POWER COUPLERS & HOM DAMPERS AT CERN

eric.montesinos@cern.ch

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

MANDATE

We are interested in the general CERN expertise with FPCs and HOMSs, specifically regarding couplers for high average power transmission

Of interest are the manufacturing experience, test results, and parameter reached

There can be a focus on your recent experience with dressing the DQW with the HOMSs, including test results of DQW FPCs and HOMSs and how you prepared for the clean room assembly

Frank – CERN & Ilan – BNL

WHAT IS A POWER COUPLER ?

Power Coupler is also known as

- FPC : Fundamental Power Coupler
- MPC : Main Power Coupler
- MC : Main Coupler
- PC : Power Coupler
- Coupler

Fundamental : with reference to the fundamental frequency of the cavity

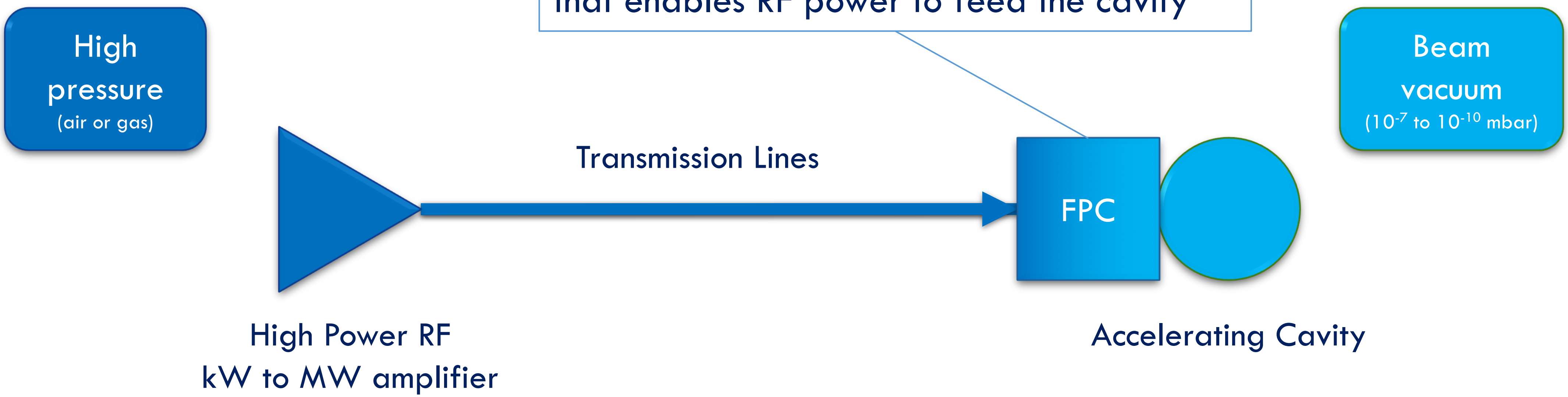
Main : as there are other couplers around the cavity, but this one is for powering the cavity

Power : as powering the cavity

eric.montesinos@cern.ch

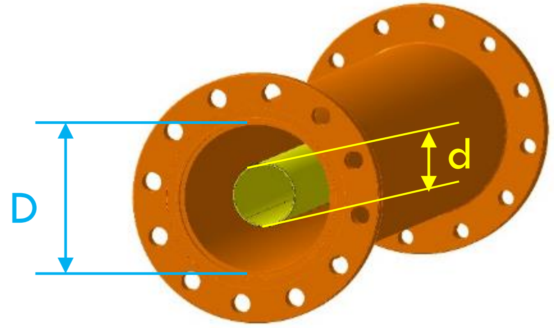
WHAT IS A POWER COUPLER ?

The FPC is a specific piece of transmission line with one side at high pressure and the other side under beam vacuum pressure that enables RF power to feed the cavity



TRANSMISSION LINES

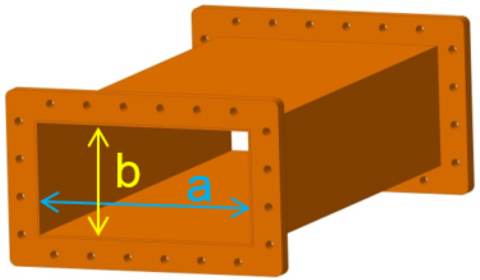
Coaxial lines



$$Z_c = \frac{60}{\sqrt{\varepsilon_r}} ln\left(\frac{D}{d}\right) \qquad Ppeakmax = \frac{{E_{max}}^2\, d^2 \sqrt{\varepsilon_r}}{480} ln\left(\frac{D}{d}\right)$$

With: $P_{peakmax}$ = Maximum peak power in watts, D = inside electrical diameter of outer conductor in mm, d = outside electrical diameter of inner conductor in mm, E_{max} = breakdown voltage gradient of the dielectric filling the line in Volt/cm (for dry air 30 kV/cm, for ambient air 10 kV/cm), ε_r = relative permittivity of dielectric

Rectangular Wave Guides (WR)



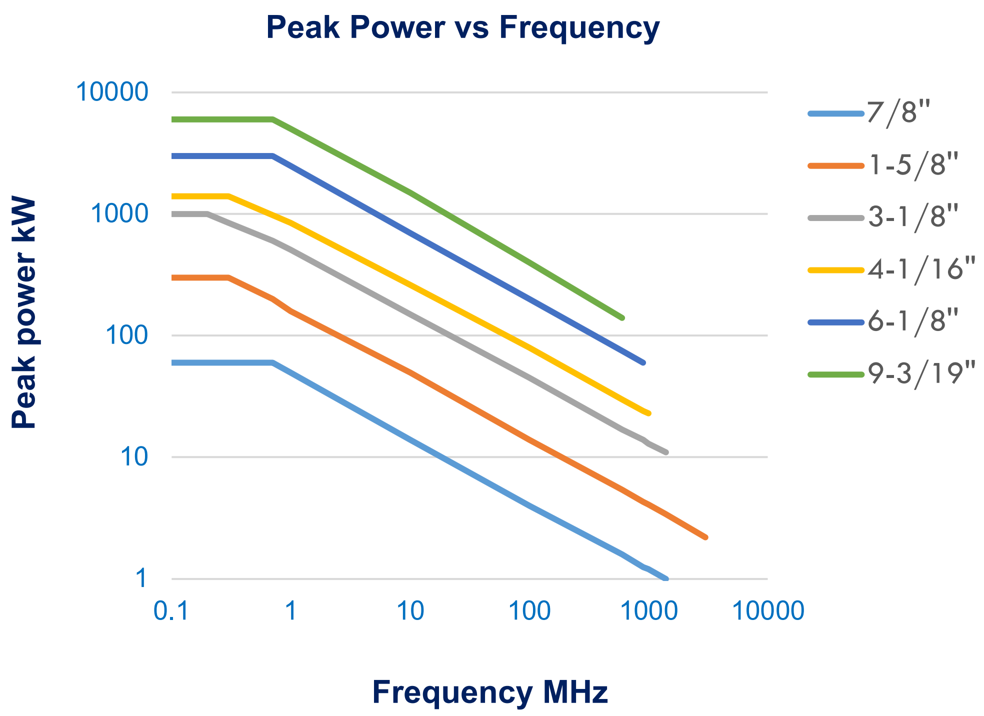
$$P_{peakmax} = 6.63\ 10^{-4}\ {E_{max}}^2 \sqrt{b^2\left(a^2 - \frac{\lambda^2}{4}\right)}$$

With: $P_{peakmax}$ = Maximum peak power in watts, a = width of waveguide in cm, b = height of waveguide in cm, λ = free space wavelength in cm, E_{max} = breakdown voltage gradient of the dielectric filling the waveguide in Volt/cm (for dry air 30 kV/cm, for ambient air 10 kV/cm)

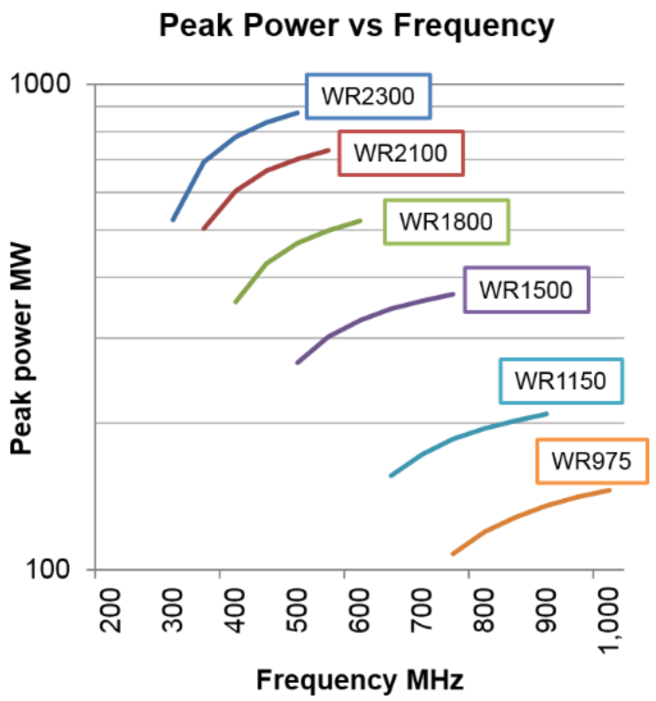
TRANSMISSION LINES

Waveguide name			Recommended frequency band of operation (GHz)	Cutoff frequency of lowest order mode (GHz)	Cutoff frequency of next mode (GHz)	Inner dimensions of waveguide opening (inch)
EIA	RCSC	IEC				
WR2300	WG0.0	R3	0.32 — 0.45	0.257	0.513	23.000 × 11.500
WR1150	WG3	R8	0.63 — 0.97	0.513	1.026	11.500 × 5.750
WR340	WG9A	R26	2.20 — 3.30	1.736	3.471	3.400 × 1.700
WR75	WG17	R120	10.00 — 15.00	7.869	15.737	0.750 × 0.375
WR10	WG27	R900	75.00 — 110.00	59.015	118.03	0.100 × 0.050
WR3	WG32	R2600	220.00 — 330.00	173.571	347.143	0.0340 × 0.0170

Coaxial lines

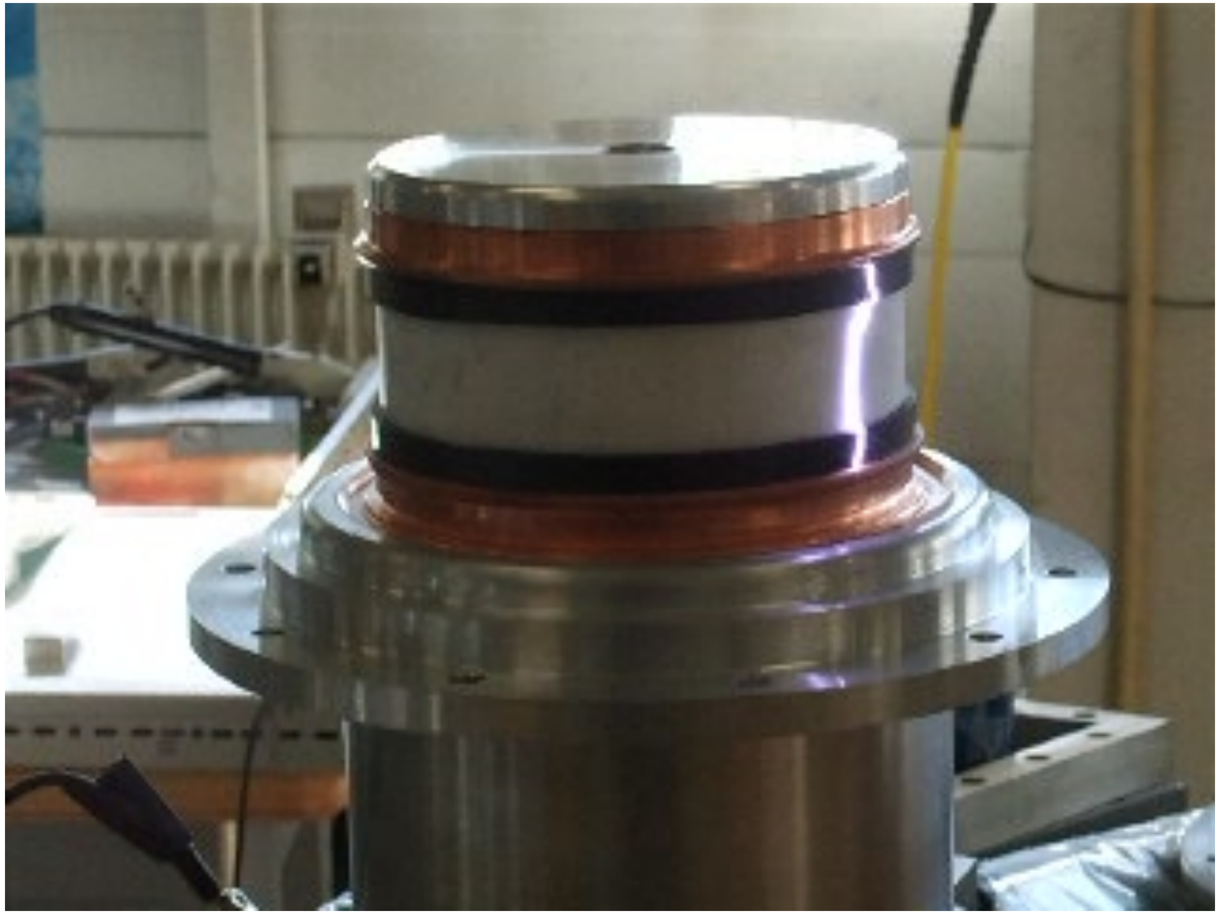


Rectangular Wave Guides (WG)



eric.montesinos@cern.ch

TRANSMISSION LINES



WINDOWS

This is the most important device of a FPC

It ensures the vacuum leak tightness of the FPC, and of the entire machine!

