Future (circular) colliders

M. Benedikt

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

http://cern.ch/fcc

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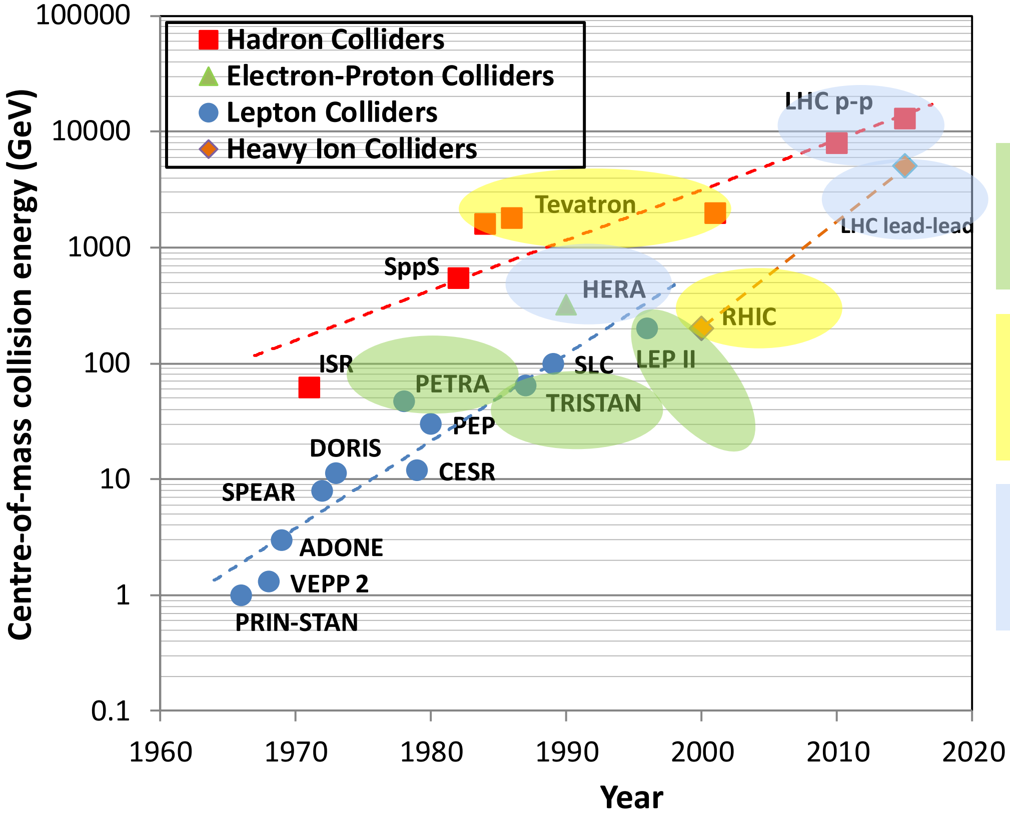
High energy accelerators & colliders

- 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):** $\mathbf{E} = \mathbf{m}c^2 \leq 2E$ beam (collider)
  - **Resolving smaller distances (according to de Broglie):** **Wavelength** $\lambda = hc/\mathbf{E}$ **for LHC** $\sim 2 \cdot 10^{-18}$ cm

Higher energy → **Increased potential for discoveries**

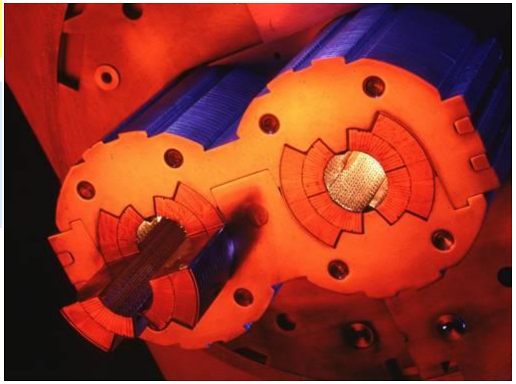
Colliders constructed and operated



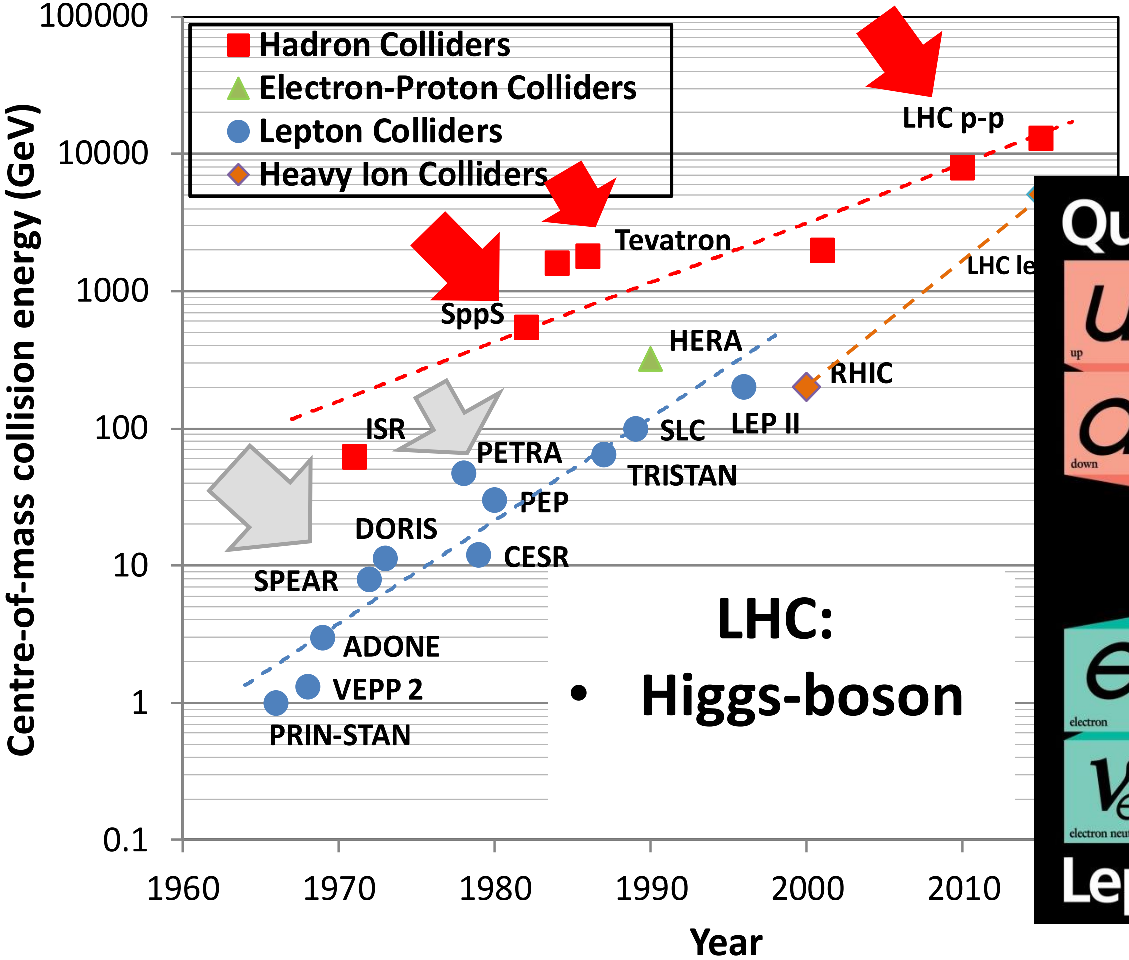
Colliders with superconducting RF system

