# FUTURE CIRCULAR COLLIDER

# UPDATE OF THE POWER DEMAND ENERGY CONSUMPTION, GRID CONNECTION FOR FCC-ee

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# Abstract

The FCC-ee will be the largest accelerator ever built and it requires to be connected to the European grid for electricity supply. The power demand is a key parameter to define the grid connection. The identification of the main loads was performed and presented in 2022 as well as the energy consumption depending on the machine configurations. The studies for grid connection were launched based on these numbers and the results will be presented. Last changes and optimisation of the machine parameters will be presented with their impact on the grid connection.

# Content

- Update of the power demand / main loads for FCC-ee
- Estimation of energy consumption per machine configurations
- Distribution of the power demand by points and by beam modes
- Grid connections

# 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

Newcomers: Solid-State amplifiers for 800MHz cavities (low power <100kW per cavity).
Booster, from H to Ttbar at 100%.
Collider, TTbar only, at 20%. 80% still with klystron.
Solid-state amplifiers have lower efficiency (60%) but the impact is limited (only 20% of the load).

Electricity & Energy Management

| Storage ring | Z, W, H |
|---|---|
| Beam Energy (GeV) | 45.6 |
| PRF (MW) | 100 |
| Klystron efficiency | 0.8 |
| PRF EL (MW) | 146 |

| Booster | Z, W |
|---|---|
| Beam Energy (GeV) | 45.6 |
| PRFb (MW) | 7.5 |
| Klystron efficiency | 0.8 |
| Booster duty cycle | 0.15 |
| PRFb EL (MW) | 2 |

| 15-Feb-23 | Z | | W | | H | | ttbar2 | | |
|---|---|---|---|---|---|---|---|---|---|
| | collider | booster | collider | booster | collider | booster | collider | collider | booster |
| RF source type | 400 MHz - 1 MW klystron | 800 MHz - 400 kW klystron | 400 MHz - 1 MW klystron | 800 MHz - 400 kW klystron | 400 MHz - 1 MW klystron | 800 MHz - 50 kW solid state amplifier | 400 MHz - 50 kW solid state amplifier | 800 MHz - 400 kW klyst ron | 800 MHz - 50 kW solid state amplifier |
| Frequency [MHz] | 400 | 800 | 400 | 800 | 400 | 800 | 400 | 800 | 800 |
| Pcav [kW] | 880 | 176 | 385 | 88 | 379 | 44 | 45 | 181 | 8 |
| Prf conditioning [kW] | 220 | 44 | 96 | 22 | 95 | 11 | 11 | 45 | 2 |
| # cavities / RF sources | 1 | 2 | 2 | 4 | 2 | 1 | 1 | 2 | 4 |
| # RF sources | 112 | 14 | 128 | 14 | 130 | 112 | 260 | 244 | 150 |

# Cryogenic systems

## Cryogenic systems needed for RF cavities

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

Proposal for R&D on high Q0 800MHz cavities.
New baseline Q0=3.$10^{10}$, 20MV/m, could reduce the cryogenics power by 27%.

Proposal for R&D on centrifugal compressors, from 230We/W to 170We/W could reduce the cryogenic power demand again by 25% (26MW for TTbar).

- **Three scenarios are considered:**
  - Conservative: 230 Wel/W or 28.8 % of Carnot efficiency (LHC-like – CDR values) the baseline!
  - Intermediate: 210 Wel/W or 31.5 % of Carnot efficiency (With an optimized process) appears not achievable
  - Optimistic: 170 Wel/W or 39 % of Carnot efficiency (With centrifugal compressors) strong R&D effort needed

| | PH [MW] | PL [MW] | Total [MW] |
|---|---|---|---|
| Z | 1.2 / 1.1 / 0.9 | 0.35 / 0.32 / 0.26 | 1.6 / 1.4 / 1.2 |
| W | 11.5 / 10.5 / 8.5 | 0.8 / 0.7 / 0.6 | 12.3 / 11.2 / 9.1 |
| H | 11.5 / 10.5 / 8.5 | 1.5 / 1.4 / 1.1 | 13 / 11.9 / 9.6 |
| ttbar | 27.6 / 25.2 / 20.4 | 7.4 / 6.7 / 5.4 | 35 / 32 / 26 |

Cryogenics only significative at Ttbar
Last 4 years of operation

| 2022 | Z | W | H | TT |
|---|---|---|---|---|
| Beam Energy (GeV) | 45.6 | 80 | 120 | 182.5 |
| Pcryo (MW) | 1,3 | 12,6 | 15,8 | 47,5 |

Q0 =3.$10^{10}$
-27% for TTbar

| 2023 | Z | W | H | TT |
|---|---|---|---|---|
| Beam Energy (GeV) | 45.6 | 80 | 120 | 182.5 |
| Pcryo (MW) | 1,5 | 12.2 | 12.9 | 35 |

# 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%.

Change since 2022:
Power dissipated in DC cables is now calculated at 24MW.
Optimization on-going.

| 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 |

Magnet losses only significative at TTbar
Last 4 years of operation

# 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 | 1.1 | 1.3 | **4.1** |
| B | 0.3 | 1 | 1.3 | **2.6** |
| D | 1.7 | 1.1 | 1.3 | **4.1** |
| F | 0.3 | 1 | 1.3 | **2.6** |
| G | 1.7 | 1.1 | 1.3 | **4.1** |
| H | 4 | 2.3 | 2.2 | **8.5** |
| J | 1.7 | 1.1 | 1.3 | **4.1** |
| L | 0.5 | 1.1 | 1.5 | **3.1** |
| | | | | |
| Total | **11.9** | **9.8** | **11.5** | **33.2** |

| 2022 | | Z | W | H | TT |
|---|---|---|---|---|---|
| Beam energy (GeV) | | 45.6 | 80 | 120 | 182.5 |
| Pcv (MW) | all | 33 | 34 | 36 | 40.2 |

-17% for TTbar

| 2023 | | Z | W | H | TT |
|---|---|---|---|---|---|
| Beam energy (GeV) | | 45.6 | 80 | 120 | 182.5 |
| Pcv (MW) | all | 25 | 26 | 29 | 33.2 |

# Estimation uncertainties

## Power demand uncertainties

The main loads RF and Magnets didn't change, but cryogenics and cooling&ventilation made strong improvement.
Update with 4 experiments (2 big, 2 small experiments), estimated at 2 * 3MW + 2 * 2MW = 10MW, was previously 8MW for 2 experiments.
Small data-centers for ee machine, 4 * 1MW, instead of 2*2MW
General services reduced to 26MW, instead of 36.
Thes change gives between -10 to 30MW compared to 2022 numbers, the global uncertainty remains < 10%.

