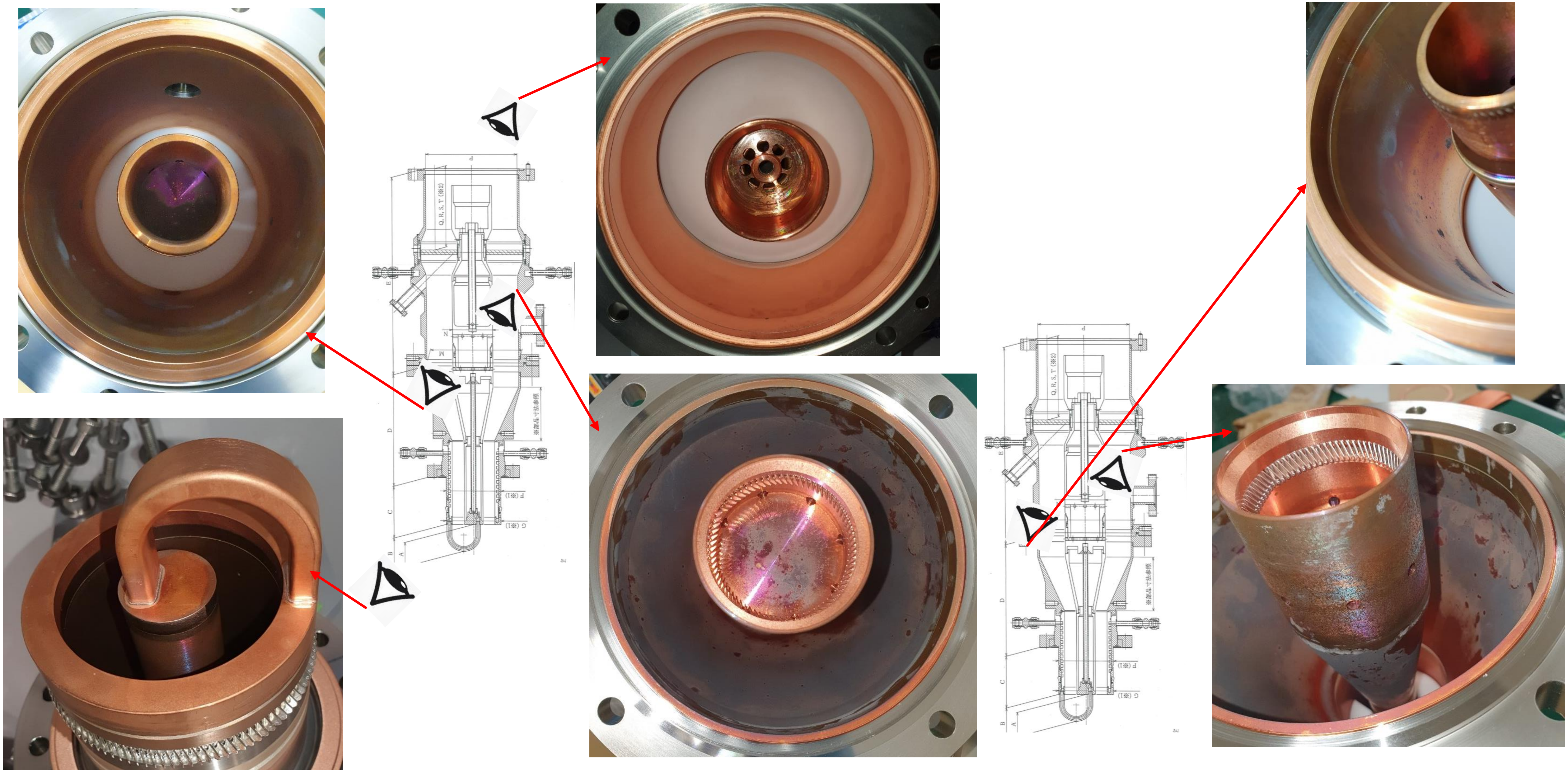
Narrow band high Q load circuit (± 5kHz)
Thermal effects detune the system → operation in CW <10s.

Vacuum pressure: 10^{-7} - 10^{-6} mBar
No amplifier available for travelling test wave → set to storage in 2016

Visual inspection after Storage. Ex.#3

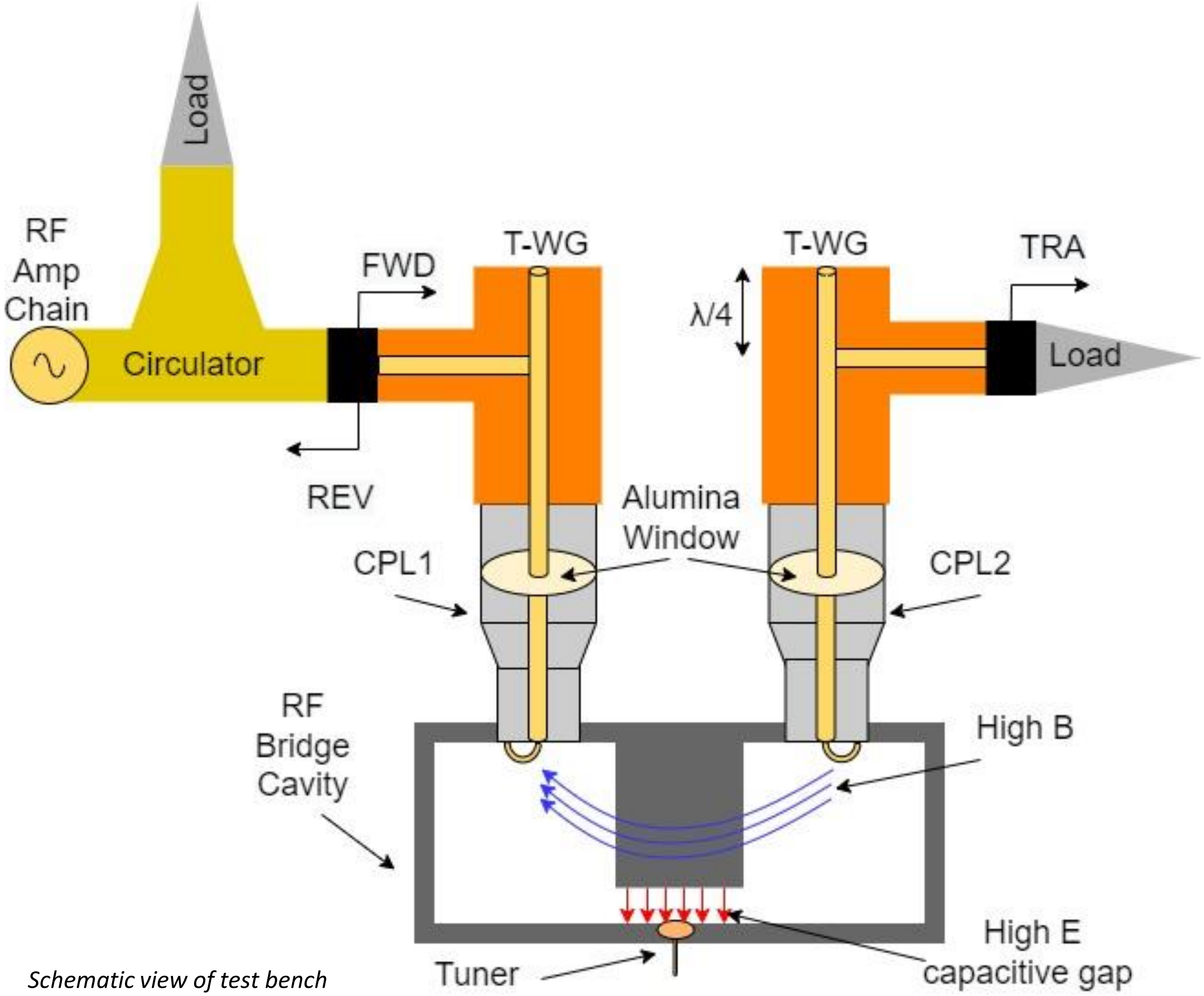


Visual inspection after Storage. Ex.#4



High Power Test Bench

Performed in 2022, after O-ring functional failure



Schematic view of test bench

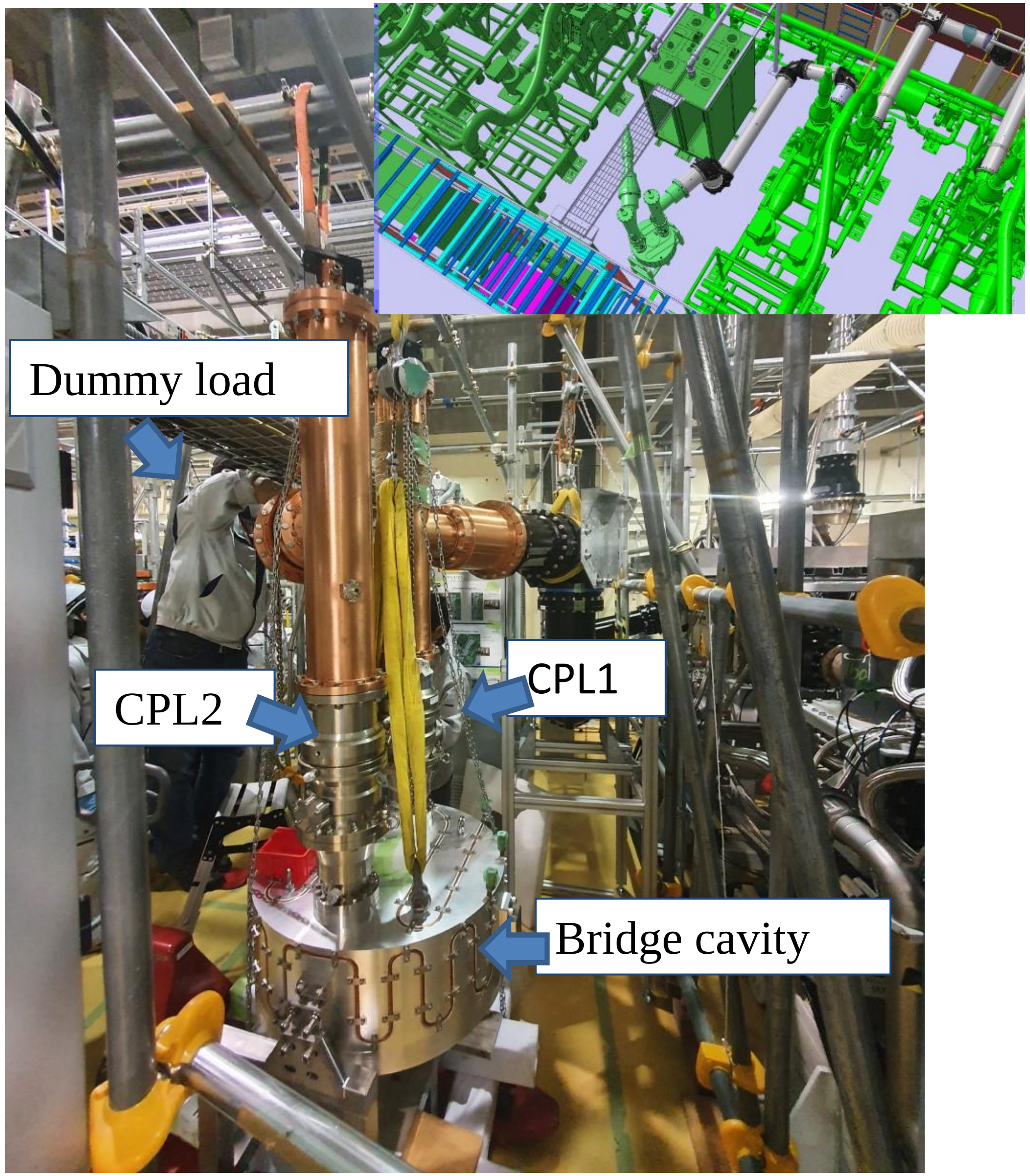
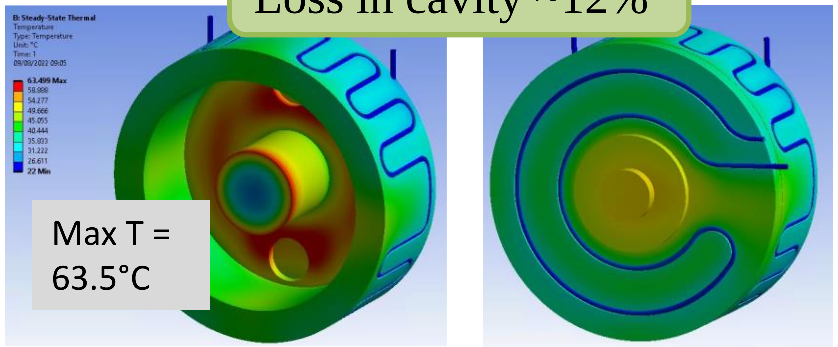


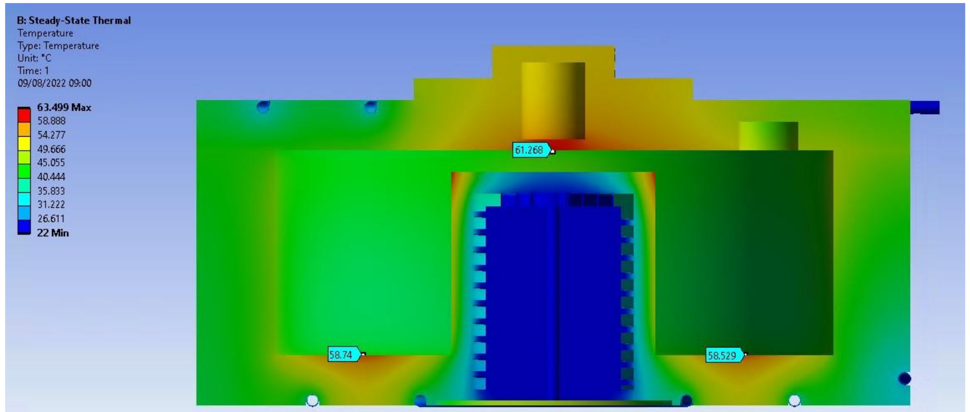
Photo during test bench assembly

Aluminum Bridge Cavity

Loss in cavity ~12%

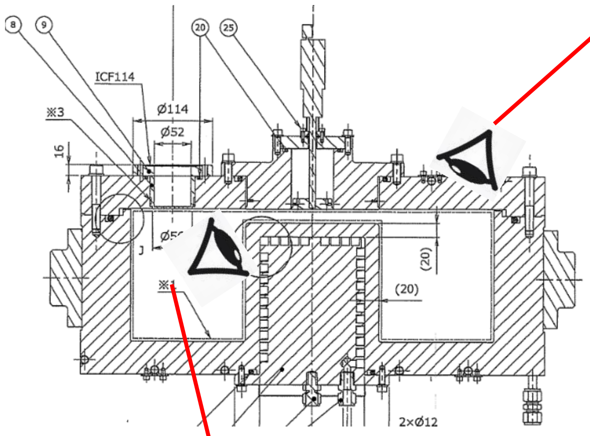


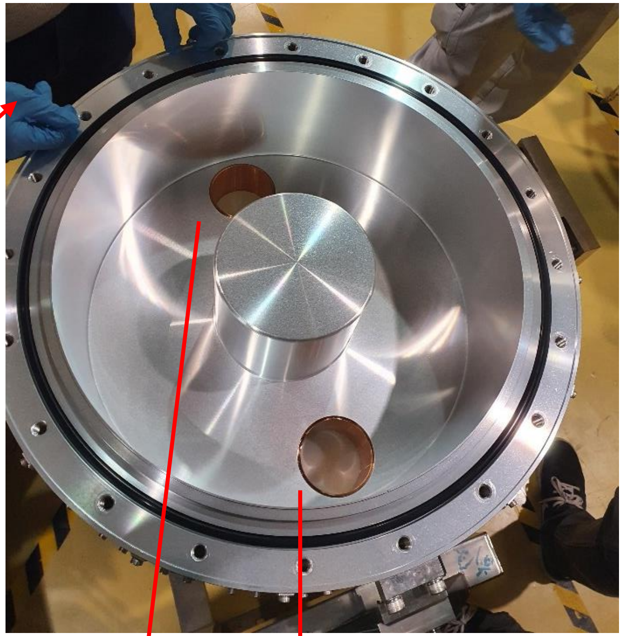
Max T =
63.5°C

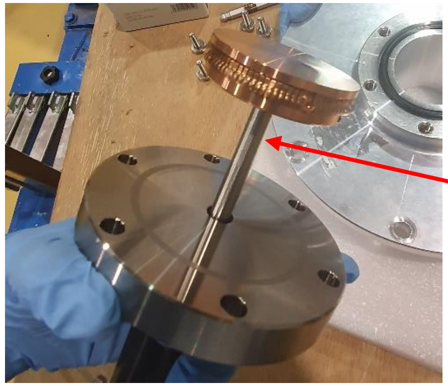


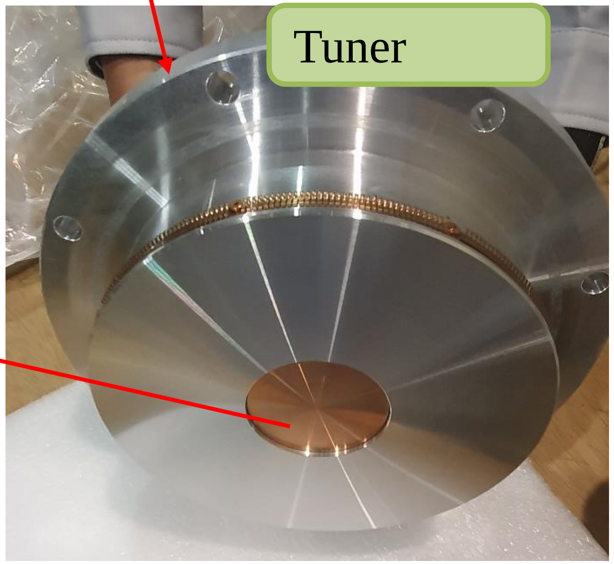
Thermal simulations of cavity at CW with FWD 220kW.

