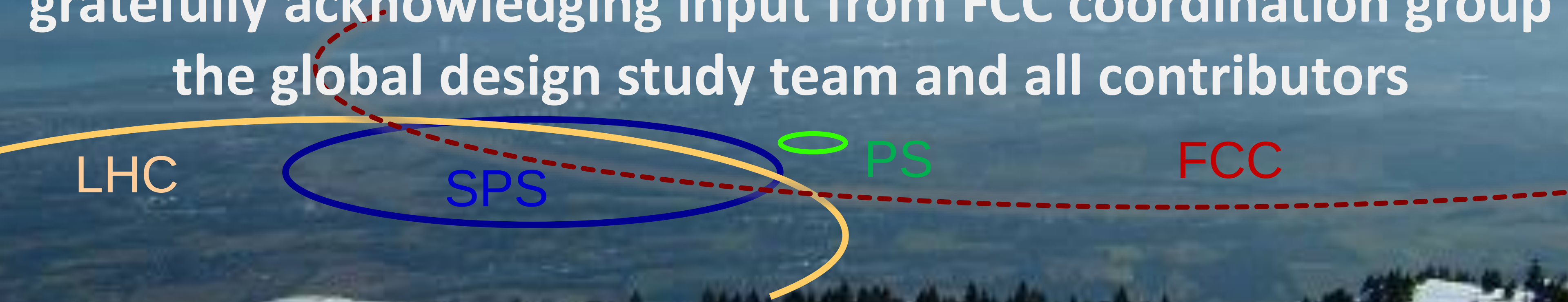
Future strategies and technologies

M. Benedikt

gratefully acknowledging input from FCC coordination group the global design study team and all contributors



http://cern.ch/fcc

*Work supported by the **European Commission** under the HORIZON 2020 project EuroCirCol, grant agreement 654305*

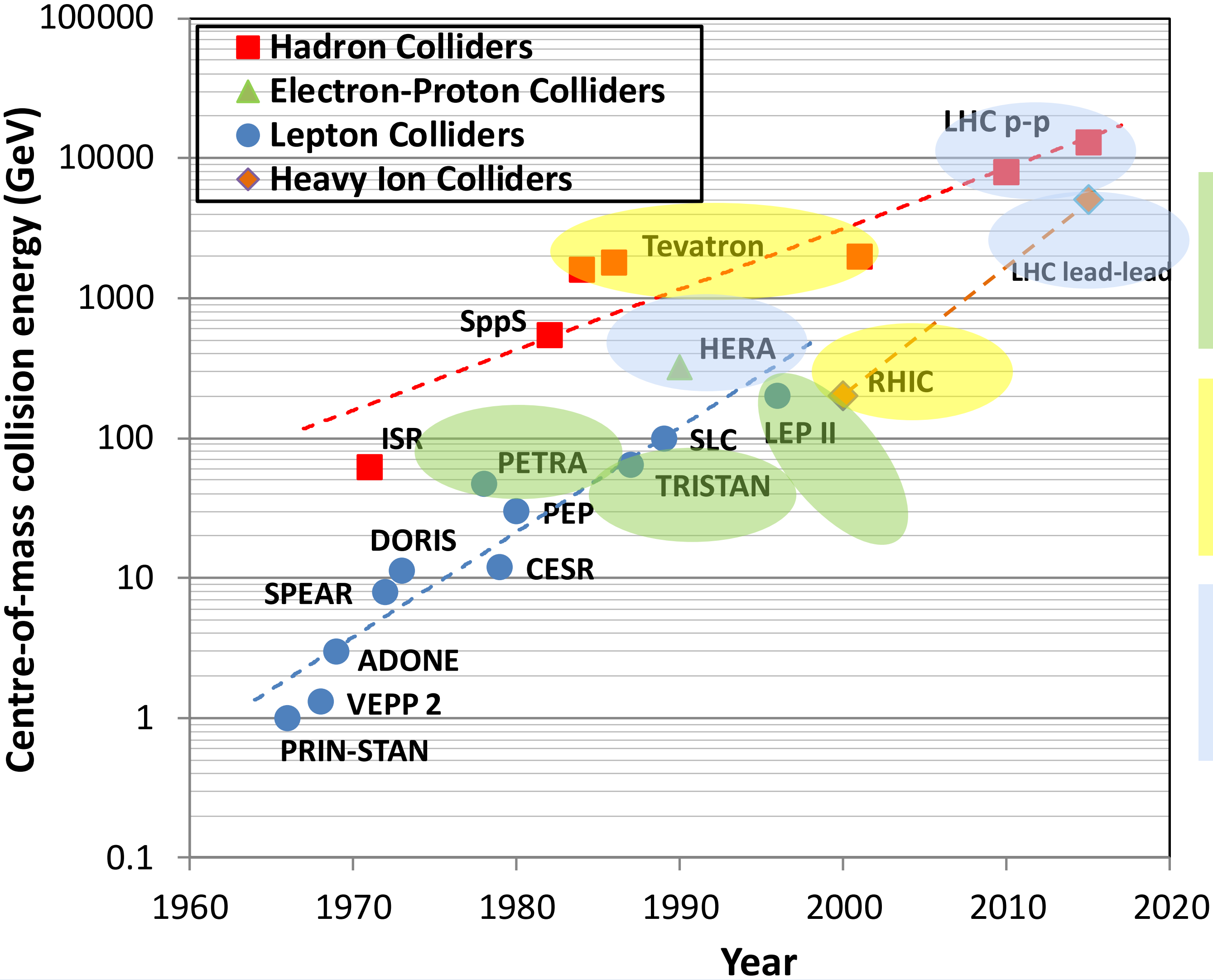
High energy accelerators & colliders

- Using **electrical fields (RF cavities)** to accelerate **and magnetic fields (accelerator magnets)** to guide and collide **charged particle beams** (electrons, protons & anti-particles)

- **Aim at higher energy accelerators for 2 reasons:**
  - **Production of new heavier particles (according to Einstein):** **E** = **m**$c^2 \leq$ 2E beam (collider)
  - **Resolving smaller distances (according to de Broglie):** **Wavelength** λ = hc/**E** **for LHC** ~ $2 \cdot 10^{-18}$ cm

Higher energy → **Increased potential for discoveries**

Colliders constructed and operated

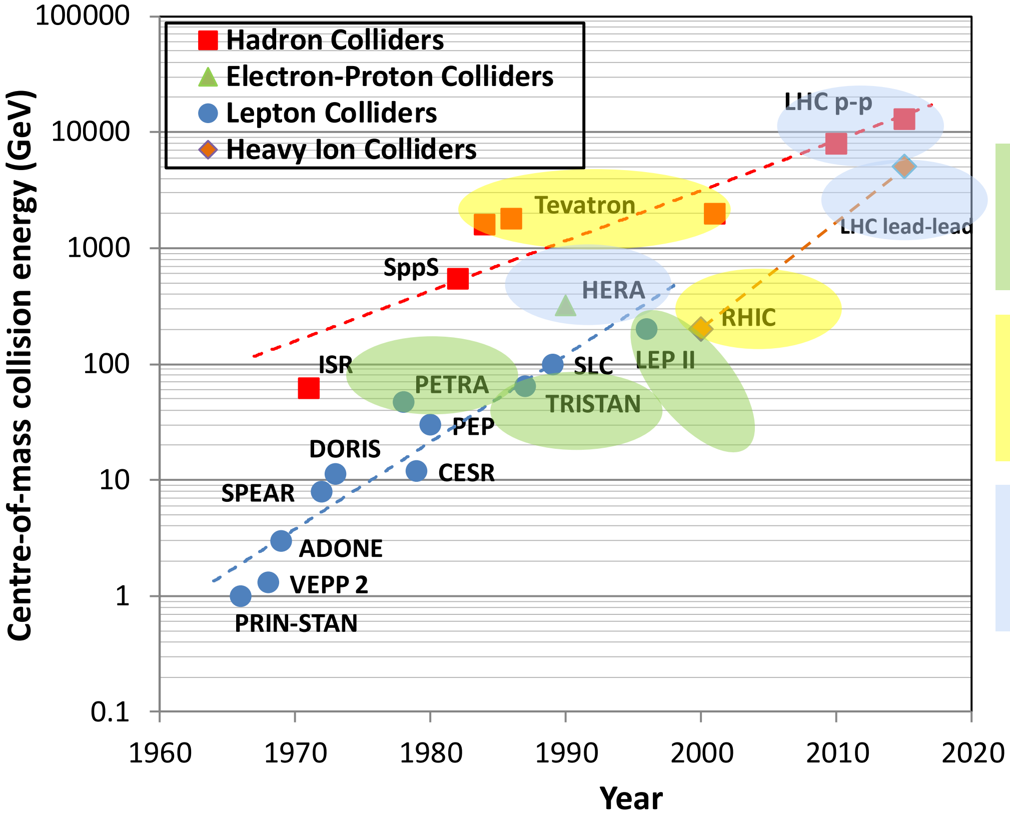


Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF

Colliders constructed and operated



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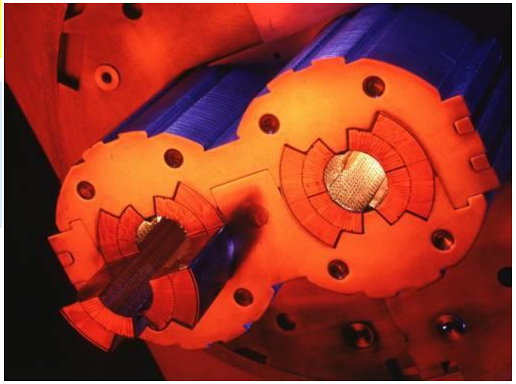
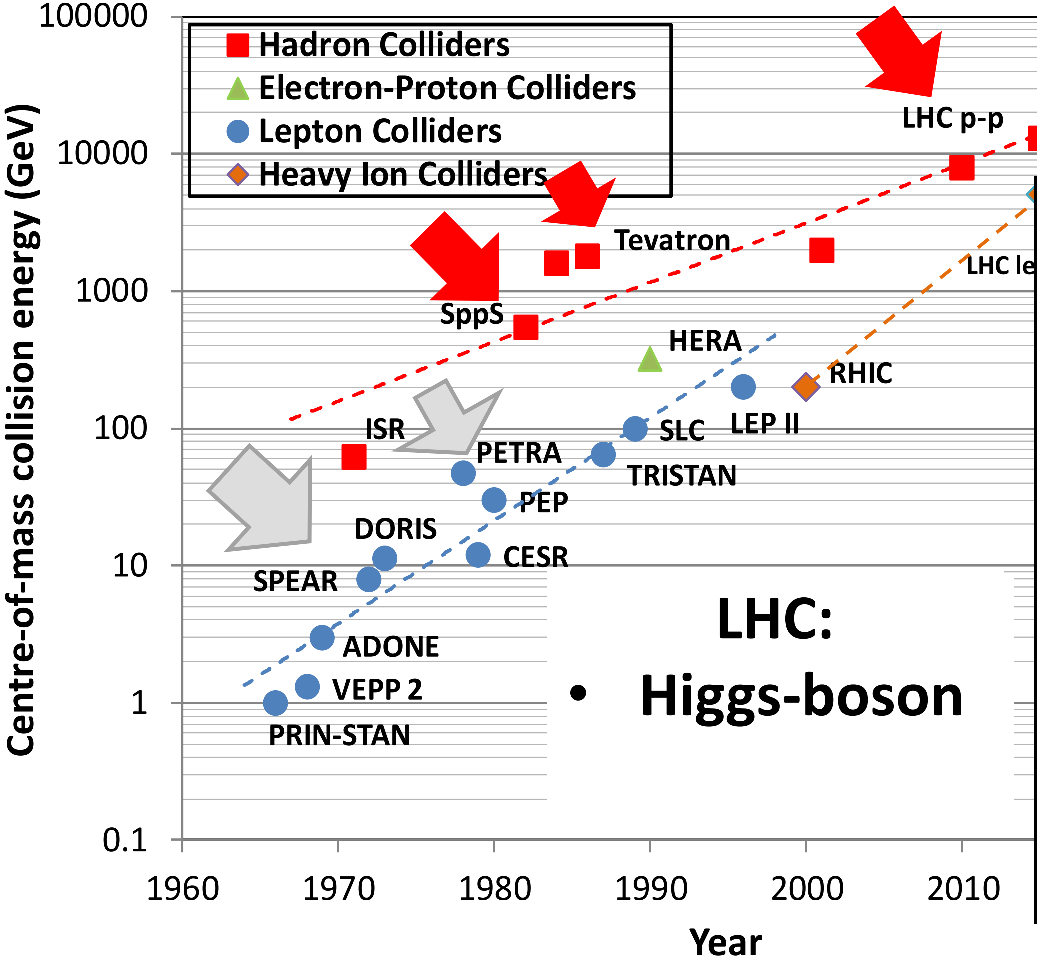
Colliders with superconducting magnet & RF



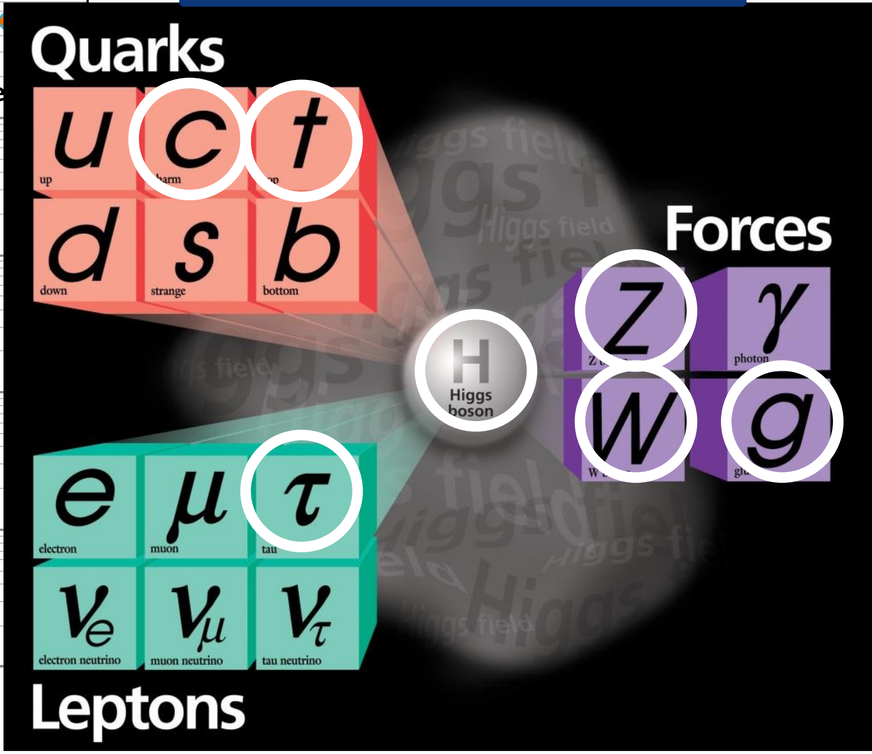
Discoveries by colliders



LHC:

- **Higgs-boson**

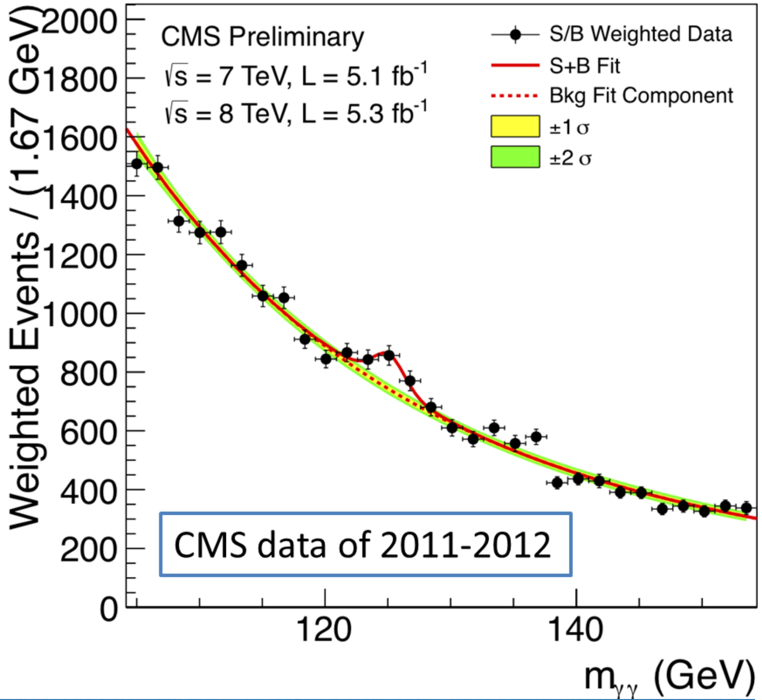
Standard Model Particles and forces



Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

LHC: present collider flagship

2012: Higgs boson discovery



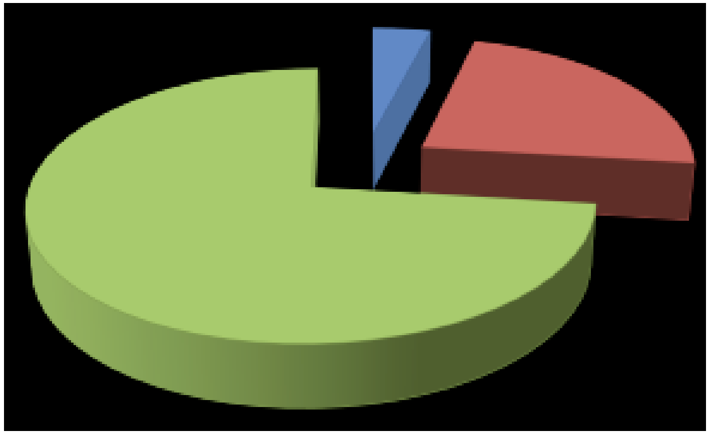
CMS data of 2011-2012

Nobel Prize in Physics 2013

François Englert
Université Libre de Bruxelles, Belgium

Peter W. Higgs
University of Edinburgh

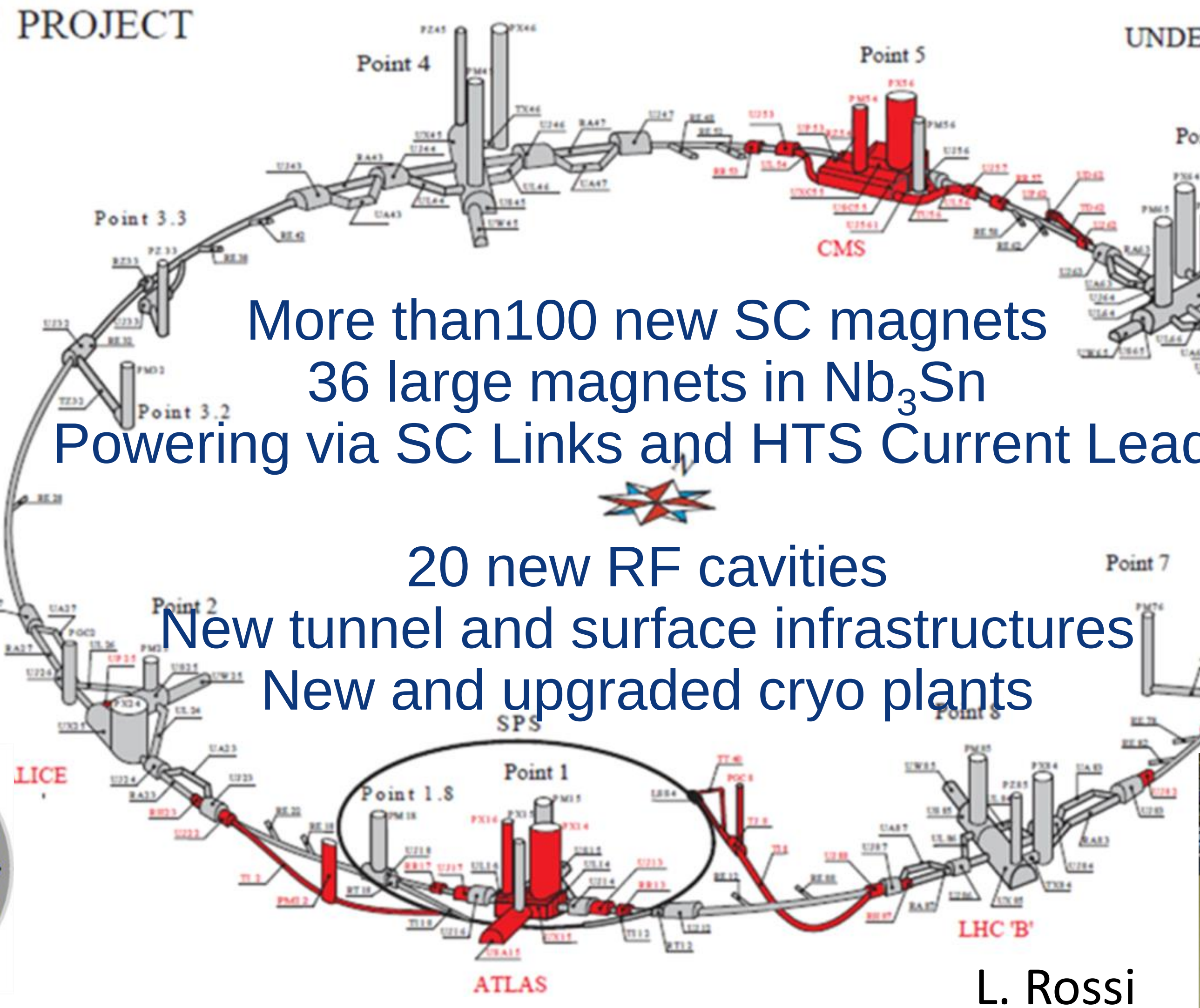
- Completes standard model describing known matter, **BUT this is only 5% of the universe!**



- what is dark matter?
- what is dark energy?
- why is there more matter than antimatter?
- what about gravity?
- etc…

→ Upgrade and full exploitation of LHC as first step

High Luminosity LHC project scope



More than100 new SC magnets

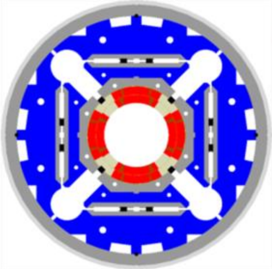
36 large magnets in Nb_3Sn

Powering via SC Links and HTS Current Leads

20 new RF cavities

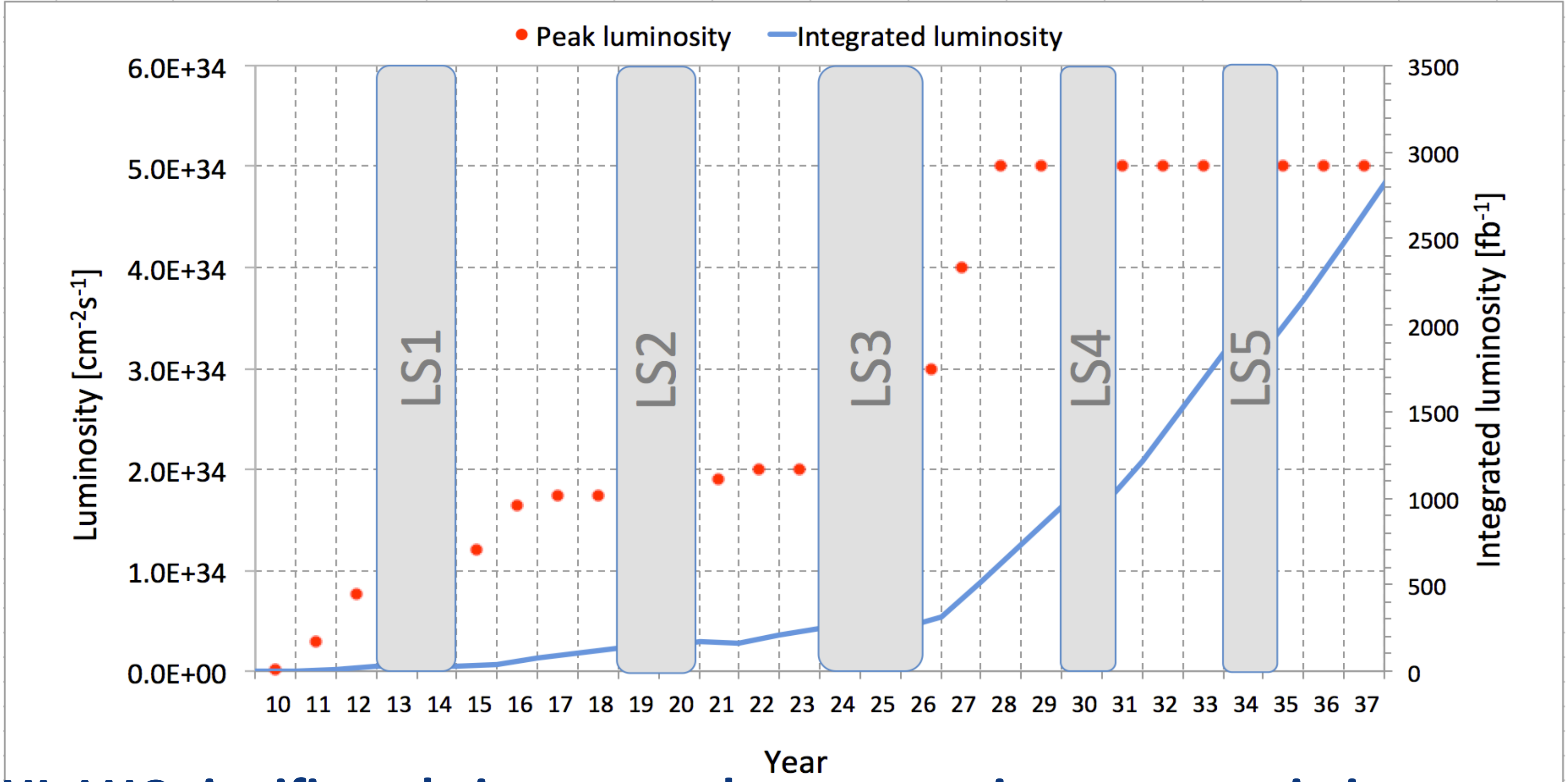
New tunnel and surface infrastructures

New and upgraded cryo plants



L. Rossi

Step 1: HL-LHC upgrade – ongoing



HL-LHC significantly increases data rate to improve statistics, measurement precision, and energy reach in search of new physics

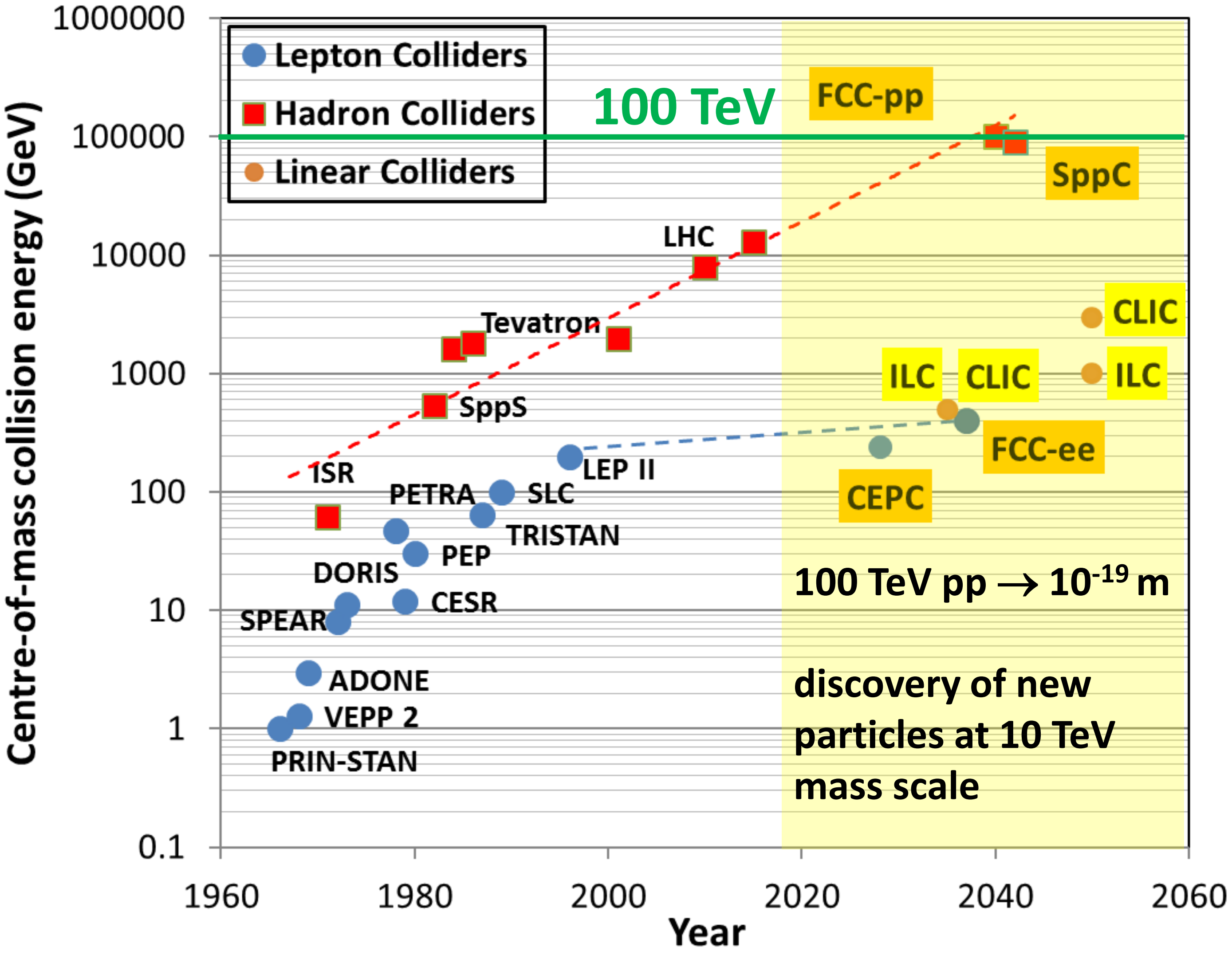
Gain of a factor 5 in rate, factor 10 in integral data wrt initial design

Step 2: Future high energy colliders

For physics beyond the LHC and beyond the Standard Model, under study (synergy of):

- **Linear e^+e^- colliders** (CLIC, ILC)
  E_{CM} up to ~ **3 TeV**
- **Circular e^+e^- colliders** (CepC, FCC-ee)
  E_{CM} up to ~ **400 GeV** - limited by $e^{\pm}$ synchrotron radiation. Ideal for **precision measurements**
- **Circular p-p colliders** (SppC, FCC)
  E_{CM} up to ~ **100 TeV**
  Ideal for **discoveries at higher energy frontiers**

High Energy Colliders under study



100 TeV pp → 10^{-19} m

discovery of new particles at 10 TeV mass scale

European Strategy Update 2013

“CERN should undertake ***design studies*** *for accelerator projects in a* ***global context****, with emphasis on proton-proton and electron-positron* ***high-energy frontier*** *machines.”*

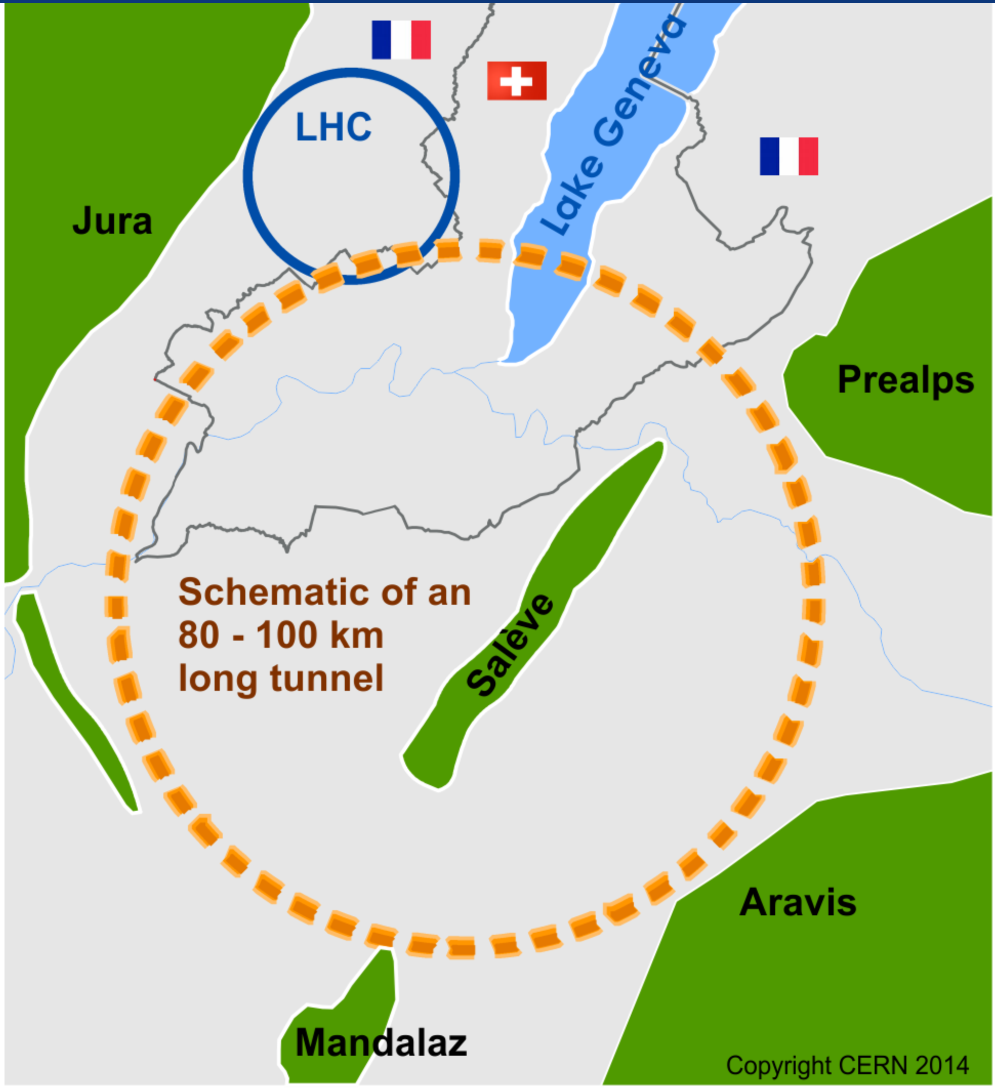
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

