Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Legnaro

INFN - RF and multipacting analysis of the high power couplers of IFMIF/EVEDA RFQ and ESS DTLs.

INFN LNL, QST, F4E, ESS
World-Wide Fundamental Power Coupler meeting #6

FRANCESCO GRESPAN-LUCA BELLAN

Contents

IFMIF/EVEDA RFQ power couplers

- The IFMIF/EVEDA RFQ couplers and performance degradation
- RF measurements and observations
- MP simulations

ESS DTL

- Description and performance degradation
- Offline RF tests
- Process of refurbishment
- Multipacting simulation
- New geometry proposal

R&D activities at LNL

- Brazing
- Coating qualification

IFMIF RFQ windows

IFMIF/EVEDA RFQ general context

IFMIF EVEDA RFQ couplers: 200 kW CW each

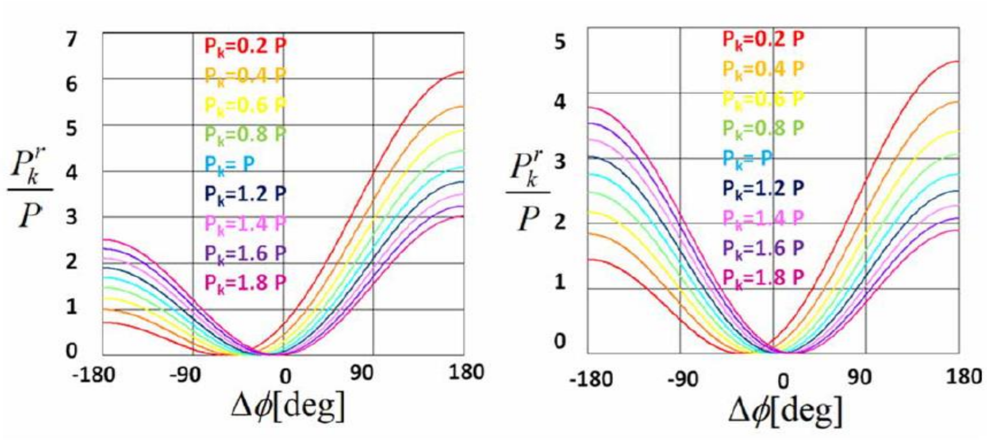
8 power couplers feeding a single cavity→ RFQ is a resonant combiner. The 8 RF chains are by LLRF with a logic 1 master+ 7 slaves.

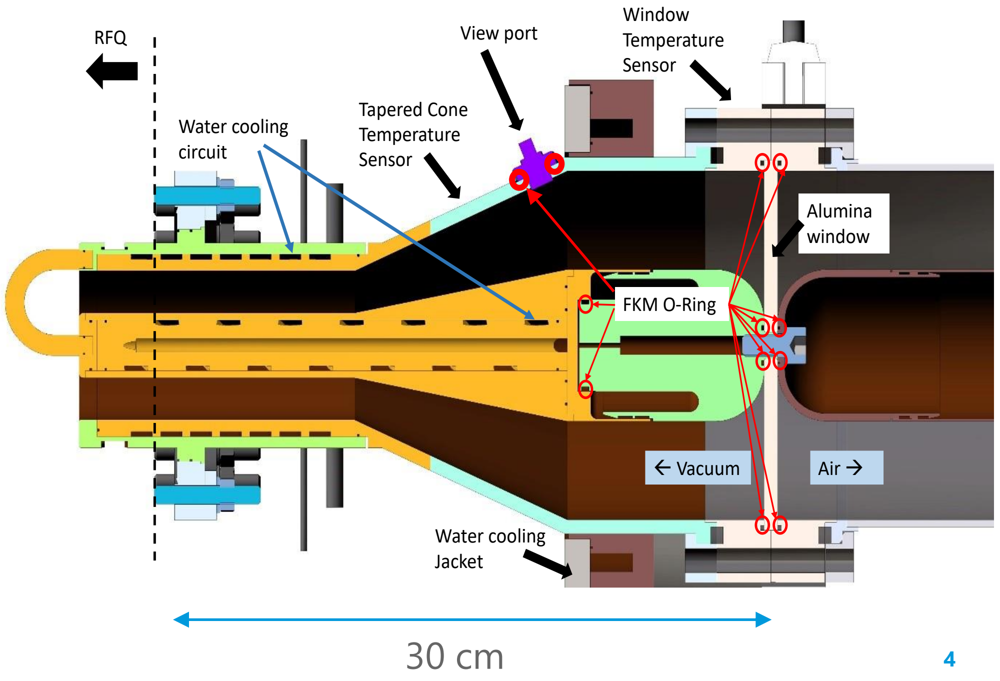
There is a complex range of reverse power possibilities, function of amplitude and phase unbalance between RF chains. There are circumstances in which one can have $\frac{P_k^{rev}}{P_k^{fwd}} > 1$. For instance, if one is feed 180° out of phase with respect to the others, one can have $\frac{P_k^{rev}}{P_k^{fwd}} > 4$.

3 o-ring seals on each coupler.

Designed and tested at full power @ LNL in 2015. For the history of issues and performance degradation **see presentations of A. de Franco e F. Cismondi.**

$$\frac{\Delta V_k^r}{V} = \begin{cases} \frac{4\beta}{1+N\beta}\sin\left(\frac{\Delta\phi}{2}\right) & if\ j \neq k \\ 2\left(1-\frac{2\beta}{1+N\beta}\right)\sin\left(\frac{\Delta\phi}{2}\right) & if\ j = k \end{cases}$$





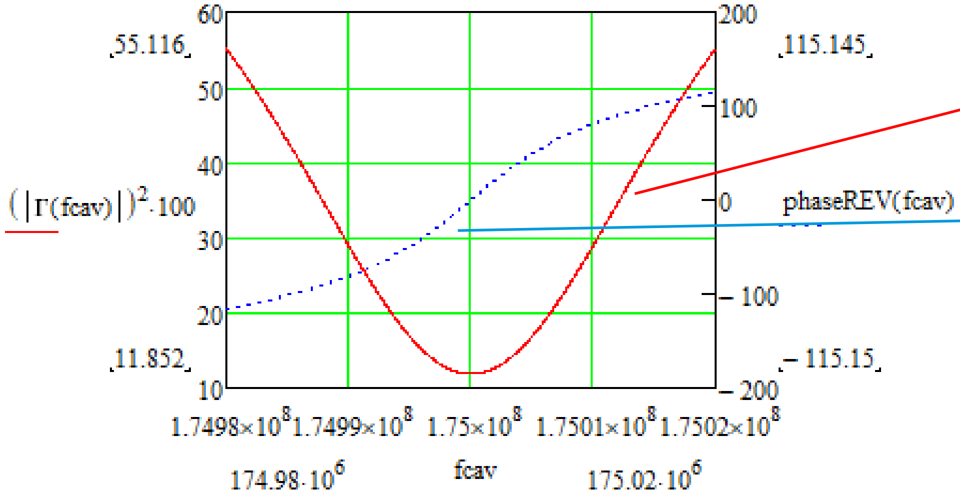
RF measurements and observations

Rev. Power amplitude and phase as a function of the cavity detuning

$$\delta(fcav) := \frac{(fRF - fcav)\cdot(fRF + fcav)}{fRF \cdot fcav}$$

$$\Gamma(fcav) := \frac{\beta - 1 - j\cdot Q0\cdot\delta(fcav)}{\beta + 1 + j\cdot Q0\cdot\delta(fcav)}$$

$$phaseREV(fcav) := \arg(\Gamma(fcav))\cdot\frac{180}{\pi}$$



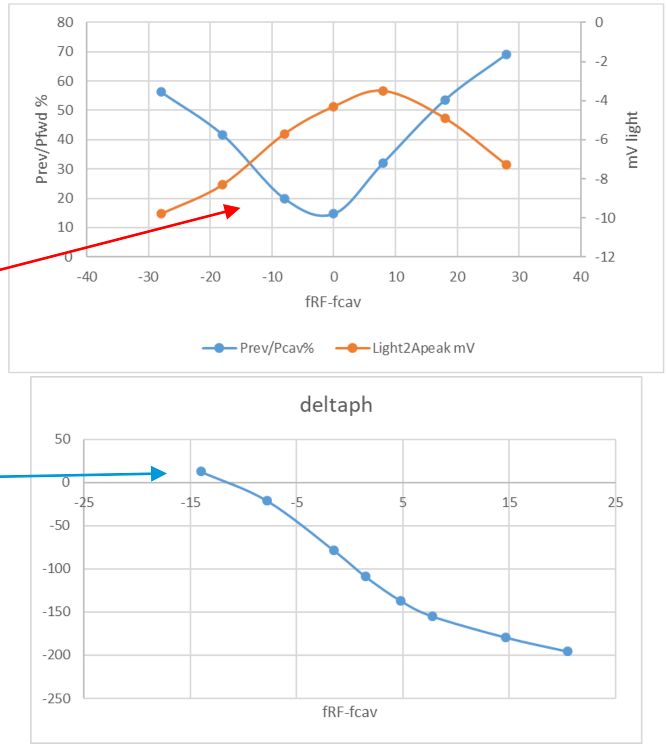
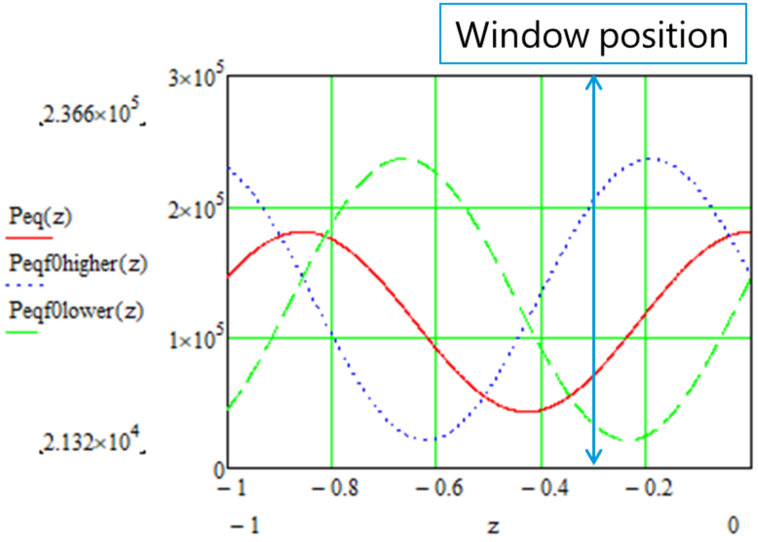


Figure 1:ligth, rev power and revphase as function of detuning. Fcav moved, fRF fixed at 175 MHz

Prev% and VrevPhase are consistent with calculation

RF measurements and observations

VSWR and light as function of the cavity detuning



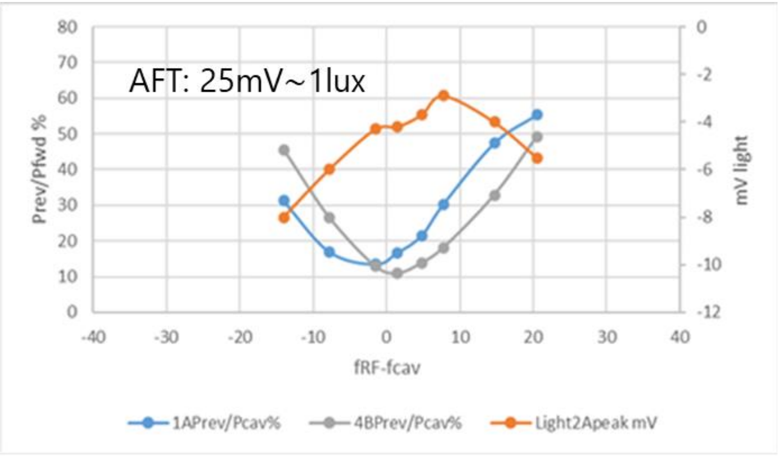
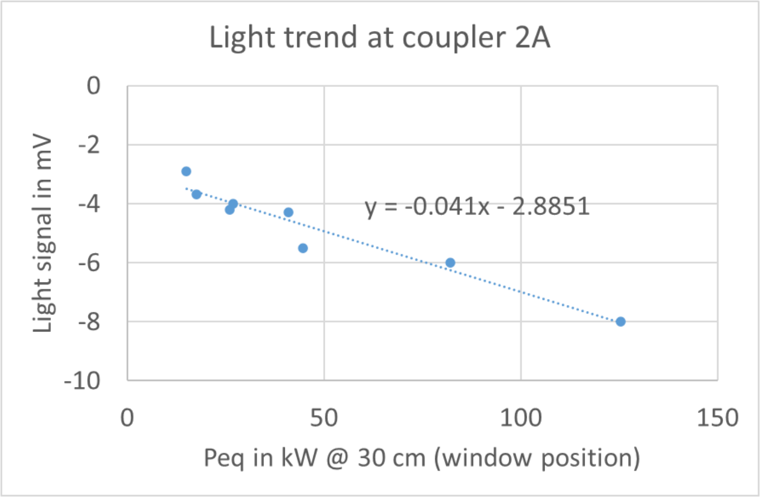


Figure 1:Rev power and light as function of detuning. fRF moved.



In this example, $P_{eq}(z) = \frac{V_{eq}^2(z)}{2Z_0} = \frac{(V_{FWD}(z)+V_{REV}(z))^2}{2Z_0}$ is shown for detuning +/- 10kHz.

Consistent with the asymmetry of the light signal: if fcav > fRF, Veq is higher, and this generates higher light.

The light signal data are quite linear with the equivalent power.

Since coupler temperatures increase even at low DC% proportionally to the light signal, we conclude a significant plasma is established on that volume by Multipacting (residual gas ionized by electrons emits light)

MP simulation with CST

General considerations

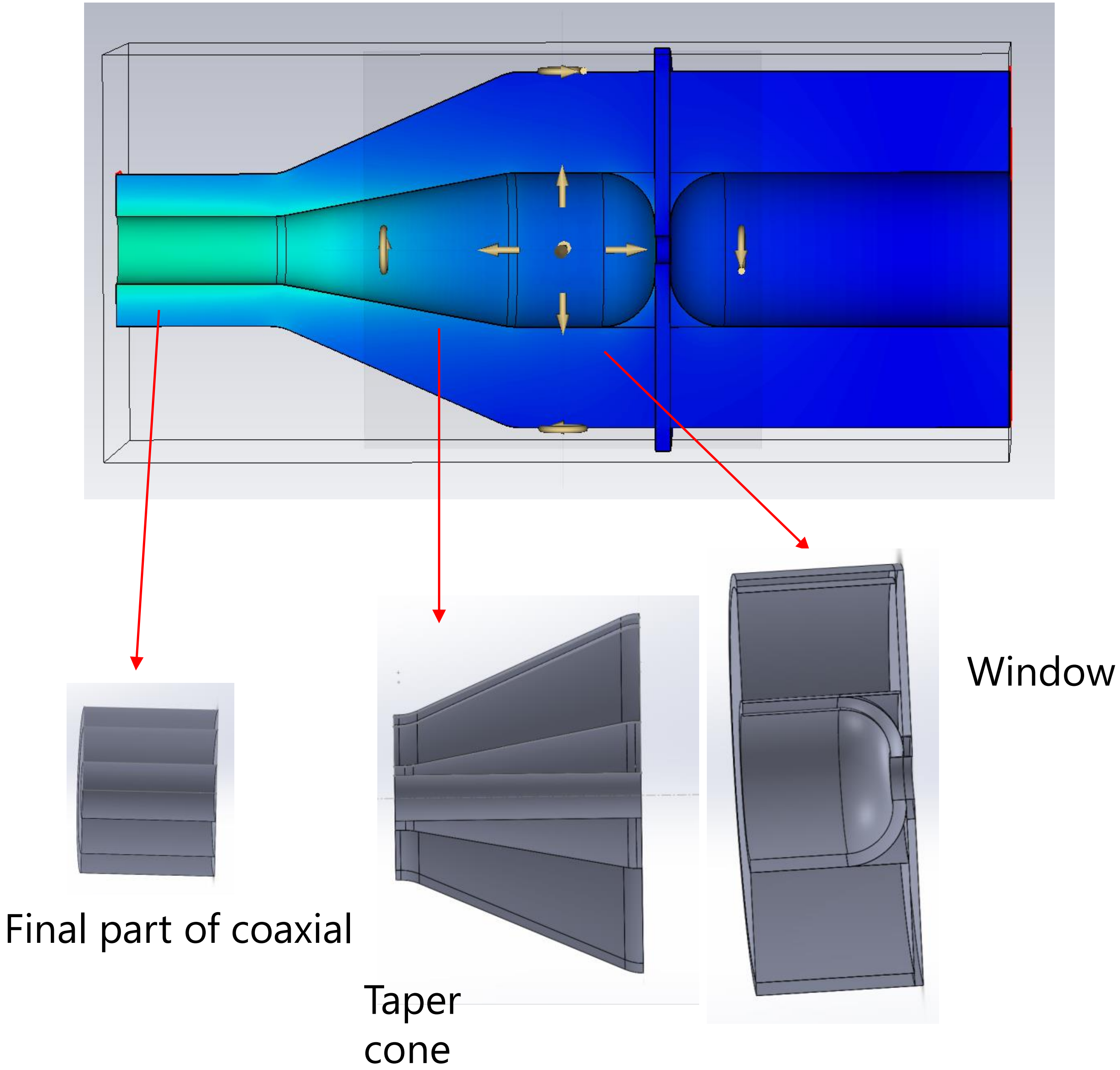
- A large section of the IFMIF windows was implemented into the CST simulation.
- We fill the region of interest with 10000 starting electrons, with energies ranging from 0.0001 eV to 10 eV, to test the possible criticalities of the geometry
- We attempted to compare the coupler's original results and damages.
- Thermal simulations were performed, based on MP simulations.
- For SEY data of copper and alumina our base references are (also for ESS):

  - [0] S. V. Langellotti et al., “CST Particle Studio Simulations of Coaxial Multipactor and Comparison with Experiments”, IEEEE Transaction on Plasma Science, Vol. 48, No. 6 June 2020.
  - [1] I. Bojko et al., “The Influence of Air Exposures and Thermal Treatments on th eSecondary Electron Yield of Copper”, LHC Project Report 376, Journal for Vacuum Science and Technology A, May/June, 2000
  - [2] J. Lokiewicz et al., “Characteristics of TiN Anti-Multipactor Layuers reached by Titaniunm Vaport Deposition on Alumina Coupler Windows”, Proceeding of the 11^{th} Workshop on RF Superconductivity, Lubeck/Travemunder, Germany, THP31, 697-699
  - [3] G. Toby et al. «Multipacting analysis of warm linac RF vacuum Windows», proc. of IPAC2021, Campinas, SP,m Brazil.

