RF systems for FCCee

Franck Peauger
on behalf of the FCC RF team

FCCIS workshop

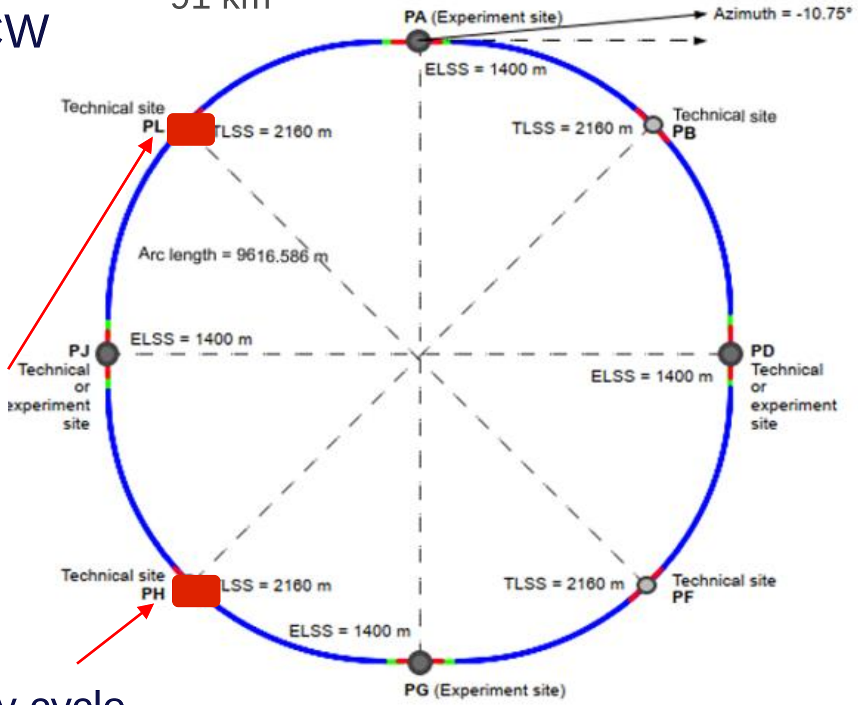
07-12-22

RF system for FCCee

Designed to provide 100 MW of RF power in CW to compensate losses by synchrotron radiation

	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.120
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3

91 km



+ Booster: 10% beam current and 15% average duty cycle

TIWG 29/09/2021

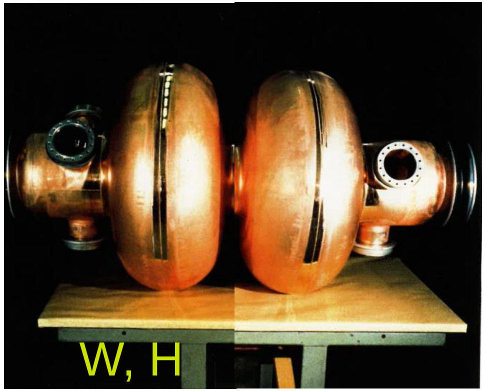
3 different types of SRF cavities for the FCC-ee RF baseline

New compared to CDR

400 MHz 1-cell cavities

Nb/Cu

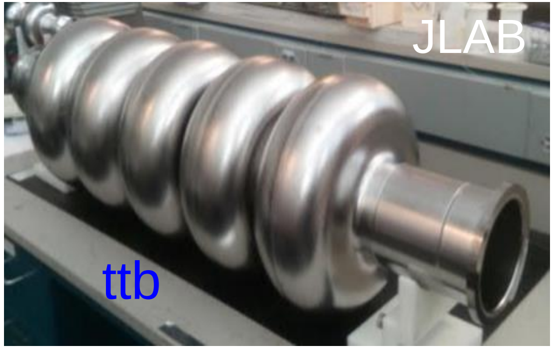
Removed after Z operation



400 MHz 2-cell cavities

Nb/Cu

2-cell is better for W working point
(reduced RF power per cav., improved HOM damping)



800 MHz 5-cell cavities

Bulk Nb

M. Benedikt
Monday

FUTURE CIRCULAR COLLIDER

Stage 1: updated parameters

K. Oide, D. Shatilov,

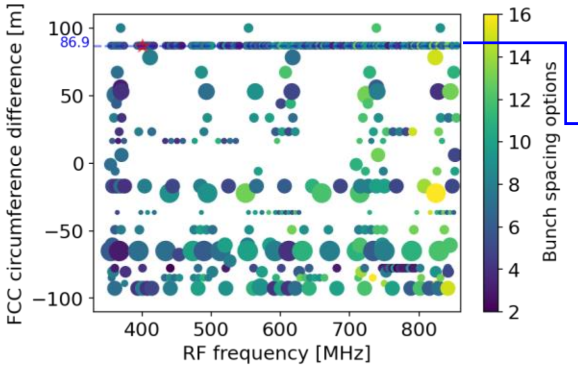
Parameter [4 IPs, 91.2 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45	80	120	182.5
beam current [mA]	1280	135	26.7	5.0
number bunches/beam	10000	880	248	36
bunch intensity [10^{11}]	2.43	2.91	2.04	2.64
SR energy loss / turn [GeV]	0.0391	0.37	1.869	10.0
total RF voltage 400/800 MHz [GV]	0.120/0	1.0/0	2.08/0	4.0/7.25
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.1	0.2	0.3	1
vertical beta* [mm]	0.8	1	1	1.6
horizontal geometric emittance [nm]	0.71	2.17	0.64	1.49
vertical geom. emittance [pm]	1.42	4.34	1.29	2.98
horizontal rms IP spot size [μm]	8	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ .159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.38 / 14.5	3.55 / 8.01	3.34 / 6.0	2.02 / 2.95
luminosity per IP [10^{34} $cm^{-2}s^{-1}$]	182	19.4	7.3	1.33
total integrated luminosity / year [ab^{-1}/yr]	87	9.3	3.5	0.65
beam lifetime (rad Bhabha + BS+lattice)	8	18	6	10

Circumference options assuming 400.79 MHz and 90.75 km +/-100 m

h_{FCC}	C_{FCC} [m]	ΔC_{FCC} [m]	h_{FCC}/h_{LHC}	h_{FCC}/h_{SPS}	Largest prime factor	Bucket spacings	Bunch spacings [ns]	Bunch spacing options
121440 = 2^5x3x5x11x23	**90836.9**	**86.9**	**92/27**	**92/7**	**23**	**1, 2, 3, 4, 5, 6, 8, 10**	**2.5, 5.0, 7.5, 10, 12.5, 15, 20, 25**	**8**
121380 = 2^2x3x5x7x17^2	90792.0	42.0	2023/594	289/22	17	1, 2, 3, 5, 6, 7, 10	2.5, 5.0, 7.5, 12.5, 15, 17.5, 25	7
121200 = 2^4x3x5^2x101	90657.4	-92.6	1010/297	1010/77	101	1, 2, 3, 4, 5, 6, 8, 10	2.5, 5.0, 7.5, 10, 12.5, 15, 20, 25	8

Linhao Zhang
Ivan Karpov
Heiko Damerau

- **h_{FCC} = 121440 is the most favorable harmonic number from the RF point of view: it has very short transfer wait time, small largest prime factor, and many bunch spacing options**
- **hFCC = 121200 can also give many bunch spacing options, but the higher larger prime factor and longer LHC-to-FCC transfer wait time**



Point size indicates the largest prime factor

Flexible options for RF frequency

400.79, 500.99, 601.19, 801.58 MHz

RF parameters table

Limiting parameters for RF

07-Dec-22	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	5.34	10.95	21.55	10.78	22.42	10.78	22.52	22.50
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.00	8.20	20.19	8.08	21.00	8.08	21.10	21.08
#cells	56	140	256	260	520	500	520	2180	2680
# cavities	56	28	128	52	260	100	260	436	536
# CM	14	7	32	13	65	25	65	109	134
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	22	0.3	163	4	158	5	158	32	5
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	2.7E+05	1.1E+06	8.3E+06	1.1E+06	1.7E+07	9.4E+06	4.2E+06	9.3E+07
Detuning [kHz]	8.939	5.126	0.472	0.131	0.096	0.013	0.031	0.028	0.002
Pcav [kW]	880	176	385	95	379	49	45	202	9
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.56	0.96	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

one RF system per beam

common RF system for both beams

- **Cavity performances: 20 % margin added on Eacc and Q0 between vertical test and operation**
- **In total: 336 cryomodules, 1344 cavities, 30% with Nb/Cu technology**

1-cell 400 MHz cavity for Z

S. Gorgi Zadeh

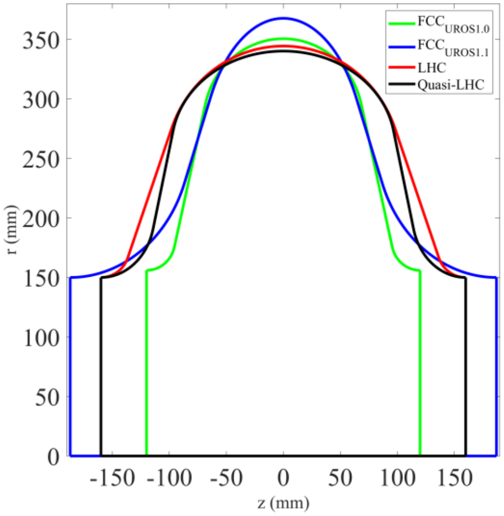
- «LHC type», Nb/Cu technology, 4.5 K

E_{acc} = 5.7 MV/m, Q_0 = 2.7e9, P_{RF} = 900 kW

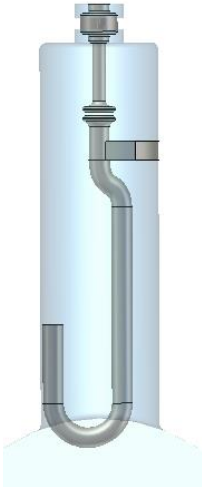
- Elliptical shape optimized to eliminate all longitudinal HOMs

- Strong transverse HOMs damping with hook type couplers

$Z_{transv.\ max}$ ~ 10 kΩ/m



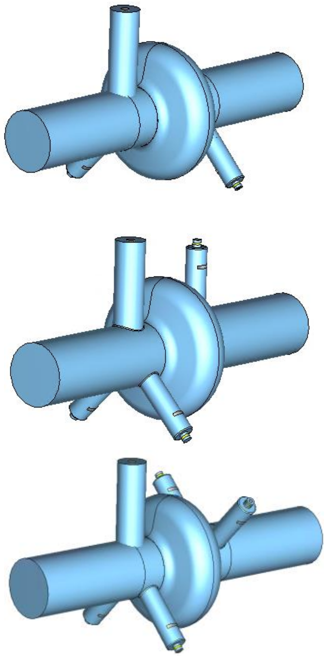
Several elliptical profiles under studies

