FCC-ee power & luminosity

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eeFACT'22 special session

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FCC-ee parameters

Parameter [4 IPs, 91.1 km, T_{rev}=0.3 ms]	Z	WW	H (ZH)	ttbar
beam energy [GeV]	45.6	80	120	182.5
beam current [mA]	1400	135	26.7	5.0
number bunches/beam	8800	1120	336	42
bunch intensity [10^{11}]	2.76	2.29	1.51	2.26
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	2.1/0	2.5/8.8
long. damping time [turns]	1170	216	64.5	18.5
horizontal beta* [m]	0.15	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]	10	21	14	39
vertical rms IP spot size [nm]	34	66	36	69
beam-beam parameter ξ_x / ξ_y	0.004/ 0.159	0.011/0.111	0.0187/0.129	0.096/0.138
rms bunch length with SR / BS [mm]	4.32 / 15.2	3.55 / 7.02	2.5 / 4.45	1.67 / 2.54
luminosity per IP [10^{34} cm^{-2}s^{-1}]	181	17.3	7.2	1.25
tot. integr. luminosity / yr [ab^{-1}/yr]	86	8	3.4	0.6
beam lifetime rad Bhabha / BS [min]	19 / ?	20 / ?	10 / 19	12 / 46

Two estimates

S. Aull et al., "Electrical Power Budget for FCC-ee,'" Proc. IPAC2016 (2016).

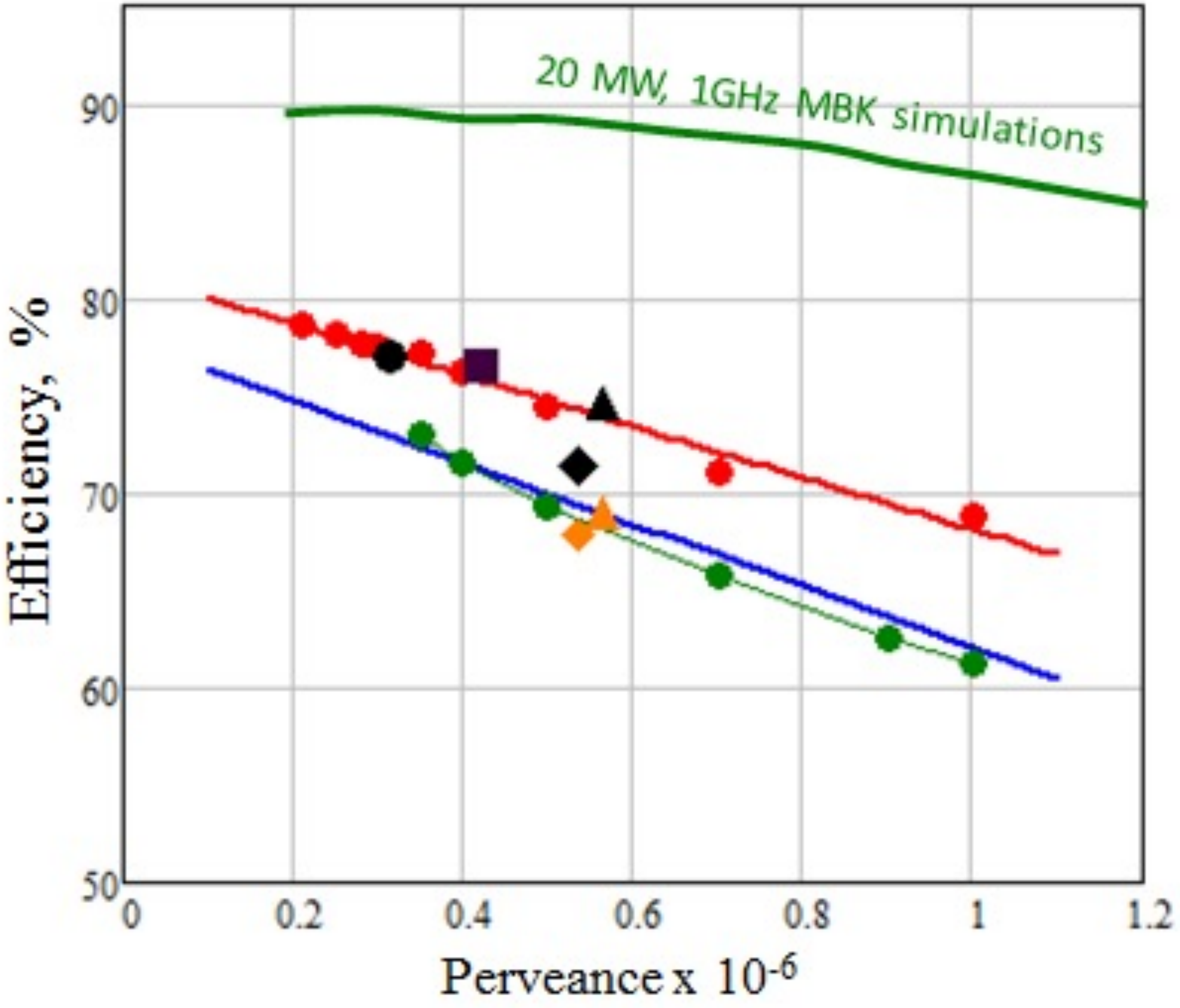
- Nb/Cu, 4.5 K, 400 MHz, $Q=3\times10^{9}$ at 10 MV/m
- 68%-77% klystron efficiency, 5% losses for AC/DC conversion, 5% losses RF distribution