Simulation strategy

CST code for RF and MP

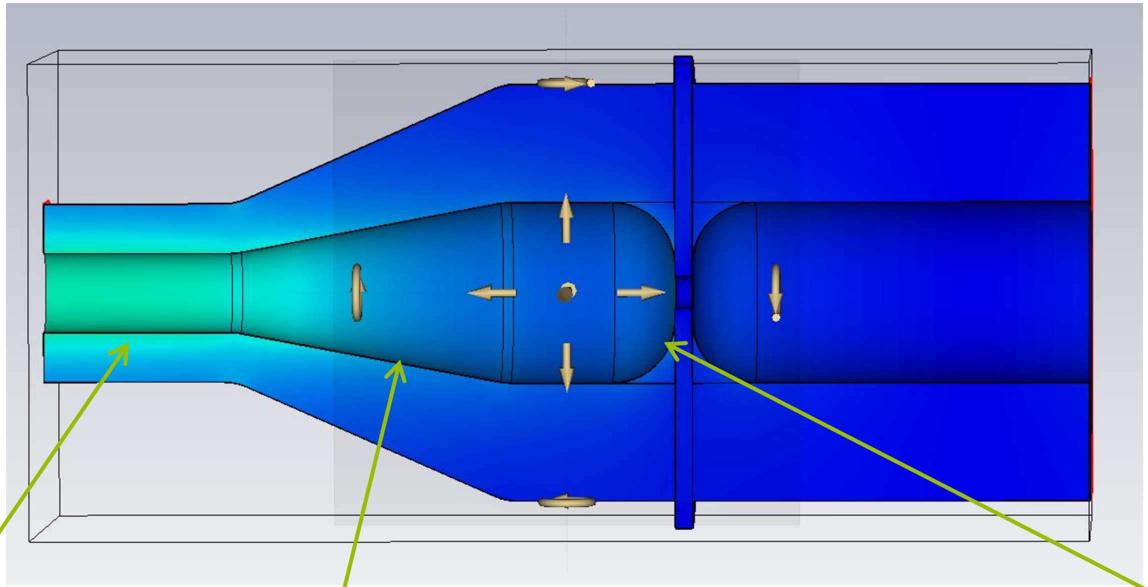
- Solve RF field on the full geometry
- For MP the coupler is divided in the 3 main sections:
    - Window
    - Taper cone
    - Final part
- First check if multipacting is established without Space Charge (SC) or "Saturation" on every macro section of the RF coupler line
- Then introduce SC saturation to evaluate number of eletrons, their energy and their contribution to power coupler heating.

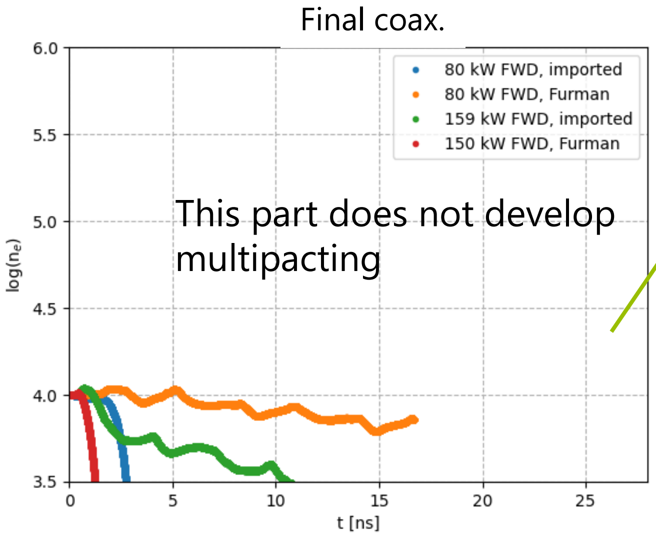


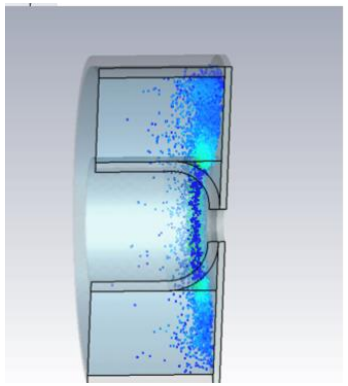
Sensitivity to MP

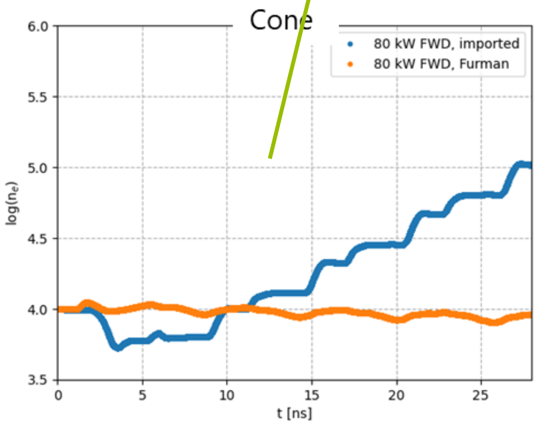
Final part of the coax do not develop MP

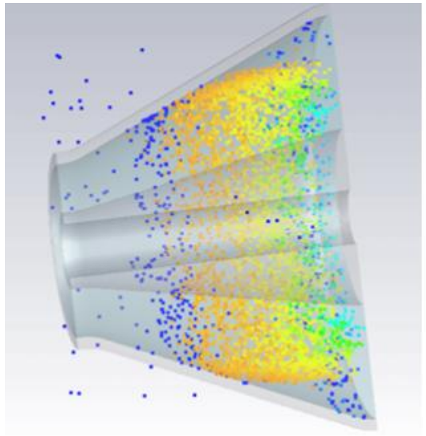
SEY of copper imported from reference paper compared with Furman curve in CST.

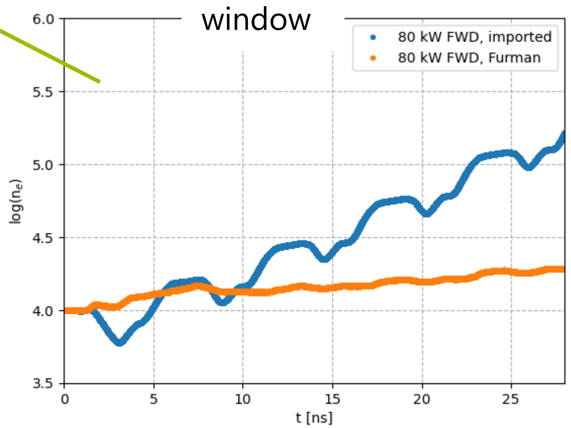






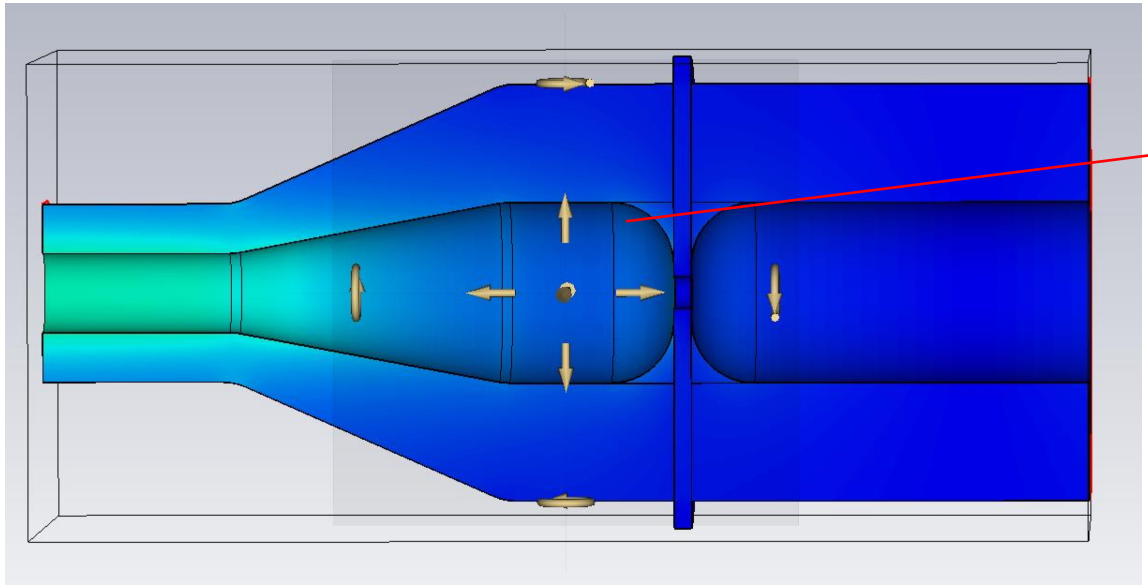


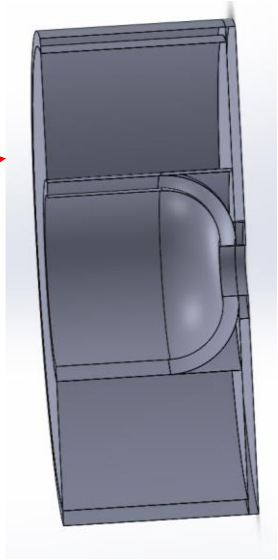




Space charge saturation

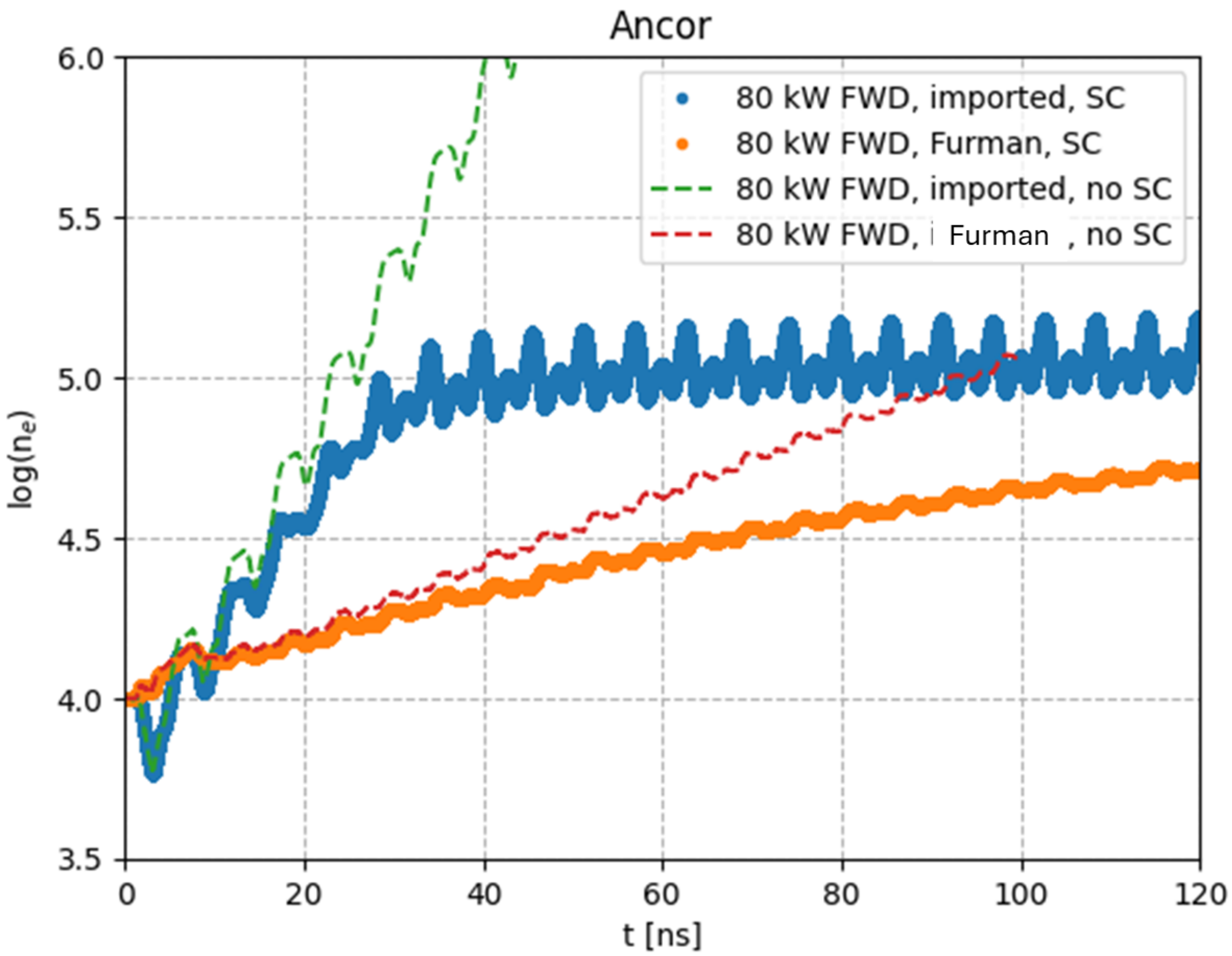
- PIC code
- Full Vlasov solver, metallic boundaries are taken into account
- 10000 macroparticles, with 500000 weight each
- We focus on the window+anchor part which is the most sensible given the presence of the alumina and o-rings





Results on the anchor-window section

Simulation at 80 kW FWD power including reverse power of 13% as in the conditioning without beam



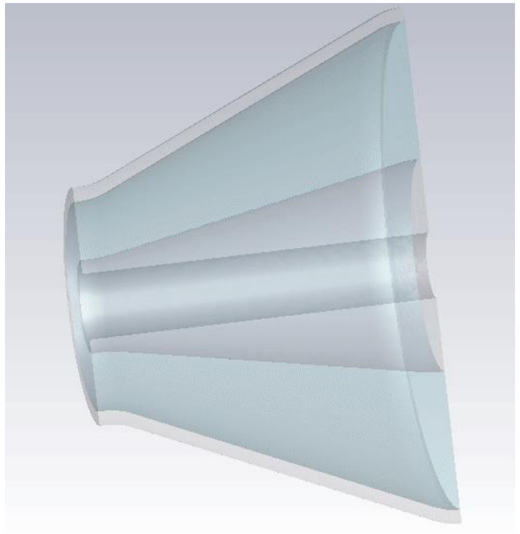
The steady-state situation is used in order to calculate the power deposition of the electron collisions onto the anchor.

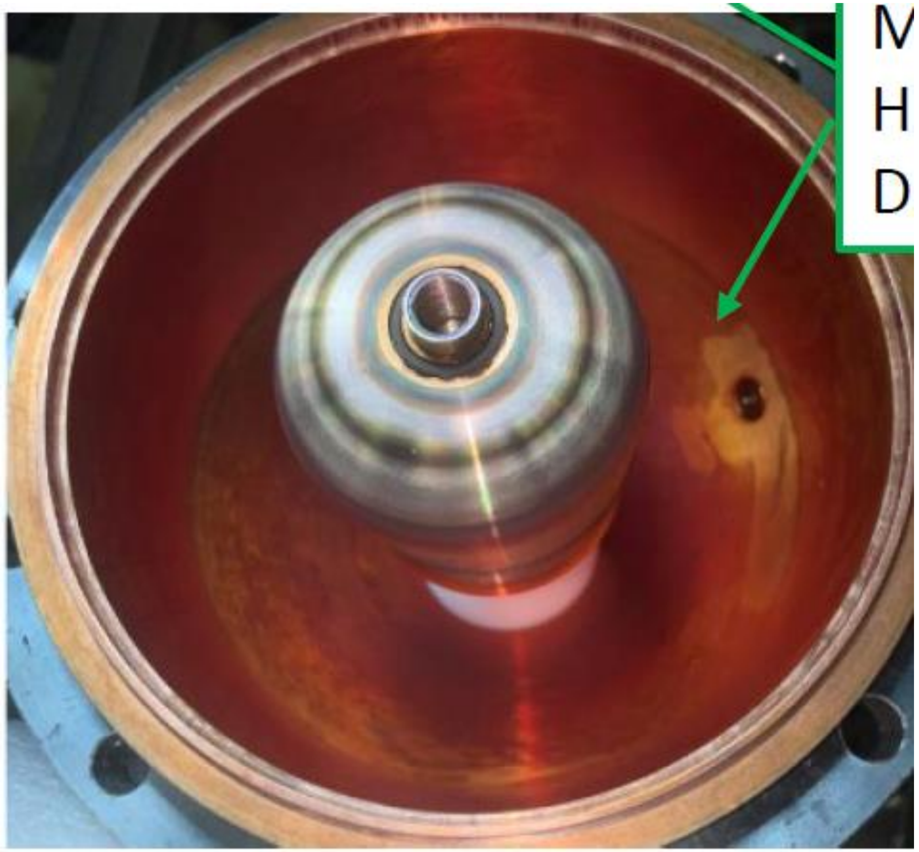
NB: n_e *are the macroparticles*, 500000 *electron each*

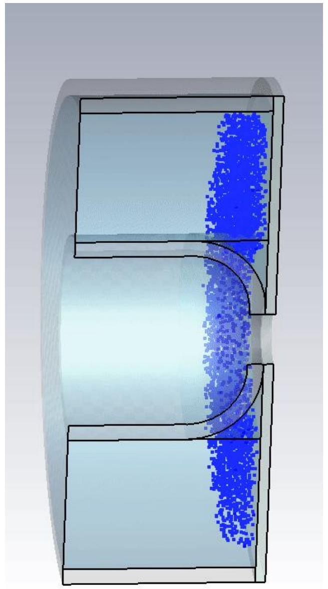
Power surface density calculation

Anchor and cone

The simulated power surface density is consistent with observation on the anchor most damaged (rainbow color)







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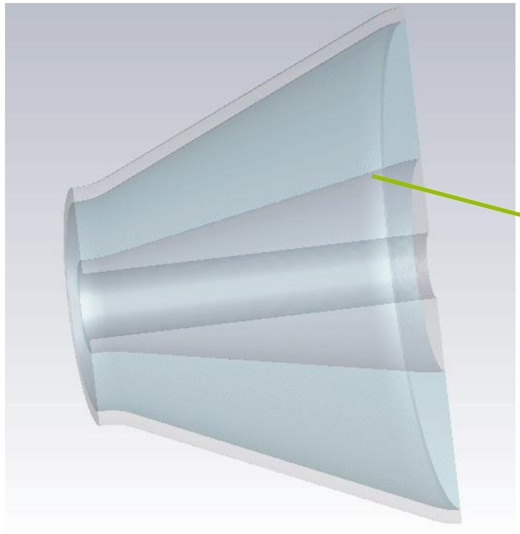
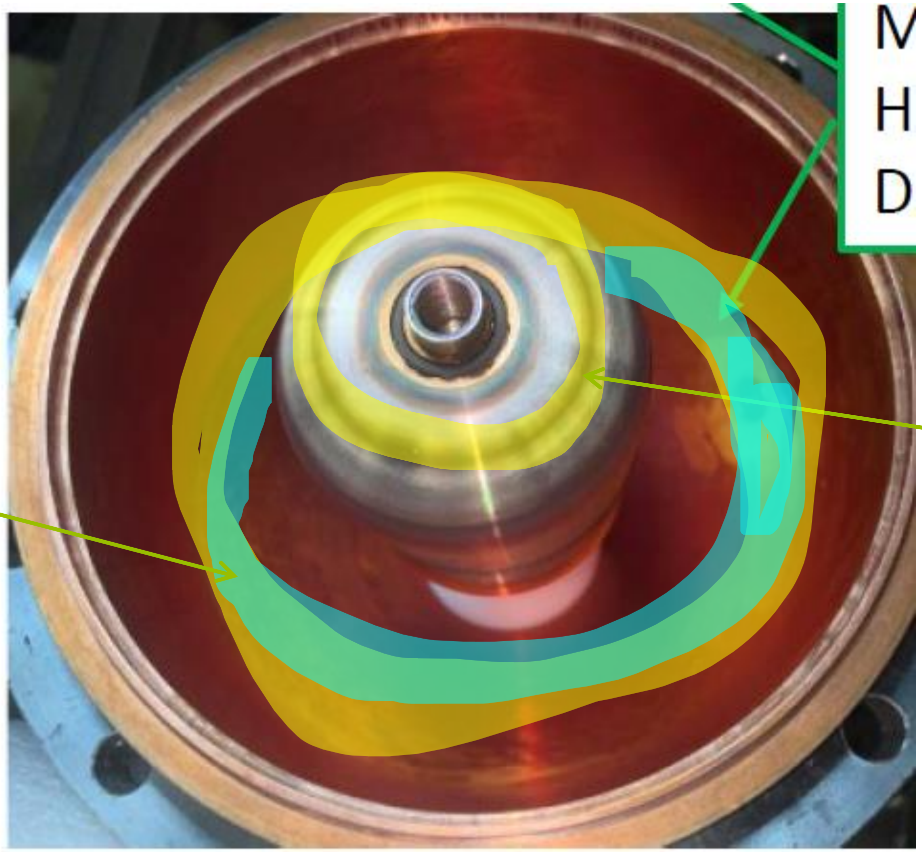
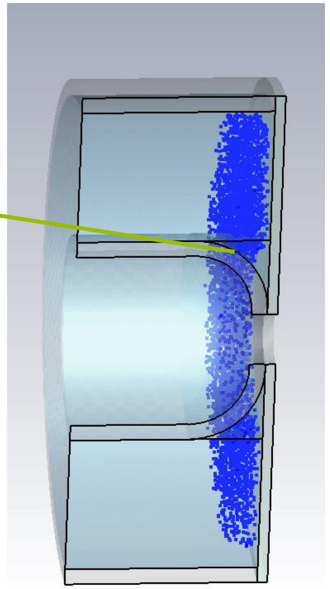