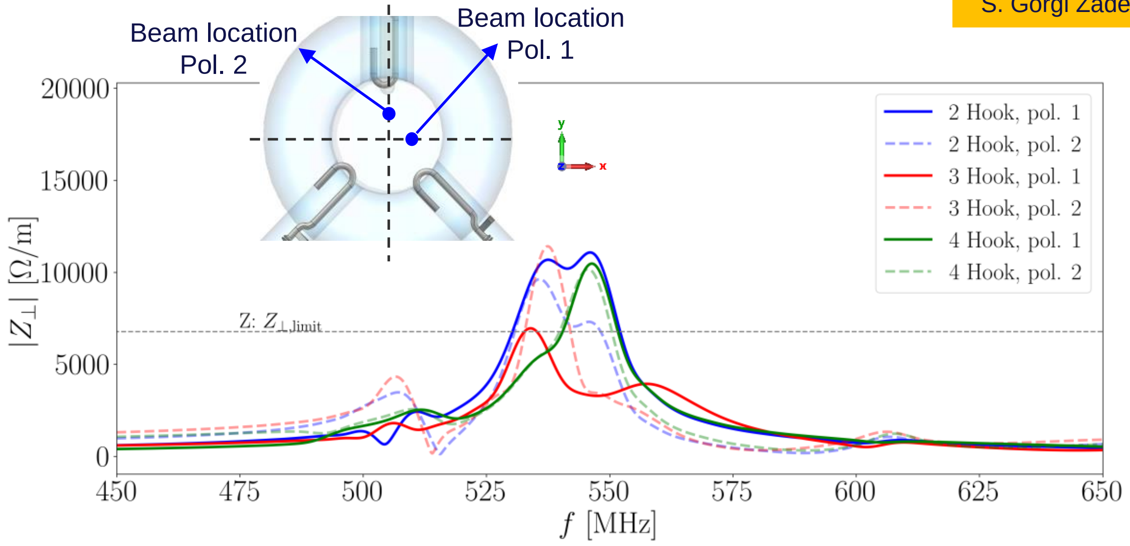


Hook type HOM coupler

Transverse impedance of the first dipole passband

S. Gorgi Zadeh





- Difficult to stay below the beam stability threshold for Z
- Bunch-by-bunch feedback system to be implemented

RF/mechanical design – choice of cavity thickness

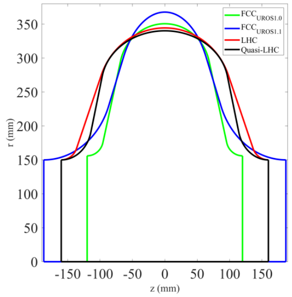
- Coupled RF/mechanical simulations using CST Studio 2022
- Simplified cavity shape : no RF ports, no helium tank

Parameters	LEP	LHC	UROS 1.1	Quasi LHC		
Thickness (mm)	3	2.75	2.75	2.75	3.5	4.25
Tuning Sensitivity Δf/Δz [kHz/mm]	-40.98	-240.05	-210.91	-257.73	-253.27	-254.24
Cavity Stiffness Kcav [kN/mm]	2.25	18.30	16.39	8.00	11.41	15.95
Lorentz Force Detuning coeff. fixed ends KL [Hz/(MV/m)^2]	-2.00	-2.22	-8.05	-1.64	-0.75	-0.44
Lorentz Force Detuning coeff. free ends KL [Hz/(MV/m)^2]	-10.20	-8.31	-19.90	-18.39	-9.99	-5.86
Pressure Sensitivity fixed ends Kp [Hz/mbar]	20.18	-11.84	-117.05	-26.41	-16.49	-11.28
Pressure Sensitivity free ends Kp [Hz/mbar]	62.90	51.60	21.50	184.17	135.04	95.11
Max VM stress fixed ends [MPa] (1 bar applied)	33.6	30	34.40	37.9	27.5	21
Max VM stress free ends [MPa] (1 bar applied)	42	35	45.10	62.8	44.6	33.7

Not decisive in CW mode (Lorentz Force Detuning rows)

→ with tuner (Pressure Sensitivity fixed ends)

→ with tuner (Max VM stress fixed ends)

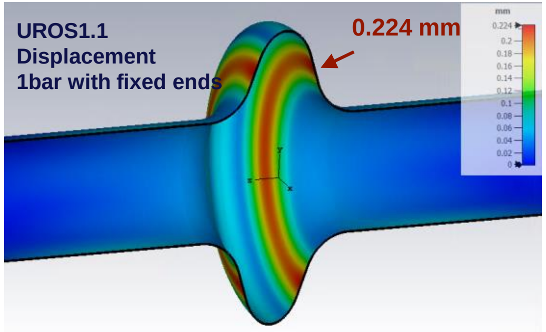


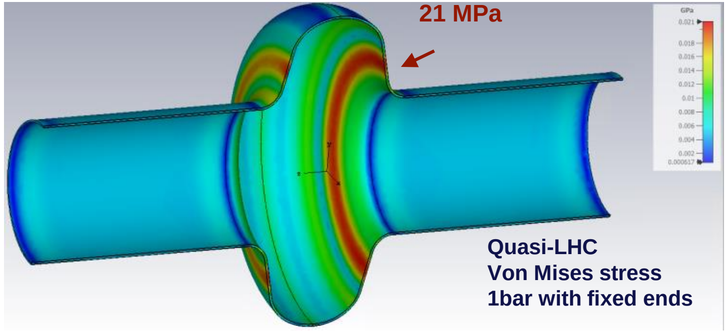
Material properties: Copper (pure)

Young's modulus = 120 kN/mm^2

Poisson's ratio = 0.33

Density = 8930 kg/m^3

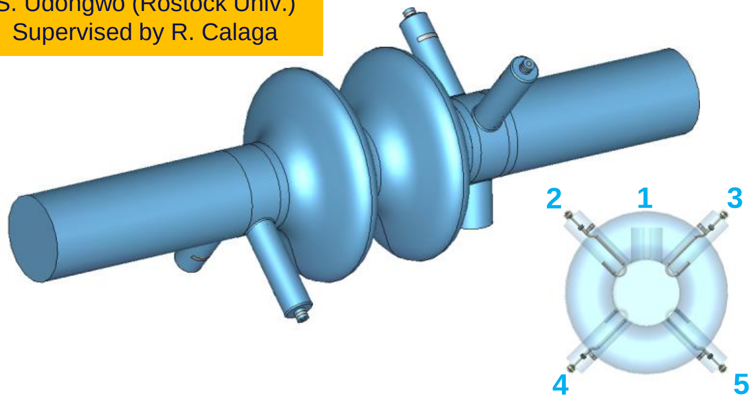




- From an RF point of view, a thickness of 4.25 mm is recommended with the “Quasi-LHC” single cell 400 MHz cavity
- Manufacturing constraints and compliance with PED to be addressed to converge to the final mechanical design

2-cell 400 MHz for W, H

S. Udongwo (Rostock Univ.)
Supervised by R. Calaga



- New type, “between LHC and LEP”
- Nb/Cu technology, 4.5 K

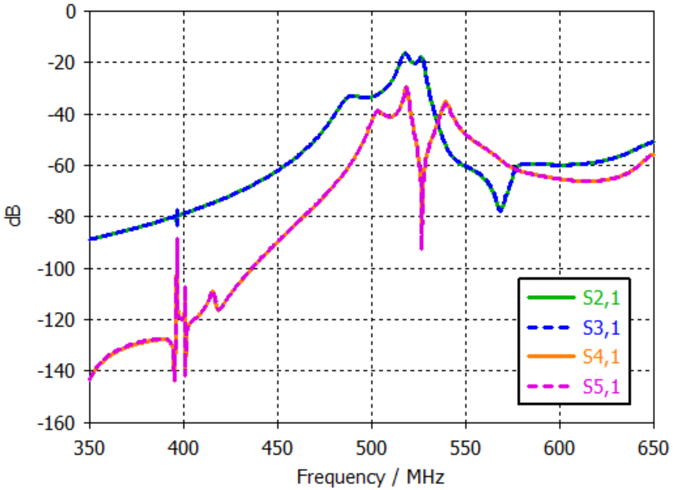
E_{acc} = 10.8 MV/m, Q_0 = 2.7e9, P_{RF} = 400 kW

- Same damping strategy as for Z

  - no longitudinal HOM,

  - hook-type couplers to damp transverse modes

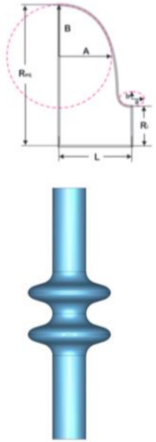
RF transmission FPC → HOM couplers



2-cell 400 MHz optimization

S. Udongwo (Rostock Univ.)
Supervised by R. Calaga

With a multi-objective shape optimization, a low longitudinal impedance cavity geometry was found.



Variable	Value
A [mm]	73.52
B [mm]	131.75
a [mm]	106.25
b [mm]	118.7
R_{eq} [mm]	369.6322
R_i [mm]	150
L [mm]	187
α [°]	107.23
R/Q [Ω]	152.80
$G.R/Q$ [Ω²]	3.0e4
E_{pk}/E_{acc} [-]	2.05
B_{pk}/E_{acc} [mT/MV/m]	6.39

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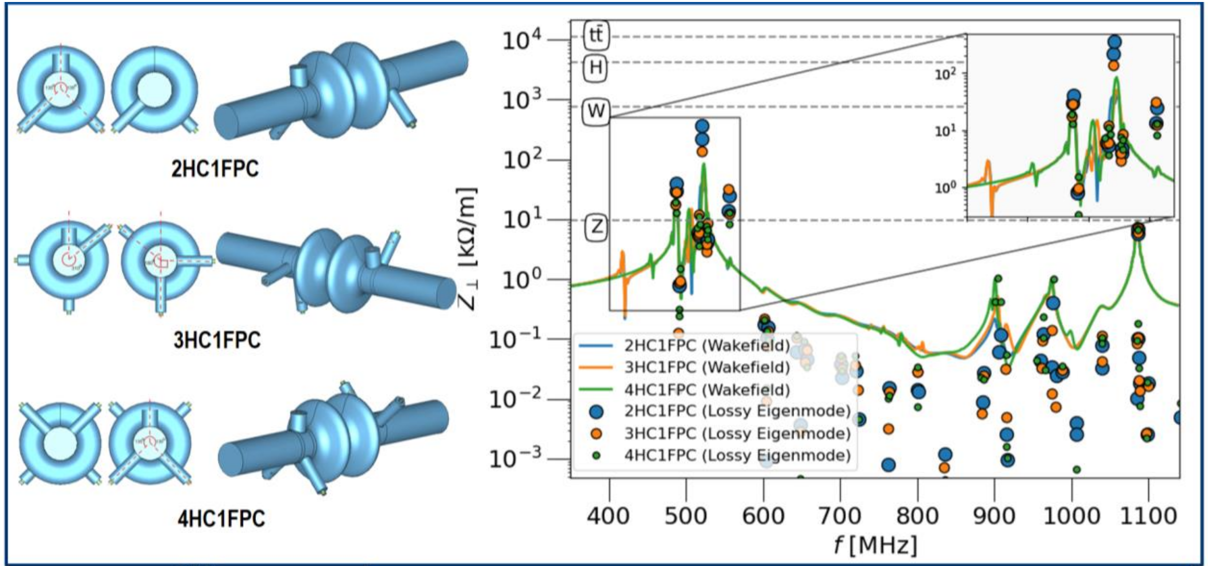

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S. Udongwo, "The Ell Cavities program at CERN: Baseline cavities designs for FCC_ee", presented at the FCC Week 2022, Paris, France, May 2022

5-cell 800 MHz for ttb and booster

- Bulk Nb, 2 K
- Similar to SNS, SPL, ESS high beta cavities
- High accelerating gradient and high Q0 are required

$$E_{acc} = 22.5\ \mathrm{MV/m},\ Q_0 = 2.7\mathrm{e}10,\ P_{RF} = 200\ \mathrm{kW}$$

- HOMs damping with HOM couplers and rect. WG (TBC)
- Considered also for the booster
- Bare simplified cavity (without ports) successfully built and tested at JLAB in 2018

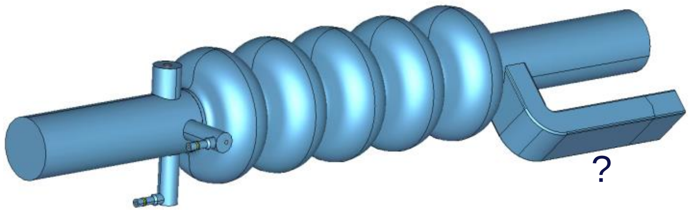


Table 4.3: RF parameters of the proposed four-cell (FCC_{UROS4}) and five-cell (FCC_{UROS5}) cavities. The cavities are compared with two five-cell cavities designed for operation in PERLE [78, p. 61].

