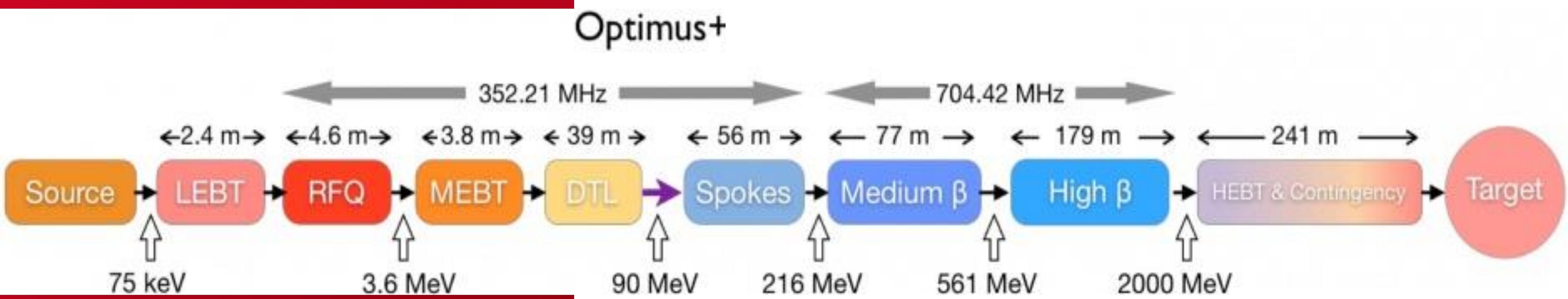
DE LA RECHERCHE À L'INDUSTRIE

ESS COUPLERS: MANUFACTURING AND CONDITIONING



C. Arcambal
CEA Paris-Saclay, 91 191 Gif-sur-Yvette, France

www.cea.fr

WORSHOP PIP-II, JULY 2022

OUTLINE

- **Overview of the ESS couplers for elliptical cavities**
  - General characteristics
  - Manufacturing of the Window, Double-wall tube and Doorknob

- **Preparation of the couplers before conditioning**
  - Inspection at the delivery of the components
  - Cleaning and assembly of the couplers on the coupling box
  - Baking

- **Conditioning**
  - Test bench and conditioning criteria
  - Results of the conditioning

- **Conclusion + comments about couplers on cryomodules**

GENERAL CHARACTERISTICS

- **120** couplers for ESS elliptical cavities (contract with PMB: **36** medium beta (MB) whose 6 pre-series couplers for the validation of the manufacturing process + **84** high beta (HB) couplers after a quality milestone about MB couplers).

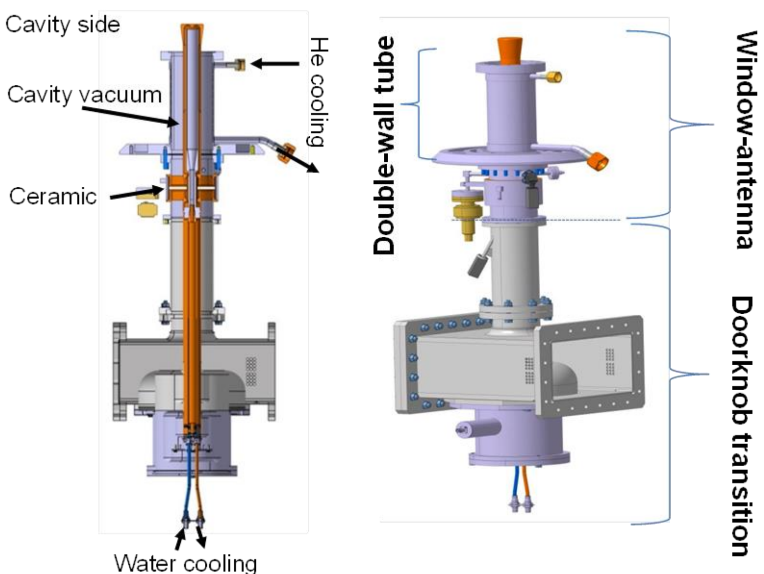
Features of the couplers

Features	Value
•RF frequency	704.42 MHz
•Repetition frequency	14 Hz
•Incident RF power	1.1 MW
•RF pulse width in full reflection (all phases)	500 µs
•RF pulse width in travelling wave	3.6 ms
•Voltage withstand (voltage between internal conductor and external conductor)	±10 kV

Nominal temperature	20°C
Temperature during baking	Max : 200°C for 100h
Water pressure in cooling circuit	3 bars
Water flow in cooling circuit	3 l/min
Water temperature in the antenna	from 20 to 25°C

Architecture of the couplers

- Three main parts: a single window with its antenna, a double-wall tube, a doorknob transition.
- Antenna window and doorknob transitions common to MB and HB cavities. Double-wall tube slightly different between the 2 kinds of cavities: only the tube length is modified



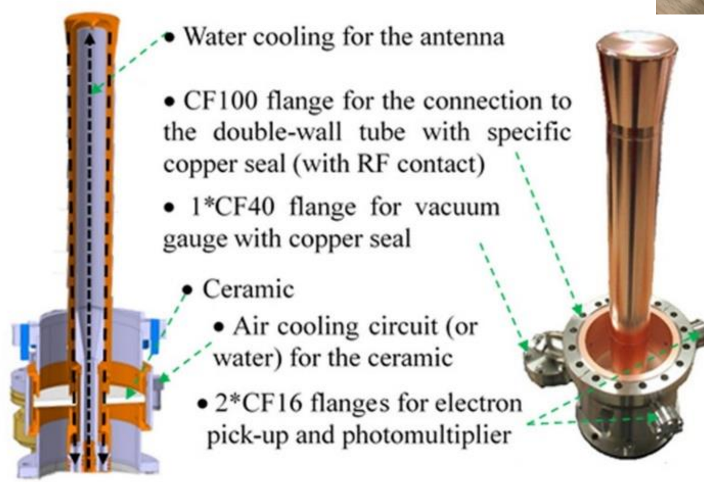
MANUFACTURING OF THE COUPLERS

MANUFACTURING OF THE WINDOW

Characteristics

- Diagnostic equipment: Electron pick-up, view port with a photomultiplier for arc detection on the vacuum side of the ceramic, IKR070 vacuum gauge from Pfeiffer
- TiN coating on the ceramic (vacuum side) (10 nm ± 5 nm thickness)
- Copper coating (30µm)
- Electropolishing of the antenna
- Electron beam welding for the antenna
- Operation steps: Brazing of the ceramic, TiN coating, EB welding

Electron pick-up

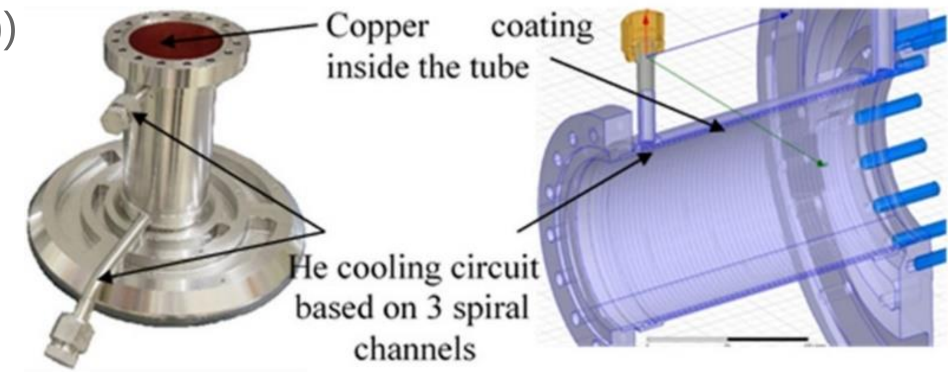


Validation during the manufacturing

- Vacuum tightness
- Water tightness
- Pressure test for the antenna cooling circuit and the ceramic cooling circuit
- Quality of the TiN coating (thickness and stoichiometric measurements on samples)
- Thickness and quality of the copper coating
- Dimensional control (antenna length, diameters of inner and outer conductors…)
- Roughness of the antenna
- Electric insulation between inner and outer conductors (>1GΩ)
- RF measurements on a window without antenna and on couplers put by pair with tubes on a coupling box

MANUFACTURING OF THE DOUBLE-WALL TUBE

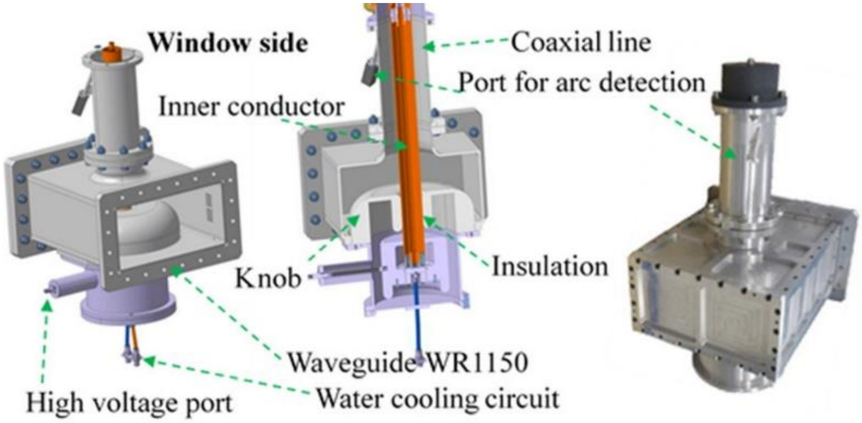
- **Characteristics**
  - Welding of the flanges
  - Copper coating (10µm, RRR∈[20;40]))