Colliders with superconducting arc magnet system

Colliders with superconducting magnet & RF



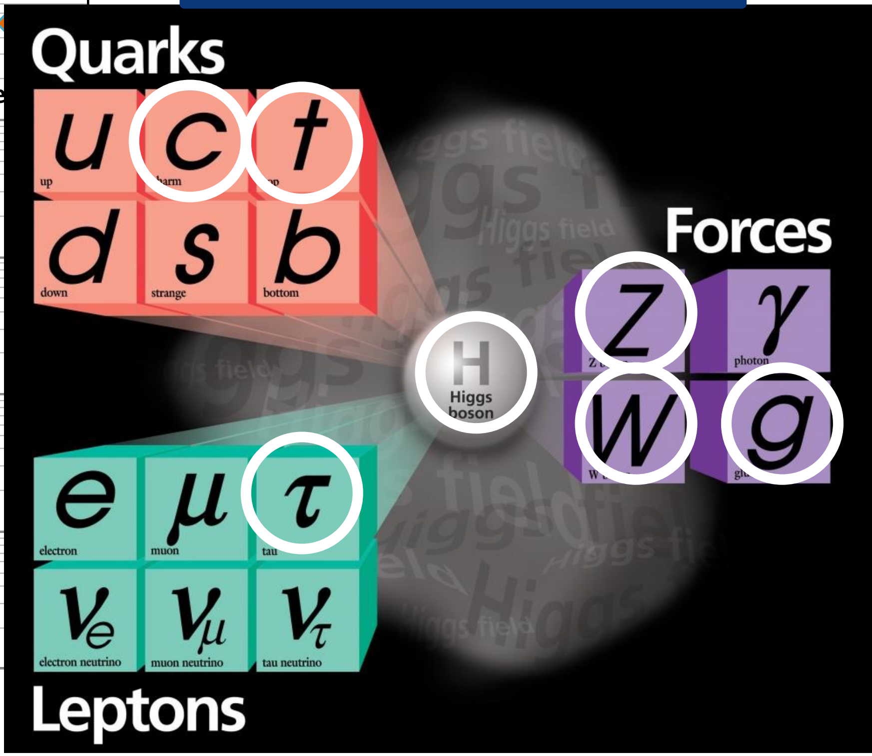
Discoveries by colliders



LHC:

- Higgs-boson

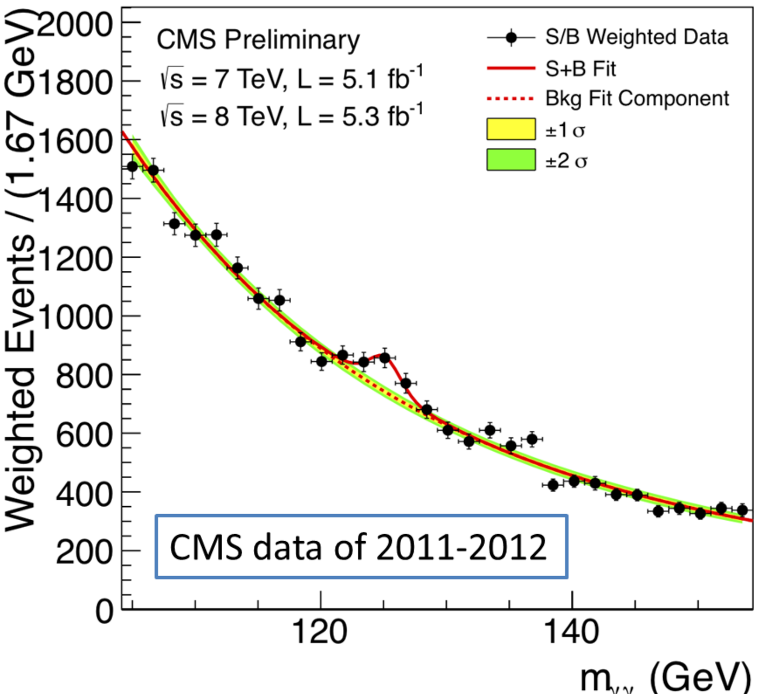
Standard Model
Particles and forces



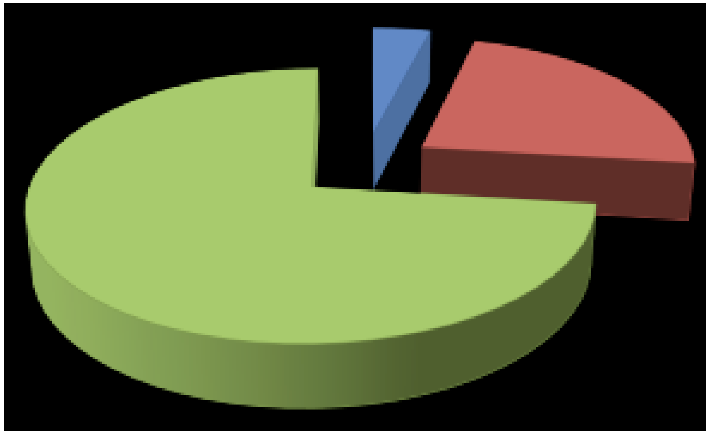
Colliders are powerful instruments in High Energy physics for particle discoveries and precision measurements

