HL-LHC WP4 (Crab Cavities): SPS Cryo-module Engineering Review

Fundamental Power Coupler and RF Transmission Lines
10 November 2015

Eric.Montesinos@cern.ch on behalf of all persons involved (special thank to Antoine Boucherie)

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Outlook

Fundamental Power Coupler (FPC)

- History
- Current status

Transmission Lines

- RF theory
- Specific design for HOM

Review Charge

Specific questions to be addressed by the review

1) Does the design meet all the functional requirements of such a cryomodule?
2) Have all important issues been covered by the project team?
3) Have all the design aspects been studied sufficiently in detail in preparation for manufacturing? Are-there particular area where extra design effort is needed?
4) Are there risks associated with the design that could or must be removed or mitigated at this stage?
5) Is the proposed schedule related to SPS tests realistic?
6) Are the general plans and criteria for cryomodule development past the SPS application and into the HL-LHC period (post-2024) correctly defined? Is there any particular area that should be studied in more detail at this stage?

FPC History, 2010

LHC-CC10, 4th LHC Crab Cavity Workshop

15-17 December 2010

W. Weingarten & E. Montesinos, Coupler (FPC & HOM) concepts for compact cavities

(https://indico.cern.ch/event/100672/session/3/contribution/30)

f_0	400 MHz
Average Power	15 kW
Q_{ext} of input coupler	Fixed
Coolant	Air cooled

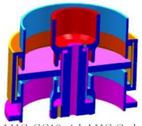
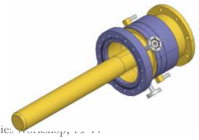
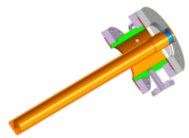
Imposes a single window FPC (→ 15 kW)

CERN's rule that we always try to apply (→ Air cooled)

FPC History, 2010

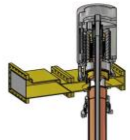
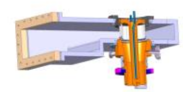
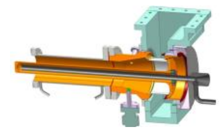
Coaxial Disk windows

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
SPS	200	550	800	16
KEKB	509	300	1420	8
CEA-HIPPI	704	120	1200	2
IHEP	500	150	270	2
JPARK	972	30	2200	23
SNS	805	78	2000	93
SPL	704	100	1000	Prototyping ongoing

One cylindrical window

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
LHC	400	550 sw cw, (i.e 2200 tw cw)	i.e. 2200 tw cw	16
LEP	352	550 tw cw	565 tw cw	252
SPS (1976-2000)	200	375	500	16
SPL	704	100	1000	Prototyping ongoing
ESRF / Soleil / APS	352	500	1000	Prototyping ongoing

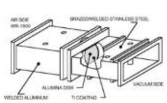




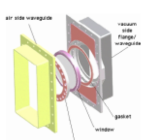
Long experience at CERN with single window couplers for high average Power:

SPS – LEP – LHC

Waveguide windows

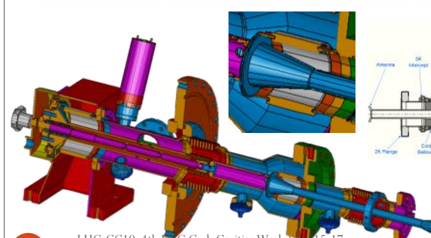
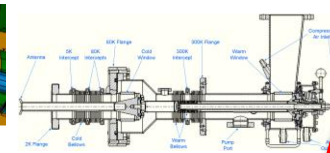
Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
SPS	801	225	225 (more ?)	8
Cornell	500	350	350	4
FNAL / TTF II	1300	4.5	1000	32
LBNL	700	800	800	4
Linac 4	352	140	1400	Prototyping ongoing






Two cylindrical windows

Coupler	Frequency [MHz]	Average Power [kW]	Peak power [kW]	# in operation or constructed
TTF family - XFEL	1300	4.5	1100	16 (+ 1064)
Cornell ERL	1300	75	75	2

Cold window (beam vacuum / coupler vacuum) is difficult to cool down enough for high average power coupler

Cold window (beam vacuum / coupler vacuum) is difficult to cool down enough for high average power coupler

High Luminosity LHC

FPC History, 2012

Parameters	
Fc	400 MHz
Pmax	50 kW cw
BW	1 MHz

LHC Crab Cavity Engineering Meeting, FNAL

13-14 December 2012

Power Coupler Interfaces & RF System

(https://indico.cern.ch/event/136807/other-view?view=standard)

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LHC Crab Cavity Engineering Meeting 13-14 December 2012

Common Crab Cavity FPC Platform

- We propose to stick to these design parameters :
  - LHC window or Disk window
  - Waveguide line to coaxial antenna
  - Plug and play waveguide
  - DC biasing (if E antenna)
  - Preferably E antenna (no stress to the ceramic)
  - Same simple straight pipe DT
  - If possible 50 Ω antenna (easier for mock-up measurements)
- Specifications from Rama :
  - cavity FPC port diameter : 40 mm / 36 mm / 40 mm
  - DT : 40 mm
  - Inner line : 17 mm
    (two tubes, cooling inlet (4/6) + cooling outlet (13/17))
- Can we increase the DT diameter ?
  - Incompatibility between the sizes and power level requested
  - Should be the main topic at the FPC dinner table tonight !

Initial sizes of 40/17 mm increased to 62/27 mm

FPC History, 2012

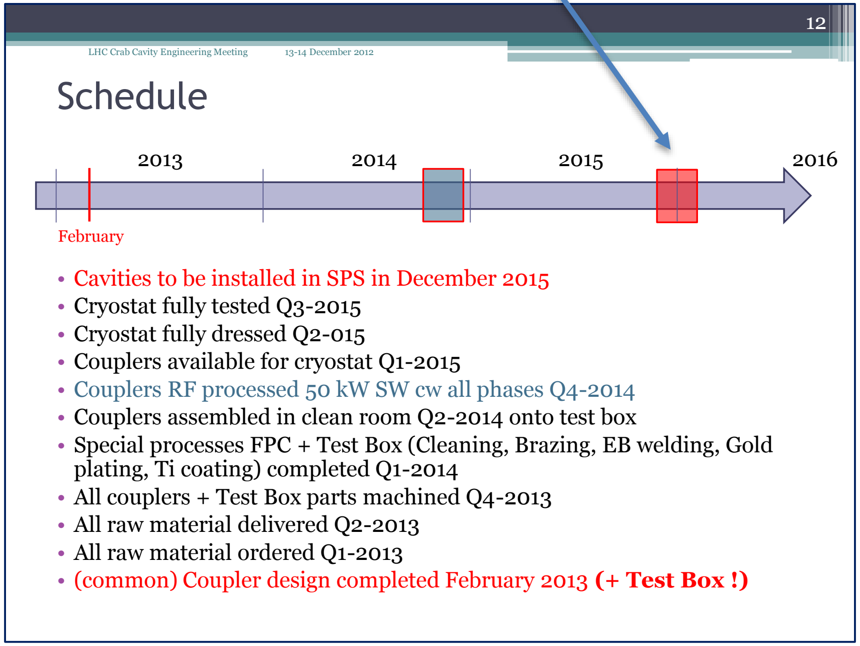
LS2 was expected 2018,
Tests in SPS during 2016 & 2017

LHC Crab Cavity Engineering Meeting, FNAL

13-14 December 2012

Power Coupler Interfaces & RF System

(https://indico.cern.ch/event/136807/other-view?view=standard)



High Luminosity LHC

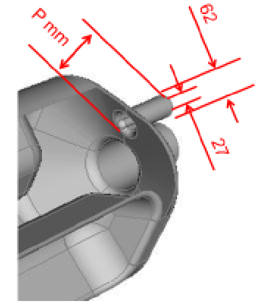
FPC History, 2013

January 2013

First FPC design proposal compatible with the three cavity designs

Double Ridge

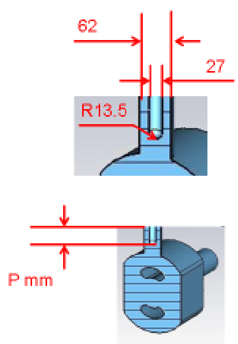
- Outer line = 62 mm
- Inner Line = 27 mm
- End shape of the antenna :
  - R 13.5 mm or shape to be provided
- Penetration distance from cavity flange P mm to be given
- Cavity port :
  - Stainless Steel 316 LN flange
  - Perpendicular to beam tube
  - Preferably on top of cavity or angle to be provided



CERN, BE-RF-PM, Eric Montesinos Crab Cavities Power Couplers 17 January 2013 3

4 rods

- Outer line = 62 mm
- Inner Line = 27 mm
- End shape of the antenna :
  - R 13.5 mm or shape to be provided
- Penetration distance from cavity flange P mm to be given
- Cavity port :
  - Stainless Steel 316 LN flange
  - Perpendicular to beam tube
  - Preferably on top of cavity or angle to be provided



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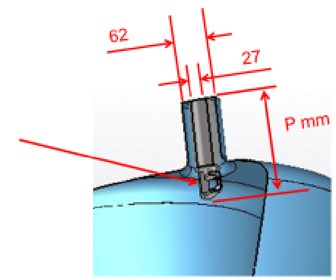
Quarter Wave

- Outer line = 62 mm
- Inner Line = 27 mm
- End shape of the antenna :
  - Special hook with no outer contact, shape to be given
- Penetration length from cavity flange :
  - P mm to be given
- Cavity port :
  - Stainless Steel 316 LN flange
  - Perpendicular to beam tube
  - Preferably on top of cavity



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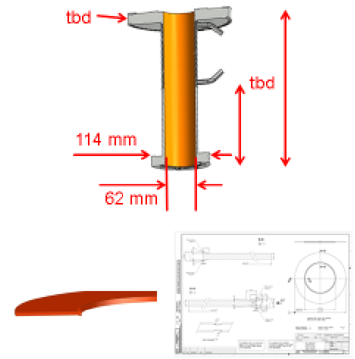
FPC History, 2013

January 2013

First FPC design proposal compatible with the three cavity designs

Double walled Tube

- CERN will provide a common Outer line to connect coupler to cavity :
  - Cavity flange DN63
  - Cryomodule flange to be defined
  - Length to be defined
- Cavity flange DN63 :
  - Inner diameter = 62 mm
  - Outer Diameter = 114 mm
- CERN will also provide specific copper gasket with RF & Vacuum function

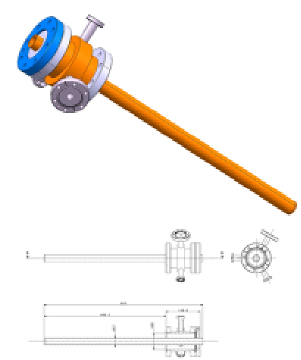


Schedule

- 3D drawings for approval : February 2013
- 2D drawings (EDMS): March 2013
- Prototypes ready for tests: March 2014
- Couplers ready for cavity assembly : December 2014

Windows

- CERN will provide windows, bodies and Antennae
  - Length defined regarding cavity input port
- These will be fully equipped with :
  - Vacuum gauge port
  - e- monitor
  - Glass window (arc detection)
  - Cooling of inner line with inner cane



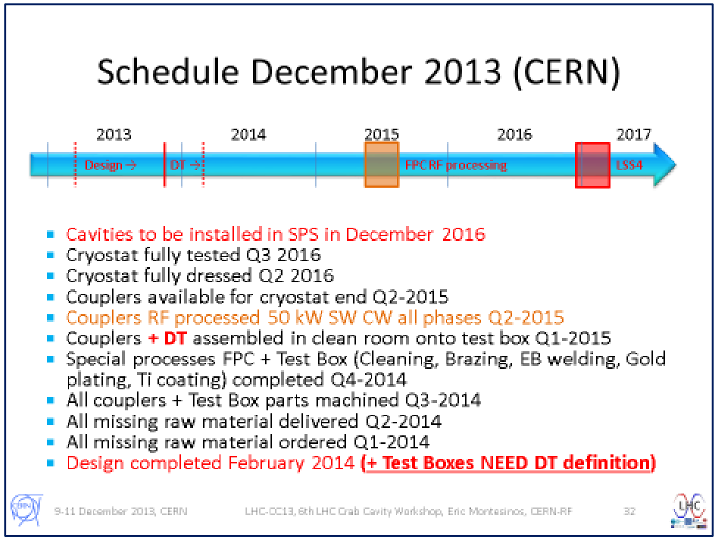
FPC History, 2013

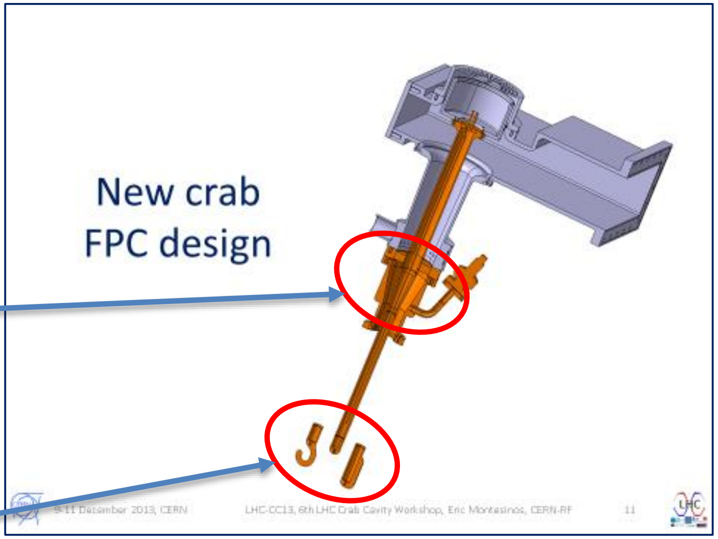
LHC-CC13, 6th LHC Crab Cavity Workshop, CERN

9-11 December 2013

FPC and Amplifier Status

(https://indico.cern.ch/event/269322/other-view?view=standard)





Conical line on the air side to sustain very high average power in full reflection (SPL experience)

Compatibility within the three FPC by modifying the antenna end tip only

FPC History, 2014

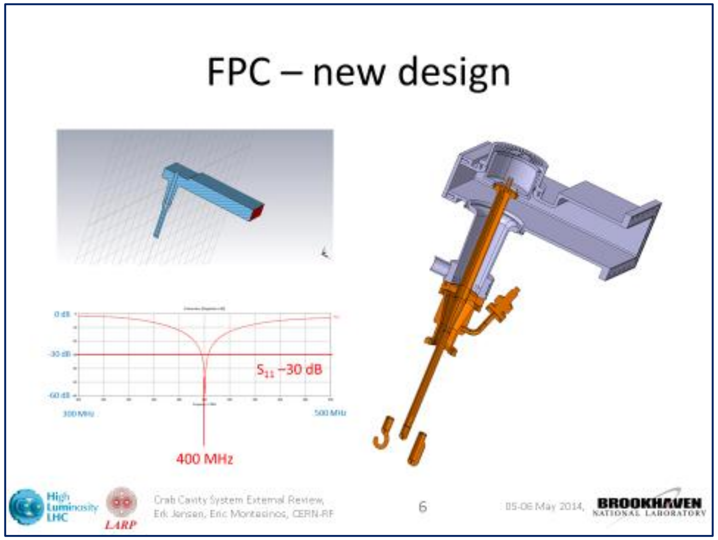
HiLumi-LHC/LARP Crab Cavity System External Review

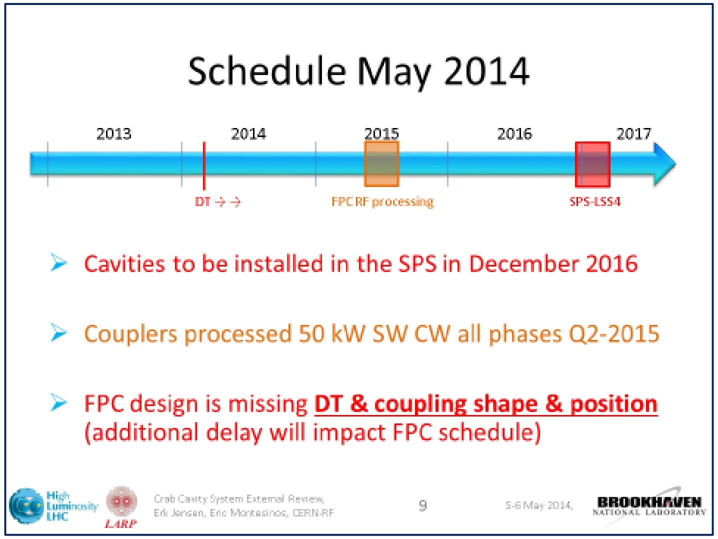
BNL

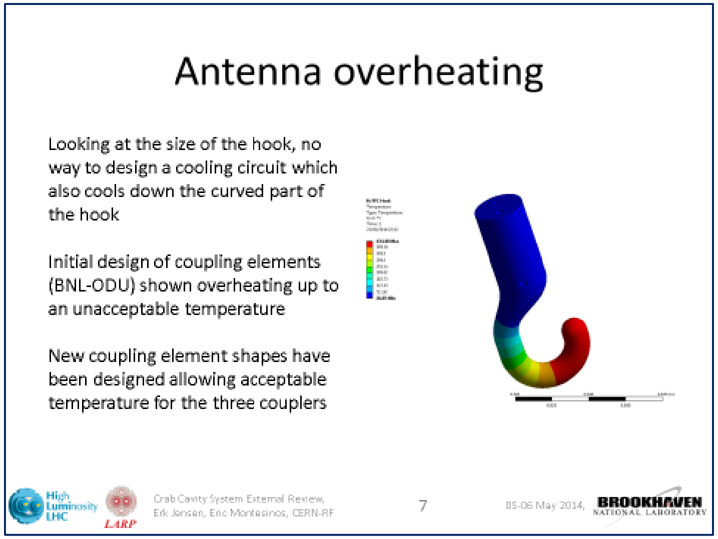
5-6 May 2014

SPS - RF Power and Coupler status

(https://indico.bnl.gov/contributionDisplay.py?contribId=20&confId=728)







