FCC - RF concepts

FCC-RF-Working Group
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With grateful appreciation to R. Calaga

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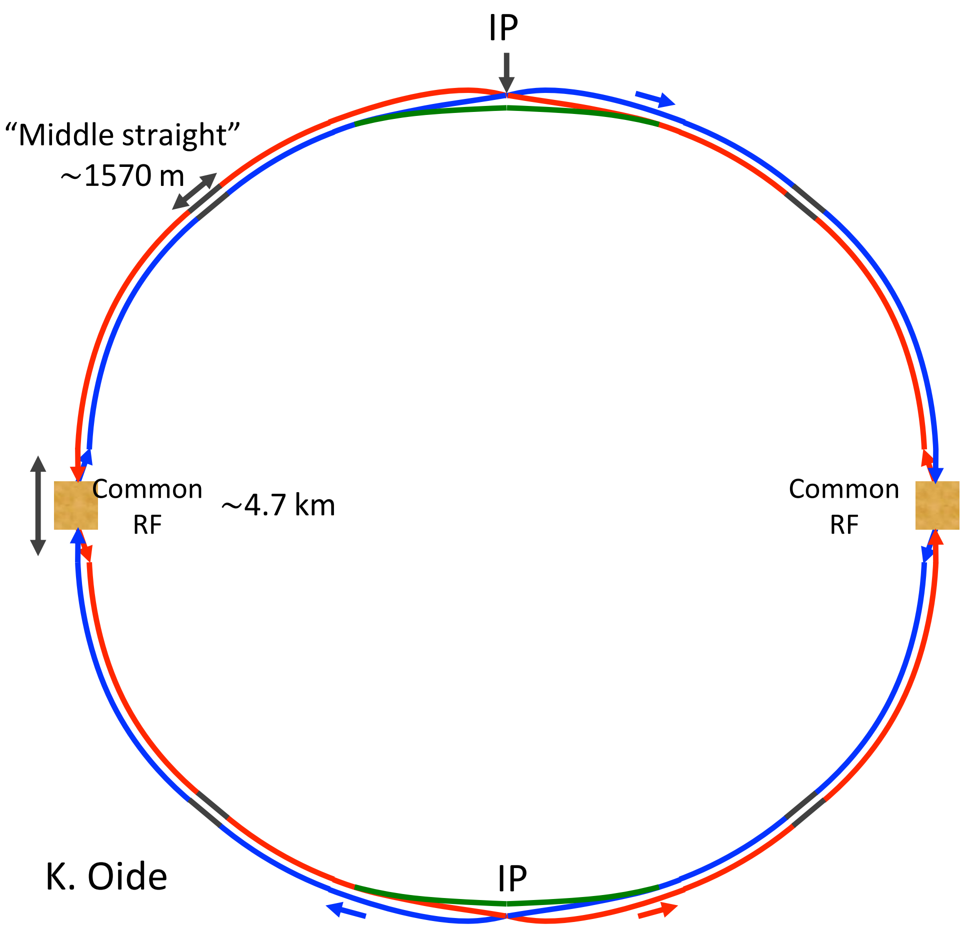
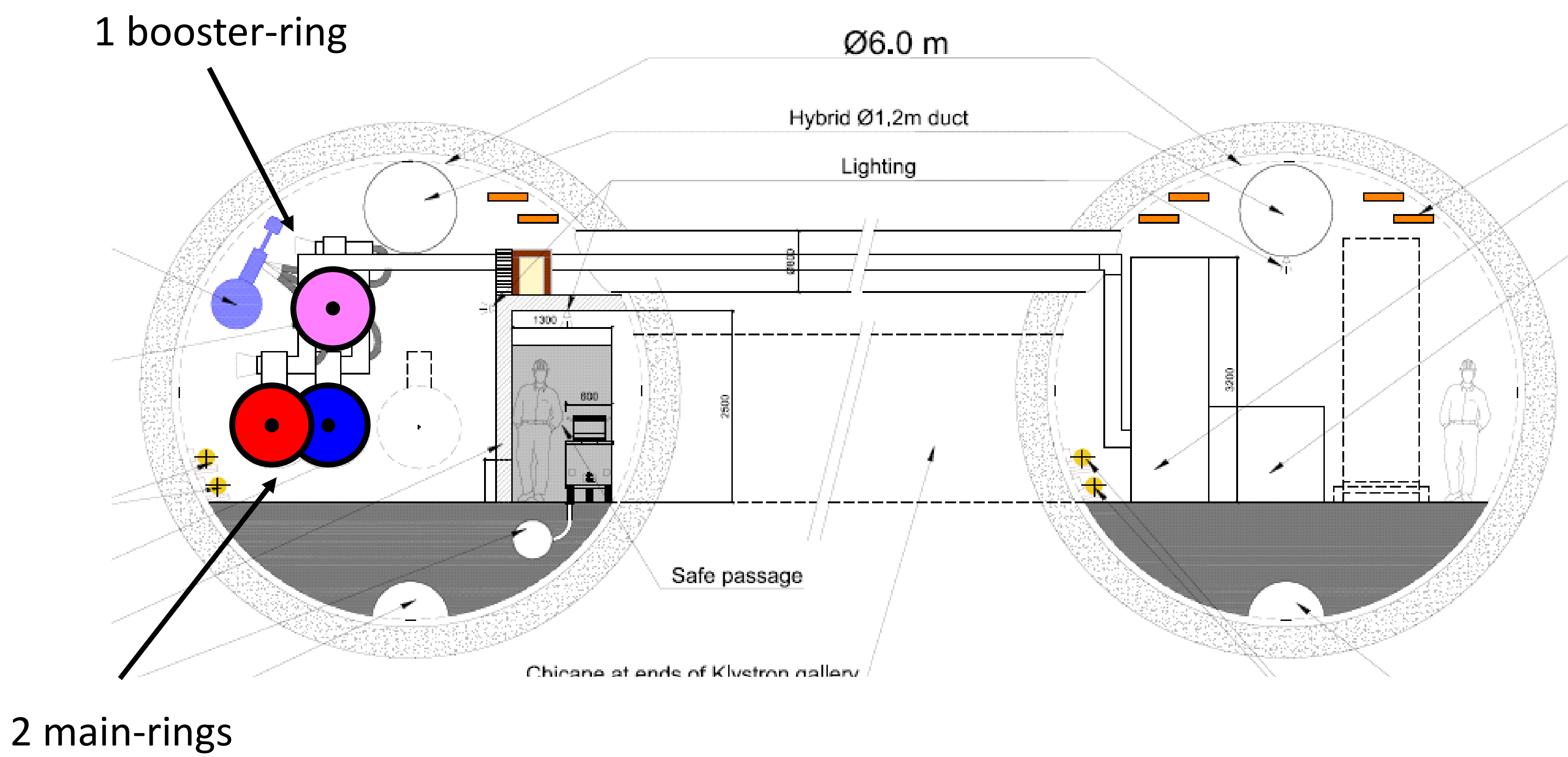
FCC-ee (-hh) layout