LHC: present collider flagship

2012: Higgs boson discovery



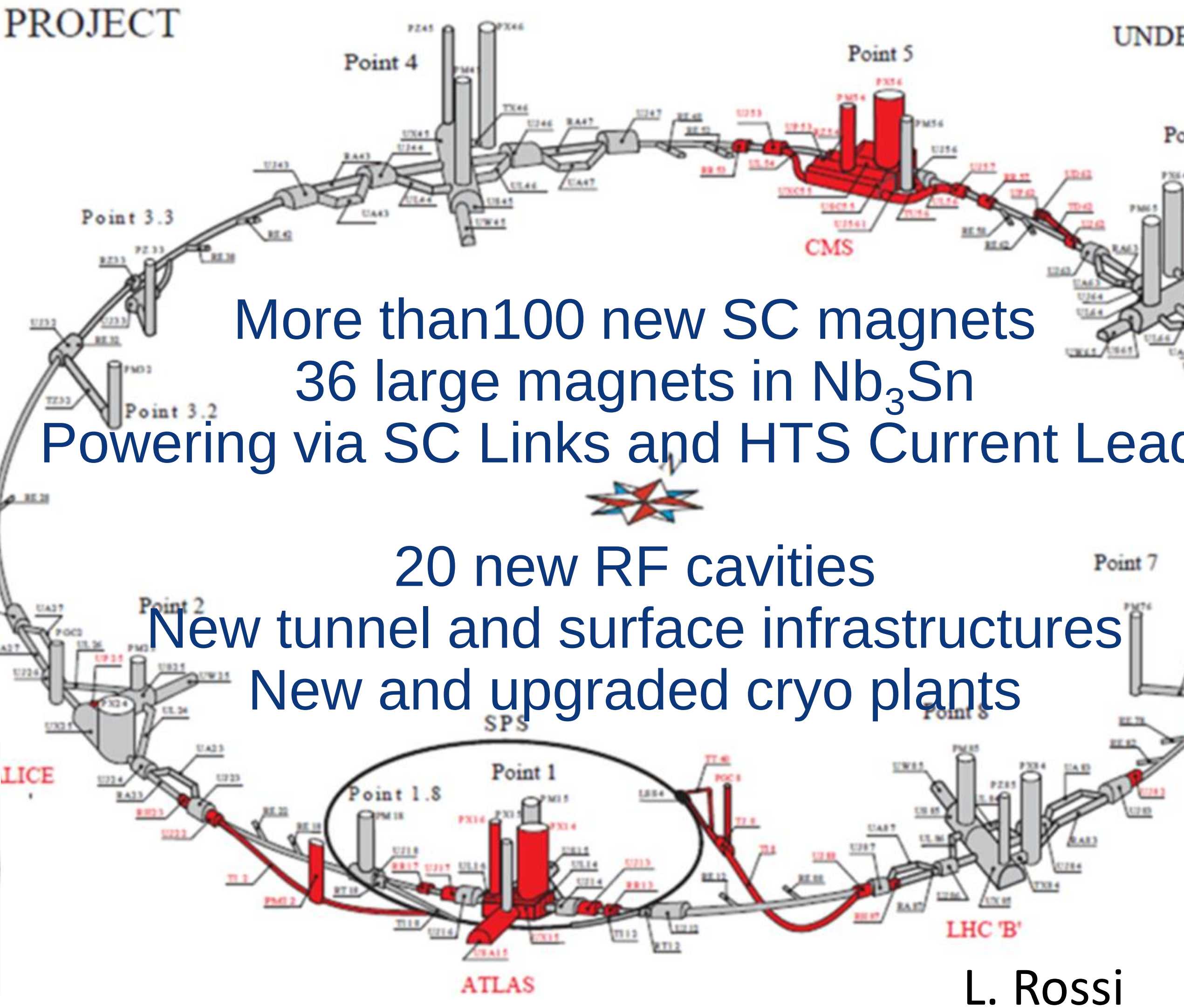
- Completes standard model describing known matter, **BUT this is only 5% of the universe!**



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

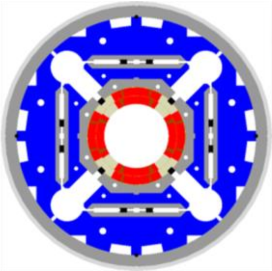
➔ Upgrade and full exploitation of LHC as first step

High Luminosity LHC project scope



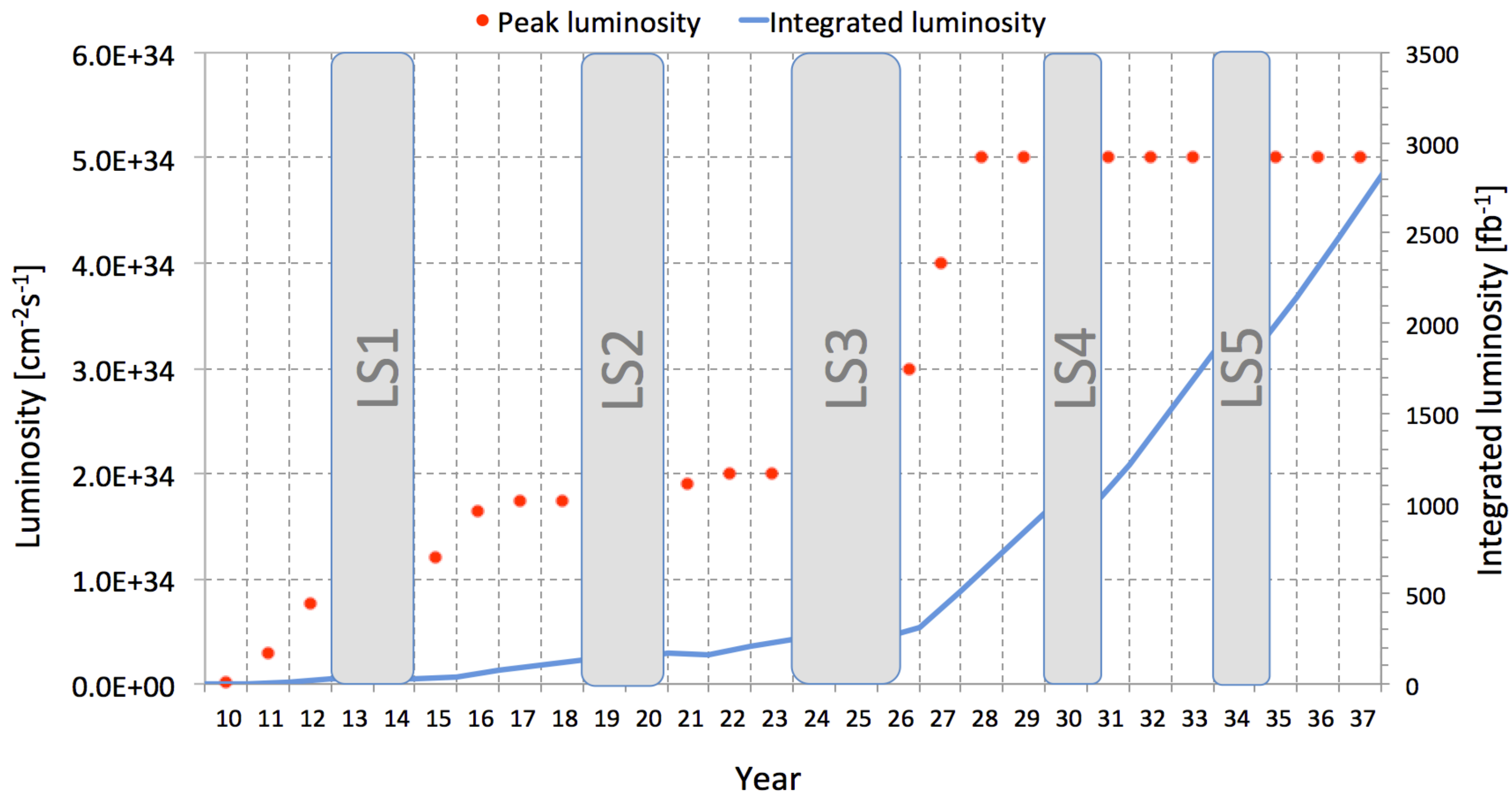
More than100 new SC magnets
36 large magnets in Nb_3Sn
Powering via SC Links and HTS Current Leads

