



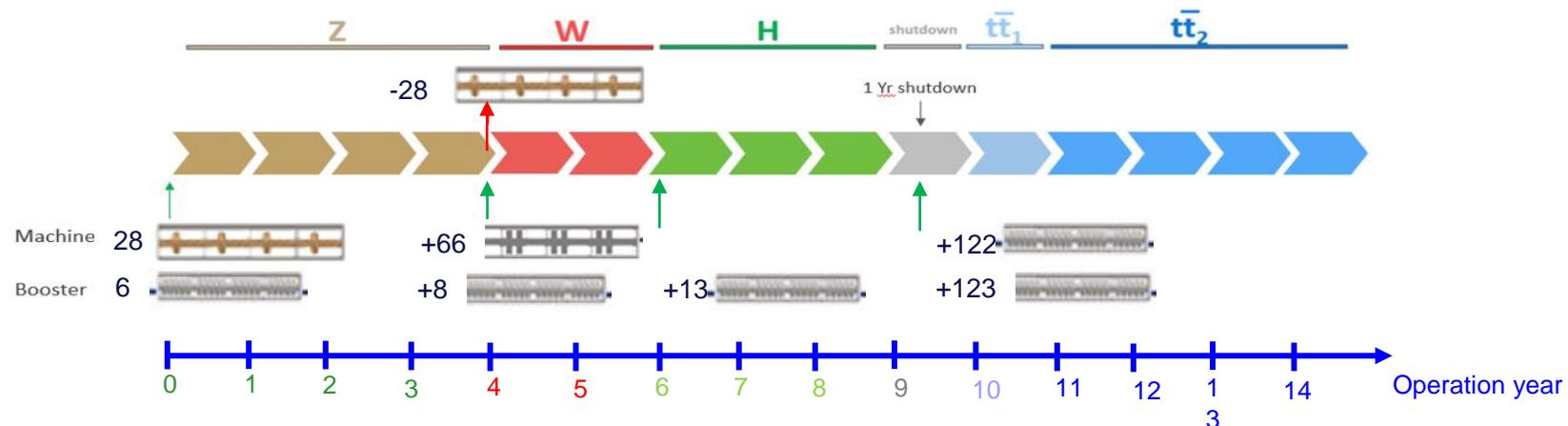
FUTURE
CIRCULAR
COLLIDER

THE FCCCEE SRF SYSTEM: MACHINE LAYOUTS AND CRYOMODULES

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with contributions from: O. Brunner, B. Bradu, K. Brodinski, O. Capatina, L. Delprat, A. Foussat, S. Gorgi Zadeh,
B. Naydenov, E. Montesinos, F. Peauger, M. Timmins, K. Turaj, F. Valchkova-Georgieva, CERN
and input from discussions with: S. Barbanotti/DESY, K. Jensch/DESY, T. Petersen/SLAC, P. Pierini/ESS,

- The RF System Layout Baseline
- Alternative Layout architectures:
 - Variants and comparison
 - CM repair intervention
- String of cavities 400 MHz and 800 MHz
- CM preliminary specs
- Summary



In total: 366 CM, 1'464 cavities (4 cavities/CM, present assumption):

- 400 MHz single-cell (Nb/Cu): 28 CM, 112 cavities (to removed after Z) → 4.5 K
- 400 MHz two-cell (Nb/Cu): 66 CM, 264 cavities → 4.5 K
- 800 MHz five-cell (bulk Nb): 272 CM, 1'088 cavities → 2 K

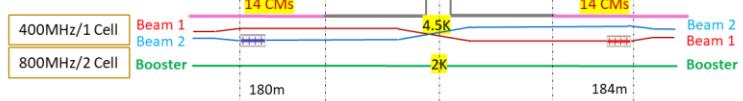
Collider (ttbar2): 188 CM (264 cavities 400 MHz, 488 cavities 800 MHz)

Booster (ttbar2): 150 CM (600 cavities 800 MHz)

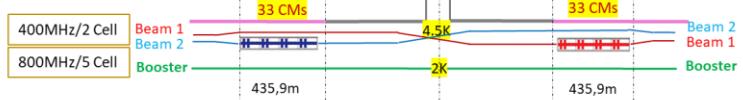
TLSS length: 2032 m

Z machine

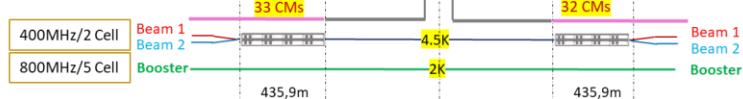
(0.24 GV, 100 MW)

W machine

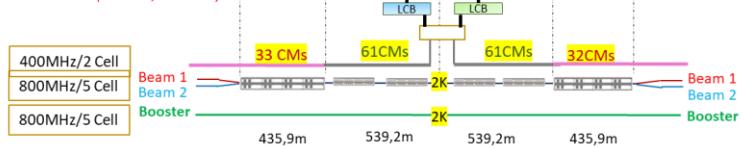
(2.1 GV, 100 MW)

H machine

(4.2 GV, 100 MW)

ttbar machine

(22.6 GV, 100 MW)

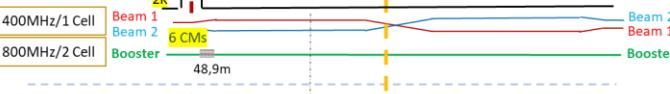


TOTAL RF LENGTH: 1950,2 m

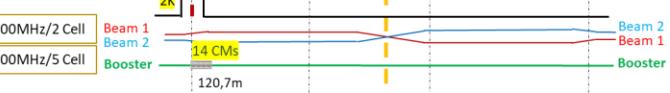
TLSS length: 2032 m

Access point LZ machine

(0.14 GV, 5 MW)

W machine

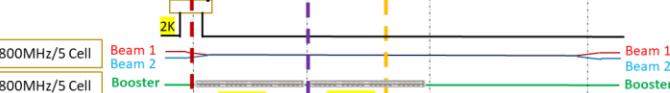
(1.05 GV, 5 MW)

H machine

(2.1 GV, 5 MW)

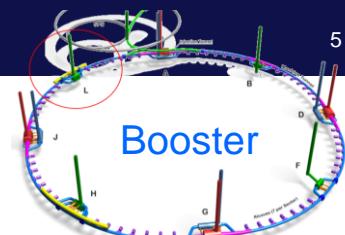
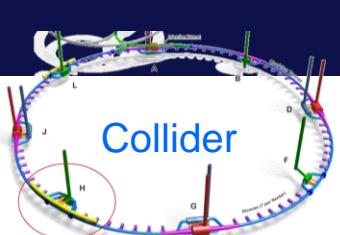
ttbar machine