FPC History, 2015

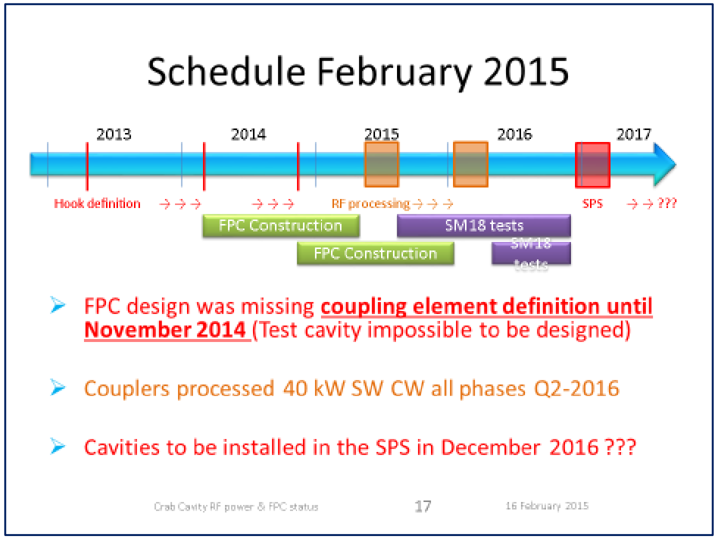
SPS CCTC

CERN

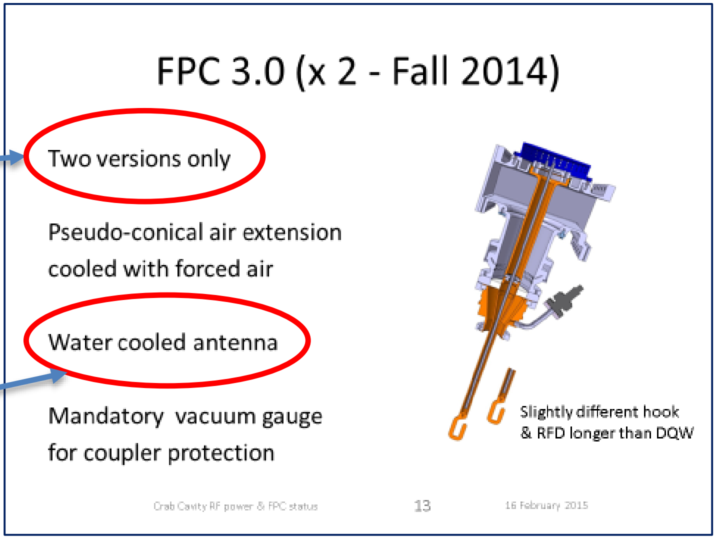
February 2015

RF power & FPC status

(https://indico.cern.ch/event/374702/)



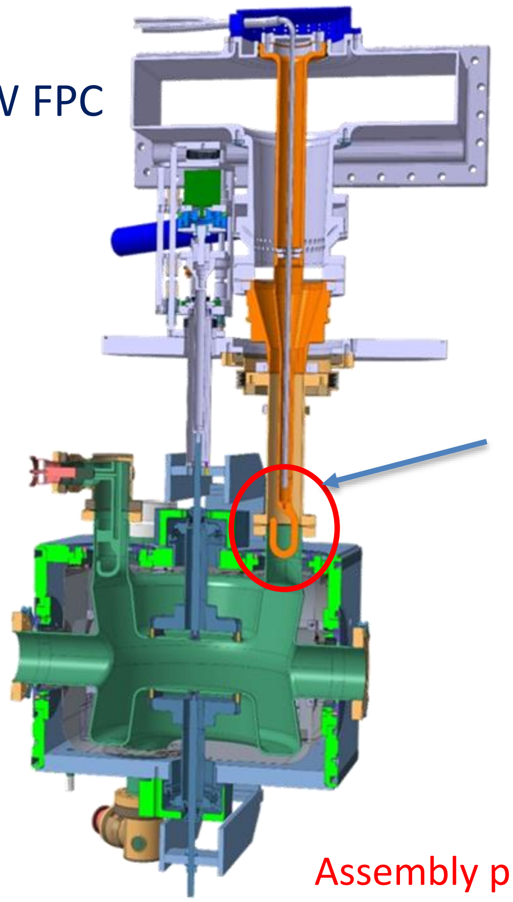
Down selection to two designs only, with similar hook



Due to high power and very small inner line, mandatory water cooled antenna

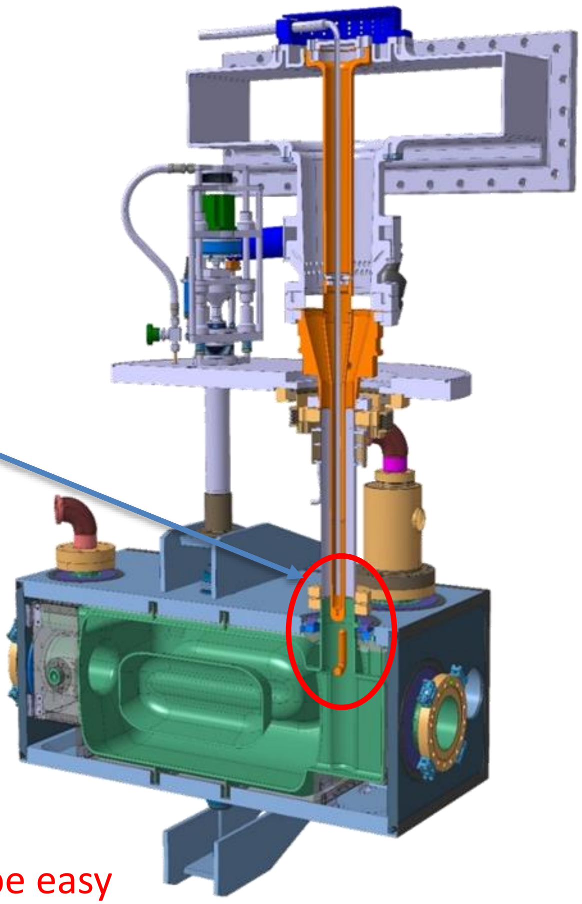
FPC History, 2015

DQW FPC



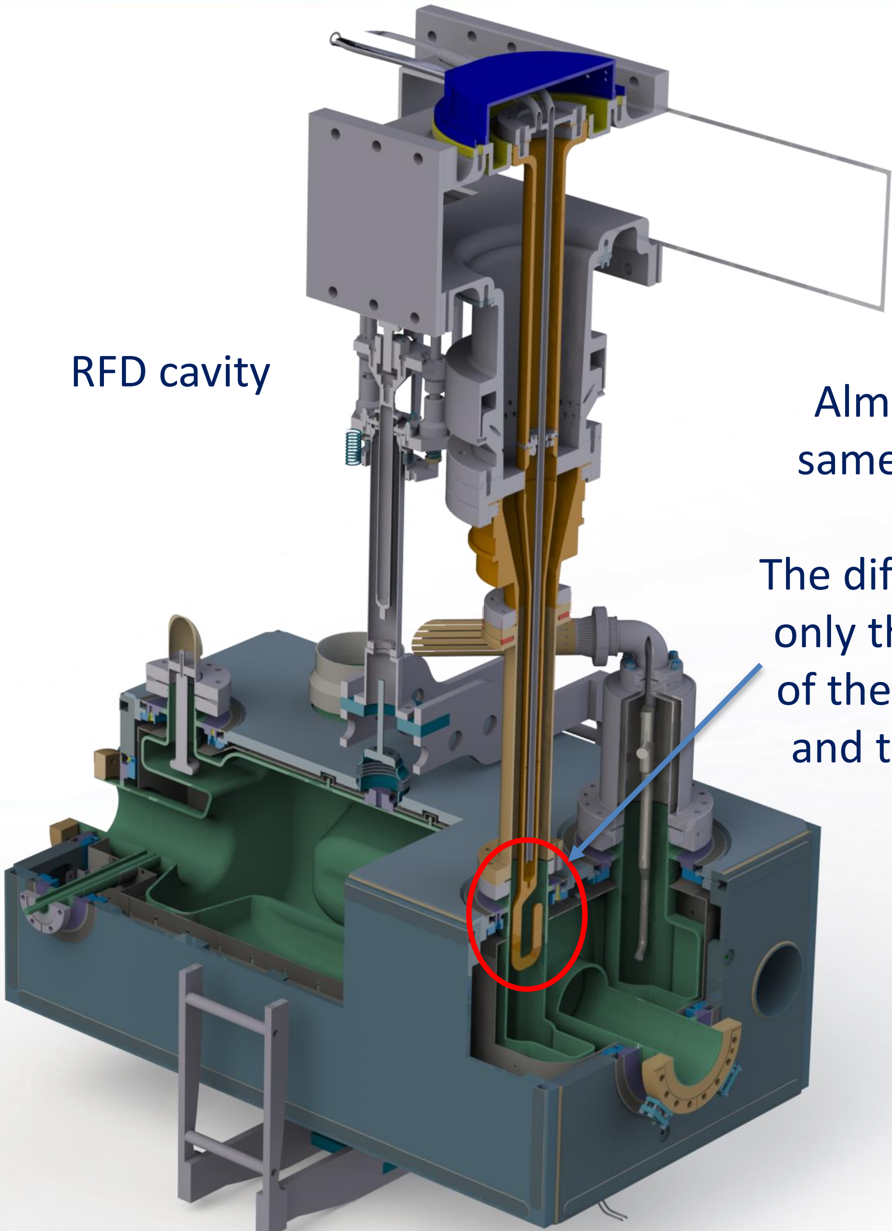
Regarding FPC the difference is only the length of the antenna and the hook

RFD FPC



Assembly procedure will not be easy
We will need some preliminary mockups in order to validate it