Any leak on the window immediately leads into degradation of the cavity and of the machine

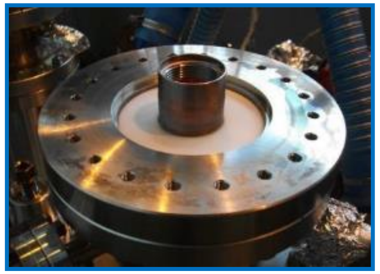
It is commonly a ceramic brazed with metal

Cylindrical windows

LHC, 400 MHz
500 kW CW

ESRF-SOLEIL-APS, 352 MHz
250 kW CW

SPL, 704 MHz
1 MW 5 % duty

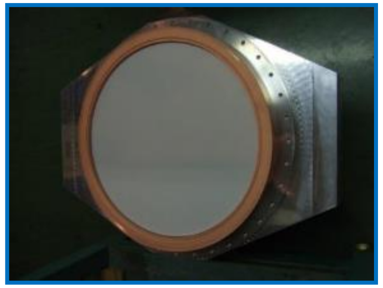


Coaxial disk windows

HL-LHC Crab, 400 MHz
100 KW CW

SPL 2.0, 704 MHz
1 MW 5 % duty

SPL 3.0, 704 MHz
2 MW (expected)
5 % duty



Disk windows

SPS, 800 MHz
150 KW CW

Linac4, 352 MHz
1 MW 10 % duty

LHC 2, 400 MHz
1 MW (expected) CW

METALLIZATION

Before brazing the metallic line, the window has to be metallized

The most common medium used is a Molly-Manganese deposition on the surfaces to be brazed

It is often painted by hands

This paint is very sensible and must be kept in movement at any time, under a controlled temperature and humidity

The metallic lines will be brazed onto that MoMn support, it is of the highest importance

A default in the metallization of the ceramic, one can easily understand that it will not be possible to braze any metallic part onto it

CERAMICS

Most of the windows are built form an Al2O3 ceramic

A very important parameter is the purity of the ceramic

A too pure ceramic will be with very few losses, that is perfect for RF power, but will be very difficult to braze as the metallization will not adhere

A ceramic with impurities will be much easier to braze, but will have a lot of losses that will induce a difficult cooling

	Purity	RF losses	Brazing
Al2O3	99.9 %	Very Low	Very difficult
Al2O3	97.6 %	Medium	Medium
Al2O3	95 %	Higher	Easier

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

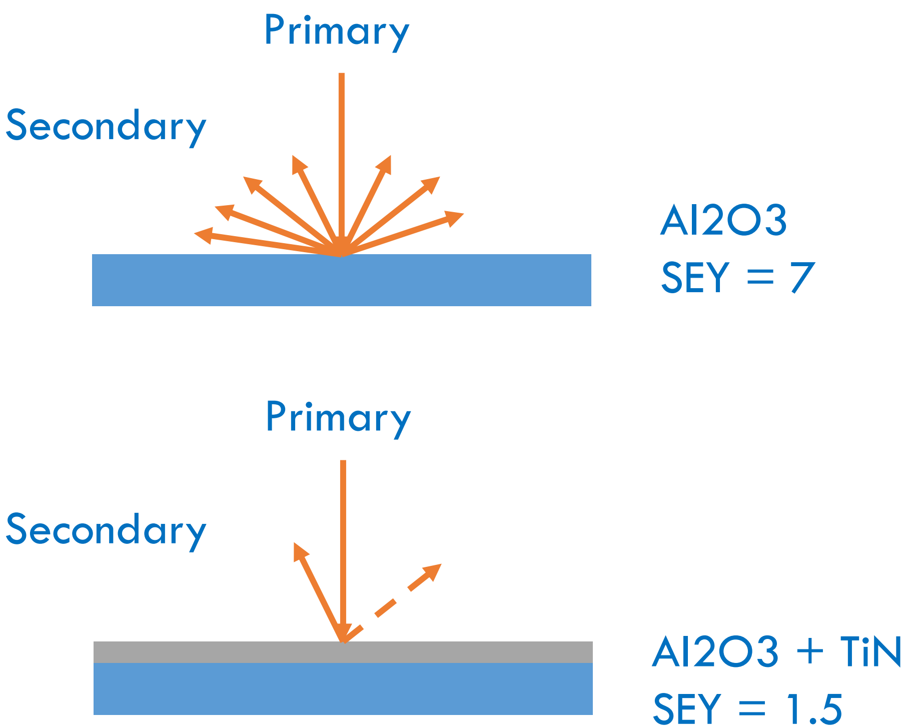
It is still in use, and all our ceramics are the Al2O3 - 97.6 % purity ones

SEY (SECONDARY EMISSION YIELD)

The difficulty of having a ceramic in the transmission line path, is that on the vacuum side, there could be multipacting

Ceramic has a propensity to provide electrons to the multipacting phenomena (SEY = 7)

In order to reduce it, a good solution is to apply a TiOx or TiN sputtering to the vacuum face of the ceramic (SEY ~ 1.5)



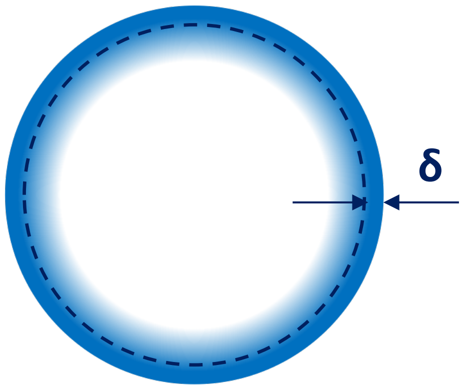
SRF CAVITIES

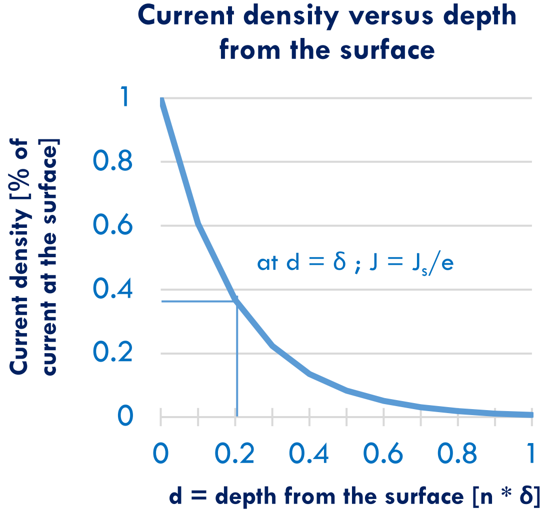
The inner line (antenna) of the FPC can remain at warm temperature (E-field antenna)

The outer line has a flange connected to the cavity and another flange connected to the external ambient air

There is a gradient of > 300 K from the cold to the warm side

RF needs only few μm of good electrical layer as cryogenic requests an as good as possible thermal isolation





$$J = Js\, e^{-\left(\frac{d}{\delta}\right)} \qquad \delta = \sqrt{\frac{2\rho}{\omega\mu}}$$

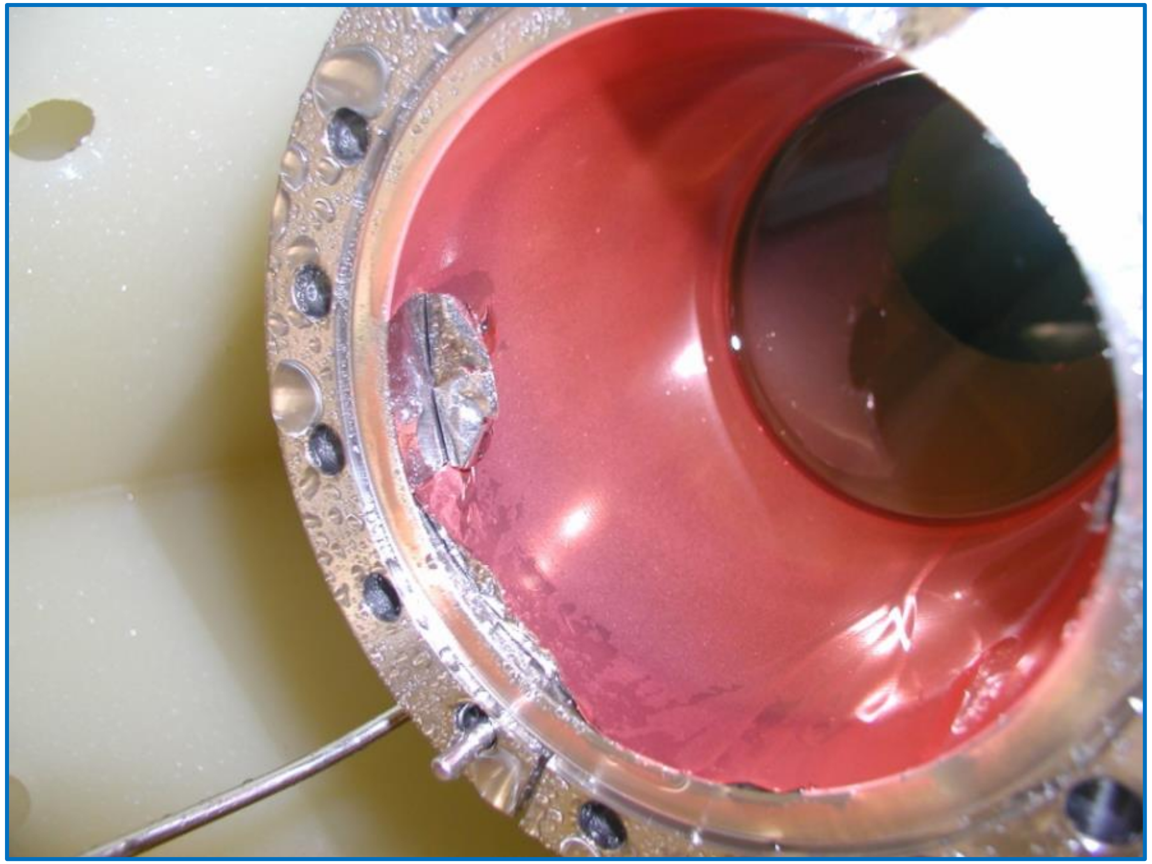
With: J = current density, J_s = current density at the surface, d = depth from the surface, δ = skin depth in which 63 % of the current flows, ρ = resistivity of the conductor, ω = 2πf, $\mu = \mu_r * \mu_0$, μ_r = relative magnetic permeability of the conductor, μ_0 = permeability of free space. For copper at 400 MHz, $\rho = 1.678 * 10^{-8}$ Ωm, $\mu_r = 0.999991$, δ = 3.26 μm

SRF CAVITIES

With SRF cavities, we usually have

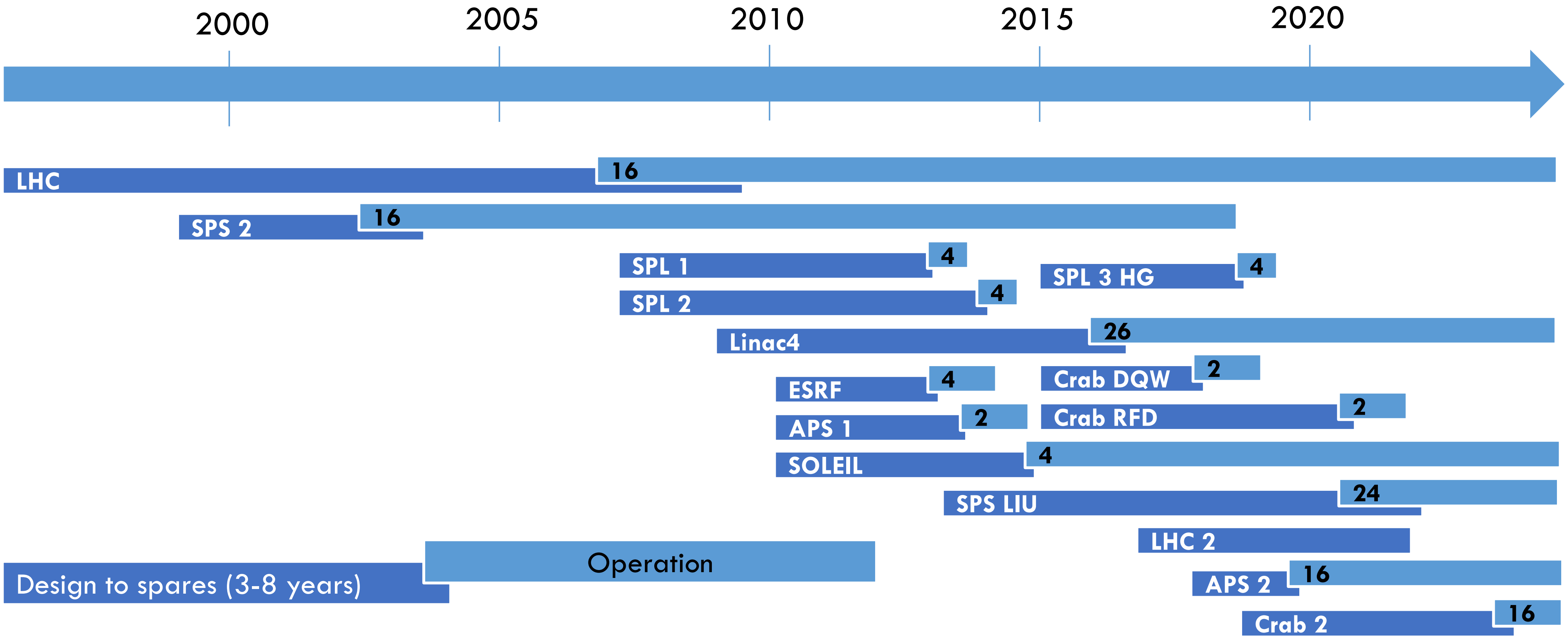
A Stainless Steel support, being the good thermal insulator

