800 MHz:
Cavity Design & Power Aspects

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With input from:
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R. Calaga
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E. Shaposhnikova

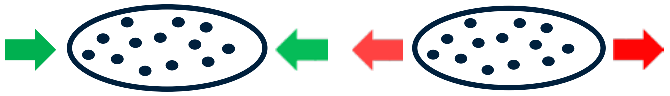
Harmonic RF System Review Meeting 3

Motivation

Idea:

- Main RF system: Existing 400 MHz LHC cavities
- Add 2nd harmonic (800 MHz):
  - Bunch profile shaping
  - Synchrotron frequency spread

    (Stability, Landau damping)



O. Bruning et al., 2002
F. Zimmermann et al., 2002
T. Linnecar, E. Shaposhnikova, 2007
C. Bhat at al., 2011
S. Fartoukh, 2011
T. Mertens, J. Jowett, 2011
D. Shatilov, M. Zobov, 2012

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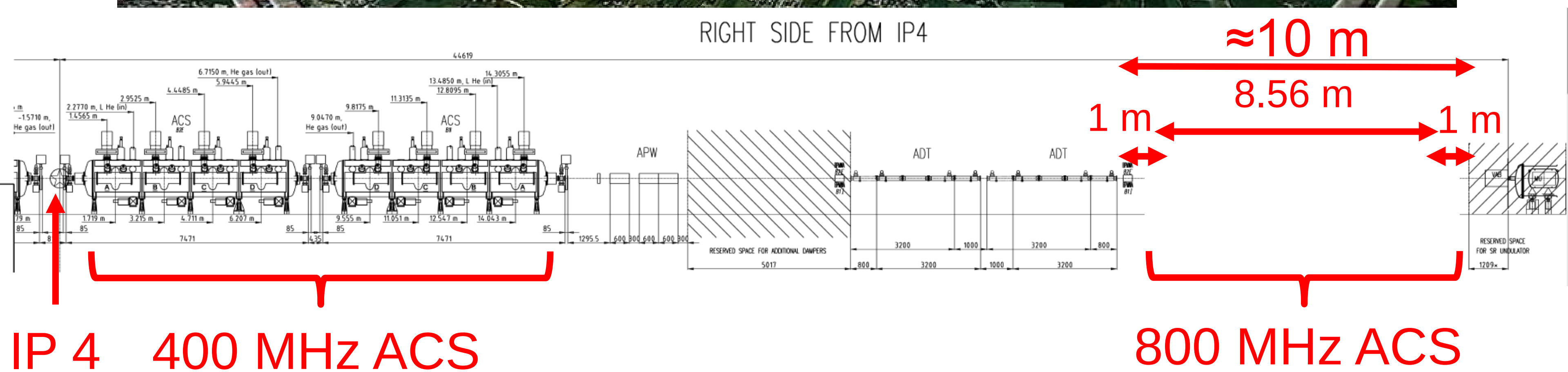
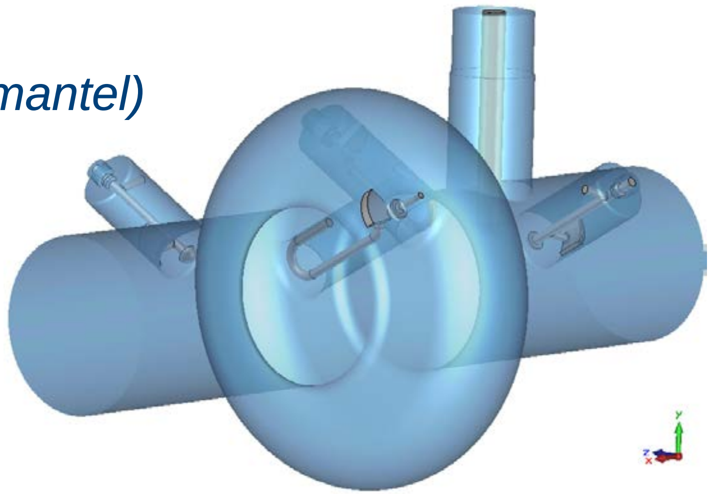


Motivation

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



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

- Cavity
- Power coupler
- HOM couplers
- RF system

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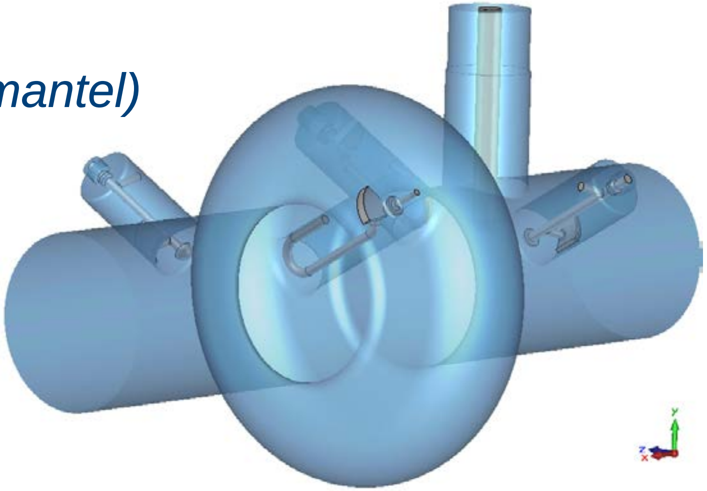
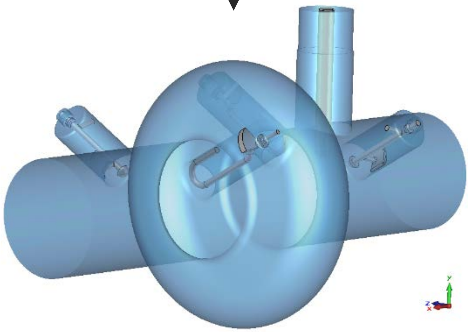
- Scale: ½ → Base line model for 800 MHz



½



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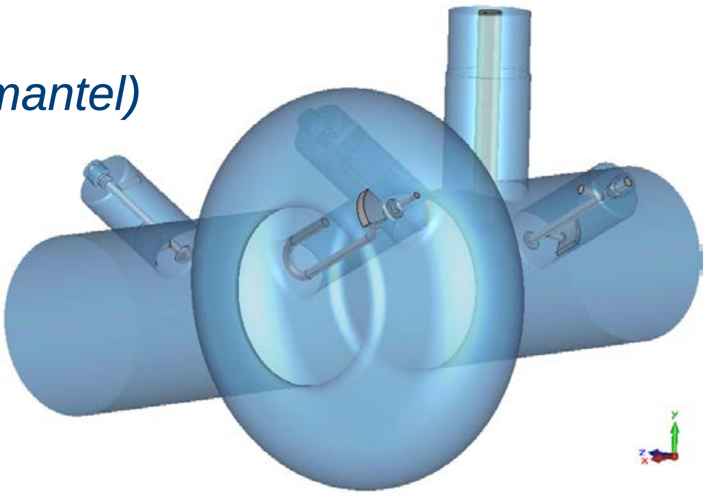

- Start design from 400 MHz LHC-ACS
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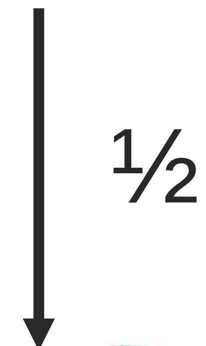
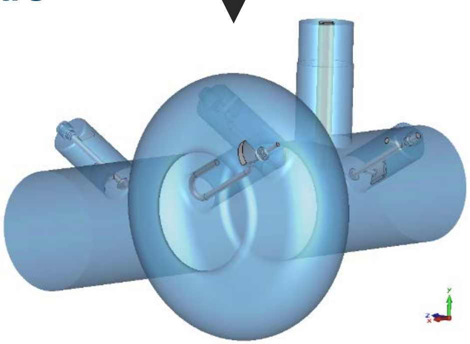
    - Cavity - HOM couplers

    - Power coupler - RF system



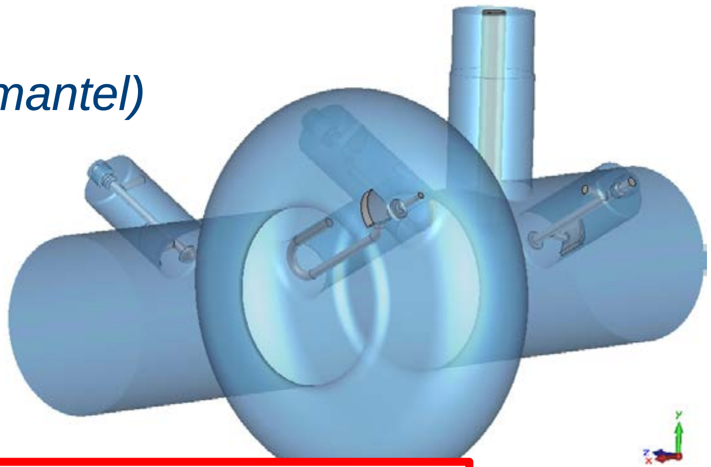
- Scale: ½ → Base line model for 800 MHz
- Not that simple: Not all optimised properties scale
  - o Cavity deformation (tuneability), HOM impedances
  - o HOM couplers