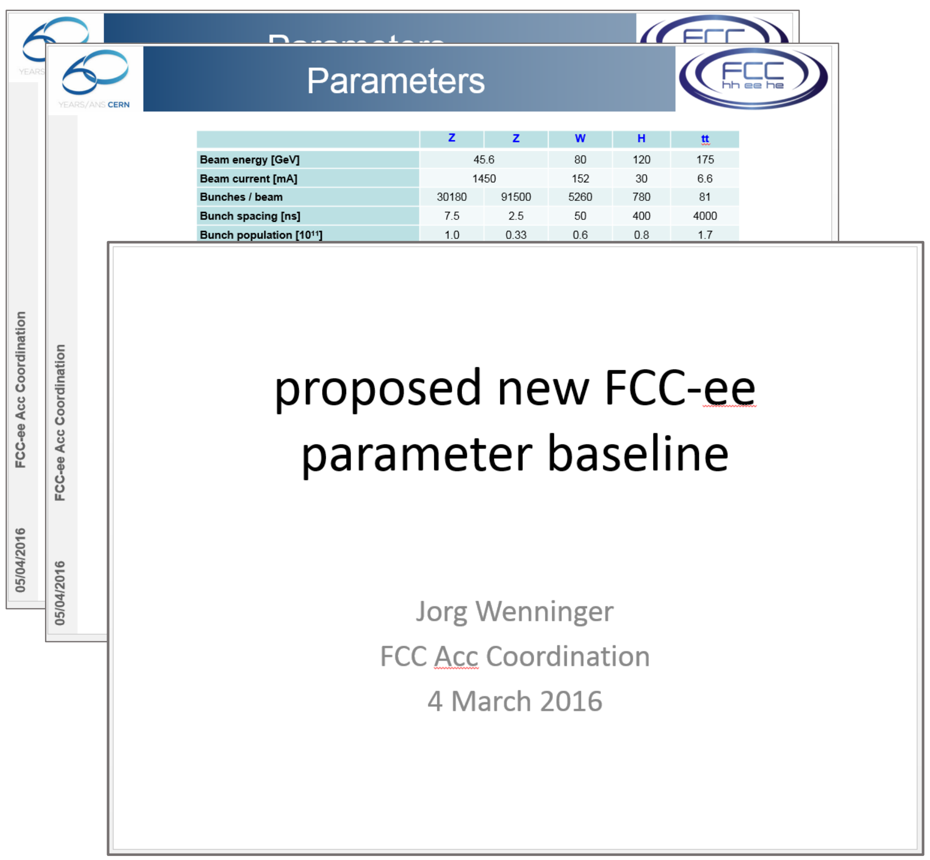




- Machine length = 100km
- RF power per beam = 50MW
- Beside the collider ring(s), a booster of the same size must provide beams for top-up injection to sustain the extremely high luminosity
    - same size of RF system, but lower power

Input

Machine Parameters & Timeline

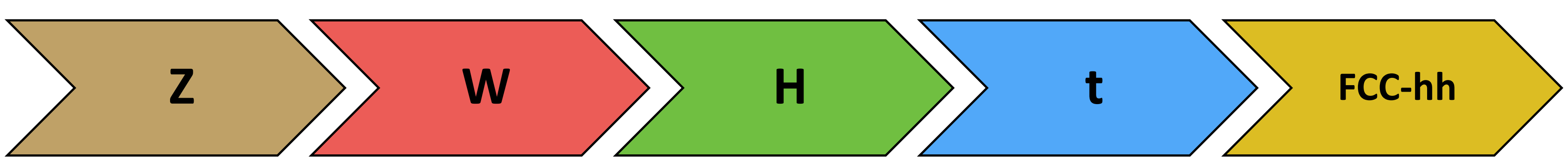


	V_tot	n_bunch	I_beam	σ	E_turnloss
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
W	0.8	5260	152	2	0.33
H	3	780	30	2	1.67
t	10	81	6.6	2.1	7.55