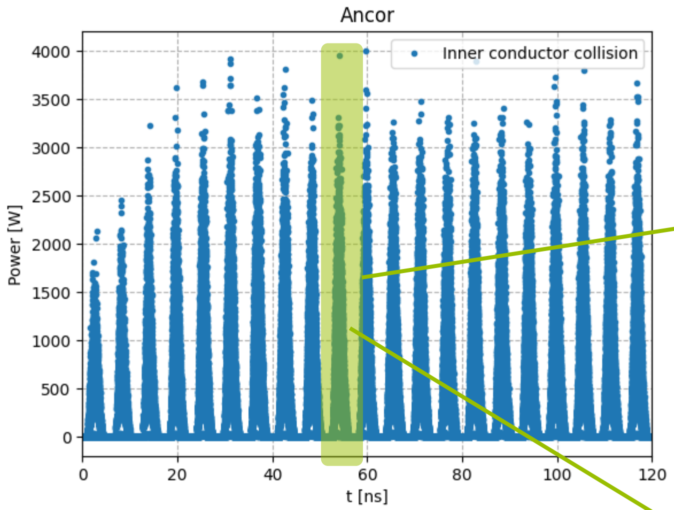


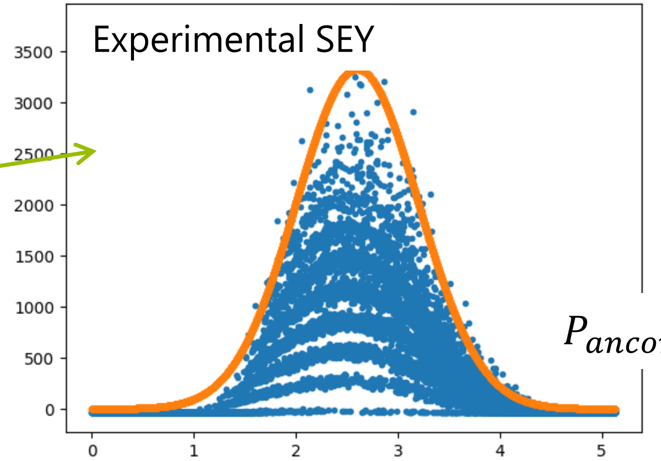


Power surface density

The power on the deposited by electrons on the surface is averaged over a period

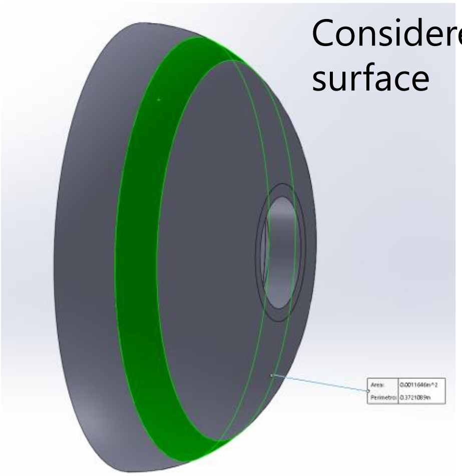
$\mathrm{DC} = 60\%$ max DC% reached before melting o-rings

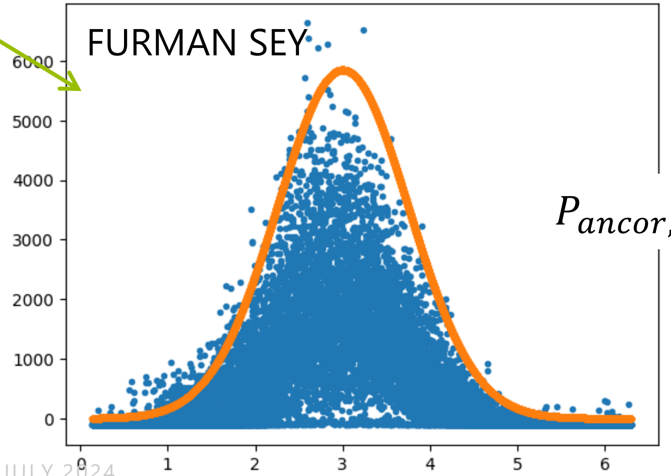




$$P_{ancor} = \mathrm{DC}\frac{\int_0^{6\,ns} P_{fit}\,dt}{6\,ns} \quad T_{RF}\sim 6\mathrm{ns}$$

$P_{ancor,surf} = P_{ancor}$/surf = 50 W/cm^2





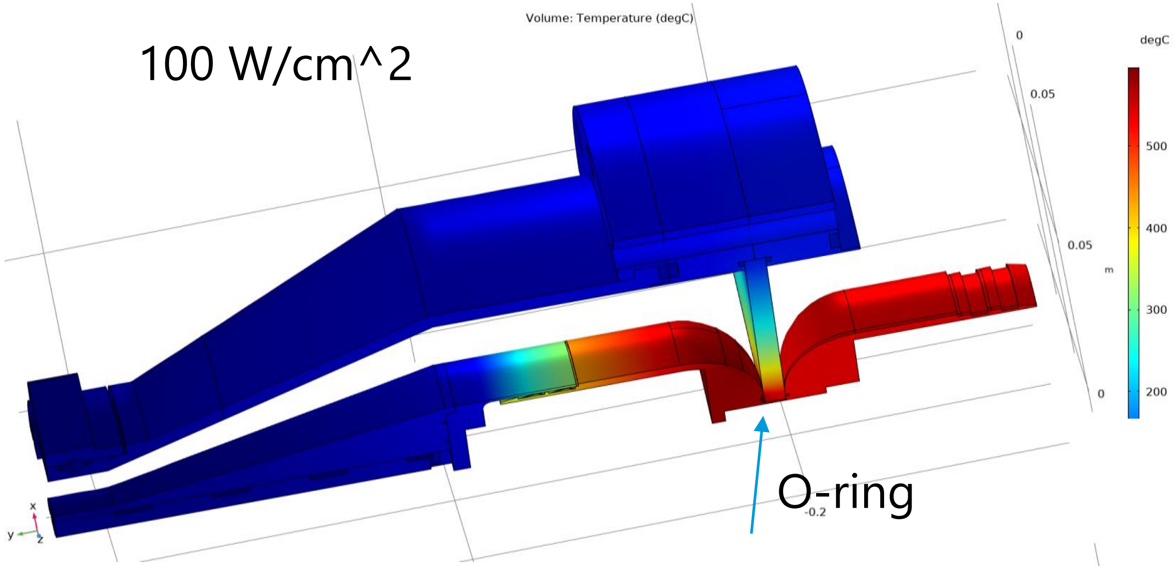
$P_{ancor,surf} = P_{ancor}$/surf = 100 W/cm^2

The current of electrons are in the order of hundreds mA.

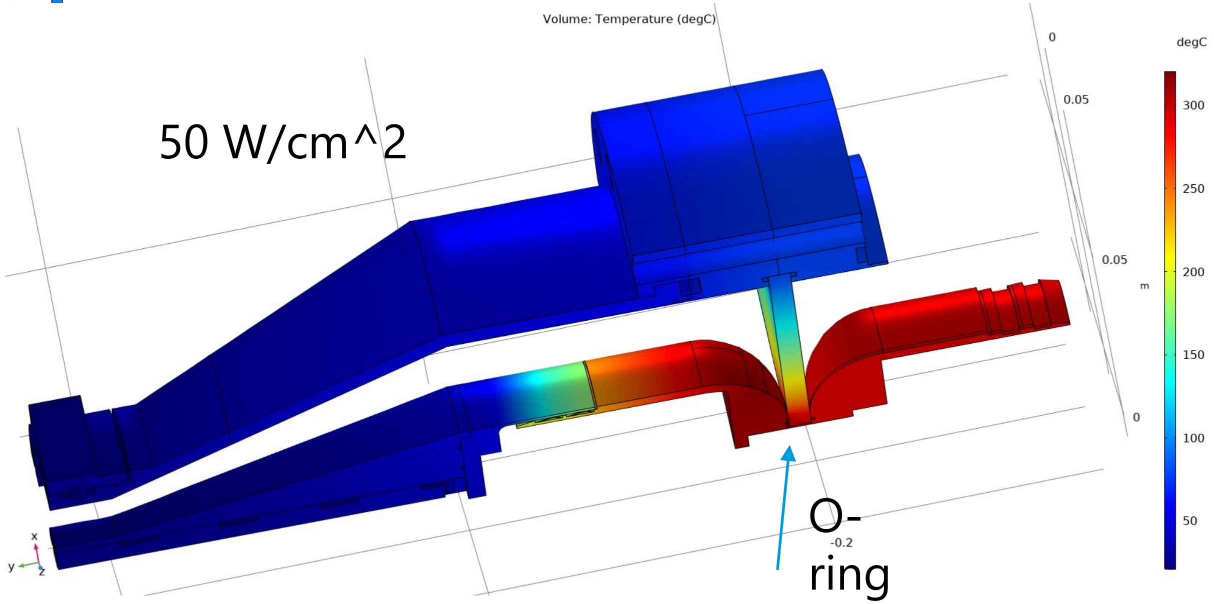
Thermal simulation

Both powers could have melted the O-ring

100 W/cm^2



50 W/cm^2



ESS DTL windows

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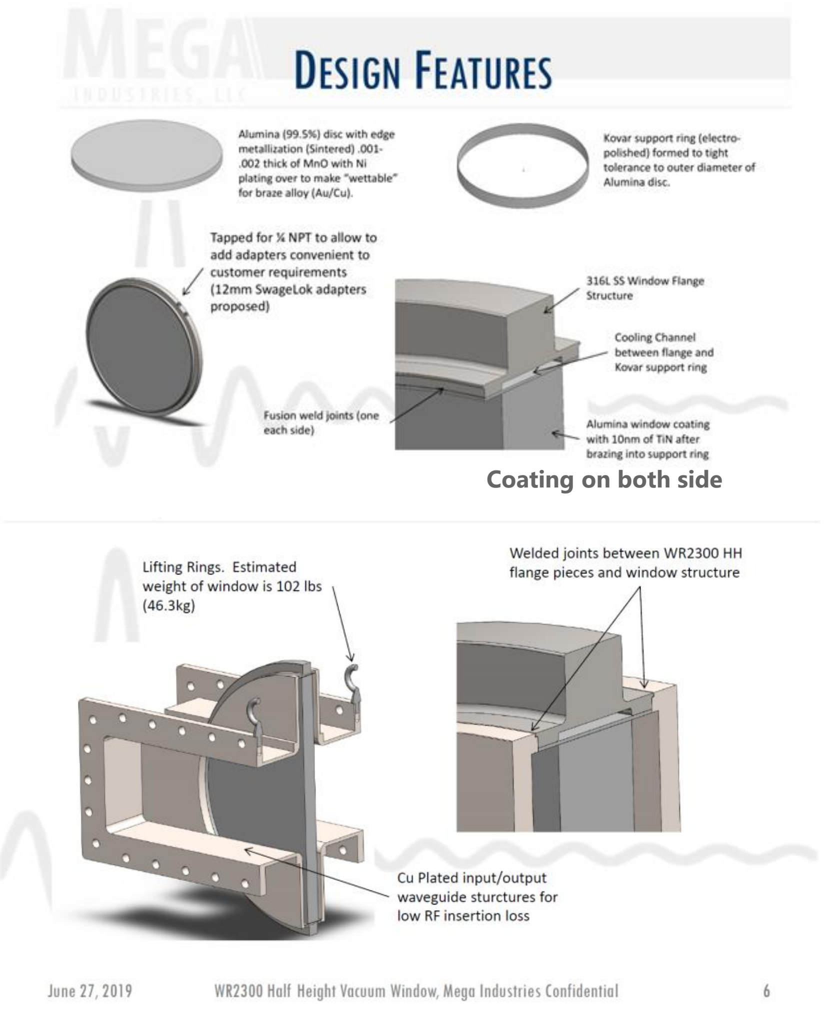
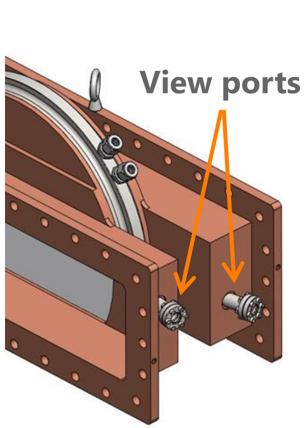
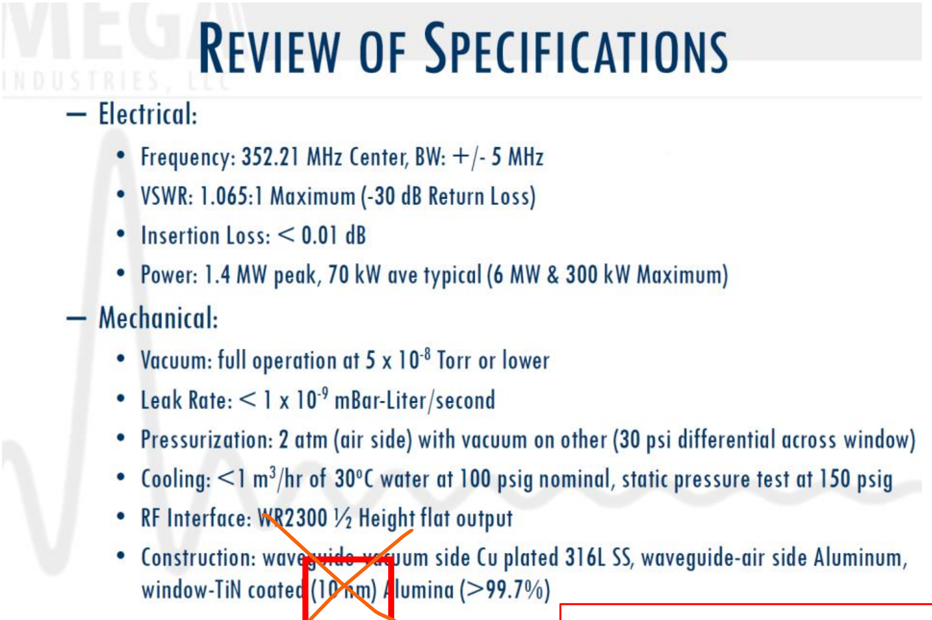
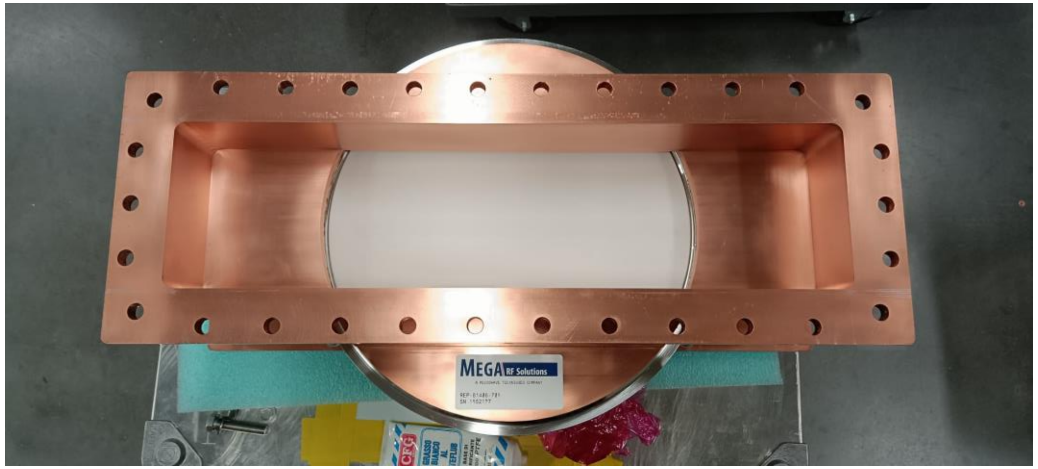
ESS DTL windows design

From MEGA technical design report



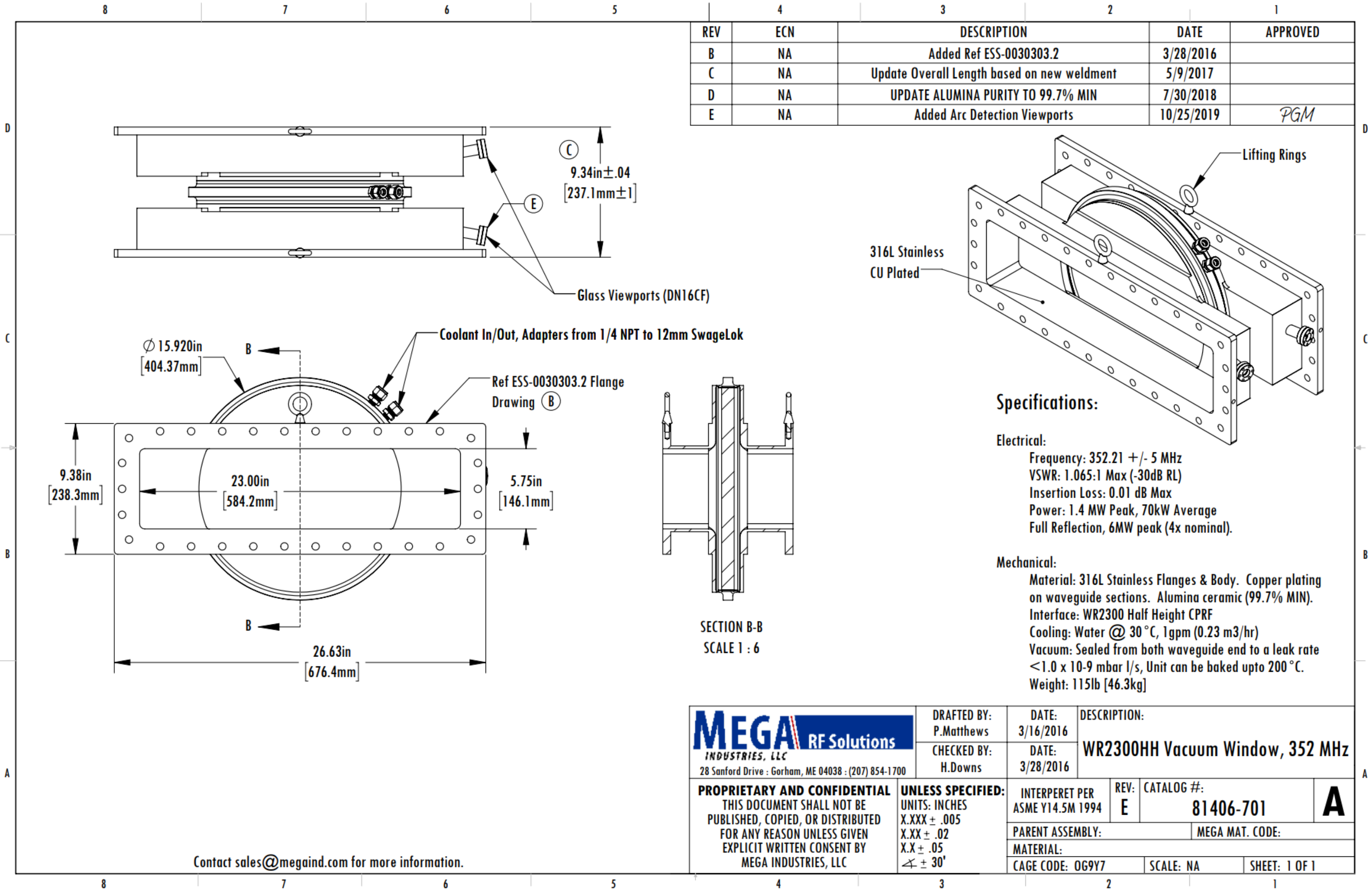






ESS DTL RF windows design

Geometry and specs



- a=584.2 mm
- b=146.1 mm
- thickness Al2O3=22.86 mm
- diam Al2O3=368.3 mm
- gap Al2O3-Pillbox=12.15 mm
- Rounded radius =12.7mm