<u>Vacuum</u>
80 L/s TMP
72 hours baking at 100°C
$10^{-7} – 10^{-6}$ mBar

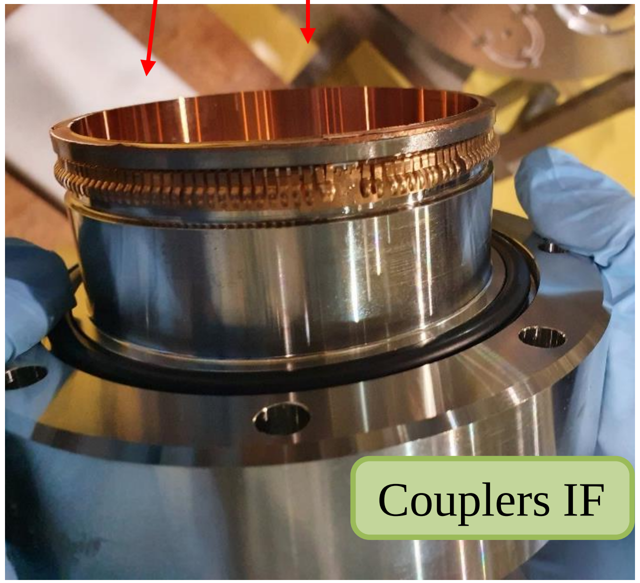








Tuner

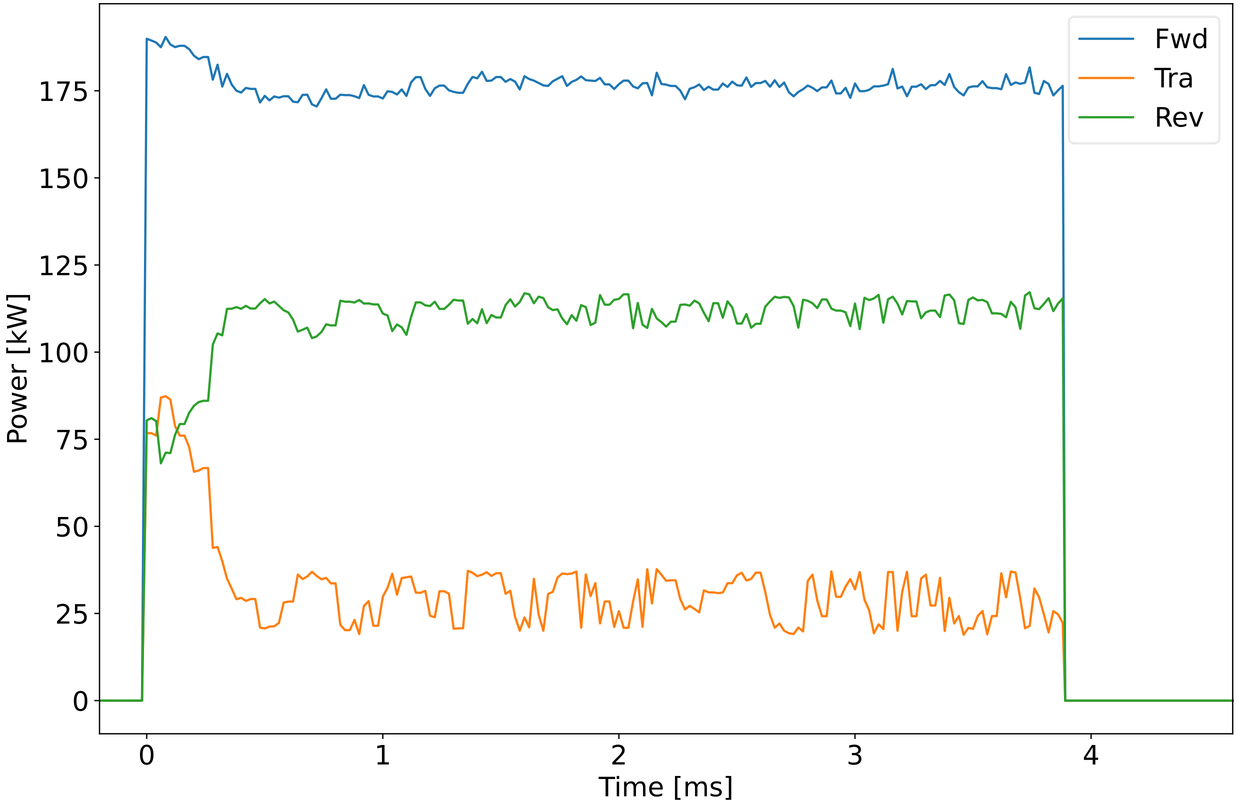


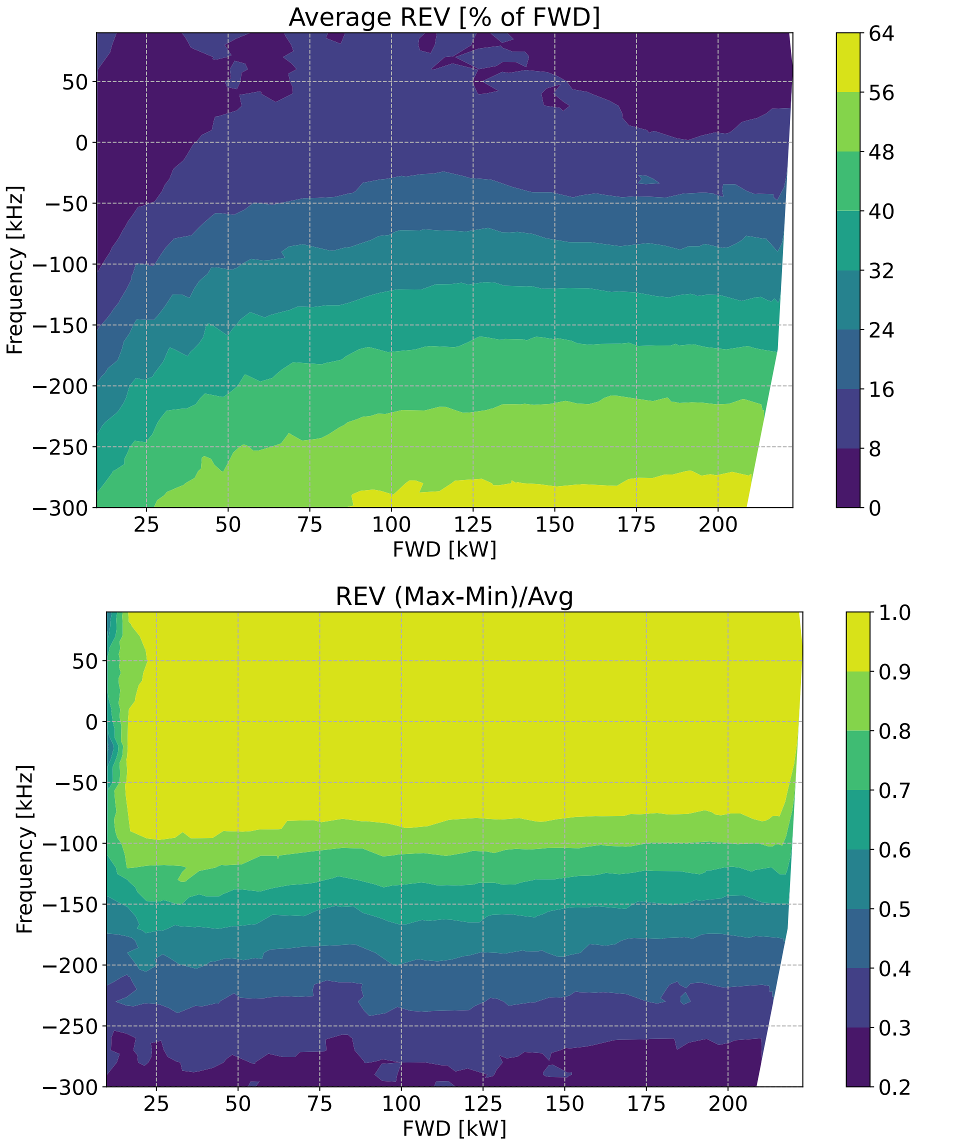
Couplers IF

HPTB Results

Multipacting/plasma is present in any combination of FWD/frequency the system is capable to operate at. Increased nonetheless duty cycle.

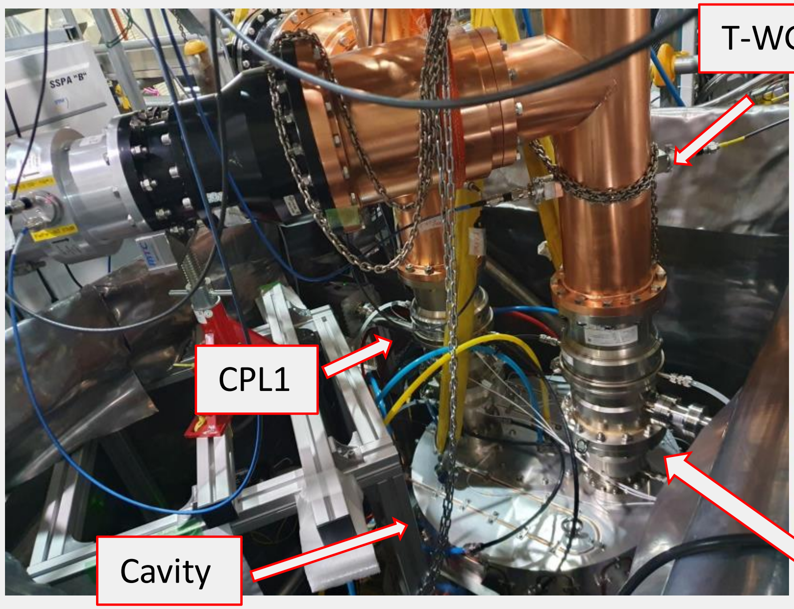
Pulse shape at 96% d.c. with at PW ~ 3.8 ms, RP = 4 ms.

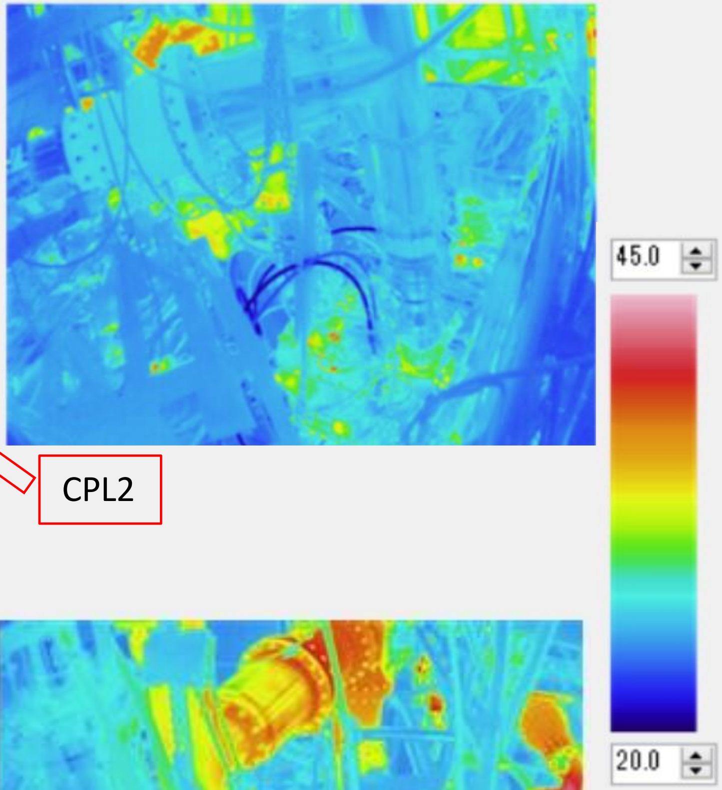


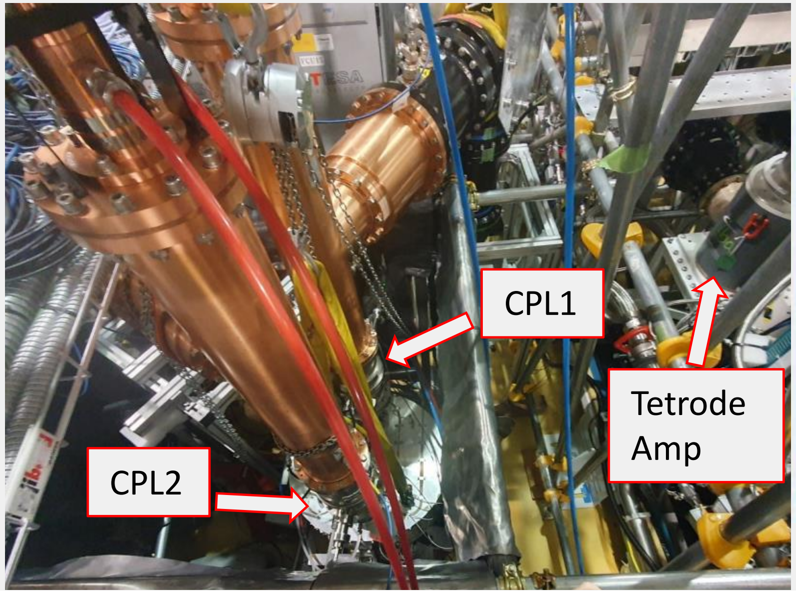


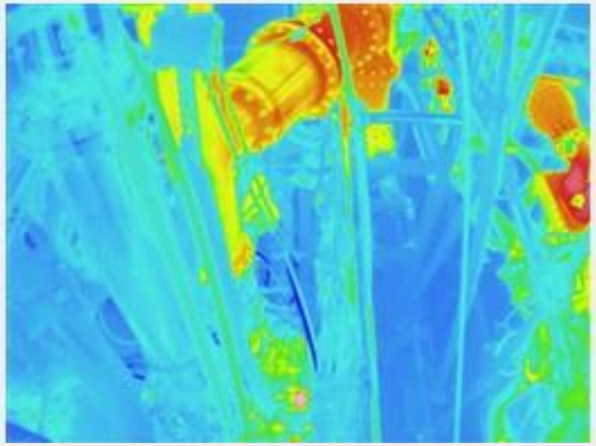
2D scan of FWD and its frequency. No overlap with flat and small on average REV.