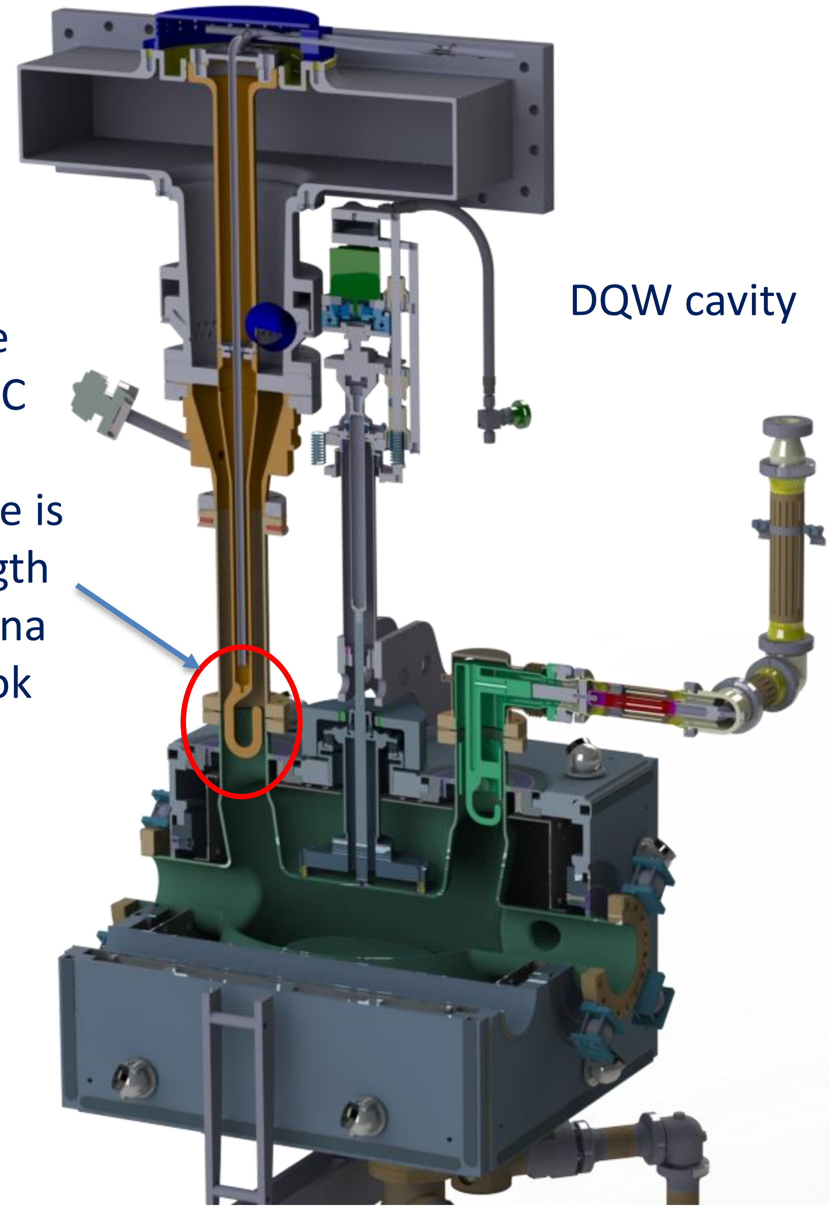
RFD cavity



Almost the same RF FPC

The difference is only the length of the antenna and the hook

DQW cavity



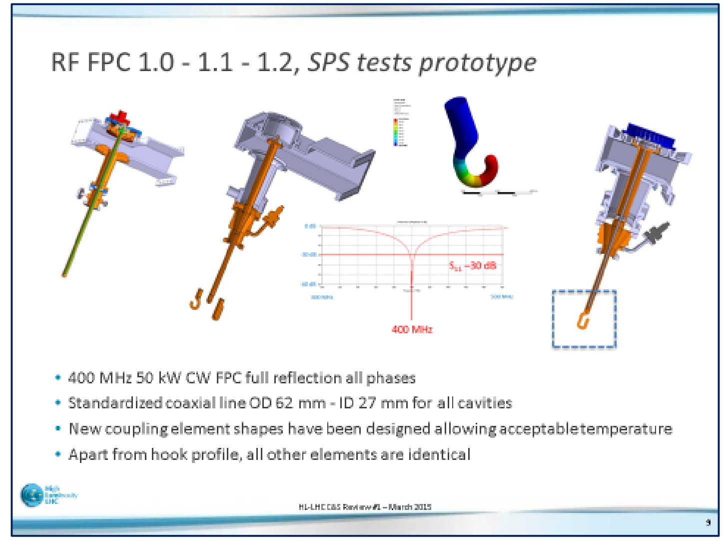
FPC History, 2015

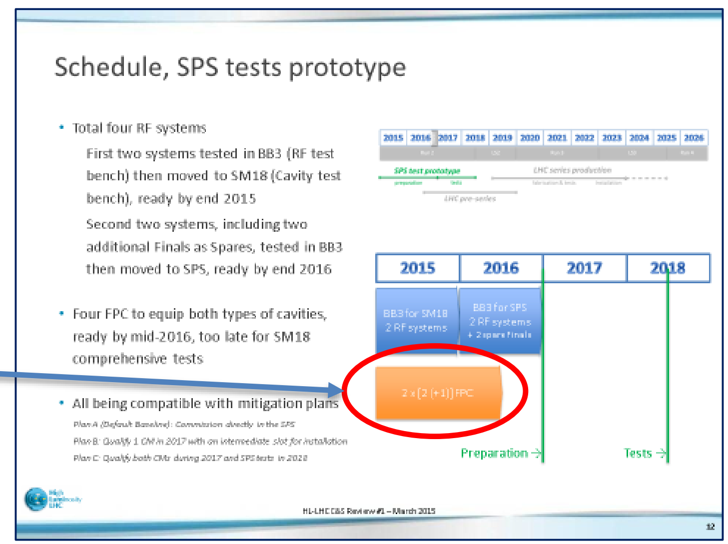
HL-LHC / LIU Cost & Schedule Review

CERN

9-11 March 2015

RF Power systems and Fundamental Power Couplers (FPC), WP 4

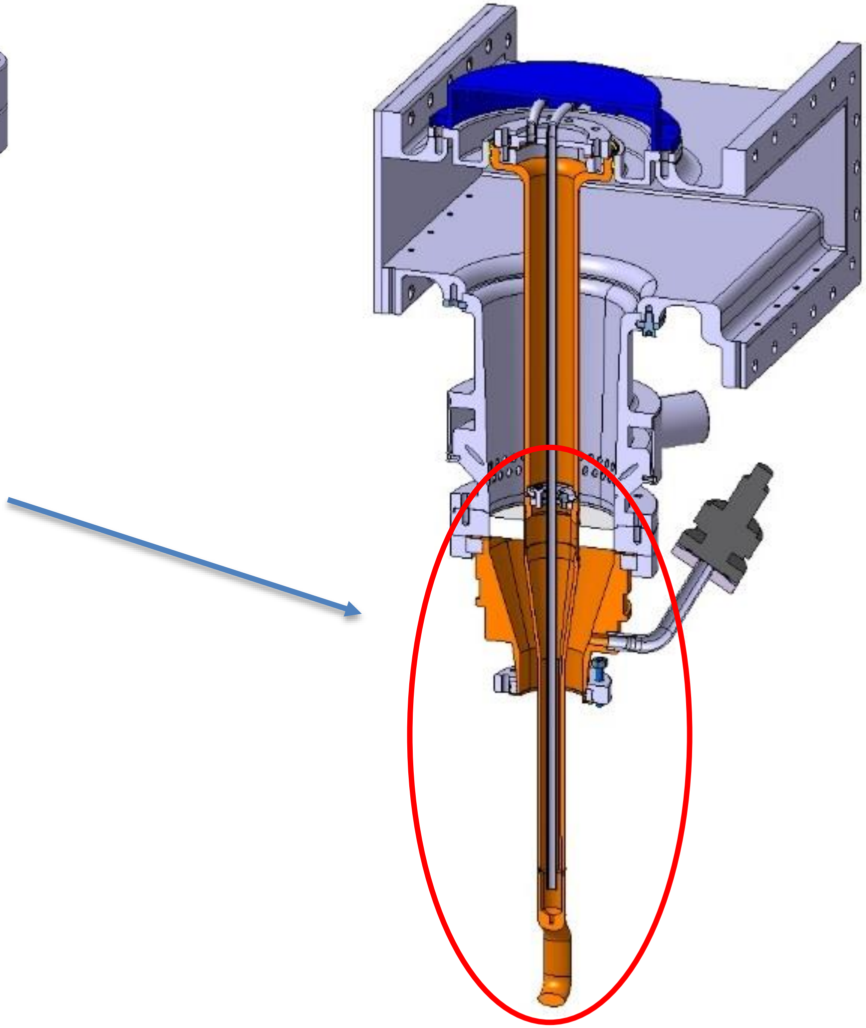




Scheduled to have 3 + 3 FPC ready by mid-2016

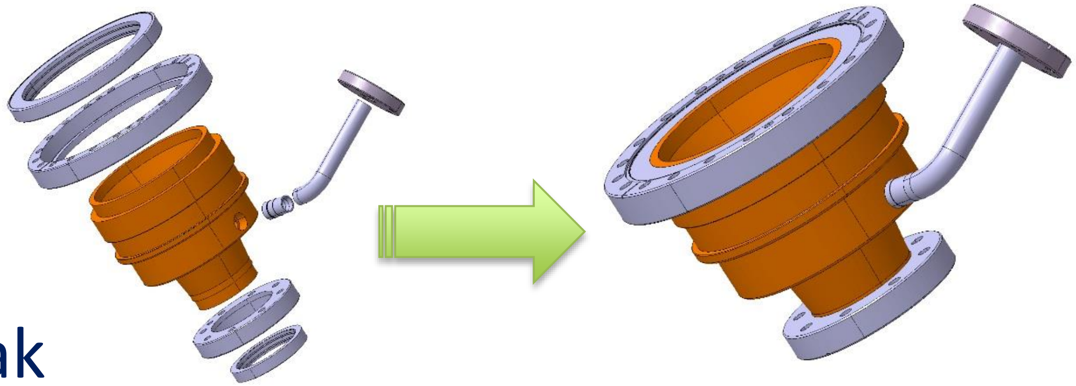
FPC current status

Air lines to be built:
2 Coaxial to WG systems



Vacuum lines
to be built:
2+1 DQW FPC
2+1 RFD FPC

FPC current status, body



8 body lines vacuum leak tested and ready since 13 August 2015

(was 3 designs x 2 + 2 spares when we launched it)

Current status, windows

2 windows leak tested end October 2015

4 windows expected by end November 2015

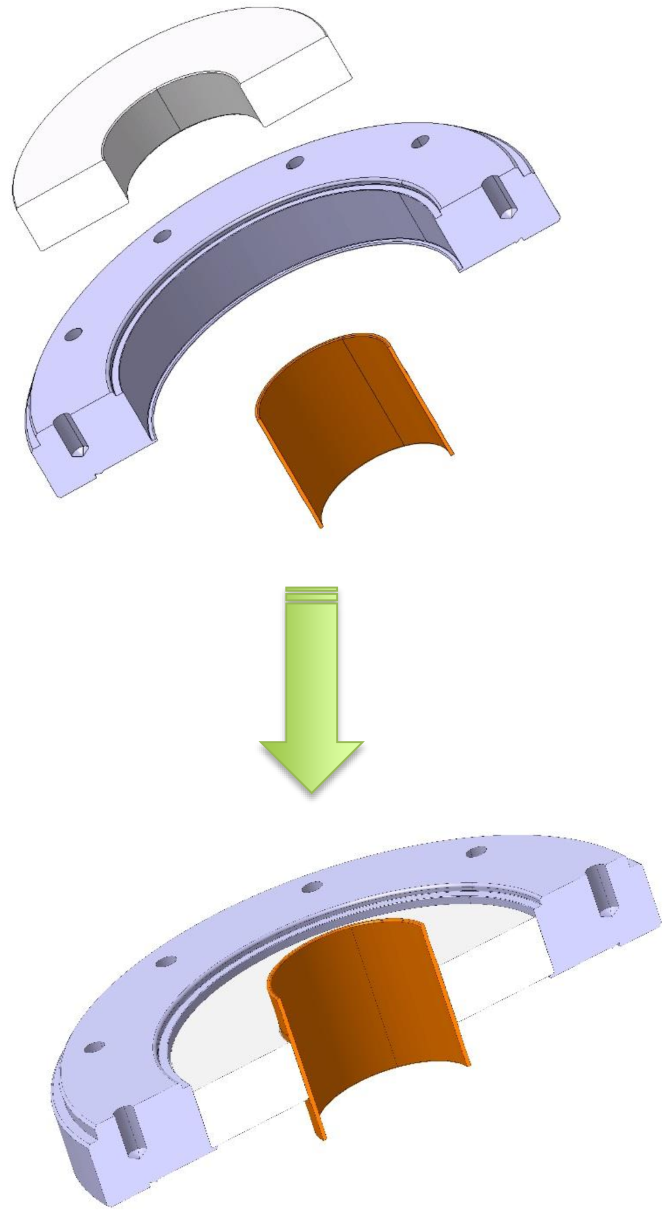
2 windows March 2016

To be fully completed, still need

- Final machining
- Titanisation
- Electron Beam Welding

6 windows end February 2016

2 windows end June 2016



FPC current status, windows

Even if we are experienced with those ceramic construction at cern, this time it has been very laborious

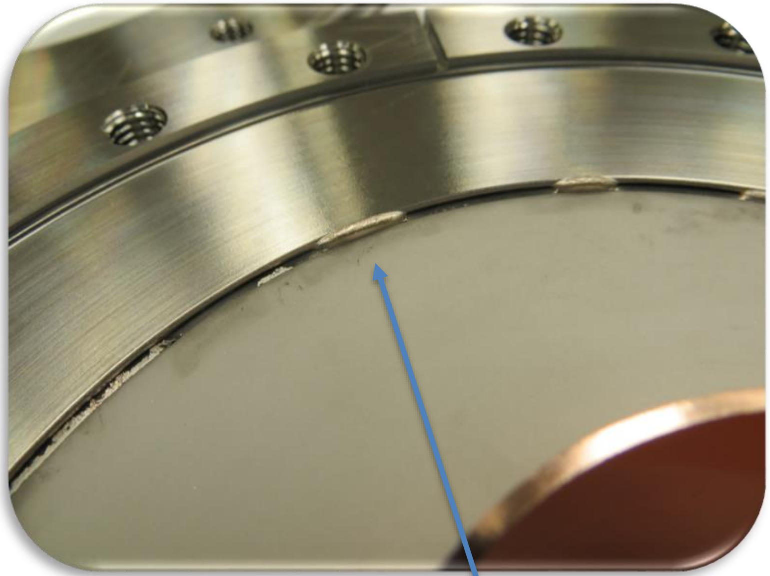
Mistake with the titanium flange machining (CERN)

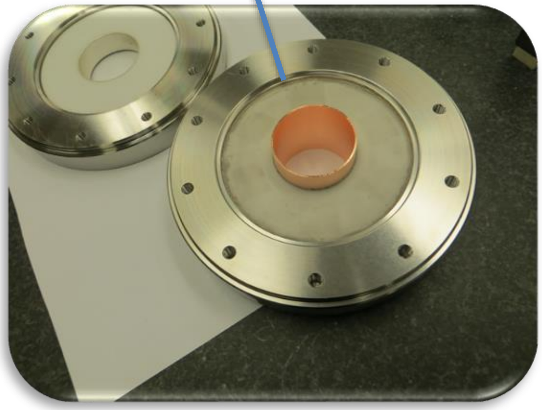
Mistake with the nickel layer (ceramic suplier)

Mistake with the silver plating layer thickness (CERN)

Mistake with the brazing process (CERN)

6 bare ceramics were expected by March 2015 (will be November)





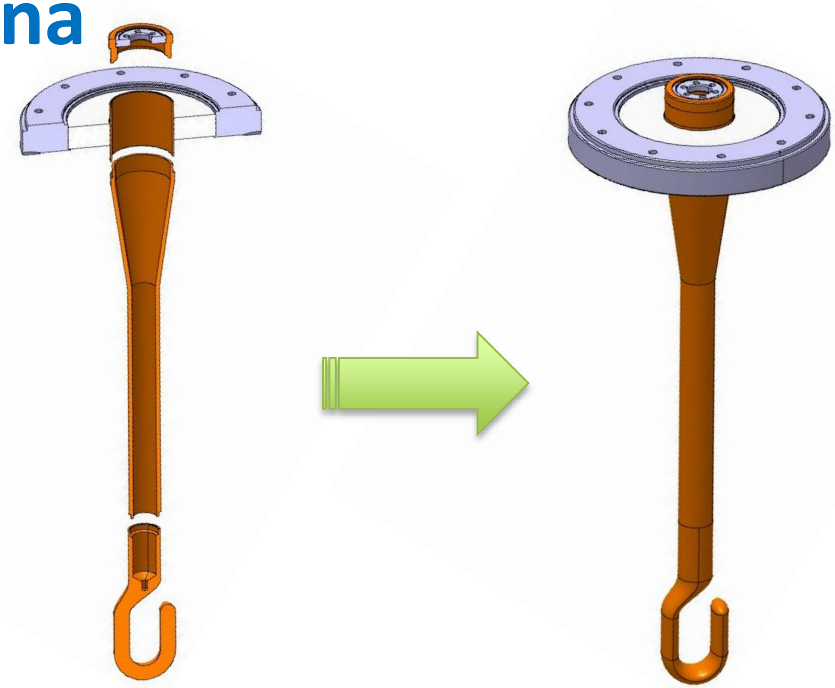
FPC current status, Antenna

Both hook versions machined

2 designs x 3 units available

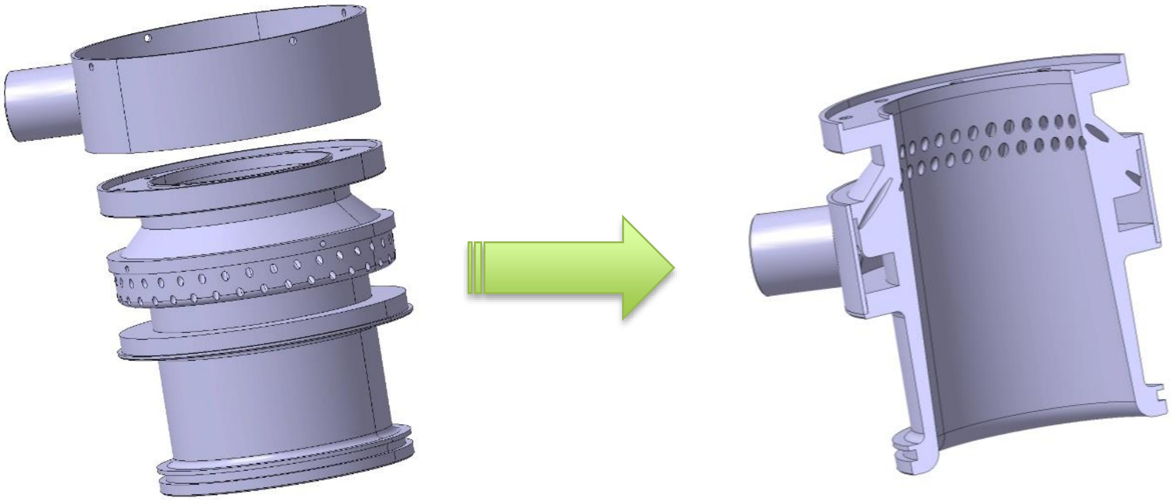
6 antennae available

6 water connections available



FPC current status, outer air line

3 outer air lines completed

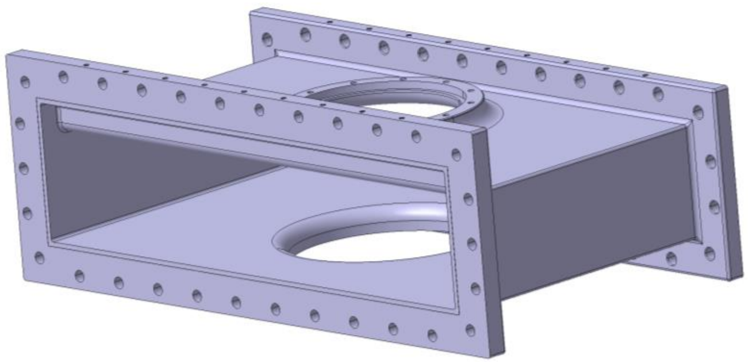


Cyclotronic air cooling

Slightly conical

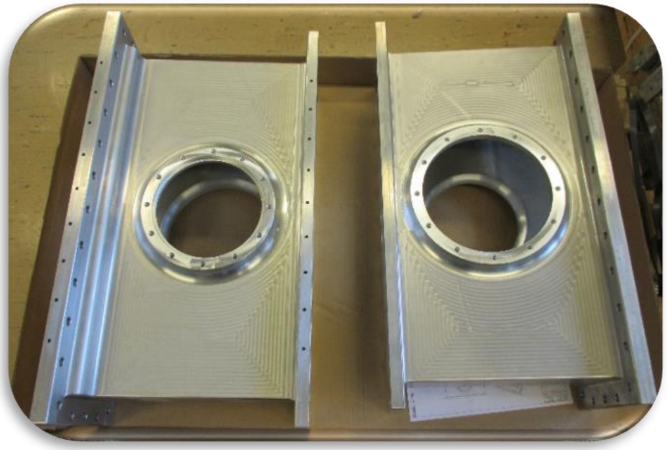
FPC current status, WG

We tried different construction processes with the specific WR2300 (1/4 H to 1/2 H step)



A first 3D printed and moulded WG, non compliant, was rejected

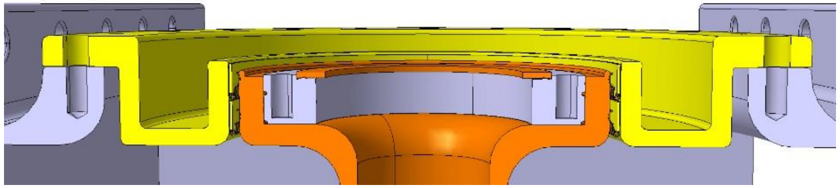
A second moulded and machined WG was not so nice



A third fully machined WG was selected (not more costly than a welded one !)