Onto which we add a thin layer of few µm of copper, being the RF conductor with minimum RF losses and as being very thin, not transmitting so well the thermal losses to the cryogenic system



A SPL outer line with its copper layer peeling from the Stainless Steel support. More than one year of work lost in a few second, more than half a year to repair

OVERVIEW OF THE CERN POWER COUPLERS SINCE THE 2000'S

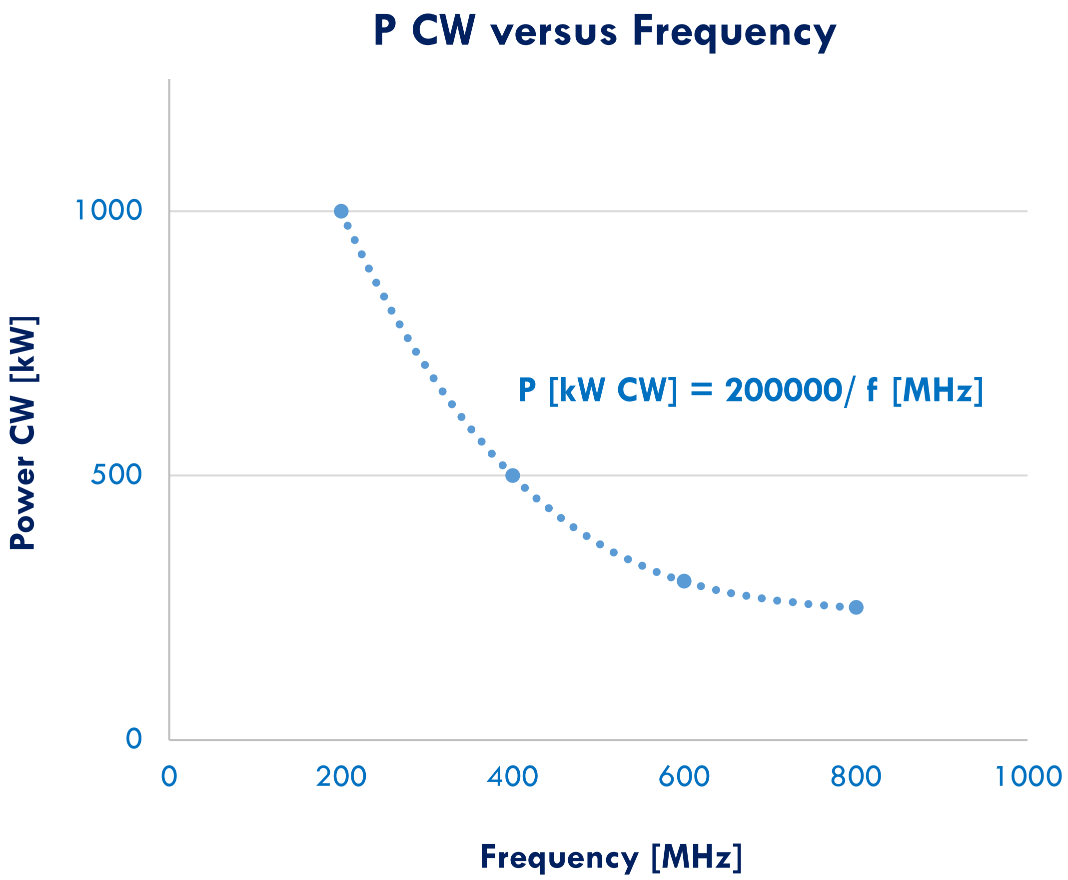


OVERVIEW OF THE CERN POWER COUPLERS SINCE THE 2000'S

LHC	**400 MHz, 500 kW CW SW**
SPS 2.0	**200 MHz, 750 kW CW TW**
SPL 1.0	**704 MHz, 900 kWp 10 % SW**
SPL 2.0	**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*
HG (SPL 3.0)	*704 MHz, 1500 kWp 10 % SW*
LHC 2.0	*400 MHz, 500 kW CW SW*
APS 2.0	*352 MHz, 250 kW CW SW*
Crab 2.0	*400 MHz, 100 kW CW SW*

OVERVIEW OF THE CERN POWER COUPLERS SINCE THE 2000'S

LHC	**400 MHz, 500 kW CW SW**
SPS 2.0	**200 MHz, 750 kW CW TW**
SPL 1.0	**704 MHz, 900 kWp 10 % SW**
SPL 2.0	**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*
HG (SPL 3.0)	*704 MHz, 1500 kWp 10 % SW*
LHC 2.0	*400 MHz, 500 kW CW SW*
APS 2.0	*352 MHz, 250 kW CW SW*
Crab 2.0	*400 MHz, 100 kW CW SW*



eric.montesinos@cern.ch

LHC

Design started in 1996

16 FPC in operation in the LHC since 2008

400 MHz 550 kW CW SW

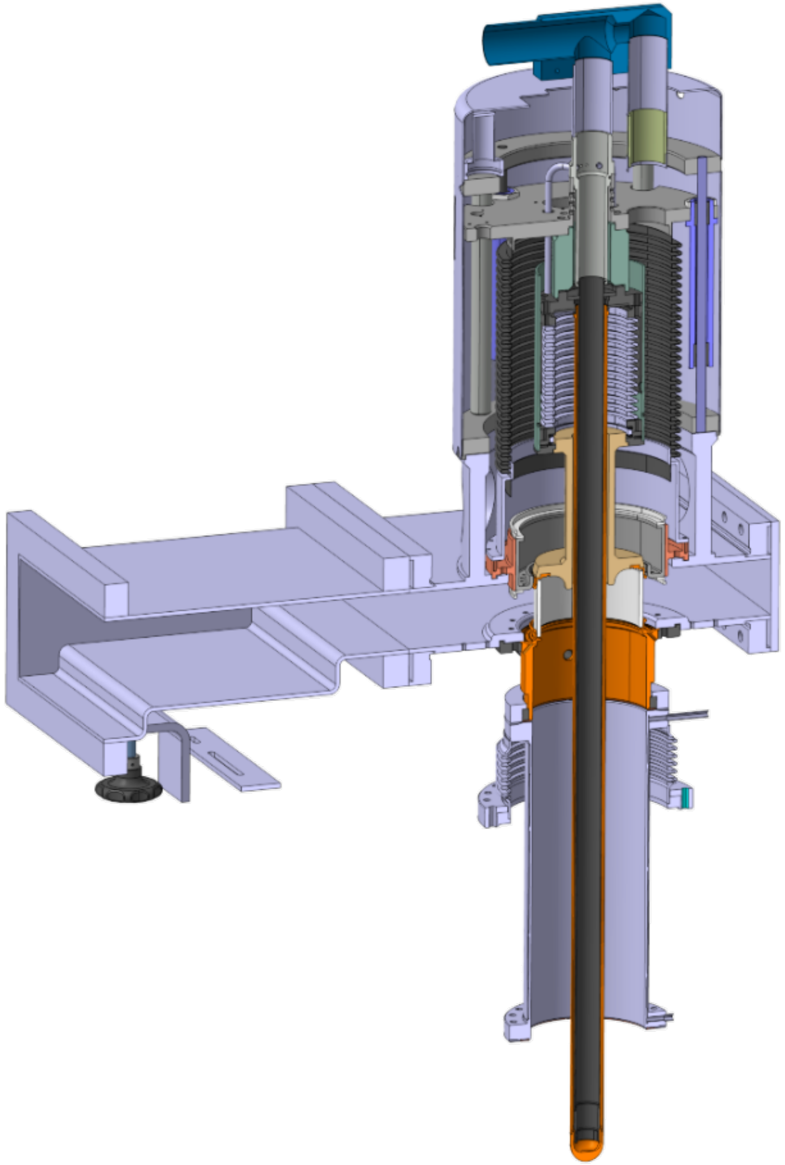
Variable coupling

Cylindrical window

Air cooled antenna

No doorknob

Two HV polarisation to block multipacting



SPL 1.0 & SPL 2.0

Design started in 2012

704 MHz

Fixed coupling

Same interface to the cryomodule

Same WG and air cooling

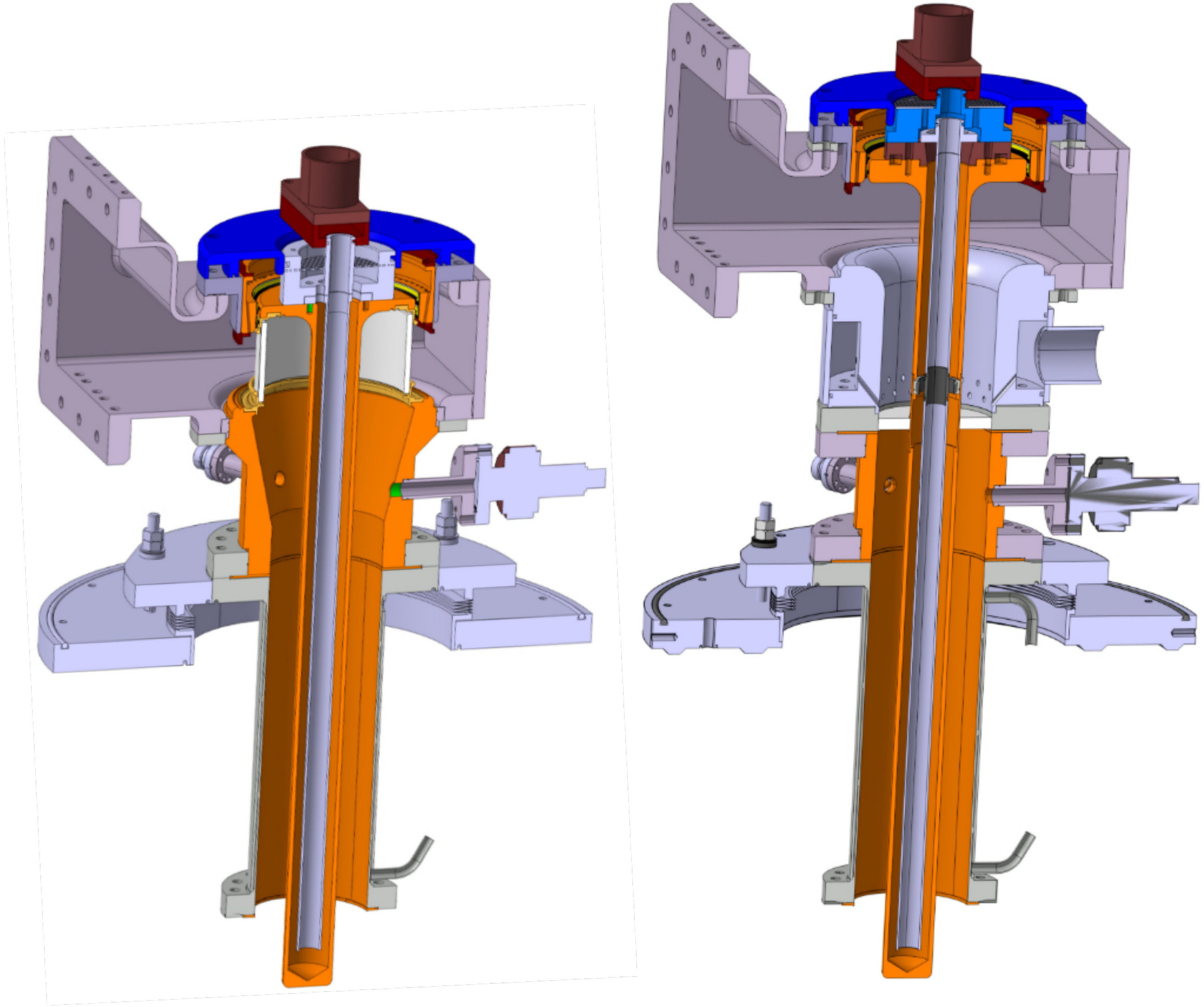
Cylindrical, 900 kW 5 ms 14 Hz SW

Coaxial, 1000 kW 5 ms 14 Hz SW

Air cooled antenna

No doorknob

Polarisation to block multipacting



eric.montesinos@cern.ch

SPL 3.0 (HG)