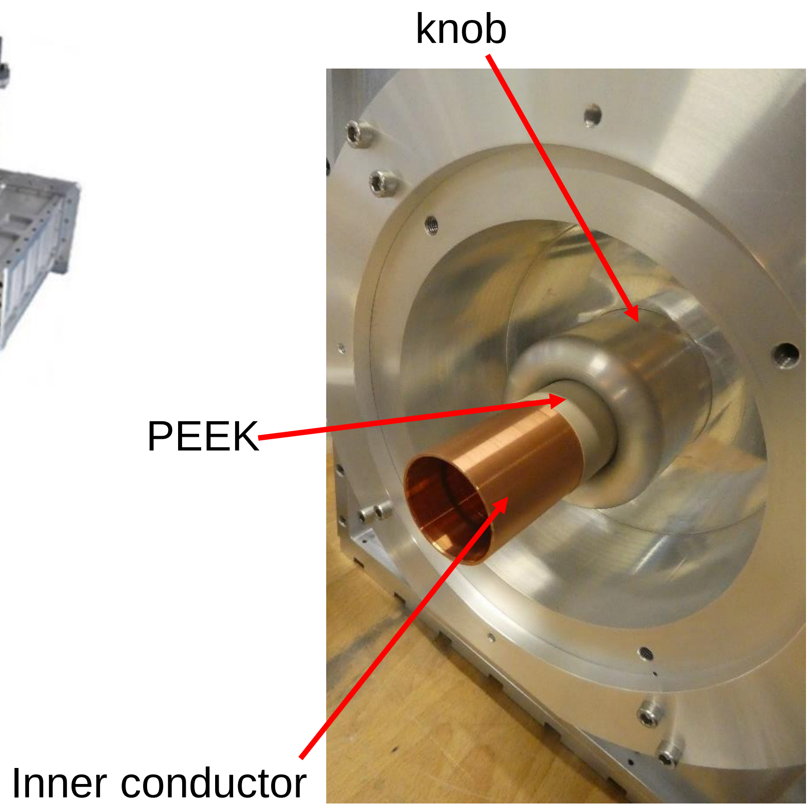


- **Validation during the manufacturing**
  - Vacuum tightness of the inner par and of the cooling circuit
  - Pressure test for the cooling circuit
  - Dimensional control (tube length, diameter of outer conductors…)
  - RF measurements with window
  - Copper layer thickness and RRR measurements on samples
  - Quality of the copper layer (no cracks, no oxidation…)
  - Thermal shock (comment: on cryomodules, temperature gradient from 2K (small flange) to ambient temperature (big flange))

MANUFACTURING OF DOORKNOB TRANSITION

- **Characteristics**
  - Insulation obtained with a material with a dielectric constant =3.3 (+/-10%) able to provide 10kV insulation (breakdown voltage ≥18kV).
    Insulation cylinder obtained from solid material and machining. No lamination, no adhesive tape, no film roll. Shrink-fitting method

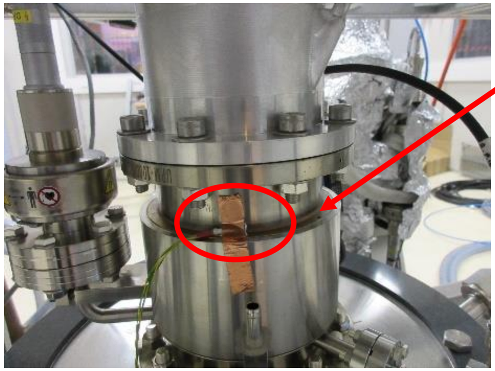


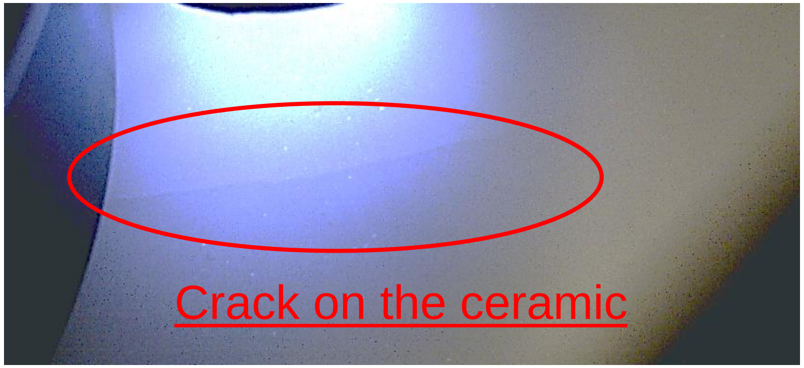


- **Validation during the manufacturing**
  - Vacuum tightness of the cooling circuit
  - Pressure test for the cooling circuit
  - Electric insulation test (10kV)
  - Dimensional control
  - RF measurements

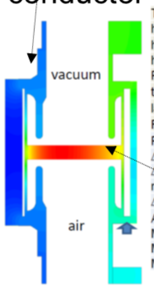
COMMENTS ABOUT MANUFACTURING: WINDOW, TIN COATING (1/2)

- **Problem with the TiN coating**
  - Conditioning OK for the 6 pre-series MB couplers
  - For the first series MB couplers, high increase of the window temperature (+22°C instead of + 1,6°C. On the first coupler, crack on ceramic during the conditioning and loss of vacuum tightness)

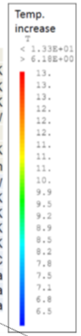




  - Simulations performed to find the origin of the temperature increase: if the ceramic losses increase by a factor 10, we can reach the measured temperature before the crack

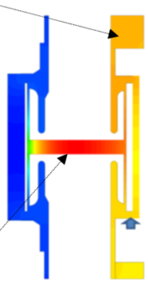


T_eau	T_air+6	
heau	500	W/m².K
h_air	5	W/m².K
h_air_canal	0.1	W/m².K
P RF (avg)	50000	W
tg delta ceram	**3.0E-04**	
lambda Cu	200	W/mK
RsCu 20°C	6.90E-03	Ohm
Pdiss_ceram	8.23	W
ΔT inner boundary	10.6	K
ΔT outer boundary	10.8	K
maximum ΔT	13.3	K
ΔT at sensor	8.84	K
Abs T at sensor	28.84	°C
Max VM Ceram	23.964	MPa
Max VM cuivre (int)	13.997	MPa
Max VM cuivre (ext)	23.744	MPa

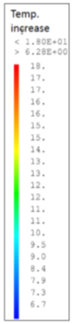


50kW average

Nominal conditions (1MW)



T_eau	T_air+6	
heau	500	W/m².K
h_air	5	W/m².K
h_air_canal	0.1	W/m².K
P RF (avg)	**6000**	W
tg delta ceram	**3.0E-03**	
lambda Cu	200	W/mK
RsCu 20°C	6.90E-03	Ohm
Pdiss_ceram	9.87	W
ΔT inner boundary	12.5	K
ΔT outer boundary	16.2	K
maximum ΔT	18	K
ΔT at sensor	14.6	K
Abs T at sensor	**34.6**	°C
Max VM Ceram	37.8	MPa
Max VM cuivre (int)	15.5	MPa
Max VM cuivre (ext)	38	MPa

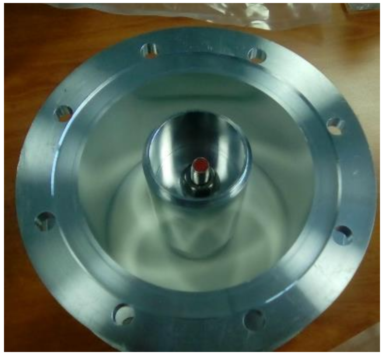


6kW average

Conditions just before the crack

COMMENTS ABOUT MANUFACTURING: WINDOW, TIN COATING (2/2)

- **Problem with the TiN coating**
  - Conditioning of a window without TiN coating: no high temperature increase but lots of electrical arcs in standing waves.
  - TiN coating on a ceramic put in a window mock-up, measurement of the equivalent dielectric losses at 1.8GHz in a resonant cavity: ceramic without TiN (εr=9.47 and tan δ= 2.78x10^{-4}) and a ceramic with bad TiN (εr=9.44 and tan δ= 2.04 x10^{-3}) (measurement correlated with simulations to extract the equivalent permittivity).



Window mock-up

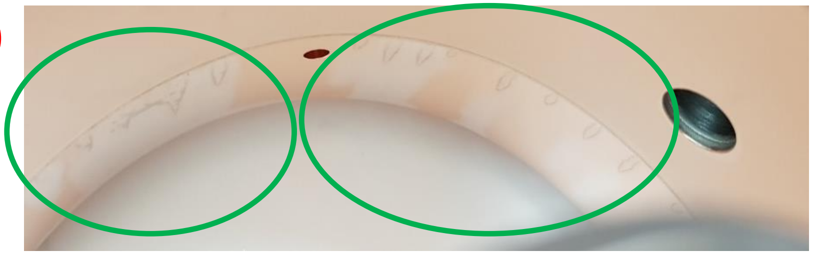
Ceramic after TiN coating (not the nominal adjustment)

  - The problem of high temperatures comes from the ceramic losses due to a bad TiN thin film
  - Change of the TiN coating adjustments (No improvement, impossible to find the changes between pre-series and series TiN coating).
  - Finally, change of the TiN subcontractor and launch of a new qualification.
  - Almost 1 year to find a correct TiN thin film.

COMMENTS ABOUT MANUFACTURING: WINDOW

- **Pollution of the ceramic**: Bad positioning of the ceramic protection during the electron beam welding (1)
- **Flow of the filler metal on the copper** during the brazing (2)
- **Weakness of the weld** close to the vacuum gauge flange (3) (2 windows with leak). As we can tilt the tube when we screw the gauge on the window flange, we can weaken the weld.

(2)

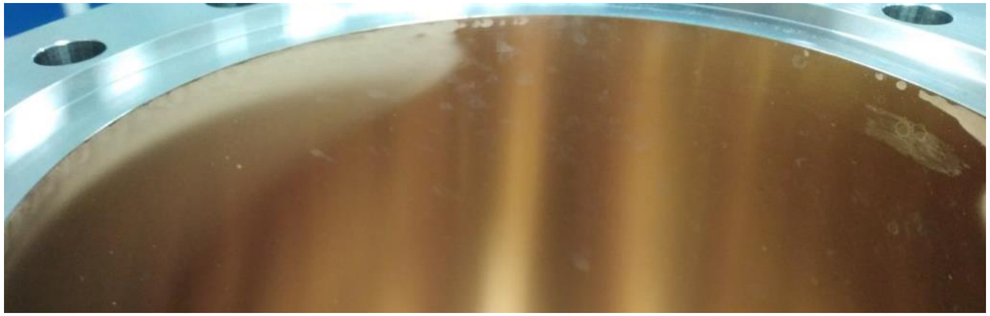


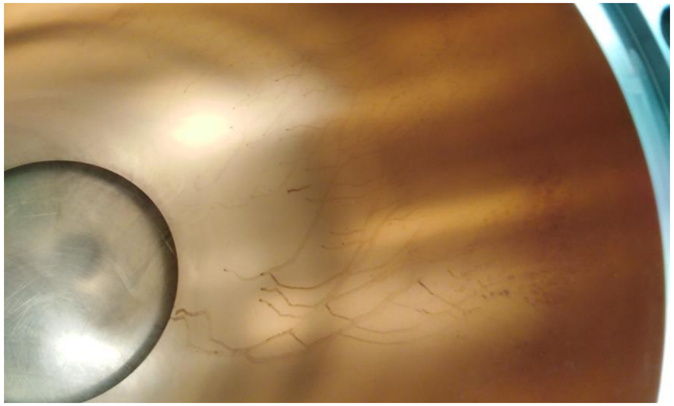
(1)

