Cavity R&D as part of optimizing the FCC Colliders

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SY/RF/SRF

26-Jan-2021

Snowmass

AF7 – Subgroup RF – miniWorkshop on Innovative Design and Modeling

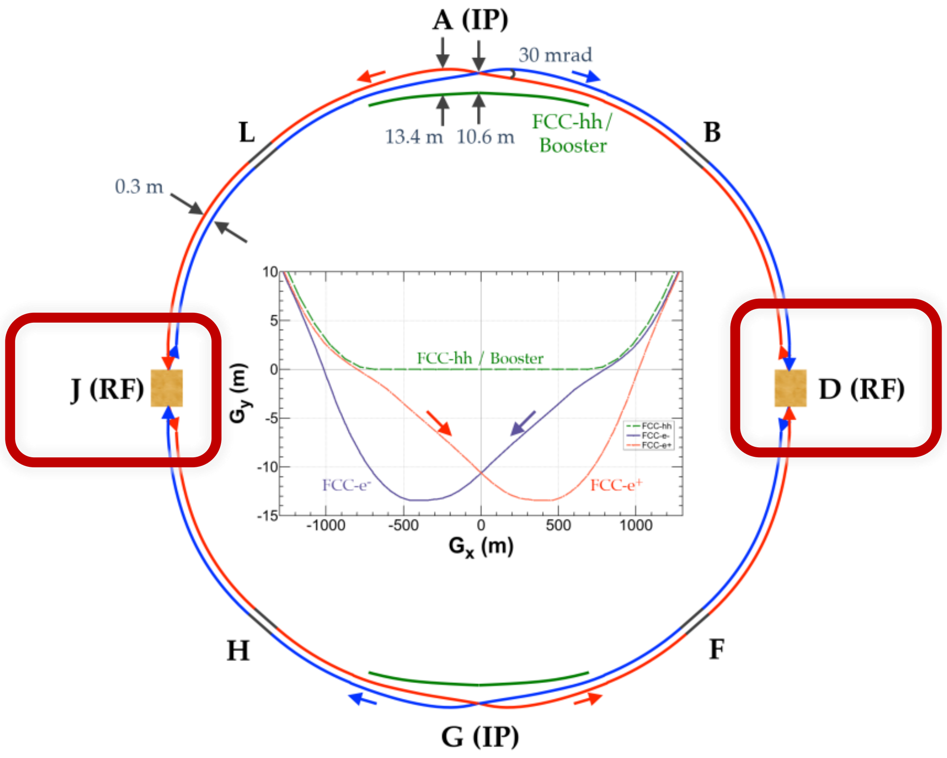
RF systems in the FCC tunnel

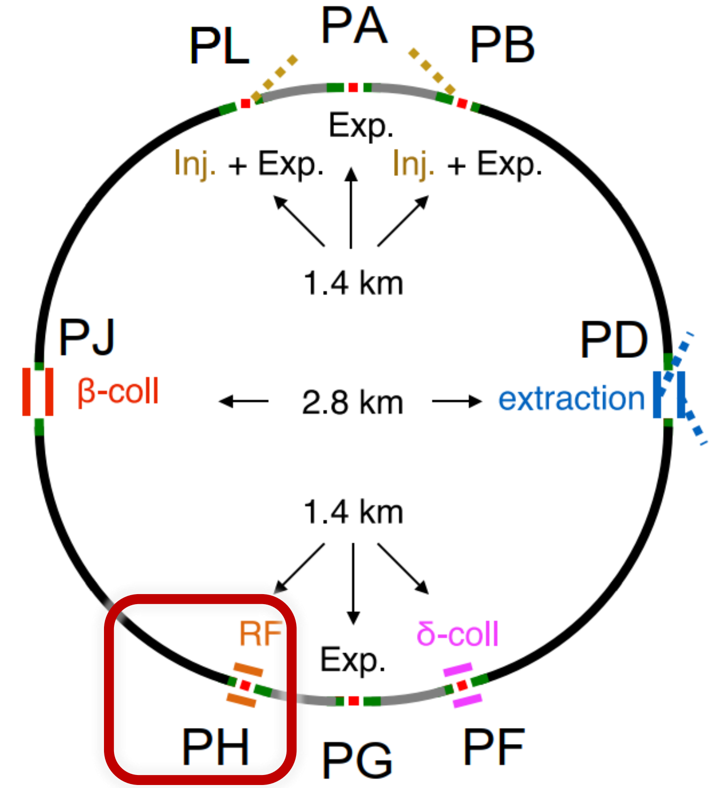
FCC ee

- Point J and point D are straight sections dedicated to RF cavities and klystrons
- Involve 1364 cavities in total
- Total length of straight section without kickers: 2.2 km

FCC hh

- The RF system is similar to the one of LHC
- Total voltage of 48 MV (24 LHC type cavities)