Design started in 2014

Constructed, to be tested end 2017

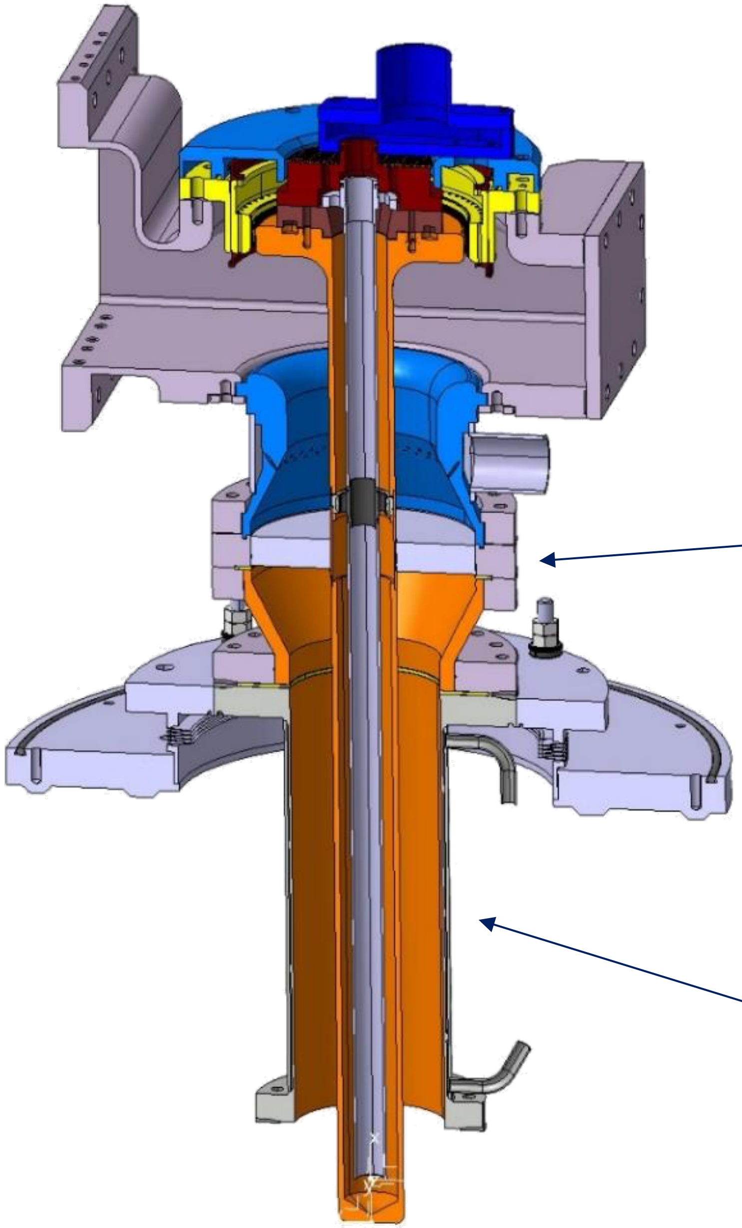
704 MHz

Fixed coupling

Coaxial Disk window, thicker ceramic

Pseudo-conical line to increase arcing limit on the air side

Cyclonic air cooling to limit air ionisation



$$Z_c = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right)$$

With $\varepsilon_r = 9.8$
and $Z_c = 50$
Ideal D/d = 13.6
(not yet here, but improved)

With $\varepsilon_r = 1$
and $Z_c = 50$
Ideal D/d = 2.3

LINAC4 WINDOW

Design started in 2013

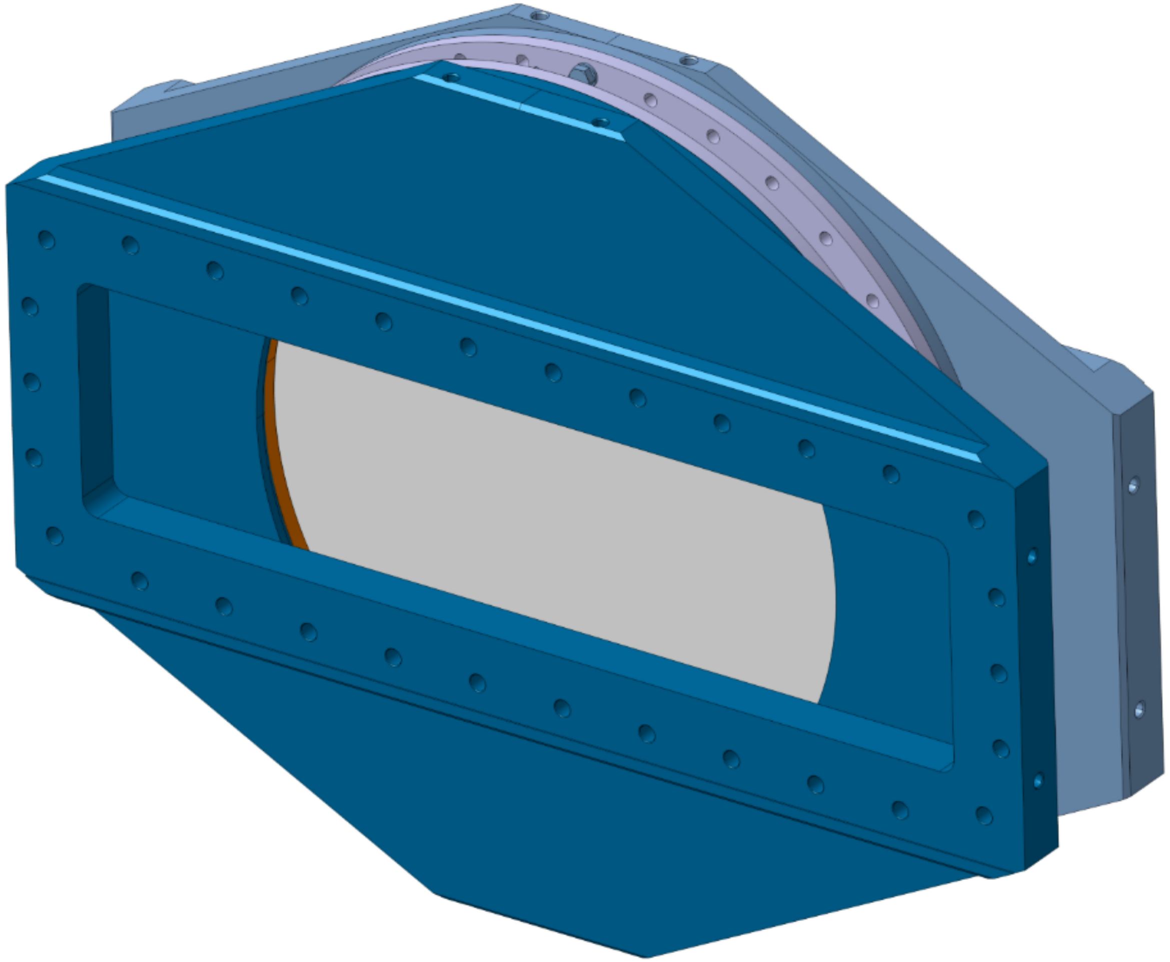
In operation in Linac4 since 2016

352 MHz 1 MW 10 ms 20 Hz SW

Disk window integrated in a WR2300

Ultra compact

Large diameter 400mm, 12 kg ceramic



eric.montesinos@cern.ch

HL-LHC CRAB

Design started in 2014

400 MHz

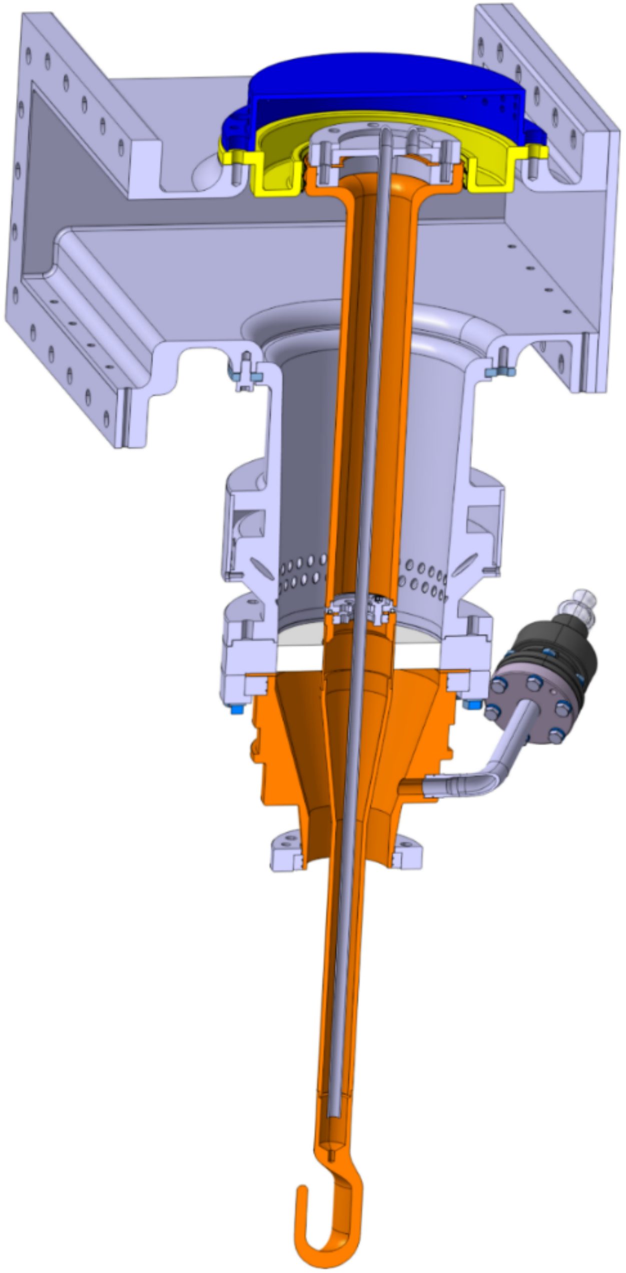
Tested up to 80 kW SW 10 %

Tested up to 30 kW CW (test box limitation)

Coaxial disk window

No doorknob

Water cooled antenna (magnetic coupling will be hot)



