FUTURE CIRCULAR COLLIDER

UPDATE OF THE POWER DEMAND FOR FCC-ee

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Abstract

The FCC-ee will be the largest accelerator ever built with kilometers of different accelerator devices.
The identification of the main loads is crucial for designing the electricity infrastructure and for evaluating its energy consumption.
An update of the FCC power demand is ongoing with the evaluation of its annual energy consumption depending on the machine configurations.
The next step is to identify how energy consumption can be reduced, by design and optimization of equipment and systems, and by optimization of the operation mode of the accelerators and their infrastructures.
The goal is to identify where the effort needs to be focused to reduce the environmental impact of the project.

Content

- Update of the power demand / main loads for FCC-ee
- Distribution of the power demand by points and by the beam energies
- Estimation of energy consumption per machine configurations
- Optimization of the accelerator systems to reduce the power demand
- Ways to reduce the energy consumption

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

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

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	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

R&D High-efficiency klystron, today 50-60%, target 80%

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
250Welec/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

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%.

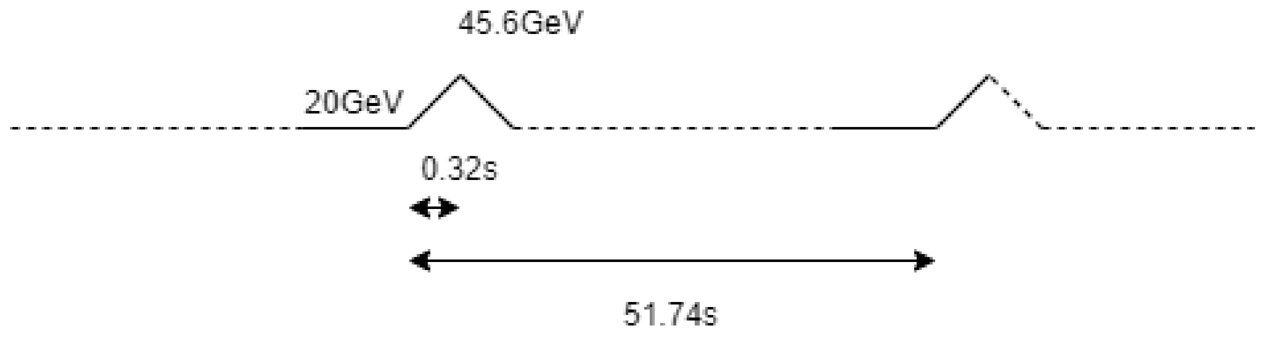
Storage Ring	Z	W	H	TT
Beam Energy (GeV)	45.6	80	120	182.5
Magnet current	25%	44%	66%	100%
Power ratio	6%	19%	43%	100%
Dipoles (MW)	0.8	2.6	5.8	13.3
Quadrupoles (MW)	1.4	4.3	9.8	22.6
Sextupoles (MW)	1.3	3.9	8.9	20.5
Power cables (MW)	1.2	3.8	8.6	20
Total magnet losses	4.8	14.7	33.0	76.4
Power demand (MW)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

