CERN FPC status and perspectives

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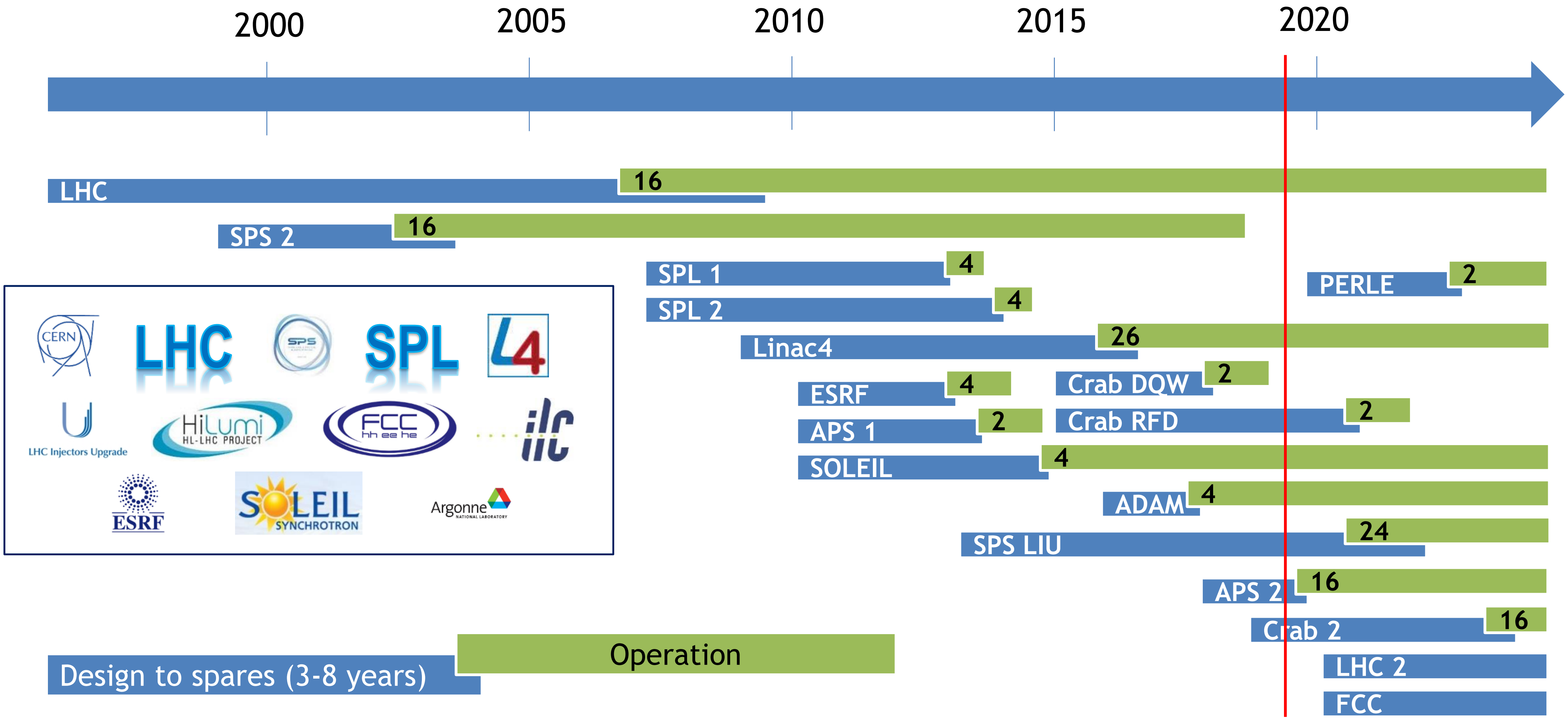
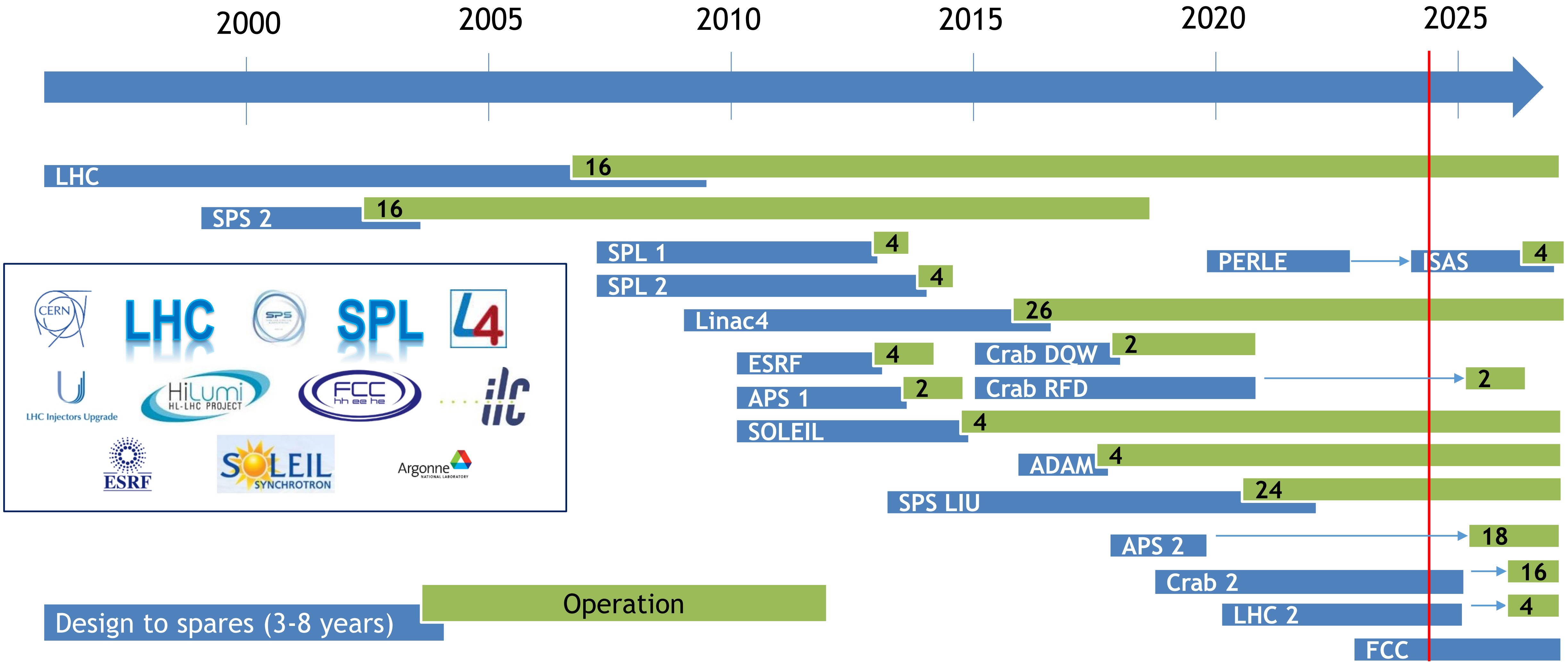
On behalf of all colleagues involved in the topic
Thanks to all of them for the tremendous amount of work and for all the invaluable competencies provided!

Overview of the couplers built up to 2019 at CERN

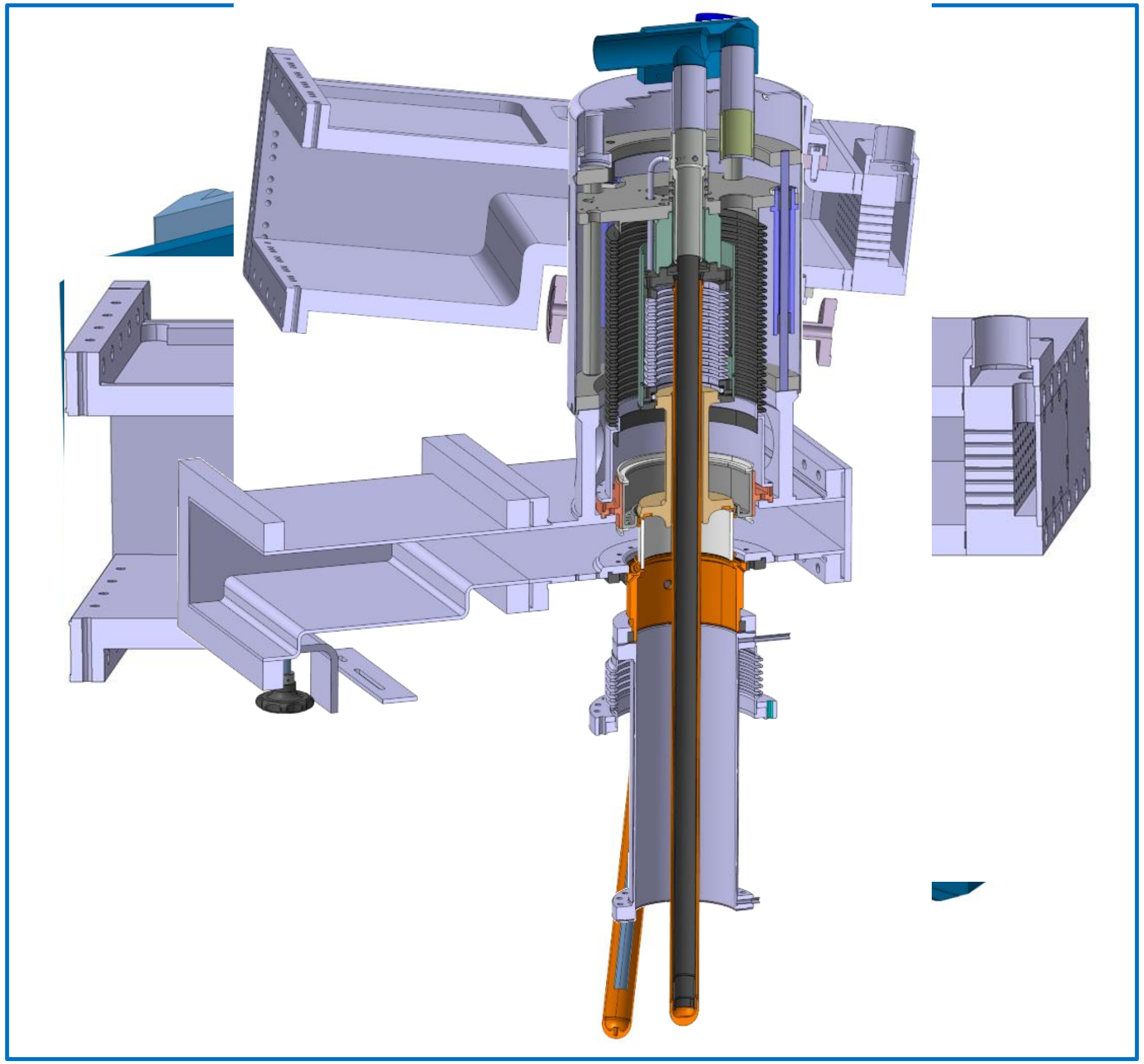


Overview of the couplers built up to 2024 at CERN



Overview of the CERN power couplers

LHC	**400 MHz, 500 kW CW SW**
SPS 2.0	**200 MHz, 750 kW CW TW**
SPL 2.0	**704 MHz, 900 kWp 10 % SW**
SPL 3.0	**704 MHZ, 1000 kWp 10 % SW**
Linac4	**352 MHz, 1000 kWp 10 % SW**
Crab DQW	**400 MHz, 100 kW CW SW**
Crab RFD	**400 MHz, 100 kW CW SW**
ESRF	**352 MHz, 200 kW CW SW**
SOLEIL	**352 MHz, 200 kW CW SW**
APS 1.0	**352 MHz, 200 kW CW SW**
SPS LIU	**200 MHz, 800 kW CW TW**
LHC 2.0	*400 MHz, 500 kW CW SW*
APS 2.0	*352 MHz, 250 kW CW SW*
FCC	*400 MHz, 1 MW CW SW*
FCC	*800 MHz, 250 kW CW SW*



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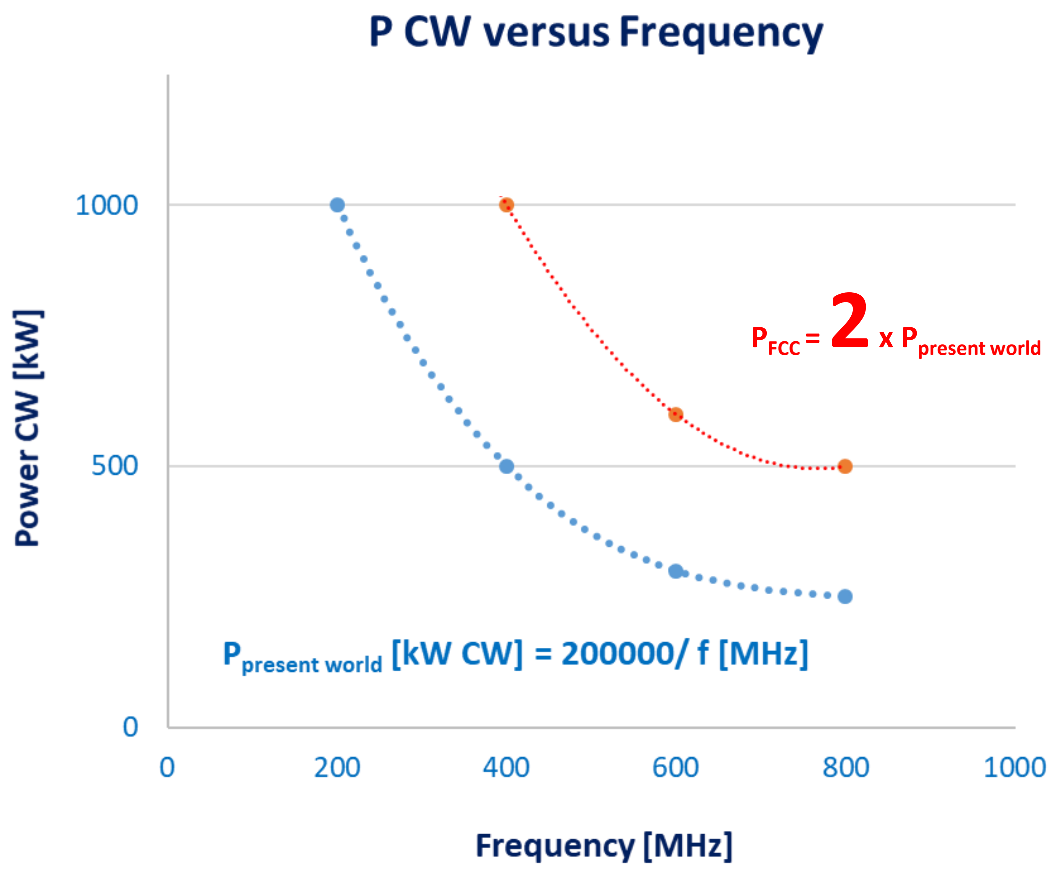
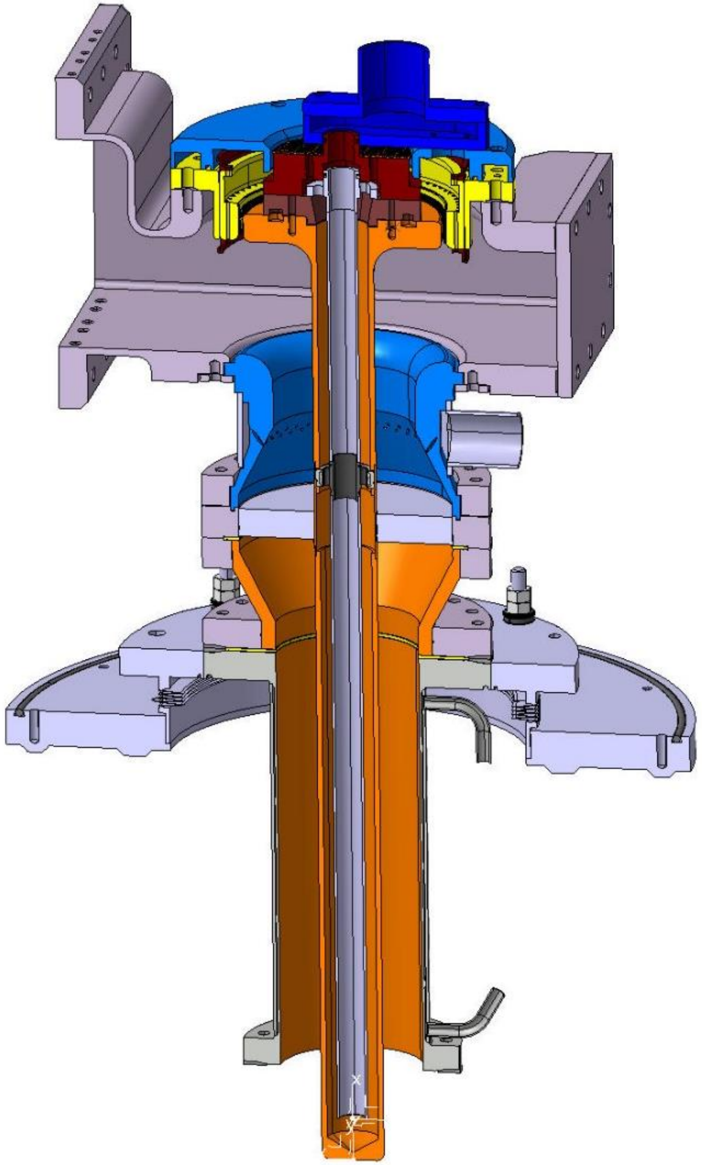
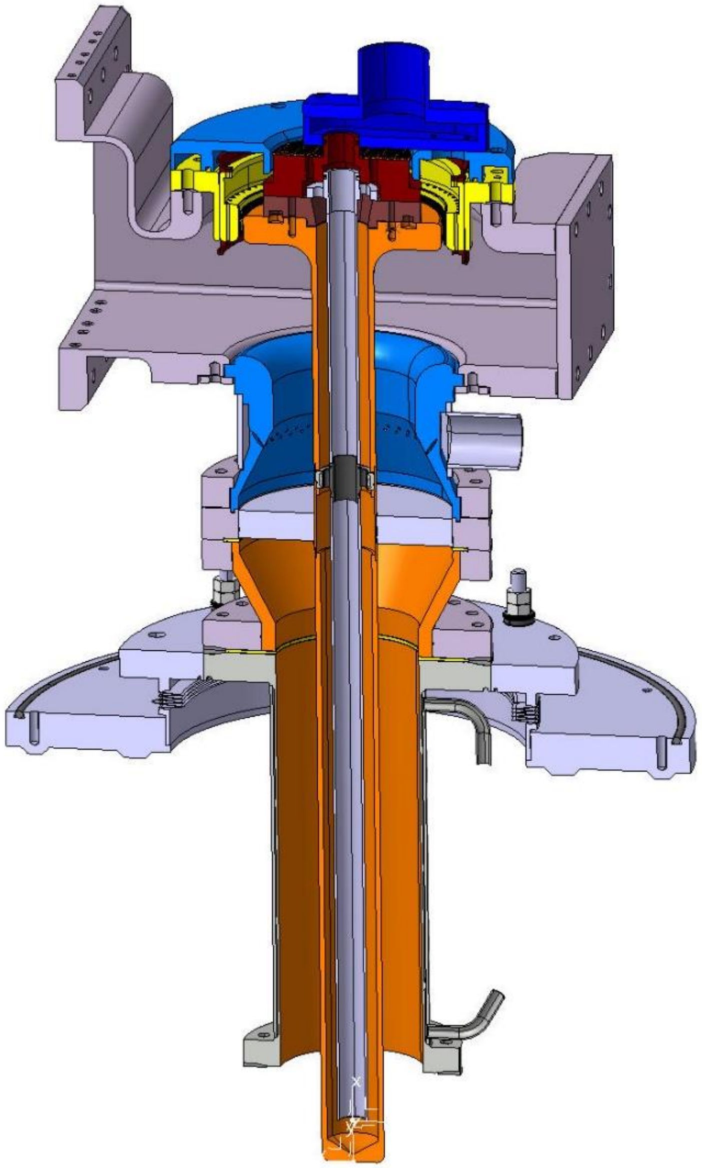


FPC design input parameters

- Ceramics
  - Ceramic material
  - Metallization
  - Window families
    - Disk
    - Cylindrical
    - Coaxial disk
  - Two windows
  - Single window
  - Solutions proposed
- Antenna
  - Adjustable coupler
  - Antenna shape
- Outer Antenna line
  - Copper for RF
  - Stainless steel
  - Bad coating
  - RF & vacuum seal
- Protection of the FPC
- Cryomodule integration
- Orientation of the FPC
- Inner antenna cooling
- WG to coax
- Multipacting
  - Ti sputtering
  - DC polarisation
- Simulation and proposed solution
  - Cylindrical Design
  - Coaxial disk
  - Disk
- Construction
- Clean room
  - Clean process study
  - Mock-ups
  - Preparation for assembly
  - Assembly in ISO 5
  - Assembly in ISO 4
- FPC test boxes
- FPC test benches
  - In clean room
  - Resonant ring
- RF conditioning
  - Ceramic cracks
  - Conditioning process
  - VCA
  - Pulses
  - Ramping
  - Repetition rate
  - TW and SW mode
  - Automated process
  - Processing time
  - Summary
- First test results
  - Arcing