(3)

COMMENTS ABOUT MANUFACTURING: DOUBLE-WALL TUBE

- **Copper coating:**
  - **Aspect:** coating is operator dependent. Last year, obligation de remove copper coat on 12 tubes (scratch, stain, mark…)

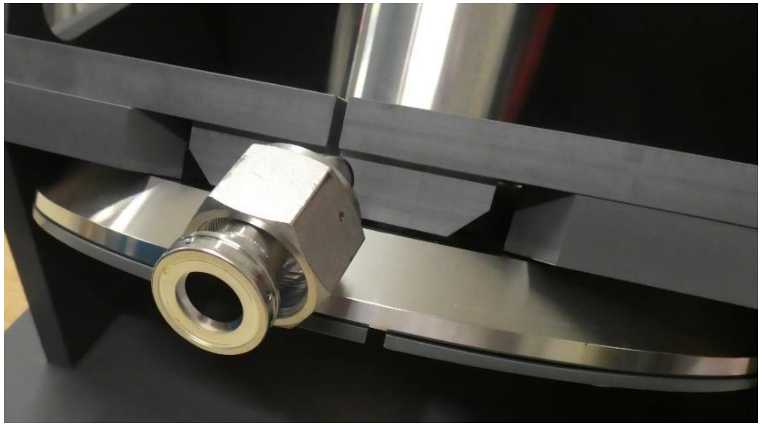




  - **RRR** measured on copper coated samples:
close to 100 instead of the range [20,40].
No influence on the He consumption of the cryomodule.

COMMENTS ABOUT MANUFACTURING: DOUBLE-WALL TUBE

- **VCR connector for the He cooling circuit:**
  - In the manufacturing of the tubes, a stress-relief heat treatment is performed at 950°C. For medium beta, the VCR connectors were assembled before heat treatment and at 950°C, the silver coat in the connector begins to flow.
  - For medium beta, we were obliged to manually silver coat the connectors of the cryomodule cooling circuit.
  - For high beta, we change the sequence of manufacturing, and the VCR connectors are put after the heat treatment



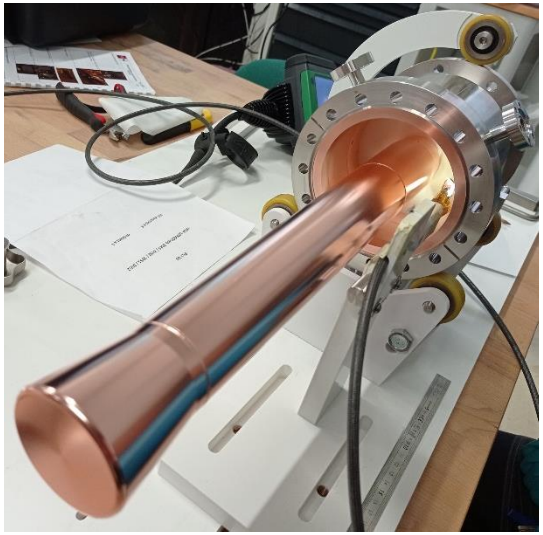
VCR connector of the double-wall tube

VCR connector of the cryomodule cooling circuit

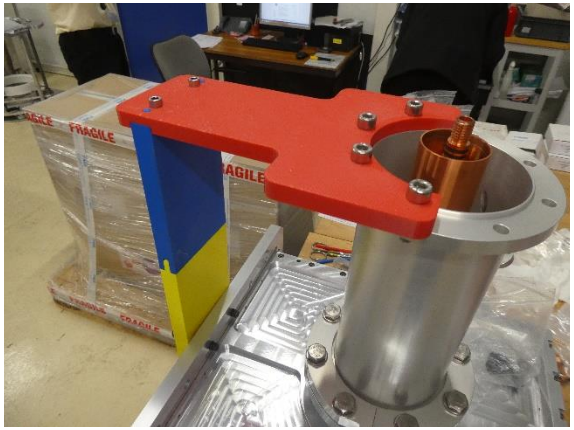
PREPARATION OF THE COUPLERS BEFORE CONDITIONING (AT CEA)

CONTROL OF THE COUPLERS

- **Window:**
  - Windows delivered in a metallic box filled with nitrogen
  - Check of the cleanliness
  - Visual control of the antenna, inner and outer conductor
  - Inspection of seal grooves, knife edge of Conflat flanges
  - Inspection of the choke with an endoscope (development of a specific tool)
  - Check of the documents
- **Tube:**
  - Tubes delivered in 2 bags under vacuum
  - Check of the cleanliness
  - Inspection of seal grooves, knife edge of Conflat flanges
  - Inspection of the copper layer
  - Inspection of the VCR connector and we screw a VCR plug to check the correct screwing
  - Check of the documents
- **Doorknob transition**:
  - Check of the documents
  - Check of the orientation of the flange
  - Check of the high voltage insulation after conditioning



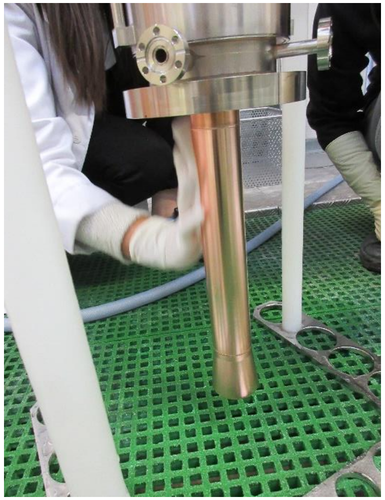
Check with endoscope



DK flange orientation

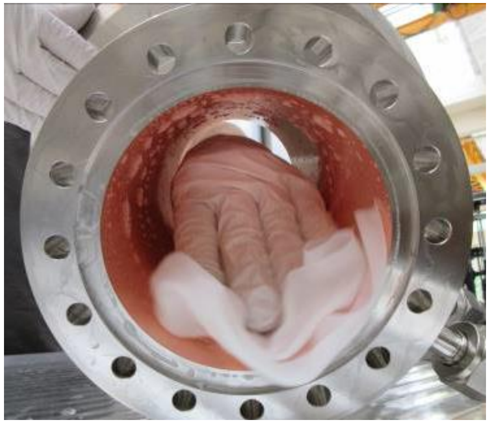
CLEANING OF THE COUPLERS

- **Window:**
  - Manual cleaning with ethanol for window and RBS T310 for the antenna
- **Tube:**
  - Ultrasonic bath with the detergent Tickopur R33 (40°C)
  - If oxidation marks, manual cleaning with RBS T310
- **Pick-up electron**: Ultrasonic bath with ethanol
- **Screw**: Ultrasonic bath with the detergent Tickopur R33 (50°C)



Manual cleaning with RBS

US cleaning with Tickopur

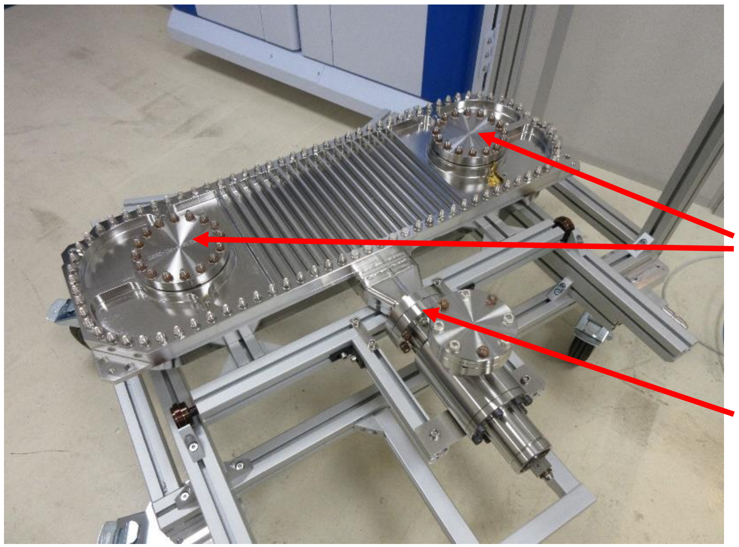


Manual cleaning with RBS

US cleaning with ethanol

THE COUPLING BOX

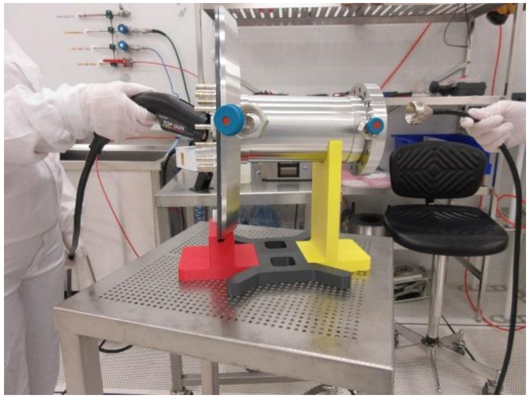
- 2 coupler ports + 1 port for a photomultiplier + 1 port for the pumping
- Aluminum wire between top and cover to ensure the vacuum tightness



Photomultiplier port

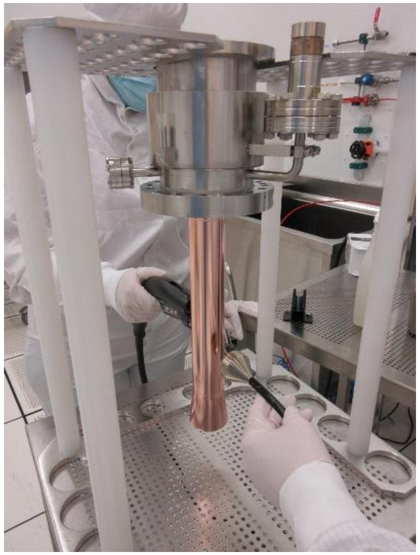
ASSEMBLY IN A CLEANROOM ISO5

- Particle counting of the tubes, windows
- Assembly of the window on the tube with a robot
- Vacuum tightness test
- Switch on the vacuum gauge to check the correct start-up