Low-loss magnets design

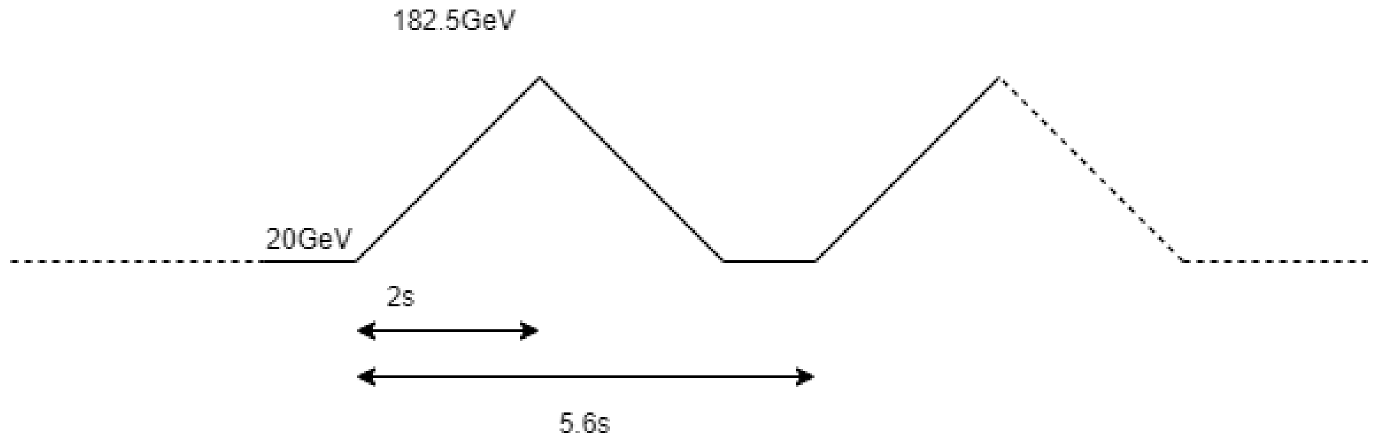
Booster Magnet systems

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



Booster Top-up operation



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

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

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

