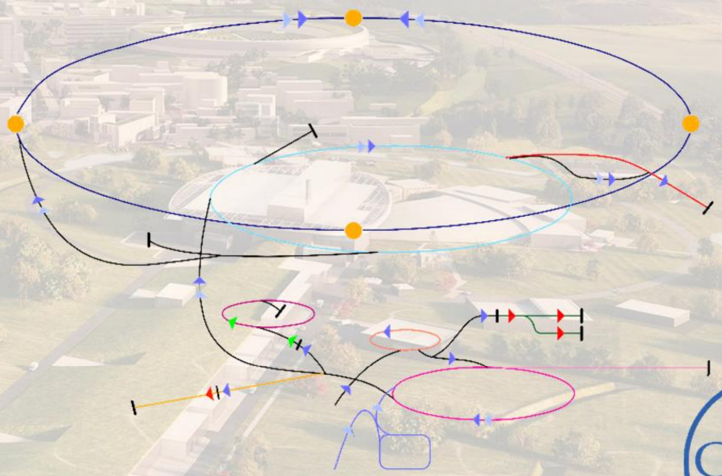
The cryogenic needs of the FCC

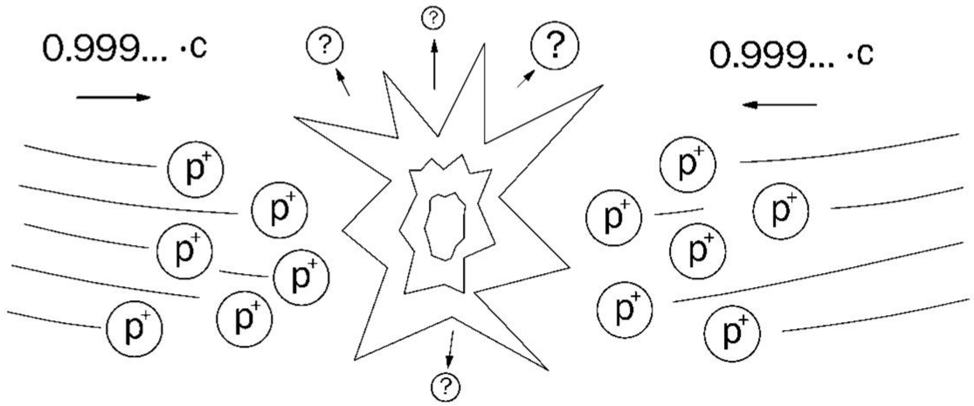
2019 European Cryogenics Days

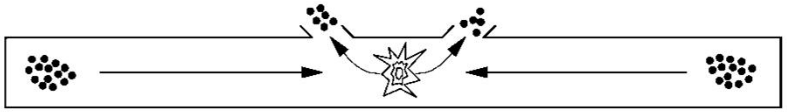
08.10.2019 in Lund, Sweden

Claudio Kotnig on behalf of the CERN Cryogenics Group

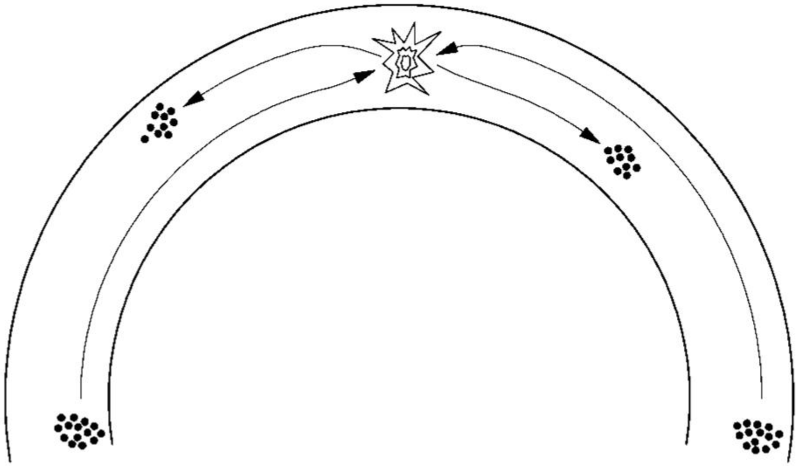


- Particle beams are accelerated to close to the speed of light
- Two opposing particle beams are brought to collision
- $E = m \cdot c^2$





... in linear colliders only one attempt



... in circular colliders non-collided particles are collected, returned and used for several attempts

→ Particle trajectories deflected by superconducting magnets (cryogenic temperatures necessary)

LEP & LHC

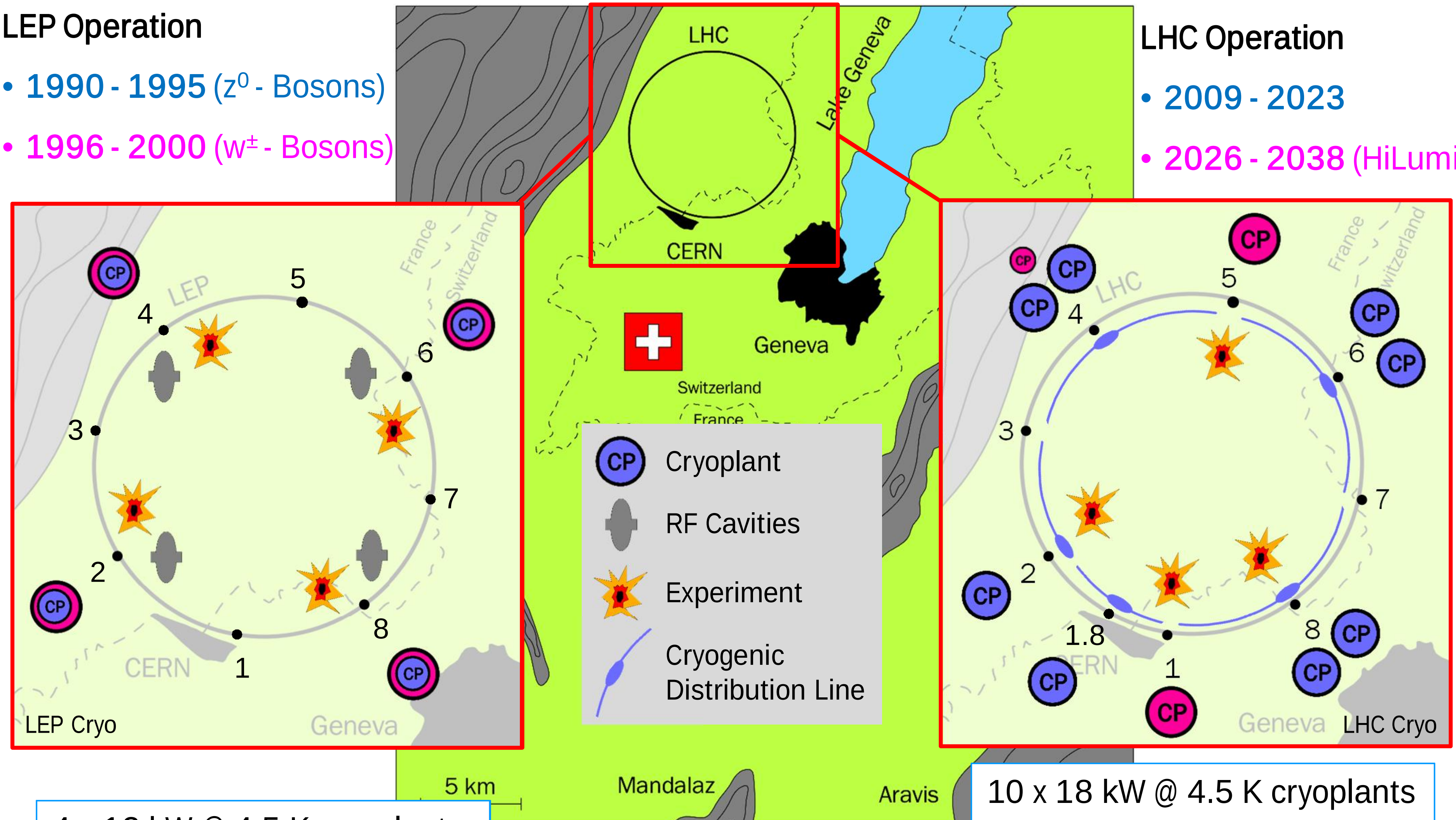
LEP Operation

- **1990 - 1995** (Z^0 - Bosons)
- **1996 - 2000** ($W^{\pm}$ - Bosons)

LHC Operation

- **2009 - 2023**
- **2026 - 2038** (HiLumi)

Geneva Basin



4 x 12 kW @ 4.5 K cryoplants

10 x 18 kW @ 4.5 K cryoplants
8 x 3.3 km of Cryogenic Distribution line

What next?

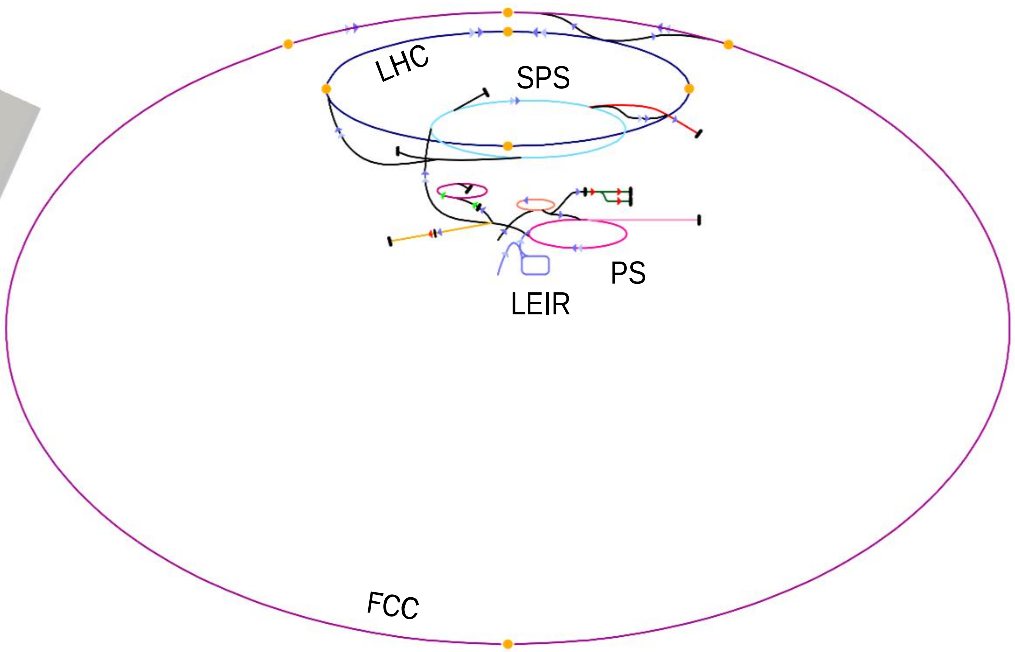
In 2013 the European Strategy for Particle Physics decided to launch studies to investigate different machines and concepts for future research in particle physics

Circular Collider Study:

Future **C**ircular **C**ollider

Integration into existing Accelerator Complex at CERN

FCC Conceptual Design Report
(issued 15.01.2019)
https://fcc-cdr.web.cern.ch/



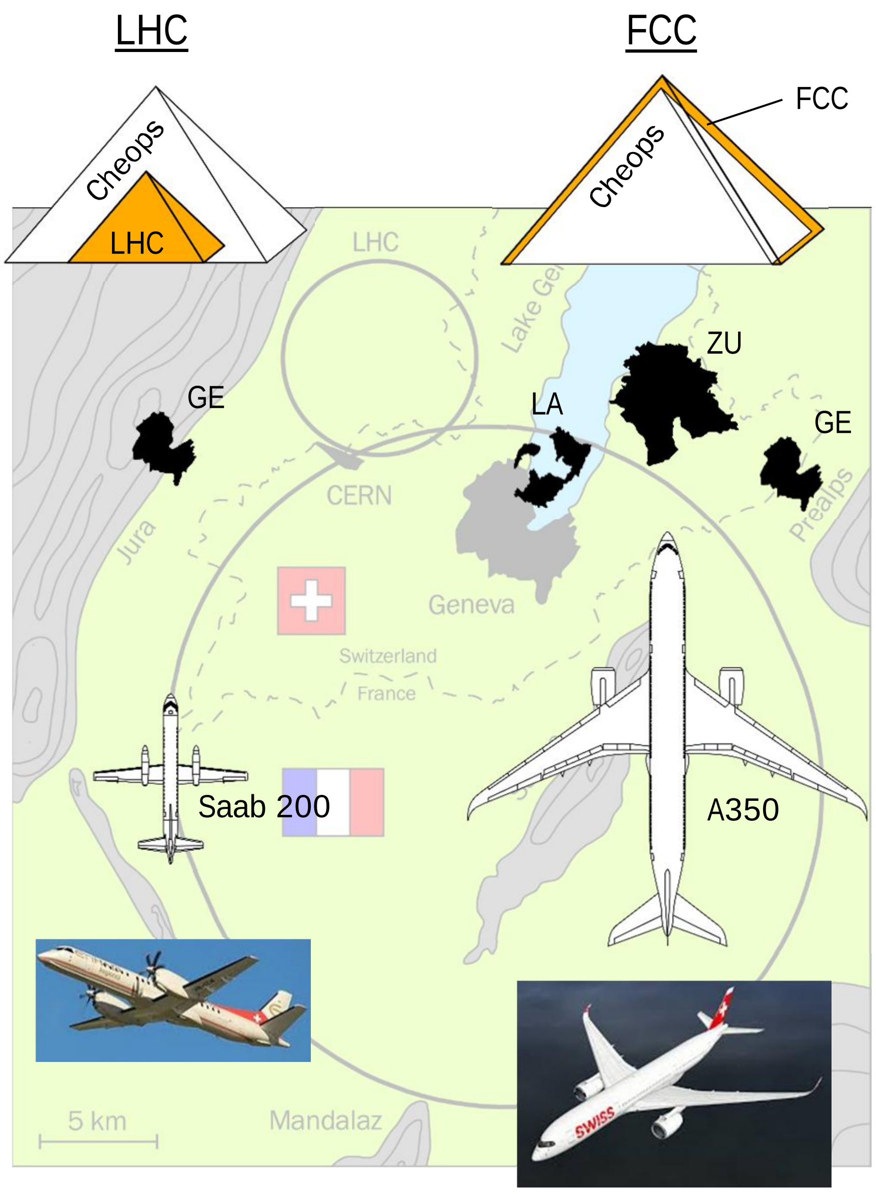
Some FCC superlatives in vivid comparisons

Timeline

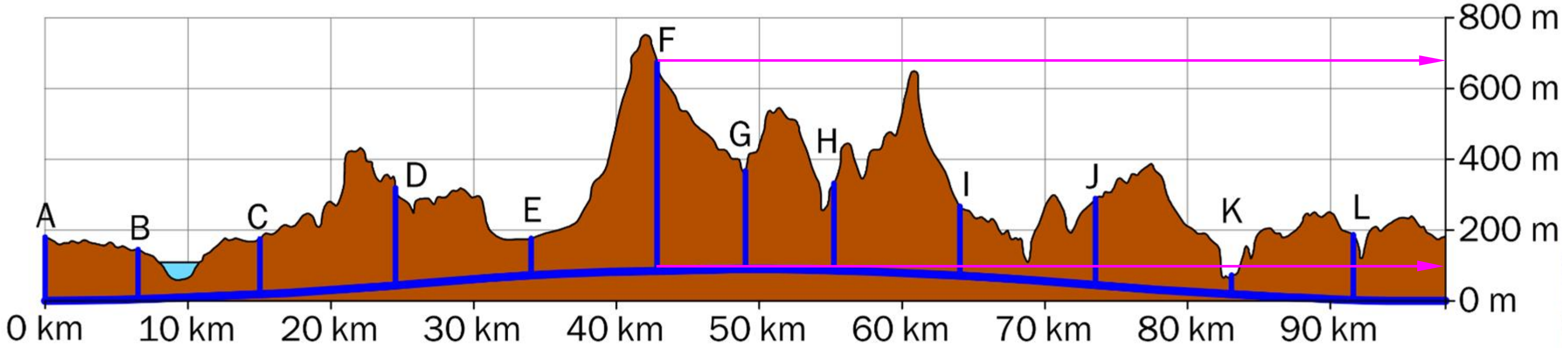
- **2014** Start FCC conceptual design phase
- **2019** CDR released 15.01.2019
- **2020 - 2028** Preparation
- **2029 - 2037** Tunneling & installation FCC-ee
- **2038 - 2053** FCC-ee operation in 4 stages
- **2054 - 2063** FCC-hh preparation & installation
- **2064 - 2090** FCC-hh operation

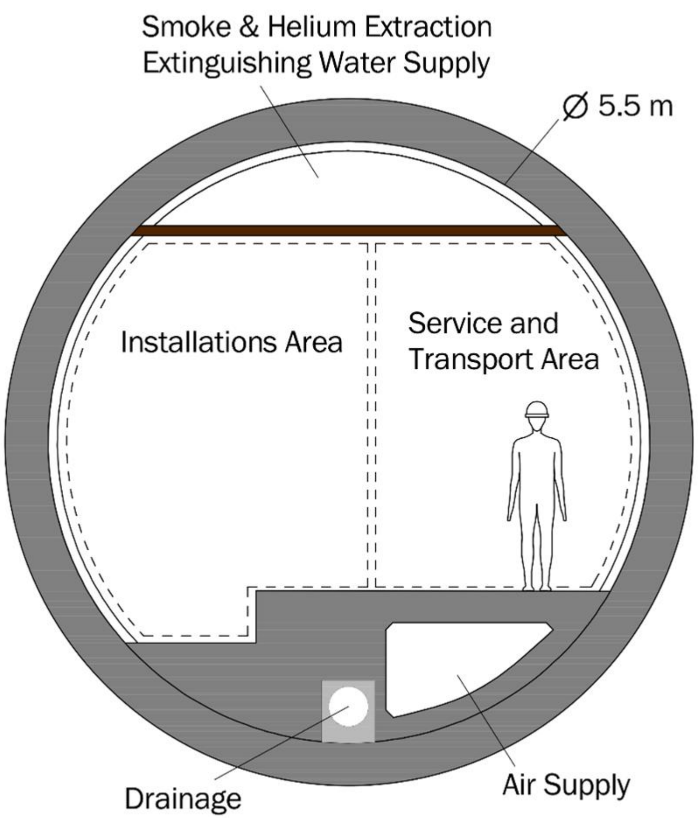
Some data

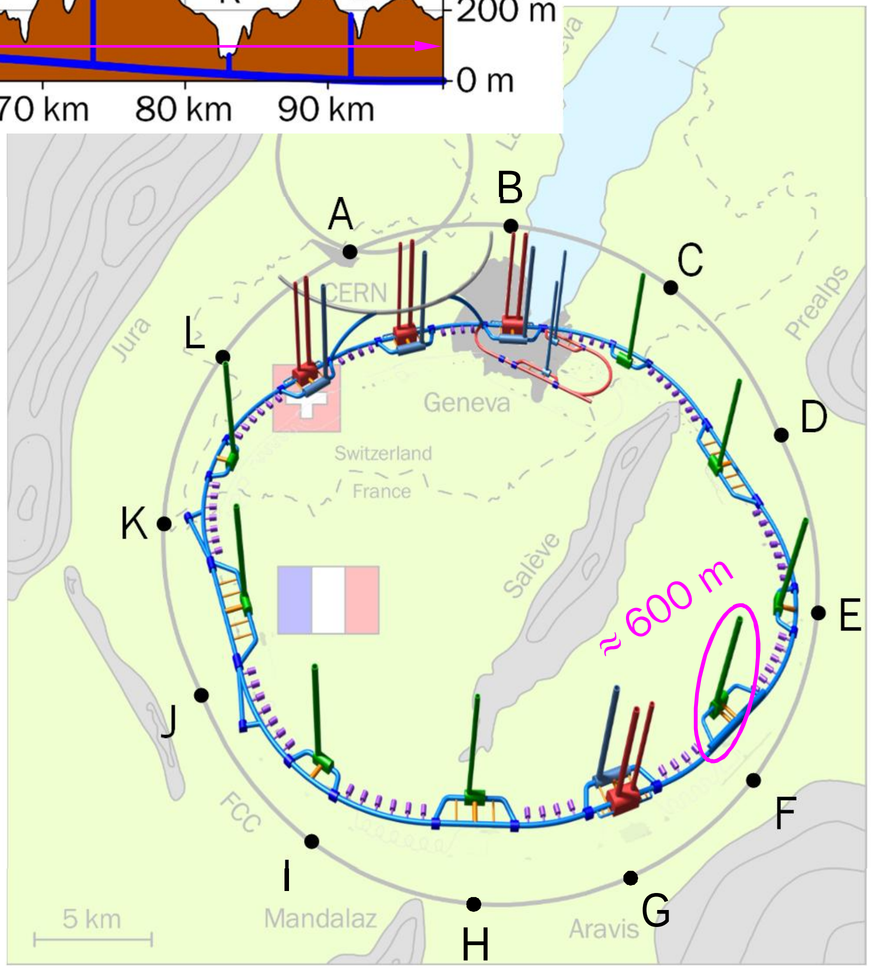
	LEP/(HL-)LHC	FCC
Circumference	27 km	100 km
Excavated soil volume tunnel	$0.42 \cdot 10^6$ m^3	$3.25 \cdot 10^6$ m^3
Electrical power consumption	200 MW	580 MW
Max. stored beam energy	0.33 GJ	8.4 GJ