| 2023 | | Z | W | H | TT |
|---|---|---|---|---|---|
| Beam energy (GeV) | | 45.6 | 80 | 120 | 182.5 |
| Experiments (MW) | Pt A, D, G, J | +2 | +2 | +2 | +2 |
| Data centers (MW) | Pt A, D, G, J | 0 | 0 | 0 | 0 |
| General services (MW) | | -10 | -10 | -10 | -10 |
| Cooling & ventilation | | -7 | -7 | -7 | -7 |
| Cryogenics | | +0.5 | +5 | -4 | -15 |
| Compared to 2022 numbers | | -15 | -10 | -20 | -30 |
| Power during beam operation (MW) | 2023 | 222 | 247 | 273 | 357 |

-10% compared to 2022

# Total power demand by machine configuration

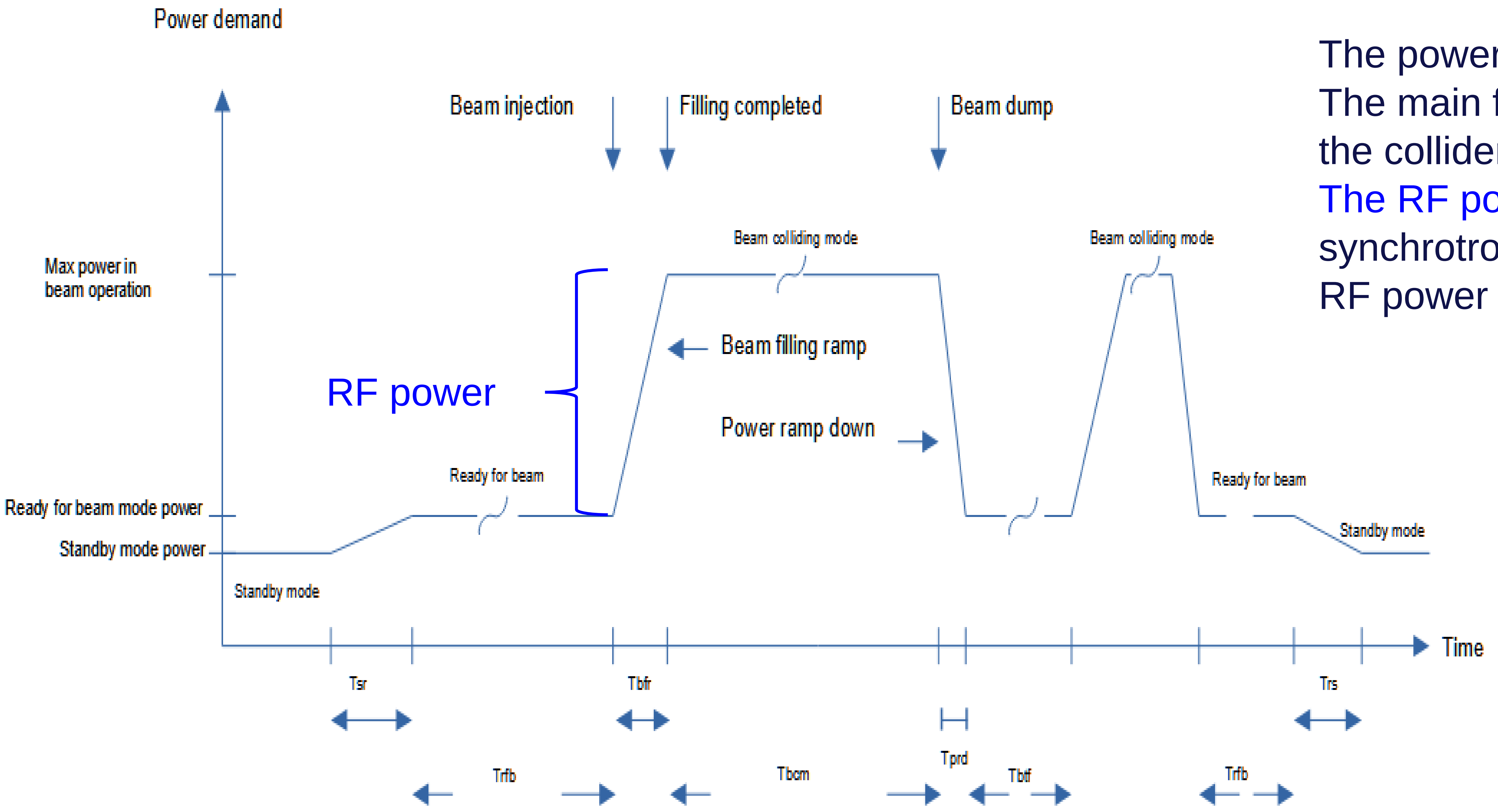
## Update of FCC-ee power demand

| 2023 | | 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) | Storage | 1.2 | 11.5 | 11.5 | 27.6 |
| Pcryo (MW) | Booster | 0.35 | 0.80 | 1.50 | 7.40 |
| Pcv (MW) | all | 25 | 26 | 28 | 33 |
| PEL magnets (MW) | Stroage | 6 | 17 | 39 | 89 |
| PEL magnets (MW) | Booster | 1 | 3 | 5 | 11 |
| Experiments (MW) | Pt A & G | 10 | 10 | 10 | 10 |
| Data centers (MW) | Pt A & G | 4 | 4 | 4 | 4 |
| General services (MW) | | 26 | 26 | 26 | 26 |
| | | | | | |
| Power during beam operation (MW) | | **222** | **247** | **273** | **357** |
| Average power / year (MW) | | 122 | 138 | 152 | 202 |

# Power cycle during beam operation

## Beam operation

The collider will operate 24h 7 days a week during the beam operation (185 days).
The beam operation can be stopped for a technical stop or by fault.




The power demand varies during the beam operation.
The main factors are the beam presence and beam current in the collider.
The RF power compensates for the losses due to the synchrotron radiations. When the machine is fully charged, the RF power is maximum.

- Standby mode: All infrastructure systems ON, Booster, and Collider OFF.
- Ready for Beam: All infrastructure systems ON, Booster ON, and magnet Collider ON.
- Beam Colliding mode: All infrastructure systems ON, Booster ON, Collider ON (Magnet and RF systems).

# Power demand during the year, consumption

## Power demand based on machine schedule

It is possible to calculate the power demand for each period of the schedule.
It depends on which systems are powered during each period.

| Power during, in MW | Z | W | H | TT |
|---|---|---|---|---|
| shutdown | 30 | 33 | 34 | 41 |
| Technical stop | 67 | 78 | 81 | 108 |
| Downtime | 67 | 78 | 81 | 108 |
| Commissioning | 144 | 163 | 177 | 233 |
| Machine Development | 96 | 121 | 147 | 231 |
| Beam operation | 222 | 247 | 273 | 357 |

- Shutdown: reduced power of all infrastructure systems, cryogenics at 20%, cooling at 50%, accelerators OFF.
- Commissioning: All infrastructure systems, and cryogenics at nominal. Start of accelerator systems, Booster ON, Collider at 50% load.
- Physics operation: all systems are ON. The electricity grid is loaded at 100%.
- Downtime: All infrastructure systems, and cryogenics at nominal. Booster and Collider systems are OFF.
- Technical stops: All infrastructure systems, and cryogenics at nominal. Booster and Collider systems are OFF.
- Machine development: all systems are ON. Reduced RF power to 15%, no physics.