LIU-SPS 200

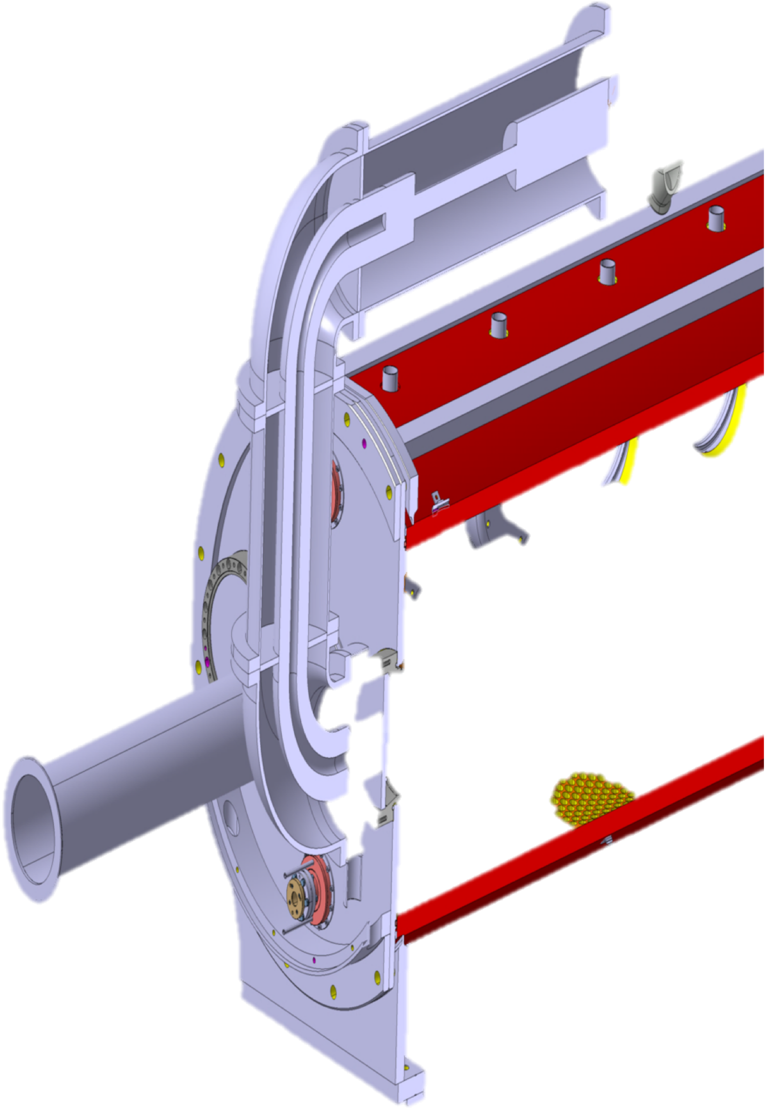
Design started in 2015

Disk window with capacitive coupling

200 MHz

Expected up to 800 kW CW TW

30 units due for end 2018



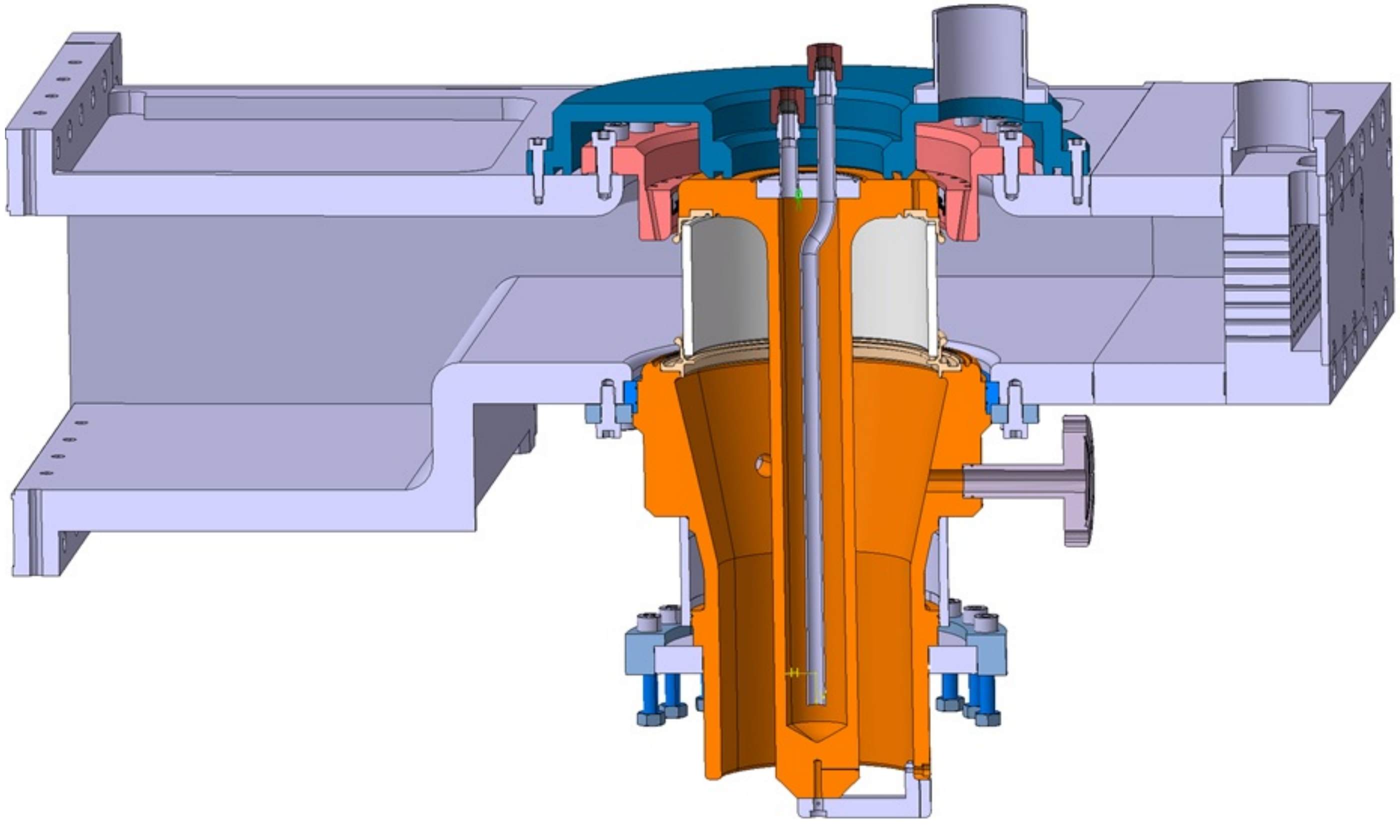
ESRF-APS

Design started in 2008

352 MHz 200 kW CW SW

Fixed coupling

Cylindrical window



SOLEIL

Design started in 2008

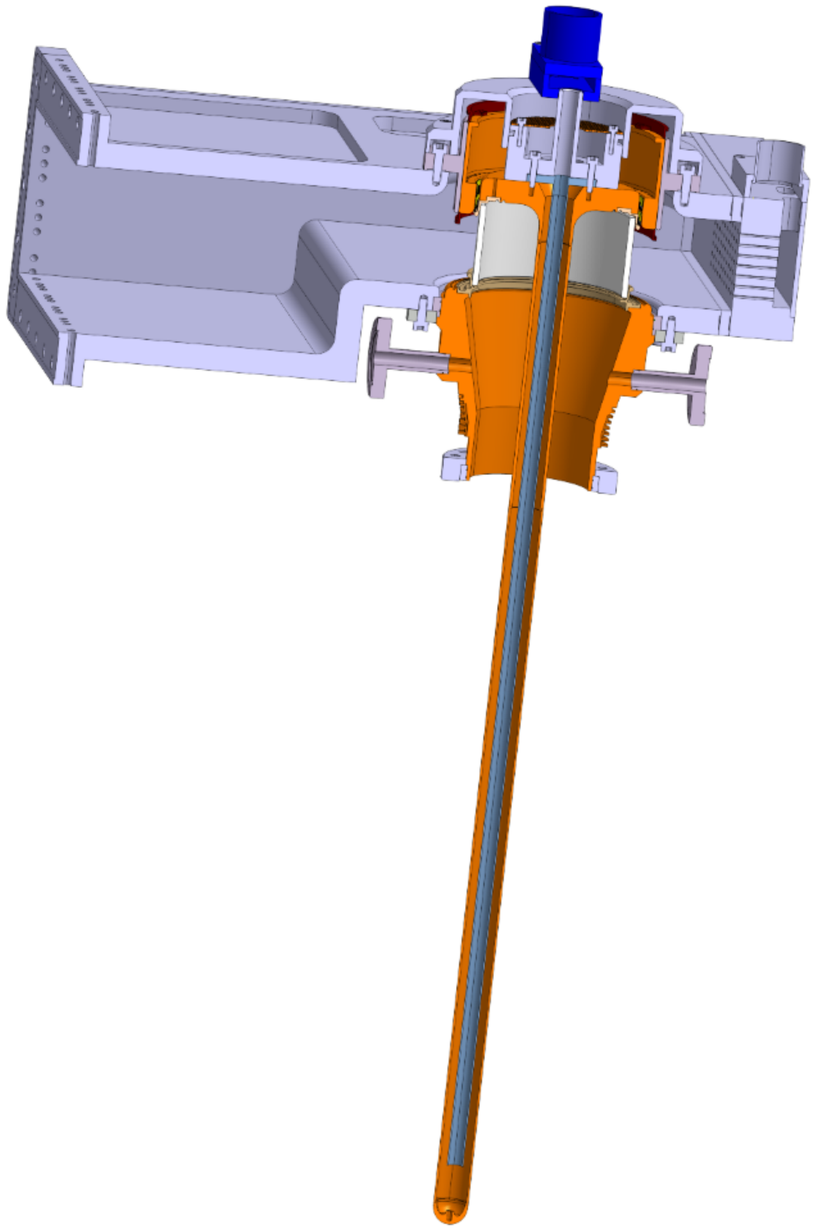
Four in operation since 2015

352 MHz 200 kW CW SW

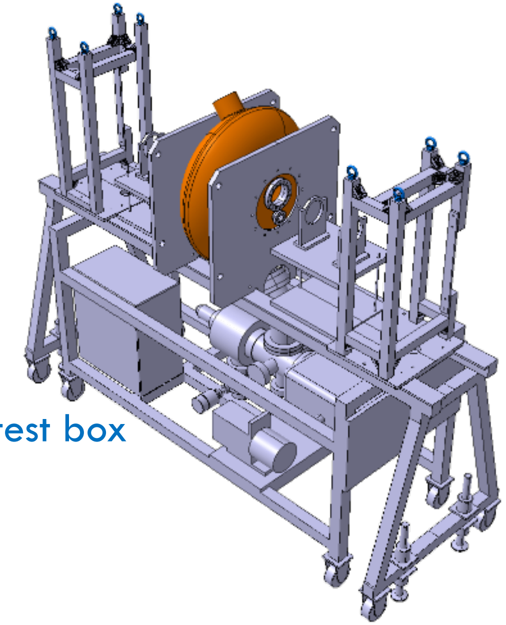
Fixed coupling

Cylindrical window

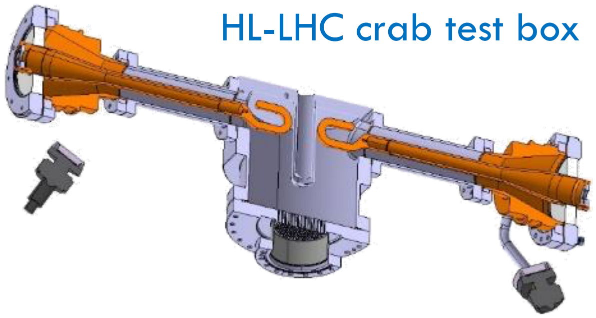
No doorknob



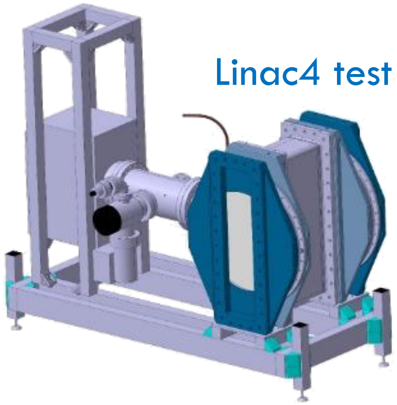
TEST BOXES & POWER STATIONS



LHC test box

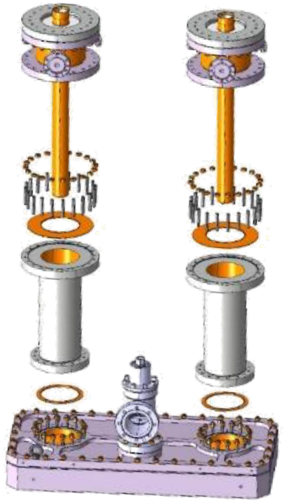


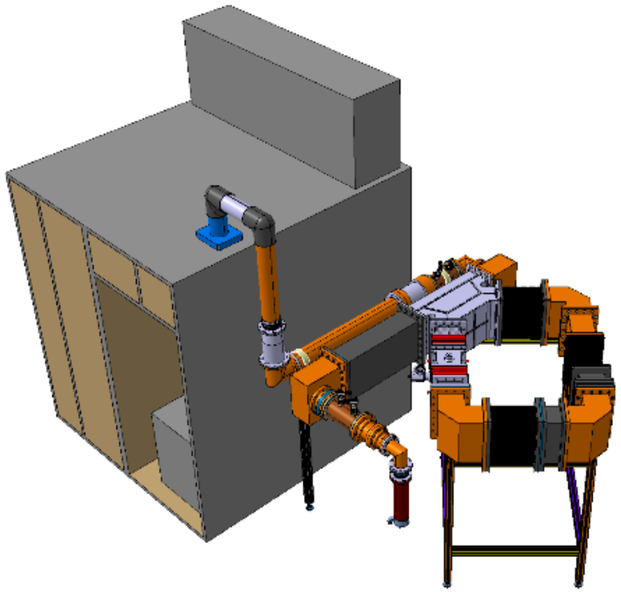
HL-LHC crab test box



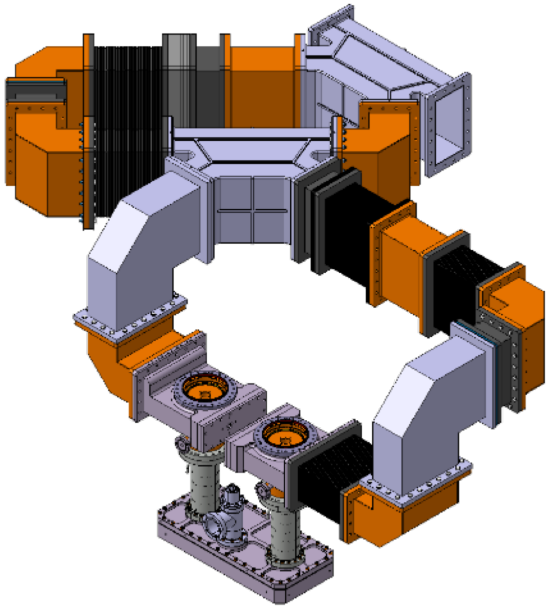
Linac4 test box

SPL test box



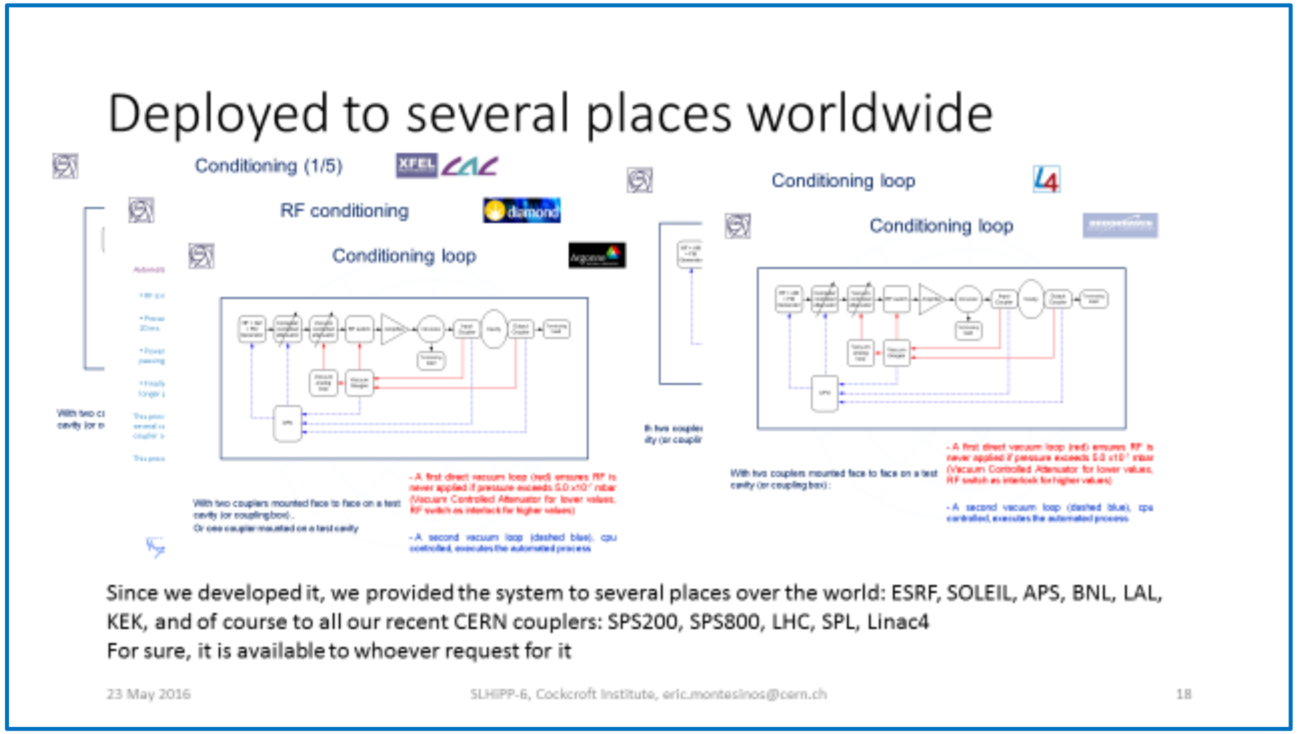


Resonant ring(s) for FPC processing



RF PROCESSING

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



WHAT IS A HOM COUPLER ?

High Order Modes (HOM) are Eigenmodes parasitically excited by a beam in a resonant RF cavity, other than the operating frequency

HOM couplers are designed to extract the power and damp these modes, and to reject the Fundamental operating mode