Surface Temperature at 96% duty cycle

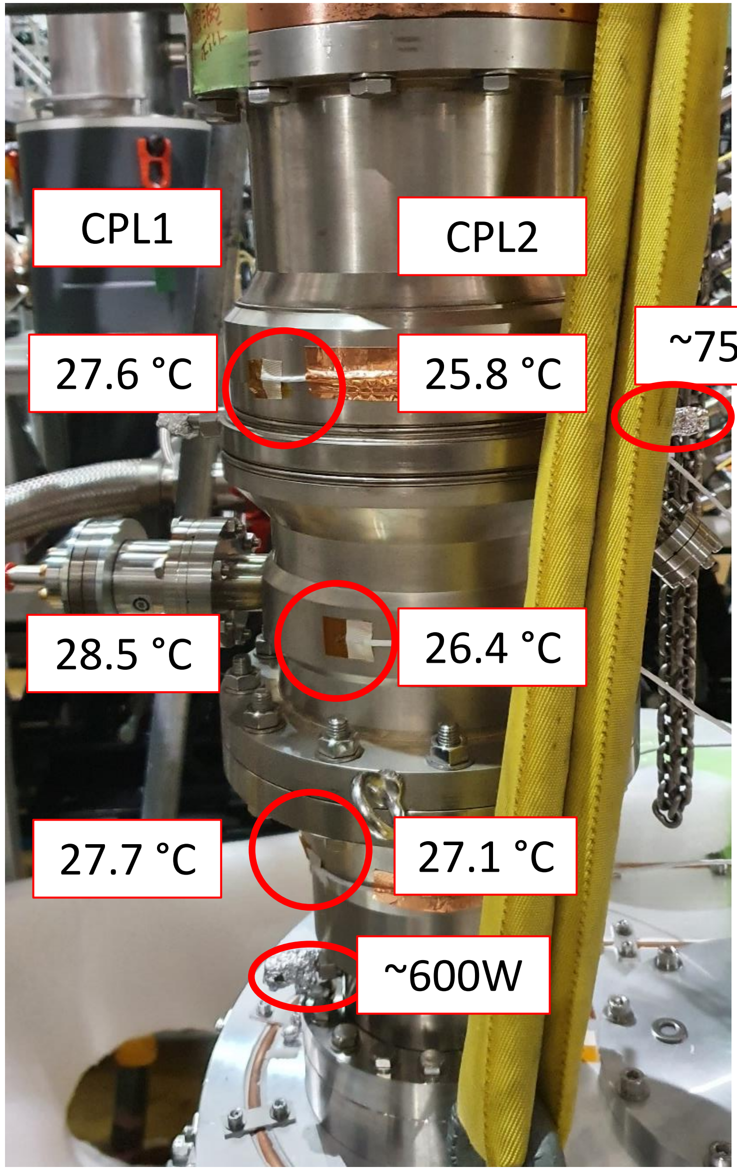








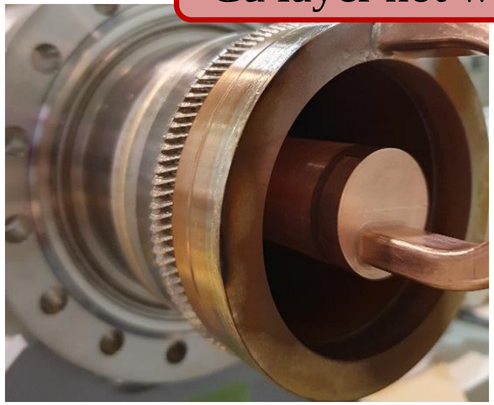
Couplers are not hot at duty cycle = 96%

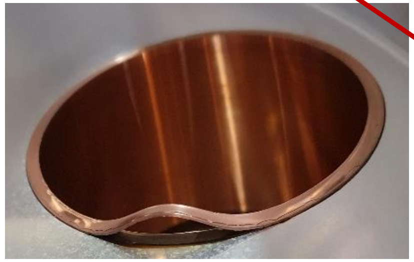


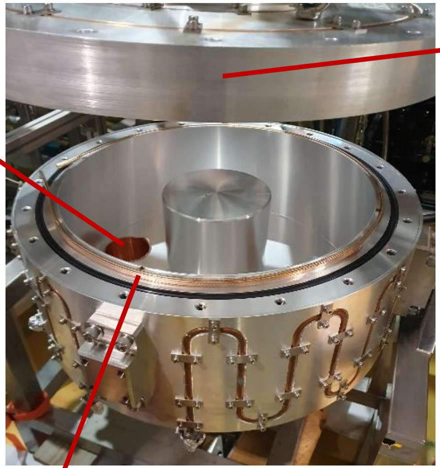
Couplers not hot at duty cycle = 96%. Heat measured with calorimetry not sufficient to explain MP in CPL1.

Cavity visual inspection after test

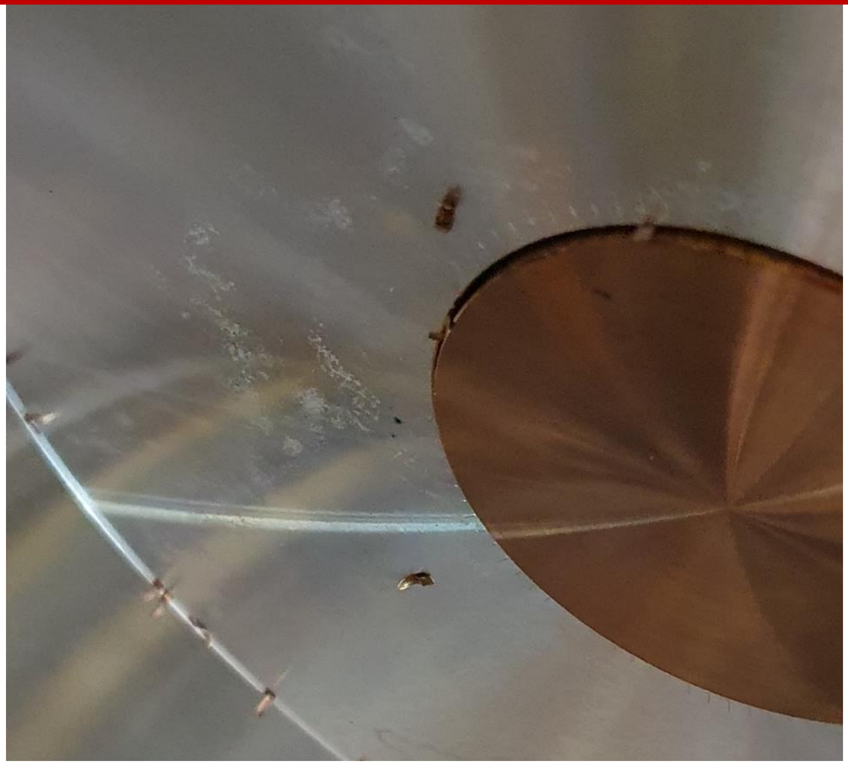
Cu layer not well attached - melted





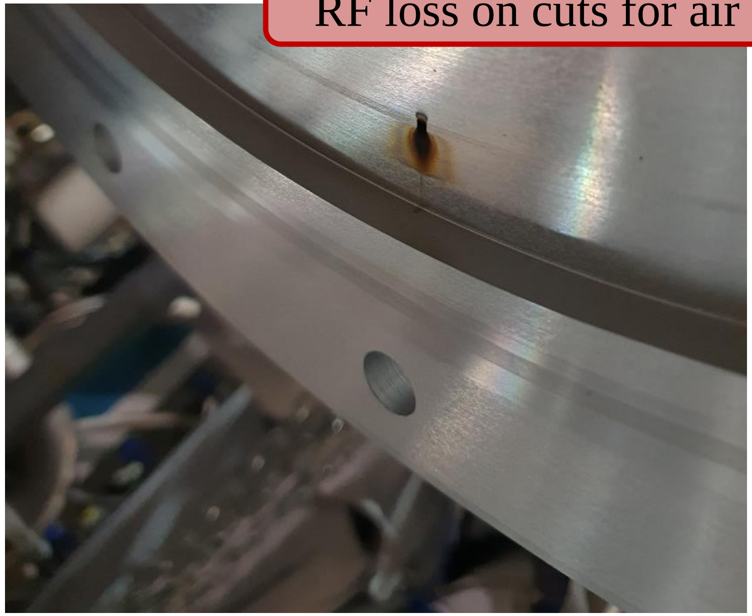


MP / Arcs , protruded and melted RF fingers



Cu layer on SUS input flange not well attached, RF enter gap and create loop, which further melt and deform. Heat marks on the nearby coupler are visible.

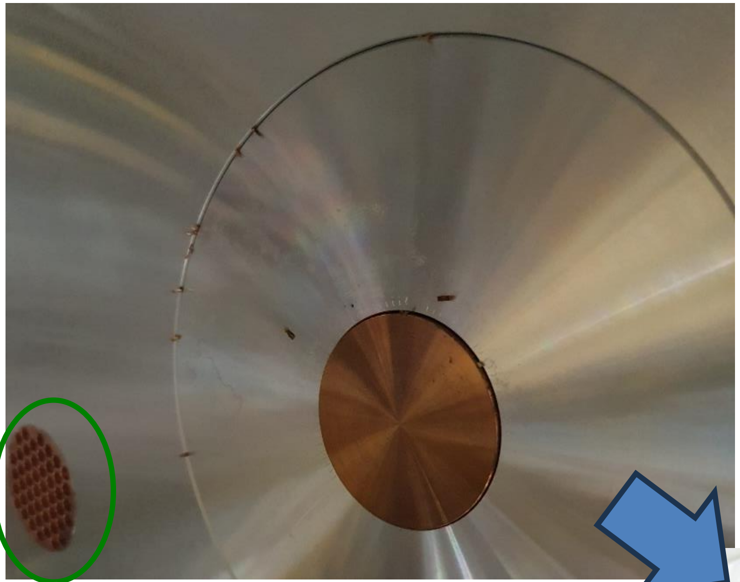
RF loss on cuts for air pocket evacuation



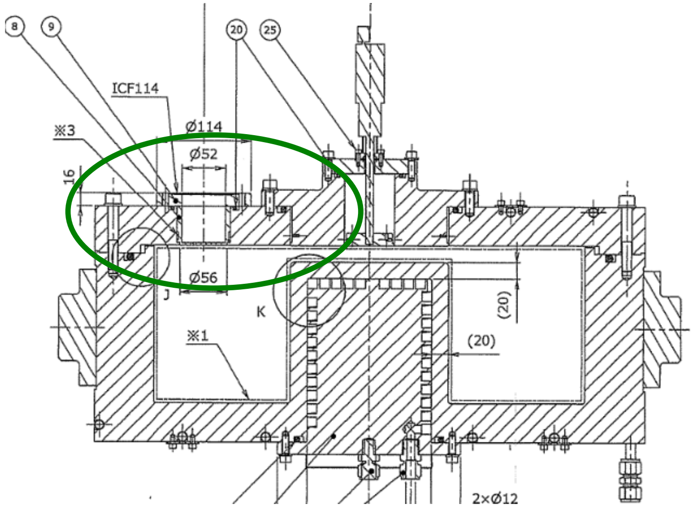
RF loss induced heat in the cuts used for evacuation of air pocket near O-ring.

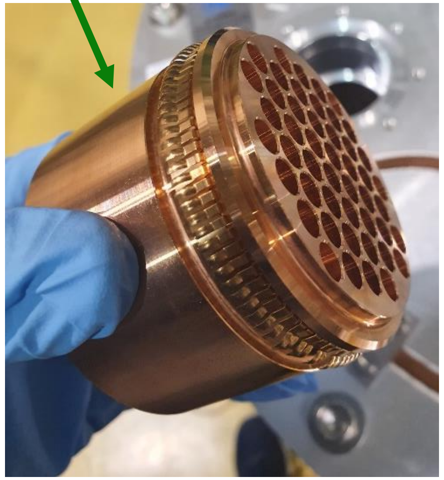
Traces of MP on cavity surface near tuner. Also,visible deformed and melted RF fingers.

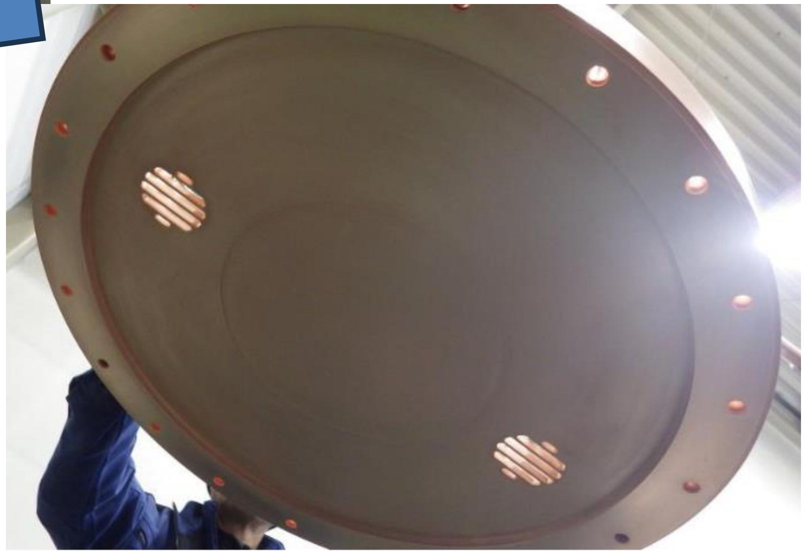
HPTB 2.0 - Cavity improvements I



Vacuum was not great (10^{-7} - 10^{-6} mBar).
→Change vacuum port flange
→Introduce 2 vacuum ports
→ Cu plating



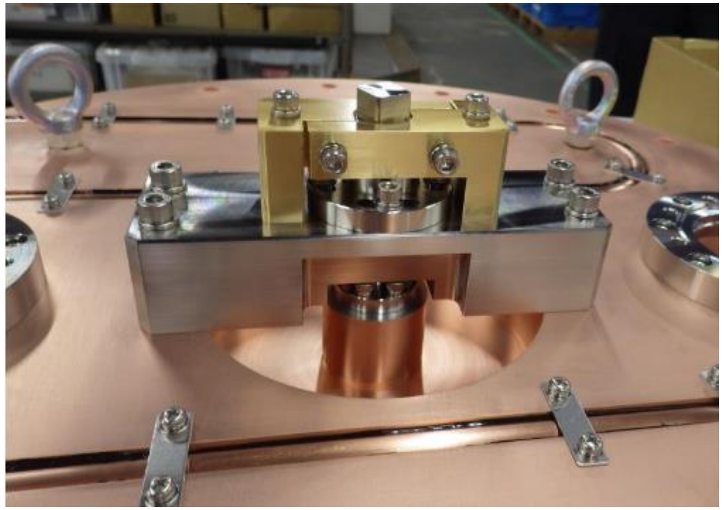


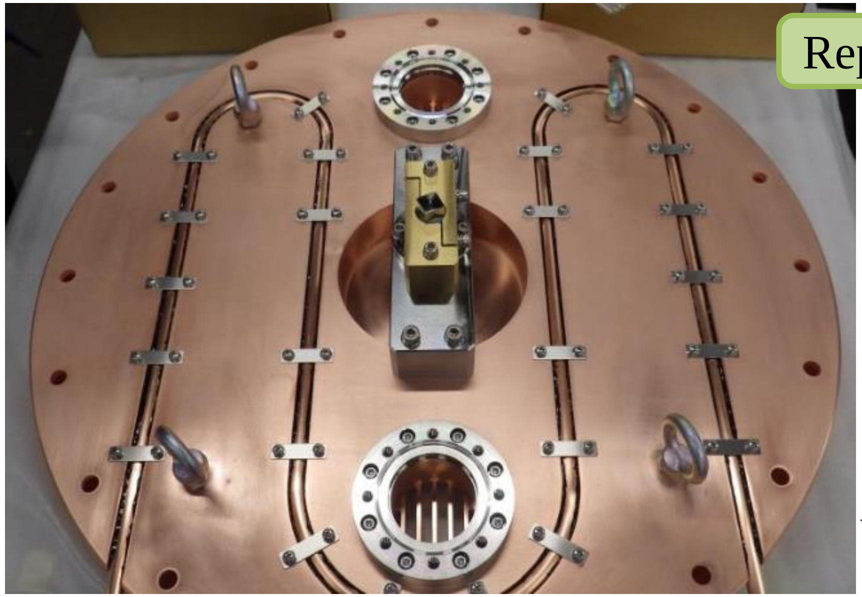


Slits machined directly into the lid.
Follow current direction & larger aperture.
<u>Vacuum pumps:</u>
Add port for
1 NEG (200 L/s SAES CapaciTorr HV200)

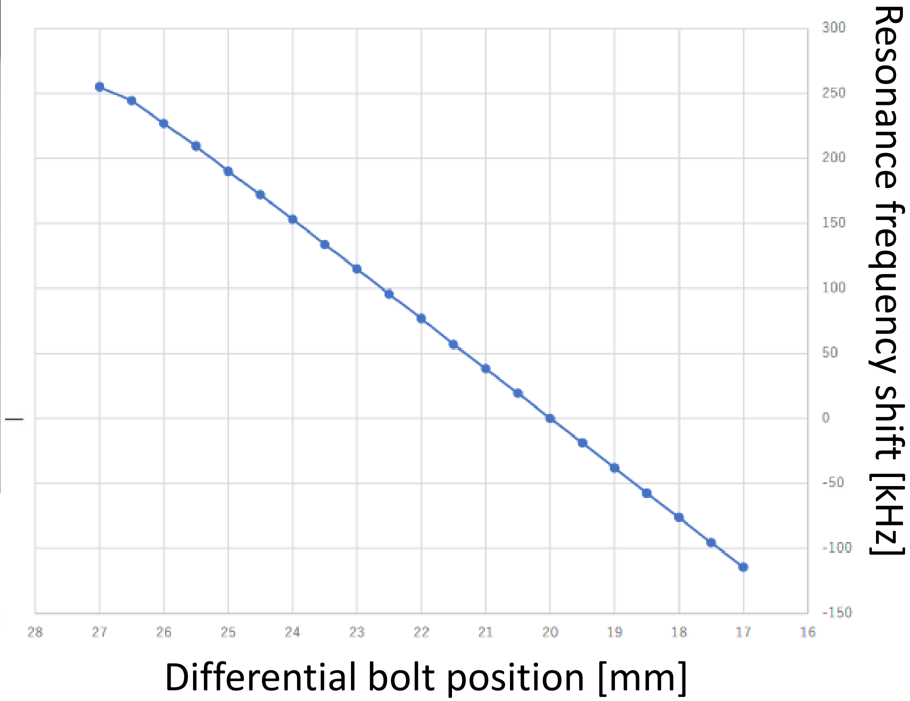
HPTB 2.0 - Cavity improvements II

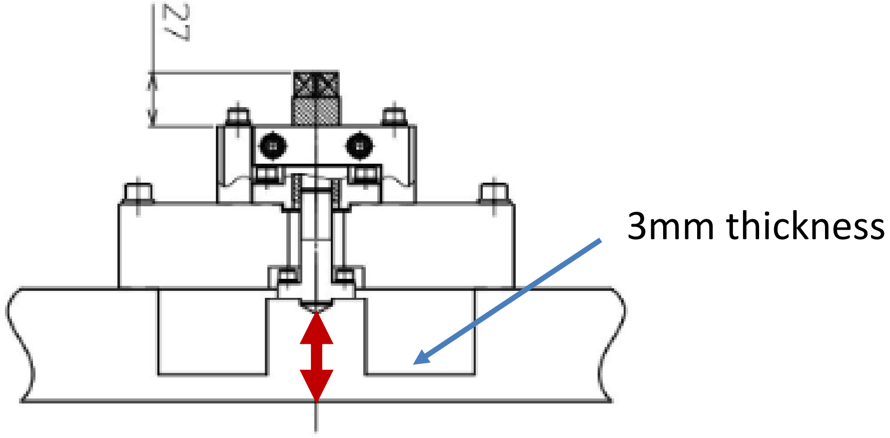
MP/Arcs on the tuner, fingers easy to break → Change tuner concept
Push/Pull from outside to slightly deform the lid and change the capacitive gap.