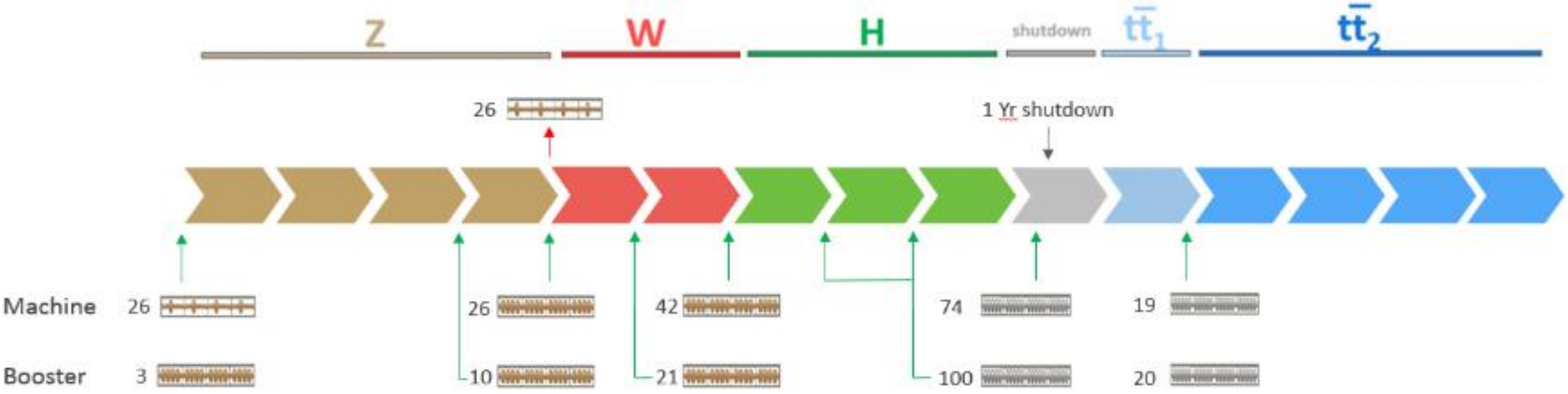




FCCee RF system baseline

WP	V_{rf} [GV]	#bunches	I_{beam} [mA]
Z	0.1	16640	1390
W	0.44	2000	147
H	2.0	393	29
ttbar	10.9	48	5.4

- **Designed for fixed synchrotron radiation power of 50 MW per beam**
- **Elliptical shape cavities in CW mode**



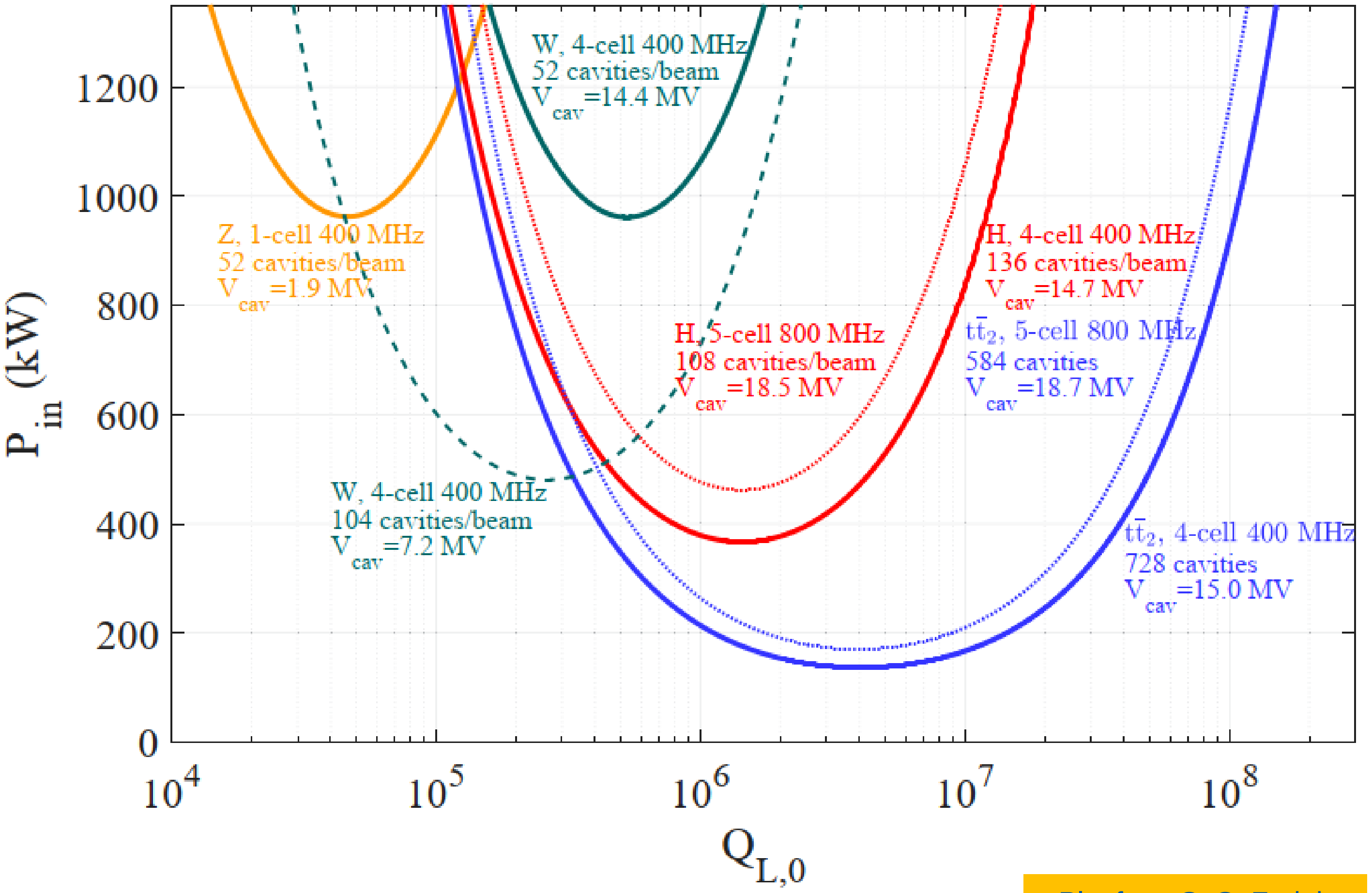
- **400 MHz 1-cell cavities**
- **Nb/Cu, 4.5 K**
- **104 cavities**
- **Eacc=5 MV/m**
- **1 MW /cav**
- **4 cav./cryom.**
- **Re-used for FCC-hh**

