SRF system options for FCC-ee

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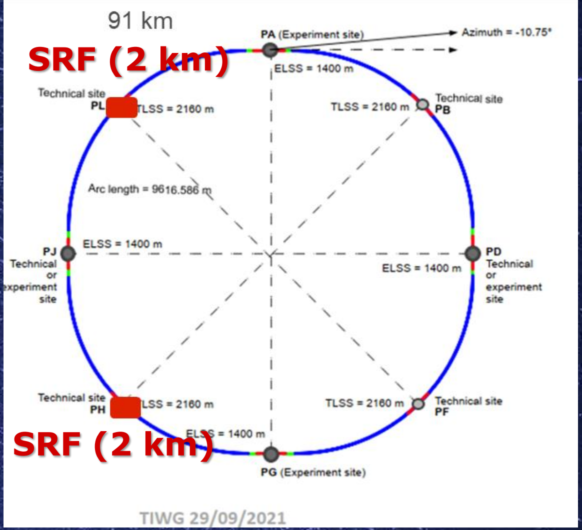
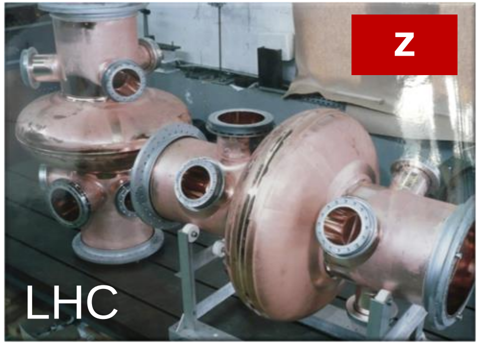
	Energy (GeV)	Current (mA)	RF voltage (GV)
Z	45.6	1280	0.120
W	80	135	1.05
H	120	26.7	2.1
ttb	182.5	5	11.3



100 MW of RF power in CW (50 MW per ring)
to compensate losses by synchrotron radiation

+ Booster (3rd ring) with 10% beam current and 15% average duty cycle

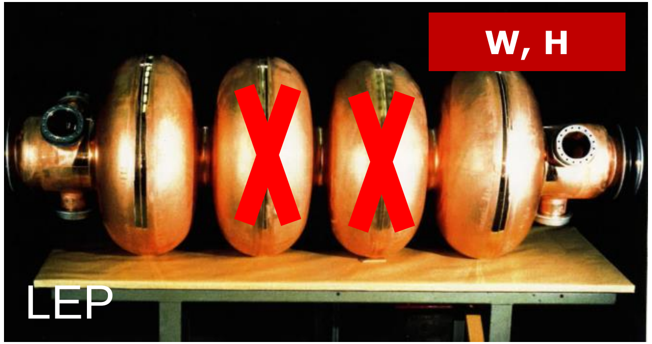
SRF system baseline



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.

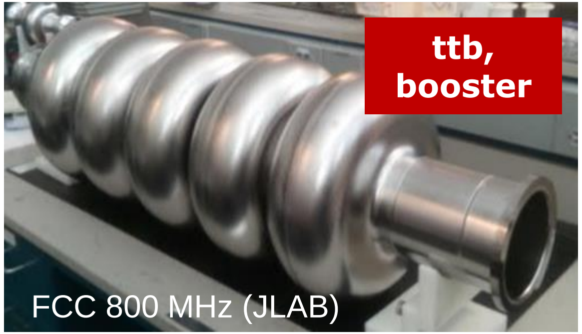
Powered by a 1 MW RF coupler and high efficiency klystron.



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)

RF specifications and parameters

20 % margin between qualification in vertical test and operation

12-May-23	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	24.5	3.8E+10	23.3	3.64E+10	22.2	3.5E+10	20.0	3.0E+10

12-May-23	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	6.23	10.61	20.01	10.61	20.76	10.61	20.12	20.10
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	7.95	18.75	7.95	19.44	7.95	18.85	18.83
#cells	56	120	264	280	528	540	528	2440	3000
# cavities	56	24	132	56	264	108	264	488	600
# CM	14	6	33	14	66	27	66	122	150
+ #CM	14	6	33	8	0	13	0	122	123
- #CM	_	-	14	-	-	-	-	-	-
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav * [W]	19	0.3	129	3	129	4	129	23	3
stat losses/cav * [W]	8	8	8	8	8	8	8	8	8
Qext	5.8E+04	3.1E+05	9.2E+05	7.6E+06	9.1E+05	1.6E+07	4.5E+06	4.2E+06	8.1E+07
Detuning [kHz]	9.885	4.385	0.575	0.140	0.106	0.012	0.009	0.056	0.002
Pcav [kW]	901	210	378	89	382	47	78	163	8
energy loss / turn ** [MV]	39.40	39.40	370.00	370.00	1890.00	1890.00	10100.00		10100.00
cos phi	0.33	0.28	0.35	0.35	0.90	0.90	0.98	0.86	0.89
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	0.010	0.0005