"Ampere-class" machine

"high gradient" machine

short bunches



Design and Technology

SRF systems design issues

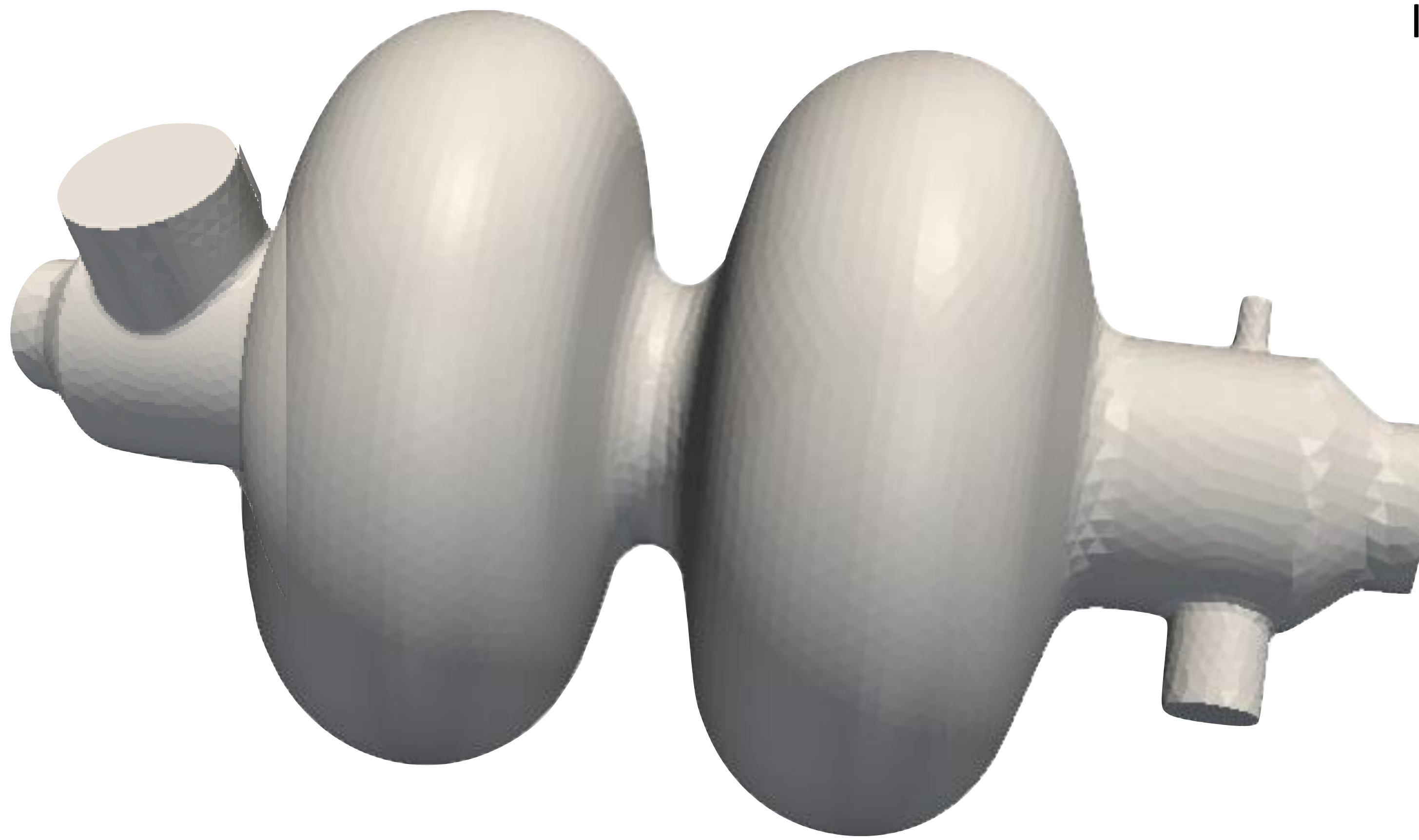
Beam loading

Surface Resistivity

Temperature

Impedance

Frequency



Beam stability

Q_{ext}

Cryogenic losses

RF power

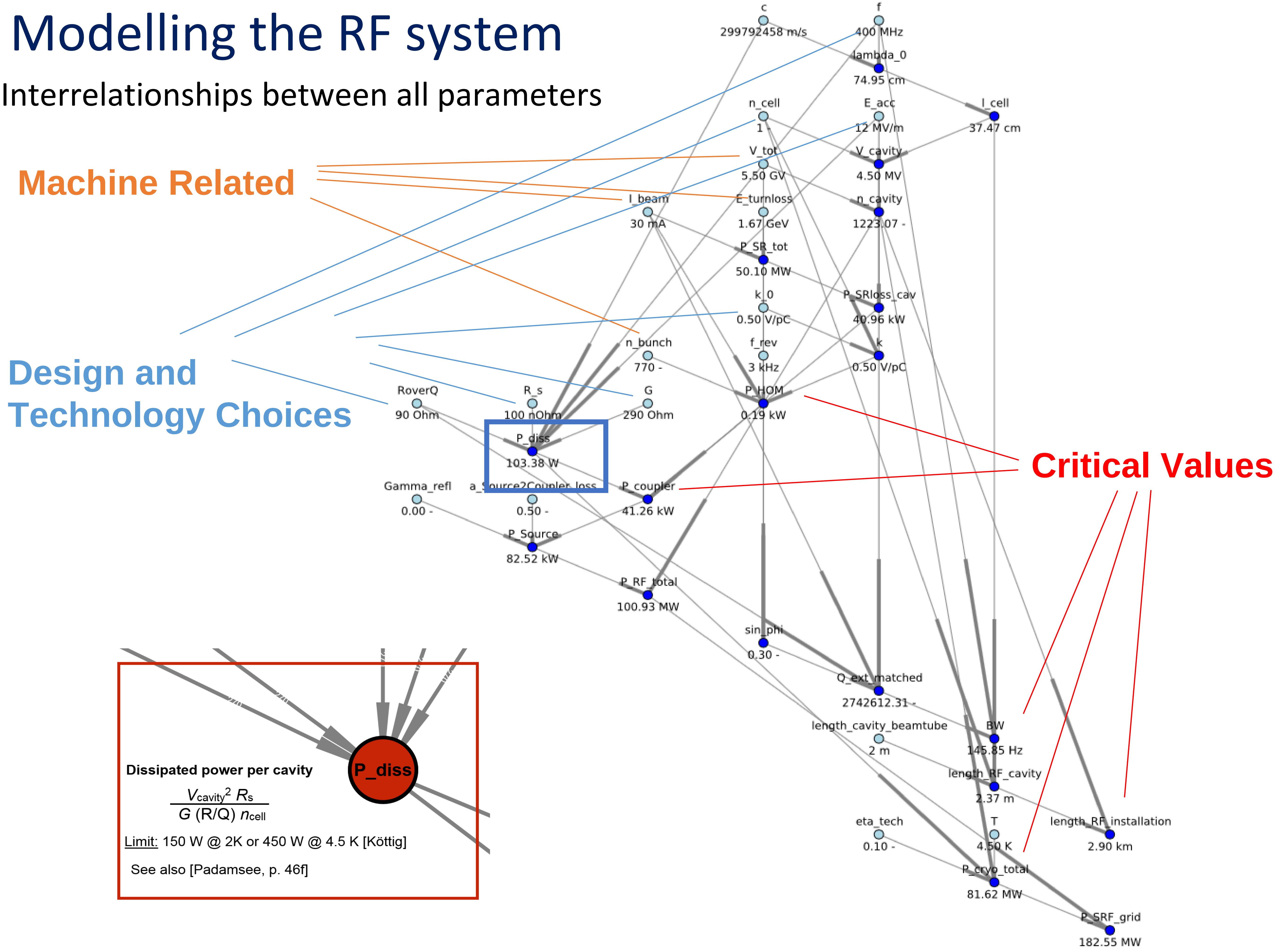
Accelerating gradient