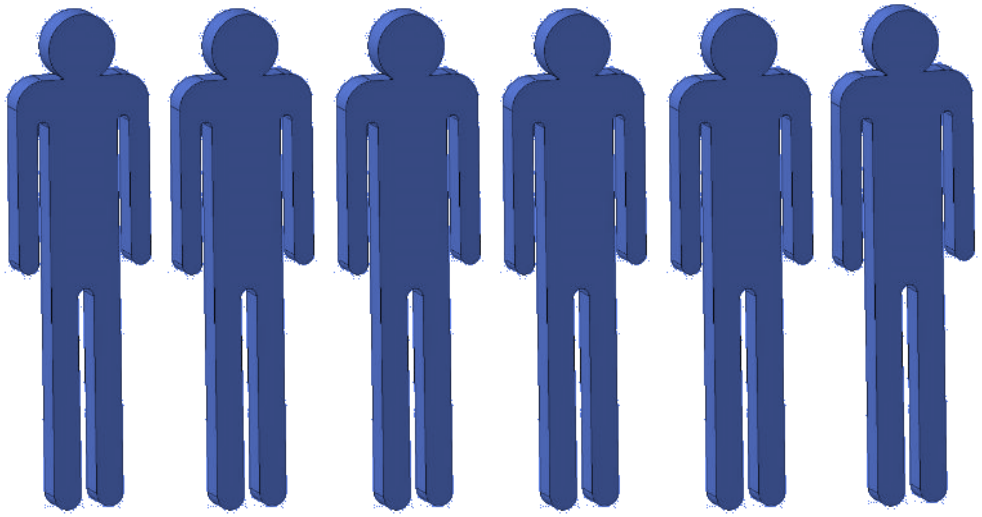
FPC design input parameters



FTE (Full Time Equivalent)

Activities	FTE year
RF Design	0.2
Mechanical Design	1.8
Raw material	0.05
External machining pilot	0.5
Internal machining	1.0
Surface treatments	0.1
Brazing	0.2
Titanium sputtering	0.1
BE welding	0.1
Metrology	0.05
Assembly	0.5
Vacuum tests	0.1
RF Conditioning	0.5
Clean room assembly	0.8
Total	**6.0**

With Respect to FPC, at CERN, since 2000's, almost everything, is done in-house



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LIU-SPS

LHC **I**njector **U**pgrade program of the CERN' **S**uper **P**roton **S**ynchrotron

Warm Travelling Wave Cavity

200 MHz

750 kW CW TW

1 MW pulsed 12 µs at 43 kHz (23.2 µs), i.e. 51.6 % average, 516 kW average

5 MHz bandwidth minimum

Two couplers per side (two input couplers and two output couplers)

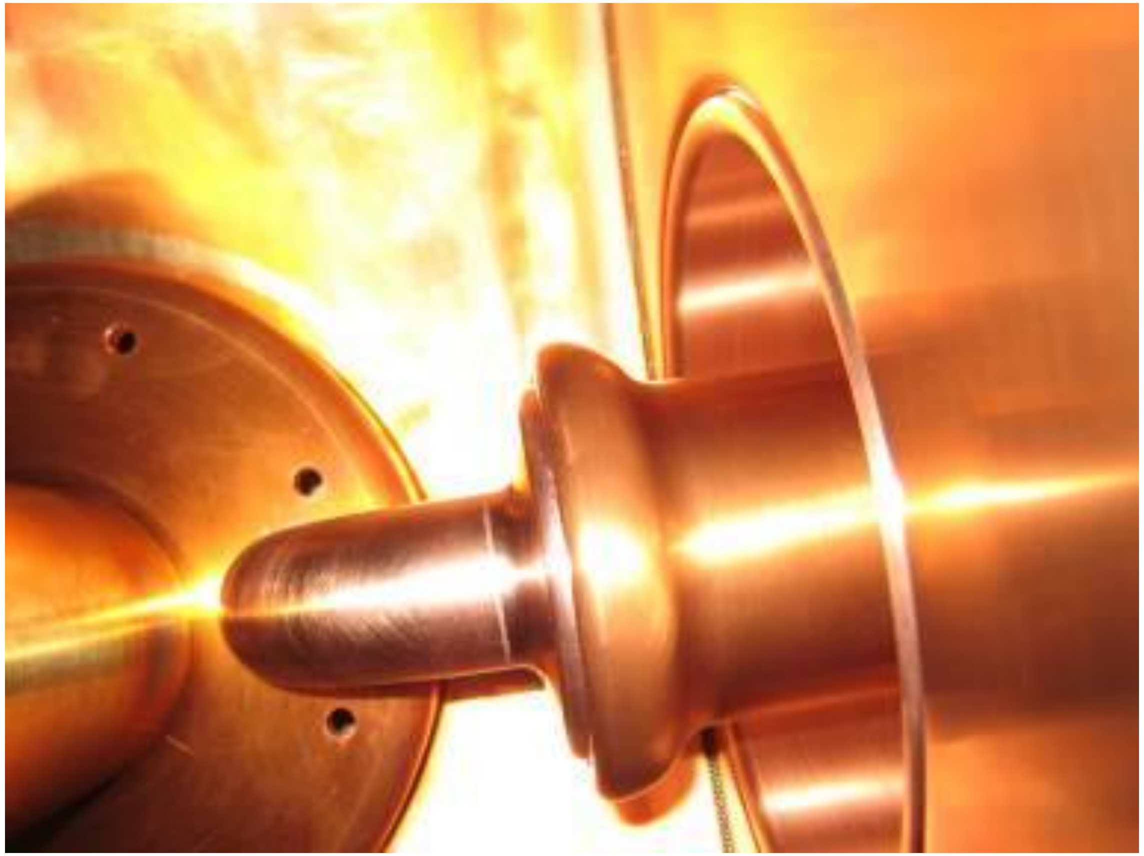
- 375 kW CW, 500 kWp per window

LIU-SPS

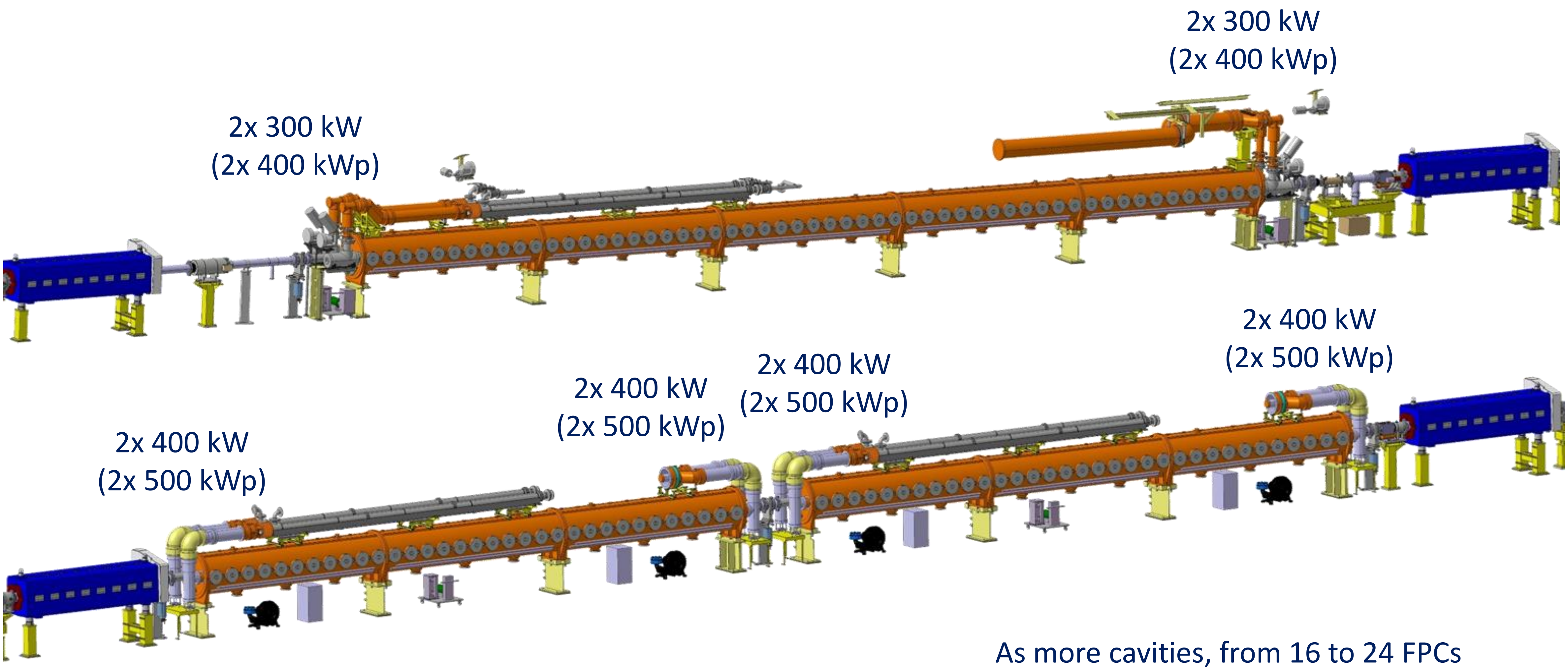
For high power RF, the identified weak point of the previous two versions was the connection to the cavity

- V1 designed for 375 kW CW / 2 = 200 kW CW
- V2 designed for 600 kW CW / 2 = 300 KW CW + 800 kWp / 2 = 400 kWp

Indeed, it was using a spiral contact that would have not been able to allow higher average power

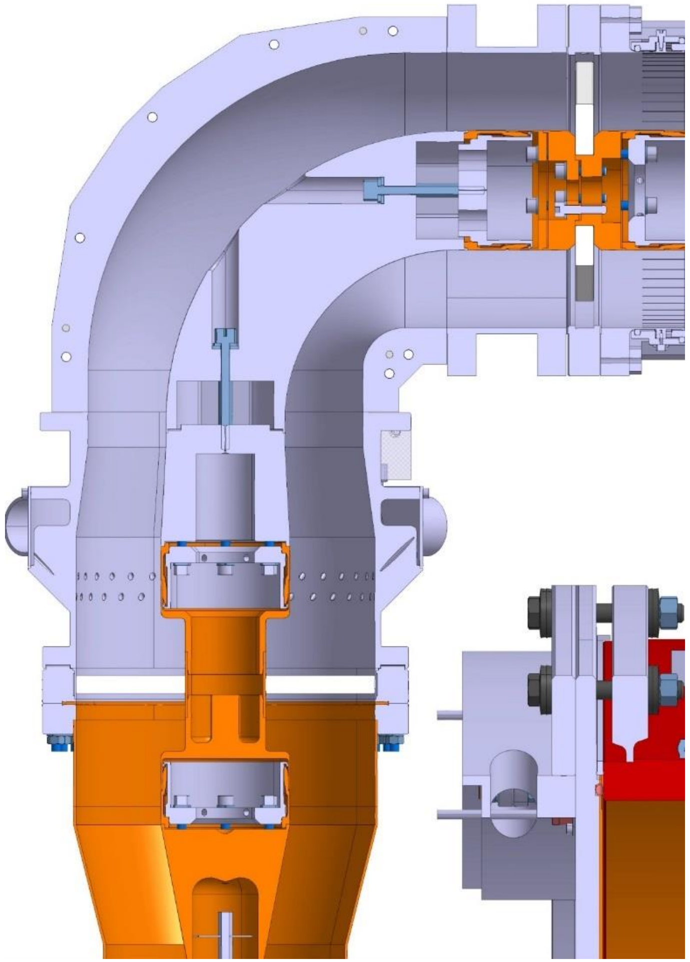


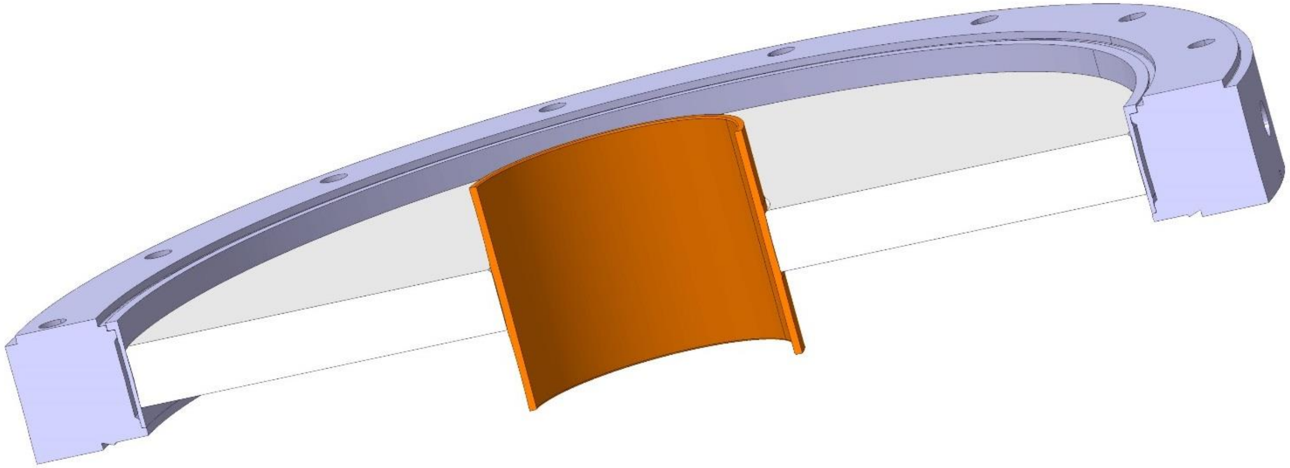
SPS to LIU-SPS

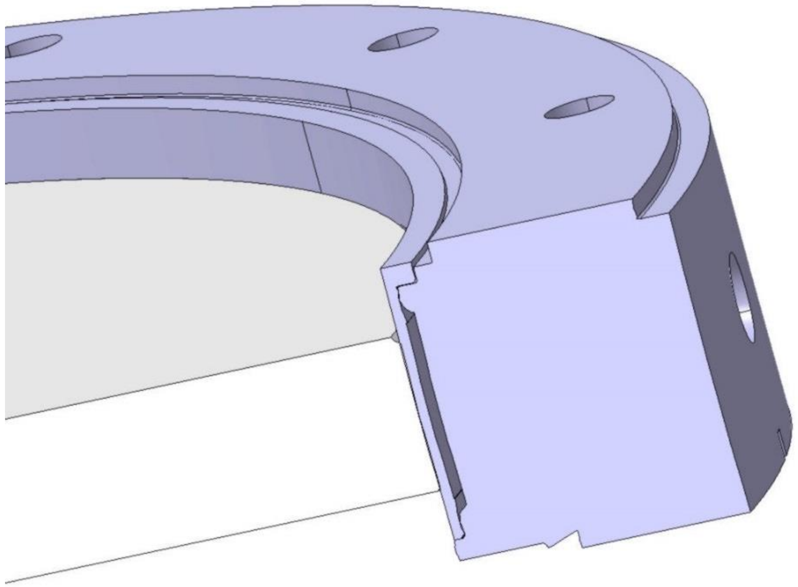


As more cavities, from 16 to 24 FPCs

LIU-SPS

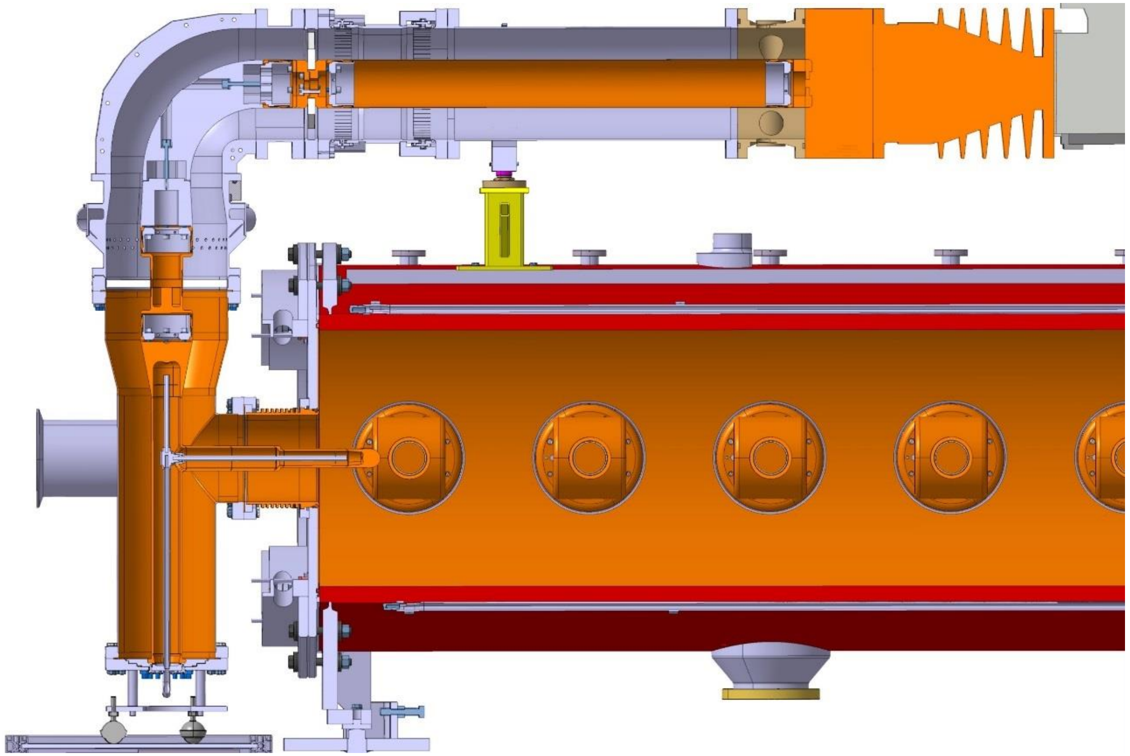


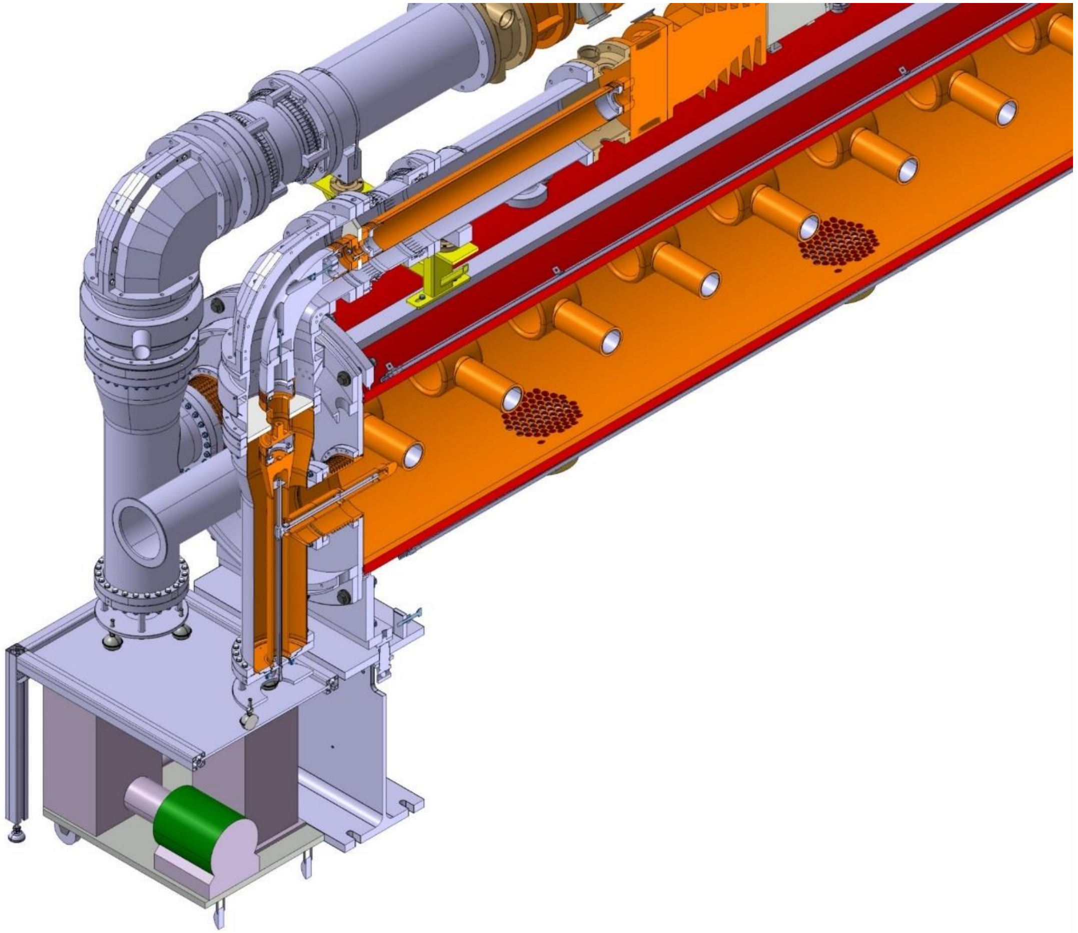




Al2O3 99.7 %
15 mm thickness
D250 mm
Ti grade 4

LIU-SPS





LIU-SPS

LIU-SPS

A special elbow with two halves outer lines to connect the window to the 14’’ coaxial lines (345 mm)