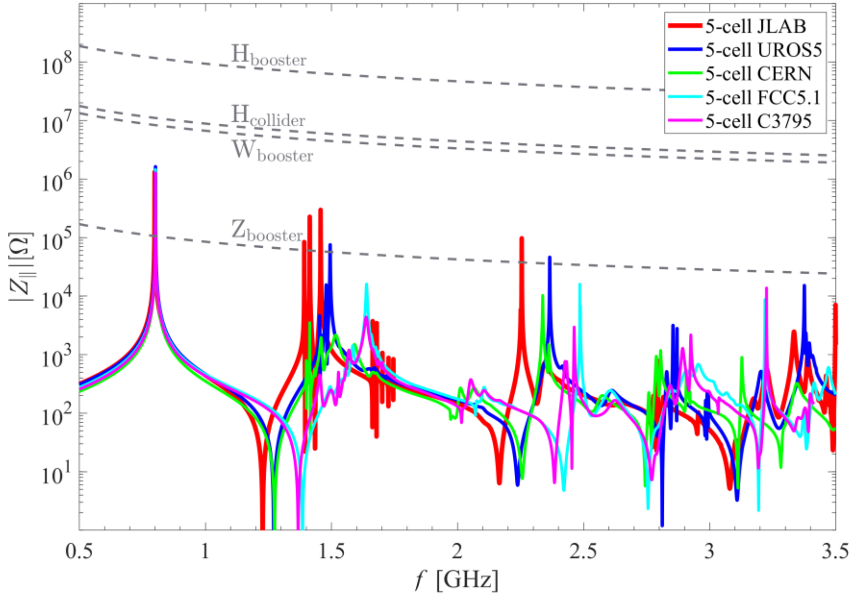
Parameters	FCC_{UROS4}*	FCC_{UROS5}*	$CERN_2$	$JLab_2$
Frequency, f_0 [MHz]	400.79	801.58	801.58	801.58
Number of cells, N_{cell}	4	5	5	5
$R/Q_{\parallel,0}$ [Ω]	411.3	520.6	393	523.9
G [Ω]	273.2	272.9	283	274.6
$G \cdot R/Q_{\parallel,0}$ [Ω²]	112367	142072	111219	143862
B_{pk}/E_{acc} (middle cell) $[\frac{mT}{MV/m}]$	4.2	4.2	4.92	4.2
E_{pk}/E_{acc} (middle cell)	2.0	2.0	2.4	2.26
Cavity active length, L_{active} [mm]	1465.1	919.5	935	917.9
Radius of the middle cells, R_i [mm]	120	60	80	65
Beam pipe radius, R_{bp} [mm]	156	78	80	65
Wall angle of middle cell, α [°]	100	100	102.5	90
k_{cc} of the middle cell [%]	2.25	2.25	5.75	3.21
k_{cc} of the cavity [%]	1.92	2.04	5.19	2.93
Field flatness, η_{ff} [%]	99	99	96	99
$k_{\parallel}$ ($\sigma_z = 2$ mm) [V/pC]	2.27	3.37	2.63	2.74
f_{cut} TE_{11} for R_{bp} [GHz]	0.563	1.126	1.10	1.35
f_{cut} TM_{01} for R_{bp} [GHz]	0.7355	1.471	1.43	1.77
N^2_{cell}/k_{cc}	833	1225	481	853

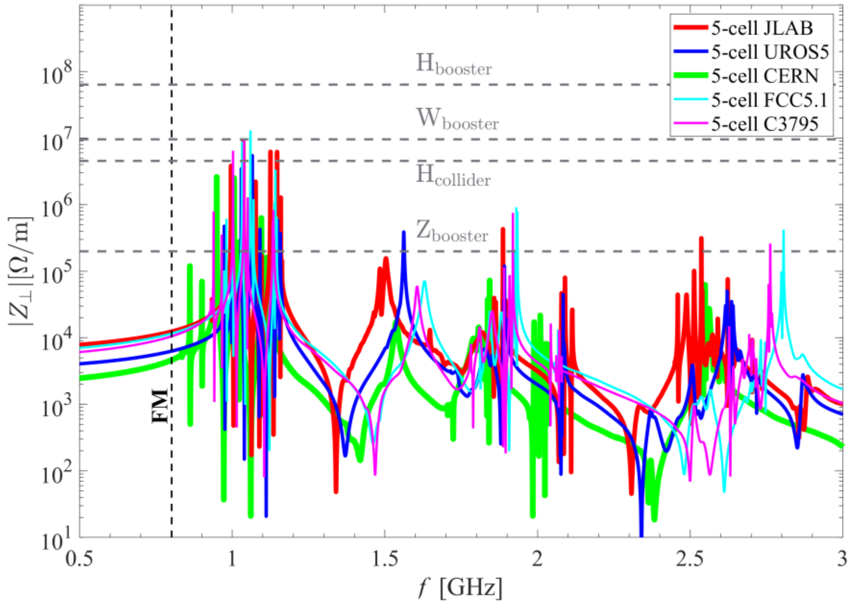
* The designed cells are adapted to a four-cell cavity at 400.79 MHz and a five-cell cavity at 801.58 MHz.

Table from S. Gorgi Zadeh's thesis

5-cell 800 MHz impedances

S. Gorgi Zadeh
S. Udongwo (Rostock Univ.)





UROS5 is the best design candidate for both the collider and the booster

RF parameters with cavity design choices

07-Dec-22	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
RF Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	5.72	5.34	10.95	21.55	10.78	22.42	10.78	22.52	22.50
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.00	8.20	20.19	8.08	21.00	8.08	21.10	21.08
#cells	56	140	256	260	520	500	520	2180	2680
# cavities	56	28	128	52	260	100	260	436	536
# CM	14	7	32	13	65	25	65	109	134
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	22	0.3	163	4	158	5	158	32	5
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	2.7E+05	1.1E+06	8.3E+06	1.1E+06	1.7E+07	9.4E+06	4.2E+06	9.3E+07
Detuning [kHz]	8.939	5.126	0.472	0.131	0.096	0.013	0.031	0.028	0.002
Pcav [kW]	880	176	385	95	379	49	45	202	9
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.56	0.96	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005
Lacc [m]	0.375	0.937	0.749	0.937	0.749	0.937	0.749	0.937	0.937
#cav/CM	4	4	4	4	4	4	4	4	4
R/Q [ohm]	79	521	152.8	521	153	521	153	521	521
G [ohm]	196.20	273.20	196.34	273.20	196.34	273.20	196.34	273.20	273.20
Q0	2.7E+09	2.7E+10	2.7E+09	2.7E+10	2.7E+09	2.7E+10	2.7E+09	2.7E+10	2.7E+10
Ep/Eacc	1.90	2.00	2.05	2.00	2.05	2.00	2.05	2.00	2.00
Bp/Eacc	4.10	4.20	6.39	4.20	6.39	4.20	6.39	4.20	4.20
Ep [MV/m]	10.86	10.67	22.44	43.11	22.09	44.83	22.09	45.05	45.01
Bp [mT]	23.44	22.42	69.94	90.52	68.86	94.15	68.86	94.60	94.51
Cavity design	UROS1	UROS5	C3794	UROS5	C3794	UROS5	C3794	UROS5	UROS5

Cavity performances specification

07-Dec-22	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
1-cell 400 MHz	6.9	3.3E+09	6.6	3.15E+09	6.3	3.0E+09	5.7	2.7E+09
2-cell 400 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 800 MHz	27.6	3.3E+10	26.3	3.15E+10	25	3.0E+10	22.5	2.7E+10

+5% margin +5% margin -10% margin

- Performances degradation between bare and dressed cavity, as well as between vertical test and cryomodule configuration are well known phenomena

  → margins refinement possible after construction and testing of few prototype cavities

- Additional margin in operation is essential for reliable operation

Nb/Cu technology: high gradient / high Q0 challenges

Compared to LHC cavities, significant **improvement of Eacc** and **reduction Q0 slope** shall be achieved for FCCee cavities. New technological process are being developed:

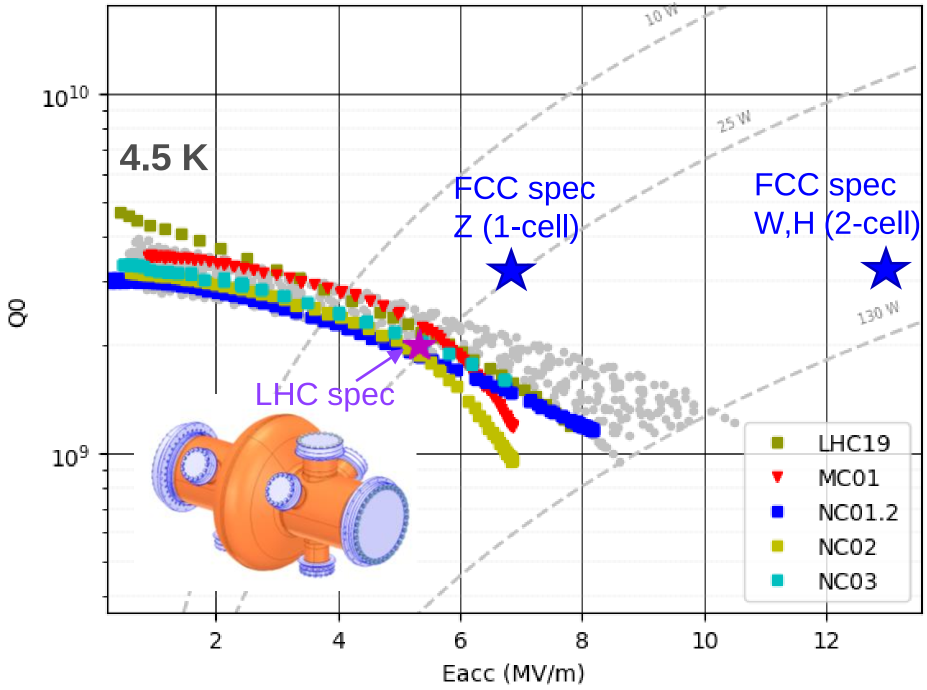
→ **Internal welding** of copper hall cells or **seamless** cavity