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 26MW

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

		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

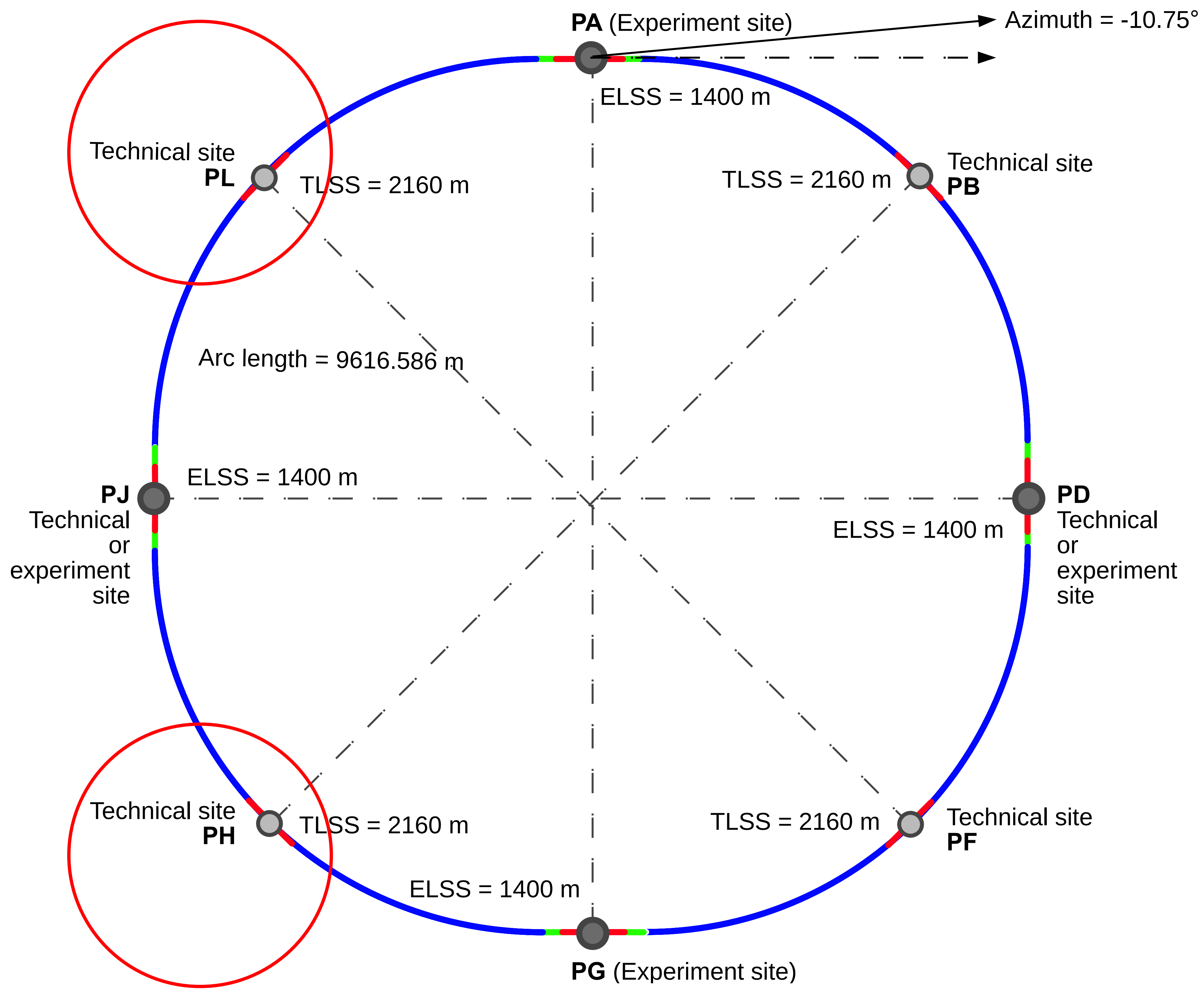
Power demand per points, focus RF loads

Infrastructure needed for FCC-ee

Strong dissymmetry of the power needs:
1 point needs 141MW
1 point needs 180MW