Number of cells

Beam – cavity interaction

Modelling the RF system

Interrelationships between all parameters



Parameter Variation and Limits

Intersecting circles?

	V_tot	n_bunch	I_beam	σ	E_turnloss
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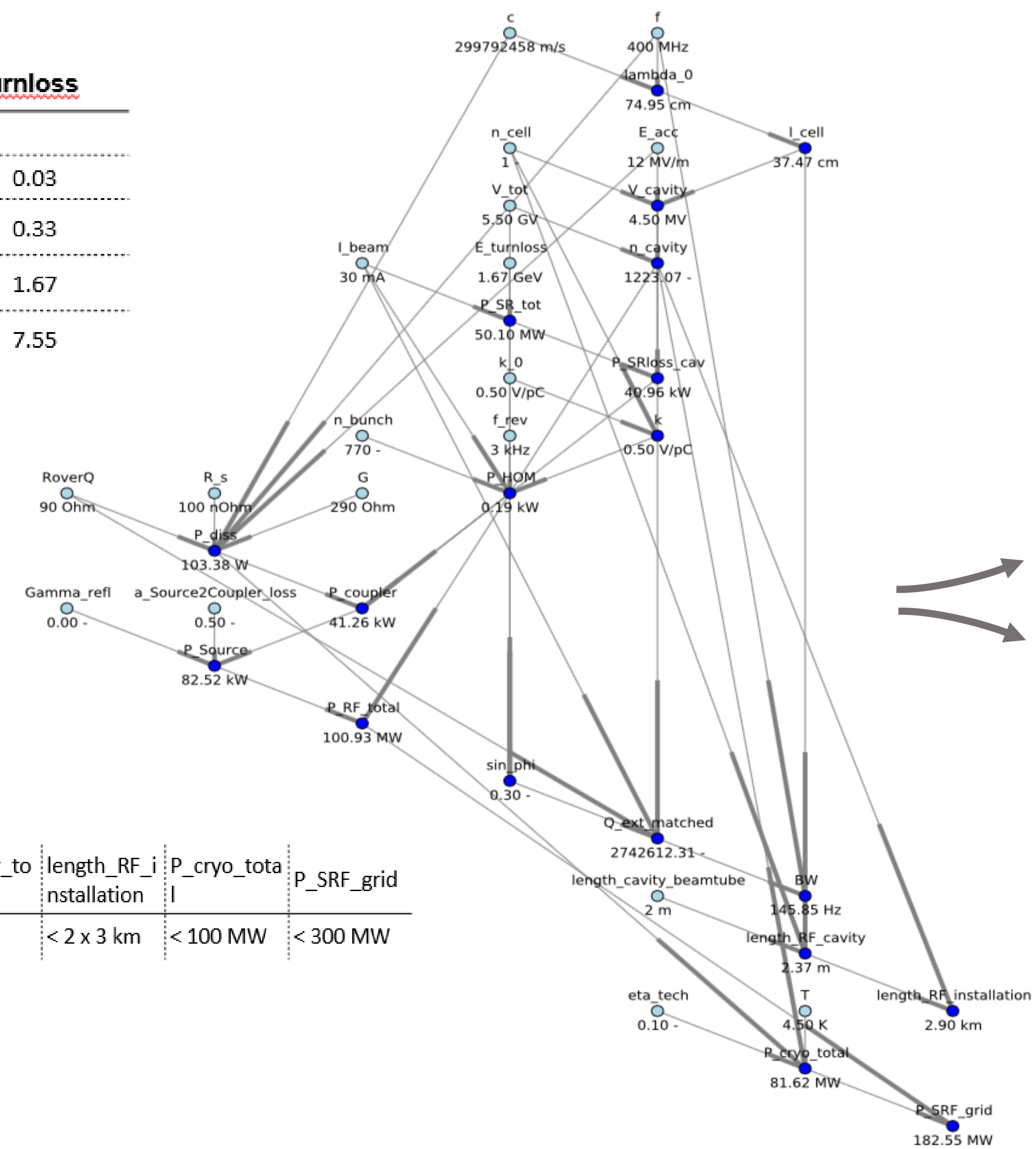
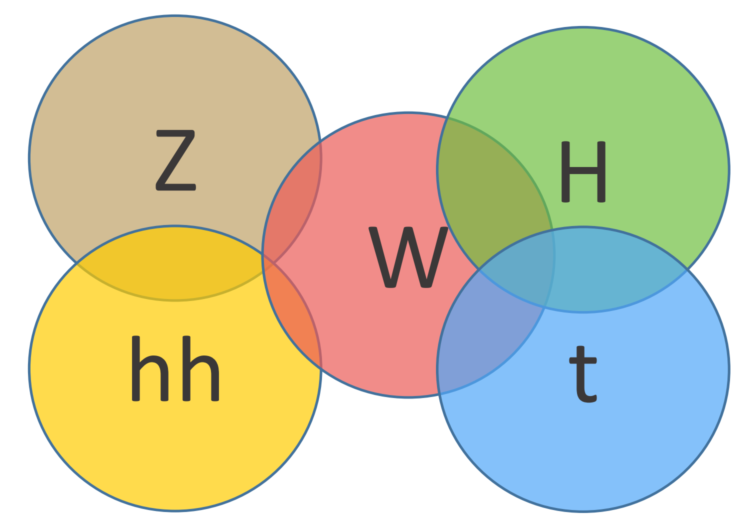