Particle counting of the tube

Window on tube



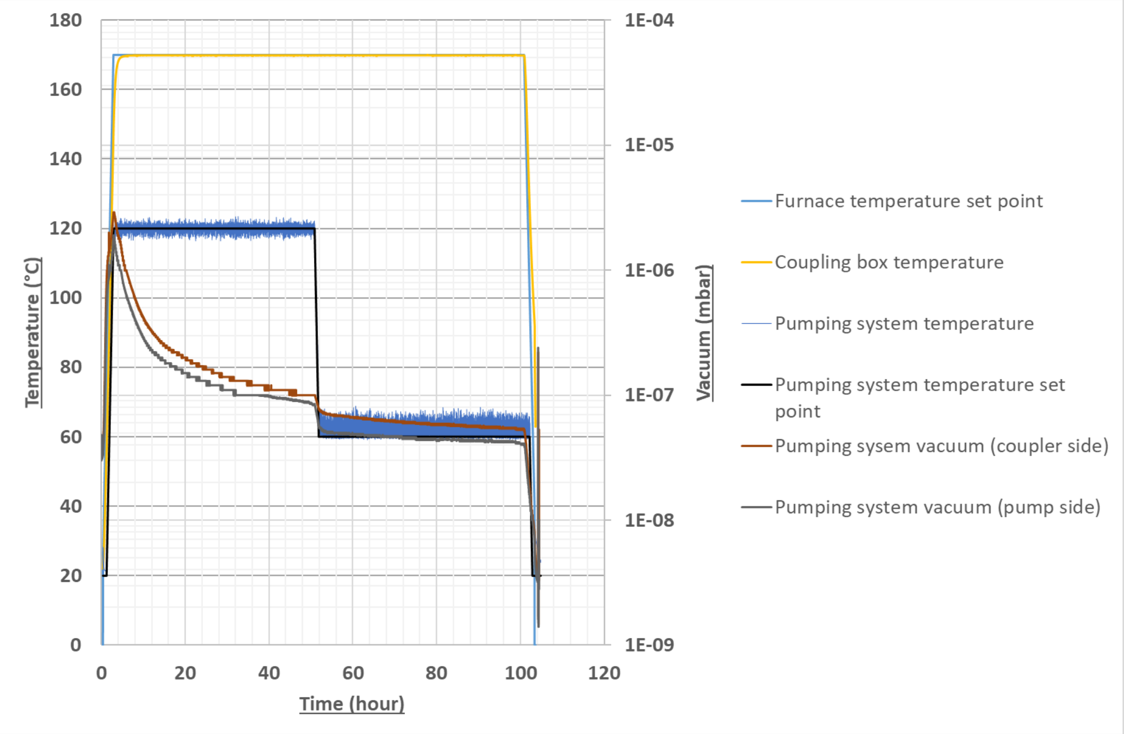
Particle counting of the window

Assembly on the coupling box

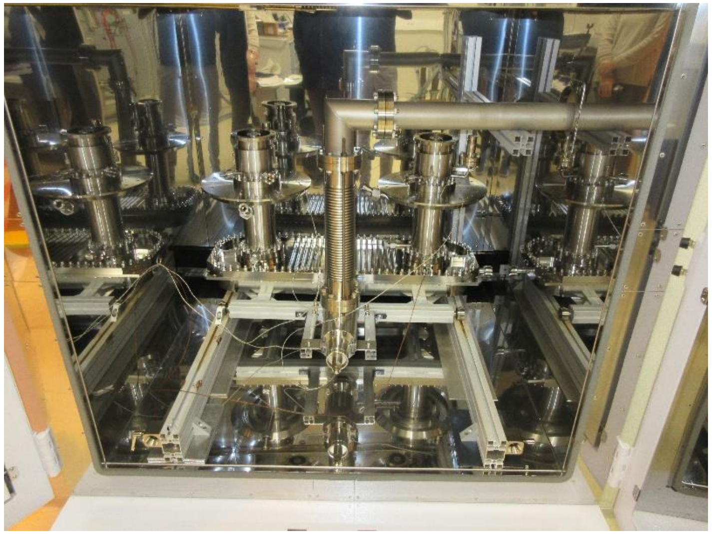
Vacuum gauge

BAKING IN A FURNACE

- Baking in an oven (couplers 170°C for 4-5 days, pumping system 120°C for 2 days then 60°C)
- Oven filled with nitrogen to limit the oxidation of the copper in the window air side.
- Pumping group is heated with heating tapes
- Residual gas analysis during the baking



Baking (temperature and vacuum)

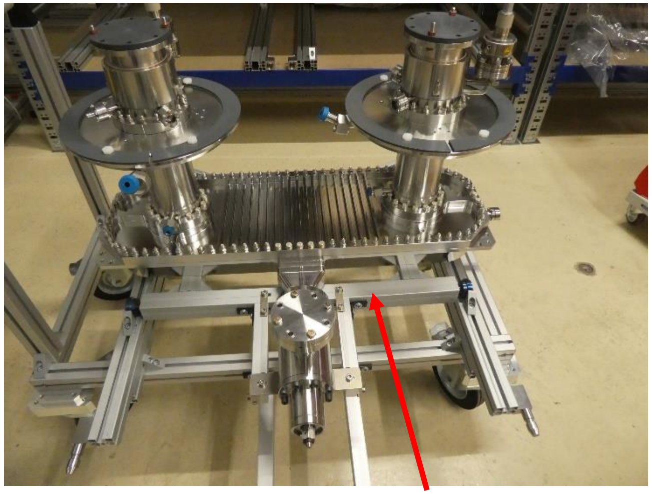


Couplers in the oven

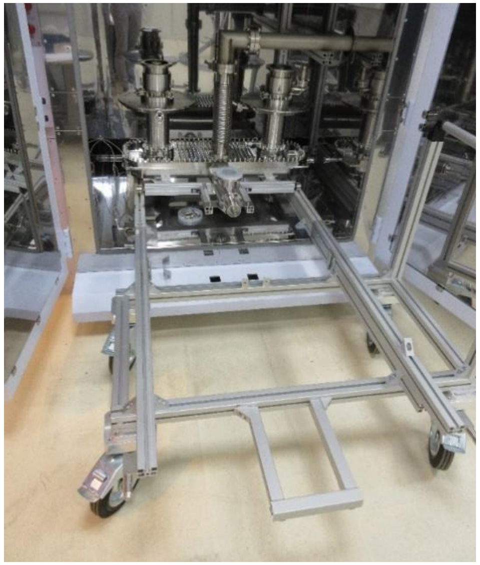
Air side

TRANSFER OF THE COUPLERS

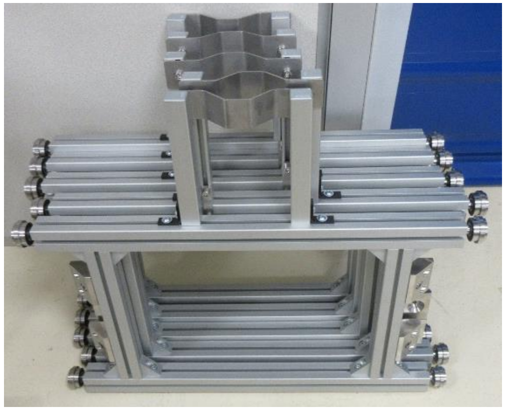
- System of rails to avoid any lifting of the couplers
  - In cleanroom, coupling box put on the trolley
  - Transfer to baking furnace
  - Transfer to conditioning bench



