Proposed FCC_ee RF scenarios

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Table 1: Latest machine parameters

Parameter	***Z***	***W***	***H***	**ttbar**
Beam energy in GeV	45.6	80	120	175
Beam current in mA	1390	147	29	6.4
Nb of bunches	16640	2000	393	48
Beam RF voltage in MV	100	440	2000	9500

Table 2: Machine timeline

	Z	***W***	***H***	**ttbar**
Runtime [years]	4	1	3	4

Note:

1. Source: FCC_ee parameters changes since Berlin, presented at the 49th FCC Coordination Group Meeting, 25 August 2017 (F. Zimmermann)
2. Main changes compare to Berlin:
    a. Nb of bunches ~ divided by 4 ! -> HOMs!!!
    b. Total RF voltage for the Z: ~ 0.1 MV only!
    c. Machine runtime: was respectively 5, 2, 6, 6 (now 1 year for the W!!)
3. Upgrades must be done during the 4 months Winter shutdowns
4. Machine options:
    a. Z, W, H, tt: 400 MHz
    b. Z, W, H: 400 MHz + tt: hybrid 400/800
    c. Z, W: 400 KHz + H, tt: hybrid 400/800
5. Booster:
    a. Duty cycle: 10 Hz, beam current: ~ 1 %
    b. Peak RF power: ~ 500 kW, average RF power: < 100 kW
6. Cryomodules:
    a. 1-cell 4 cavity & 4-cells 4 cavity at 400 MHz
    b. 5 cell 4 cavity at 800 MHz (shall continuous CM be considered?)
7. Limits:
    a. E_{acc} = 10 MV/m for Nb/Cu, 20 MV/m for bulb Nb
    b. P_{cav} = 1 MW at 400 MHz, 500 kW at 800 MHz

option 1: 400 MHz for Z, W, H, ttbar

	Z		W		H		ttbar	
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster
Total RF voltage [MV]	100	36	440	340	2000	1720	9500	7800
frequency [MHz]	**400**							
RF voltage [MV]	100	36	440	340	2000	1720	9500	7800
E_{acc} [MV/m]	5.1	10	5.6	10	10		10	
# cell / cav	1	4	4		4		4	
V_{cavity} [MV]	1.91	15	8.4	15	15		15	
# cavities	52	4	52	24	136	116	636	520
# CM	13	1	13	6	34	29	159	130
system length [m]	130	12	156	72	408	348	1908	1560
T operation [K]	4.5		4.5		4.5		4.5	
dyn losses/cav [W]	14	210	66	210	210		210	
stat losses/cav [W]	8		8		8		8	
P_{cav} [kW] *	960	125	960	21	368	4.5	79	1
P_{HOM} / cav [kW]	**>20**		**>5**					

(machine: CW power, booster: peak power)*

Machine upgrade:

Z: 2x13 CM_{400_1cell}
W: replace all $CM_{400\text{-}1cell}$ by 4-cell $CM_{400\text{-}4cell}$
H: W RF system + add 2x21 $CM_{400\text{-}4cell}$
ttbar: re-align H, + add 91 $CM_{400\text{-}4cell}$
booster: 1 CM_{400_4cell} (Z) => +5 (W) => + 24 (H) => +106 (ttbar)

RF power upgrade:

Z: 2x52 1 MW RF power sources per beam
W: = Z RF power system
H: W at 800 kW/cavity, + add 2x84 ~100 kW
~~split W in 2 (208cav) + add 2x32 1 MW~~

ttbar: ~~split W in 2 (208cav) + 2x84+ add 260 x 100 kW~~
H (no splitting) (104cav) + 2x84 + add 364 x 100 kW (400 MHz)

Notes:

- RF power splitting! Compatibility with fast feedback???
- Power splitting => move 50% of the power stations + cabling + control!!! (2-3 days per station (52 stations)

option 2: 400 MHz for Z, W, H + hybrid 400/800 for ttbar

	Z		W		H		tt	
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster
Total RF voltage [MV]	100	36	440	340	2000	1720	9500	7800
frequency [MHz]	**400**							
RF voltage [MV]	100	36	440	340	2000	1720	4000	1720
E_{acc} [MV/m]	5.1	10	5.6	10	10		10	
# cell / cav	1	4	4		4		4	
V_{cavity} [MV]	1.91	15	8.4	15	15		15	
# cavities	52	4	52	24	136	116	272	116
# CM	13	1	13	6	34	29	68	29
system length [m]	130	12	156	72	408	348	816	348
T operation [K]	4.5		4.5		4.5		4.5	
dyn losses/cav [W]	14	210	66	210	210		210	
stat losses/cav [W]	8		8		8		8	
P_{cav} [kW] *	960	125	960	21	368	4.5	88	5
P_{HOM} / cav [kW]	**>20**		**>5**					
frequency [MHz]	**800**							
RF voltage [MV]							5500	6080
E_{acc} [MV/m]							20	
# cell / cav							5	
V_{cavity} [MV]							18.75	
# cavities							296	328
# CM							74	82
system length [m]							740	820
T operation [K]							2	
Q dyn/cav [W]							52	
Q stat [W]							8	
P_{cav} [kW] *							88	1.6
P_{HOM} / cav [kW]								

(machine: CW power, booster: peak power)*

Machine upgrade:

Z, W, H: see option1

ttbar: re-align H, + add 74 $CM_{800\text{-}5cell}$

booster: 1 CM_{400_4cell} (Z) => +5 (W) => + 24 (H) => +82 CM_{800_5cell} (ttbar)