J.-P. Burnet, "Update of the Power Demandfor FCC-ee," FCC Week 2022, Paris (2022); https://indico.cern.ch/event/1064327

Reference (LEP): Energie Electrique, Rapport Mensuel Decembre 2000, Bilan Annee 2000", CERN internal report (2000).

2016 estimate (S. Aull, M. Koratzinos, F. Zimmermann et al.)

subsystem	Z		W	ZH	$t\bar{t}$	LEP2 (av.2000*)
luminosity/IP [10^{34} cm^{-2}s^{-1}]	207	90	19	5	1.3	0.012
collider total RF power	163		163	145	145	42
collider cryogenics	3	2	5	23	39	18
collider magnets	3		10	23	50	16
booster RF + cryo	4		4	6	7	-
booster magnets	0		1	2	5	-
injector complex	10		10	10	10	<10
physics detectors (2)	10		10	10	10	9
cooling & ventilation***	47		49	52	62	16
general services	36		36	36	36	9
total	276	**275**	**288**	**308**	**364**	**120**


20 MW, 1GHz MBK simulations
Efficiency, %
Perveance x 10^{-6}
90
80
70
60
50
0
0.2
0.4
0.6
0.8
1
1.2

I. Syratchev

2022 estimates (J.-P. Burnet)

Radio-frequency systems

- **Energy loss from synchrotron radiation limited to 50MW per beam**

- Power demand for RF Storage ring Z, W, H
- P_{RF} = 100MW
- P_{EL} = 100 / ηklystron / ηmodulator / ηdistribution
- P_{EL}= 100 / 0.8 / 0.9 / 0.95 = 146MW

Storage ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRF (MW)	100	100	100	100
Klystron efficiency	0.8	0.8	0.8	0.8
PRF EL (MW)	146	146	146	146

- Booster
- P_{RF} = 15% P_{RF} storage (1 beam) = 7.5MW
- P_{EL} = 7.5 / ηklystron / ηmodulator / ηdistribution
- P_{ELav} = P_{EL} * booster duty cycle = 1.7MW

- The Booster duty cycle has a huge impact on its power demand. With a low duty cycle, the power demand is very low

Booster	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
PRFb (MW)	7.5	7.5	7.5	7.5
Klystron efficiency	0.8	0.8	0.8	0.8
Booster duty cycle	0.15	0.15	0.15	0.15
PRFb EL (MW)	2	2	2	2

- Electricity & Energy Management

R&D High-efficiency klystron, today 50-60%,
target 80% - however operational margin needed ...

