800 MHz HOM coupler simulations

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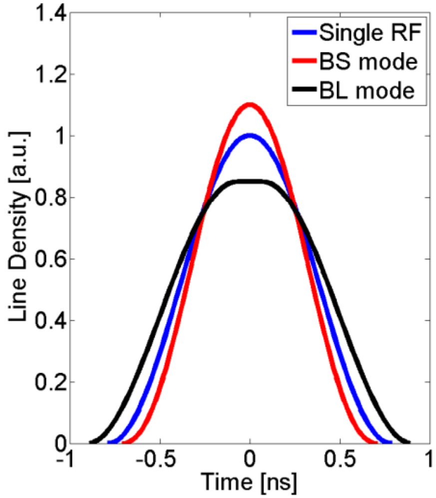
Motivation

800 MHz 2nd harmonic RF system

- In conjunction with 400 MHz Main RF system
- Instrument to enable:
  - Increase (high intensity) beam stability threshold: increasing <u>synchrotron frequency spread</u> to avoid multi-bunch instabilities (Landau damping)
  - <u>Bunch profile shaping:</u> BS (BL)
- Relatively small system (BS)



Motivation

Many good reasons to have this system:

- Short bunches (F. Zimmermann et al., 2002, S. Fartoukh, 2011)
- Flat long bunches (F. Zimmermann et al.)
- Increase beam stability (T. Linnecar, E. Shaposhnikova, 2007)
- Reduce beam induced heating and e-cloud effect (C. Bhat et al., 2011)
- Reduce IBS effect and beam losses on FB (T. Mertens, J. Jowett, 2011)
- Decrease of luminosity pile-up density (S. Fartoukh, R. Tomas)

(E. Shaposhnikova, 4th Joint HiLumi LHC-LARP Annual Meeting 2014)

(Juan F. Esteban Müller, R. Calaga, E. Shaposhnikova, Lower or higher harmonic RF system in the LHC, Joint LIU / HL-LHC meeting, 15/10/2015)

From HiLumi LHC-LARP Annual Meeting 2014

T. Roggen et Al.

Conclusions:

- RF Cavity: RF design optimized for 800 MHz HH system
- HOM couplers: Hook and (Probe) tuned to 800 MHz specs
- Power requirements:

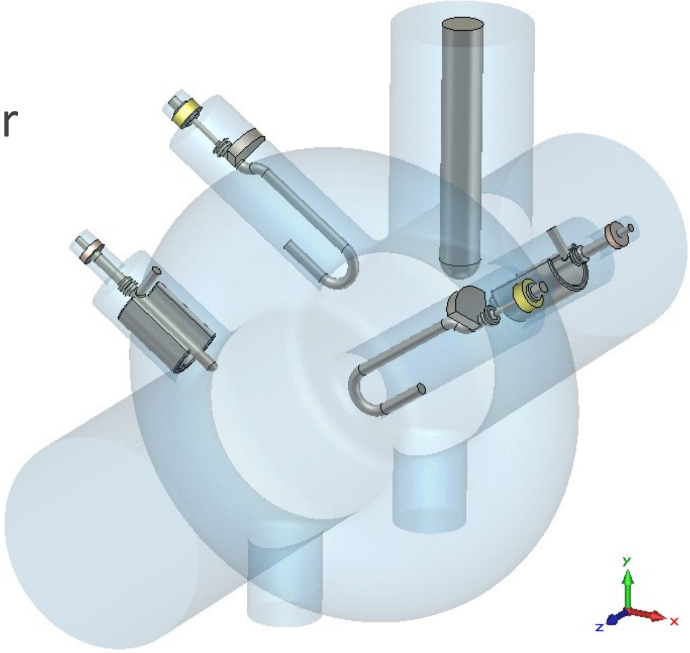
Full detuning	BL optimisation	BS optimisation
P_{BL}	300 kW	-
P_{BS}	180 kW	60 kW

- Power coupler: Fixed & > 300 kW (= challenge)
- Power sources: TBD (Klystrons, IOT's)
- Cavity layout: # 10 cells / beam (if BL), spacing ≈2λ (⟷ 10 m)
- Heat load: 35 W/cavity (4.5 K)

High Luminosity LHC

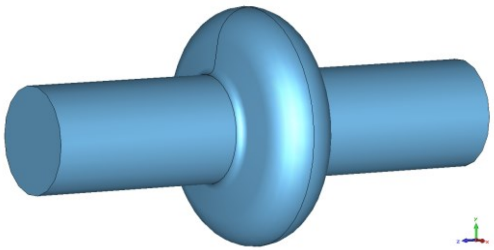
Outline

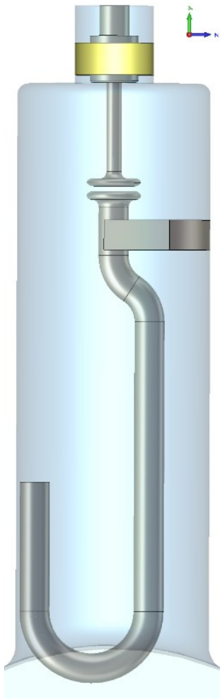
- Motivation
- Higher Order Modes
- HOM couplers
- Coupler mounting aspects
- Estimate on beam induced HOM power
- Trapped and coupled modes
- Prototype cavity layout & Cryomodule
- Conclusions & outlook



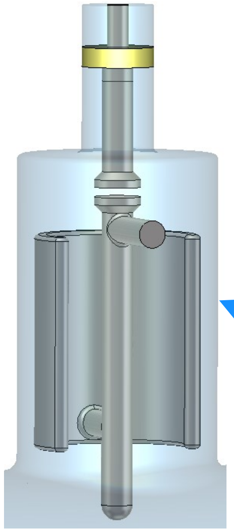
Higher Order Modes

Bare cavity





Hook type coupler



Probe type coupler

Below cut-off

Propagating

Mode	f [MHz]	R/Q$_{\|\|}$ [Ω]	R/Q$_{\perp}$ [Ω/m]	Angle [°]
TM_{010}	801.4	45	≈ 0	-
TE_{111}	1047	0.2	2.3	0 + 90
TM_{110}	1087	1.4	13.6	0 + 90
TM_{210}	1488	≈ 0	0.1	0 + 45
TE_{211}	1541	≈ 0	≈ 0	0 + 45
TM_{020}	1616	3.1	0.1	-
TM_{011}	1630	24	0.2	-
…	…	…	…	…

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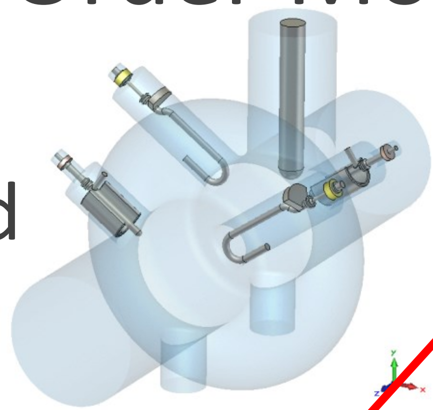
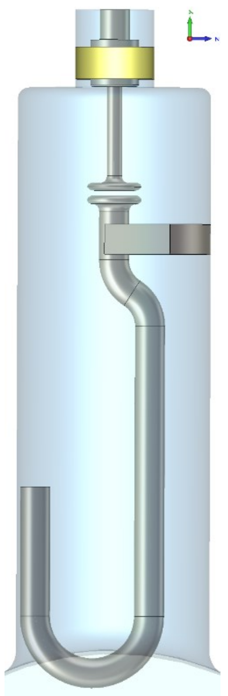
Higher Order Modes

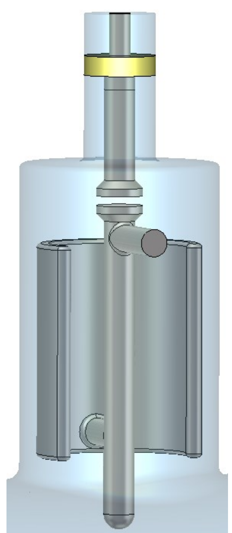
Dressed





Hook type coupler

TE11 in beam pipe



Probe type coupler

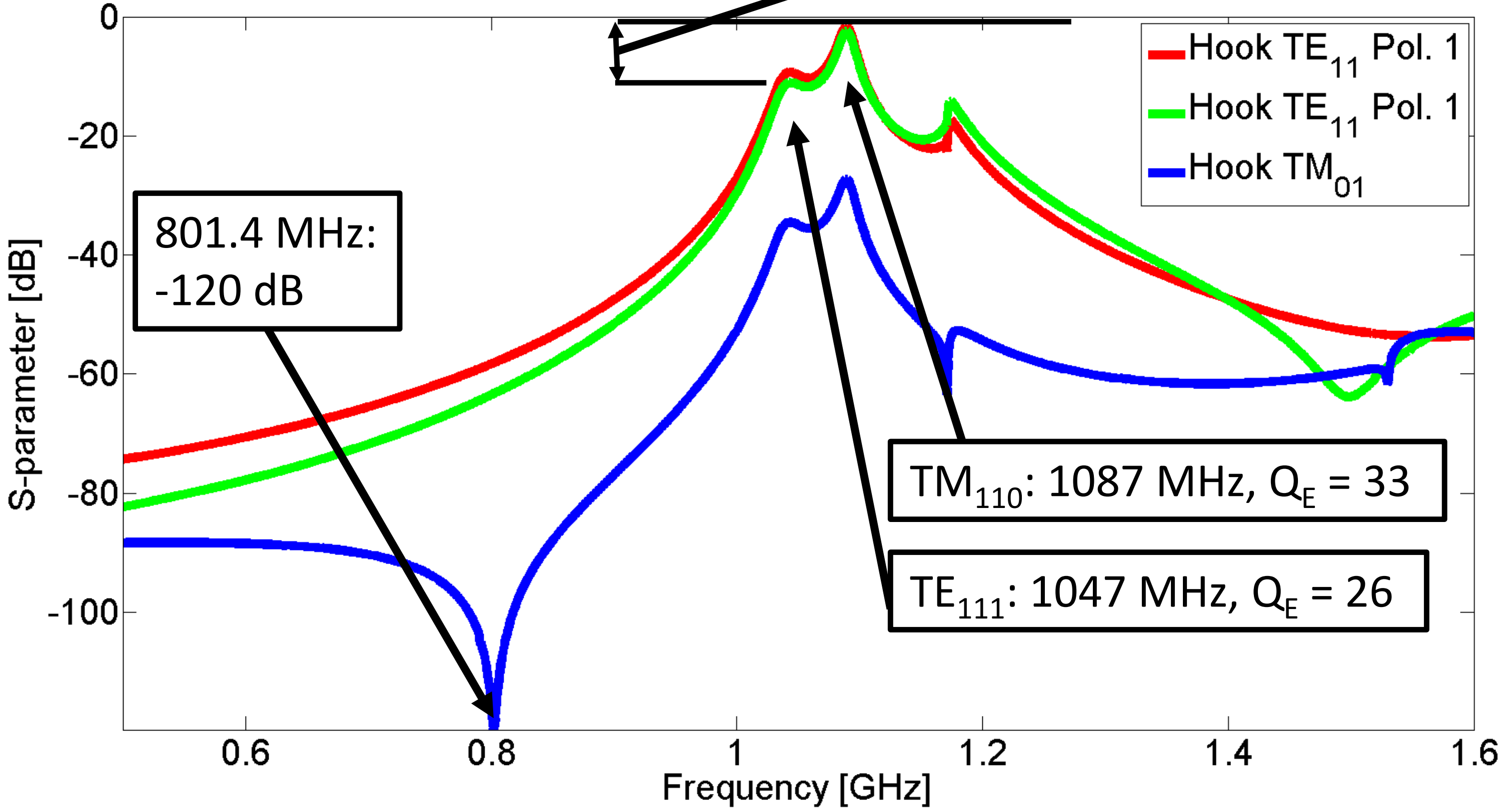
Mode	f [MHz]	$R/Q_{\|\|}$ [Ω]	$R/Q_{\perp}$ [Ω/m]	Q_E
TM_{010}	801.4	**45**	≈ 0	12e4
TE_{111}	1017.6	1.4	**6.01**	7800
	1030.0	0.9	**3.174**	121
TM_{110}	1060.7	1.3	**5.72**	373
	1075.1	1.0	**9.70**	373
	1098.6	0.5	**2.13**	205
	1101.5	0.4	**3.74**	241
TM_{210}	1485.5	0.03	**0.126**	3040
	1486.9	0.04	**0.09**	2030
TE_{211}	1521.5	0.1	**0.5**	1420
	1541.2	0.3	**0.2**	1420
TM_{020}	1592.9	**18.6**	0.3	32
	1616.1	**13.4**	0.2	32
	1668.6	**3.19**	0.2	7

(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

Hook type:

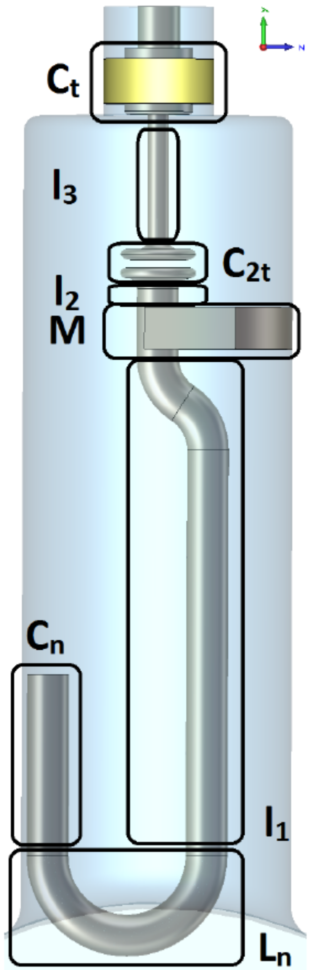
$$\frac{(R/Q)_{TE111}}{(R/Q)_{TM110}} = \frac{2.3}{13.6} = \text{-7 dB}$$