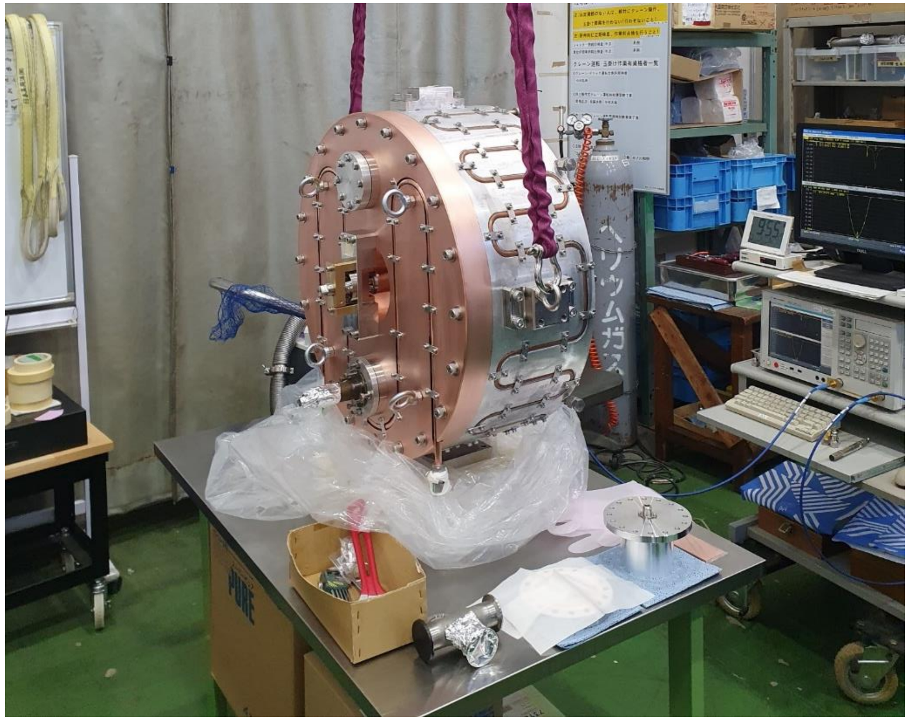


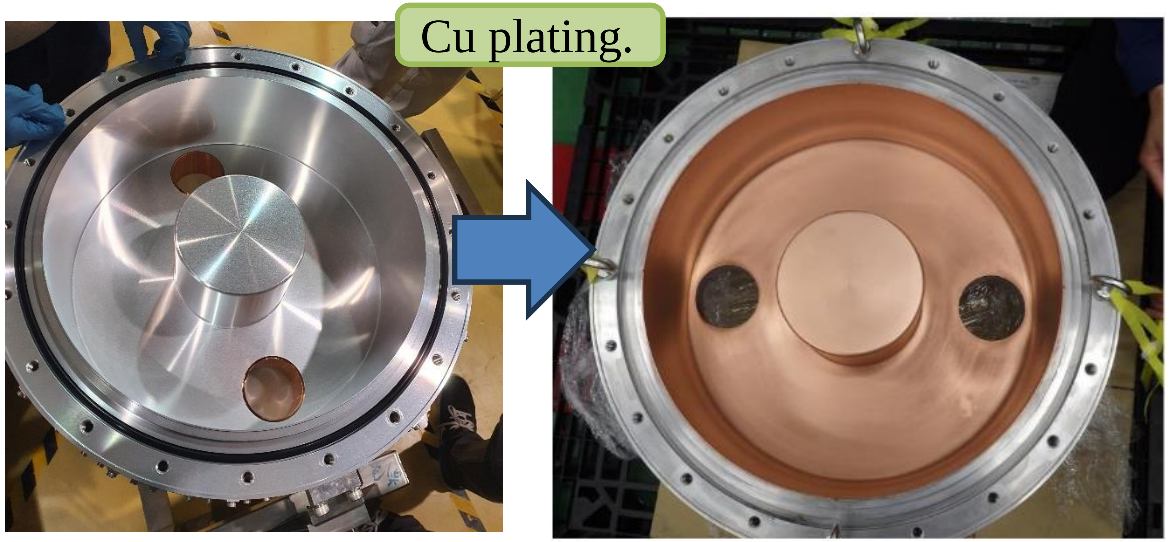
Reproducible and linear within band of >300kHz

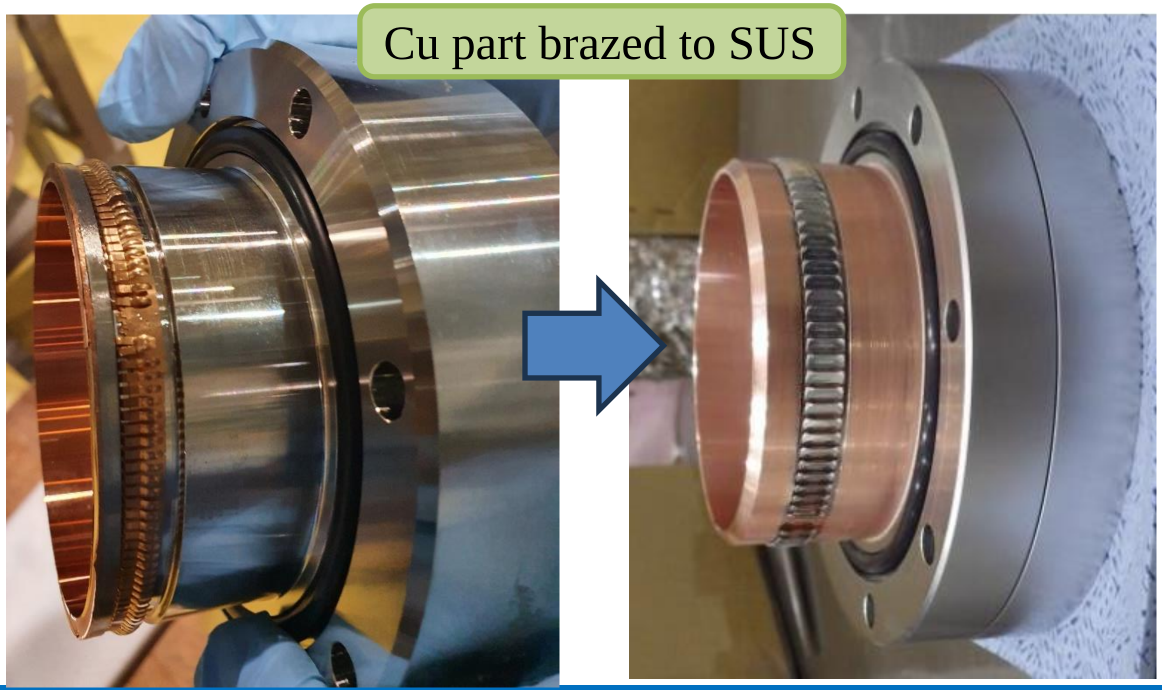




HPTB 2.0 - Cavity improvements III







Insertion Loss: 12% → 7%
Vacuum (after baking): ~8 $\cdot 10^{-7}$ mBar → ~2$\cdot 10^{-8}$ mBar

Conclusions

LIPAc RFQ O-ring couplers

- Affected by severe MP that results in damage to FKM O-rings.
- Not fit for LIPAc operations in CW

<u>Open questions:</u>

- Why only 5 units?
- Why the effect onsets and it is not recoverable?
- Can MP be mitigated by external B-fields?

<u>Recommendations (at this freq/ power):</u>

- Round shape near ceramic not recommended as it might stimulate MP
- O-rings not recommended, as unable to withstand MP heat

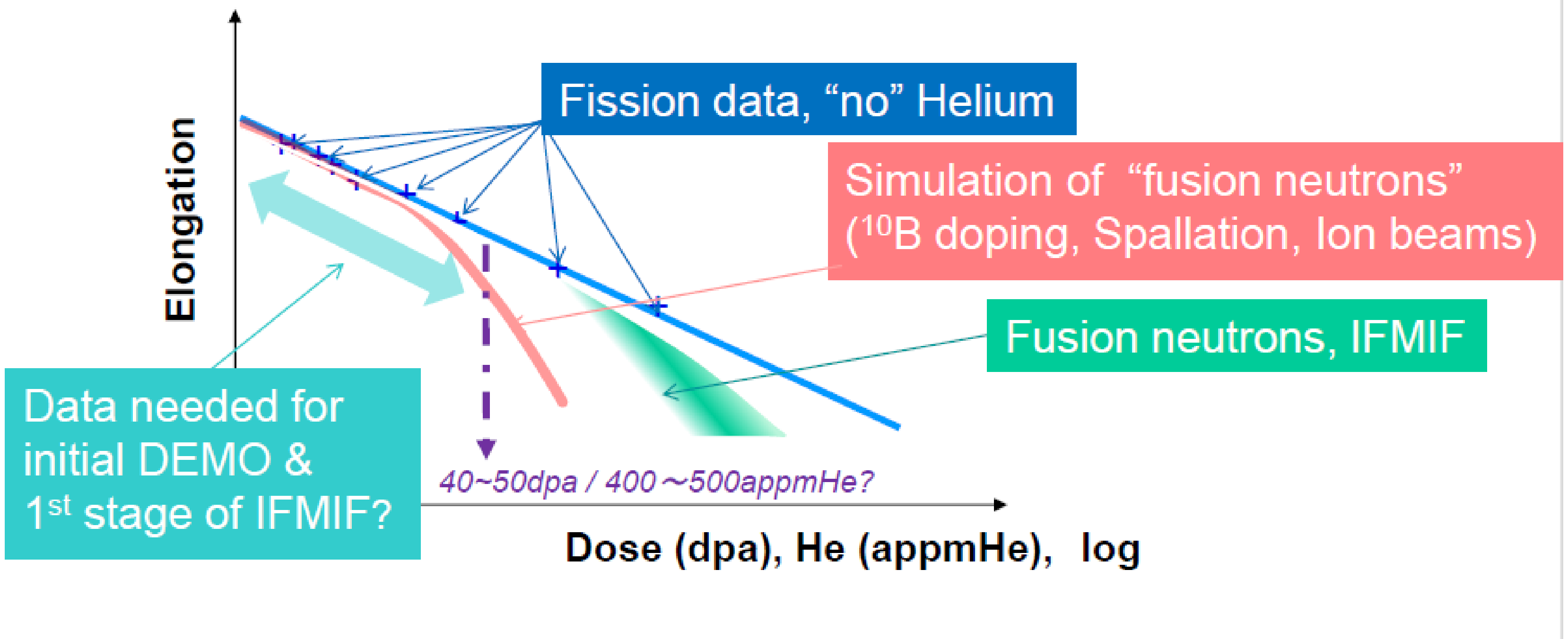
LIPAc RFQ Brazed couplers

- Poorly stored. Completion of validation tests planned in 2024.
- If successful will be installed in RFQ in 2025.

<u>Recommendations (at this freq/ power):</u>

- Invest in good quality test cavity.
- Test cavity with external push tuner to avoid edges/gaps (tbc).

Backup



- The atomistic details of the displacement damage process are similar for fission and fusion neutron irradiations; the main difference on evolution of radiation effects is associated with the higher He (and H) production levels for fusion compared to fission neutron irradiations.
- Since these He-related differences are rather modest up to 20 dpa, there is high scientific confidence in being able to predict the properties of fusion materials up to damage levels of at least 20 dpa.

Working Group of expetrts on Couplers

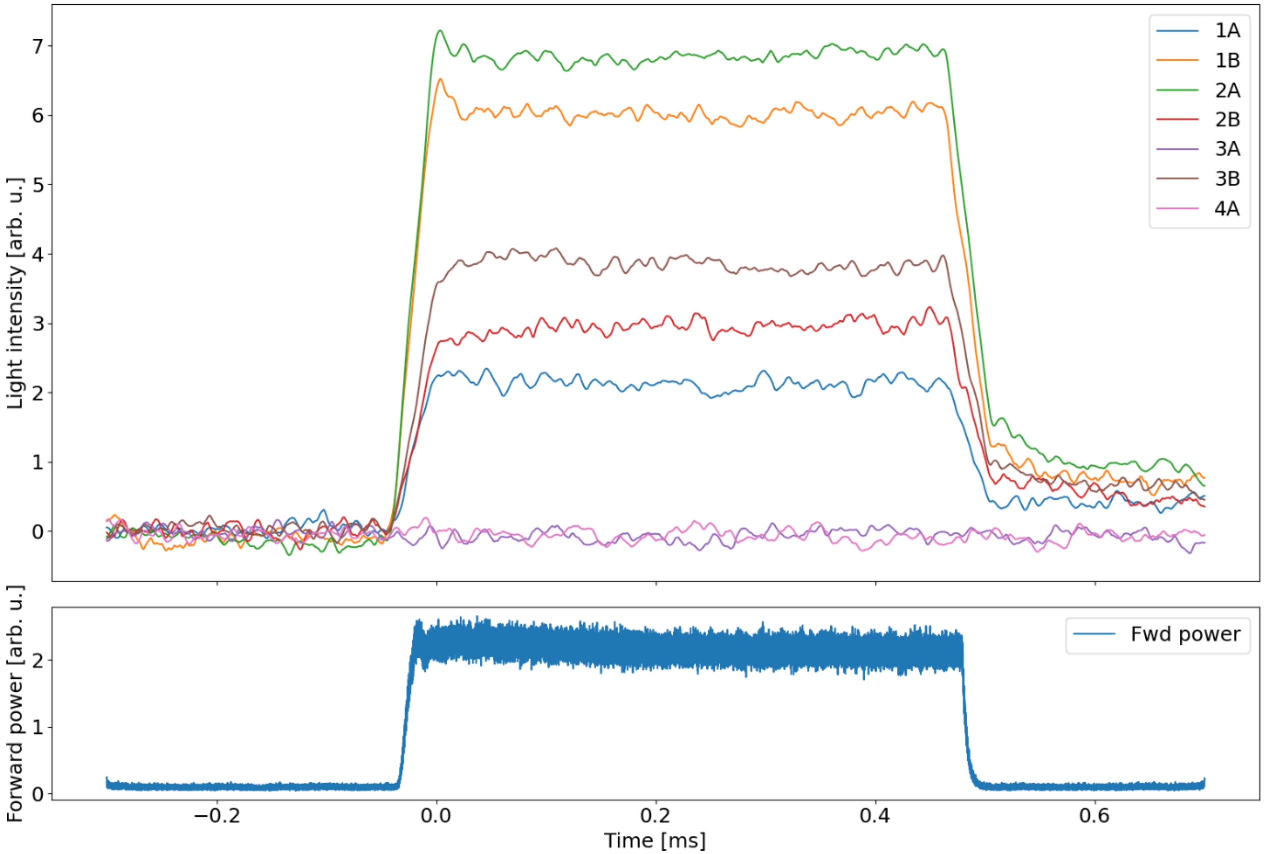
- **LIPAc o-ring couplers: it is commonly agreed that**
  - Unexpected MP is the root of the overheating observed in LIPAc O-ring couplers
  - O-ring couplers will not survive high DC during conditioning or beam operation unless MP root is understood and eliminated
  - Extra efforts should not be spent on refurbishing the O-ring couplers
- **LIPAc brazed couplers: it is commonly agreed that**
  - Poor visual aspect of brazed coupler does not necessarily translate into poor RF performances
  - By limited and non-invasive cleaning, the brazed couplers would be ready for tests (on the bridge cavity or on the RFQ)
- **On the further tests recommended concerning the brazed couplers the experts are divided**
  - **One group** thinks that additional test benching and conditioning is mandatory to verify if their bad aspect generates overheating, MP, high reflected power and/or vacuum tightness (with respect to the pressure and spectrum), and to reduce the risk of polluting the cavity.
  - **The second group** thinks that it is not useful to spend more time on the test benching and conditioning, which is time, money and man power consuming, without granting that the couplers will not face MP heat load once installed on the cavity. MP heat load is indeed much higher than RF losses and arises in conditions that are almost impossible to generate on the test benches: therefore test benching (slightly) reduces but doesn't eliminate the risk to pollute the cavity.
- **Conditioning and operational strategy**
  - The second group considers that the tests already performed on the present brazed couplers have demonstrated that all the windows are not faulty, then the main point is to know whether these couplers suffer MP and whether their thermo-mechanical design allows them to manage it. They suggest installing a couple of them ASAP on the RFQ cavity before taking any other decision that would imply long delays. A second point inherent to the present brazed couplers performances on the RFQ is the size of the loop, which could affect the vane voltage profile. It is commonly agreed that pick up signals should be recorded before and after any change so that they can be compared to quantify the change. Nevertheless beam transmission is the ultimate judge to evaluate whether any observed change is prohibitive or not.
  - It is commonly agreed that
    - ✓ considering the plan of LIPAc to stop beam operation starting from summer 2024 and in the year to come for the cryomodule installation, the project should make an effort to accommodate tests of the brazed couplers on the RFQ. Whatever the outcome of these tests, a step forward will be made in the commissioning of LIPAc.
    - ✓ modifications should be tested in small numbers (not all couplers at once) and in identical/similar operating conditions to be able to quantify improvements. Several hints are indicated to improve the design of new brazed couplers, but operation results from the present brazed couplers are of major importance and priority.