- **400 MHz 4-cell cavities**
- **Nb/Cu, 4.5 K**
- **408 cavities**
- **Eacc=10 MV/m**
- **1 MW to 200 kW per cav.**
- **4 cav./cryom.**

- **800 MHz 5-cell cavities**
- **bulk Nb, 2 K**
- **852 cavities**
- **Eacc=20 MV/m**
- **200 kW/cav.**
- **4 cav./cryom.**

RF power & FPC coupling requirements

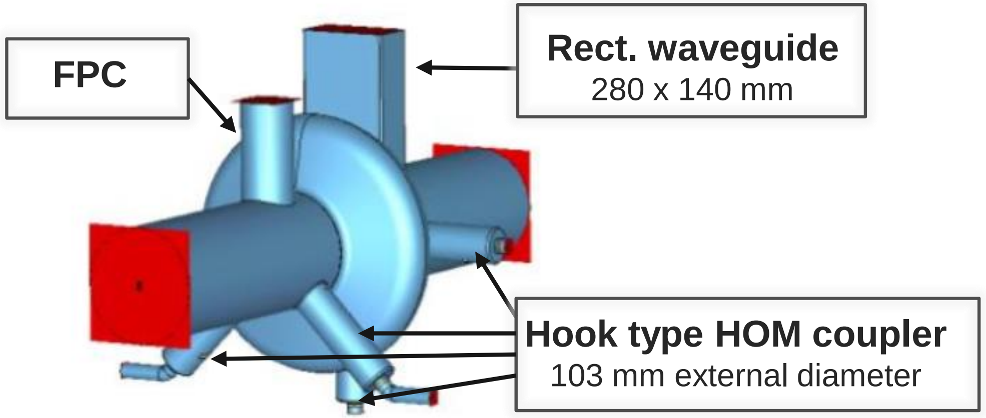
- The FCCee RF system baseline design requires the development of different types of klystrons, delivering different RF power levels (from 200 kW to 1 MW)
- Variable RF Fundamental Power Couplers (FPC) at 1 MW are also needed
- It will be necessary to switch back from H to Z operation at lower beam current, in order to perform physics calibration

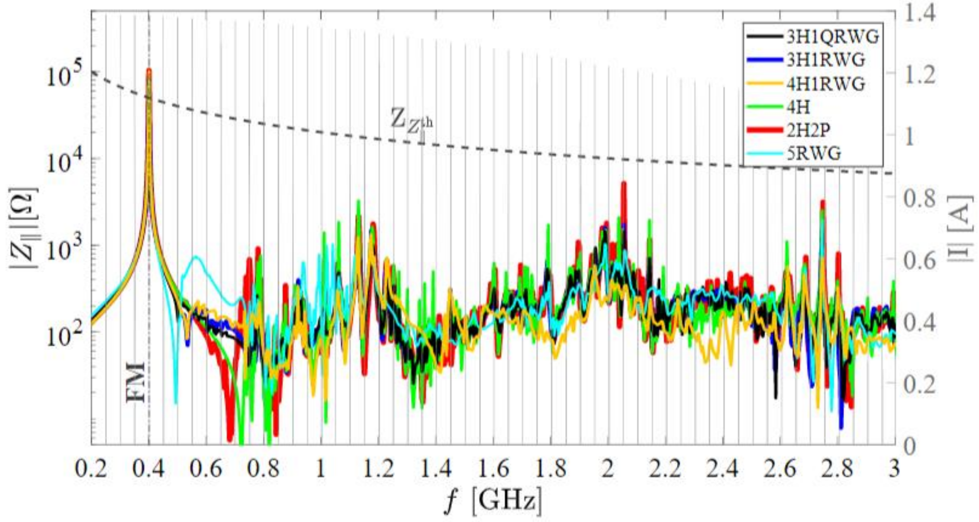


Plot from S. G. Zadeh (University of Rostock)