→ **Electropolishing** of the copper cavity

→ Highly performant niobium coating :**HiPIMS**
Magnetron Sputtering with a high voltage pulsed power source

→ Application of modern surface preparation and clean room procedures to reach high gradients

New LHC spare cavities performances



G. Rosaz, W. Venturini Delsolaro, M. Garlasche, G. Bellini, L. M. Antunes Ferrera, C. Pereira Carlos, L.Vega Cid, A.Bianchi, G. Pechaud

SRF studies with 1.3 GHz cavities

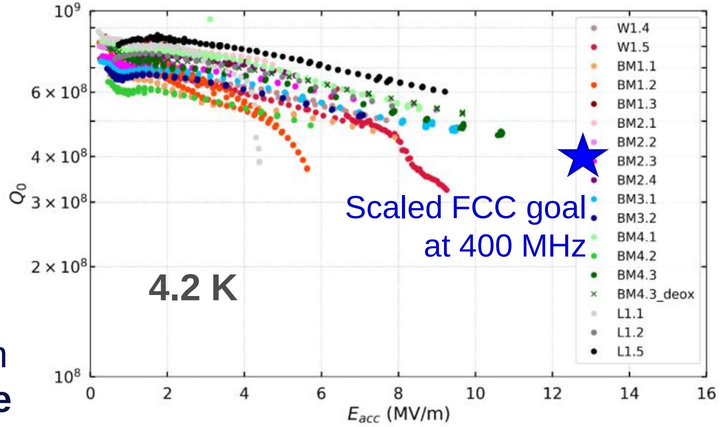
Synergy (and co-funding) with general SRF R&D project

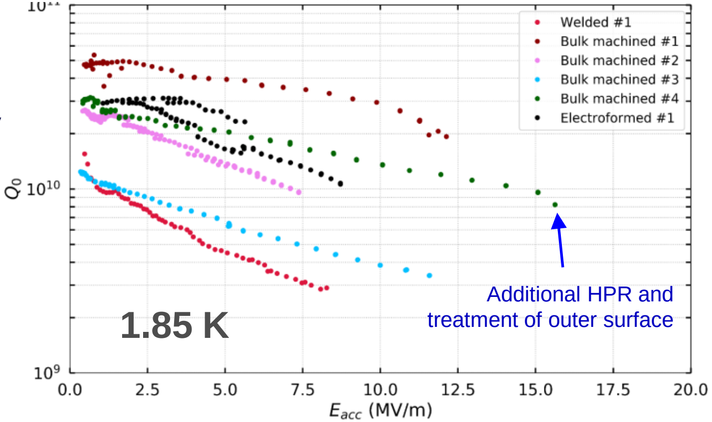
Several types of copper substrates studied
(BM = machined from bulk, W = welded, L = electrodeposited)

Electropolishing + HiPIMS coating

At 4.2 K, good reproducibility. The tests are stopped are 10 MV/m for administrative limits. Extrapolated at 400 MHz, the **results are already satisfactory.**

At 1.8 K, a large scatter of the results is observed and not yet fully understood. The Q0 slope is cancelled in some cases.





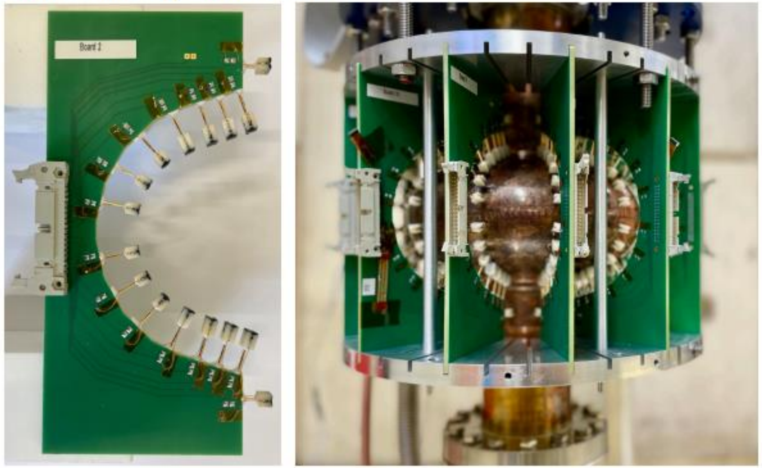
L. Vega Cid, "RF tests of Nb/Cu 1.3 GHz elliptical cavities", presented at the FCC Week 2022, Paris, France, May 2022

L. Vega Cid, "Study of the influence of the manufacturing process and thermal cycling on the RF performance of 1.3 GHz Nb/Cu SRF cavities", presented at the 10th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, JLAB, Newport News, USA, Sept. 2022

Temperature mapping system for Nb/Cu cavities

A.Bianchi

Twelve boards (~200 thermometers):

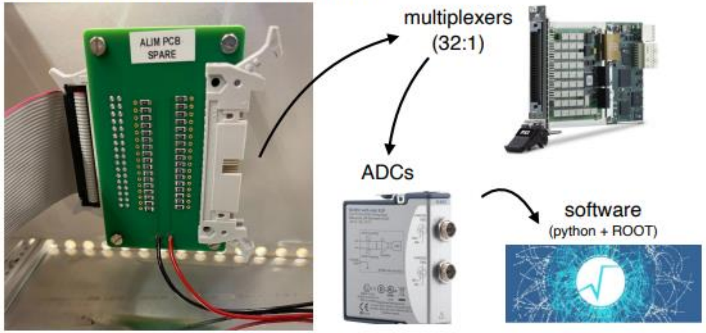


- **~200 thermometers**
- **~500 feedthroughs** in 3 SMT/SMD PCBs
- **6 multiplexers**
- **12 ADC channels** (maximum sampling rate: 100 kS/s)

  → possibility of **high-speed temperature mapping**

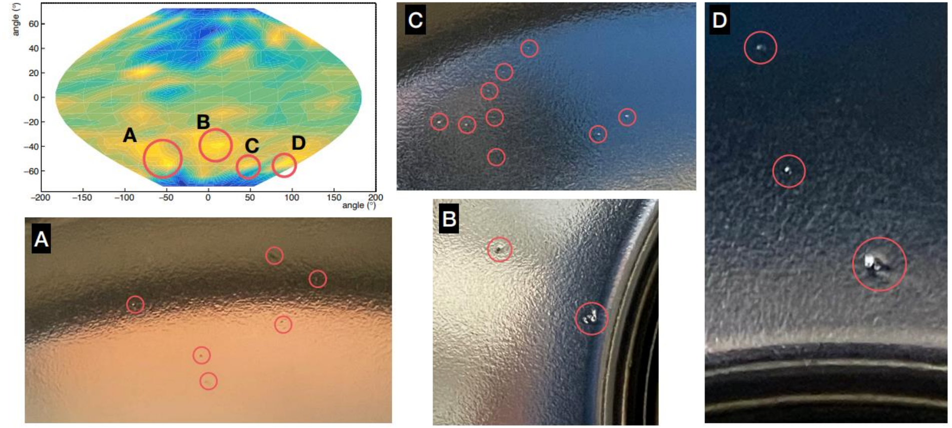
Five hundreds feedthroughs in three SMT/SMD PCBs:

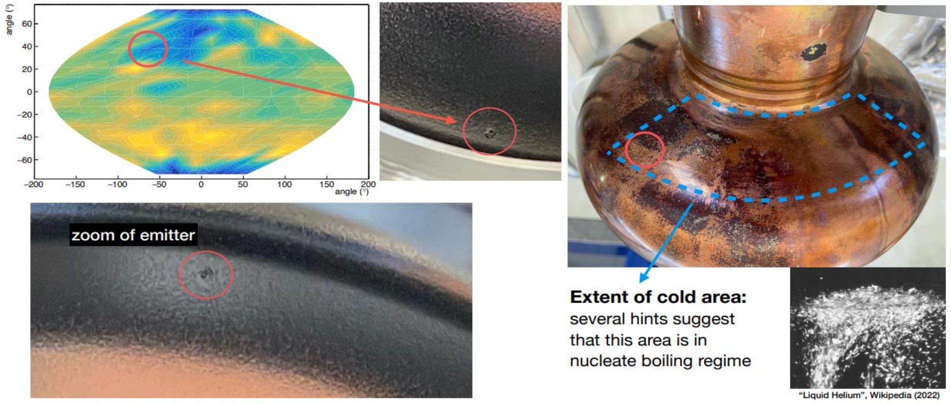
Twelve PCBs for electrical circuit:



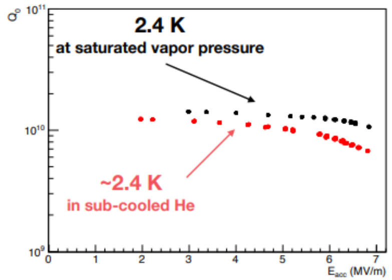
A. Bianchi, "Temperature Mapping of Niobium-coated 1.3 GHz Copper Cavities", presented at the 10th International Workshop on Thin Films and New Ideas for Pushing the Limits of RF Superconductivity, JLAB, Newport News, USA, Sept. 2022

Temperature mapping vs optical inspection

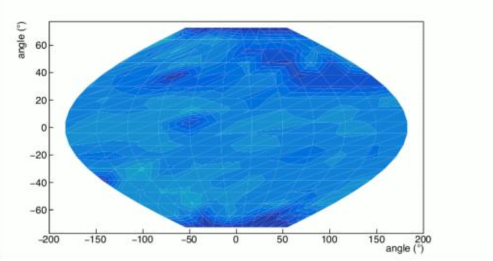




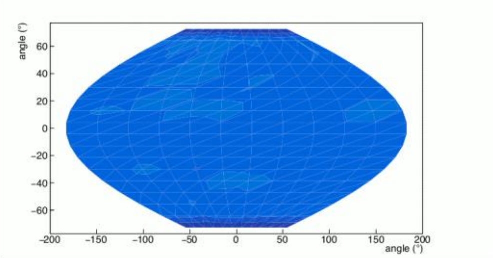
Temperature mapping during Q_0 vs E_{acc} scan



