FCC

SRF system options for FCC-ee

CEPC workshop

24/10/2023

Franck Peauger

Site location study

- Rings of 90568.154 m circumference (compatible with FCC-hh and injection from LHC at 400.79 MHz)
- Two straight sections of 2 km long for RF

PA – Ferney Voltaire (FR, 01) – experiment

PB – Choulex (CH) – technical

PD – Nangy (FR, 74) – experiment

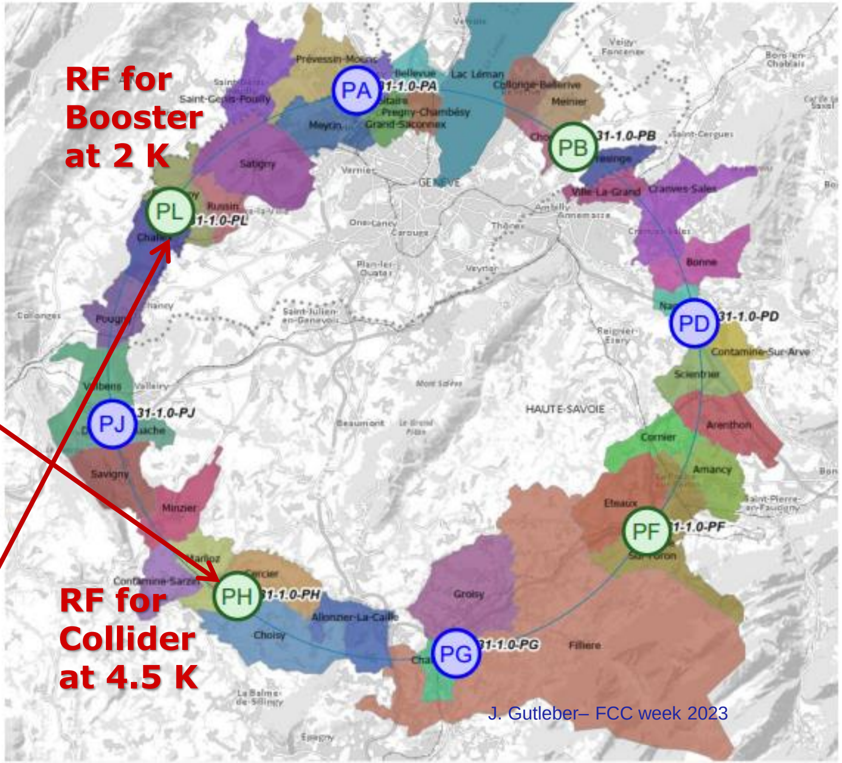
PF – Etaux/La Roche-sur-Foron (FR, 74) - technical

PG – Charvonnex/Groisy (FR, 74) - experiment

PH – Cercier/Marlioz (FR, 74) – technical, main RF

PJ – Vulbens/Dingy en Vuache (FR, 74) – experiment

PL – Challex (FR, 01) – technical, booster RF



High level RF requirements

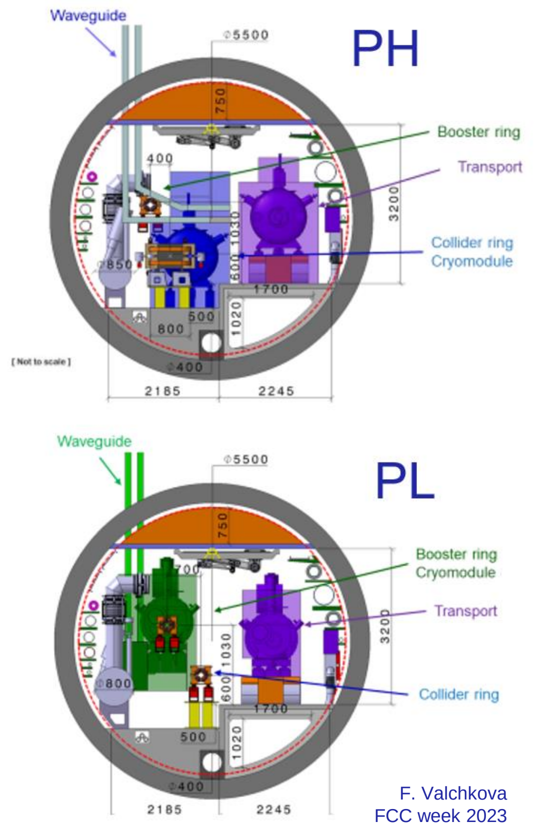
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.080
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

High current machine

High gradient machine

- Collider (2 rings): 100 MW of RF power in CW (50 MW per ring) to compensate losses by synchrotron radiation
- Booster (3^{rd} ring) to accelerate from 20 GeV to the final energy with 10% beam current and 15% average duty cycle
- Availability in operation of 80%

- Tunnel diameter = 5.5 m



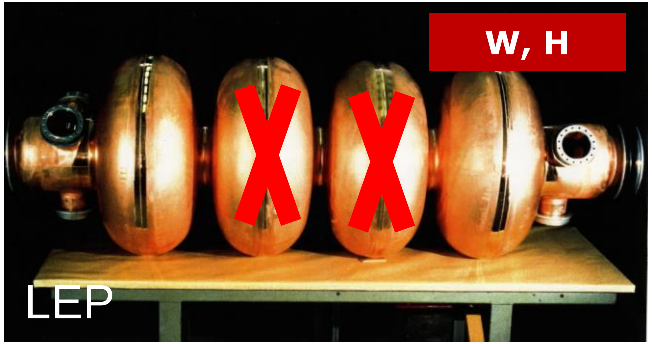
F. Valchkova
FCC week 2023

SRF cavities for the baseline scenario

400 MHz 1-cell cavities
Nb/Cu, 4.5 K

Low frequency (400 MHz), low R/Q cavity shape optimized to minimize the higher order modes (HOM) population.

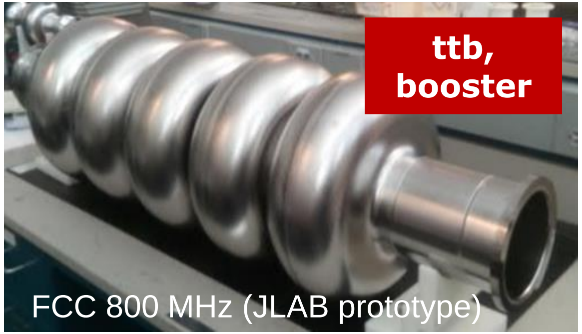
Powered by a 1 MW RF coupler and high efficiency klystron.



400 MHz 2-cell cavities
Nb/Cu, 4.5 K

Moderate accelerating gradient and HOM damping requirements.

500 kW RF per cavity allowing the re-use of the 1 MW klystrons already installed for the Z machine.



800 MHz 5-cell cavities
Bulk Nb, 2 K

Very high RF voltage achieved by multicell cavities.

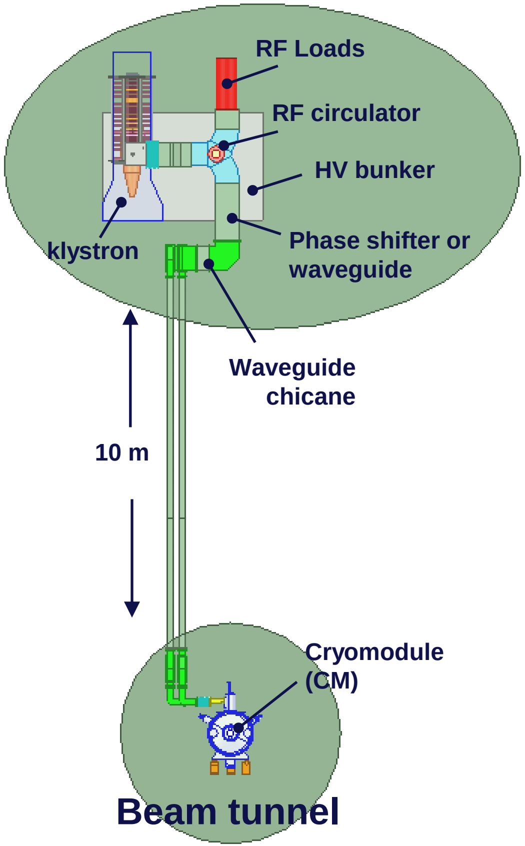
Higher frequency cavities to reach high gradient and reduce overall footprint.