Two WG are available

FPC current status, Antenna connection

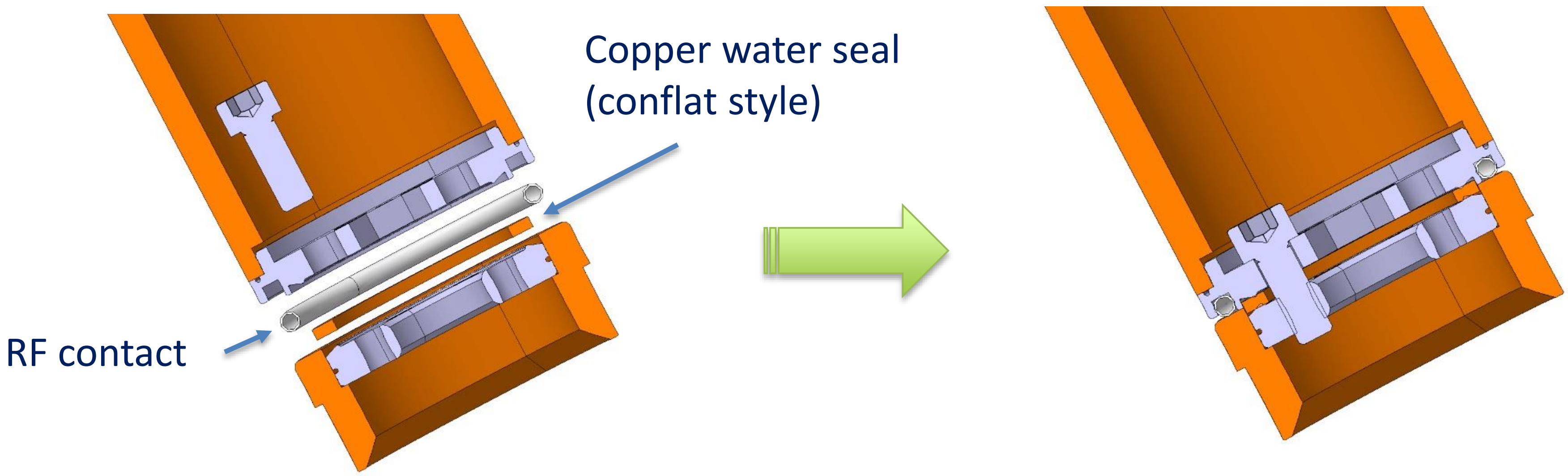


2 antenna connection are available

+

2 are ready to be mounted

FPC current status, antenna air side



4 antenna connections are available

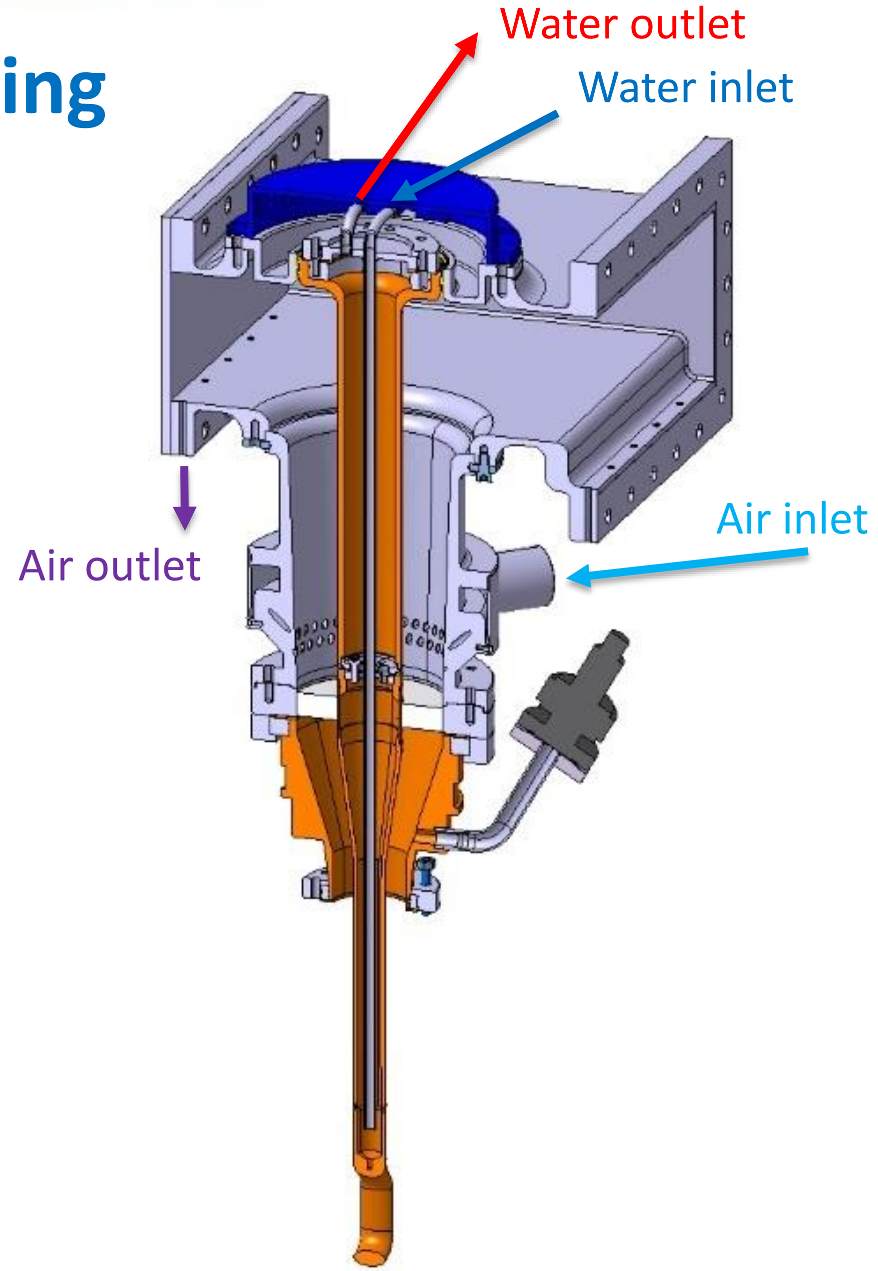
FPC current status, cooling

Outer coaxial air cooled

- Cyclotronic air input
- Air exhaust through bottom holes in WG flanges

Inner antenna water cooled

- Against CERN's rules, need an exception as mandatory with respect to high average power and so small inner conductor (only 27 mm)
- Inlet pipe diameter even only 10 mm
- (see Federico Carra talk at 14:10 & spare slides)
- Specific water station to avoid any damages



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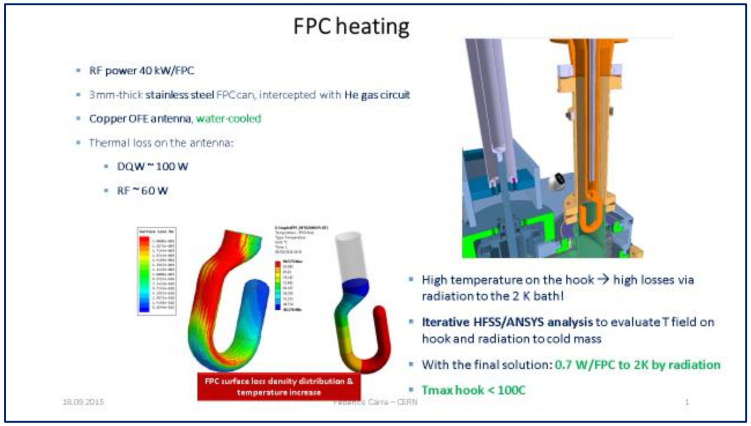

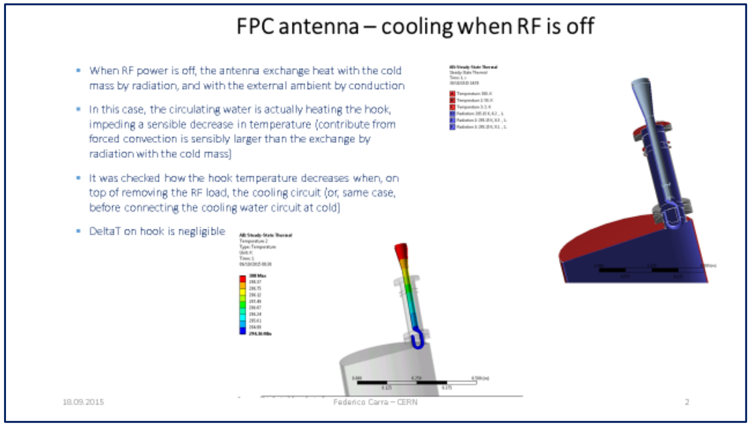

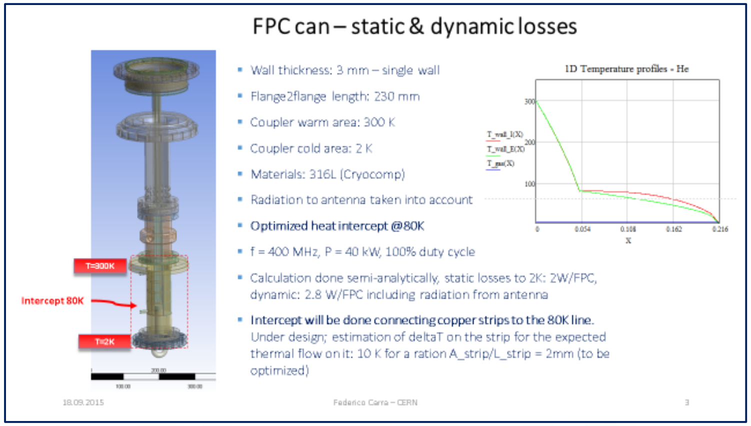

High Luminosity LHC

FPC current status, cooling

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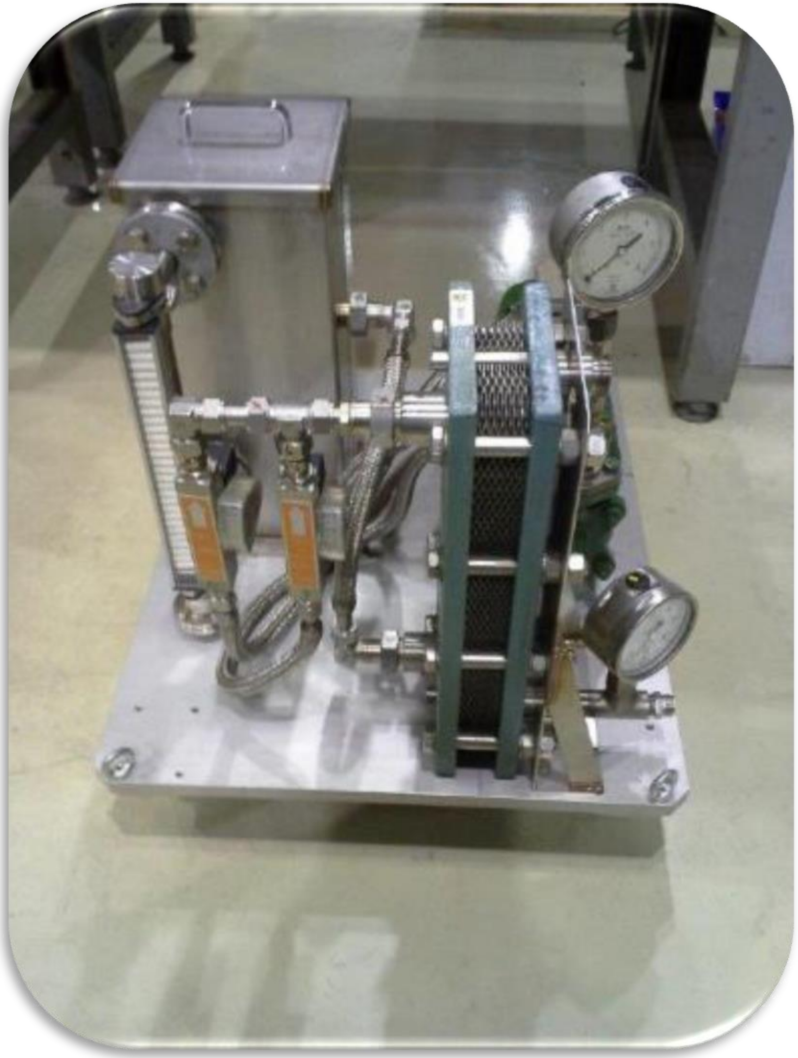


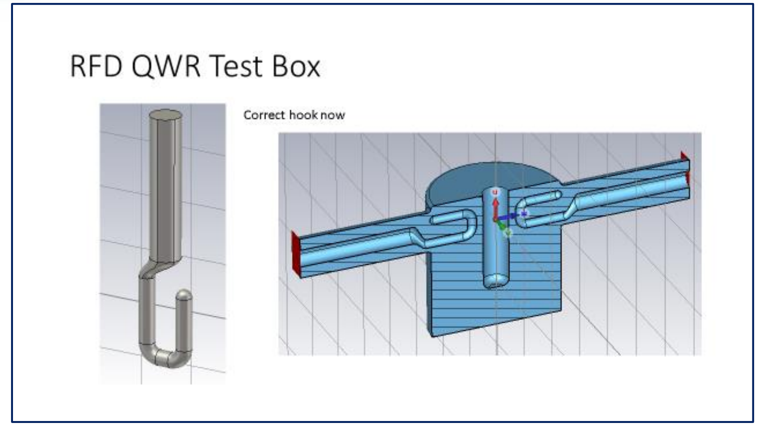
FPC current status, test boxes

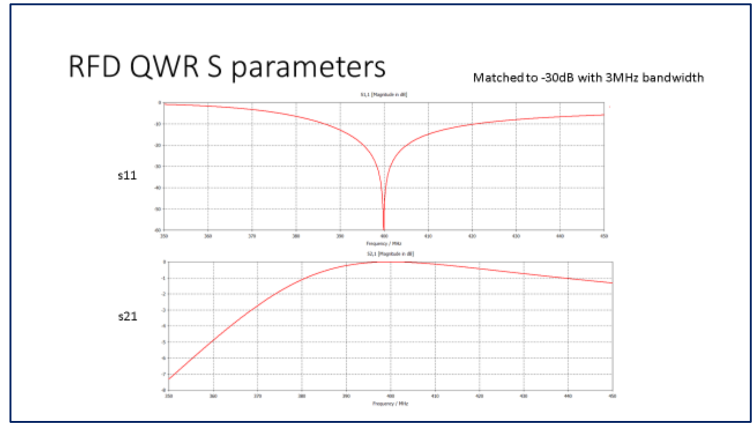
Two tests boxes have been simulated

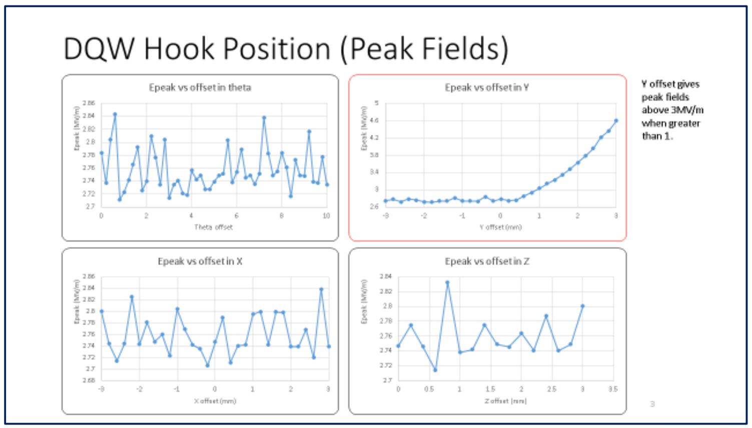
(See Adam Tutte spare slides, excellent job)

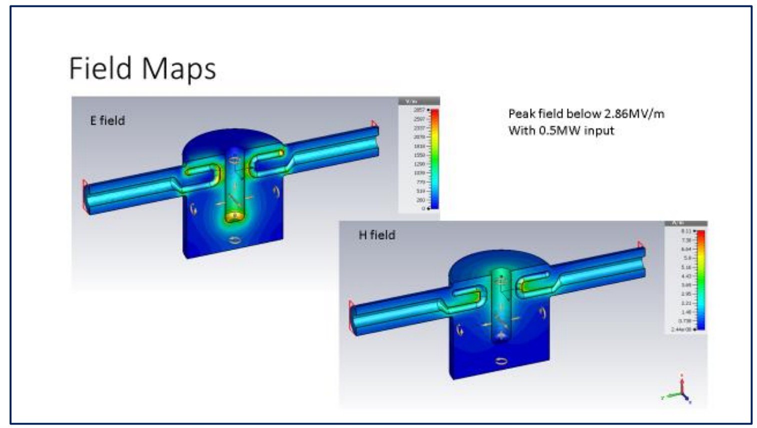
Drawings are being prepared

1 + 1 test boxes available by April 2016



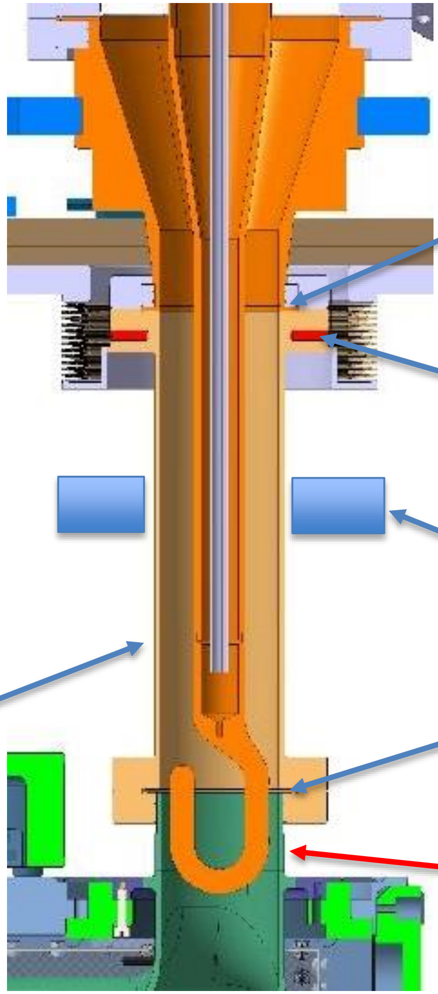






FPC Single Walled Tube

Not anymore a RF device
Only the outer line of a RF transmission line
From RF point of view, we only need few µm of copper
(see Federico Carra talk at 14:10)