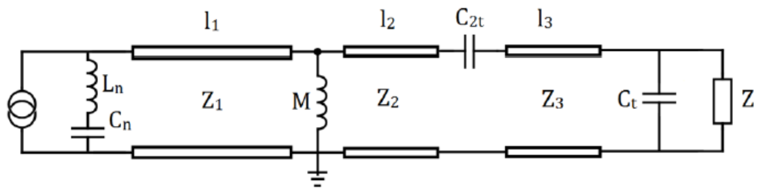
(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

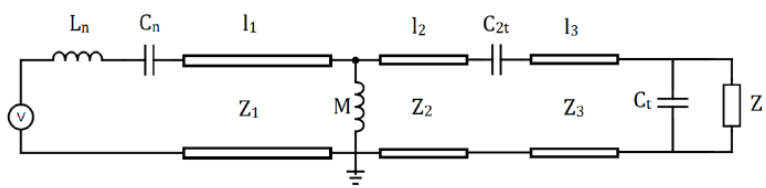
Hook type:



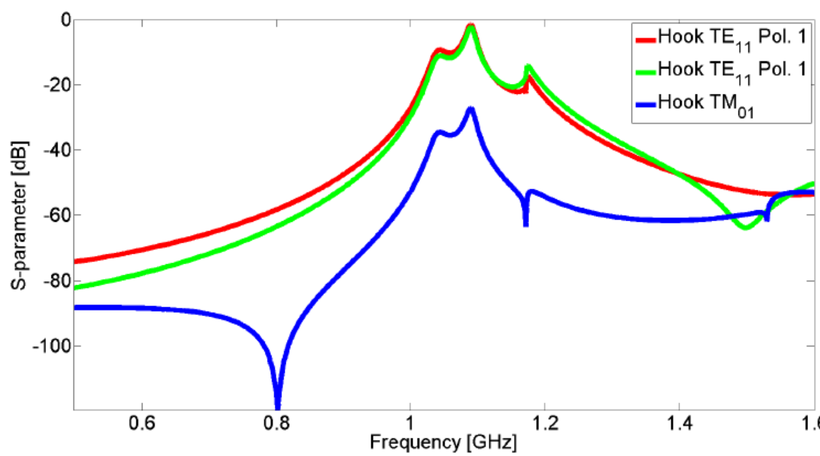
(a)



(b)



(c)



(d)

Tuning procedure:

- Equivalent circuit: Component optim. based on S_{21}
- 3D model
- Fine tuning

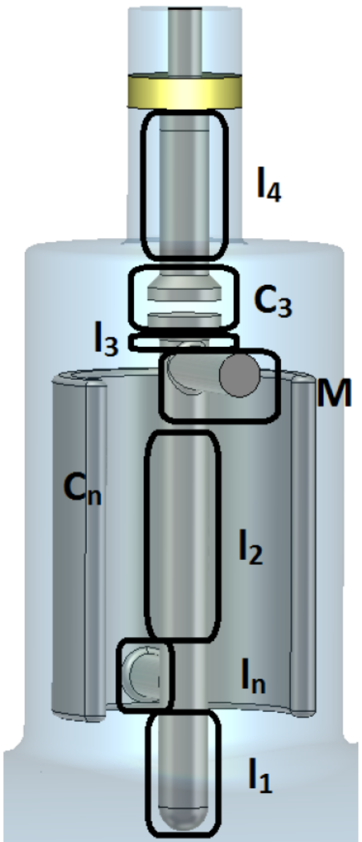
TE_{111} $Q_E = 26$

TM_{110} $Q_E = 33$

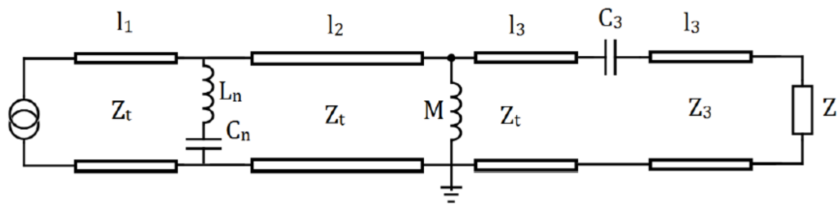
(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

Probe type:



(a)



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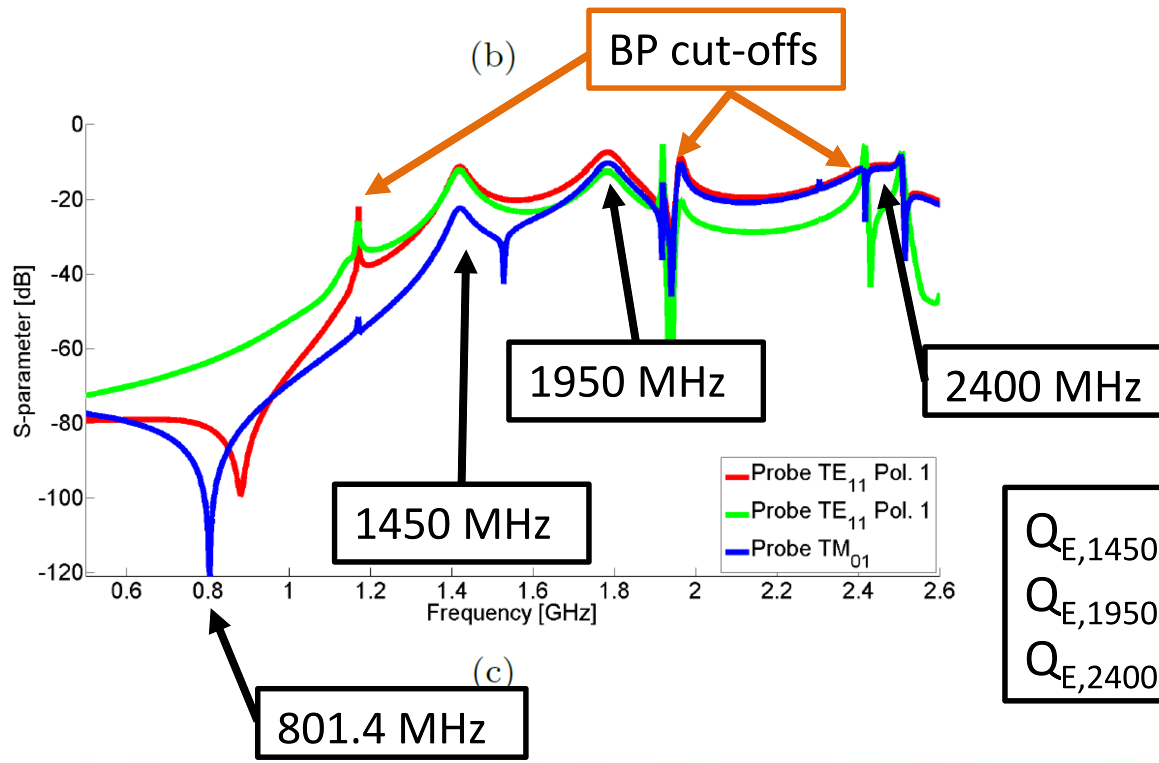


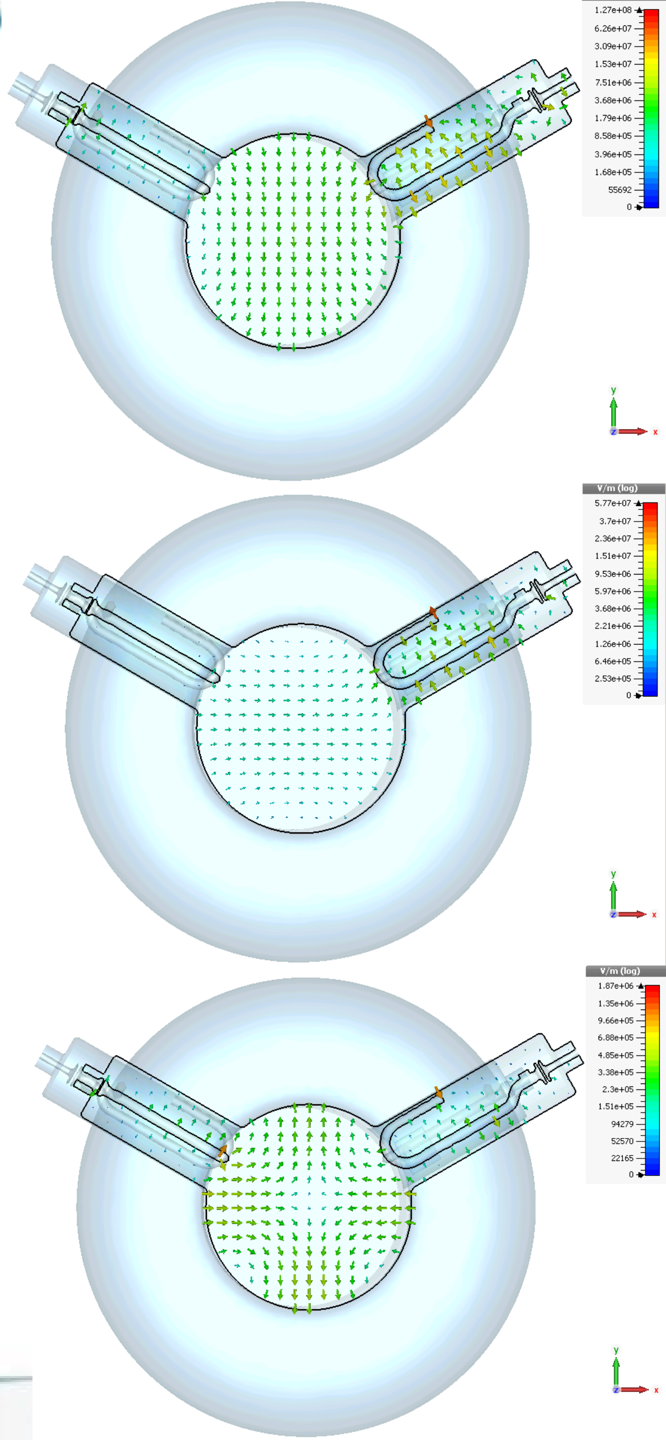
(c)

$Q_{E,1450} = 21$
$Q_{E,1950} = 14$
$Q_{E,2400} = 7$

HOM couplers: Mounting aspects

Installation angle on beam pipe

- Upper half restriction: Helium cooling
- In beam pipe: TE_{111} and $TM_{110} \rightarrow TE_{11}$
- Two polarisations each, and ⊥
- Asymmetry introduced by HOM + FPC enforces 0° and 90°
- 45° seems obvious choice
- But inefficient for higher HOMs



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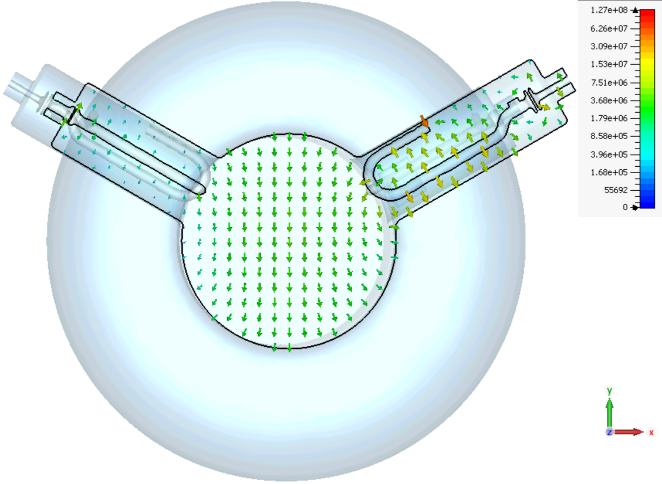
HOM couplers: Mounting aspects

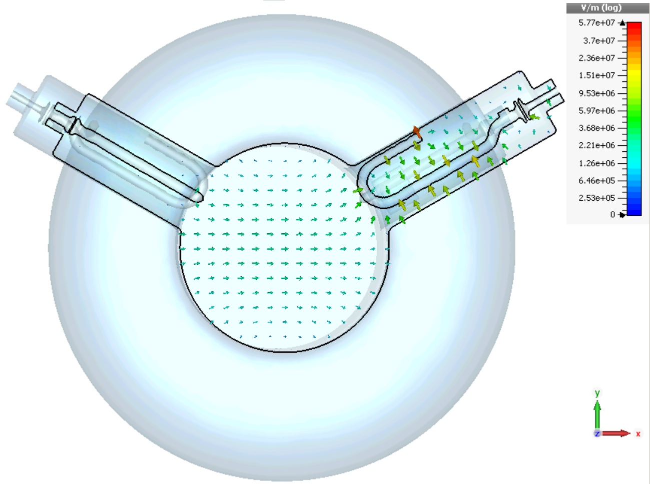
Installation angle on beam pipe

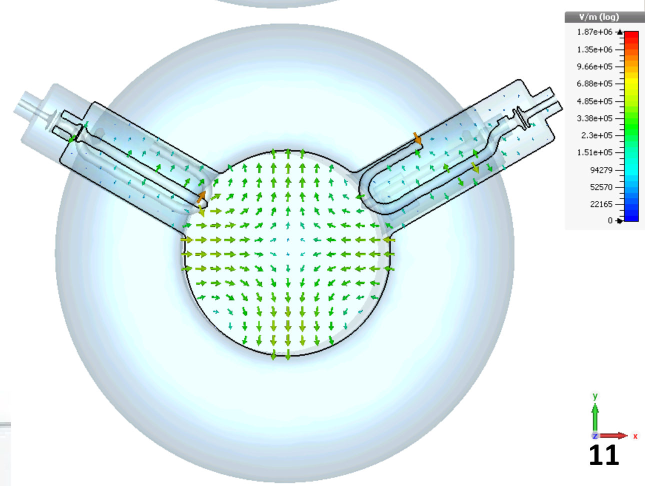
- Different “optimum angle” algorithms could be thought of:
  - $\overline{\phi} = 55°$
  - $\overline{\phi\, R/Q} = 55.6°$
  - $\overline{\phi\, (R/Q)\, d\mathbf{E}/d\phi} = 45.3°$
  - …