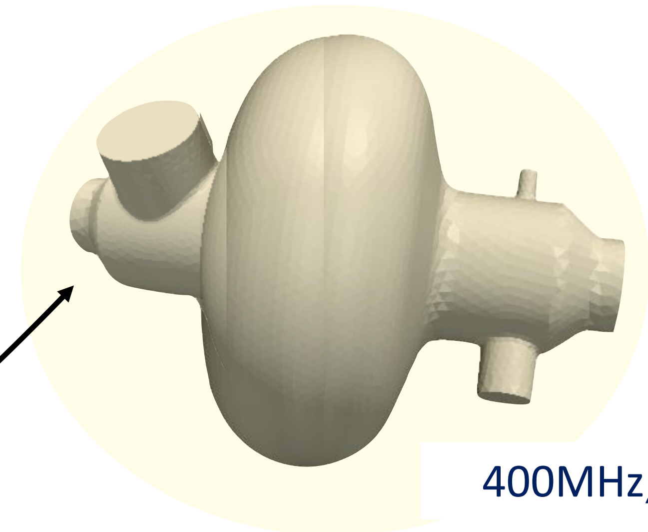
Quantity	P_diss	P_coupler	Q_ext_matched	Bandwidth	n_cavity_total	length_RF_installation	P_cryo_total	P_SRF_grid
Limit	< 450 W	< 500 kW	< 1e+7	> 100 Hz	< 3000	< 2 x 3 km	< 100 MW	< 300 MW

Limits should be examined closely to see if they can be improved by further R&D

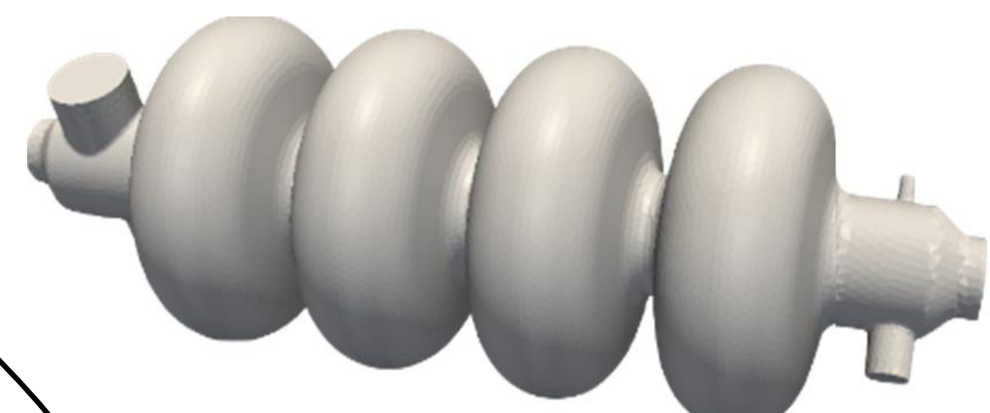
Preliminary Cavity Design Choices

➔It is not optimal to try to make one RF configuration cover all options

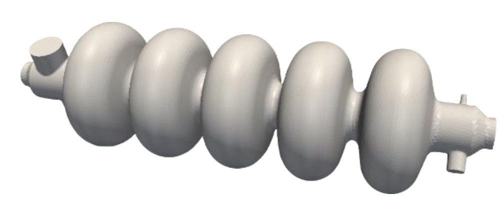
➔Selection of designs to cover FCC-ee and FCC-hh machines