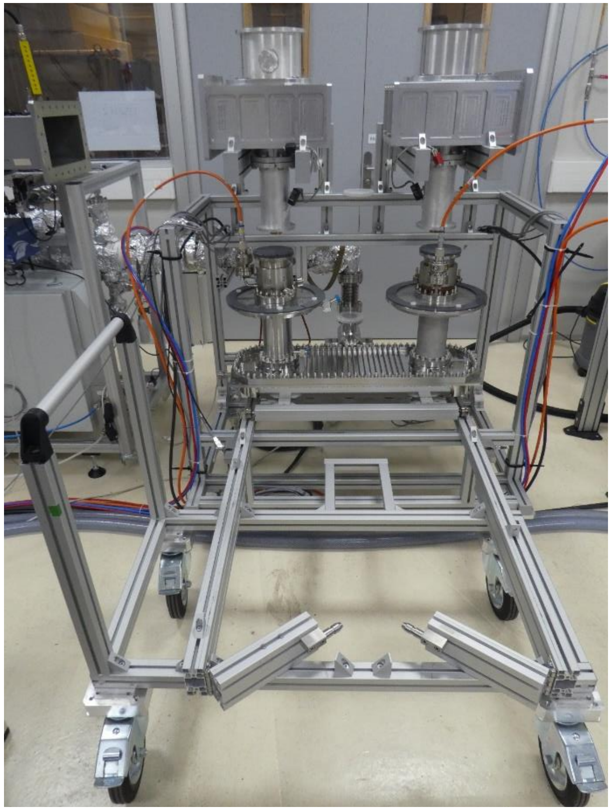
Coupling box on the trolley



Furnace



Trolleys



Conditioning bench

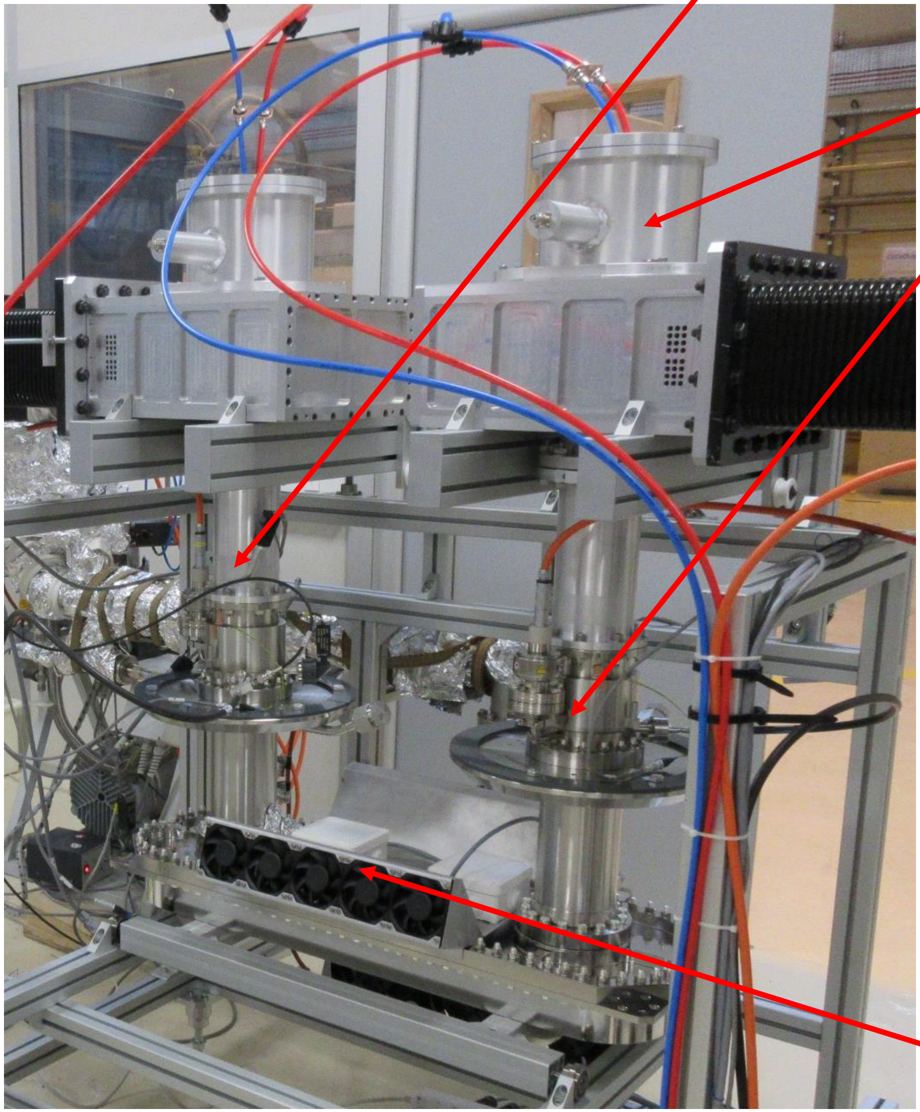
CONDITIONING

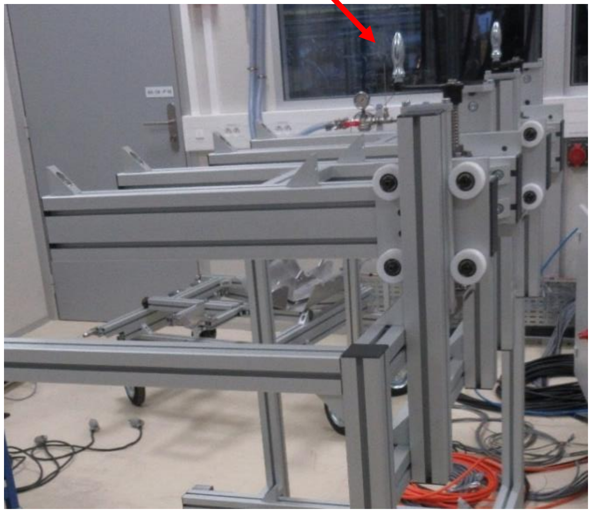
CONDITIONING AT CEA SACLAY

- 2 klystrons to perform conditioning of 2 couplers pairs in parallel.
- Couplers conditioned by pair on a coupling box in travelling waves (at 1 Hz then 14Hz) and standing waves (at 1 Hz then 14Hz) for 2 positions of the short circuit (minimum then maximum electric field close to the ceramic).
- Pumping system: effective speed ≈ 20l/s, whole conductance≈ 24l/s. Turbo pump: 300l/s.

CONDITIONING TEST BENCH

- Zoom on the couplers

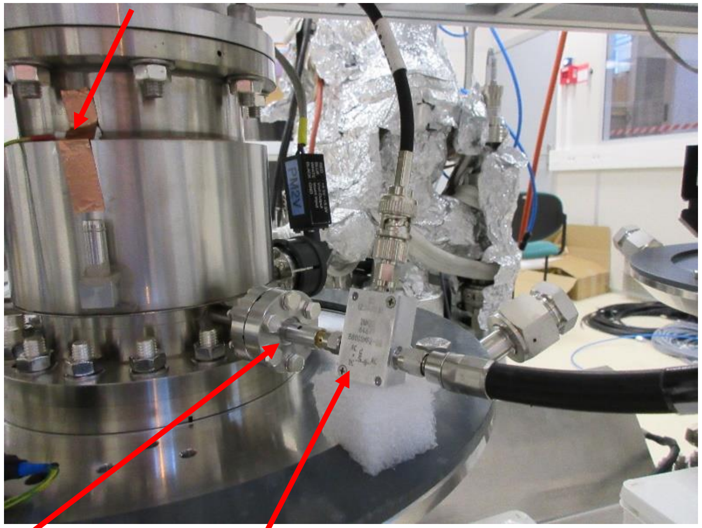




DIAGNOSTIC COMPONENTS

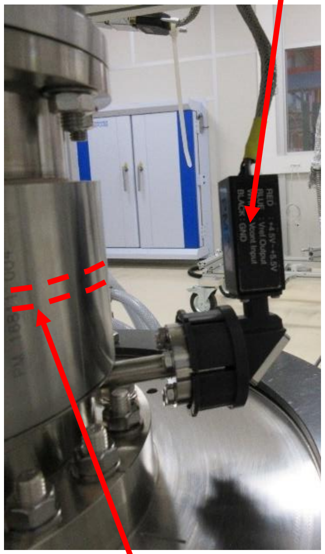
- Control instruments on the ESS couplers:
  - Vacuum gauge (IKR070 from Pfeiffer)
  - Window for photomultiplier (model H10721-110 from HAMAMATSU) (ceramic on the vacuum side)
  - Photomultiplier on the doorknob transition (ceramic on the air side)
  - Electron pick-up (for multipactor + RF coupling)
  - Temperature probe on each window
- Control instruments on the coupling box and pumping system:
  - Window for photomultiplier on the coupling box
  - Vacuum gauges on the pumping system
  - Temperature probe on the coupling box

Temperature probe



Pick-up with its bias tee

Photomultiplier (vacuum side)



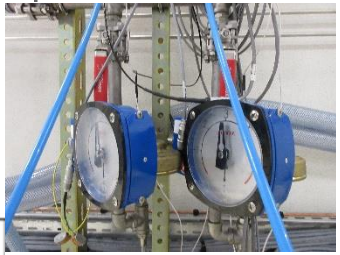
Position of the ceramic disk

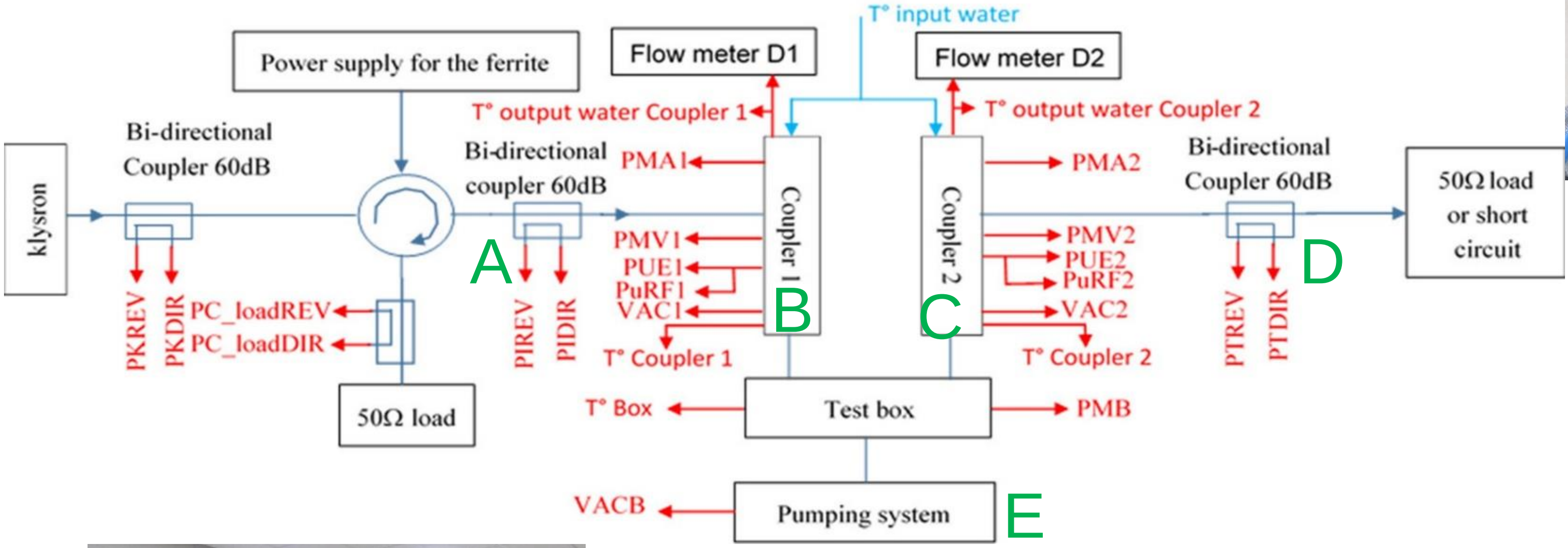
Photomultiplier (air side)

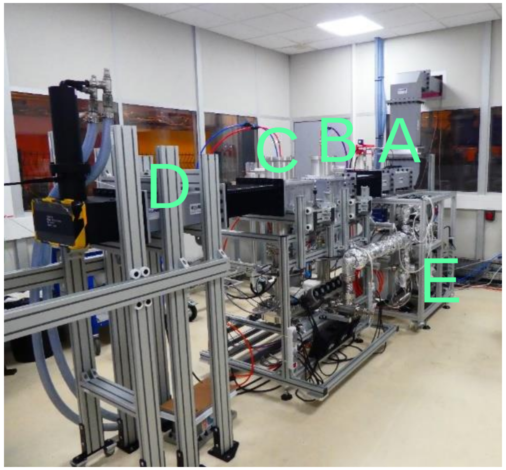
RF TEST STAND

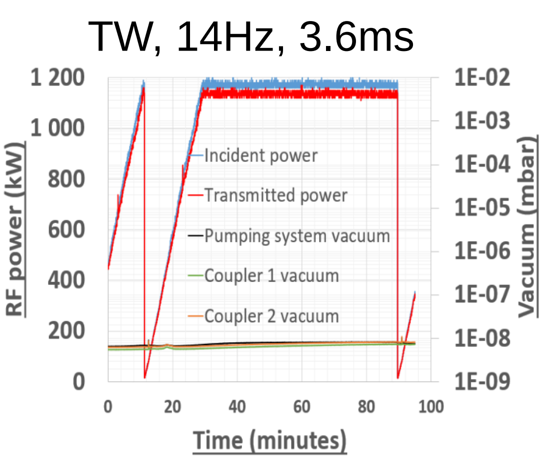
RF conditioning

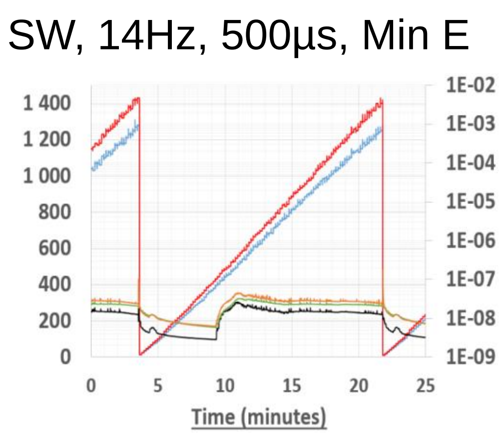
- Check of the incident reverse RF powers, vacuum, electric arcs, multipactor, temperature, water flow