2.4 K – 80 mbar



~2.4 K – Patm

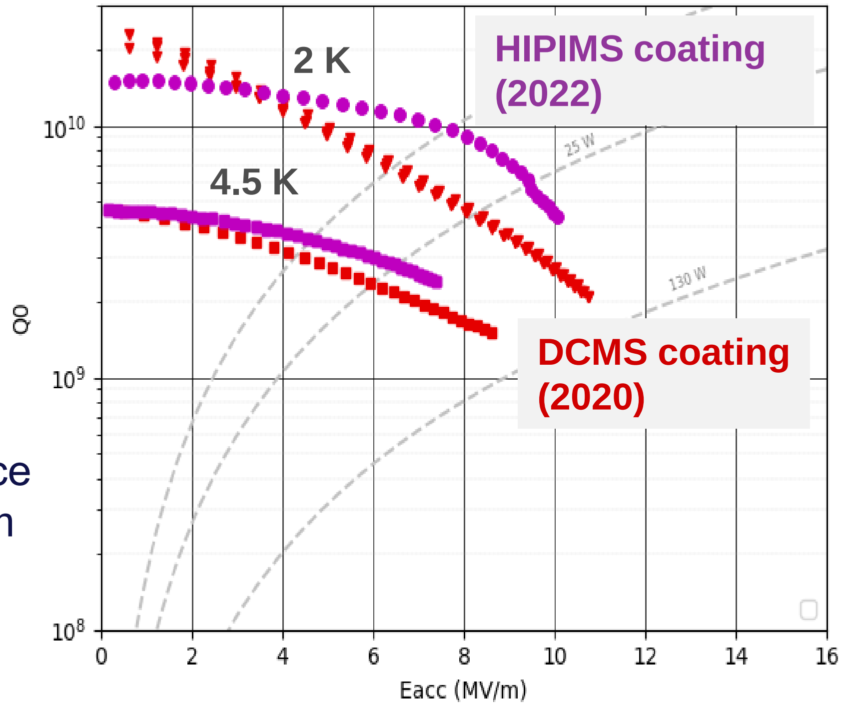


First attempt of HiPIMS coating on a 400 MHz cavity

Reduction Q_0 slope is confirmed

Encouraging result obtained without electropolishing

Test limited by field emission → a new surface preparation in clean room is planned in Q12023 (with niobium coated flanges and HPR)

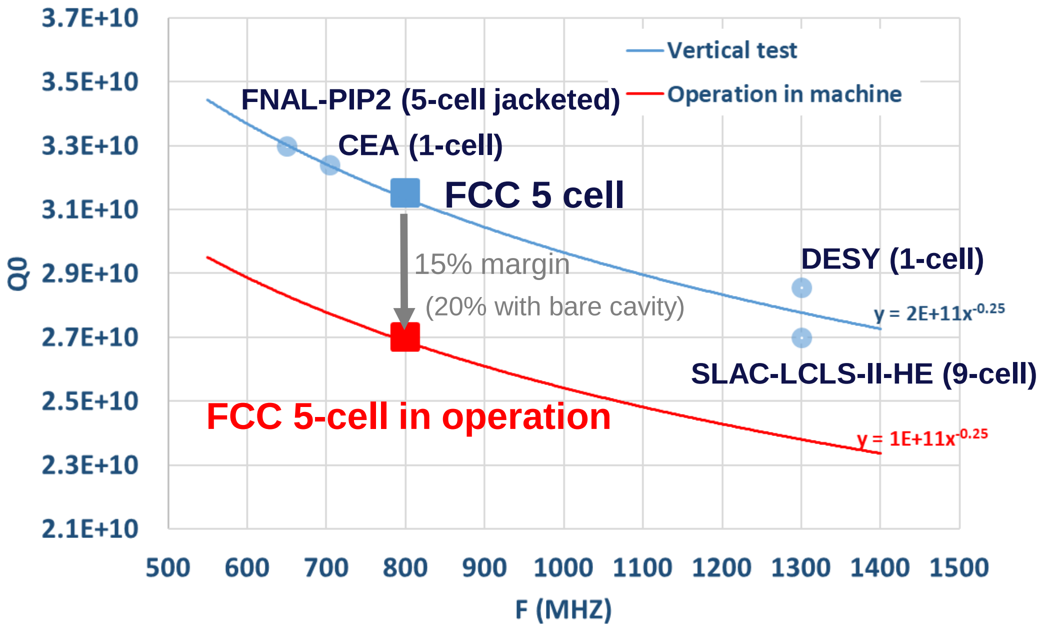


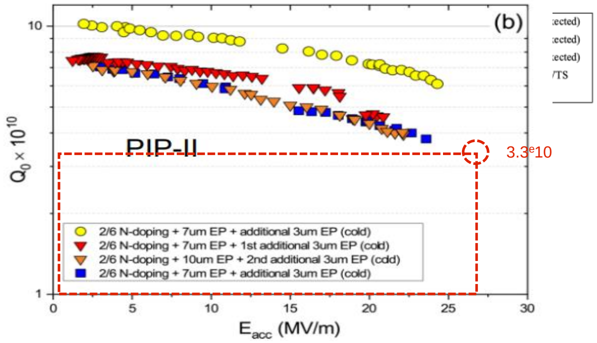
G. Rosaz, J. Walker, Y. Cuvet, G. Pechaud

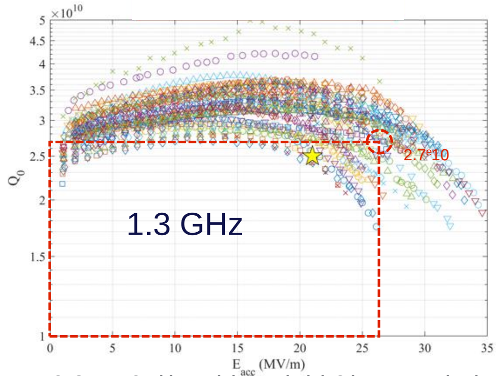
PC04 cavity on vertical insert in SM18

Bulk Niobium SRF technology: high gradient / high Q0 challenges

- Cavities with special nitrogen doping and heat treatments
- Scaling function Q0 vs RF frequency (empirical) at high gradient (25-27 MV/m)







LCLS-II-HE Cavities - High Q and High G in Mass Production
James Maniscalco
TTC 2022 Oct 11 – 14, 2022

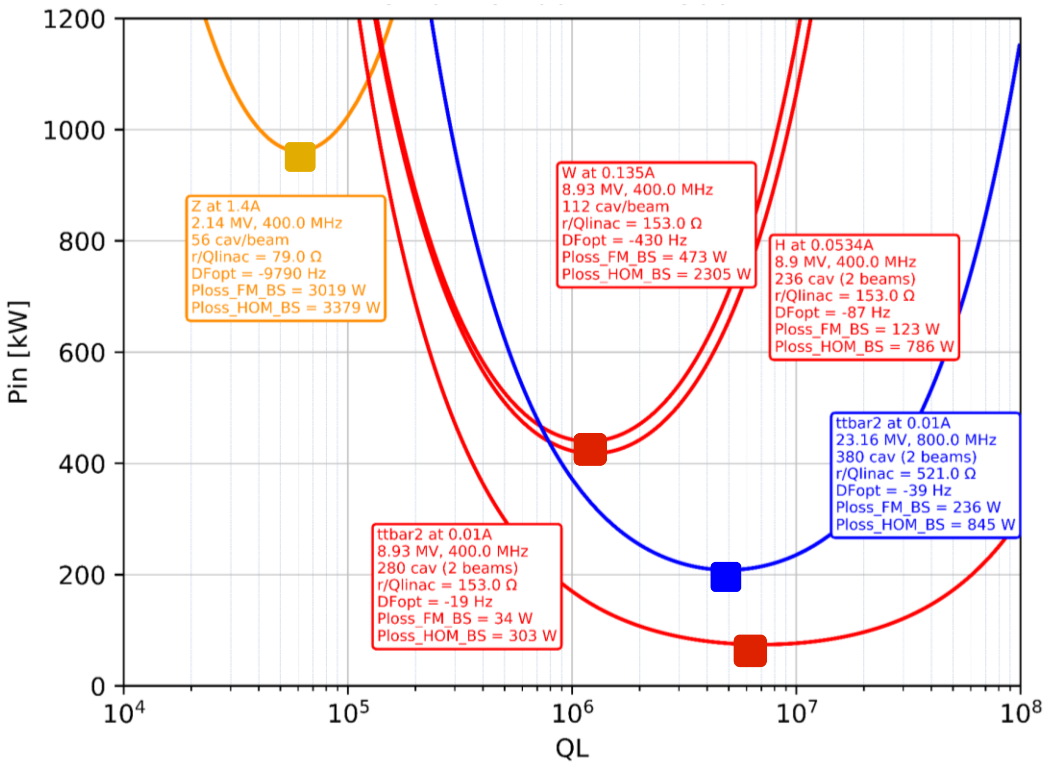
Power requirements for RF Couplers

CW operation

Fundamental Power Couplers:

- 900 kW - 400 MHz fixed couplers for single cell cavities
- 400 kW → 50 kW - 400 MHz variable couplers for 2-cell cavities
- 200 kW - 800 MHz fixed couplers for 5-cell cavities

HOM couplers: ~ 1 kW per coupler at 400 MHz



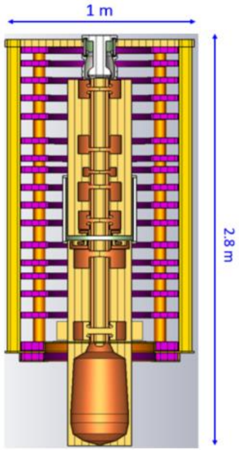
RF power sources

07-Dec-22	Z		W		H		ttbar2		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF source type	**400 MHz 1 MW klystron**	**800 MHz 500 kW klystron**	**400 MHz 1 MW klystron**	**800 MHz 500 kW klystron**	**400 MHz 1 MW klystron**	**800 MHz 50 kW solid state amplifier**	**400 MHz 50 kW solid state amplifier**	**800 MHz 500 kW klystron**	**800 MHz 50 kW solid state amplifier**
Frequency [MHz]	400	800	400	800	400	800	400	800	800
Pcav [kW]	880	176	385	95	379	49	45	202	9
Prf conditioning [kW]	220	44	96	24	95	12	11	51	2
# cavities / RF sources	1	2	2	4	2	1	1	2	4
# RF sources	112	14	128	13	130	100	260	218	134

Ultra-high efficiency Klystron (Two Stages)

- Developed by CERN
- 400 MHz – 1 MW
- Efficiency = 80%

Y. Syratchev,
Z. Un Nisa,
J. Cai,
G. Burt



High efficiency klystron

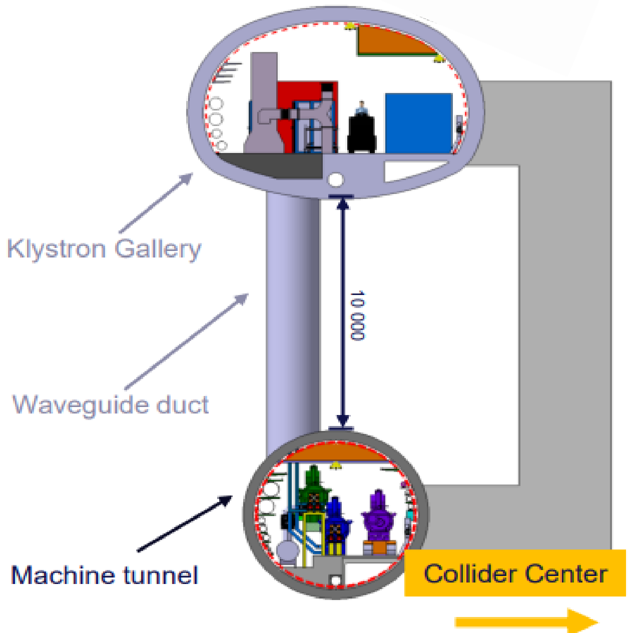
- Suppliers: Thales, CPI
- 800 MHz – 500 kW
- Efficiency = 65%