Main change compare to 2022: Experiment, data centers and general services charged at 50% during shutdown.

# Power and consumption for Z mode operation

## Z machine schedule

The machine's schedule defines different periods during the year.
The table below presents the power demand during the year for the Z mode.

| Z operation mode | | | Beam Operation | Commissioning | Machine Development | Technical Stop | Winter Shutdown | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Beam operation | 139 | 3336 | 222 | | | | | 740530 | MWh | 69% |
| Downtime with machine acces | 16 | 384 | 67 | | | | | 25542 | MWh | 2% |
| Downtime between cycle | 16 | 384 | 74 | | | | | 28256 | MWh | 3% |
| Downtime long stop | 14 | 336 | 67 | | | | | 22350 | MWh | 2% |
| Hardware + Beam commissioning | 30 | 720 | | 144 | | | | 103859 | MWh | 10% |
| MD | 20 | 480 | | | 96 | | | 46005 | MWh | 4% |
| technical stop | 10 | 240 | | | | 67 | | 15964 | MWh | 1% |
| Shutdown | 120 | 2880 | | | | | 30 | 86410 | MWh | 8% |
| | 365 | 8760 | | | | | | **1.07** | **TWh** | |

92% of the energy is consumed during Beam period.

# Power and consumption for TT mode operation

## TT machine schedule

The machine's schedule defines different periods during the year.
The table below presents the power demand during the year for the TT machine.

| TT operation mode | | | Beam Operation | Commissioning | Machine Development | Technical Stop | Winter Shutdown | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Beam operation | 139 | 3336 | 357 | | | | | 1192437 | MWh | 67% |
| Downtime with machine acces | 16 | 384 | 108 | | | | | 41623 | MWh | 2% |
| Downtime between cycle | 16 | 384 | 209 | | | | | 80274 | MWh | 5% |
| Downtime long stop | 14 | 336 | 108 | | | | | 36420 | MWh | 2% |
| Hardware + Beam commissioning | 30 | 720 | | 233 | | | | 167702 | MWh | 9% |
| MD | 20 | 480 | | | 231 | | | 111028 | MWh | 6% |
| technical stop | 10 | 240 | | | | 108 | | 26015 | MWh | 1% |
| Shutdown | 120 | 2880 | | | | | 41 | 117443 | MWh | 7% |
| | 365 | 8760 | | | | | | **1.77** | **TWh** | |

93% of the energy is consumed during Beam period.

# FCC-ee new location for SRF

## SRF layout change in October 22

At FCC week 2022, Booster SRF systems were in point L, as 400MHz collider SRF .

800MHz collider SRF systems for TTbar were split between L and H.

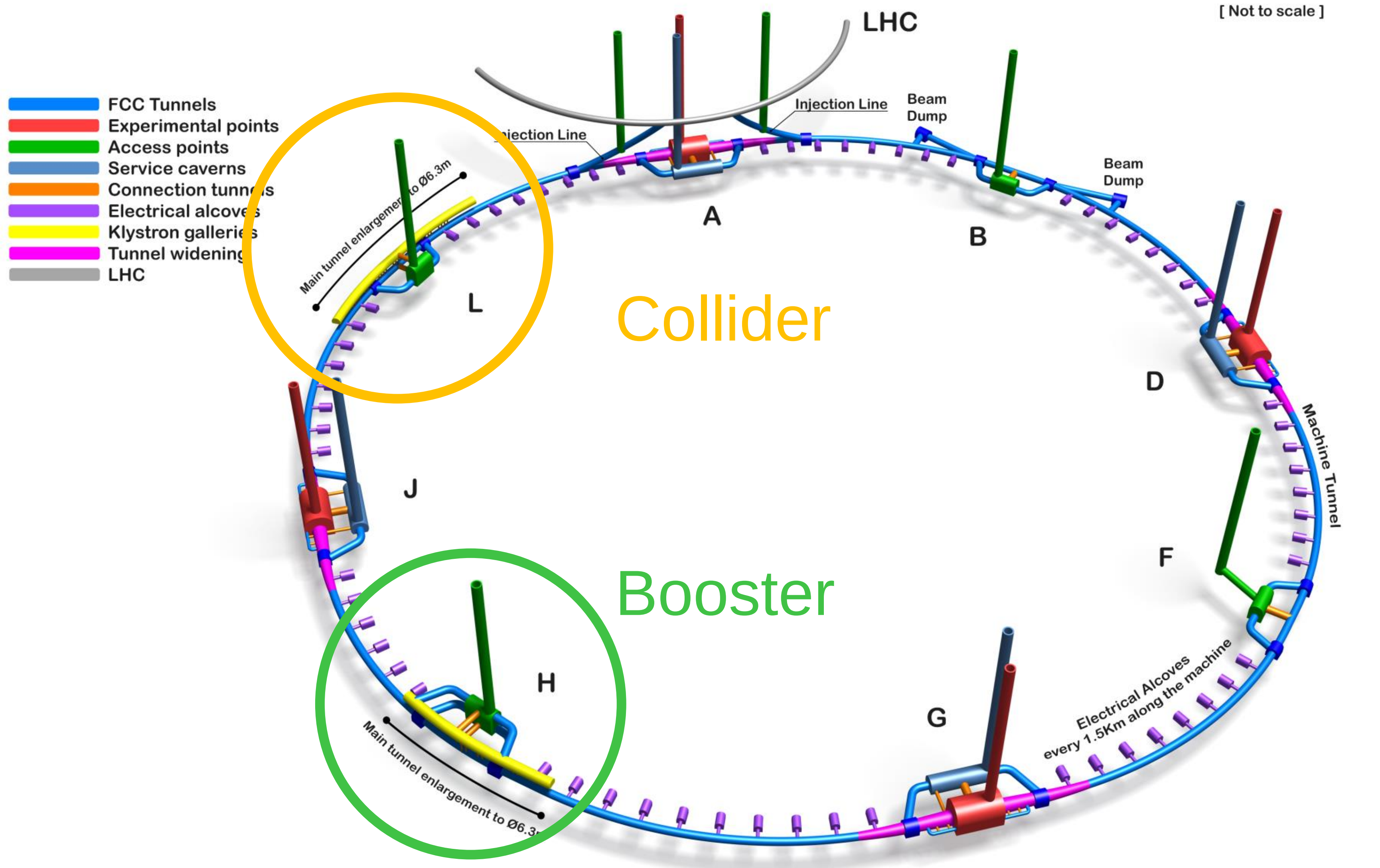
After the review of SRF systems layout (3-4 October 22), the SRF location changed:

All collider SRF systems are placed in point L

All Booster SRF systems are placed in point H

Link to the review
https://indico.cern.ch/event/1184683/

Conclusions presented here
https://indico.cern.ch/event/1203850/#6-summary-and-follow-ups-from