Each has HOM couplers which provide a transmission path at the HOM frequencies but act as a stop-band to the fundamental mode

With future machines (especially true for circular) the HOM couplers have to extract large amount of power (few kW), becoming like FPC

Several names for the same device

HOM Couplers

HOM Filters

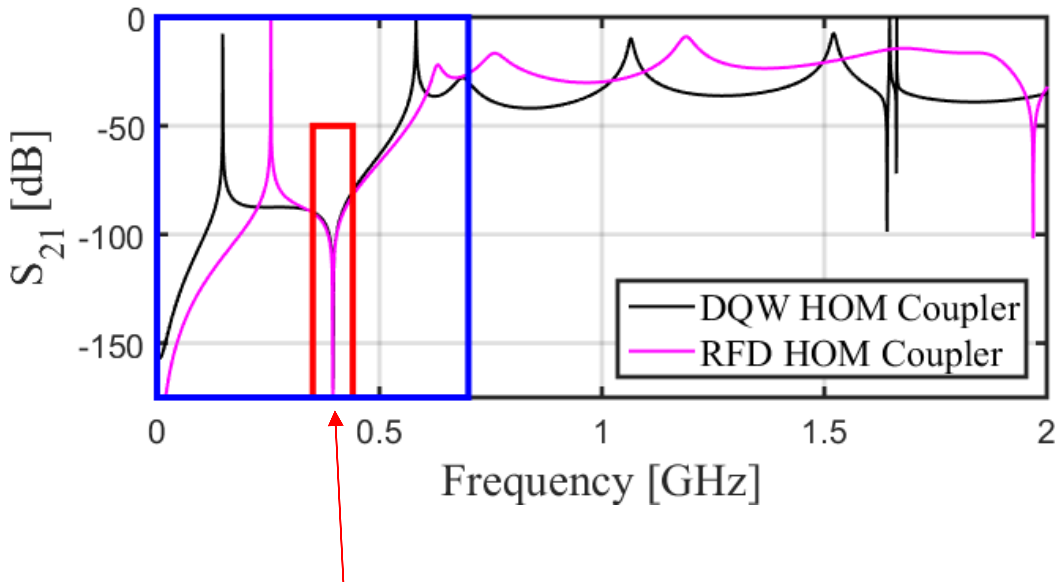
HOM Dampers

HOM Suppressors

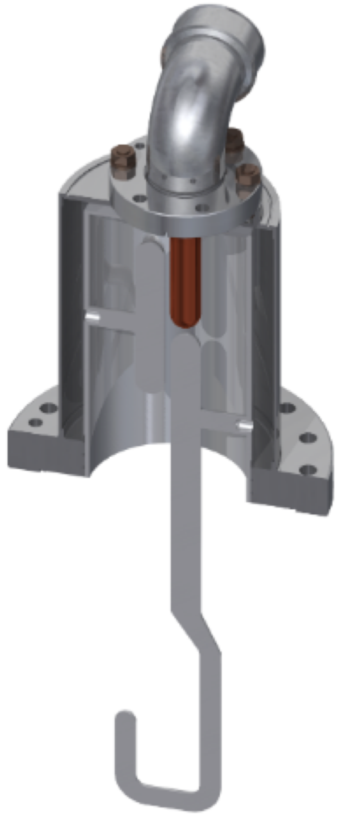
eric.montesinos@cern.ch

HL-LHC CRAB HOM COUPLERS

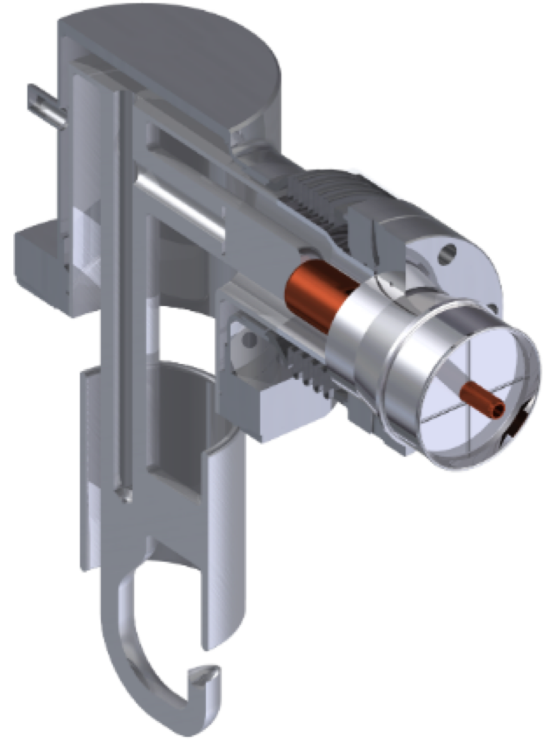
Courtesy of Rama Calaga and HL-Crab team



No transmission at the operating frequency



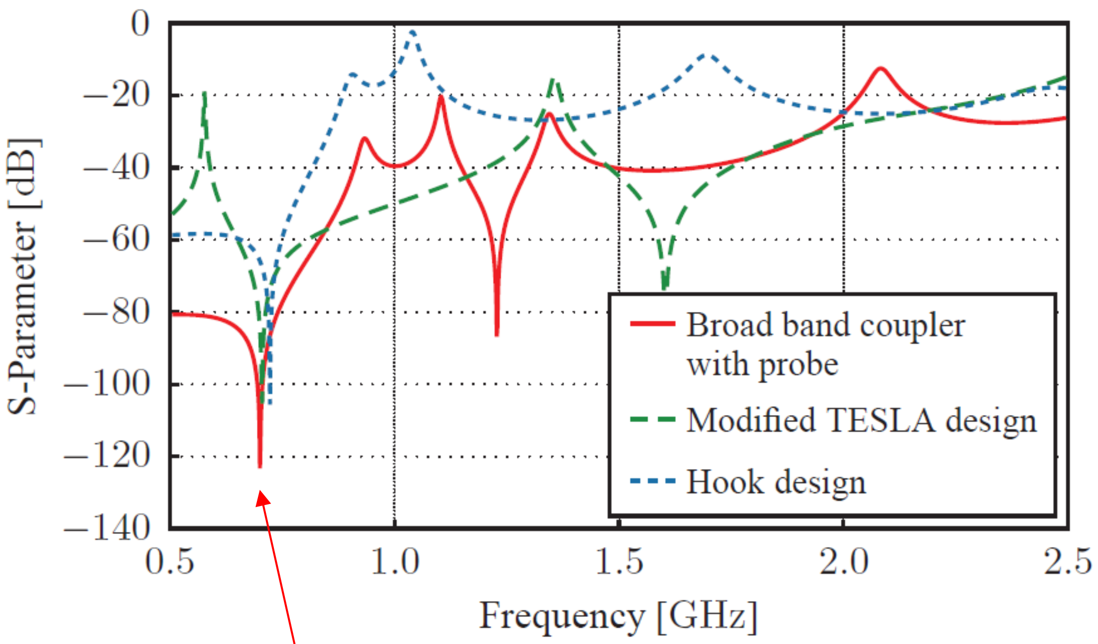
HL-LHC RFD HOM coupler



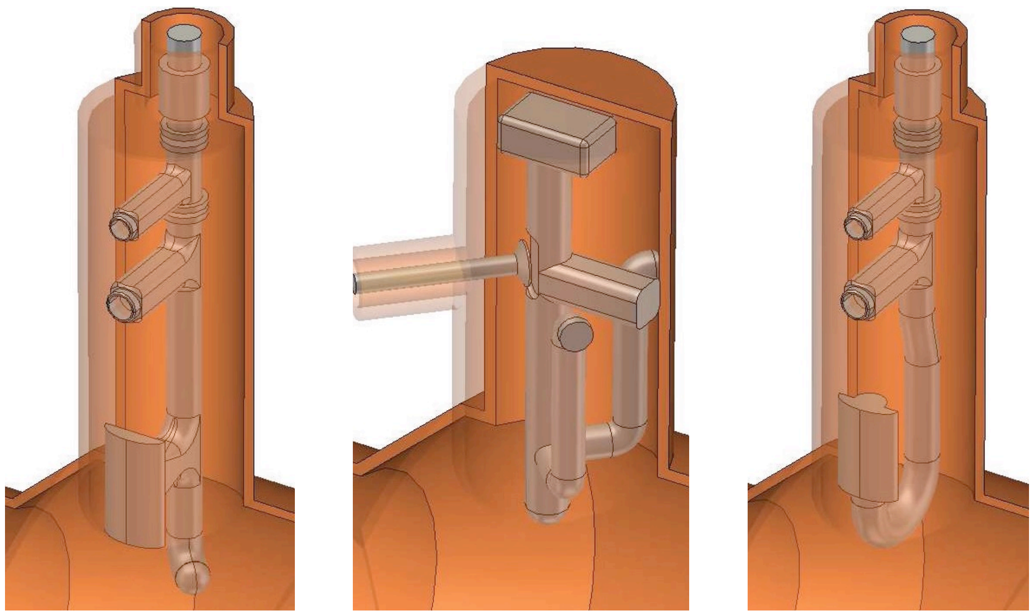
HL-LHC DQW HOM coupler

SPL HOM COUPLER

Courtesy of Kai Papke
and SPL team



No transmission at the operating frequency



Design approaches of HOM coupler
probe coupler, modified TESLA design, hook coupler

CLEANLINESS

Especially for SRF cavities, none of the peripherals should pollute the cavity

Specific clean room assembly processes must be applied

We developed specific tooling, recently 3D printed with accura 25 ® (Polypropylene-like) as being qualified particle free for ISO 4 clean room

The use of robot is also a key for success

Mounting of the HL-LHC crab HOM couplers with accura 25 3D printed guiding systems in ISO 4 clean room