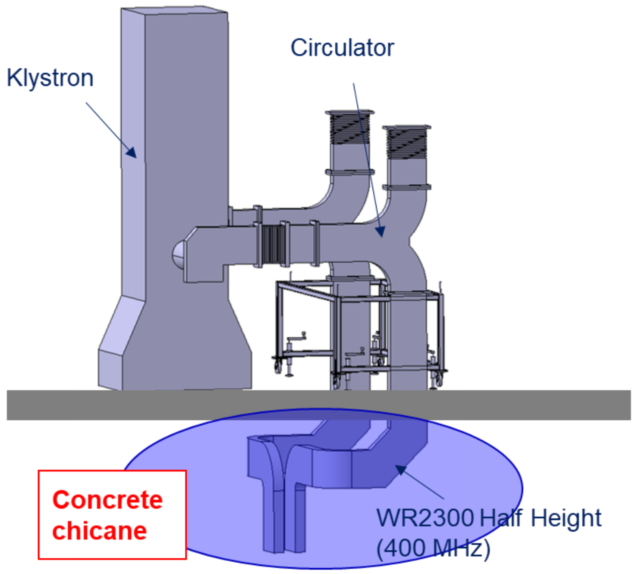
Example of SNS Oak Ridge (long pulse)

RF integration and waveguide distribution

O. Brunner
F. Valchkova

- Vertical arrangement provides benefits:
  - Concrete chicane (Linac 4) in the WG duct to protect from the emission of X-rays (access to klystron galleries during commissioning and operation is required), facilitates the WG path in the machine tunnel and the WG installation
- 1 MW 400 MHz klystrons can be used for:
  - Z: re-combine 2 WG to 1 cavity (in the tunnel)
  - W and ZH: power 2 cavities

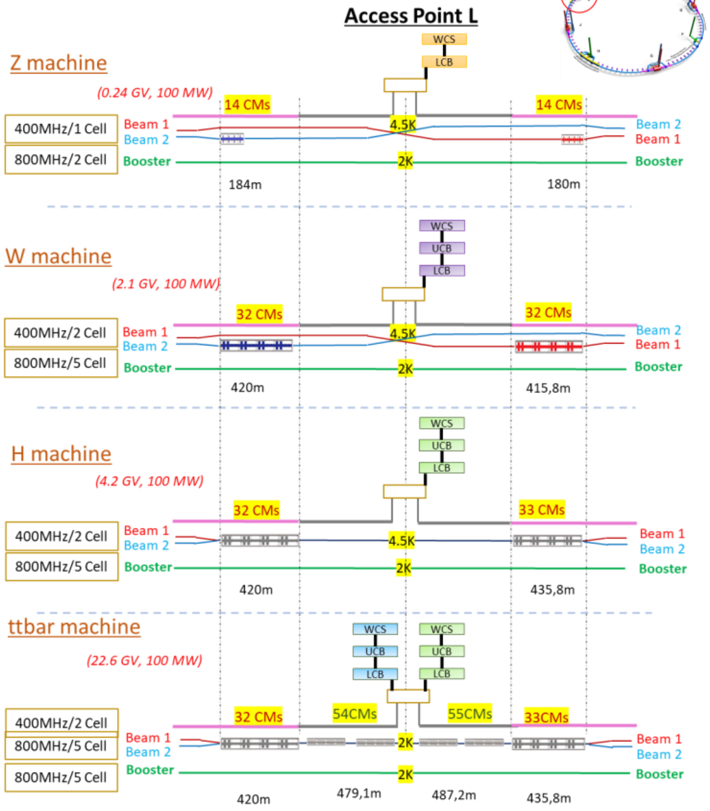




L.Delprat, B.Bradu, K.Brodzinski, F. Valchkova, V. Parma

Cryogenic distribution

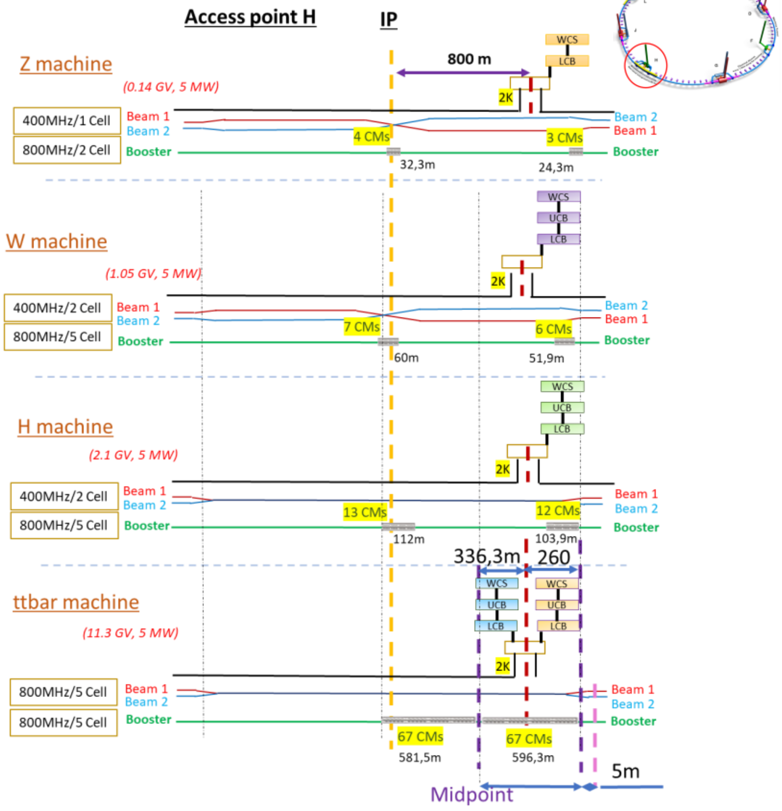
RF for COLLIDER



TLSS length: 2160 m

TOTAL RF LENGTH: 1822,1 m

RF for BOOSTER

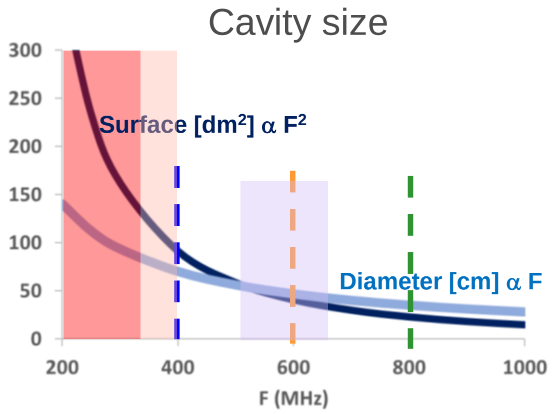


TLSS length: 2160 m

RF section TOTAL RF LENGTH: 1177,8 m

The 600 MHz RF Frequency option

scaling laws for single cell elliptical cavity

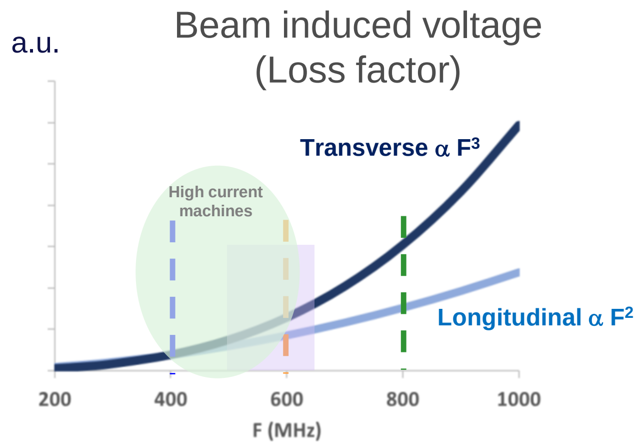


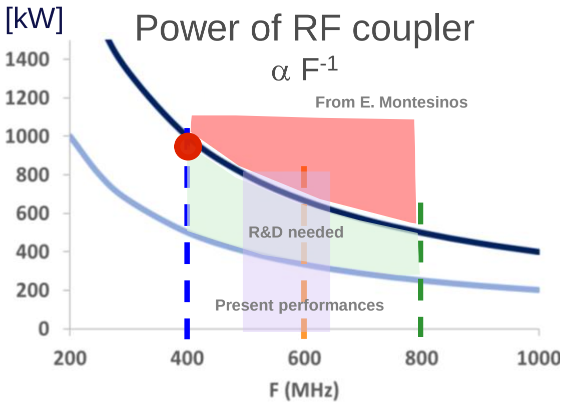
400 MHz — LHC, FCCee Z, W, H, FCChh

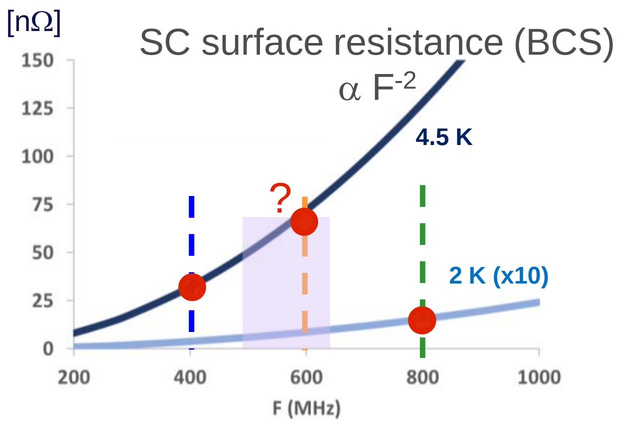
800 MHz — FCC ttb – 2nd harm

600 MHz — SWELL option

SUPER KEKB, EIC, PIP2, CEPC, …







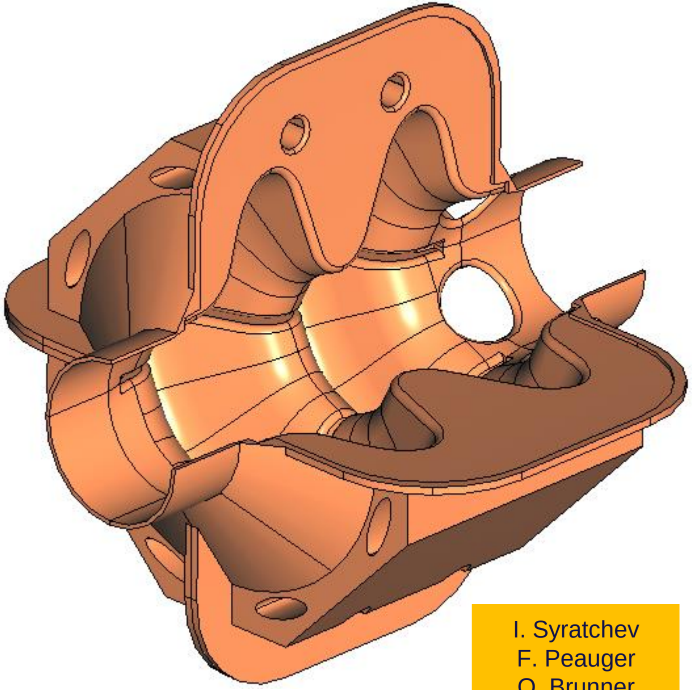
SWELL 2-cell 600 MHz cavity for Z, W, H

SWELL

- Very interesting **alternative cavity option** which would cover three machines (no need to remove cryomodules after operation at Z)
- Highly damped RF cavity for transverse HOMs thanks 4 waveguide slots and coaxial RF lines