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

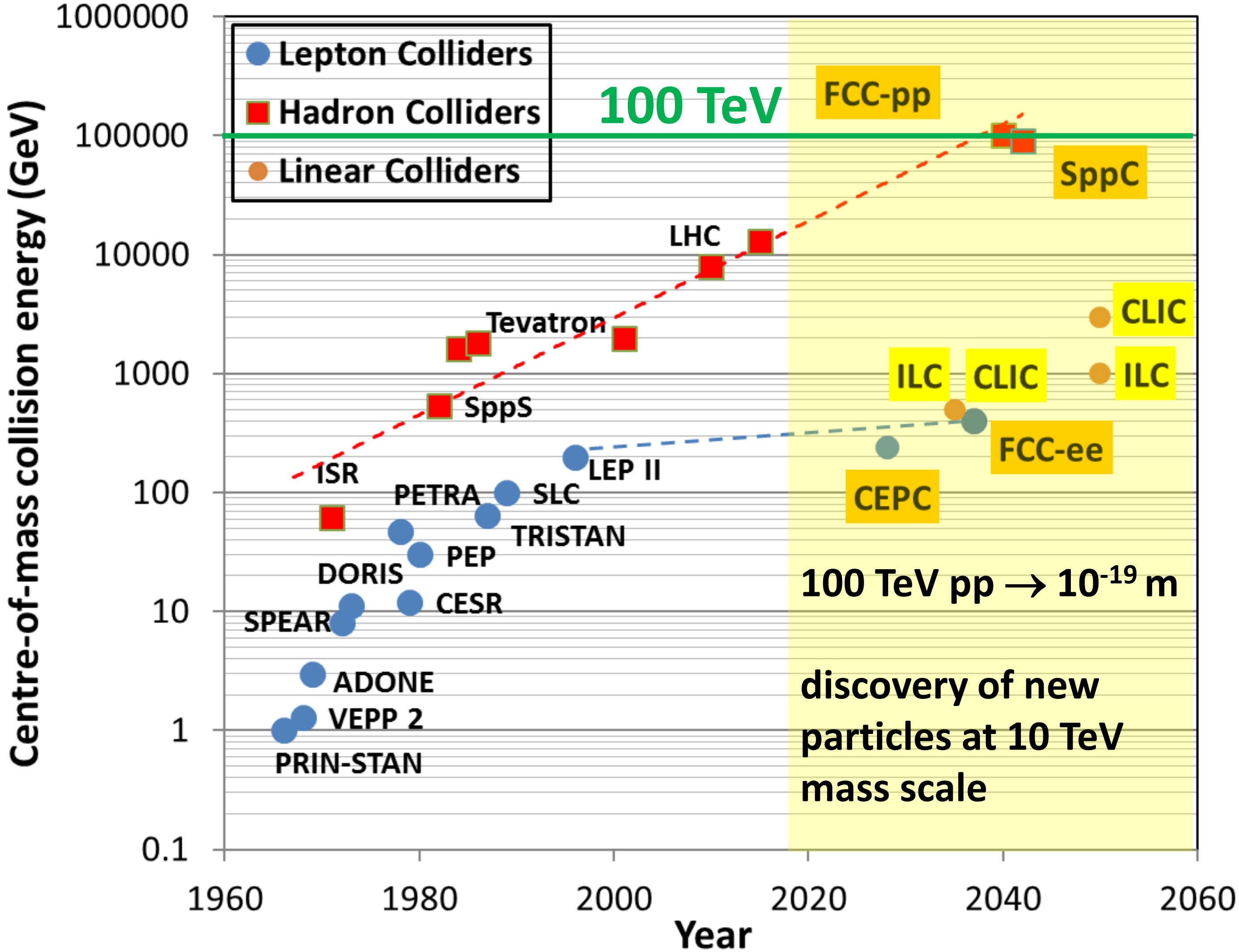
For physics beyond the LHC and beyond the Standard Model, under study (synergy of):

- **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



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."*

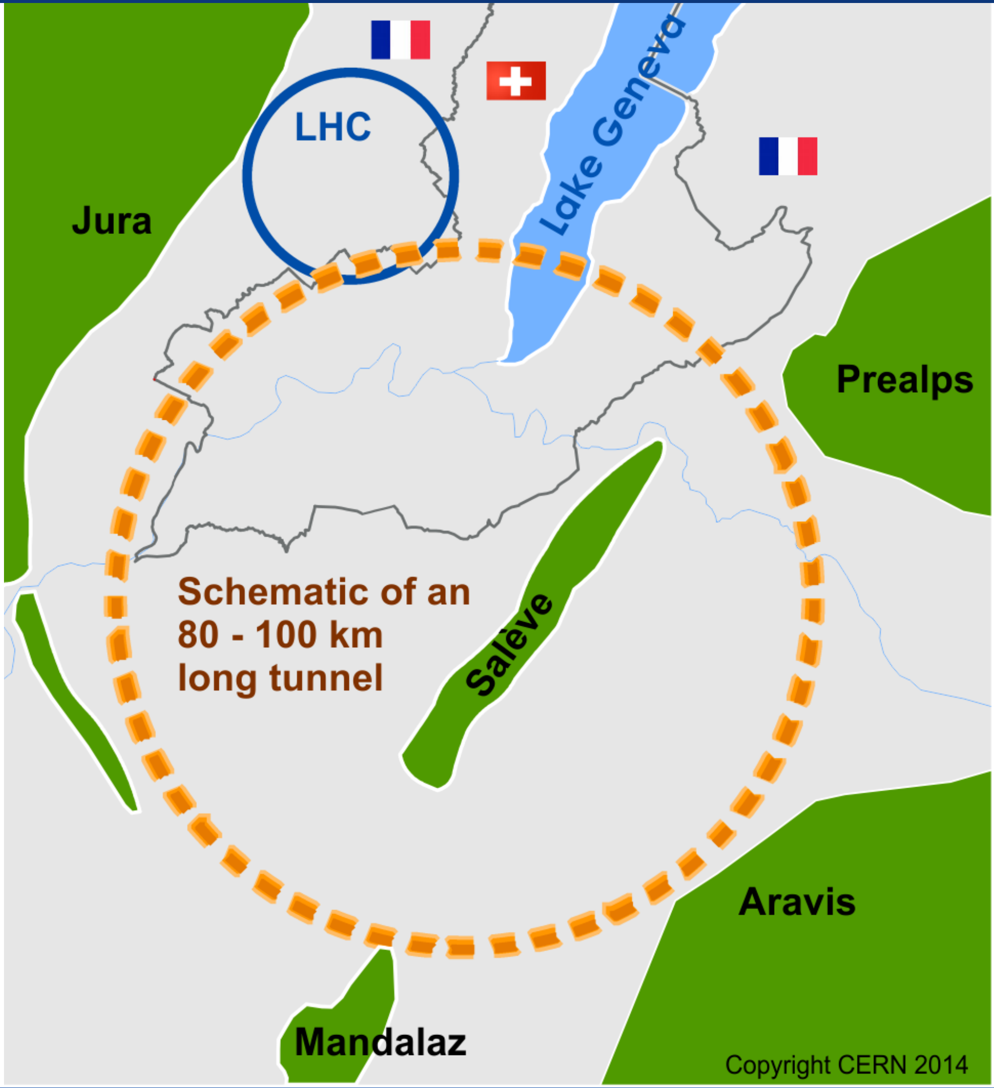
Future Circular Collider Study
GOAL: CDR and cost review for the next ESU (2019)

