800 MHz Harmonic System: Design & RF Power

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With input from:
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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.

Motivation

Harmonic RF system for HiLumi LHC:

- 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)

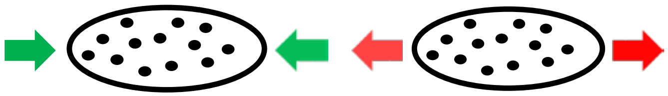
(E. Shaposhnikova, this Annual Meeting)

Motivation

Idea:

- Main RF system: - Existing 400 MHz LHC cavities
- 2nd harmonic: - 800 MHz system
  - High intensity beam: In case of multi-bunch instabilities:

    → increase synchrotron frequency spread (Landau damping)
  - Bunch profile shaping (heating, pile up)



High Luminosity LHC

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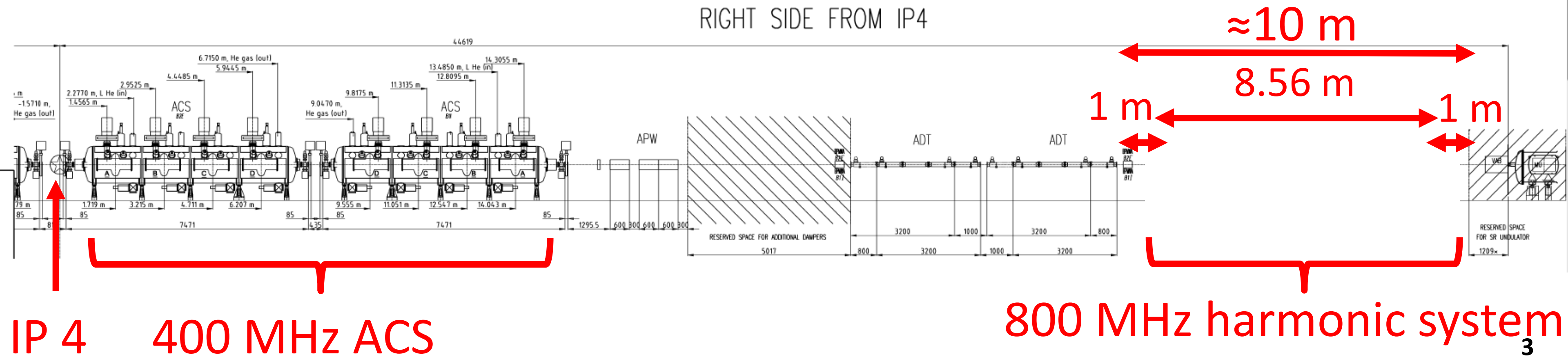
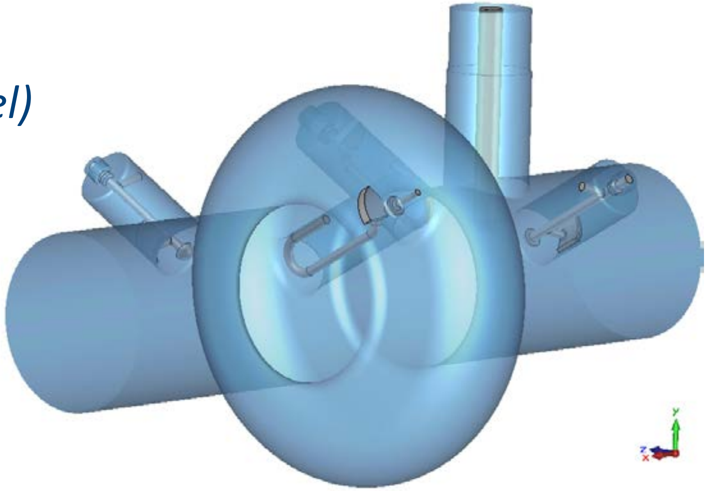


Motivation

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



- Start design from 400 MHz LHC-ACS
  - Highly optimized for LHC (impedance, power)
  - Proved functionality and reliability in operation

- Cavity - HOM couplers

- Power coupler - RF system

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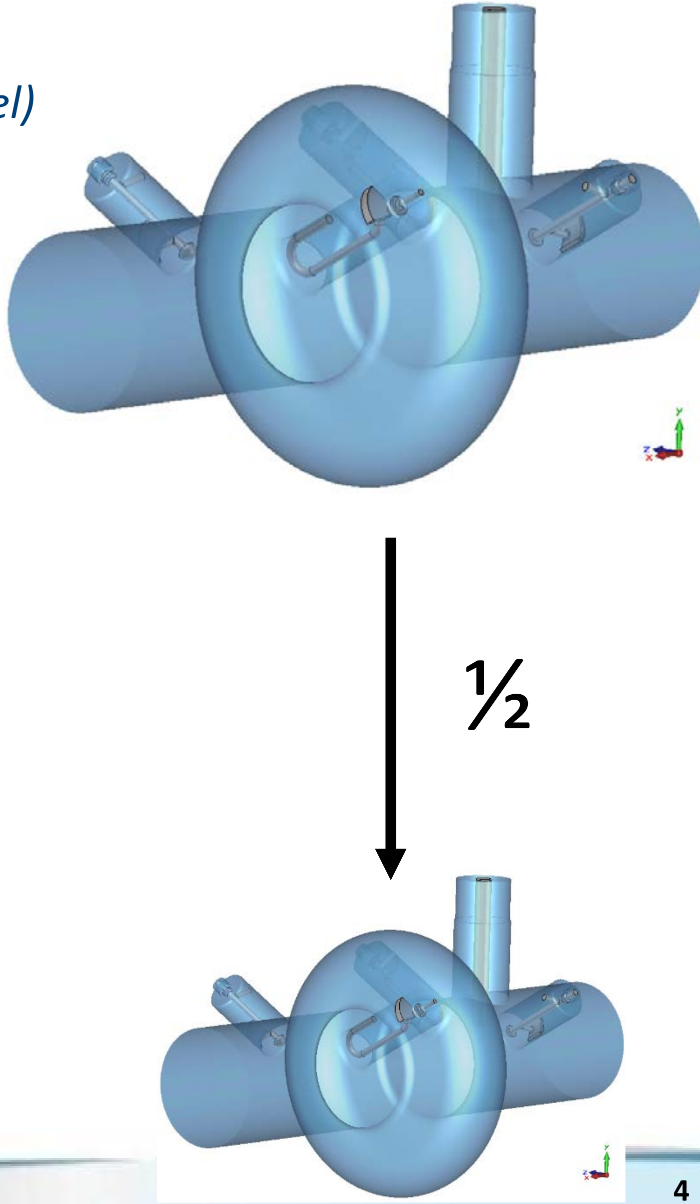
- Scale: ½ → Base line model for 800 MHz



High Luminosity LHC

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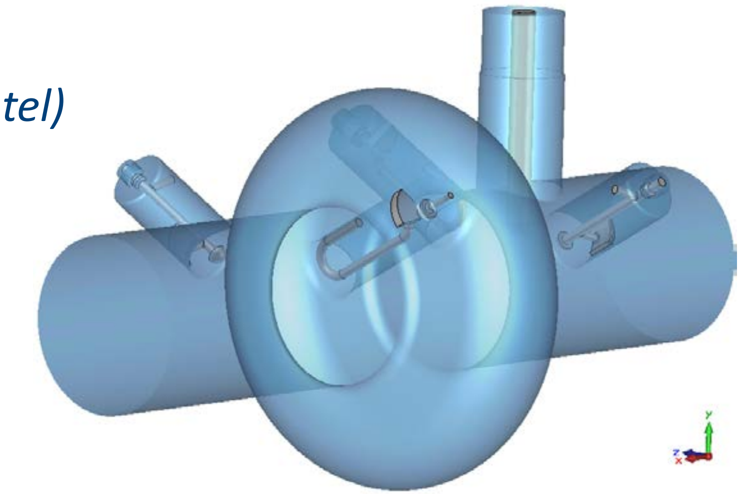
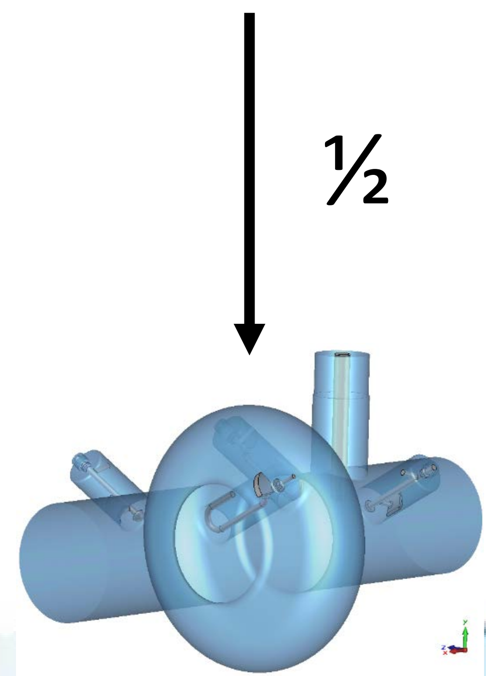
    - Power coupler - RF system

- Scale: ½ → Base line model for 800 MHz
- Not that simple: Not all optimized properties scale
  - HOM impedances
  - Cavity deformation (tunability)
  - HOM couplers