E_{acc} = 12.5 MV/m, P_{RF} = 600 kW

- Robust against microphonics and Lorentz forces
- Innovative concept compatible with Nb/Cu technology (open RF structure, easy to coat and inspect)



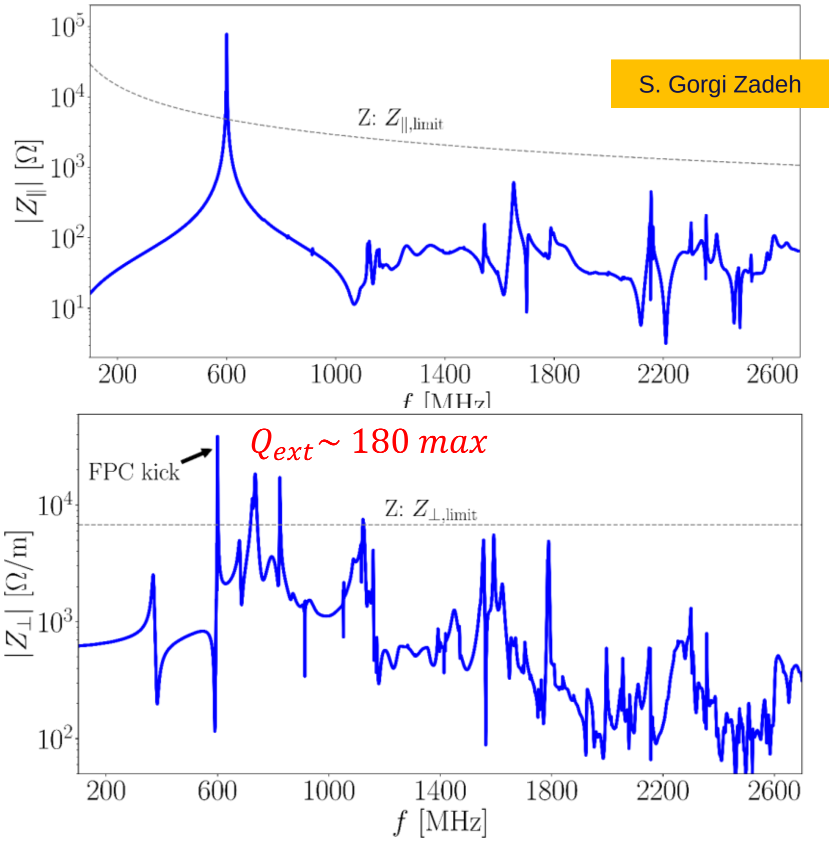
I. Syratchev
F. Peauger
O. Brunner
S. Gorgi Zadeh

F. Peauger et al, SWELL and Other SRF Split Cavity Development, in Proc. LINAC'22, Liverpool, England, Sept. 2022

Impedance and HOM damping of SWELL

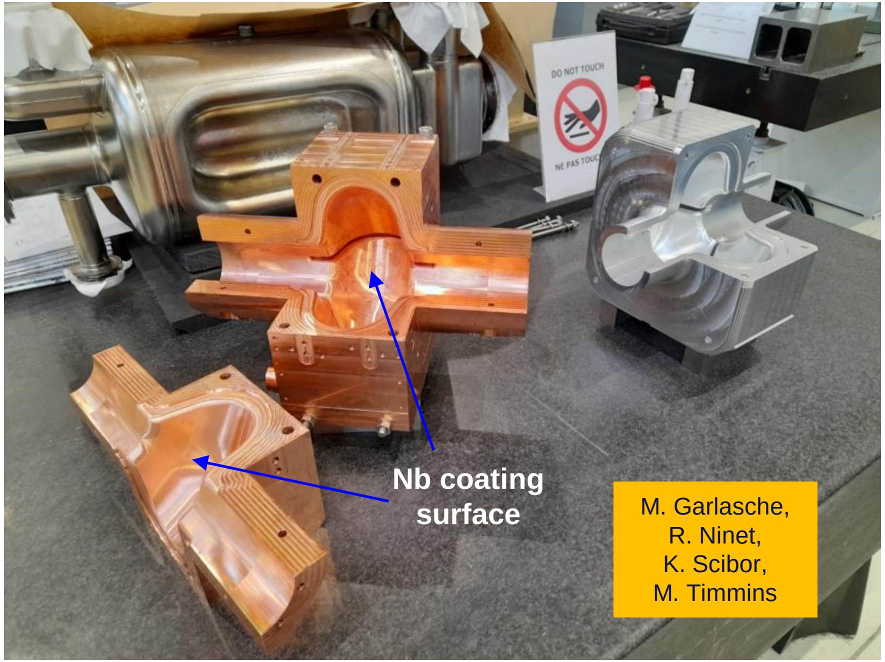
- Longitudinal coupled bunch instabilities due to the FM will be mitigated by direct RF feedback, as performed in the LHC

- Three transverse modes remain above the stability threshold:
  - Spike at the FM frequency is due to coupler and tuning plunger asymmetry and can be compensated by alternating their orientation along the accelerator
  - For the two other modes at 748 and 830 MHz a bunch-by-bunch feedback system with a damping time of about 100 turns

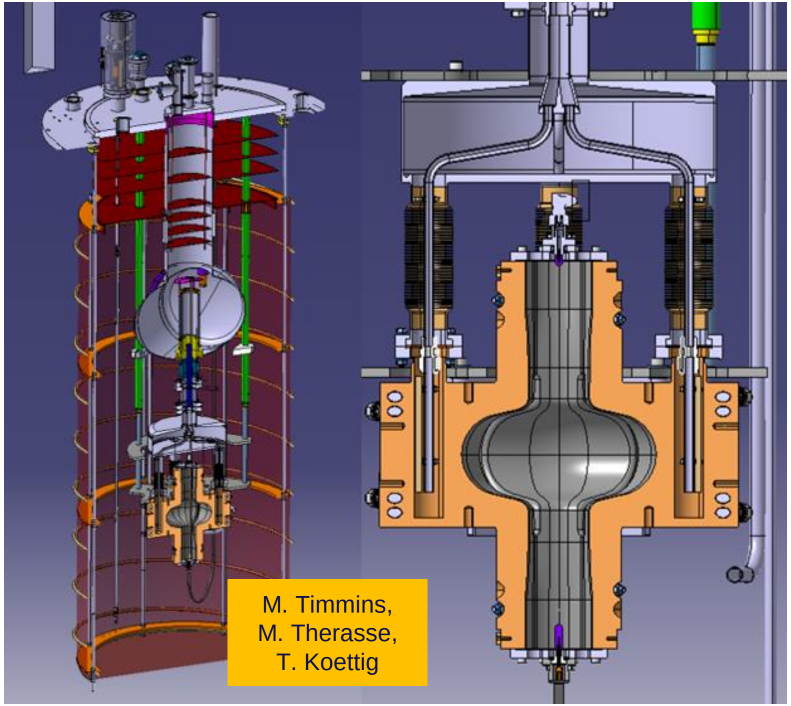


SWELL concept feasibility demonstration

Prototype at reduced scaled (1.3 GHz) successfully machined and ready to be niobium coated



Vertical test at 4.5 K planned in SM18 at CERN in 2023



Collaboration with CNRS – LPSC on multipacting studies

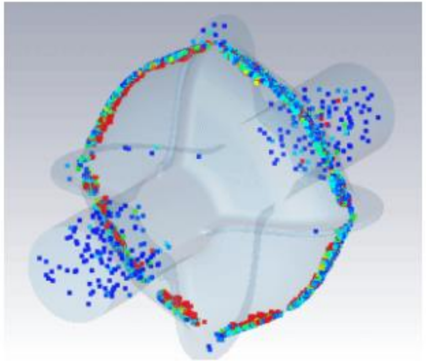


Figure 4: $E_{acc} = 6\,\mathrm{MV\,m^{-1}}$, multipactor in the equatorial plane. CST simulation, Nb baked (according to SPARK3D, no multipactor at this E_{acc}!).

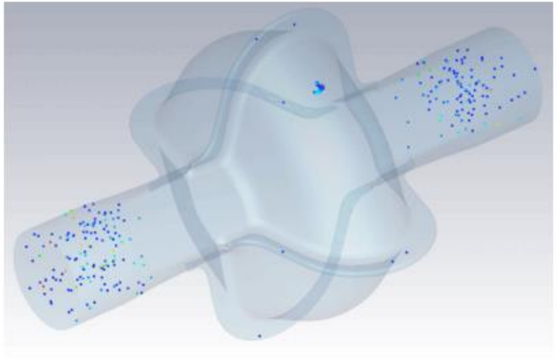


Figure 5: $E_{acc} = 20\,\mathrm{MV\,m^{-1}}$, multipactor at single point. CST simulation, Nb baked.