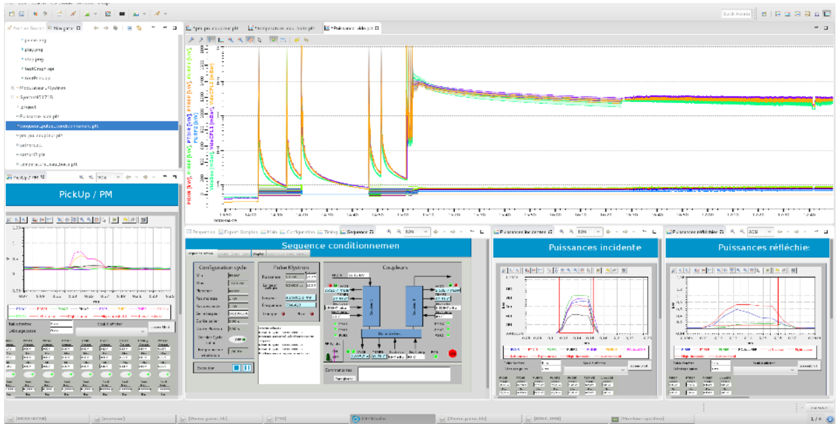






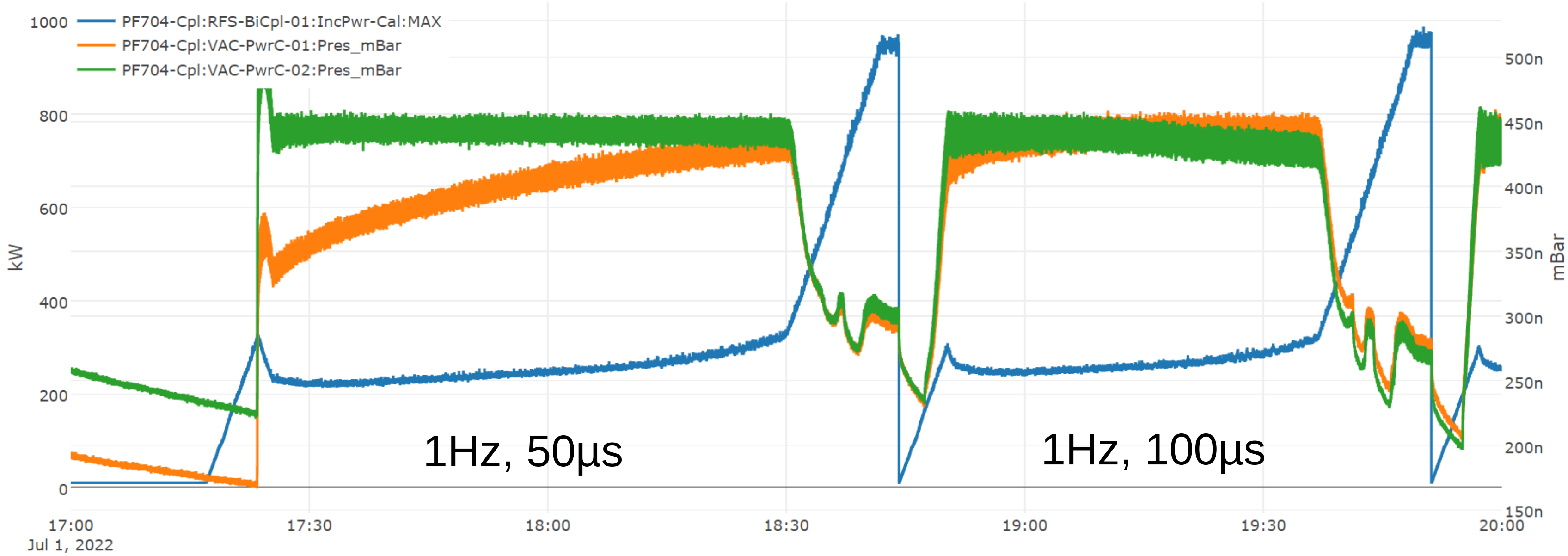
CONDITIONING PROCEDURE

- RF power ramps from around 10 kW to 1.1 MW (pulse width from 50µs to 3.6ms), increase step by step (usually 1 kW per second)
- Conditioning mainly on the vacuum (definition of a variable vacuum threshold to increase or decrease the power in function of outgassing)
- RF power switched off when
  - Outgassing with a vacuum level exceeding a hardware threshold defined at $1x10^{-6}$ mbar
  - Presence of electrical arcs whose intensity is greater than around 3 lux (photomultiplier),
  - Presence of electrons whose intensity is greater than 8 mA (detected with the pick-up electron).
  - Temperature of the coupler greater than 45°C or T° of the coupling box greater than 60°C
- The automated handling of all the conditioning sequences, the interlocks and the data recording are controlled with EPICS



CONDITIONING

- Beginning of the conditioning: 1Hz, travelling waves. Vacuum threshold fixed at 4.5x10^{-7} mbar

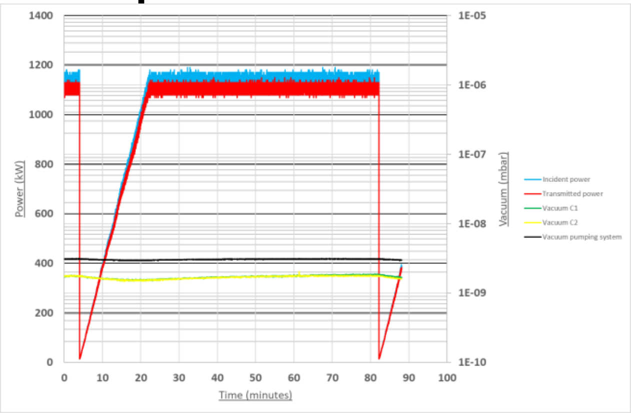


- Acceptance criteria: (defined after the conditioning of 8 prototype couplers)
  - Outgassing lower than 2x10^{-8} mbar
  - TW sequence time lower than 120 RF hours (not really applicable)
  - No parasitic activity (light or electron). RF ramps performed without high voltage bias on the antenna.
- Possibility to apply a HV bias on the antenna: up to 10kV. During conditioning, electron activity rather weak. With a 500V Bias, possibility to reduce activity.

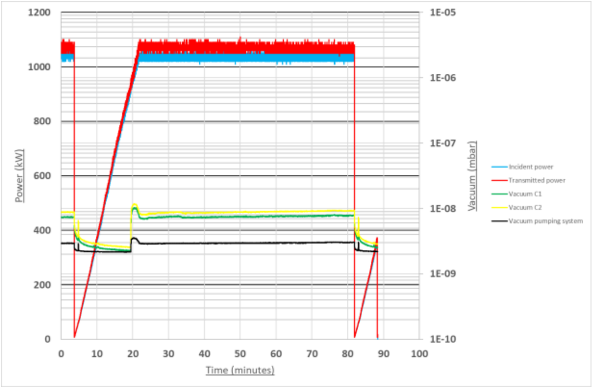
CONDITIONING RESULTS OF MEDIUM BETA COUPLERS (1/3)

- We have conditioned all the 36 medium beta couplers
- In travelling waves (14Hz, 3.6ms, power ramp+ plateau 1H), 3 kinds of behavior:
  - No outgassing (eg 2025-2026)
  - 1 or 2 outgassing phenomena (at 70kW + around 1040kW or/and at 1.1MW) (eg 2035-2036)
  - “Random” outgassing at 1.1MW (eg 2013-2014)