6 points need <30MW
High RF loads move from PL to PH.

		Max power (MW)
Point A	Experiment	27
Point B		21
Point D		21
Point F		21
Point G	experiment	27
Point H	RF TT	141
Point J		21
Point L	RF Z,W,H	180

Z,W,H, RF point, 180MW



TT, RF point, 141MW

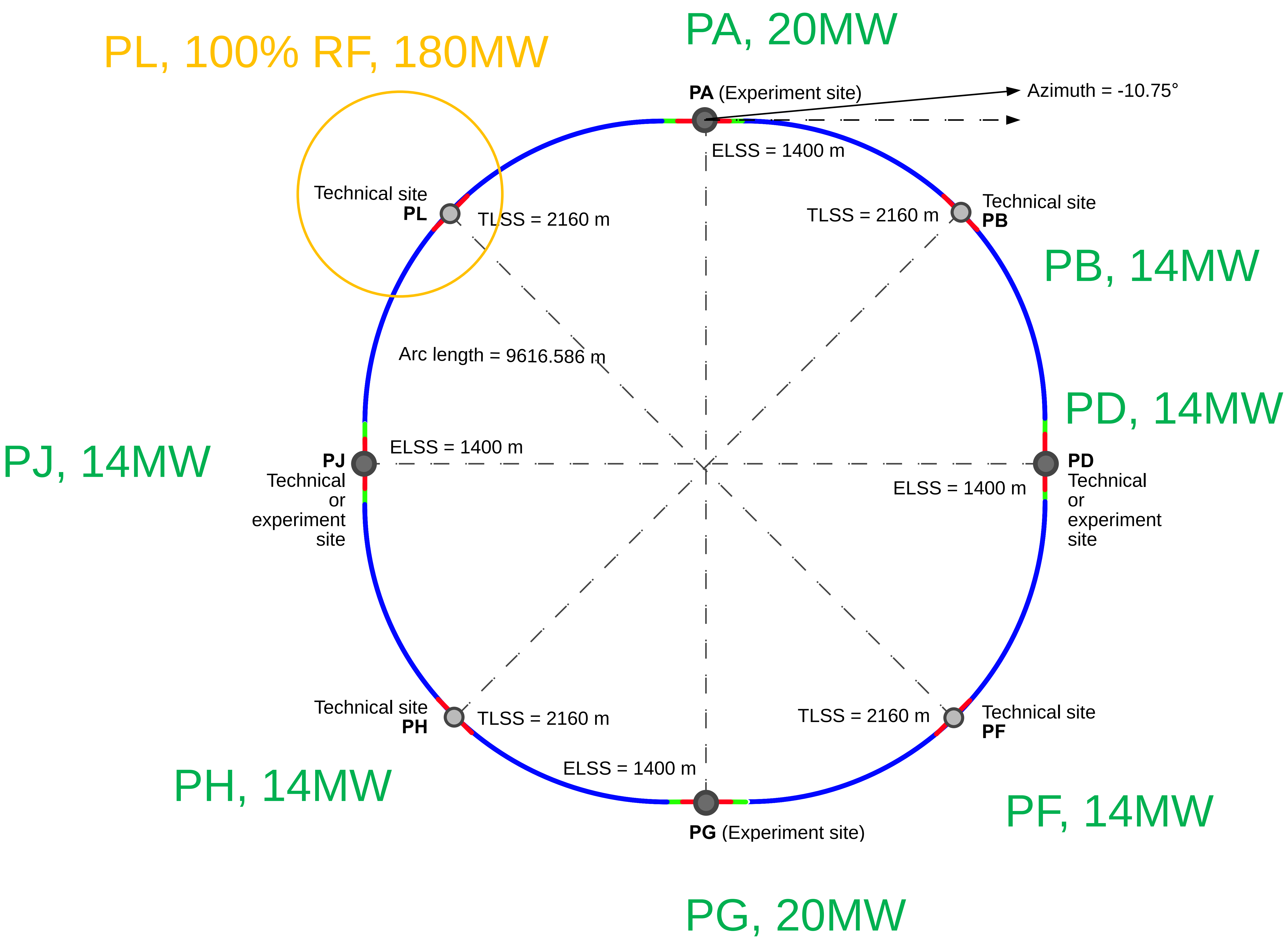
Power demand per points, configuration Z, W, H