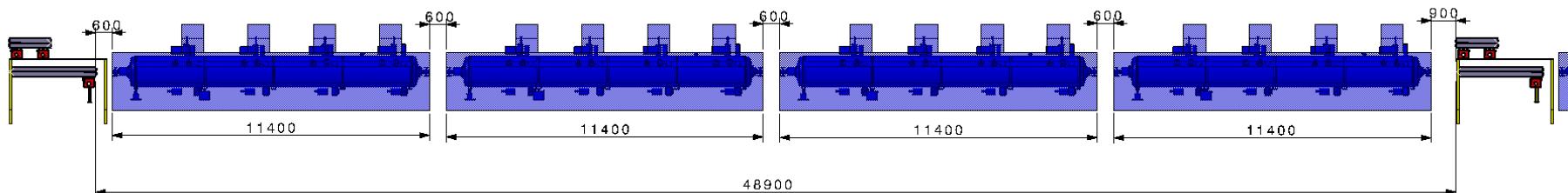
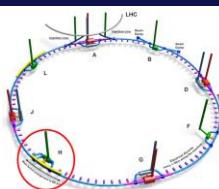
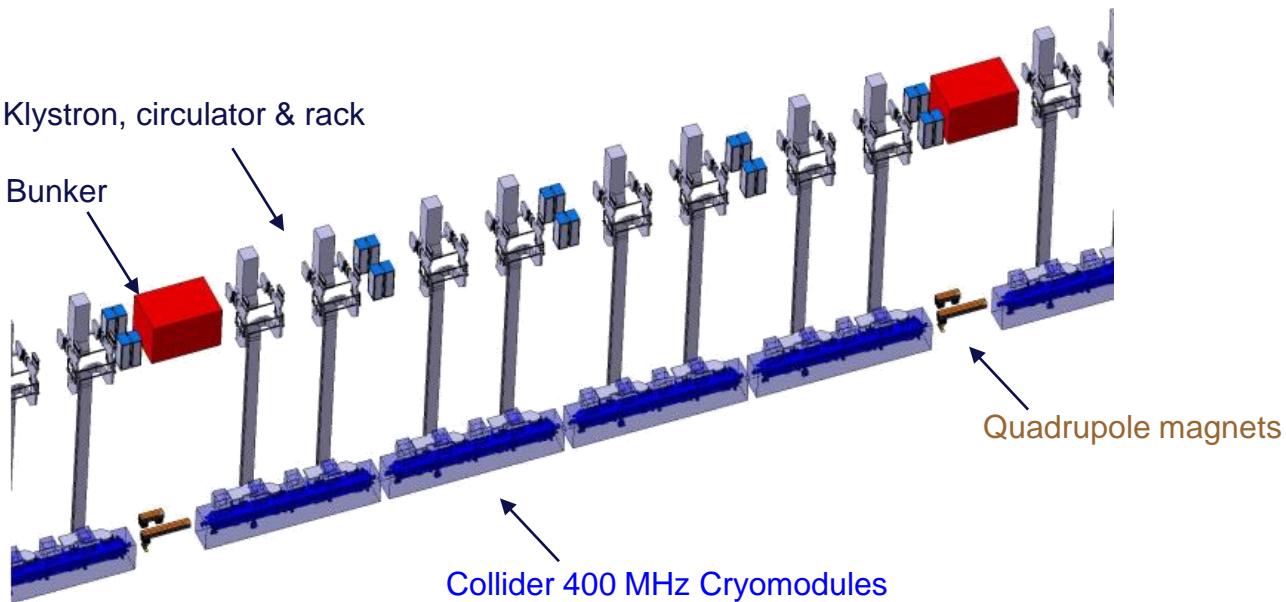
(11.3 GV, 5 MW)

Midpoint
RF section

TOTAL RF LENGTH: 1297m

5

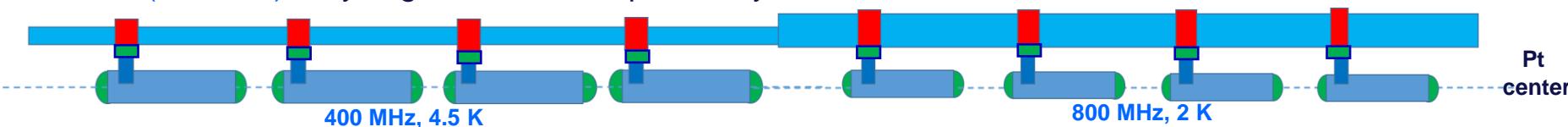




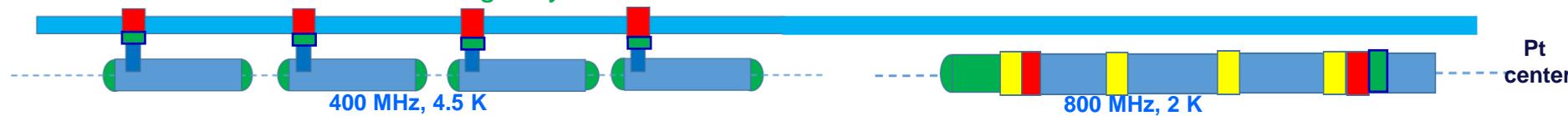
Collider architecture options (top view, ½ LSS, quads not shown)

(for detailed comparison see presentation in Technical Infrastructures: RF Points for FCC-ee)

- **A1** (baseline): fully segmented with separate cryo line



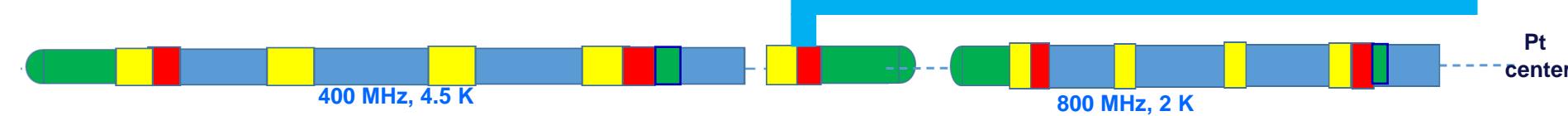
- **AC2**: 800 MHz cont. with integr. cryo lines



- **AC3**: 400 MHz vac. cont. with separate cryo line; 800 MHz cont. with integr. cryo lines.



- **AC4**: 400 MHz and 800 MHz cont. with integrated cryo lines;



End Cap module

CM interconnection

Service Module

Vac.Barr.

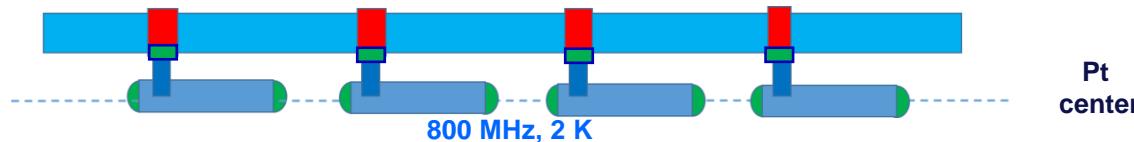
Jumper

(quads not shown)

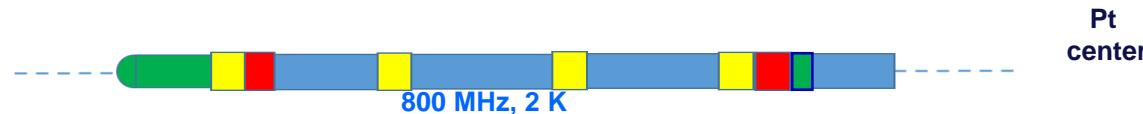
FCC Booster architecture options (top view, $\frac{1}{2}$ LSS, quads not shown)

(for detailed comparison see presentation in Technical Infrastructures: RF Points for FCC-ee)