Significant RF power (200 kW) per cavity limiting the frequency to the second harmonic (800 MHz)

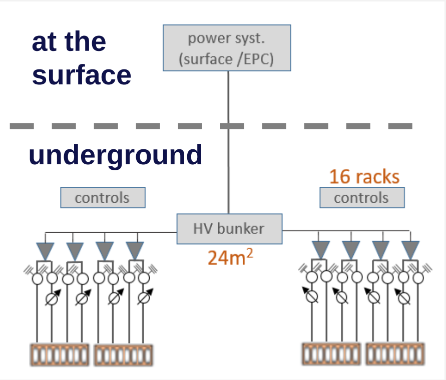
Accelerator tunnel and klystron gallery

RF system configuration for the Higgs factory

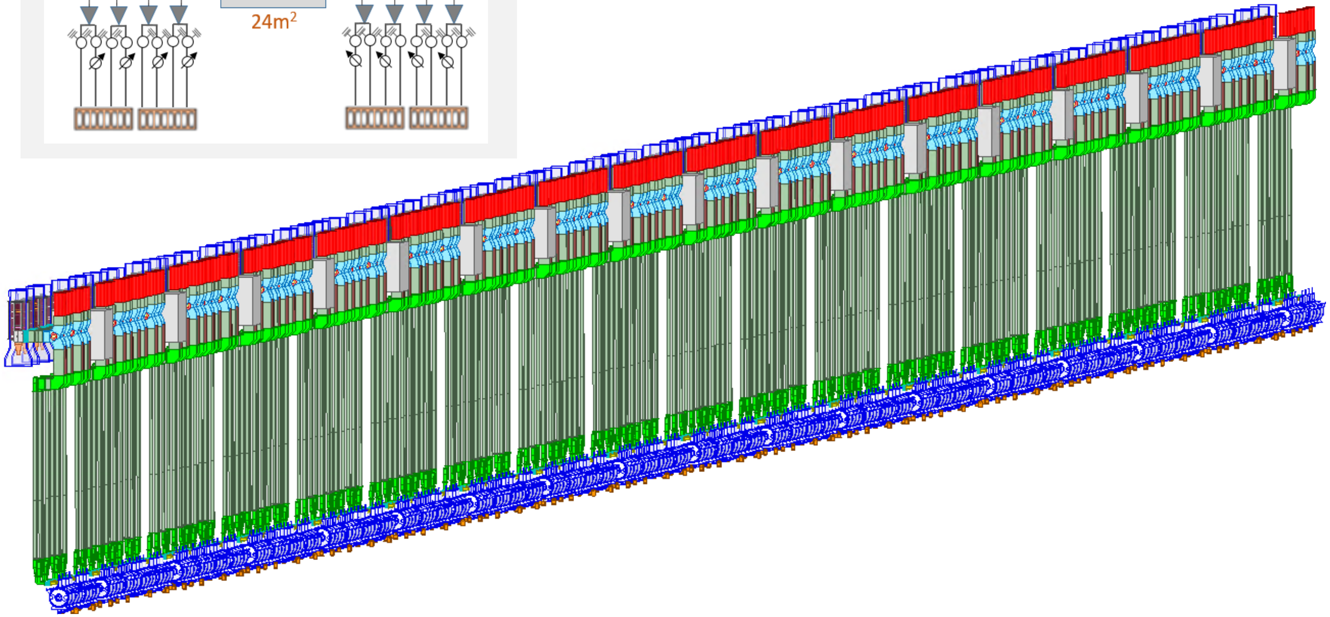
Klystron gallery



RF Unit



- 17 x RF Units = 900 m
- 66+2 cryomodules
- 272 cavities (4 cav/CM)



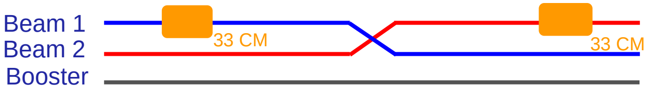
RF parameters

Limiting parameters
Cavities qualified in VT with 20% margin on Q0 and Eacc

	Z		W		H		ttb		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
Cavity type	1-cell	5-cell	2-cell	5-cell	2-cell	5-cell	2-cell	5-cell	5-cell
Eacc [MV/m]	3.8	6.2	10.6	20.1	10.6	20.1	10.6	20.1	20.1
Q0	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	2.7E+09	3.0E+10	3.0E+10
Epeak [MV/m]	8.4	12.8	21.2	41.2	21.2	41.2	21.2	41.2	41.2
Bpeak [mT]	20.4	27	56.6	87.2	56.6	87.2	56.6	87.2	87.2
Beam current [mA]	1280	128	135	13.5	53.4	2.7	10	10	0.5
RF power [kW]	900	210	378	89	382	45	78	163	8
Optimum Qext	2.6E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.5E+07	4.5E+06	4.2E+06	8.1E+07
Optimum detuning [kHz]	13.662	4.385	0.575	0.140	0.106	0.013	0.009	0.056	0.002
Operating temp. [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	9	0.3	129	3	129	3	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
# CM (with 4 cav/CM)	14 per beam	6	33 per beam	14	66	28	66	122	150

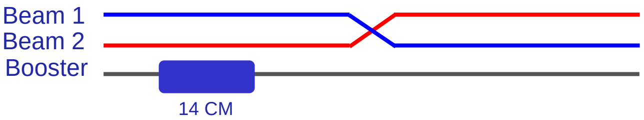
* Heat loads from power coupler and HOM couplers not included

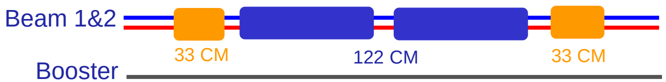
PH



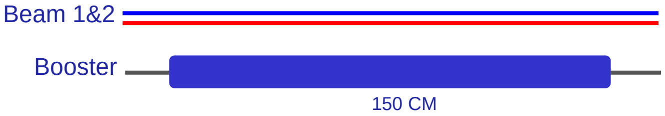
one RF system per beam

PL





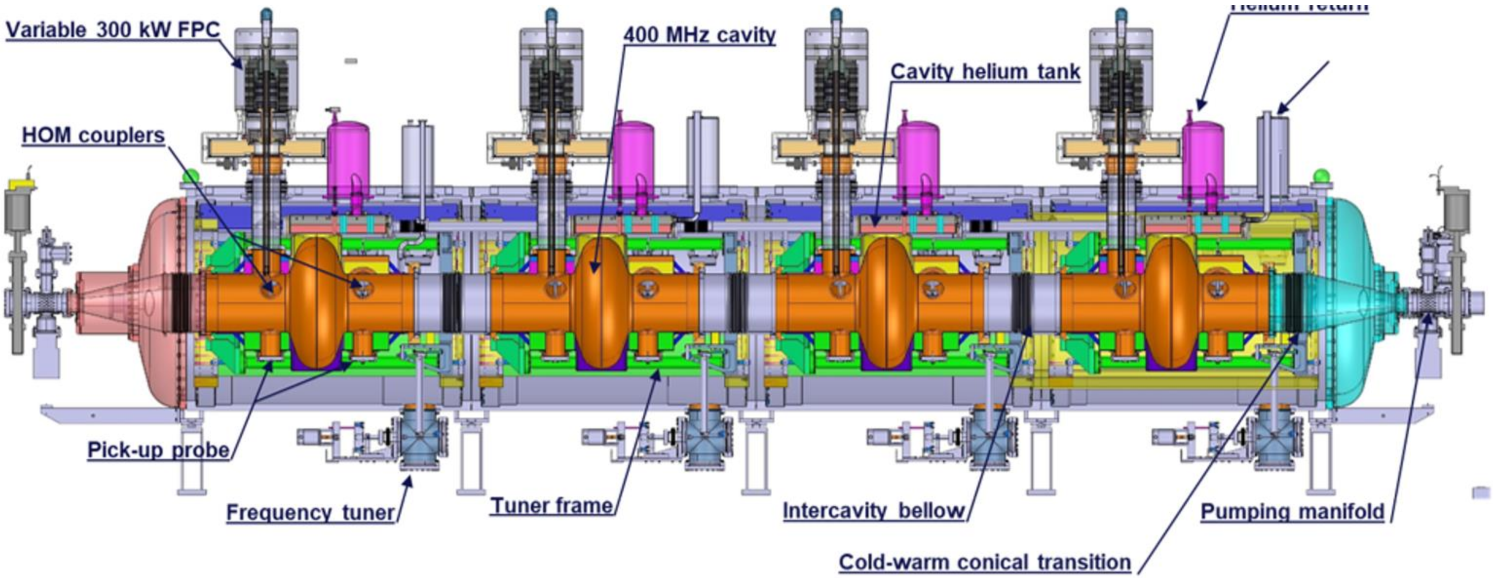
common RF system for both beams
beam current is multiplied by two