Infrastructure needed for FCC-ee Z, W,H

Very high power demand on point L, 180MW.

2 experiments, point A and G.

		Max power (MW)
Point A	Experiment	20
Point B		14
Point D		14
Point F		14
Point G	experiment	20
Point H	RF TT	14
Point J		14
Point L	RF Z,W,H	180

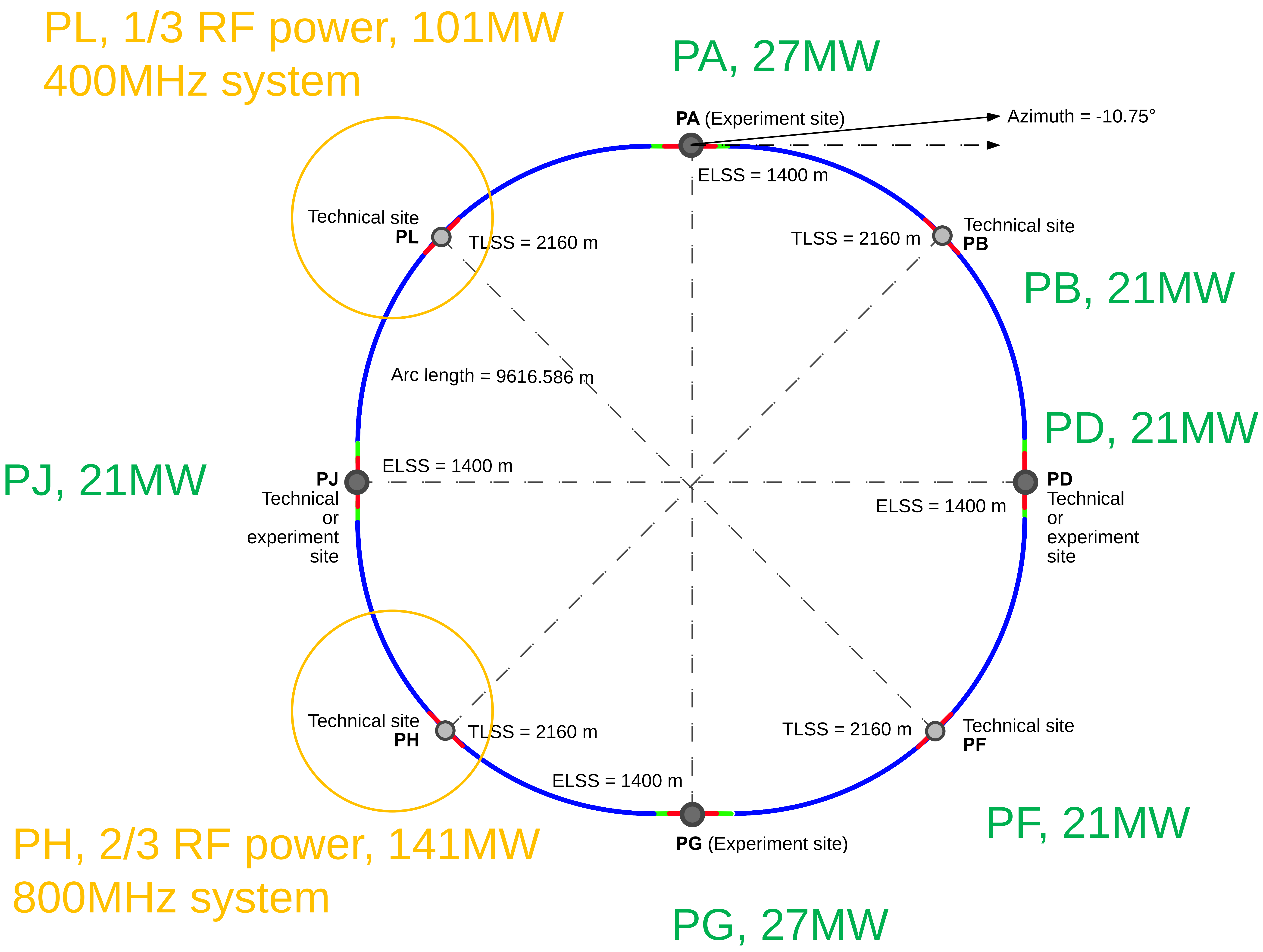


Power demand per points, configuration TTbar

Infrastructure needed for FCC-ee TTbar

2 high power demands,
Point L 101MW, 40% 400MHz
Point H, 141MW, 60% 800MHz

		Max power (MW)
Point A	Experiment	27
Point B		21
Point D		21
Point F		21
Point G	experiment	27
Point H	RF TT	141
Point J		21
Point L	RF Z,W,H	101