} Re-optimize





High Luminosity LHC

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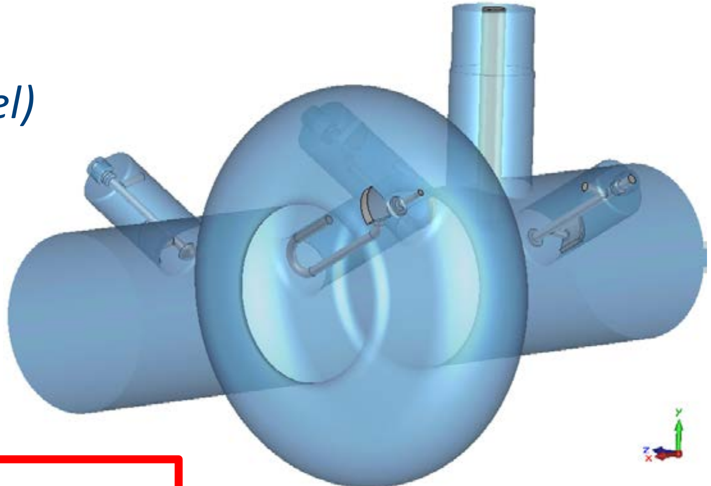
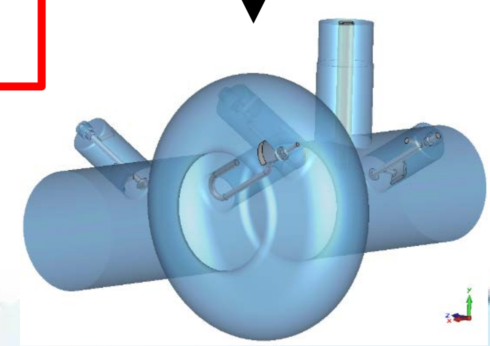


Challenges: p^+: 2.2x10^{11}
Beam loading + RF power

½

  - HOM impedances
  - Cavity deformation (tunability)
  - HOM couplers

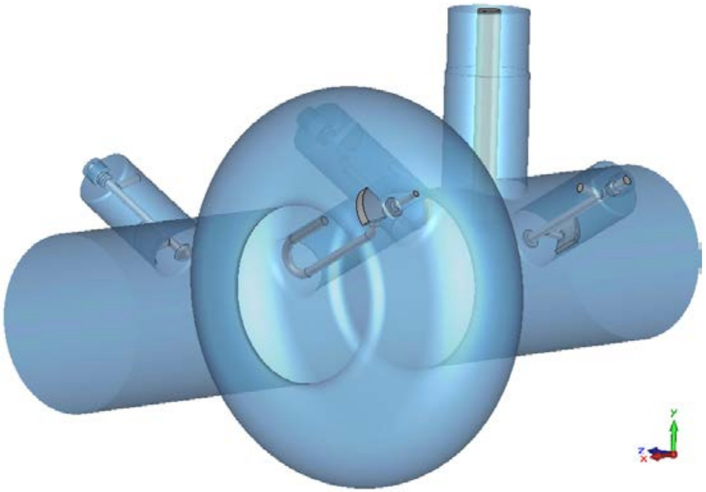
Re-optimize



High Luminosity LHC

Overview

- Motivation
- RF cavity
- HOM couplers
- RF power
- Cavity layout
- Heat load
- Conclusions & outlook

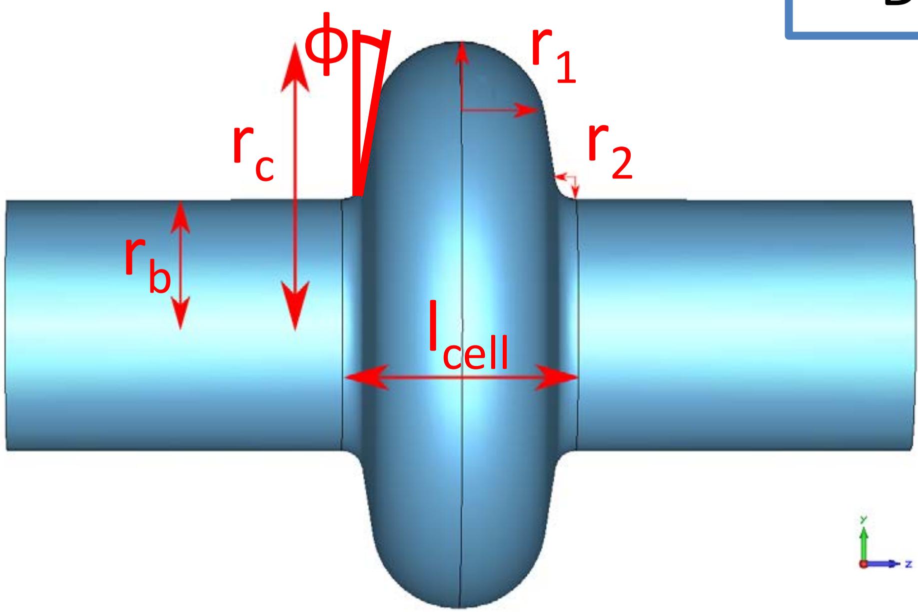


RF cavity

Parameter sensitivity study

- r_b, r_c, ϕ, r_1, r_2, l_{cell}

Goals:
- Impedance: High FM / low HOM
- HOM freq. >> FM freq.
- HOM freq. above cut-off
- Deformable / tunable cavity



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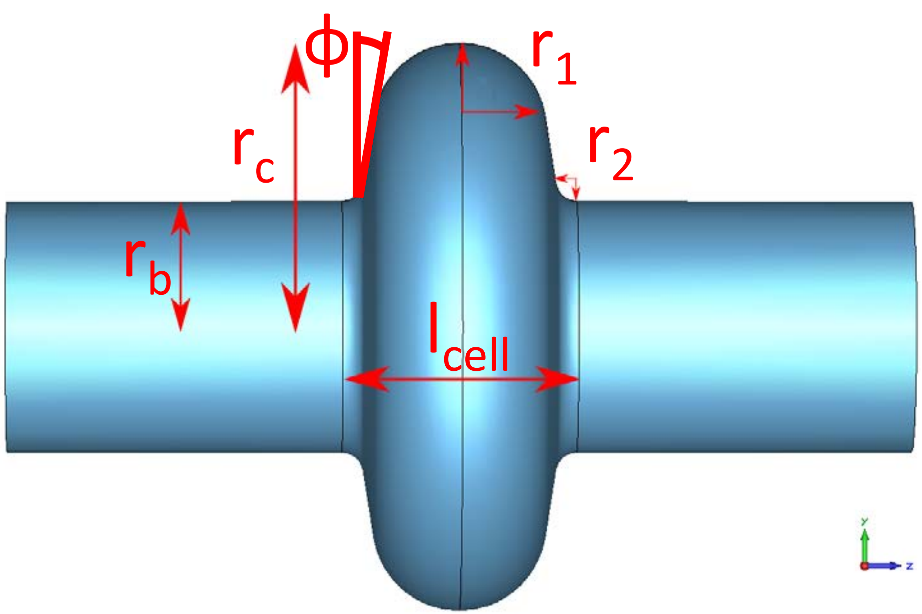
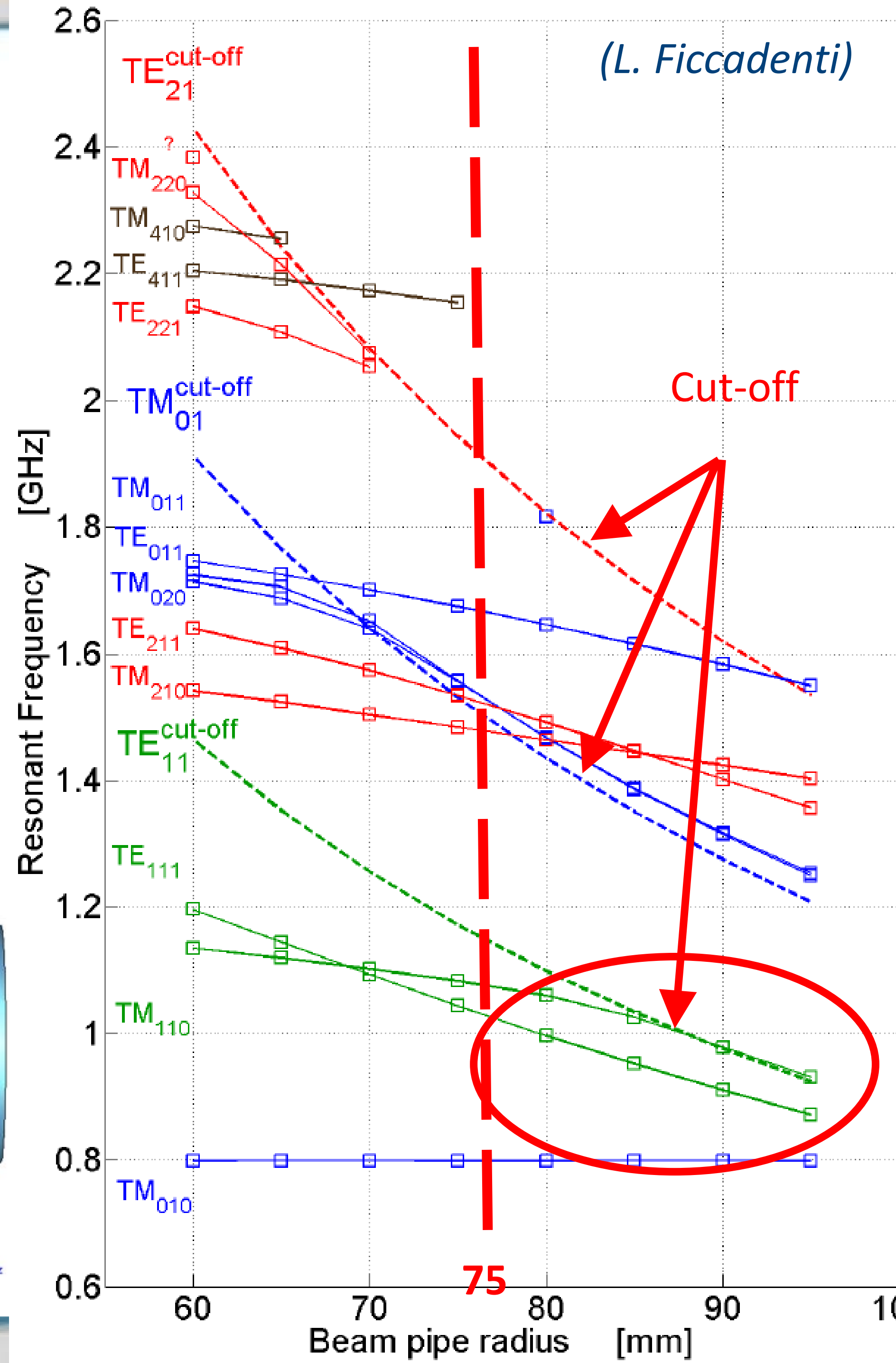
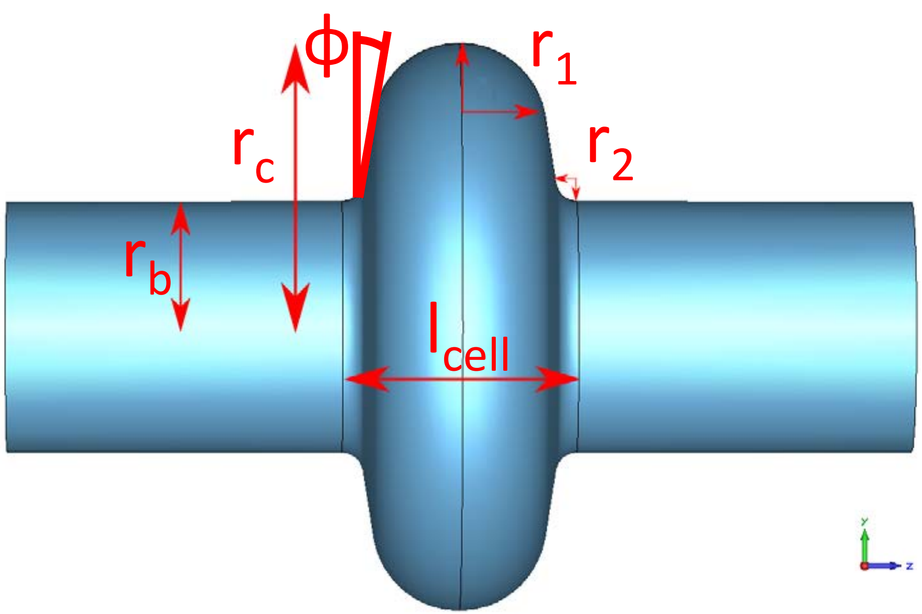