→ Conservative:

$\phi = 55°$ for good overall coupling

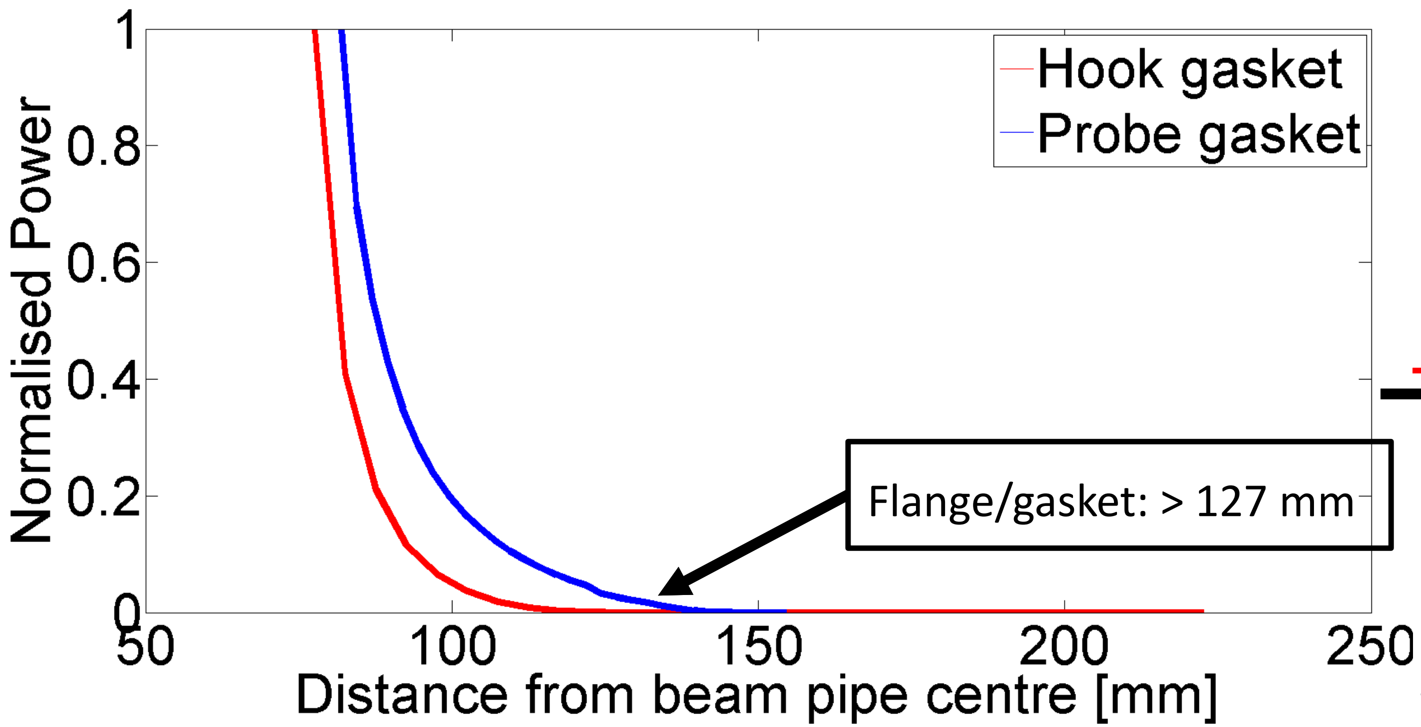


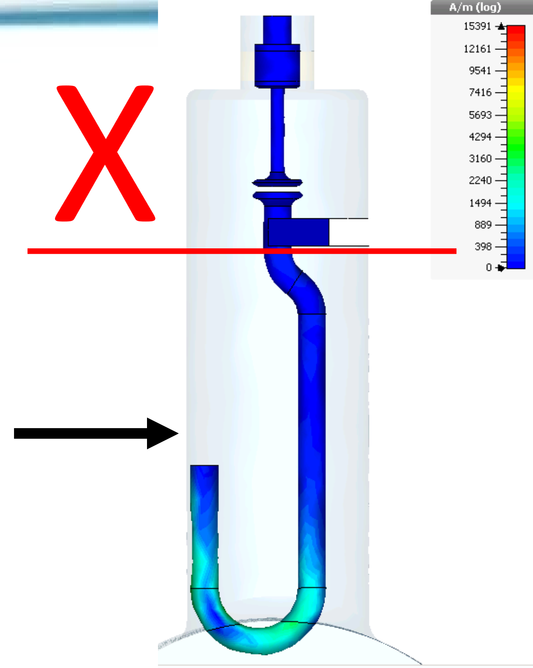


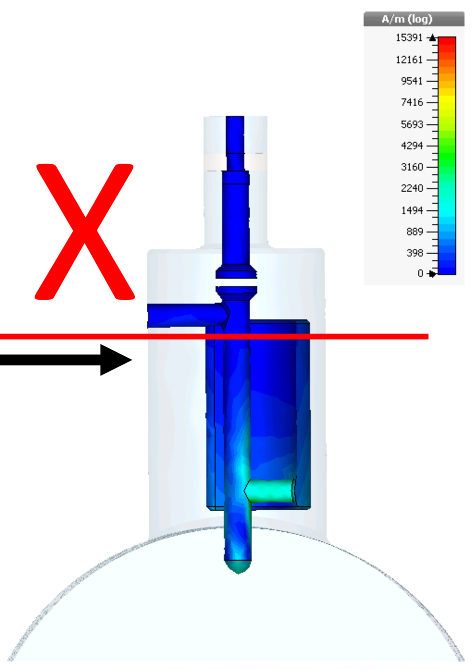


HOM couplers: Mounting aspects

- Vacuum flange: Allow dismounting
- Low wall current region (shorted FM)
- $P_{gasket, hook} = 0.1$ mW | $P_{gasket, probe} = 1.4$ mW



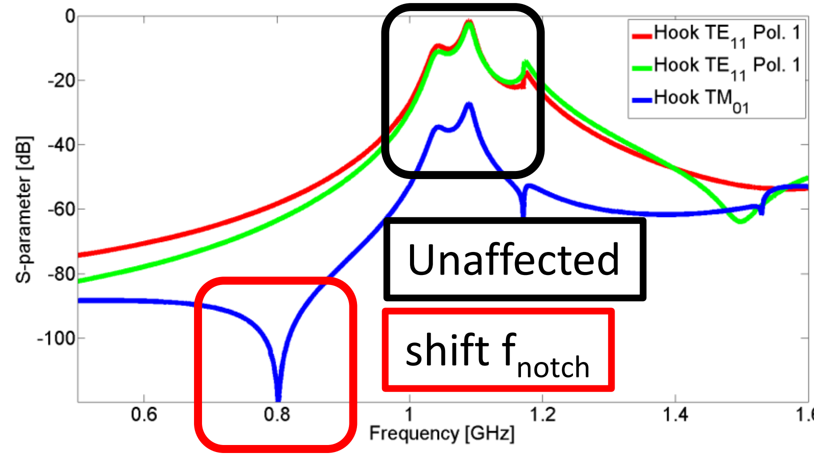


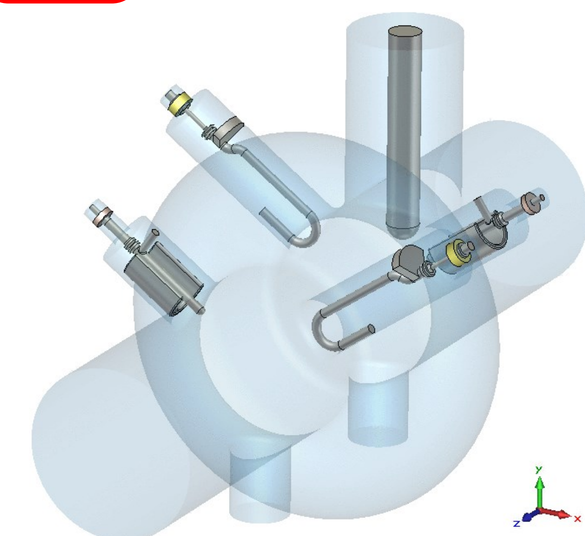


HOM couplers: Mounting aspects

Position of the hook/probe:

- For optimal coupling: See drawings: ⊥
- In practice: (To avoid confusion)
  - Notch tuning by rotation is possible





HOM couplers: Mounting aspects

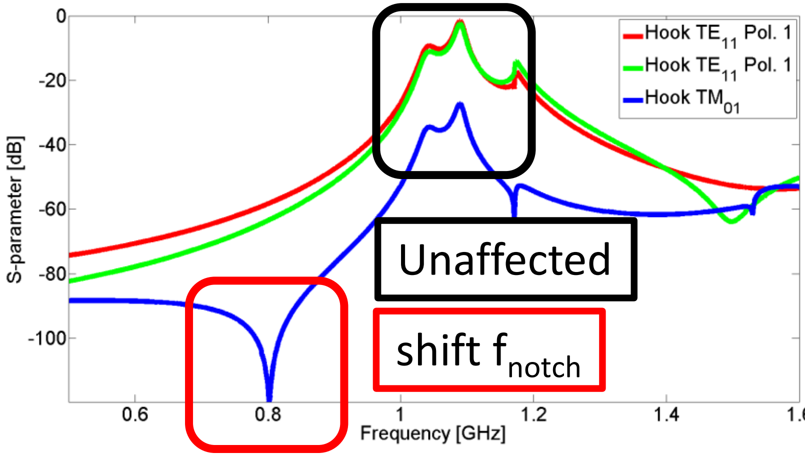
Position of the hook/probe:

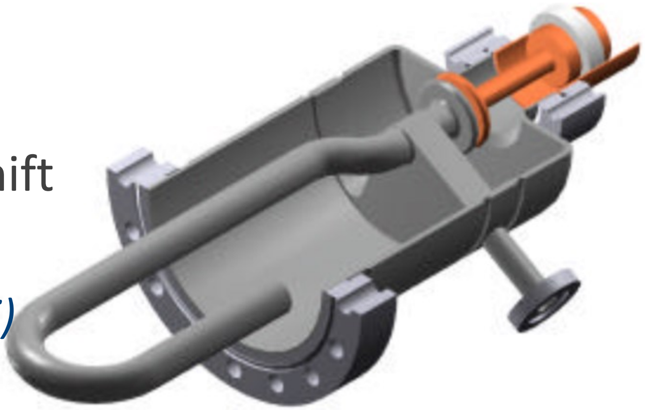
- For optimal coupling: See drawings: ⊥
- In practice: (To avoid confusion)
  - Notch tuning by rotation is possible, but
  - Precision in required Δf_{notch} << Δf bolt pattern shift

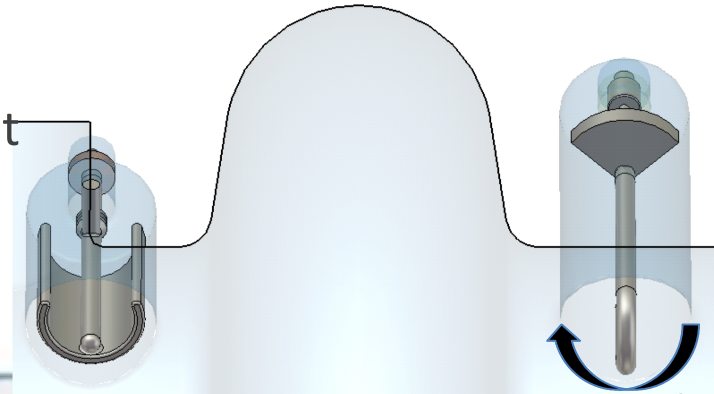
  (22.5° vs. 25 MHz / 50 MHz (probe/hook) per 5°)

  (L. Ficcadenti)
  - → Flange not connected to coupler
  - → Independently rotatable flange
  - Mount → Measure → Rotate → clamp gasket

  → sub-degree mounting precision







High Luminosity LHC

Estimate on beam induced HOM power

HOM power to be extracted for baseline HL-LHC beams

(HL-LHC 25 ns std, HL-LHC 25 ns BCMS, HL-LHC 50 ns, Nom. LHC)

- Different methods implemented: [1, 2, 3, 4]

  - Subtleties in approach and mode excitation

- Benchmarked to 400 MHz ACS and LHC beam as in [1]

[1] Z.T.Zhao et al., "Estimation of the Higher-Order Mode Power in the 400 MHz Superconducting Cavities of the LHC", CERN SL/Note 97-10, CERN (1997).

[2] R. Calaga, B. Salvant, "Comments on Crab Cavity HOM Power", CERN ACC note 2015-0024, CERN (2015).

[3] H. Padamsee et al., *RF Superconductivity for Accelerators*, Weinheim: Wiley-VCH, 2008, 521.

[4] A.W. Chao, M. Tigner, *Handbook of accelerator physics and engineering*, Hackensack: World Scientific, 2013, 802.