FCC tunnel



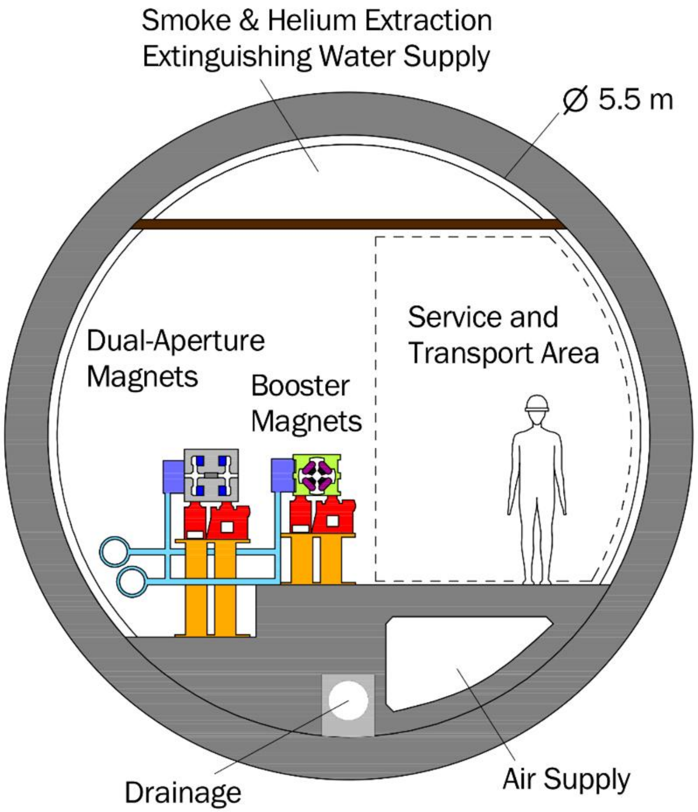




Courtesy of J.Osborne

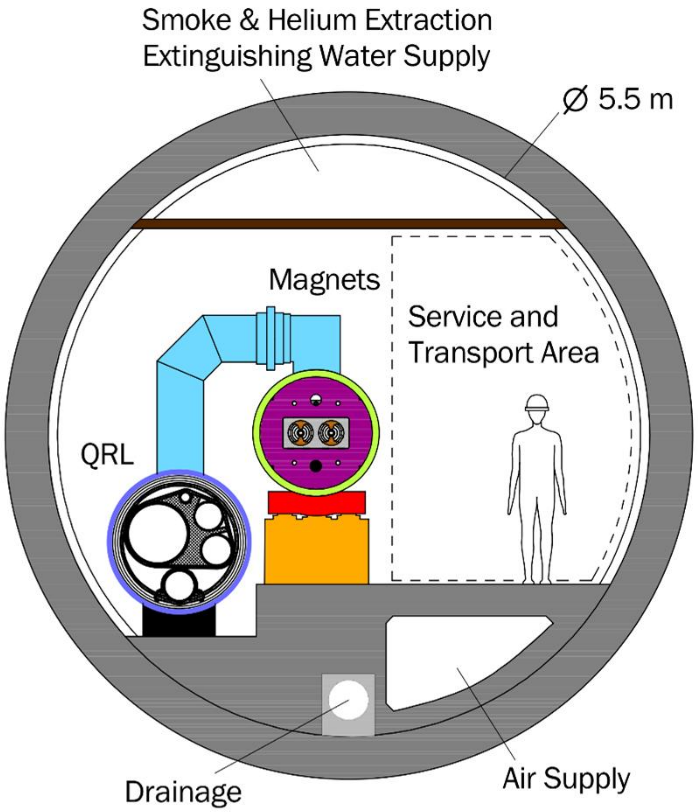
FCC machines

FCC-ee machine



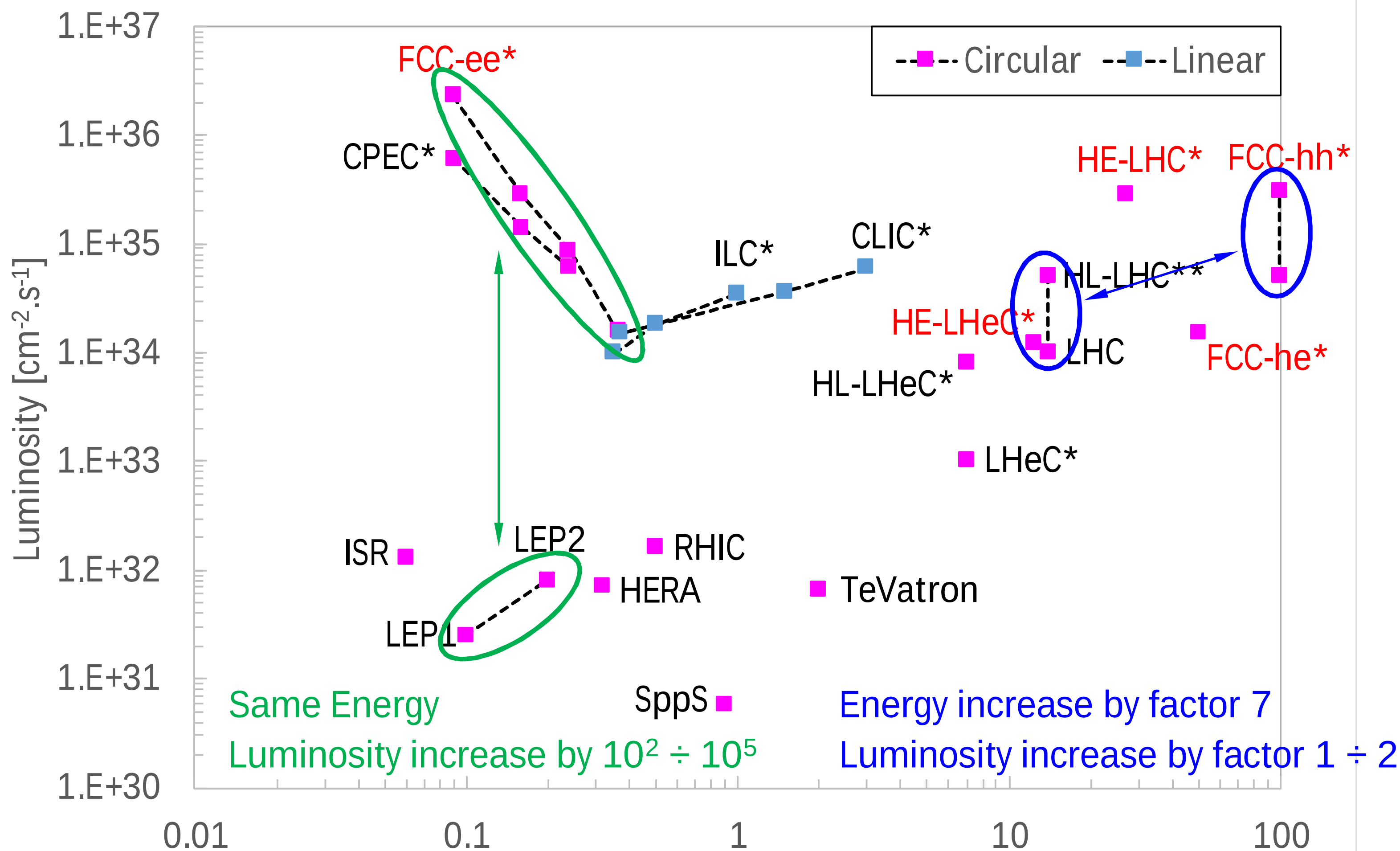
Precise measurements: Beam energy tuned to create certain particles

FCC-hh machine



Discovery machine: Beam energy maximized to create new particles

Benefits for particle physics research



*: under study

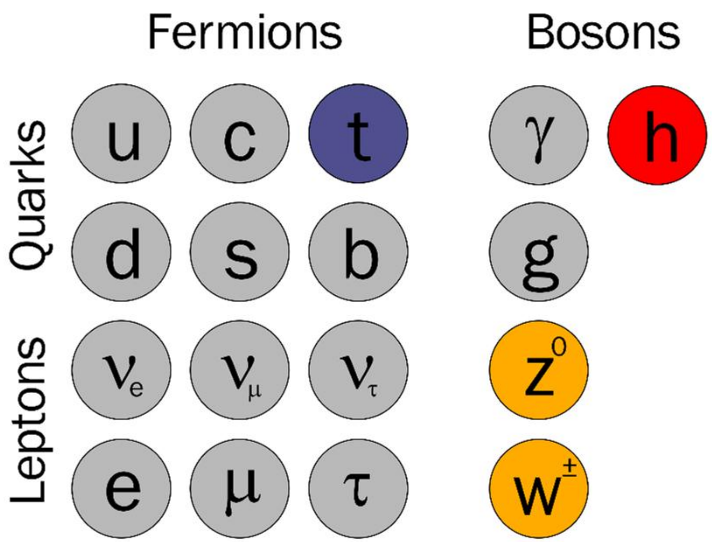
**: under construction

Courtesy of L.Tavian

FCC-ee Cryogenics: Research Goal in 4 Stages

Research goal

- In-depth exploration to find
  - confirmation of or
  - deviations from the Standard Model
- Optimized to study 4 particles at highest luminosity



The 4 Stages Plan

1. Stage (2038 - 2041): z^0-Bosons (E_{Beam} = 45.6 GeV)
2. Stage (2042 - 2044): $w^\pm$-Bosons (E_{Beam} = 80 GeV)
3. Stage (2045 - 2047): Higgs Bosons (E_{Beam} = 120 GeV)

2048 – 2049: 1 year installation, upgrade & rearrangement

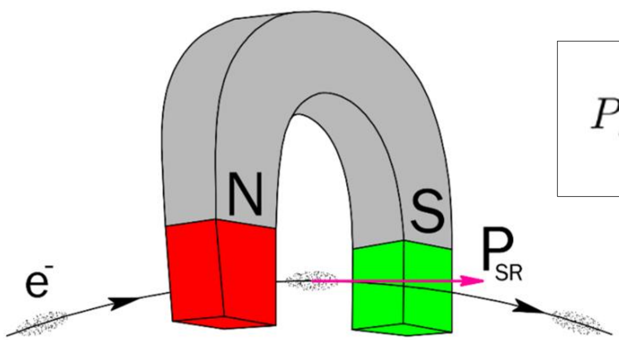
4. Stage (2049 - 2053): Top Quarks (E_{Beam} = 175 | 182.5 GeV)

Increasing cryogenic requirements

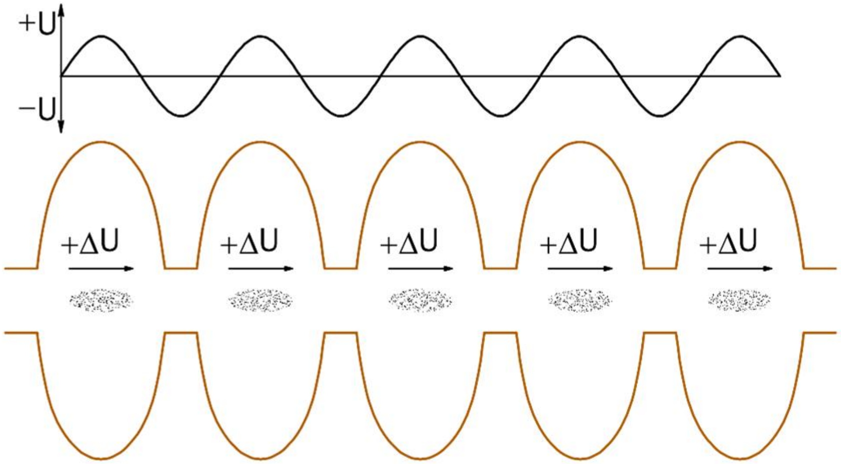
Cryogenic Applications

RF Cavities

- Accelerating the lepton bunches
- Compensate for the energy losses due synchrotron radiation P_{SR}



$$P_{SR} \propto \frac{E_R^4}{m_0^4 r}$$



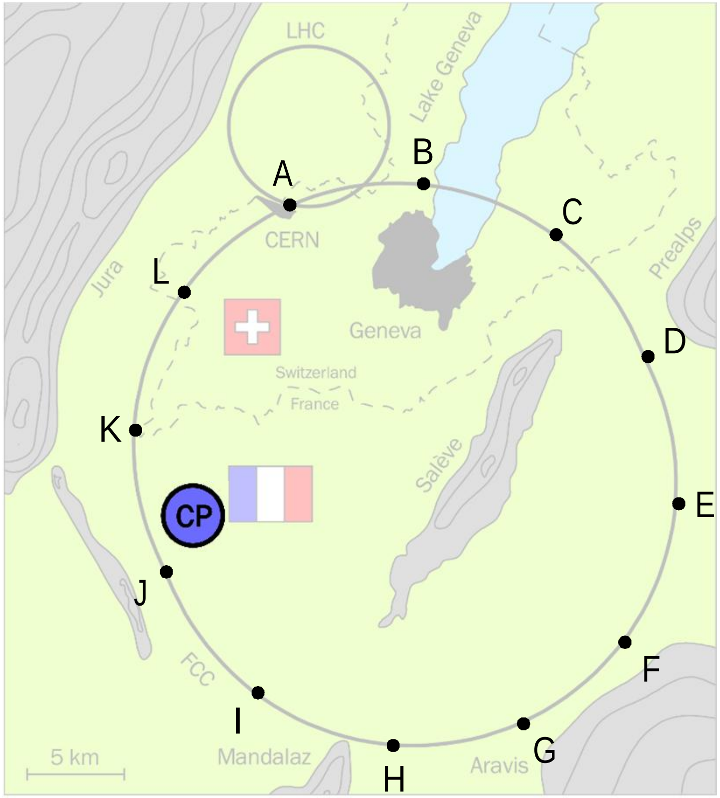
Courtesy of JLAB

Energy losses per turn:

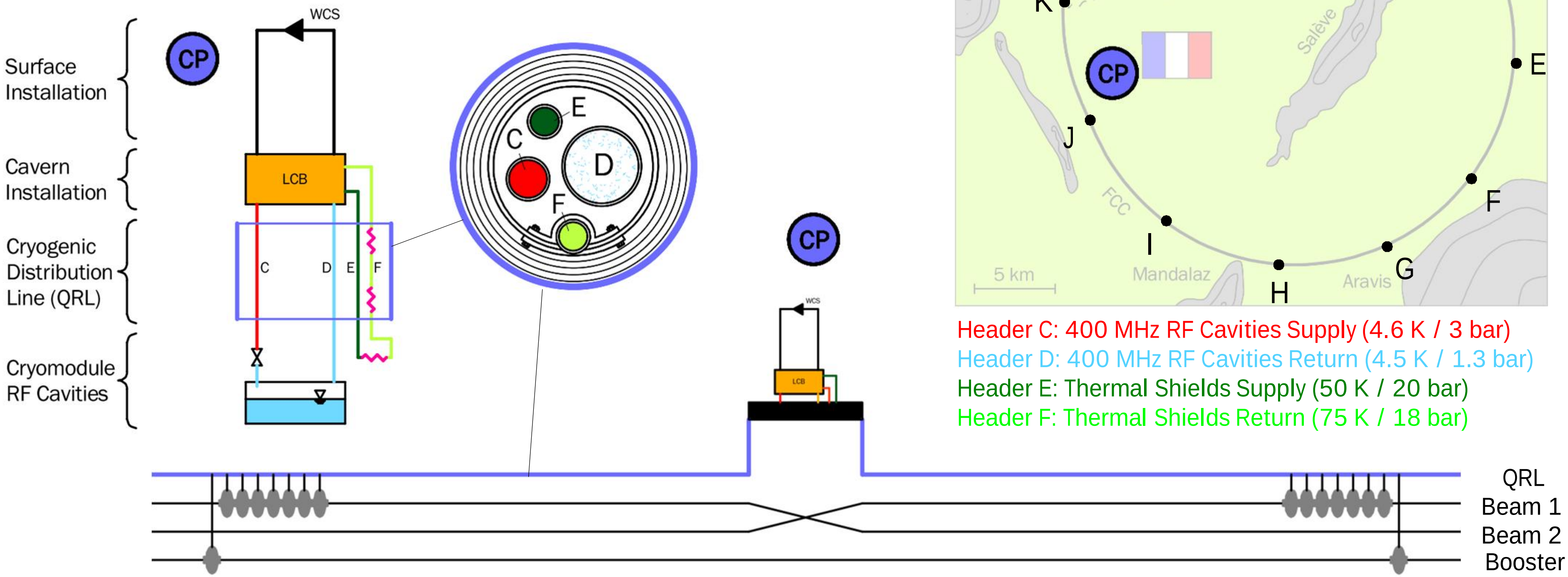
Stage 1 (z^0)	0.036 GeV
Stage 2 ($w^{\pm}$)	0.34 GeV
Stage 3 (Higgs)	1.72 GeV
Stage 4 (Top Quark)	7.8 / 9.2 GeV

FCC-ee Cryogenics: Stage 1/4 (z-Boson)

1. Stage: z^0-Bosons (E_{Beam} = 45.6 GeV)
2. Stage: $w^{\pm}$-Bosons (E_{Beam} = 80 GeV)
3. Stage: Higgs Bosons (E_{Beam} = 125 GeV)
4. Stage: Top Quarks ($E_{Beam} \geq$ 173 GeV)



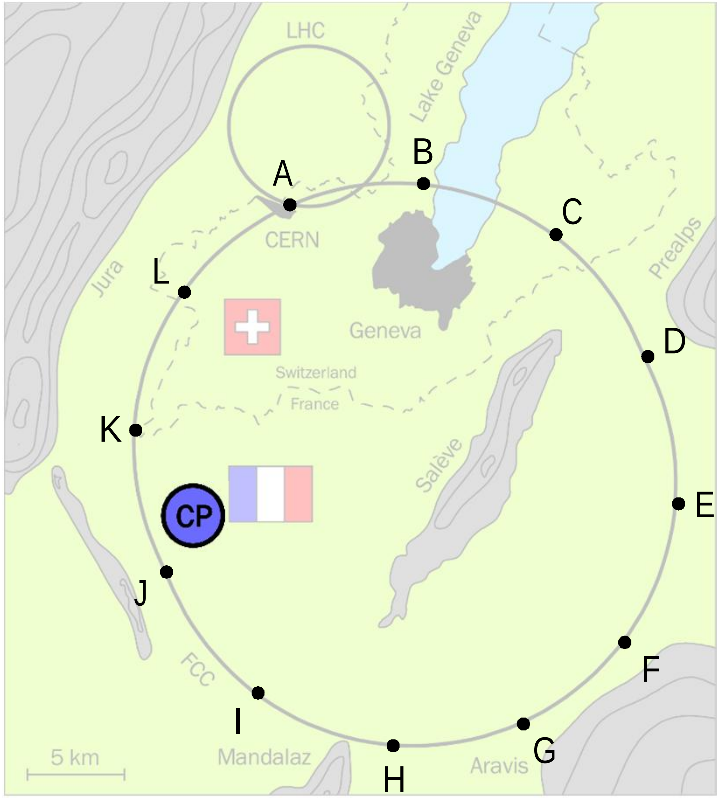
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)



Newly installed 400 MHz RF Module @ 4.5 K | Formerly installed 400 MHz RF Module @ 4.5 K | Newly installed 800 MHz RF Module @ 2.0 K

FCC-ee Cryogenics: Stage 2/4 (w-Boson)

- 1. Stage: z^0-Bosons (E_{Beam} = 45.6 GeV)
- 2. Stage: $w^{\pm}$-Bosons (E_{Beam} = 80 GeV)
- 3. Stage: Higgs Bosons (E_{Beam} = 125 GeV)
- 4. Stage: Top Quarks ($E_{Beam} \geq$ 173 GeV)



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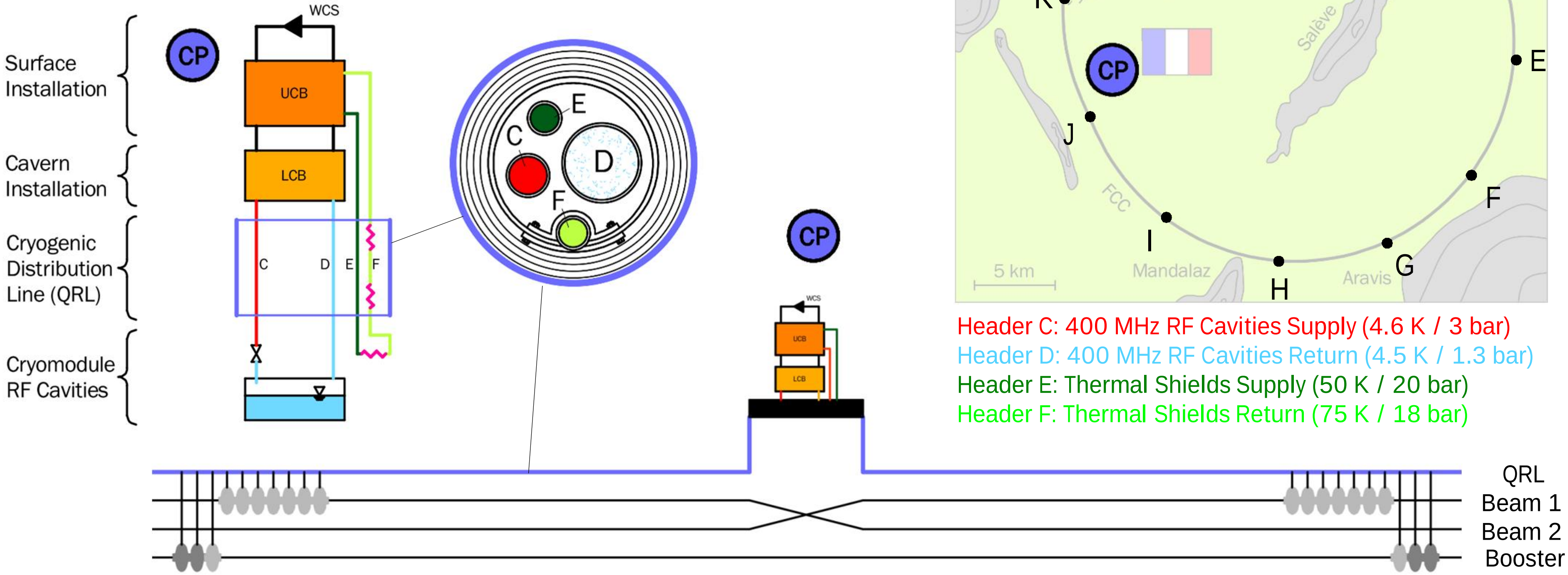
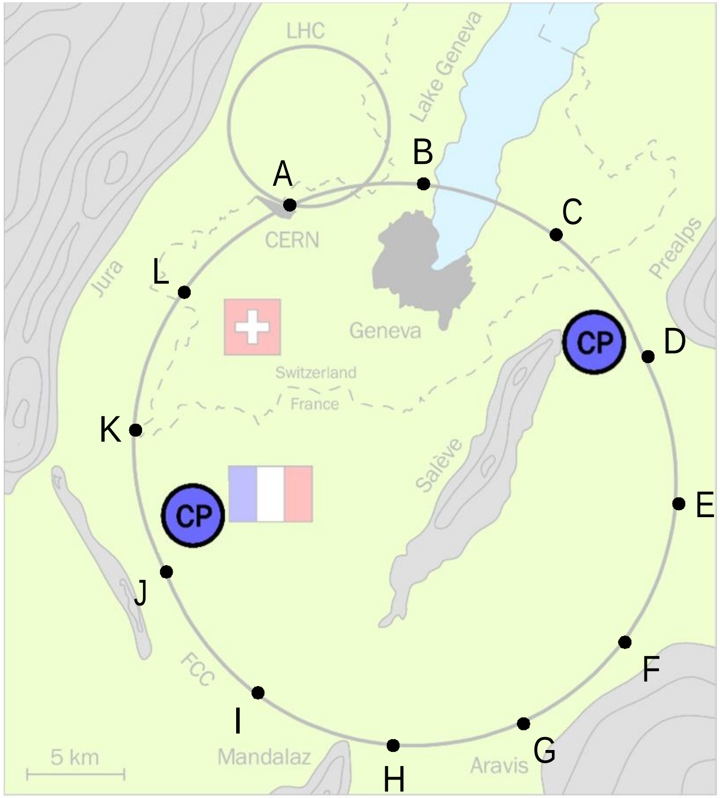