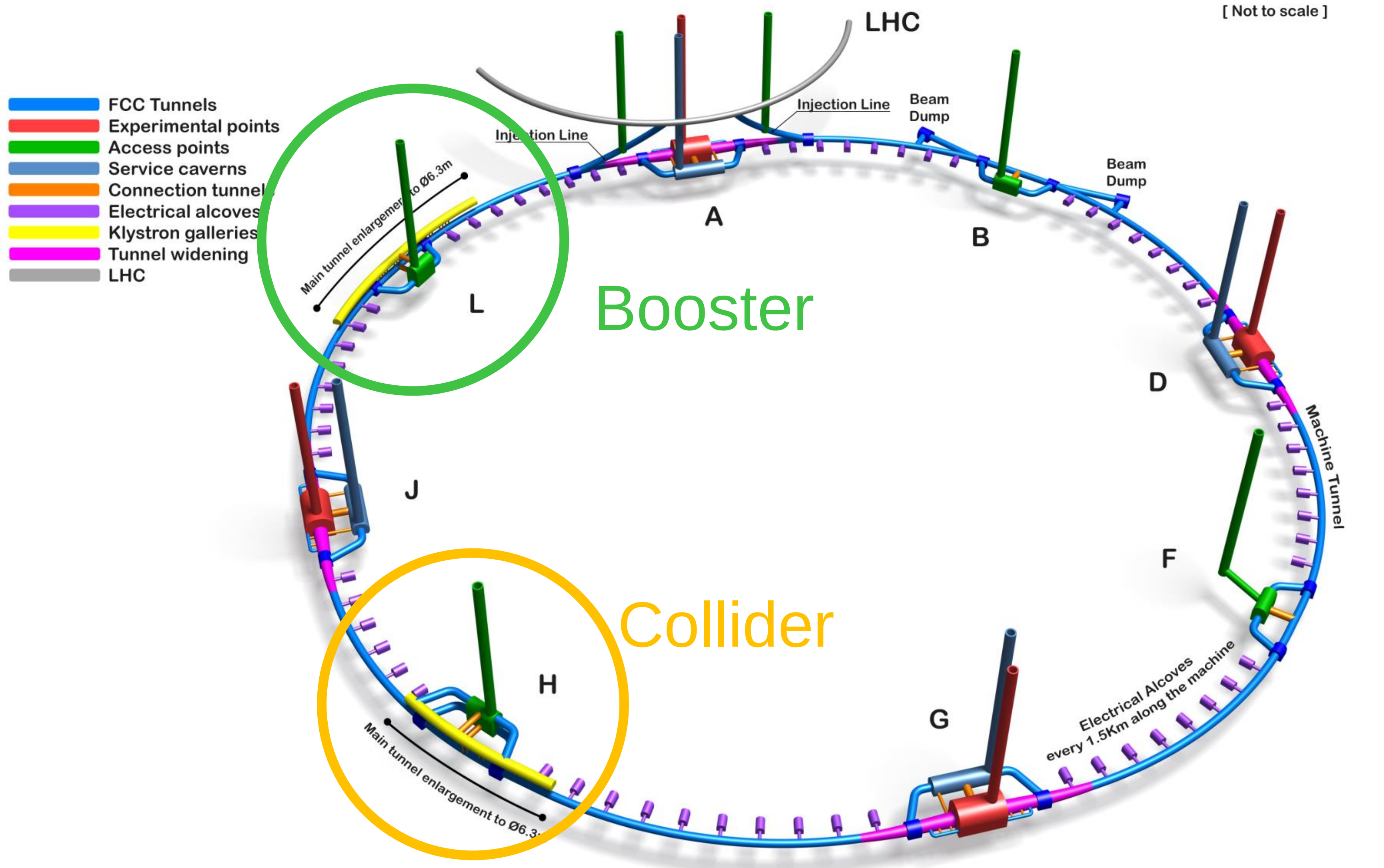

## SRF layout change in March 23

With the surface layout is challenging in point L. The proposal was to exchange RF systems between L and H.

All collider SRF systems are placed in point H

All Booster SRF systems are placed in point L

Proposal presented here:
https://indico.cern.ch/event/1249818/
Approval here:
https://indico.cern.ch/event/1235646/



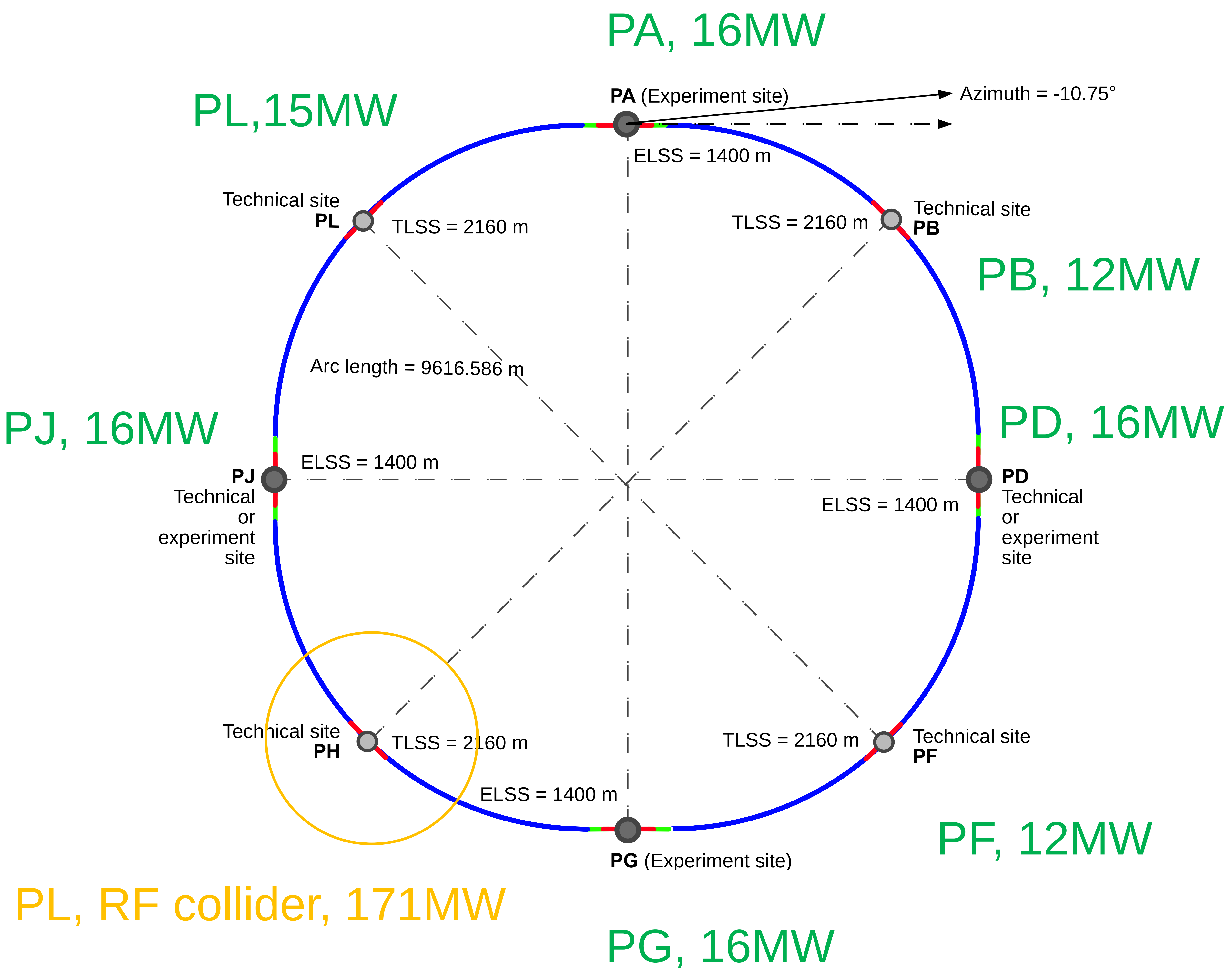
# Power demand per points, configuration Z, W, H