International FCC collaboration (CERN as host lab) to study:

- ***pp*-collider (*FCC-hh*)**
  → main emphasis, defining infrastructure requirements

~16 T ⇒ 100 TeV *pp* in 100 km

- **80-100 km tunnel infrastructure** in Geneva area, site specific
- ***e^+e^-* collider (*FCC-ee*),** as potential first step
- ***p-e* (*FCC-he*) option,** integration one IP, FCC-hh & ERL
- **HE-LHC** with *FCC-hh* technology



Tevatron (closed)

Circumference: **6.2 km**

Energy: **2 TeV**

Large Hadron Collider

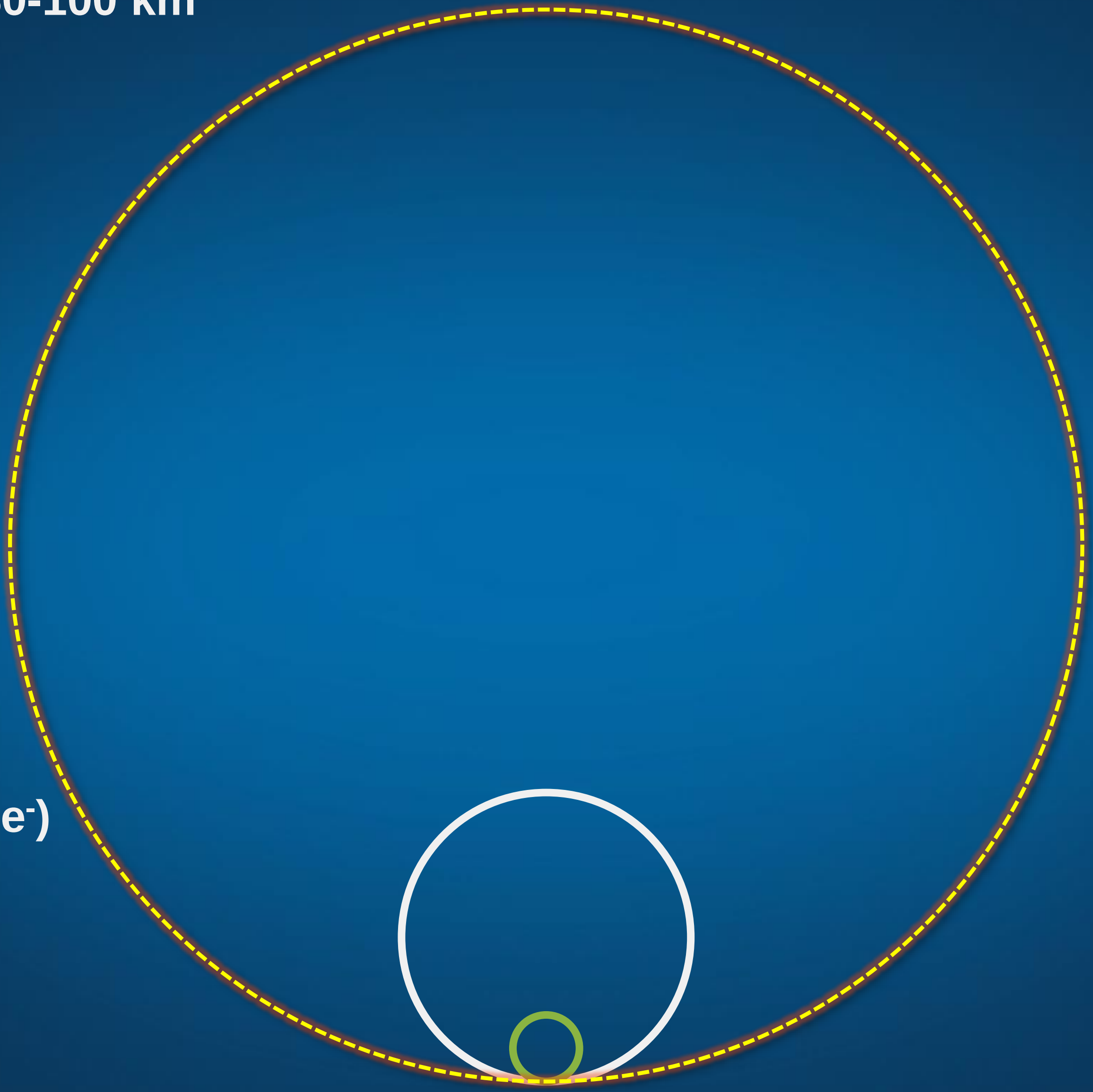
Circumference: **27 km**

Energy:

- **14 TeV (pp)**
- **209 GeV (e^+e^-)**

Future Circular Collider

Circumference: **80-100 km**



Energy:

- **100 TeV (pp)**
- **>350 GeV (e^+e^-)**

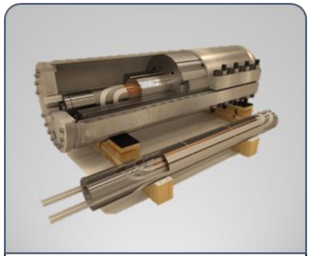
FCC Scope: Accelerator and Infrastructure

Collider Designs

FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs

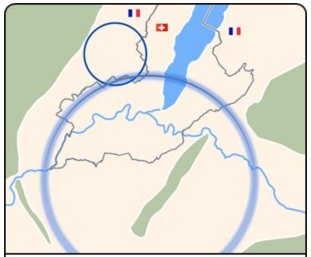
FCC-ee: **e^+e^- collider**, potential intermediate step

HE-LHC: **based on FCC-hh technology**



R&D Programs

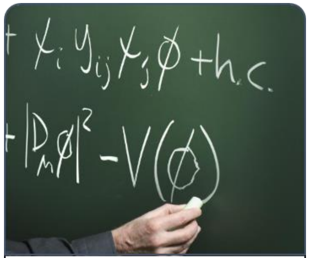
Launch R&D on key enabling technologies in dedicated R&D programmes, e.g.
16 Tesla magnet program, cryogenics, SRF technologies and RF power sources



Infrastructures

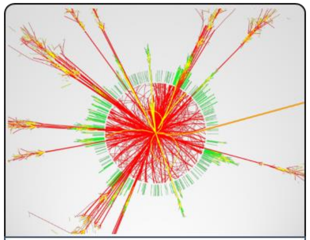
Tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European strategy

FCC Scope:
Physics & Experiments



Physics Cases

Elaborate and document
- **Physics opportunities**
- **Discovery potentials**



Experiments

Experiment concepts for hh, ee and he
Machine Detector Interface studies
R&D needs for **detector technologies**

Cost Estimates

Overall **cost model for collider scenarios** including infrastructure and injectors
Develop **realization concepts**
Forge **partnerships with industry**

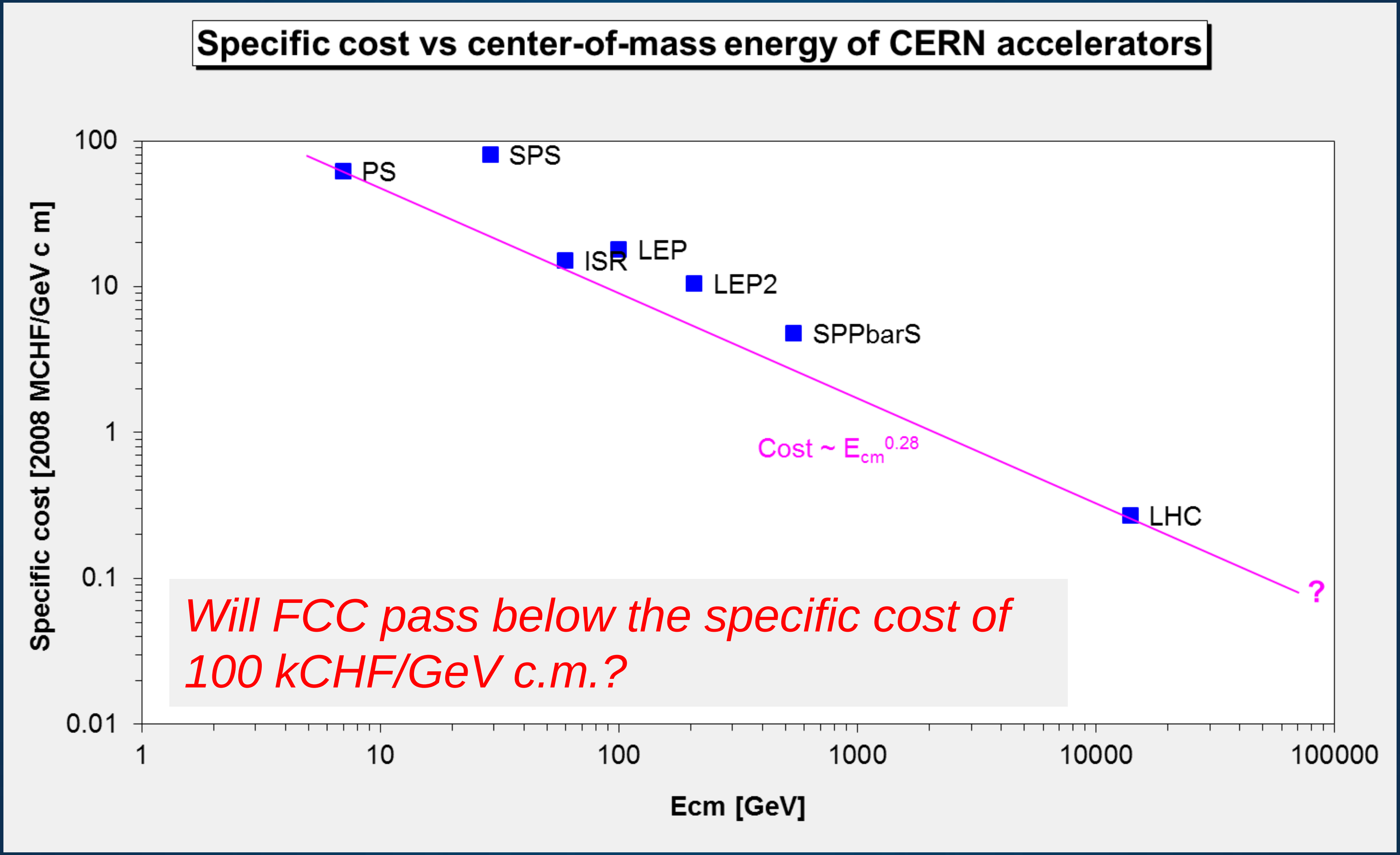
Role of CERN

- **Host** the study
- **Prepare** organisation frame
- **Setup** collaboration
- **Identify** R&D needs
- **Estimate** costs

Strategic Goals

- **Make funding bodies aware** of strategic needs for research community
- **Provide sound basis to policy bodies** to establish long-range plans in European interest
- **Strengthen capacity** and **effectiveness** in high-tech domains
- Provide a **basis for long-term attractiveness of Europe** as research area

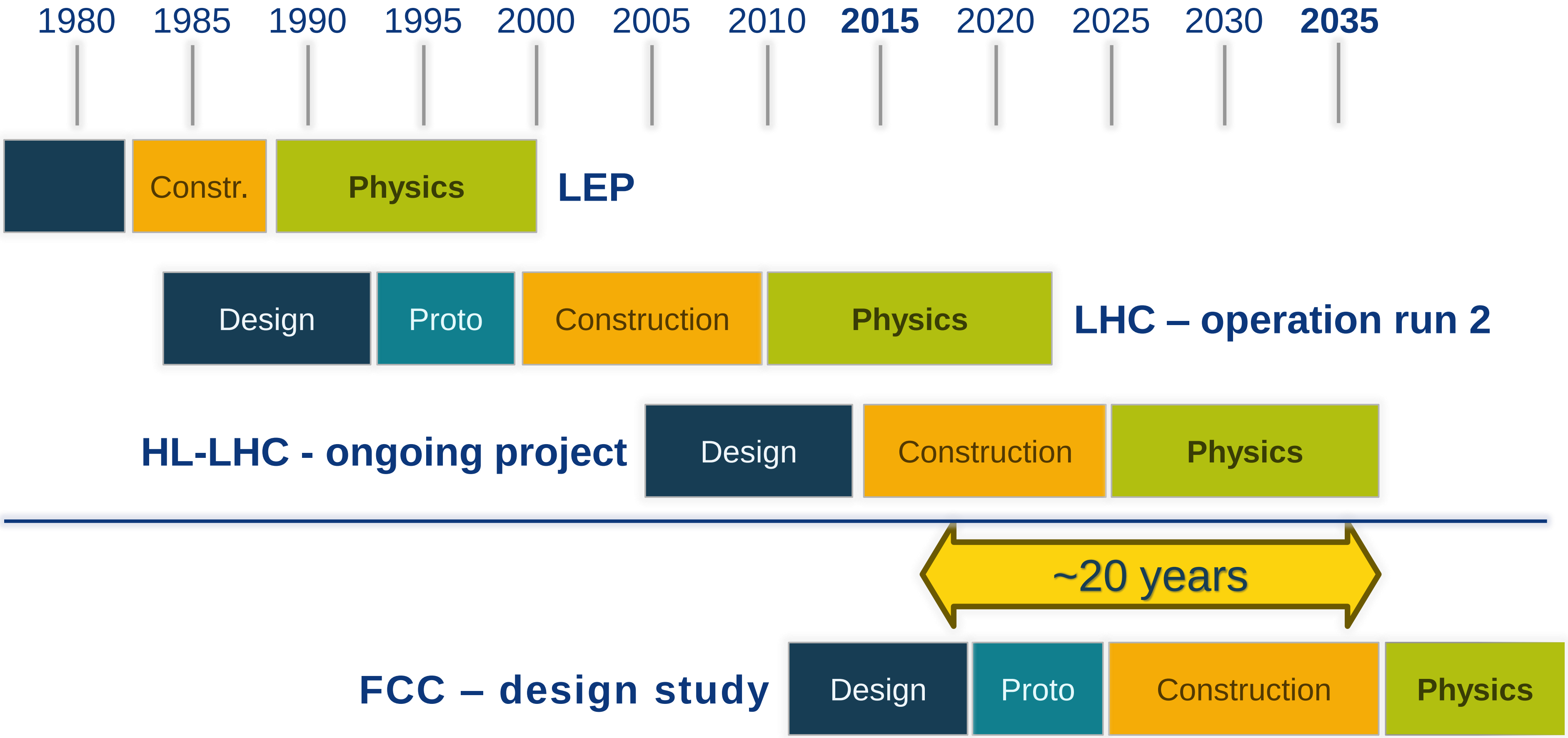
A sustained decrease in specific cost



Specific cost vs center-of-mass energy of CERN accelerators

Will FCC pass below the specific cost of 100 kCHF/GeV c.m.?