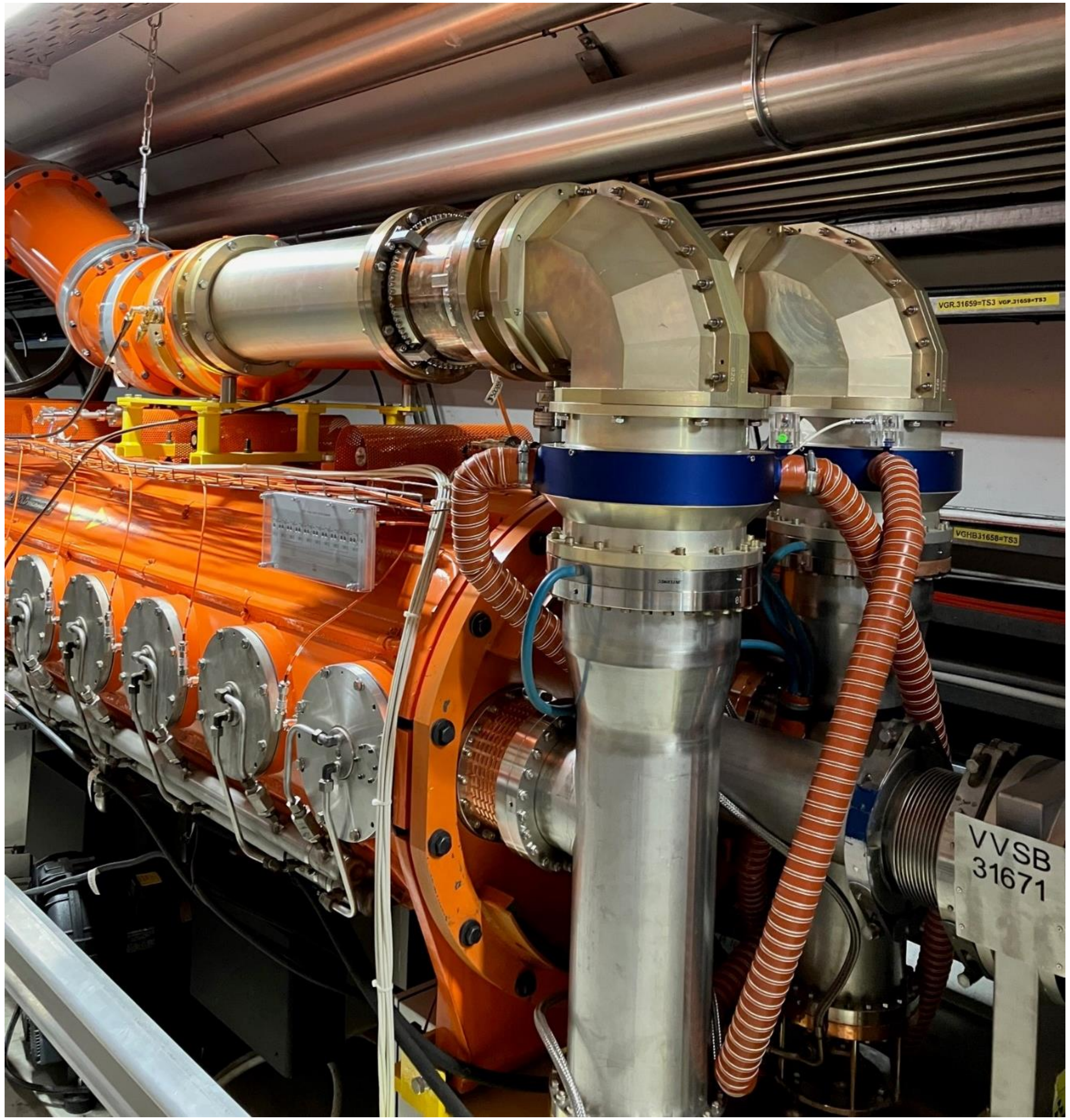
LIU-SPS

24 couplers in operation since 2021

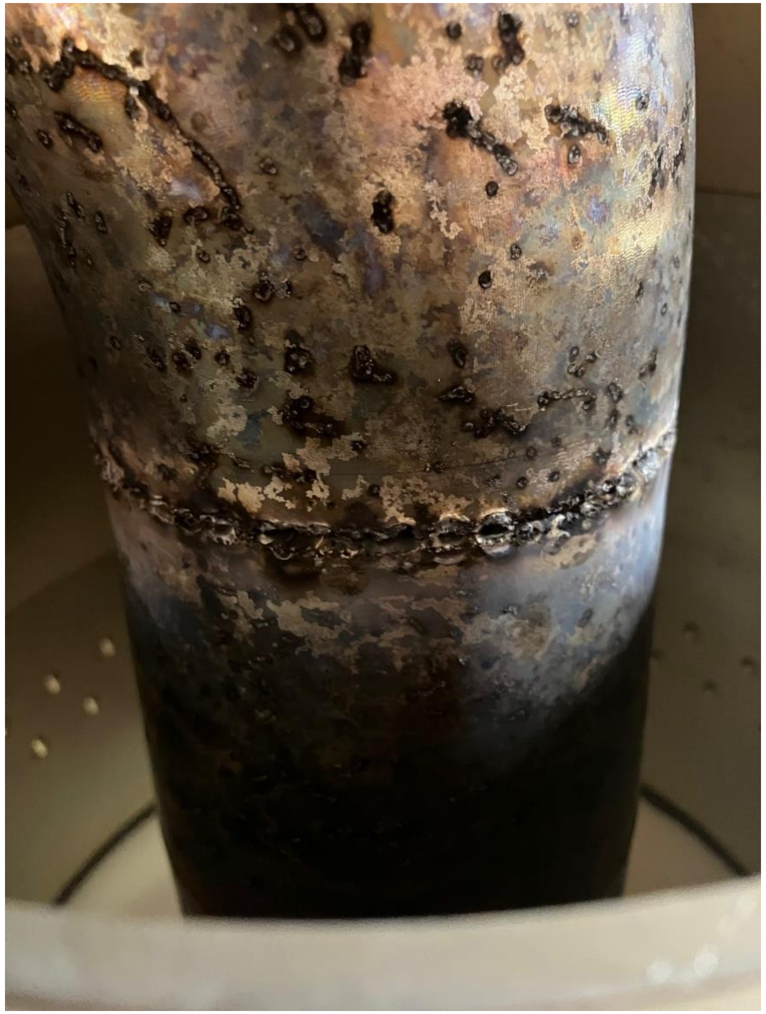
It took almost all 2021 to 2023 to have a stable vacuum under all beam conditions

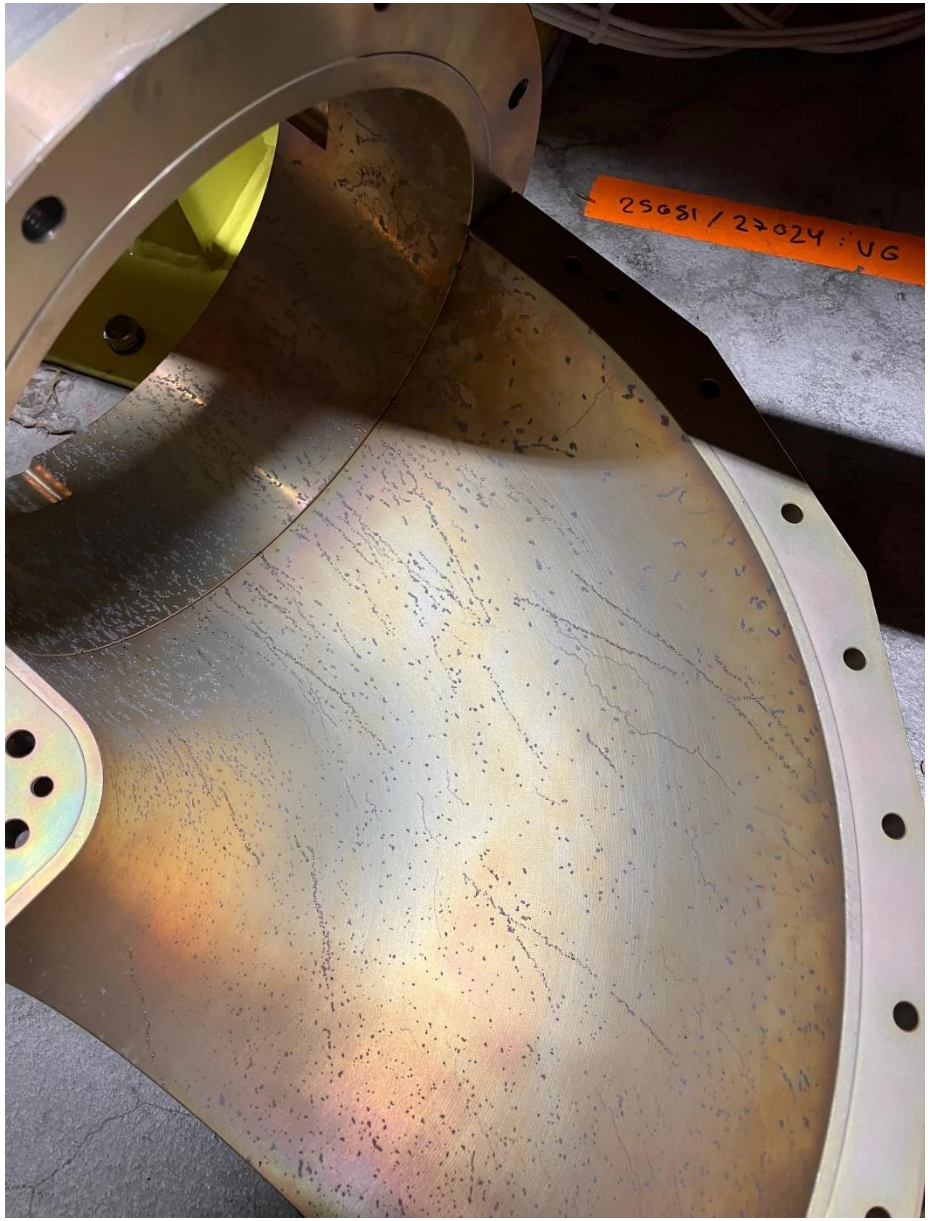
Looks normal given that the cavities are 800 mm diameter and 16 meters long of 10 mm copper thickness

As they have been vented for days twice (removal and réinstallation, vacuum in between), getting a good static vacuum was difficult (no possibility to do a bake out)



LIU-SPS true life





LIU-SPS

In total, we produced, and RF processed 32 FPC

Since 2021, we have 24 FPCs operating in the SPS

Despite the troubles with the input and output RF lines, to date, not a single failure with the windows…

PIXE & ELISA

Proton **I**nduced **X**-ray **E**mission at INFN

Experimental **Li**nac for **S**urface **A**nalysis at CERN’ Science Gateway

Warm compact RFQ

750 MHz

100 kW pulsed 200 µs at 250 Hz (4 ms), i.e. 5 % average, 5 kW average

0.5 MHz bandwidth minimum

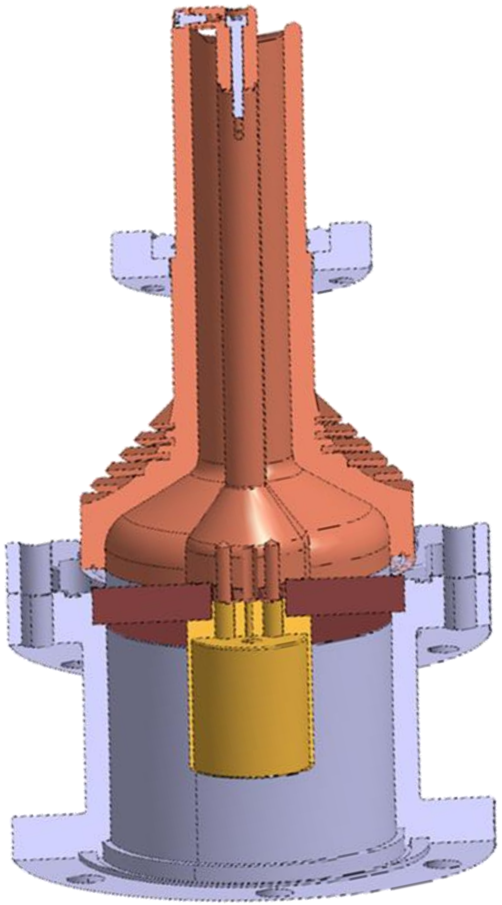
PIXE & ELISA

The window is a disk of PEEK and it is only air cooled

(We also designed, and produced, two ceramic window couplers, but they are not used for the time being)

To date we only produced three of these PEEK couplers

- One is operated at INFN Firenze, Italy
- One is operated at CERN Science Gateway
- One is a spare



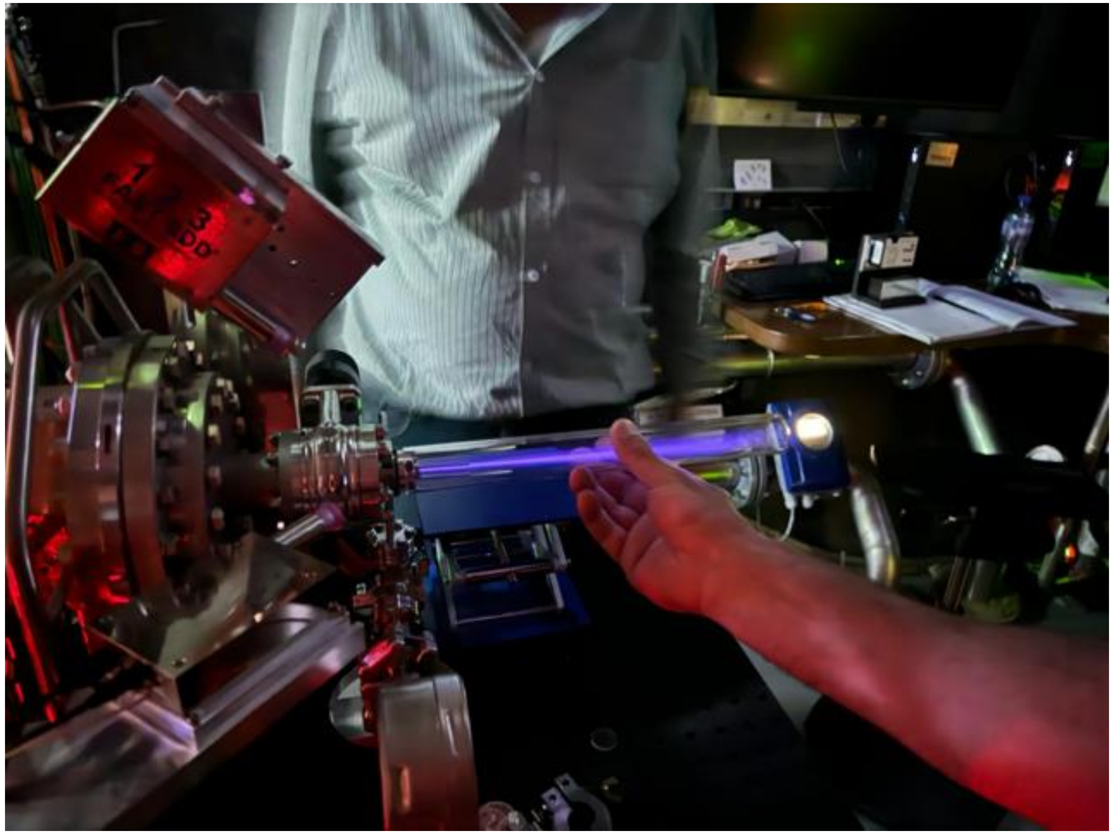
PIXE & ELISA

We tested two PEEK window couplers face to face up to

- 10 kW CW TW
- 100 kWp 500 µs at 50.3 Hz

The two windows were perfectly ok

ELISA



HL-LHC crab

Design started in 2012

Three cavities, down selected to two cavities in 2015

2 K cavities

400 MHz

100 kW CW

reduced to 50 kW CW & 100 kWp for 1 ms maximum

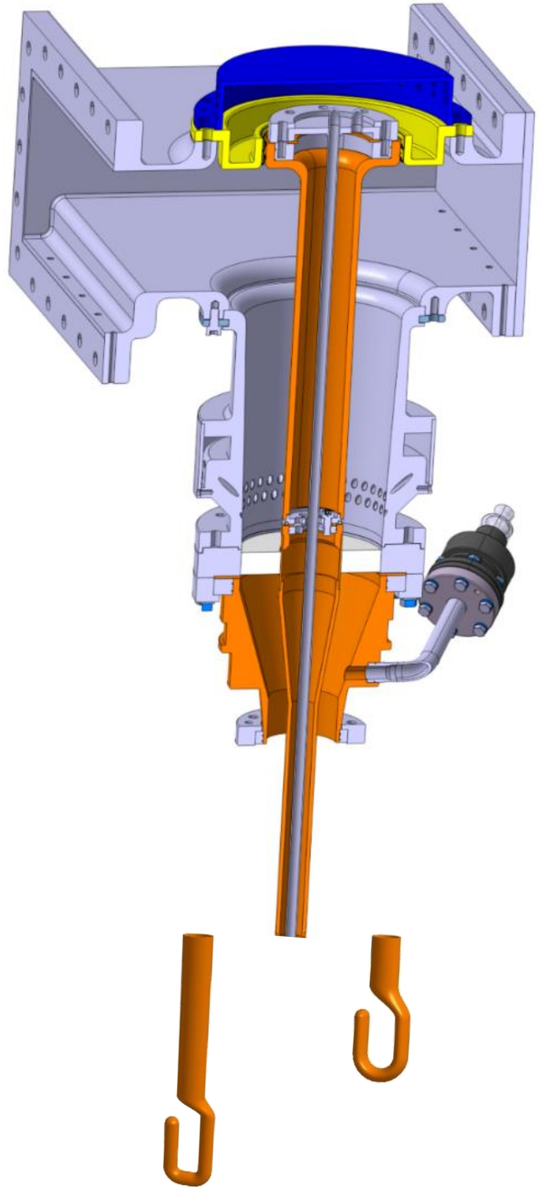
1 MHz bandwidth minimum requested by LLRF

Single coaxial disk window

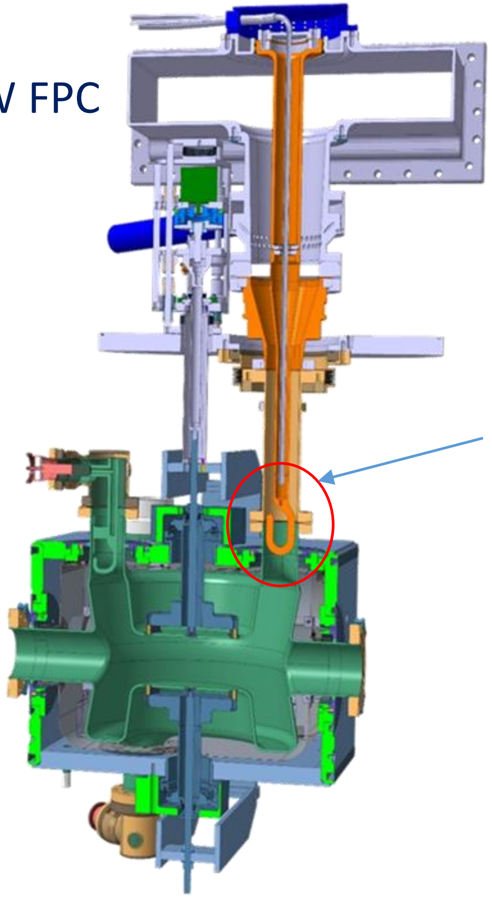
No doorknob, WG to coaxial transition instead

Water cooled antenna

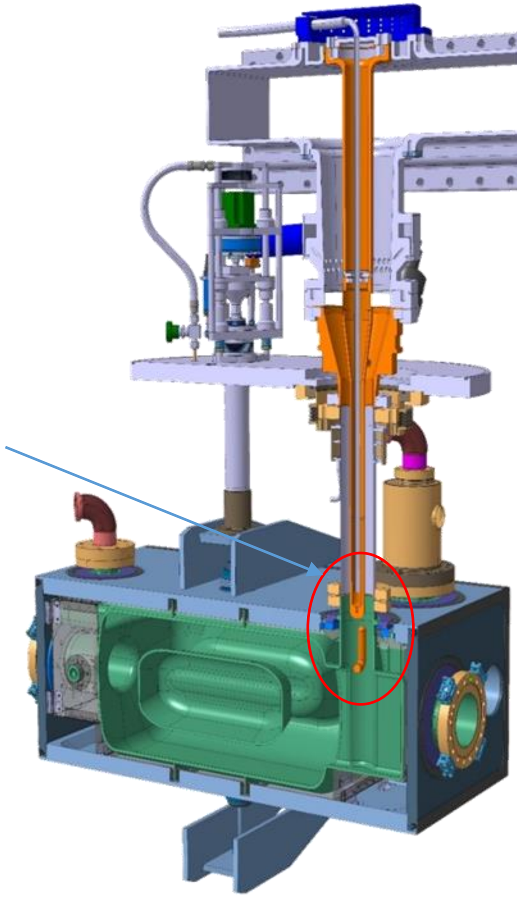
Vacuum gauge for coupler protection



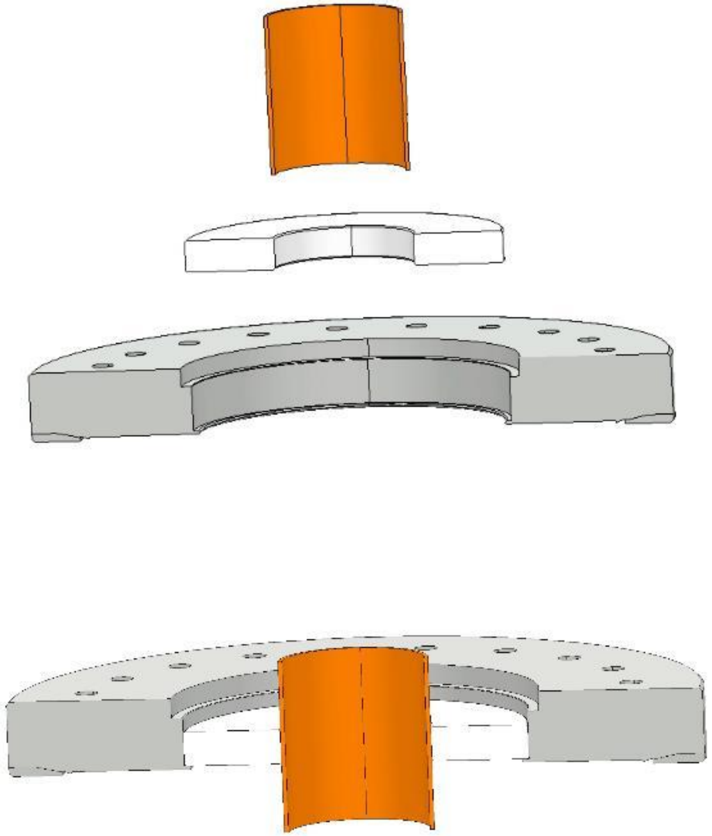
HL-LHC crab



Regarding FPC the difference is only the length of the antenna and the shape of the hook