2022 estimates (J.-P. Burnet)

Cryogenic systems

- **Cryogenic systems needed for RF cavities**

- Storage ring
- Cryo power demand varies Z, W, H, ttbar

24th May 2022	Z		W		H		ttbar2		
	per beam	booster	per beam	booster	2 beams	booster	2 beams	2 beams	booster
Frequency [MHz]	400	800	400	800	400	800	400	800	800
RF voltage [MV]	120	140	1000	1000	2480	2480	2480	9190	11670
Eacc [MV/m]	5.72	6.23	11.91	24.26	11.82	25.45	11.82	24.52	25.11
# cell / cav	1	5	2	5	2	5	2	5	5
Vcavity [MV]	2.14	5.83	8.93	22.73	8.86	23.85	8.86	22.98	23.53
#cells	56	120	224	220	560	520	560	2000	2480
# cavities	56	24	112	44	280	104	280	400	496
# CM	14	6	28	11	70	26	70	100	124
T operation [K]	4.5	2	4.5	2	4.5	2	4.5	2	2
dyn losses/cav [W]	19	0.5	174	7	171	8	171	51	8
stat losses/cav [W]	8	8	8	8	8	8	8	8	8
Qext	6.6E+04	3.2E+05	1.2E+06	8.9E+06	1.5E+06	1.2E+07	8.3E+06	4.9E+06	5.3E+07
Detuning [kHz]	8.939	4.393	0.430	0.115	0.123	0.031	0.025	0.040	0.005
Pcav [kW]	880	205	440	112	352	95	62	207	20
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	0.36	0.36	0.74	0.74	0.70	0.90	0.85
Beam current [A]	1.280	0.128	0.135	0.0135	0.0534	0.005	0.010	0.010	0.001

Cavities with very low static losses
High-efficiency cryoplant
250 Welec/W@4.5K (as LHC)

Storage ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Pcryo (MW)	1,3	12,6	15,8	47,5

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2022 estimates (J.-P. Burnet)

Storage Ring Magnet systems

- **Energy loss in magnets**

- Magnet losses storage ring
- $P_{magnets}$ = 56MW from CDR
- P_{cables} = 20MW (rough estimation)
- $P_{ELmagnets}$ = 76 / ηconversion / ηdistribution
- $P_{ELmagnets}$ = 76 / 0.9 / 0.95 = 89MW

- A lot of magnet families still unknown, inner triplet, single quadrupoles, octupoles, correctors…
- They should have a limited impact on the power demand <10%.

Storage Ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipoles (MW)	0.8	2.6	5.8	13.3
Quadrupoles (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	1.3	3.9	8.9	20.5
Power cables (MW)	1.2	3.8	8.6	20
Total magnet losses	4.8	14.7	33.0	76.4
Power demand (MW)	5.6	17.2	38.6	89

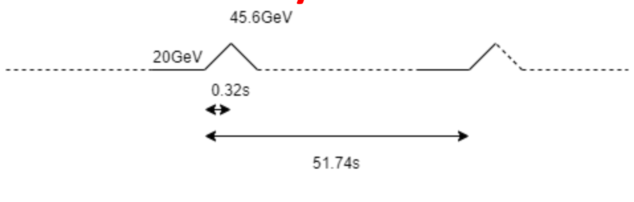
Low-loss magnets design

Booster Magnet systems

2022 estimates (J.-P. Burnet)

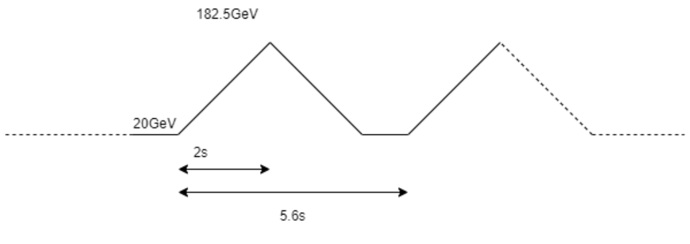
- **Energy loss in magnets**

- We made the assumption that the magnets are the same as the storage ring, except sextupole (half power).
- The duty cycle taken for calculation is 15%, one Booster cycle of 4s every 26.6s.