CERN Circular Colliders & FCC



1980 1985 1990 1995 2000 2005 2010 **2015** 2020 2025 2030 **2035**

Constr. | **Physics** | **LEP**

Design | Proto | Construction | **Physics** | **LHC – operation run 2**

HL-LHC - ongoing project | Design | Construction | **Physics**

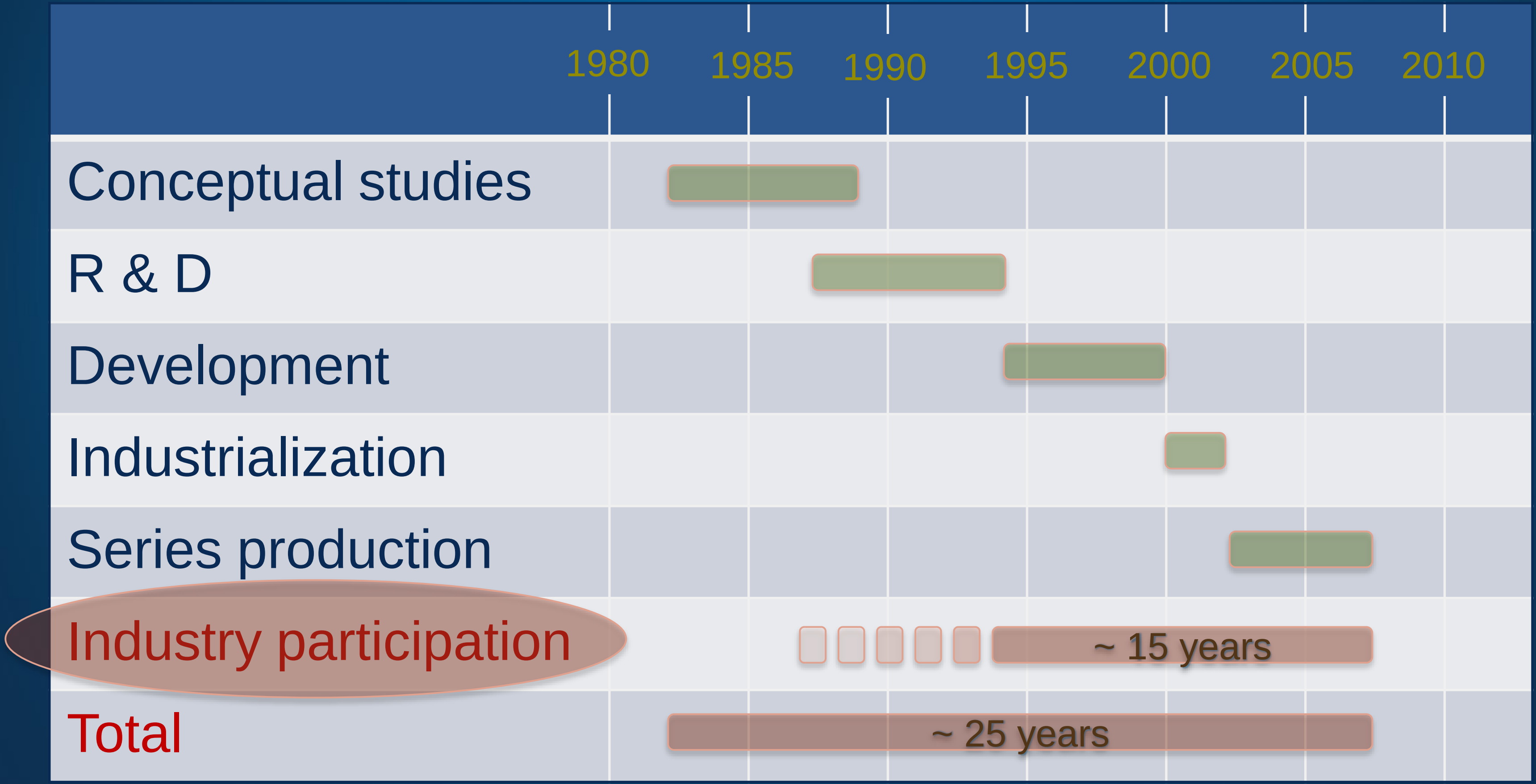
~20 years

FCC – design study | Design | Proto | Construction | **Physics**

Must advance fast now to be ready for the period 2035 – 2040
Goal of phase 1: CDR by end 2018 for next update of European Strategy

Time Indicator

Case: LHC superconducting dipole magnets



Conceptual studies

R & D

Development

Industrialization

Series production

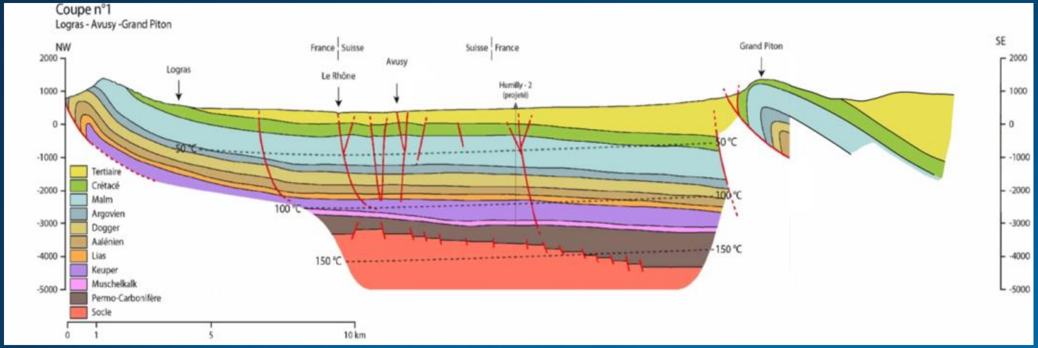
Industry participation

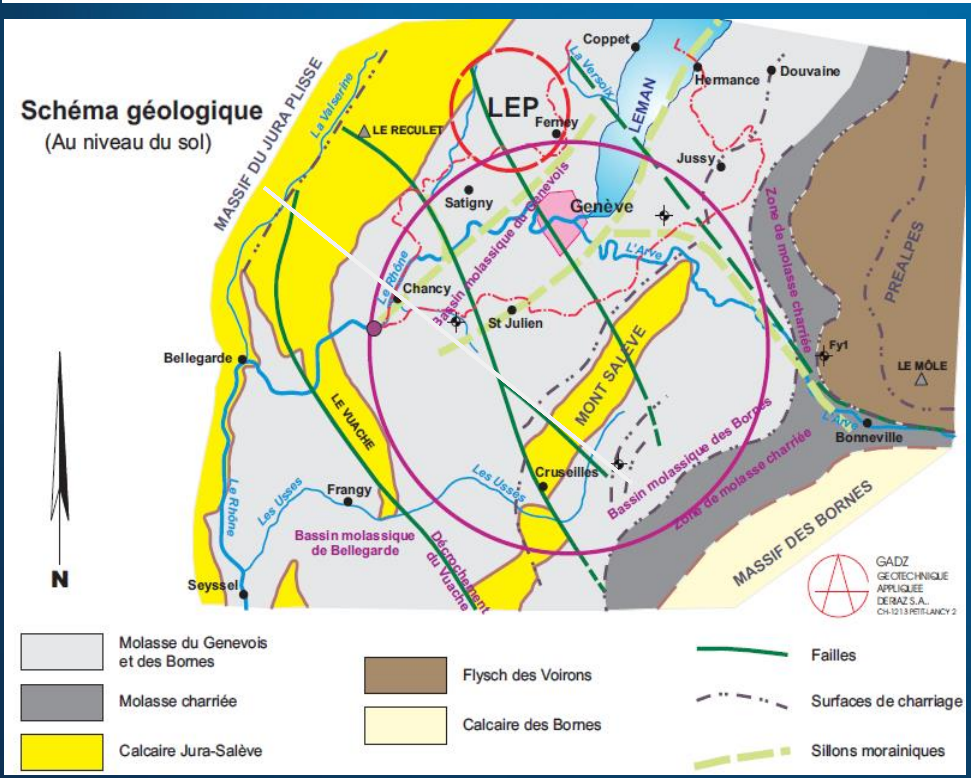
~ 15 years

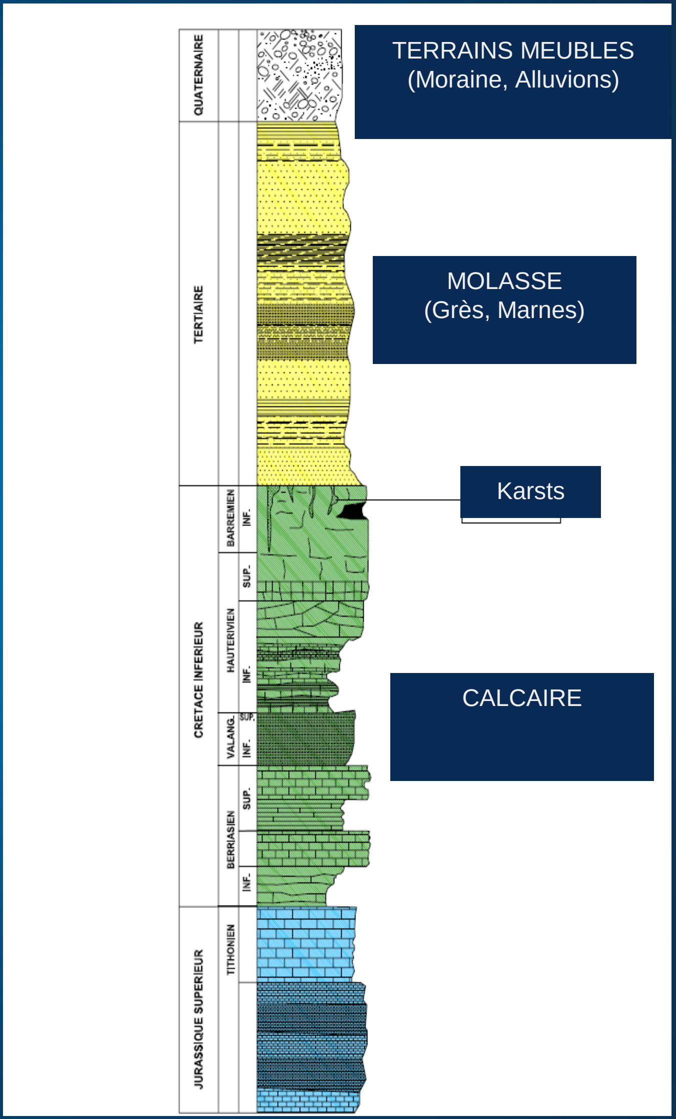
Total

~ 25 years

Geological background







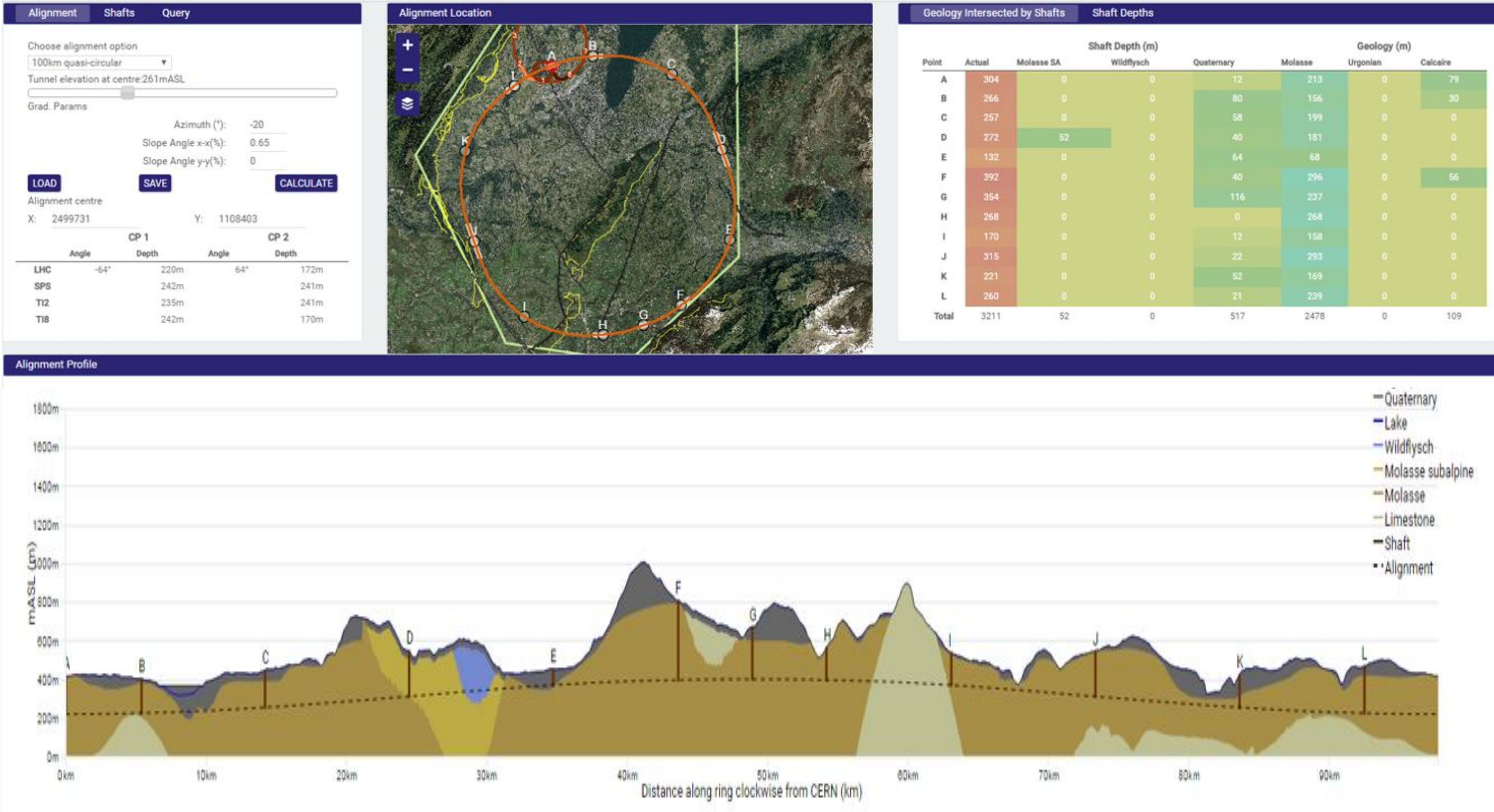
TERRAINS MEUBLES
(Moraine, Alluvions)

MOLASSE
(Grès, Marnes)

Karsts

CALCAIRE

Progress on site investigations



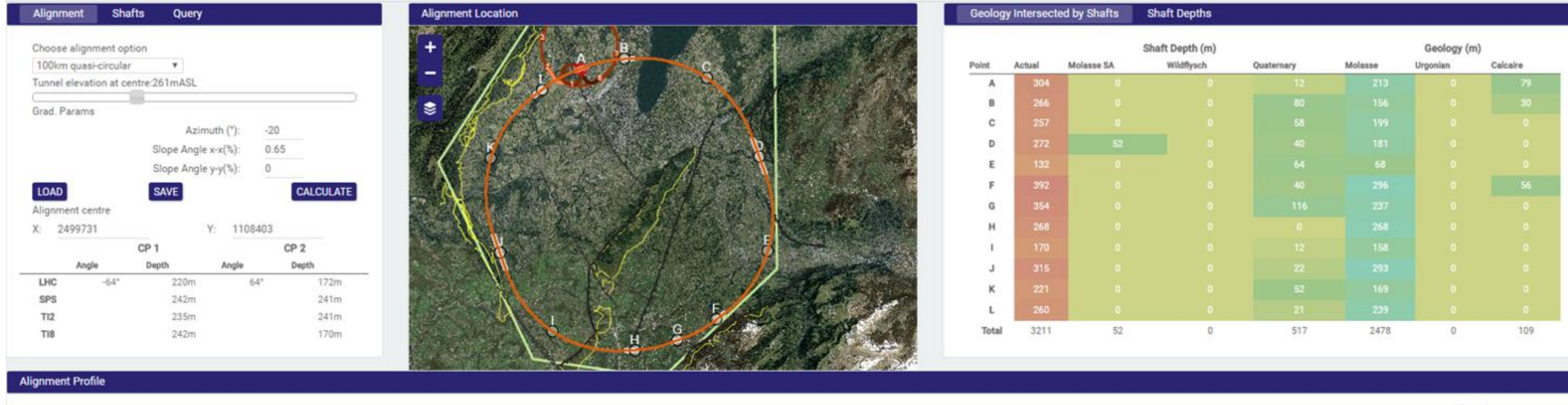
Choose alignment option
100km quasi-circular
Tunnel elevation at centre:261mASL
Grad. Params
Azimuth (°): -20
Slope Angle x-x(%): 0.65
Slope Angle y-y(%): 0

Alignment centre
X: 2499731
Y: 1108403

	CP 1		CP 2	
	Angle	Depth	Angle	Depth
LHC	-64°	220m	64°	172m
SPS		242m		241m
TI2		235m		241m
TI8		242m		170m

	Shaft Depth (m)			Geology (m)			
Point	Actual	Molasse SA	Wildflysch	Quaternary	Molasse	Urgonian	Calcaire
A	304	0	0	12	213	0	79
B	266	0	0	80	156	0	30
C	257	0	0	58	199	0	0
D	272	52	0	40	181	0	0
E	132	0	0	64	68	0	0
F	392	0	0	40	296	0	56
G	354	0	0	116	237	0	0
H	268	0	0	0	268	0	0
I	170	0	0	12	158	0	0
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