High Luminosity LHC

Estimate on beam induced HOM power

HOM power to be extracted for baseline HL-LHC beams

- Applied to 800 MHz with different beam line spectra
  - Each HOM f falls on a resonance ← **Worst case**
  - Each HOM f falls in between two resonances
  - Realistic beam spectrum

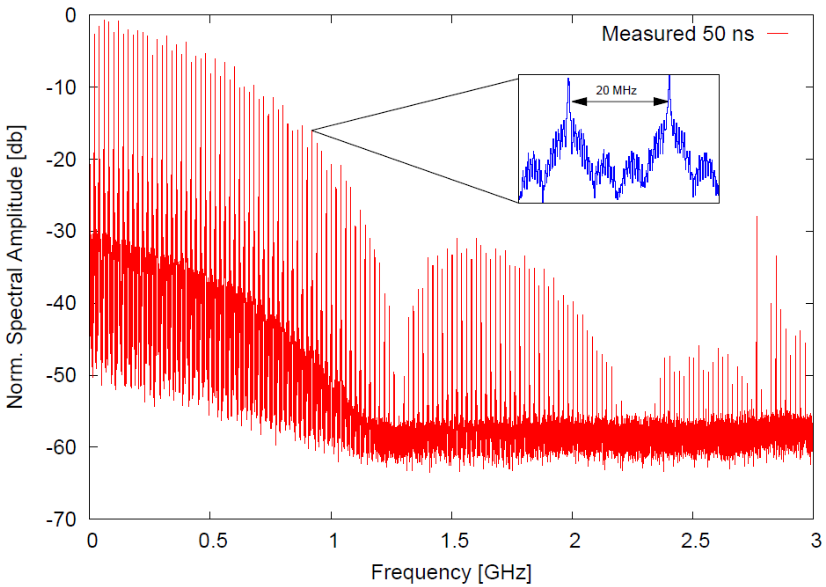
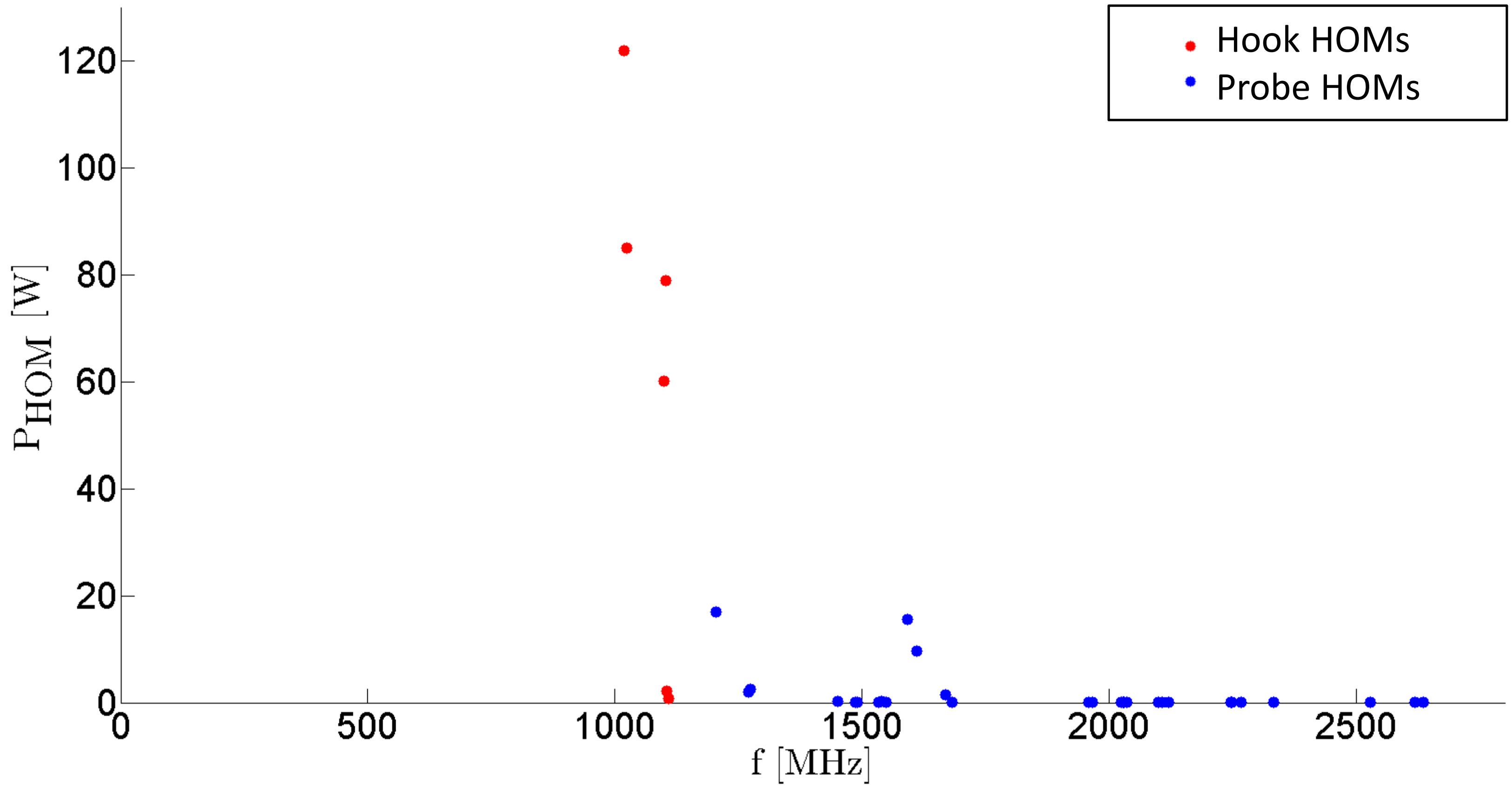


Image courtesy: R. Calaga

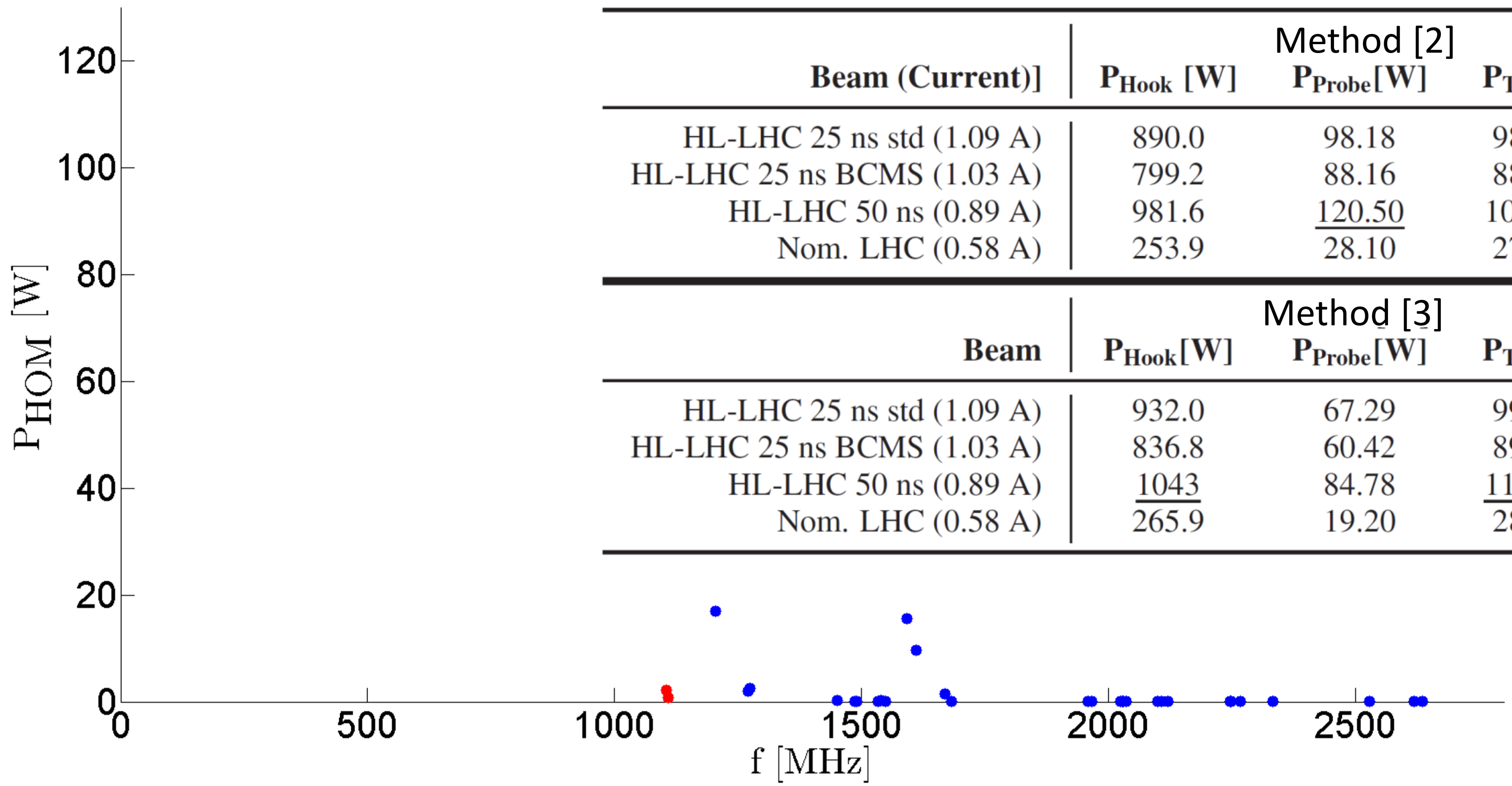
Estimate on beam induced HOM power

Worst case scenario: Each HOM f falls on a resonance



Estimate on beam induced HOM power

Worst case scenario: Each HOM f falls on a resonance



Beam (Current)]	P_{Hook} [W]	P_{Probe} [W]	P_{Tot} [W]
	Method [2]		
HL-LHC 25 ns std (1.09 A)	890.0	98.18	988.18
HL-LHC 25 ns BCMS (1.03 A)	799.2	88.16	887.36
HL-LHC 50 ns (0.89 A)	981.6	120.50	1092.10
Nom. LHC (0.58 A)	253.9	28.10	275.00
	Method [3]		
Beam	**P_{Hook}[W]**	**P_{Probe}[W]**	**P_{Tot}[W]**
HL-LHC 25 ns std (1.09 A)	932.0	67.29	999.29
HL-LHC 25 ns BCMS (1.03 A)	836.8	60.42	897.22
HL-LHC 50 ns (0.89 A)	1043	84.78	1127.80
Nom. LHC (0.58 A)	265.9	19.20	285.10

Estimate on beam induced HOM power

Worst case scenario: Each HOM f falls on a resonance

Hook-type: ≈ 2x 525W
Probe-type: ≈ 2x 60W

↔ Hardware limitations: 1 kW [1]

Method [2]

Beam (Current)]	P_{Hook} [W]	P_{Probe} [W]	P_{Tot} [W]
HL-LHC 25 ns std (1.09 A)	890.0	98.18	988.18
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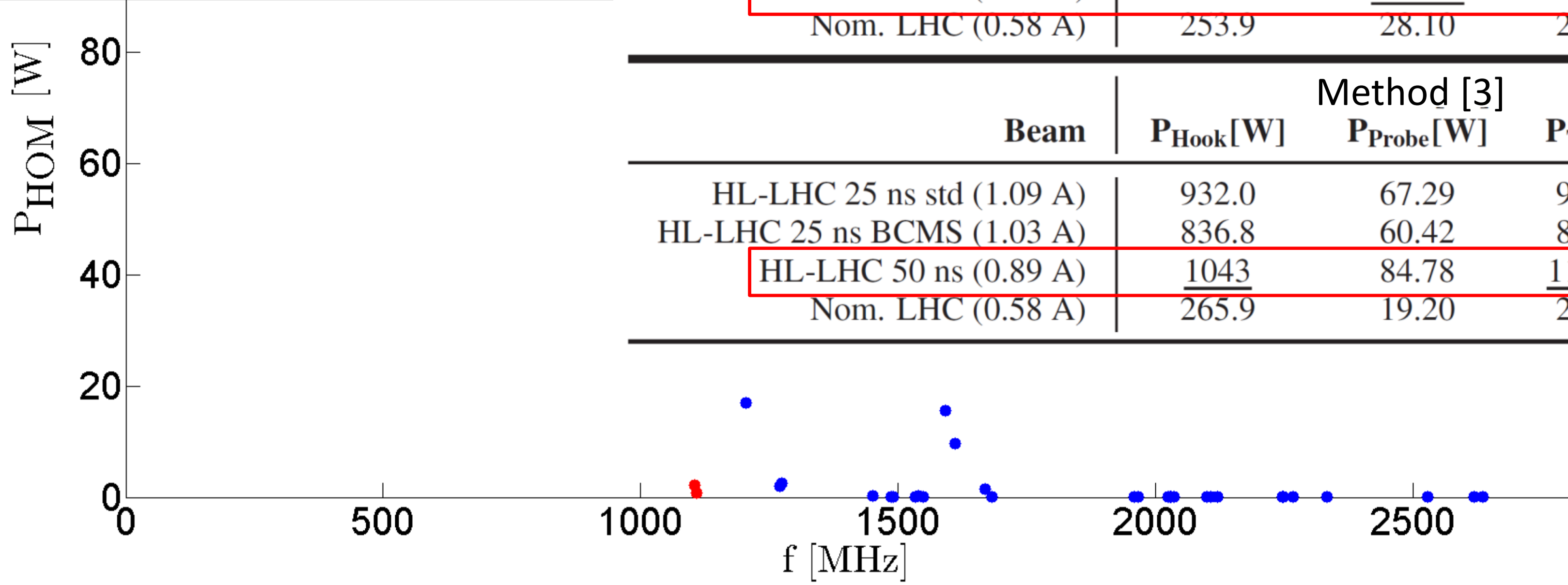
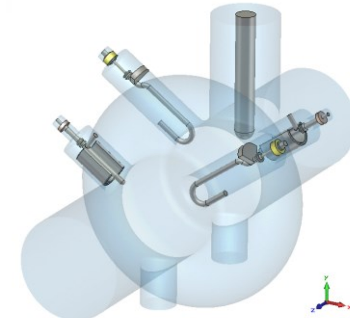