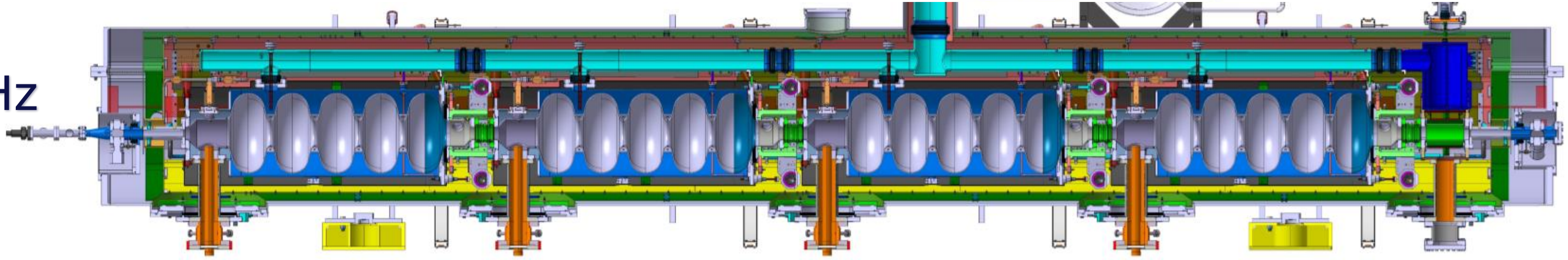
Total of ~370 cryomodules and 1500 cavities with 25% in "thin film on copper" technology

Cryomodule experience at CERN for elliptical cavities

LHC 400 MHz
4.5 K
[in operation]

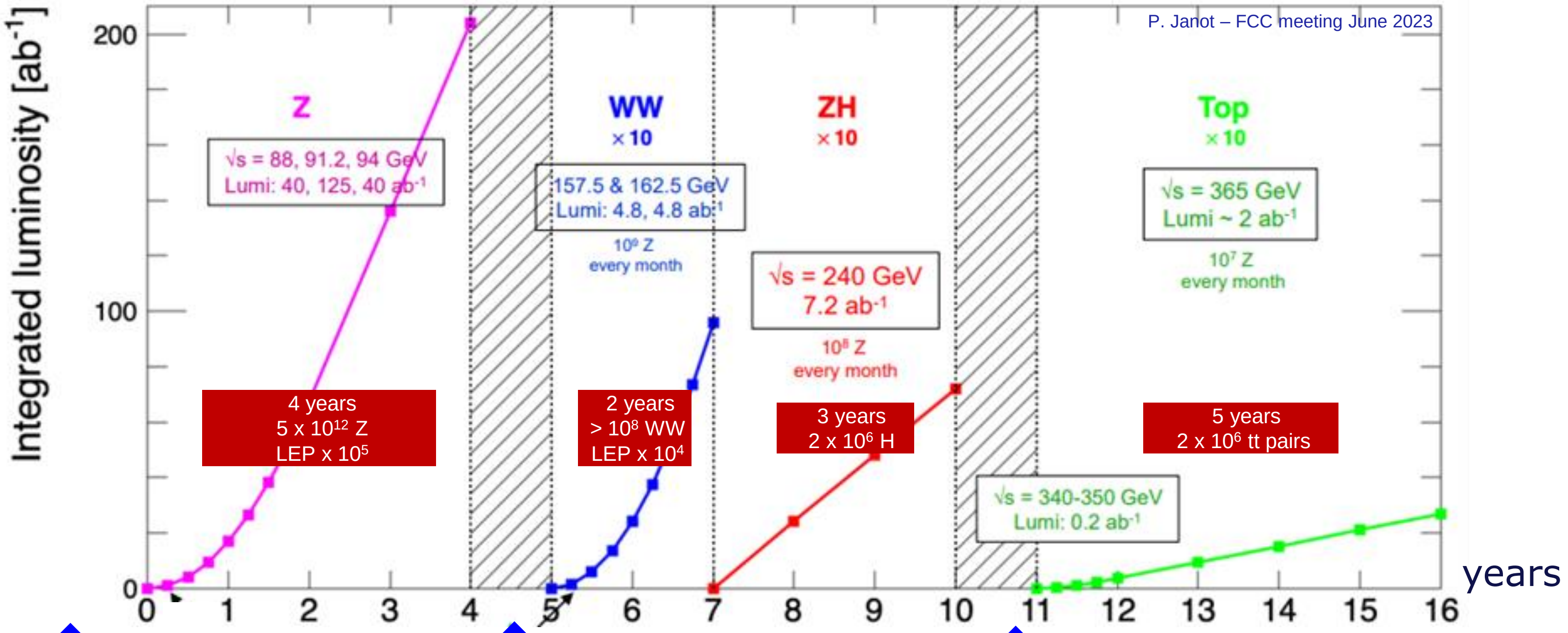


SPL 704 MHz
2 K
[study]



New cryomodule design are on-going for FCC

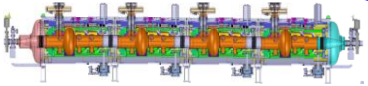
Integrated luminosity and installation sequence

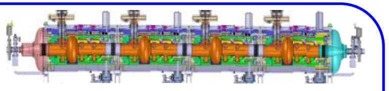


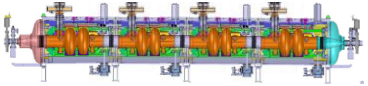
1 CM installed per week

2 CM installed per week

Collider

28 

- 28 

+ 66 

+ 122 

Booster

6 

+ 22 

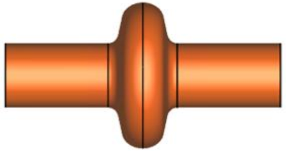
+ 122 

Cavity design

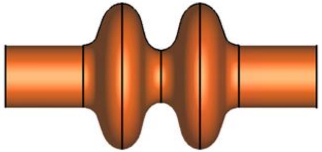
- Designed by Shahnam Gorgi Zadeh (CERN)
- Optimized with genetic algorithm to minimize peak surface fields, HOM contains and loss factors

	LHC (reference)	***FCC 1 – cell***	***FCC 2 – cell***	***FCC 5–cell***
frequency [MHz]	400.79	400.79	400.79	801.58
R/Q [linac Ω]	88.1	87.6	181.1	521
G [Ω]	252	238.5	234.7	272.9
E_{pk}/E_{acc}	2.3	2.2	2.0	2.05
B_{pk}/E_{acc} [mT/(MV/m)]	5.1	5.36	5.33	4.33
$k_{\|\|}$ [V/pC]	0.146 σ_z=12.1mm	0.132 σ_z=12.1mm	0.380 σ_z=8 mm	2.78 σ_z=2.75 mm