HL-LHC crab



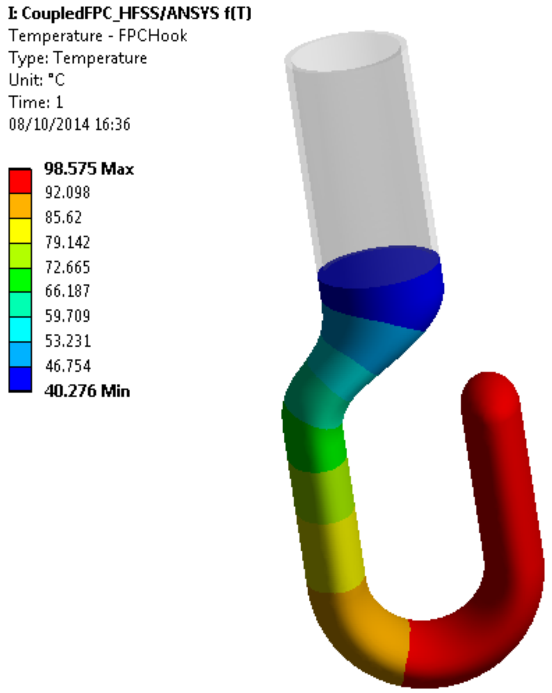
Hook cooling

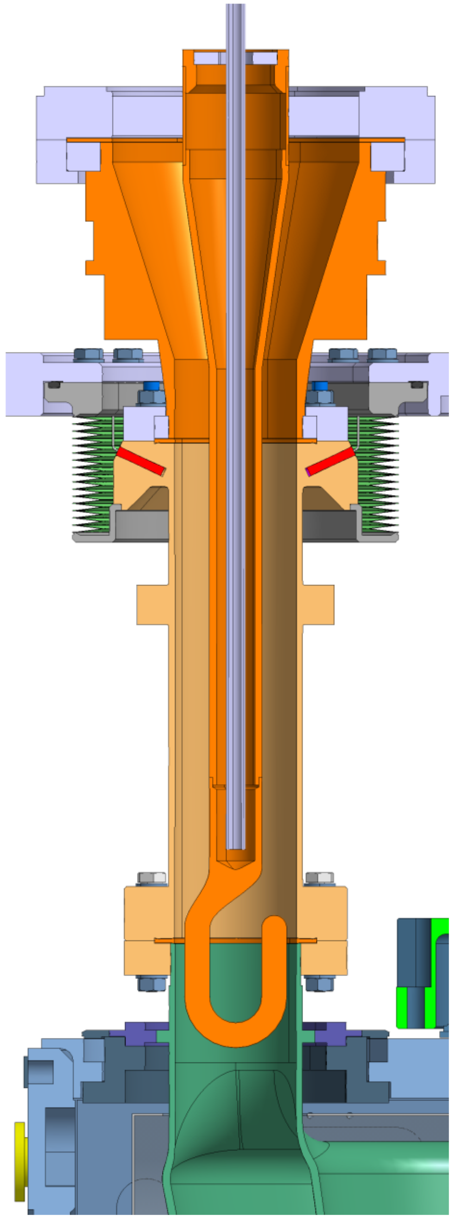
Simulations shown that with an air-cooled system, the hook would heat up to over 400 C

A water-cooled system was designed in order to keep the hook temperature to 100 C maximum

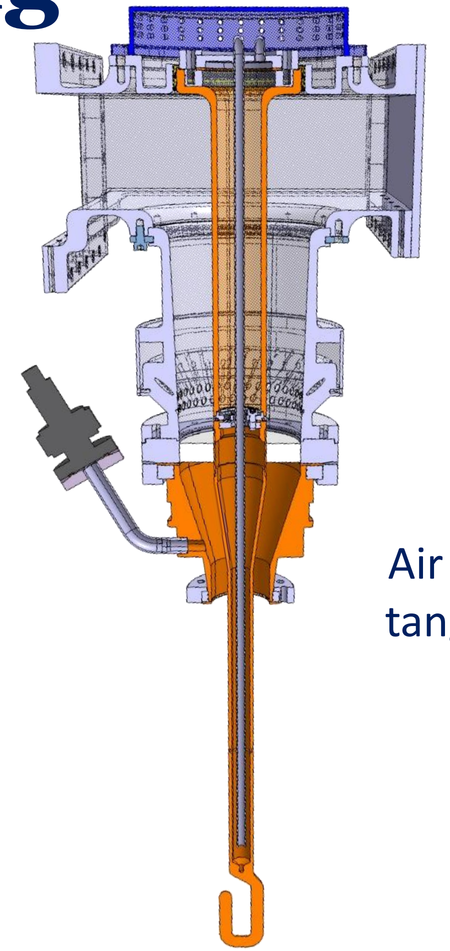
At CERN, we do not like it, the hook will be EBW

In addition, to guaranty there will be no water overpressure, we will have a FPC dedicated water-cooling plant with a heat exchanger and a little FPC water pump





Cyclotronic© air cooling

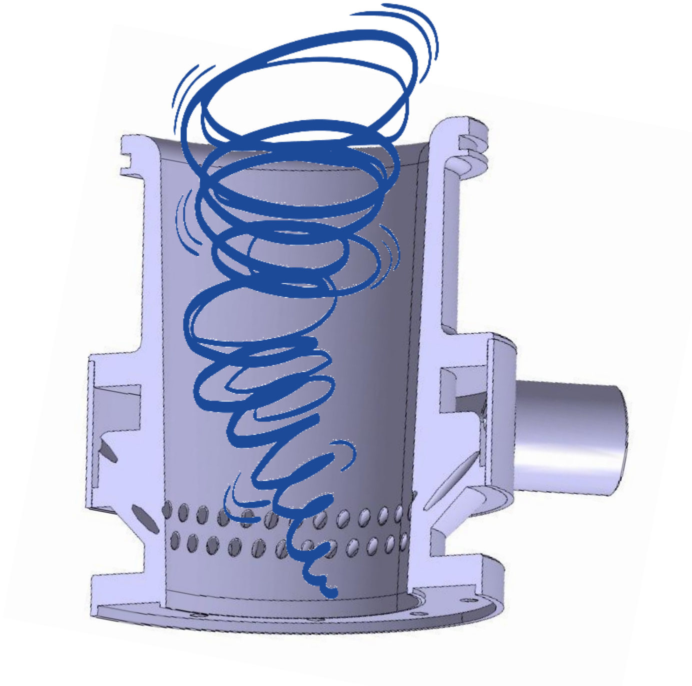


In order to cool down the ceramic from the air side, we invented the cyclotronic air cooling system

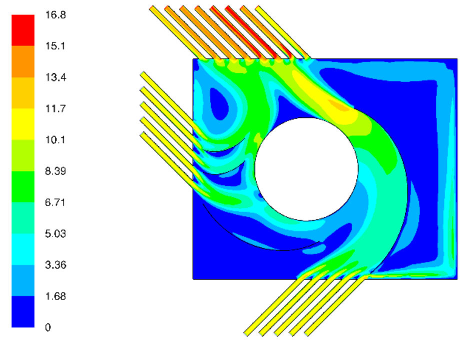
The goal is to avoid any ‘no air flow area’ that would generate a hot spot

To do so, the air is directed down to the ceramic and with a tangential angle

This was proven very efficient with the SPL couplers



Air inlet directed to the ceramic and with a tangential angle to avoid ‘no air flow areas’
Cyclotronic © air cooling



Specific Outer line "RF and vacuum" seal

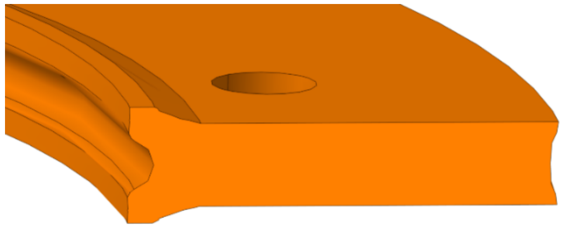
Specific shape designed for RF perfect continuity and vacuum sealing

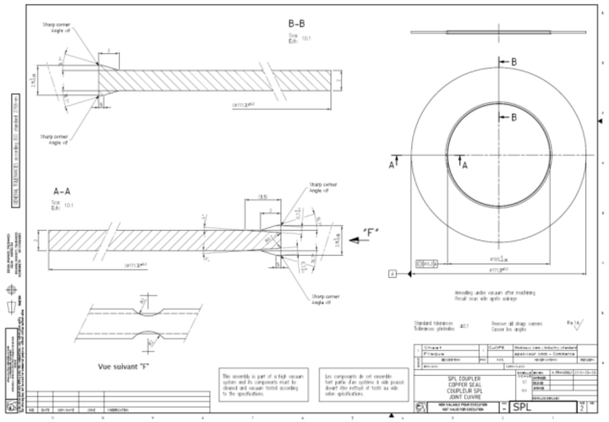
It has been designed for LEP couplers, then re-used with LHC and HL-LHC crab couplers

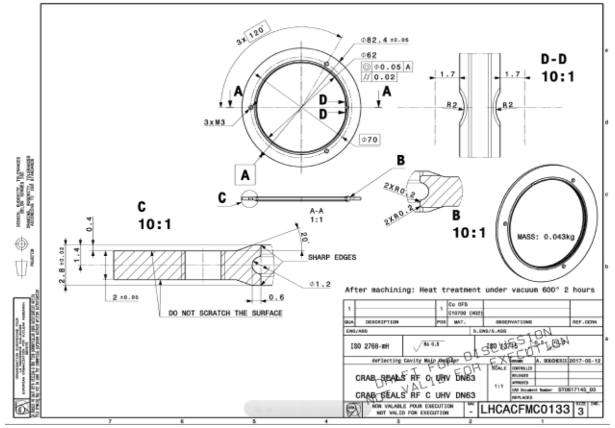
Following Sergey Belomestnykh idea, we implemented an improved version for easier mounting at cold

For bake out compatibility

- MATERIAL : Cu OFE for low temperature operation
- SURFACE STATE : Rolled bright, free of scratches and burrs

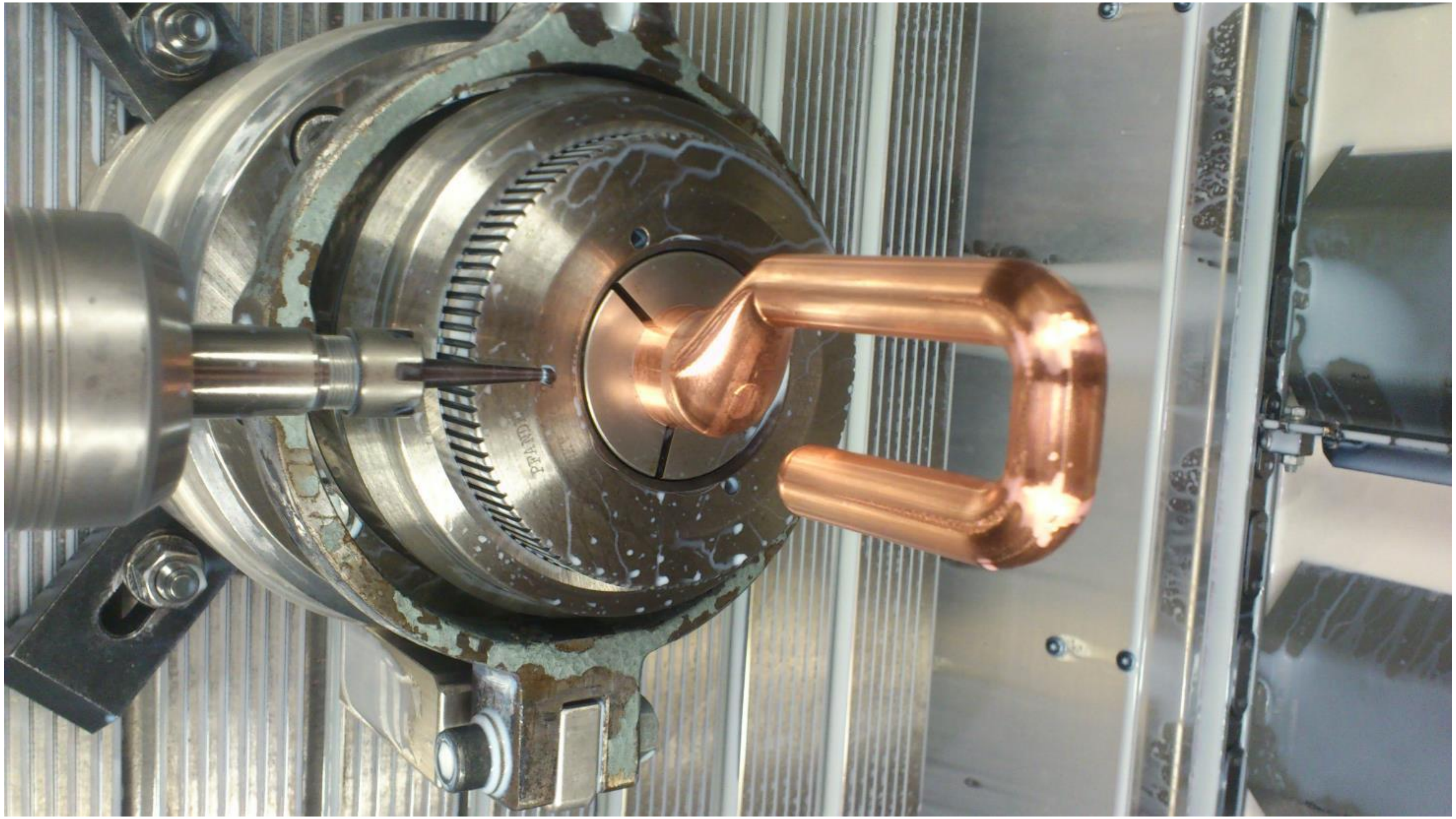




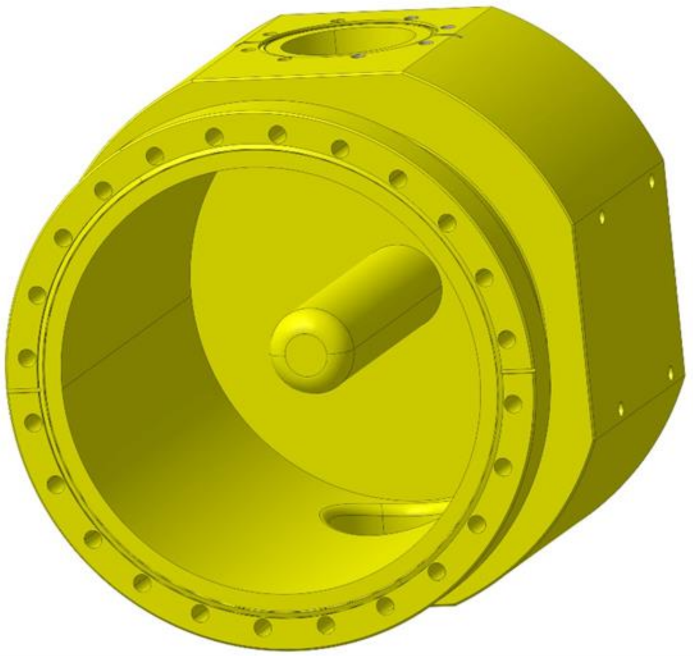


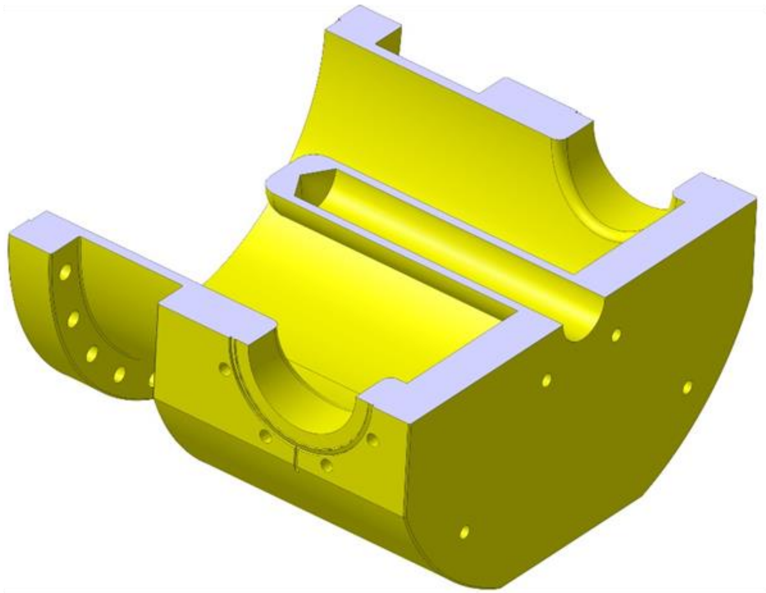
HL-LHC crab

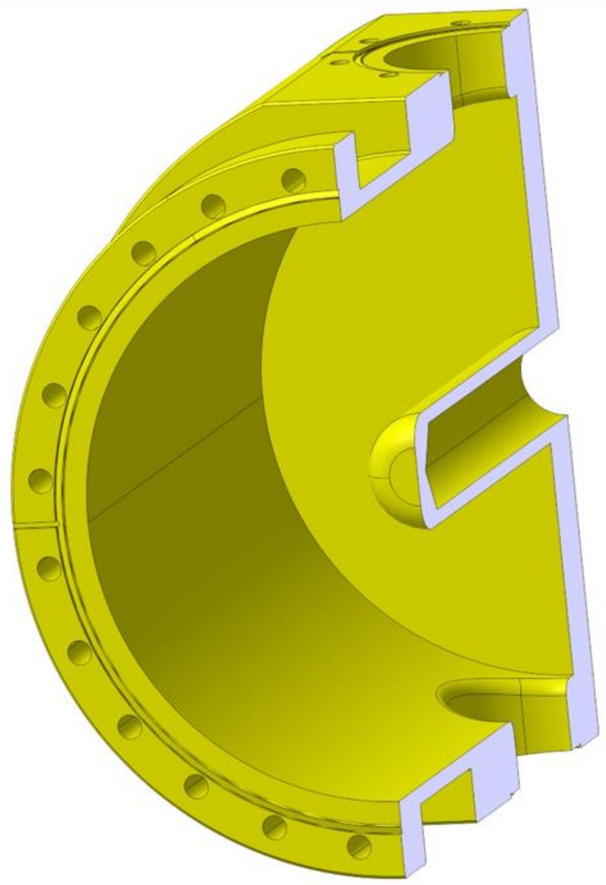
All copper parts are 3D forged copper machined for massive raw copper



HL-LHC crab test box

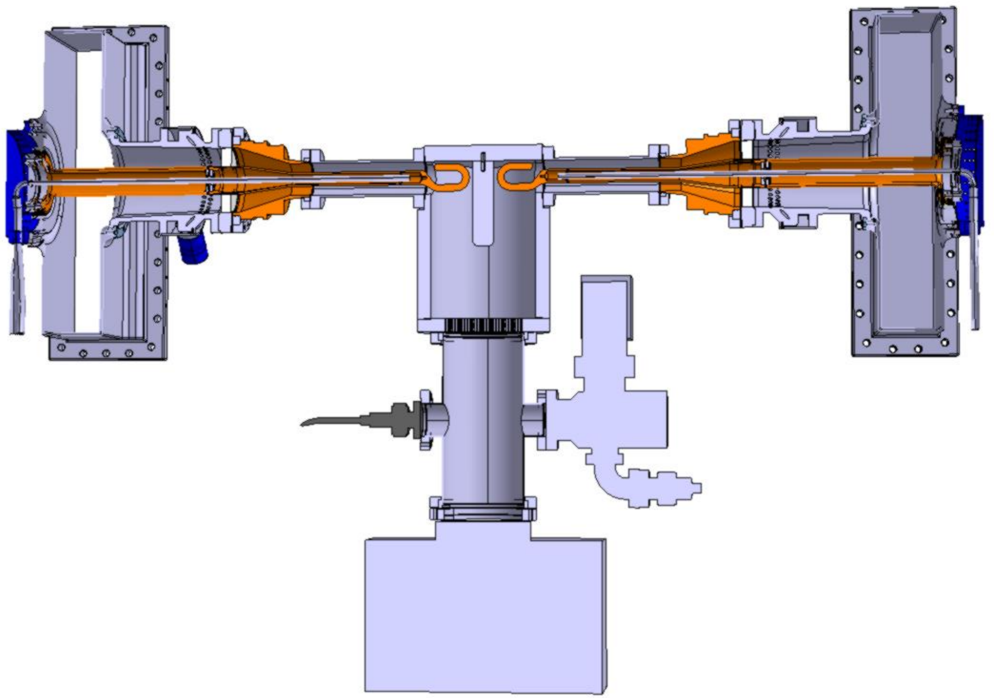


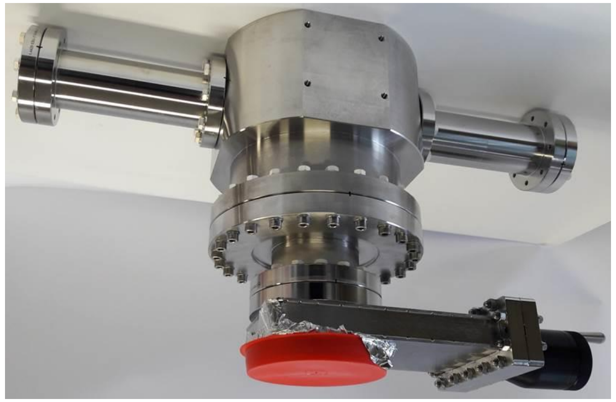


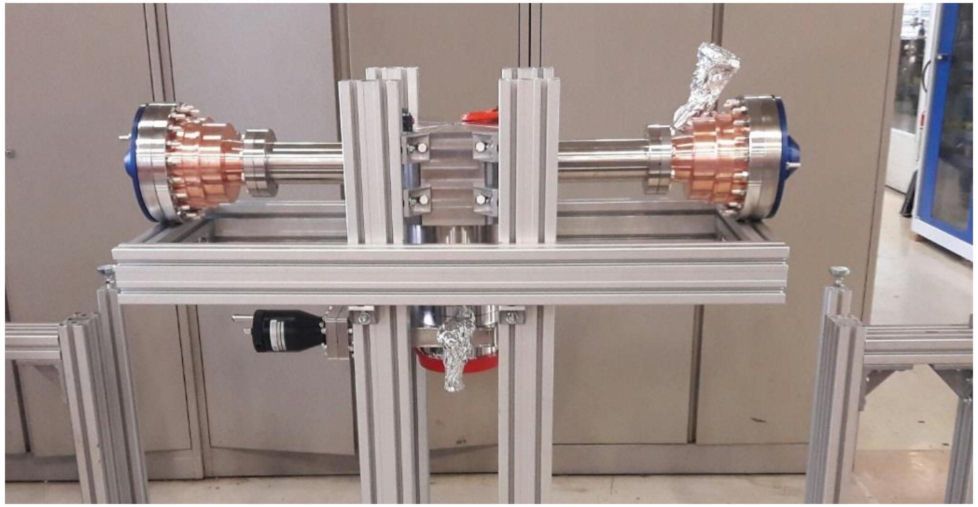


A first test box in Stainless Steel 304 L (vacuum usage) was constructed all in one machined
An exact same design in Aluminium EN AW-6082, all in one machined as well, with 0.1 to 0.3 µm Alodine 1200 was tested and has proven to be re-usable
We then constructed several Aluminium test boxes