Cavity Design for the Z machine

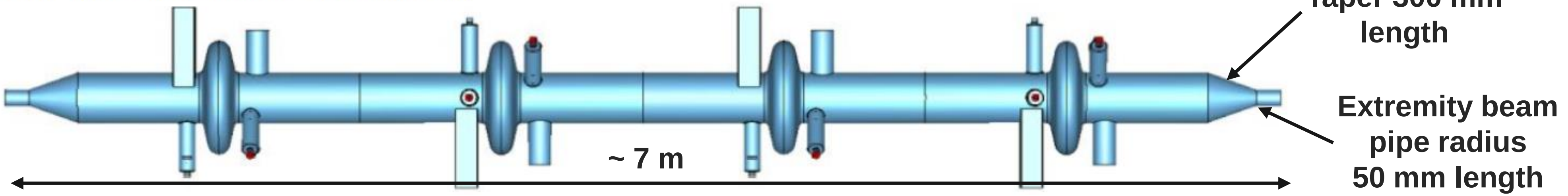
- First step for FCCee
- Single cell elliptical cavity, strongly damped for high current operation (1.39 A)
- Studied by S. G. Zadeh (Univ. of Rostock)





(c) Longitudinal impedance of the four-cavity module with tapering

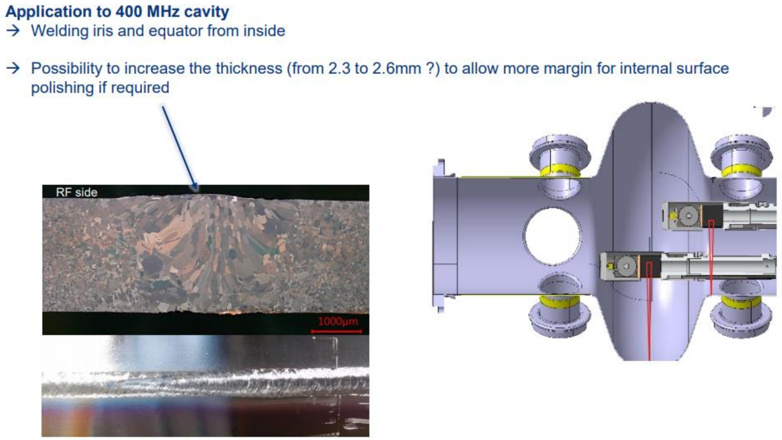
- ✓ F = 400.79 MHz
- ✓ Eacc = 5.1 MV/m
- ✓ Vcav = 1.9 MV
- ✓ P_{input} = 1 MW



Cavity fabrication technologies R&D

Improvement of engineering technics of elliptical coated copper cavities

- Half cells manufacturing
- Seamless technics
- Internal electron beam welding
- Chemical electropolishing



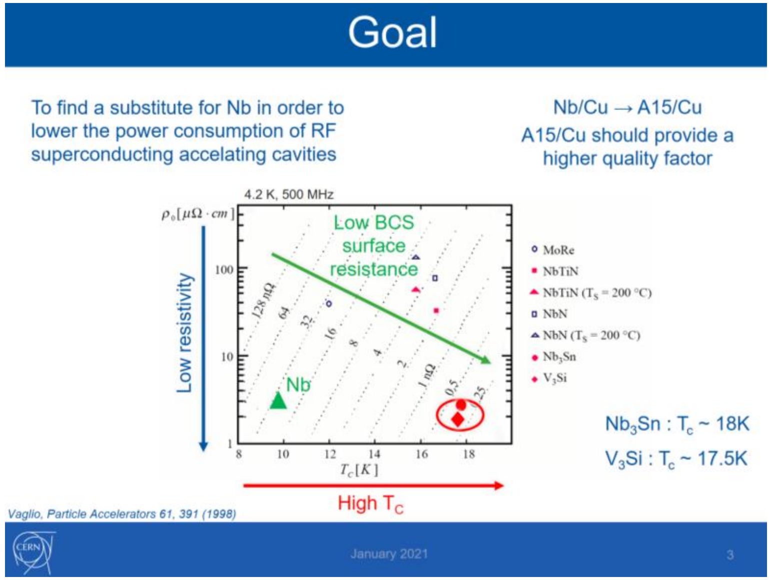
T. Demazière, G. Fabre (CERN)