- A1 (baseline): fully segmented collider with separate cryo line



- AB1: 800 MHz cont. with integr. cryo lines



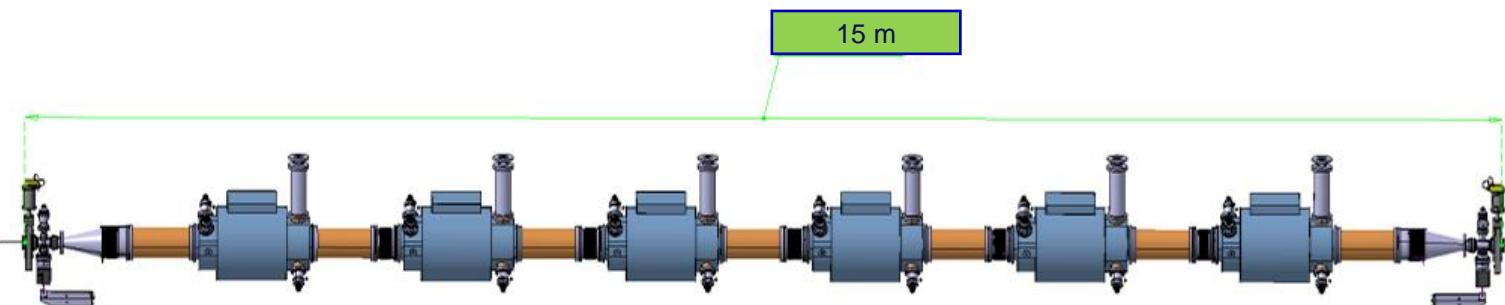
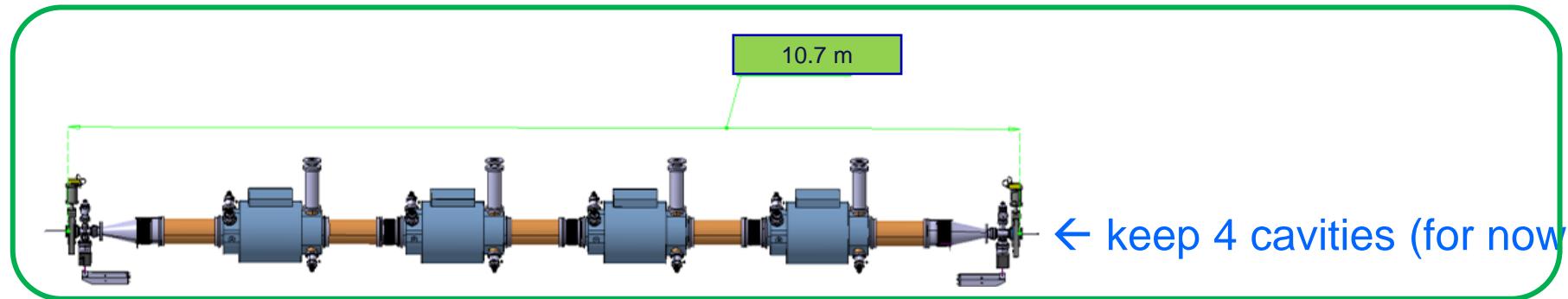
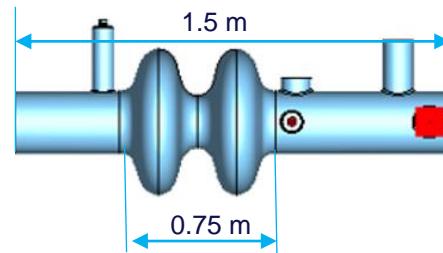
Cavity strings and Cryomodules

O_{FCC} # of 400 MHz 2-cell cavities per CM ?

10

400 MHz (2 cell cavities): from 4 to 6 cavities ?

- 6 cavities is at the limit for road transport (15m LHC dipoles) and handling (overhead cranes >15t, tunnel shafts ~ 16m)

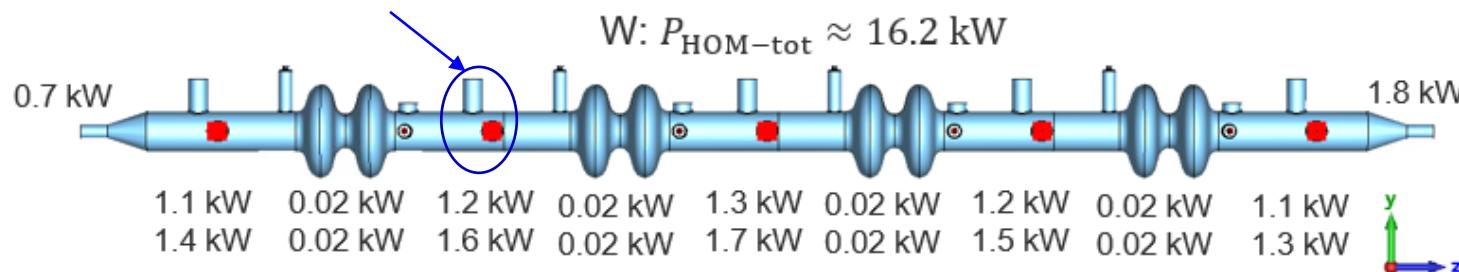


<i>Top level preliminary parameters/requirements</i>	Value	Remarks
# CM units	65	
Cavities per cryomodule	4	6 makes CM very long
Cavity gradient Eacc (MV/m)	12 / 10.08	<i>CM test / CM in accelerator</i>
Qo	3.0E+09 / 2.7E+09	<i>CM test / CM in accelerator</i>
CM length (GV flange to flange)	10.7 m	
CM width	<i>TBD</i>	depends on design
Cavity (Nb/Cu) operating temperature	4.5 K	
Beamline vacuum at 2 K	1×10^{-8} Pa	<i>TBC</i>
Layout architecture	Proposal: continuous ins.vac. with external cryogenic line	<i>TBC, still under discussion with cryo</i>
Tunnel Integration	Supported on floor	
Tunnel inclination (Pt. H&L)	0.25%	affects liquid levels

CM preliminary requirements	Value	Remarks
Dyn. HL (CW)/cavity at 4.5 K	129 W	W, H, ttbar
Stat. HL/cavity at 2 K	< 8 W	depends on CM design
Environ. Magnetic field	≤ 5 mG	TBC
Max FPC power/cavity (CW)	901 kW	Z
FPC orientation/WG connection	Vertical/Top	accessible from CM top
Q_{ext} W / H / ttbar	9.2E+05/9.1E+05/4.5E+06	adjustable FPC
HOM power extraction per CM: W / H / ttbar	16.2 kW/ 6.4 kW/ 3 kW	HOM hook-type and coax.extract.
Helium Gas Return Pipe diameter (inside CM)	<100 mm (TBD)	Depends on cryo cell length
2-phase pumping line diam. (inside CM)	<100 mm (TBC)	depends on slope/cryo cell length/vapor vel. (<5m/s)
"uniform" CD of cavities	TBD	limit thermo-electric currents
Thermal shielding T	50-75 K	TBC
Heat intercepts between from low T to RT	TBD	Vapor cooled ? Liquefaction needs
MAWP for cryo circuits	TBD	

CM 400 MHz (2-cell): HOM power extraction

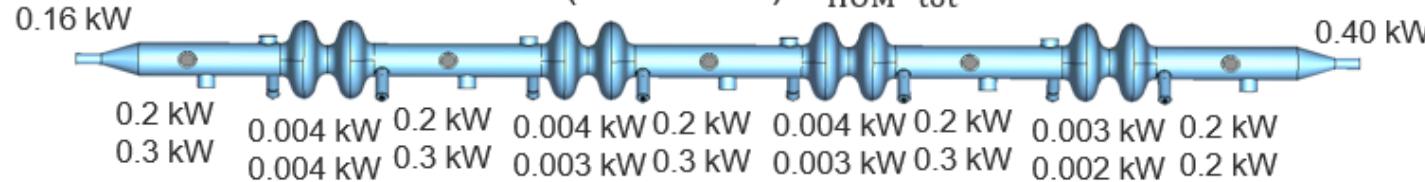
2 coax. extractors/cavity (size comparable to FPC)