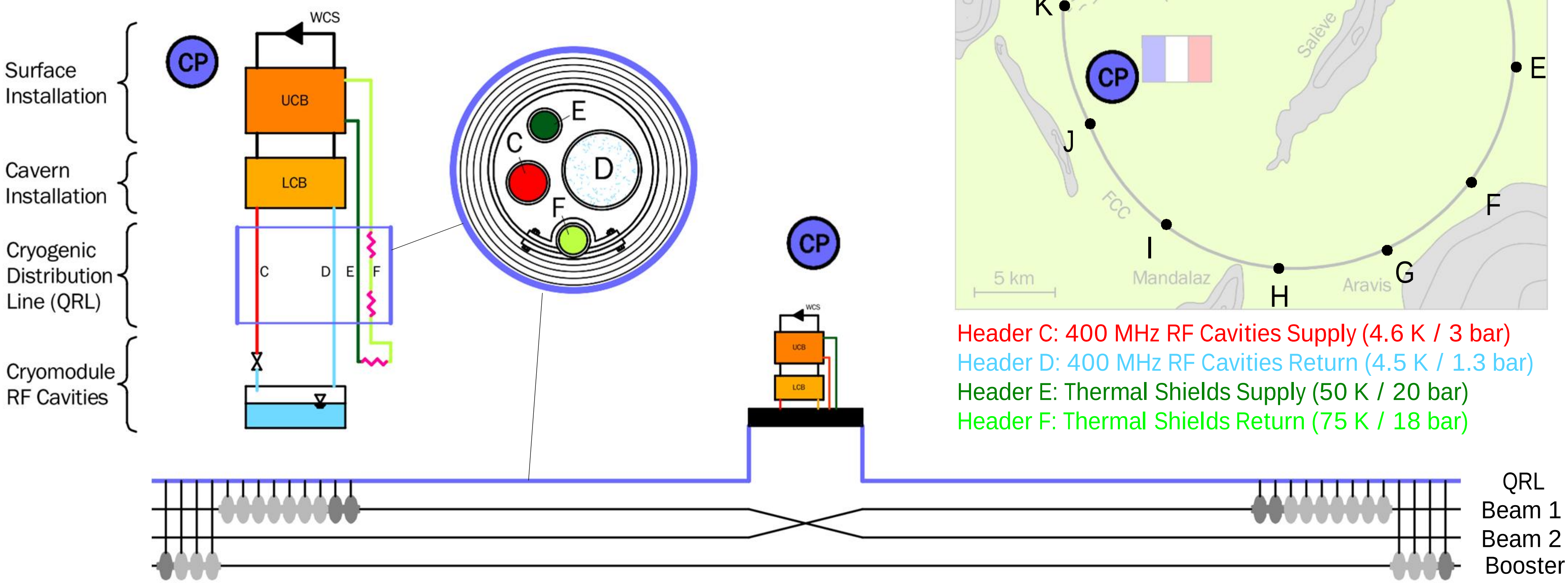
Newly installed 400 MHz RF Module @ 4.5 K
Formerly installed 400 MHz RF Module @ 4.5 K
Newly installed 800 MHz RF Module @ 2.0 K

FCC-ee Cryogenics: Stage 3/4 (Higgs Boson)

1. Stage: z^0-Bosons (E_{Beam} = 45.6 GeV)
2. Stage: $w^{\pm}$-Bosons (E_{Beam} = 80 GeV)
3. **Stage: Higgs Bosons (E_{Beam} = 125 GeV)**
4. Stage: Top Quarks ($E_{Beam} \geq$ 173 GeV)



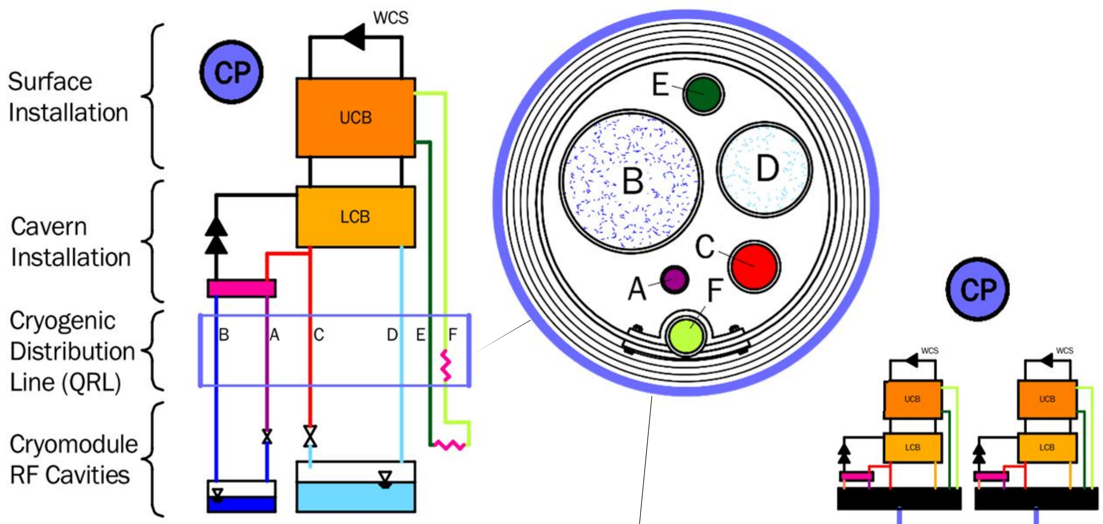
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)

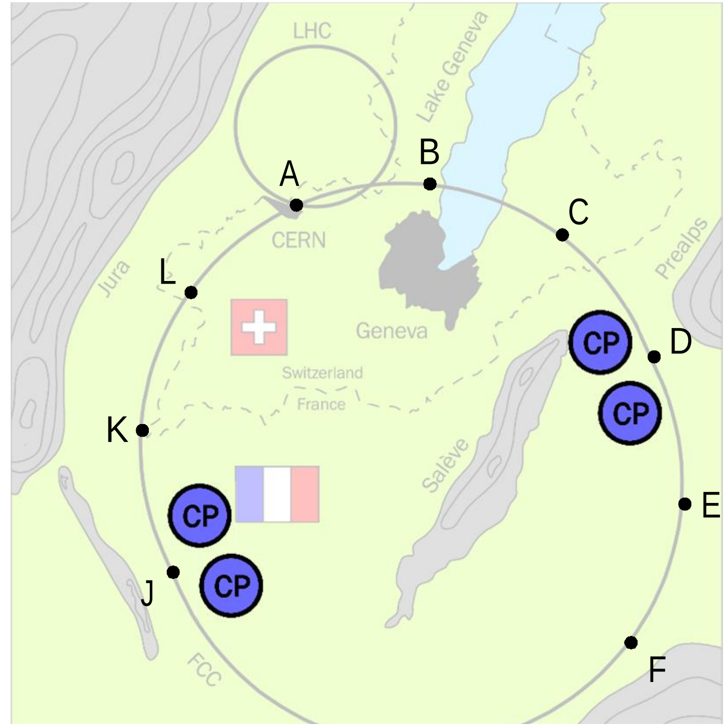


Newly installed 400 MHz RF Module @ 4.5 K
Formerly installed 400 MHz RF Module @ 4.5 K
Newly installed 800 MHz RF Module @ 2.0 K

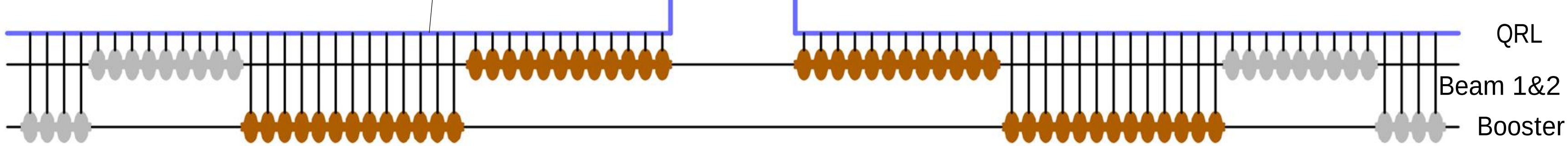
FCC-ee Cryogenics: Stage 4/4 (Top Quark)

1. Stage: z^0-Bosons (E_{Beam} = 45.6 GeV)
2. Stage: $w^\pm$-Bosons (E_{Beam} = 80 GeV)
3. Stage: Higgs Bosons (E_{Beam} = 125 GeV)
4. Stage: Top Quarks ($E_{Beam} \geq$ 173 GeV)





Header A: 800 MHz RF Cavities Supply (2.2 K / 1.3 bar)
Header B: 800 MHz RF Cavities Supply (2.0 K / 30 mbar)
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)



Newly installed 400 MHz RF Module @ 4.5 K
Formerly installed 400 MHz RF Module @ 4.5 K
Newly installed 800 MHz RF Module @ 2.0 K

FCC-ee Cryo Summary

	Stage 1 (z^0)		Stage 2 ($w^{\pm}$)		Stage 3 (Higgs)		Stage 4 (Top Quark)	
Time	2038 - 2041		2042 - 2044		2045 - 2047		2049 - 2053	
Frequency	400 MHz	800 MHz	400 MHz	800 MHz	400 MHz	800 MHz	400 MHz	800 MHz
T_{sat} (p_{Sat})	4.5 K (1.3 bar)	2.0 K (30 mbar)	4.5 K (1.3 bar)	2.0 K (30 mbar)	4.5 K (1.3 bar)	2.0 K (30 mbar)	4.5 K (1.3 bar)	2.0 K (30 mbar)
Number Cryoplants	1 CP @ Point J	-	1 CP @ Point J	-	1 CP @ Points D & J	-	2 CPs @ Points D & J	2 CPs @ Points D & J
RF voltage	0.1 GV	-	0.75 GV	-	2 GV	-	4 GV	5.4 / 6.9 GV
Cryopower	1 x 4 kW @ 4.5 K		1 x 41 kW @ 4.5 K		2 x 41 kW @ 4.5 K		4 x 41 kW @ 4.5 K 4 x 12 kW @ 2.0 K	
Cryopower @ 4.5 K	4 kW @ 4.5 K		41 kW @ 4.5 K		82 kW @ 4.5 K		252 kW @ 4.5 K	
Electrical Power Consumption	0.9 MW		9.5 MW		19 MW		58 MW	

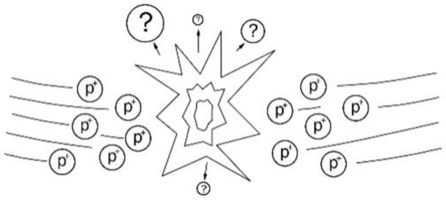
Helium Inventory

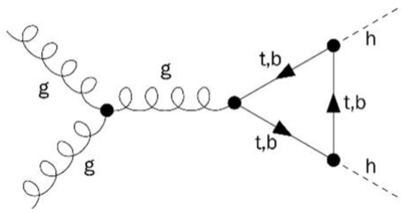
Cryomodule	1.2 t	1.6 t	4.1 t	11.0 t ÷ 12.6 t
Distribution	7.9 t	7.9 t	7.9 t	8.9 t
Cryoplant	1.0 t	1.0 t	2.0 t	4.0 t
Total	10 t	10 t	14 t	24 t ÷ 26 t

FCC-hh Cryogenics: Research Goal

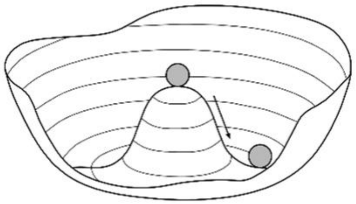
Research goal

- Production of new particles

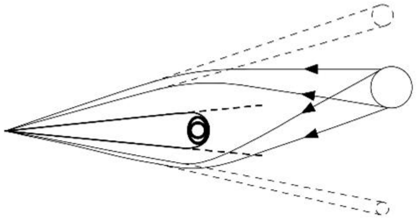




- Precise measurement of the Higgs self-coupling

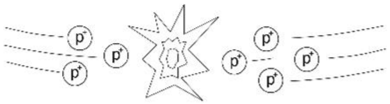


- Exploration of the electroweak symmetry breaking
- WIMPs (warm interacting massive particles) as candidates for dark matter can be discovered or ruled out

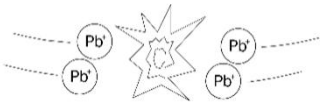


4 collision modes

- Hadron – Hadron

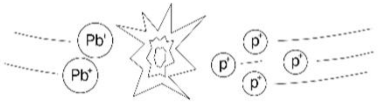


- Ion – Ion



- Hadron – Lepton

- Ion – Proton



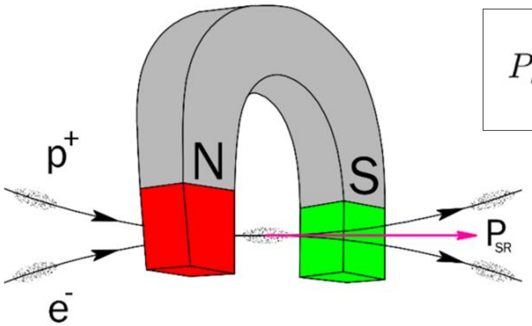
Challenge # 1: Cryogenics is an ancillary application

Main purpose of the FCC is particle physics
Cryogenics has to be adapted to enable it

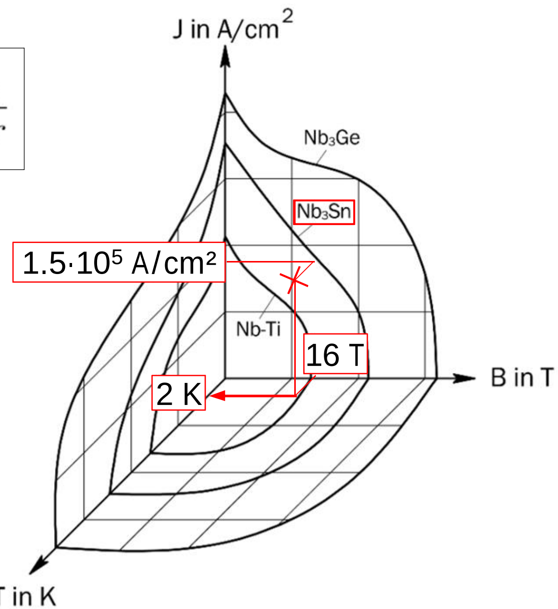
Why superconductivity?

e^- $m_{e^-} = 0.51\ \text{MeV}/c^2$

p^+ $m_{p^+} = 938.27\ \text{MeV}/c^2$



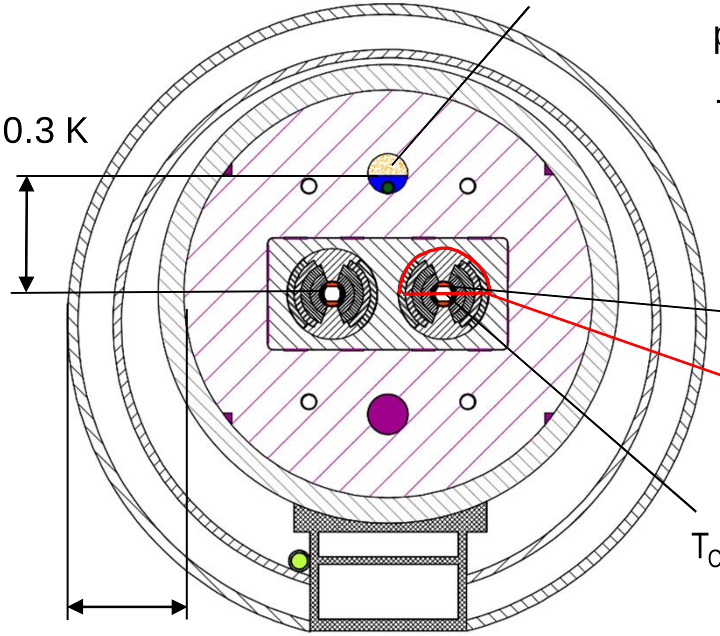
$$P_{SR} \propto \frac{E_R^4}{m_0^4 r}$$



Heat sink: Saturated two-phase helium flow

p_{min} = 16 mbar

$\rightarrow T_{sat} \approx 1.8$ K



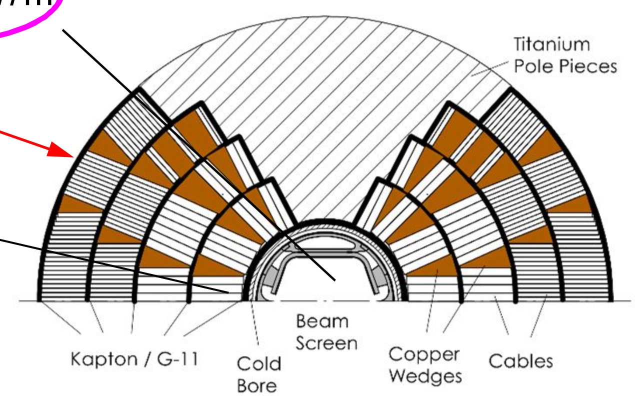
$P_{SR} \approx 30$ W/m

$T_{Coil} < 2.15$ K

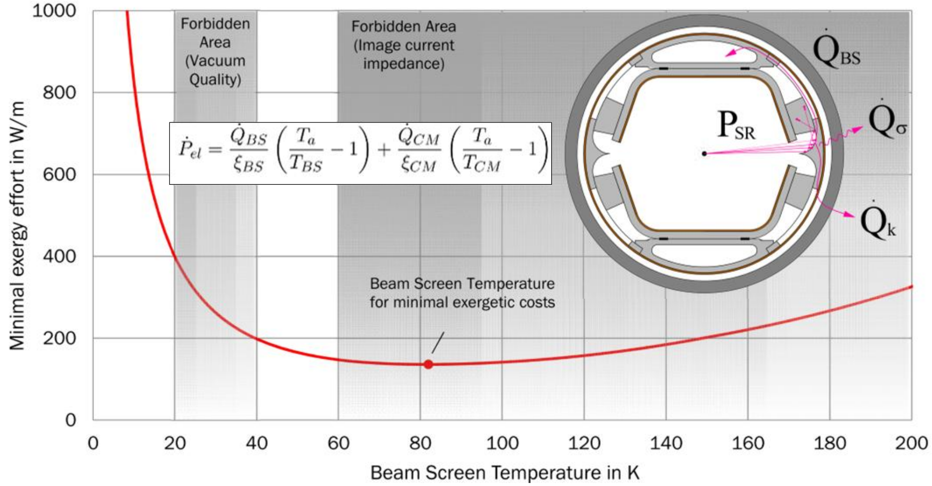
$$\epsilon_C = \frac{T_a}{T} - 1$$

$\rightarrow P_{min}$ = 750 MW

(Must be intercepted)



Challenge #1: Physics is the boss

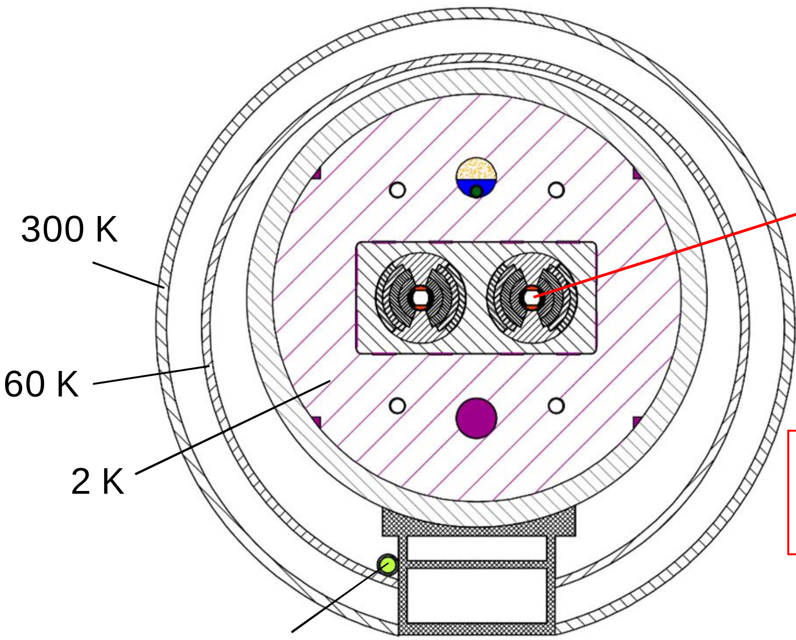


Temperature range (40 ÷ 60 K) chosen to

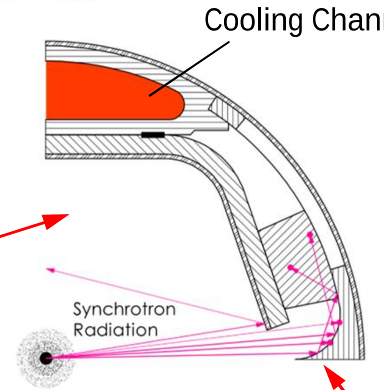
- Preserve vacuum quality
- Keep image current impedance low
- Decrease exergetic costs

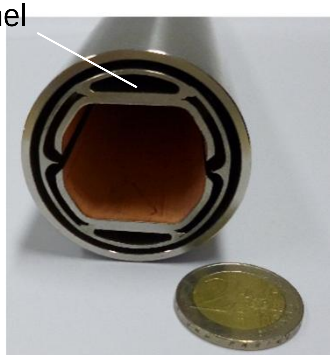
High pressure level (50 bar) chosen to

- Decrease pressure losses
- Decrease compression ratio



Thermal shields: Operated in series after cooling the beam screens

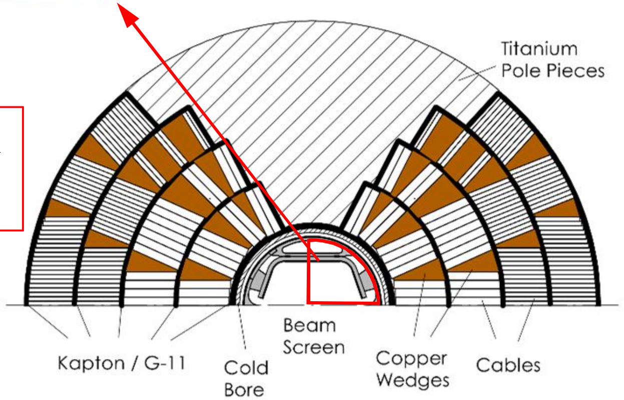




Courtesy of Cedric Garion

T_{BS} = 40 ÷ 60 K

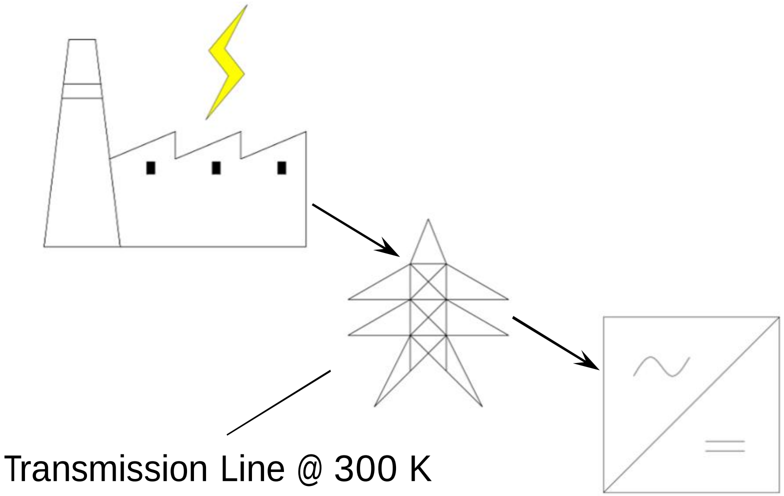
p_{BS} = 50 bar



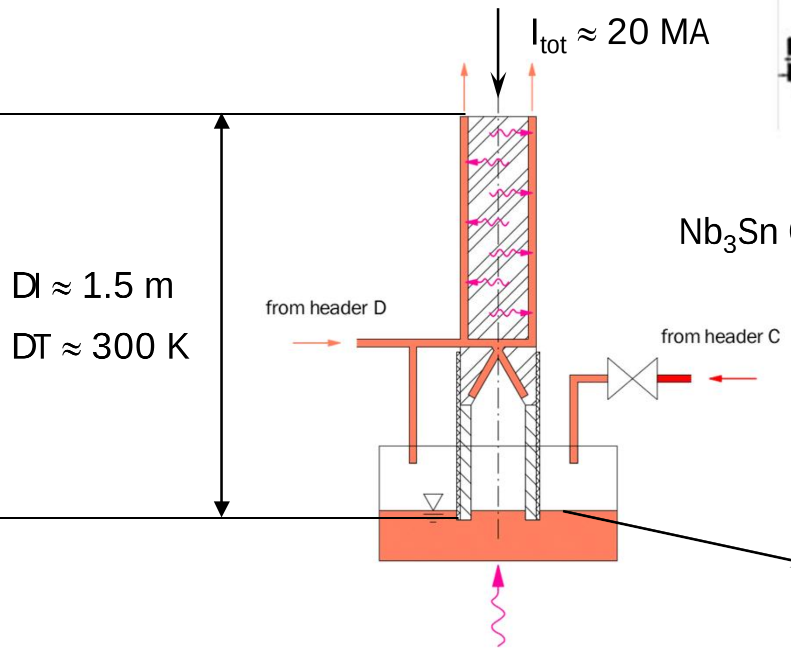
Challenge #1: Physics is the boss

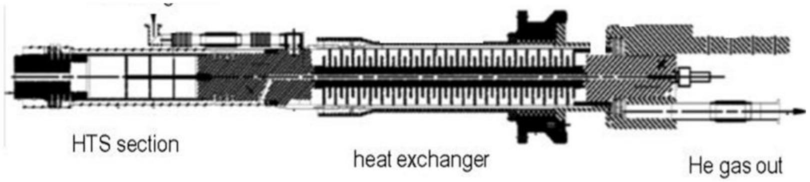
<u>Current Leads</u>

- Electrical power to feed electromagnets is delivered by transmission lines at ambient temperature level
- The conductors transmitting the current to the Nb_3Sn cables have to cooled down from 300 K to 2 K
- Wiedemann-Franz law: Good electrical conductors are good thermal conductors → sophisticated design needed to reduce heat leaks