Working Group of expetrts on Couplers

- Brazed couplers show several promising design choices and appropriate cooling.
- Some brazed couplers show poor surface conditions after test in standing wave and poor storage. It is difficult to explain the cause without further details of tests performed.
- **Visually poor surfaces might not be an indicator of poor RF performances. All brazed couplers are likely usable with ethanol cleaning only and eventually vacuum leak test.**
- Surface conditions after standing wave tests suggests they might suffer of MP (the region near window excluded). Cooling seems adequate to withstand eventual extra heat from MP.
- WG is divided whether is best **to install at least 2 brazed couplers in RFQ as soon as possible, or to consider HPTB mandatory before tests into the RFQ.** It is nevertheless unanimously recognized that the HPTB tests shall not delay the final tests in the RFQ. Considering the information received by the LIPAc project, it looks there is enough time for the HPTB, but they should be done w/o delay.
- Test existing brazed couplers after cleaning (only perform minimal cleaning of brazed couplers with ethanol): test in travelling wave up to 200kW in CW compatibly with the time schedule. First pair should be the one previously tested on HPTB. Second pair should be among worst apparent conditions (#4 and #5)
- Further improvements of the brazed couplers are likely not necessary and not recommended before completion of HPTB. If additional units are to be procured, the following could be considered Vs. cost and delivery times:
    - ✓ Smooth edge of vacuum port with a radius and plate its entire pipe;
    - ✓ Manufacture outer conductor in bulk copper only if structural integrity is ensured;
    - ✓ Add grooves on inner and outer conductor against MP;
    - ✓ Better balance of inlet/return cooling channel sizes inside the inner conductor

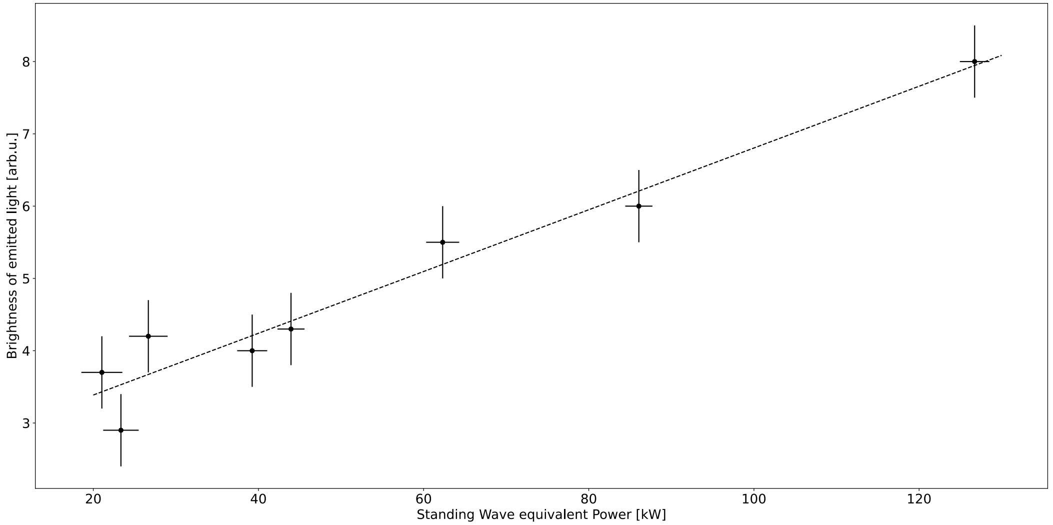
Light signals in conditioning and beam operation

Light emission detected in all 5 warm couplers during conditioning and beam operation. Present in a wide band of power (70-140kW) and frequency (±50kHz).



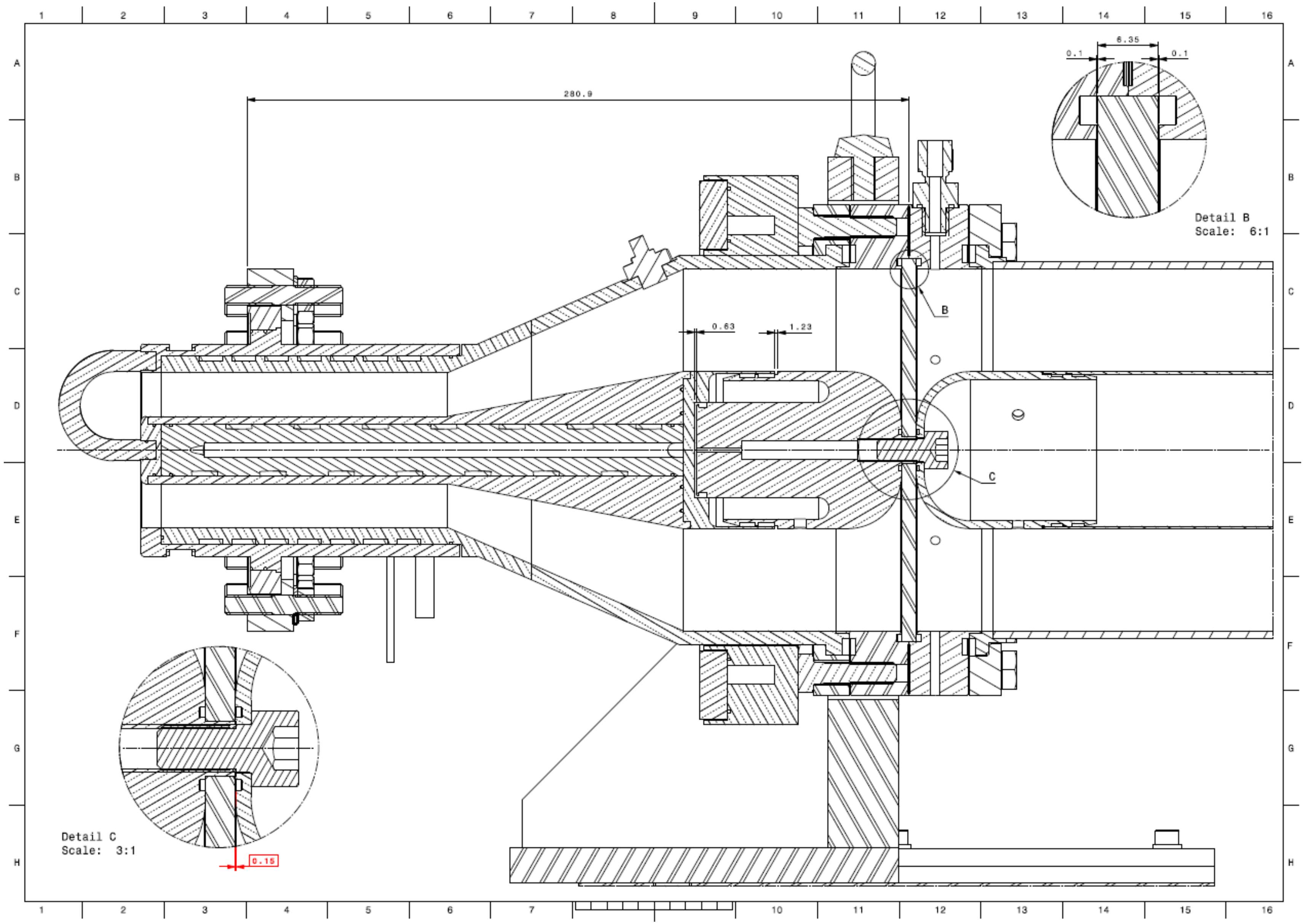
Light brightness measured for different combination of Fwd and Rev (using frequency mismatch). Light brightness seems to scale linearly with quantity:

$$P_{SW}(x) = P_{fwd} + P_{rev} + 2 \cdot \sqrt{P_{fwd} \cdot P_{rev}} \cdot \cos\left(\theta + \frac{2\pi x}{\lambda}\right)$$

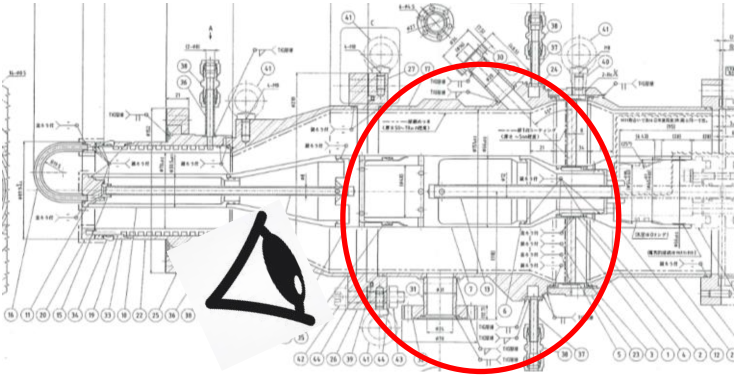


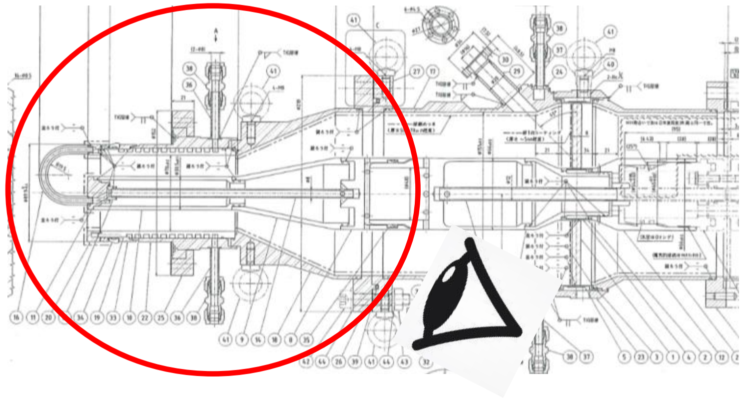
Swapped 1B(hot) and 4B(cold) coupler and tuned both to ideal beta coupling. The same coupler (in different position) are hot/cold.

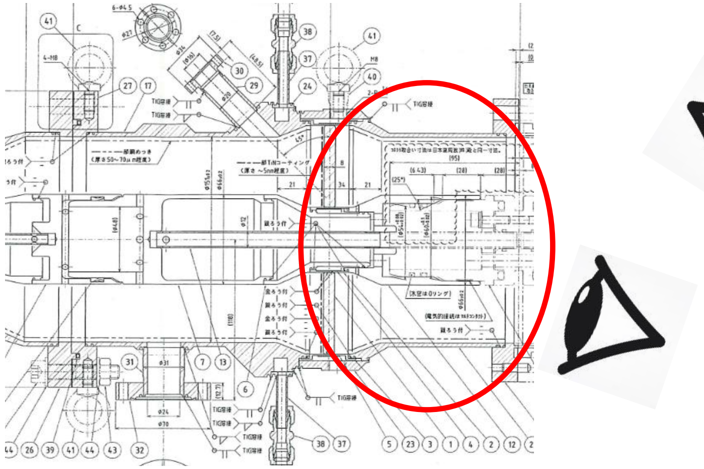
O-ring coupler with new anchor

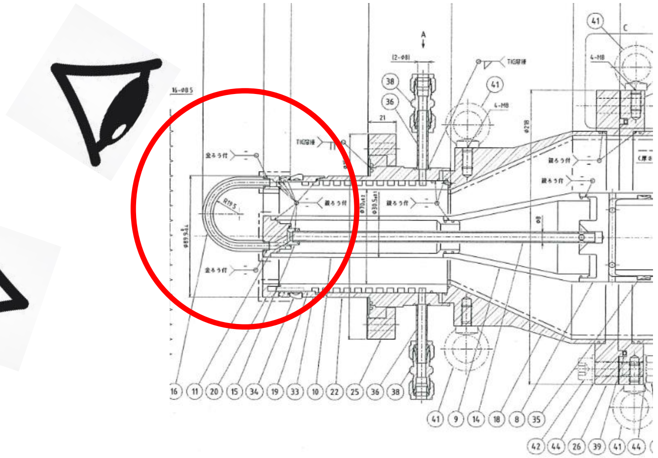


Slide format





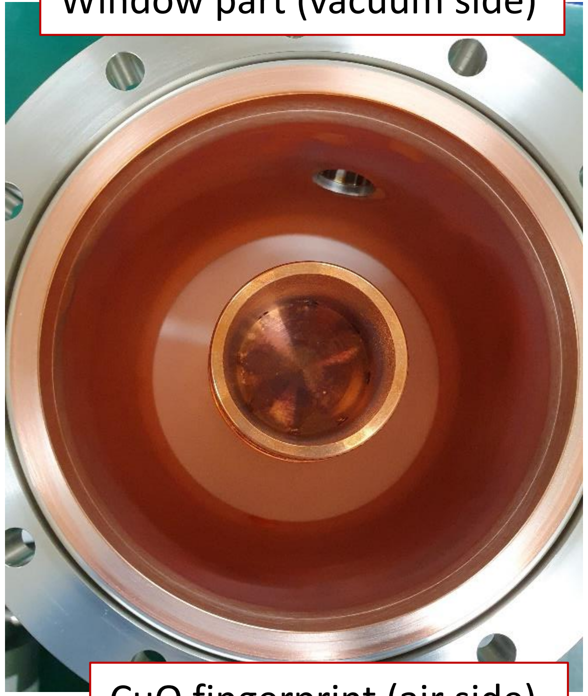




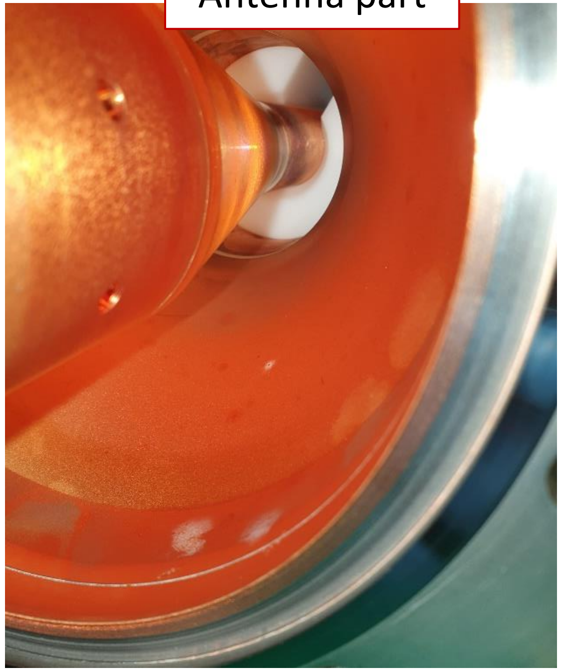
Details/ Points of interest

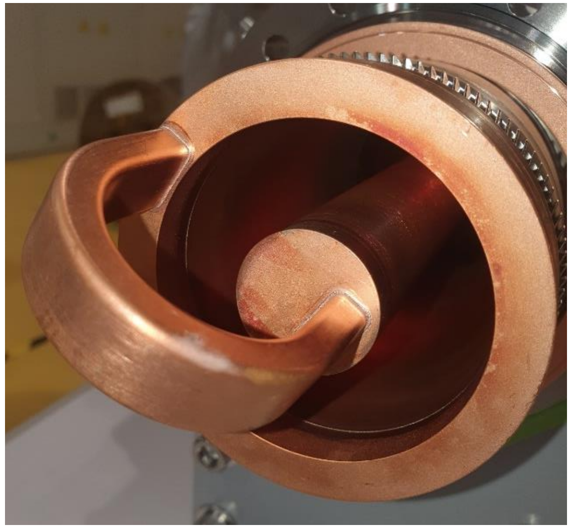
#1

Window part (vacuum side)