HL-LHC crab test box



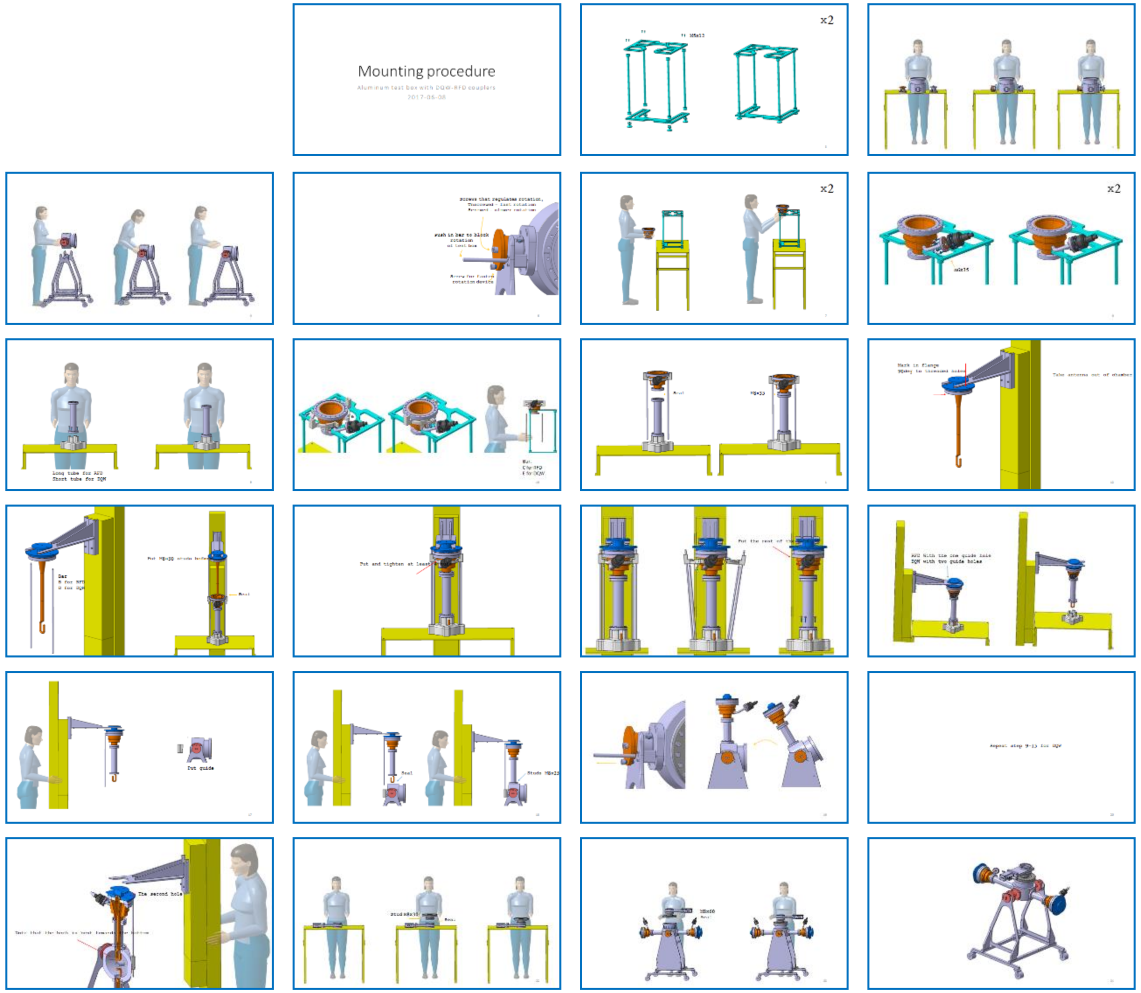




HL-LHC crab test box

As Crab is with high gradient, we needed to take care of the FPC in clean room from the first day, including assembly on the test box

We first prepared all actions on a flip book, we trained ourselves on mock-ups outside clean room



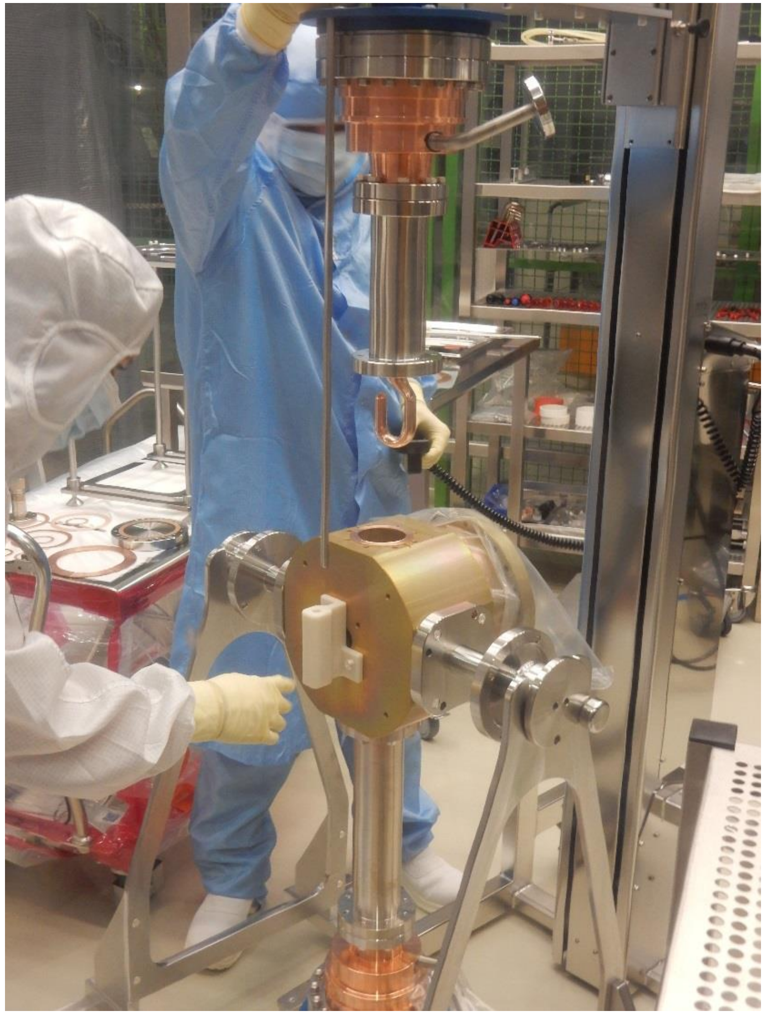
HL-LHC crab test box

During the assembly in clean room, we learnt a lot on many details, and we improved our processes and tooling

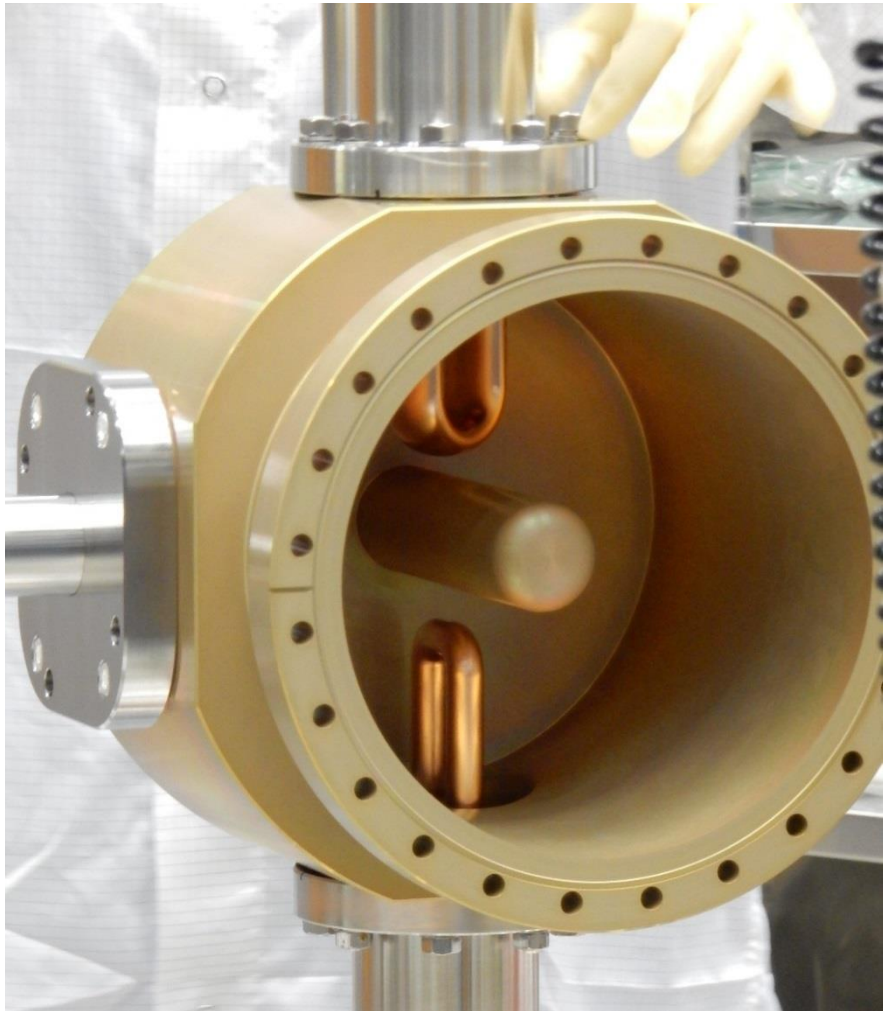
We 3D printed several tools in Acura 25 that allows to avoid polluting the items

HL-LHC crab test box

HL-LHC crab test box



HL-LHC crab test box

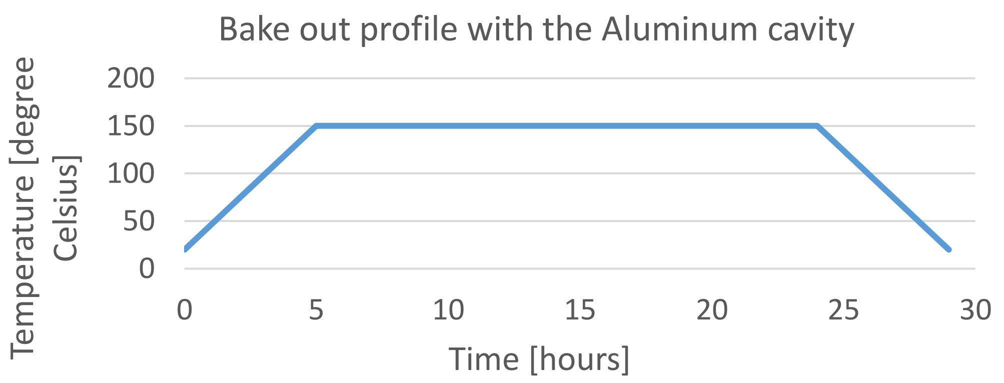


HL-LHC crab test box

Following the experience with all the couplers we built over the last decades; we learnt that a well done bake out process considerably help to speed up the RF processing time

With the aluminium test box, we had to define a safe cycle, so we bake out the two couplers with the following programme

- Up to 150 °C with 30 °C/h
- 18 hours at 150 °C
- Down to room temp with 30 °C/h



HL-LHC crab test box

Couplers are processed face to face first in TW

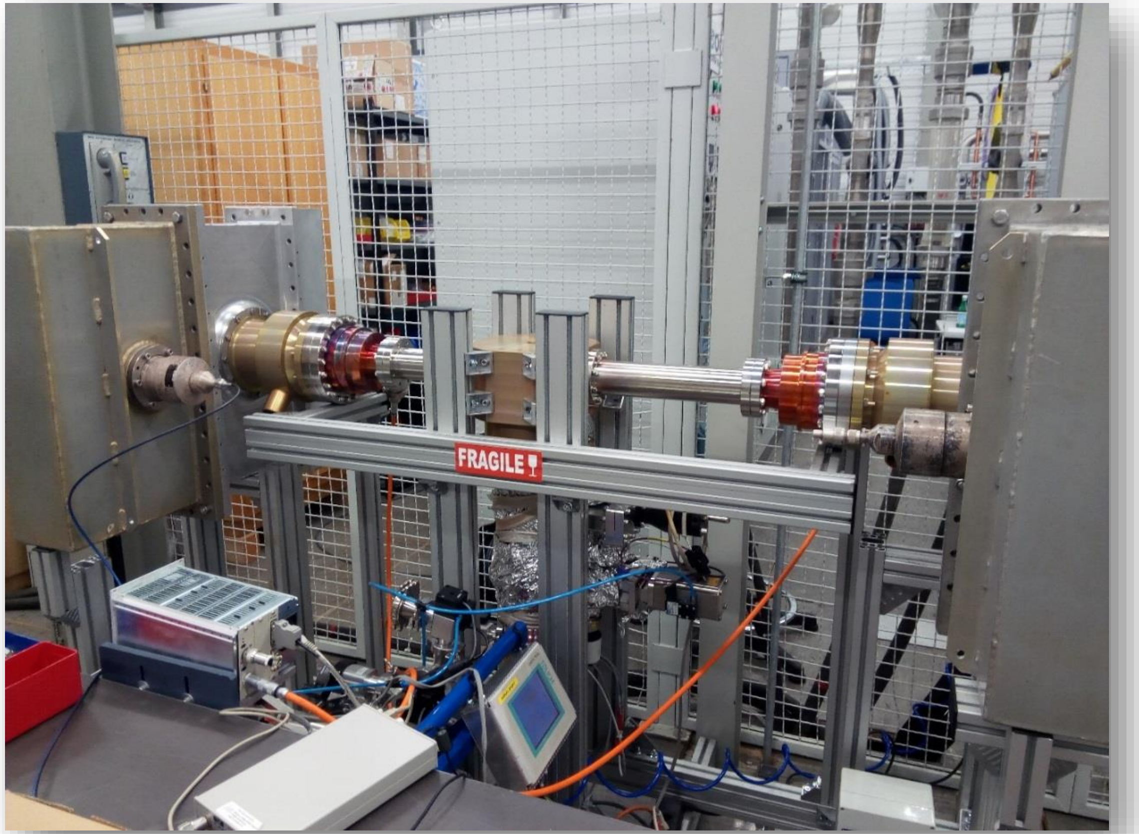
- 75 kW pulsed 10 ms @ 52.6 Hz
- 50 kW CW

We also processed them at the same values in SW, full reflection all phases

To date, we processed

- 6 x DQW
- 4 x RFD

Next couplers (12+12 total) are due until end of 2025



HL-LHC crab Assembly in clean room

Once the FPC have been RF processed, they are stored under vacuum until we assemble them in clean room ISO4

Here the process as done at CERN

HL-LHC crab Assembly in clean room

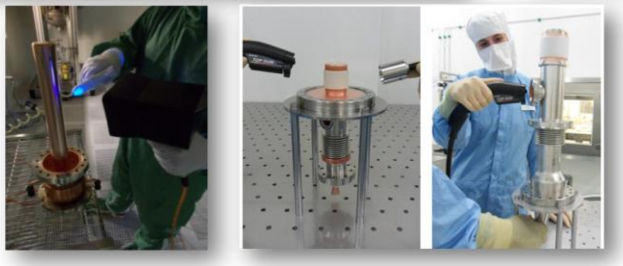
Preparation in the UK at
STFC clean room facilities

HL-LHC crab Assembly in clean room

Cleanroom requirements

In summary, cleanliness aspects must also be though from the very beginning such that cavities are not polluted