Booster Top-up operation

- However, in CDR, the repetition rate is up to 1 cycle every 5.6s.



Booster Top-up operation

Booster	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipole (MW)	0.8	2.6	5.8	13.3
Quads (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	0.6	2.0	4.4	10.25
Power cables (MW)	1.2	3.8	8.6	20
Booster duty cycle	0.15	0.15	0.15	0.15
Total magnet losses	0.6	1.9	4.3	9.9
Power demand (MW)	0.7	2.2	5.0	12

Low-loss magnets design

- Electricity & Energy Management

2022 estimates (J.-P. Burnet)

Cooling and Ventilation systems

- **Power demand for cooling and ventilation systems**
- Power demand is constant for RF loads
- It varies for cryogenics and magnets depending on the machine configuration Z, W, H, ttbar.

Electrical consumption (MW)	Cooling	Chillers	Ventilation	Total
POINT				
A	1.7	1.2	1.3	**4.2**
B	0.3	1.0	1.3	**2.6**
D	1.7	1.1	1.3	**4.2**
F	0.3	1.0	1.3	**2.6**
G	1.7	1.2	1.3	**4.2**
H	3.3	2.1	2.1	**7.5**
J	1.7	1.1	1.3	**4.2**
L	5.5	2.6	2.5	**10.6**
Total	**16.3**	**11.2**	**12.7**	**40.2**

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Pcv (MW)	all	33	34	36	40.2

2022 estimates (J.-P. Burnet)

Total power demand by machine configuration

- **Update of FCC-ee power demand**

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Magnet current		25%	44%	66%	100%
Power ratio		6%	19%	43%	100%
PRF EL (MW)	Storage	146	146	146	146
PRFb EL (MW)	Booster	2	2	2	2
Pcryo (MW)	all	1,3	12,6	15,8	47,5
Pcv (MW)	all	33	34	36	40.2
PEL magnets (MW)	Stroage	6	17	39	89
PEL magnets (MW)	Booster	1	3	5	11
Experiments (MW)	Pt A & G	8	8	8	8
Data centers (MW)	Pt A & G	4	4	4	4
General services (MW)		36	36	36	36
Power during beam operation (MW)		237	262	291	384
Average power / year (MW)		143	157	173	224

The previous estimation (2018) was from 259 to 359MW

System	Power [MW]			
	Z	W	H	tt
RF	163	163	145	145
Collider cryogenics	**1**	**9**	**14**	**46**
Collider magnets	**4**	**12**	**26**	**60**
Booster RF & cryogenics	**3**	4	6	**8**
Booster magnets	0	1	2	5
Pre-injector complex	10	10	10	10
Physics detectors (2)	**8**	**8**	**8**	**8**
Data centres (2)	**4**	**4**	**4**	**4**
Cooling & ventilation	**30**	**31**	**33**	**37**
General services	36	36	36	36
Total	**259**	**278**	**284**	**359**

Estimation uncertainties

2022 estimates (J.-P. Burnet)

- **Power demand uncertainties**

- The main loads are known for the storage ring, still, a lot of equipment is not defined.
- Also, a lot of unknown on the Booster, equipment and operation mode (types of cycle)
- Power cables, 20MW, can be optimized, 50% gain?
- Option for 4 experiments, 4 * 4MW
- General services** are over-estimated (estimation based on LHC, but with mixed loads), should be below 26 MW

**Lightings, pumps, vacuum systems, wall plugs, environmental and radiation monitoring, access systems, safety systems, communication networks, secured power systems, electrical power distribution networks, alignment systems, and transport systems (etc.).