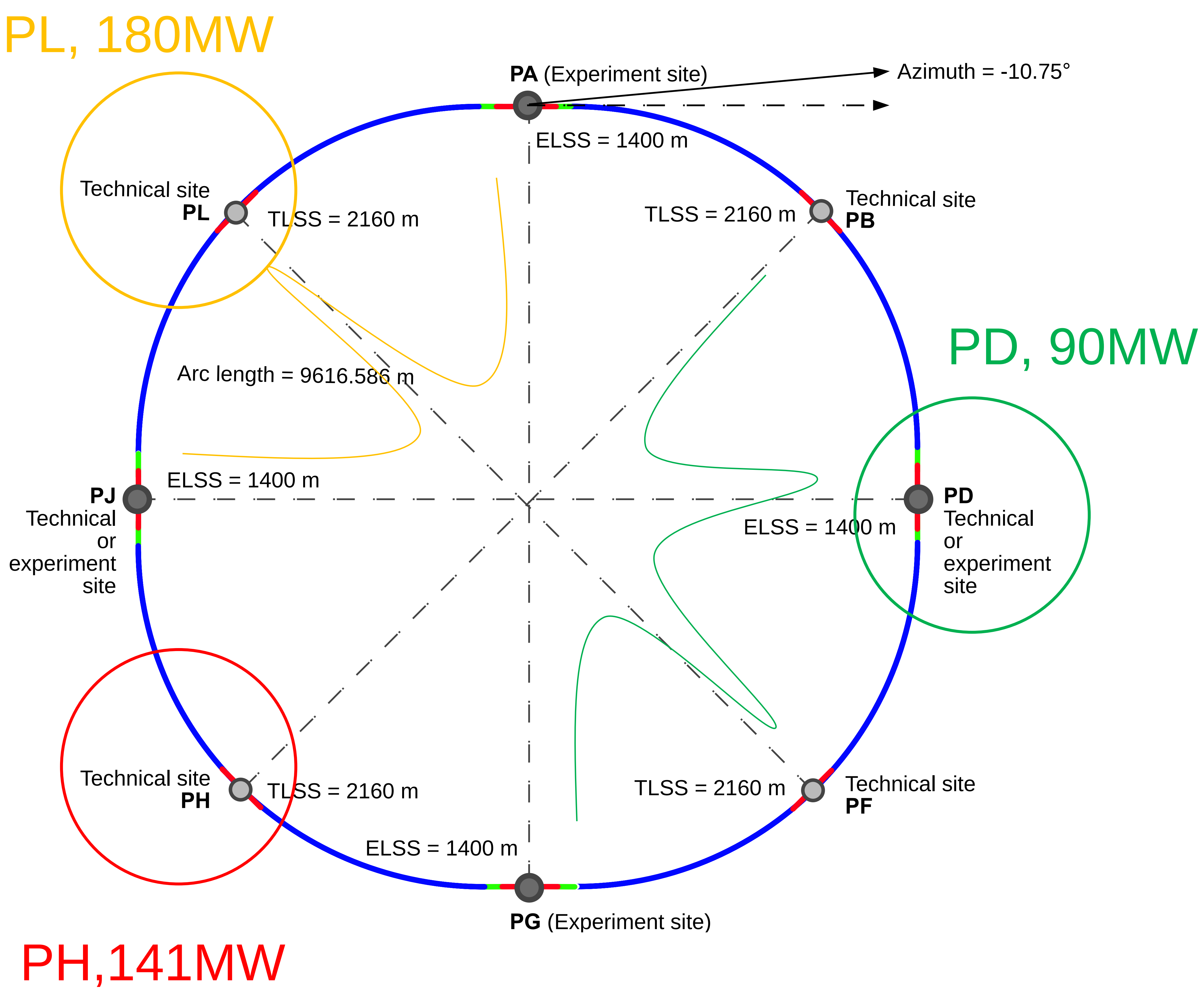


Electrical sub-stations, FCC-ee

Infrastructure needed for FCC-ee

2 high power demands,
Point L 101MW, 40% 400MHz
Point H, 141MW, 60% 800MHz
Need 2 main sub-stations for RF loads.
Need an additional sub-station for East part of the machine.

		Max power (MW)
Point A	Experiment	28
Point B		22
Point D		22
Point F		22
Point G	experiment	28
Point H	RF TT	141
Point J		22
Point L	RF Z,W,H	101