This covers design of the couplers themselves, and also tooling and processes



Specific cleaning process

ISO5 preparation of FPC and test boxes

ISO4 FPC on cavities

APS

352 MHz

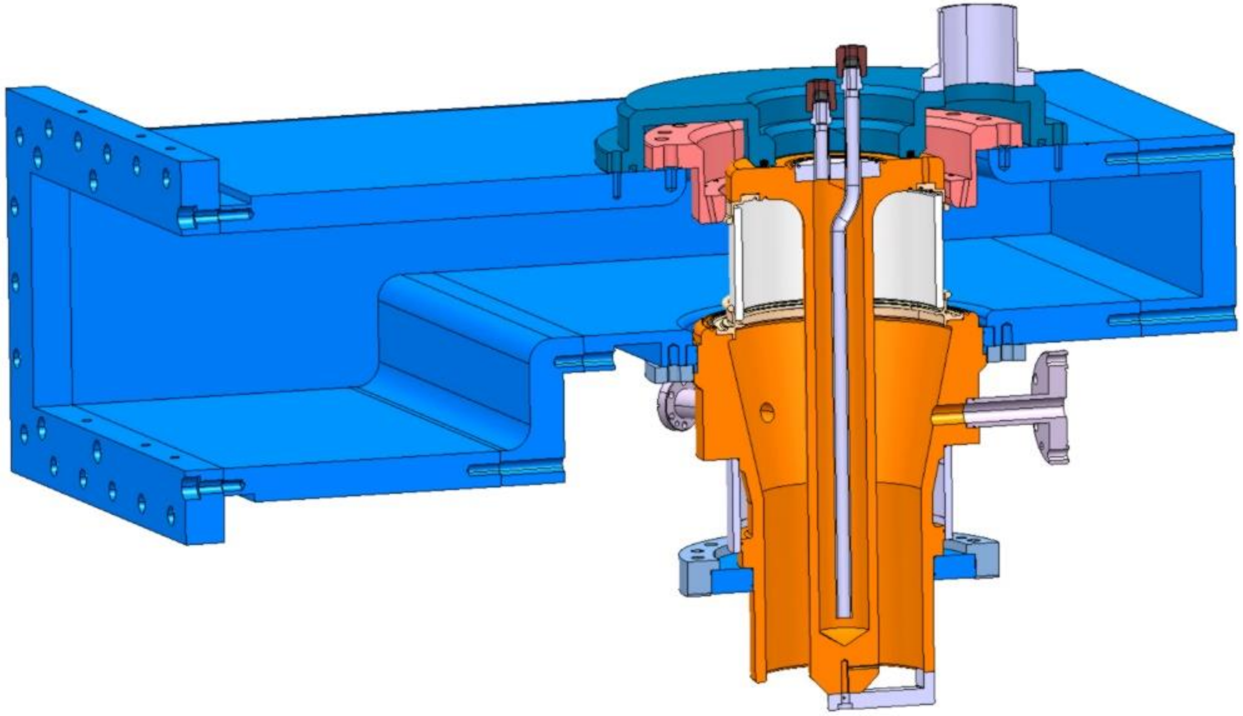
300 kW CW

LHC type cylindrical single window

No doorknob, WG to coaxial transition instead

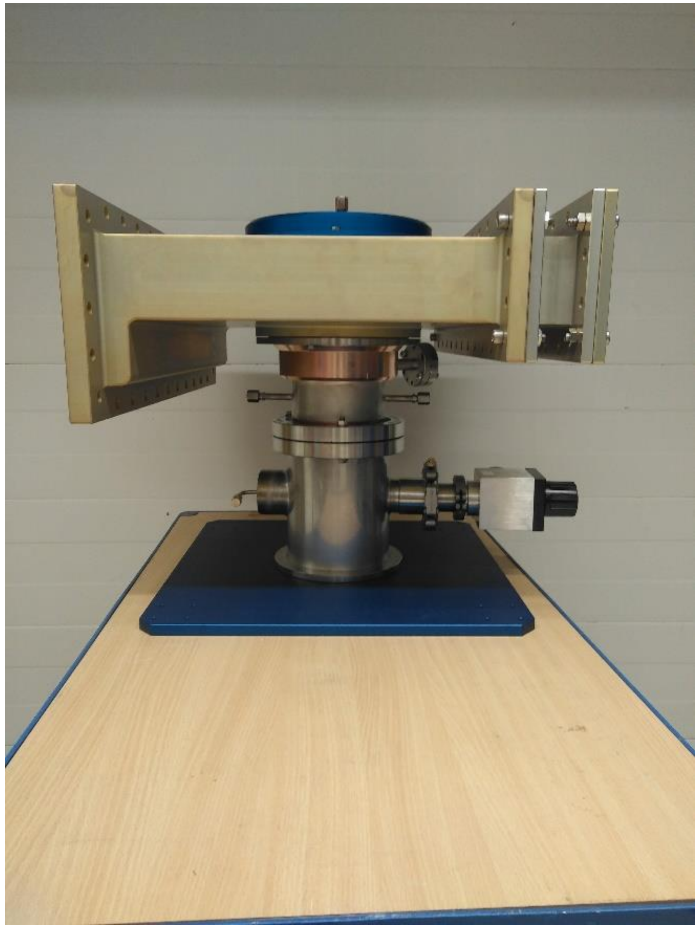
Water cooled antenna

Vacuum gauge for coupler protection

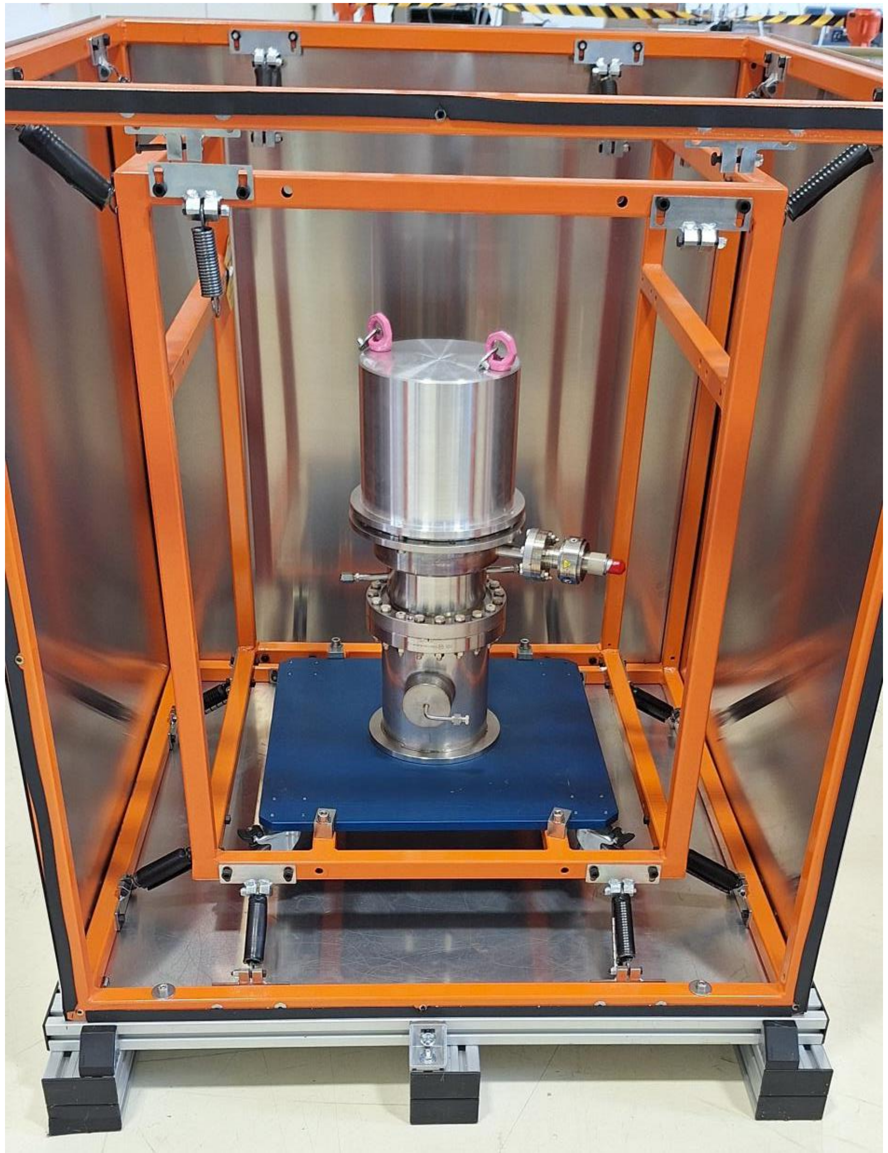


APS

Despite we were very careful, we broke two windows during high power tests



APS



In order to deliver from Europe to the USA, we developped a two metalic frame with springs in all axes to reduce any stress to the window that can occur at any time

This has proven to be very effective, and we also use it for the Crab project.

FCC

Room for R&D

SRF

High gradient

400 MHz

1 MW CW

Waveguide disk window

No doorknob, WG to coaxial transition instead

Water cooled antenna

SRF

High gradient

800 MHz

500 kW CW

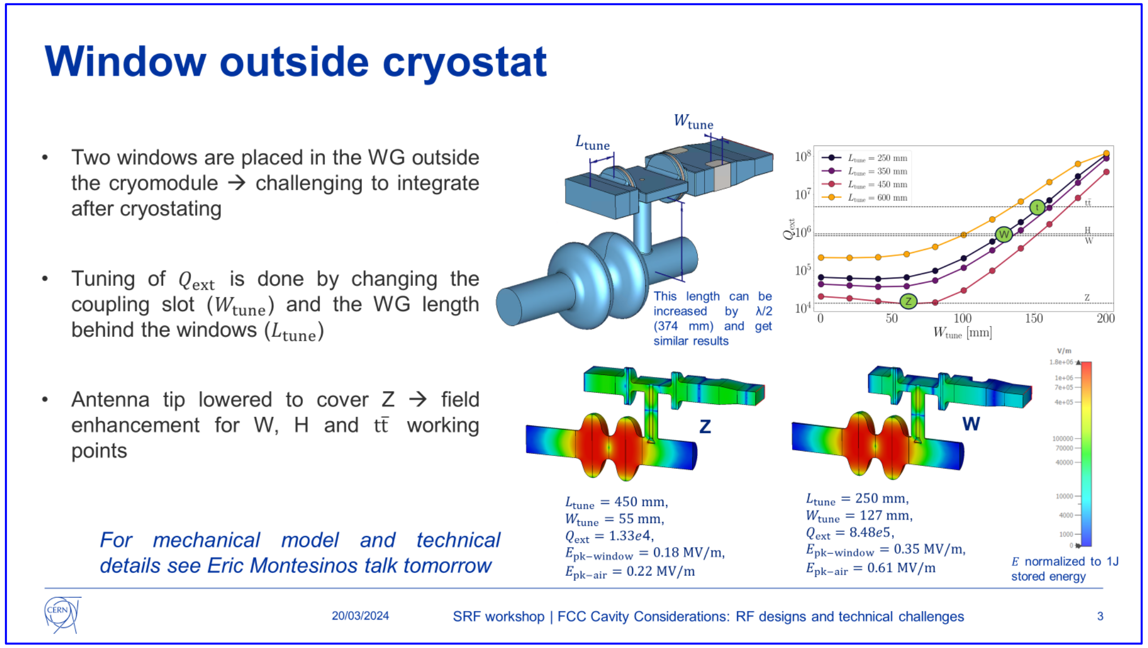
Coaxial disk window

No doorknob, WG to coaxial transition instead

Water cooled antenna

FCC

Courtesy Shahnam Gorgi Zadeh

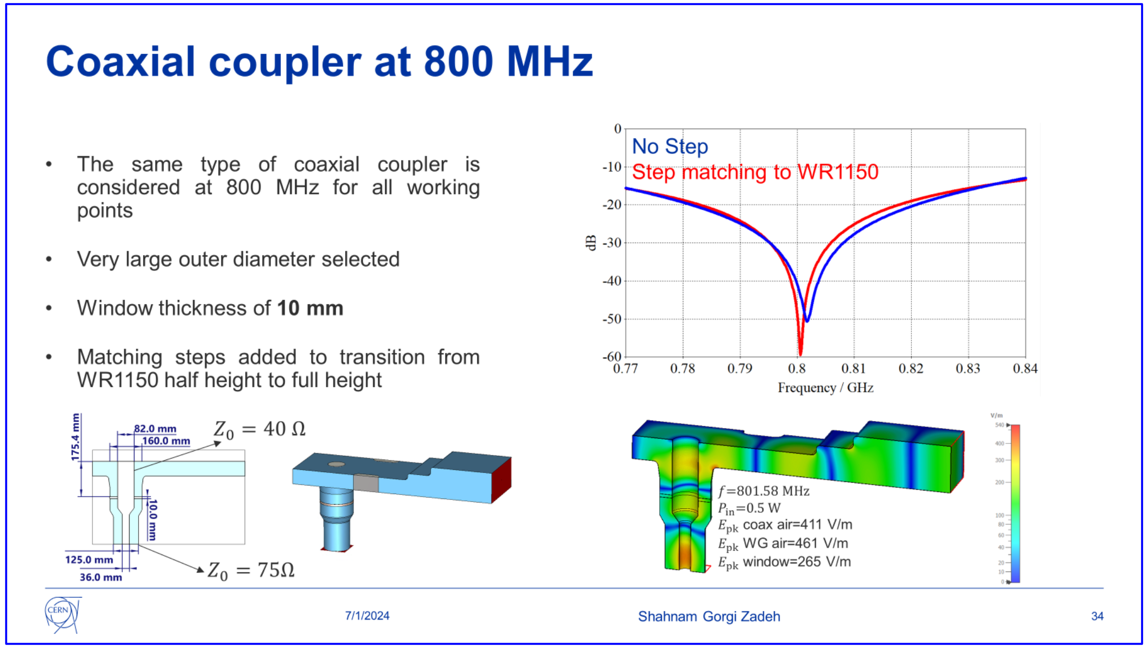


Window outside cryostat

- Two windows are placed in the WG outside the cryomodule → challenging to integrate after cryostating
- Tuning of Q_{ext} is done by changing the coupling slot (W_{tune}) and the WG length behind the windows (L_{tune})
- Antenna tip lowered to cover Z → field enhancement for W, H and $t\bar{t}$ working points

For mechanical model and technical details see Eric Montesinos talk tomorrow

20/03/2024 SRF workshop | FCC Cavity Considerations: RF designs and technical challenges 3



Coaxial coupler at 800 MHz

- The same type of coaxial coupler is considered at 800 MHz for all working points
- Very large outer diameter selected
- Window thickness of **10 mm**
- Matching steps added to transition from WR1150 half height to full height

7/1/2024 Shahnam Gorgi Zadeh 34

Ceramic material

CERN published a reference document in 1996 (10 pages) explaining all the parameters that a ceramic for RF window shall fulfil

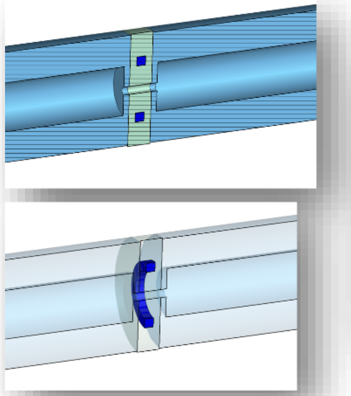
http://cds.cern.ch/record/91419?ln=fr

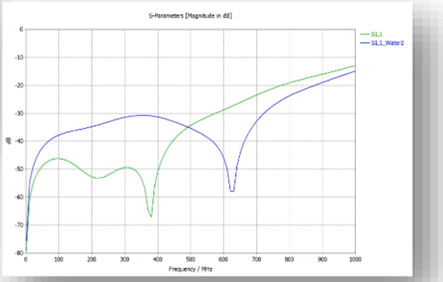
It is still in use, and all our ceramics are the Al2O3 - 97.6 % purity ones

	Purity	RF losses	Brazing
Al_2O_3	99.9 %	Very Low	Very difficult
Al_2O_3	97.6 %	Medium	Medium
Al_2O_3	95 %	Higher	Easier

This is one of our first topic for R&D with respect to FCC high power requirements, ***we launched a program to master how to braze 99.9 % purity ceramics with the sizes we need (thickness and diameter)***

Water cooled from the inside ceramics

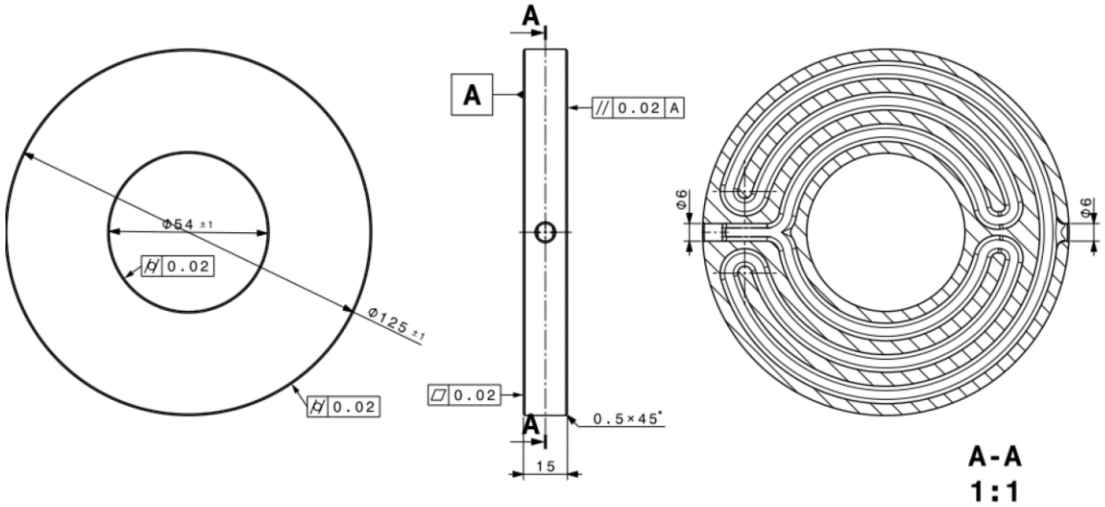


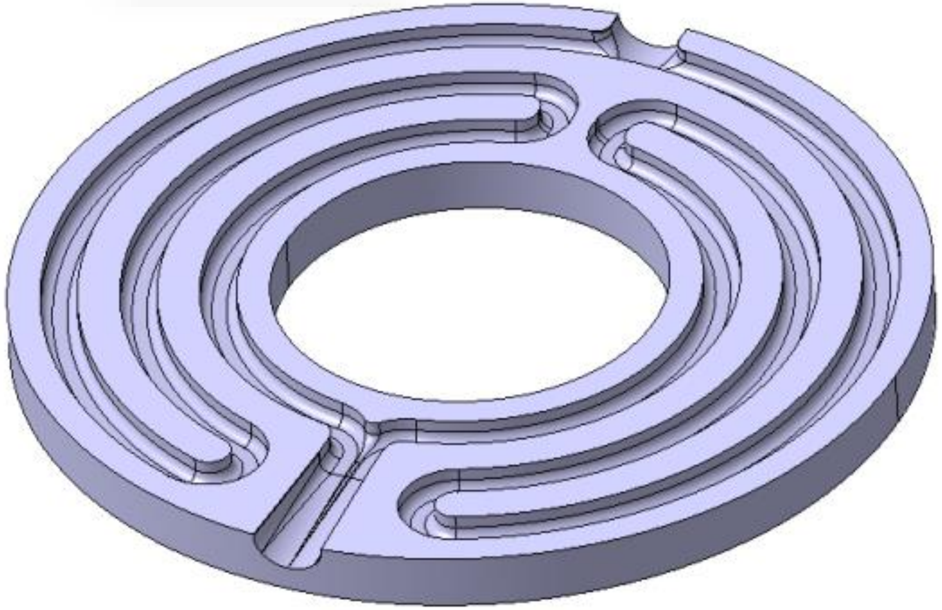


With the help of or mechanical experts, we launched a prototyping of a 3D printed ceramic with water channels cooling down the ceramic from the inside

This should help getting to higher power handling

The construction is ongoing, but not easy at all, several prototypes failed





FCC

Over the last 3 years, power level requirements and frequencies have often changed

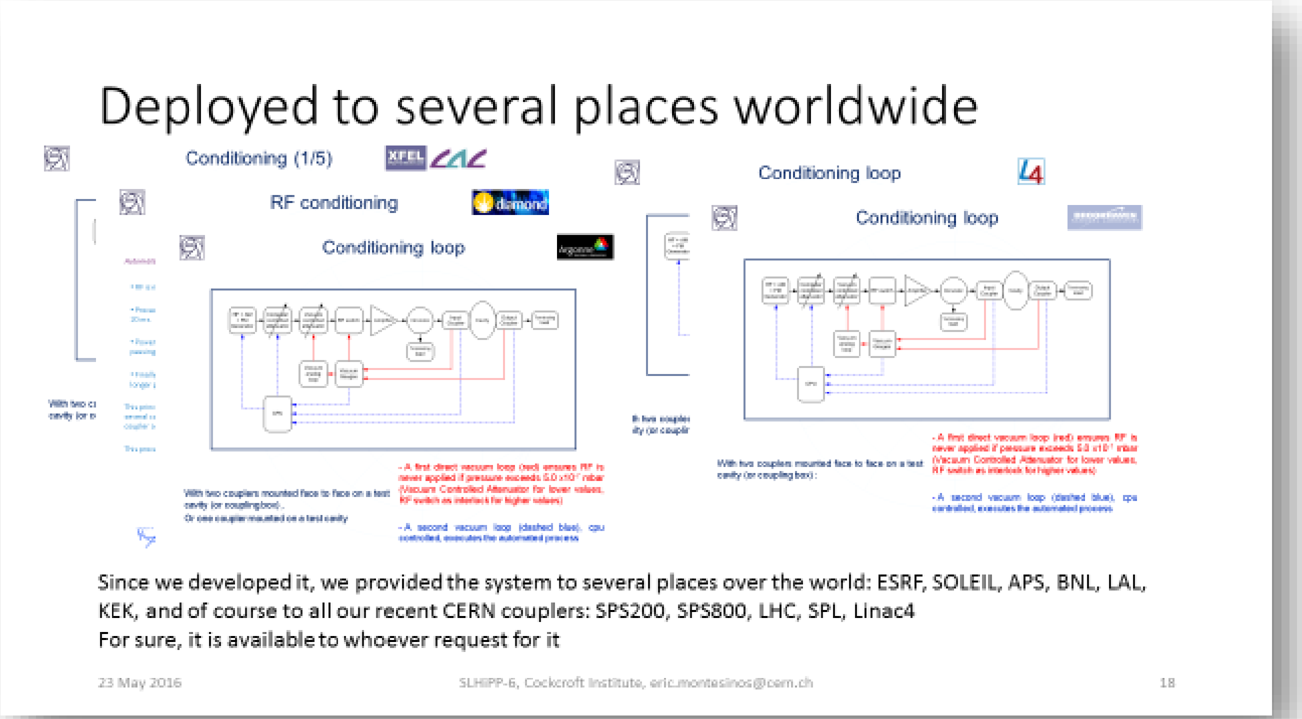
We now have a robust plan to develop LHC compatible FPC and to test them after Long Shutdown 3 (2026-2029) to validate the concept for FCC

For the 400 MHz version, this will be a disk window(s) in the waveguide with a target at 1 MW CW SW, with an assembly in a dedicated clean room (ISO5?)