H (two beams): $P_{\text{HOM-tot}} \approx 6.4 \text{ kW}$



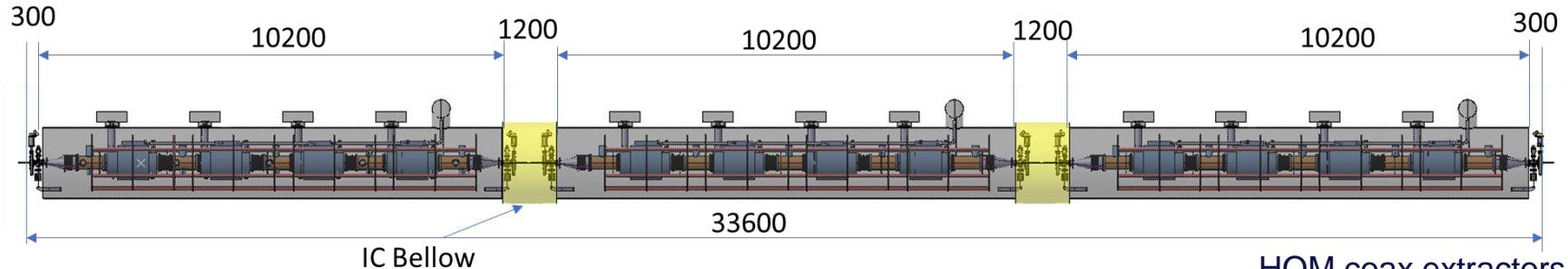
tt (two beams): $P_{\text{HOM-tot}} \approx 3.0 \text{ kW}$



CM 400 MHz 2-cell cavities

14

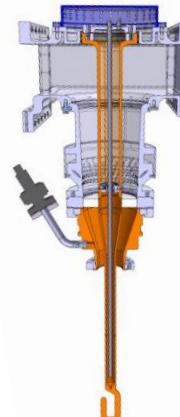
Conceptual studies



Ongoing work:

- *FPC design/integration*
- *HOM coax. Extractors design/integration*
- *Sizing of cryolines (pumping, 2-phase, etc.)*

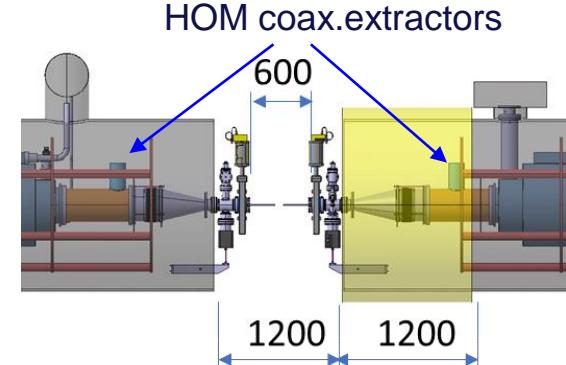
(concept only, not to scale)



(E. Montesinos)

FPC:

- *1 MW FPC, single window*
- *Adjustable*



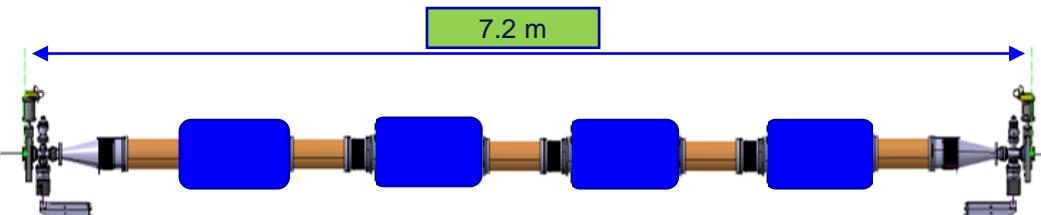
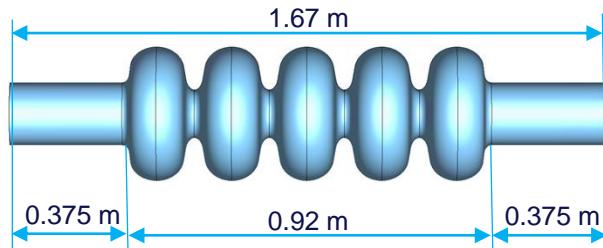
○_{FCC} # of 800 MHz cavities per CM ?

15

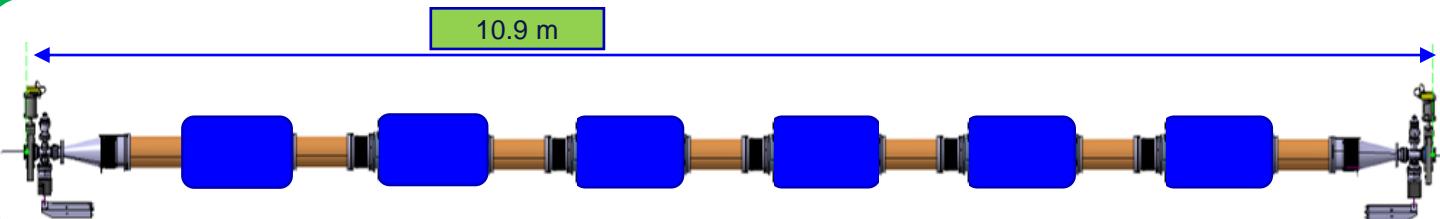
800 MHz (5 cell cavities, bulk Nb): 4 or 6 or 8 cavities ?

- ✓ not studied yet, but smaller cavities:

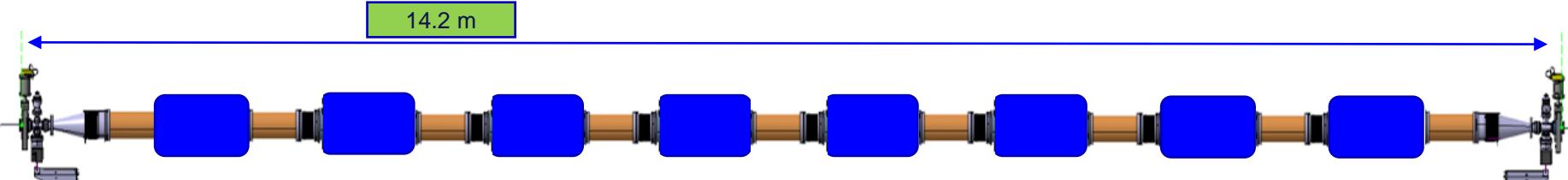
UROS5



← today's baseline



← 6 cavities
reasonable



CM 800 MHz cavities (5-cell, bulk Nb)