400MHz, 1 cell, Nb/Cu



400MHz, multi-cells, Nb/Cu



800MHz, multi-cells, Nb/Cu - bulk Nb

optimize cell shape with regard to HOMs

aim at acceleration efficiency

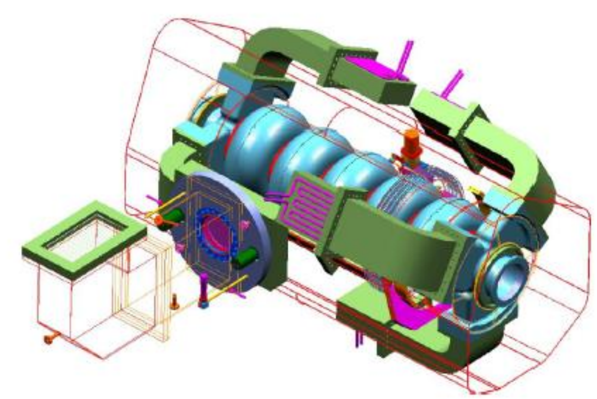
"Z" machine: design considerations

High luminosity calls for short bunch length and high bunch charge

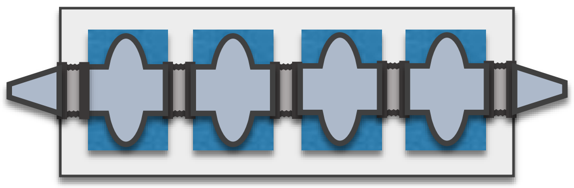
	Z	Z
Beam energy [GeV]	45.6	
Beam current [mA]	1450	
Bunches / beam	30180	91500
Bunch spacing [ns]	7.5	2.5
Bunch population [10^{11}]	1.0	0.33
Horizontal emittance [nm] Vertical emittance [pm]	0.2 1	0.09 1
Momentum comp. [10^{-5}]	0.7	0.7
Betatron function at IP - Horizontal [m] - Vertical [mm]	 0.5 1	 1 2
Crossing angle at IP [mrad]		
Bunch length [mm] - Synchrotron radiation - Total	 0.9 6.7	 1.6 3.8
Energy loss / turn [GeV]	0.03	
Total RF voltage [GV]	0.4	0.2
RF frequency [MHz]		
Synchrotron tune Q_s	0.036	0.025
Interaction region length L_i [mm]	0.66	0.62
Hourglass factor H (L_i)	0.92	0.98
Luminosity/IP for 2IPs [10^{34} cm^{-2}s^{-1}]	**207**	**89.4**

→"High" HOM powers (dozen of kW):
Compact "highly damped" cavities
Beam pipe absorbers (KEKB)
Waveguide couplers (JLAB)

→"Medium" HOM power levels (few kW)
HOM antennas (LHC, Soleil,..)