Improvement of thin film deposition technics of RF superconductors

- Niobium on Copper sputtering
- HIPIMS
- A15 on copper

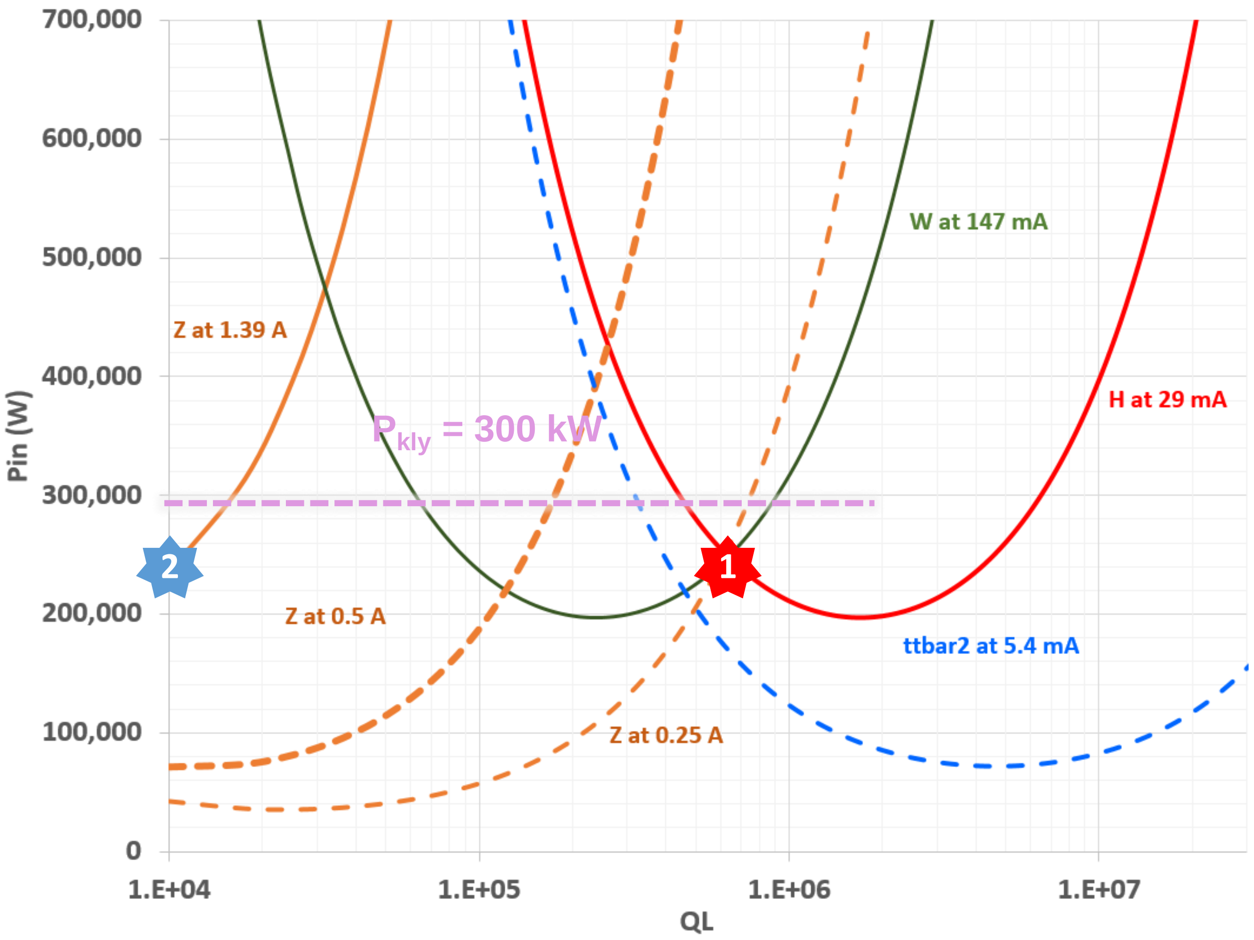
→ See talk at TTC meeting – Stephanie Fernandez (CERN) (21th of Jan. 2021)

TTC 2021, TESLA Technology Collaboration (19-21 January 2021): Nb3Sn and V3Si as thin films on Cu toward SRF applications (15+5) · DESY-Konferenzverwaltung (Indico)



Challenging the high level RF parameters of FCCee

Can we find an alternative cavity design to optimize the whole RF system configuration and operation ?