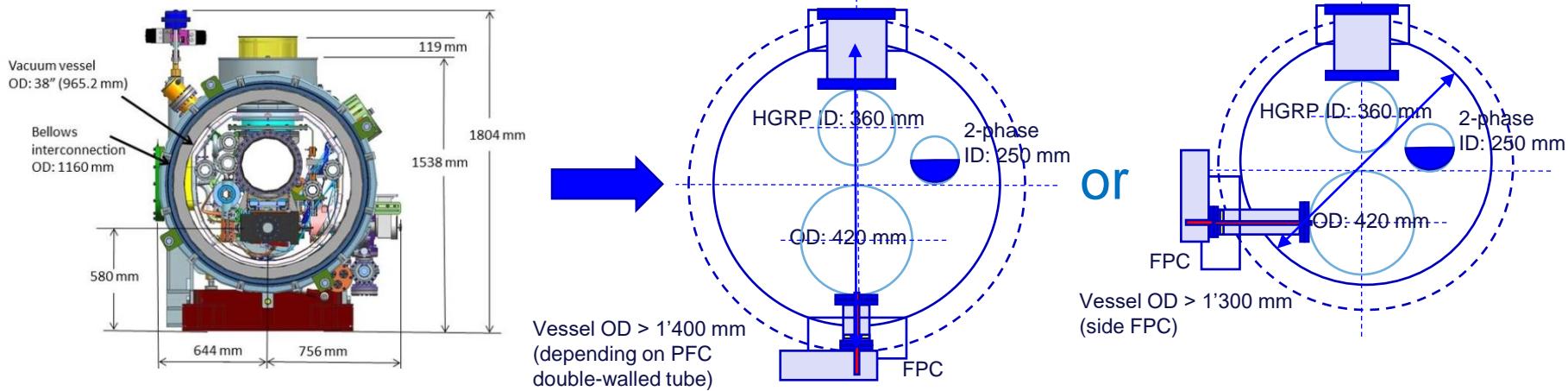
<i>Top level preliminary parameters/requirements</i>	Value	Remarks
# CM units	182	same design collider/booster
Cavities per cryomodule	6	TBC
Cavity gradient Eacc (MV/m)	22.2 / 20	CM test / CM in accelerator
Qo	3.5E+10 / 3.0E+10	CM test / CM in accelerator
CM length (GV flange to flange)	10.9 m	TBC
CM width	TBD	depends on design
Cavity operating temperature	2.0 K	
Beamlime vacuum at 2 K	1×10^{-8} Pa	TBC
Layout architecture	Proposal: continuous ins.vac. with integrated cryo lines	TBC, still under discussion with cryo
Tunnel Integration	Collider on floor Booster elevated	subject to evolution
Tunnel inclination (Pt. H&L)	0.25%	affects liquid levels

CM preliminary requirements	Value	Remarks
Dyn. HL (CW)/cavity at 2 K	23 W / 3 W	Collider-ttbar / Booster-ttbar
Stat. HL/cavity at 2 K	< 8 W	depends on CM design
Environ. Magnetic field	≤ 5 mG	Magnetic shielding
FPC power/cavity (CW)	163/210 kW	Collider-ttbar / Booster-Z
FPC orientation/WG connection	vertical/bottom or horizontal/side	depends on FPC design and CM assy principles
Q_{ext} B-Z / B-W / B-H / C-ttbar / B-ttbar	3.1E+05 / 7.6E+06/1.6E+07/4.2E+06/8.1E+07	adjustable tuner
HOM power extraction	TBD	
Helium Gas Return Pipe diameter	360 mm	defined by booster length
2-phase pumping line diam.	250 mm (TBC)	depends on slope/cryo cell length/vapor vel. (<5m/s)
"fast" CD of cavities	> 2-3 K/min across 9.2 K	TBD
Thermal shielding T	50-75 K	TBC
Heat intercepts between low T to RT	TBD	Vapor cooled ? Liquefaction needs
MAWP for cryo circuits	TBD	

Cryomodule design options

- Adaptation of existing concepts (XFEL, PIPII...)?

➤ XFEL (1.3 GHz): rescaled to 800 MHz



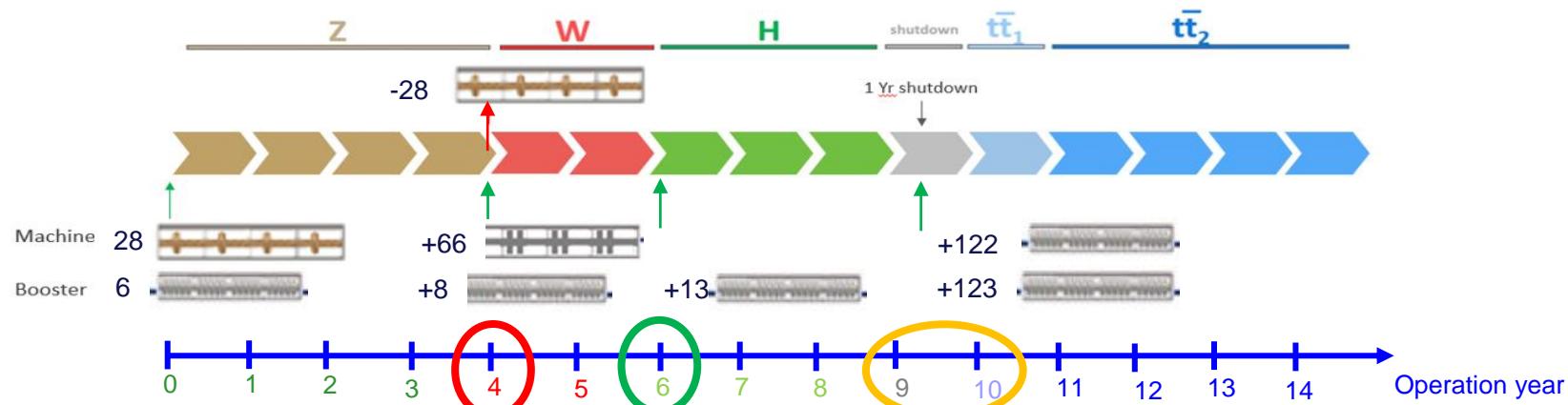
- New CM concepts ?

- Present baseline features fully segmented linacs, for 400 MHz and 800 MHz of both Collider and Booster
- Clear interest in moving towards continuous ins. vacuum cryostat, but still under development (cryogenics schemes)
- Need to look more into detail into beam instrumentation needs (not yet discussed) and if they can be cold
- String of cavities layout are being detailed
- Specs for single CMs at 400 MHz and 800 MHz are taking shape



Thank you
for your attention.

Reference documents and spare slides



Assumption: 120 days of yearly Shutdowns (SD) \rightarrow 17 weeks

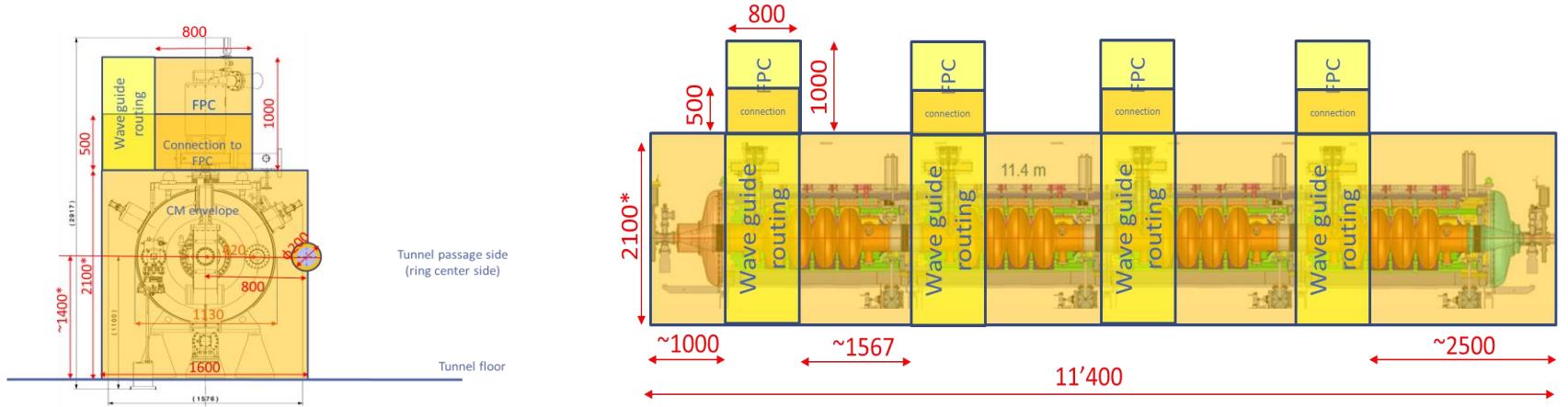
Year 4 (17 weeks): Remove 28 CM; Install 74 CM \rightarrow ~ 4.3 CM/wk