Progress on site investigations



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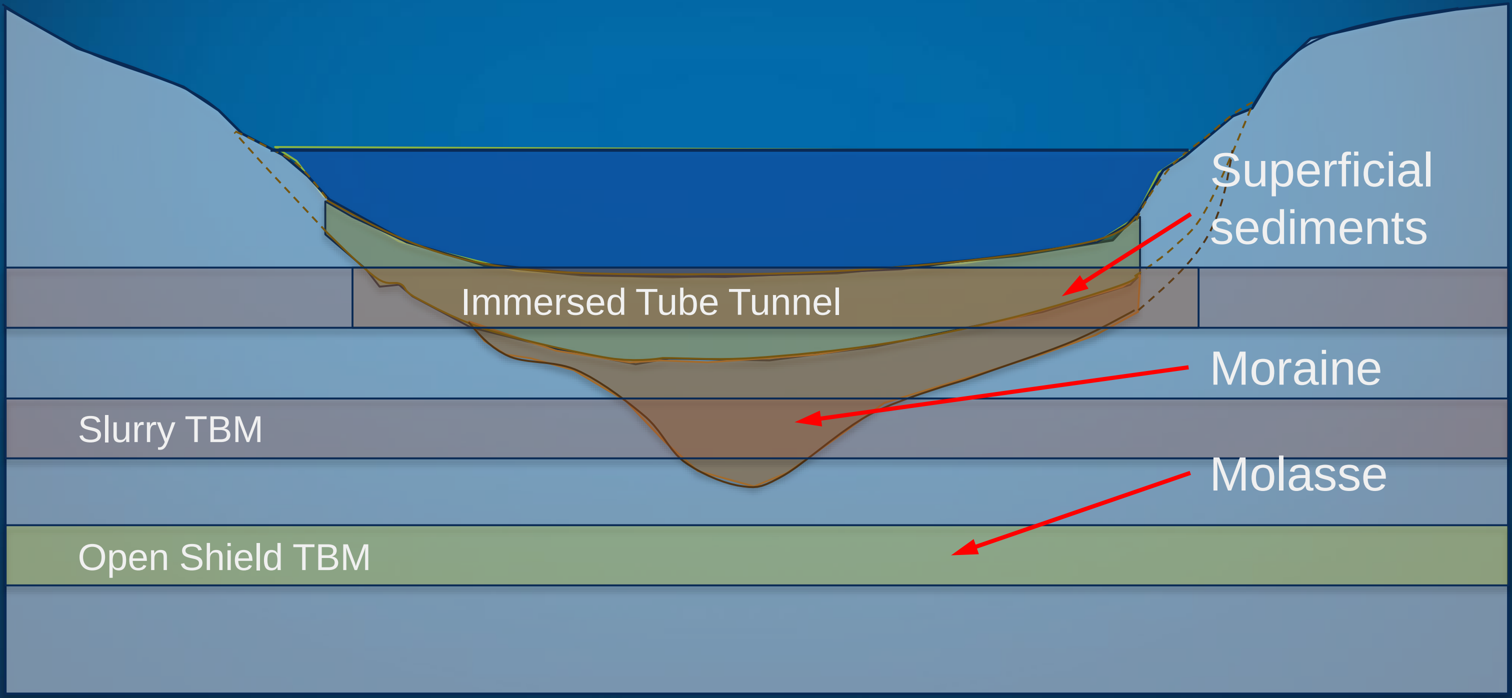
J	315	0	0	22	293	0	0
K	221	0	0	52	169	0	0
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is now being studied in more detail

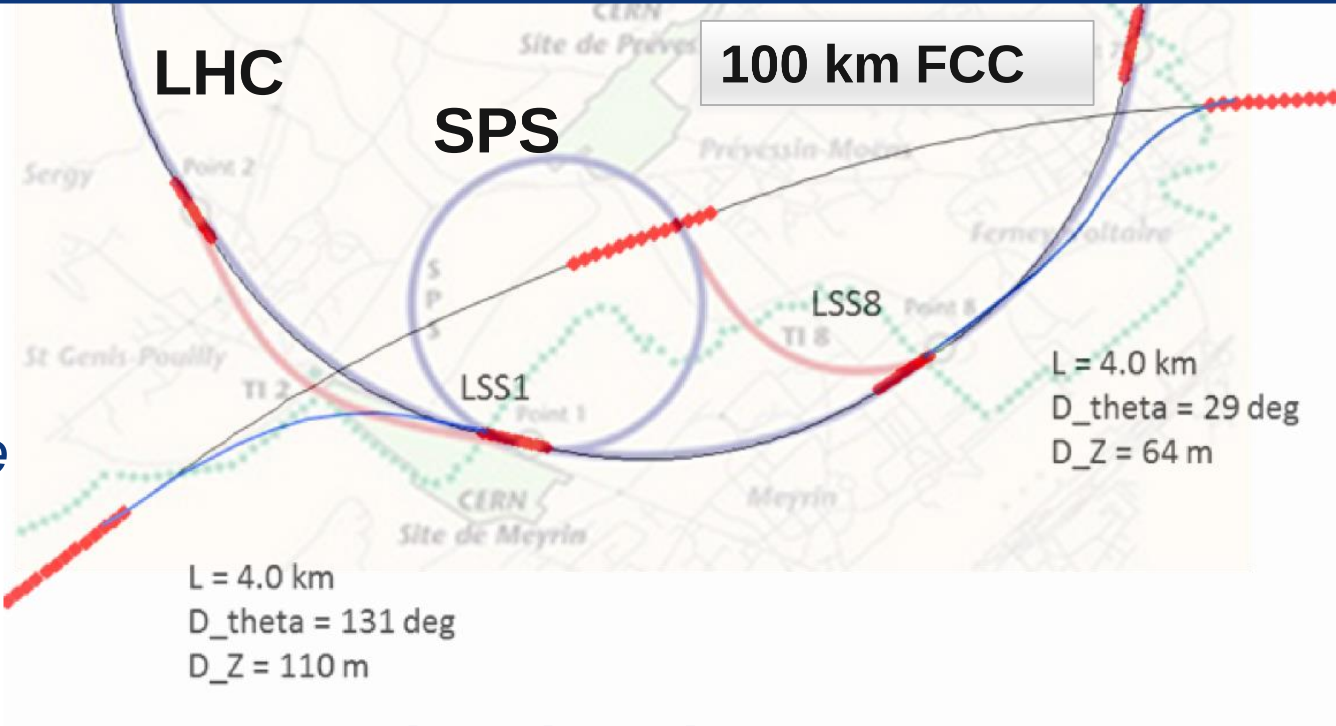
Tunnelling options for crossing the lake



FCC-hh injector considerations

High energy and large size of the ring requires a pre-injector chain:

“gear-box” principle



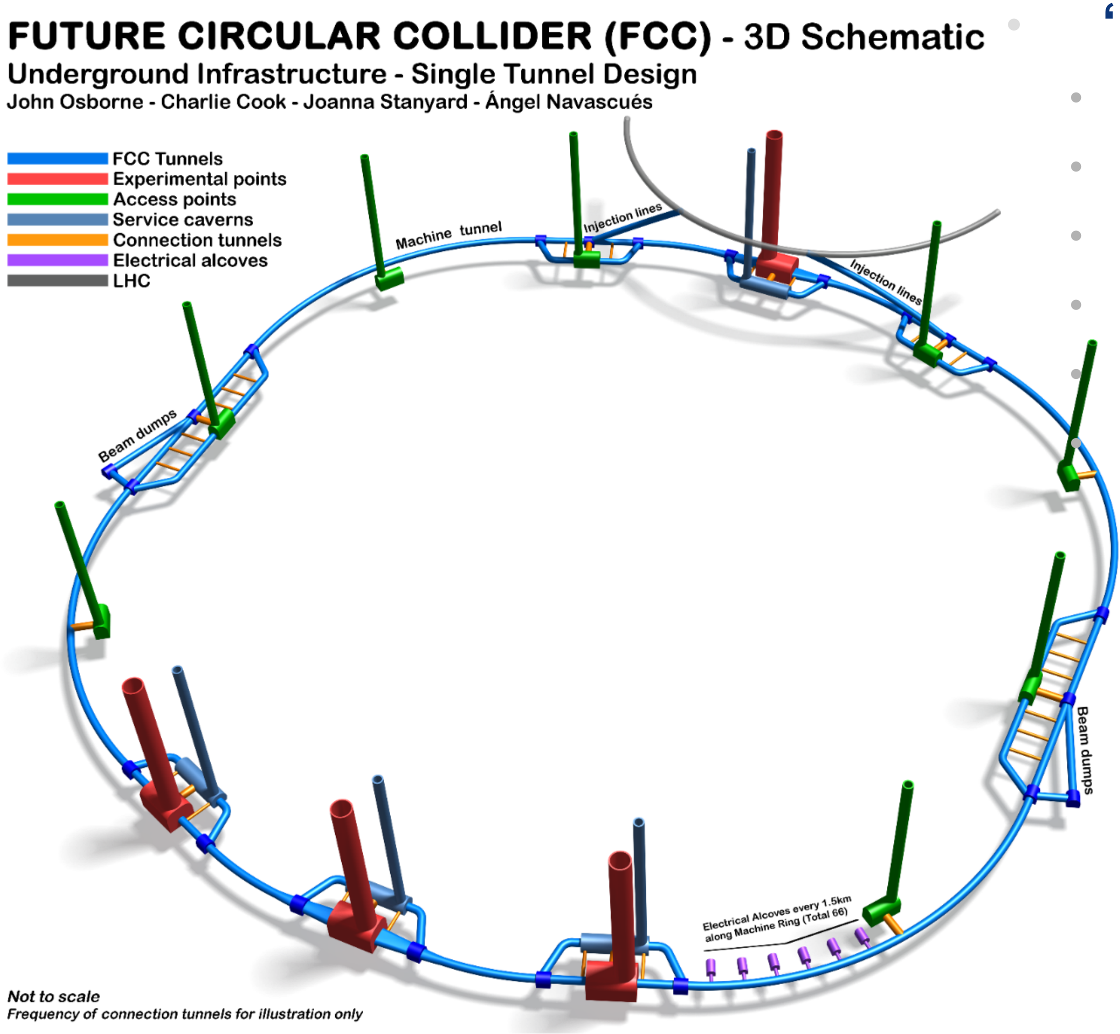
Baseline:

- **3 TeV, directly from LHC, reusing the whole CERN complex**

Alternative:

- **1.5 TeV with new SPS (7 km machine circumference) based on fast-cycling SC magnets, 6-7T, ~ 1T/s ramp**

FCC Tunnel Layout



FUTURE CIRCULAR COLLIDER (FCC) - 3D Schematic

Underground Infrastructure - Single Tunnel Design

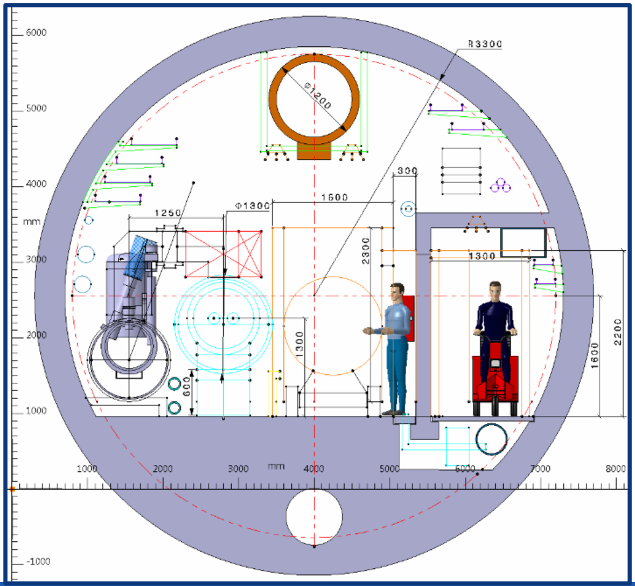
John Osborne - Charlie Cook - Joanna Stanyard - Ángel Navascués

Not to scale

Frequency of connection tunnels for illustration only

‘Baseline’ Layout

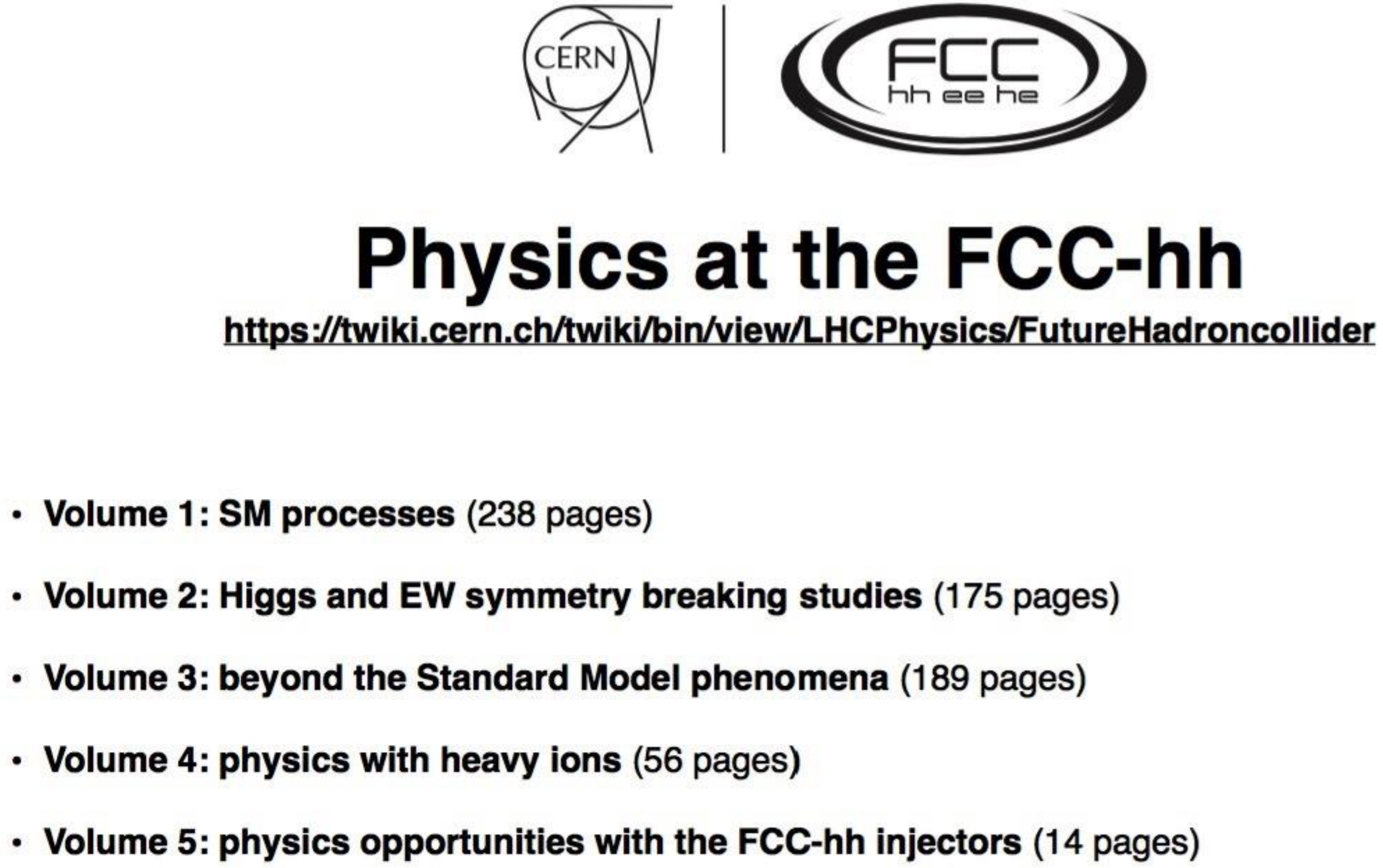
- 100 km tunnel 6 m inner diameter
- 4 large experimental caverns
- 8 service caverns for infrastructure
- 12 & 4 vertical shafts (3 km integral
- 2 transfer tunnels (10 km)
- 2 beam dump tunnels (4 km)



Hadron collider parameters

parameter	FCC-hh		HE-LHC* *tentative	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity $[10^{11}]$	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP $[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}]$	5	20 - 30	>25	(5) 1
events/bunch crossing	170	<1020 (204)	850	(135) 27
stored energy/beam [GJ]	8.4		1.2	(0.7) 0.36
synchrotron rad. [W/m/beam]	30		3.6	(0.35) 0.18

Physics prospects



Physics at the FCC-hh

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/FutureHadroncollider

- **Volume 1: SM processes** (238 pages)
- **Volume 2: Higgs and EW symmetry breaking studies** (175 pages)
- **Volume 3: beyond the Standard Model phenomena** (189 pages)
- **Volume 4: physics with heavy ions** (56 pages)
- **Volume 5: physics opportunities with the FCC-hh injectors** (14 pages)

- **Being published as CERN yellow report**

Key Technologies

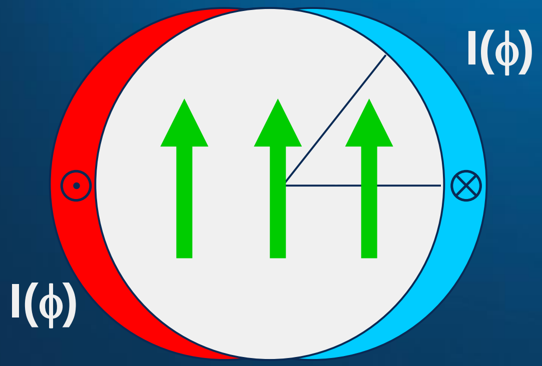
- 16 T superconducting magnets
- Synchrotron radiation
- Affordable & reliable cryogenics
- Superconducting RF cavities
- RF power sources
- Reliability & availability concepts