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**

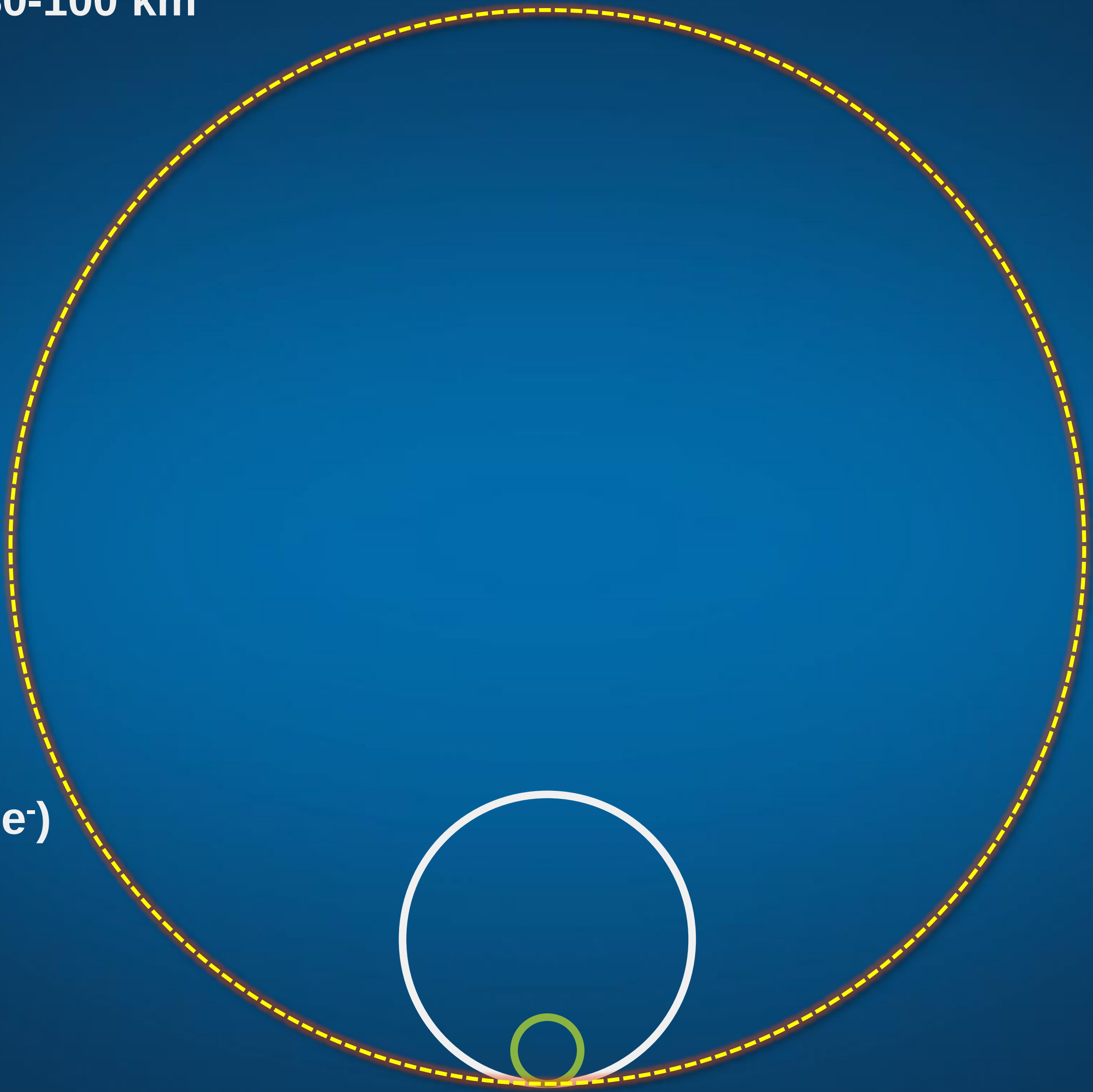
Energy:

- 14 TeV (pp)

- 209 GeV (e^+e^-)

Future Circular Collider

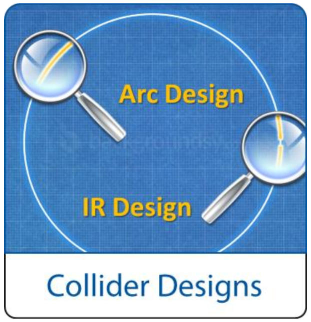
Circumference: **80-100 km**



Energy:

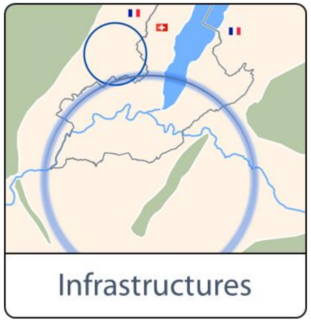
- **100 TeV (pp)**
- **>350 GeV (e^+e^-)**

FCC Scope: Accelerator and Infrastructure



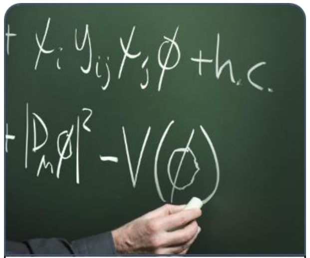
FCC-hh: **100 TeV pp collider as long-term goal**
→ defines infrastructure needs
FCC-ee: **e^+e^- collider**, potential intermediate step
HE-LHC: **based on FCC-hh technology**

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



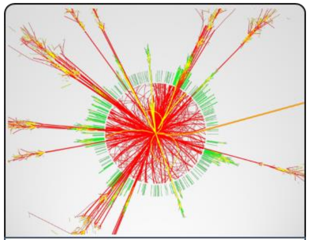
Tunnel infrastructure in Geneva area, linked to CERN accelerator complex;
site-specific, as requested by European strategy