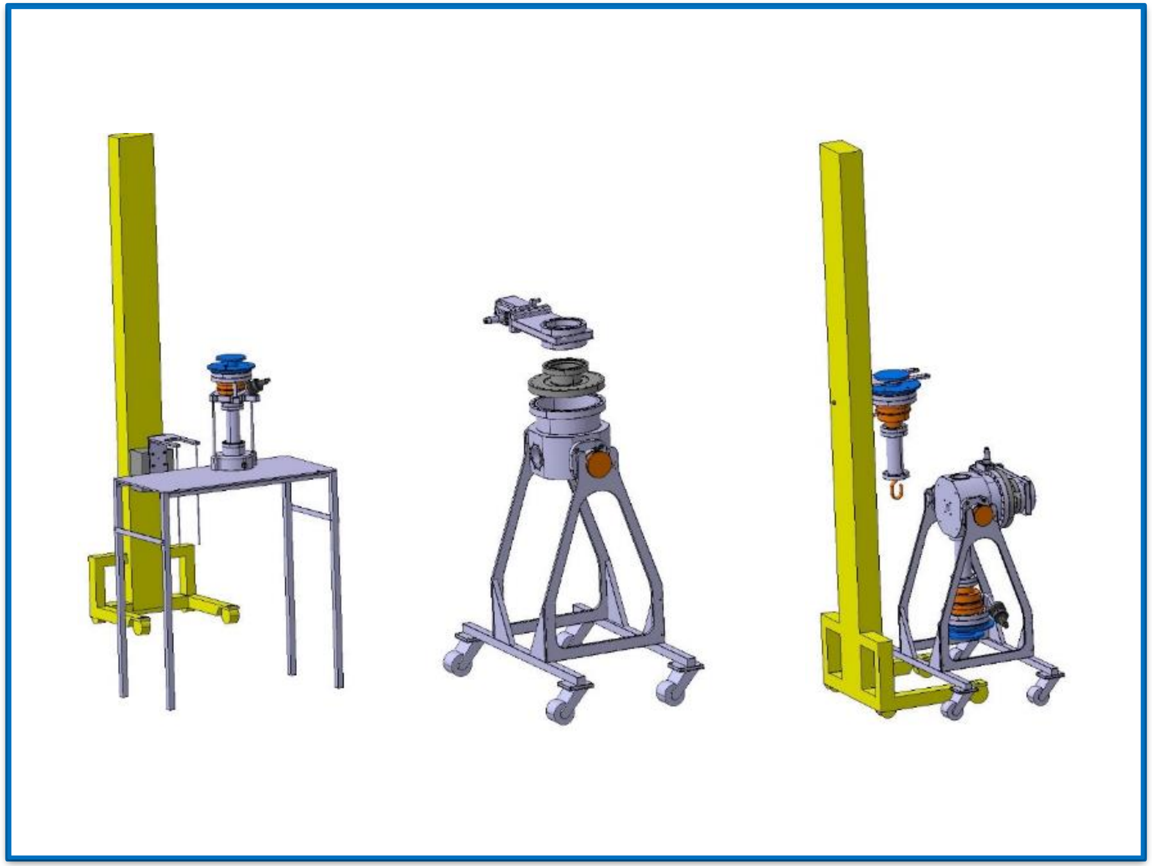
CLEANLINESS

Especially for SRF cavities, none of the peripherals should pollute the cavity

Specific clean room assembly processes must be applied

We developed specific tooling, recently 3D printed with accura 25 ® (Polypropylene-like) as being qualified particle free for ISO 4 clean room

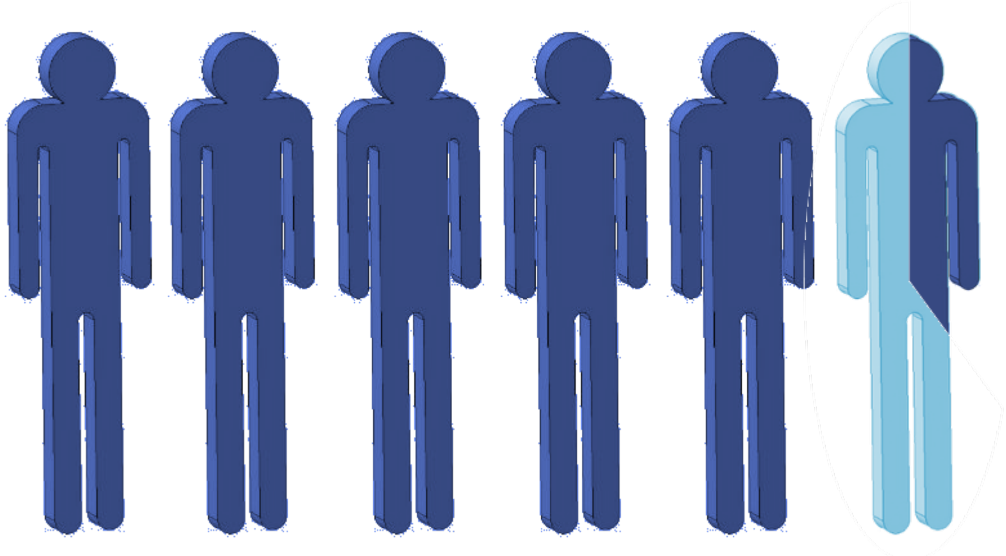
The use of robot is also a key for success



The DQW FPC assembly onto their test box with accura 25 3D printed guiding systems and a robot to have the operators as far as possible from the sensitive items, in ISO 5 clean room

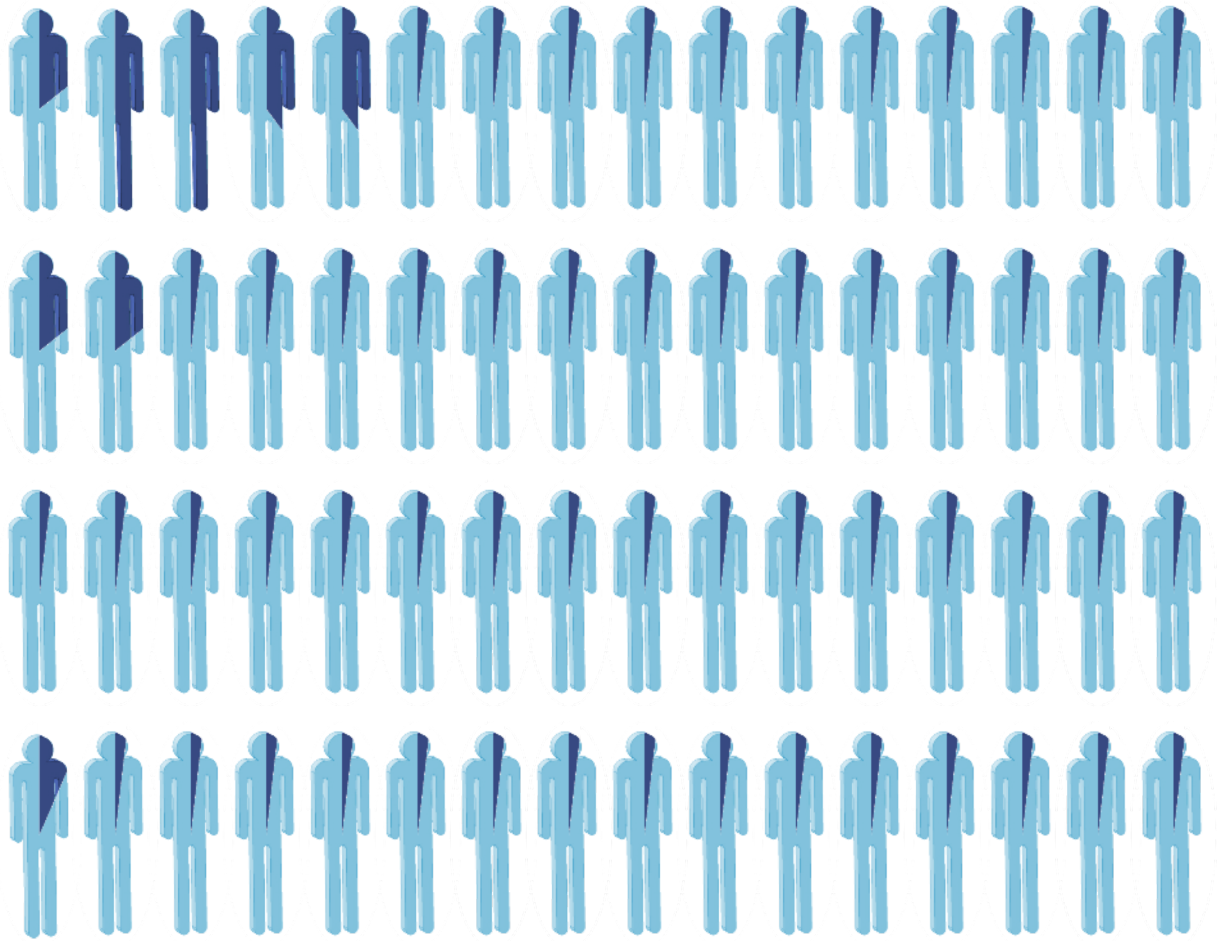
RESOURCES

Activities	5.3 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	0.1



RESOURCES

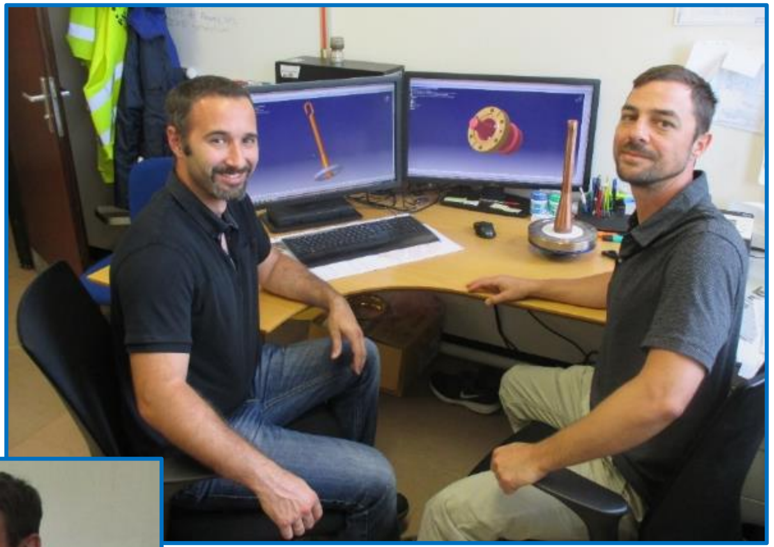
Activities	5.3 FTE year
RF Design	0.2
Mechanical Design	1.8
Raw material	0.05
External machining pilot	0.5
Internal machining	1.0
Surface treatments	0.1
Brazing	0.2
Titanium sputtering	0.1
BE welding	0.1
Metrology	0.05
Assembly	0.5
Vacuum tests	0.1
RF Conditioning	0.5
Clean room assembly	0.1



RESOURCES

Activities	5.3 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	0.1

RF simulations with MWS or HFSS, both available at cern



3D modelling and 2D drawings with Catia

RESOURCES

Activities	5.3 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	0.1

Going from computer drawings to real life requires a lot of specialists, including raw material qualification

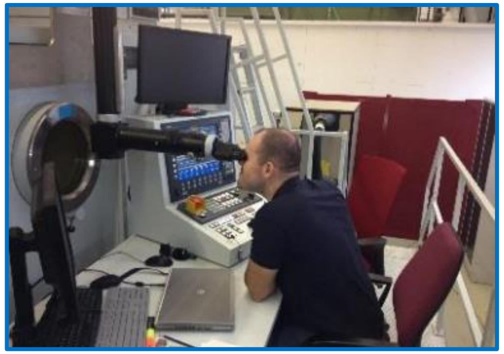
Waiting that the technology will enable us to have fully 3D printed couplers (metal + ceramic), we use 3D printing to RF check the designs (with metallic paint) prior to machine all the components

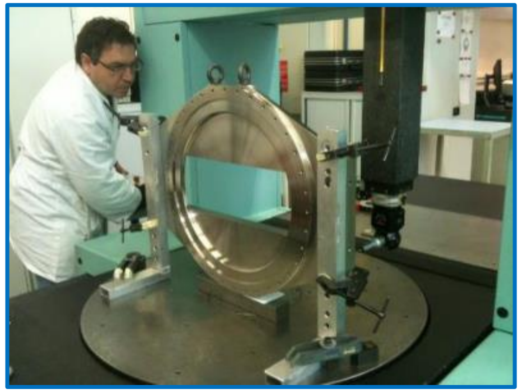
eric.montesinos@cern.ch

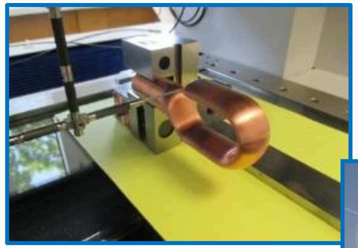
RESOURCES

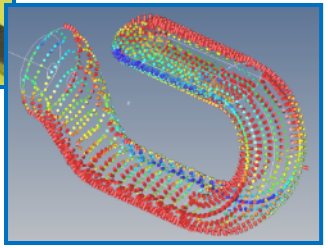
Activities	5.3 FTE year
RF Design	0.2
Mechanical Design	1.8
Raw material	0.05
External machining pilot	0.5
Internal machining	1.0
Surface treatments	0.1
Brazing	0.2
Titanium sputtering	0.1
BE welding	0.1
Metrology	0.05
Assembly	0.5
Vacuum tests	0.1
RF Conditioning	0.5
Clean room assembly	0.1

Brazing, EB welding, laser welding, are key processes for the FPC









Metrology is also a key for success in couplers

RESOURCES

Activities	5.3 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	0.1

Assembly of the components must be done very carefully by experienced teams as often being after two years of construction