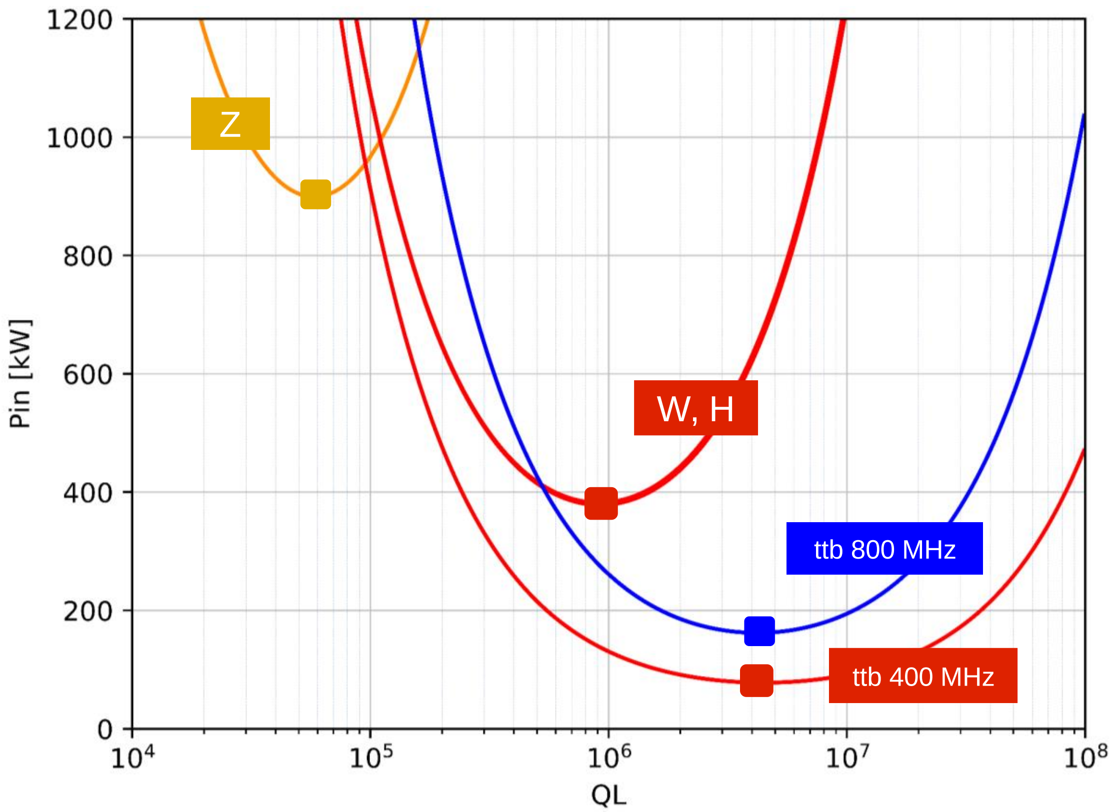
* Heat loads from power coupler and HOM couplers not included
** Energy loss / turn from K. Oide table Jan. 19, 2023