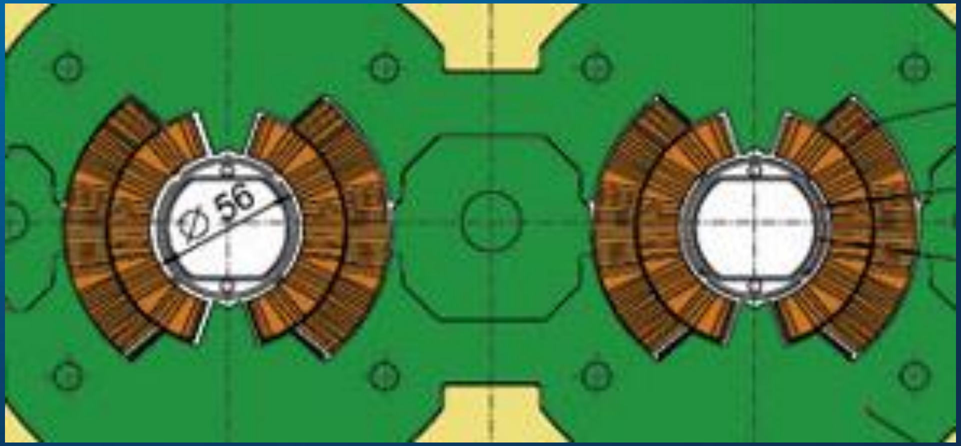
High –field SC dipoles

- **SC dipole: field defined via current distribution**
  - High current densities close to the beam for high fields
  - Only possible with super conductors I > 1 kA/mm2

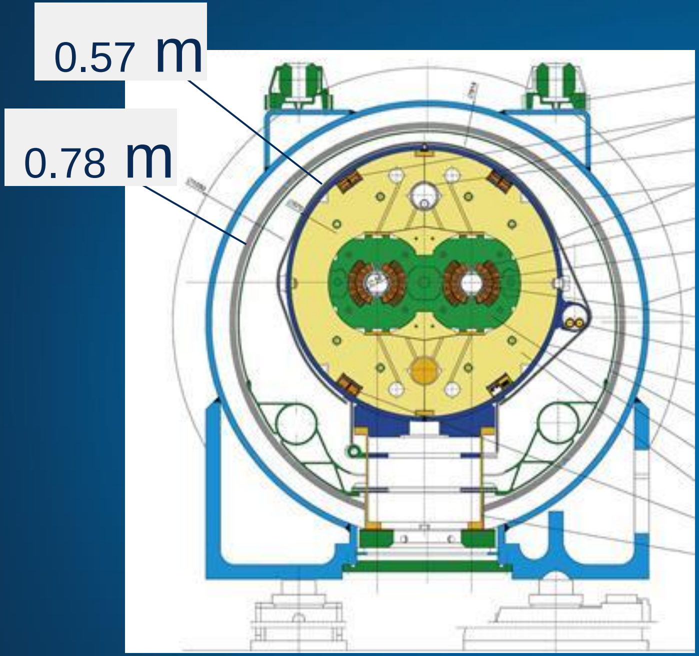
- **Ideal coil geometry for dipolar fields:**
  - Azimuthal current distribution **$I(\phi) = I_0\cos(\phi)$ Dipol,** ($I_0\cos(2\phi)$ Quadrupol)
  - 2 horizontally displaced circles

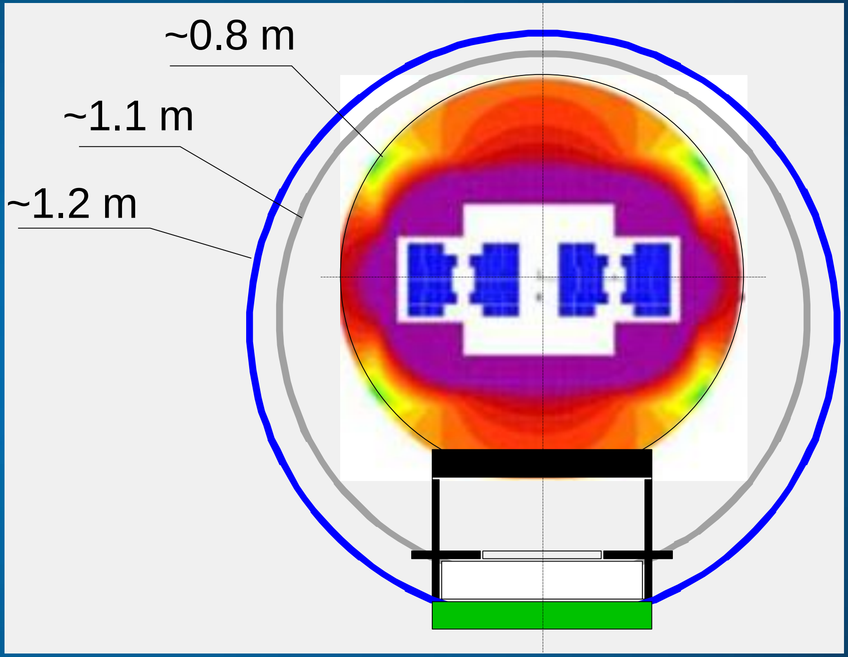
Cross section





Cryo-magnet cross sections





LHC
cos theta

FCC-hh
block coil
Nb3Sn as SC material

Main SC Magnet system FCC (16 T) vs LHC (8.3 T)

FCC

Bore diameter: 50 mm

Dipoles: $\boldsymbol{4578\ units, 14.3\ m\ long, 16\ T \Leftrightarrow \int Bdl \sim 1\ MTm}$

$\textbf{Stored energy} \sim \textbf{200 GJ (GigaJoule)} \sim \textbf{44 MJ/unit}$

Quads: $\boldsymbol{762\ magnets,\ \ 6.6\ m\ long, 375\ T/m}$

LHC

Bore diameter: 56 mm

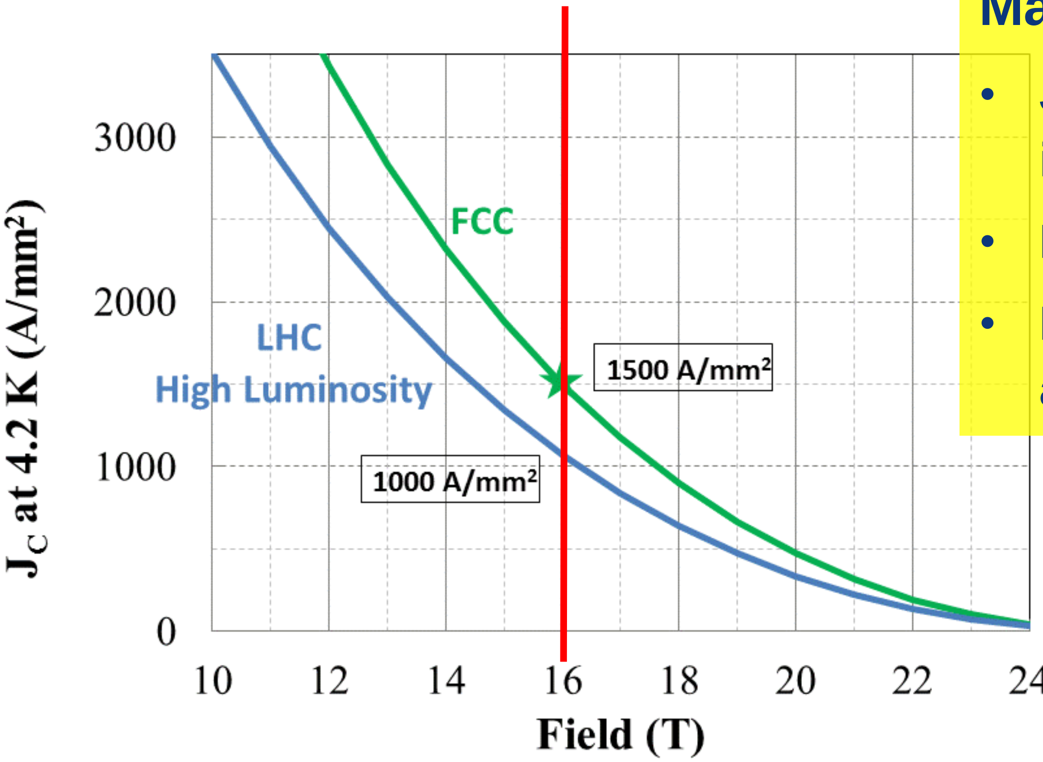
Dipoles: $\boldsymbol{1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl \sim 0.15\ MTm}$

$\textbf{Stored energy} \sim \textbf{9 GJ (GigaJoule)} \sim \textbf{7 MJ/unit}$

Quads: $\boldsymbol{392\ units,\ 3.15\ m\ long, 233\ T/m}$

Nb_3Sn conductor program

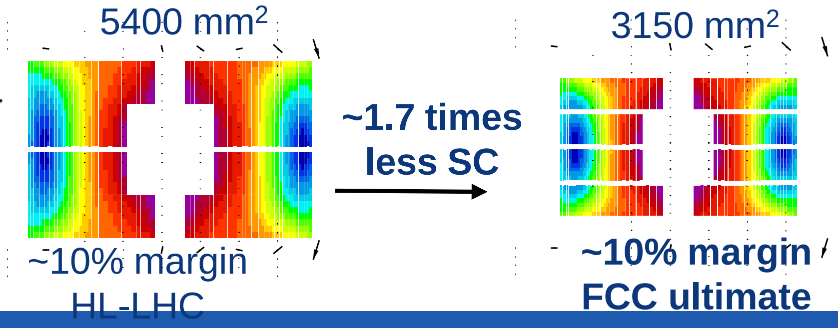
Nb_3Sn is one of the major cost & performance factors



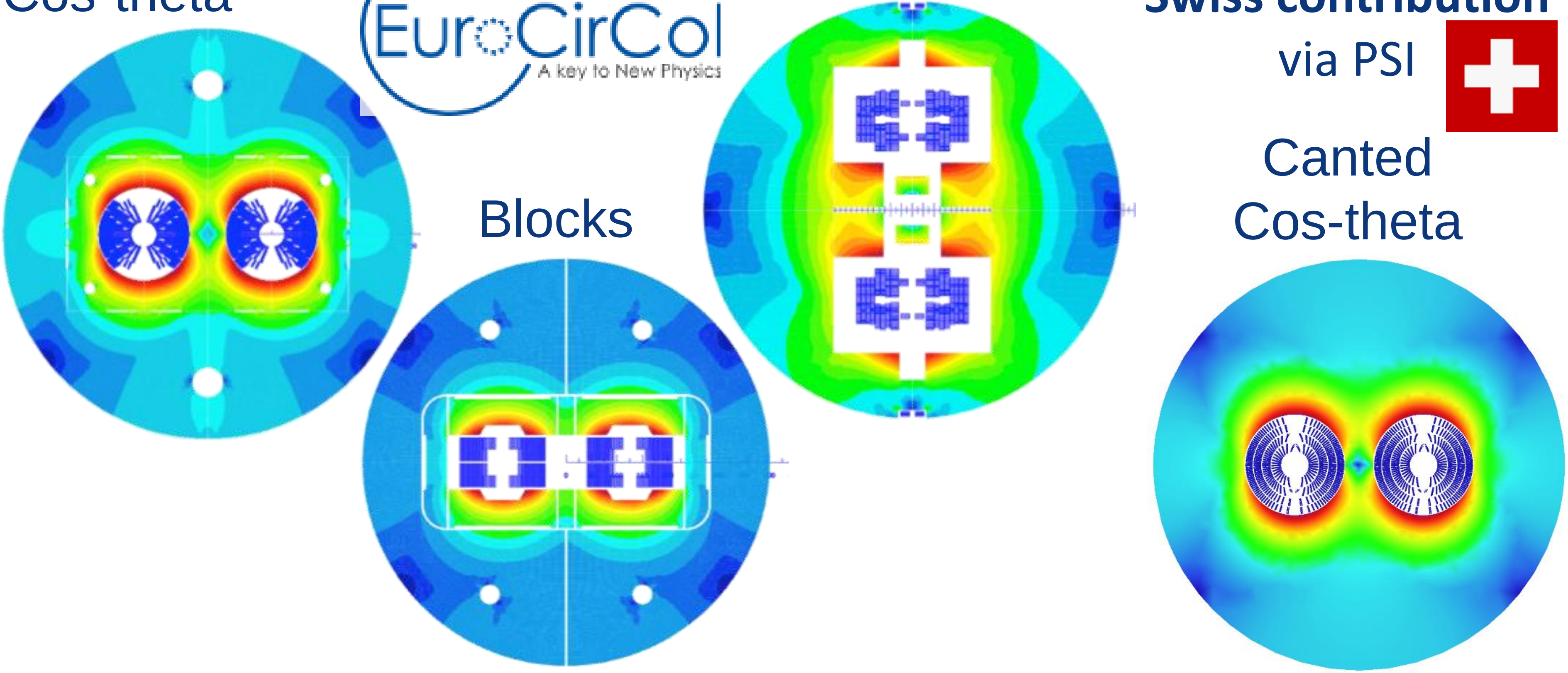
Main development goals until 2020:

- J_c increase (16T, 4.2K) > 1500 A/mm² i.e. 50% increase wrt HL-LHC wire
- Reference wire diameter 1 mm
- Potentials for large scale production and cost reduction

Impact on coil section and conductor mass



16 T dipole options under consideration



Cos-theta

Blocks

Common coils

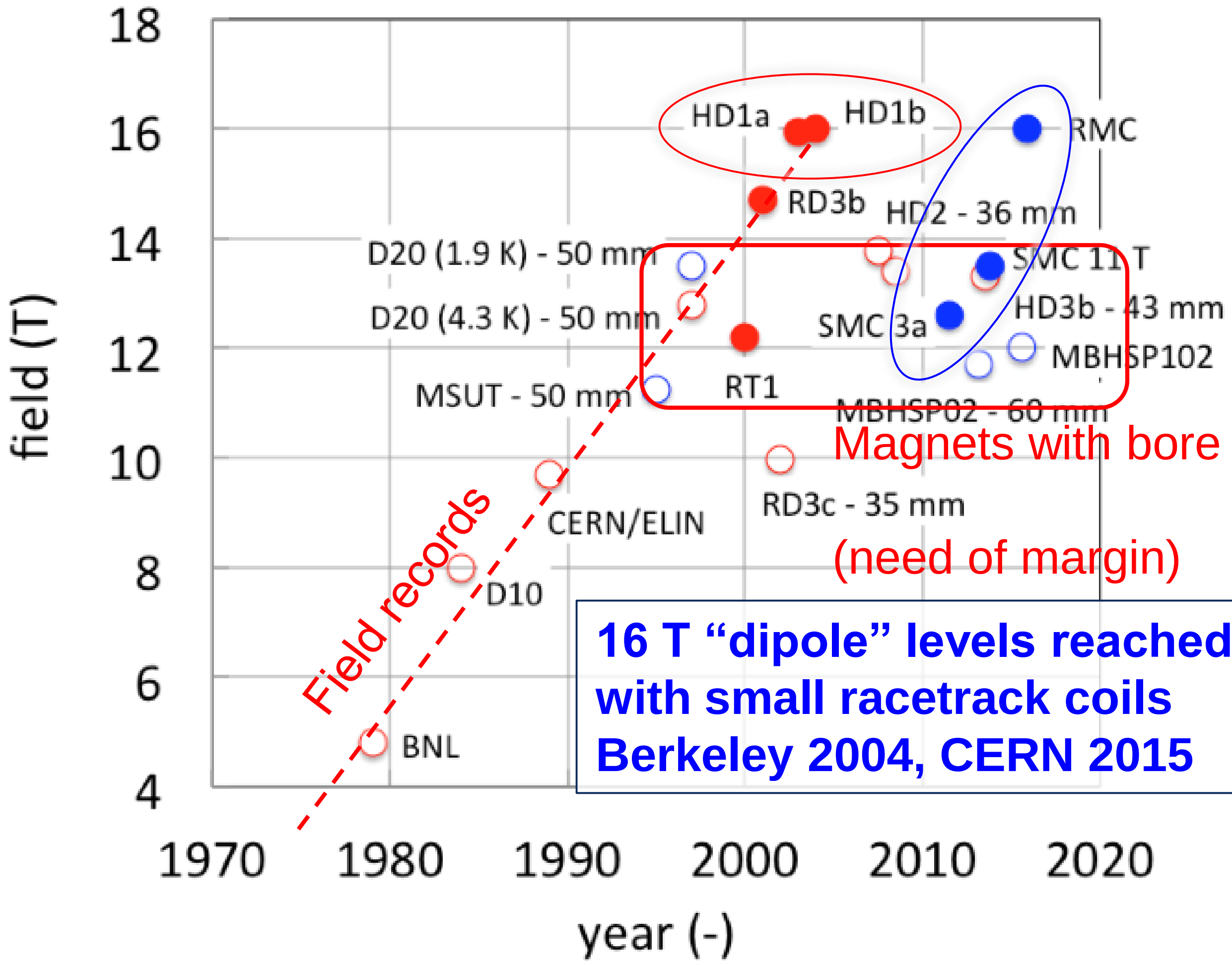
Swiss contribution
via PSI

Canted
Cos-theta

Down-selection of options end 2017 for more detailed design work
Prototyping with short (~1.5 m) model magnets 2017 - 2021

Towards 16T magnets

Record fields for SC magnets in “dipole” configuration



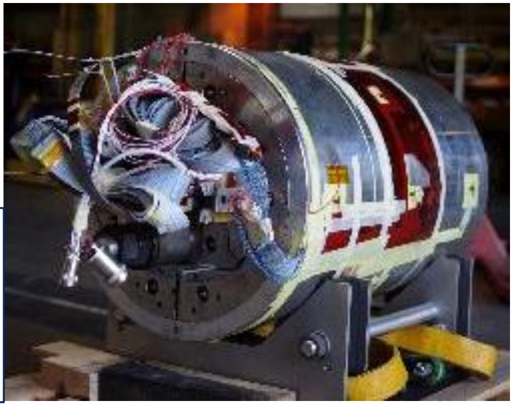
Field records

Magnets with bore

(need of margin)

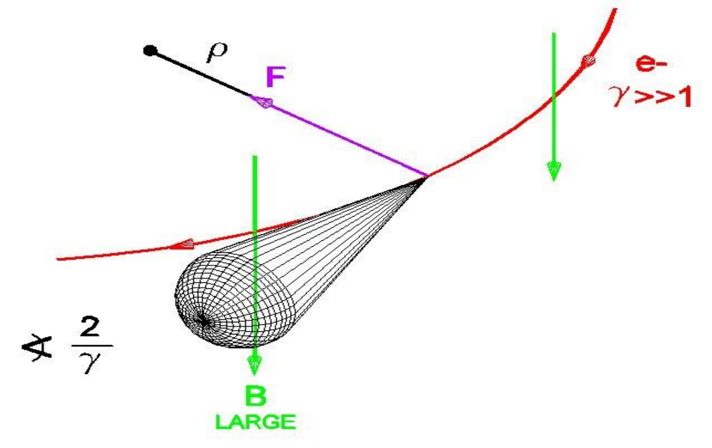
16 T “dipole” levels reached with small racetrack coils Berkeley 2004, CERN 2015

LBNL HD1



CERN RMC

Synchrotron radiation



- **Charged particles on a curved trajectory irradiate energy:**

$$\boxed{\Delta E \sim \text{const}\cdot\gamma^4/r = \text{const}\cdot(E/E_0)^4/r = \textit{konst}\cdot(E/m_0)^4/r}$$

  - **Energy loss ΔE must be compensated and corresponding heat has to be removed from cold mass of SC magnets (for hadron collider)**

$$\boxed{\Delta W = \Delta Q\cdot(T - T_{tief}) / T_{tief} = \Delta Q\cdot(300 - 1.9) / 1.9 \sim 155\cdot\Delta Q}$$

For realistic process efficiency is ~1000: 1 W@1.9 K == 1 kW @ room temp.