## Infrastructure needed for FCC-ee Z, W,H

Very high power demand on point L, 175MW for RF collider.

4 experiments, point A,D, G and J.

| | | Max power (MW) |
|---|---|---|
| Point A | Experiment | 16 |
| Point B | | 12 |
| Point D | Experiment | 16 |
| Point F | | 12 |
| Point G | Experiment | 16 |
| Point H | RF collider | 171 |
| Point J | Experiment | 16 |
| Point L | RF booster | 15 |

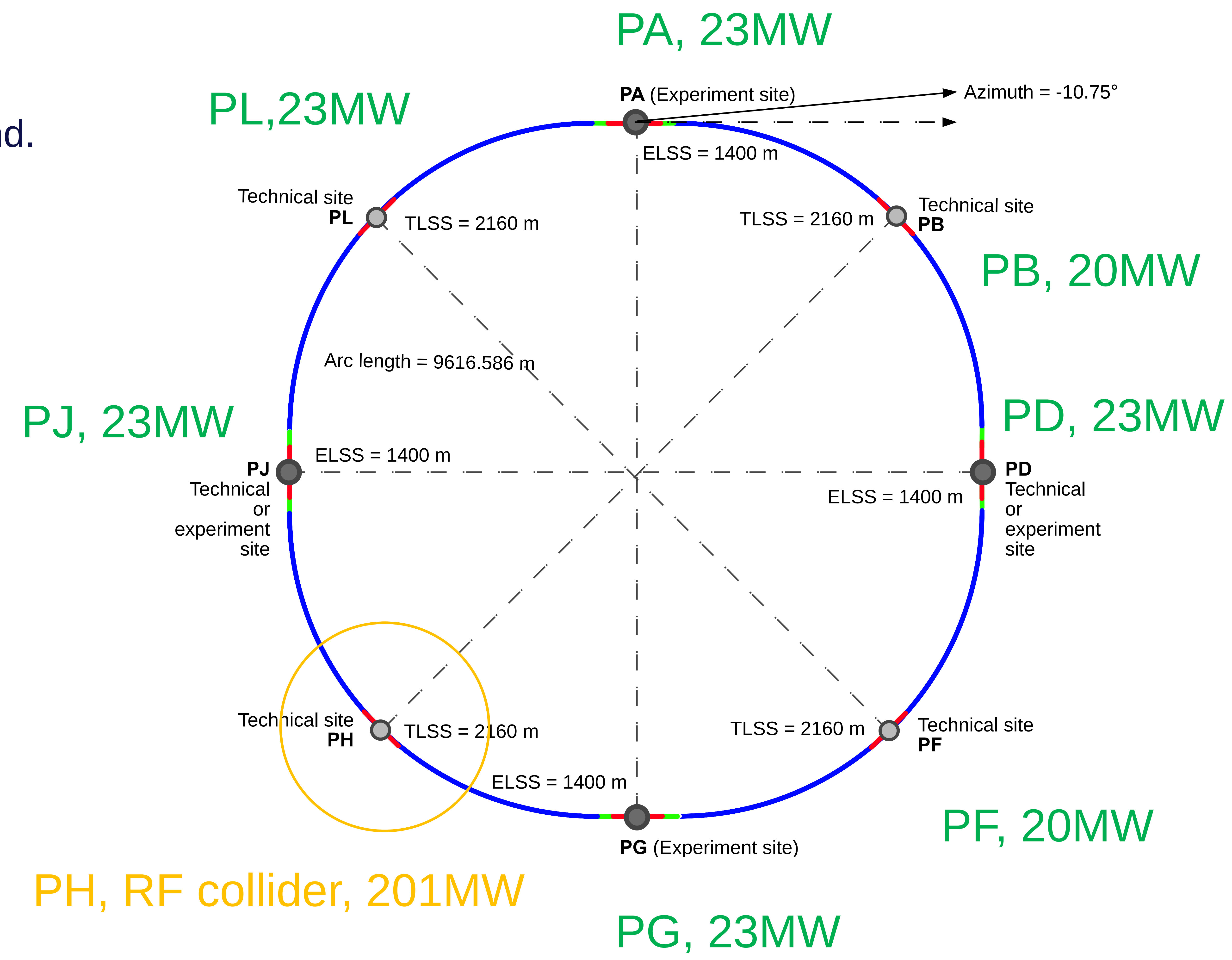


# Power demand per points, configuration TTbar

## Infrastructure needed for FCC-ee TTbar

Only one point with high power demands.
Increased by cryogenics loads and associated cooling demand.

| | | Max power (MW) |
|---|---|---|
| Point A | Experiment | 23 |
| Point B | | 20 |
| Point D | Experiment | 23 |
| Point F | | 20 |
| Point G | Experiment | 23 |
| Point H | RF collider | 201 |
| Point J | Experiment | 23 |
| Point L | RF booster | 23 |