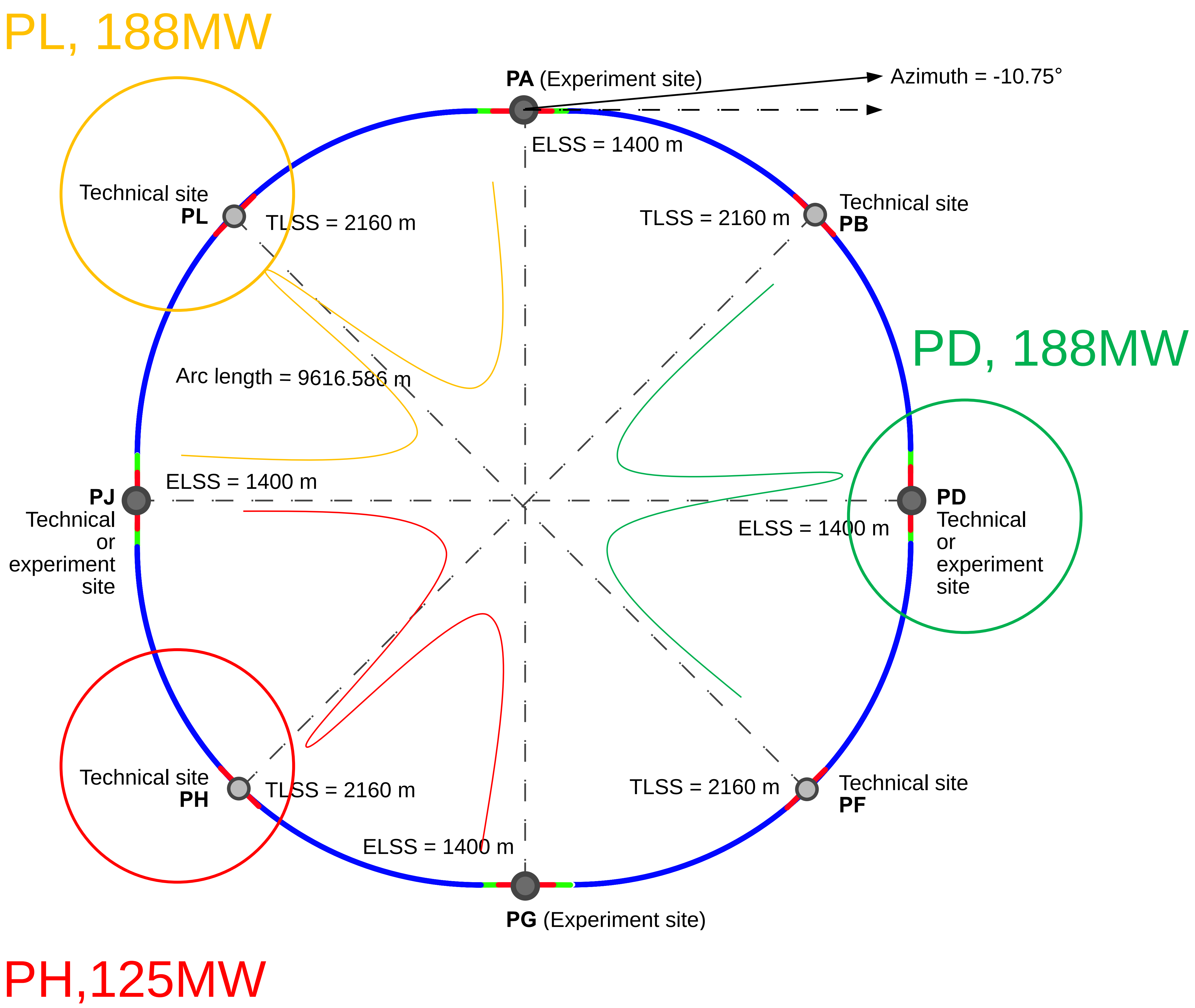
Electrical sub-stations, FCC-hh

Infrastructure needed for FCC-hh

The power demand will be spread all around the machine, due to the cryogenic needed for superconducting magnets distributed all around the machine.
500MW / 8 = 62.5 MW per point

Need 3 substations for hh configuration, rated at ~200MW .

Interesting scheme also for redundancy.