- Re-optimize

Motivation

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

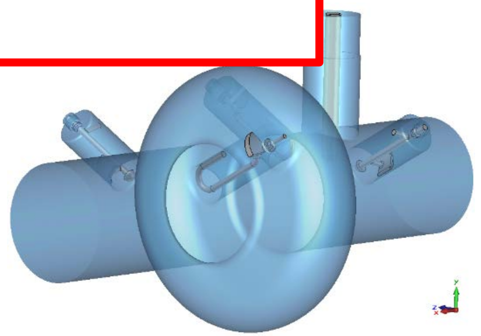


- Start design from 400 MHz LHC-ACS
  - Highly optimised for LHC (impedance, power)
  - Proved functionality and reliability in operation

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

½

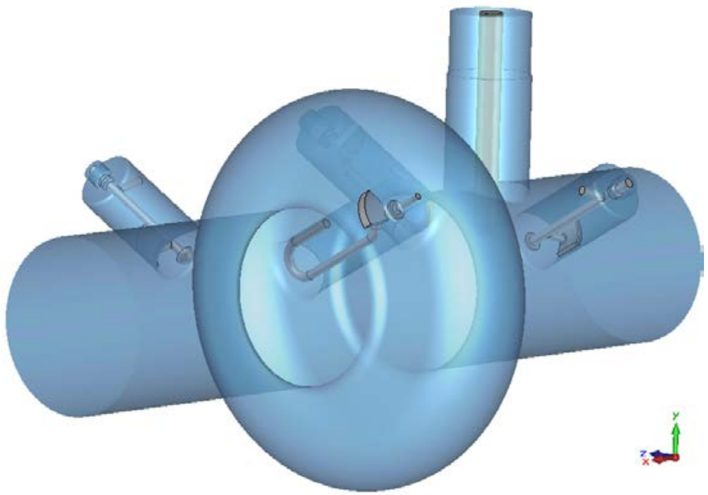
  - Low HOM impedances
  - Cavity deformation (tuneability)



- Re-optimize

Overview

- Motivation
- RF Cavity
- HOM couplers
- Power requirements
- Power coupler
- Power sources
- Cavity layout
- Heat load
- Other thoughts
- Conclusions & outlook



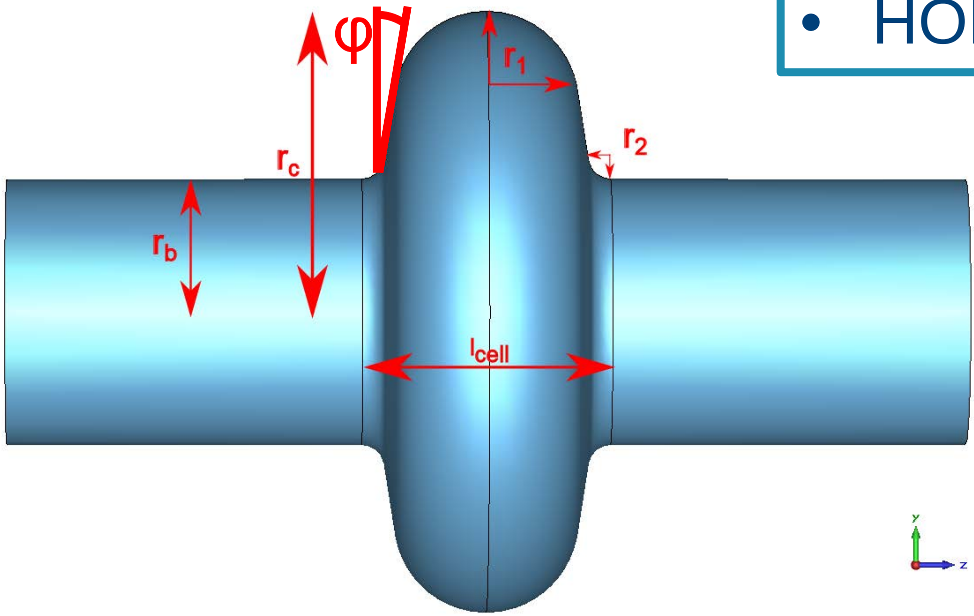
RF cavity

Parameter sensitivity study

- r_b, r_c, φ, r_1, r_2, l_{cell}

Goals:

- Deformable / tunable cavity
- High FM / low HOM impedances
- HOM freq. >> FM freq.
- HOM freq. above cut-off



RF cavity

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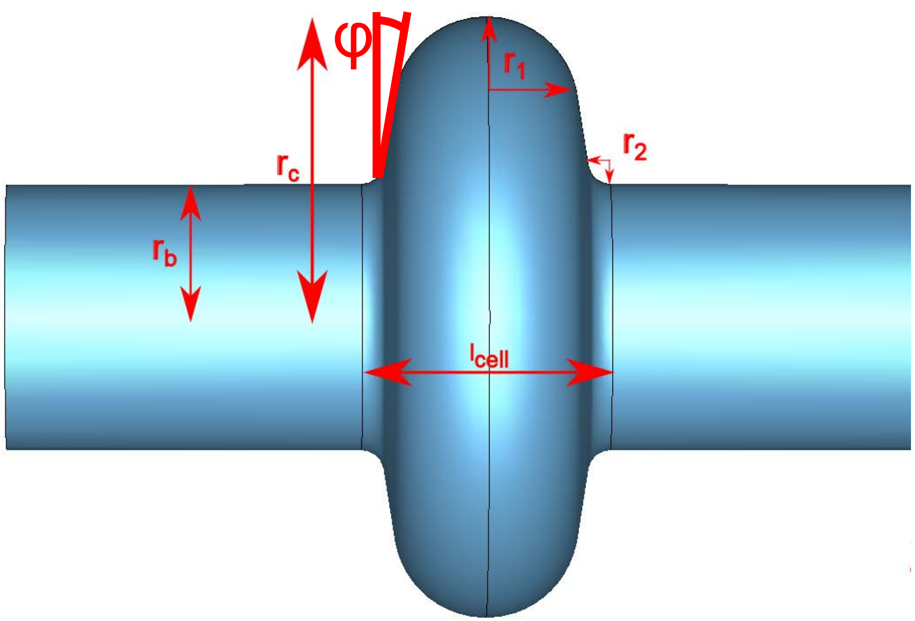
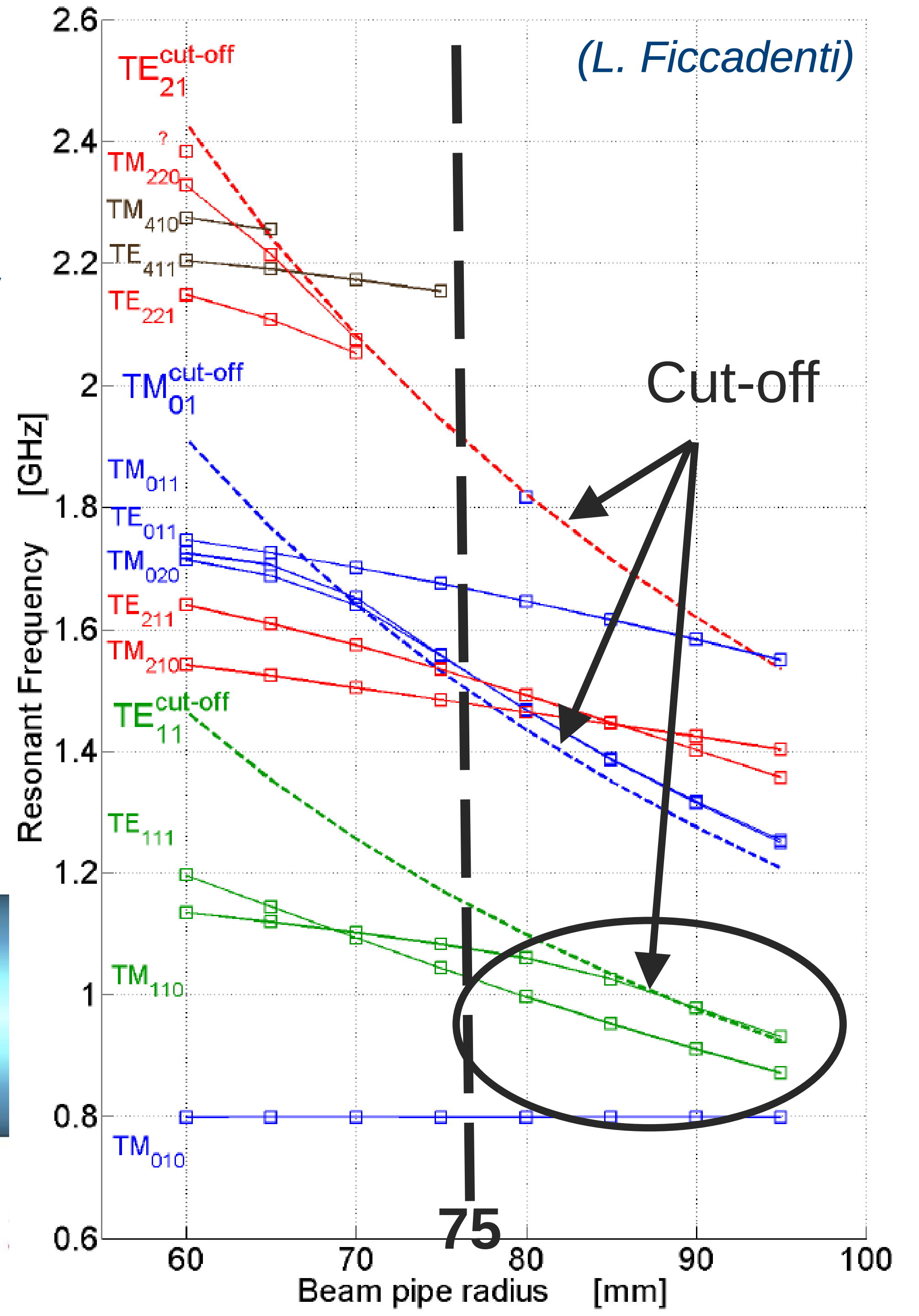
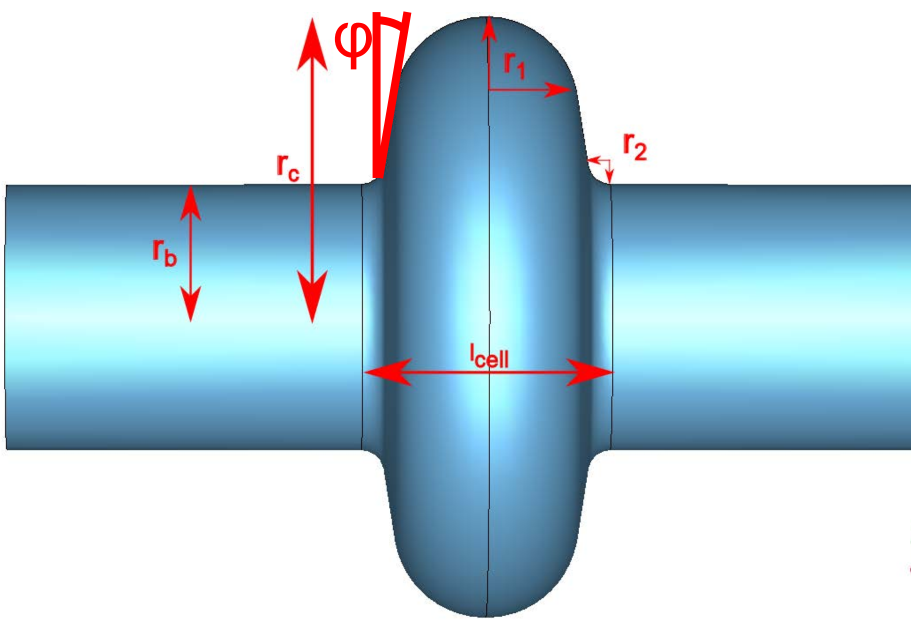