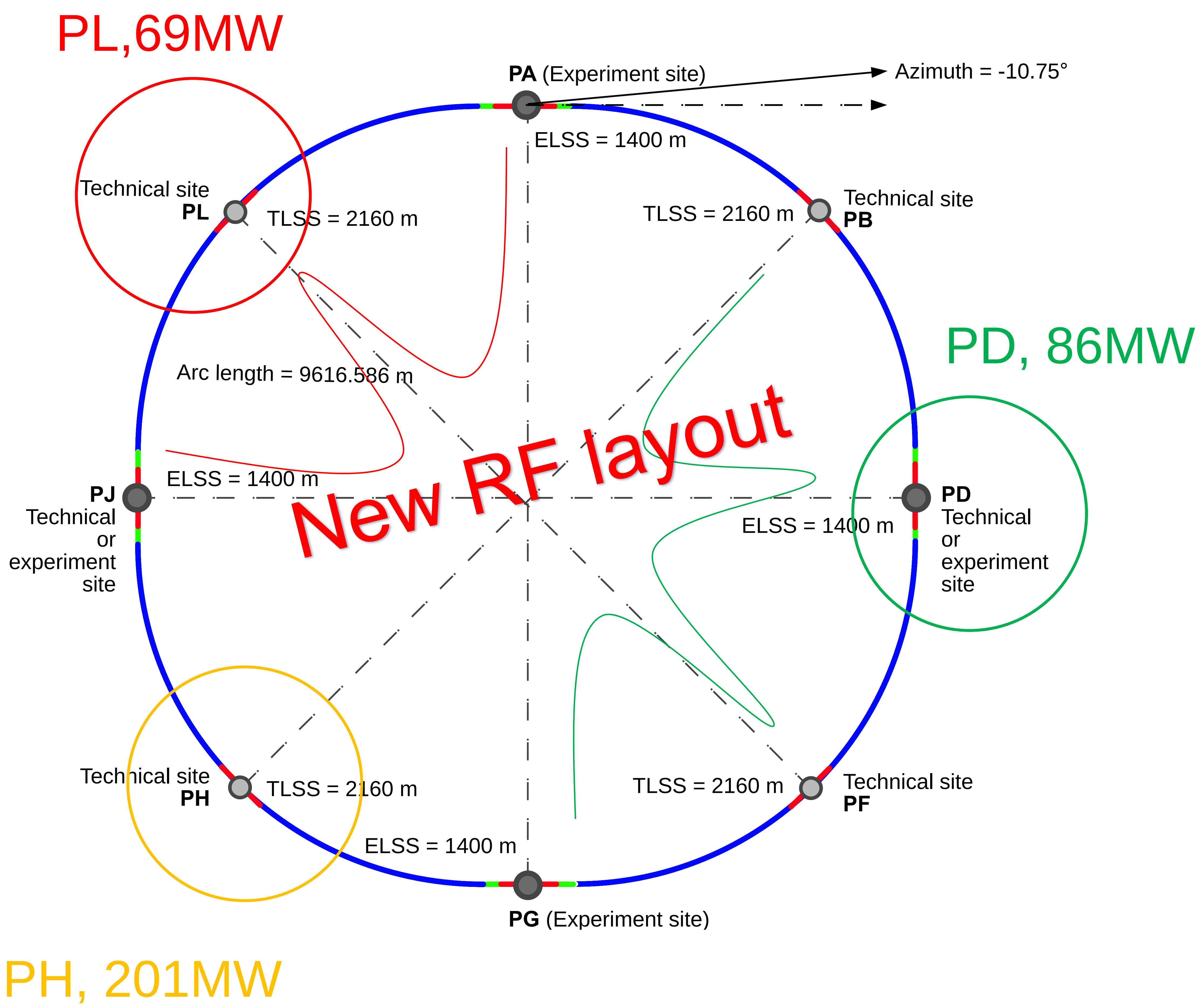
# Electrical sub-stations, FCC-ee

## Max power load by sub-stations, FCC-ee

The loads could be charged on the three sub-stations as follows:

Point H with a dedicated sub-station for RF collider
Point L, with a sub-station covering PJ – PL – PA
Point D, with a sub-station covering PB – PD – PF – PG

| | | Max power (MW) |
|---|---|---|
| PDL1 | PL | 69 |
| PDL2 | PD | 90 |
| PDL3 | PH | 215 |



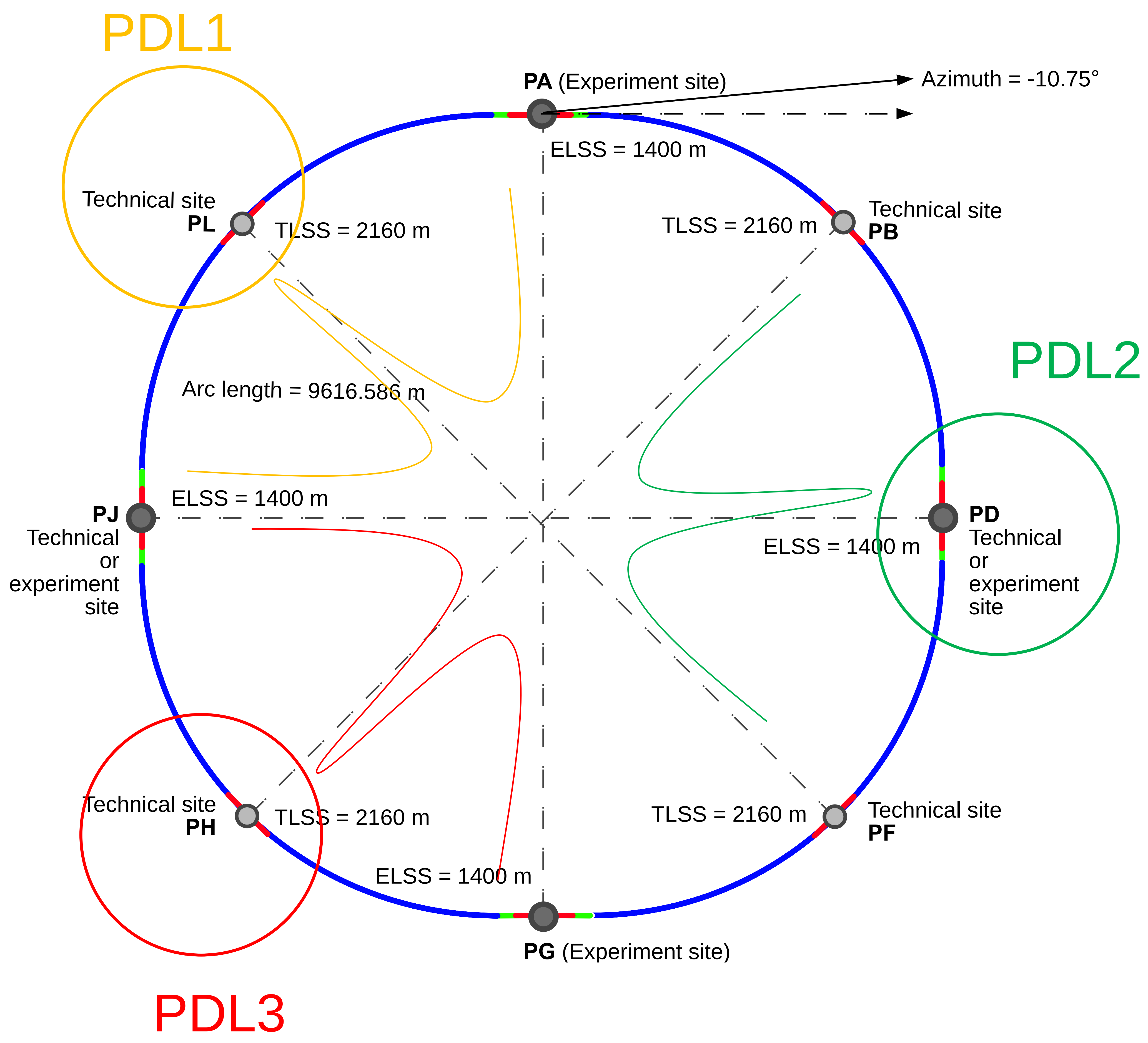
# Request made for delivery points

## Infrastructure needed to cover all FCC configurations

The goal is to built an electrical infrastructure which will cover all the configuration of the FCC machine without need to built new sub-stations.
This proposal includes also the possibility to operation the machine without one sub-station, which will ease the maintenance and repairs.