RF / UHV seal (LHC type)

Heaters (Power ~45W against icing)

80K thermalisation (cooled by conduction from thermal screen)

St Steel 316LN single tube pipe
First layer of NEG : 0.5µm
Second layer copper coating : 7µm
(pipes ordered for coating tests)

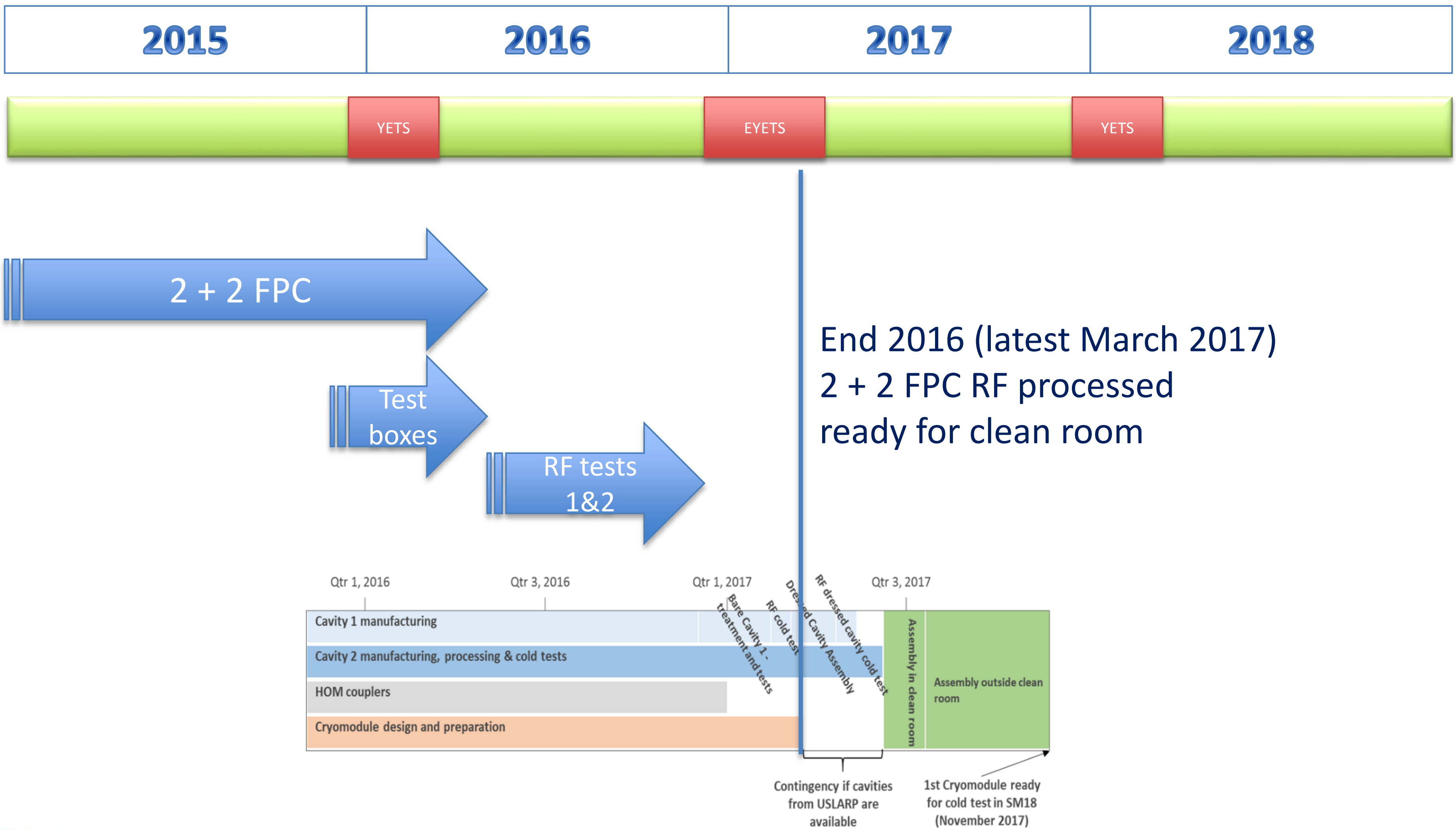
RF / UHV seal (LHC type)

Very small gap between the hook and the cavity

FPC current status, construction summary

Item	Minimum qty	Today qty	April 2016 qty
Brazed ceramic	4	2	8
Body	4	8	✓
Antenna vacuum side	2+2	3+3	✓
Hook	2+2	3+3	✓
Vacuum Assembly	**2+2**	**-**	**3+3**
Outer air line	2	3	✓
WG	2	2	✓
WG/Antenna connection	2	2 (+2)	✓
Antenna air side	2	4	✓
Air assembly	**2**	**2**	✓
FPC water cooling station	1	2	✓
Test boxes	1+1	-	✓

FPC Schedule, November 2015



HOM RF Coaxial lines

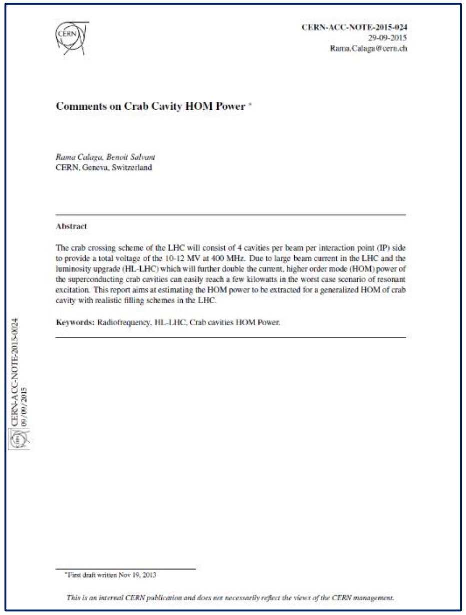
Almost all simulated modes are lower than ~ 100 W, except two modes that are higher power level

From those, we assumed a 1 kW and up to 1 GHz ratings for the HOM couplers, and HOM coaxial line

(https://cds.cern.ch/record/2050944/files/CERN-ACC-NOTE-2015-0024.pdf)

(https://indico.cern.ch/event/450955/contribution/1/attachments/1182564/1712742/Heating_HL-LHC_TC_nov_2015_v3.pptx)

The SPS test will be the validation of this assumption (could show that we need much less power capability)



CERN-ACC-NOTE-2015-024
29-09-2015
Rama.Calaga@cern.ch

Comments on Crab Cavity HOM Power *

Rama Calaga, Benoit Salvant
CERN, Geneva, Switzerland

Abstract

The crab crossing scheme of the LHC will consist of 4 cavities per beam per interaction point (IP) side to provide a total voltage of the 10-12 MV at 400 MHz. Due to large beam current in the LHC and the luminosity upgrade (HL-LHC) which will further double the current, higher order mode (HOM) power of the superconducting crab cavities can easily reach a few kilowatts in the worst case scenario of resonant excitation. This report aims at estimating the HOM power to be extracted for a generalized HOM of crab cavity with realistic filling schemes in the LHC.

Keywords: Radiofrequency, HL-LHC, Crab cavities HOM Power.

CERN-ACC-NOTE-2015-0024
09/09/2015

*First draft written Nov 19, 2013

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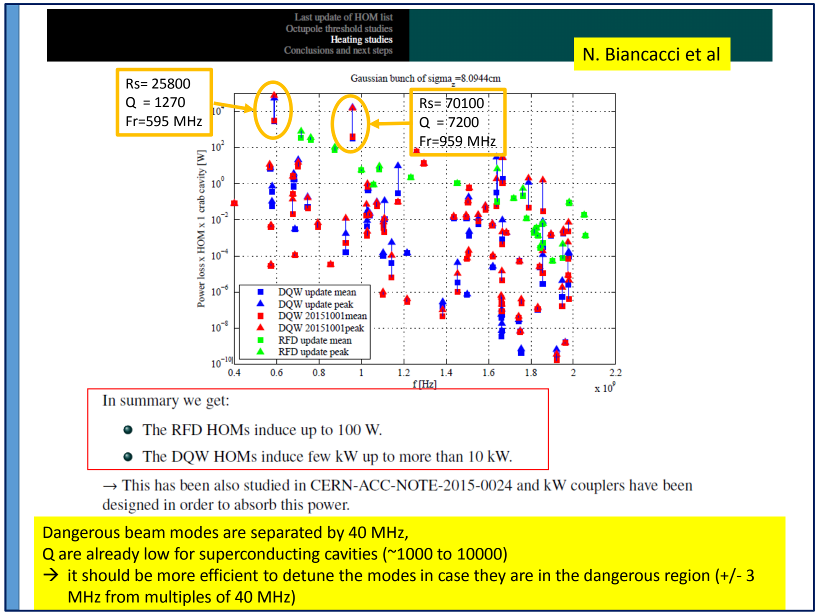
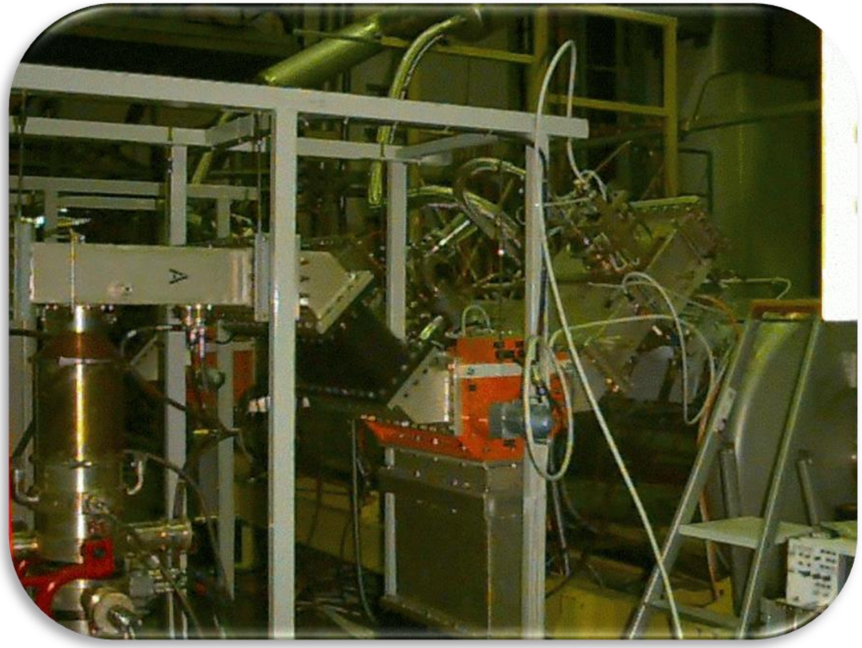


RF transmission lines

The HOM have been requested to sustain 1 kW up to 1 GHz

SPS 1996 with the LHC prototype cavities

- Too much RF power in HOM
- RF cables were damaged
- 1998 all HOM cables had to be exchanged
- All cryomodules have been opened in-situ



SPS RF amplifier and cryomodule in 1996
All four cryomodules opened to exchanged the HOM cables

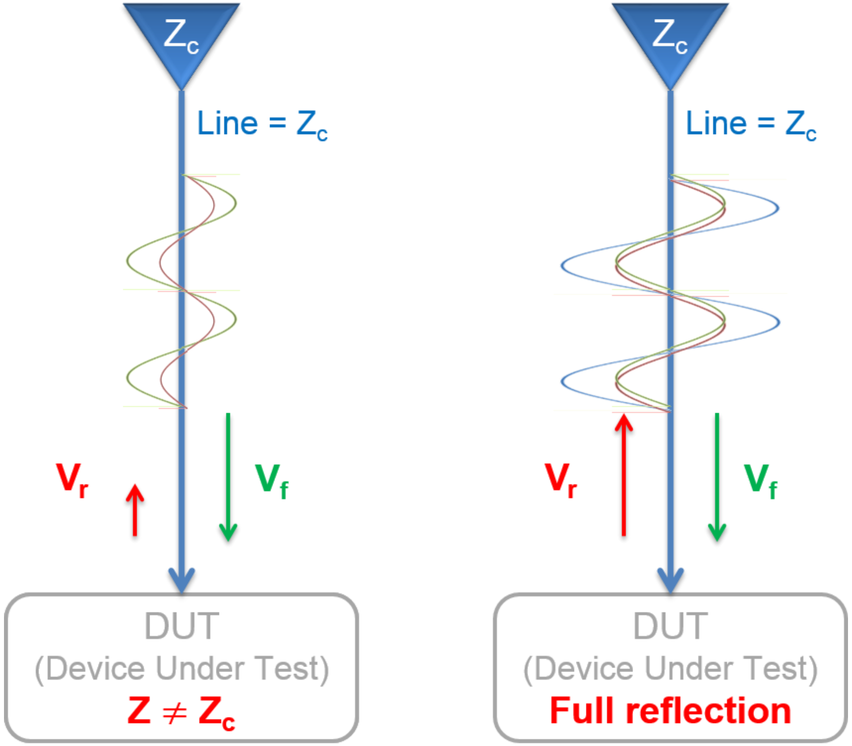
RF transmission lines

In case of full reflection at the load, maximum standing wave and voltage along the line will be up to twice the nominal forward voltage

- $V_{total} = V_f + V_r$
- With full reflection $V_r = V_f$
- So $V_{total} = 2\ V_f$
- $P_{maximum} = 4\ P_f$

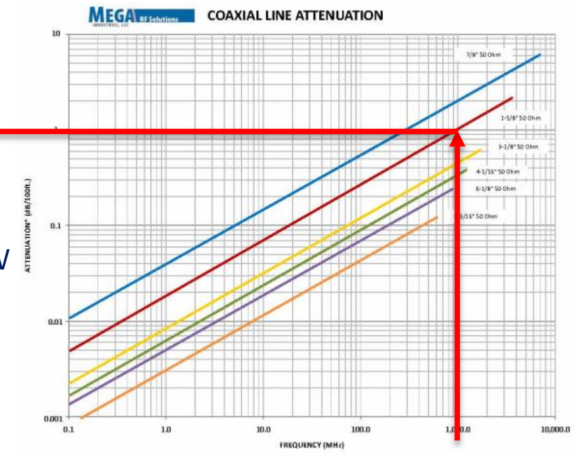
In our case, the source will be the HOM, and the load at the air side

- In case of a load failure, there will be full reflection back to the HOM
- The RF lines have to be correctly chosen to avoid any damages



Transmission lines

1 dB/100 ft
0.03 dB / m
With a 1 meter line and 1 kW @ 1 GHz losses would be 7 W in ambient air at room temperature



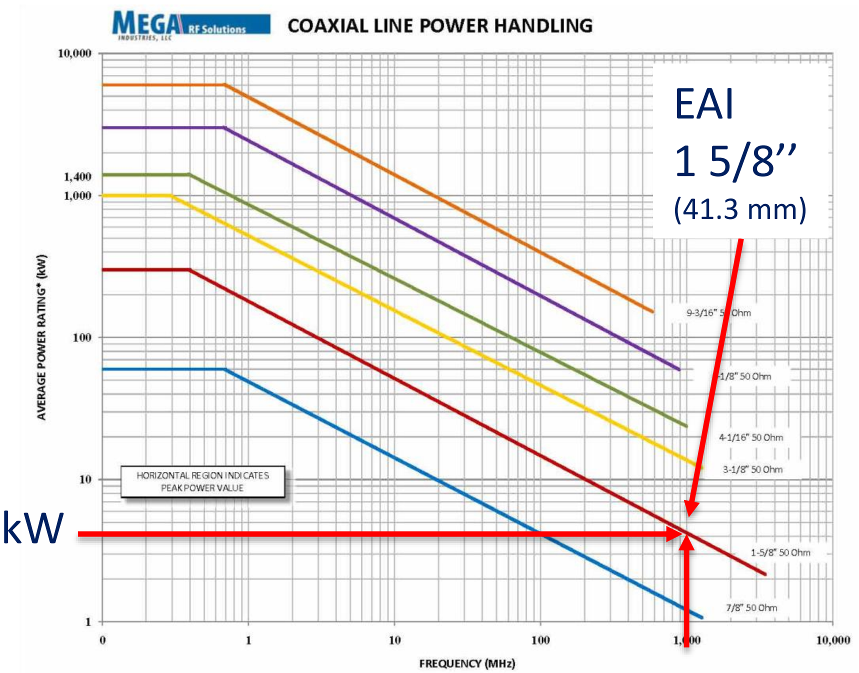
1 GHz

Crab HOM suppressors designed for

1 GHz and 1 kW

For RF transmission lines between the HOM and the cryomodule, to be conservative

- translated to 4 kW at 1 GHz
- No data for operation under vacuum, but compatible with ceramic insulators