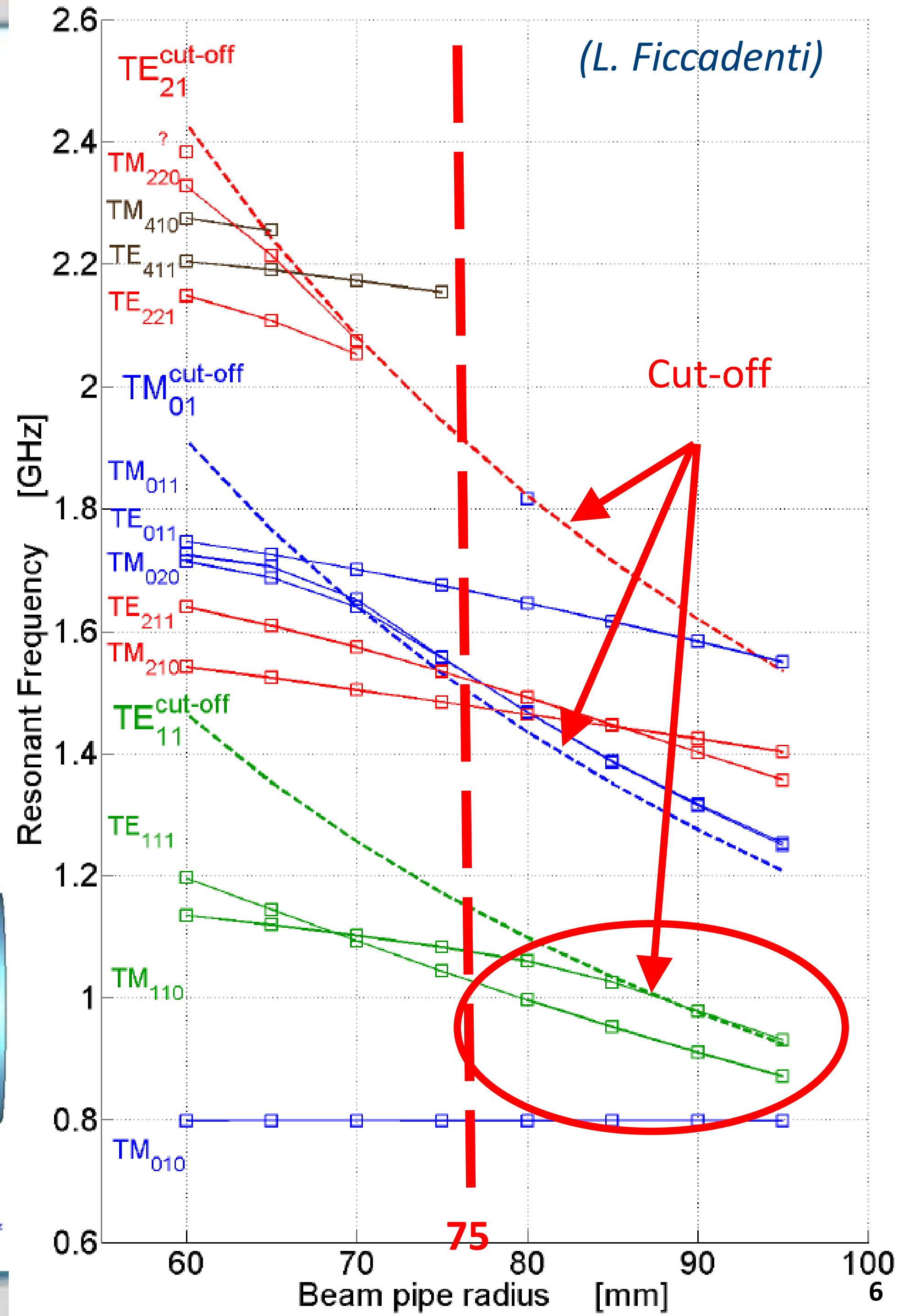


RF cavity

Parameter sensitivity study

- r_b, r_c, ϕ, r_1, r_2, l_{cell}
- Rigidity: ϕ: 19.5° → 10°
- L_{cell}: 160 mm → 140 mm





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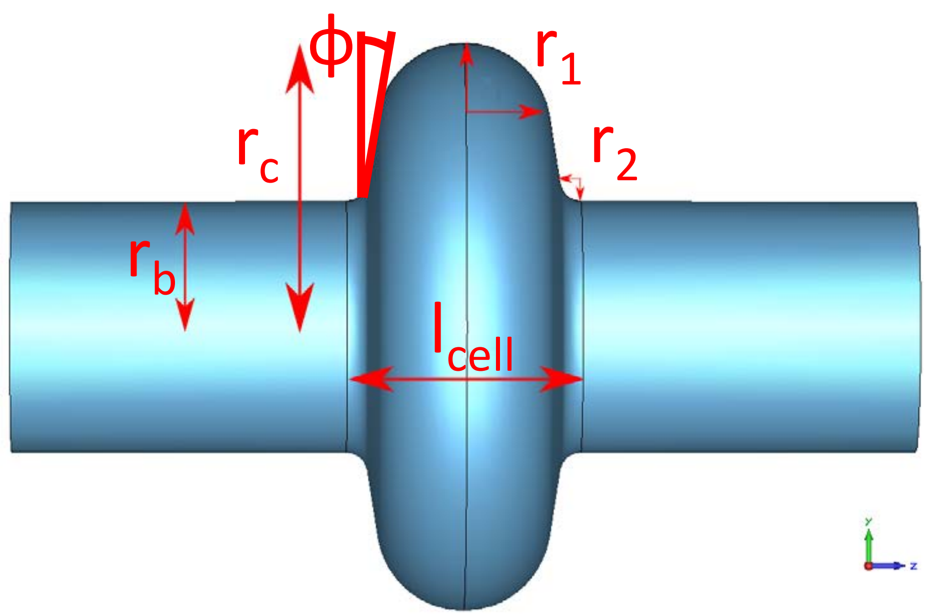
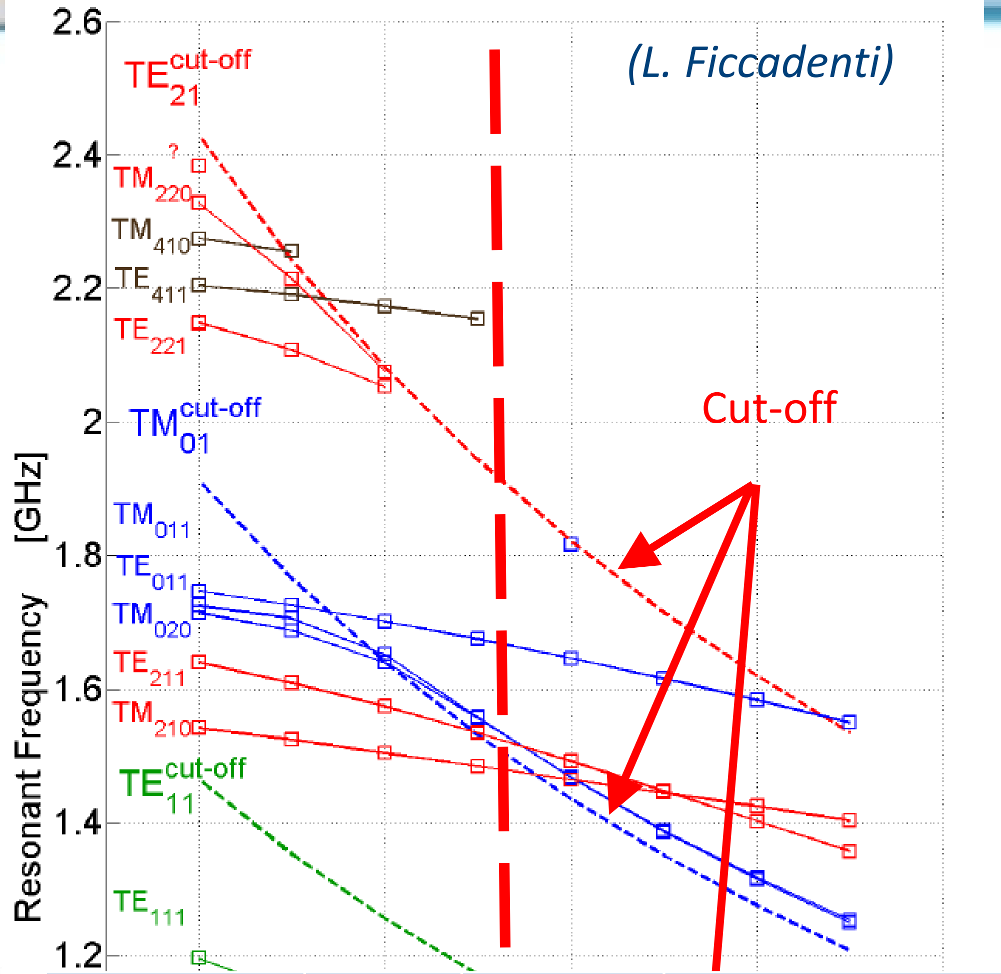