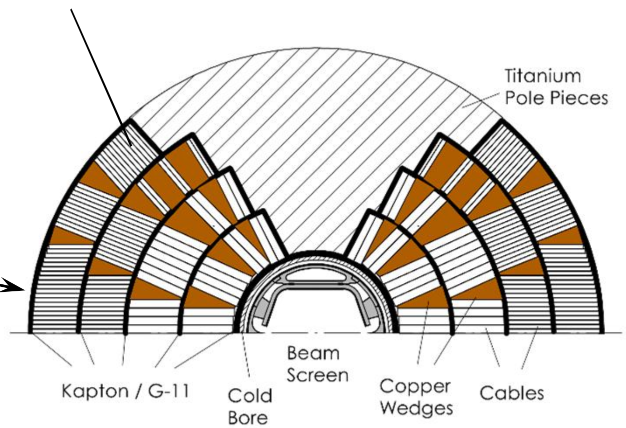
Courtesy of CERN





Courtesy of Amalia Ballarino

Nb_3Sn Cables @ 2 K



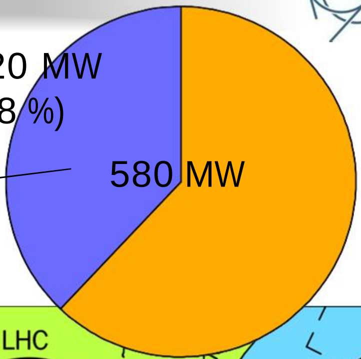
Challenge # 1: Cryogenics is an ancillary application

Challenge # 2: Much power for low temperature

A second Geneva– electrically spoken

Challenge #2: Get the power

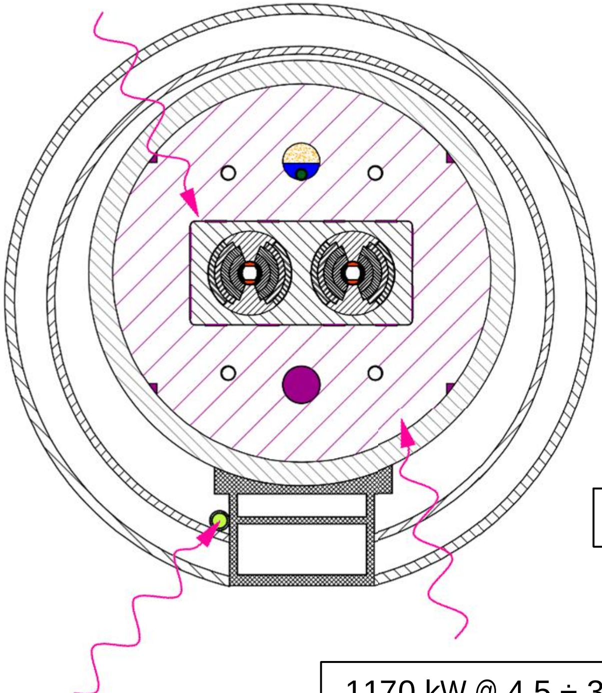
Cycle	Q_{Load} in kW	P_{min} in MW	P_{real} in MW
CMC+B	140	18	130
BS+TS	5800	29	81
CL	1170	2	7



Electrical Power Consumption of CERN during FCC-hh operation

Cold Mass Cooling & Header B heat leaks

140 kW @ 1.8 K

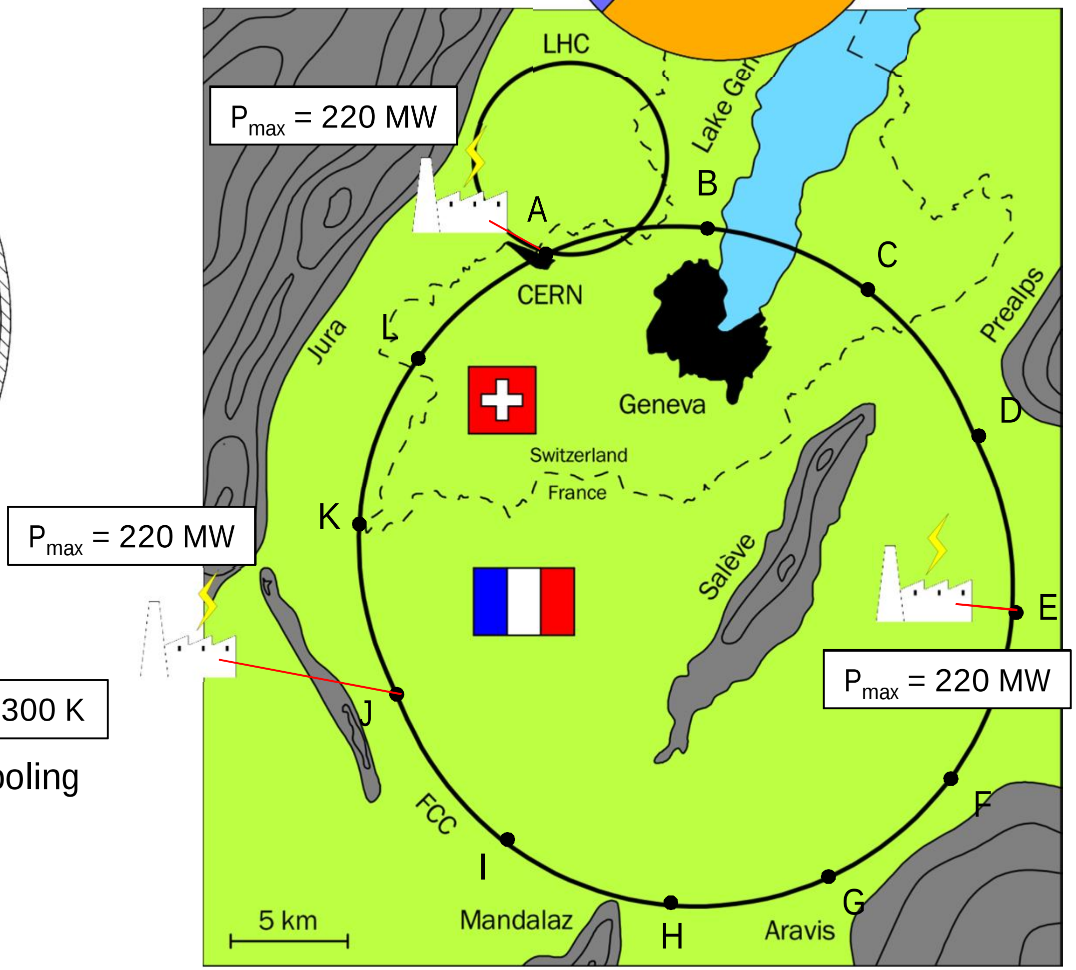


5800 kW @ 40 ÷ 60 K

Beam Screen Cooling & Thermal Shields

1170 kW @ 4.5 ÷ 300 K

Current Lead Cooling



Challenge # 1: Cryogenics is an ancillary application

Challenge # 2: Much power for low temperature

Challenge # 3: Efficiency vs. Simplicity

CAPEX vs. OPEX

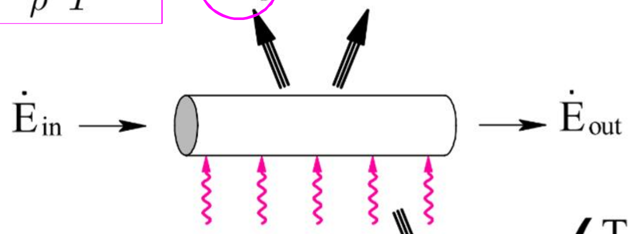
Economics vs. Availability

Ingenuity vs. Beauty

Challenge #3: Compromises

$$\dot{E}_{\Delta p} = \frac{\dot{m}}{\rho}\frac{T_a}{T}\Delta p$$

$$\dot{E}_{\Delta p} + \dot{E}_{\Delta T} = \dot{E}_{loss}$$



$$\dot{Q}_{Load} = \dot{q}_{Load} \cdot L_{Cooled}$$

$$\dot{Q}_{Load} \cdot \left(\frac{T_a}{T} - 1\right)$$

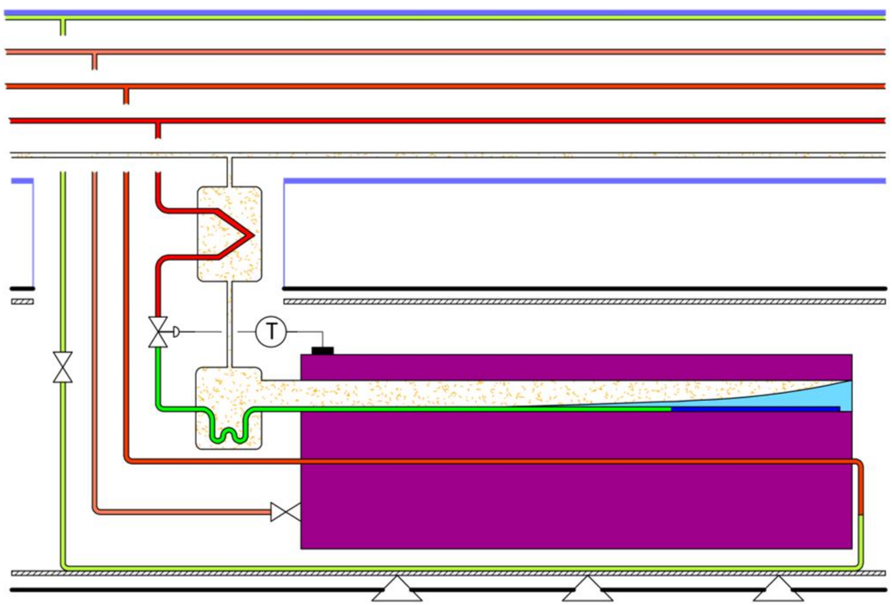
$$\dot{m} = \frac{\dot{q}_{Load}\, L_{Cooled}}{c_p\, \Delta T}$$

$$\Delta p = \frac{f\, L_{Cooled}}{2\, d_h\, A^2}\frac{\dot{m}^2}{\rho}$$

$$\Delta p = \frac{f\, \dot{q}_{Load}^2}{2\, d_h\, A^2\, c_p\, \Delta T^2\, \rho} L_{Cooled}^3$$

$$\rightarrow \quad \dot{E}_{\Delta p} \propto L_{Cooled}^3$$

To keep the efficiency high, the separated cooling loops have to be short!



Shortest possible cooling loop: 1 Magnet (15 m)

For 5500 arc magnets (dipoles and quadrupoles)

- Minimal 16500 Valves, 5500 heat exchangers, 5500 separators, ...

→ Large controlling effort

→ High CAPEX

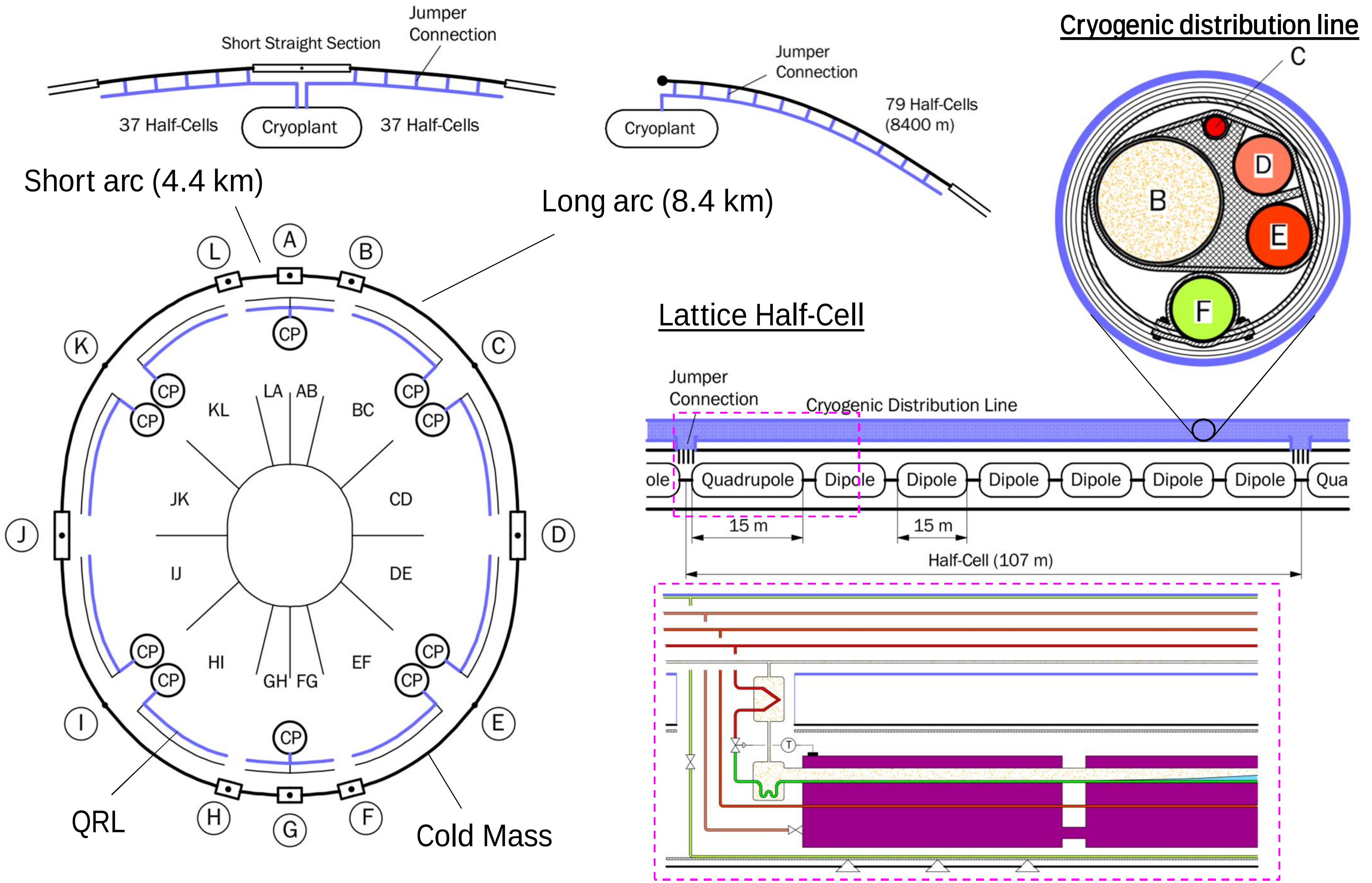
→ Decreased availibilty

→ Error-prone installations

Same question/consideration for the level above:

How many magnets are supplied by the same Cryoplant?

Challenge #3: Compromises



Challenge # 1: Cryogenics is an ancillary application

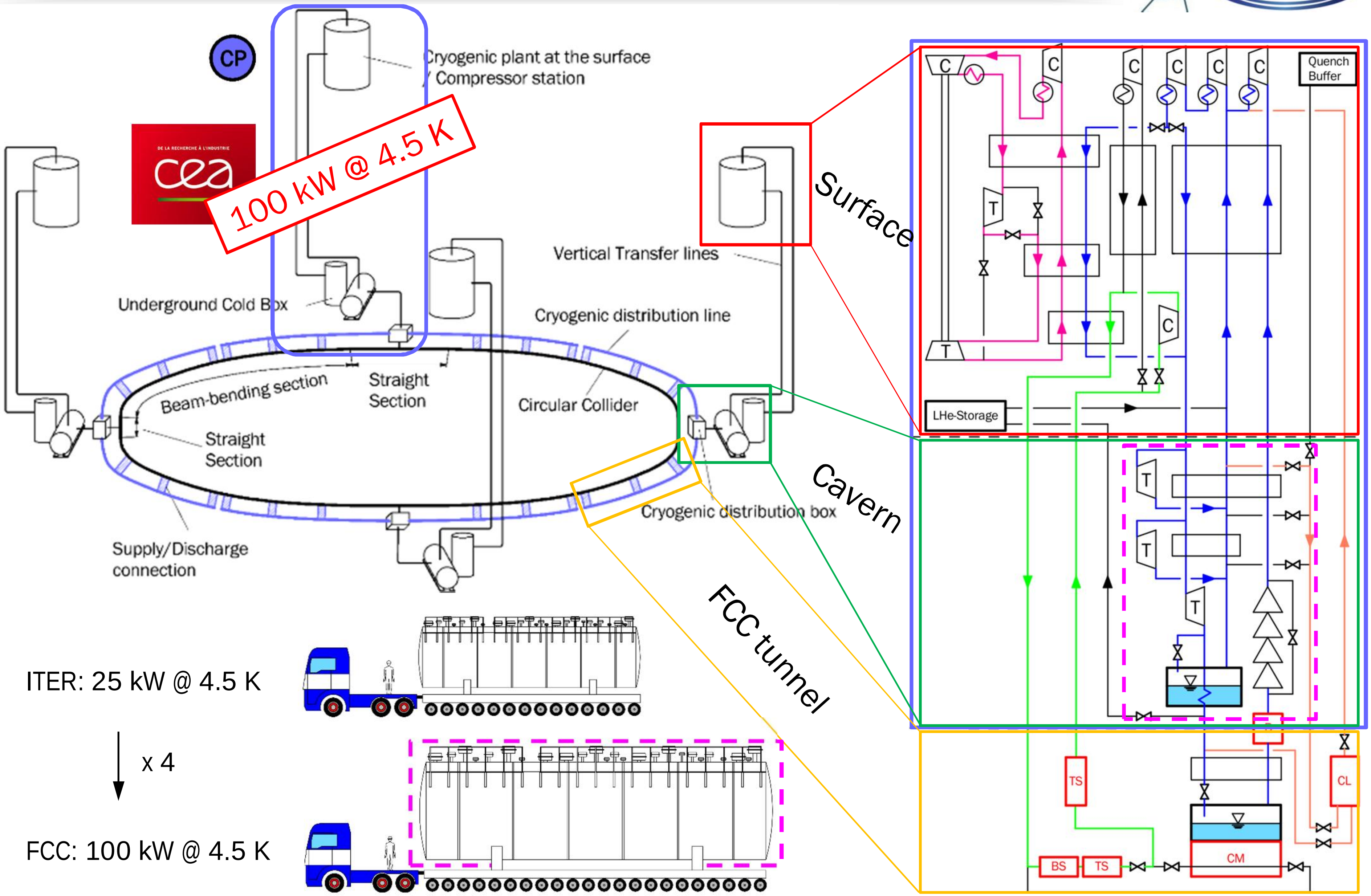
Challenge # 2: Much power for low temperature

Challenge # 3: Efficiency vs. Simplicity

Challenge # 4: As big as possible

Compromise between the largest available
and the smallest acceptable

Challenge #4: Size matters



ITER: 25 kW @ 4.5 K

x 4

FCC: 100 kW @ 4.5 K

Challenge #4: Size matters

Courtesy of CERN

Courtesy of CERN

60 x Gaseous He (250 m^3, 20 bar)

156 x Quench Buffer (250 m^3, 20 bar)

10 x Gaseous He (250 m^3, 50 bar)

10 x Nelium (250 m^3, 50 bar)

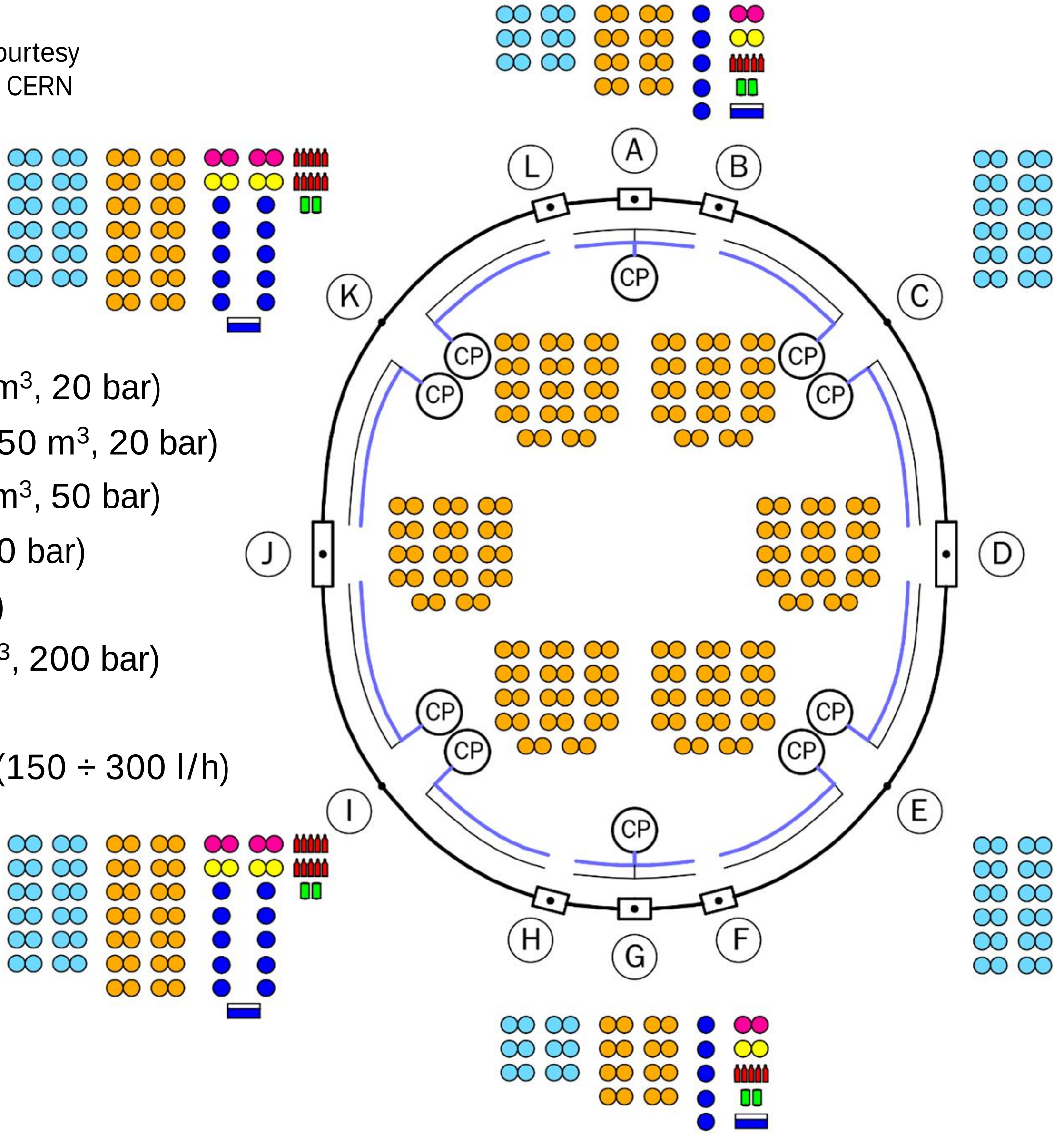
50 x Liquid He (120 m^3)