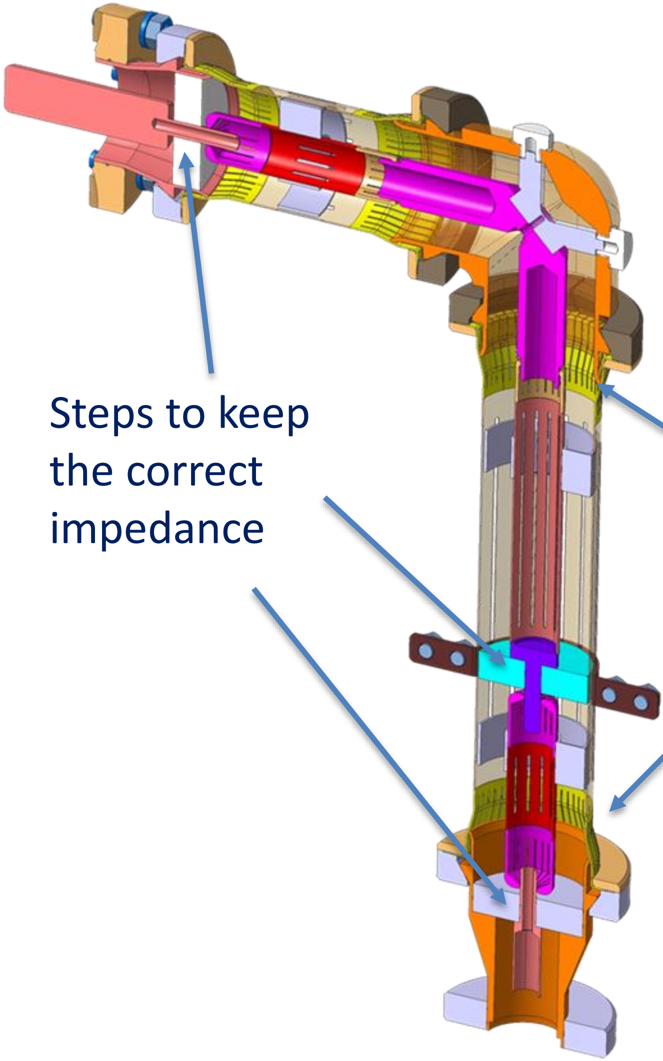


1 GHz

Transmission lines

Specific transmission lines are being developed (Teddy) in order to allow expansion due to thermal cycles without damaging the lines

Federico Carra 14:10
https://indico.cern.ch/event/435319/contribution/46



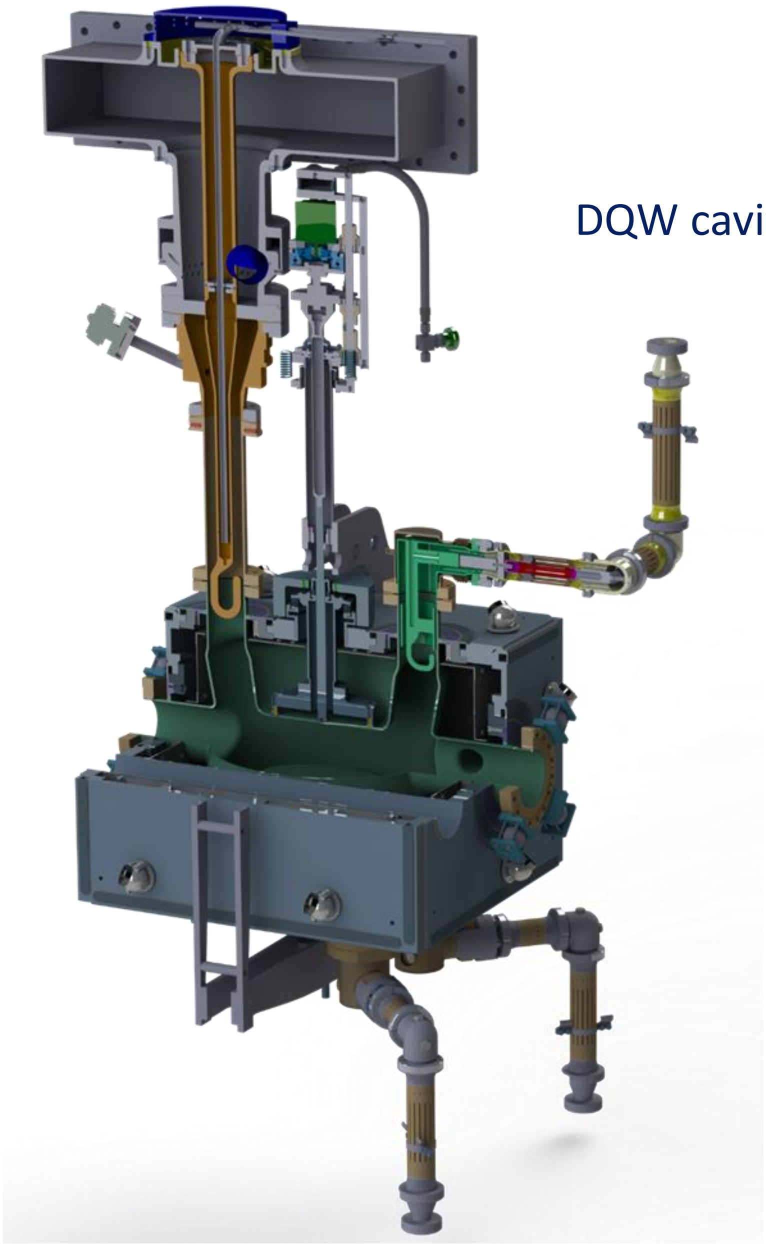
Steps to keep the correct impedance

Sliding contacts for thermal variation

Transmission lines

Design of those transmission lines is still under work, including integration

Next step will be to build a line prototype and try to destroy it with RF ! (in order to check that the maximum ratings are ok)



DQW cavity

Conclusion

RF FPC

- TD definition was provided late
- Hooks definitions were provided late
- Construction of ceramic windows has been very difficult
- We are very late compare to our initial schedule
- No more showstoppers, we will not relax the schedule to try to be in advance compare to cavities
- Still have to work on the assembly procedure, including mockups to test it

Transmission lines

- Design to be completed
- Prototype to be constructed
- Test of the prototype to RF validate the lines design

High Luminosity LHC

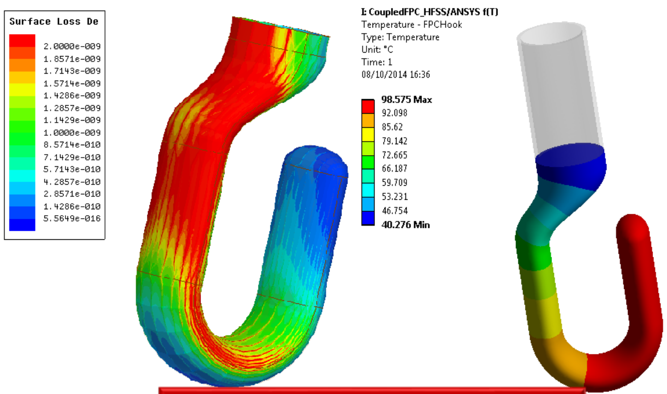
Thank you very much for your attention

The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

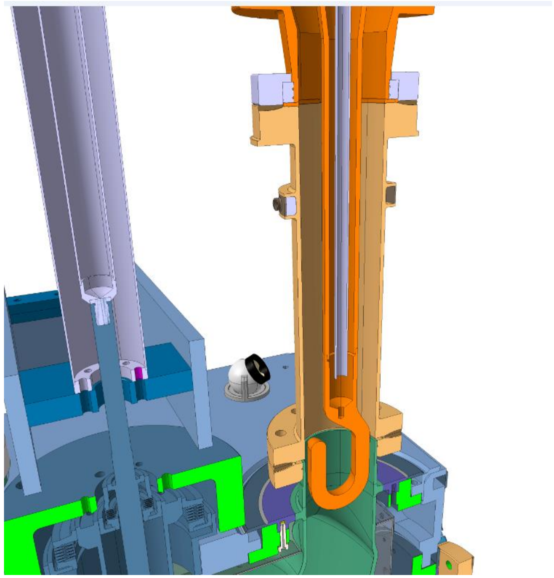
Spare slides

FPC heating

- RF power 40 kW/FPC
- 3mm-thick **stainless steel** FPC can, intercepted with **He gas circuit**
- **Copper OFE antenna**, water-cooled
- Thermal loss on the antenna:
  - DQW ~ 100 W
  - RF ~ 60 W



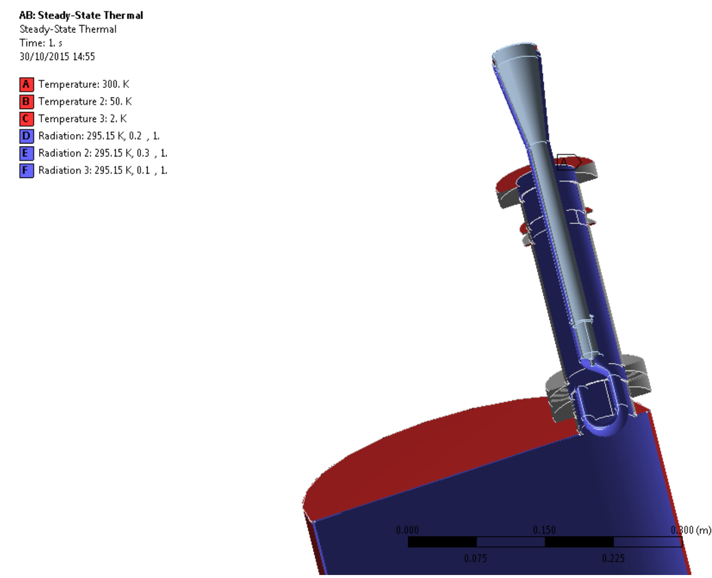
FPC surface loss density distribution & temperature increase

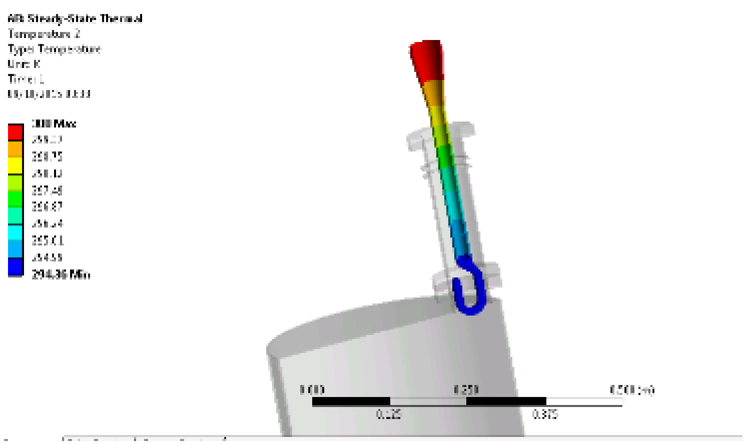


- High temperature on the hook → high losses via radiation to the 2 K bath!
- **Iterative HFSS/ANSYS analysis** to evaluate T field on hook and radiation to cold mass
- With the final solution: **0.7 W/FPC to 2K by radiation**
- **Tmax hook < 100C**

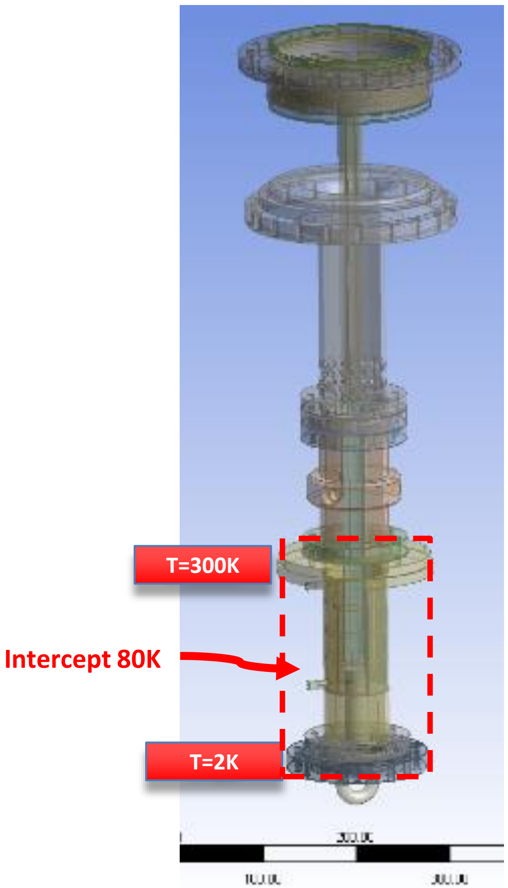
FPC antenna – cooling when RF is off

- When RF power is off, the antenna exchange heat with the cold mass by radiation, and with the external ambient by conduction
- In this case, the circulating water is actually heating the hook, impeding a sensible decrease in temperature (contribute from forced convection is sensibly larger than the exchange by radiation with the cold mass)
- It was checked how the hook temperature decreases when, on top of removing the RF load, the cooling circuit (or, same case, before connecting the cooling water circuit at cold)
- DeltaT on hook is negligible

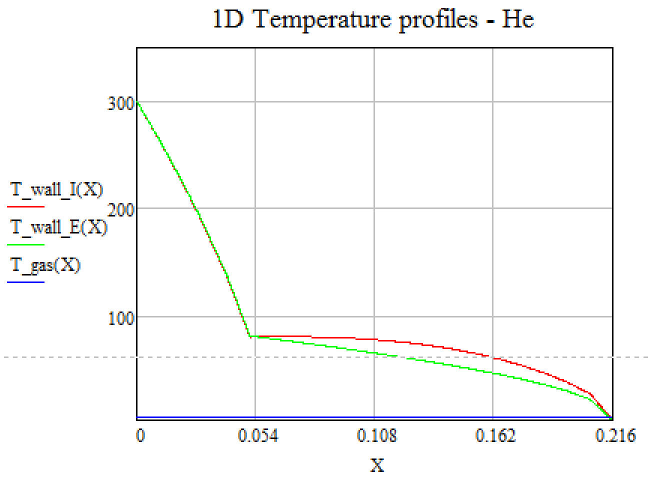




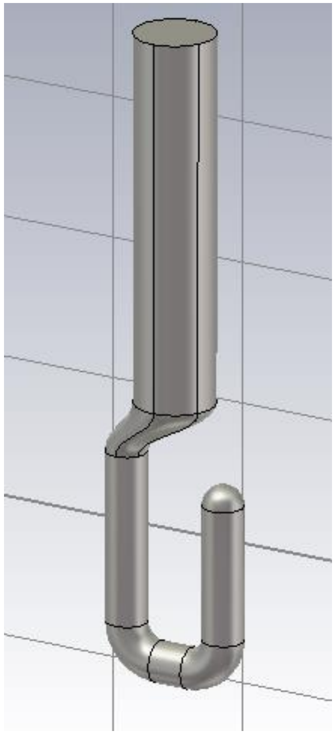
FPC can – static & dynamic losses



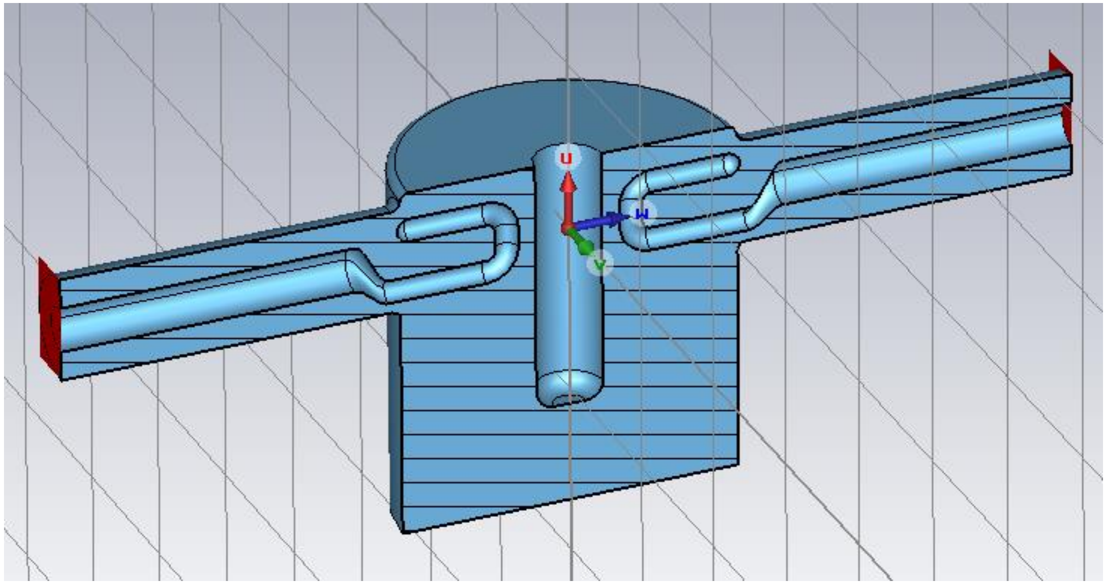
- Wall thickness: 3 mm – single wall
- Flange2flange length: 230 mm
- Coupler warm area: 300 K
- Coupler cold area: 2 K
- Materials: 316L (Cryocomp)
- Radiation to antenna taken into account
- **Optimized heat intercept @80K**
- f = 400 MHz, P = 40 kW, 100% duty cycle
- Calculation done semi-analytically, static losses to 2K: 2W/FPC, dynamic: 2.8 W/FPC including radiation from antenna
- **Intercept will be done connecting copper strips to the 80K line**. Under design; estimation of deltaT on the strip for the expected thermal flow on it: 10 K for a ration A_strip/L_strip = 2mm (to be optimized)