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**

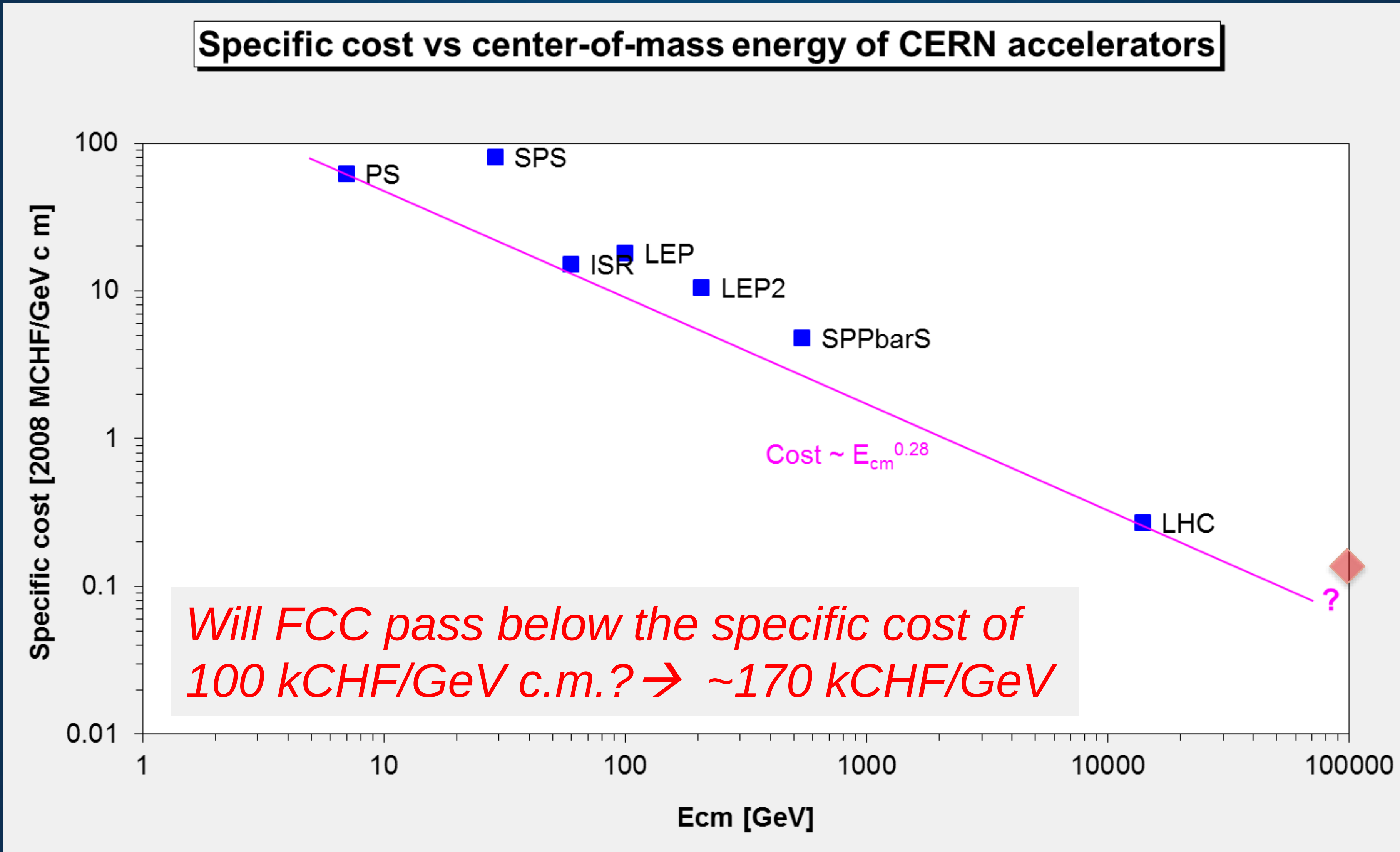
Role of CERN

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

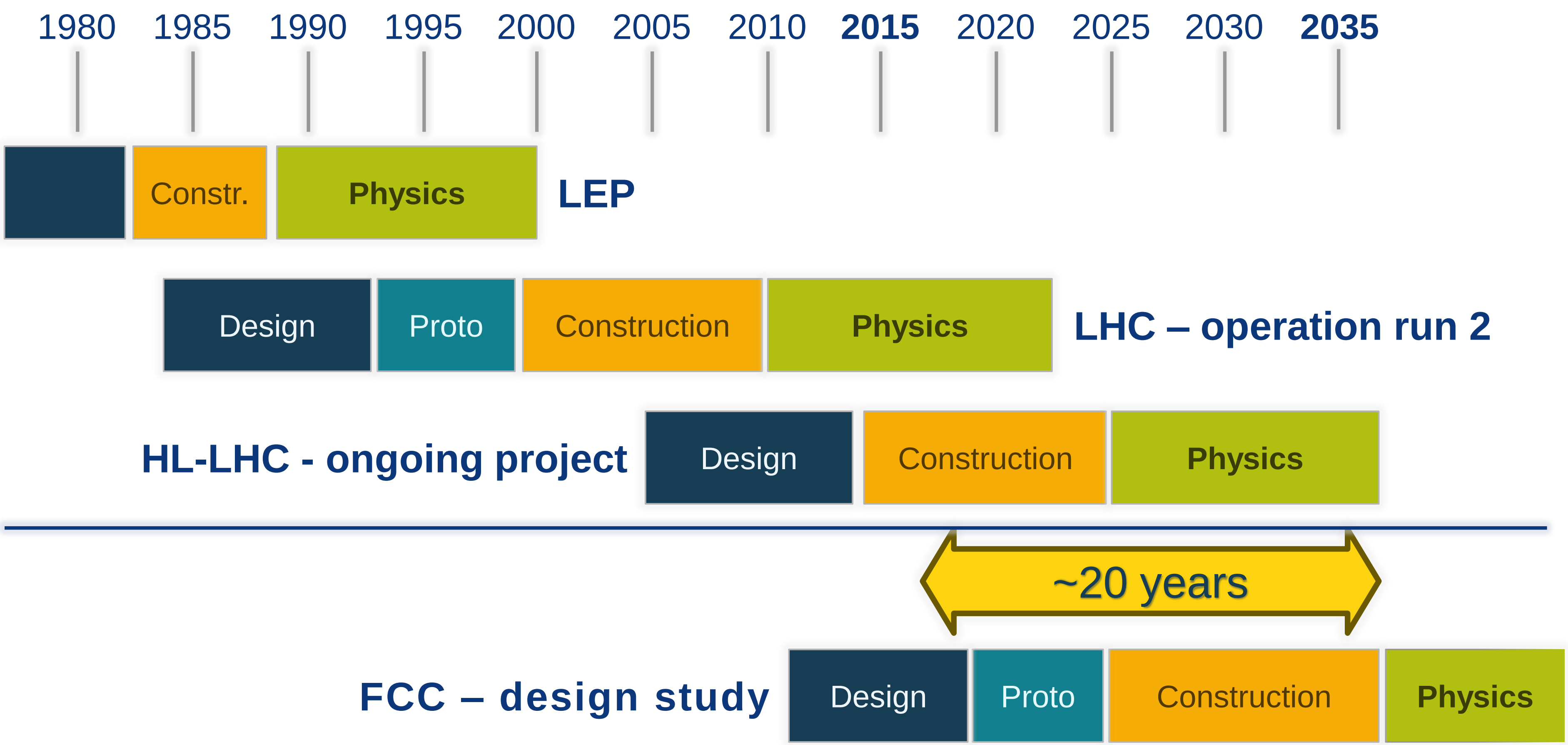
Strategic Goals

- **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