Antenna part

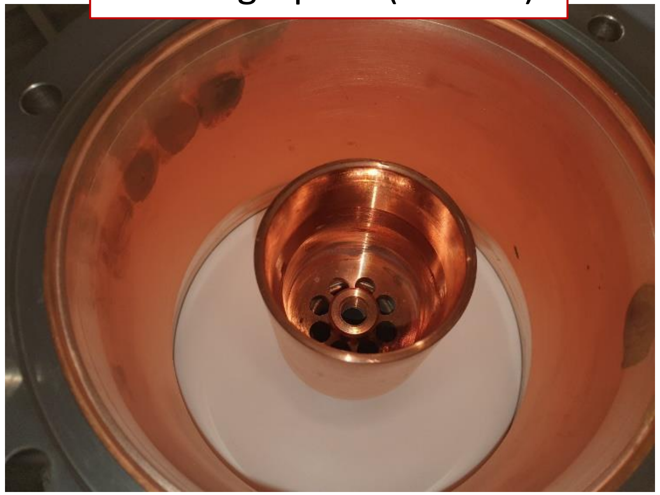




Oxidation marks
around brazing point of ceramic

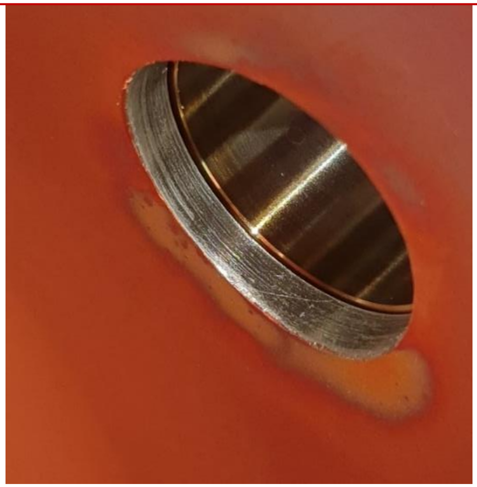
Significant oxidation marks
On straight near antenna

CuO fingerprint (air side)



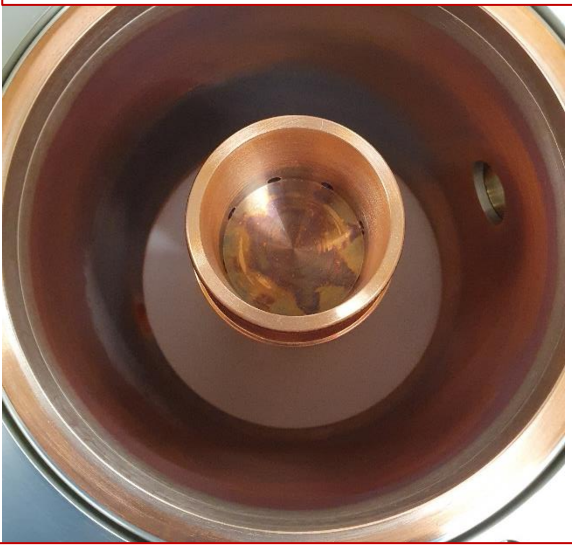
Gray/white dotted ceramic
(uneven TiN? Sparks?)

Severe loss of Cu near vacuum port. Edges are sharp…

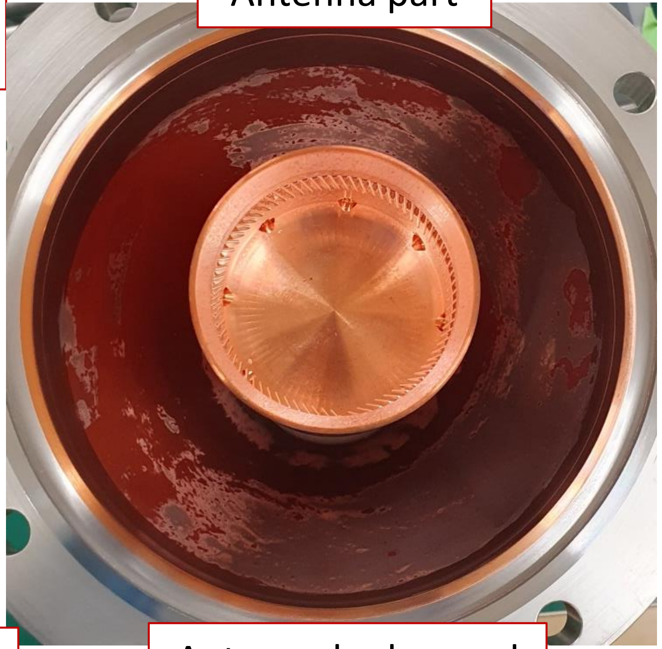


#2

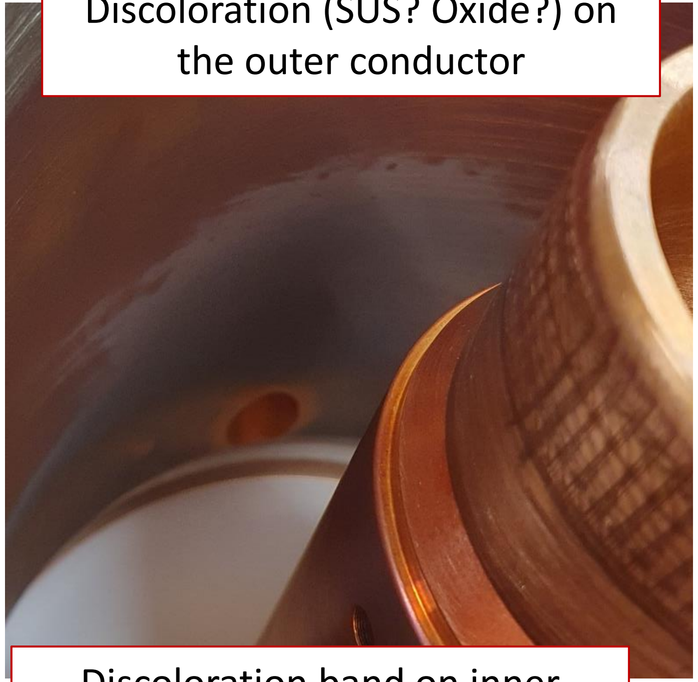
Window part (vacuum side)
Outer cond. surface a bit rough



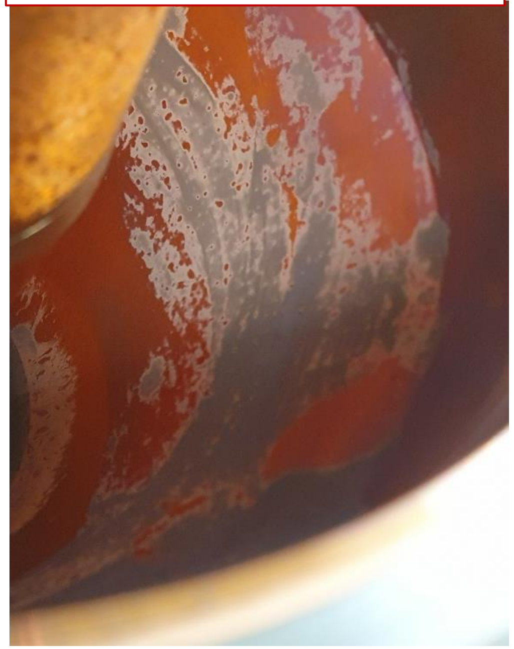
Antenna part



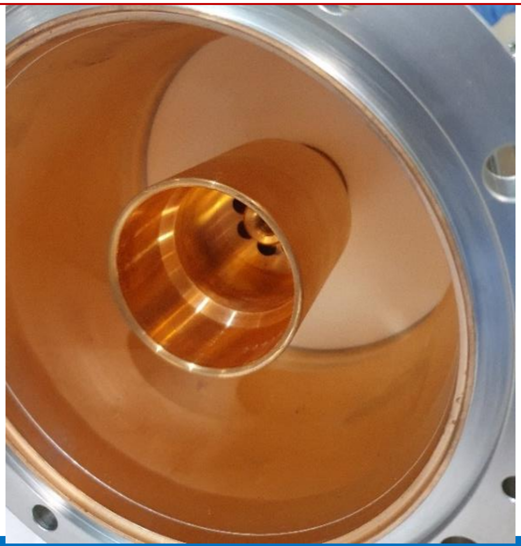
Discoloration (SUS? Oxide?) on the outer conductor



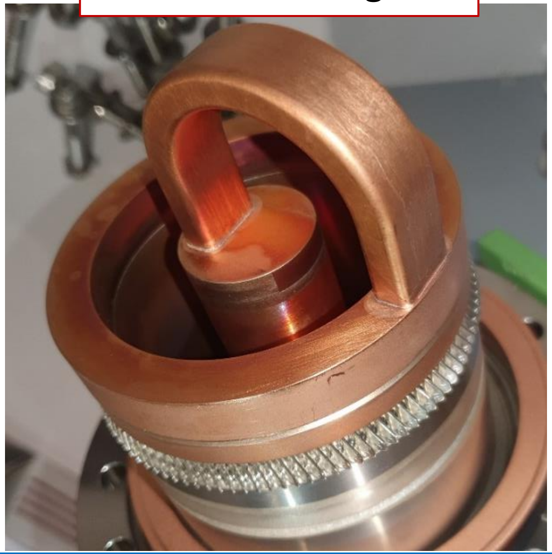
Arcs?SUS?CuO?



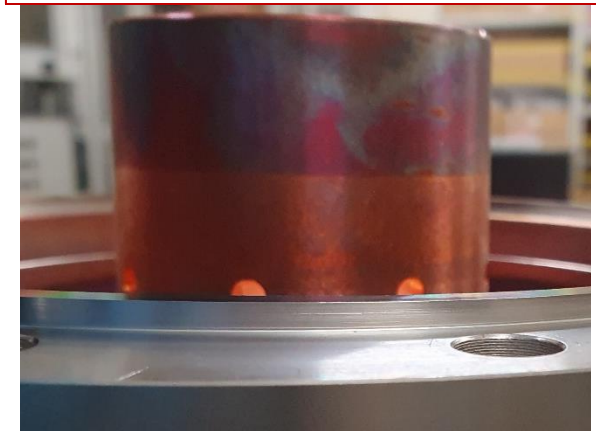
Minor CuO fingerprint on air side

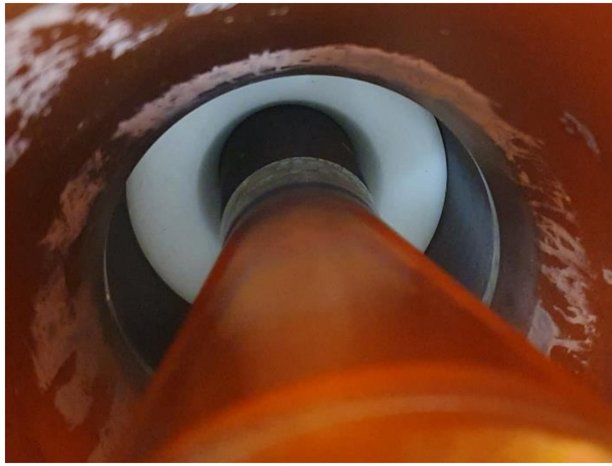


Antenna looks good

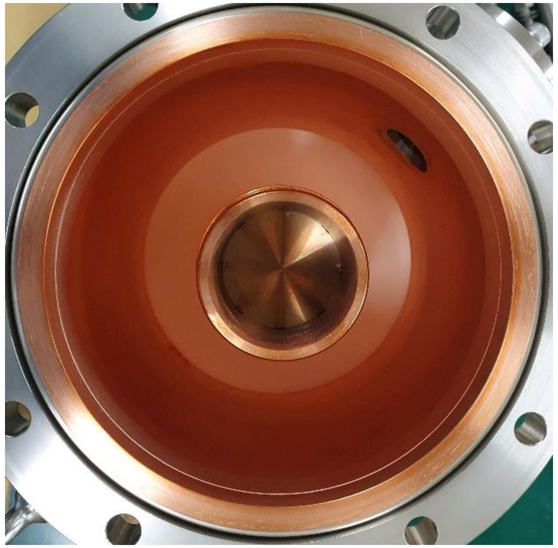


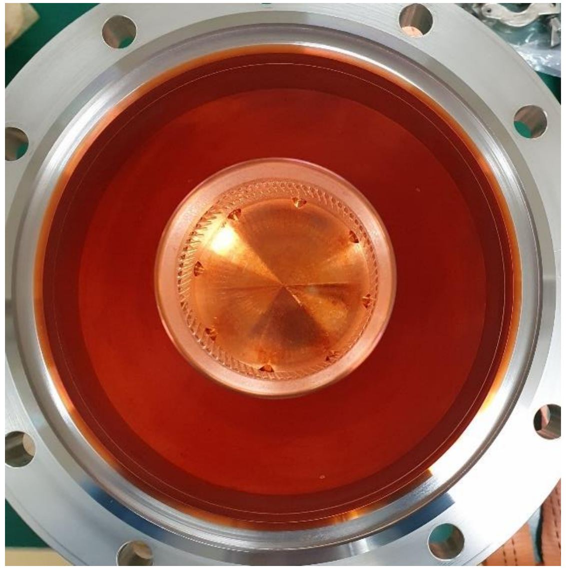
Discoloration band on inner conductor



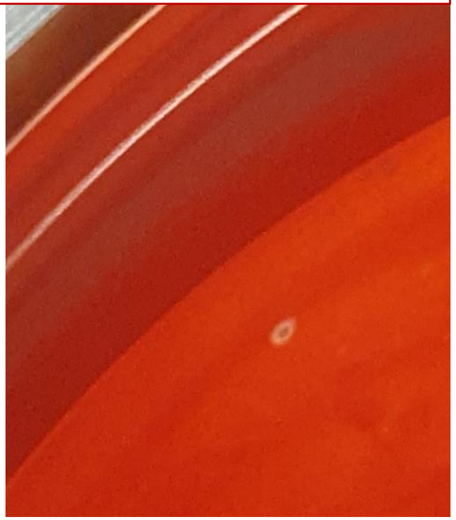


#3

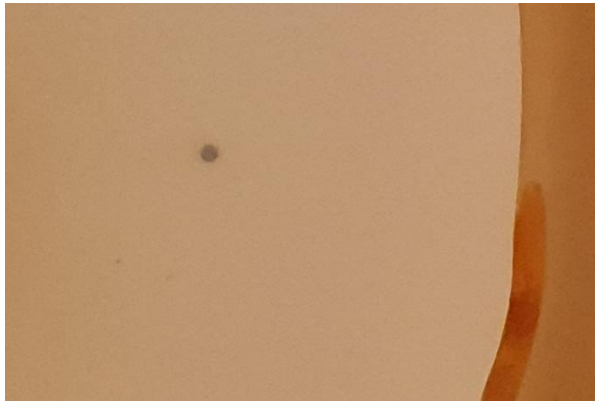




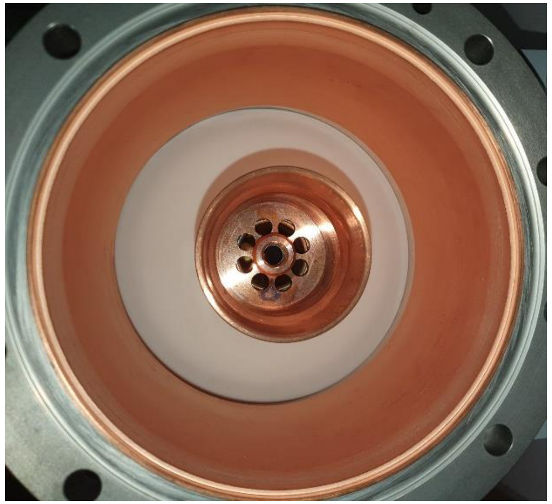
Minor arc – Outer cond.

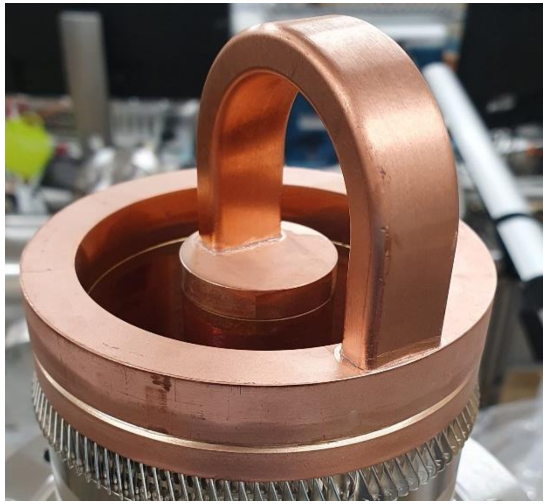


Minor arc – Ceramic

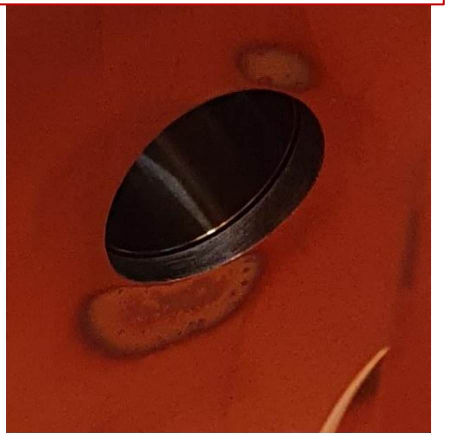


Looks rather good everywhere!