10 x Gaseous Ne (10 m^3, 200 bar)

6 x Liquid N (50 m^3)

6 x He Boil-off liquefier (150 ÷ 300 l/h)

Courtesy of CERN



Courtesy of CERN

Challenge # 1: Cryogenics is an ancillary application

Challenge # 2: Much power for low temperature

Challenge # 3: Efficiency vs. Simplicity

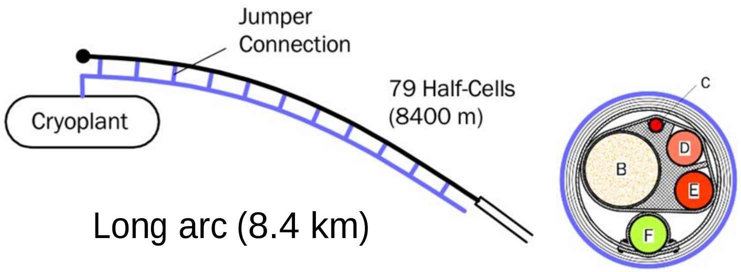
Challenge # 4: As big as possible

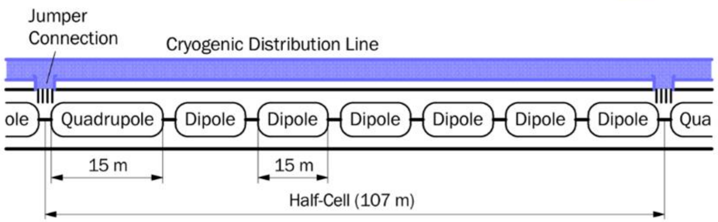
Challenge # 5: Attempt for new technology

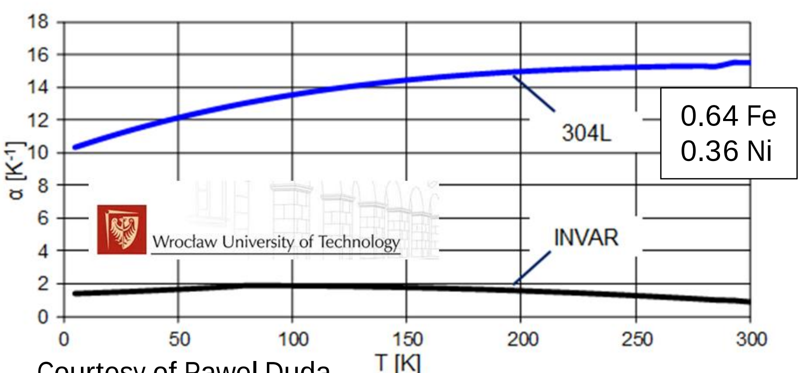
New solutions for old problems

Challenge #5: Sometimes change a winning team

Invar technology for the QRL







Courtesy of Pawel Duda

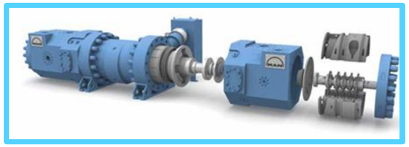
Cool down: 300 K → 60 K

304L: DL ≈ 28 m   Invar: DL ≈ 3.5 m

Nelium Brayton Cycle

TECHNISCHE UNIVERSITÄT DRESDEN

Courtesy of MAN



Efficiencies of centrifugal compressors higher than for screw compressors

→ Helium compressors need to be very large due to low density

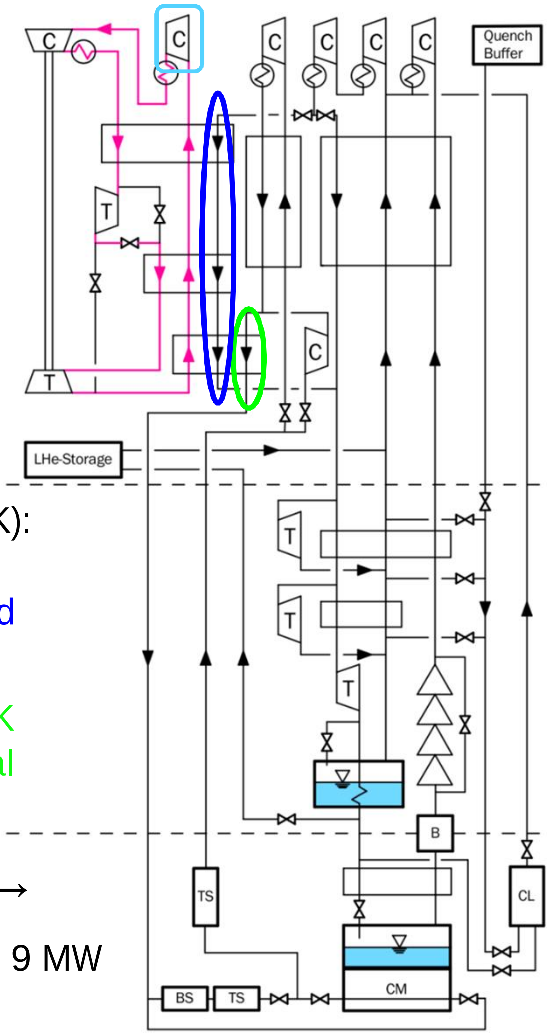
Nelium is a blend of helium (75 %) and neon (25 %)

Cooling Capacity (@ 40 ÷ 300 K):

- 270 kW @ 40 ÷ 300 K (Cold Mass & Current Leads)
- 700 kW @ 40 ÷ 63 K (Beam Screen & Thermal Shield)

Assumed Carnot efficiency 0.42 →

Electrical Power $P_{el} \approx 9$ MW



Cool Down with N_2 (80 K)

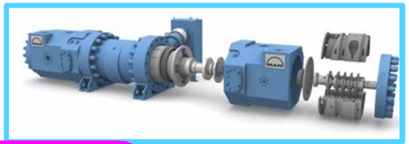
For the same CD timescale (≈ 10 d):

- 10 trucks per hour (nonstop)
- Nitrogen Storage (60000 m³)

6 x 

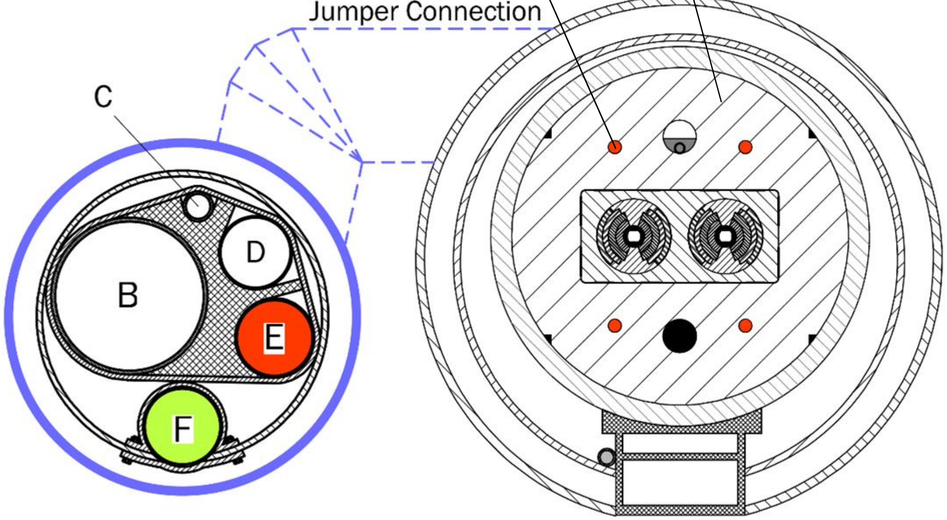
Courtesy of CERN

Courtesy of MAN

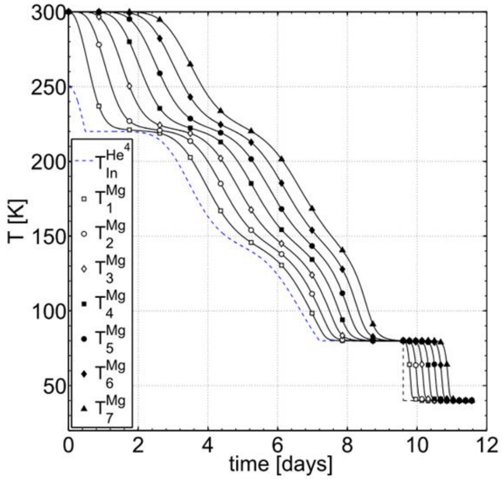


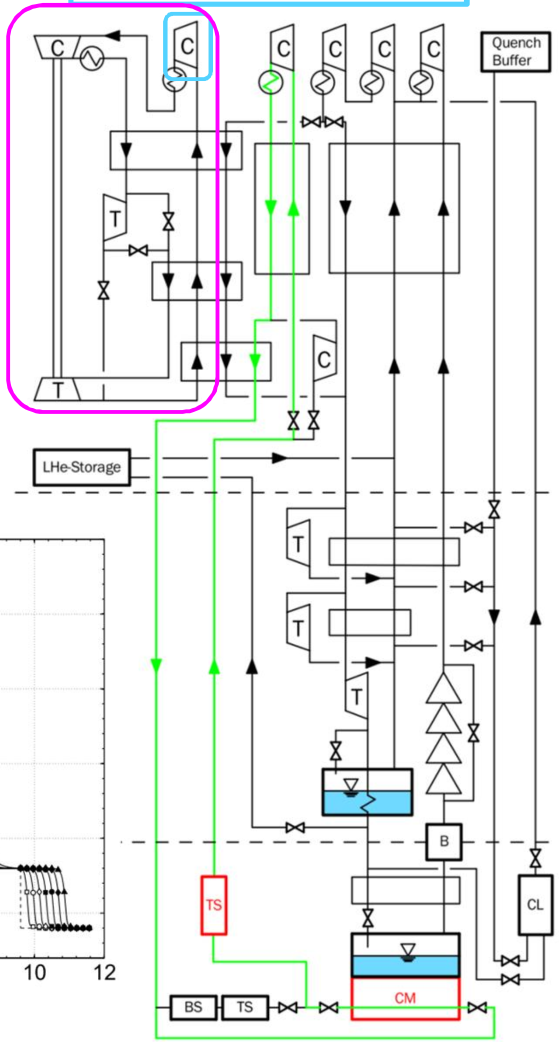
Cool Down with Nelium Cycle (40 K)

Cool Down and Warm Up operations with the Beam Screen Cooling Warm Compressor and the Nelium Cycle



Courtesy of Hugo Correia Rodrigues





Challenge # 1: Cryogenics is an ancillary application

Challenge # 2: Much power for low temperature

Challenge # 3: Efficiency vs. Simplicity

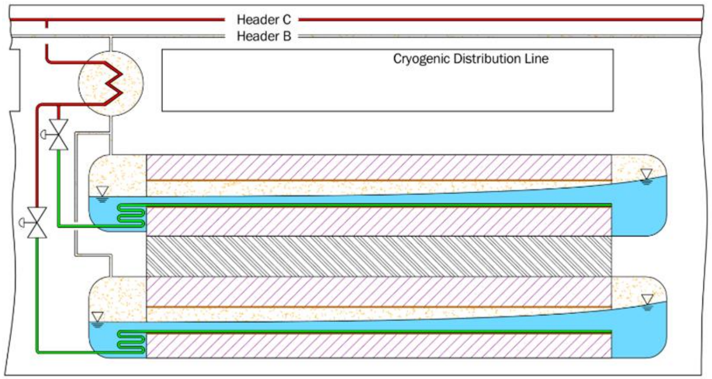
Challenge # 4: As big as possible

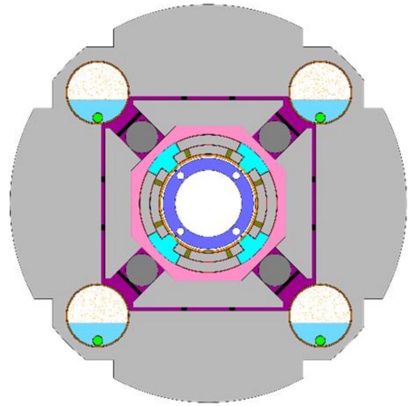
Challenge # 5: Attempt for new technology

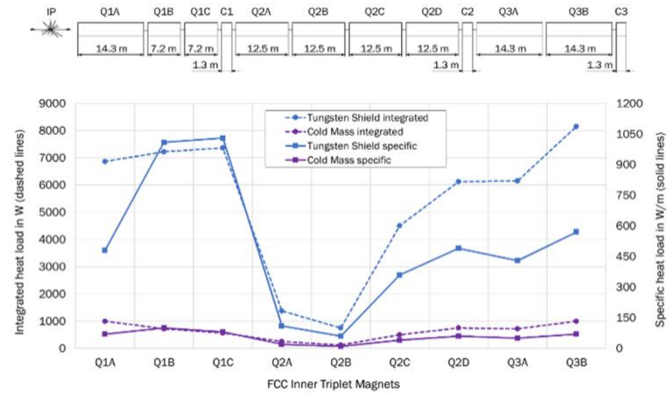
Challenge # 6: Little big problems

Find a solution for 99 % of the machine doesn‘t mean to have solved 99 % of the problems

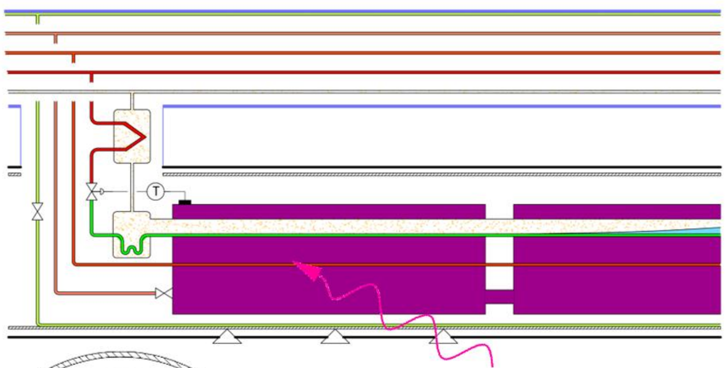
Example # 1: Inner Triplet Cooling

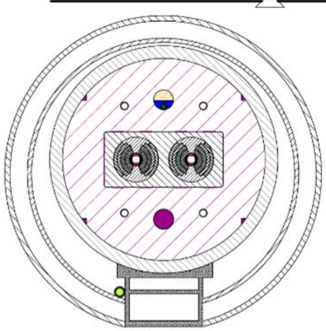






Example # 2: Quenching

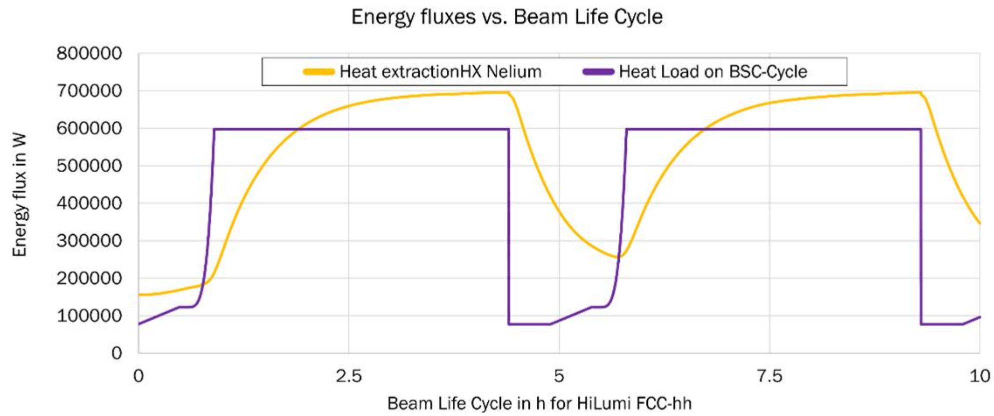




35 MJ / Magnet

Max. allowed pressure 20 bar
Capacity of header D
Capacity of quench buffers
...

Example # 3: BSC-Cycle Transient for HiLumi-FCC



HiLumi-Beam Life Cycle: 4.5 hours
→ Beam Screen Cooling system never reaches steady-state operation

FCC-hh Cryogenics: Overview

FCC-hh Cryo Summary	Cold Mass Cooling	Current Lead Cooling		Beam Screen Cooling & Thermal Shiedling
Heat Load	155 kW	1.7 kW	1165 kW	5980 kW
Temperature level	2.05 K	4.5 K	36 ÷ 300 K	40 ÷ 62 K
Minimal electrical power (Carnot)	17500 kW	112 kW	1641 kW	29100 kW
Electrical Power Consumption	131.5 MW	6.8 MW		80.3 MW
Overall exergetic efficiency	0.13	0.26		0.36
Cryopower @ 4.5 K / Cryoplant	103 kW @ 4.5 K (x 10 Cryoplants)			

Cryogen Inventory during nominal operation

	Helium	Neon	Nelium	Nitrogen
Cold Mass	400 t	-	-	-
Distribution System	350 t	-	-	-
Cryoplants (+ Shafts)	8 t	5 t	39 t	-
Storage	88 t	10 t	1 t	242 t
Sum	846 t	15 t	40 t	242 t

LEP vs. FCC-ee

	LEP		FCC-ee			
Research object	z^0	$w^\pm$	z^0	$w^\pm$	h	t_1 & t_2
Number Cryoplants	-	4	1	2	2	4
Total Cryopower [kW @ 4.5 K]	-	48	4	41	82	126
Total Cryopower per cryoplant [kW @ 4.5 K]	-	12	4	41	41	63

Factor 5 ÷ 6

HL-LHC vs. FCC-hh

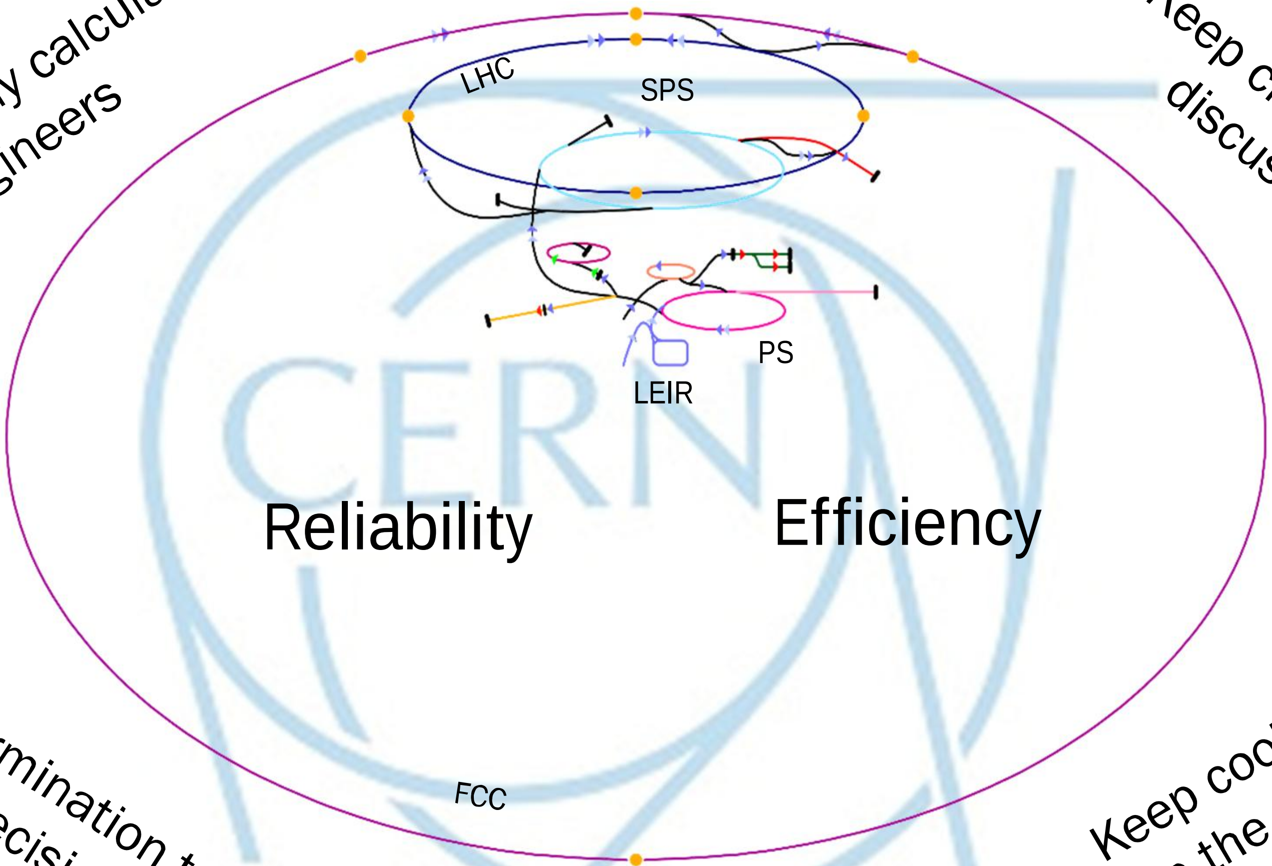
= 4 x state-of-the-art capacity

	HL-LHC	FCC-hh	
Number Cryoplants	10	10	
Total Cryopower per cryoplant [kW @ 4.5 K]	18	103	Factor 5 ÷ 6
Total electric power consumption (w/o IPs) [MW]	42	220	Factor 5 ÷ 6
Max. Distribution Distance (long sector) [m]	3300	8400	Factor 2 ÷ 3
Overall storage capacity [m^3]	16400	65400	Factor 4
Helium inventory [t]	145	846	Factor 6 ÷ 7
Neon inventory [t]	0	25	
Nitrogen inventory [t]	40.5	242	Factor 6

The FCC cryogenic needs

Cold-bloodedly calculating Engineers

Keep chilled in hot discussions



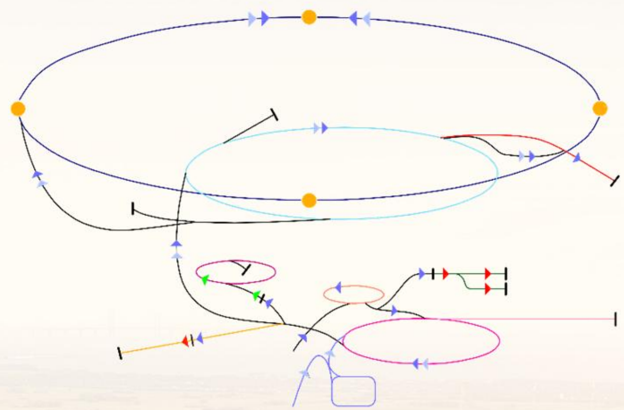
Reliability

Efficiency

Icy determination to make decisions

Keep cool heads upon the challenges

... and who shall deliver that if not Cryogenics?