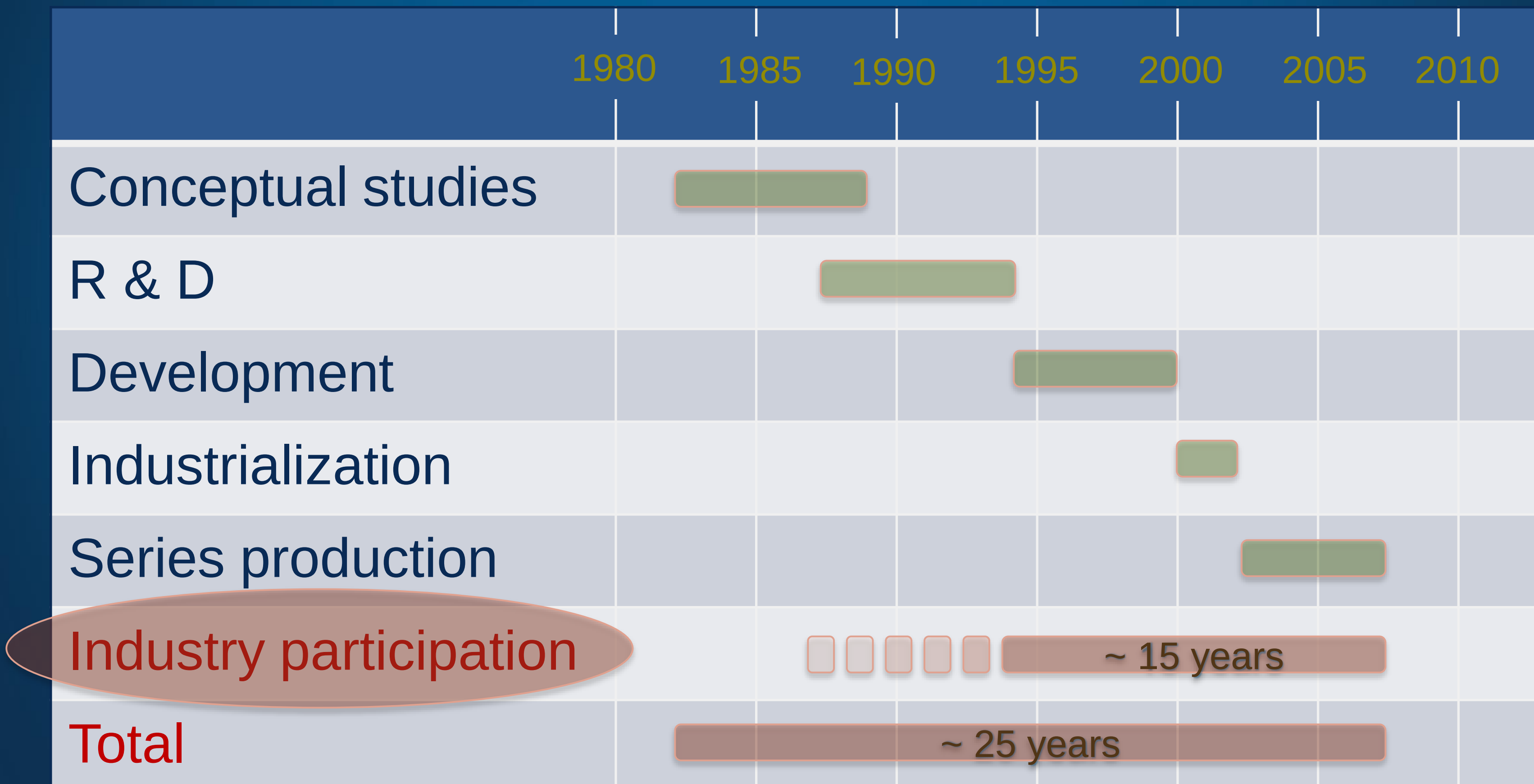
CERN Circular Colliders & FCC



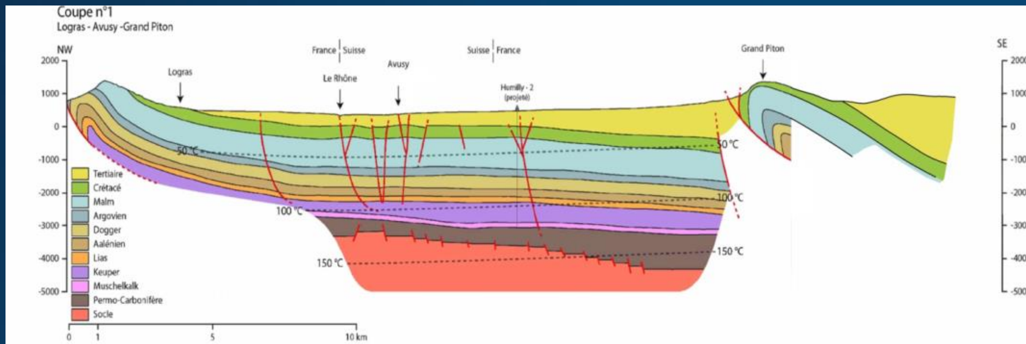
Must advance fast now to be ready for the period 2035 – 2040
Phase 1 completed: CDR for update of European Strategy by end 2018