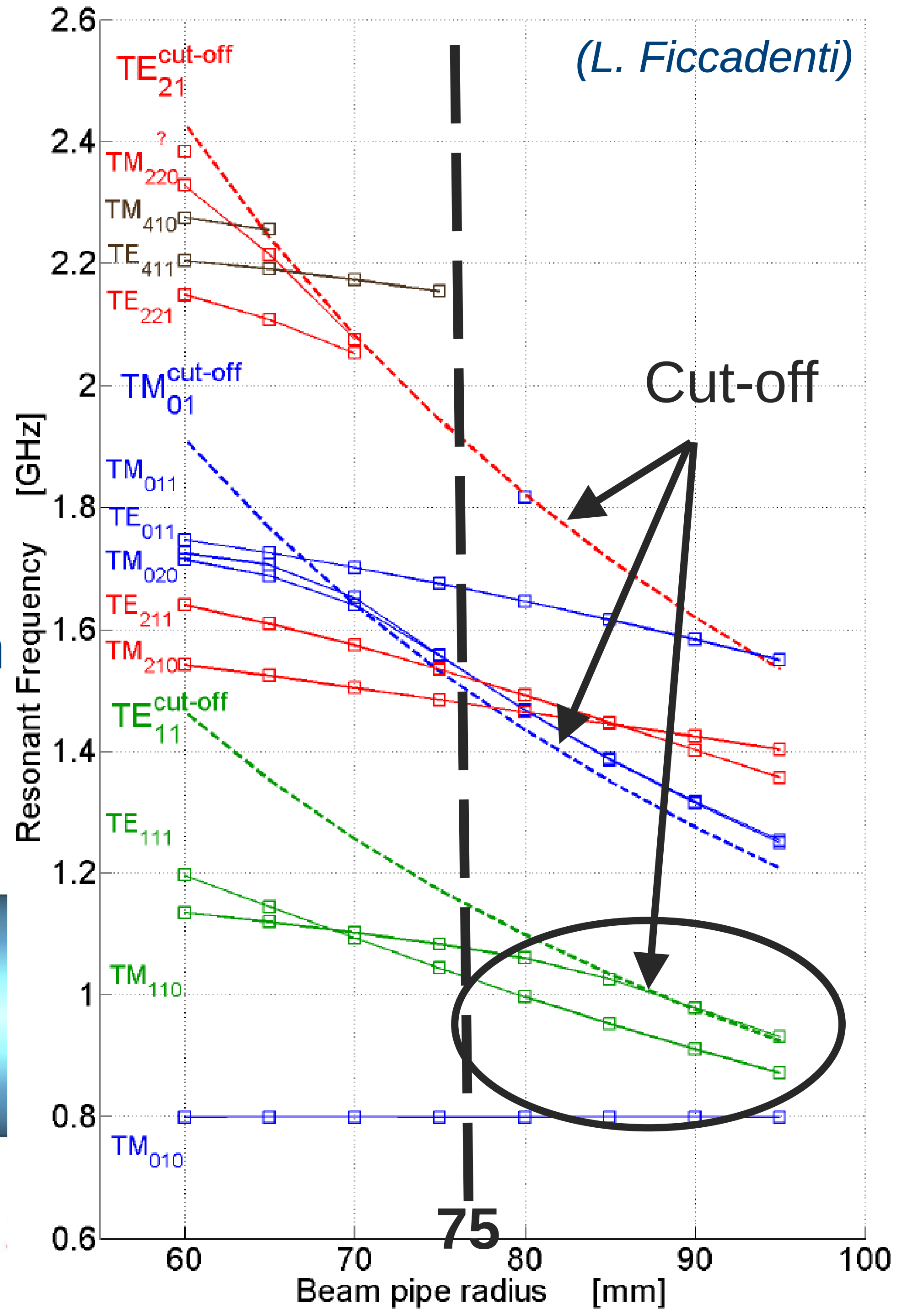


RF cavity

Parameter sensitivity study

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





RF cavity

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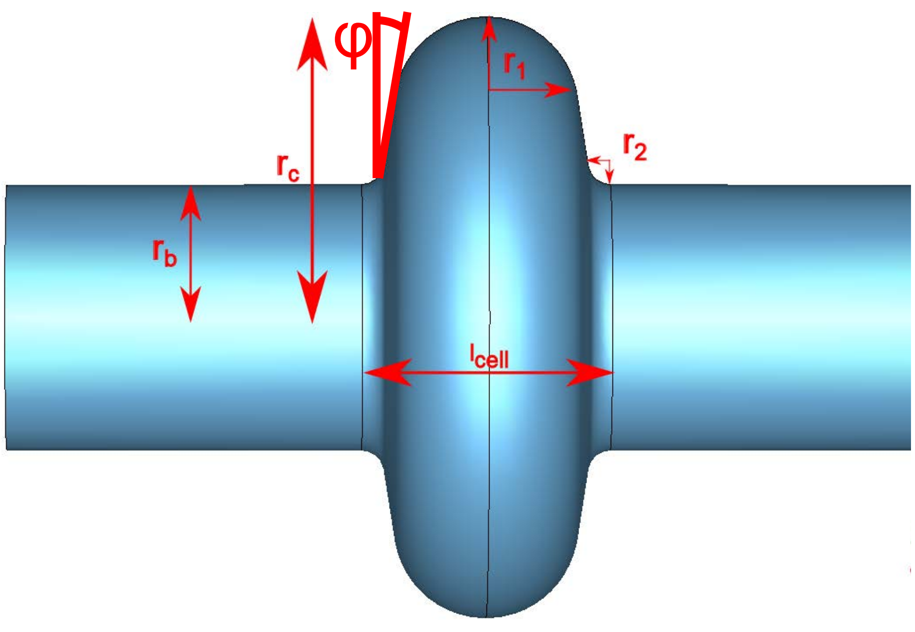
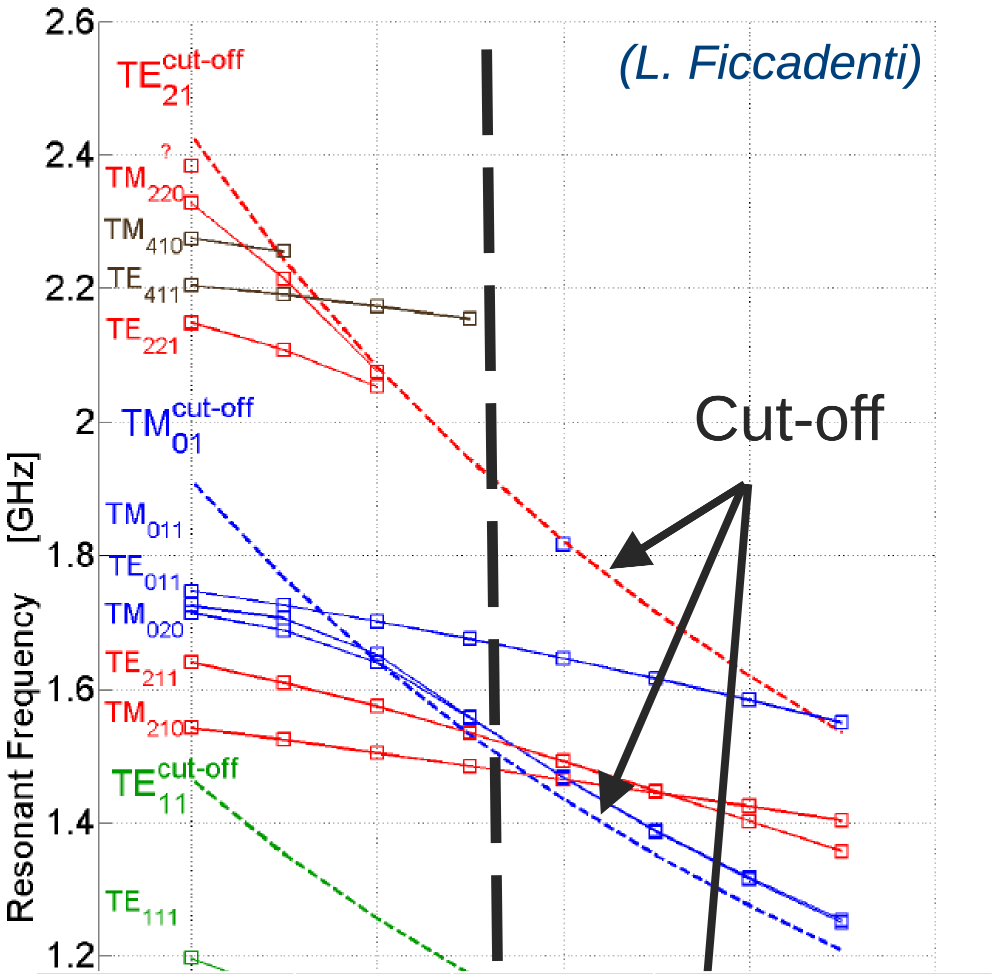




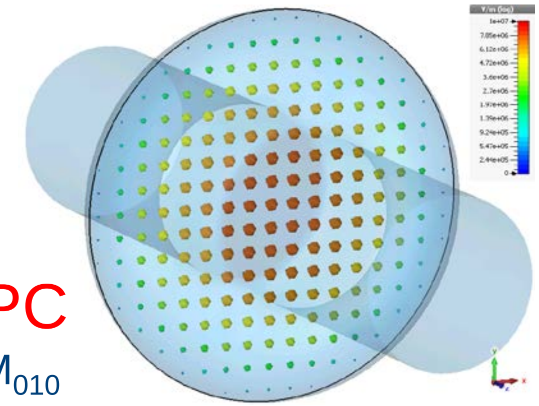
Parameter	[mm]	Spec.	Value
r_b	75	f	801.4 MHz
r_c	169.3	R/Q	45 Ω
r_1	52	E_p / V_{acc}	14.6 m^{-1}
r_2	12.5	H_p / V_{acc}	28.2 mT / MV
l_{cell}	140		

HOM couplers

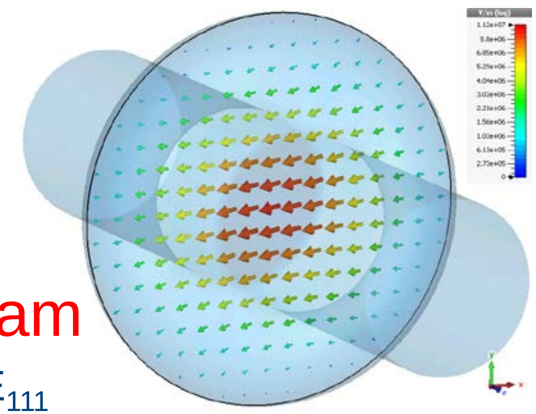
Why do we need HOM couplers?

Below cut-off

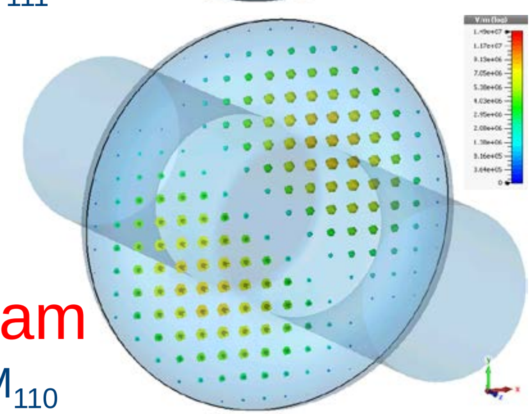