Energy consumption, 45,6 GeV (Z)

Estimation of energy consumption, 1.25TWh

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% croy, 0% RF + magnets
Shutdown	20% cryo, 50%CV, 0% RF + Magnets

45,6 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	237					813125	MWh
Downtime operation	42	1008	85					85413	MWh
Hardware, Beam commissioning	30	720		114				82299	MWh
MD	20	480			133			63707	MWh
technical stop	10	240				81		19489	MWh
Shutdown	120	2880					65	186342	MWh
Energy consumption / year	365	8760						1.25	TWh
Average power								143	MW

Energy consumption, 80 GeV (H)

Estimation of energy consumption, 1.35TWh

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

80 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown		
Beam operation	143	3432	257					881810	MWh
Downtime operation	42	1008	93					94153	MWh
Hardware, Beam commissioning	30	720		123				88553	MWh
MD	20	480			148			71275	MWh
technical stop	10	240				83		20020	MWh
Shutdown	120	2880					66	191232	MWh
Energy consumption / year	365	8760						1.35	TWh
Average power								154	MW

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

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

Energy consumption, 182.5 GeV (TT)

Estimation of energy consumption by systems

Energy consumption FCC alone.

182.5 GeV	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown			
RF systems	165	3960	150					594000	MWh	29%
Magnets	180	4320	90					388800	MWh	19%
Cryogenics	245	5880	47,5				10	322800	MWh	16%
Cooling & Ventilation	245	5880	40				20	292800	MWh	14%
General services	365	8760	26	26	26	26	26	227760	MWh	11%
Experiments + data centers	365	8760	24	24	24	24	24	210240	MWh	10%

CERN energy consumption with Meyrin site, SPS and FCC

Estimation of CERN global energy consumption

Meyrin site, with all facilities, is around 27MW, 202 GWh/y
SPS with North Area is around 60MW, 362 GWh/y

2018 consumption	Days	Hours	Power OP	Power Com	Power MD	Power TS	Power Shutdown			Year
Meyrin site	300	7200	27	20	27	20	15	207000	MWh	2018
SPS with North Area	275	6600	60	30	60	15	5	362000	MWh	2018

FCC injector won’t increase the energy consumption, it has a minor impact compare to SPS with North Area.

Prevessin data center (up to 12MW) not included !

CERN Meyrin, SPS, FCC	Z	W	H	TT
Beam energy (GeV)	45.6	80	120	182.5
Energy consumption (TWh/y)	1.82	1.92	2.09	2.54

Optimization of the accelerator systems

Focus on reduction of the power demand

FCC team has already identified the main accelerator systems which need to be optimized to reduce the energy consumption.

High-efficiency klystron, target 80%
Low-loss magnet design
Low static losses of RF cavities
High-efficiency cryoplant

The power demand estimation is already based on these optimisations!

Nice behaviour of FCC-ee: RF power (150MW) is present only with beam operation!

Power demand drops when there is no beam, be careful with electrical network stability!

Ways to reduce energy consumption

Focus on reduction of the energy consumption

For beam operation, the only way to reduce the energy consumption is to work on accelerator systems optimisation, see the previous slide.

A lot of energy is consumed without beams, this is also where energy saving can be developed.

High-Q cavities, which can bring down the Cryo power (50%), R&D effort to be pursued
Economic mode for magnets (Switch-off magnets during short or long stops)
Economic mode for cryoplant (Static losses represent less than 10%, can we operate cryoplants at 20%,50% for short or long stop?)
Economic mode for cooling an ventilation

can we reduce the tunnel ventilation when nobody is inside or regulated it on temperature? Different from fixed speed.
can we adapt the water flow rate depending on the power dissipation? Motor drive systems regulated on power demand.
can we modulate the cooling tower with the power dissipation? Motor drive systems regulated on power demand.

Economic mode for experiments

can we identify some systems that can be put in sleep mode?
…

Under discussion, a proposal for a working group on energy saving
Target 10% ? 200GWh

Summary

- The main loads of the machine are known
- An estimation of the power demand was presented depending of the machine configuration, with an uncertainty around 5%
- The power demand is known by point of the machine which allows for defining the electrical infrastructure
- The energy consumption of FCC was detailed
- The way to reduce the energy consumption was highlighted

Next steps

- Define the electrical infrastructure based on these numbers
- Work on the reduction of the energy consumption
- Keep updated the power demand with new inputs
- Introduce energy production and energy recovery

Thank you for your attention