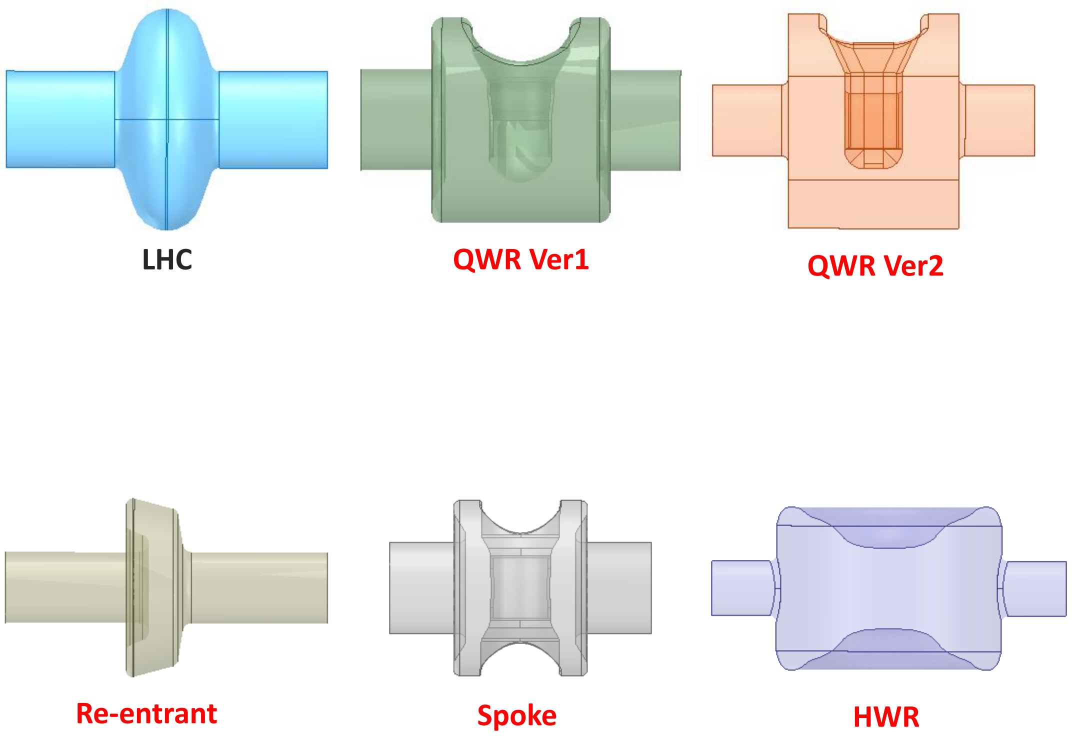


- **Changing of the cavity parameters brings very interesting opportunities**
- **For example:**
  - Point 1 : Q_L=6e5, P_{in} =250 kW
    - H energy at nominal current
    - W energy at nominal current
    - Z energy at 0.25 A (for physics calibration)
  - Point 2: Q_L=1e4, P_{in} = 240 kW
    - Z energy at nominal current
  - Spanning Q_L from 1e4 to 6e5 with a 100 mm variable FPC is typically equivalent to 60 mm range antenna displacement (same as LHC cavities)
  - Common RF input power of 300 kW for the klystrons (same as LHC klystrons)

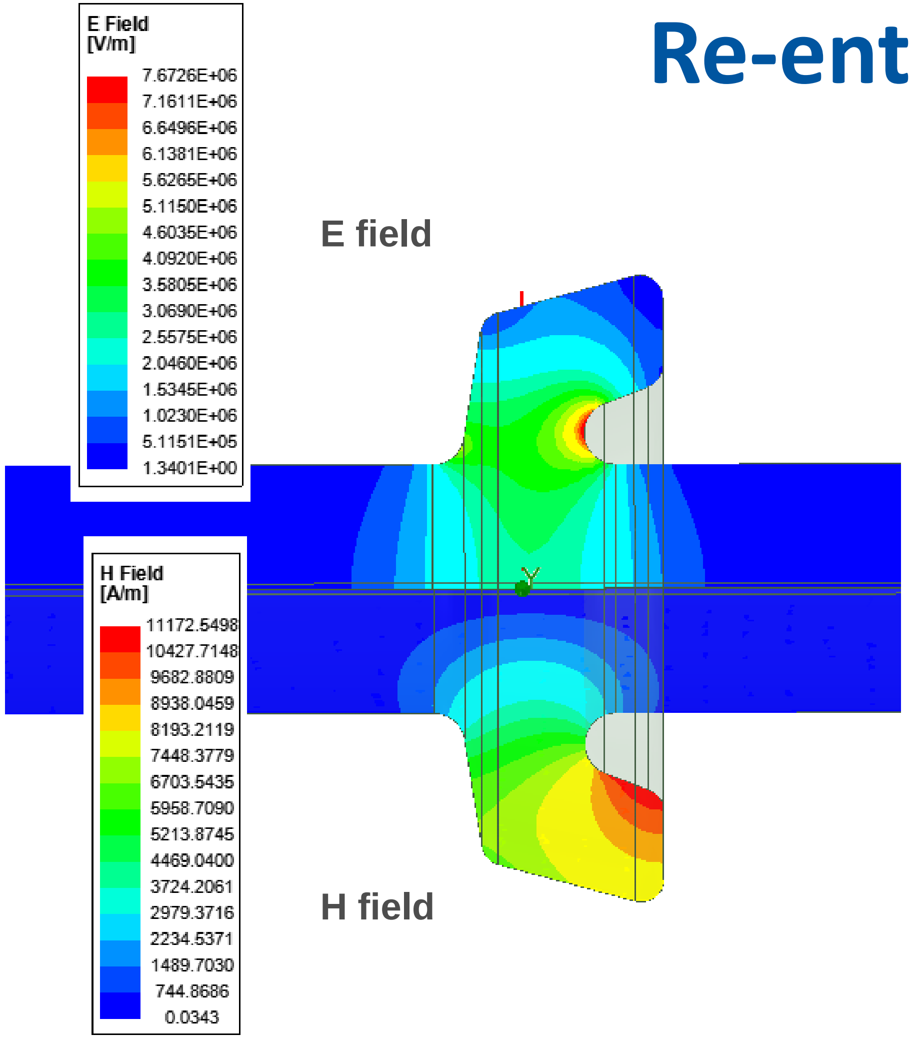
Alternative cavity design studies

- Tentative design of various cavity shapes
- Peak fields optimization at fixed r/Q