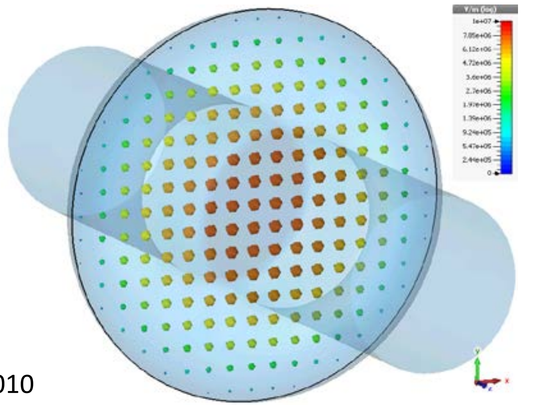


Parameter	[mm]	Spec.	Value
r_b	75	f	801.4 MHz
r_c	169.3	R/Q	45 Ω
r_1	52	E_p / V_{acc}	14.6 m^{-1}
r_2	12.5	H_p / V_{acc}	28.2 mT / MV
l_{cell}	140		

HOM couplers

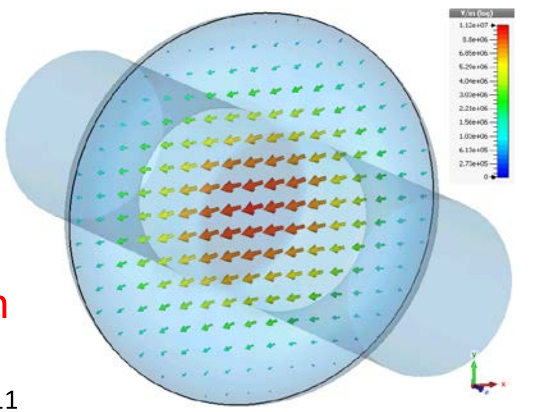
Why do we need HOM couplers?

Mode	f [MHz]	$R/Q_{\|\|}$ [Ω]	$R/Q_{\perp}$ [Ω]	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	3.0	0.1	-
TM_{011}	1630	24	0.2	-
…	…	…	…	…



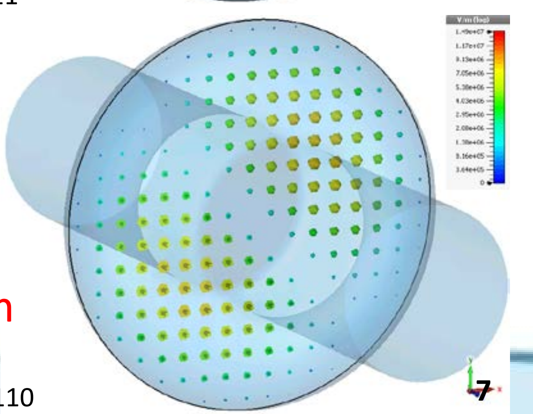
FPC

TM_{010}



Beam

TE_{111}



Beam

TM_{110}

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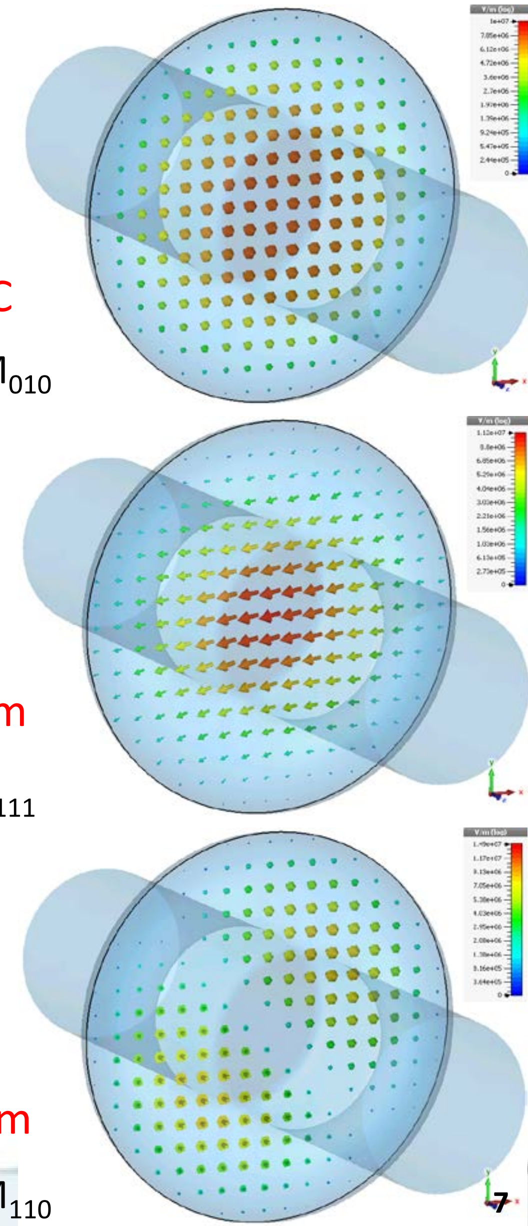

FPC

TM_{010}

Beam

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Beam

TM_{110}

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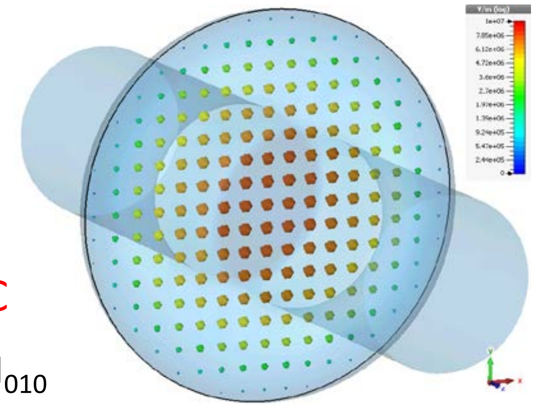

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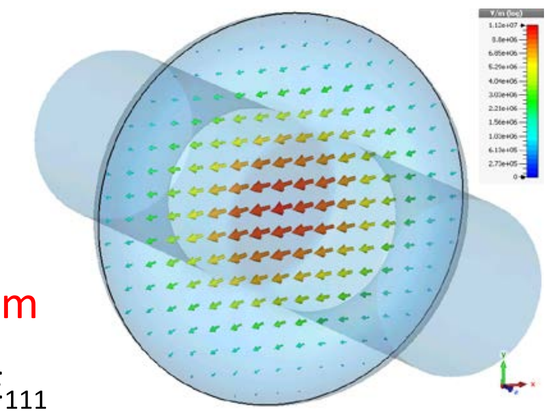

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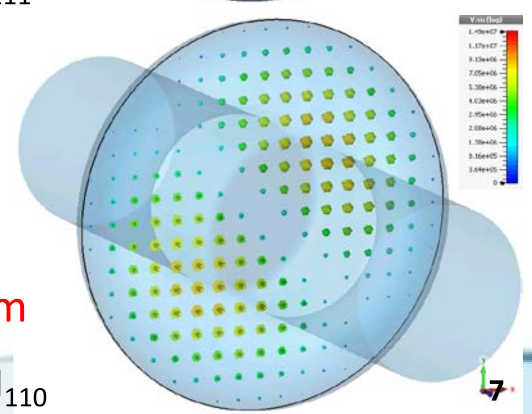

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(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

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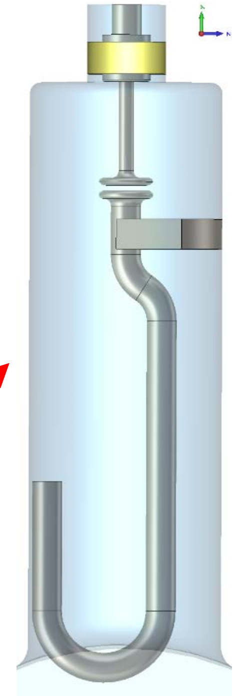
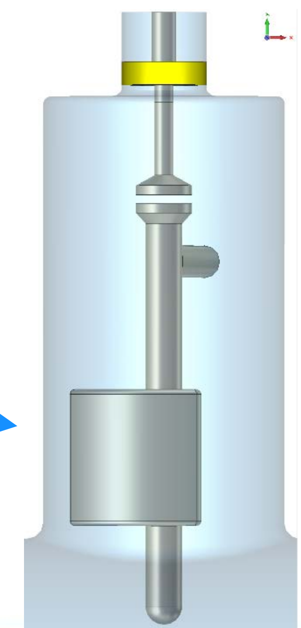