Year 6 (17 weeks): 13 CM in 17 wks \rightarrow < 1 CM/wk

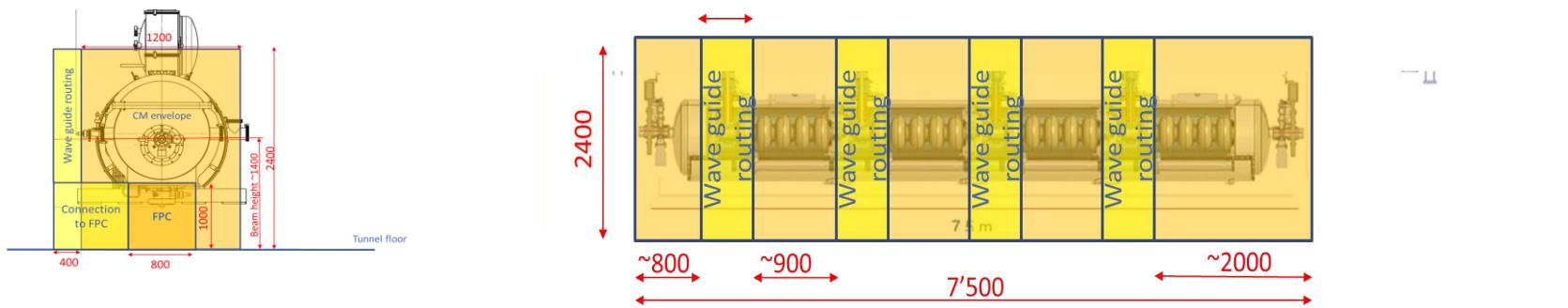
Year 9 (17+52 weeks): 244 CM \rightarrow ~ 3.5 CM/wk

Note: yearly shutdowns will be needed for preventive and repair maintenance too

400 MHz Cryomodule (based on LEP, 4-cell cavities)



800 MHz Cryomodule (based on SPL, 704 MHz)



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

	12-May-23	Z		W		H		ttbar2			25
		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	800	
RF voltage [MV]	120	140	1050	1050	2100	2100	2100	2100	9200	11300	
Eacc [MV/m]	5.72	6.23	10.61	20.01	10.61	20.76	10.61	20.12	20.12	20.10	
# cell / cav	1	5	2	5	2	5	2	5	5	5	
Vcavity [MV]	2.14	5.83	7.95	18.75	7.95	19.44	7.95	18.85	18.85	18.83	
#cells	56	120	264	280	528	540	528	2440	2440	3000	
# cavities	56	24	132	56	264	108	264	488	488	600	
# CM	14	6	33	14	66	27	66	122	122	150	
+ #CM	14	6	33	8	0	13	0	122	122	123	
- #CM	-		14				-	-	-	-	
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2	2	
dyn losses/cav * [W]	19	0.3	129	3	129	4	129	23	23	3	
stat losses/cav * [W]	8	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	0.056	0.002	
Pcav [kW]	901	210	378	89	382	47	78	163	163	8	
energy loss / turn ** [MV]	39.40	39.40	370.00	370.00	1890.00	1890.00	1890.00	10100.00	10100.00	10100.00	
cos phi	0.33	0.28	0.35	0.35	0.90	0.90	0.98	0.86	0.86	0.89	
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.003	0.010	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	0.937	
#cav/CM	4	4	4	4	4	4	4	4	4	4	
R/Q [ohm]	87.6	521	181.1	521	181.1	521	181.1	521	521	521	
G [ohm]	238.50	272.90	234.70	272.90	234.70	272.90	234.70	272.90	272.90	272.90	
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	3.0E+10	
Ep/Eacc	2.20	2.05	2.00	2.05	2.00	2.05	2.00	2.05	2.05	2.05	
Bp/Eacc	5.36	4.33	5.33	4.33	5.33	4.33	5.33	4.33	4.33	4.33	
Ep [MV/m]	12.58	12.76	21.23	41.03	21.23	42.55	21.23	41.25	41.25	41.21	
Bp [mT]	30.65	26.96	56.57	86.66	56.57	89.87	56.57	87.13	87.13	87.05	
Cavity design	QUASI-LHC	UROSS5	2CELLV2	UROSS5	2CELLV2	UROSS5	2CELLV2	UROSS5	UROSS5	UROSS5	
Prf no beam [kW]	225.14	52.53	94.60	22.30	95.57	11.68	19.49	40.68	40.68	2.10	

* Heat loads from power coupler and HOM couplers not included

** Energy loss / turn from K. Oide table Jan. 19, 2023

12-May-23	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 - 60 kW solid state amplifier	400 MHz - 100 kW solid state amplifier	800 MHz - 500 kW klystron	800 MHz - 60 kW solid state amplifier
Frequency [MHz]	400	800	400	800	400	800	400	800	800
Pcav [kW]	901	210	378	89	382	47	78	163	8
Prf no beam [kW]	225	53	95	22	96	12	19	41	2
# cavities / RF sources	1	2	2	4	2	1	1	2	4
# RF sources	112	12	132	14	132	108	264	244	150
RF power overhead [%]	11	19	32	40	31	28	28	54	78

In-tunnel repair on CMs (400 MHz)

- Intervention needing WU and ins.vac.vent. (e.g. tuner, HOM, coax cables connectors), assuming 1 day repair

In-tunnel CM repair (Collider, 400 MHz)	Baseline	comments	AC3: continuous with cryo line	comments	AC4: continuous with integrated cryo line	comments
#	Operation	No.work days		No.work days		No.work days
1	Warm up of CM	3	Estimate. 1 CM, cryoline cold	7	Estimate. 10 CM (~150 m ins. Vac.), cryoline cold	14
2	Vent CM Ins.vac.	0.5		2	venting only ins.vac. Sect.	5
3	Repair	1	assumption	1	assumption	1
5	Pump down ins.vac.	2	1 CM	5	10 CM	7
6	Cool down CM	2	Estimate. 1 CM	5	Estimate. 10 CM	10
7	Cavities RF conditioning	21	LHC CM experience	21	with parallel automated RF conditioning	21
Total		29.5		41		58
Total # weeks		4.2		5.9		8.3

- ✓ Intervention time up to ~6/8 weeks (AC3/AC4) (including RF conditioning)
- ✓ All architectures compatible with 17 weeks yearly shut-downs

Replacement of CM (400 MHz)