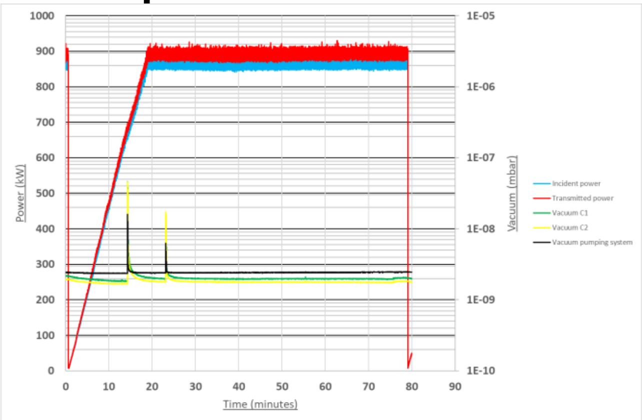
Couplers 2025-2026



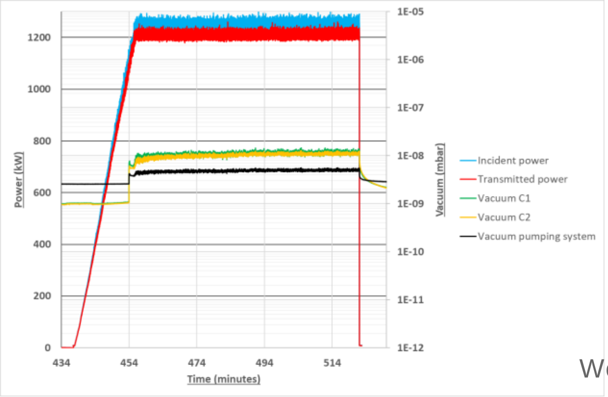
Couplers 2035-2036



Couplers 2013-2014

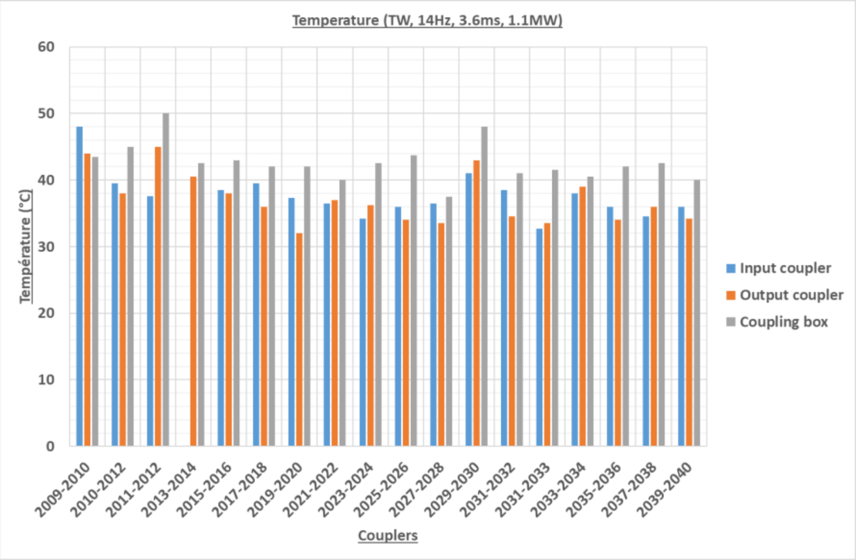


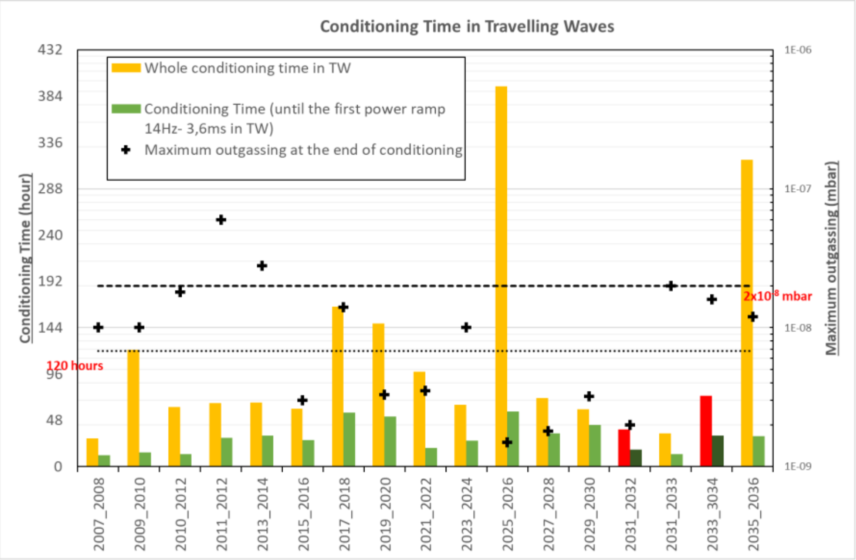
Couplers 2009-2010



CONDITIONING RESULTS OF MEDIUM BETA COUPLERS (2/3)

- In travelling waves
  - Maximum temperature in the range [32°C;45°C] for the maximum average power
  - RF time lower than120H (our defined threshold). On 2 pairs, this time is more important because we wanted to see if we could improve the coupler behavior. Outgassing rather lower than our criterion (2x10^{-8} mbar)

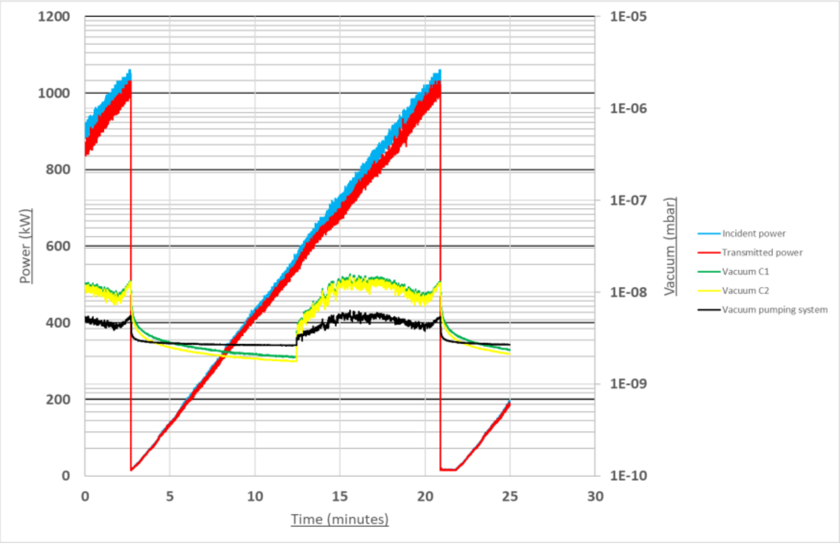




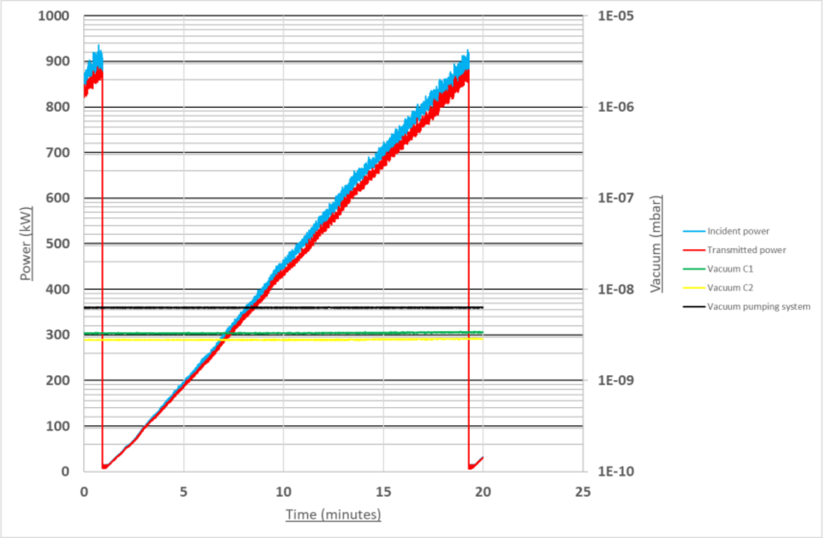
CONDITIONING RESULTS OF MEDIUM BETA COUPLERS (3/3)

- In standing waves
  - Position of the short-circuit with maximum electric field close to the ceramic: no parasitic activity
  - Position of the short-circuit with minimum electric field close to the ceramic: outgassing lower than our threshold

SW min E 14Hz, 500µs

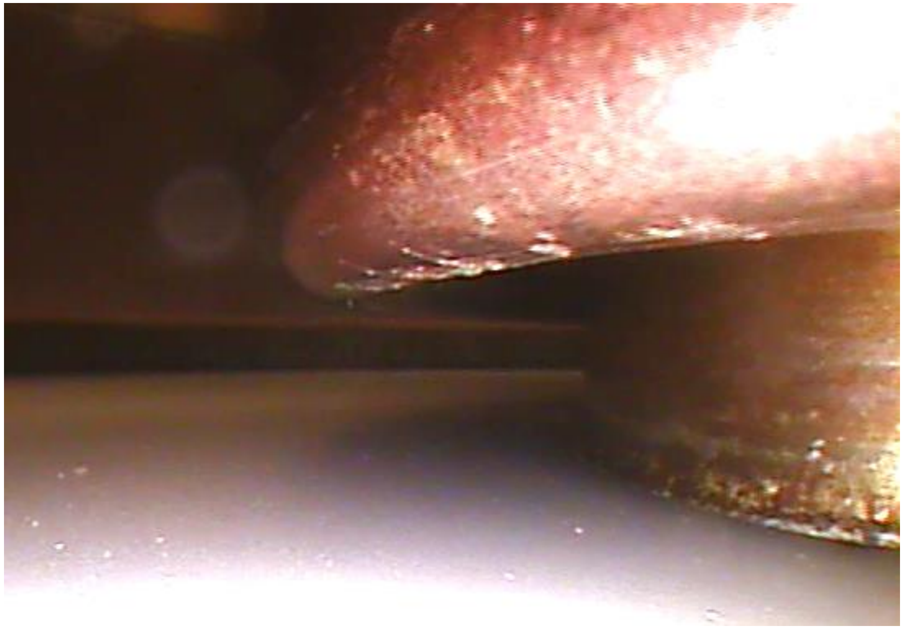


SW max E 14Hz, 500µs



SYNTHESIS

- High Beta couplers (84 couplers to be conditioned): currently, 38 couplers are conditioned. 4 couplers are on the conditioning benches.
- During the medium and high beta couplers conditioning (36+38=74 couplers), we have rejected
  - 11 windows: 6 windows due to a bad TiN coating (high temperature in the window), 5 windows because of electrical arcs (after inspection, we saw that the chokes were damaged).
  - 1 tube due to a scratch

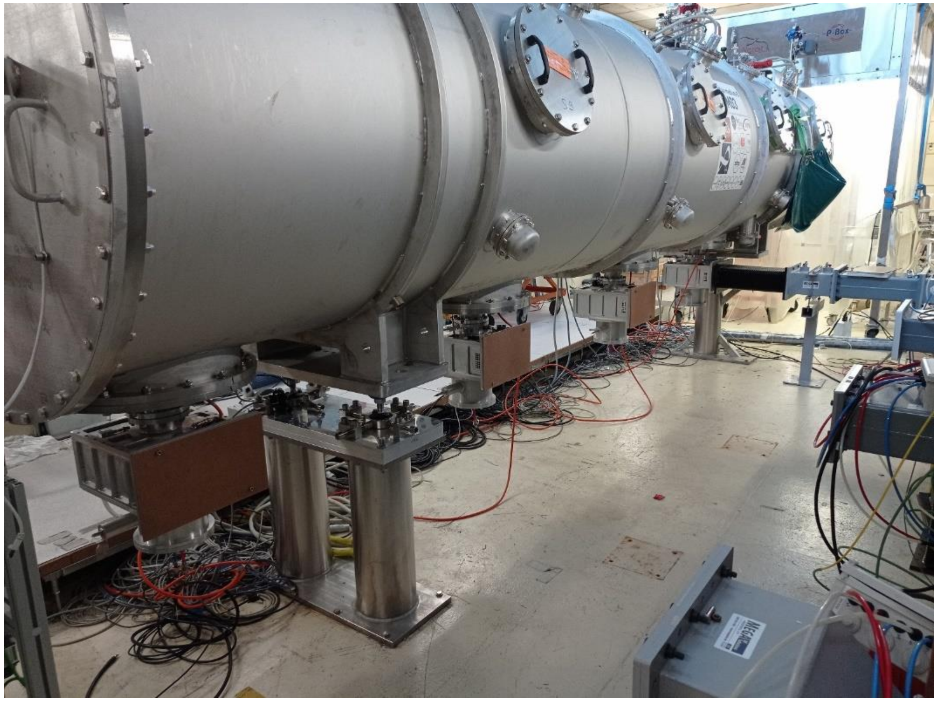


CONCLUSION

- Successful conditioning of 74 medium and high beta couplers (46 couplers have to be conditioned).
- Manufacturing:
  - The most critical aspect is the Tin coating quality
  - Copper coating is operator dependent (slight default)
- Conditioning mainly on the vacuum. We try to have no activity (no electrical arcs and electron). We accept an outgassing lower than $2x10^{-8}$ mbar (pumping speed ≈20l/s)