RESOURCES

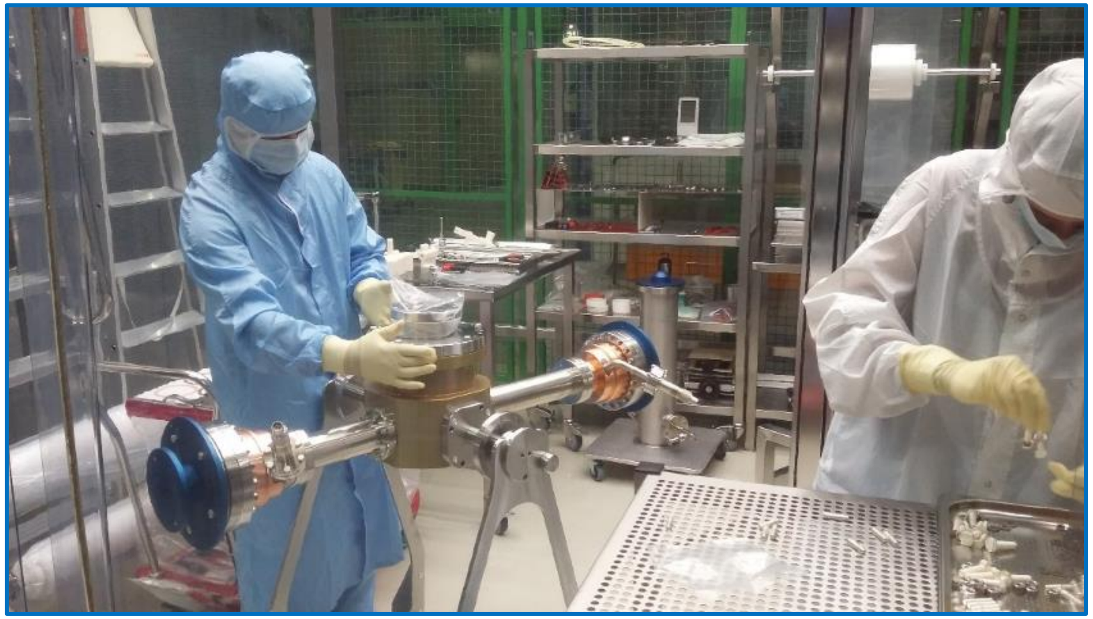
Activities	5.3 FTE year
RF Design	0.2
Mechanical Design	1.8
Raw material	0.05
External machining pilot	0.5
Internal machining	1.0
Surface treatments	0.1
Brazing	0.2
Titanium sputtering	0.1
BE welding	0.1
Metrology	0.05
Assembly	0.5
Vacuum tests	0.1
RF Conditioning	0.5
Clean room assembly	0.1

Preparation of the test boxes for conditioning is also requiring a lot of work

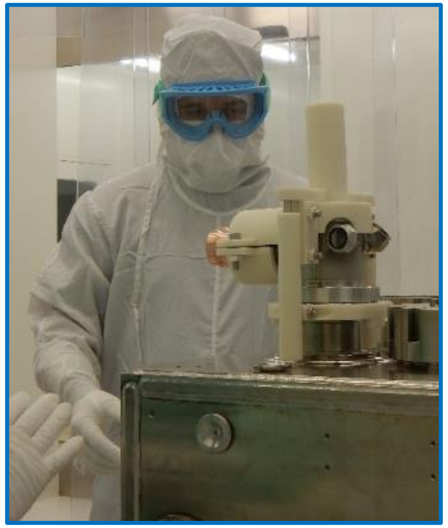
Even if automated, RF processing must be done very carefully as being the last step prior to installation on the cavity

RESOURCES

Activities	5.3 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	0.1



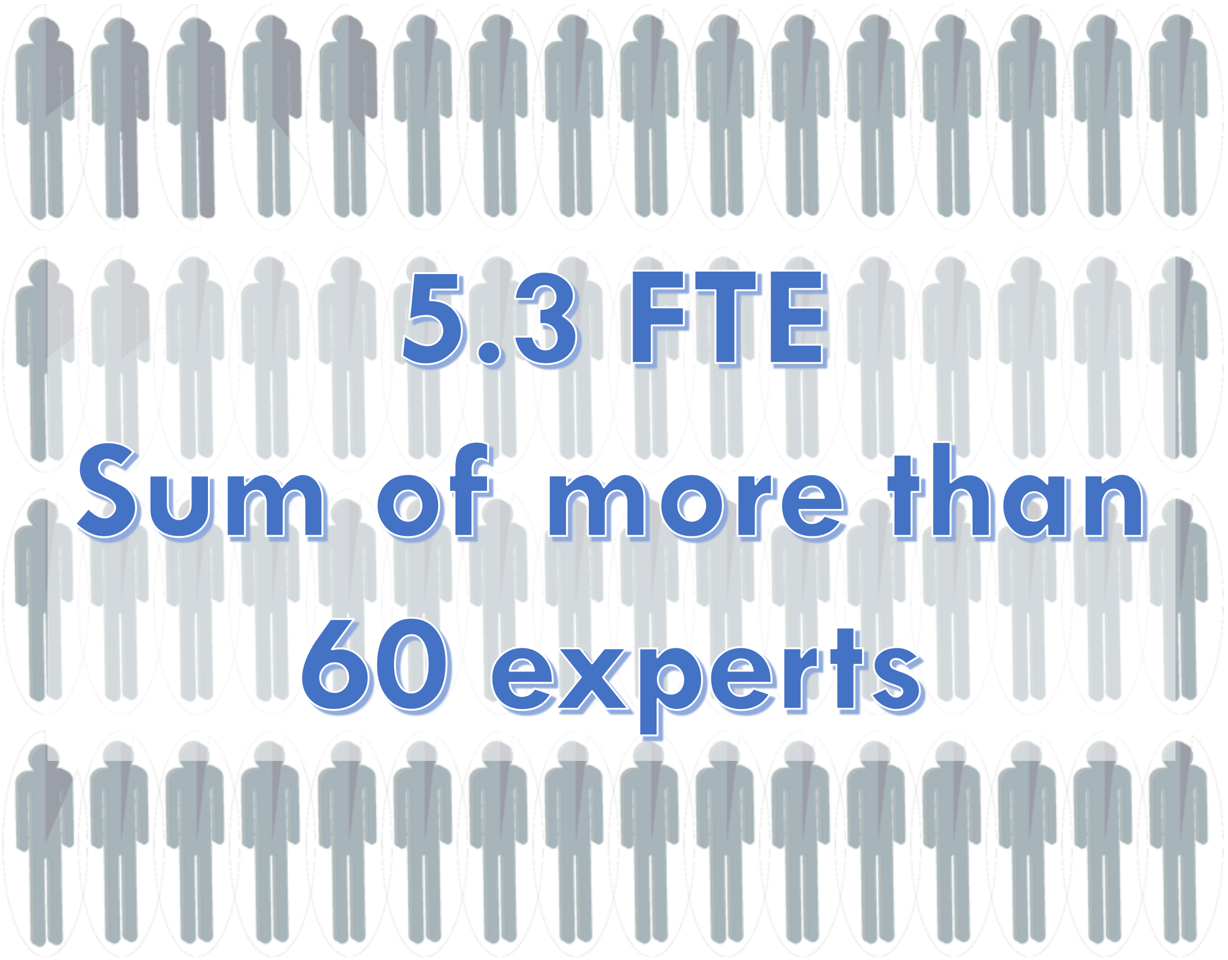
Assembly in clean room with the use of 3D printed guiding system and the use of robot is mandatory for the success of the FPC and HOM couplers



eric.montesinos@cern.ch

RESOURCES

Activities	5.3 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	0.1

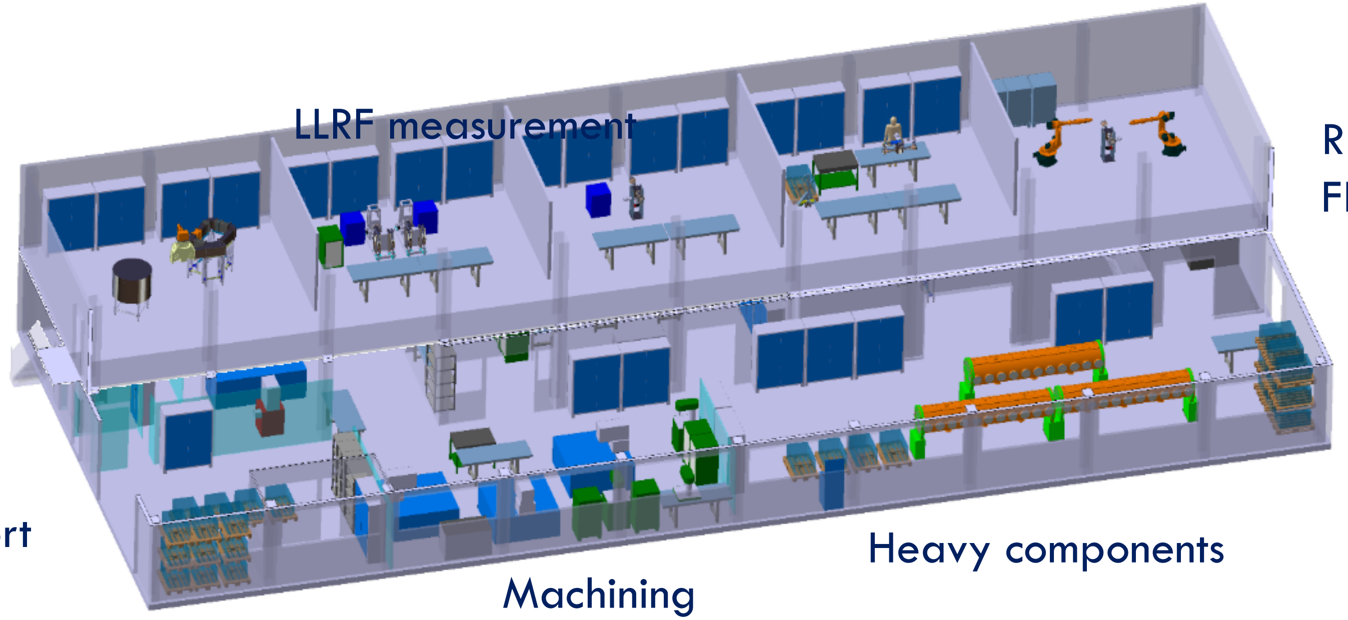


CERN FPC R&D CENTRE

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

WORLD WIDE FUNDAMENTAL POWER COUPLER (WWFPC) MEETINGS

CERN	Eric Montesinos
KEK	Eiji Kako
DESY	Wolf-Dietrich Möller
KEK	Yasuchika Yamamoto
RIKEN	Kazutaka Ozeki
IHEP	Tong ming Huang
LAL	Walid Kaabi
IPNO	Emmanuel Rampnoux
BNL	Wencan Xu
IBS	Ilkyoung Shin
CEA	Guillaume Devanz
Cornell	Vadim Veshcherevich
JLAB	Robert Rimmer
ORNL	Mark Champion
FNAL	Sergey Kazakov
SLAC	Chris Adolphsen

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)
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/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 ?

SOME PREVIOUS TALKS ON THE TOPICS

Date		Event	Talk
Jul	2017	WWFPC meting #3	WWFPC meeting #3 indico link
Jul	2016	WWFPC meting #2	WWFPC meeting #2 indico link
Jun	2015	WWFPC meting #1	WWFPC meeting #1 indico link
May	2017	FCC week #3	FPC challenges and perspectives for FCC
Nov	2016	6th HL-LHC Collaboration Meeting, Paris	High Power RF and FPC progress
Oct	2016	Review of clean room procedures for the Crab Cavity, CERN	Fundamental power coupler assembly in clean room
Jul	2016	WWFPC2, CERN	Last year experiences at CERN with FPC and future perspectives
May	2016	6th SLHiPP, Cockcroft	coupler conditioning at CERN
Nov	2015	HL-LHC SPS Cryo-module Engineering Review, CERN	Fundamental Power Coupler and RF Transmission Lines
Mar	2015	FCC week, Washington	Fundamental power couplers
May	2014	CWRF workshop, Trieste	20 years of high average Fundamental Power Coupler designs at CERN
Dec	2013	6th LHC Crab Cavity Workshop, Chicago	FPC and Amplifier Status
Nov	2013	LCWS13, Tokyo	Choice of one/two RF windows
Dec	2012	Superconducting technologies workshop, CERN	Challenges in RF Fundamental Power Coupler (FPC) Technology
Dec	2012	SPL seminar, CERN	Status of SPL high-power couplers
May	2012	CWRF workshop, Port Jefferson	RF fundamental power coupler news
Dec	2011	First SLHiPP collaboration meeting, CERN	Recent fundamental power coupler designs and tests
Nov	2010	5th SPL Collaboration meeting, CERN	Status of SPL RF coupler development
May	2010	CWRF workshop, Barcelona	CERN SPL proposed RF power couplers
Mar	2010	Review of SPL RF power coupler, CERN	SPL power coupler possible designs Part I: General considerations SPL power coupler possible designs Part II: Designs comparison

FINAL COMMENTS

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 !)

Please, do not hesitate to challenge us !
Let us know your wishes, we will try to realize them

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

THANKS FOR LISTENING

They did not know it was impossible, so they did it …

(Mark Twain)

eric.montesinos@cern.ch