HOM	f [MHz]	$R/Q_{\parallel}$ [Ω]	$R/Q_{\perp}$ [Ω]	Q_0	Angle [º]
TM_{010}	801.4	45	≈ 0	30800	-
TE_{111}	1047	0.2	2.3	36600	0 + 90
TM_{110}	1087	1.4	13.6	36900	0 + 90
TM_{210}	1488	≈ 0	0.1	40500	0 + 45
TE_{211}	1541	≈ 0	≈ 0	39000	0 + 45
TM_{020}	1616	3.0	0.1	42200	-
TM_{011}	1630	24	0.2	32400	-
…	…	…	…	…	…



FPC
TM_{010}



Beam
TE_{111}



Beam
TM_{110}

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

HOM couplers

Why do we need HOM couplers?

Below cut-off

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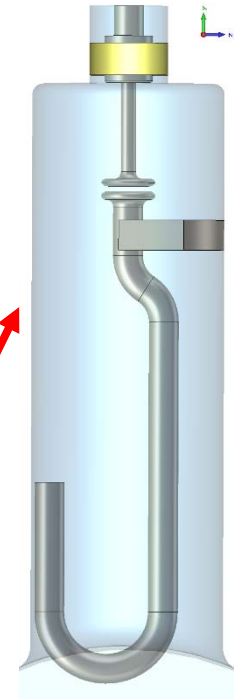
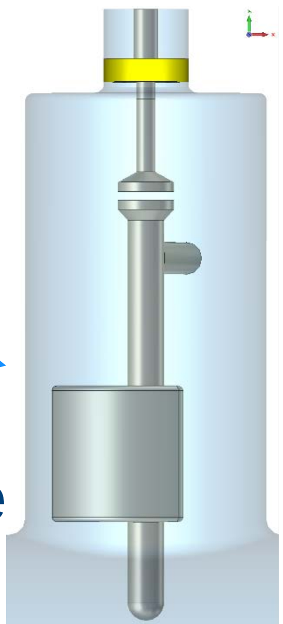