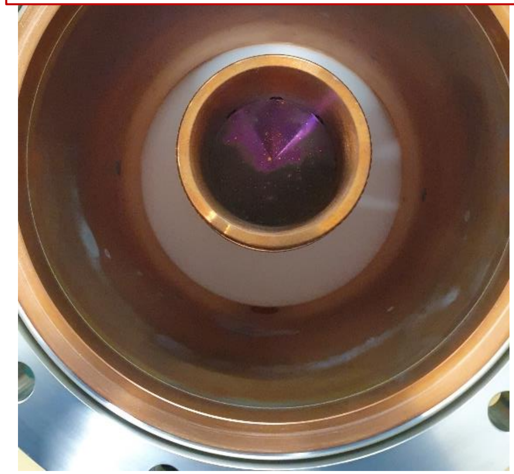


Marks near vacuum orifice

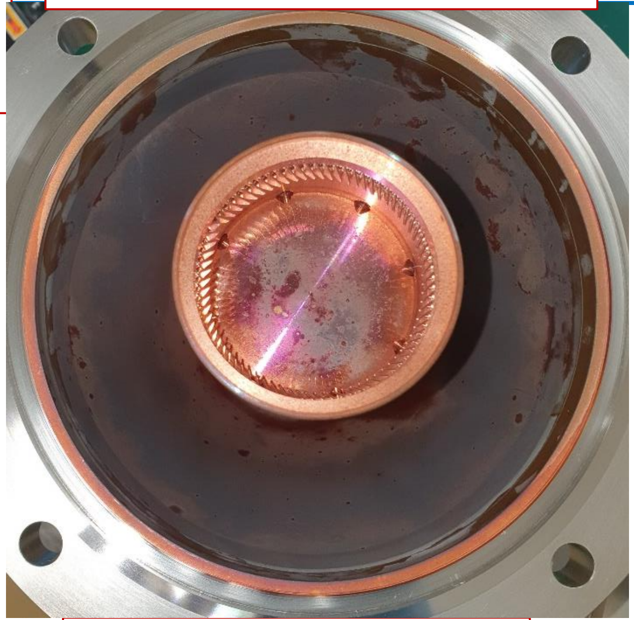


#4

Marks on outer cond. – heat inside inner cond.
Power test without cooling?



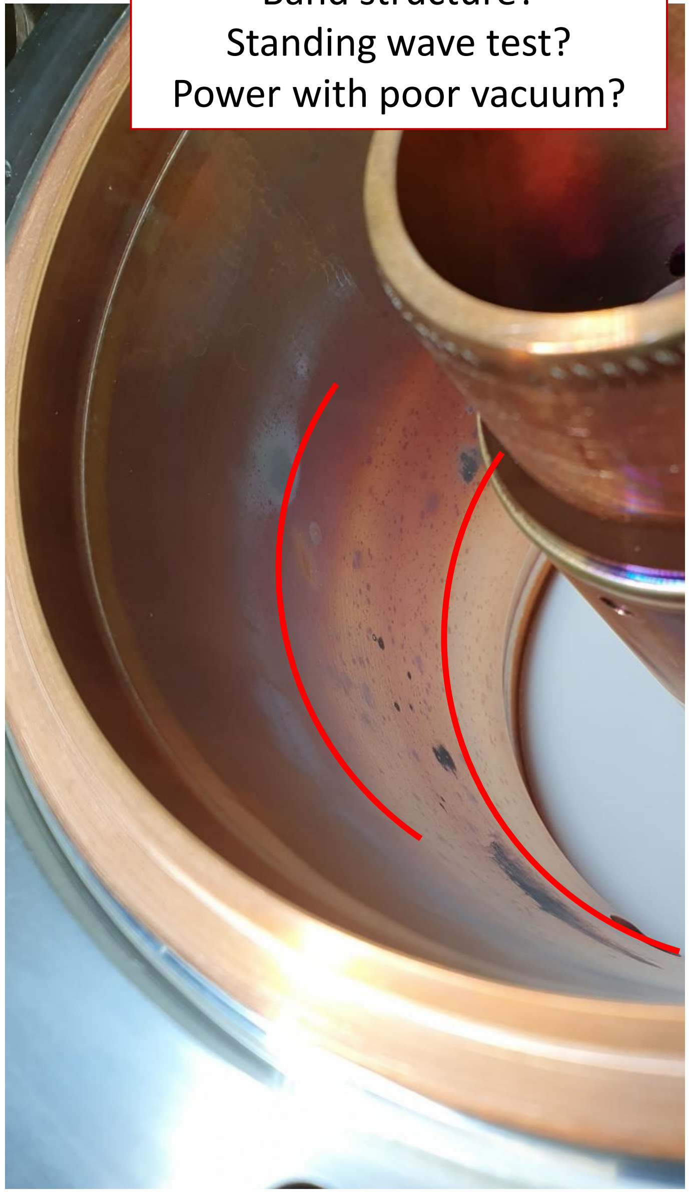
???

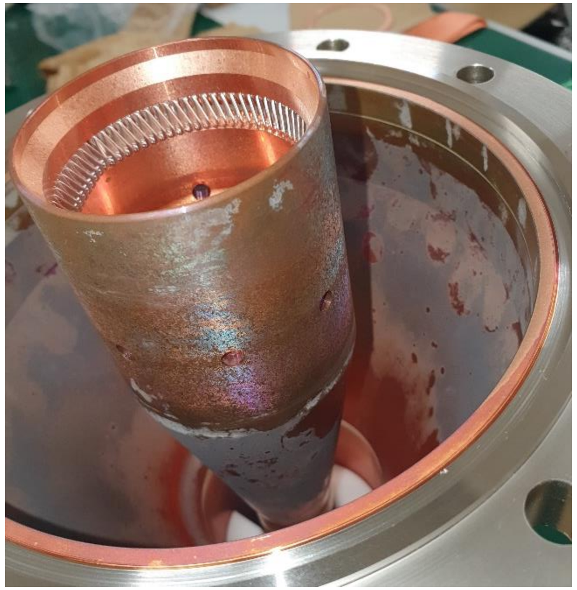


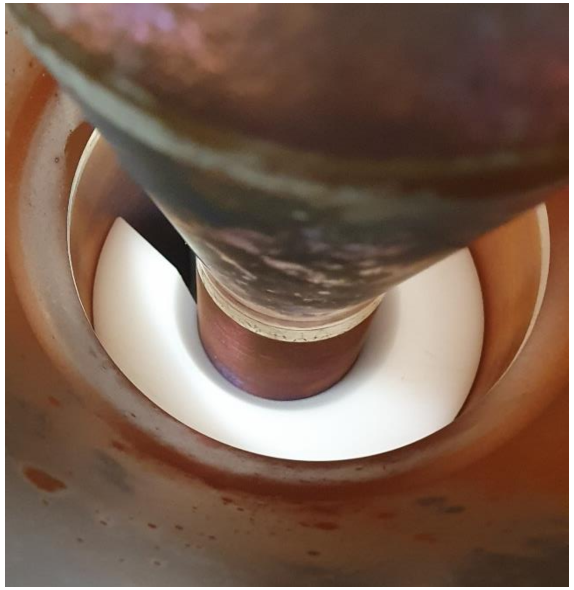
Ceramic (air) looks good
minor arcs on outer cond.

Antenna looks good

Band structure?
Standing wave test?
Power with poor vacuum?



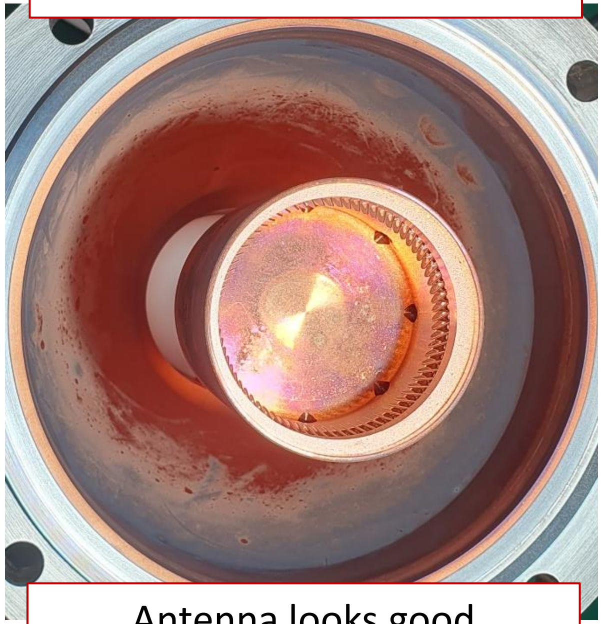




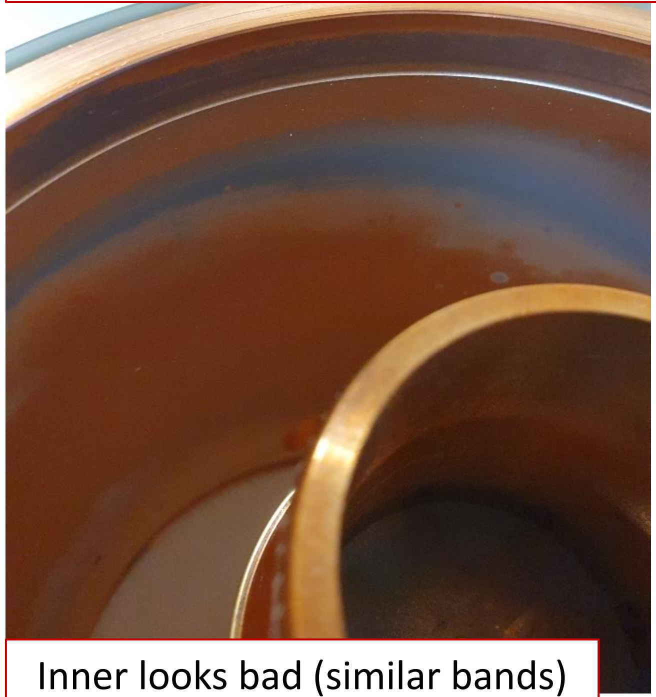
#5

Marks on outer cond. – heat inside inner cond.

???



Bands – same and different places



Vacuum port…

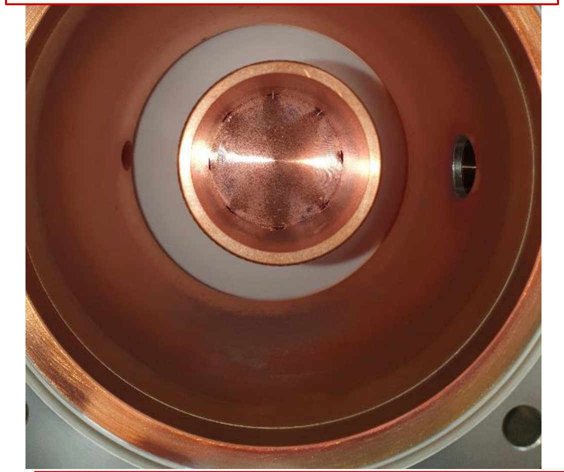
A bit of CuO (air)

Antenna looks good

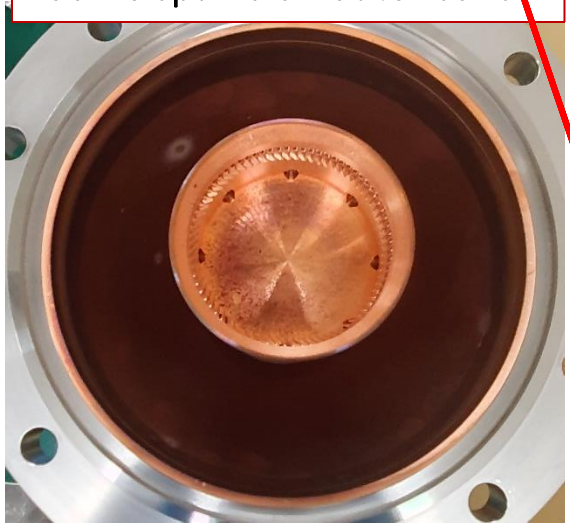
Inner looks bad (similar bands)

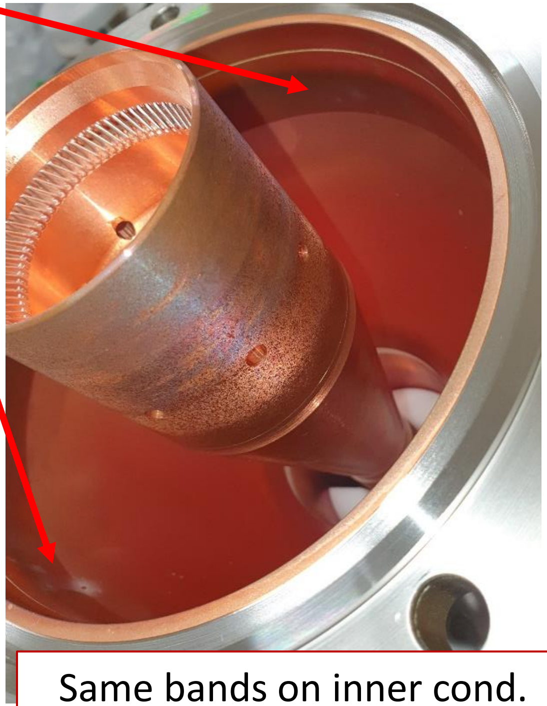
#6

Some sparks / minor discoloration band on outer cond.



Black band close to flange
Some sparks on outer cond.

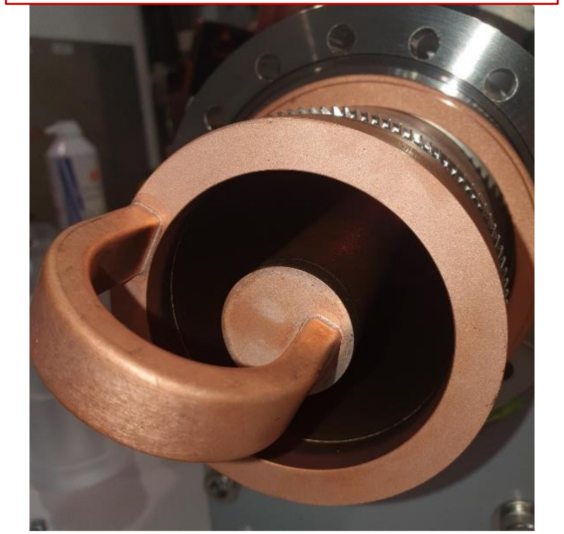




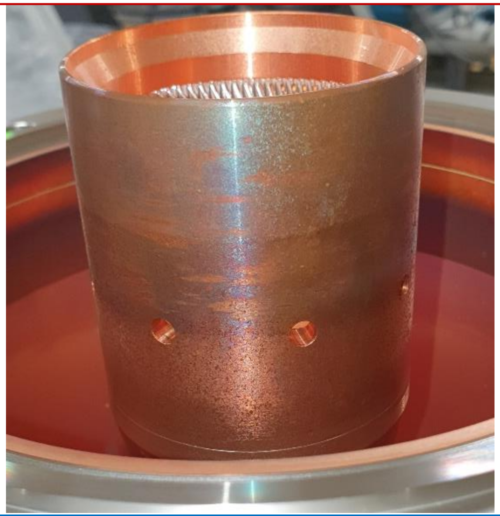
Arcs/MP on outer cond.
Isolated island

A bit of CuO (cooling line)

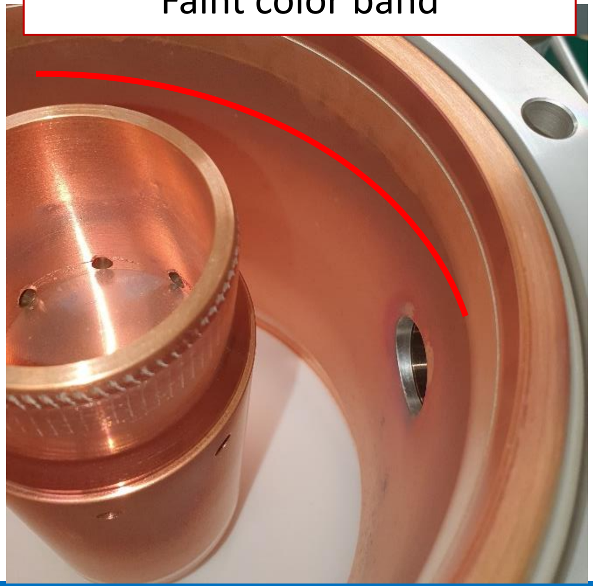
Antenna looks good



Same bands on inner cond.