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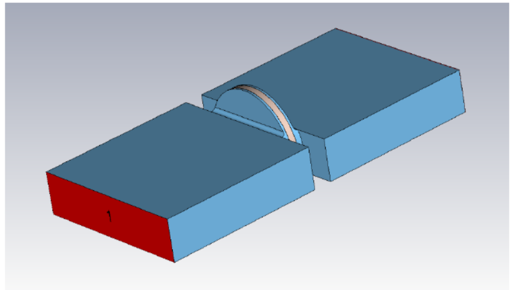
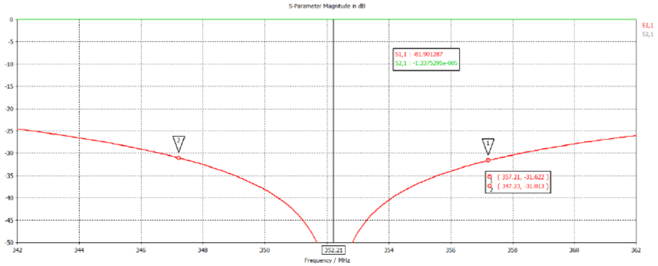
ESS DTL RF windows design

RF simulations

MEGA INDUSTRIES, LLC

Electrical Performance

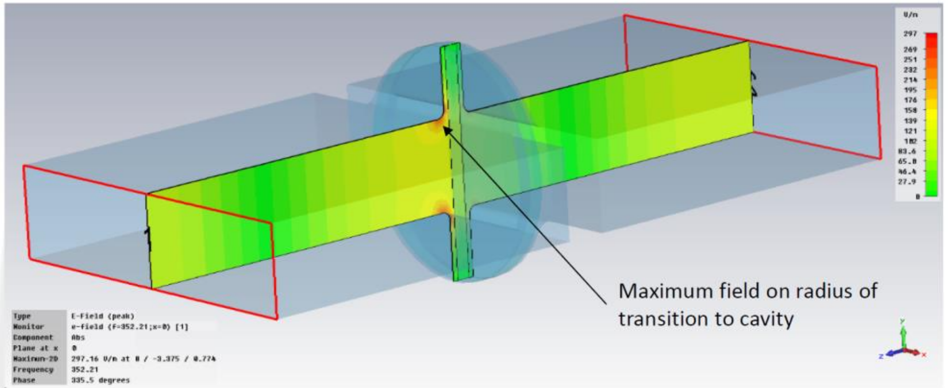




- "Traditional" transition geometry, short cylindrical cavity in front of the alumina window. Very compact design.
- Window diameter and cavity spacing optimized to get s-parameter results shown.
- VSWR Numbers:
  - 1.056 Max (-31.3 dB RL) at 352.21 +/- 5 MHz
  - -.003 dB Insertion Loss (theoretical)
- Disc geometry:
  - 14.5" (368.3mm) dia. x 0.9" (22.86mm) Thick

June 27, 2019 WR2300 Half Height Vacuum Window, Mega Industries Confidential 8

Electrical Performance, Field

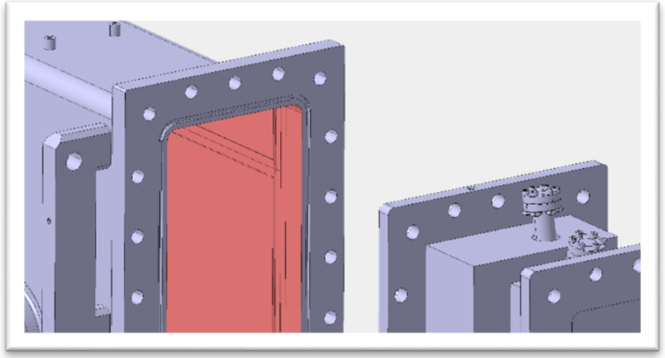


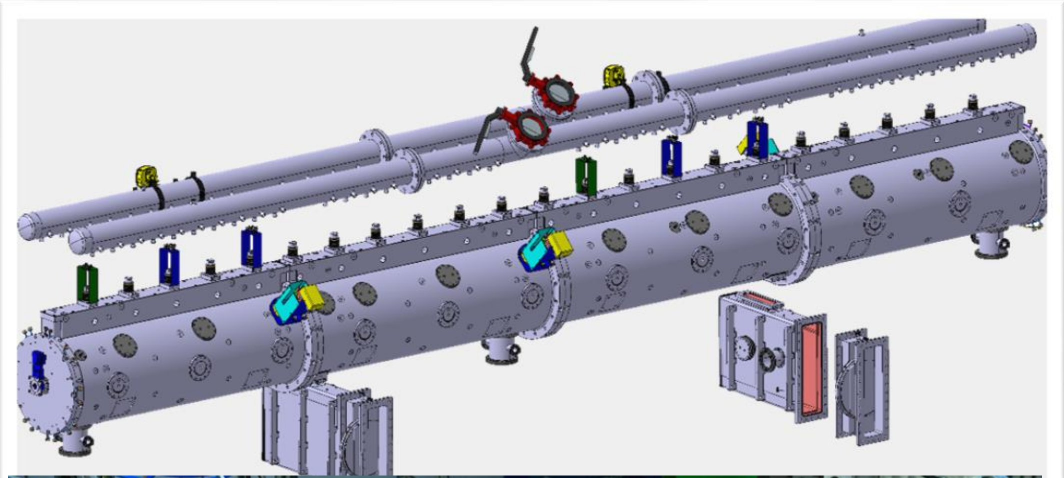
- Electric field is only enhanced by a factor of 2.8 over that in half height guide. This indicates that window should easily handle the 1.4 MW of peak power.
- Maximum field occurs where expected at the transition from waveguide to cylindrical cavity. Transition has large radius to minimize field strength enhancement.

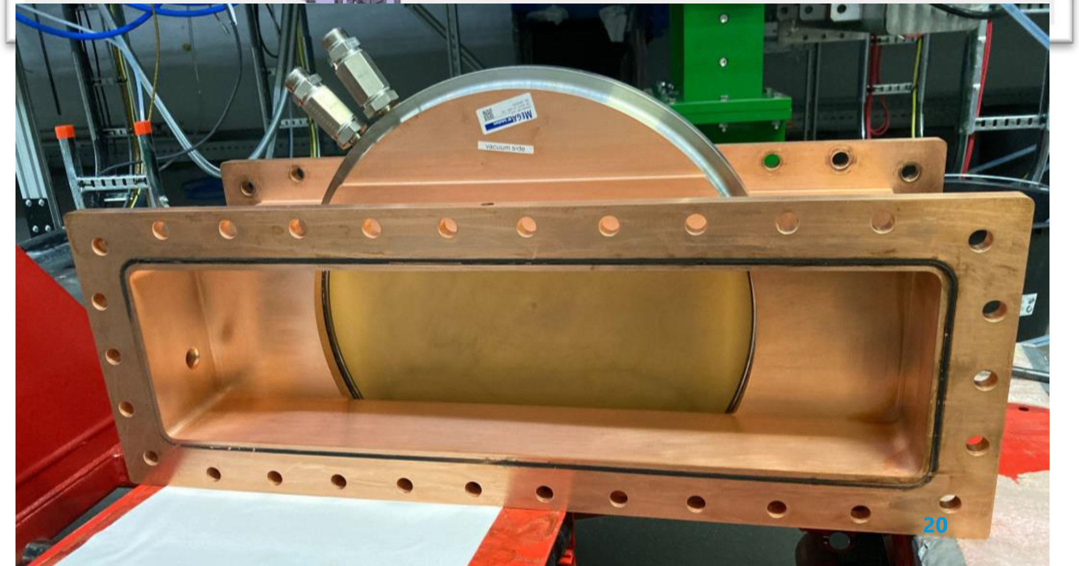
June 27, 2019 WR2300 Half Height Vacuum Window, Mega Industries Confidential 9

Round corner good for RF but not for Multipacting

Installation on DTLs







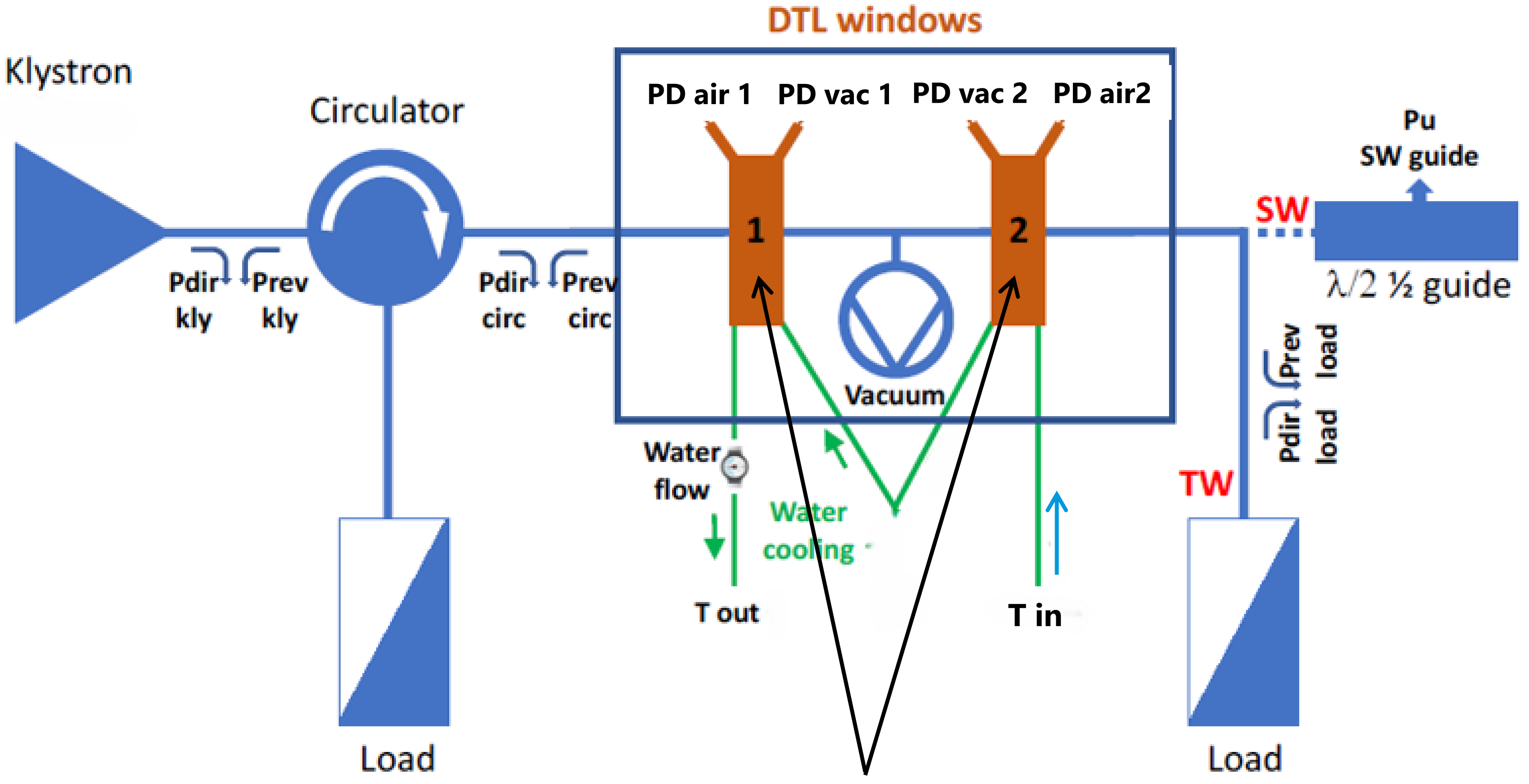
Each DTL has 2 power couplers.
The HH-WR2300 are coupled to the cavity through an iris slot on the bottom of the tank.
The seal between the RF window an coupler box is an EPDM gasket.
No RF joints to protect orings.

After approximately 1 month of high-power conditioning, ligth started on both vacuum and air side on DTL2 and DTL3. No Rev power, no overheating.
DTL1 and DTL4 ok.
O-rings were found to be melted.
Coloration: The windows show a yellow colour on the rectangular exposed to RF and a whiter colour on the hidden surfaces. Moreover there are trace of dark shadows over the surfaces.

Planned actions

1. new metallic gasket
2. retest window offline

ESS RF window conditioning test bench



Temperature sensors are placed on the window pillbox walls, to monitor temperature in case of multipacting

High-power tests @ESS

S/N 2056606 (report just one window test as example)

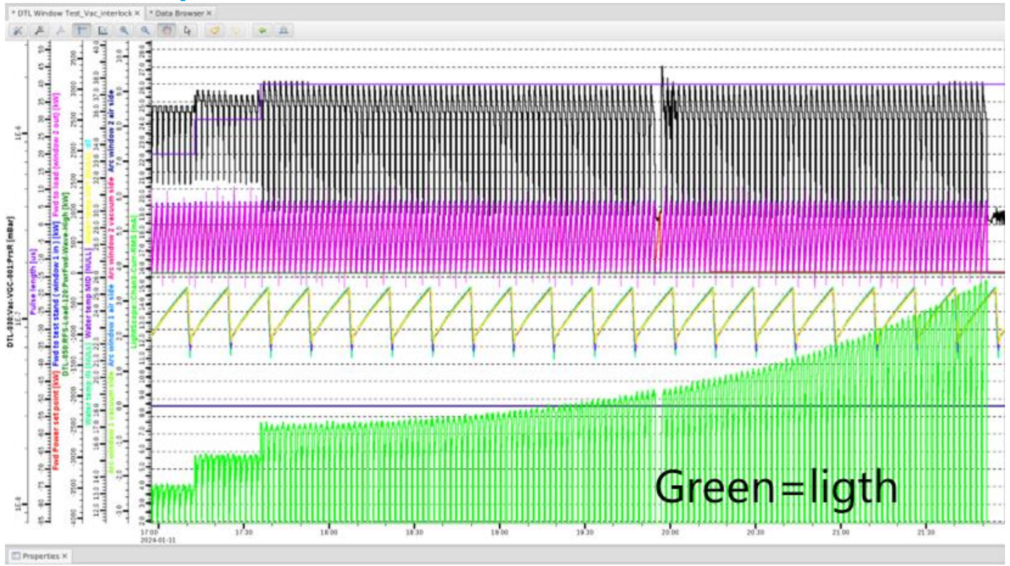
Vacuum at 1e-06 mbar.

Outgassing below 500 kW.

Light, vacuum and reverse power effects

Initially conditioned away.

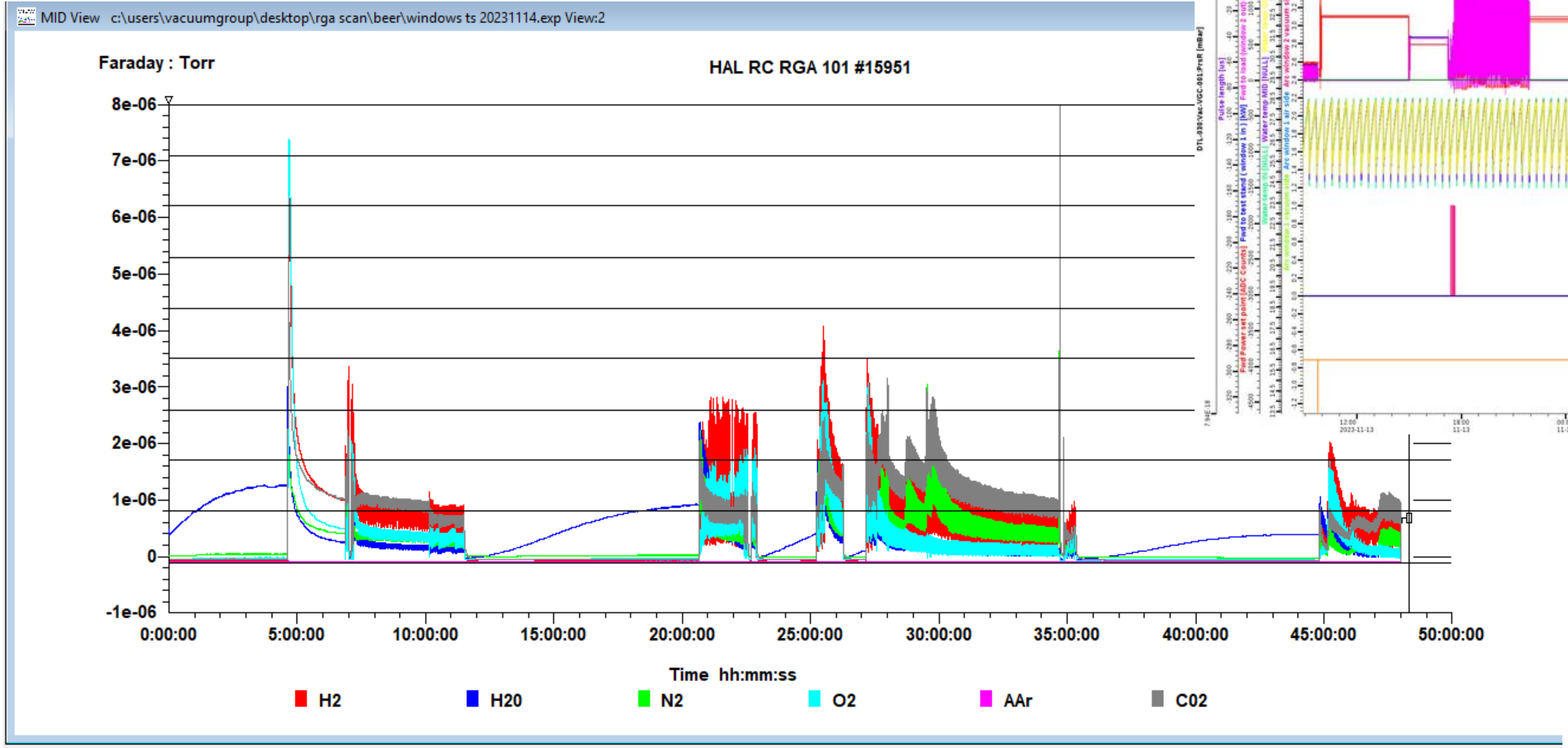
Then at 40us light diverging (deconditioning). Ramping 10-1000 kW @14Hz.