RFD QWR Test Box



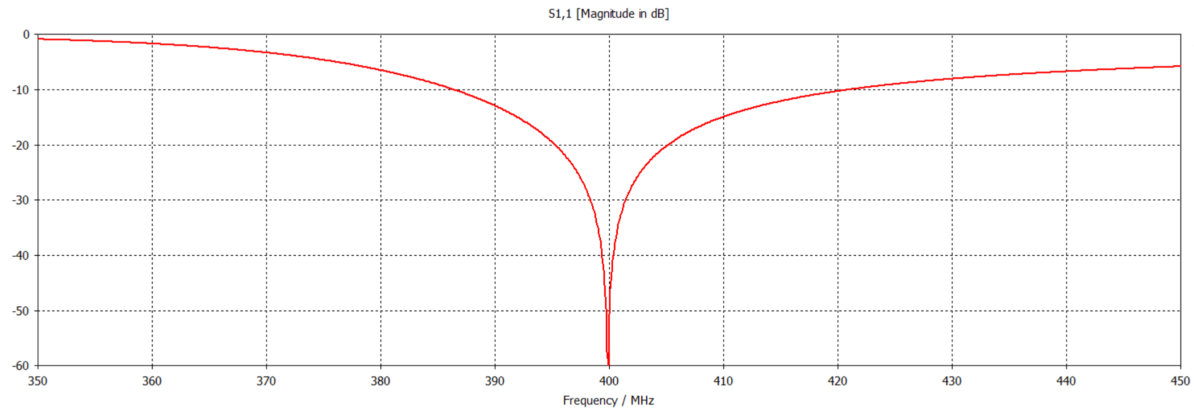
Correct hook now



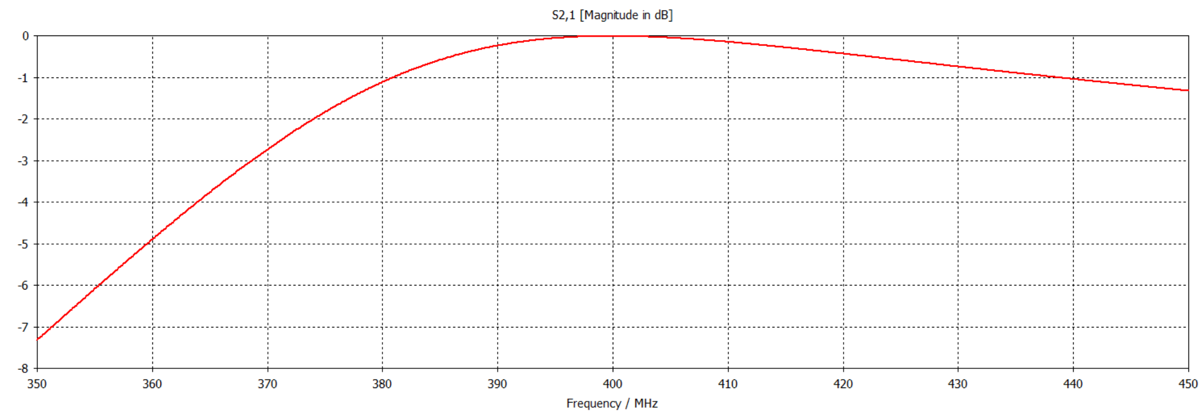
RFD QWR S parameters

Matched to -30dB with 3MHz bandwidth

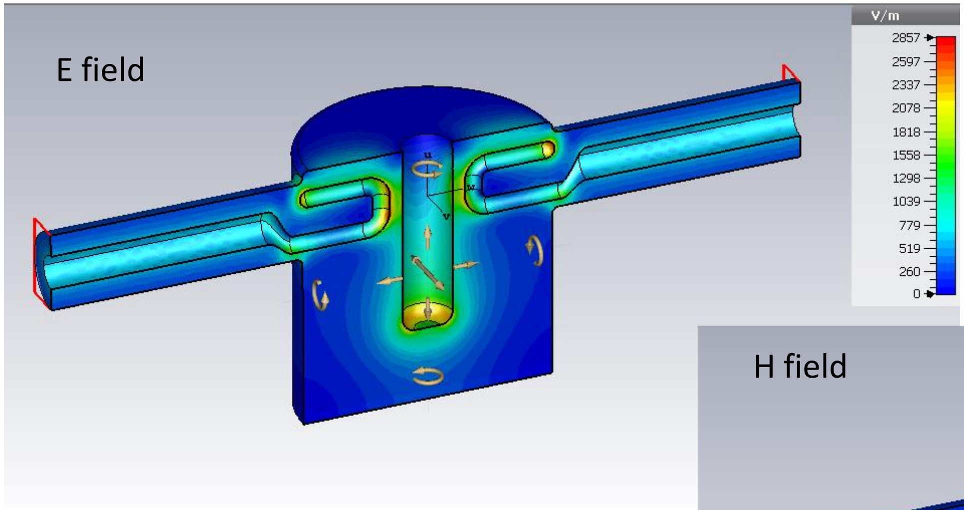
s11

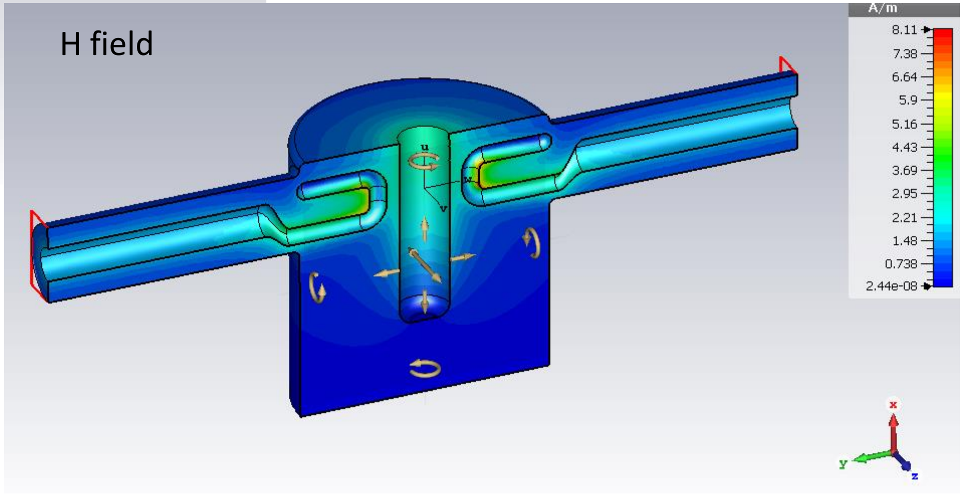


s21



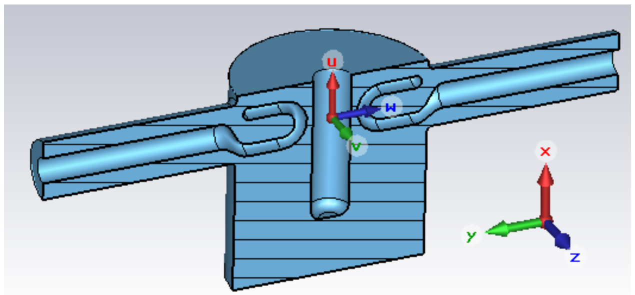
Field Maps





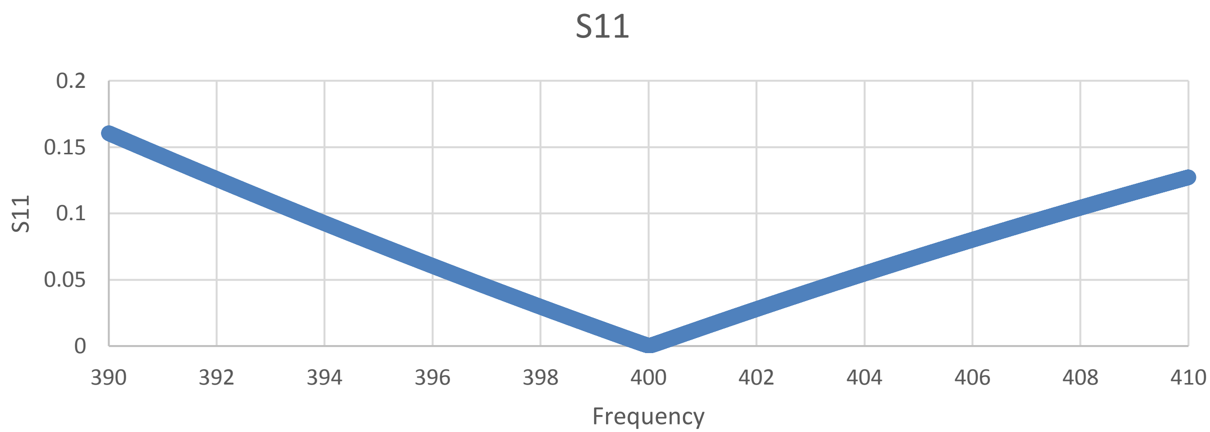
Peak field below 2.86MV/m
With 0.5MW input

DQW Nominal



Parameter List

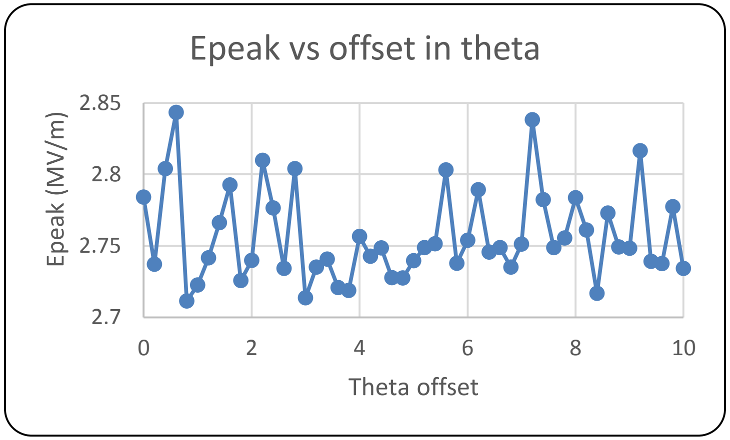
Name	Expression
separation	= 50
hooklength	= 97.3
portposition	= 300
outerlength	= 200
outer	= 100
inner	= 20
innerlength	= 140.15
hookholeblend	= 5

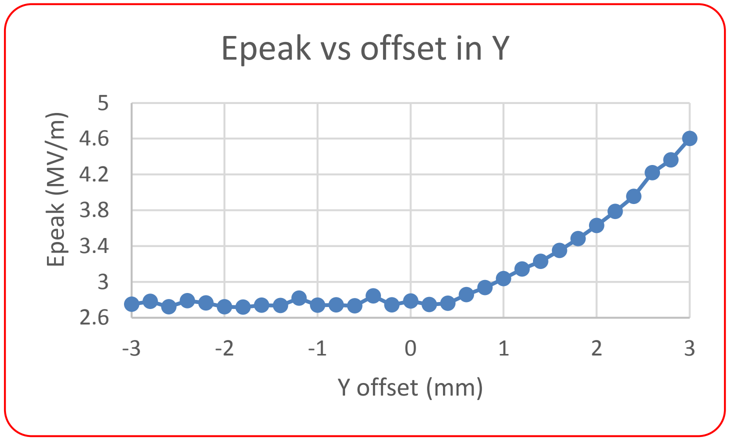


Epeak = 2.732586 MV/m

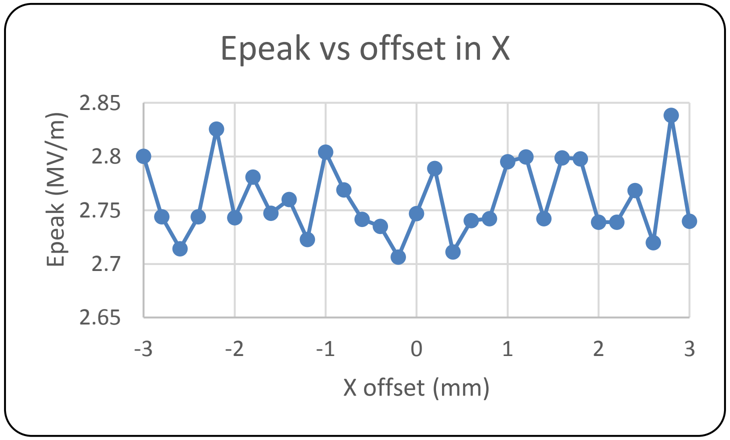
-30dB @ ± 2MHz

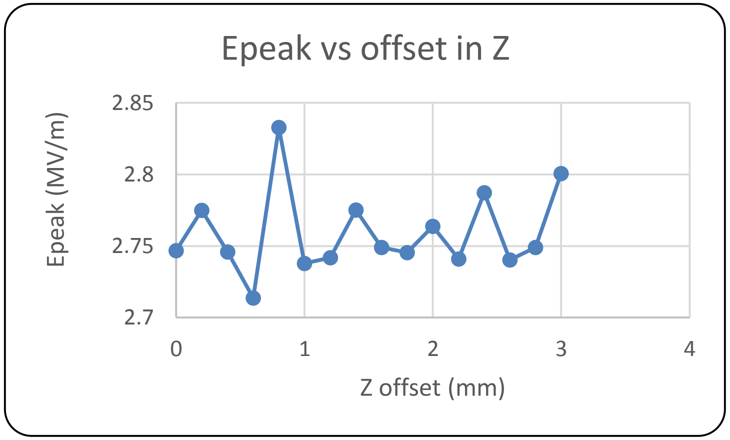
DQW Hook Position (Peak Fields)



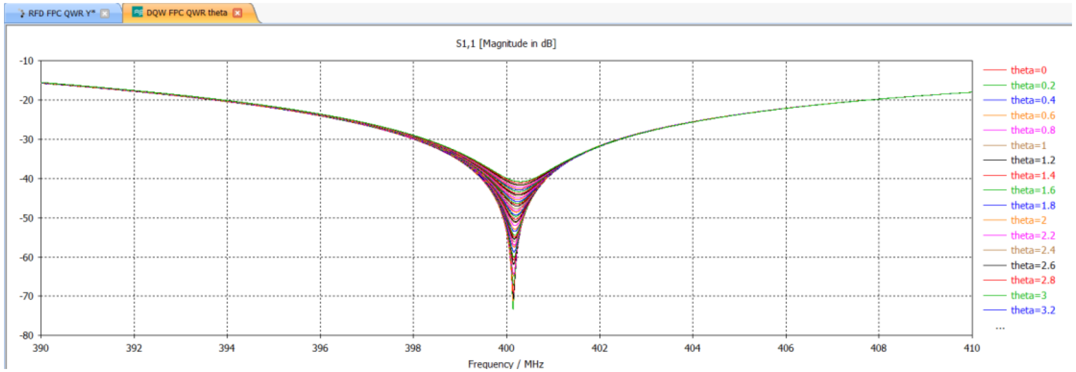


Y offset gives peak fields above 3MV/m when greater than 1.