Hook type coupler

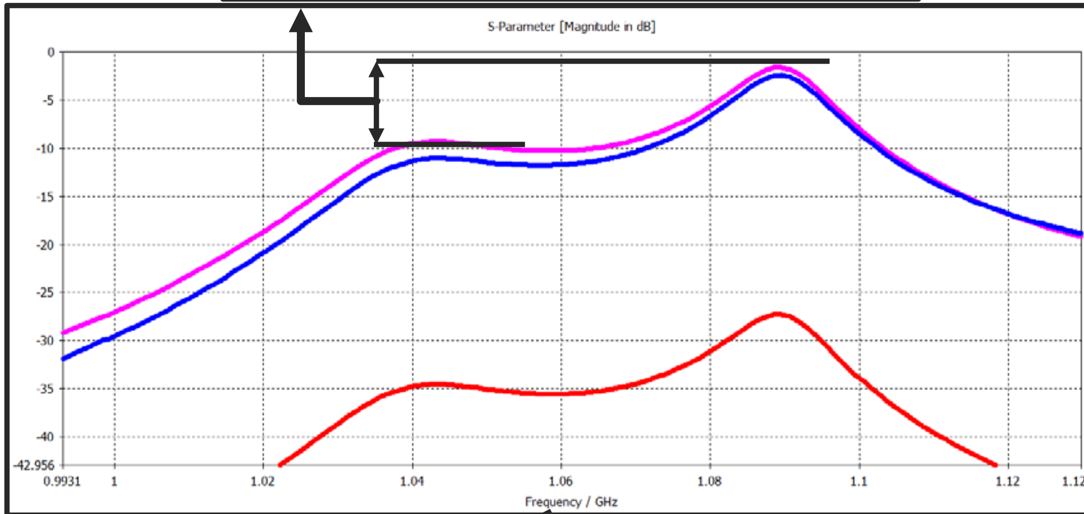


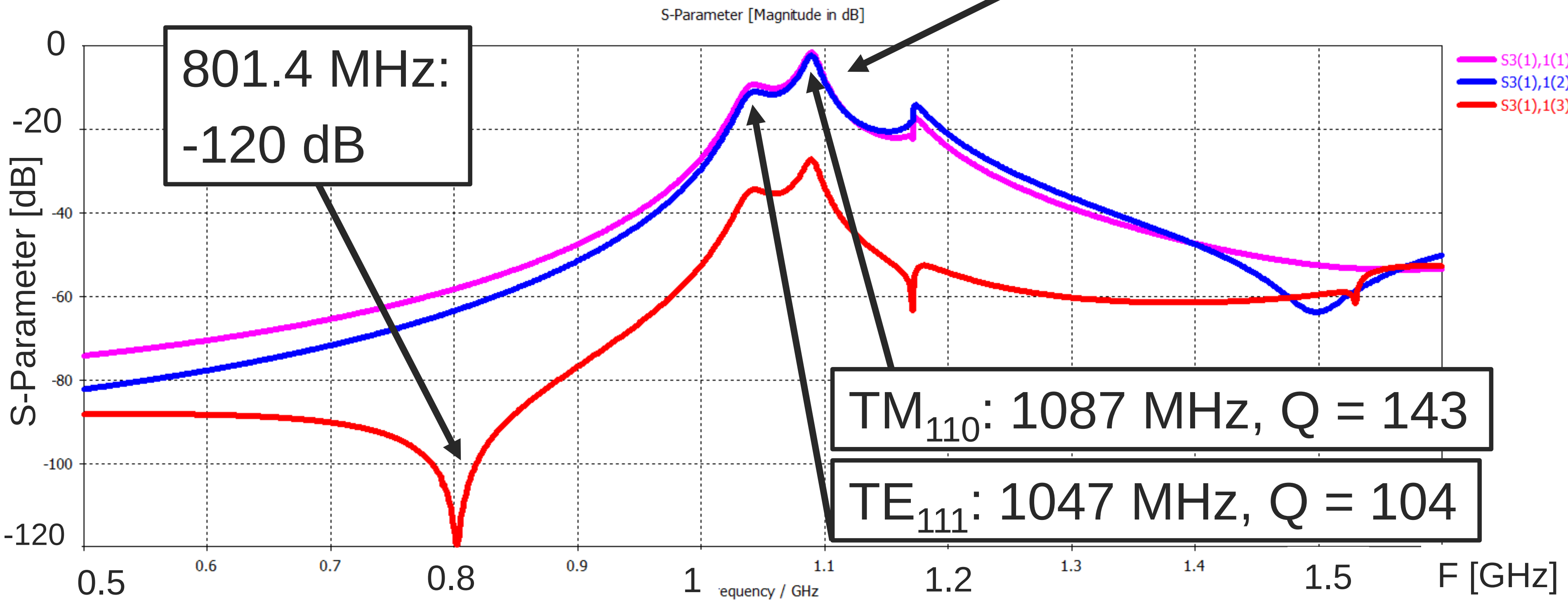
Probe type coupler

HOM couplers

- Hook type:

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





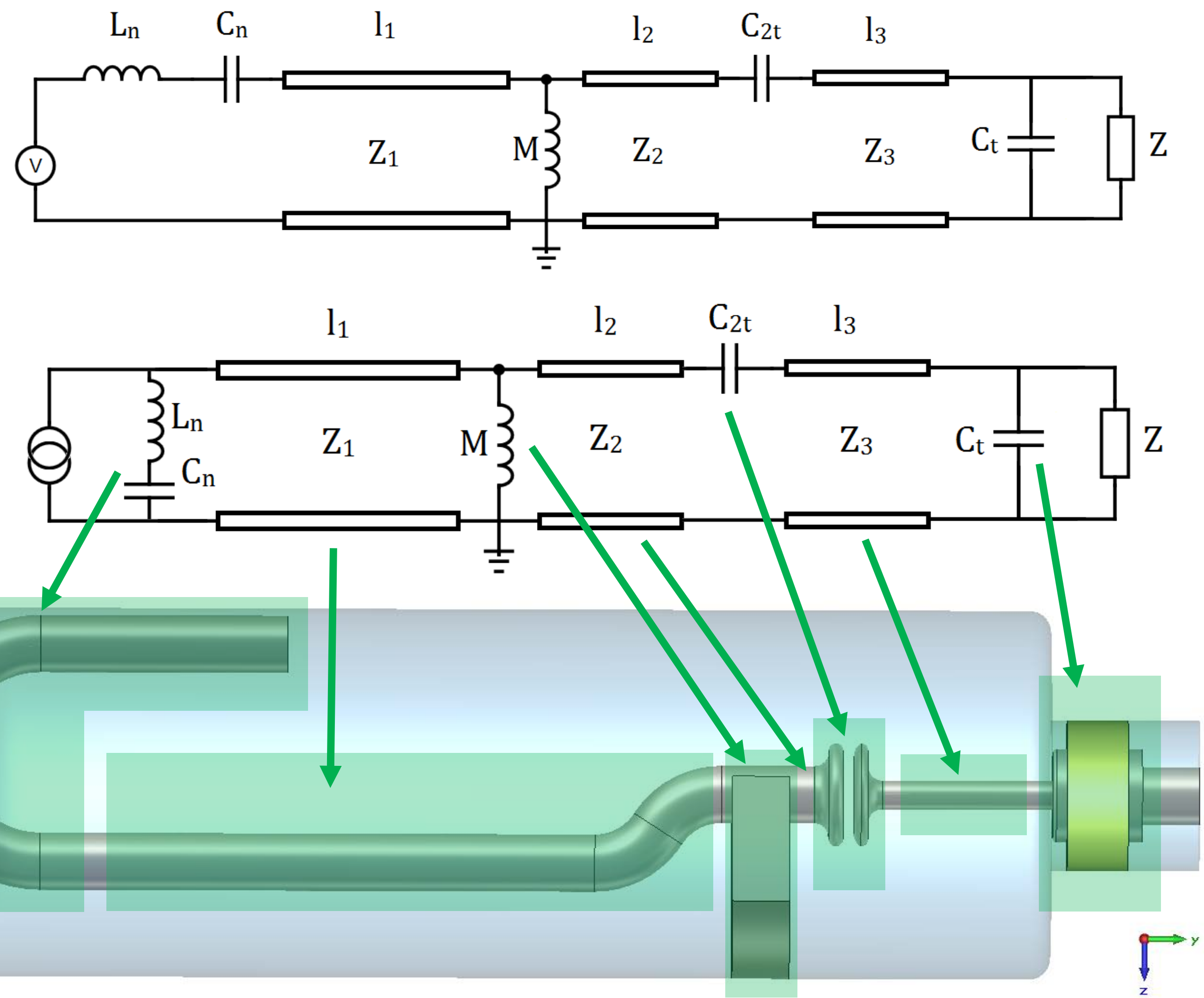
(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

- Hook type:

TM_{01} mode:
Magnetic Coupling

TE_{11} mode:
Electric Coupling



TM_{01} **B**
TE_{11} **B**
FM

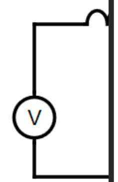
(F. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

- Tuning procedure:
  - Equivalent circuit
  - Component optimisation based on S_{21} curve
  - Convert to 3D model
  - EM simulations: Fine tuning (3D components)

- Hook type:

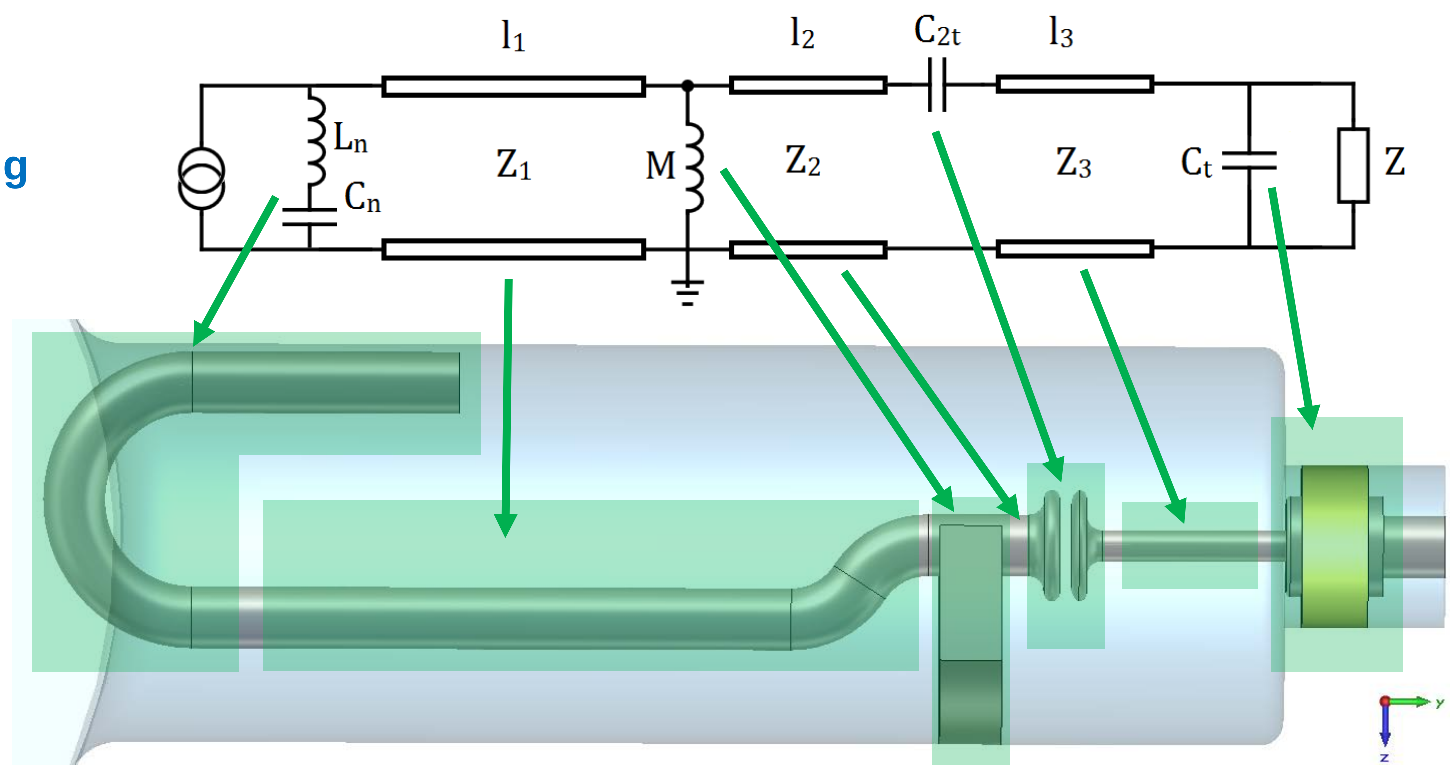
TM_{01} mode:
Magnetic Coupling



TE_{11} mode:
Electric Coupling

TM_{01}
TE_{11}
FM

B B

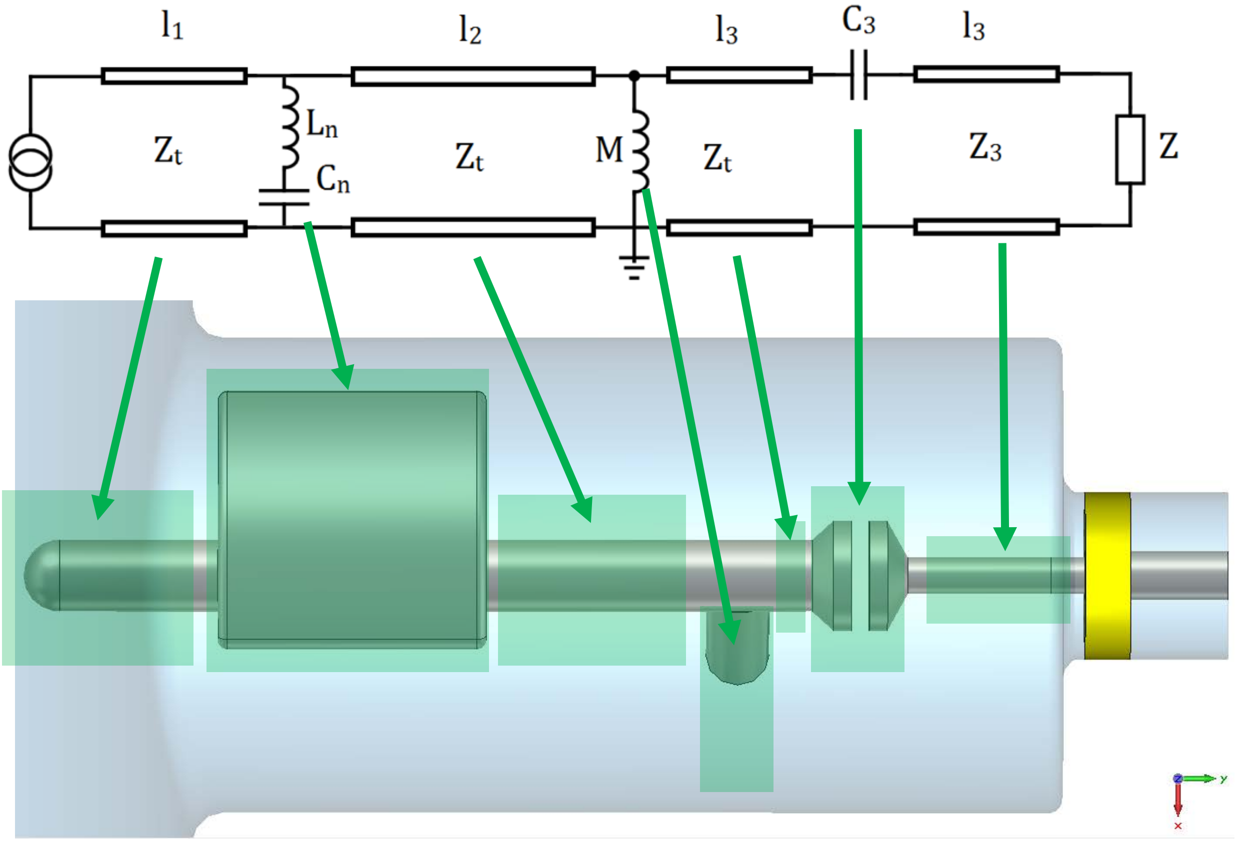


(E. Haebel, V. Rödel, F. Gerigk, Z.T. Zhao)