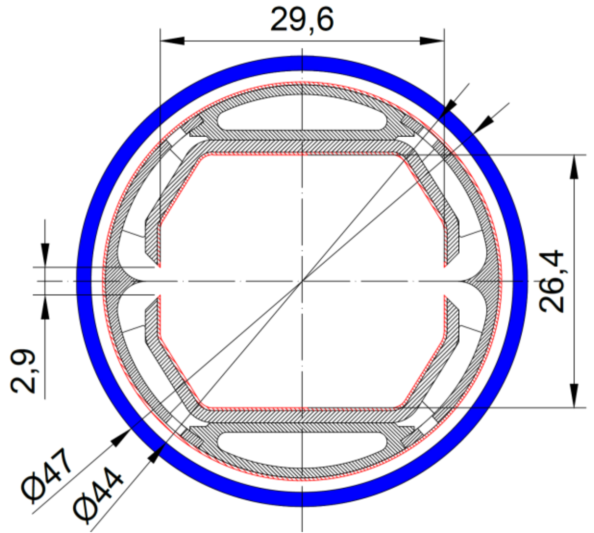
Synchrotron radiation beam screen prototype

High synchrotron radiation load of proton beams @ 50 TeV:

- **~30 W/m/beam (@16 T)** (LHC <0.2W/m)
- **5 MW total in arcs (@1.9 K!!!)**

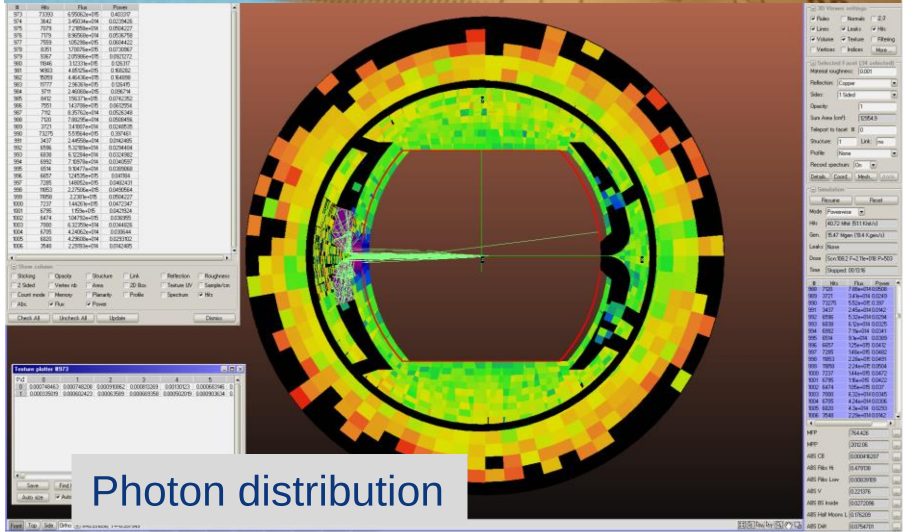
New Beam screen with ante-chamber

- absorption of synchrotron radiation at 50 K to reduce cryogenic power
- factor 50! reduction of power for cryo system



First FCC-hh beam screen prototype

Testing 2017 in ANKA within EuroCirCol

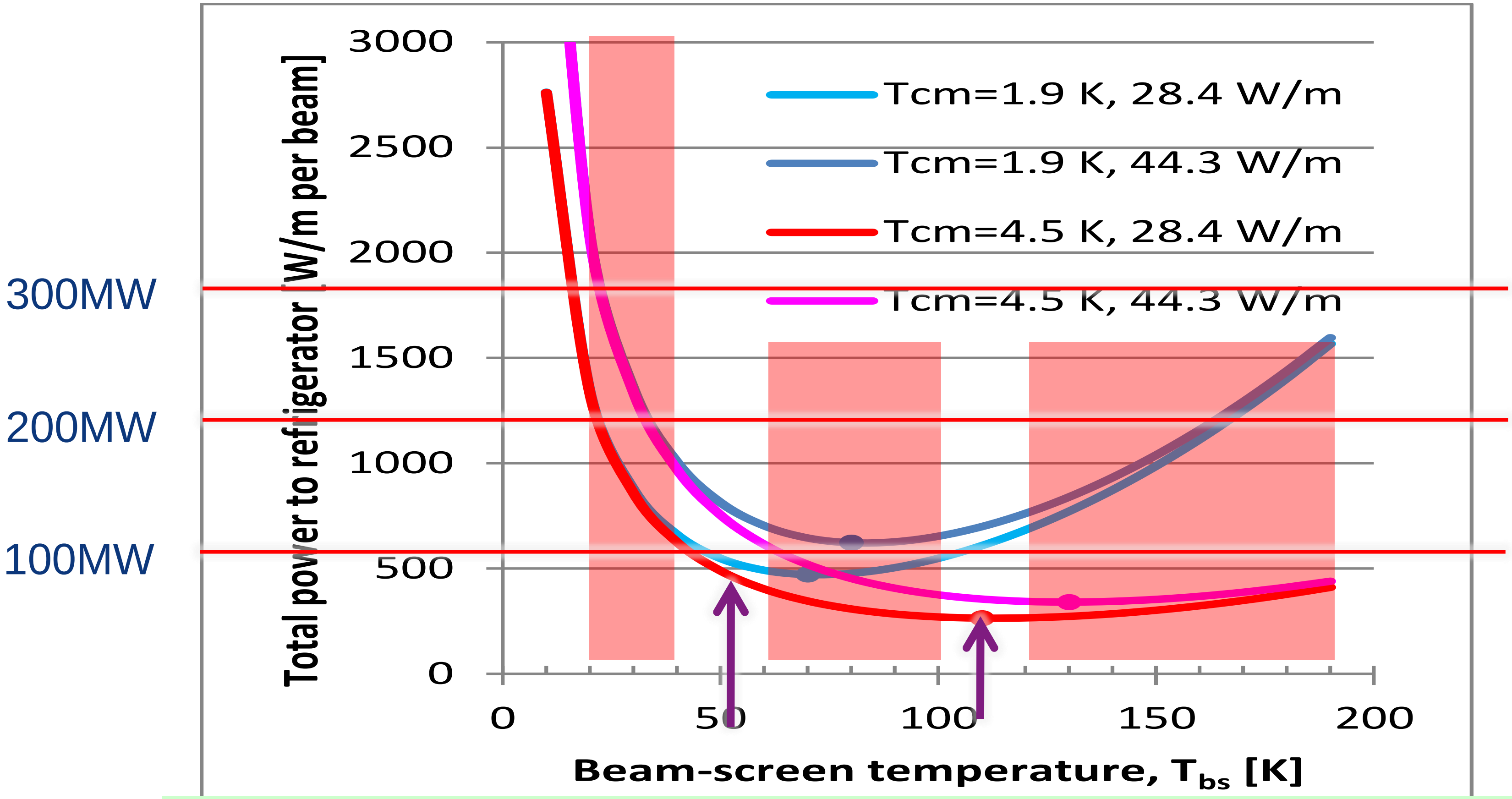


Photon distribution

Cryo power for cooling of SR heat

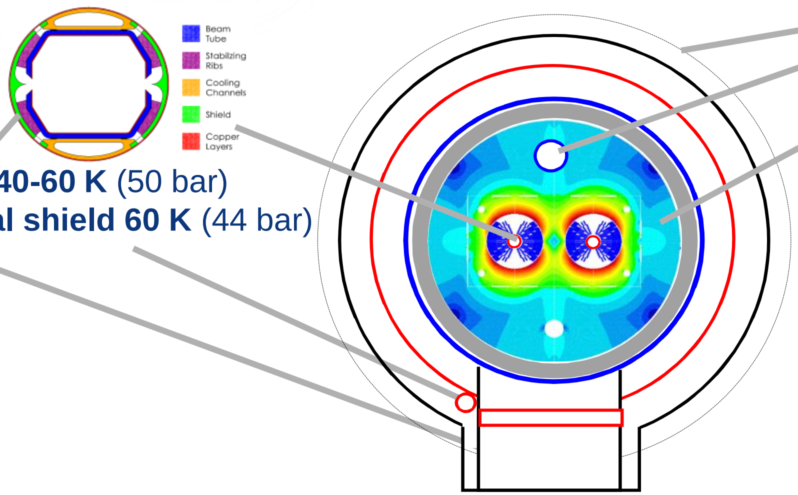
Overall optimisation of cryo-power, vacuum and impedance

Termperature ranges: <20, 40K-60K, 100K-120K



Multi-bunch instability growth time: 25 turns 9 turns (ΔQ=0.5)

Main cryogenics parameters and layout



Vacuum vessel
Bayonet heat exchanger, 1.85 K saturated
Cold mass, 1.9 K (1.3 bar)

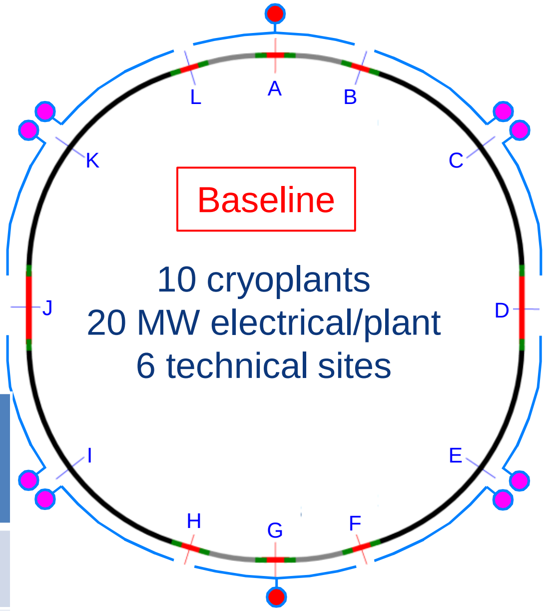
Beam screen, 40-60 K (50 bar)
Magnet thermal shield 60 K (44 bar)
Support post

Temperature level	[W/m]
1.9 K, cold mass of magnets • Beam losses • Resistive heating of splices	**1.4**
40-60 K, beam screen, thermal shield • Synchrotron radiation • Beam Image current	**71**

Total load
1 MW equivalent @4.5 K

Cryoplant	40-60 K [kW]	1.9 K [kW]
🔴	592	11
🟣	618	12

Cryoplants overall layout



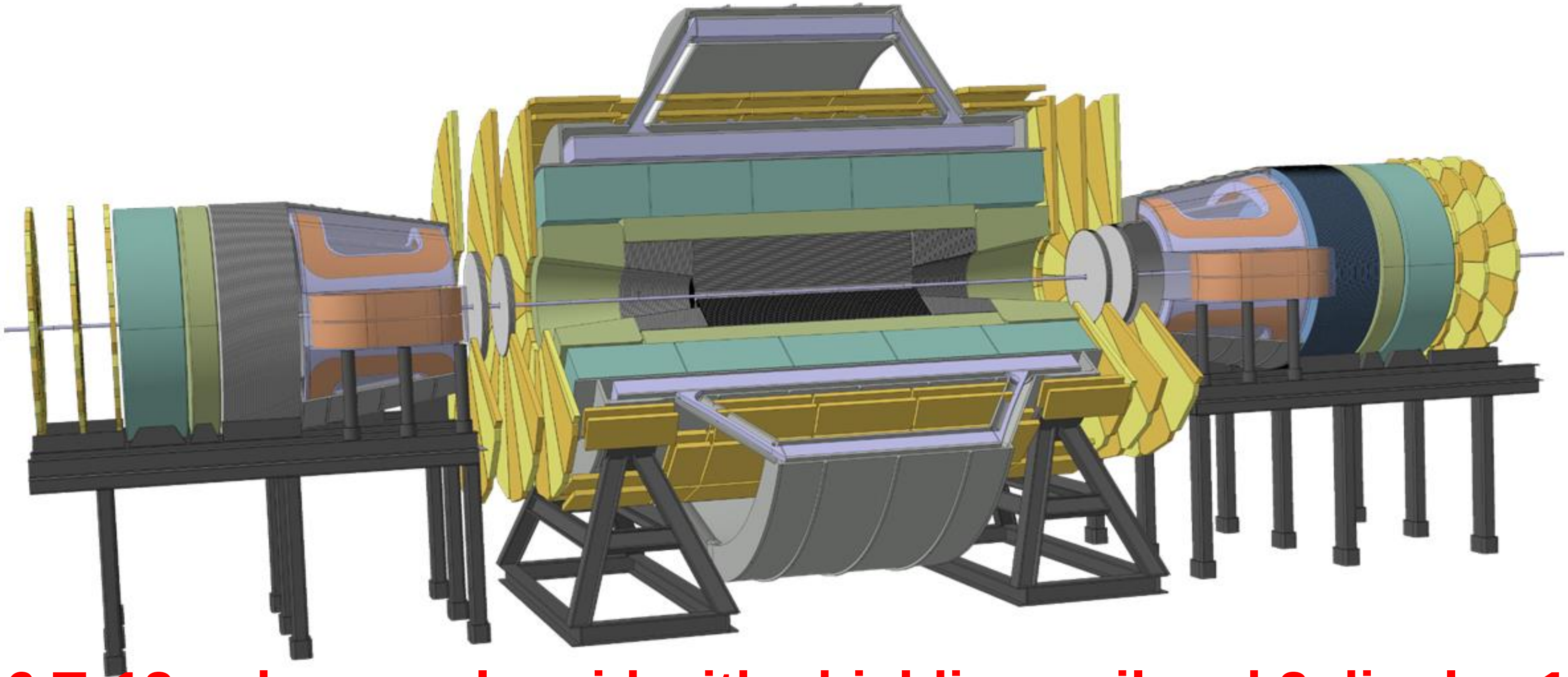
Baseline

10 cryoplants
20 MW electrical/plant
6 technical sites

Detector Concepts for 100 TeV pp

Very large volume of high magnetic field needed to measure momentum of charged particles.

Expanding from LHC detector concepts:

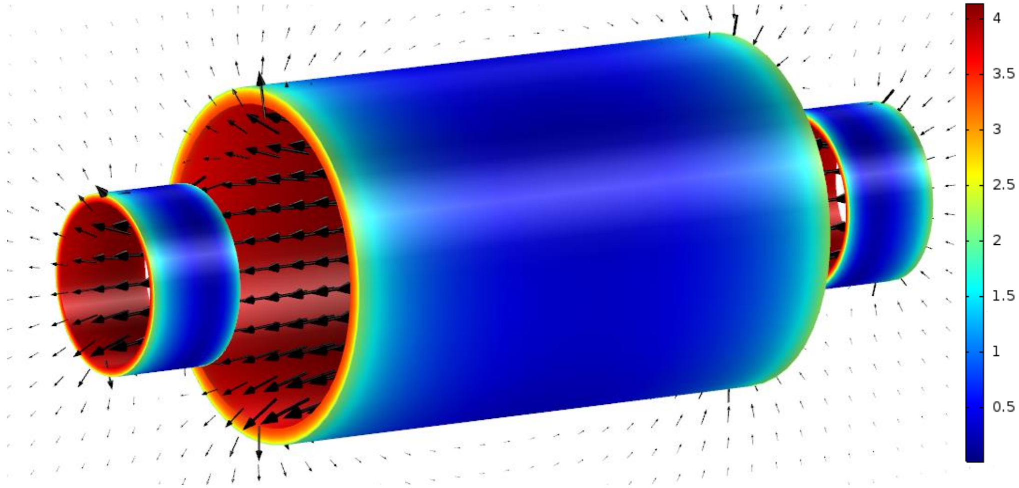


B=6 T, 12 m bore, solenoid with shielding coil and 2 dipoles 10 Tm.