Limiting parameters for RF

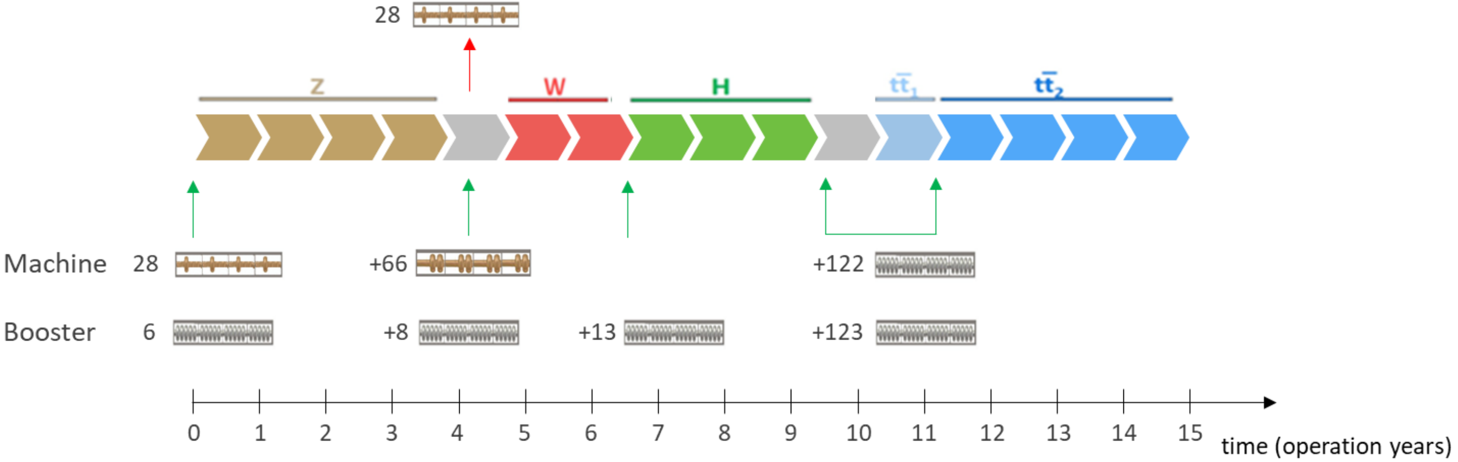
one RF system per beam — common RF system for both beams

Total of 364 cryomodules, 1456 cavities, 25% with Nb/Cu, 75% with bulk niobium

RF power and FPC requirements



Installation sequence



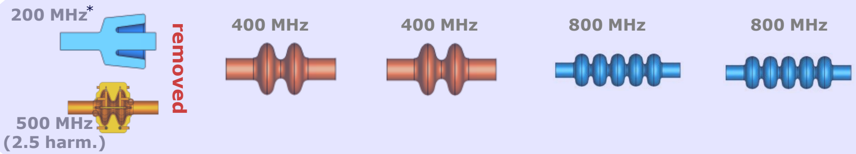
- Start by running the machine four years at the Z-pole with 14 cryomodules (CM) per beam for the collider and 6 CM for the booster
- Removal of the single cell cavities and installation 66 + 8 CM needed for the W RF system. Preparation and pre-testing of the RF stations are important to respect the planning.
- The evolution from W to H requires 13 additional CM for the booster ring as well as the realignment of the beam on a common axis.
- Massive installation of a total of ~1000 bulk Nb cavities during a long shutdown
- Alternative scenario allowing the start at the H production energy under study

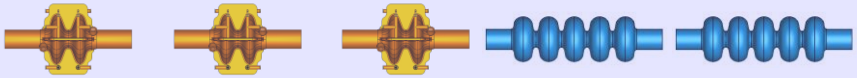
400/800 MHz options

	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) see Oleg, Anne-Marie, Alice, Shahnam, Joanna, Carlota, Akira, Sam, Vittorio's talks
Higgs first	removed		removed			Less optimized for the planning and workload (~100 additional cryomodules to install or remove)
Higgs "only"						Alternative 800 MHz cavity specially designed for high current operation - see Sosoho's talk
Z with 2-cell	Partially removed/re-installed					Very promising to optimize the cost and schedule The beam current at Z might be slightly reduced
Z with 2-cell ttbar with 6-cell	Partially removed/re-installed			6-cell		6-cell (or more) at 800 MHz allowing a reduction of the number of cavities - see Shahnam's talk
Full thin films						Very ambitious, allows for material cost savings Ideal to push the Nb/Cu technology towards the high gradient world
Full 4.5 K with A15 (Nb3Sn) materials						Extremely ambitious (?) for very high operational savings. RF tuning will be a challenge.

Options at alternative RF frequencies

	Z	W	H	ttb	booster	Comments
Multifrequencies	200 MHz* / 500 MHz (2.5 harm.) — removed	400 MHz	400 MHz	800 MHz	800 MHz	Allows larger RF acceptance at Z (improve beam stability) More complex and expensive RF system Cavity size and footprint of RF system seems too large at 200 MHz
SWELL 600 MHz						Innovative approach at a single RF frequency No cryomodule removal at all stages Reduced number of cavities, High accelerating voltage expected Robust structure against microphonics and LFD Reduced volume of helium, etc... Beam current at Z slightly reduced see Marc+Franck, Torsten's talks





* R. Calaga, R. Tomas, A 200 MHz SC-RF SYSTEM FOR THE HL-LHC, IPAC2016

Thank you for your attention