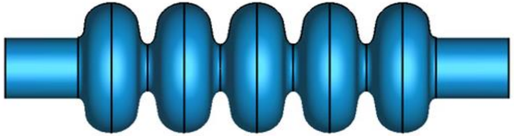
1-cell 400 MHz



2-cell 400 MHz



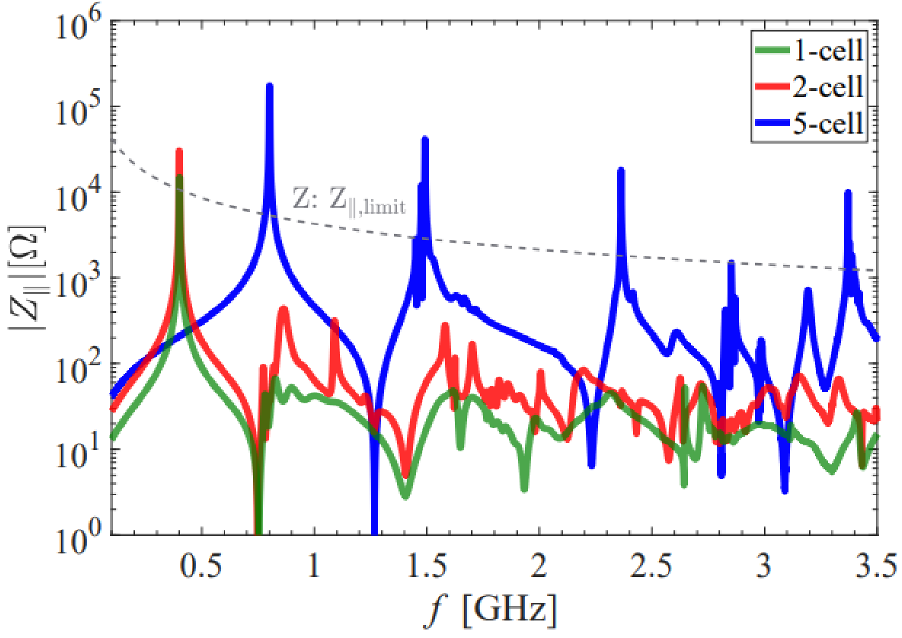
5-cell 800 MHz



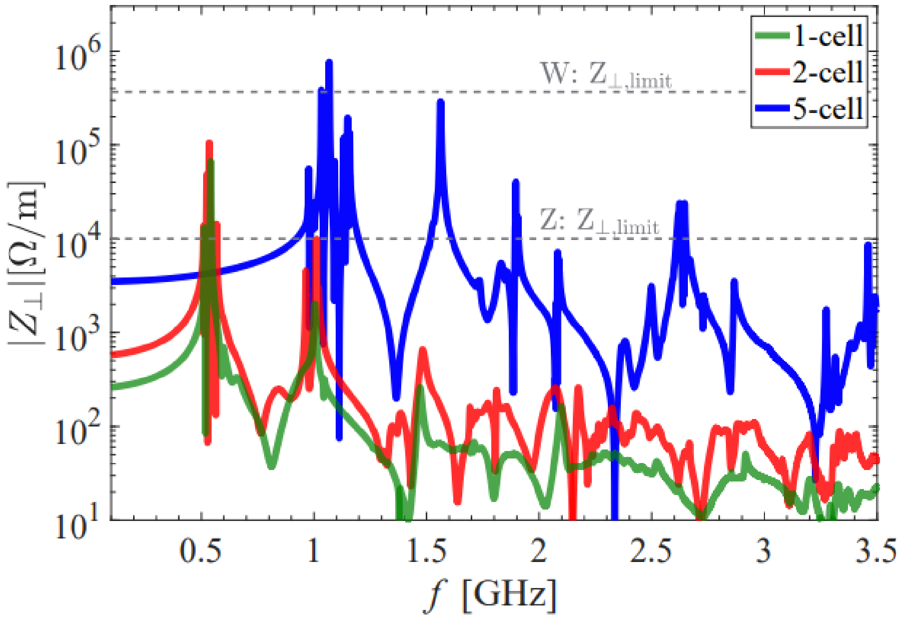
Cavity impedance

- Beam coupling impedance of each cavity type obtained without any additional HOM damping
- Coupled bunch instability thresholds shown without LLRF feedback loops

Longitudinal

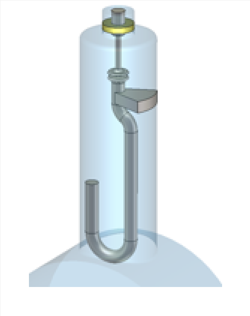


Transverse

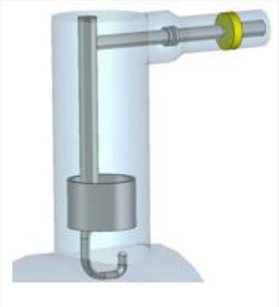


HOM couplers

- Coaxial couplers (with FM rejection) for dipole and monopole mode damping
- Near the cavity cell

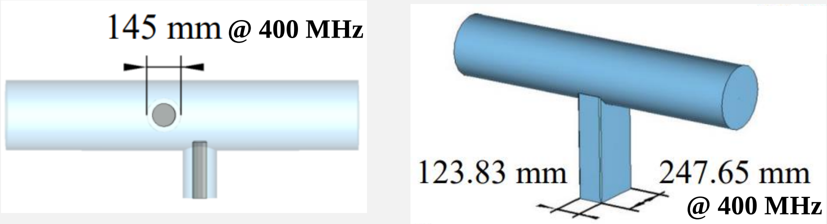


400 MHz



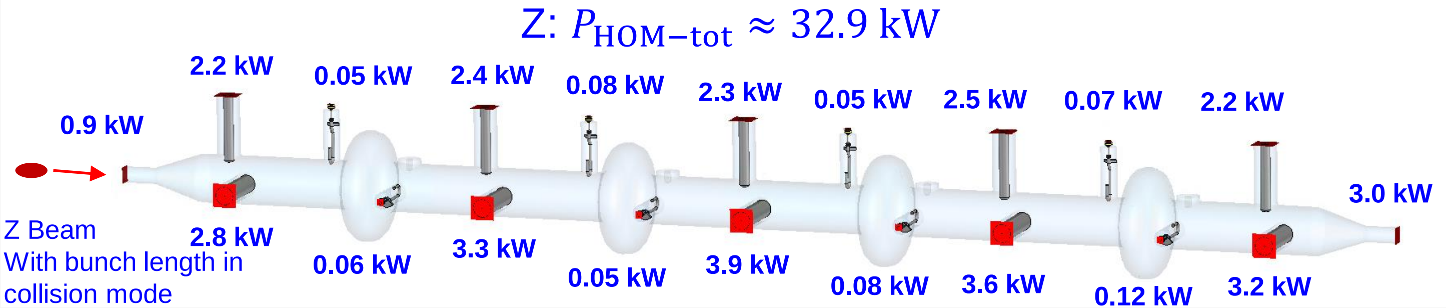
800 MHz

- Coaxial or waveguide couplers for extraction of the high frequency broadband part of the cavity impedance spectrum
- Far away from the cavity cell



400 MHz and 800 MHz

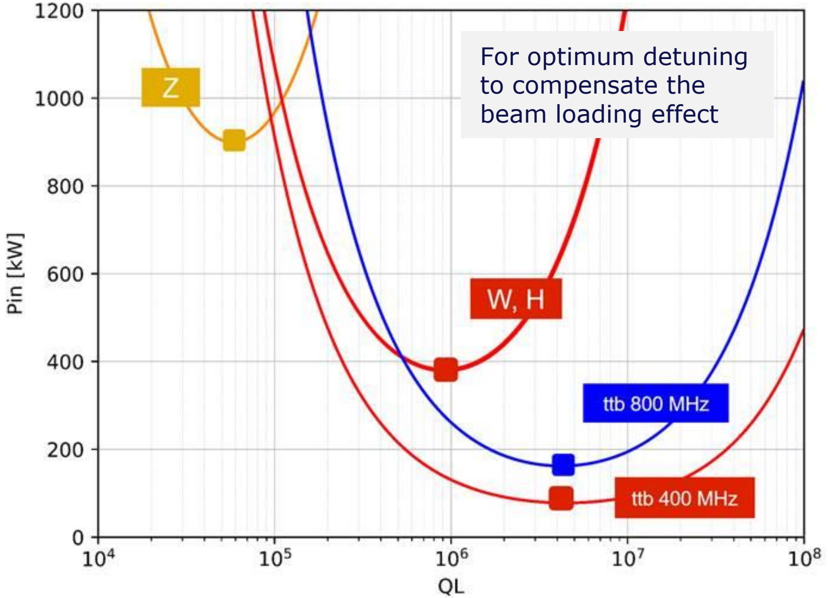
- Example of HOM damping and extraction scheme in a 1-cell cavity cryomodule