For the 800 MHz version, this will be a coaxial window close to the beam axis with a target at 500 kW CW SW, with an assembly before cryostating in ISO4 clean room

Conditioning processes

[Dedicated talk at the 6th Open Collaboration Meeting on Superconducting Linacs for High Power Proton Beams (SLHiPP-6)]



Conditioning processes

It In order to be safe, we first ramp RF power with very short pulses from zero to full power

We then restart with longer pulses, again from zero to full power

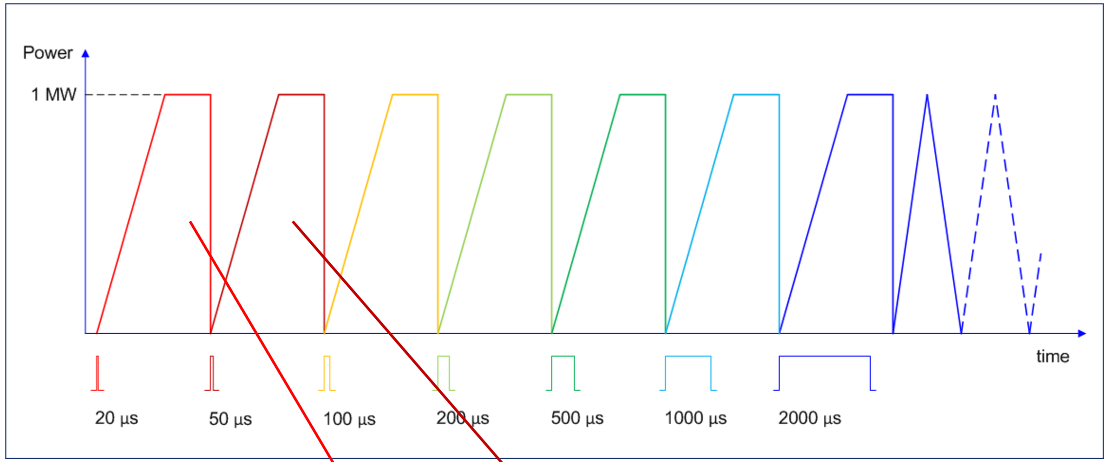
We repeat the process until maximum pulse duration, that could be CW

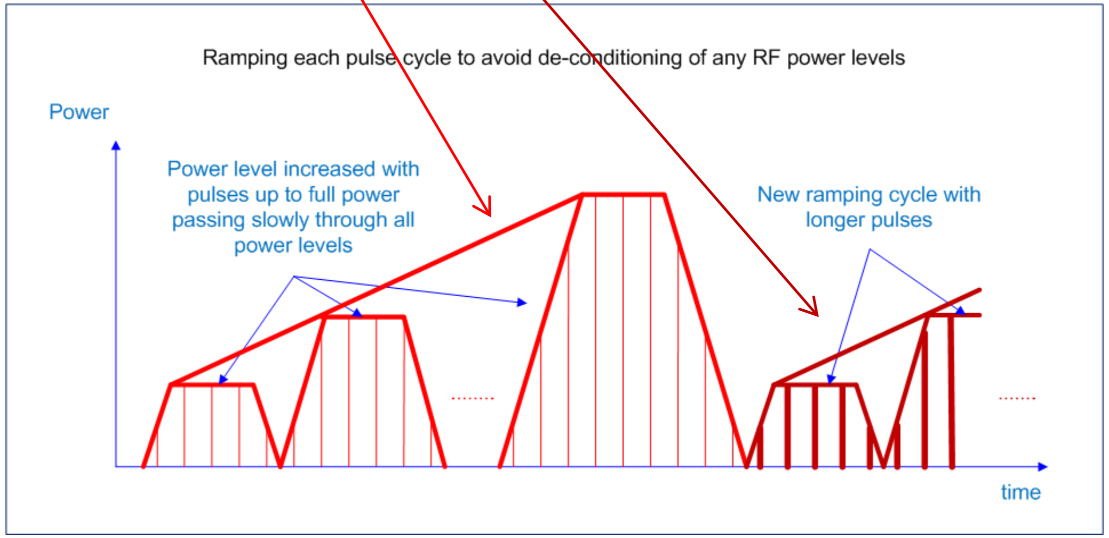
What we also noticed is that making a 'straight ramping' could be dangerous

Indeed, a higher power level can 'de-condition' a lower power level previously processed

So inside one envelope, we ramp up and we ramp down to guaranty that ALL power levels have been processed with the shorter pulses

This process ensures that the lowest energy is deposited into an arc if it should occur

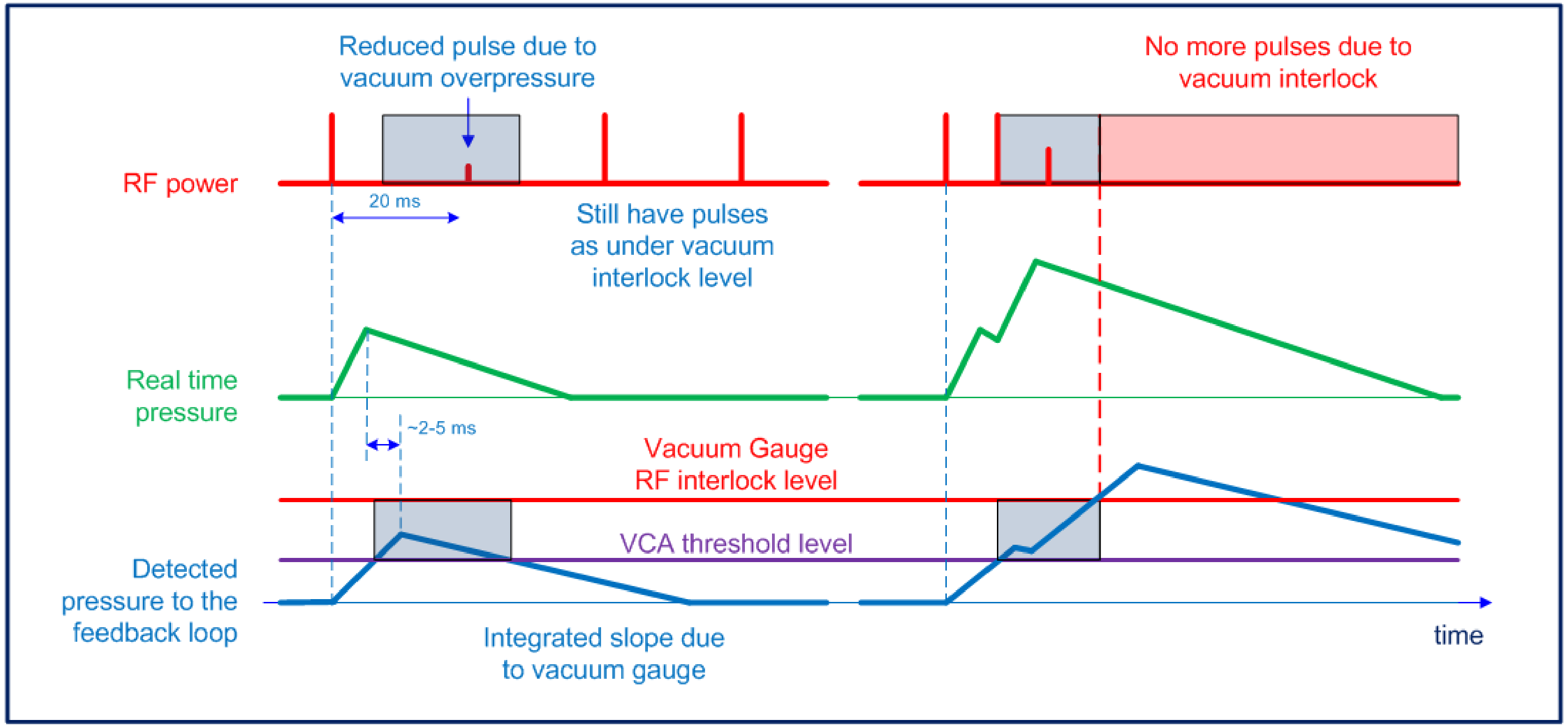




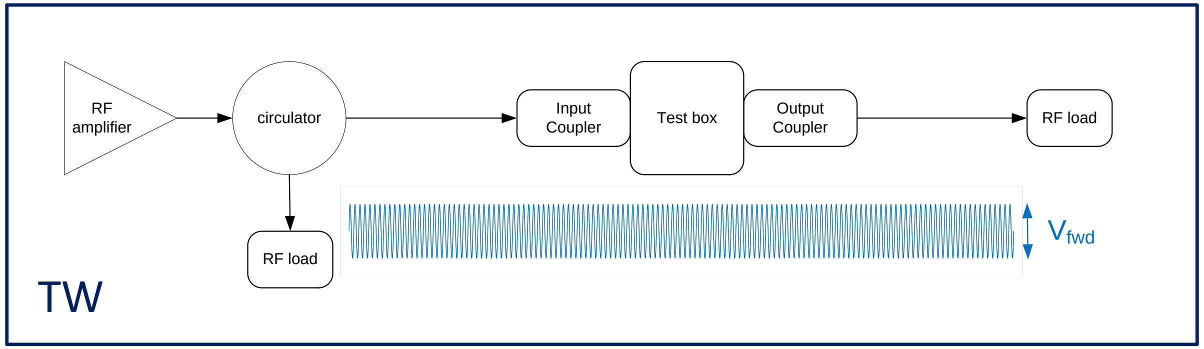
Conditioning processes

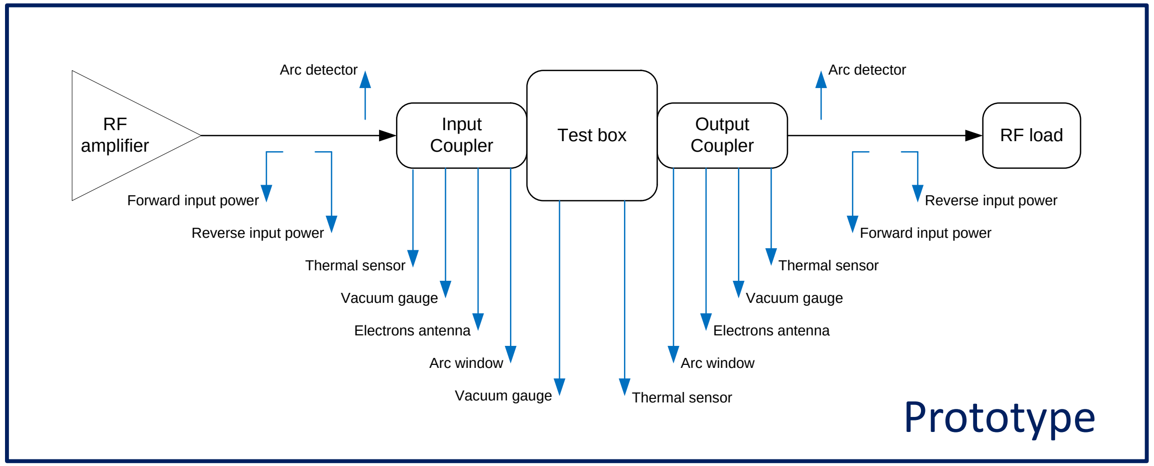
It is important to keep the repetition rate low enough to allow enough time to the vacuum gauge to detect the pressure rise

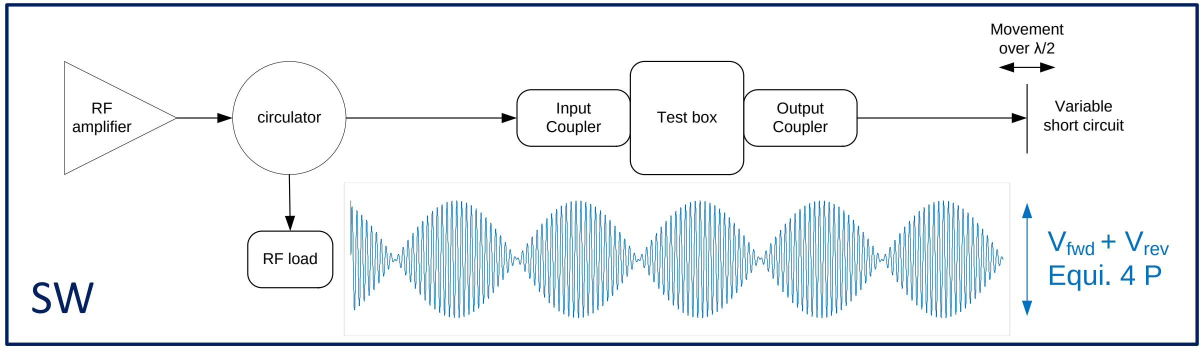
This allows not to stop the system, only few pulses are missed

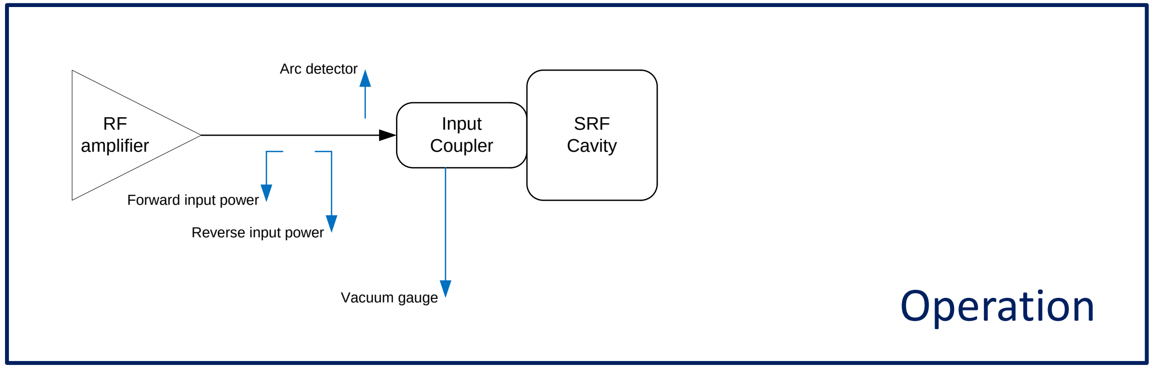


Conditioning processes



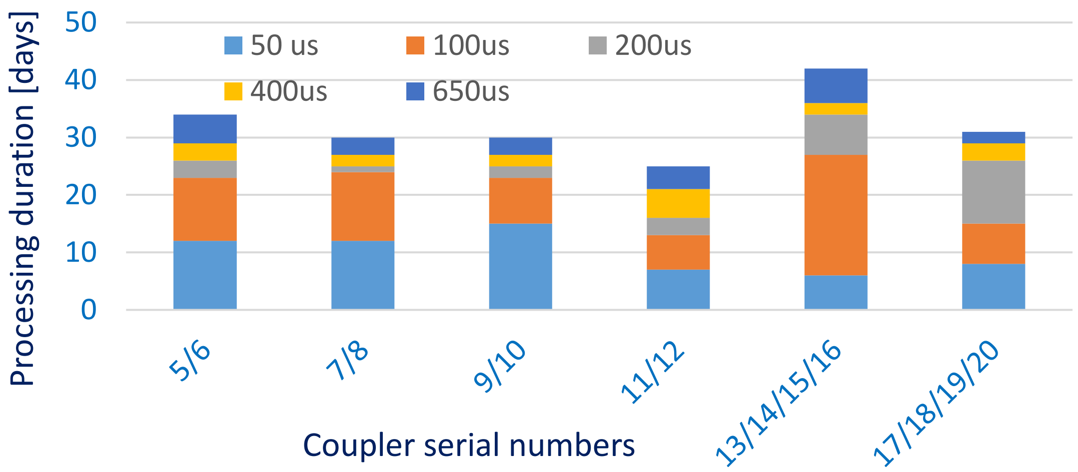






RF processing

We need to define the best RF processing strategy in order to guaranty mass production delivery schedule



Total duration 2 windows + 2 windows = **64 days**

Exchange Windows 2 days | Processing 2 windows 30 days | Exchange Windows 2 days | Processing 2 windows 30 days

Preparation next 2 windows, 5 days | Bake out 5 days | Preparation next 2 windows, 5 days | Bake out 5 days

Total duration 4 windows = **37 days**

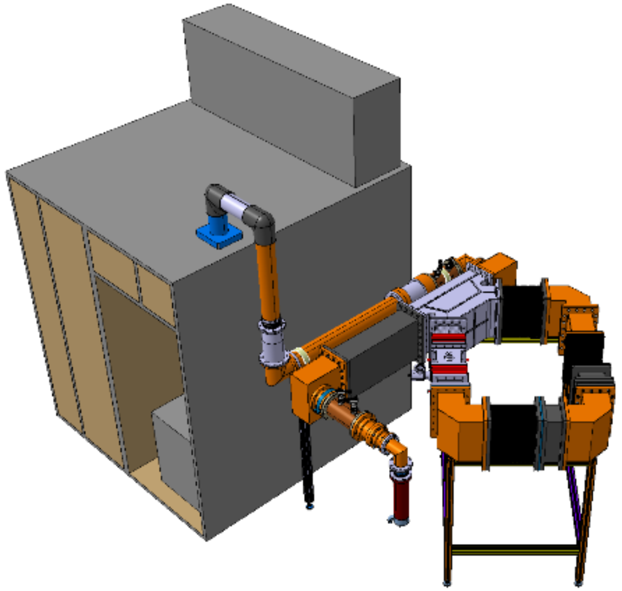
Exchange Windows 2 days | Processing 4 windows 35 days

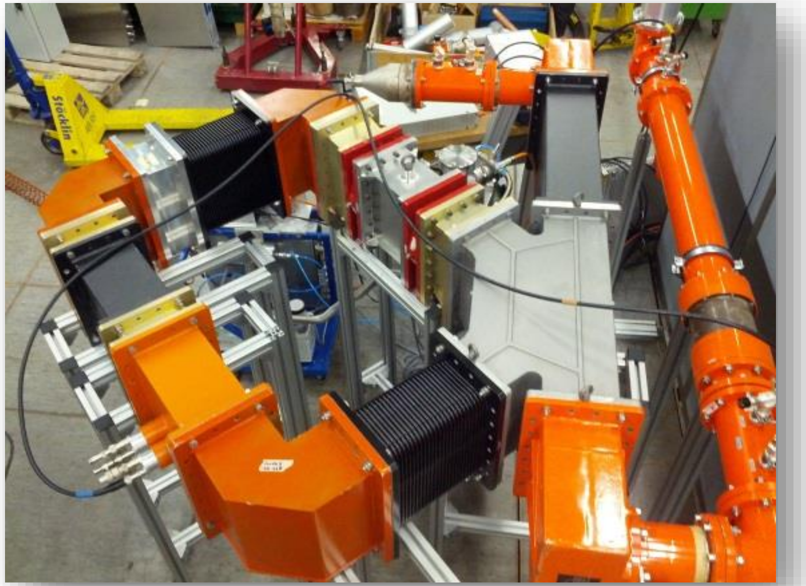
Preparation next 4 windows, 6 days | Bake out 5 days

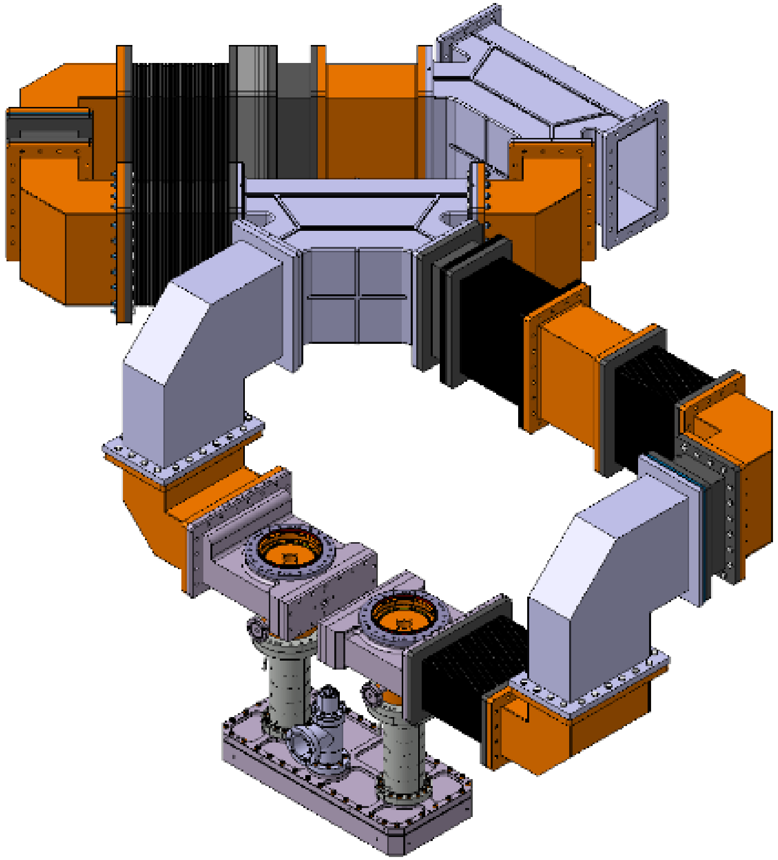
With Linac 4 windows, we did some tests with four windows in series, and we were much faster than two plus two windows

Resonant rings

No progress







Resonant ring are one of the most important way to make huge savings with test benches, we still have it in our plans

CERN FPC R&D Centre, done, and operational

Robots

Metrology

Vacuum

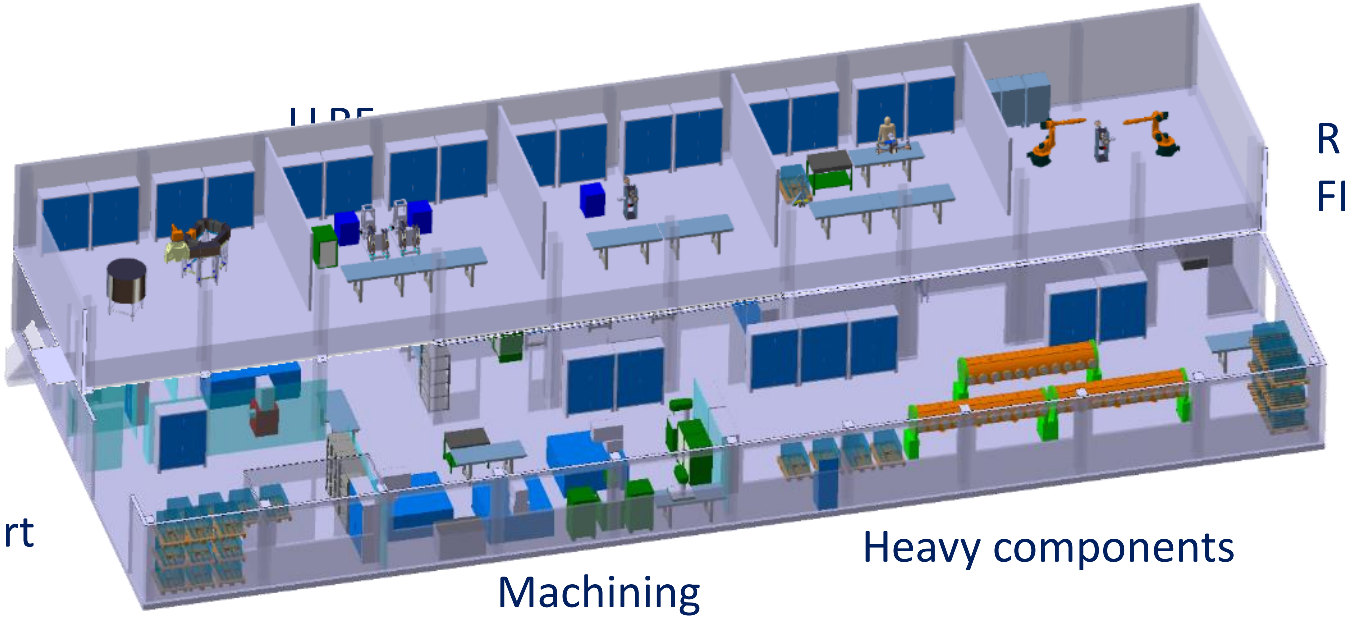
Test boxes

RF components

Deepest thanks to the CERN management that agreed to invest in a new FPC R&D Centre

200 m² First Floor

600 m² Ground floor



RF power for FPC processing

Assembly

Transport

Machining

Heavy components

CERN FPC R&D Centre & WWFPC meetings topics for discussion

Design
Maximum power per coupler ?
Multi couplers per cavity ?

Ceramic
Sputtering: TiOx – TiN ?
Control of the process ?
Qualification (*** Sergio/Fritz)
New ceramic without treatment ? (KEK/CERN – Thales/CERN)
Gray deposit ?
How to qualify ? (*** Sergio/Fritz – Wolf-Dietrich – Walid)

Coating
Copper plating (launch a program) how to make it correct ?
Common classification of defects acceptance criteria ?