HOM couplers

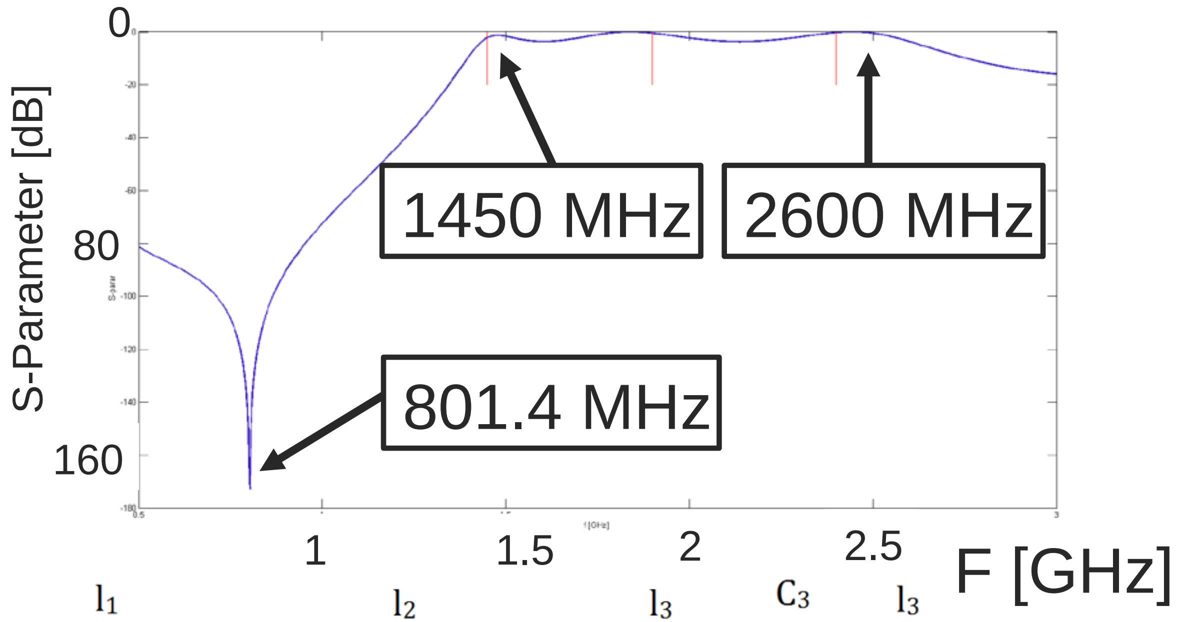
- Probe type: Equivalent circuit

TE_{11} mode:
Electric Coupling



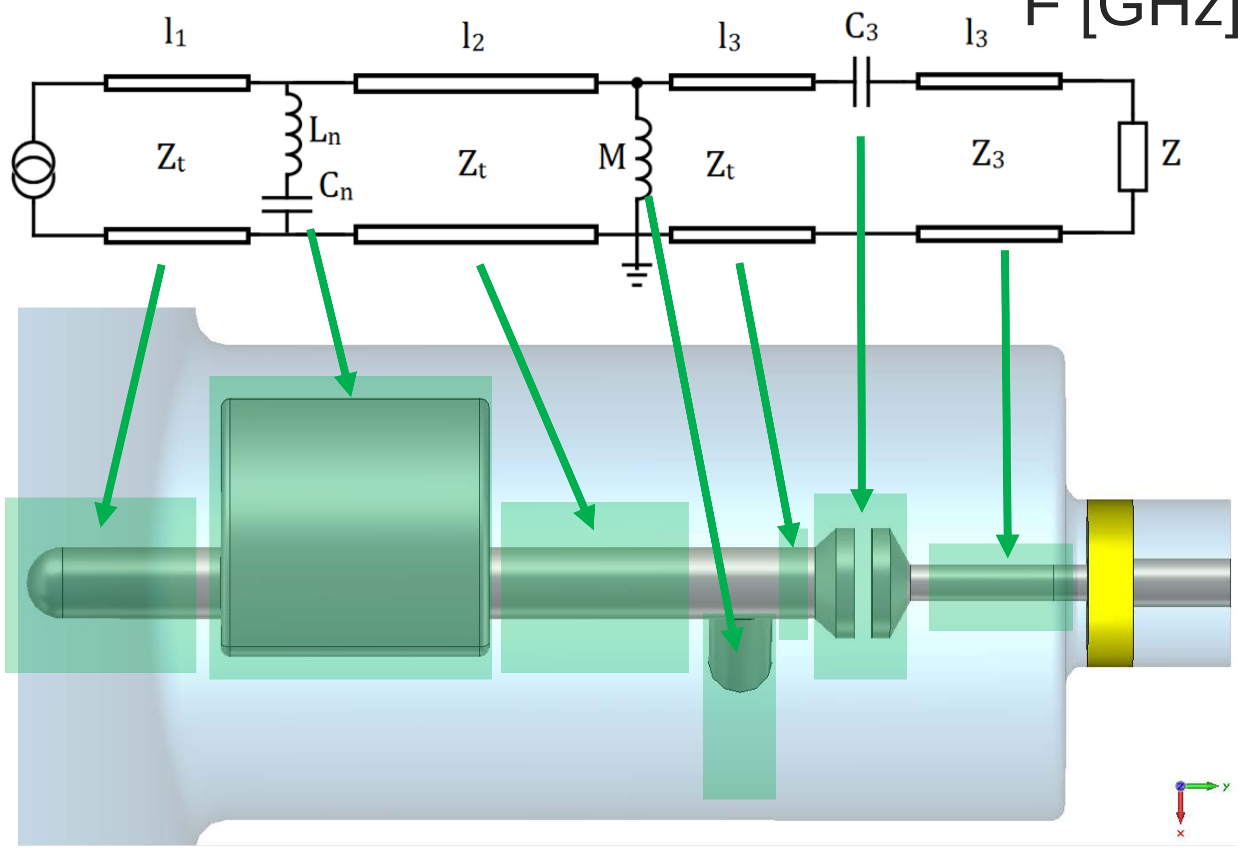
HOM couplers

- Probe type:



TE$_{11}$ mode:

Electric Coupling



Power requirements

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

- V(t) and RF peak power constant → = Imposed = requires power

→ Fixed bucket distance

(zero phase modulation: $\varphi = 180^o$)

→ (no) beam: Const. P_{peak}

→ Limitation: Available $P_{peak} < 300$ kW

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

- Keep klystron current real (with RF feedb & 1T-feedb: define set point.) = Allow beam to modulate phase ($\varphi(t)$ instead of $\varphi = 180^o$)
- Result:
  - Non equally spaced bunches
  - Minimized klystron power demand if $\varphi(t)$ centred around zero.

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

Power requirements

800 MHz harmonic system: "Full detuning scheme" *(P. Baudrenghien)*

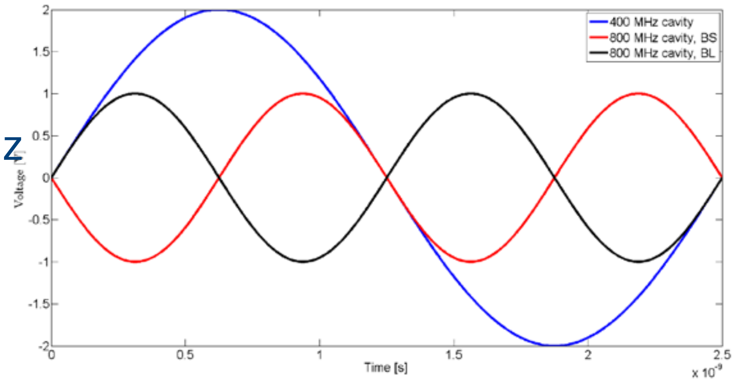
- Imposed: $V_{800,total}$ = 8 MV = 0.5 x $V_{400,\ total}$
- Imposed: Follow phase modulation φ(t) of 400 MHz
  - BS: Power reduction
  - BL: Power increase
- Take into account 300 kW power limit
- BL mode: Reduce V_{800} = 1.0 MV → 0.8 MV

  → more cavities: 8 → 10

  - P ≈ 290 - 300 kW
  - BS mode P ≈ 175 kW (fixed coupler)
  - BS mode P ≈ 57 kW

    + 1.4 MV in cavity (variable coupler)
- More power required: - Shorter bunches

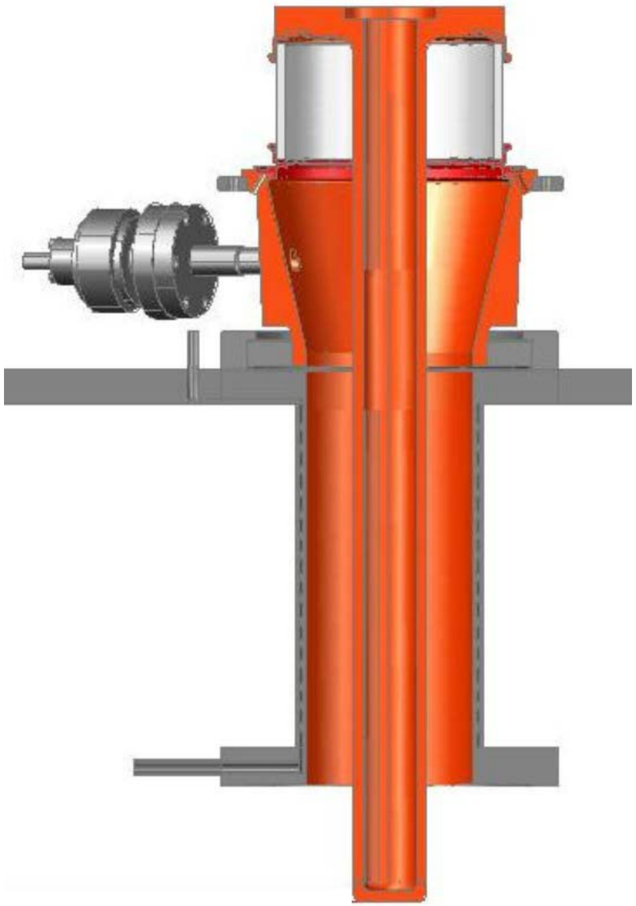
  - Shorter bunch spacing
  - More p^+



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

Power coupler

- Requirements:
  - → movable (fixed)
  - → Q_{ext} range (TBD)
  - → CW Power > 300 kW +20%
    - (↔ 300 kW limit)
  - → Size: Ø 100 mm
- Start from SPL- like design:
  - → > 300 kW +20%
  - → Challenge 2 ?
  - → Challenge 3 ?