HOM couplers: Trapped modes



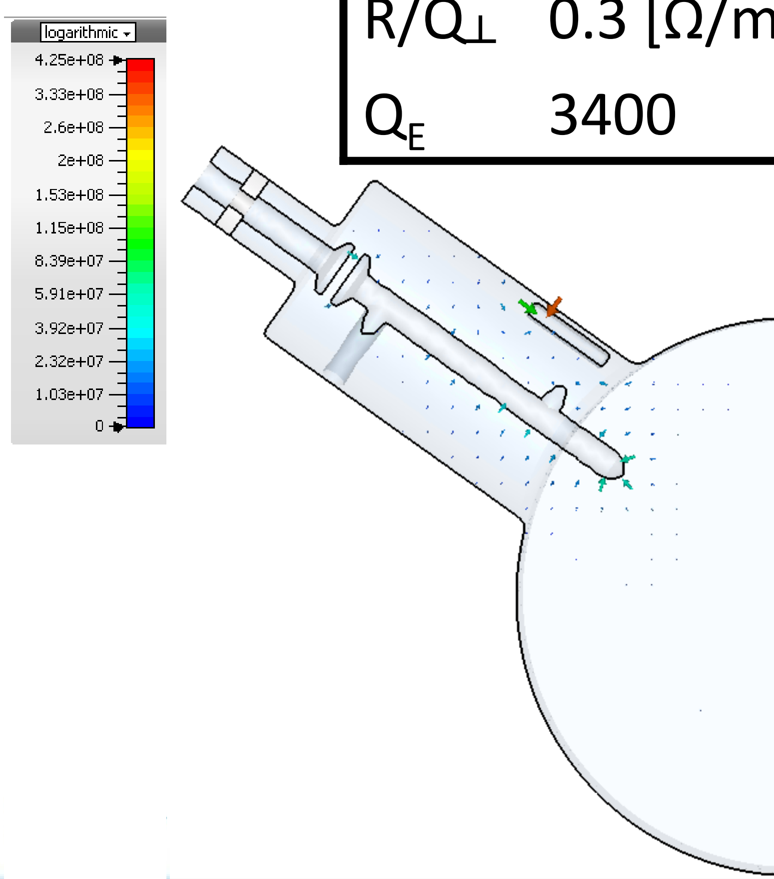
Trapped modes in the coupler structure

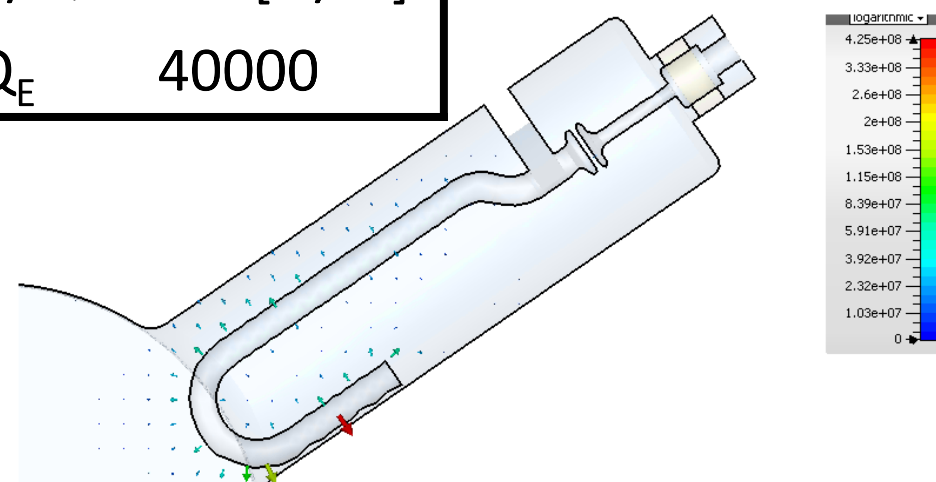
Probe

f	264 MHz
R/Q⊥	0.3 [Ω/m]
Q_E	3400

Hook

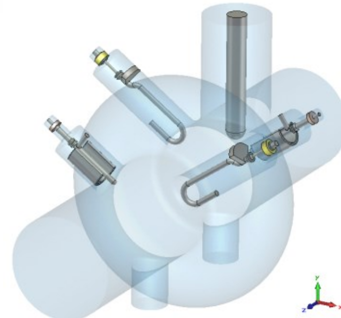
f	320 MHz
R/Q⊥	0.6 [Ω/m]
Q_E	40000





- Field component near beam axis nearly zero
- Equivalent trapped modes present in 400 MHz design
- Some additional He consumption if excited: To be quantified

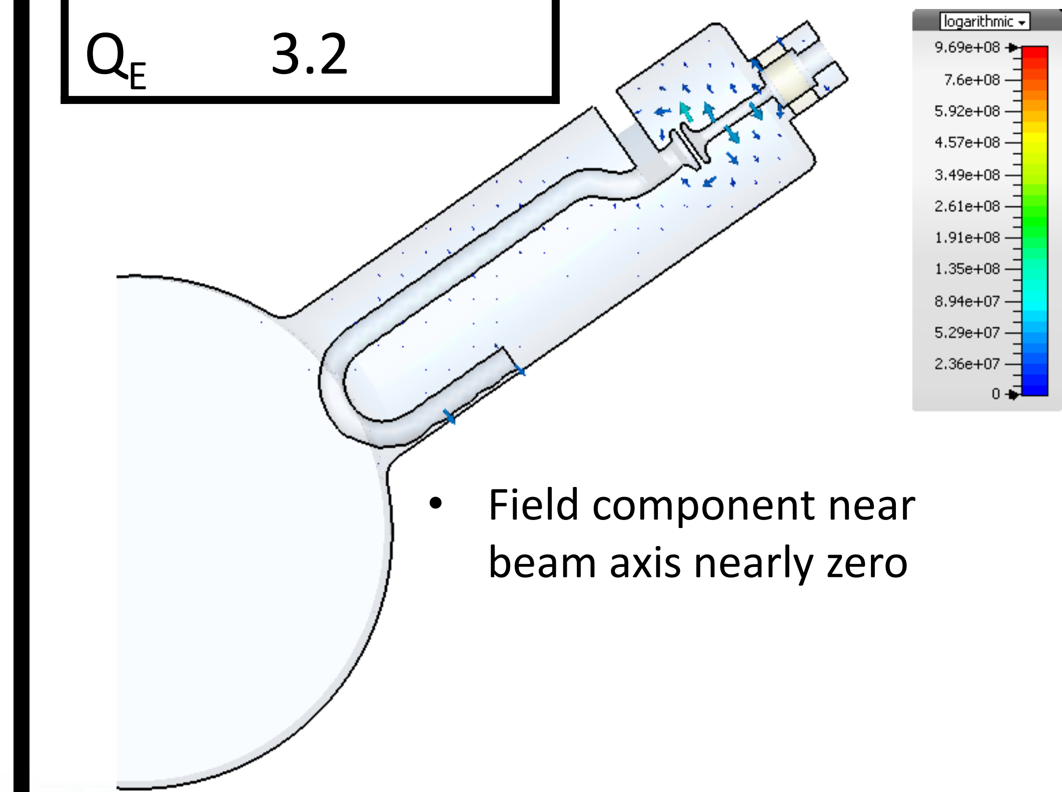
HOM couplers: Trapped modes



Trapped modes in the coupler structure

f	915 MHz
$R/Q_{\perp}$	≈ 0 [Ω/m]
Q_E	3.2

Hook



- Field component near beam axis nearly zero

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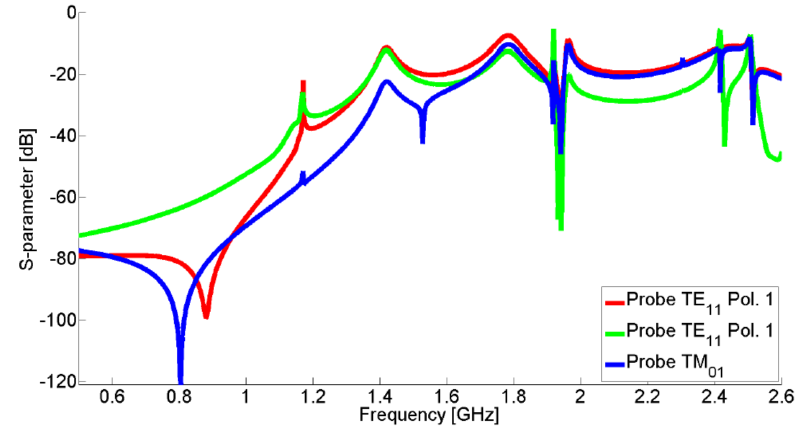
HOM couplers: Trapped modes

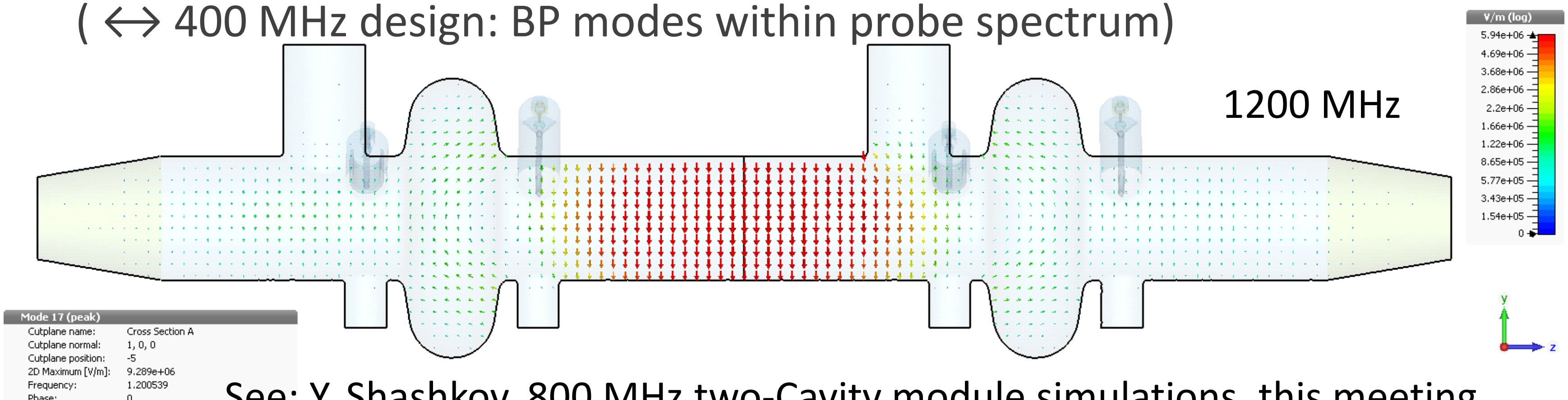
Coupled modes in the beam pipe for two-cavity module:

- 1200-1280 MHz
- Possibly harmful
- Not detectable in single cavity
- Outside probe coupler bandwidth

(↔ 400 MHz design: BP modes within probe spectrum)



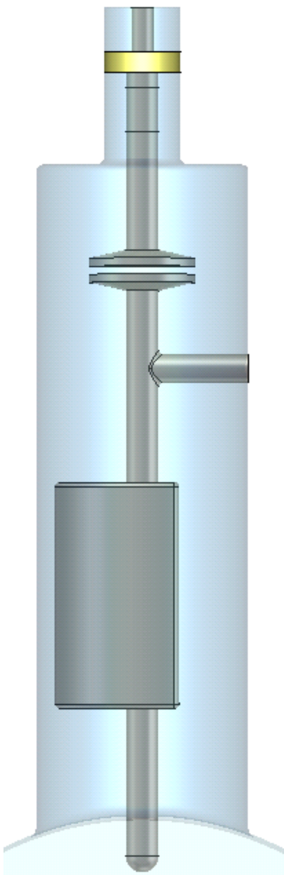
1200 MHz



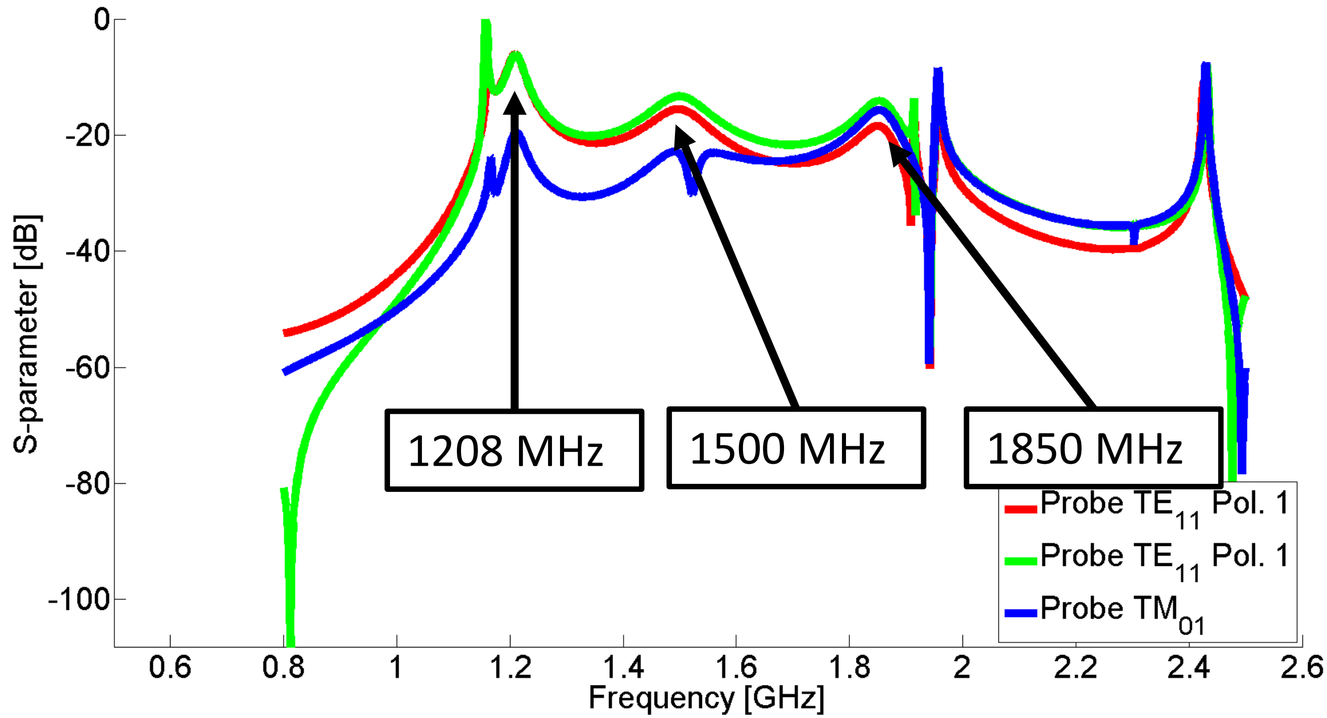
See: Y. Shashkov, 800 MHz two-Cavity module simulations, this meeting