Exchange of 1 CM (Collider 400 MHz)		Baseline	comments	AC3: continuous with cryo line	comments	AC4: continuous with integrated cryo line	comments
#	Operation	No.work days		No.work days		No.work days	
1	close 4 warm gate valves of CM	0.5					
2	Close cryo valves to isolate CM	0.5					
3	Warm up of entire linac (33 CM)	14	Estimate. No cutting with cold cryo line.	14	Estimate no cutting with cold cryo line.	14	Entire linac (33 CM) venting ins.vac. Sect.
4	CM Ins.vac.venting	0.5		2	venting ins.vac. Sect.	2	
5	Dismount warm beam lines	0.5					
6	Open jumper IC and cut cryo lines	3		3			
7	Open 2 IC, beam vac.line only			1.5			
8	Open 2 IC, beam vac.line + cryo lines					5	
9	Exchange of CM	1		1		1	
10	Close jumper (weld cryo lines +th.shields,etc.)	2		2		2	
11	Close 2 IC, beam vac.line + cryo lines					5	
12	Close 2 IC, beam vac.lines only			2			
13	Mount warm beam lines, vac.cond. and pumping	2					
14	Pump down ins.vac. and purge cryo lines	7	Entire linac (33 CM)	7	Entire linac (33 CM)	7	Entire linac (33 CM)
15	Cool down CM	10	Entire linac (33 CM)	10	Entire linac (33 CM)	10	Entire linac (33 CM) with parallel automated RF conditioning
16	Cavities RF conditioning	21	LHC CM experience	21	with parallel automated RF conditioning	21	
Total Work days		62		63.5		65	
Total # weeks	8.9			9.1		9.3	

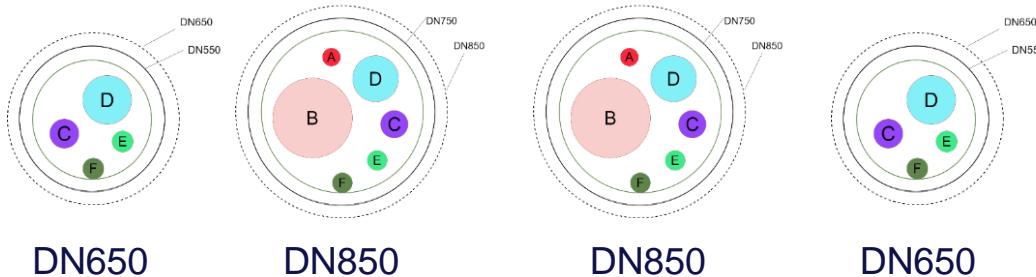
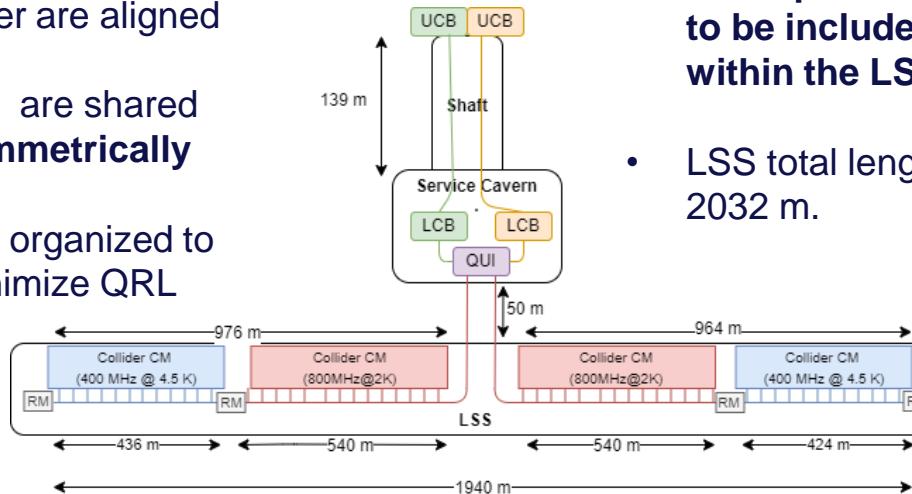
- ✓ Intervention time up to ~9/10 weeks (AC3/AC4) (including RF conditioning), no advantage in segmented baseline (unsafe cutting cryo lines with cold adjacent equip.)
- ✓ All architectures compatible with 17 weeks yearly shut-downs

Notes:

- XFEL (estimate): WU/vent/pump./CD/RF.cond: ~ 7-9 weeks (WU of linac: 3-4 w; ins.vac.vent.:1-2 d; ins.vac.pump.: ~5 d; CD of linac: 3-4 w; RF cond.: 1-2 d)
- LHC dipole replacement: WU/vent/pump./CD: ~ 10 weeks (WU sect.:3.5 w; ins. ins.vac.vent.:~3 d; ins.pump.: 5 d; CD: 6.5 weeks); dipole replacement: ~ 5 weeks

FCC-ee cryoplants at point H (ttbar)

- Service cavern & LSS center are aligned
- CM are shared **symmetrically**
- CM organized to minimize QRL



- **EM separators have to be included within the LSS too.**

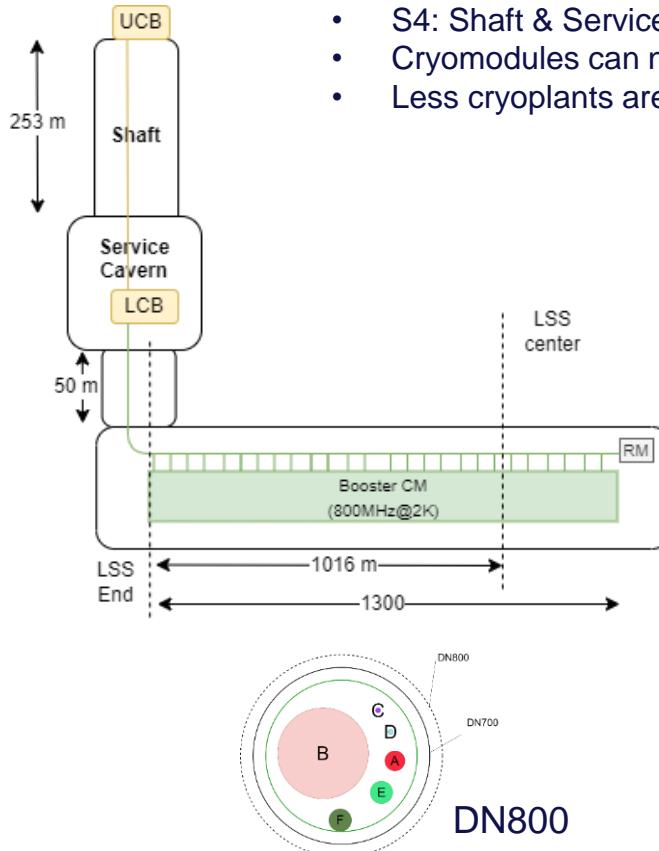
- LSS total length is of 2032 m.

QRL Header & Process values	Diameter (mm)
A : 1.3 bar , 2.2 K ($\Delta P=25$ mbar)	72
B : 30 mbar , 2 K ($\Delta P=2$ mbar)	320
C: 3 bar, 4.6 K ($\Delta P=130$ mbar)	110
D: 1.3 bar, 4.5 K ($\Delta P=70$ mbar)	185
E: 20 bar, 50 K ($\Delta P=10$ mbar)	80
F: 18 bar, 75 K ($\Delta P=15$ mbar)	80
Vacuum jacket (400MHz)	550*
* +100 mm for bellows and flanges	750*

- **RF-cryo CM string with baseline scenario fits within the LSS.**
 - Alternative scenarios under discussions
- **EM separators may not have enough space. To be checked with respective teams.** Source: <https://indi.to/WpWr7> !