- 6 cryomodules tested in CEA or ESS and accepted
  - Conditioning at ambient temperature (Standing waves)
  - Conditioning at nominal temperature (flange cavity: 2K) (Standing waves)
  - Nominal field in the cavities: MB 16.7MV/m and HB 19.9 MV/m
  - On the cryomodules, the short circuit position is different from the two positions tested during the couplers conditioning
  - Electron activity can be conditioned rather quickly (≈ 5 hours)

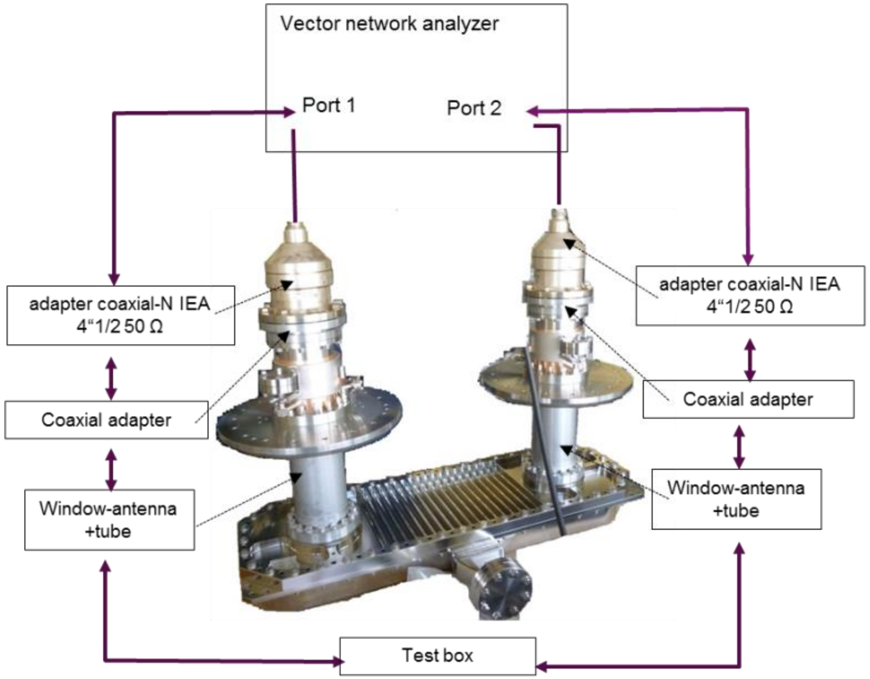
Thanks for your attention



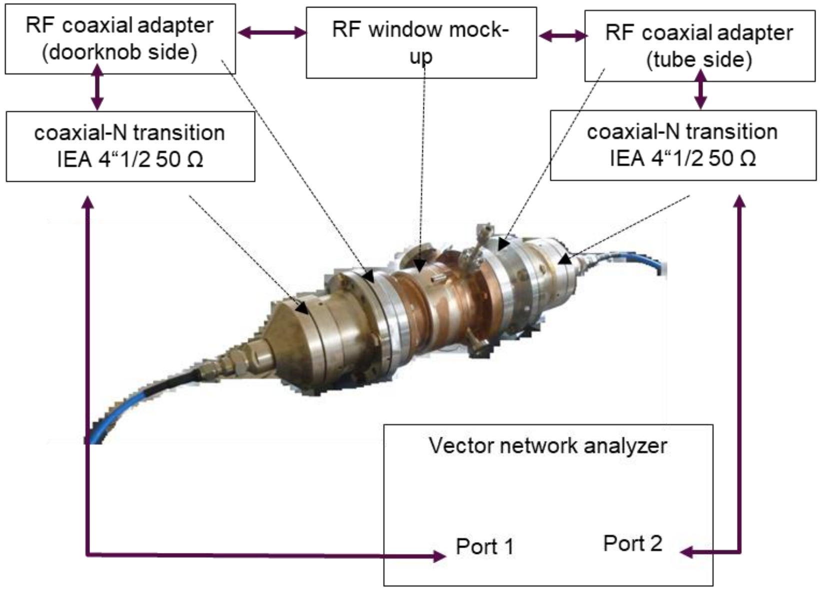
APPENDICES

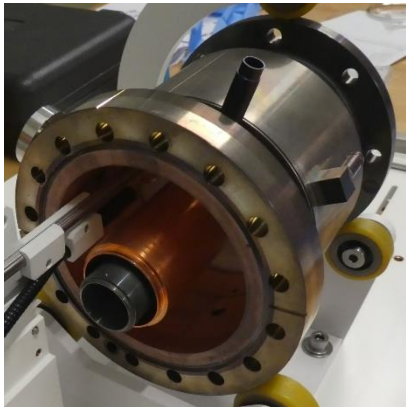
RF CHARACTERIZATIONS OF COUPLERS

2 couplers on a coupling box



Window without antenna





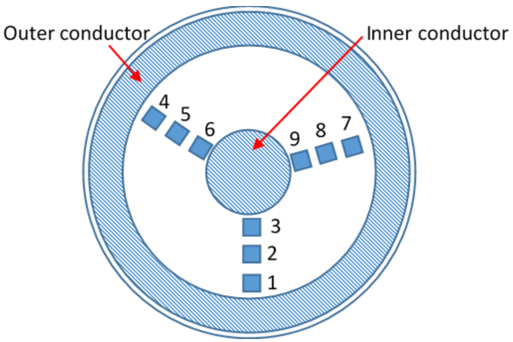
Window mock-up without antenna

TIN COATING

- To check the compliance of the TiN coating, Stoichiometric (XPS method, X-ray photoelectron sprectroscopy) and thickness measurements (Secondary Ion Mass Spectrometry-SIMS method) on
  - 1 vitreous carbon sample put on the cavity flange for each window
  - 8 vitreous carbon samples put on the ceramic in a window mock-up

N° Sample	Ti (%)	N (%)	O (%)
2	42.2	31.7	24.5
5	41.7	37	19.6
8	42.2	32.3	24
10	42.7	41.6	15.7

Pre-series (1st TiN subcontractor)



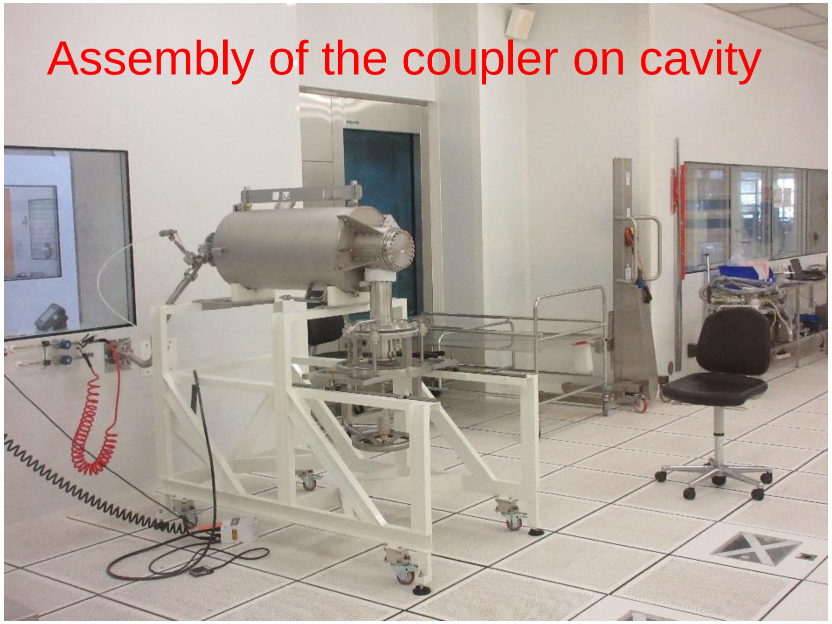
Sample from window	Ti (%)	N (%)	O (%)	C(%)
2011	16.5	13.8	22.7	46.4
2014	19.9	18.2	25.1	36.5
2016	19.4	17.3	25.1	37.6
2018	18.8	17.1	23.5	40.0
2021	20.0	17.1	26.9	35.5
2025	18.8	17.4	24.9	37.9

Series (2nd sub-contractor)

- Stoichiometric measurement on vitreous carbon samples on the flanges of the series couplers: Ti present in TiO_2, TiO_xN_y and TiN form
- Measurement of the dielectric properties of a ceramic with the new TiN coating
  - $\varepsilon r=9.46$, tan $\delta=2.65\times10^{-4}$
  - a ceramic without TiN ($\varepsilon r=9.47$ and tan $\delta= 2.78\times10^{-4}$)

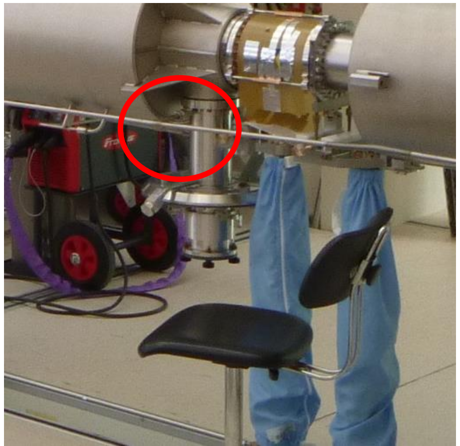
COUPLER ON CAVITY

- Transfer of couplers to industrial partner for the assembly of couplers on cavity



Bellow bell

- Difficulties to obtain vacuum tightness on some interfaces
  - VCR connector
  - Coupler bellow bell



Commissariat à l'énergie atomique et aux énergies alternatives
Centre de Saclay | 91191 Gif-sur-Yvette Cedex
T. +33 (0)1 69 08 xx xx | F. +33 (0)1 69 08 99 89

Etablissement public à caractère industriel et commercial | RCS Paris B 775 685 019

DSM
Irfu