HOM couplers: Trapped modes

Coupled modes in the beam pipe for two-cavity module:

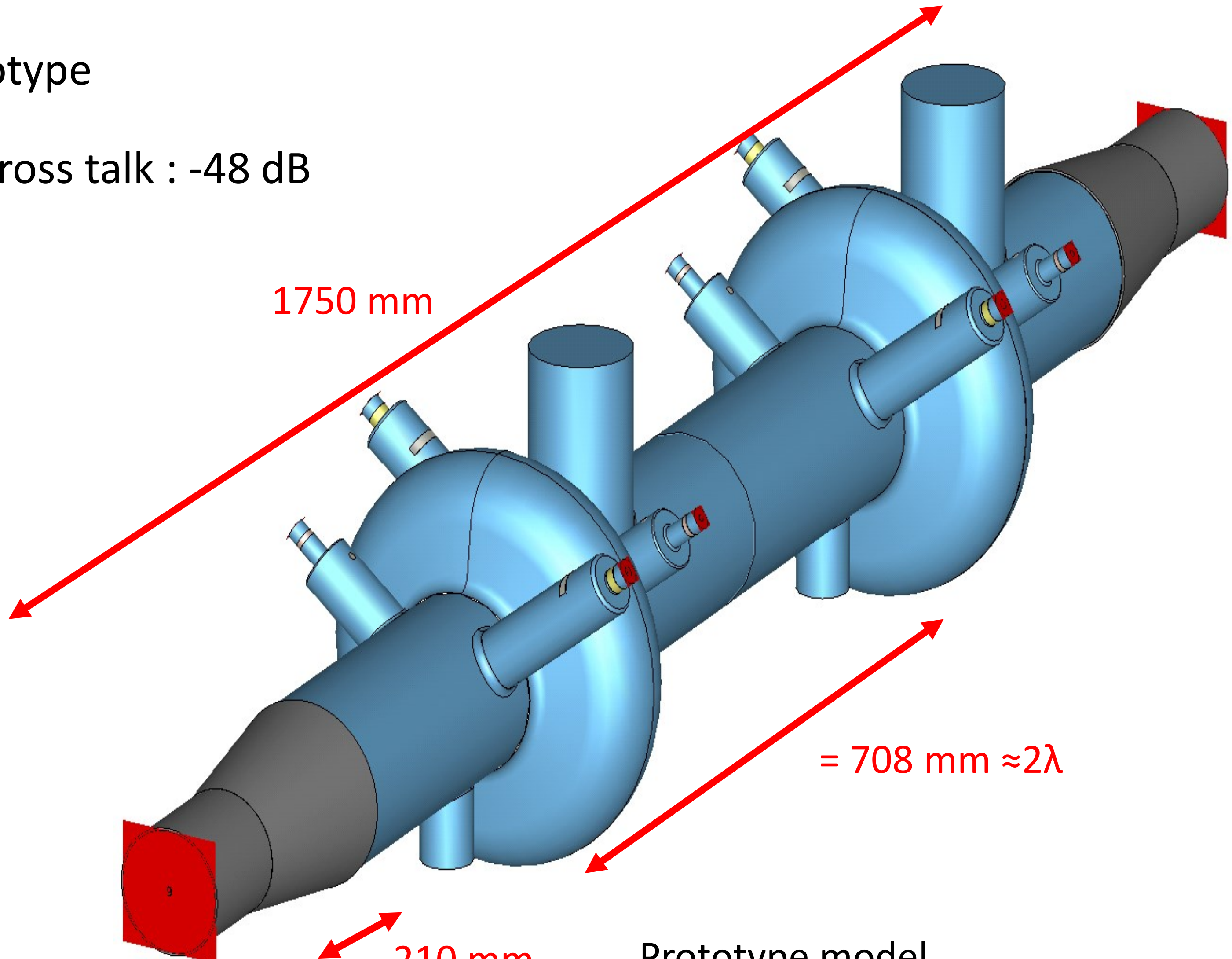


Probe coupler transmission adapted



Prototype cavity layout

- Two-cell prototype
- ≈ 2λ spacing cross talk : -48 dB

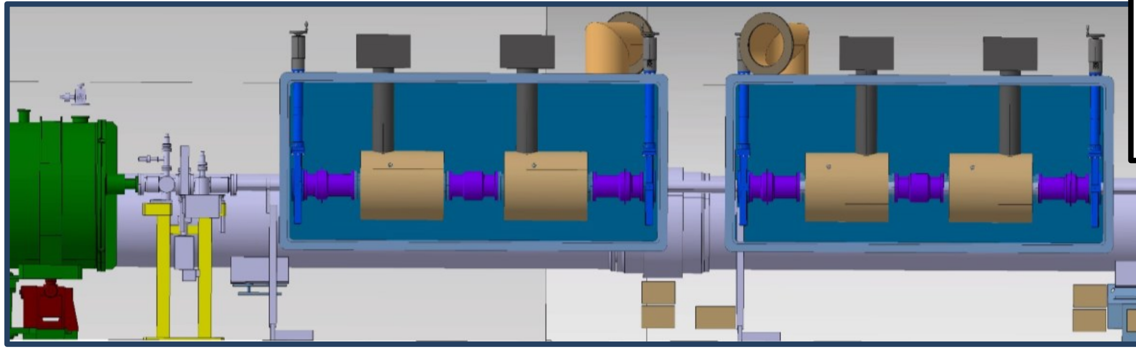


Prototype model

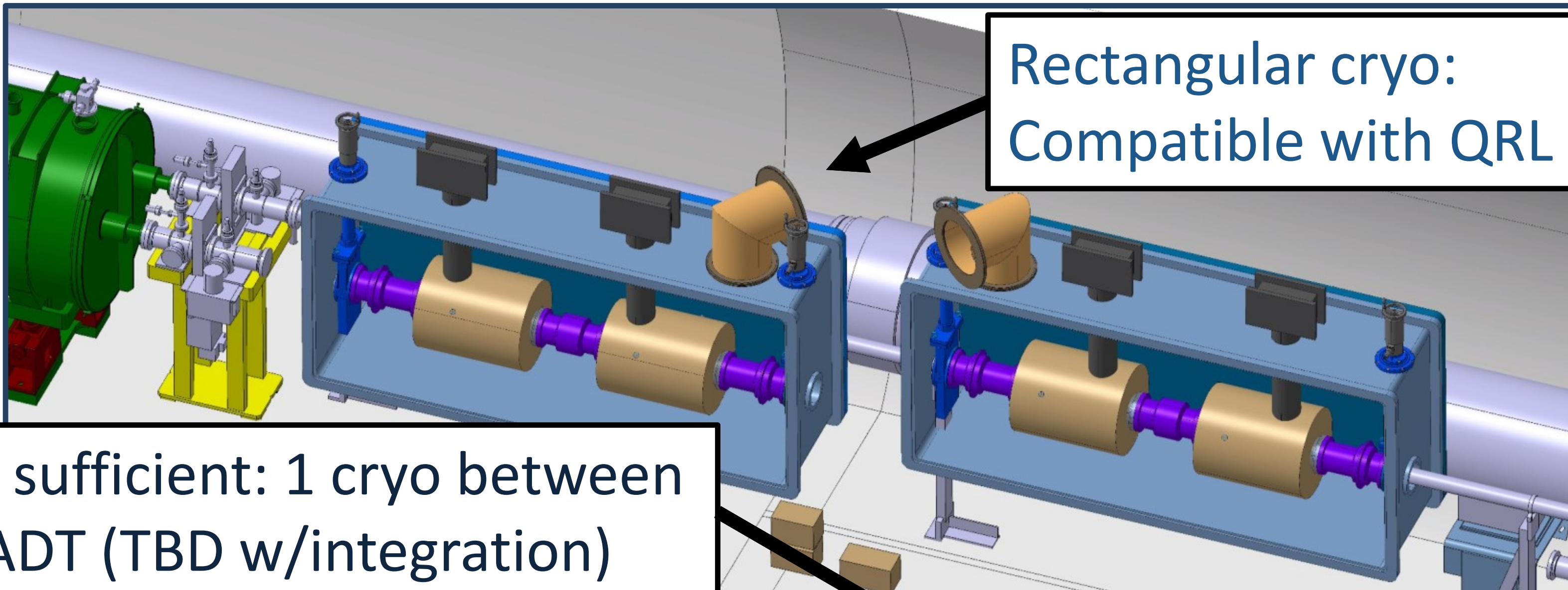
Preliminary cryomodule integration at IR4

C5L4
(Left side)

Exact longitudinal position TBD with RF power

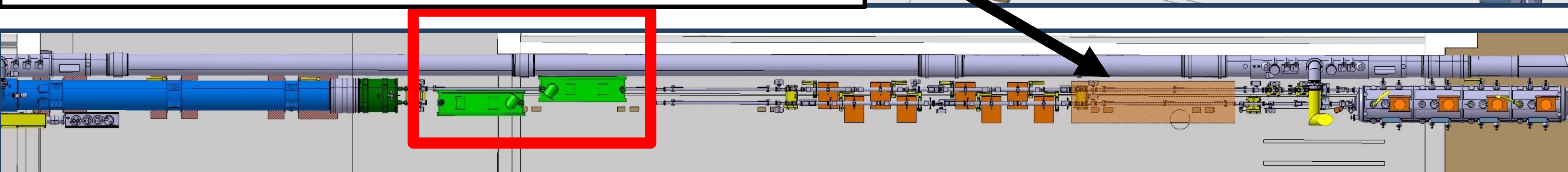


Based on Crab cavity cryo



Rectangular cryo: Compatible with QRL

When 4 MV sufficient: 1 cryo between ACS-400 & ADT (TBD w/integration)



(Courtesy: G. Villiger, O. Capatina)

Conclusions & outlook

Conclusions:

• HOM couplers:	HOM RF design in final stage Mounting: angle $\phi = 55°$, rotation $\perp$ BP Gasket: < 127 mm: $P_{Gasket} = 1.4$ mW Rotatable flange for notch tuning
• Estimated beam induced HOM power:	Hook: ≈ 525W, Probe: ≈ 60W (⟷ Hardware limit: 1 kW)
• Trapped modes (coupler):	Identified in hook and probe Considered harmless
• Coupled modes (BP):	Identified Potentially dangerous Probe coupler transmission spectrum changed to 1200 MHz
• Two-cell prototype:	Under study (see next presentation) Preliminary cryomodule integration study

Conclusions & outlook

Outlook:

- Mechanical design and cavity tolerances: fabrication tolerances (ongoing), Lorentz force detuning, microphonics
- Heat load studies including FPC, HOMs, different ports, gaskets etc
- Power coupler (fixed/variable) and consequences for injection, ramp and flattop
- HOM coupler multipacting (ongoing) and consequence on HOM damping & power extraction
- Alternative design for HOM coupler (hybrid version to reduce the number of HOM couplers, ongoing, see next presentation)
- Cavity/coupler failure scenarios
- Build prototype: 2-cavity 800MHz (Nb-Cu)
- FPC Power coupler design
- Operational challenges (Voltage program, sensitivity to phase errors)
- Cavity/RF system failure procedure