		Z	W	H	TT
Beam energy (GeV)		45.6	80	120	182.5
Experiments (MW)	Pt A, D, G, J	16	16	16	16
Data centers (MW)	Pt A, D, G, J	8	8	8	8
General services (MW)		26	26	26	26
Compare to previous slide (MW)		+2	+2	+2	+2
Power during beam operation (MW)		239	264	293	386

- Despite of a lot of unknown of the accelerator systems, the global uncertainty is < 5%

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Energy consumption, 120 GeV (W)

- **Estimation of energy consumption, 1.52TWh**
- Energy consumption FCC alone.

Beam operation	All systems ON
Downtime operation	0% RF, 100% cryo, 50% magnets
Hardware + Beam commissioning (COM)	50% magnets, 50% RF+Cryo
Machine Development (MD)	30% RF, 100%Cryo, 100%magnets
technical stop (TS)	20% cryo, 0% RF + magnets
Shutdown	20% cryo, 50%CV, 0% RF + Magnets

120 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	293					1005644	MWh
Downtime operation	42	1008	109					110266	MWh
Hardware, Beam commissioning	30	720		139				100079	MWh
MD	20	480			177			85196	MWh
technical stop	10	240				87		20985	MWh
Shutdown	120	2880					69	199872	MWh
Energy consumption / year	365	8760						1.52	TWh
Average power								174	MW

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Energy consumption, 182.5 GeV (TT)

- **Estimation of energy consumption, 1.97TWh**
- Energy consumption FCC alone.

Beam operation	All systems ON
Downtime operation	0% RF, 100% cryo, 50% magnets
Hardware + Beam commissioning (COM)	50% magnets, 50% RF+Cryo
Machine Development (MD)	30% RF, 100%Cryo, 100%magnets
technical stop (TS)	20% cryo, 0% RF + magnets
Shutdown	20% cryo, 50%CV, 0% RF + Magnets

182.5 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	387					1329001	MWh
Downtime operation	42	1008	149					149702	MWh
Hardware, Beam commissioning	30	720		178				128301	MWh
MD	20	480			248			119208	MWh
technical stop	10	240				98		23595	MWh
Shutdown	120	2880					78	224928	MWh
Energy consumption / year	365	8760						1.97	TWh
Average power								225	MW

- Electricity & Energy Management

Name	FCC-ee	FCC-ee	FCC-ee
Beam energy [GeV]	45.6	120	182.5
Average beam current [A or mA]	1400	26.7	5
Total SR power [MW]	100	100	100
Collider cryo power [MW]	1	17	50
Collider RF power [MW]	146	146	146
Collider magnet power [MW]	6	39	89
Cooling & ventilation power [MW]	33	36	40
General services power [MW]	36	36	36
Injector cryo power [MW]	1	1	1
Injector RF power [MW]	2	2	2
Injector magnet power [MW]	0	2	4
Pre-injector power (where applicable) [MW]	10	10	10
Detector power (if included) [MW]	8	8	8
Data center power (if included) [MW]	4	4	4
Total power [MW]	247	301	390
Luminosity [10^(34) /cm^2/s]	193	7.7	1.3
Total integrated luminosity / year [1/fb/yr]	46000	1900	330
Effective physics time per year asumed/needed to achieve integrated annual luminosity [10^7 s]	1.3	1.3	1.3
Energy Consumption / year [TWh]	1.25	1.52	1.97

luminosity challenges, risks, and possible mitigations

- dynamic aperture with errors and corrections (factor 2?)
- beam-beam limit with impedance & errors (goal: 1.5-2x higher than LEP2)
- effects seen at SuperKEKB (sudden beam loss) or LHC/HERA (dust)

→ Overall performance risk: factor ∼3

- On the other hand, machine with 4 IPs could achieve ∼2x performance
  for 2 IPs, injector could support shorter beam lifetime, and simulated
  vertical emittance is often much smaller than design