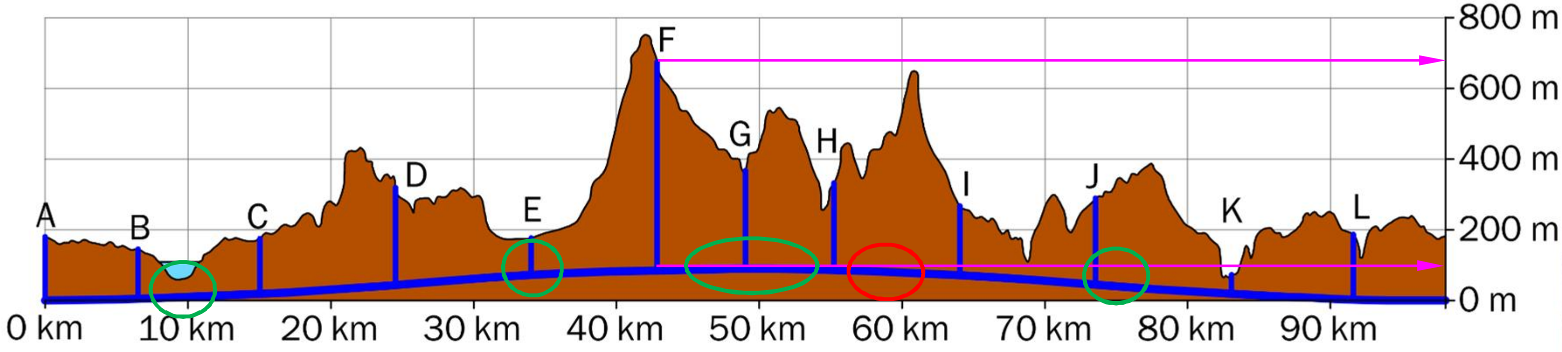
"What starts out as science fiction today may wind up being finished tomorrow as a report.“

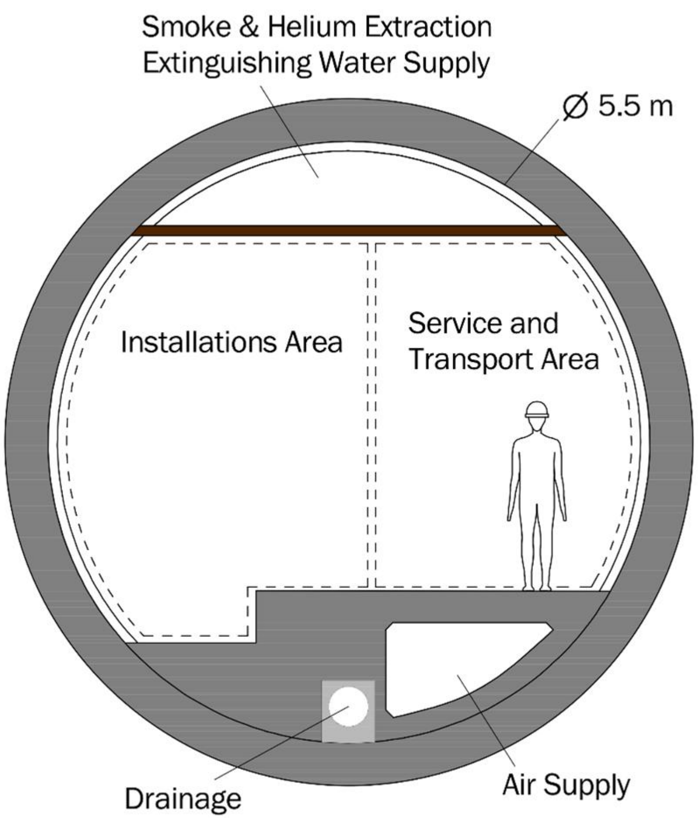
Norman Mailer

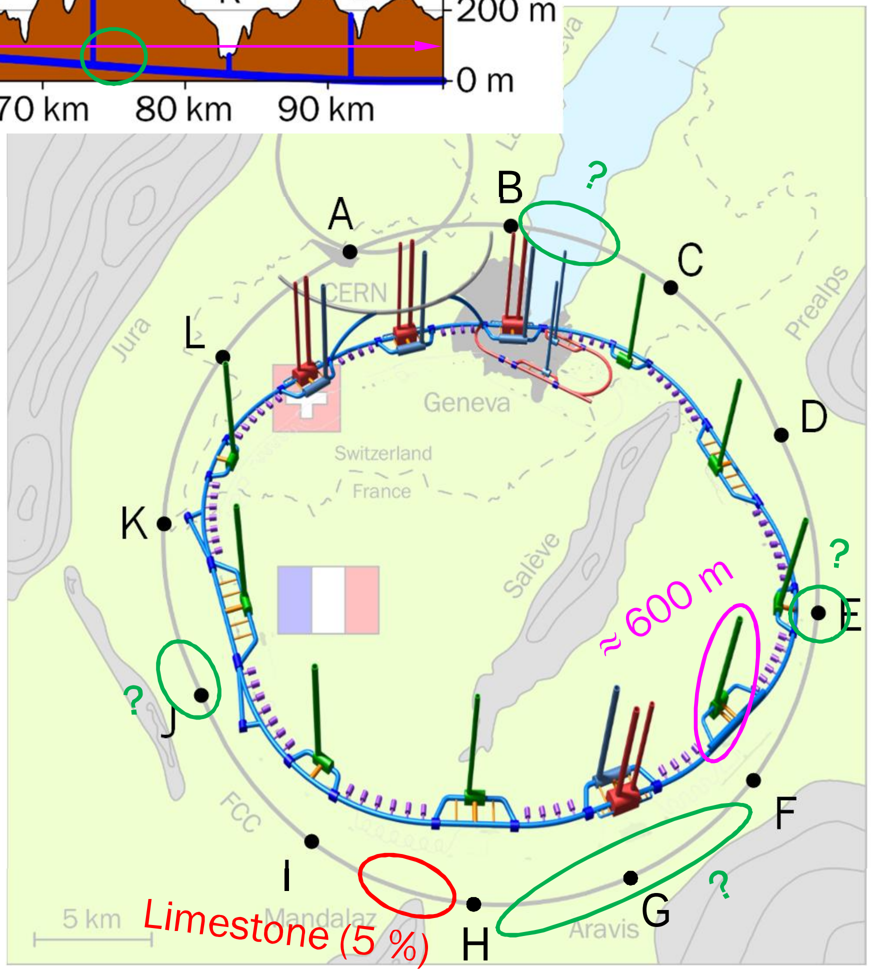
The cryogenic needs of the FCC

2019 European Cryogenics Days 08.10.2019 in Lund, Sweden

A brief overview: The FCC





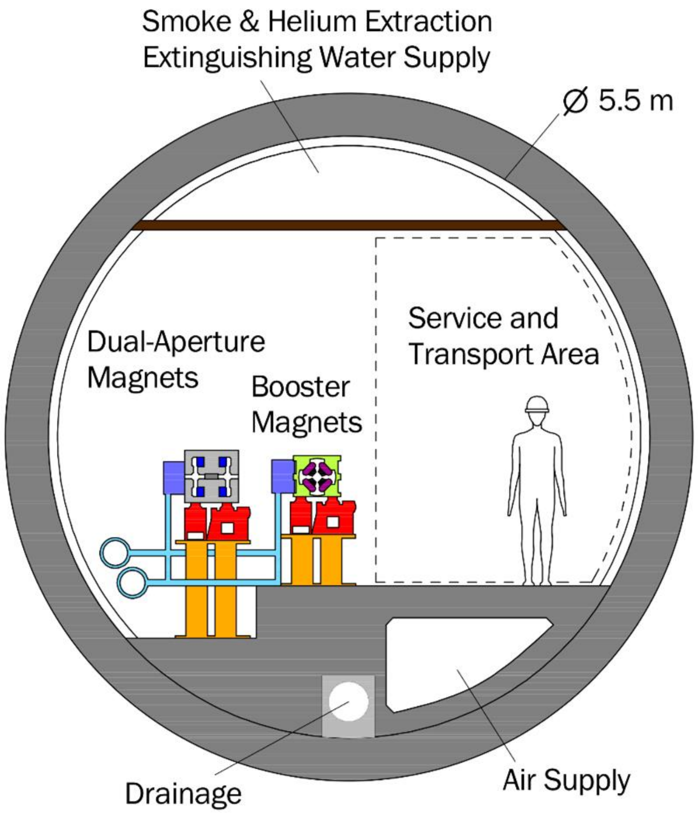


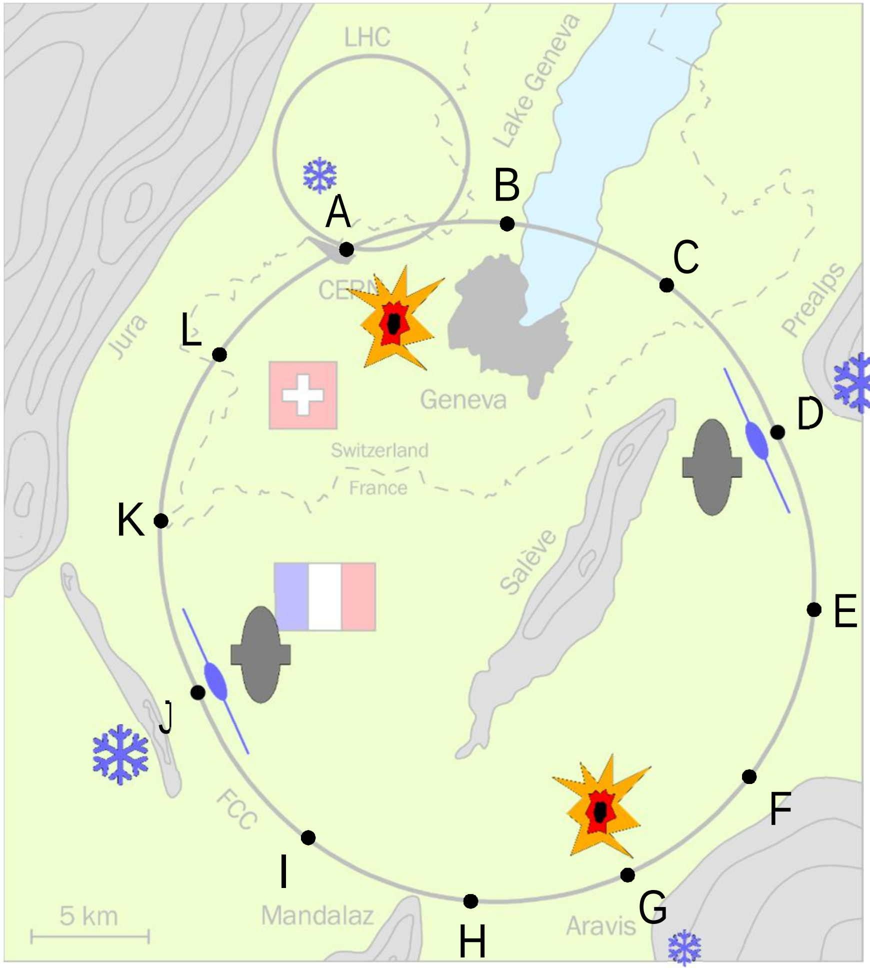
Courtesy of J.Osborne

Lepton Collider to study 4 particles: z^0-Boson, $w^{\pm}$-Boson, Higgs Boson, Top Quark

Two experiments (interaction points) with small cryogenic needs in the Points A & G

Large cryogenic consumers are the RF Cavities located in the Points D & J (+ distribution)

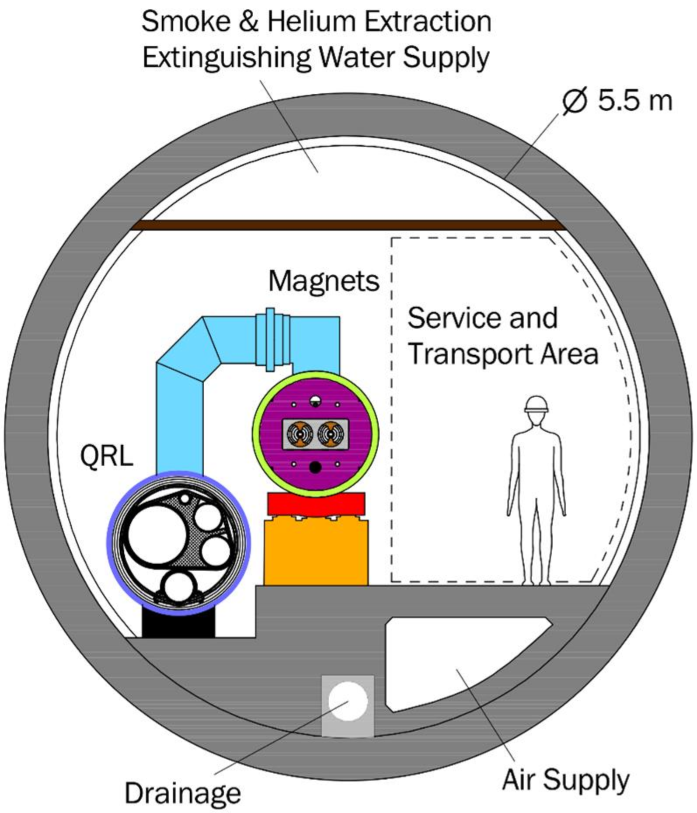


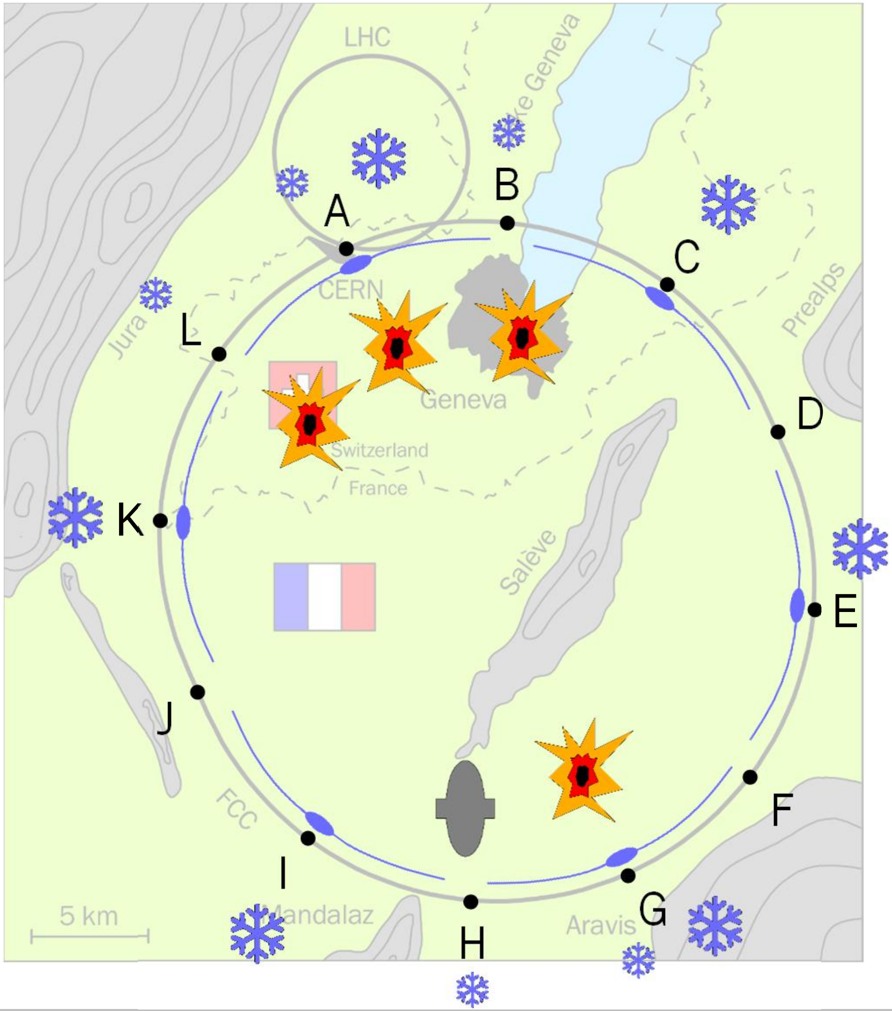


Hadron Collider to study massive particles and eventually discover new physics (e.g. SUSY)

Four experiments (interaction points) and superconducting RF Cavities with small cryogenic needs in the Points A, B, G, H & L

Large cryogenic consumers are the magnets to bend and focus the hadron beams (+distribution)





Benefits for the research

Lepton Colliders

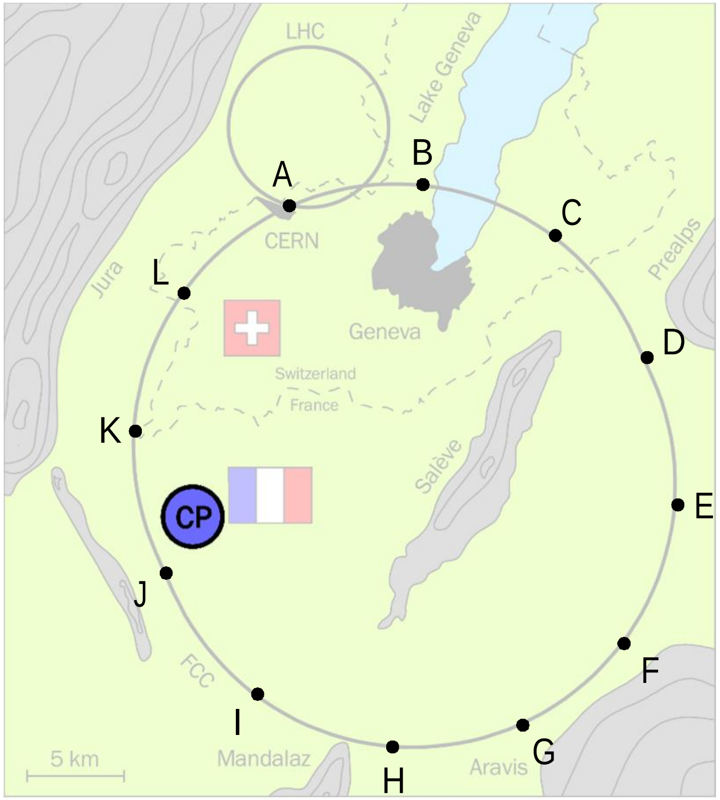
	LEP		FCC-ee				
Research object	z^0	$w^{\pm}$	z^0	$w^{\pm}$	h	t_1	t_2
Particle Energy [GeV]	60 (max.)	105 (max.)	45.6	80	120	175	182.5
Beam Current [mA]	8.4	6.2	1390	147	29	6.4	5.4
Luminosity / IP [$nb \cdot s^{-1}$]	0.0085	0.025	230	28	8.5	1.8	1.55
RF voltage [GV]	0.4	4.1	0.1	0.75	2.0	4.0 / 5.4	4.0 / 6.9
RF frequency [MHz]	352.2		400			400 / 800	

Hadron Colliders

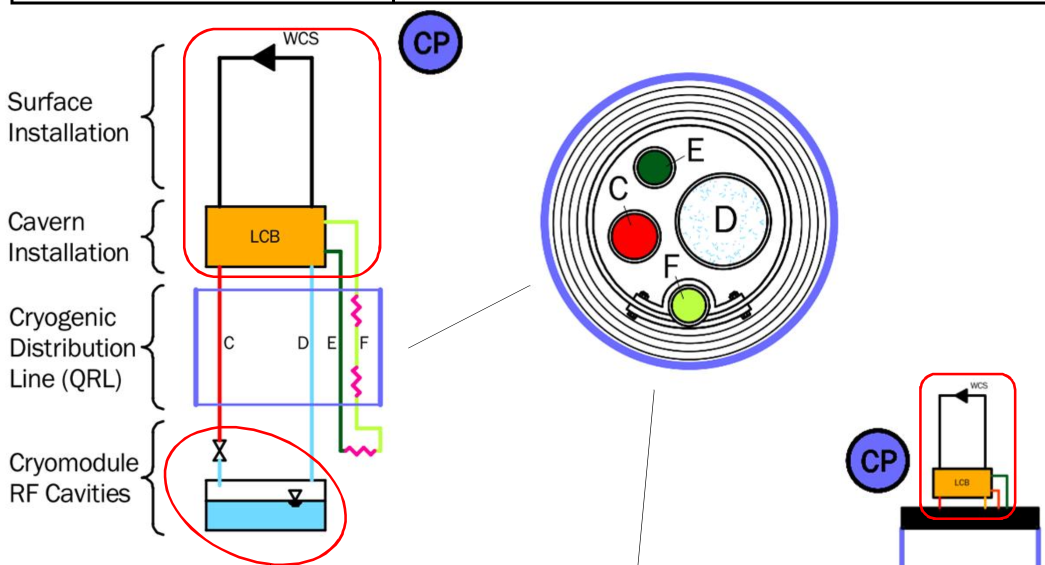
	LHC		HL-LHC		FCC-hh	
Research object	p^+	Pb	p^+	Pb	p^+	Pb
Nucleon Energy [TeV]	7	1.38	7	1.38	50	19.7
Total Beam Energy [MJ]	392	1.9	694	3.4	8300	362 ÷ 709
Beam Current [mA]	584	< 1	1120	< 1	500	< 1
Luminosity / IP [$nb \cdot s^{-1}$]	2.5	$0.5 \cdot 10^{-6}$	12.5	$6 \cdot 10^{-6}$	12.5 ÷ 75	$80 \cdot 10^{-6} \div 320 \cdot 10^{-6}$
Dipole Field [T]	8.33				16	

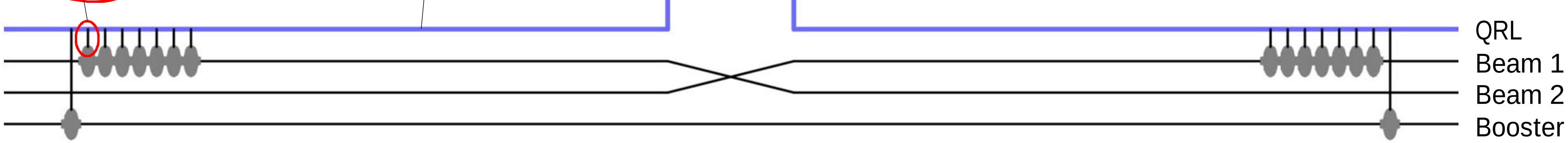
FCC-ee Cryogenics: Stage 1/4 (z-Boson)

Frequency	400 MHz	800 MHz
T_{sat} (p_{Sat})	4.5 K (1.3 bar)	2.0 K (30 mbar)
Number Cryoplants	1 CP @ Point J	-
RF voltage	100 MV	-
Cryopower / Cryoplant	4 kW @ 4.5 K	
Total Cryopower @ 4.5 K	4 kW @ 4.5 K	
Electrical Power	0.9 MW	



Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)

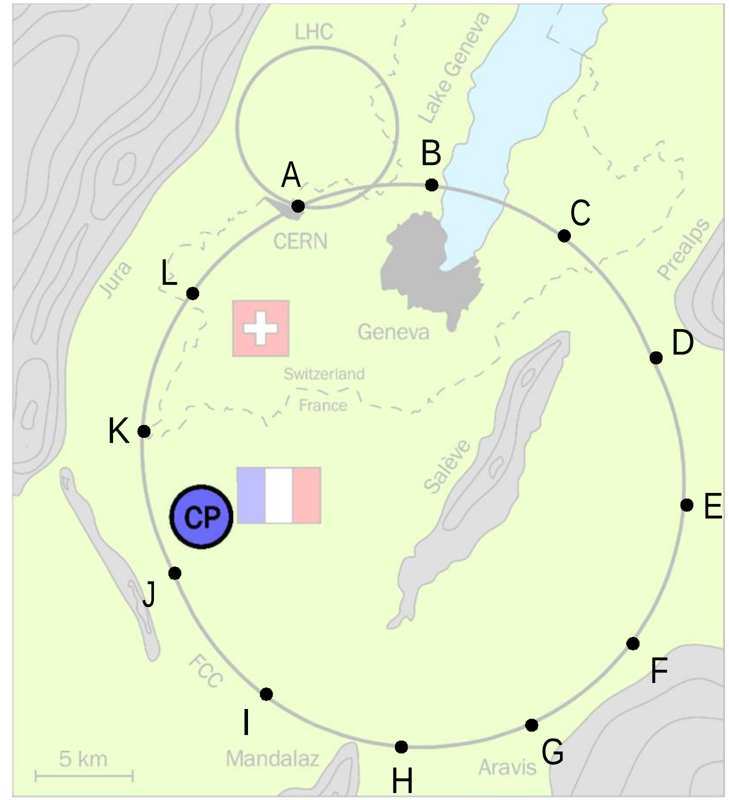




Newly installed 400 MHz RF Module @ 4.5 K Formerly installed 400 MHz RF Module @ 4.5 K Newly installed 800 MHz RF Module @ 2.0 K

FCC-ee Cryogenics: Stage 2/4 (w-Boson)

Frequency	400 MHz	800 MHz
T_{sat} (p_{Sat})	4.5 K (1.3 bar)	2.0 K (30 mbar)
Number Cryoplants	1 CP @ Point J	-
RF voltage	750 MV	-
Cryopower / Cryoplant	41 kW @ 4.5 K	
Total Cryopower @ 4.5 K	41 kW @ 4.5 K	
Electrical Power	9.5 MW	

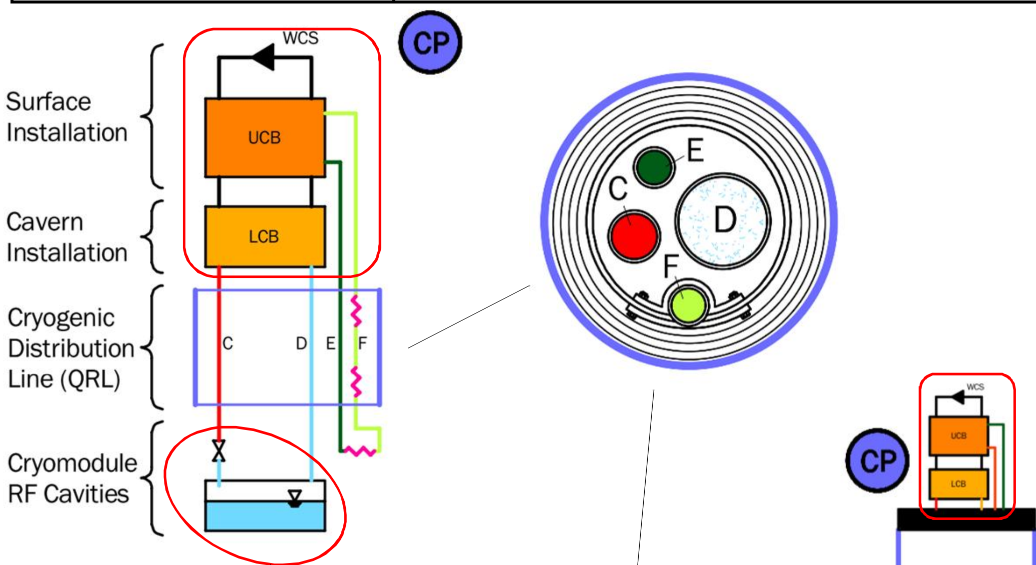


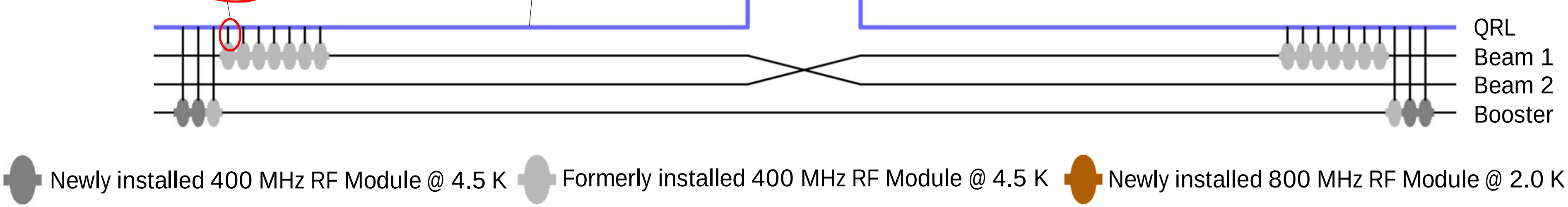
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)

Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)

Header E: Thermal Shields Supply (50 K / 20 bar)

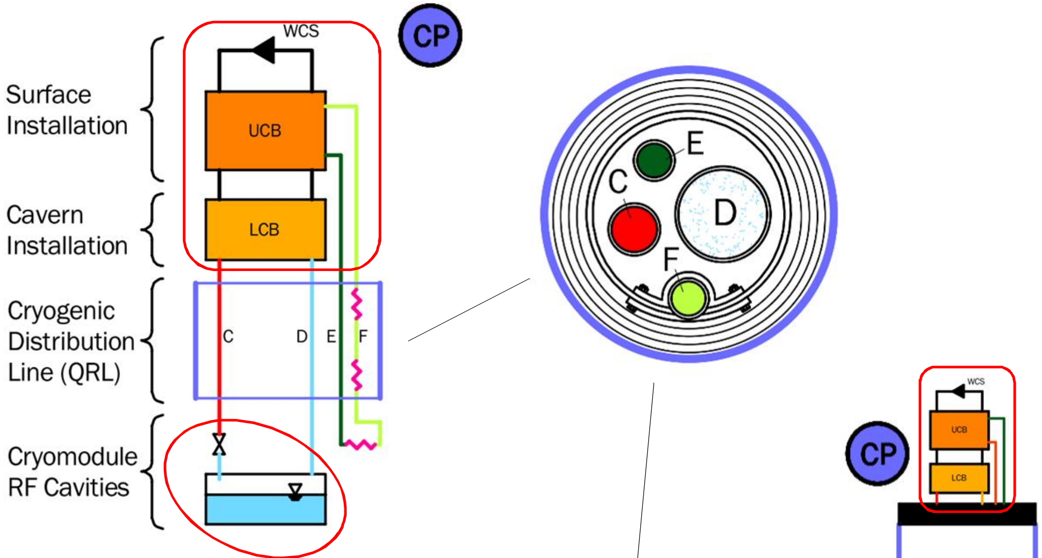
Header F: Thermal Shields Return (75 K / 18 bar)

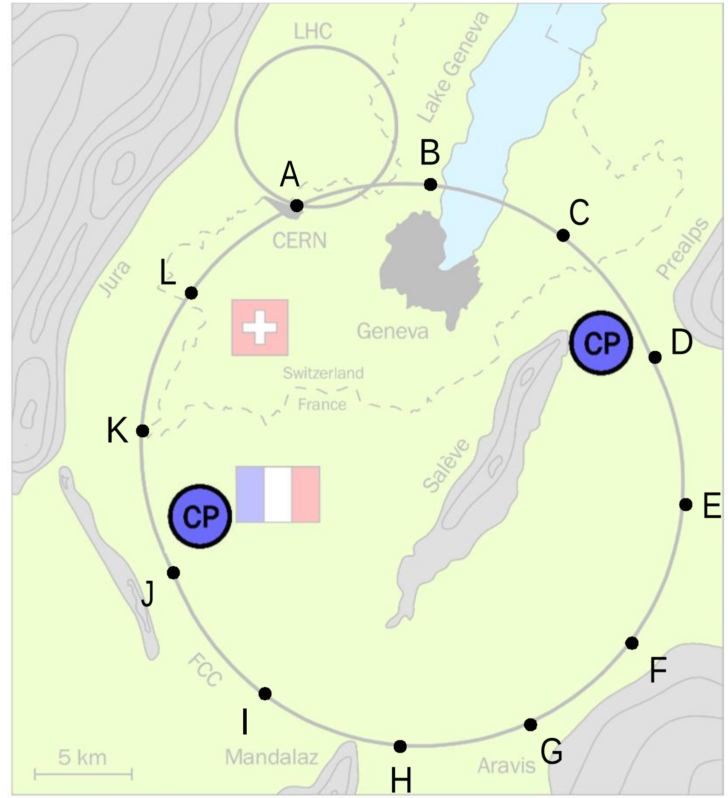




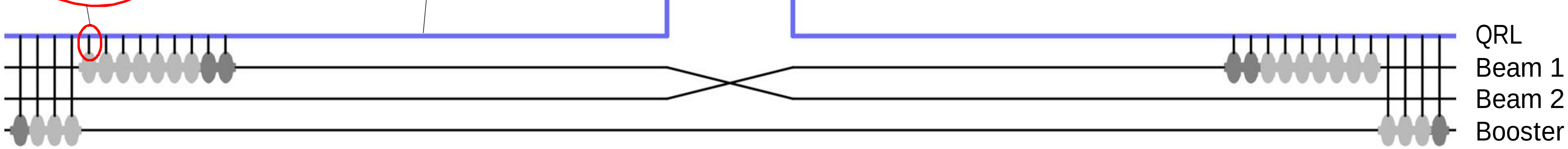
FCC-ee Cryogenics: Stage 3/4 (Higgs Boson)

Frequency	400 MHz	800 MHz
T_{sat} (p_{Sat})	4.5 K (1.3 bar)	2.0 K (30 mbar)
Number Cryoplants	1 CP @ Point J & D	-
RF voltage	2000 MV	-
Cryopower / Cryoplant	41 kW @ 4.5 K	
Total Cryopower @ 4.5 K	82 kW @ 4.5 K	
Electrical Power	19 MW	





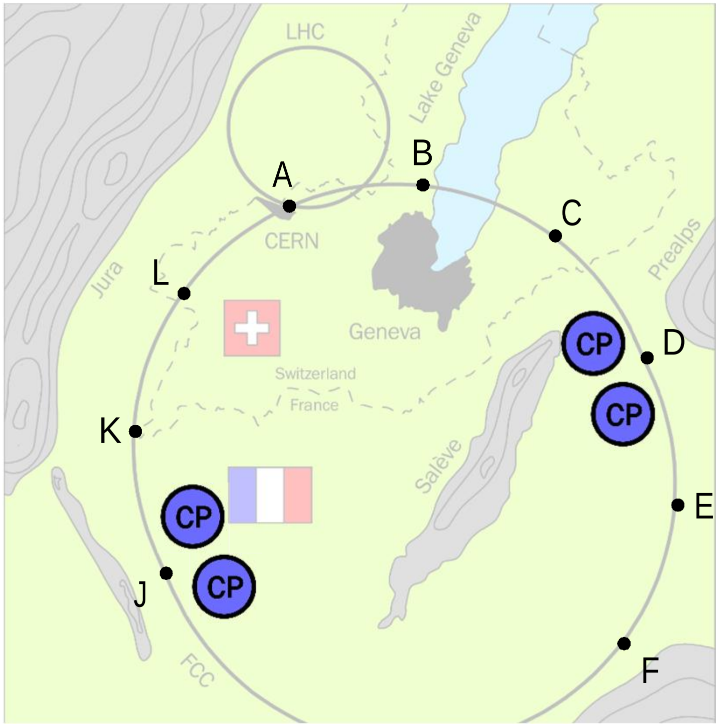
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)

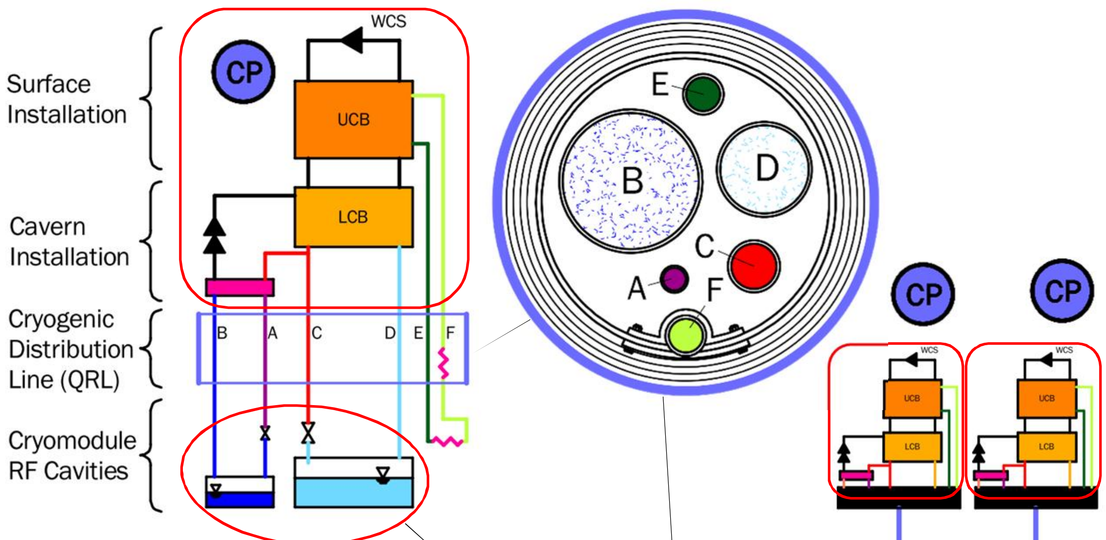


Newly installed 400 MHz RF Module @ 4.5 K   Formerly installed 400 MHz RF Module @ 4.5 K   Newly installed 800 MHz RF Module @ 2.0 K

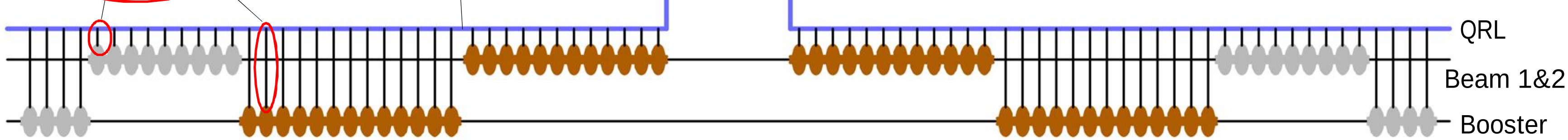
FCC-ee Cryogenics: Stage 4/4 (Top Quark)

Frequency	400 MHz	800 MHz
T_{sat} (p_{Sat})	4.5 K (1.3 bar)	2.0 K (30 mbar)
Number Cryoplants	2 CPs @ Point J & D	2 CPs @ Point J & D
RF voltage	4000 MV	5400 / 6900 MV
Cryopower / Cryoplant	41 kW @ 4.5 K & 12 kW @ 2.0 K	
Total Cryopower @ 4.5 K	252 kW @ 4.5 K	
Electrical Power	58 MW	





Header A: 800 MHz RF Cavities Supply (2.2 K / 1.3 bar)
Header B: 800 MHz RF Cavities Supply (2.0 K / 30 mbar)
Header C: 400 MHz RF Cavities Supply (4.6 K / 3 bar)
Header D: 400 MHz RF Cavities Return (4.5 K / 1.3 bar)
Header E: Thermal Shields Supply (50 K / 20 bar)
Header F: Thermal Shields Return (75 K / 18 bar)



Newly installed 400 MHz RF Module @ 4.5 K
Formerly installed 400 MHz RF Module @ 4.5 K
Newly installed 800 MHz RF Module @ 2.0 K

Cold Mass Cooling

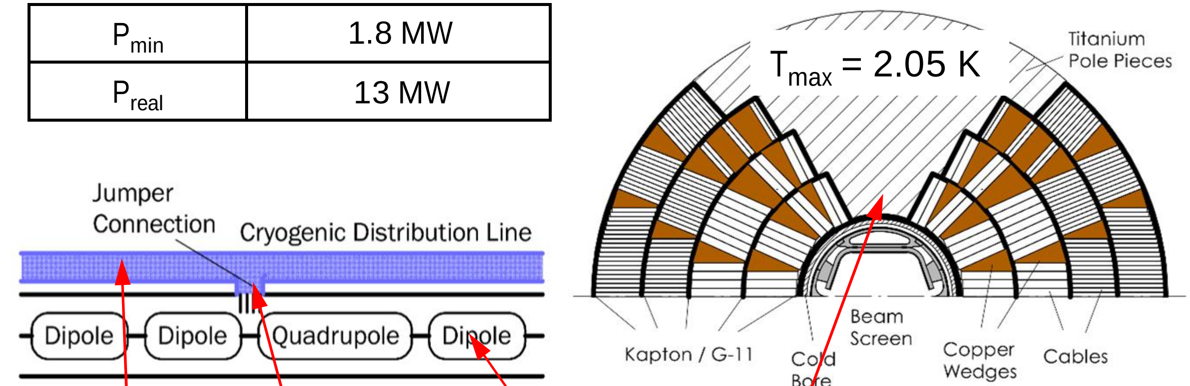
Values for one long sector:

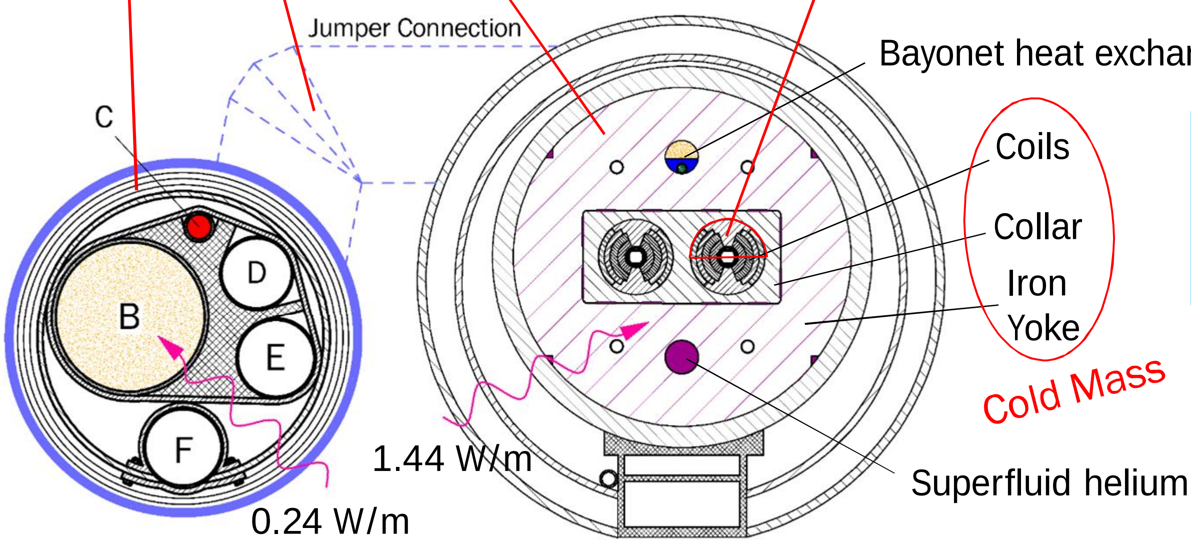
Q_{CM}	12.1 kW
Q_B	2 kW

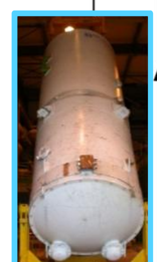
@ 1.8 K

P_{min}	1.8 MW
P_{real}	13 MW

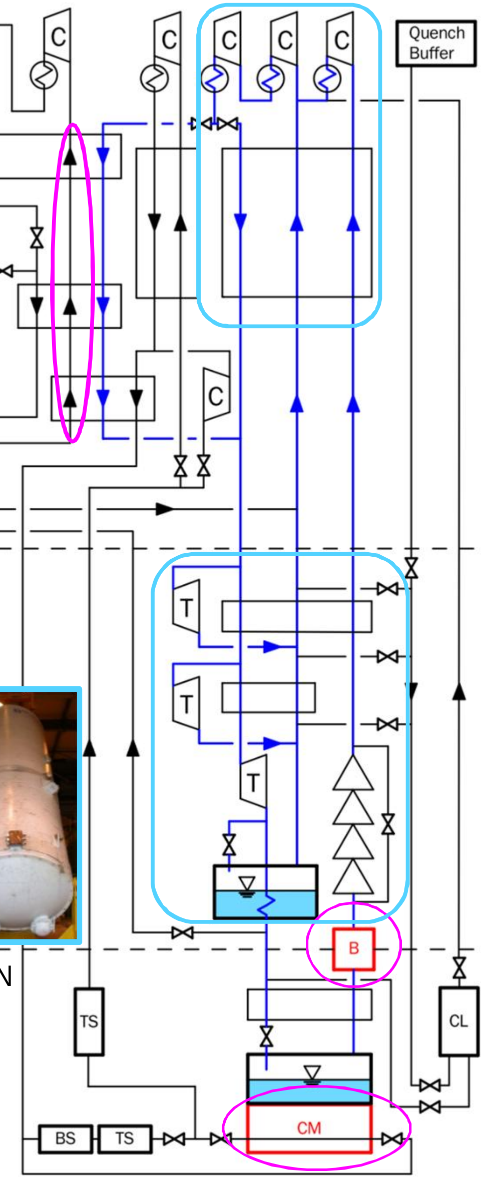
Courtesy of CERN







Courtesy of CERN



Beam Screens and Thermal Shields (Baseline)

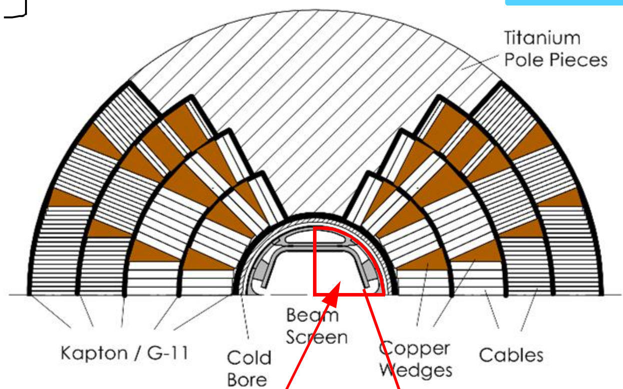
Values for one long sector:

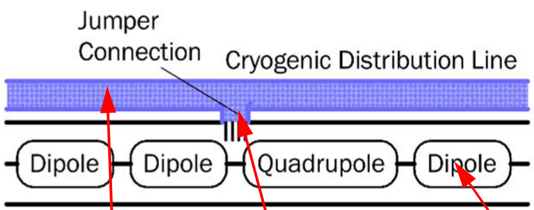
Q_{BS}	520 kW
Q_{TS}	80 kW
P_{Circ}	100 kW