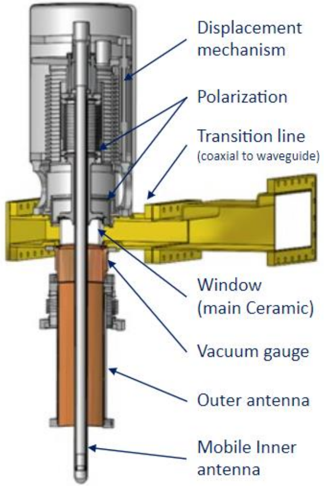
Fundamental Power Couplers

- For the collider:

	Beam energy	Frequency	Operating mode	Type	Peak RF power with beam	Qext	Quantity
Type 1	Z	400 MHz	CW	Fixed	900 kW	5.8×10^4	112
Type 2	W, H and ttb	400 MHz	CW	2 positions	385 kW	9.15×10^5	264
					80 kW	4.5×10^6	
Type 3	ttb	800 MHz	CW	Fixed	165 kW	4.2×10^6	488

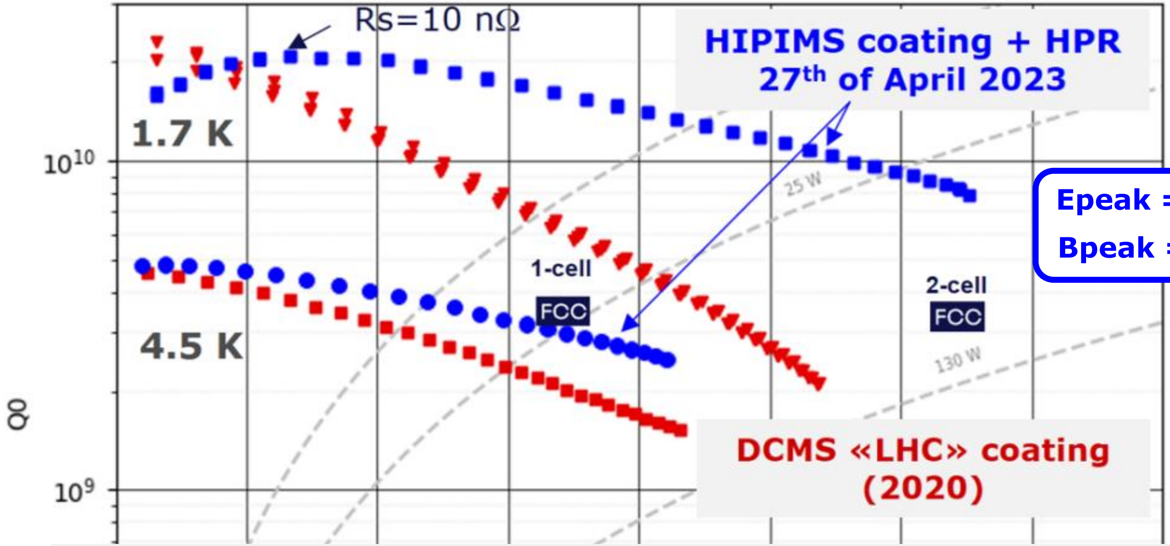


Example of LHC 400 MHz 300 kW CW variable coupler



- For the booster: 800 MHz - 210 kW pulsed – with variable coupling

R&D on 400 MHz Nb/Cu cavity

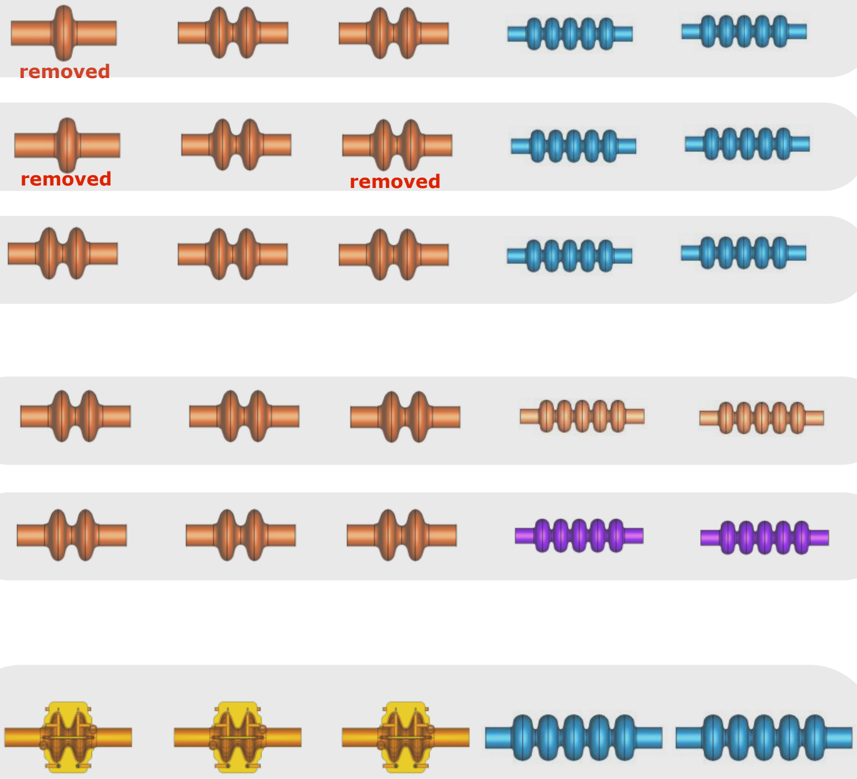


Epeak = 30 MV/m
Bpeak = 66.3 mT

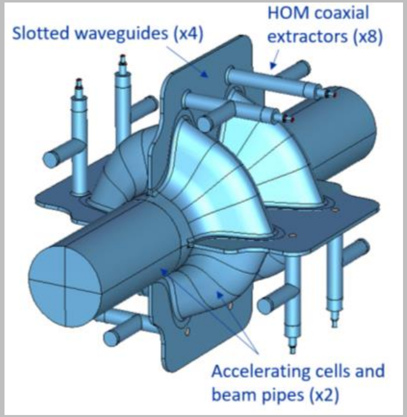
- **Improvement of Q slope, no Field Emission**
  - ➢ **Very encouraging result !**
- Next steps:
  - ➢ Seamless cavity
  - ➢ Electropolishing of the inner surface
  - ➢ Optimized HiPIMS coating process
  - ➢ Improved cryogenics cooling

Baseline & alternative options

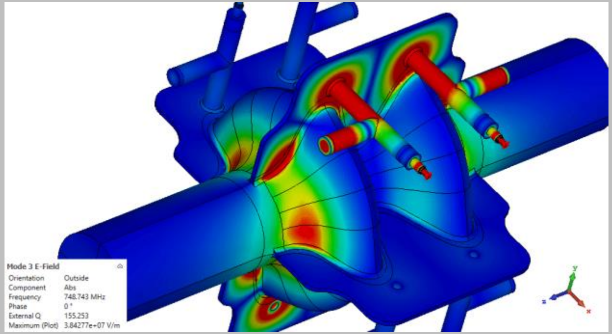
	Z	W	H	ttb	booster	Comments
Baseline	removed					Solid scheme with good margin for reliable operation Clear R&D paths identified (seamless copper cavities, HiPIMS coating, high Q0 bulk Nb cavities)
Higgs first	removed		removed			Less optimized for the planning and workload (~100 additional cryomodules to install or remove)
Z with 2-cell						Very attractive to optimize the cost and schedule The beam current at Z shall be reduced.
Full thin films						Very ambitious, allows for material cost savings Ideal to push even more the Nb/Cu technology
Full 4.5 K with A15 (Nb3Sn) materials						Extremely ambitious (?) for very high operational savings
SWELL 600 MHz						Innovative approach at a single RF frequency Adapted to width variety of coatings No microphonics and LFD Reduced volume of helium Beam current at Z slightly reduced