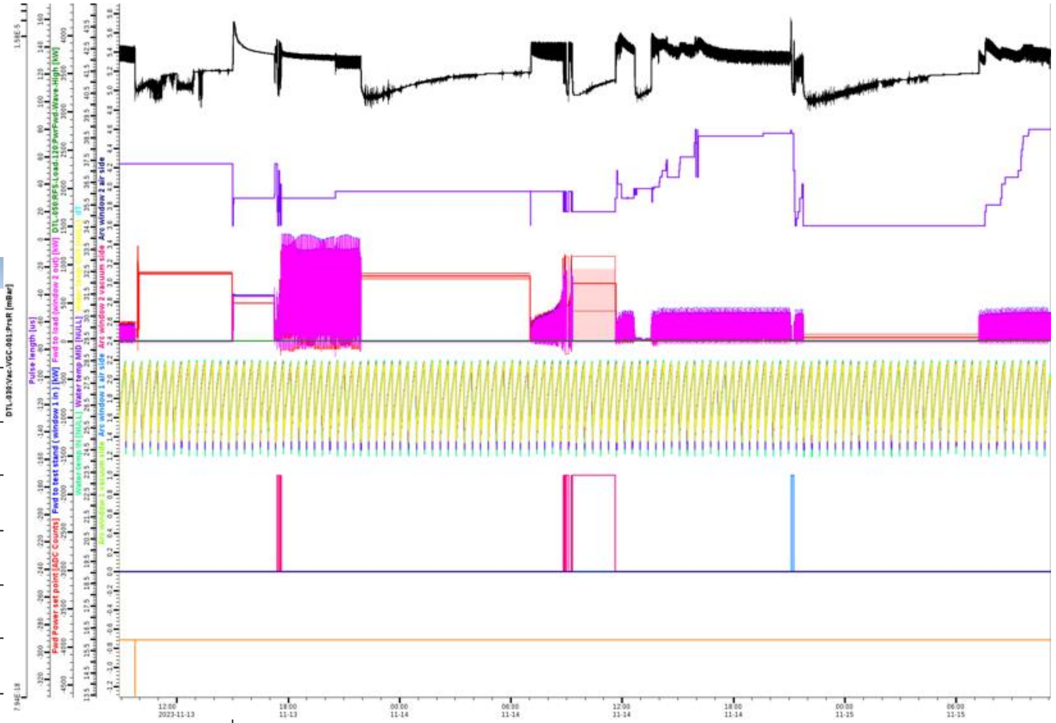


RGA over 48 hours

O-ring permeation during the night RF stop

When RF on, water (the blue) decreases with time, while increase gradually after RF off.
To be compare with **vacuum (the black** in rigth picture) over same time period.
At the RF ON, other gas (H2, CO2, N2, N2) are higher than water(H2O)
→ Released by RF conditioning of the window





Summary of the first phase of offline test

October 2023-April2024

We re-tested offline 5 windows which showed light on the DTLs:

- 4 windows still lightening.
- 1 window passed the test → somehow reconditioned, no light.

1 more window, never installed on the DTLs, was tested and passed the test.

2 windows have been installed on DTL5. So now DTL1-4-5 are equipped with window.

The waveguide vacuum box did not perform good vacuum because of Oring seals and Poor conductance.

Designed new aluminum seal and new vacuum box (ESS vacuum group).

We will use it on the spare's window tests.

Test of spare windows

3 spares windows at ESS

1952776,1952177 by ESS + 1735696 by INFN.

High power test in vacuum never completed at CEA and IPNO in the previous phases (2018, 2020) because of the failure of the pair windows.

High power test was completed in air to proof thermal behaviour.

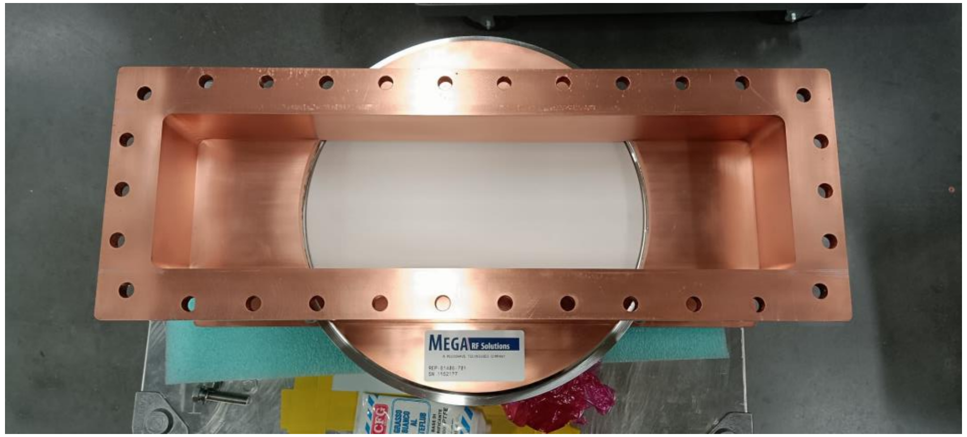
Coloration and visual inspection are good.

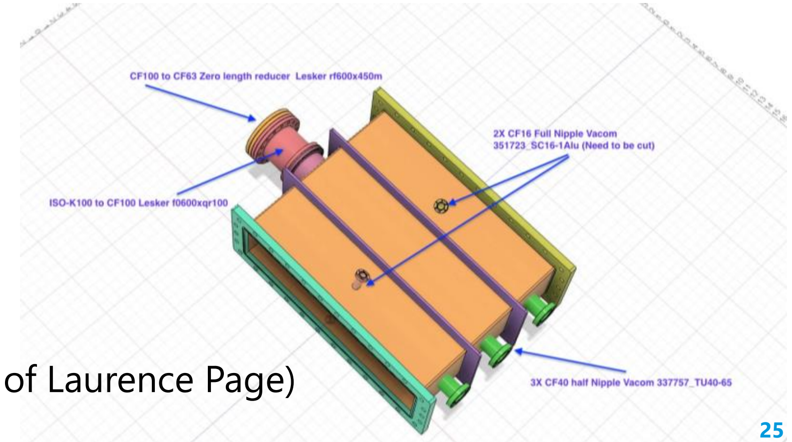
An updated vacuum box will be used to have a better vacuum level (starting <1.0E-7 mbar).

Aluminum gasket→no baking

Narrower soft thresholds on vacuum (2.5 E-7mbar) and light (45mV).

Under test right now. Reached full power, now under endurance test 🤞





(courtesy of Laurence Page)

ESS RF window conditioning procedure

Improved routine with narrow soft threshold

RF high power conditioning is controlled by an automatic routine in python.

We perform RF power ramps from around 10 kW to 1.4 MW. We switch off the RF power when one of the following events occurs:

- Outgassing with a vacuum level exceeding a hardware threshold defined at 1x10-6 mbar,
- Presence of electrical arcs whose intensity is greater than around 2 lux (AFT photodiode"< 25 mV at < 1 Lux")
- Water T outlet – Water T inlet > 0.6 degC (each window by design should give dT ≈ 0.3 degC)

The RF power is increased step by step 1 kW per second). The power increases if the vacuum pressure is lower than a soft threshold placed at 5x10-7 mbar or lower. The soft threshold is defined to allow some dynamic to RF with the initial conditions. If the outgassing is larger than this soft threshold, we decrease the RF power of 10 kW or more if needed, to keep the vacuum lower than the threshold.

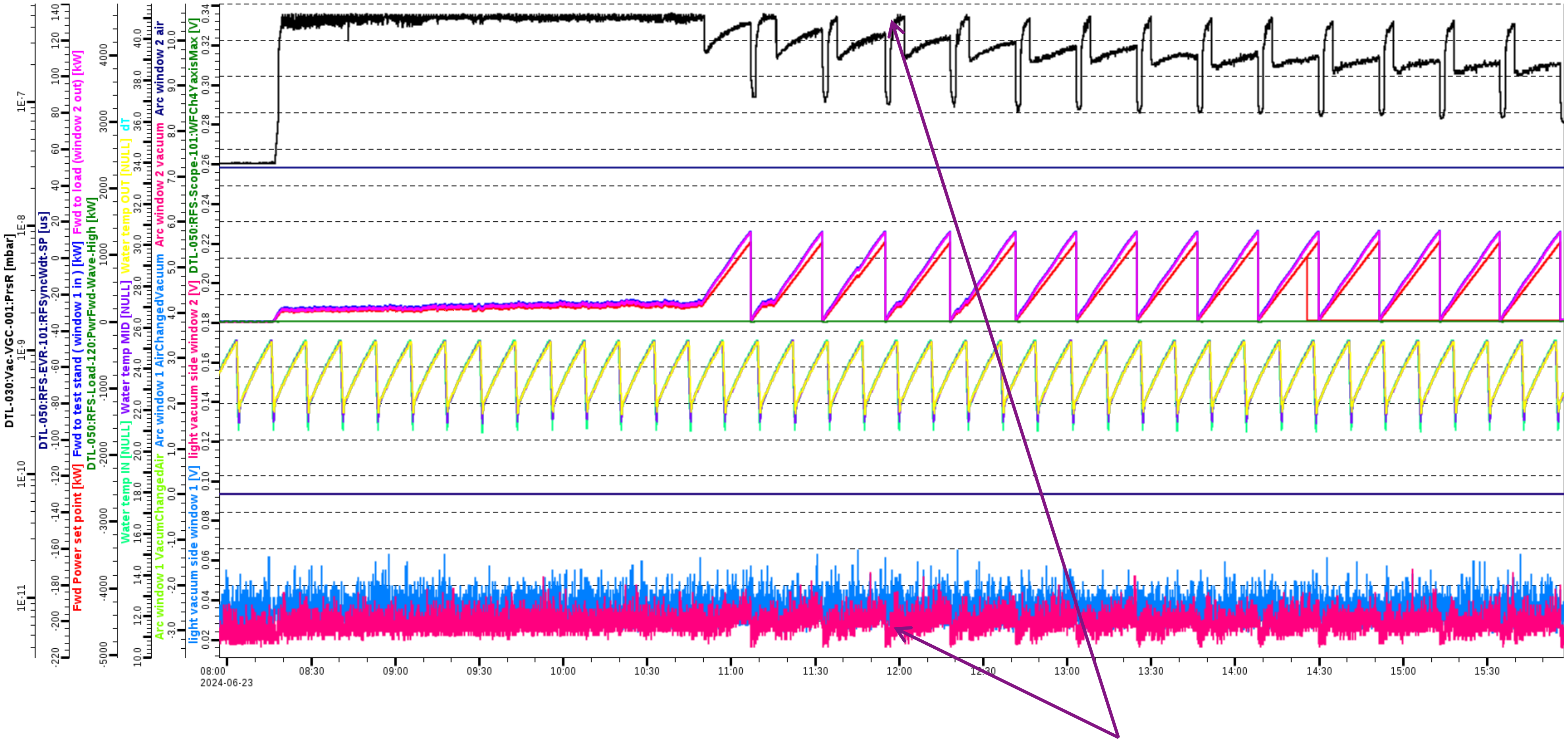
A similar soft threshold logic is setup on the light signal level being lower than 65 mV. The analogic signal of the AFT module is acquired on an oscilloscope.

Once the vacuum is correct, RF power can increase. RF power ramps start with repetition rate of 1 Hz. The sequence is the following:

- Conditioning in travelling wave at rep rates 1-2-3.5-7-14 Hz
- For rep rate each configuration, we change the pulse width from short pulse widths ≈25 µs to 3.6 ms doubling the pulses at the end of each power ramp.
- 12 hrs endurance test in travelling wave at 14 Hz – 3.2ms
- Conditioning in standing wave, ramping power at 25-50-100 us 1 Hz and 14 Hz
- 2 hrs endurance test in SW at 100 us – 14Hz
- The test will be carried out at 8 specific phase angles from a variable length short circuit

Zoom on power ramps at 1Hz-50us

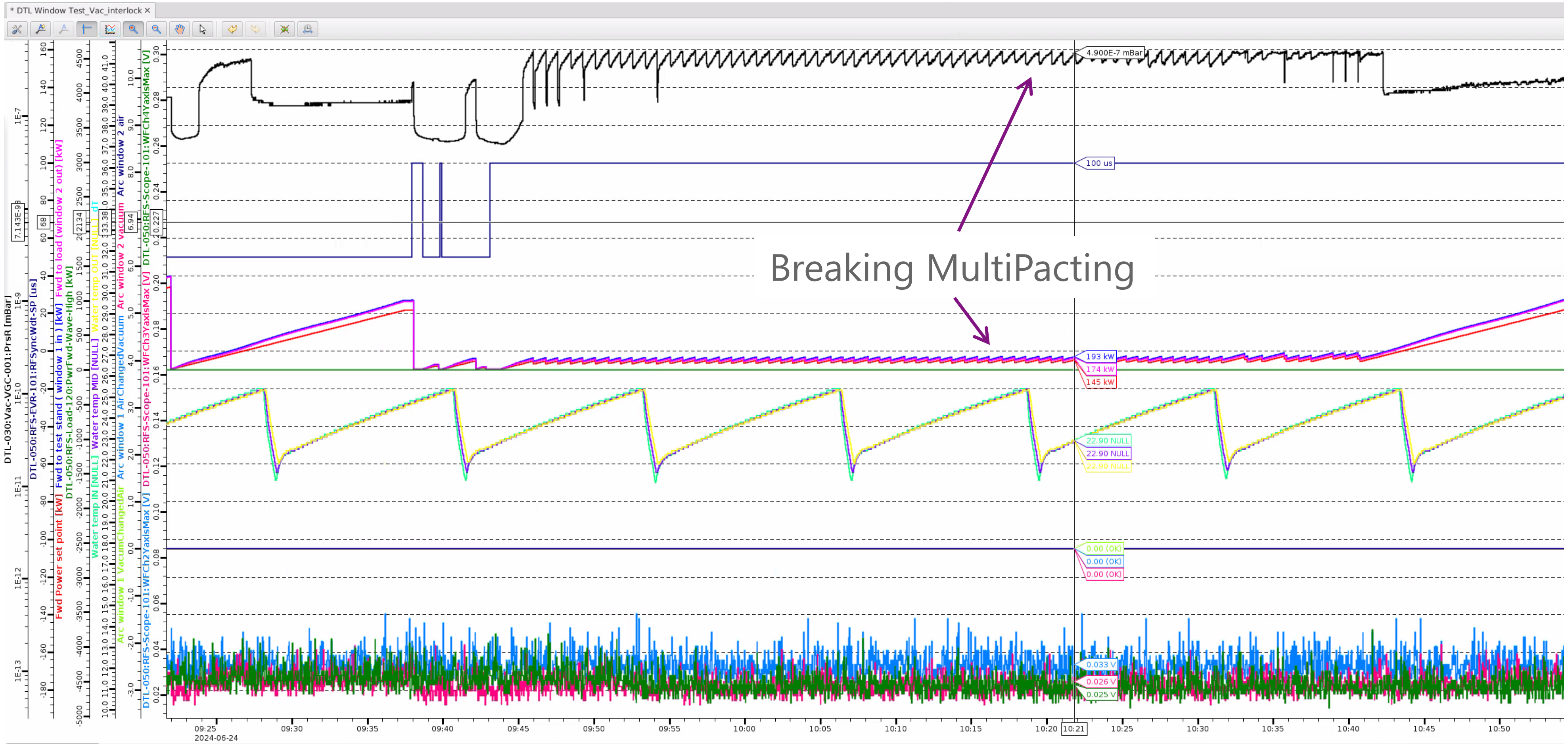
Light and MP are present but conditioned away, with patience



Some light on window 2 in correspondence of vacuum jump-up

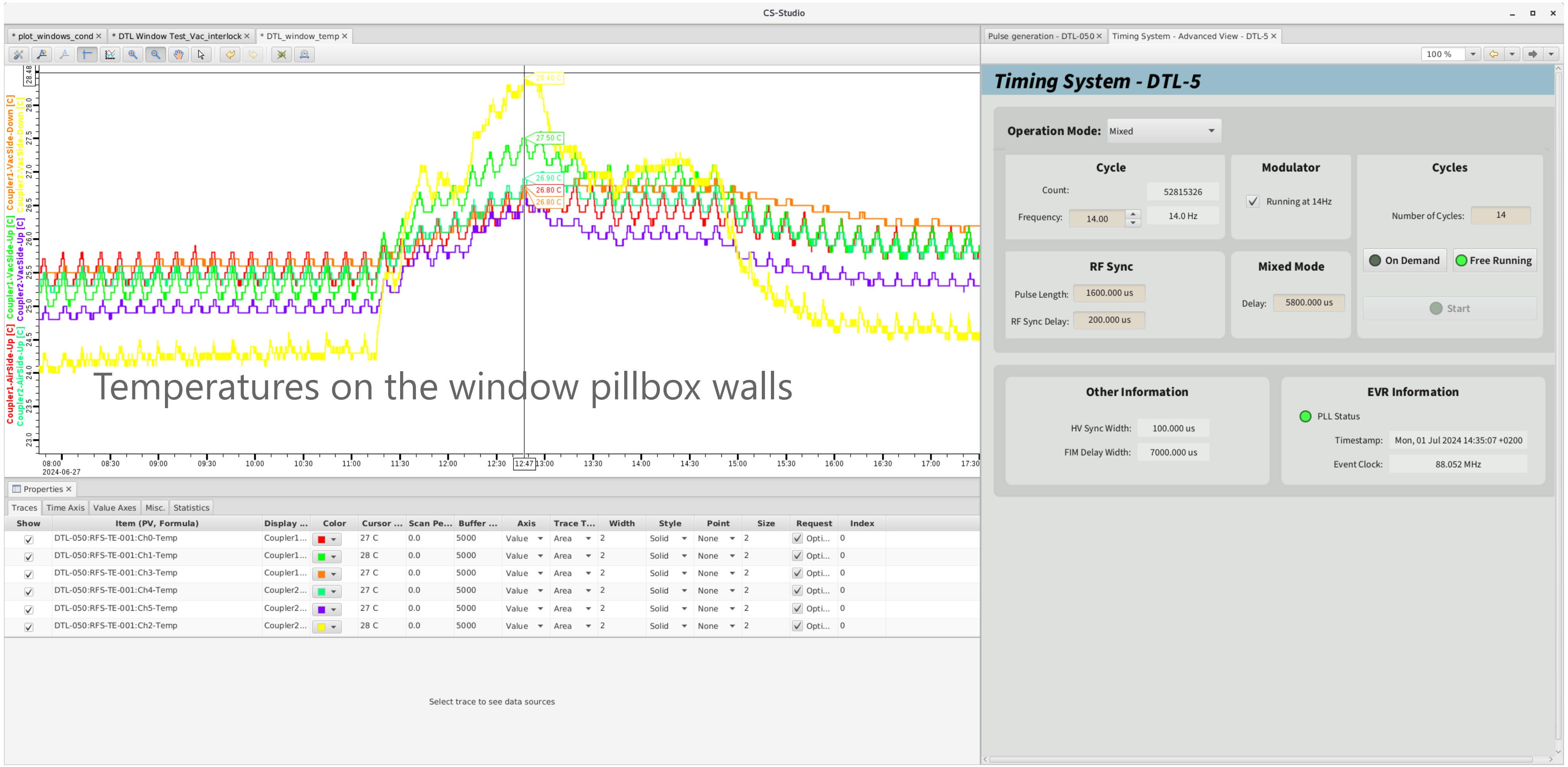
Zoom on power ramps at 1Hz-100us

Zoom on MP barrier at 400 kW



Conditioning MP and temperatures

3.2 ms – 14 Hz – 10 to 400 kW



Refurbishment by MEGA

Refurbishment of alumina (production of new windows takes >12months)

3 windows have been shipped in February to MEGA for refurbishment of the alumina.

They will start form a single window to proof the effectiveness of the refurbishment.

In the discussion with company, it came out that the specs of the TiN were changed in 2019 from 10-20 nm to 1-2 nm. The exact reason for this change in specifications has not been identified, neither communicated to INFN.

It is agreed to increase the thickness of coating deposition during the refurbishment to 10 nm over a single side.

Final offer received on April 23 after weekly technical contacts (including visit at CERN).