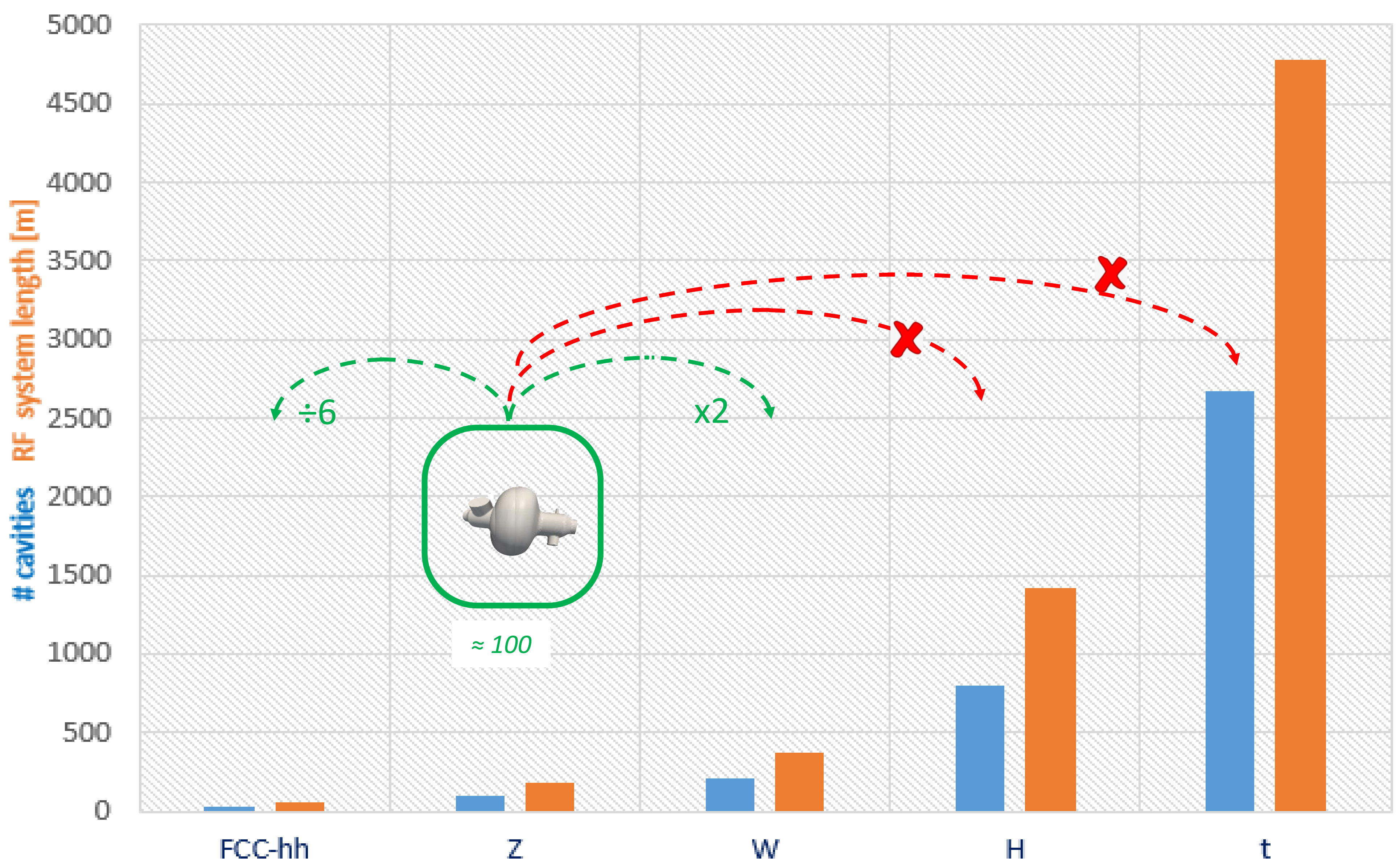


- Favours low frequency and low number of cells: lets adopt 400 MHz and 1-cell for now
- Cryomodules (k_{CM} ≈ 10 V/pC): P_{HOM} ≈ 70 kW – 200kW per cryomodule (≈ 2–5MW tot)



→Optimize (& freeze) machine parameters
→Optimize cell shape with regard to HOMs
→Carefully design cryomodule and HOM dampers (e.g. shielded bellow, tapers, …)
→Damp propagating HOMs (in "external" HOM loads and in the warm sections between cryostats)

Z design compatibility



- 400MHz single cell cavities preferred for FCC-hh
- RF power ≈ 500 – 700 kW per cavity
- Single cell not efficient for high energies

(See E. Shaposhnikova 's Presentation)

“Higgs”(and t) machines

optimize acceleration efficiency

	V_tot	n_bunch	I_beam	σ	E_turnloss
FCC-hh	0.032		500		
Z	0.4 / 0.2	30180 / 91500	1450	0.9/1.6	0.03
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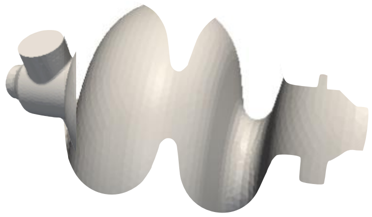
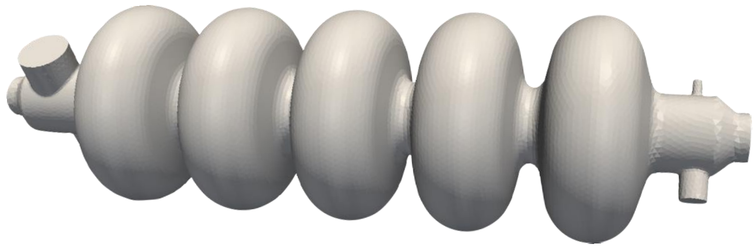
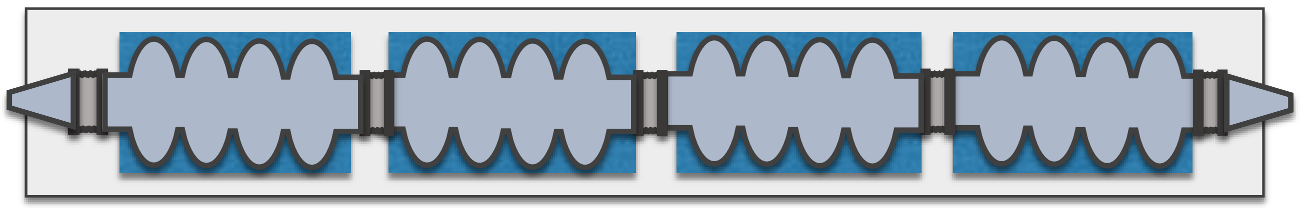




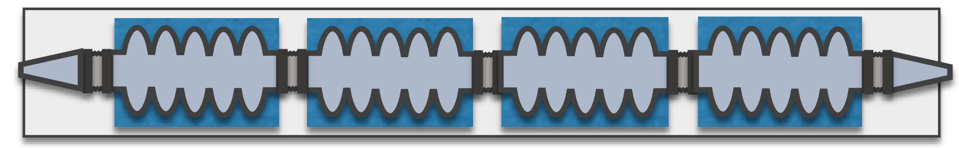
- Need acceleration efficiency (3 -> 10GV) > Large RF systems: 800 – 2700 cells per beam
- Optimize technology choice (e. g. cryogenic losses) (See S. Aull’s Presentation)
  - 400MHZ @ 10MV/m, 4.5K <-> 800MHz @ 20MV/m, 2K
  - Advantage of operating at 4.5K: simpler cryostat design, cheaper, more reliable, simpler cryogenic plant, minimum transverse impedance…
  - Long term: Nb3Sn like components offer potential significant cryogenic cost savings
- Efficient RF power sources (See I. Syratchev’s Presentation)

CM design considerations

H and t scenarios can be optimized with 400 MHz or 800 MHz (or both)



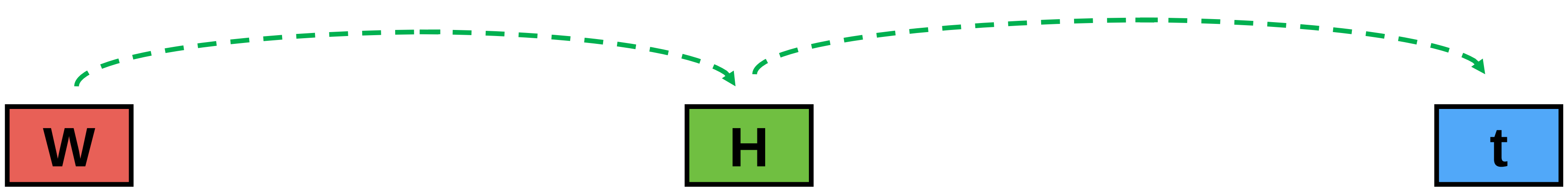
LEP-like CM @ 400MHz (≈ 50 x12m)