Length 64 m, diam. 30 m, magnet 7000 tons, stored energy 50 GJ

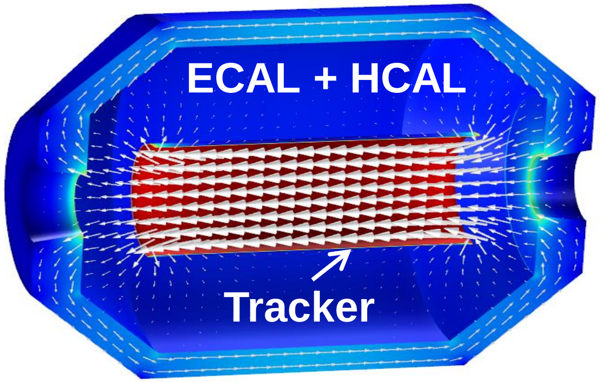
Detector Magnet Studies

Designs for physics-performing and cost-efficient magnet systems



Today's baseline:

4T/10m bore 20m long Main Solenoid
4T Side Solenoids – all unshielded
14 GJ stored energy, 30 kA and
2200 tons system weight



Alternative challenging design:

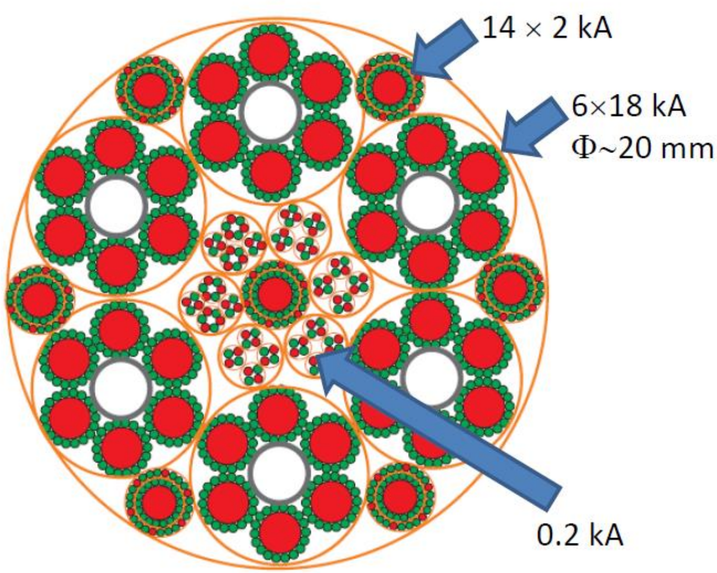
4T/4m Ultra-thin, high-strength Main Solenoid allowing positioning inside the e-calorimeter, 280 MPa conductor (side solenoids not shown)
0.9 GJ stored energy, elegant, 25 t only, but needs R&D!

SC links for circuit powering

MgB_2 industrial conductor, He gas cooled

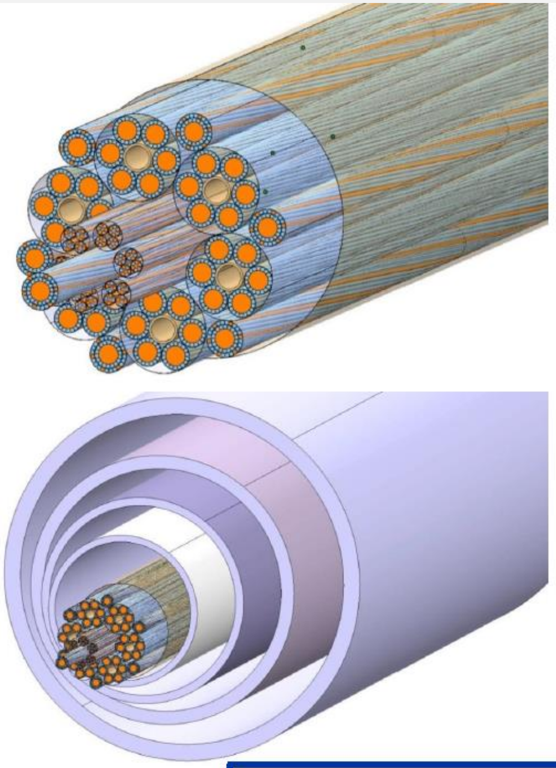
Example HL-LHC (I_{tot} up to ~|150 kA| @ 25 K)

All circuits in single cryostat – compact & efficient

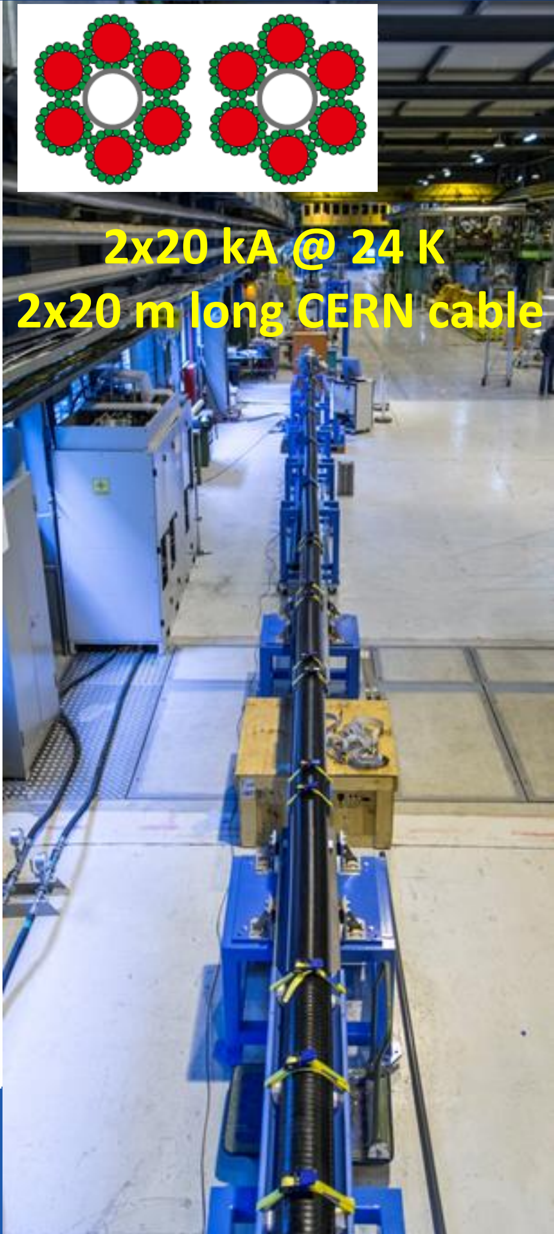


Φext ~ 65 mm
|Itot| ~ 150 kA

Mass ~ 11 kg/m



Φext ~ 220 mm



2x20 kA @ 24 K
2x20 m long CERN cable

Beam power & machine protection

Stored energy 8.4 GJ per beam

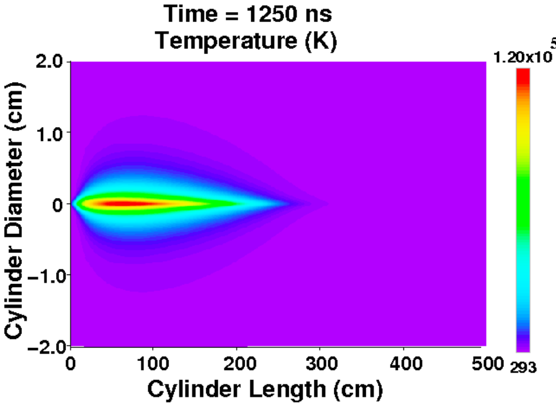
- Factor 25 higher than for LHC, equivalent to A380 (560 t) at nominal speed (850 km/h). Can melt 12t of copper.

- **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**
- **Injection, beam transfer and beam dump all critical.**

Machine protection issues to be addressed early on!

Damage of a beam with an energy of 2 MJ

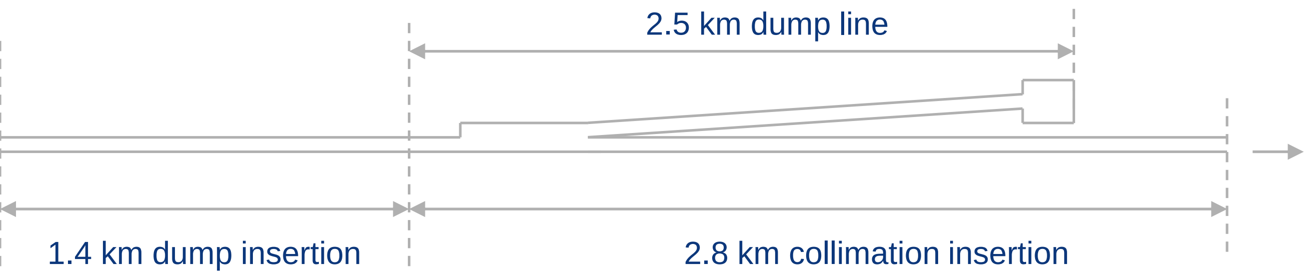
Hydrodynamic tunneling:
beam penetrates ~**300 m** in Cu



FCC-hh beam dilution system

Huge energy to be extracted and dumped => need large dump section

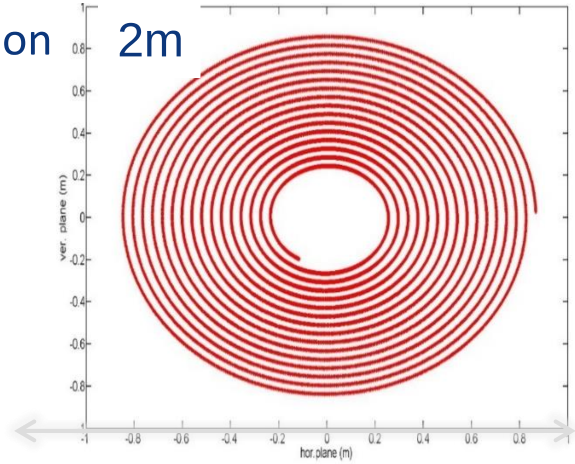
Beam rigidity: 167 T.km => need long way to dilute beam ~2.5km!

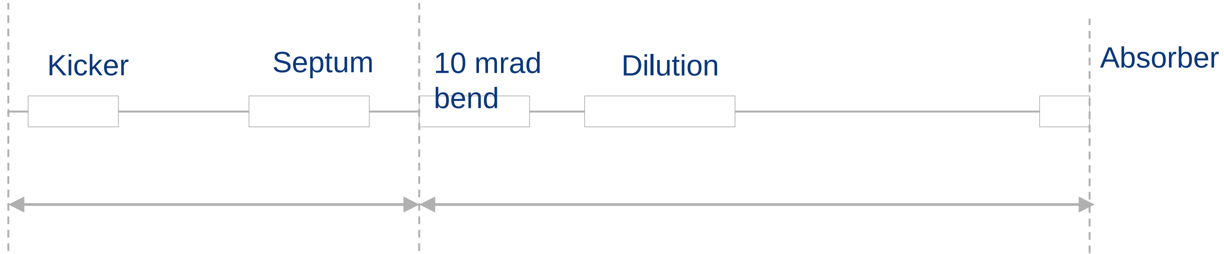


2.5 km dump line

1.4 km dump insertion

2.8 km collimation insertion





Kicker

Septum

10 mrad bend

Dilution

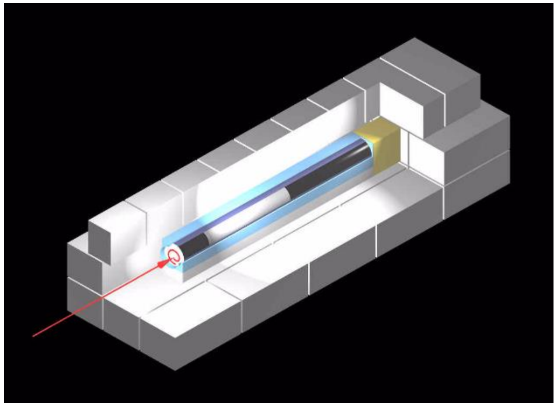
Absorber

Fluka studies:

- Bunch separation >1.8 mm
- Branch separation: 4 cm
- Keeps T<1500°C

Very reliable kickers, high segementation, new methods for triggering (laser)

SC septum



FCC Collaboration & Industry Relations

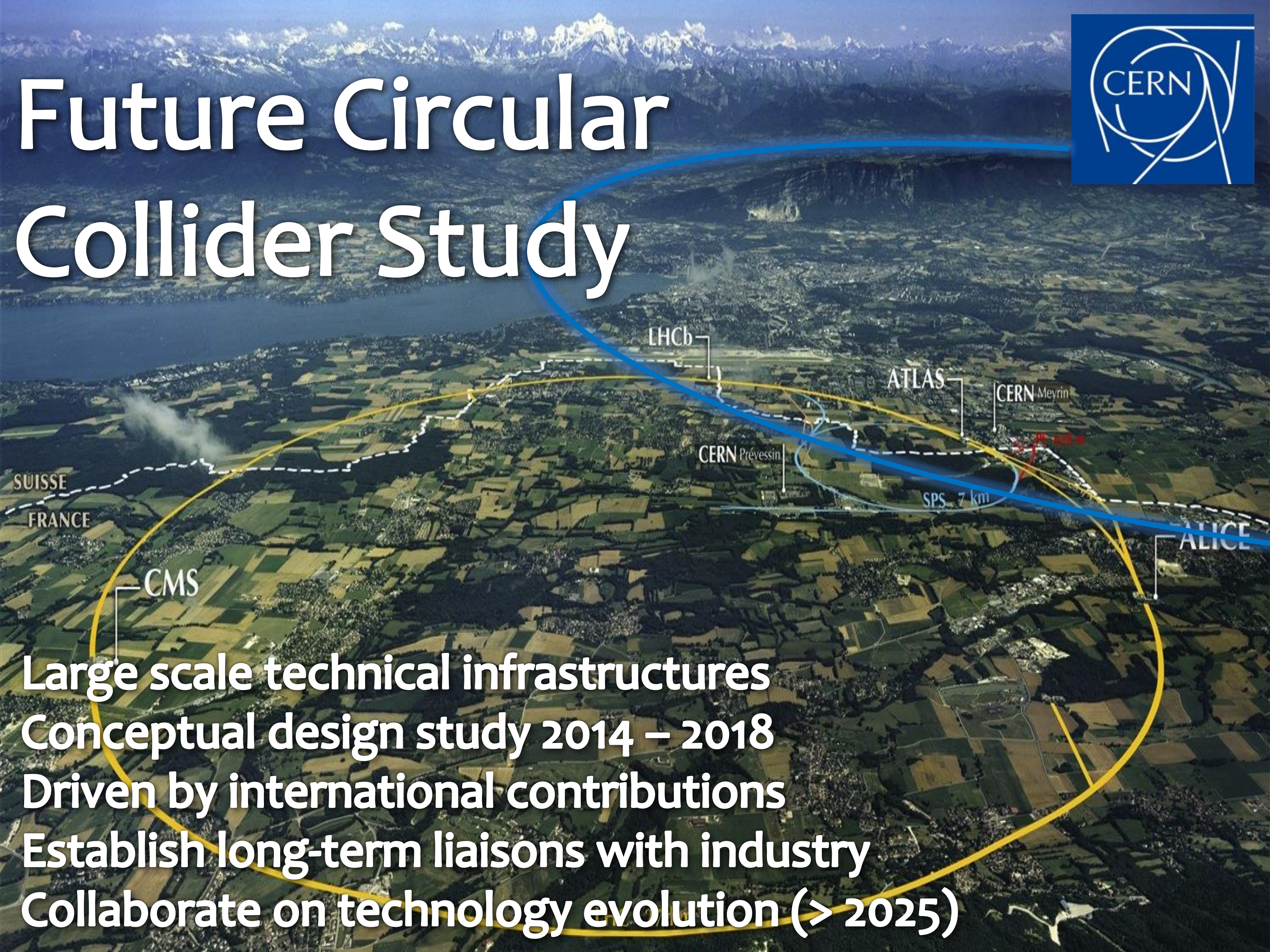
111 Institutes

25 Companies

32 Countries

EC
H2020

Future Circular Collider Study



Large scale technical infrastructures
Conceptual design study 2014 – 2018
Driven by international contributions
Establish long-term liaisons with industry
Collaborate on technology evolution (> 2025)

FCCWEEK2017

Future Circular Collider Conference

BERLIN, GERMANY

29 MAY - 02 JUNE

fccw2017.web.cern.ch