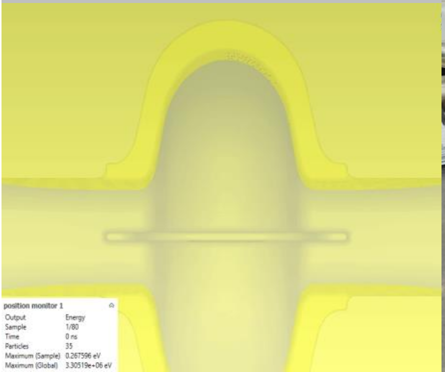


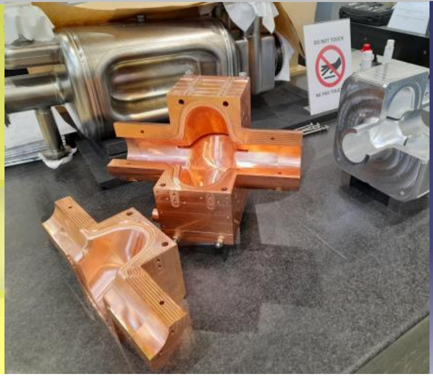
SWELL cavity development

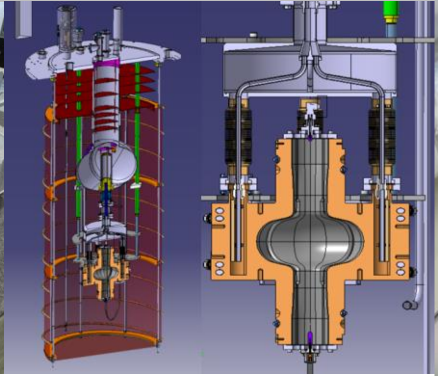


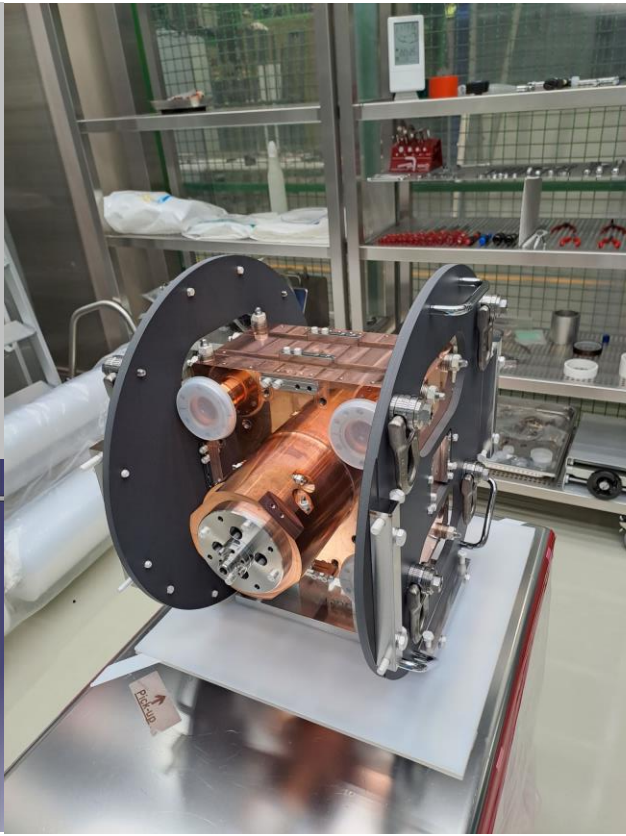
SWELL: Slotted Waveguide ELLiptical cavity