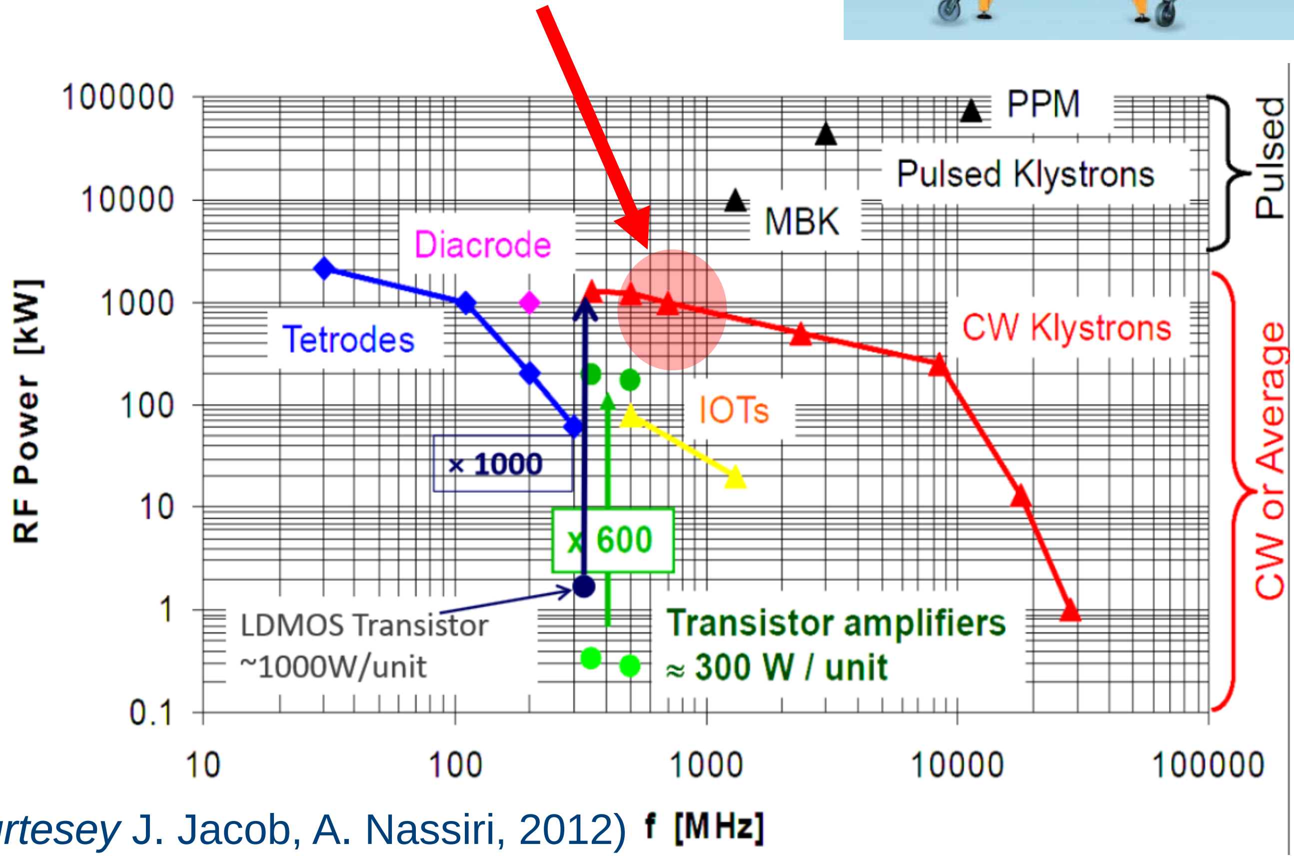


SPL power coupler design (Courtesy: E. Montesinos)

Power sources

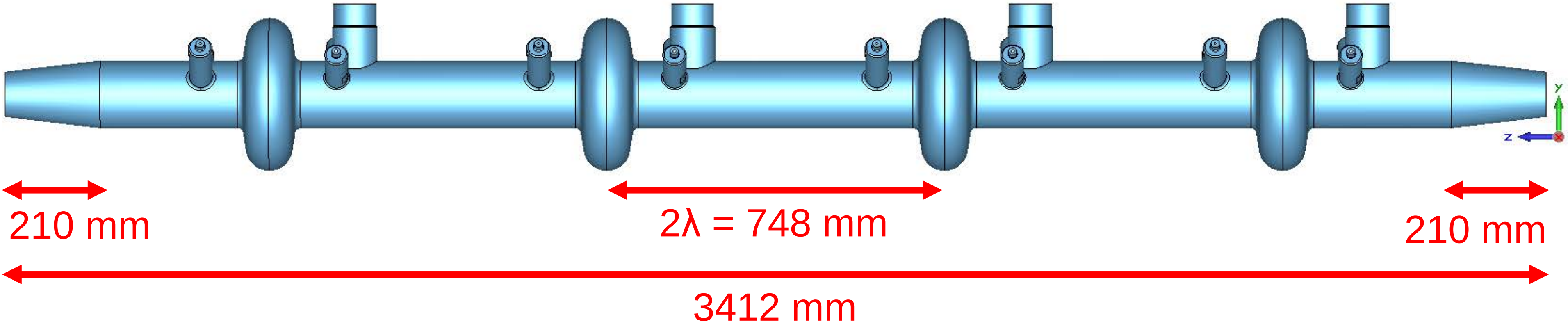
Klystron for the 400 MHz
ACS System: 300 kW
Thales TH 2167.

- > 300 kW + 20%
- CW
  - Klystrons?
  - IOT?
  - Tetrodes?



(*Courtesey* J. Jacob, A. Nassiri, 2012)

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 ↔ 10 m)
- Dimensions subject to change → detailed engineering

(Courtesy: R. Calaga)

Heat load

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

(Courtesy: R. Calaga)

Other thoughts

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

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

(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)

Conclusions & outlook

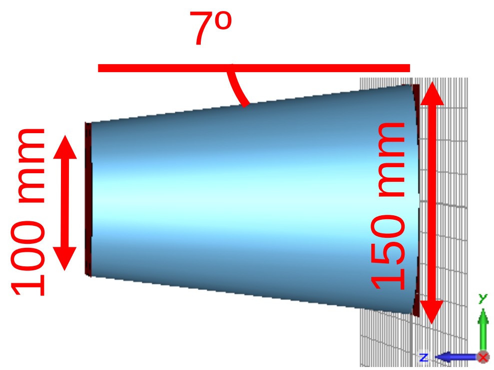
- Conclusions:
  - RF Cavity: EM design optimised for 800 MHz
    HH system
  - HOM couplers: Tuned to 800 MHz specifications
  - Power requirements: "Full detuning" scheme: V_{800} = 0.8 MV
    $P_{BL} \approx$ 300 kW, (>> P_{BS})
  - Power coupler: Movable & > 300 kW + 20%
    (↔ 300 kW limit + size)
  - Power sources: TBD (Klystrons)
  - Cavity layout: #10 cells / beam, spacing 2λ (↔ 10 m)
  - Heat load: 35 W/cavity (4.5 K)

Conclusions & outlook

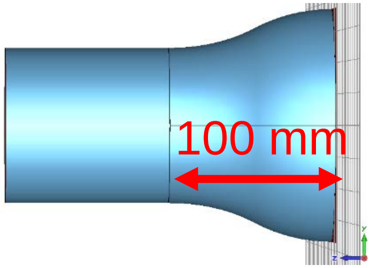
- Outlook:
  - Build prototype: 2-cavity 800MHz (Nb-Cu)
  - Power coupler design
  - Operational challenges
  - Cavity/RF system failure procedure

Appendix

- Tapers:



Scaled version: 210 mm



Special taper: 105 mm

Equal transmission characteristics

Engineering difficulties?

Deformation → sensitivity?