RF power upgrade:

Z, W, H: see option 1

Ttbar: H + add 74 x 100 kW (800 MHz)

Option 3: 400 MHz for Z, W + hybrid 400/800 for H, ttbar

	Z		*W*		*H*		tt	
	per beam	booster	per beam	booster	per beam	booster	2 beams	booster
Total RF voltage [MV]	100	36	440	340	2000	1720	9500	7800
frequency [MHz]	**400**							
RF voltage [MV]	100	36	440	340	780	340	1560	340
E_{acc} [MV/m]	5.1	10	5.6	10	10		10	
# cell / cav	1	4	4		4		4	
V_{cavity} [MV]	1.91	15	8.4	15	15		15	
# cavities	52	4	52	24	52	24	104	24
# CM	13	1	13	6	13	6	26	6
system length [m]	130	12	156	72	156	72	312	72
T operation [K]	4.5		4.5		4.5		4.5	
dyn losses/cav [W]	14	210	66	210	210		210	
stat losses/cav [W]	8		8		8		8	
P_{cav} [kW] *	960	125	960	21	900	4.5	89	1.2
P_{HOM} / cav [kW]	**>20**		**>5**					
frequency [MHz]	**800**							
RF voltage [MV]					1220	1380	7940	7460
E_{acc} [MV/m]					20		20	
# cell / cav					5		5	
V_{cavity} [MV]					18.75		18.75	
# cavities					68	76	432	400
# CM					17	19	108	100
system length [m]					170	190	1080	1000
T operation [K]					2		2	
Q dyn/cav [W]					52		52	
Q stat [W]					8		8	
P_{cav} [kW] *					~100	5	~90	1.2
P_{HOM} / cav [kW]					**??**			

Machine upgrade:

Z, W: see option1

H: W RF system + add 2x17 $CM_{800\text{-}5cell}$

ttbar: re-align H, + add 74 $CM_{800\text{-}5cell}$

booster: 1 CM_{400_4cell} (Z) => +5 (W) => + 19 CM_{800_5cell} (H) => +81 (ttbar)

RF power upgrade:

Z, W: see option 1

H: W at 800 kW + add 2x68 x 100 kW (800 MHz)

W at 800 kW + add 2x34 x 200 kW (800 MHz) (split in 2)

ttbar: H + add 296 100kW (800 MHz)

Note: H, P_{HOM} @ 800 MHz ??

Summary & cost

	# cav $_{400MHz\ 1\ cell}$	# cav $_{400MHz\ 4\ cells}$	# cav $_{800MHz\ 5\ cell}$	# ~1 MW RF	# ~ 0.1 MW RF
Z	2x 52		-	2 x 52	-
W	-	2 x 52	-	-	-
$H_{1,2}$	-	2 x 136	-	2 x 52	2 x 84
$ttbar_1$	-	636	-	104	532
$ttbar_2$	-	272	296	104	464
H_3	-	2 x 52	2 x 68	2 x 52	2 x 68
$ttbar_3$	-	104	432	104	432

booster	# cav $_{400MHz\ 1\ cell}$	# cav $_{400MHz\ 4\ cells}$	# cav $_{800MHz\ 5\ cell}$	# ~ 0.1 MW RF	# ~ 0.1 MW RF
Z	-	4	-	4	-
W	-	24	-		
$H_{1,2}$	-	116	-		
H_3	-	24	76		
$ttbar_1$	-	520	-		
$ttbar_2$	-	116	328		
H_3	-	24	76		
$ttbar_3$	-	24	400		

Option 1	Z	W	H	ttbar	total
Cryomodules	52	+ 47	+ 76	+ 166	341
RF power	145	+ 0	+ 62	+ 135	342
Booster CM	1.8	+ 9	+ 44	+ 193	248
Booster RF power	1.5	+ 1	+ 2.3	+ 10	15
Total					**946**

Option 2	Z	W	H	ttbar	total
Cryomodules	52	+ 47	+ 76	+ 176	351
RF power	145	+ 0	+ 62	+ 108	315
Booster CM	1.8	+ 9	+ 44	+ 195	250
Booster RF power	1.5	+ 1	+ 2.3	+ 9	14
Total					**930**

Option 3	Z	W	H	ttbar	total
Cryomodules	52	+ 47	+ 81	+ 176	356
RF power	145	+ 0	+ 50	+ 110	305
Booster CM	1.8	+ 9	+ 45	+ 192	248
Booster RF power	1.5	+ 1	+ 2	+ 8.5	13
Total					**922**

Total # of CM to be installed

	Z	*W*	*H*	ttbar
Runtime [years]	4	1	3	4

machine	Z	W	H	ttbar
option1	26	26	42	91
option2	26	26	42	74
option3	26	26	34	74

booster	Z	W	H	Ttbar
option1	1	5	24	106
option2	1	5	24	82
option3	1	5	19	81

Note:

- Z machine with very high P_{HOM} => x 4
- 2 K cryomodules => consider continuous CM

Conclusions

- 400 MHz for Z and W
- Hybrid options 400/800 for ttbar (and H) seem favourable (cost & installation schedule)
- Power splitting options are not compatible with machine timeline
- 800 MHz for the H machine maybe risky (risk of high HOM power)

- Z machine: High HOM power (i.e. >> kW / cav) => big impact on CM cost (+ >150 MCHF), big impact on integration (cavity separation incompatible with W machine => all RF power station must be moved (Z -> W) ≠ timeline!!