The proposal is to have 3 PDL rated at 200MW .
This proposal is under study by French Transmission Operation, RTE.

RTE: Reseau de Transport d'électricité= French transmission operator
PDL: Point de livraison = Delivery point



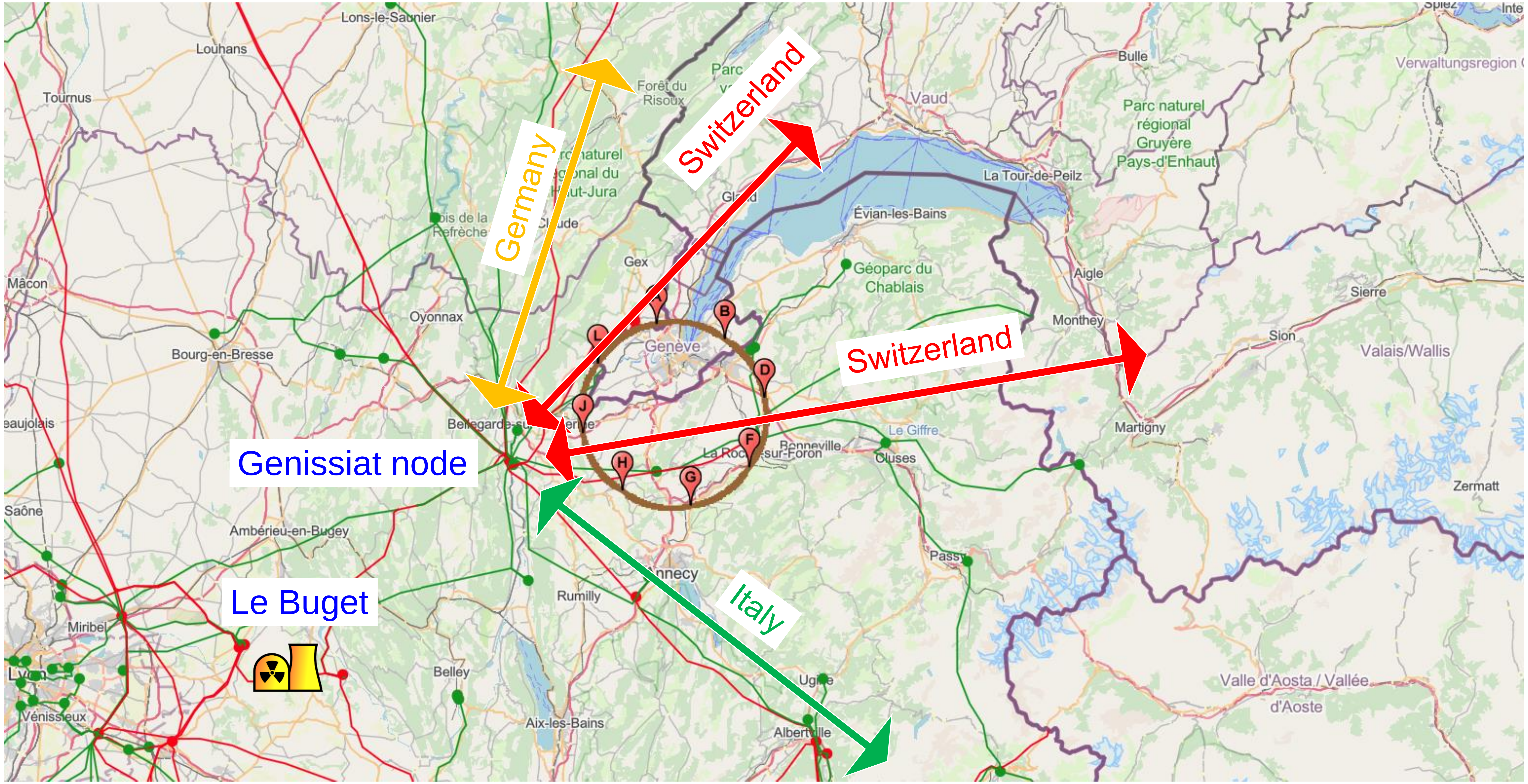
# Request made to RTE for delivery points

## Strong network connection

FCC well situated on a strong electricity node.

but priority of these 400 – 225 kV lines are for energy exchange between countries.