Discoloration of ceramic
Is superficial oxidation or discoloration a problem ? (*** identification Walid)
Before/after RF processing
To gray after RF conditioning at XFEL
To yellow due to multipacting ?
To brown after X-ray

Specific constraints for operation reasons
No brazing-welding-soldering between liquid coolant and vacuum (proven EBW should not be on the list)
No liquid cooled couplers
Do you have the same constraints ?
Do you have statistics linked to these constraints ?

Tests
TW? SW? TW & SW ?
Test boxes in 3D printing copper plated ? Acceptable or incompatible with cleanliness requirements ?
Arcing and air cooling
Is lower pressure creates arc ?
Is N2 worse than air ?
Do we need vacuum gauge for series production FPC ?
BNL, SNS, DESY do not use DC bias, prefer a good conditioning, afraid of gas accumulation (use multipacting simulation tool in order to make a multipacting free coupler)
Amplifiers for tests
Prototype processes versus series processes
What margin do we need between pre-series and series ?

Diagnostics
R&D and prototyping
Operation in accelerators

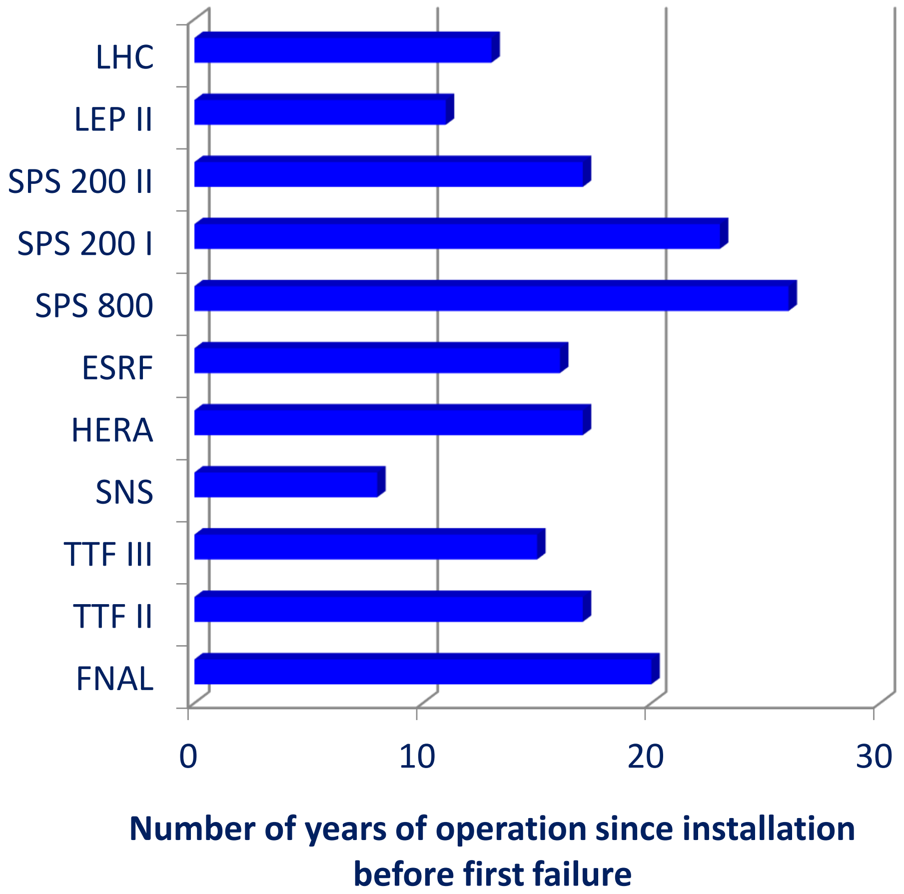
Statistics
How to list all couplers operated in accelerators ?
Degradation of characteristic over time of operation
How to share these information ?
This meeting ? Mandatory in talks ?
Make pictures of work environments !

World Wide Program ?
How to organise it ?
Who can do what ?
Who want to do what ?

Statistics

Quite poor statistics of couplers over the world

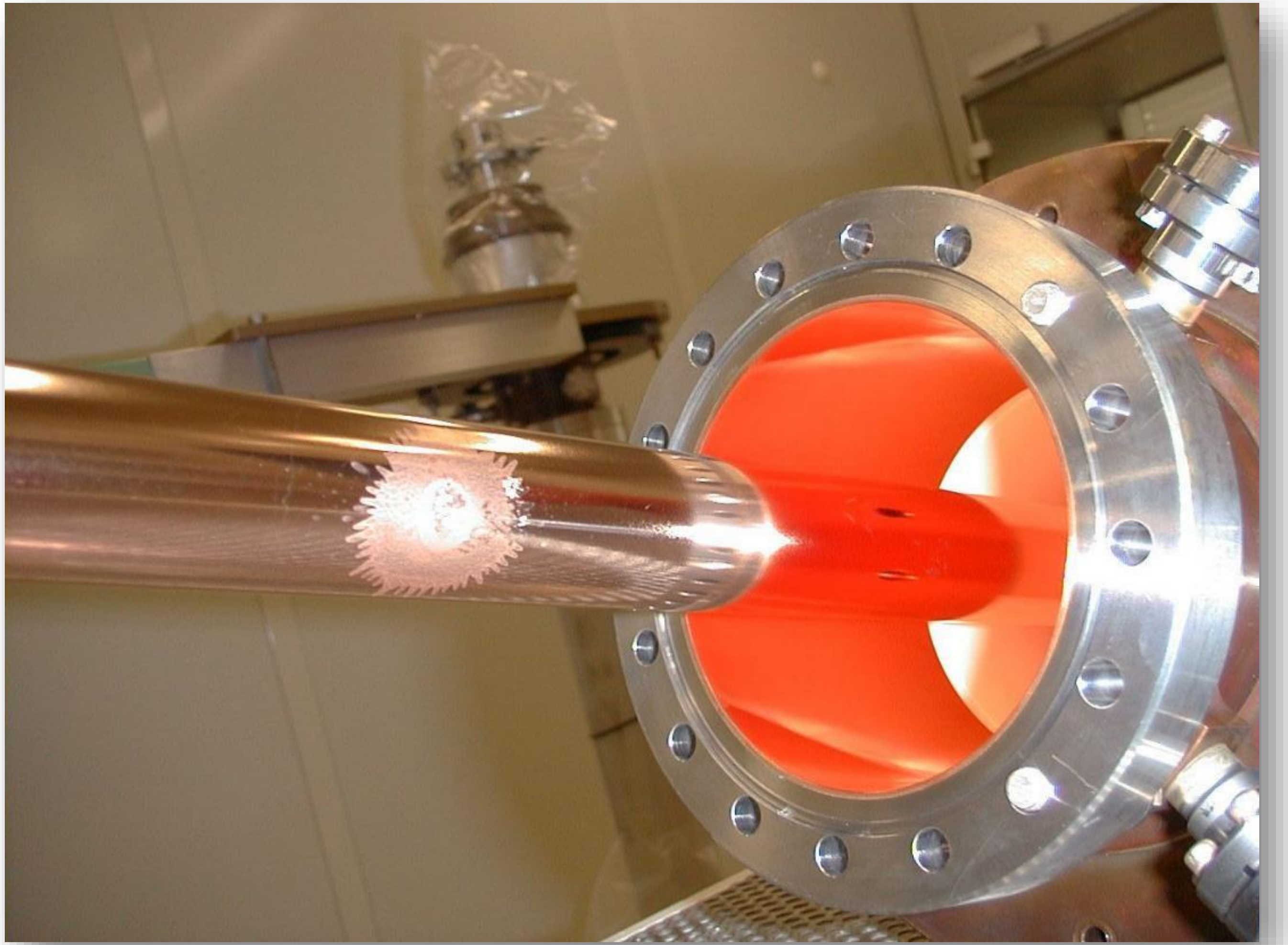
May I ask you to provide me with relevant numbers



Miscellaneous

Miscellaneous

Miscellaneous



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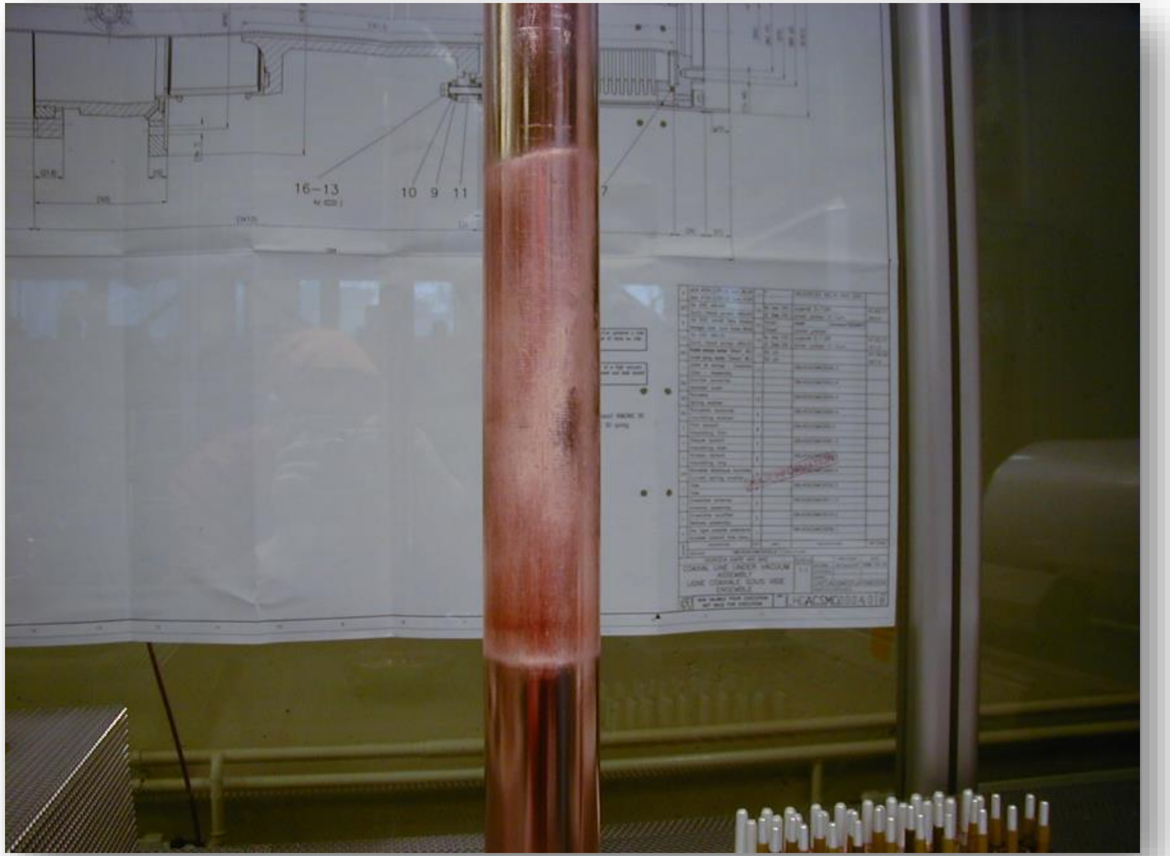

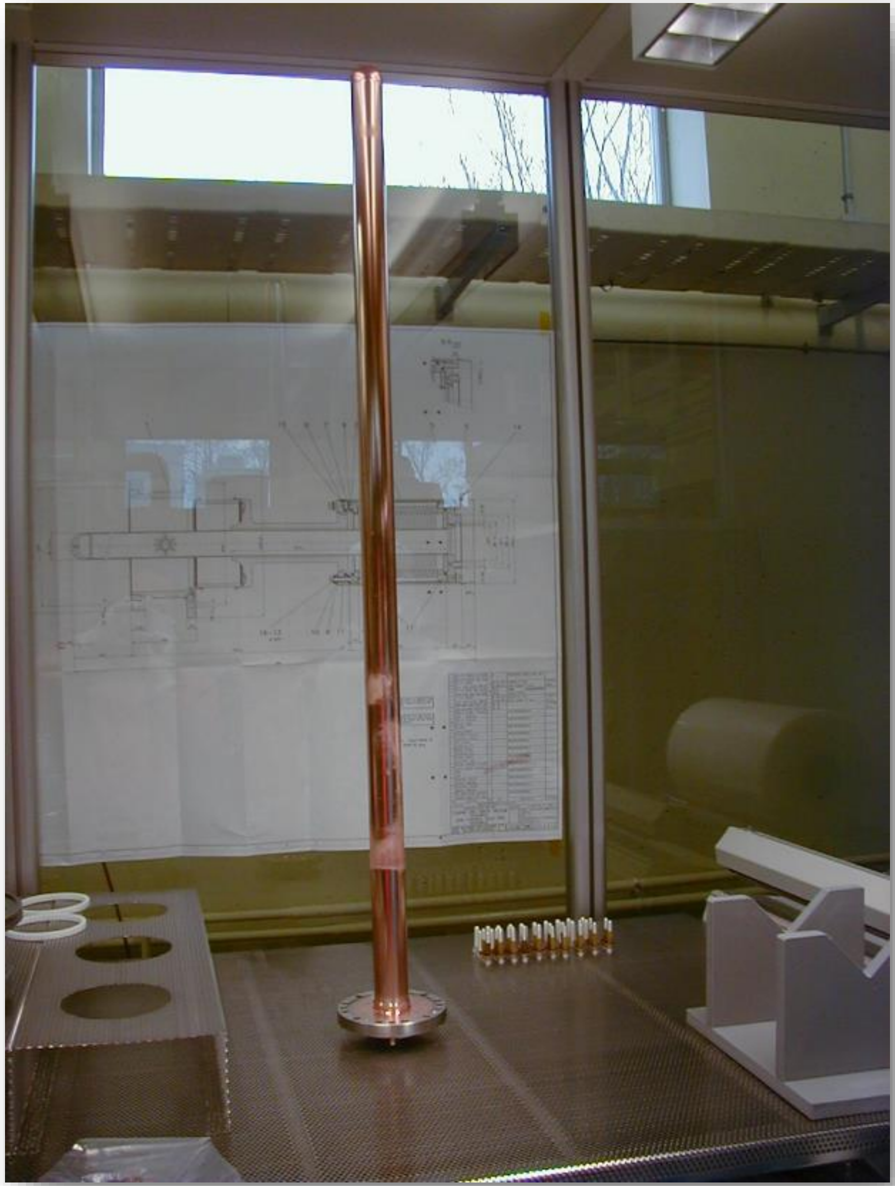

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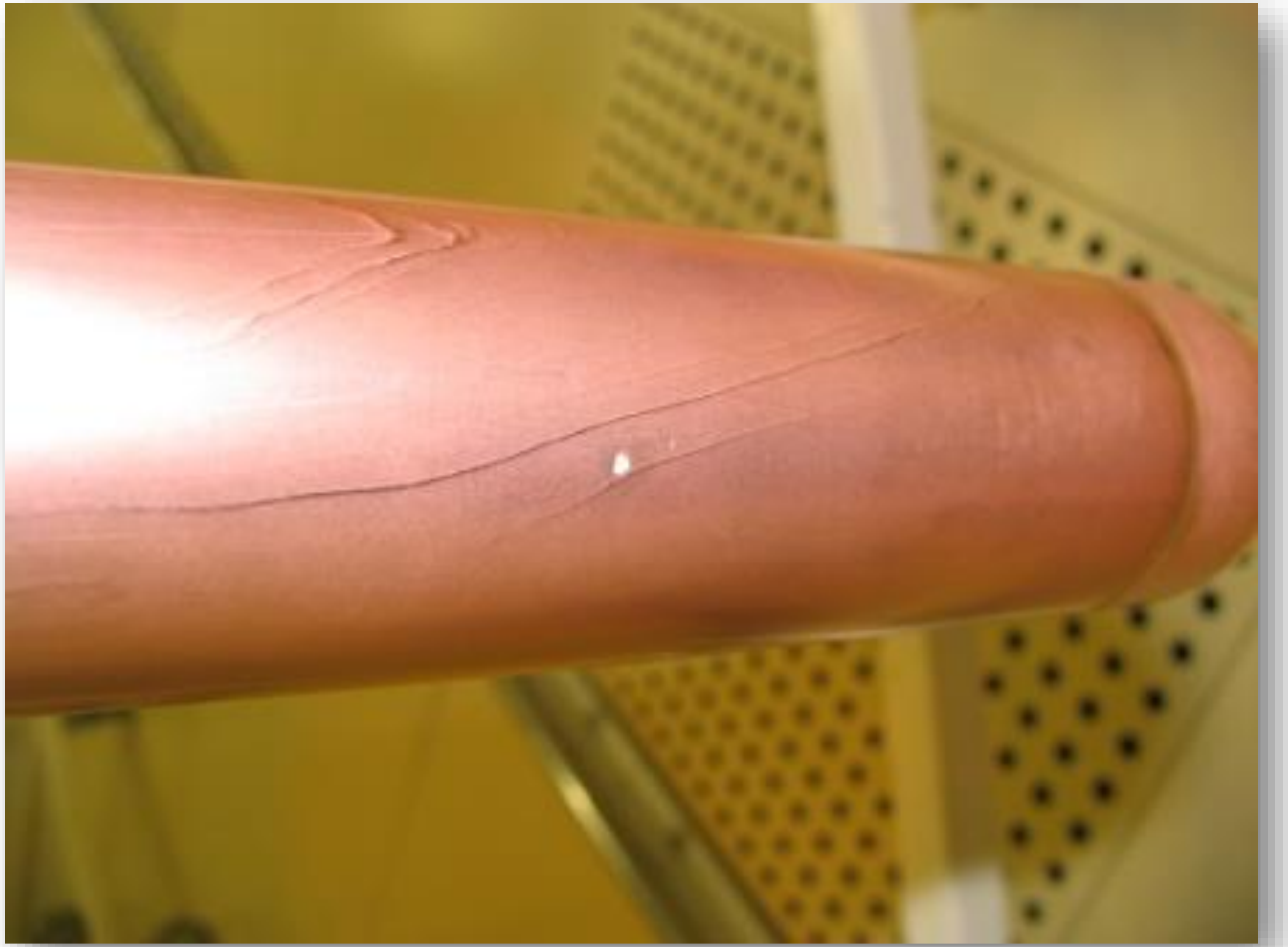

Miscellaneous

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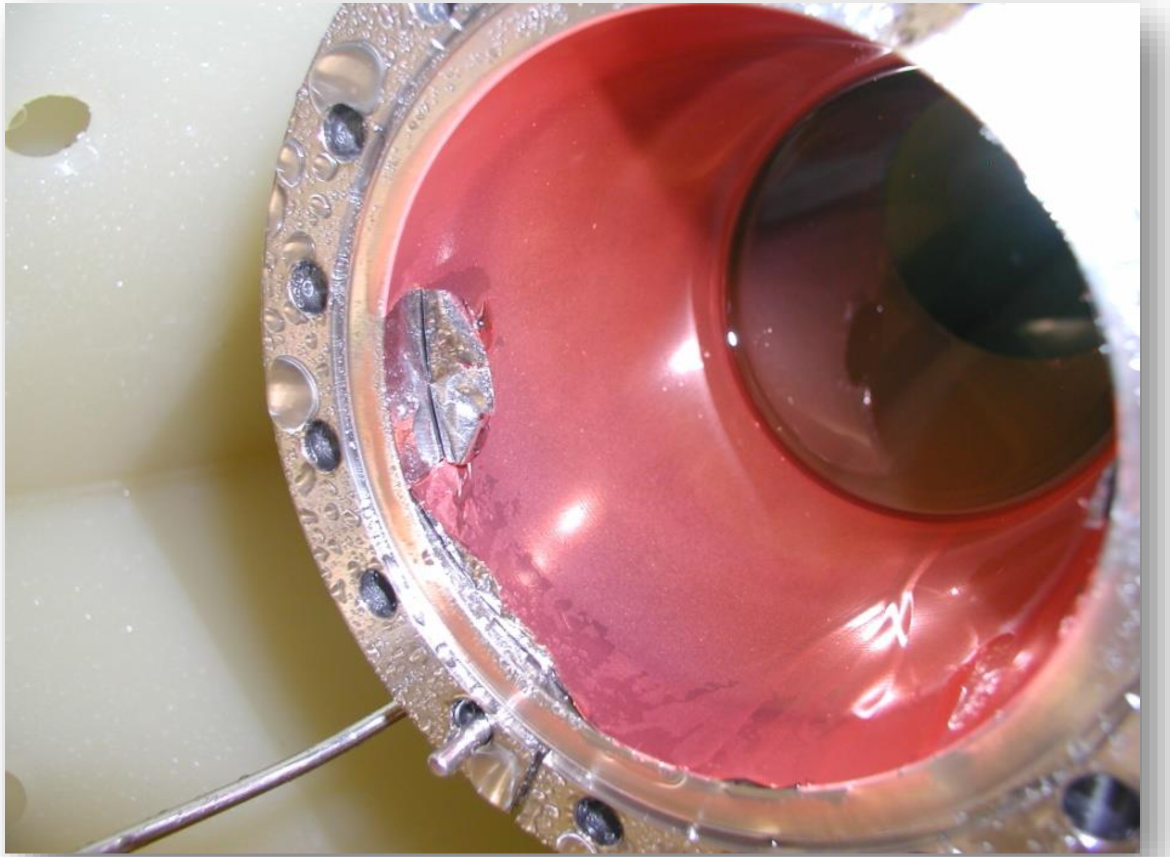

Despite we do all our couplers the same way, copper coating is always a challenge

HL-LHC crab was as always, complex before being successful

Final comment

Message that I deliver to my management as often as I can

We are passionate to work on this fantastic topic

CERN is very active with respect to FPC activities
(thanks to the management for supporting the team since decades!)

Thanks to all the FPC colleagues over the world for the so open-minded constructive contributions

International collaborations between FPC experts is always very fruitful

Thank you again for being here today !