A. Plaçais, Y. Gomez Martinez, F. Bouly

FCCee parameters at 600 MHz (alternative option)

with SWELL 2-cell and elliptical 5-cell cavities

	Z		W		H		ttb2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	600	600	600	600	600	600	600	600	600
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	9200	11300
Eacc [MV/m]	2.67	9.34	10.72	21.01	10.72	22.12	10.72	22.45	22.39
# cell / cav	2	5	2	5	2	5	2	5	5
Vcavity [MV]	1.33	11.67	5.36	26.25	5.36	27.63	5.36	28.05	27.97
#cells	180	60	392	200	784	380	784	1640	2020
# cavities	90	12	196	40	392	76	392	328	404
# CM	22.5	3	49	10	98	19	98	82	101
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	4	1.5	64	7	64	8	64	56	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	1.9E+04	6.4E+05	6.8E+05	1.1E+07	6.8E+05	2.3E+07	3.9E+06	6.0E+06	1.2E+08
Detuning [kHz]	45.582	1.646	1.185	0.075	0.238	0.007	0.054	0.024	0.001
Pcav [kW]	547	411	251	123	251	65	44	252	12
rhob [m]	9937	9937	9937	9937	9937	9937	9937	9937	9937
Energy [GeV]	45.6	45.6	80.0	80.0	120.0	120.0	182.5		182.5
energy loss [MV]	38.49	38.49	364.63	364.63	1845.94	1845.94	9875.14		9875.14
cos phi	0.32	0.27	0.35	0.35	0.88	0.88	0.82	0.90	0.87
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.0027	0.0100	0.0100	0.0005

281 cryomodules
1124 cavities
~35% in Nb/Cu

→ total number of cryomodules reduced by ~ 16 % compared to the 400/800 MHz baseline

SRF cavities and power RF sources specification at 600 MHz

→ only two types of SRF cavities and one type of high efficiency klystron to develop

07-Dec-22	Bare cavity in vertical test stand		Jacketed cavity with HOM couplers in vertical test stand		Cryomodule (with FPC) in horizontal test stand		Operation in the machine	
	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0	Eacc (MV/m)	Q0
2-cell 600 MHz	13.2	3.3E+09	12.6	3.15E+09	12	3.0E+09	10.8	2.7E+09
5-cell 600 MHz	27.6	3.3E+10	26.3	3.15E+10	25	3.0E+10	22.5	2.7E+10

07-Dec-22	Z		W		H		ttbar2		
	collider	booster	collider	booster	collider	booster	collider	collider	booster
RF source type	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 600 kW klystron	600 MHz 65 kW solid state amplifier	600 MHz 65 kW solid state amplifier	600 MHz 600 kW klystron	600 MHz 50 kW solid state amplifier
Frequency [MHz]	600	600	600	600	600	600	600	600	600
Pcav [kW]	547.4	410.6	251.1	123.1	251.5	64.9	43.9	252.4	12.2
Prf conditioning [kW]	136.9	102.6	62.8	30.8	62.9	16.2	11.0	63.1	3.1
# cavities / RF sources	1	1	2	4	2	1	1	2	4
# RF sources	180	12	196	10	196	76	392	164	101

Summary

- **Solid baseline at 400 / 800 MHz** with **three types** of elliptical cavities to cover the **four working points** of FCCee.
- Intense activity around **longitudinal beam dynamics**, **cavity RF design** and **high efficiency klystron** simulations (not reported here).
- **Hardware R&D program** oriented towards the **improvement of Nb/Cu technology** which represents almost 400 cavities and covers the full physics program of Z, WW and ZH.
- **High Q_0 bulk niobium cavities** becomes new area of interest for the ttb machine

  → CERN needs strong collaborations with external labs specialized in this field (SLAC, FNAL, …)
- New innovative concept of **600 MHz SWELL cavity** under evaluation – seems very promising to reduce the overall cost, simplify the installation scenario of the RF system and its development phase.

Thank you for your attention

Questions ?

Acknowledgements

Olivier Brunner, Frank Gerigk, Ivan Karpov, Alice Vanel, Igor Syratchev, Rama Calaga, Heiko Damerau, Shahnam Gorgi Zadeh, Eric Montesinos, Said Atieh, Allessandro Dallochio, Marco Garlasche, Ofelia Capatina, Marc Timmins, Vittorio Parma, Mathieu Therasse, Guillaume Rosaz, Walter Venturini Delsolaro, Sosoho-Abasi Udongwo, Ursula Van Rienen

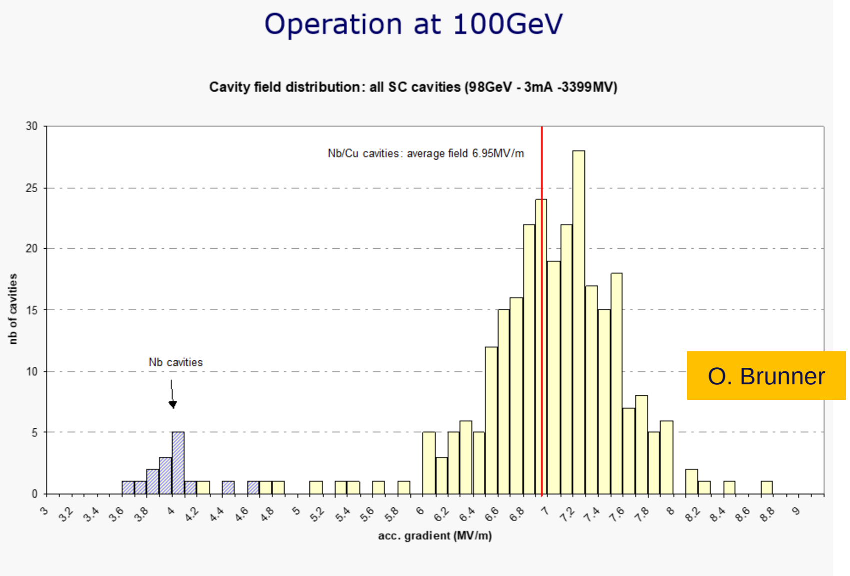
Why 4 → 2-cells ?

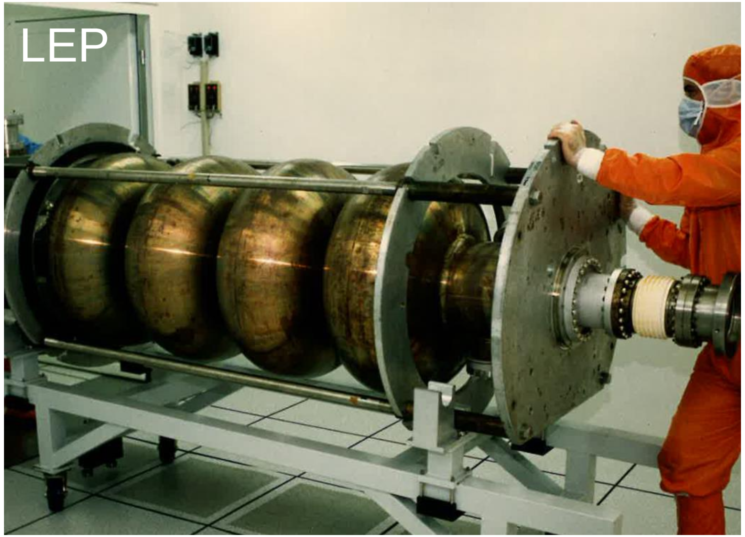
Eacc limited to ~ 7 MV/m in LEP

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

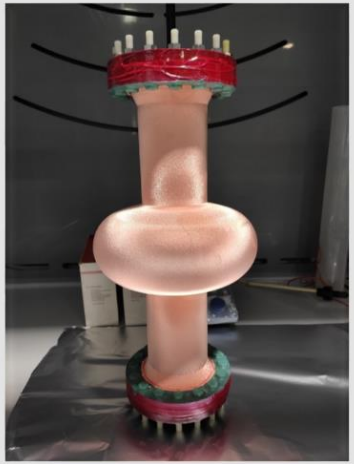




1.3 GHz preparation and test workflow

L. Vega Cid

Substrates manufacturing



EN-MME, TE-VSC, collaborations with INFN/LNL, JLab…

Surface treatments + Coating

TE-VSC-SCC

1.5 week

Cleanroom assembly

SY-RF-SRF

1 day

RF testing

SY-RF-SRF, TE-CRG

1 week

Double frequency RF system

A. Vanel
I. Karpov

Objective: use the RF cavities at $f_1 = 400\ MHz$ and $f_2 = 800\ MHz$.

Choose the offset phase Φ_2 in order to minimise the required voltage V_2 to achieve a total voltage V_tot $= U_0/e = 10\ GV$.

There are 2 constraints:

$$\begin{cases} V_{\text{tot}} = V_1 \sin\phi_s + V_2 \sin(n\phi_s + \Phi_2) = 10\ \text{GV} \\ Q_s^2 = \dfrac{\omega_{s0}^2}{\omega_0^2} = C\left[\cos\phi_s + n\dfrac{V_2}{V_1}\cos(n\phi_s + \Phi_2)\right] = (0.0890)^2 \end{cases}$$

$$C = -\frac{h_{\text{FCC}}\eta q V_1}{2\pi\beta^2 E_0}$$

$$n = \frac{f_2}{f_1} = \frac{800\ \text{MHz}}{400\ \text{MHz}} = 2$$

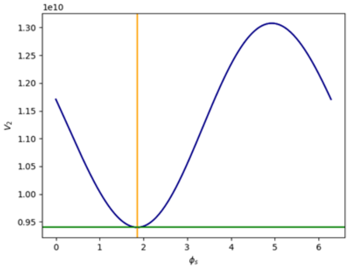
After some trigonometry, we get

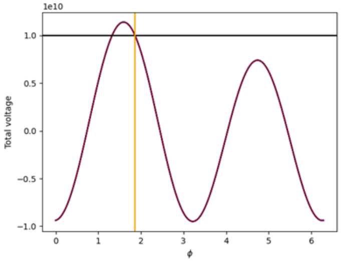
$$V_{2,\min} = \text{argmin}_{\phi_s\in[0,2\pi]}\left[V_1\sqrt{\frac{(A-\cos\phi_s)(B-\sin\phi_s)}{n^2}}\right]$$

↓ ϕ_s fixed

$$\Phi_2 = \pi - \arcsin\frac{B-\sin\phi_s}{r} - n\phi_s$$

Gain: 11.22 – 9.40 = 1.82 GV





$V_{2,\min} = 9.40$ GV $\quad \phi_s = 1.86 \quad \Phi_2 = -1.619$

$$P_{400} + P_{800} = [V_1 \sin\phi_s + V_{2,\min}\sin(n\phi_s + \Phi_2)]I = 9.58 + 40.4 = 50.0\ \text{MW}$$

CDR FCC-ee: The Lepton Collider, 2019

Table 3.12: Detailed RF configuration of each machine and booster ring.

	Z		**WW**		**ZH**		$t\bar{t}_1$		$t\bar{t}_2$	
	per beam	booster booster	per beam	boo-ster	per beam	booster booster	2 beams	booster	2 beams	booster
Total RF voltage [MV]	100	140	750	750	2000	2000	9500	9500	10930	10930
Frequency [MHz]	**400**									
RF voltage [MV]	100	140	750	750	2000	2000	4000	2000	4000	2000
E_{acc} [MV/m]	5.1	8	9.6	9.6	9.8	9.8	10		10	
# cell / cav	1	4	4		4		4		4	
V_{cavity} [MV]	1.92	12	14.4	14.4	14.7	14.7	15		15	
# cavities	52	12	52	52	136	136	272	136	272	136
# CM	13	3	13	13	34	34	68	34	68	34
T operation [K]	4.5		4.5		4.5		4.5		4.5	
Dyn losses/cav [W]	14	11	210	26	202	29	210	30	210	30
Stat losses/cav [W]	8		8		8		8		8	
Q_{ext}	$4.4\ 10^4$		$6.6\ 10^5$		$1.9\ 10^6$		$4\ 10^6$		$4.7\ 10^6$	
P_{cav} [kW]	962		962		368		175		149	
Frequency [MHz]	**800**									
RF voltage [MV]							5500	7500	6930	8930
E_{acc} [MV/m]							19.8	20	19.8	19.8
# cell / cav							5		5	
V_{cavity} [MV]							18.6	18.75	18.6	18.6
# cavities							296	400	372	480
# CM							74	100	93	120
T operation [K]							2		2	
Dyn losses/cav [W]							66	10	66	10
Stat losses/cav [W]							8		8	
Q_{ext}							$3.9\ 10^6$		$5.6\ 10^6$	
P_{cav} [kW]							176		155	