Order on going for the 1st unit by INFN (some bureaucratic issue as usual in Italy)

Tentative repair plan of the 1st window:

- Test trial, remove Alumina brazement/Kovar ring assembly housing utilizing a non-deliverable rejected unit
- remove Alumina brazement/Kovar ring assembly for housing EDM (submerged in deionized water)
- Abrasive blast/clean Alumina surface both sides in house (remove TiN)
- Recondition or re-make housing/flange (qty 2 per Window)
- TiN coat one side of Alumina brazement/Kovar ring assembly 10nm (USA supplier)
- RF check (IL, VSWR)
- TiG weld Alumina brazement/Kovar ring assembly in house
- water pressure check, Vacuum and leak test
- RF Condition of RF Window @ ESS→ August 2024

Summary of ESS DTL windows

13 windows, 6 installed, 2 spares under conditioning, 1 tentative refurbishment, 1spare to be tested, 3 to be decided

S/N	Vacuum seal	Retested offline	Light during the test	Position
1952778	Oring	NO		DTL4-C1
1952779	Oring	NO		DTL4-C1
2056263	Aluminium	Yes	No	DTL5-C1
2056264		YES	Yes	@MEGA, 1st refurbishment
2056606		YES	YES	@MEGA
2056277	Aluminium	YES	No	DTL5-C2
2056278	Oring	NO		DTL1-C1
2056614		YES	Yes	@MEGA
2056613		YES	Yes	@ESS
2056607	Oring	NO		DTL1-C2
Spares				
1952776	Aluminium	On going		offline test
1952177	Aluminium	On going		offline test
1735696		TBD		

Multipacting studies

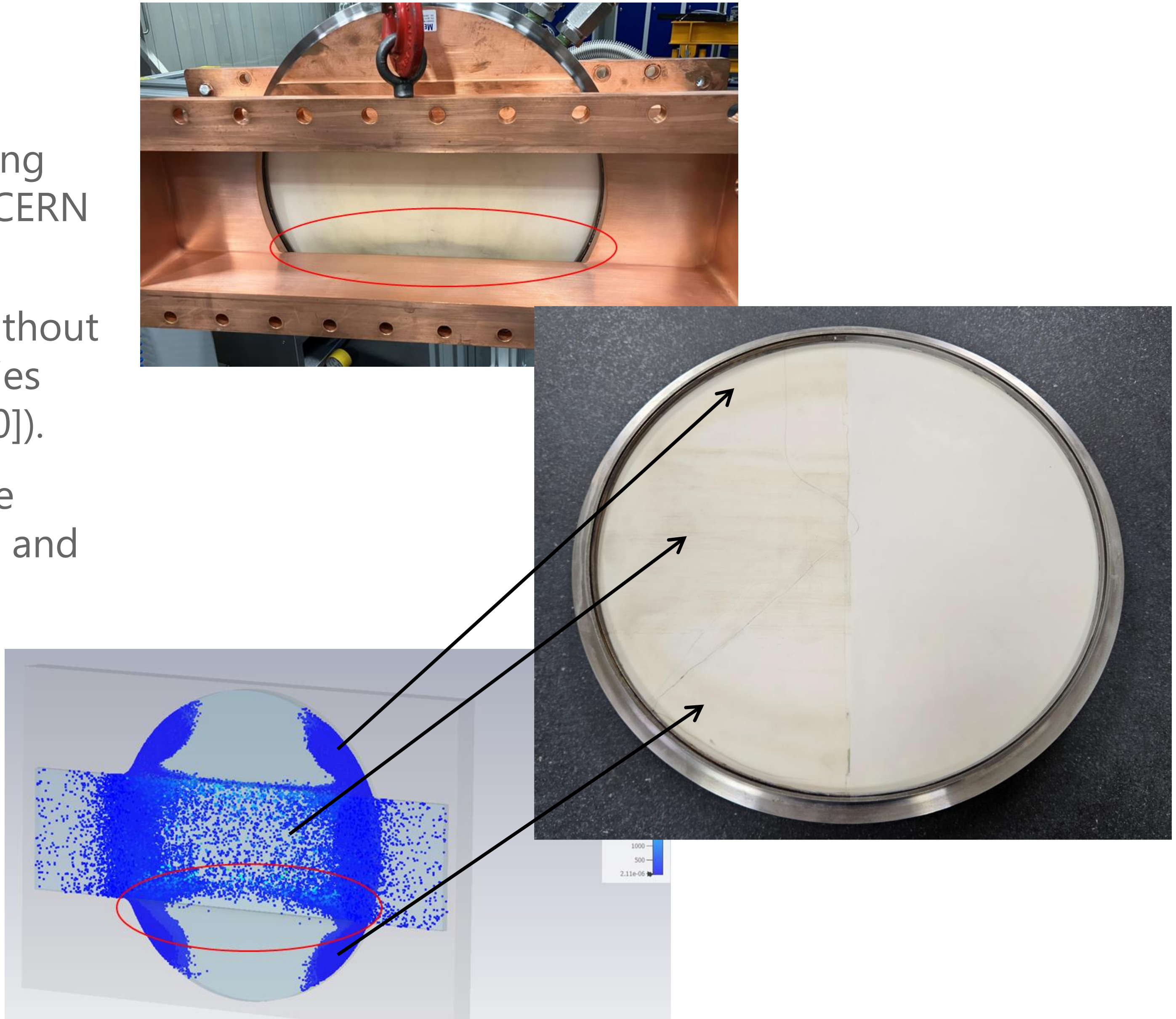
Present geometry analysis

CST studies of MP has been performed using SEY of alumina and copper from paper of CERN and DESY.

Electron multiplication studied with and without space charge (procedure follows SNS studies performed by G. Toby [3] and Langellotti [0]).

The method is validated by recognizing the colored MP zone observed on the alumina and the highest reaction at 300 kW.

The method has been validated also in the framework of IFMIF programme.



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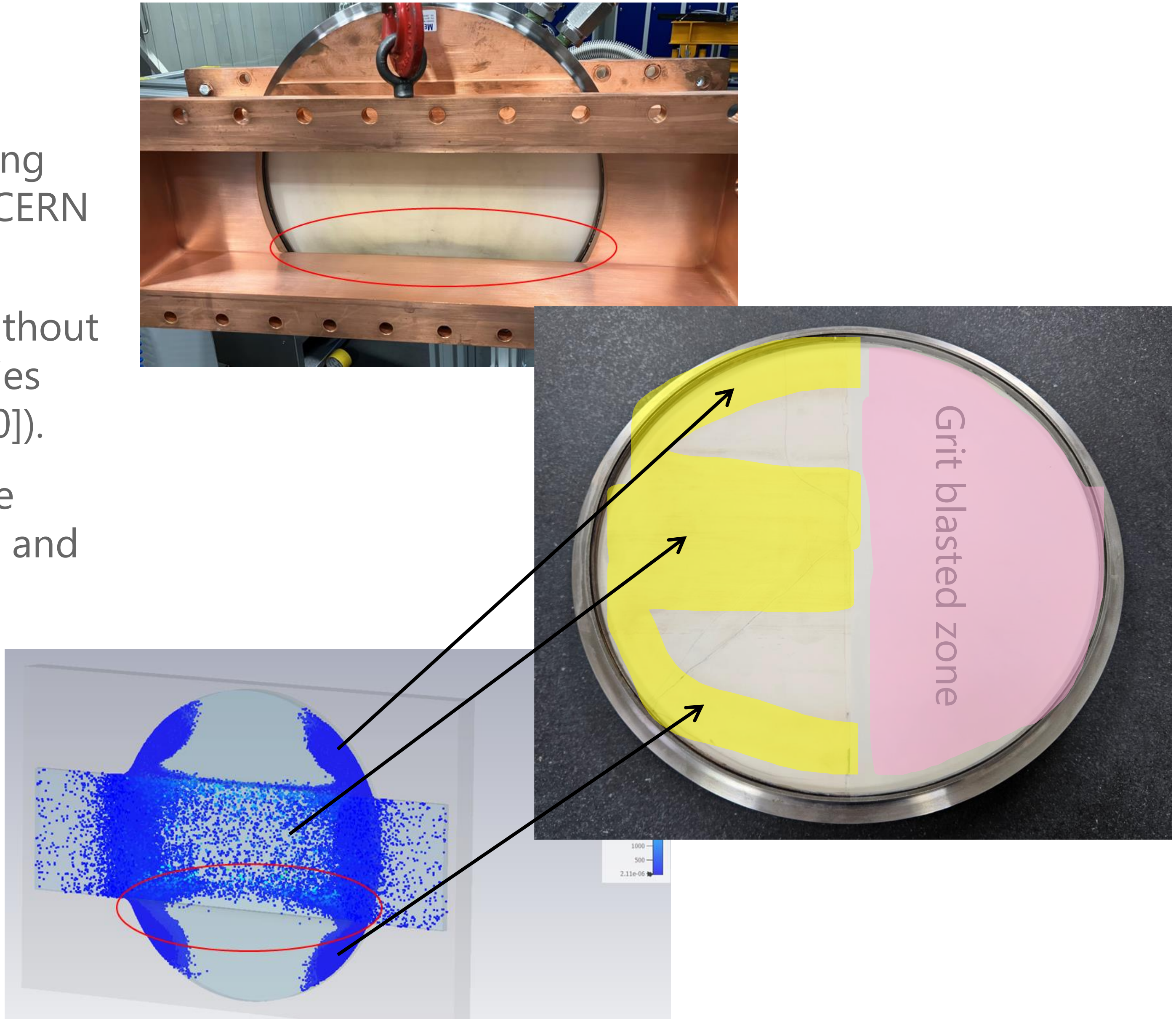
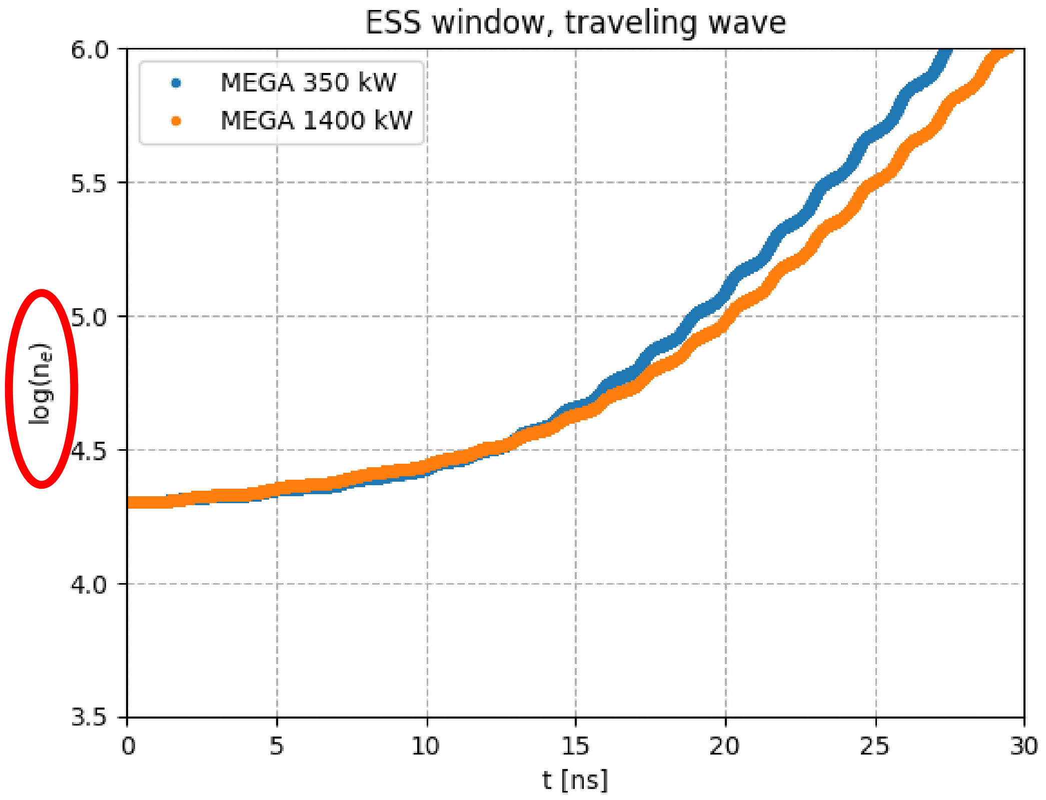


Multipacting 350 kW, 1400 kW

Present geometry analysis

- 20000 electrons, no .s.c.
- Alumina SEY as [2] for 5 nm→our case is 2nm, so it should be worst
- Copper SEY as Furmann
- Maxwellian distributed electrons [3]
- No space charge

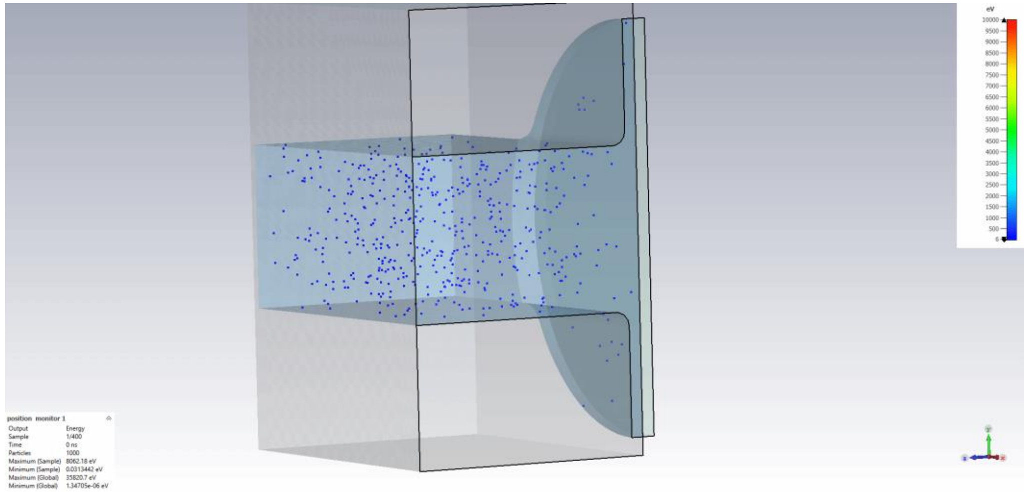


NB: for calculation without space charge saturation, we often compare results using Furman's SEY and Imported SEY from ref. [1].

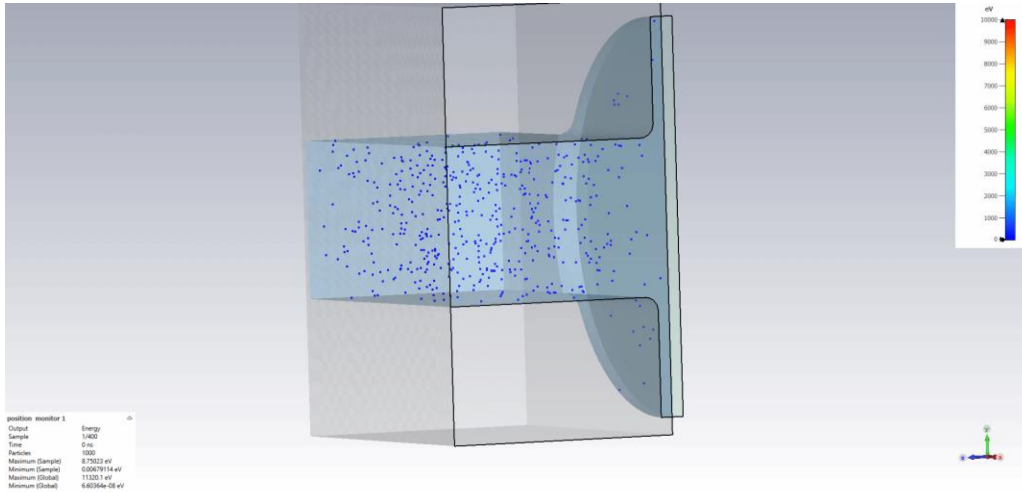
We do not use Furmann for calculation with space charge.

Multipacting movie

Present geometry analysis



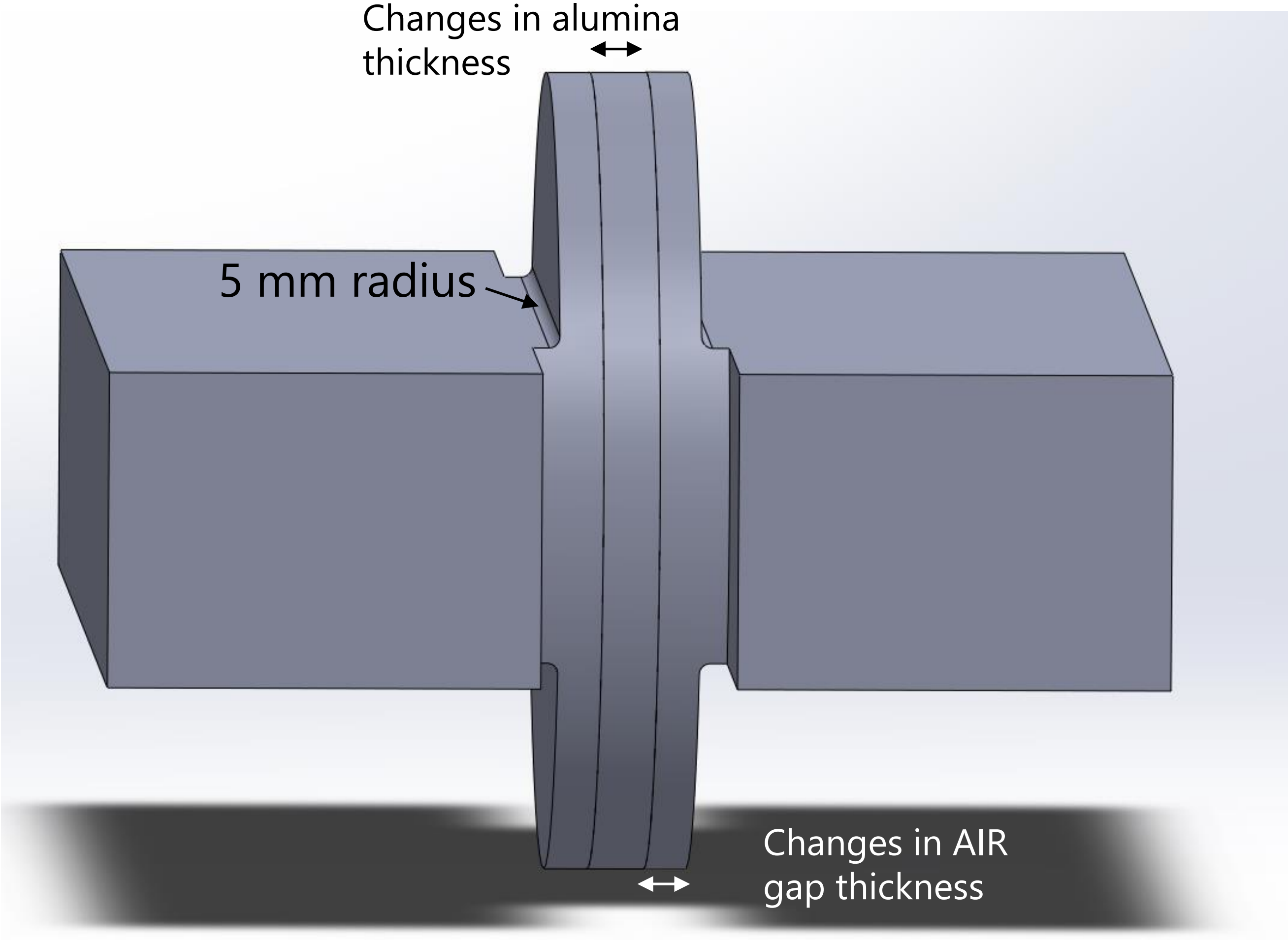
1400 kW



350 kW

For visualization proposes, the number of electrons have been decreased from 20000 to 1000