Hook type coupler

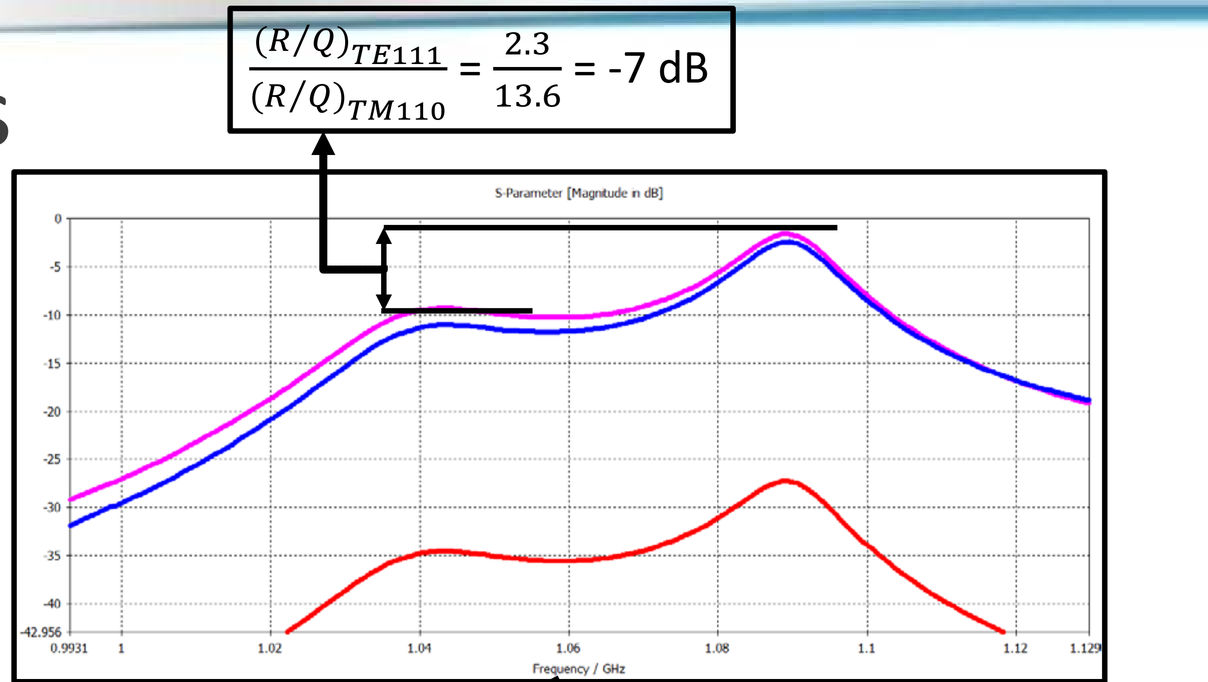


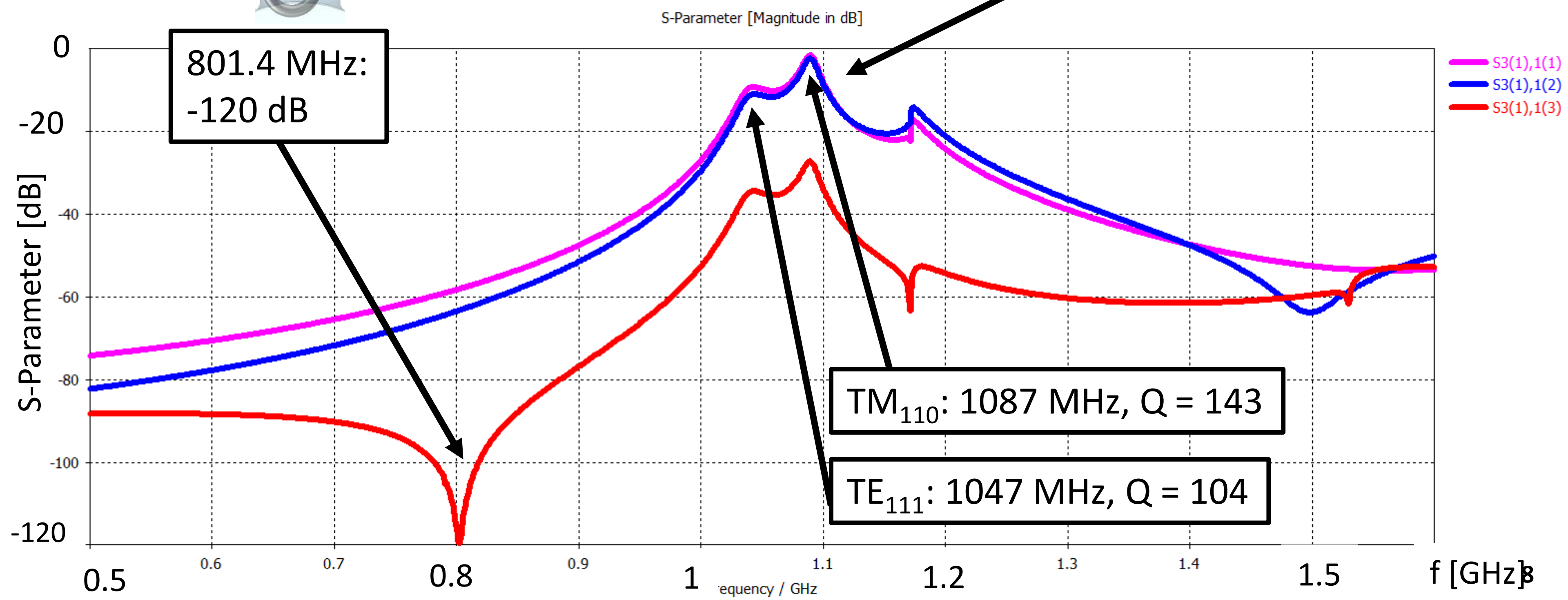
Probe type coupler

High Luminosity LHC

HOM couplers

- Hook type:





HOM couplers

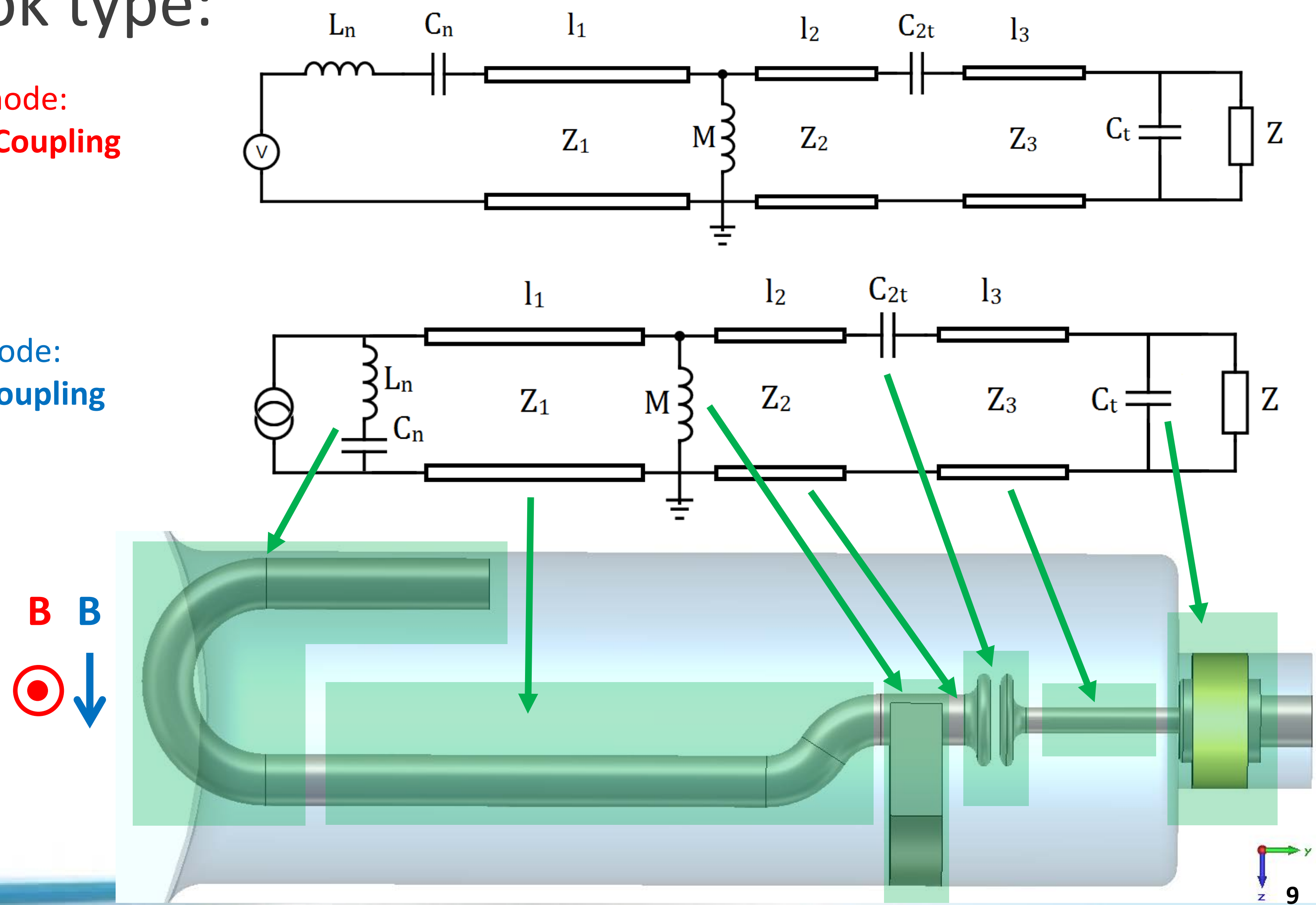
(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

- Hook type:

TM_{01} mode:
Magnetic Coupling

TE_{11} mode:
Electric Coupling

TM_{01}
TE_{11}
FM



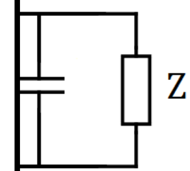
HOM couplers

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

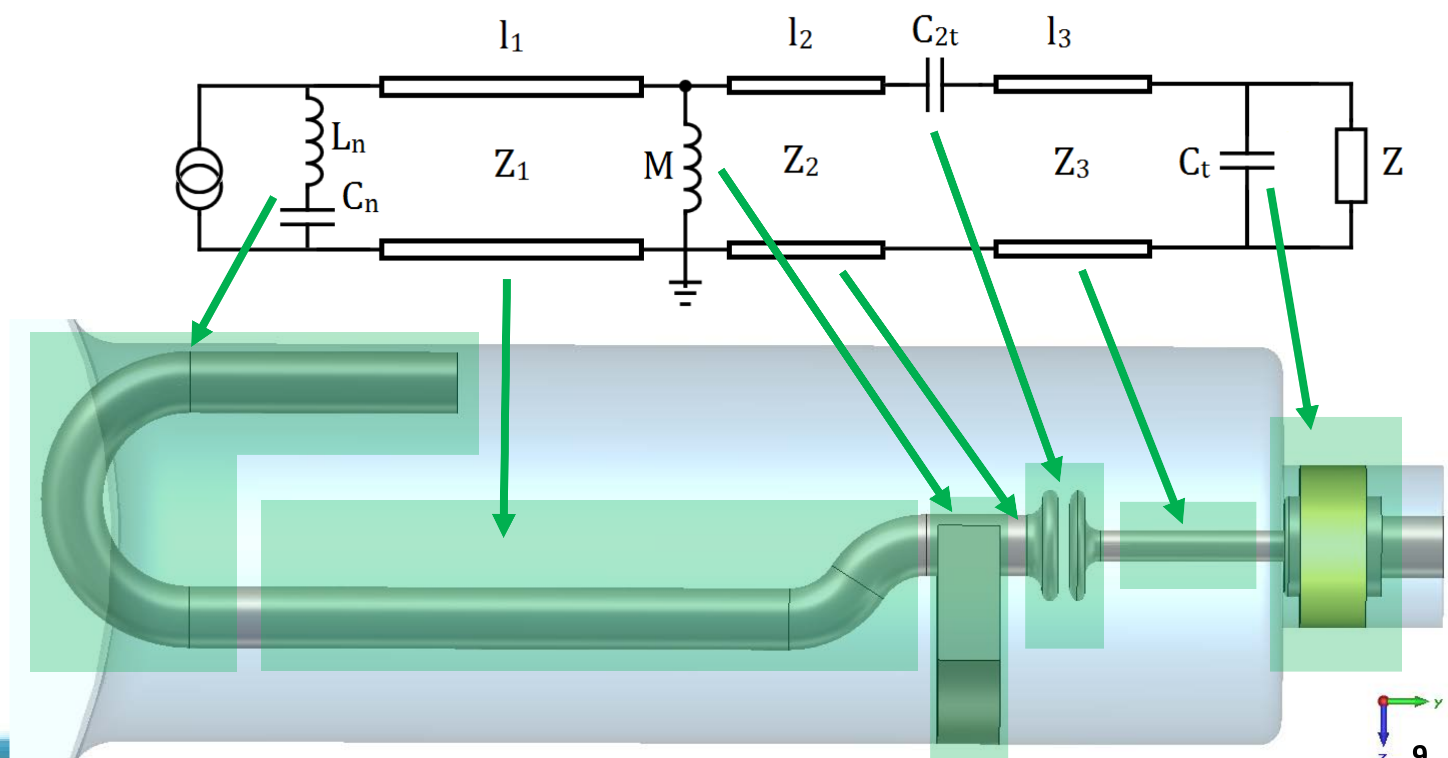
Tuning procedure:

- Equivalent circuit: Component optimization based on S_{21} curve
- Convert to 3D model
- EM simulations: Fine tuning → S_{21} curve

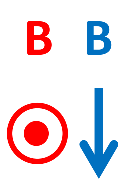
Ma



TE$_{11}$ mode:
Electric Coupling



TM$_{01}$
TE$_{11}$
FM



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

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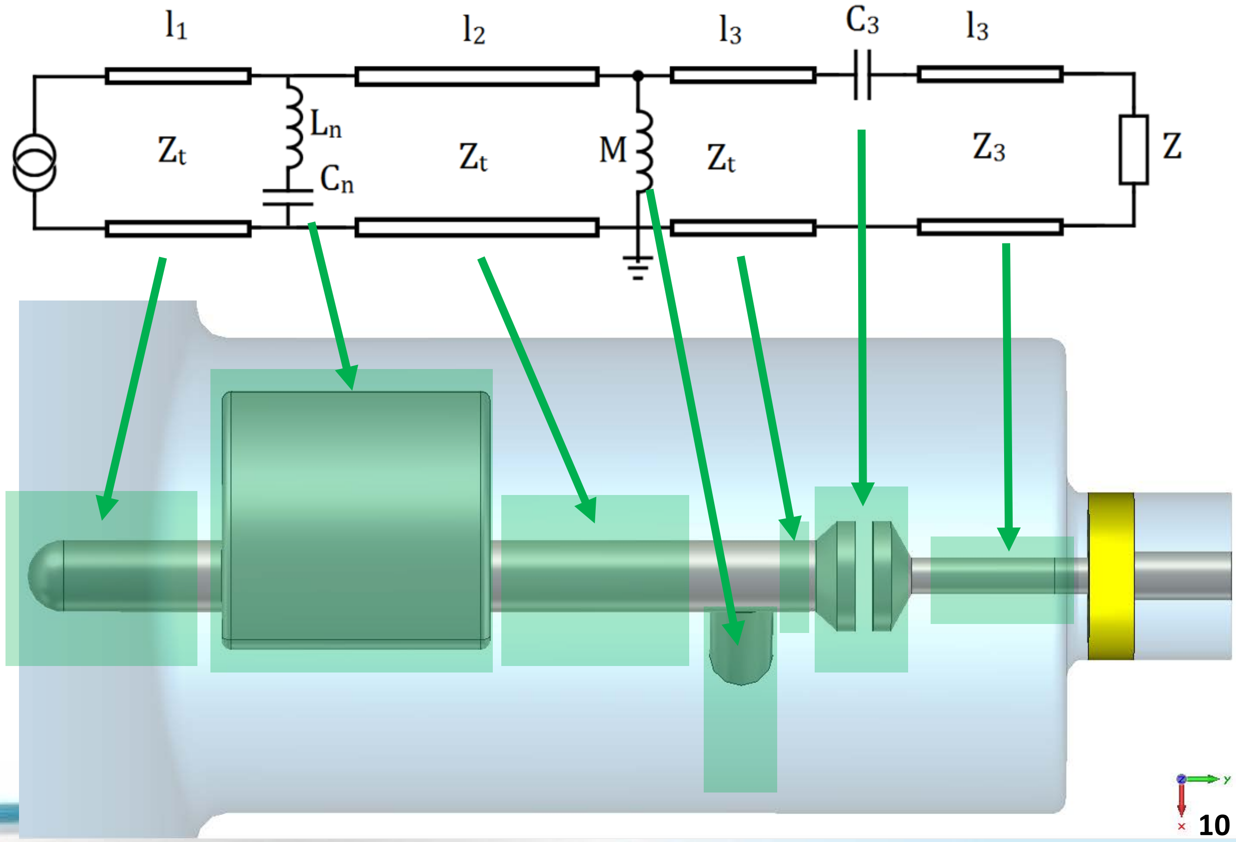

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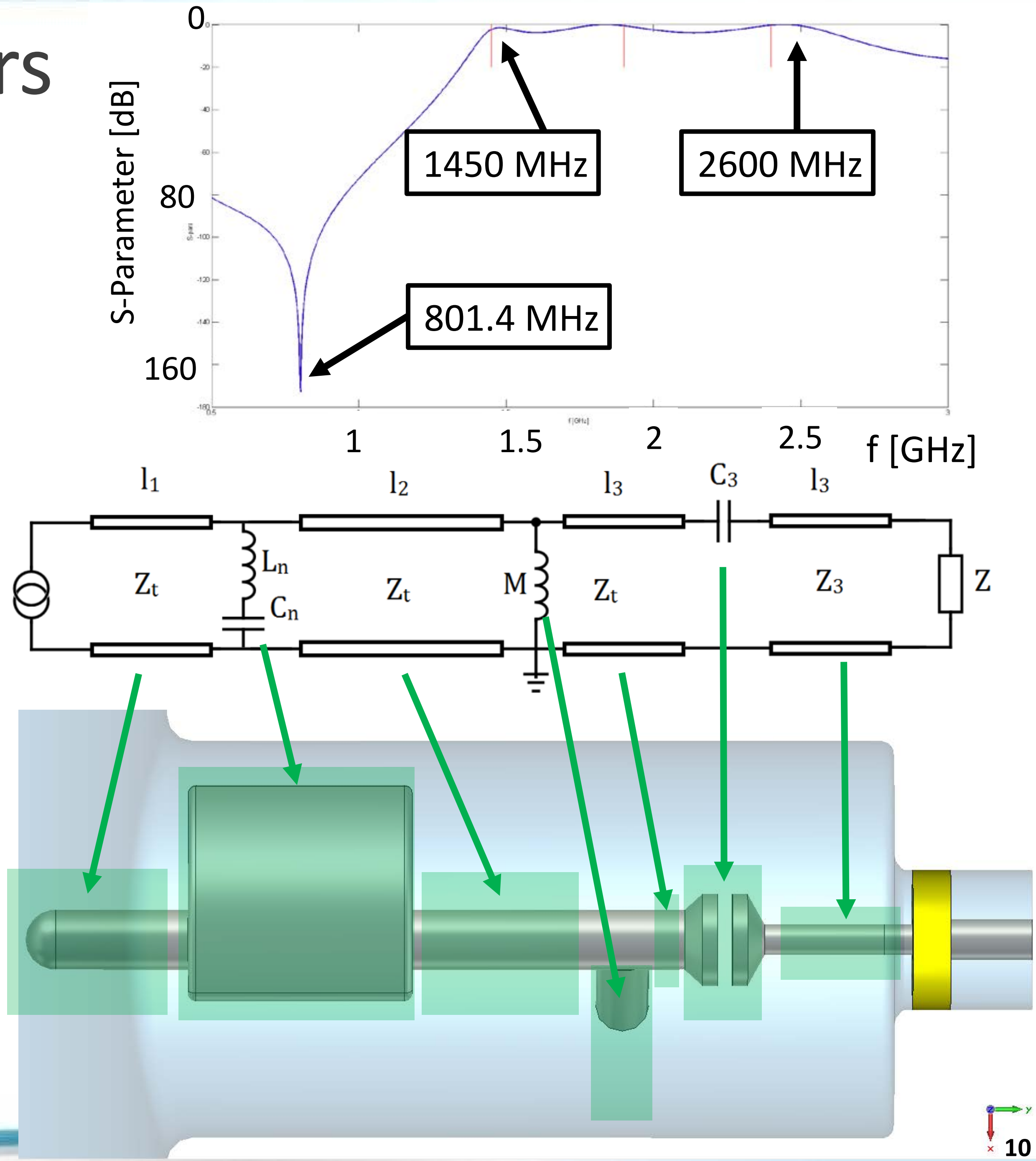