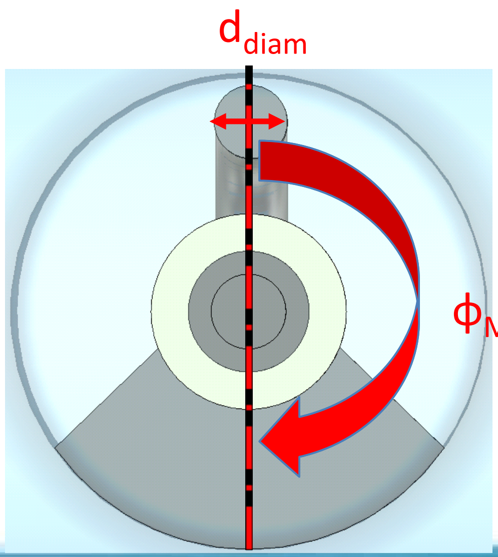
High Luminosity LHC

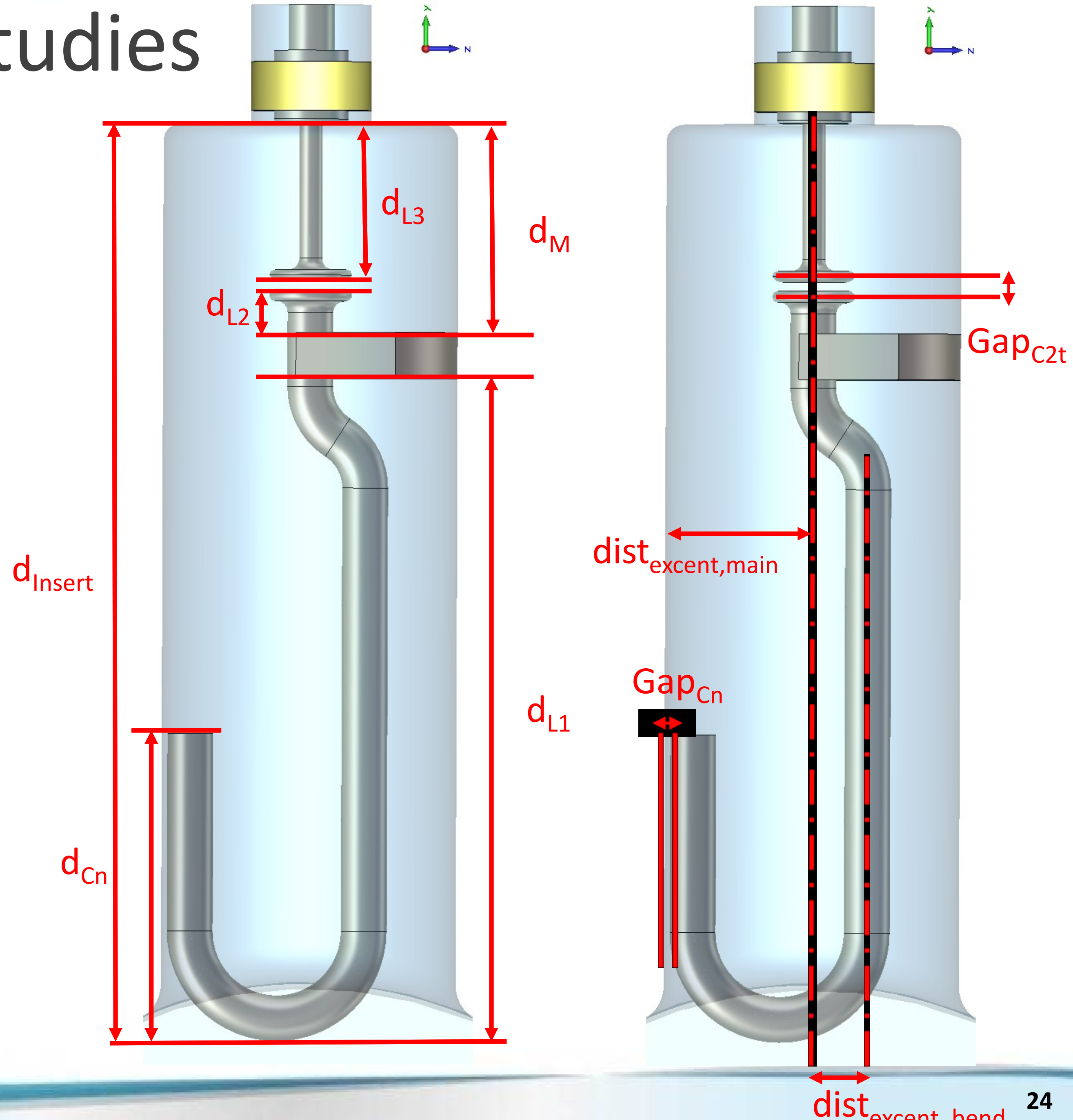
The HiLumi LHC Design Study is included in the High Luminosity LHC project and is partly funded by the European Commission within the Framework Programme 7 Capacities Specific Programme, Grant Agreement 284404.

Tolerance studies

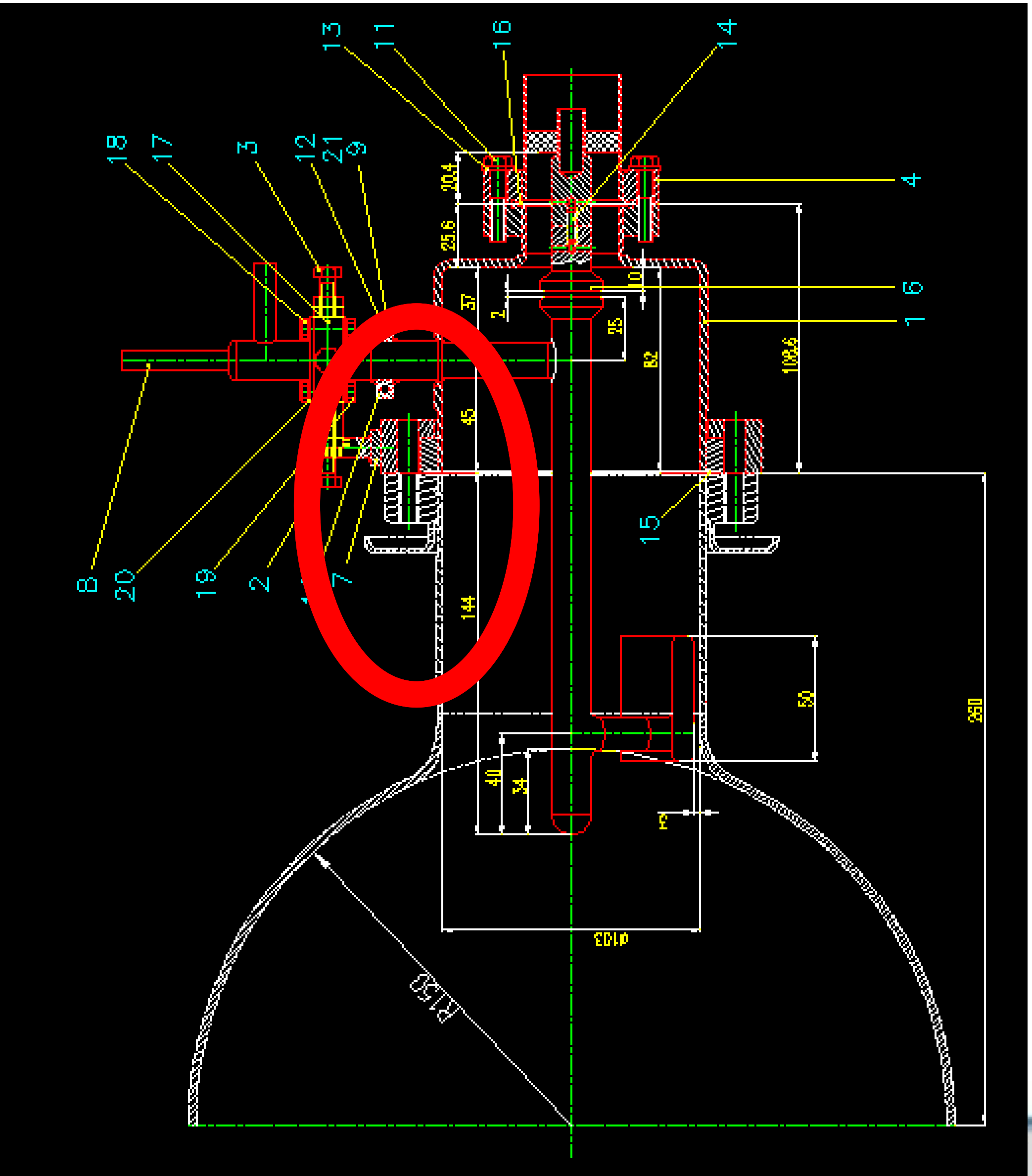
- RF cavity
- Hook coupler
- Probe coupler

→ Ongoing





Appendix



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25.6
37
10
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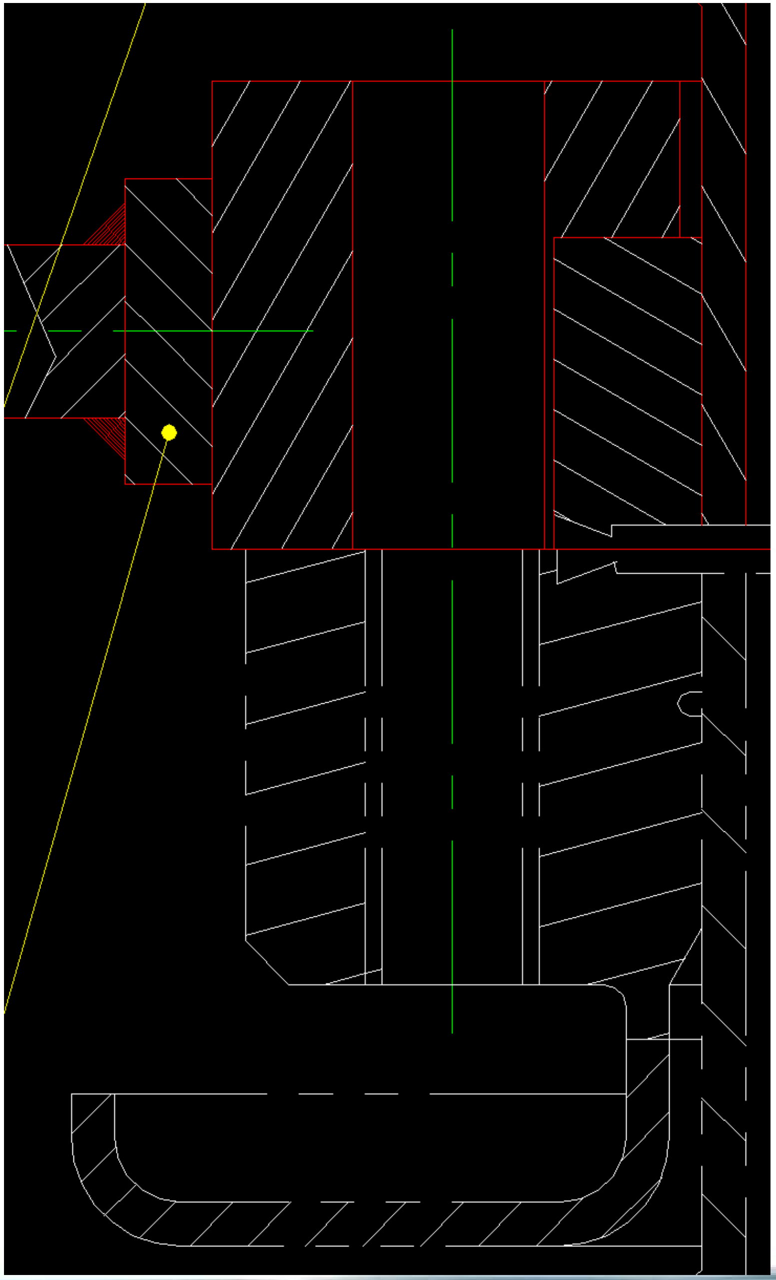
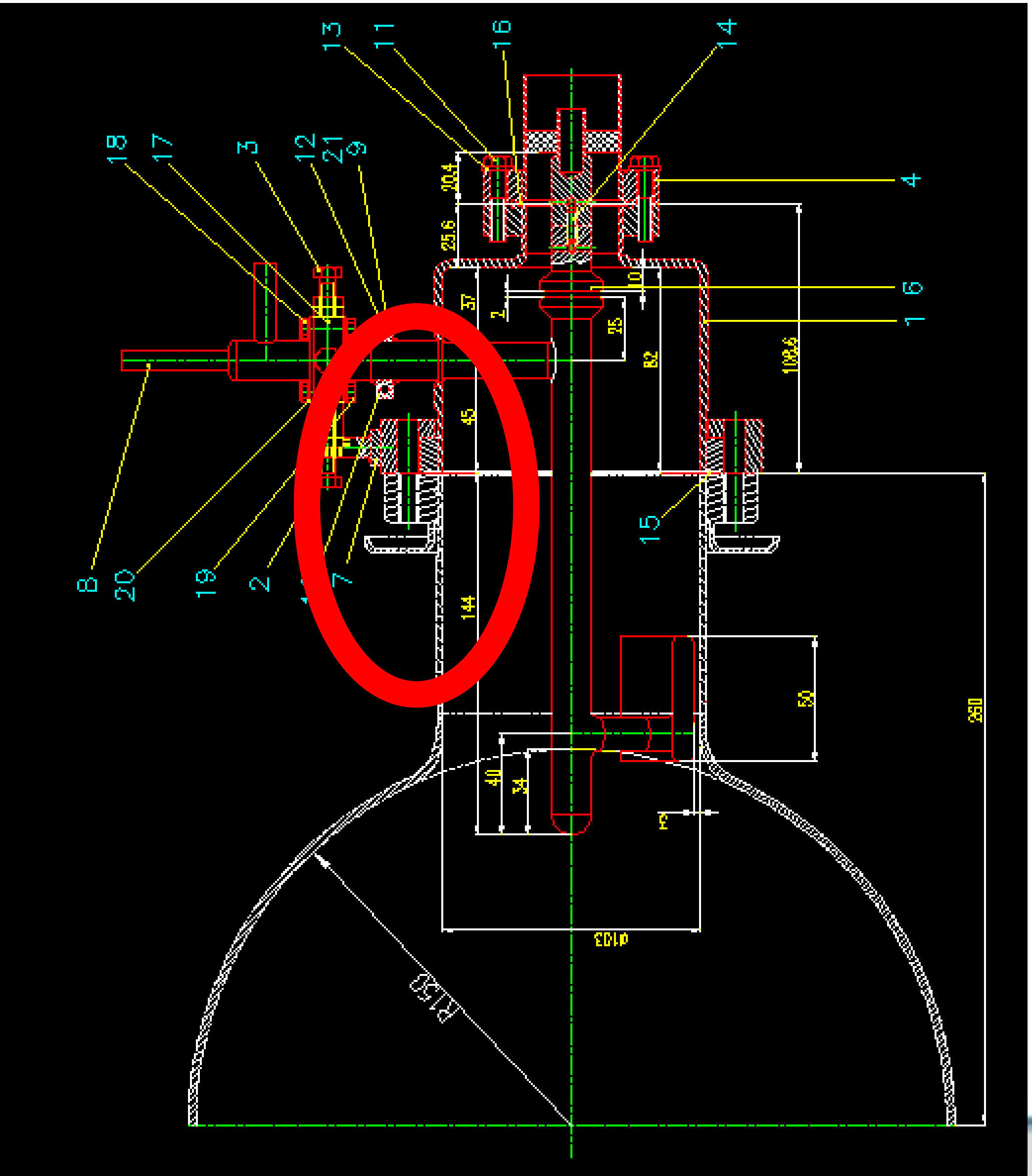
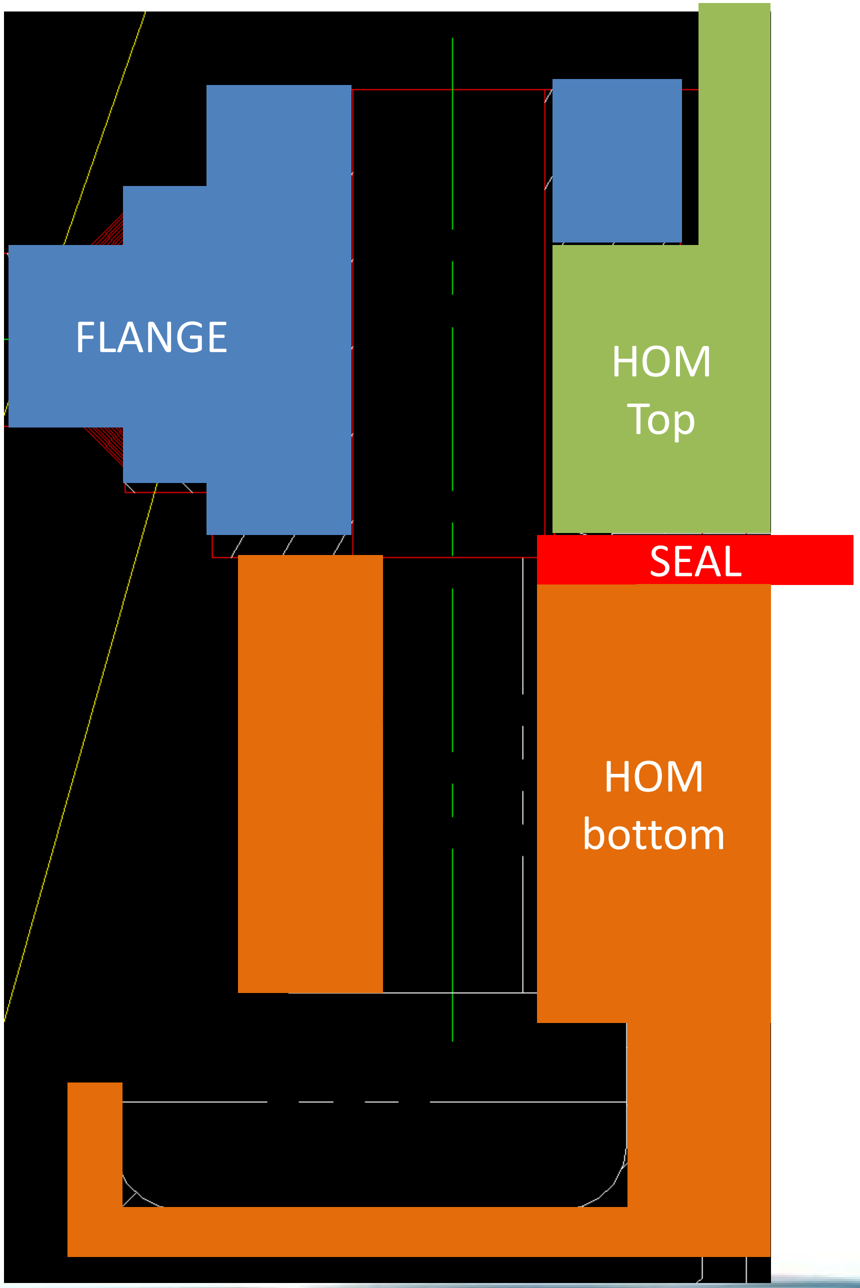
82
108.6
45
144
50
260
40
34
φ103
R150