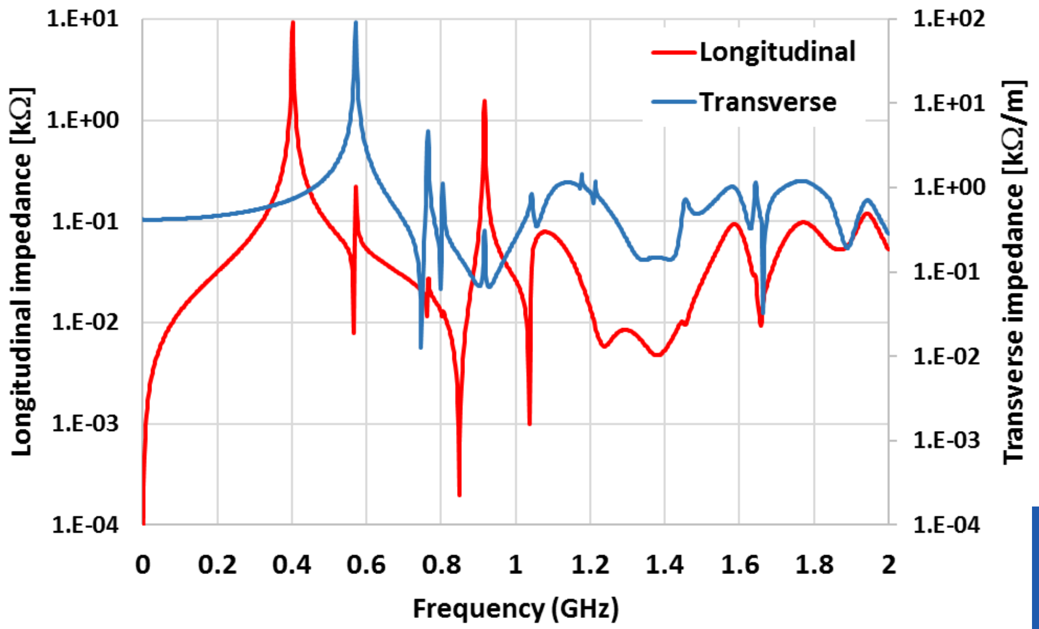
Parameters	LHC	HWR	Re-entrant	QWR Ver1	QWR Ver2	Spoke
Frequency [MHz]	400.79					
Operating temperature [K]	4.5					
Nominal Accelerating Voltage $V_{acc} = (E_{acc} \times L_{acc})$ [MV]	4					
Accelerating gradient E_{acc} [MV/m]	10.6					
Circuit r/Q [Ω] at $\beta=1$	42.7	41.9	44.33	46.69	44.8	63.25
E_{pk}/E_{acc} at $\beta=1$	2.4	2.15	6.05	3.92	3.97	3.85
B_{pk}/E_{acc} [mT/(MV/m)] at $\beta=1$	5.08	5.25	11.05	7.22	7.31	10
Max. surface field E_{pk} [MV/m]	25.7	23	64.7	42	42.77	41.14
Max. surface magnetic field B_{pk} [mT]	54.3	56.3	118.2	77.4	78.88	106.75
Stored energy [J] at nominal E_{acc} and $\beta=1$	74	76	71.48	67.8	70.3	50.32
Aperture [mm]	300	170	220	313.5	220	283.7
Cavity envelope [mm]	688	790	556	637	665	543.8



Re-entrant cavity



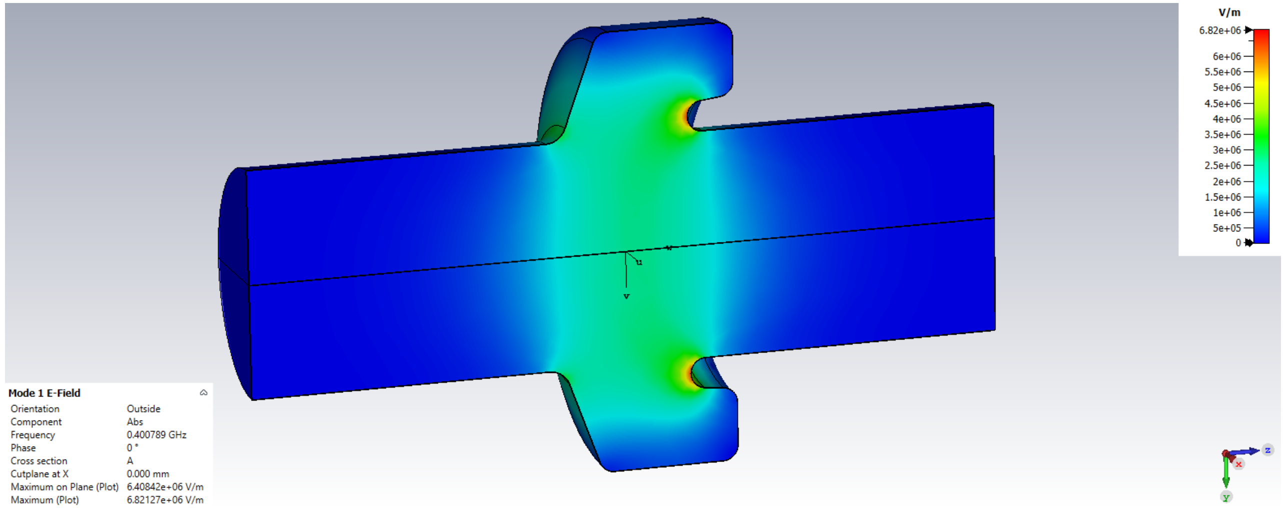
Parameters	LHC	Re-entrant cavity	
Frequency [MHz]	400.79	401.8	
Nominal Accelerating Voltage [MV]	2	2	4
Circuit r/Q [Ω] at β=1	42.7	44.33	
G [Ω]	256.9	126.7	
E_{pk}/E_{acc} at β=1	2.4	6.05	
B_{pk}/E_{acc} [mT/(MV/m)] at β=1	5.08	11.05	
Max. surface field E_{pk} [MV/m]	12.85	32.43	64.87
Max. surface magnetic field B_{pk} [mT]	27.11	59.23	118.45
Stored energy [J] at nominal E_{acc} and β=1	18.5	17.87	71.48
Aperture [mm]	300	220	
Cavity envelope [mm]	688	556	