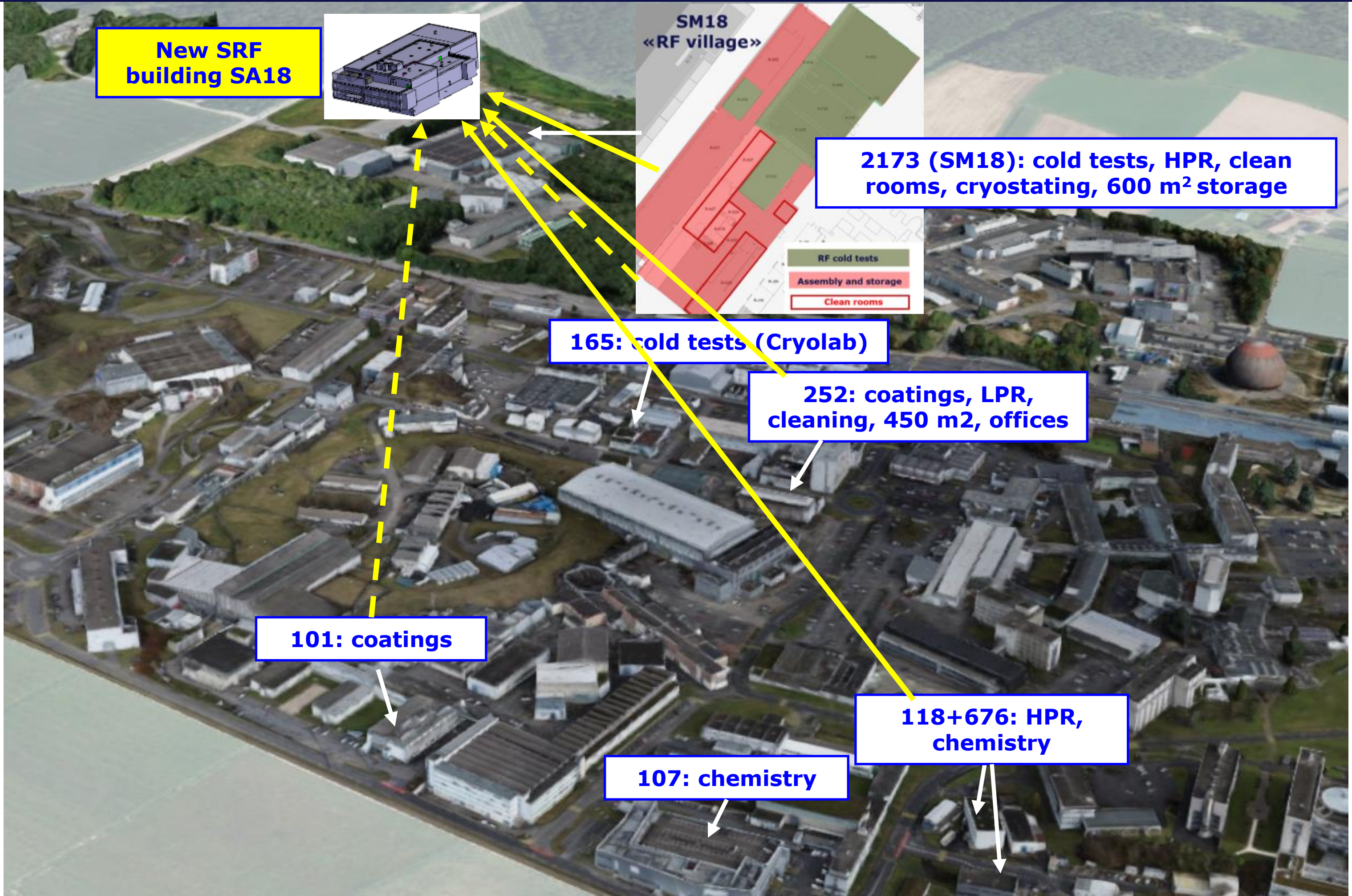




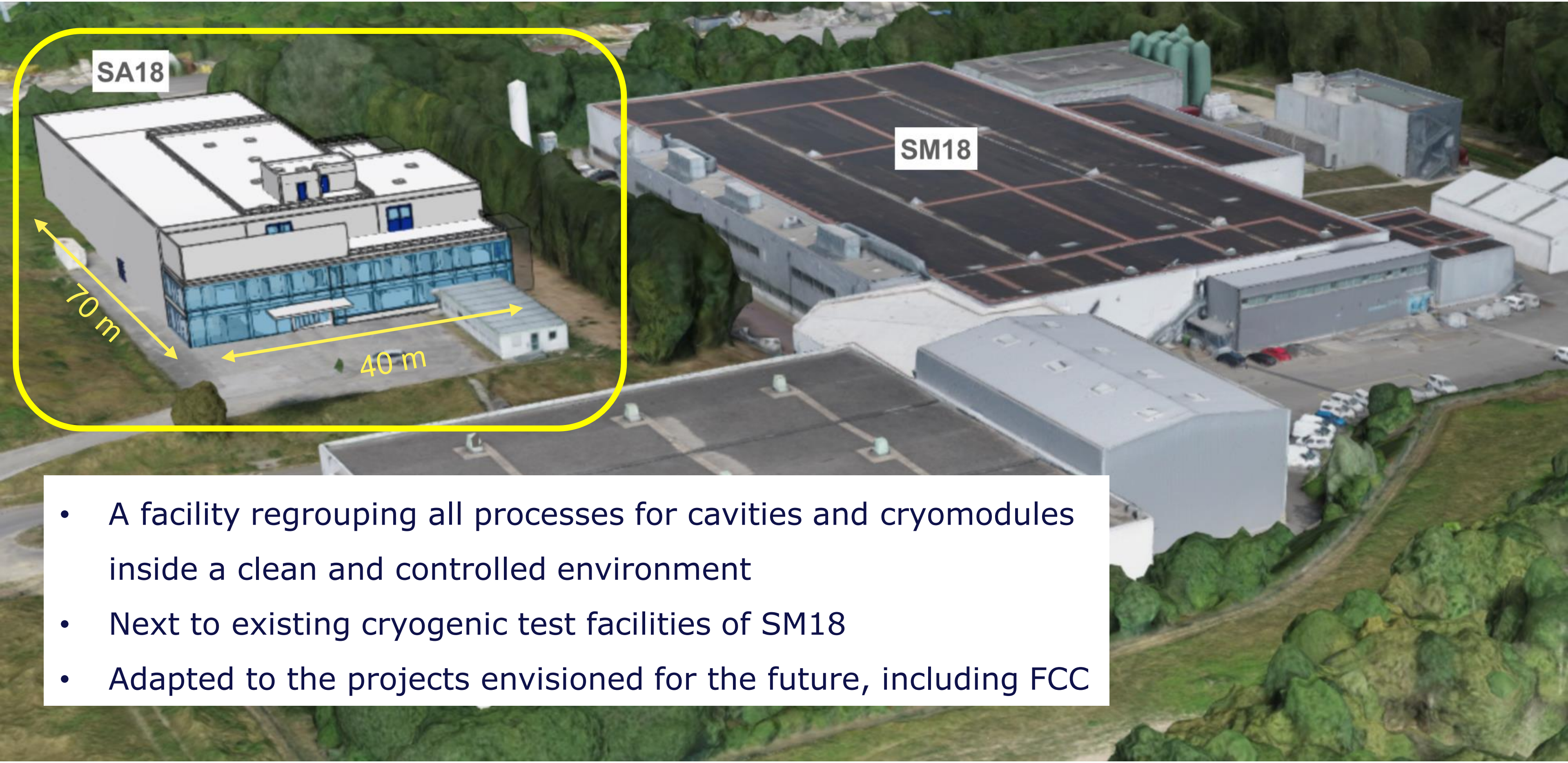




Present SRF infrastructures at CERN



SA18 building implantation



- A facility regrouping all processes for cavities and cryomodules inside a clean and controlled environment
- Next to existing cryogenic test facilities of SM18
- Adapted to the projects envisioned for the future, including FCC

SA18 building layout

General Area
Personnel & Visitor Entrance
Open space workstations
meeting room,…

Sputtering Lab
(5 positions)

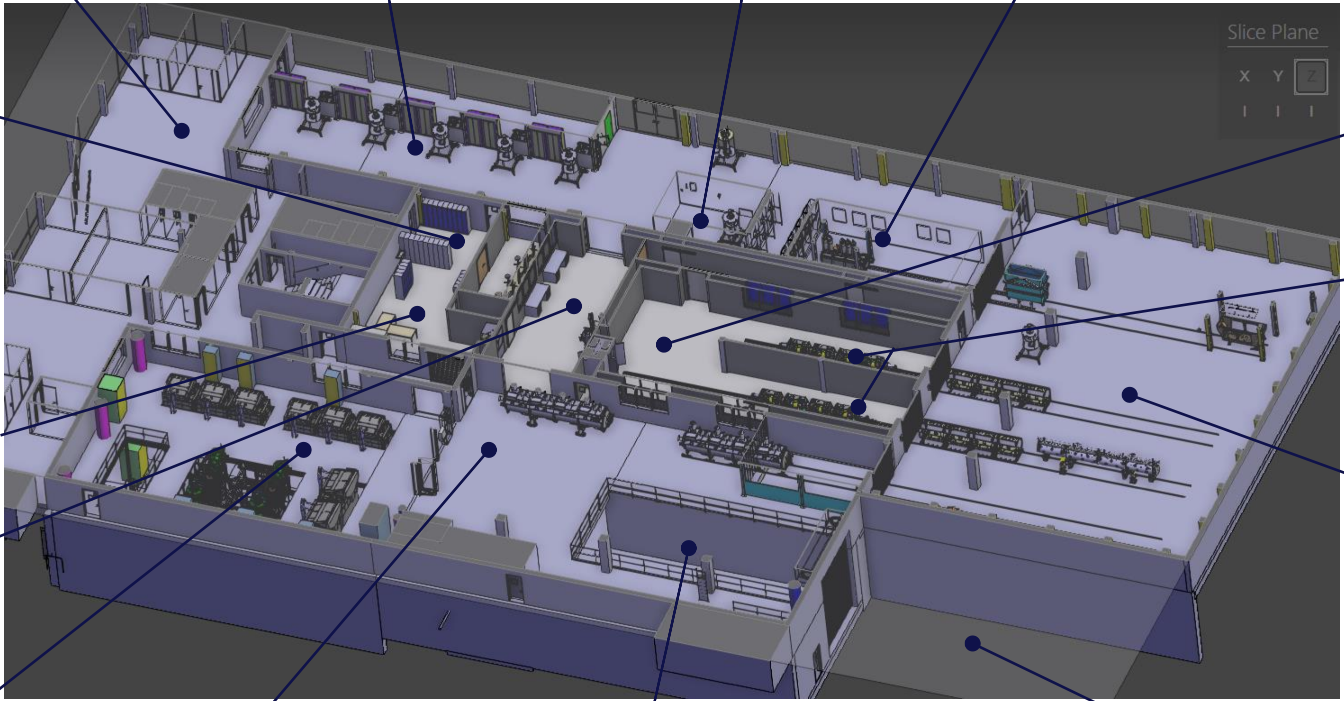
LPR / HPR & Cathode Assy ISO 4 Cleanroom
Horizontal airflow

HIE ISOLDE CM Assy ISO 4 Cleanroom
Horizontal airflow

Gowning Area
Personnel access
to cleanrooms

Cavity assembly ISO 4 Cleanrooms
Vertical airflow

Cavity string assembly lines 1&2 ISO 4 Cleanroom



Preparation area
For small components
Prior to entering cleanrooms
+ component washer

Main Hall Cryostating ISO 8 Cleanroom

QA/QC Room ISO5
+ HPR

Surface Treatment workshop
for Nb and Cu cavities

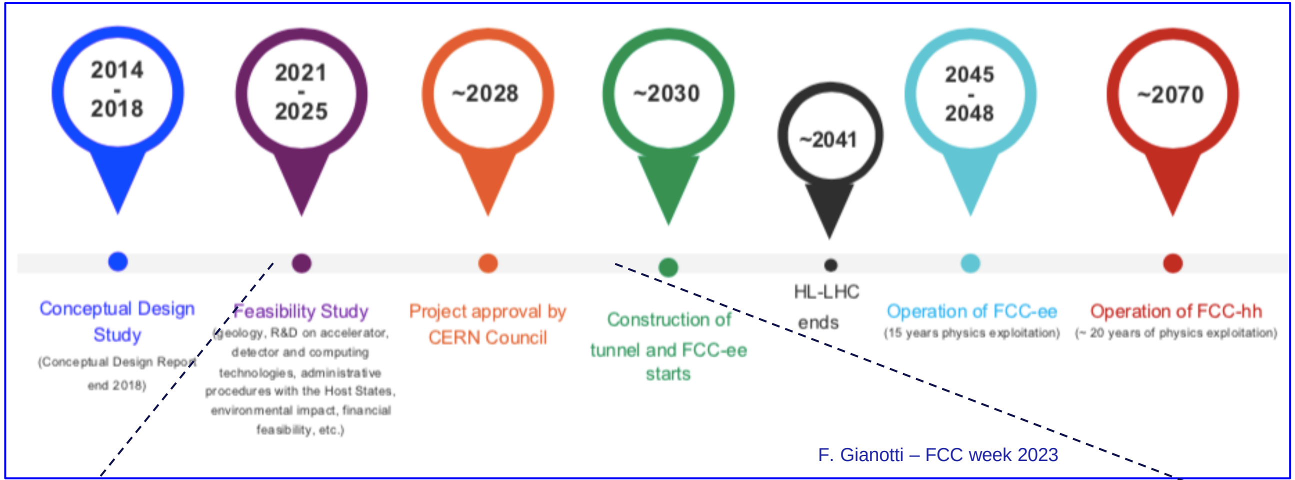
Reception Hall

Loading Bay
(access to basement)