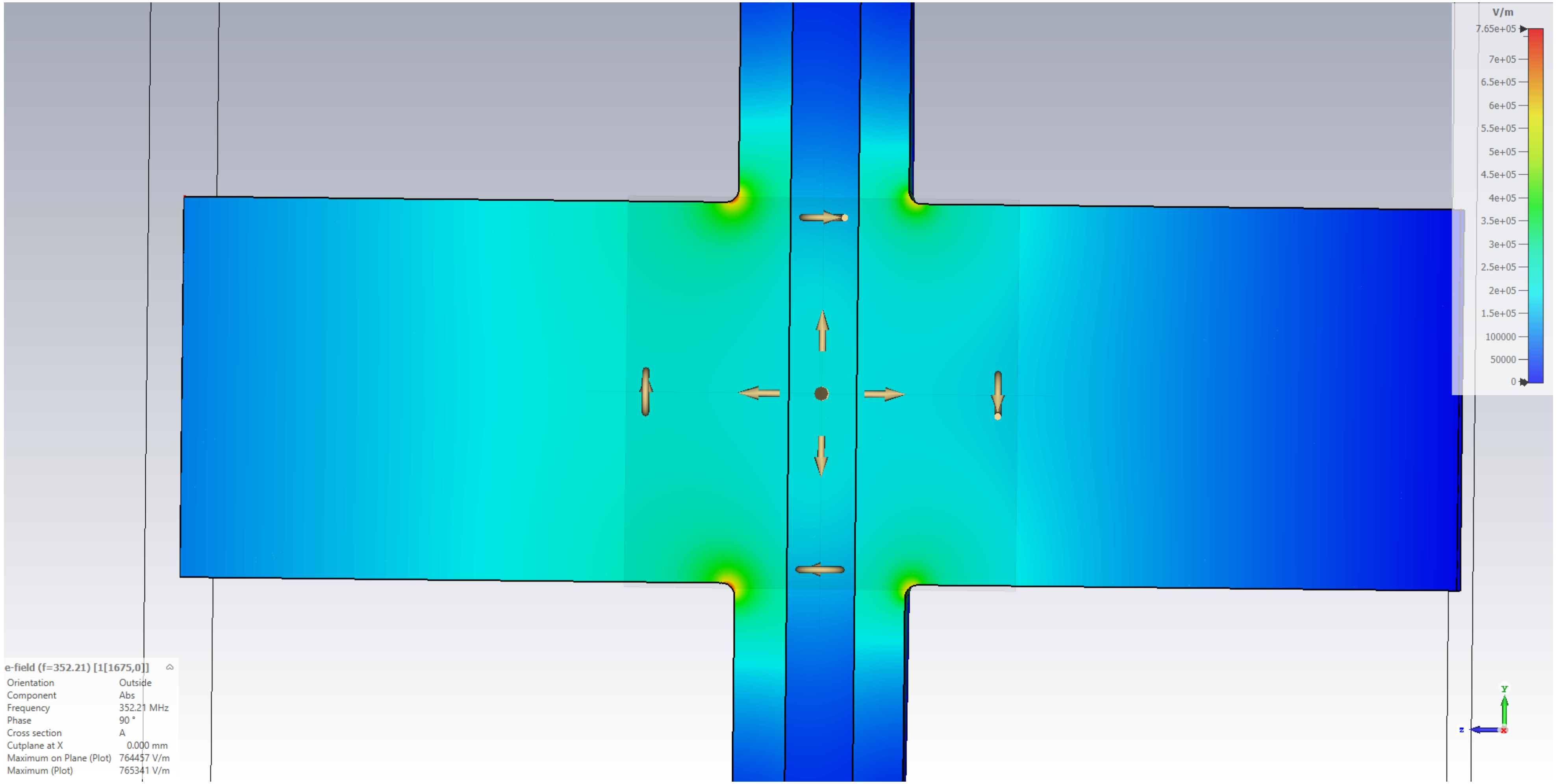
RF Matching procedure for a new geometry



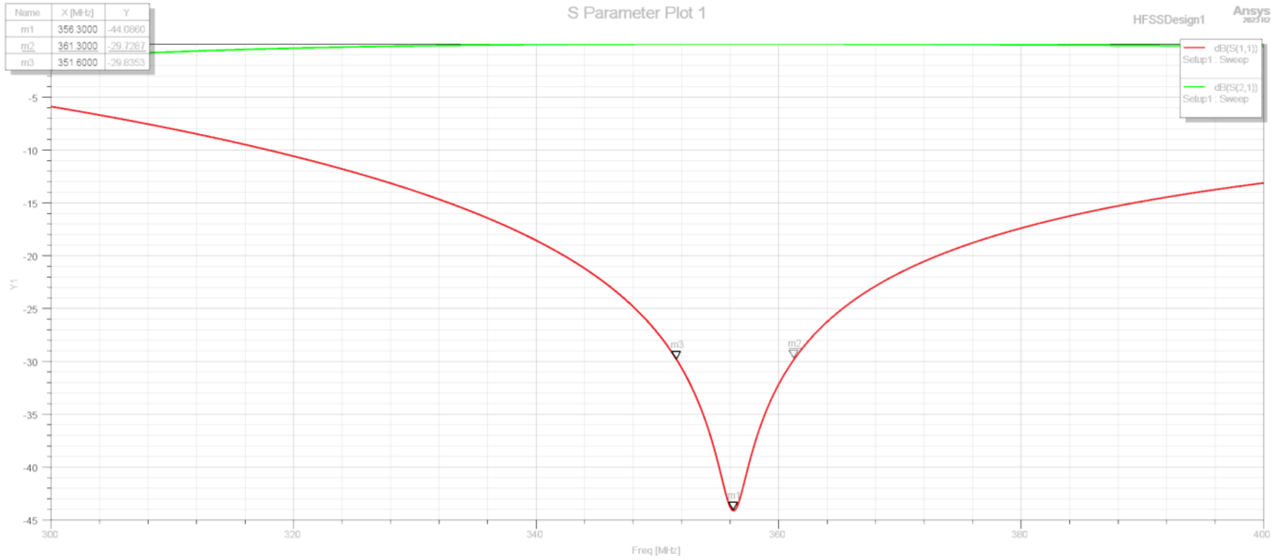
The dimensions of the VACUUM-side geometries zone are determined by the MP simulations.
In case we RF match using air-side.

E Peak field

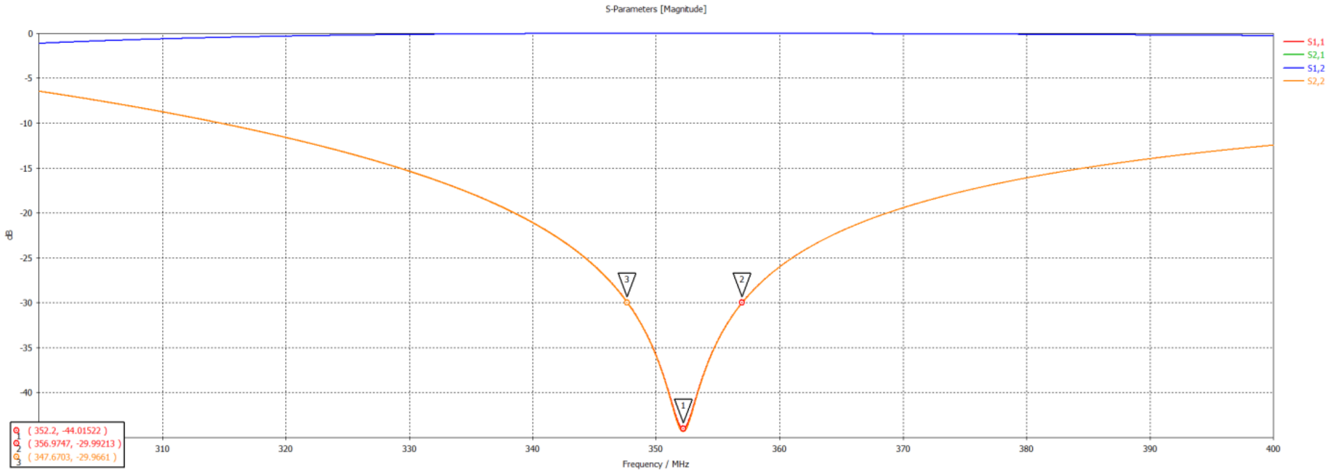
Calculated with CST

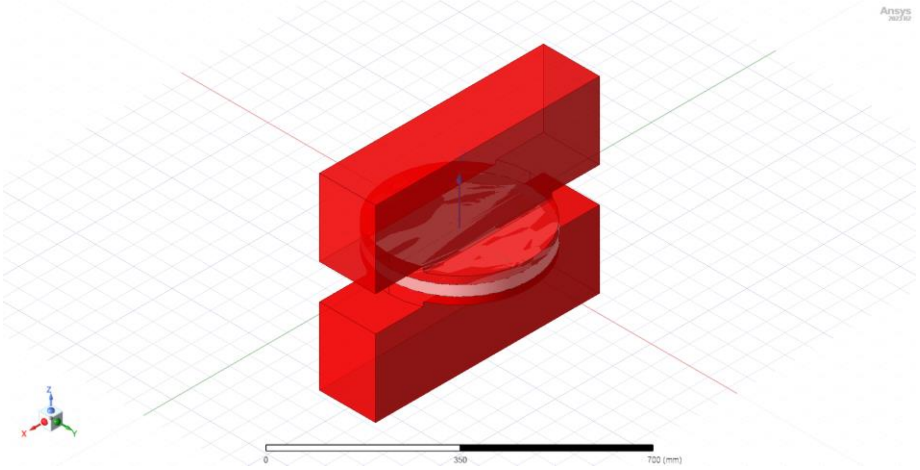


Result of matching procedure



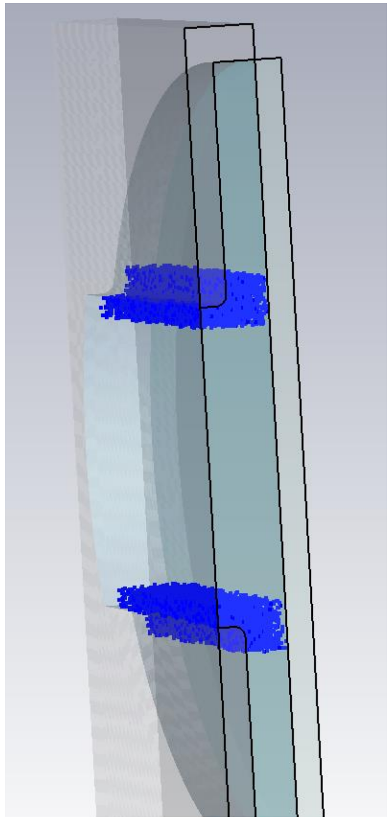
- -43.8 dB, peak
- 10 MHz band at -30 dB
- Alumina 99.5% purity, loss free
- Dielectric constant 9.8



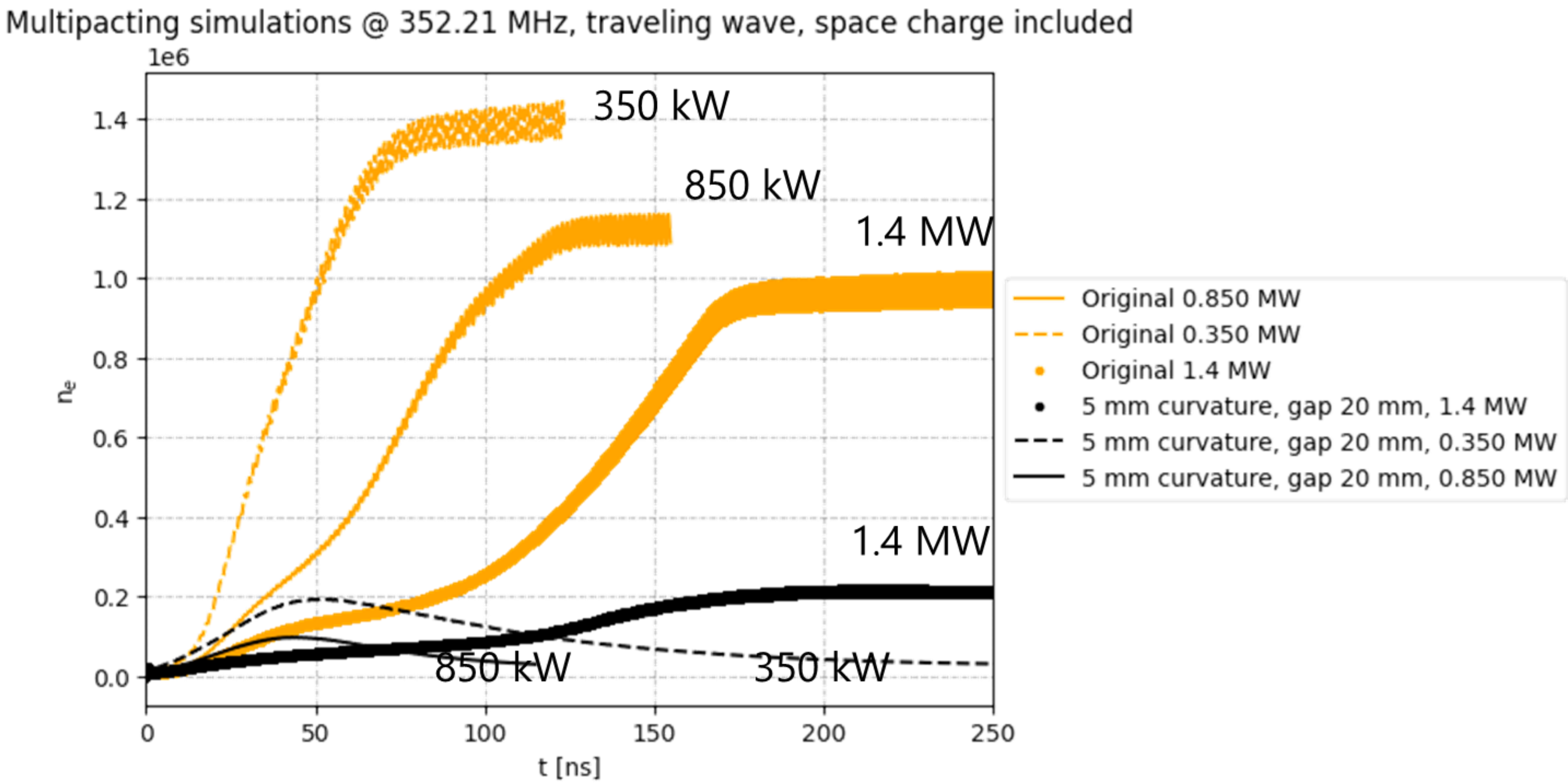


Multipacting simulations – imported SEY

20000 macro-electrons around the edges, starting energies between 1e-4eV and 10eV uniformly distributed. [ref 0]
SEY on Copper [ref1] interpolated at 150 degC
SEY on allumina [ref2] 200 degC, 5 nm alumina

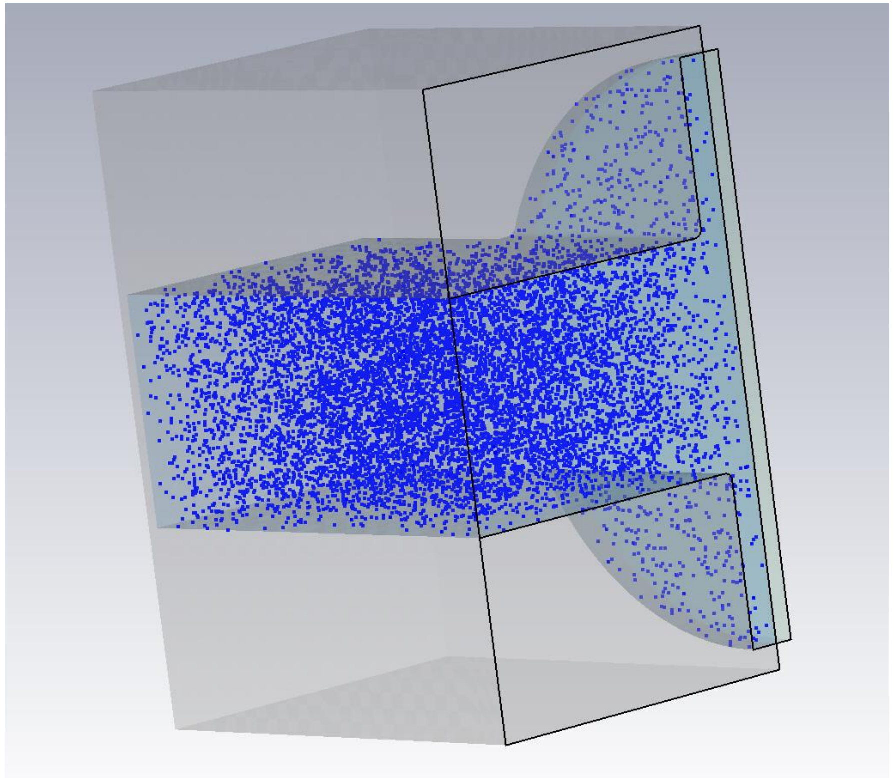


Starting position of macro-electrons

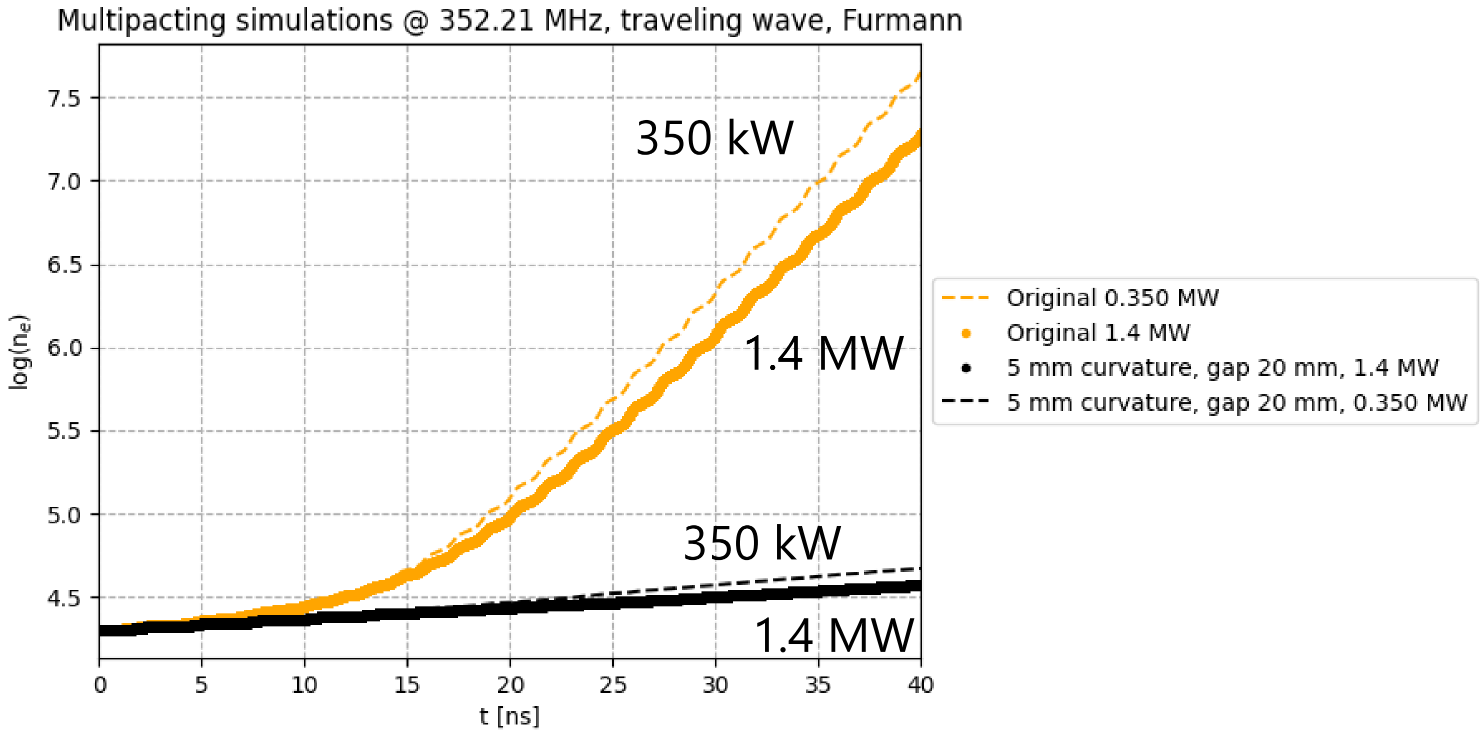


Window + waveguide, Furmann SEY

- 20000 electrons, no .s.c.
- Alumina SEY as [2]
- Copper Furmann
- Maxwellian distributed electrons [3]