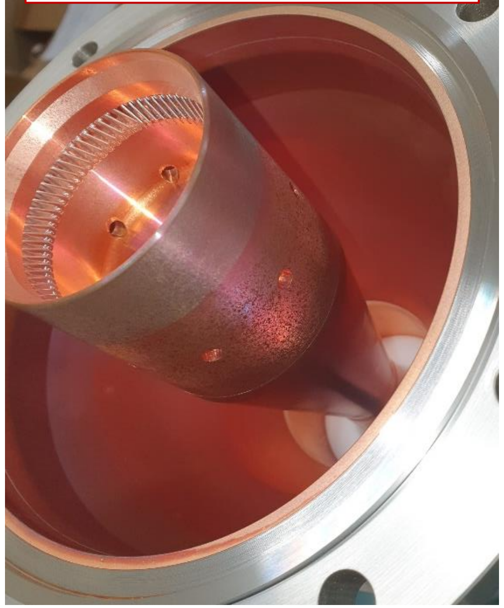
Faint color band



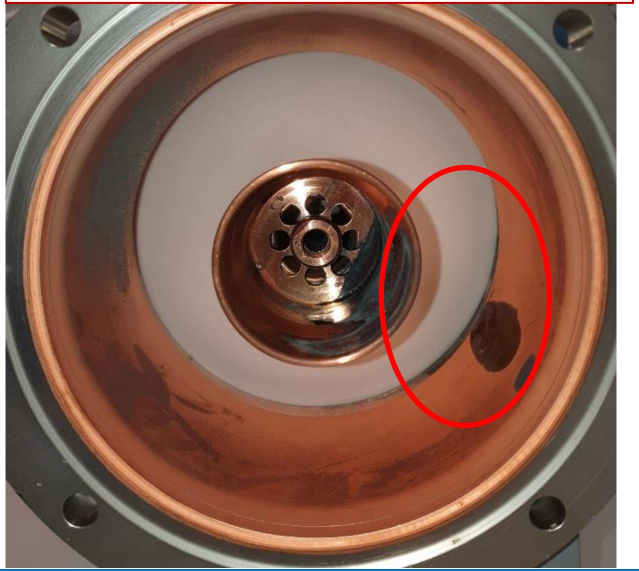
#7

Looks OK
Heat inside inner?

Outer looks OK

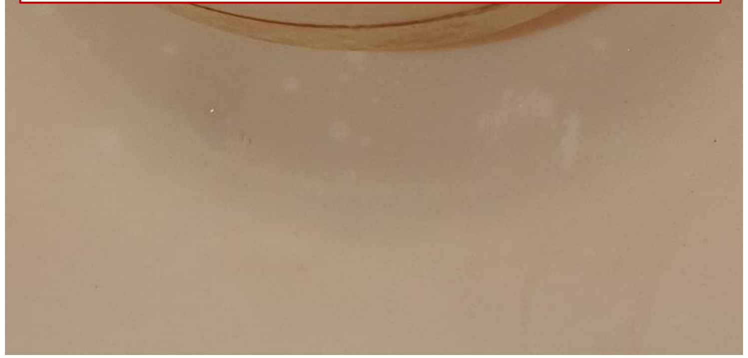


Major oxide (also near brazing)



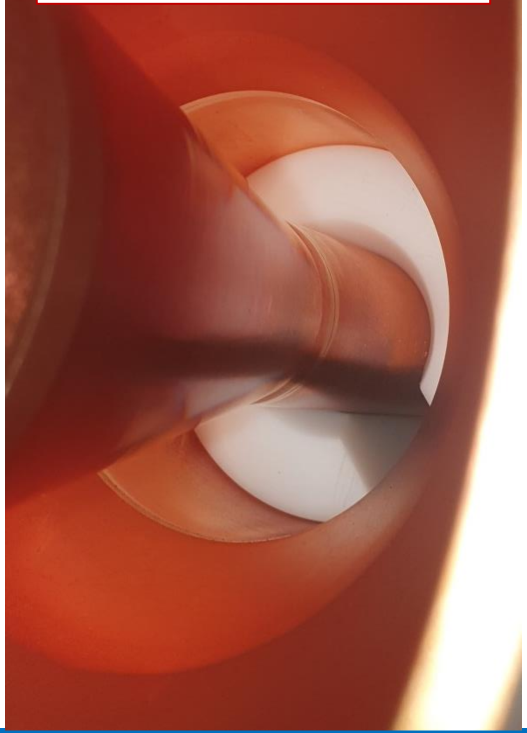
Antenna looks good

White spots on ceramic - vacuum

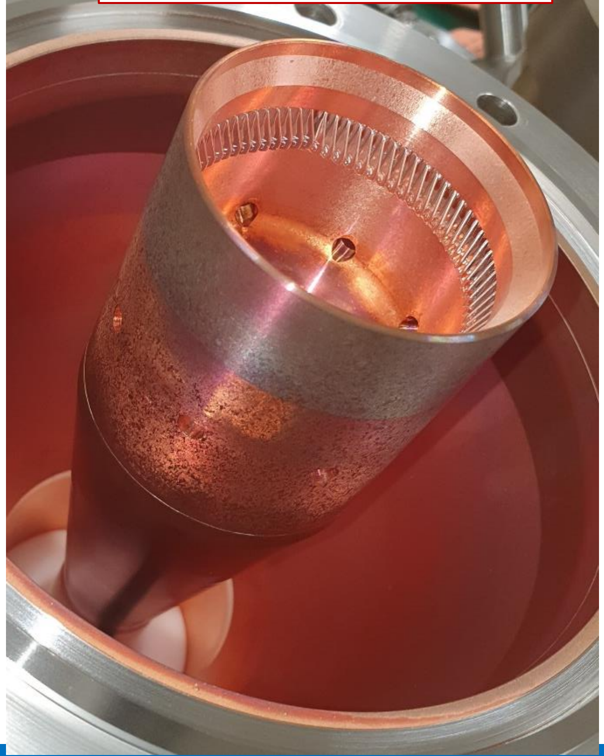


Black spot on ceramic - vacuum

Looks OK

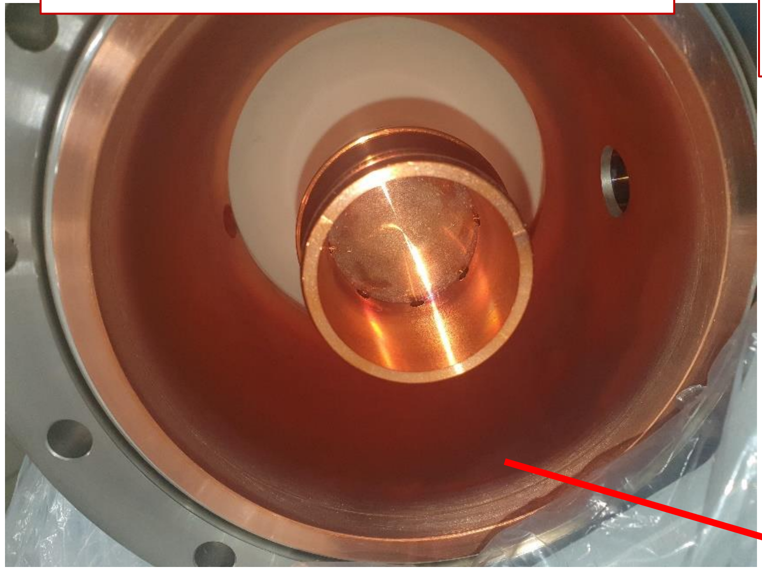


Mark bands on inner

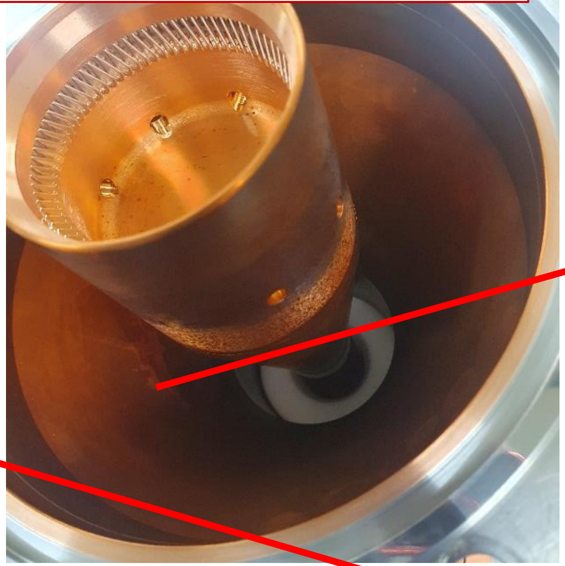


#8

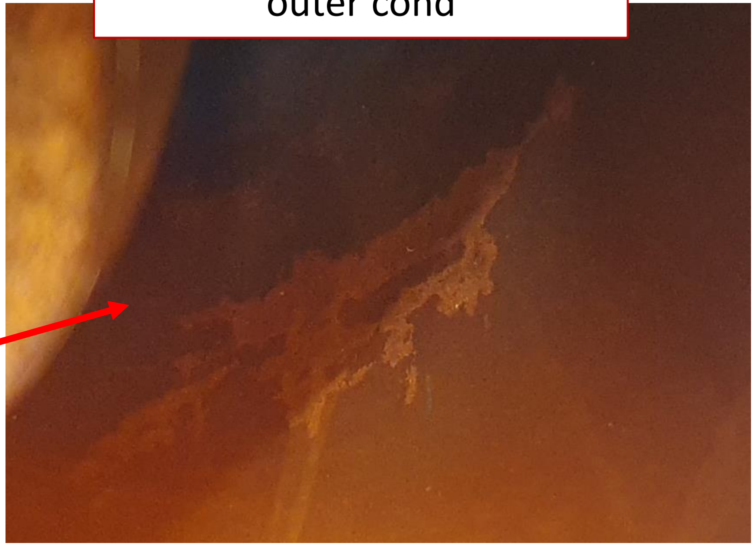
A band of arcs/MP on outer cond



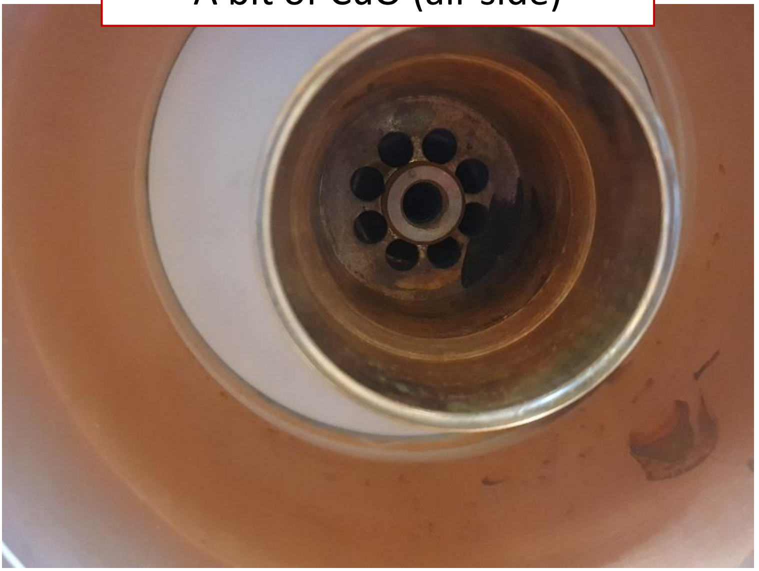
An island of sparks/MP on outer cond



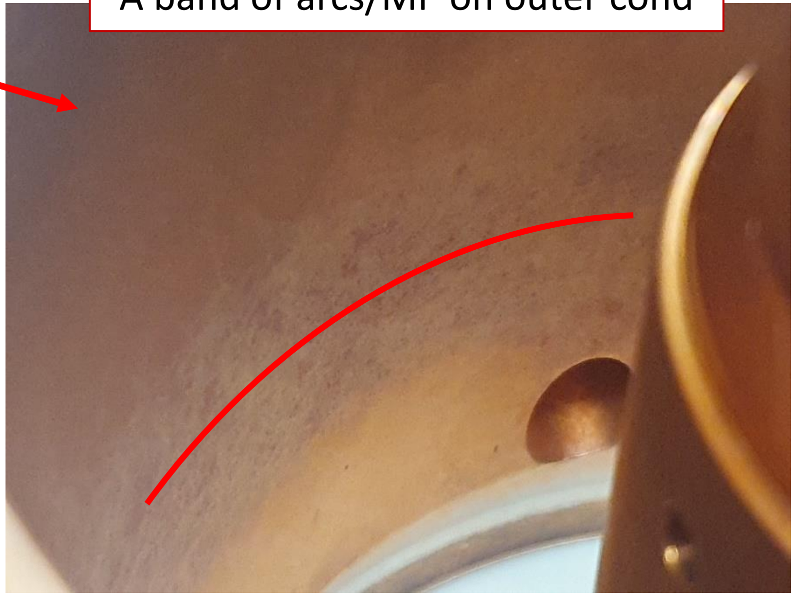
An island of sparks/MP on outer cond



A bit of CuO (air side)

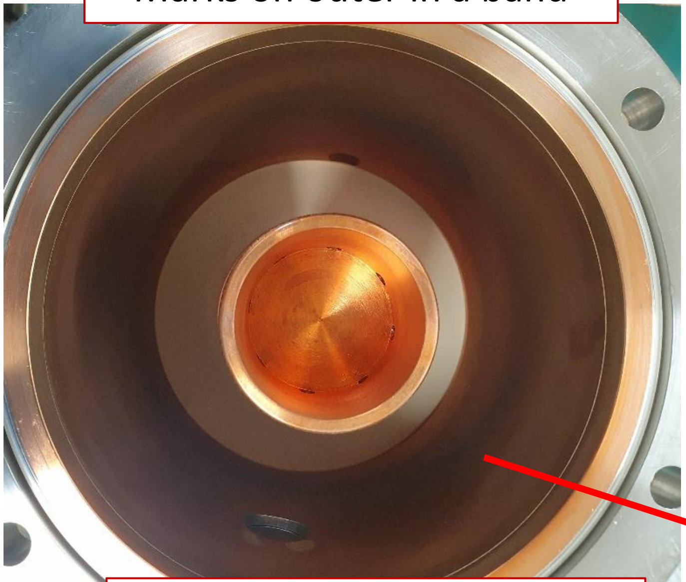


A band of arcs/MP on outer cond



#9

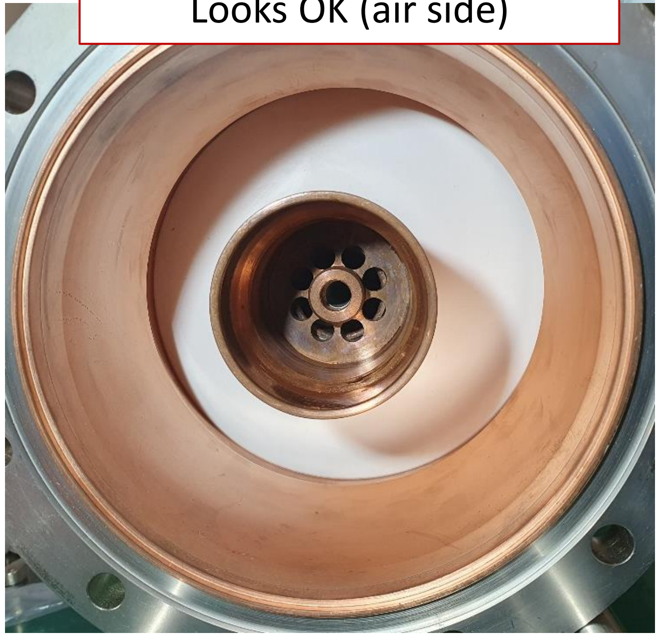
Marks on outer in a band



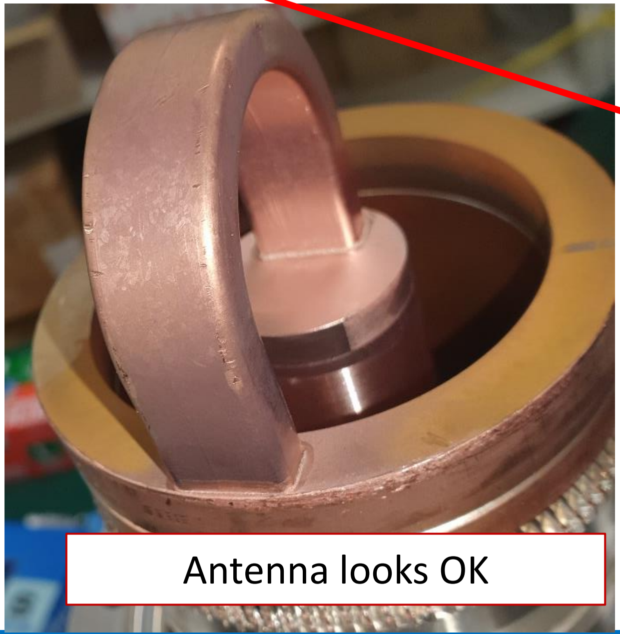
Some marks on outer in a band

Some marks on outer in a band

Looks OK (air side)



Antenna looks OK



Marks on outer in a band

Marks on vacuum port