RF power

400 MHz ACS: “Half detuning scheme” *(D. Boussard)*

- V(t) and RF peak power constant (↔ beam loading)

→ Fixed bucket distance (ϕ = 180°)

→ Beam and gap: Const. P_{peak}

→ Limitation: Available P_{peak} < 300 kW (↔ beam intensity)

SOLUTION: 400 MHz ACS: Switch to "full detuning scheme”

- Keep klystron current real (with RF feedb. & 1T-feedb: define set point)

= Allow the beam to modulate phase (ϕ(t) instead of ϕ = 180°)

- Result:
  - Minimized klystron power demand if ϕ(t) over one turn centred around zero
  - Allow for higher intensities
  - Non equally spaced bunches

(D. Boussard, P. Baudrenghien, T. Mastoridis)

RF power

800 MHz harmonic system: Consequences

- Required: $V_{800,total} = V_{400,\ total} / 2 = 8$ MV
- Required: Follow phase modulation ϕ(t) 400
  - P_{BS}: Reduction
  - P_{BL}: Increase

$$P_{pk} \sim \left(\left| \frac{n\Delta\omega_{400}}{\Delta\omega_{800}} \mp 1 \right| \right) \frac{V_{800} I_{b,pk}}{8}$$

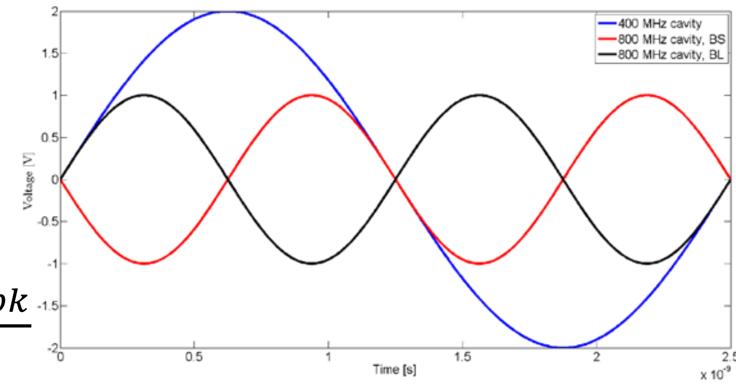
- Todays technology: 300 kW CW limit
- BL mode: Reduce V_{800} = 1.0 MV → 0.8 MV

  → more cavities: 8 → 10

  - P_{BL} ≈ 290 - 300 kW
  - BS mode P_{BS} ≈ 175 kW (fixed FPC)
  - BS mode P_{BS} ≈ 57 kW

  + 1.4 MV in cavity (variable FPC)

(P. Baudrenghien)



Bunch	
p^+	$2.2e^{11}$
Bunch length [ns]	1
Bunch spacing [ns]	25
# (filled) bunch places	(2808) 3564
β	1
T_{gap} [μs]	3.2

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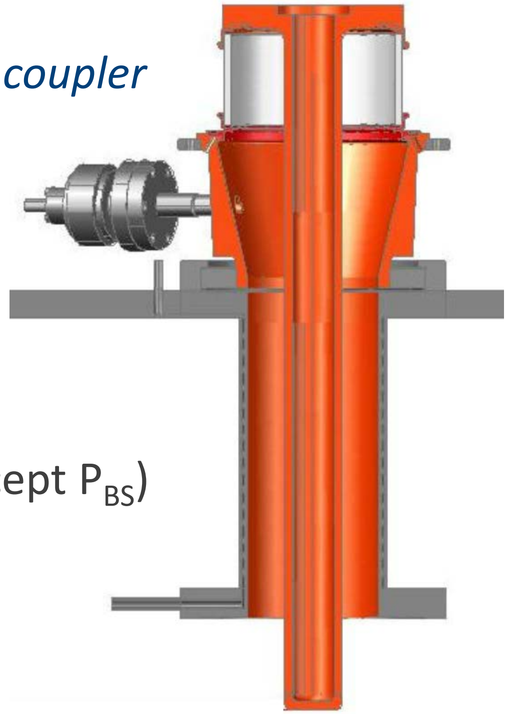
RF power *(Courtesy: E. Montesinos)*

- Power coupler:
  - → CW Power > 300 kW (↔ 300 kW limit)
  - → Fixed (movable) : (Optimize towards P_{BL} ↔ accept P_{BS})
  - → Q_{ext} = 1.5×10^4 ($10^4 - 10^5$)
  - → Size: Ø 100 mm (Ø 125 mm)
  - → Start from SPL-like design
- Power source:
  - → CW Power > 300 kW (↔ 300 kW limit)
  - → Klystrons, IOT's

SPL power coupler



LHC Klystron 400 MHz
300 kW CW
(Thales TH 2167)

SPS IOT 801 MHz
2x240 kW CW

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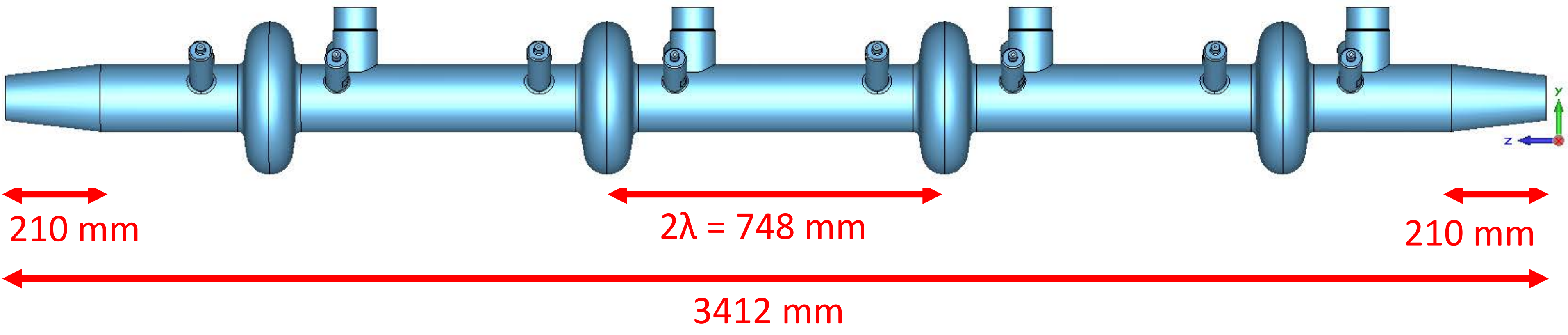
Cavity layout



- 10 cells / beam (↔ 10 m)
- 2λ spacing cross talk : -48 dB
- 2 or 4 cavities / cryo
- Two 4-cavity cryo's + one 2-cavity cryo (8530 mm)
- Five 2-cavity cryo's (longer + modular ↔ 10 m)
- Preliminary estimates → detailed engineering

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

400 MHz ACS cryomodule

→ Preliminary estimates

Conclusions & outlook

- Conclusions:
  - RF Cavity: EM design optimized for 800 MHz HH system
  - HOM couplers: Tuned to 800 MHz specifications
  - Power requirements: "Full detuning" scheme: V_{800} = 0.8 MV
    $P_{BL} \approx$ 300 kW, (>> P_{BS})
  - Power coupler: Fixed & > 300 kW
    (↔ 300 kW limit + size)
  - Power sources: TBD (Klystrons, IOT's)
  - Cavity layout: # 10 cells / beam, spacing 2λ (↔ 10 m)
  - Heat load: 35 W/cavity (4.5 K)

Conclusions & outlook

- Outlook:
  - Build prototype: 2-cavity 800MHz (Nb-Cu)
  - Power coupler design
  - Operational challenges (Voltage program, sensitivity to phase errors)
  - Cavity/RF system failure procedure

High Luminosity LHC

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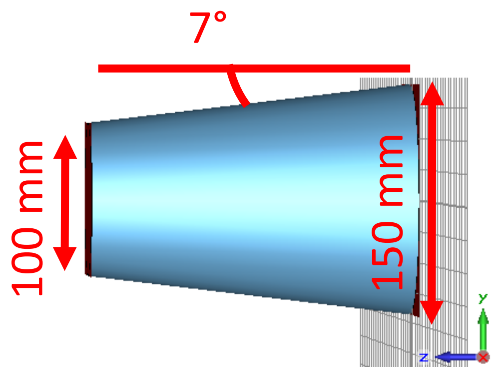
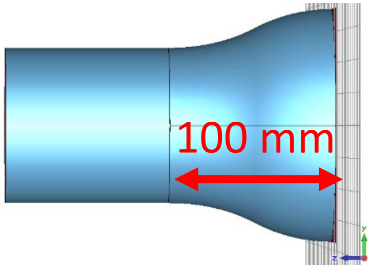
Appendix

- Tapers:



Scaled version: 210 mm

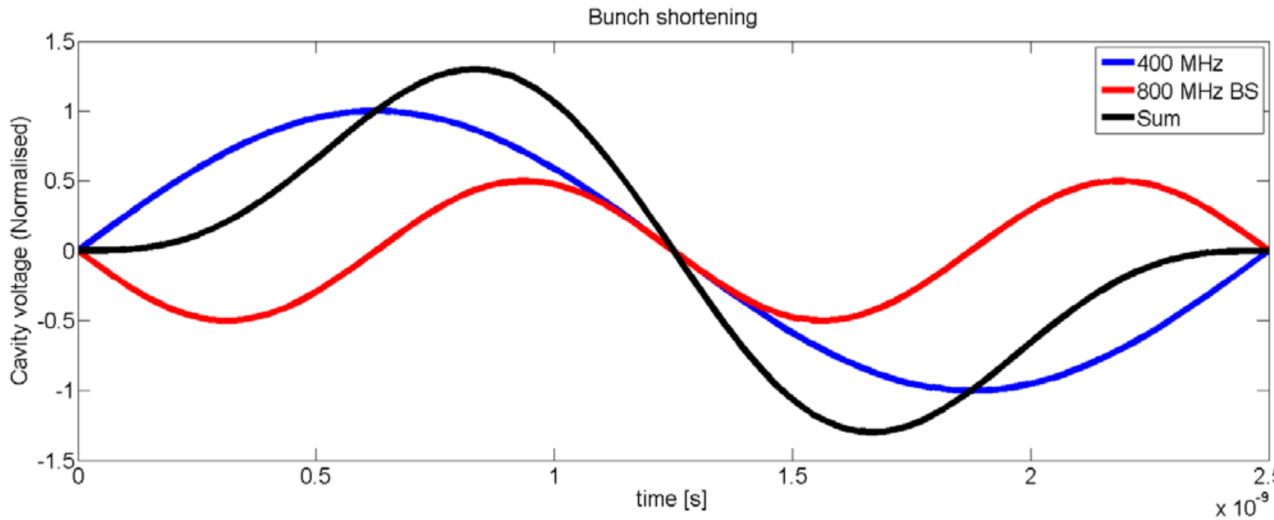


Special taper: 105 mm
Equal transmission characteristics
Engineering difficulties?
Deformation → sensitivity?

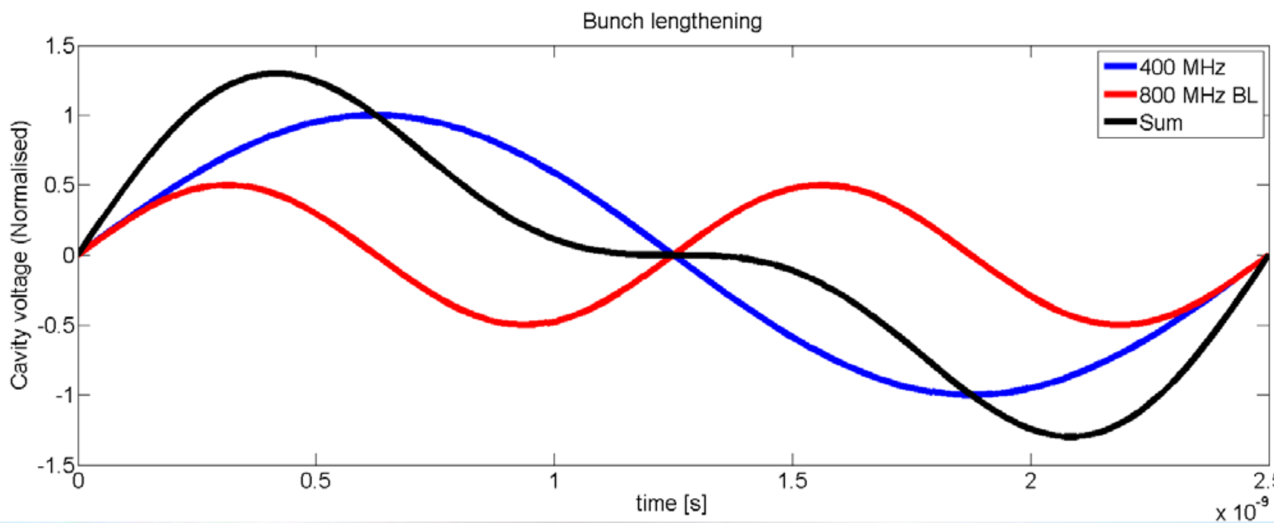
Appendix

- Cavity voltage seen by the beam:

BS



BL



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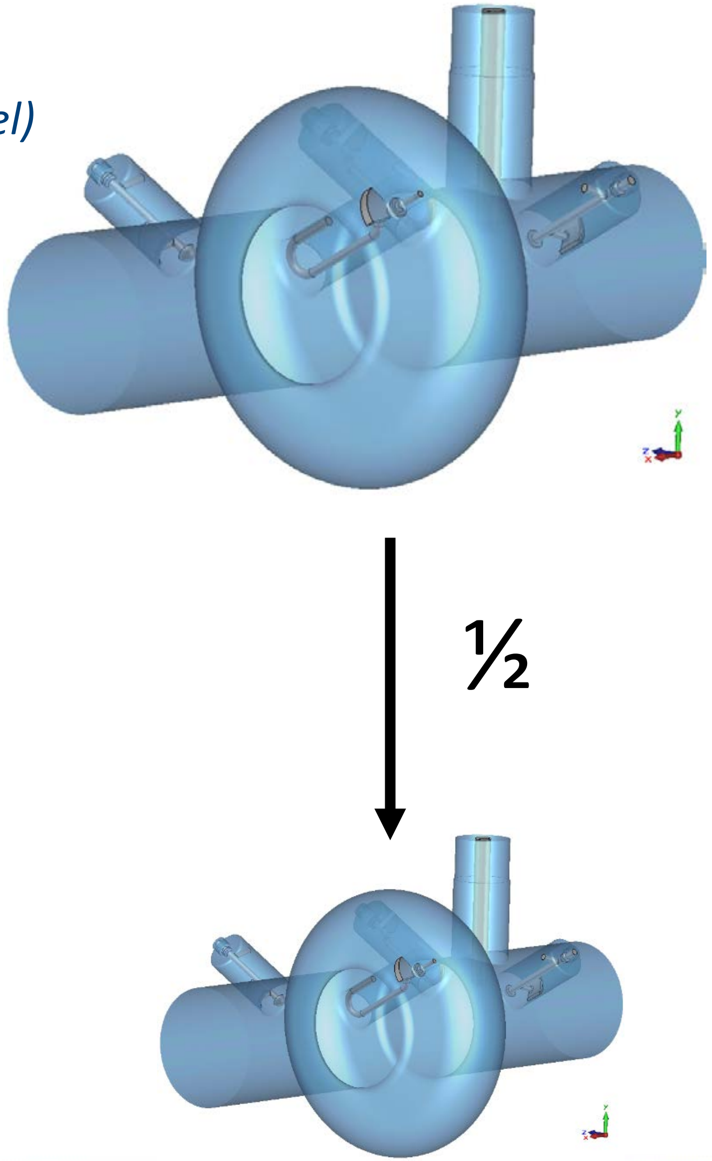
Appendix

- 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



High Luminosity LHC

(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)

(Courtesy: R. Calaga)

Other thoughts

- Cavity/RF system failures:
  - 400 MHz cavity failure
    - Scenario's: Reduce / keep V_{800}? Abort beam?
  - 800 MHz cavity failure
    - Scenario's: Reduce / keep V_{800}? Abort beam? Compensate with the other cavities? (Available power + in BL / BS mode)

Power requirements

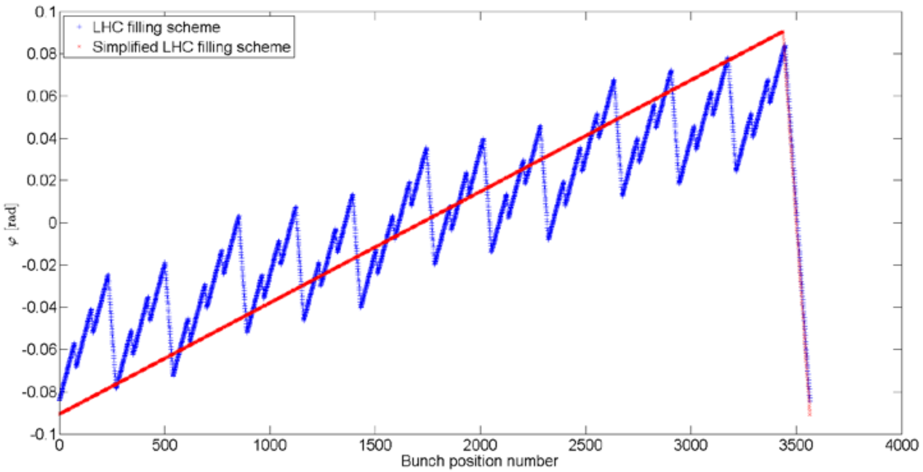
400 MHz ACS: “Half detuning scheme”

- V(t) and RF power constant → Enforce

→ Fixed bucket dista

→ (no) beam: Const.

→ Limitation: Availal



400 MHz ACS: Switch to "full detuning scheme”

Injection, ramp, flat top (last: worst case) See RC sl

800 MHz: Consequences # cavities: 10,

$V_{800} = 0.5xV_{400}$

- BS
- BL

Bunch	
p^+	$2.2e^{11}$
Bunch length [ns]	1
Bunch spacing [ns]	25
# (filled) bunch places	(2808) 3564
β	1

$$P_g(t) = \frac{V_0^2}{8\,R/Q}\frac{Q_e}{Q_L^2}\frac{1}{(\cos\varphi(t))^2} \approx \frac{V_0^2}{8\,R/Q}\frac{1}{Q_L}\frac{1}{(\cos\varphi(t))^2}$$