ESS-like CM @ 800MHz (≈ 40 x 7m)

- Optimize cell shape with regard to accelerating mode (aim at high shunt impedance)
- Carefully optimize number of cells per cavities
  - beam-cavity interaction: tailor HOM spectrum to avoid strong beam harmonics (danger of resonant built up by the beam)
  - RF power distribution
- HOM power (≈ 6 - 8 kW) per cryomodule
- Matched $Q_L \approx 5.10^5$(W), 2.10^6(H), $0.6\text{-}1.10^7$(t)
- Cost comparison (2K vs 4.5K) will help determining the best option

Staging scenarios:

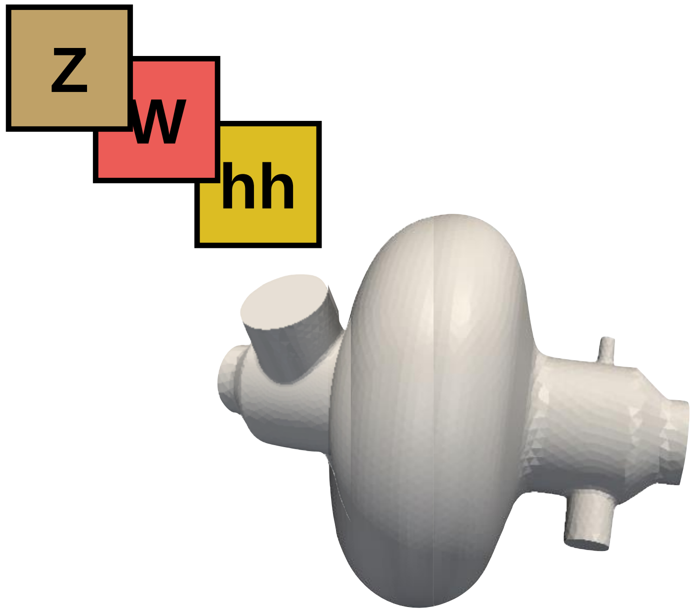


≈ 200 cells per beam
(+ 200 for booster ring)

≈ 800 cells per beam
(+ 800 for booster ring)

≈ common 2600 cells for both beams
(+ 2600 for booster ring)

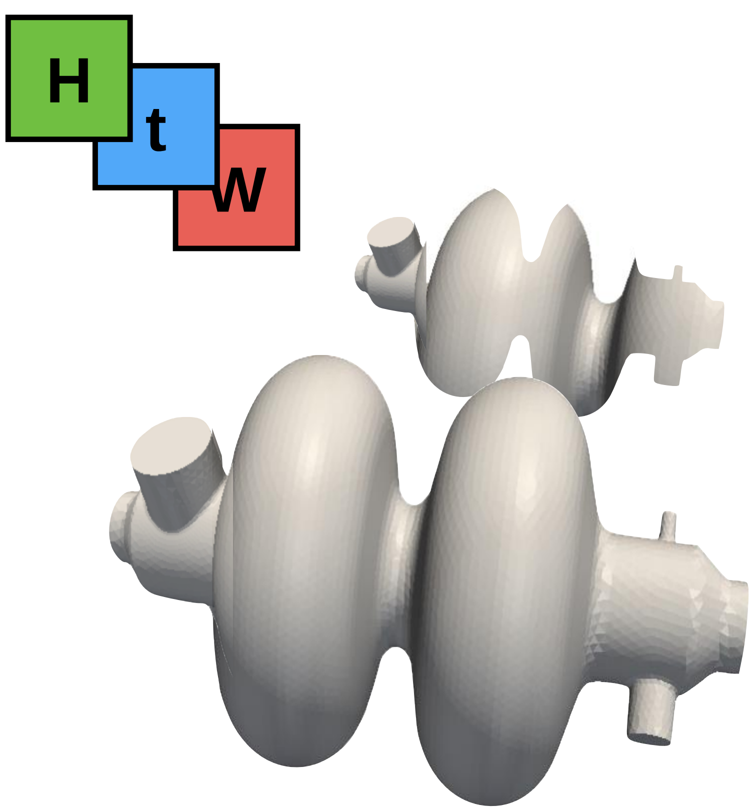
two designs - common R&D



400 MHz (1 cell) *x 300*

RF Power ≈ 0.5 - 1 MW

HOM Power damping



400/800 MHz (multi-cells) *x >thousands*

RF Power ≈ few kW

Cryo Losses >> MW

Niobium on Copper @ 4.5 K

New materials

Common R'n'D Topics (selection)

Cavity Design

High Efficiency Power Production

Fundamental Power Coupler

HOM Damping

Beam Dynamics

LLRF Control

Cavity Fabrication

New Materials

Summary & Outlook

- It is not optimal to try to make one RF configuration cover all options
  - Selection of two designs to cover FCC-ee and FCC-hh machines
  - Analysis highlighted some limitations -> should be examined closely to see if they can be improved by further R&D
- Common areas of R&D/challenges identified
  - Beam dynamics limitations
  - Cavity design
  - Cavity materials
  - Power couplers
  - RF power sources
- Scenarios optimization
  - Detailed RF optimization would need some stability in the machine parameters
  - Beam-cavity interaction study -> danger of resonant built up by the beam + electro-acoustic instability
    - Max n_cell per cavity?
    - Frequency choice?
  - Cost estimates of different options -> Advantage of operating at 4.5K

End

— Discussion and Comments —