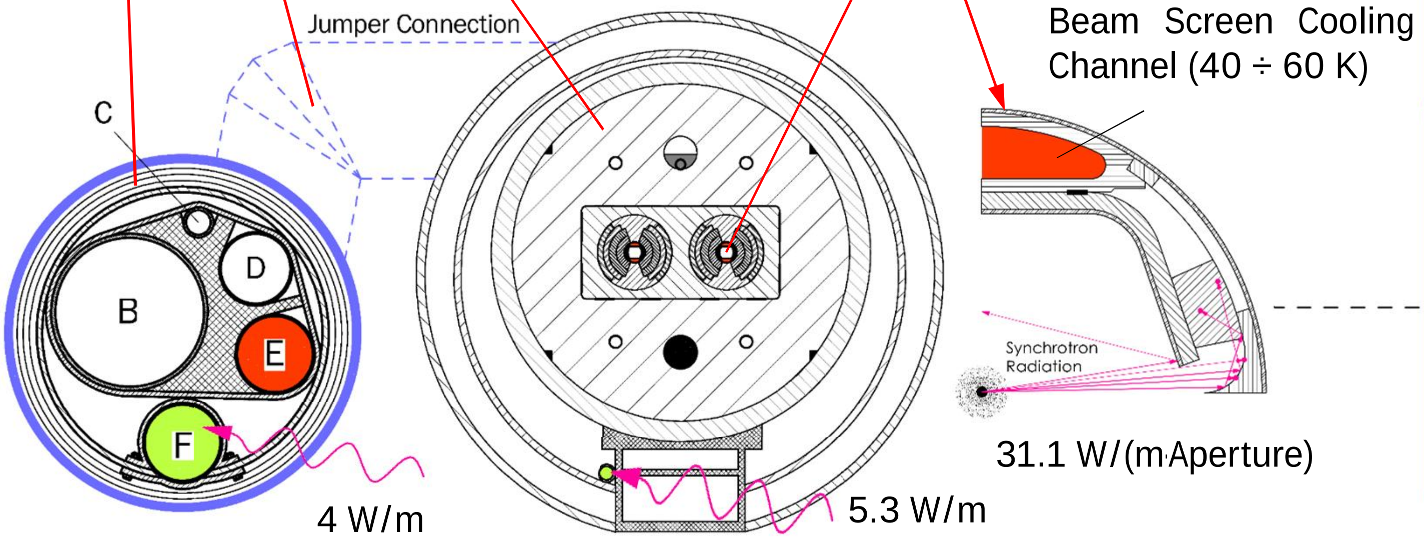
@ 40 ÷ 62 K

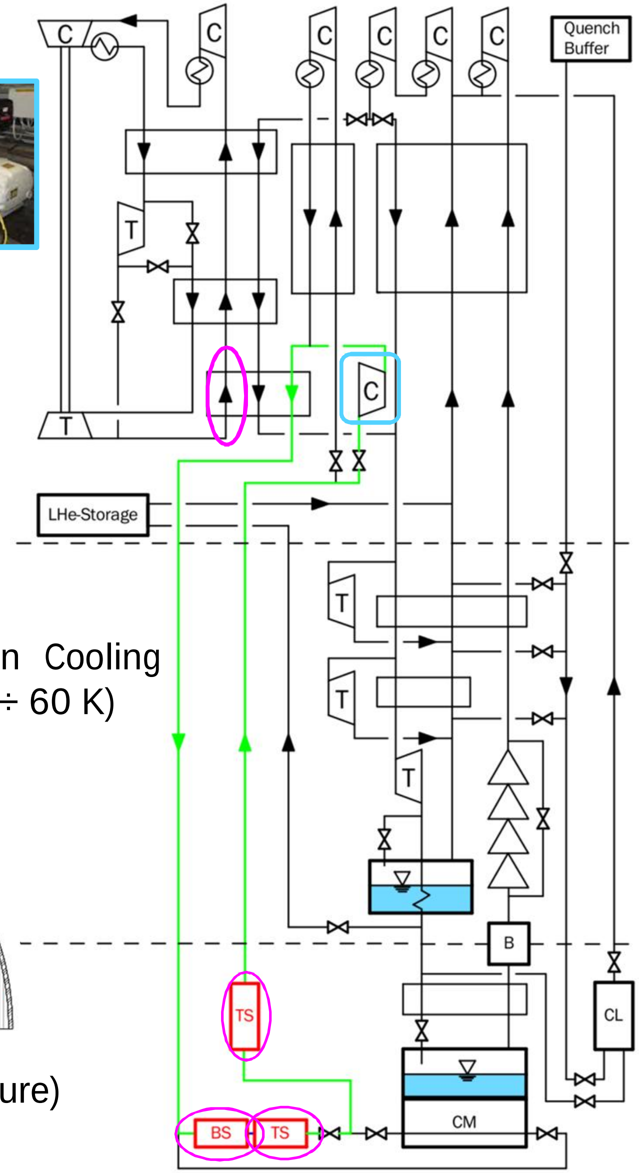
P_{min}	2.9 MW
P_{real}	8.1 MW

Courtesy of CERN









Beam Screens and Thermal Shields (Option)

Values for one long sector:

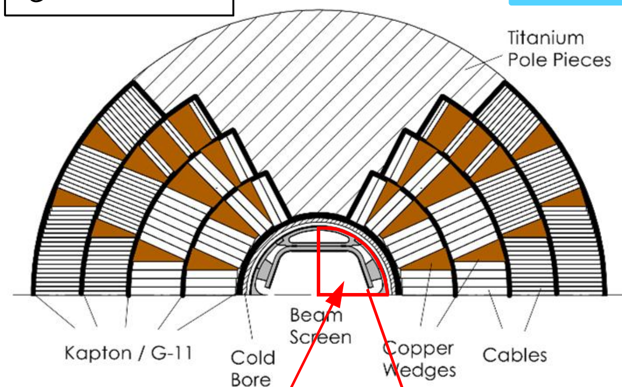
Q_{BS}	520 kW
Q_{TS}	80 kW
P_{Circ}	370 kW

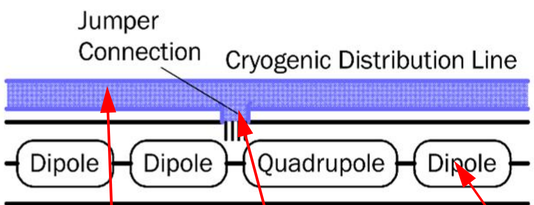
Q_{BS}, Q_{TS}: @ 40 ÷ 62 K

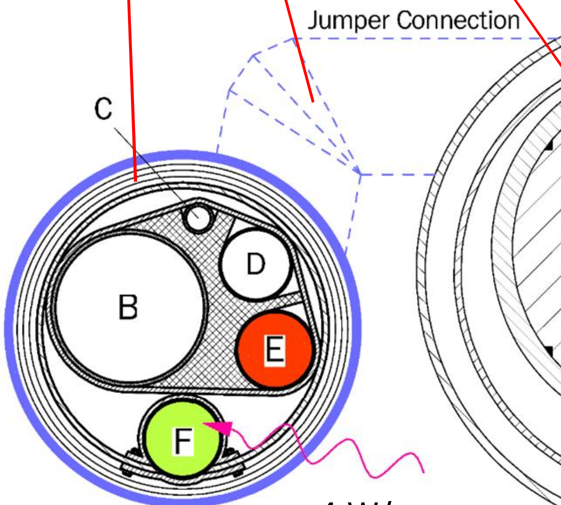
P_{Circ}: @ 40 ÷ 300 K

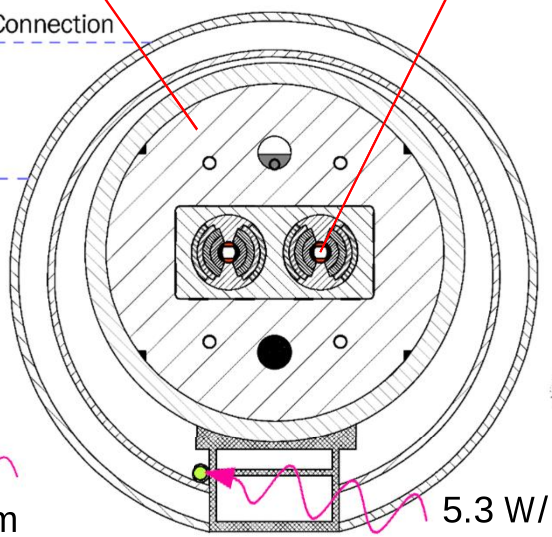
P_{min}	2.9 MW
P_{real}	8.7 MW

Courtesy of CERN

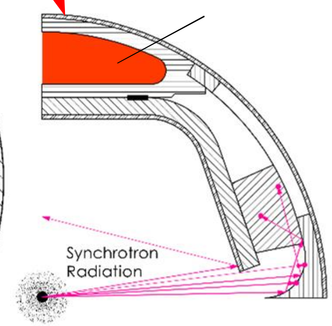




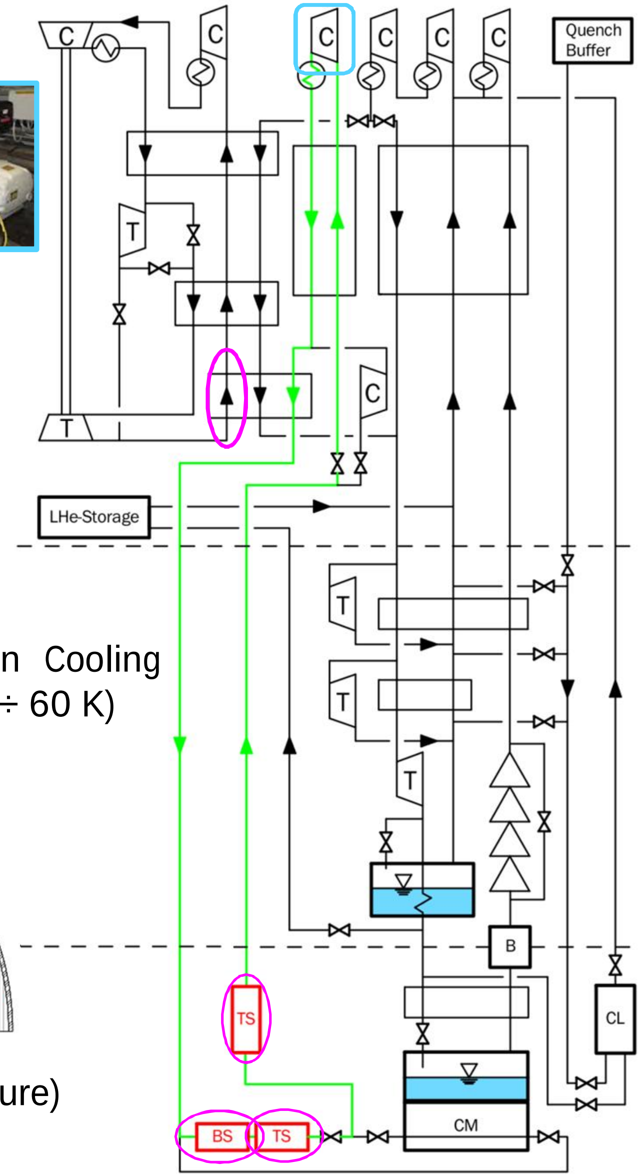


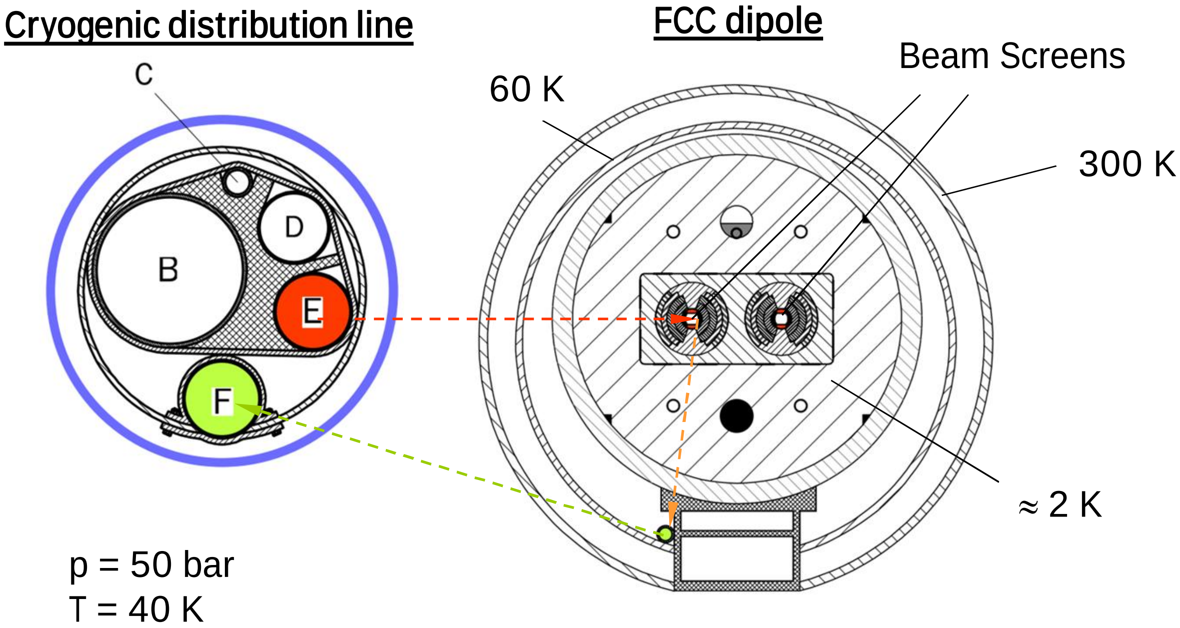


Beam Screen Cooling Channel (40 ÷ 60 K)



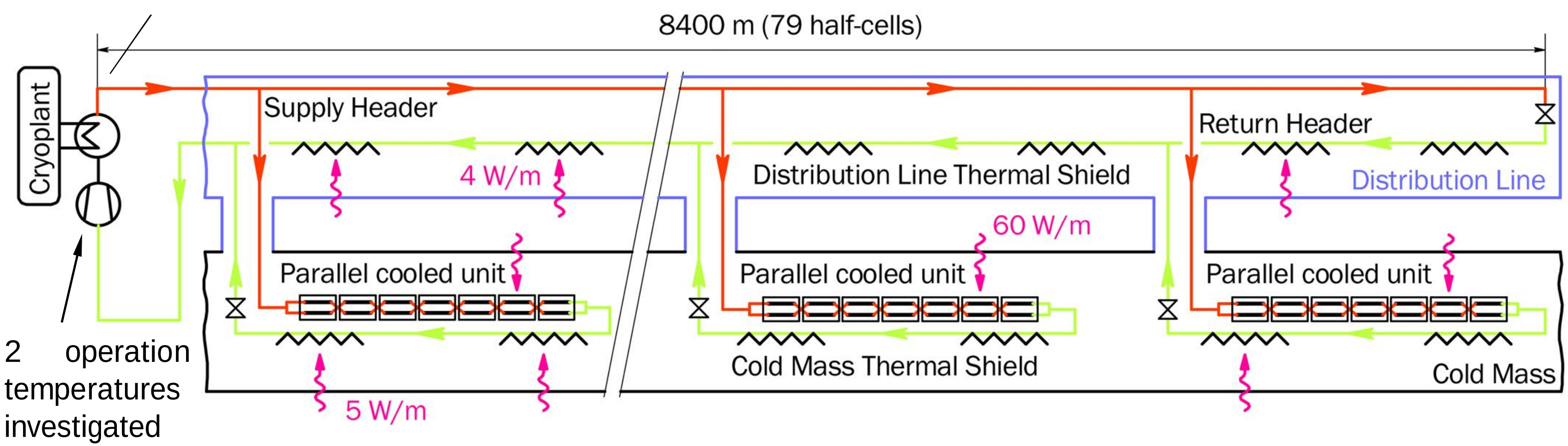
31.1 W/(m·Aperture)





Beam screens works as thermal barriers to shield the cold mass (T < 2 K) against beam induced heat loads

1. The branched flow is divided and passes 4 cooling channels in 2 beam screens
2. Heat sources generate a heat load of about 60 W/m on the beam screens in total

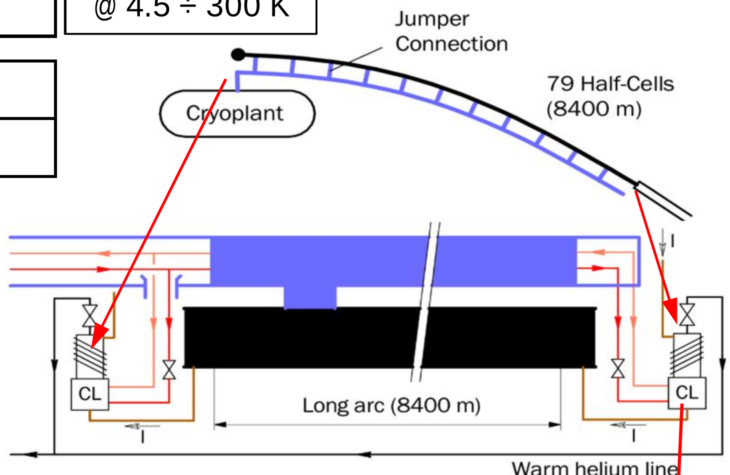


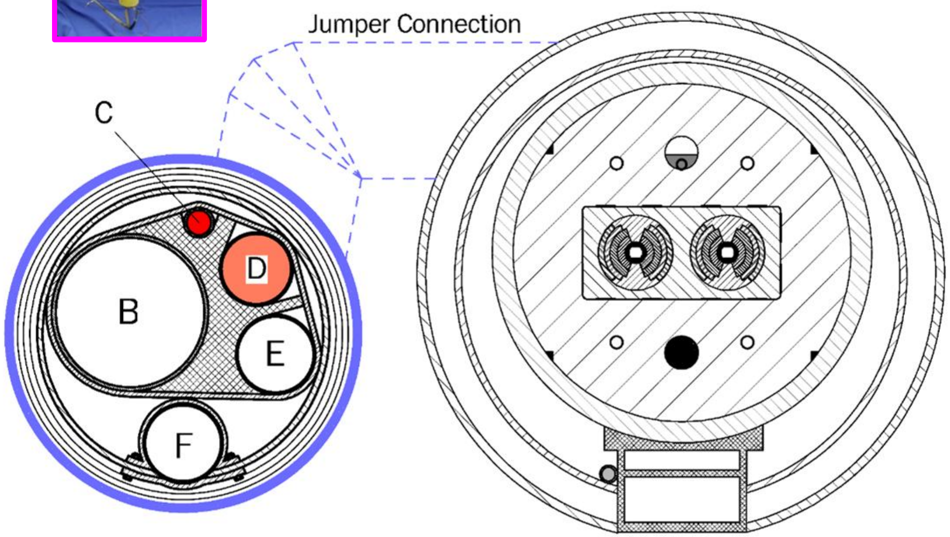
Current Leads

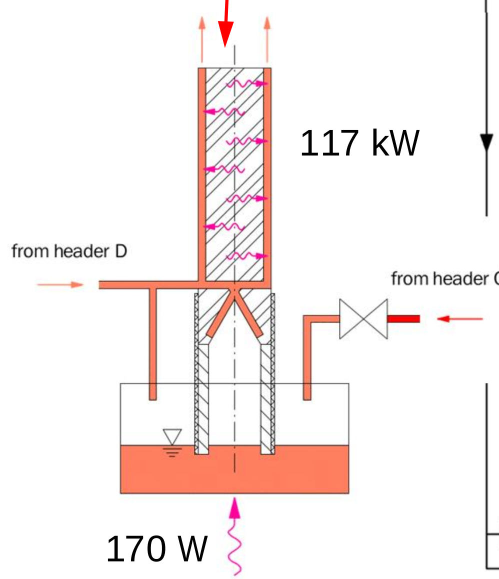
Values for one long sector:

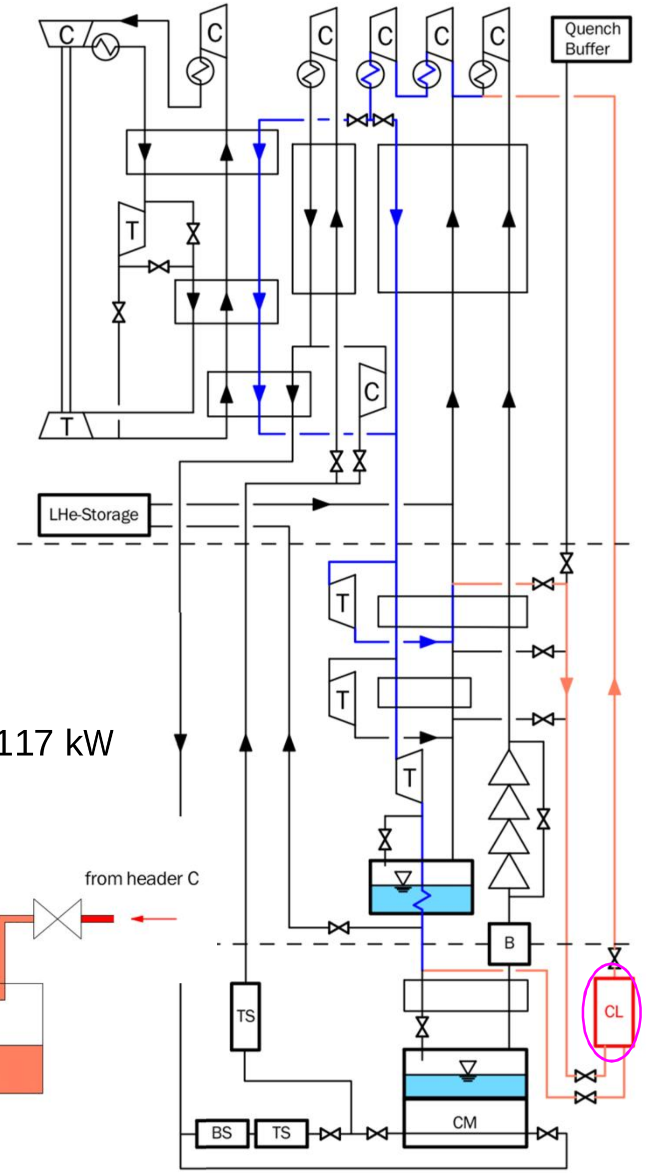
Q_{CL}	117 kW	@ 4.5 ÷ 300 K
P_{min}	175 kW	
P_{real}	680 kW	

Courtesy of CERN









FCC-hh Cryogenics: Nelium Cycle

Nelium Brayton Cycle

- Uses a blend of helium (75 %) and neon (25 %)
  → Increased density:
    - Higher pressure ratios per stage
    - Centrifugal instead of volumetric machine
- Cooling Capacity (@ 40 ÷ 300 K):
    - 700 kW @ 40 ÷ 63 K (Beam Screen & Thermal Shield)
    - 270 kW @ 40 ÷ 300 K (Cold Mass & Current Leads)

Cool-Down and Warm-Up Operations

- Baseline: Cool Down and Warm Up operations with the Beam Screen Cooling flow scheme, a Warm Compressor and the Nelium Cycle