Appendix





Challenge to maintain the RF phase

- 800 MHz cavity phase fixed w.r.t. 400 MHz ACS
- Full detuning: Allow phase modulation in 400 MHz (≈72ps, ≈ 21° per turn)
- → 800 MHz cavity must follow:
  - BL: within 1°-5° to ensure stability (feasible? → yes/no)
  - BS: very forgiving
- Injection: 400 MHz ACS @ ½ detuning for efficient beam transfer from SPS

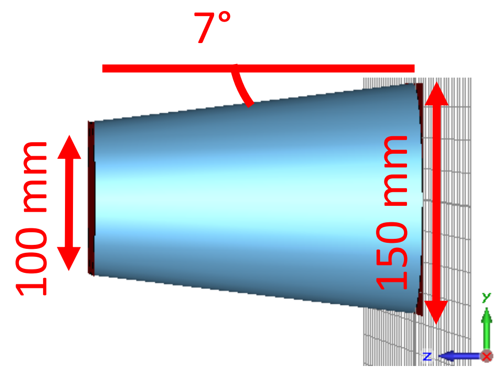
→ 800 MHz: ??? Passively damping / reduced voltage / counter phasing ???

High Luminosity LHC

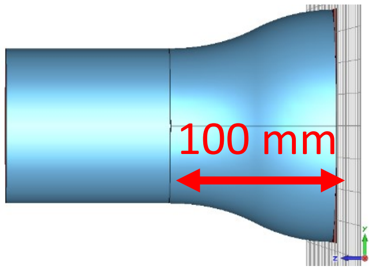
Wakefield simulations

Appendix

- Tapers:



Scaled version: 210 mm



Special taper: 105 mm
Equal transmission characteristics
Engineering difficulties?
Deformation → sensitivity?

Heat load

(Courtesy: R. Calaga)

Heat load @ 4.5 K / cavity	400 MHz [W]	800 MHz [W]
Static	50	10
Dynamic (cavity)	25 (@ 2 MV)	15 (@ 1 MV)
Dynamic (other)	10	10
Total	**85**	**35**
Total 4 cavities	340	140

→ Preliminary estimates

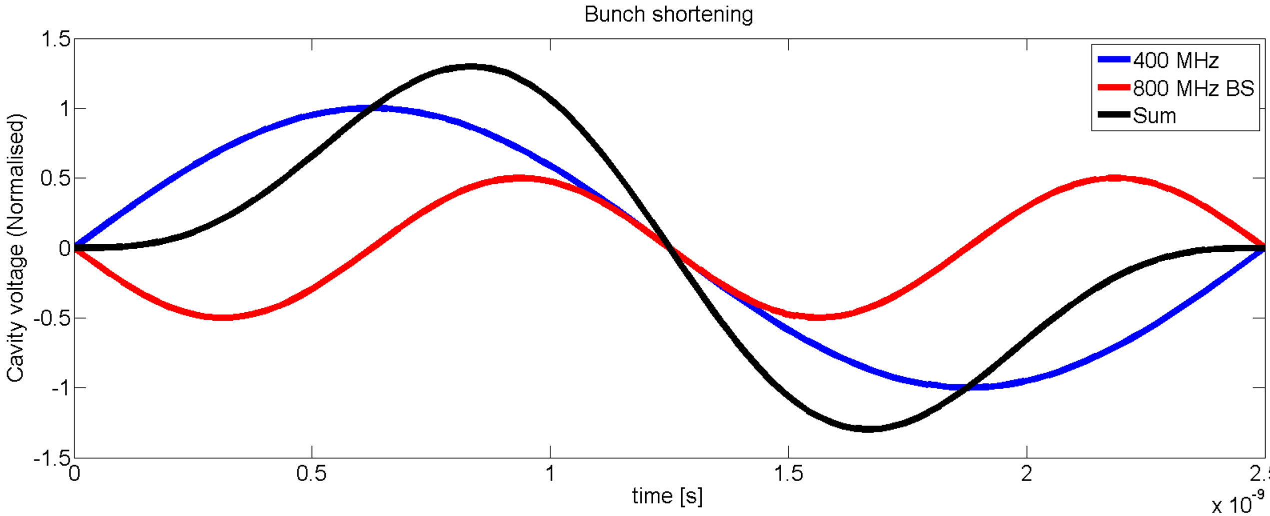
400 MHz ACS cryomodule

High Luminosity LHC

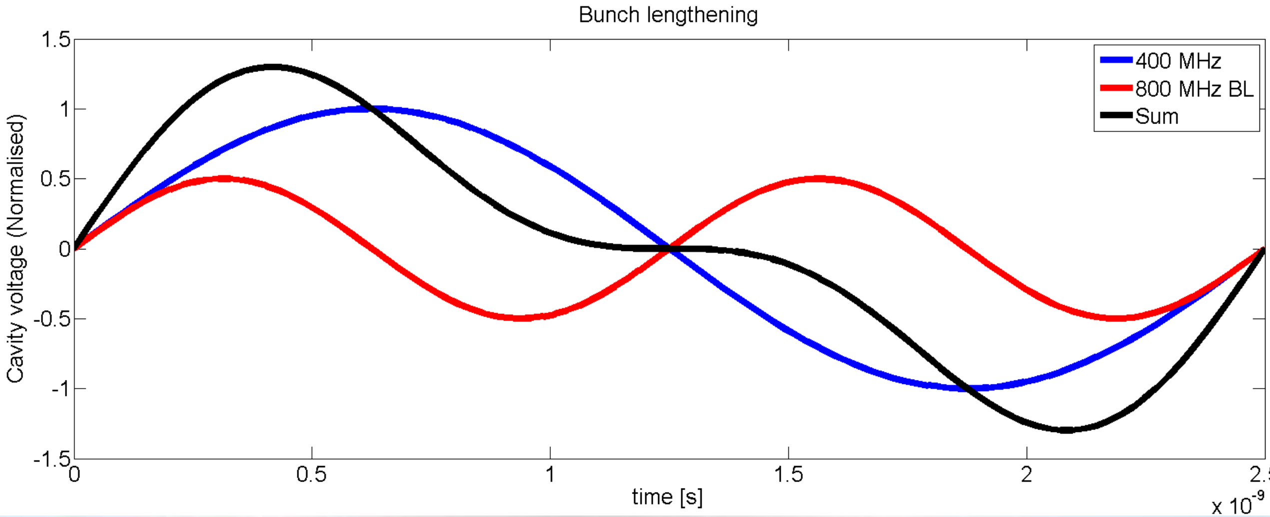
Appendix

- Cavity voltage seen by the beam:

BS



BL



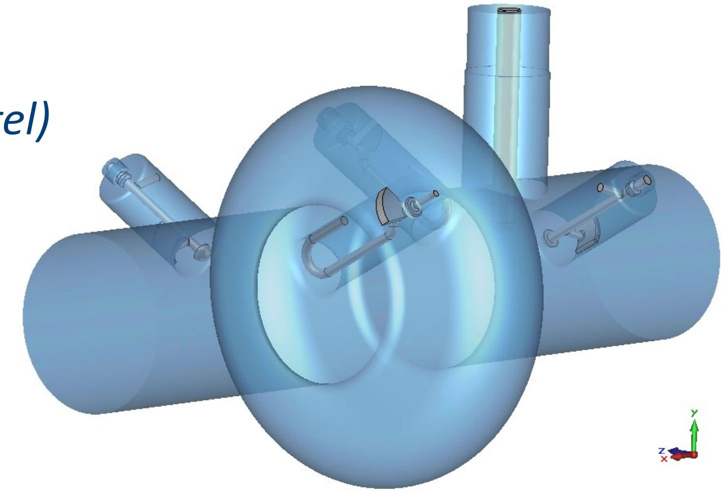
Appendix

- Power Sources:
  - IOT: SPS: 2 x 240 kW CW operating at 801 MHz (! footprint)
  - MB IOT (multi beams): prototype ordered by ESS & CERN → 3-5 years.
  - Klystron: SM18 (Olivier Brunner).
  - SSPA: Solid state (! footprint)

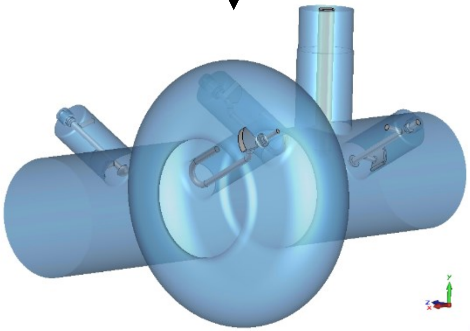
Appendix

Approach: *(R. Calaga, L. Ficcadenti, J. Tückmantel)*

	LHC-ACS	800 MHz Harmonic system
Frequency [MHz]	400	800
Voltage [MV / cavity]	2	0.8
Phase	Leading	Following (0 / π)
Material	Nb/Cu (4.5 K)	Nb/Cu (4.5 K)
Power coupler	CW (300 kW)	CW (300 kW)
Q_{ext}	$2x10^4 – 1.8x10^5$	TBD
Power source	Klystron (300 kW)	Klystron (300 kW)
HOM couplers	2 narrow band 2 broad band	2 narrow band 2 broad band



½



(Courtesy: R. Calaga)

Other thoughts

- Operational challenges
  - 800 MHz cavity voltage programmes
    - flat top: BS / BL
    - flat bottom, ramp: need for 800 MHz?

      If not: $V_{800} = 0.5xV_{400}$? Reduce V? Detune cavity…
  - Sensitivity to phase errors on ϕ(t): What if 800 MHz system cannot keep up?
    - Analytical / develop dynamic model (power)

High Luminosity LHC