Red lines : 400kV
Green lines: 225kV



# Alternative with present CERN connection

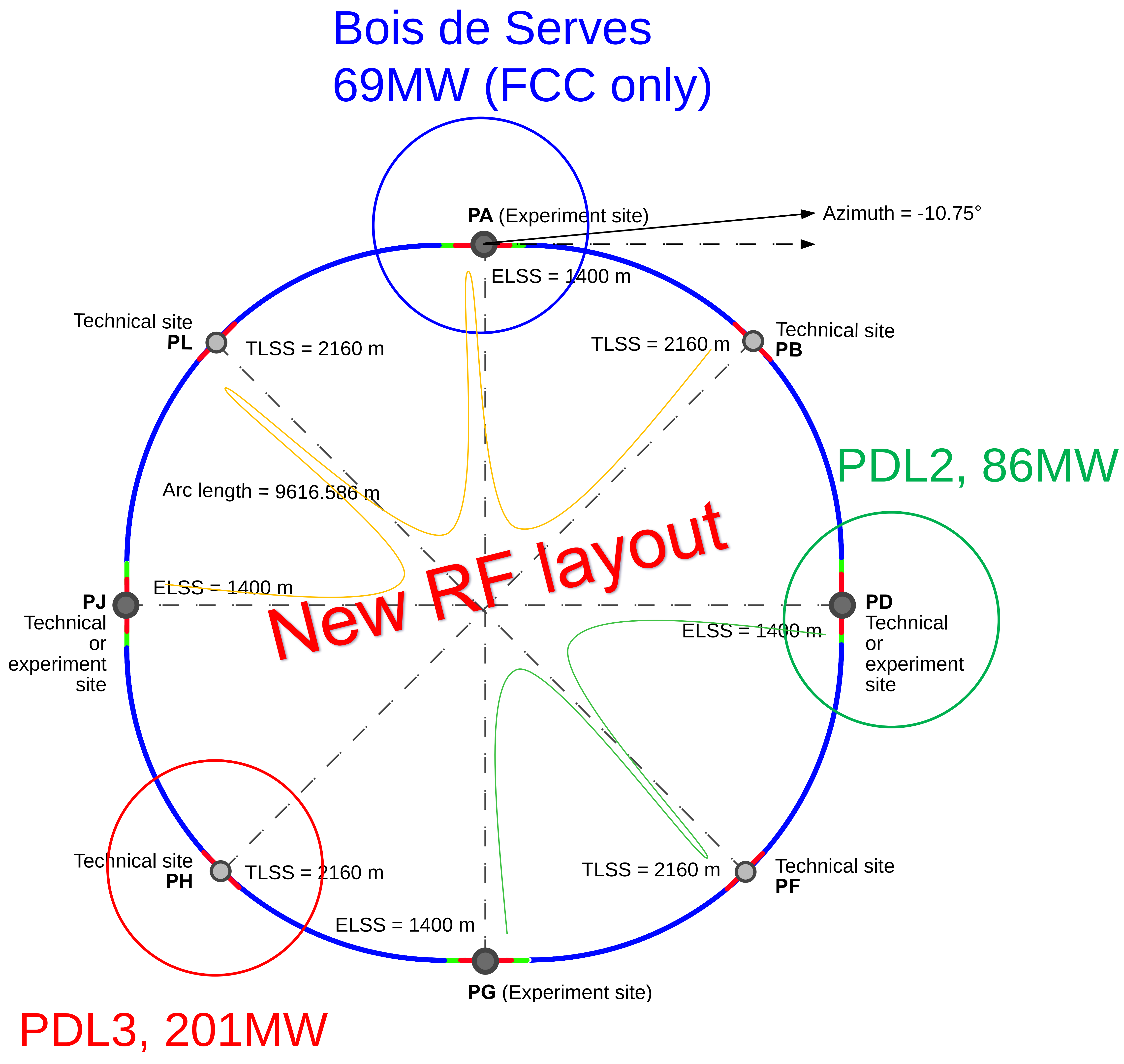
## Point L with low charge

Point L has not enough charge to justify a new delivery point.
An alternative would be to reuse present connection (Prevessin) to Bois de Serves (installed power 220MW), and to built a new sub-station at point A.

A new line between Prevessin site and point A is needed (through the road or better through the beam transfer tunnel).

Bois de Serves, with a sub-station covering PJ – PL – PA - PB
Point D, with a sub-station covering PD – PF – PG
Point H with a dedicated sub-station for RF collider

| | | Max power (MW) |
|---|---|---|
| PDL1 | Bois de Serves | 69 |
| PDL2 | PD | 86 |
| PDL3 | PH | 201 |



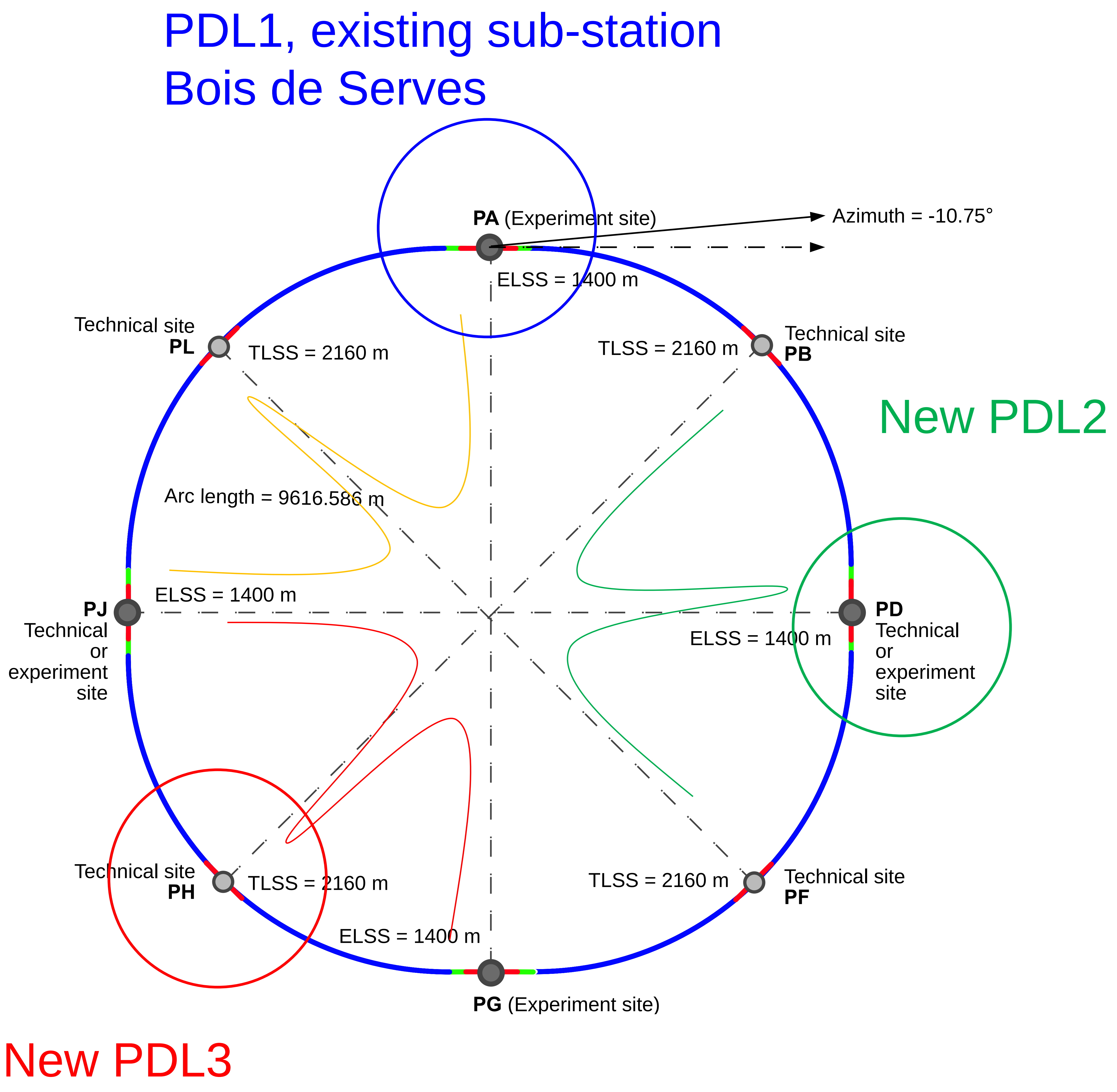
# New proposal for delivery points

## Infrastructure needed to cover all FCC configurations

This configuration will require only 2 new delivery points for RTE.

No new 400kV sub-station in Challex, which should be welcomed.

The proposal is to have 3 PDL rated at 220MW with the possibility to operate with only 2 sub-stations (redundancy).



# Summary

- The RF systems location changed the distribution of the power demand.
- Only point H has now a very high power demand level.
- A new scheme, for the delivery points, is been proposed with only two new delivery points.
- The energy consumption during the shutdown was reduced taking account of the reduced power demand from the experiments and general services. This leads to a reduction of the energy consumption of 5%.
- The new estimate for cooling and ventilation, plus the reduction of cryogenics power, thanks to high Q0 cavities, gives another reduction of 5% of the energy consumption.

The next steps are:

- Validation of the delivery points with RTE.
- Validation of the delivery points on the local 20kV for the civil engineering phase.
- Pursuit the effort on the reduction of energy consumption .

# Thank you for your attention