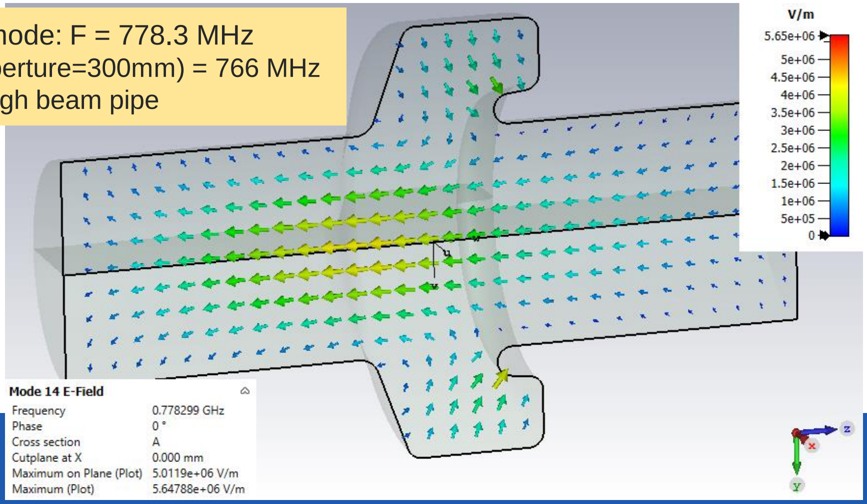
➢ Very compact and very few number of Higher Order Modes

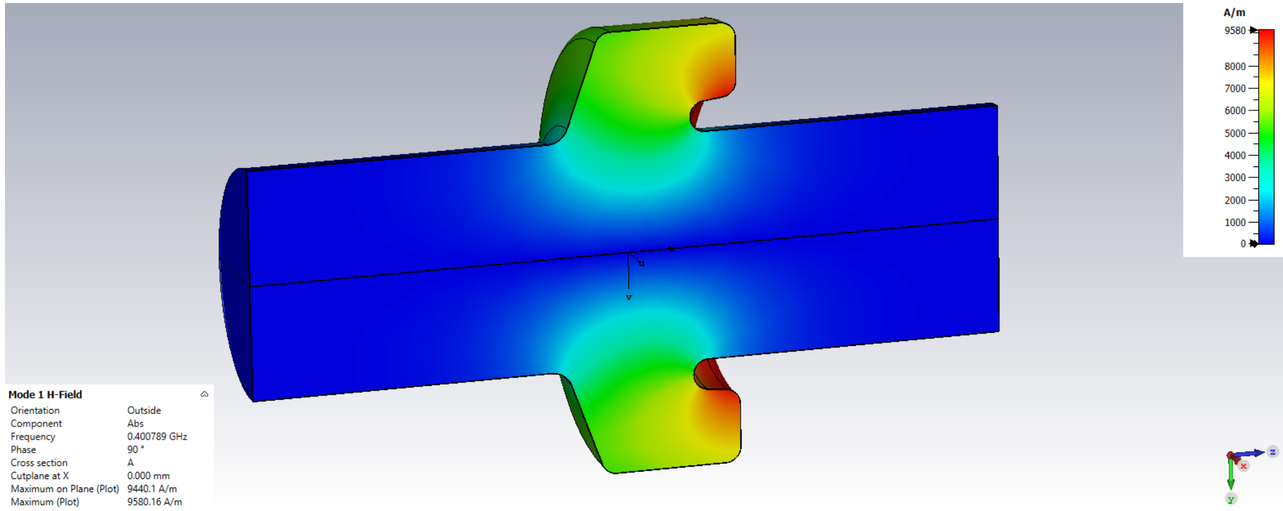
Re-entrant cavity with 300 mm aperture

Parameters	LHC	Re-entrant cavity V2
Frequency [MHz]	400.79	400.82
Nominal Accelerating Voltage [MV]	2	2
Circuit r/Q [Ω] at β=1	42.7	41
G [Ω]	256.9	
E_{pk}/E_{acc} at β=1	2.4	5.35
B_{pk}/E_{acc} [mT/(MV/m)] at β=1	5.08	9.74
Max. surface field E_{pk} [MV/m]	12.85	28.6
Max. surface magnetic field B_{pk} [mT]	27.11	52.1
Stored energy [J] at E_{acc} and β=1	18.5	19.3
Aperture [mm]	300	300
Cavity envelope [mm]	688	580



TM$_{011}$ longitudinal mode: F = 778.3 MHz
Fcutoff (TM$_{01}$ with aperture=300mm) = 766 MHz
→ Propagation through beam pipe





Summary

- In the next 5 years, the FCC SRF team will focus on various R&D topics, including:
  - Review of the operational scenarii (Z <-> W <-> H <-> ttb machines)
  - RF design of various cavity shapes
    - Including beam dynamics and LLRF studies
  - New manufacturing technics (seamless cavities, internal EB welding and electropolishing of copper cavities)
  - Optimisation of coating process including HIPIMS
  - R&D on A15 materials on copper substrates
    - Important for energy savings
  - High power RF coupler up to 1 MW in CW at 400 MHz and HOM power extraction schemes (especially for the Z machine)
  - Review of the RF power sources choices and RF distribution configuration in the tunnel

- Building prototype cavities and a cryomodule demonstrator is also the target