FCC-ee cryoplants at point L (ttbar) – S4

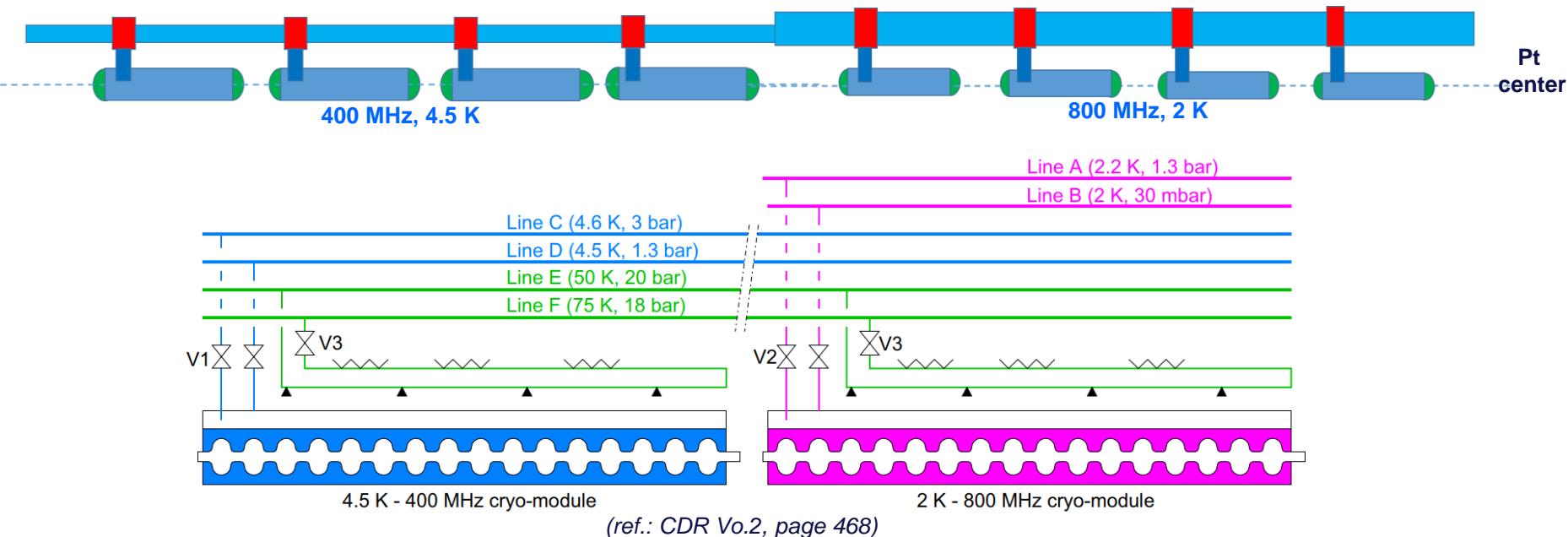
- S4: Shaft & Service cavern are at the end of the LSS.
- Cryomodules can not be distributed. One long string is the only possibility.
- Less cryoplants are needed at the cost of operability and maintainability.



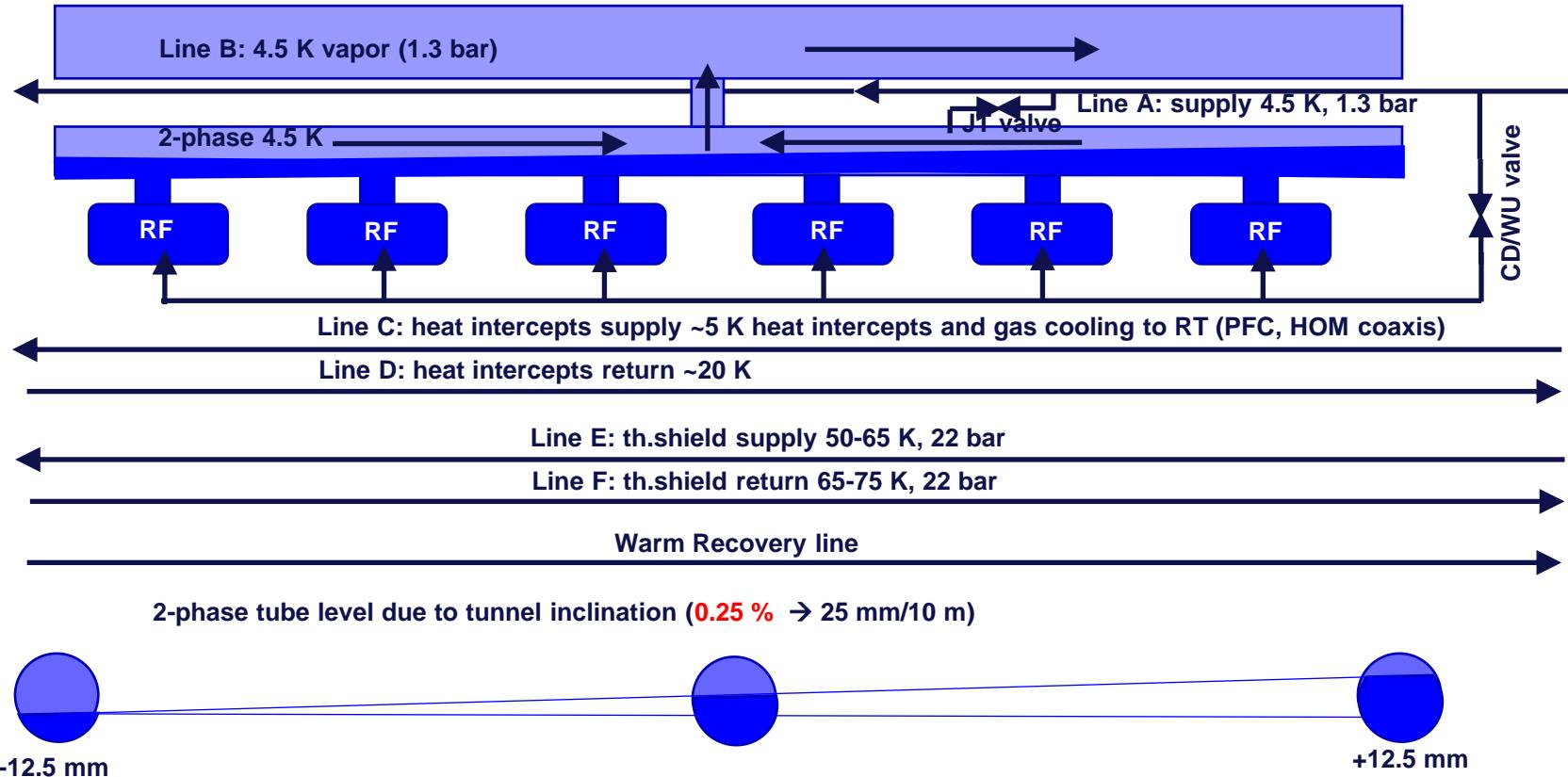
QRL Header	Diameter (mm)
S4	
A : 1.3 bar , 2.2 K ($\Delta P=25$ mbar)	80
B : 30 mbar , 2 K ($\Delta P=2$ mbar)	360
C: 3 bar, 4.6 K ($\Delta P=130$ mbar)	-
D: 1.3 bar, 4.5 K ($\Delta P=70$ mbar)	-
E: 20 bar, 50 K ($\Delta P=5$ mbar)	90
F: 18 bar, 75 K ($\Delta P=10$ mbar)	90
Vacuum jacket right	700*

* +100 mm for bellows and flanges

- A1: fully segmented collider with separate cryo line (present layout)



Cryogenic scheme 4.5 K (400 MHz)



Cryogenic scheme 2K (800 MHz)