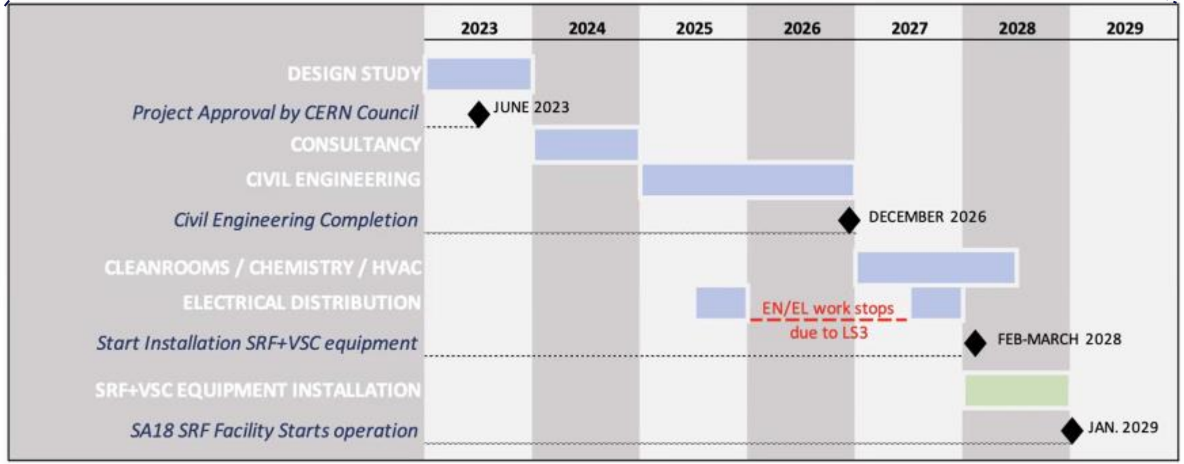
Access from/to SM18

Timeline

FCC



SRF building SA18



D. Smekens

Conclusion

- Solid SRF system baseline based on a strong experience at CERN, especially on Nb/Cu thin films technology. The detailed design of the cavities is progressing well.
- In parallel some R&D activities on innovative ideas are pursued, in order to decrease the construction and operational costs.
- The recent decision to build a new SRF infrastructure is a great news and will clearly support the future SRF developments for FCC.

Thank you for your attention

Acknowledgments (CERN): S. Atieh, O. Brunner, A. Butterworth, R. Calaga, O. Capatina, M. Chiodini, Y. Cuvet, H. Demerau, M. Garlasche, F. Gerigk, M. Gourragne, S. Gorgi Zadeh, I. Karpov, E. Montesinos, V. Parma, G. Pechaud, G. Rosaz, D. Smekens, Y. Syratchev, M. Therasse, M. Timmins, W. Venturini Delsolaro

Why 4 → 2-cells ?

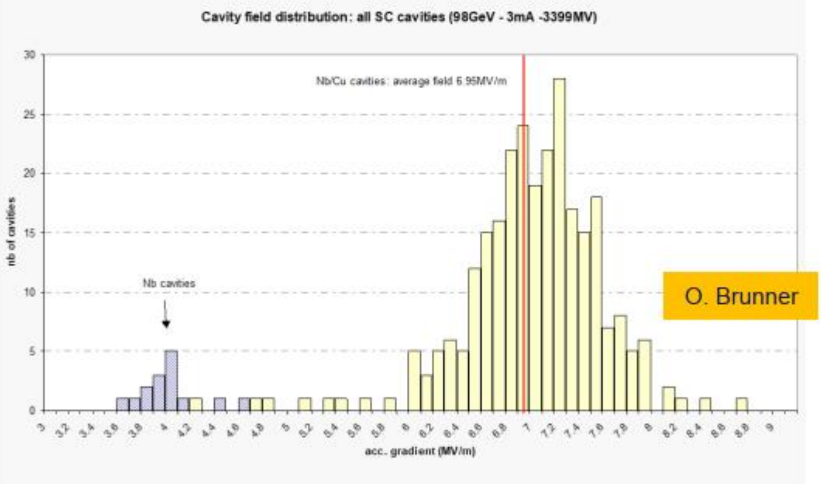
Eacc limited to ~ 7 MV/m in LEP

Very large superconducting surface (~5 m^2) → more “chance” to have surface defects

Such large cavities require significant SRF infrastructures upgrades at CERN

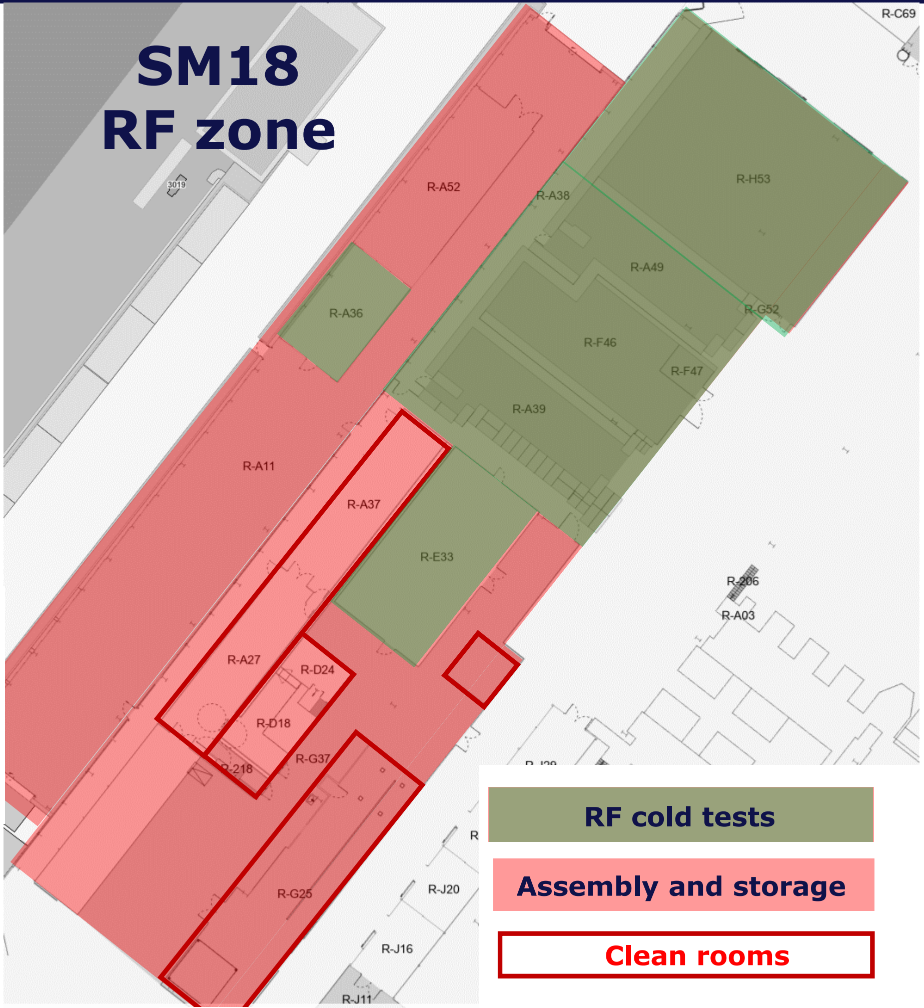
Surface treatments recipes for high accelerating gradient will be very painful to adapt

Operation at 100GeV



O. Brunner

SM18 RF zone



1	Large clean room : ISO4, ISO5, HPR cabinet
2	Cryostating (external rail system)
3	Clean room with horizontal flow (HIE ISOLDE)
4, 5	Baldaquins
6	Control room: Faraday cage with measurement stand
7	Horizontal bunker M7, M9: Cryomodule Test
8	Vertical cryostats V3, V4, V5, V6 for testing of bare and dressed cavities
9	Extension: ~600 m^2 of the reception and storage space