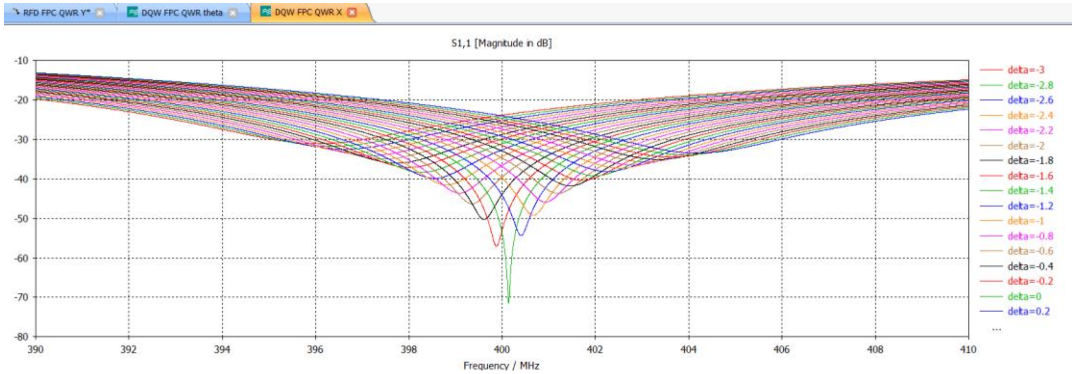




DQW Hook Position (Transmission)



Theta:

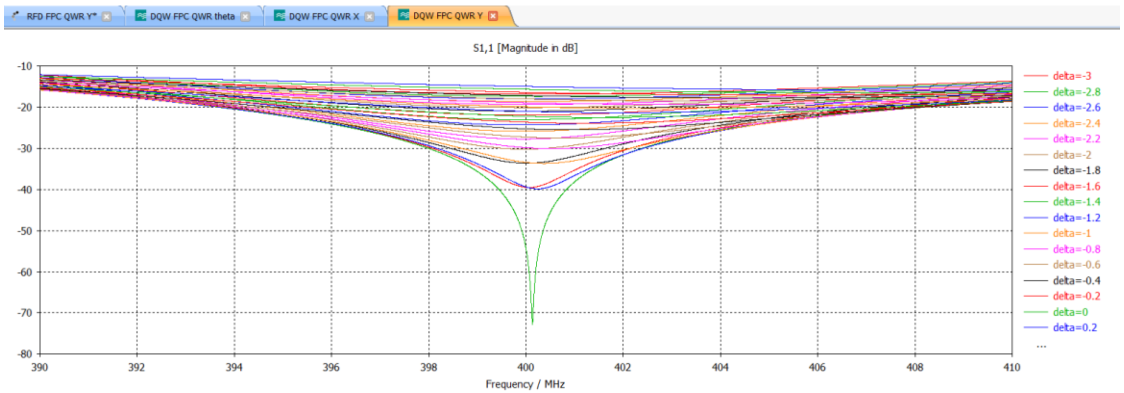


X:

Needs to be within 1mm of nominal

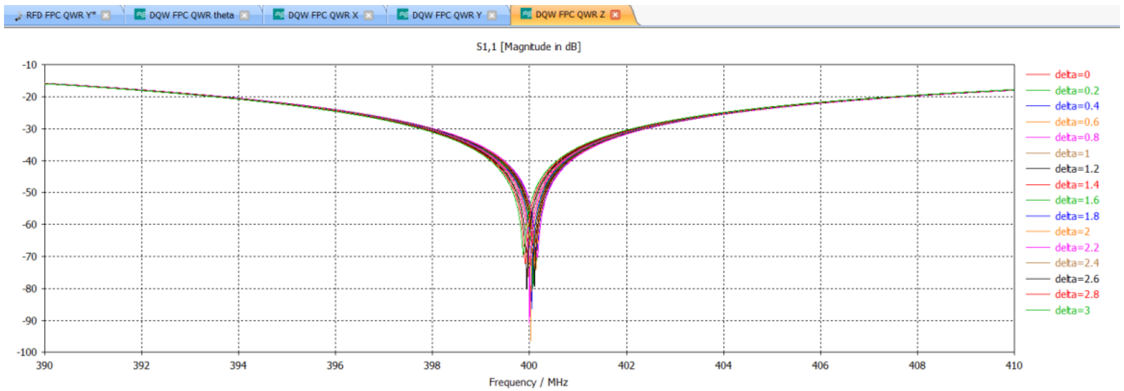
High Luminosity LHC

DQW Hook Position (Transmission)



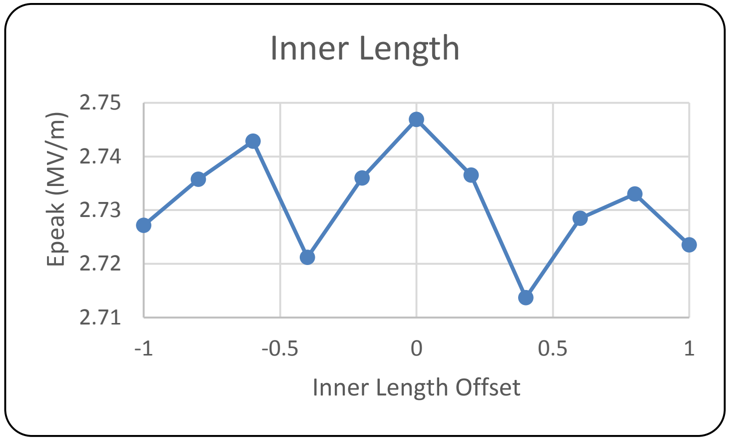
Y:

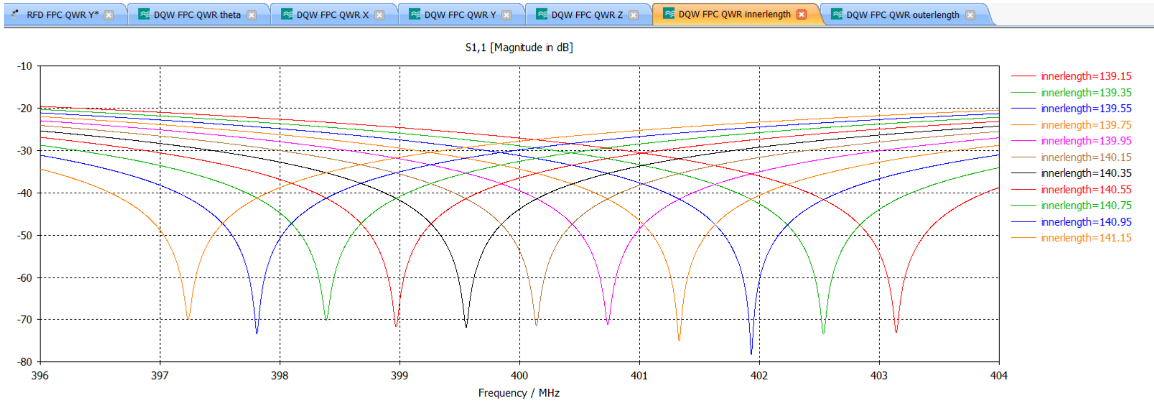
Needs to be within 0.4mm to keep -30dB over ±0.5MHz



Z:

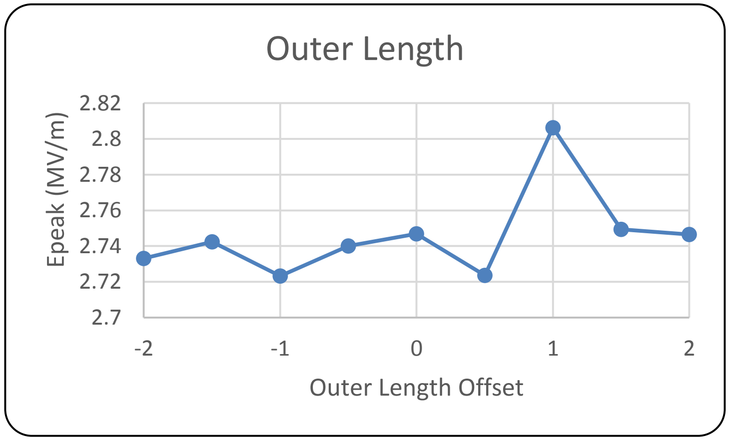
DQW QWR Dimensions

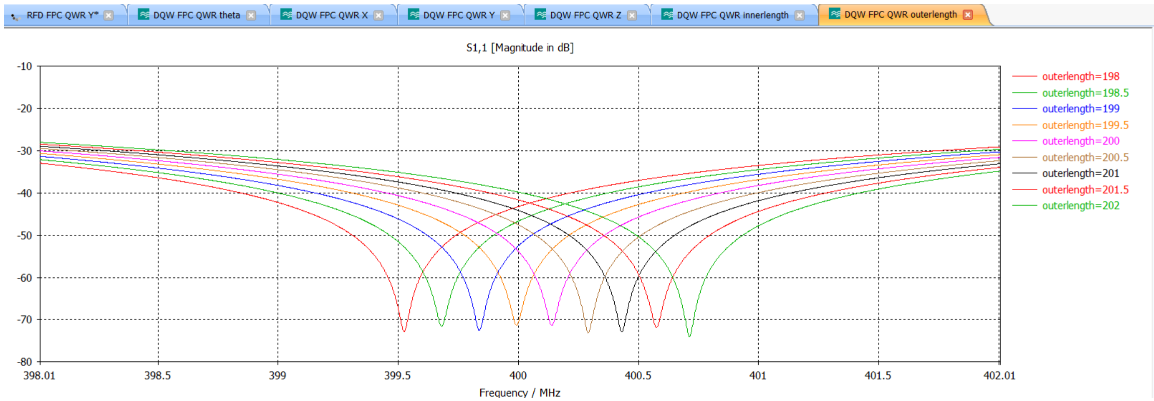




Inner:

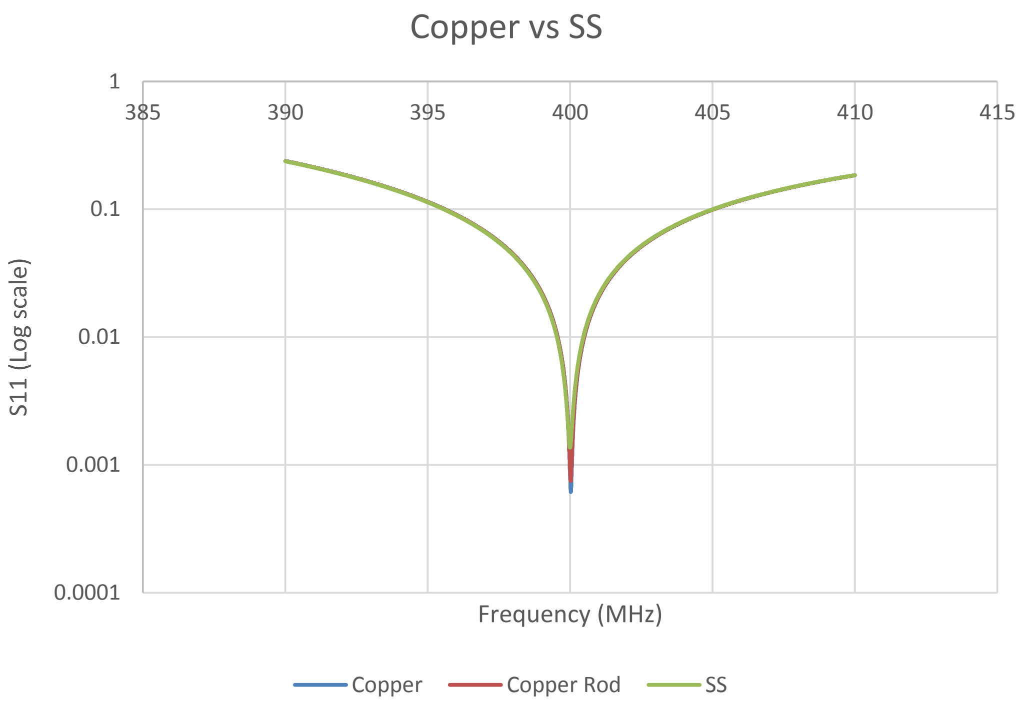
Still have S11<-30dB at 400MHz with inner length 0.6mm from nominal value





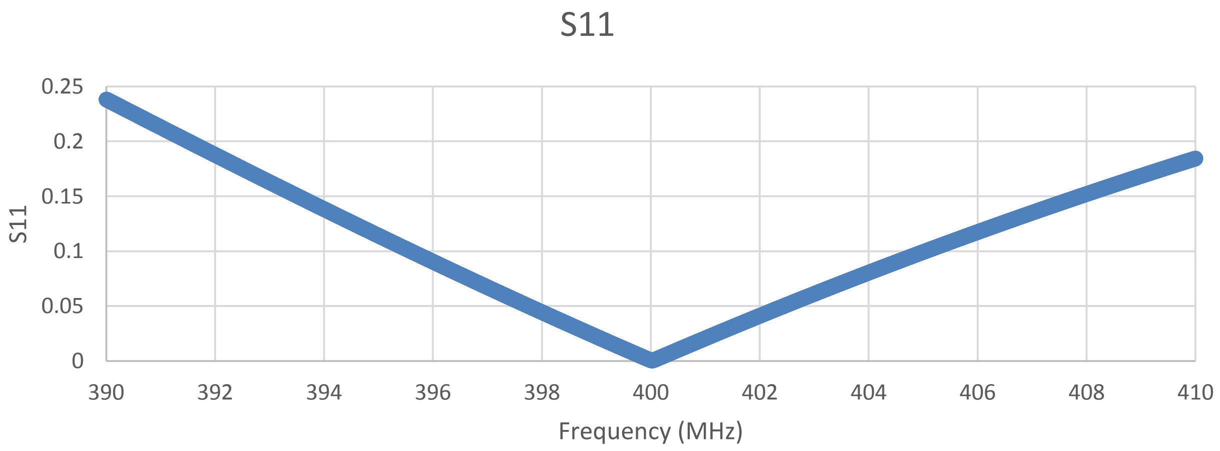
Outer:

DQW SS vs Copper



	Peak Field (MV/m)
Copper	2.703132
Copper Rod	2.690658
SS	2.805031

RFD Nominal



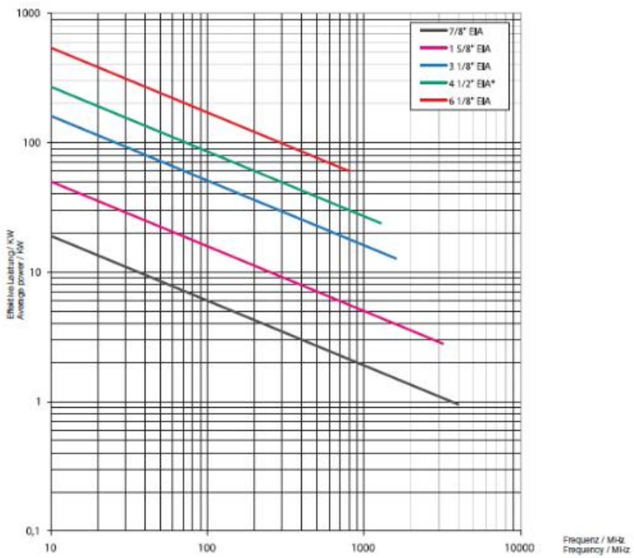
Epeak = 2.850504 MV/m

Transmission lines

SPINNER || BROADCAST

KABELSTECKVERBINDER
CABLE CONNECTORS

Maximale Anschlussleistung
Maximum Power rating



*339 IEC 50-105

Alle Leistungsangaben beziehen sich auf das angegebene Stecksystem bei +40 °C Umgebungstemperatur und einer Innenleitertemperatur von +120 °C.

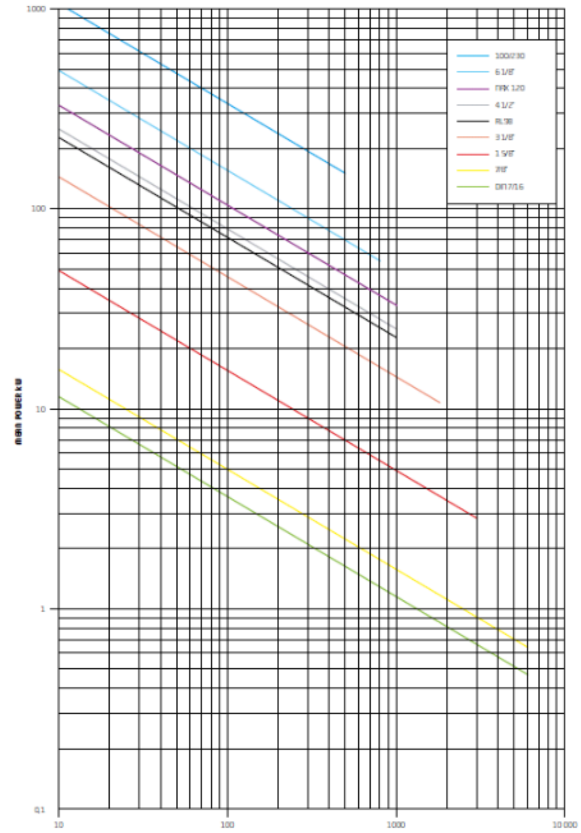
Achtung:
Die Höhe der übertragbaren Leistung kann durch das am Steckverbinder montierte Kabel reduziert werden.

All power ratings apply to the according connector system at +40 °C ambient temperature with an inner conductor temperature of +120 °C.

Note:
The power rating may be reduced by the cable attached to the connector.

Power Rating

Data based on: Ambient T=40°C, Inner T=120°C



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