Starting position of electrons

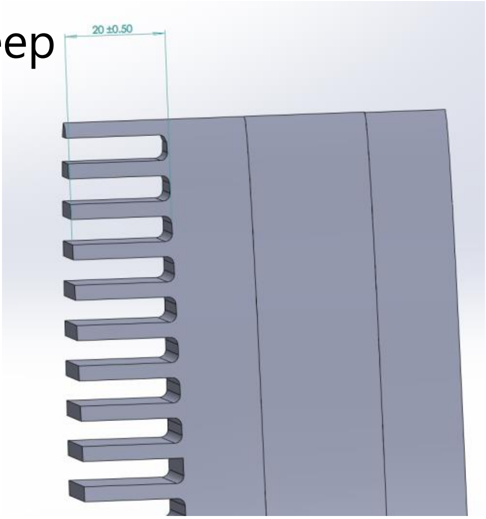


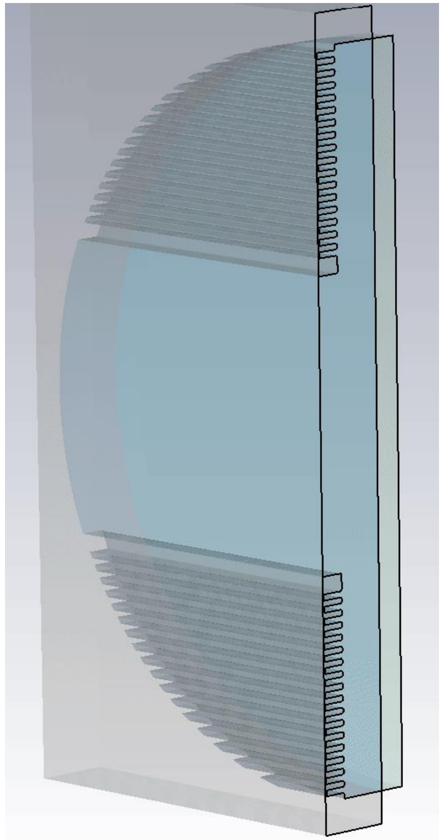
R&D on MP suppression

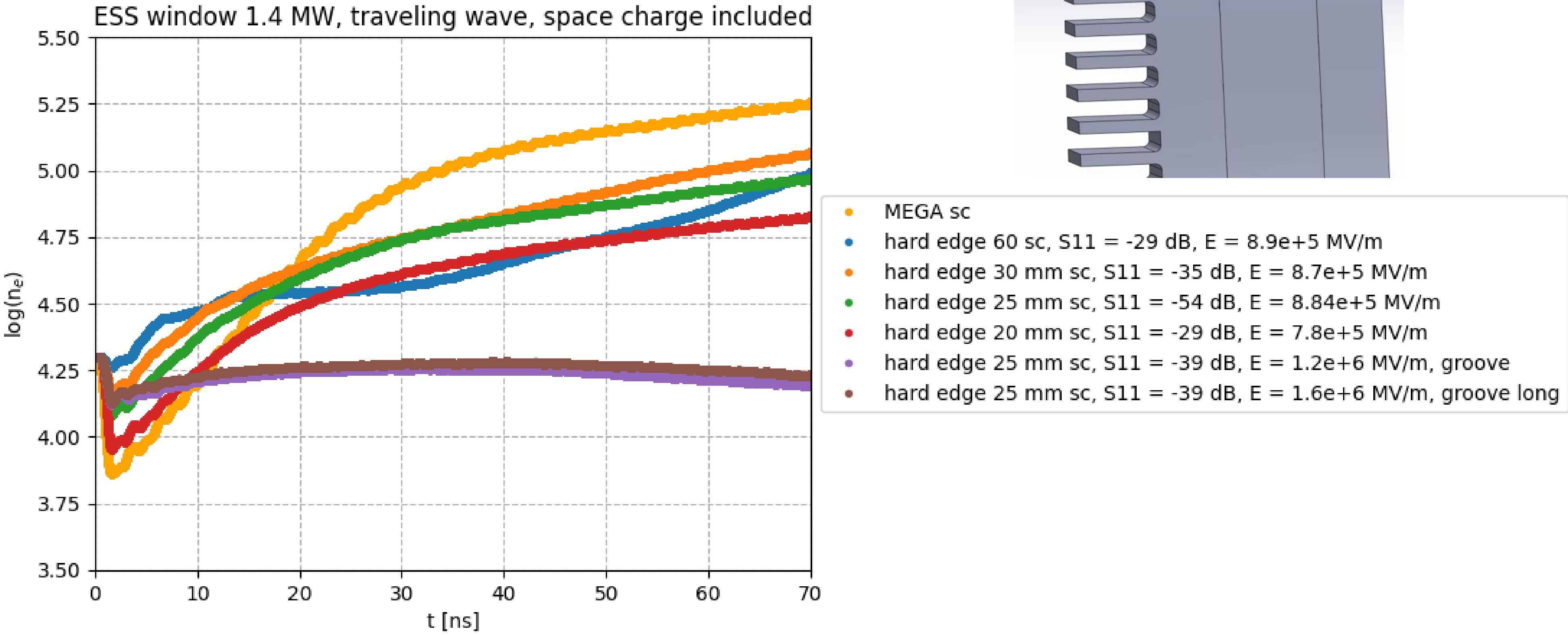
Use of the grooves to trap electrons

20 -12 mm deep

5 mm wide







LNL R&D

Design, coating, brazing

In the last years INFN has developed various high-power couplers.

Such devices have shown good performances, with some time limits in term of reliability and durability.

In view of future projects, we started a consolidation program on coupler design and realization. The development of a coupler is a multidisciplinary enterprise, that involves **mechanics, RF and vacuum expertise, material science.**

- We just showed some recent results on MP studies, moreover…
- LNL has internally brazing, coating and material analysis facilities and expertise
- We can set up a qualification process for the Ti(N) coating of different shapes of alumina windows (discs, coaxial, cylinders), able to evaluate composition, thickness and uniformity of the deposition. The qualification should be based on RBS or SEM on appropriate samples, then on resistivity measurements on the final parts.
- We want internally develop the brazing process ceramic-to-metal, which is a key asset for the coupler production, being nowadays one of the most time-demanding steps on the procurement chain **(adding 6-9 months)**

First calibration run at CERN

Layout for deposition test for RF windows: TiN or Ti coating qualification

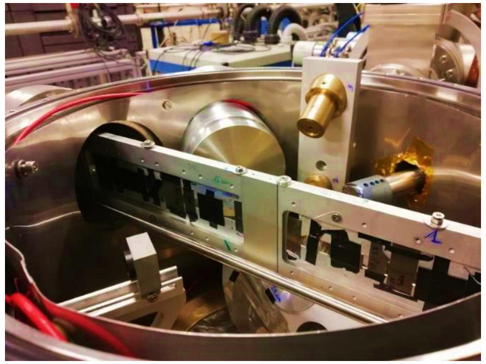
Sample description:

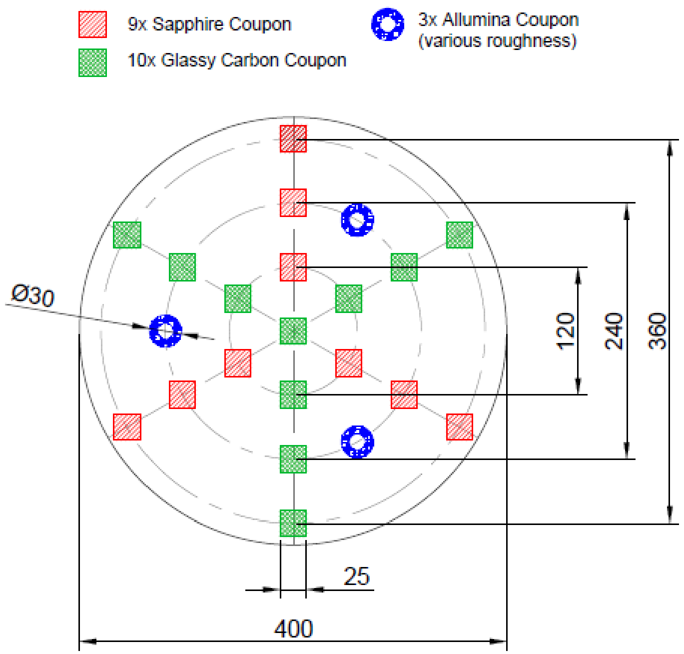
- Glassy carbon thickness: 2mm
- Sapphire thickness: 0.5mm
- Alumina samples if available at LNL.

Interested analysis:

- RBS and NRA for areal density and composition using glassy carbon substrates (@LNL).
- Roughness and further resistivity measurements on sapphire substrates (@LNL).
- SEY on Alumina substrates (@CERN).

Then we want to apply same calibration and qualification approach to multiple vendors.





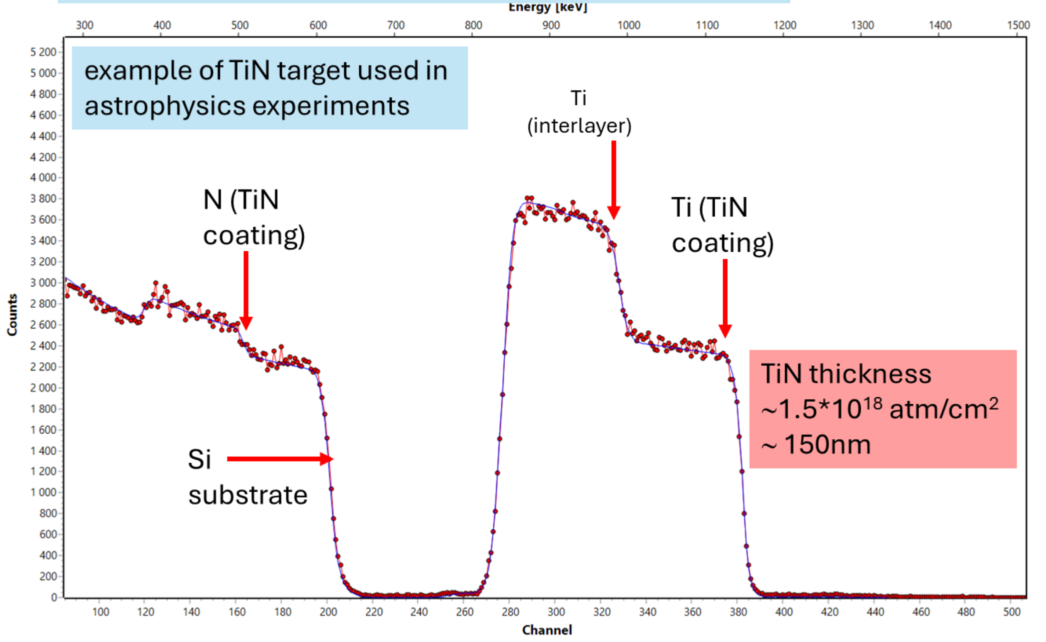
Courtesy of Wil Vollemberg -CERN
Matteo Campostrini and Carlo Roncolato - LNL

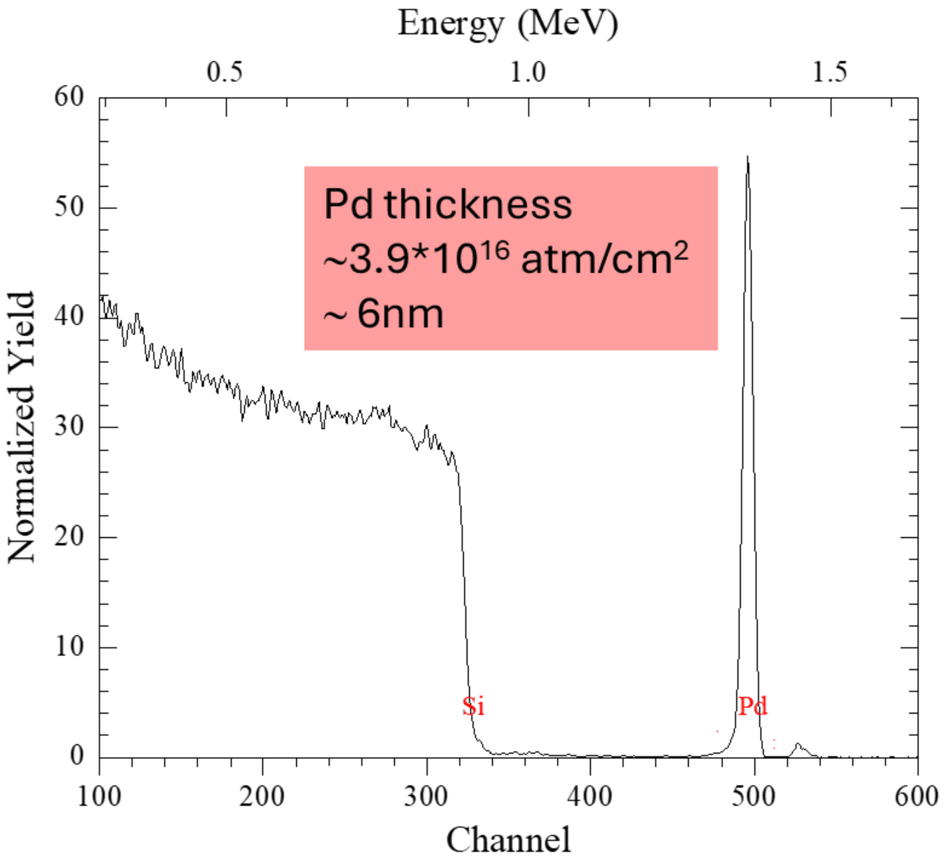
RBS analysis at LNL

Capability of analysis of tin layers and TiN sputtering (examples not from RF windows)

RBS spectrum of Pd/Si coating (solid angle internal standard) α Beam 1.6MeV [AN2000 facility LNL]

RBS spectrum of TiN/Ti/Si coating
α Beam 1.6MeV [AN2000 facility LNL]





Courtesy of Matteo Campostrini

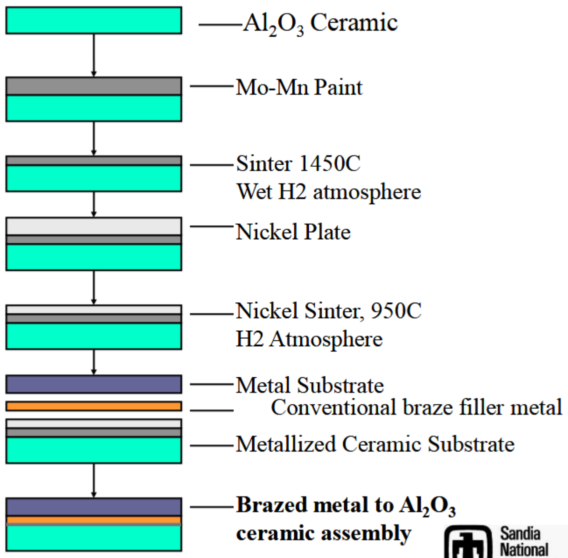
Brazing development

Active Brazing Alloys as alternative to make MoMnO+Ni metallization

Molybdenum-Manganese / Nickel Plate

Advantages
- Mature technology
- Proven history
- Easily brazed using standard filler metals
- Commercial Suppliers Available

Disadvantages
- Time consuming
- Multiple-step process
- Requires specialized equipment
- Nickel plating depletion
- Expensive



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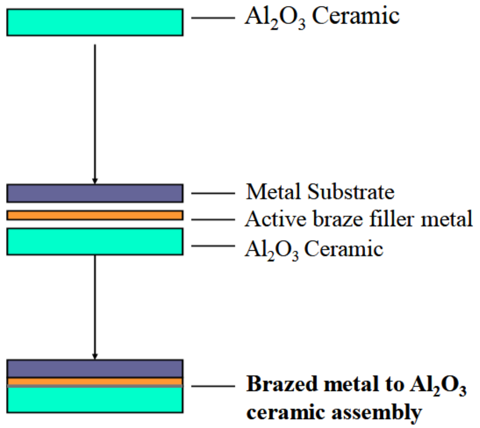
7

Active Filler Metal Brazing

Advantages
- Ease of use
- Variety of filler metal schemes & temperature ranges
- No specialized metallization equipment or processes required
- Easily brazed using standard filler metals

Disadvantages
- Requires specialized equipment/atmosphere control
- Not usable with all joint designs
- Size constraints



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17

C.A.Walker, Welding Journal 2008

Brazing development

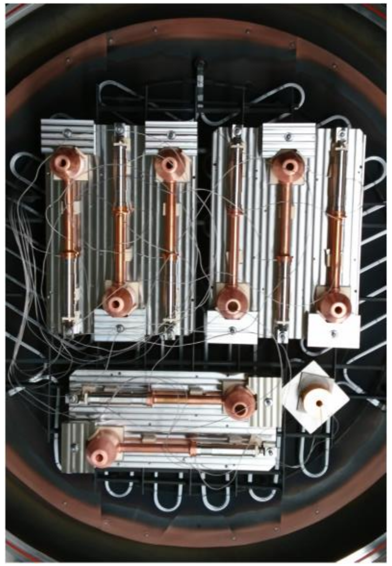
Active Brazing Alloys as alternative to make MoMnO+Ni metallization

LNL has long experience on traditional brazing techniques (IFMIF RFQ, ESS DTL).

Ordered at ITALBRASS/Kyocera a set of alumina disks (diam=25 mm, thickness=4mm) and ABA paste.

First test of brazing small samples on the small LNL vacuum furnace. Then actual geometries on the big vacuum furnace.

After brazing, the same samples will be used to characterize the SEY at different roughness values (1.6um and smoothest), provided that the coating thickness is the same→good input for simulations.



Brazing alloys Italbrass:
- paste CB10 (B-Ag64,8CuTi 780/805)
- Wire Cb4 (70.5Ag, 26.5Cu, 3Ti filo)

Both have an higher content of Ti, which is important for ceramic-metal bonding.

KYOCERA

DEGUSSIT AL23

2023.04.03

Material Type: Aluminium oxide (α-Al_2O_3)

MECHANICAL & PHYSICAL CHARACTERISTICS (TYP.)

Purity		[wt.-%]	>99.5
Density		[g/cm^3]	3.70-3.95[1)]
Open porosity		[vol.-%]	0
Average size of crystallites		[µm]	10
Bending strength σ_m DIN EN 843-1		[MPa]	300-350[1)]
Compressive strength		[MPa]	2500
Young's modulus (static)		[GPa]	380
Poisson's ratio		[-]	0.22
Hardness HV1		[-]	1740
Maximum service temperature in air		[°C]	1950
Linear coefficient of expansion	20 - 1000°C	[10^{-6}/K]	8.2
Specific heat 20 °C		[J/(kg*K)]	900
Thermal conductivity	20 °C 1000 °C 1500° C	[W/(m*K)]	34.9 6.8 5.3
Dielectric strength		[kV/mm]	20-30[1)]
Typical colour		[-]	ivory

[1)] Dependent on manufacturing method

Courtesy of Luigi Ferrari

Conclusions

Present design and next geometries

Ingredient for good RF window performances:

- RF design checked for multipacting → there is always a possible optimization
- General quality control, carefully qualification of TiN coating vendors.
- Avoid o-rings in proximity of the RF window
- High power RF must be run only at good vacuum level (< 1.0e-7 mbar)
- Automatize conditioning procedure
- Take your time for conditioning keeping light and vacuum below narrow thresholds
- RF windows remember their own history→ difficult (**but possible?**) to re-condition it
- Good handling, good coating and good vacuum cannot be replaced by a good design.

Recent issues have triggered a fast-learning curve of LNL task force.

Thank you for the attention