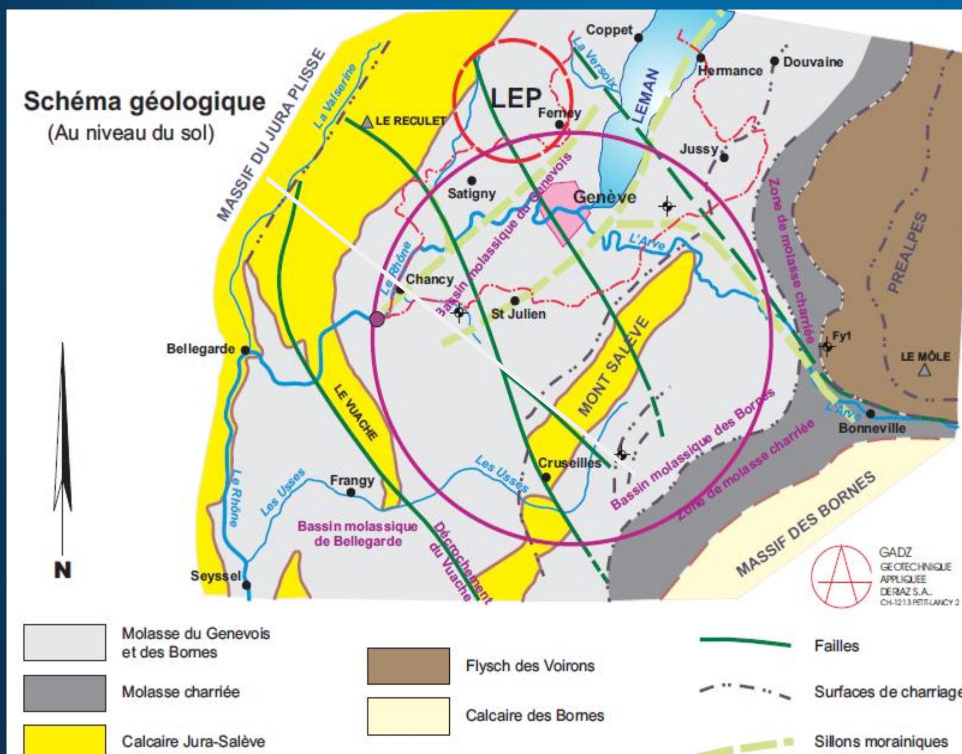
Time Indicator

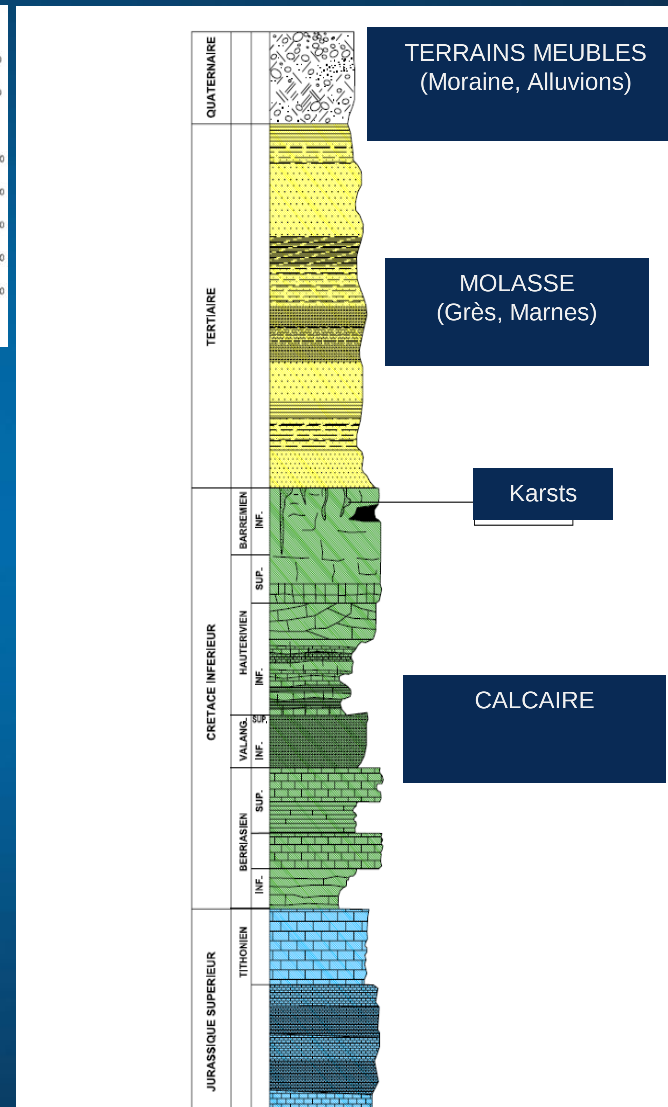
Case: LHC superconducting dipole magnets



Geological background







Progress on site investigations

Alignment | Shafts | Query

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

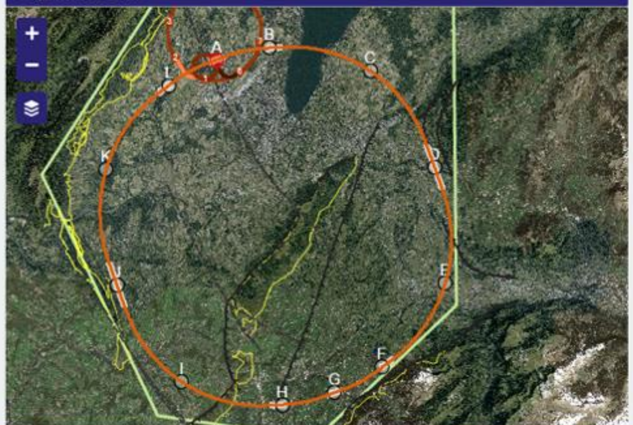
LOAD | SAVE | CALCULATE

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

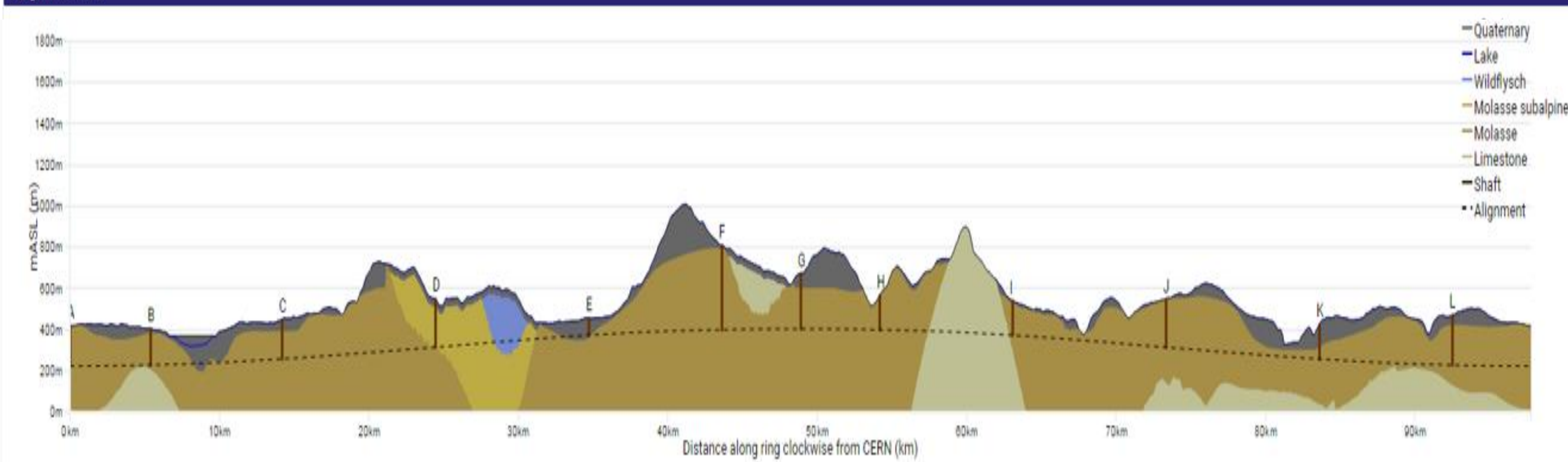
Alignment Location



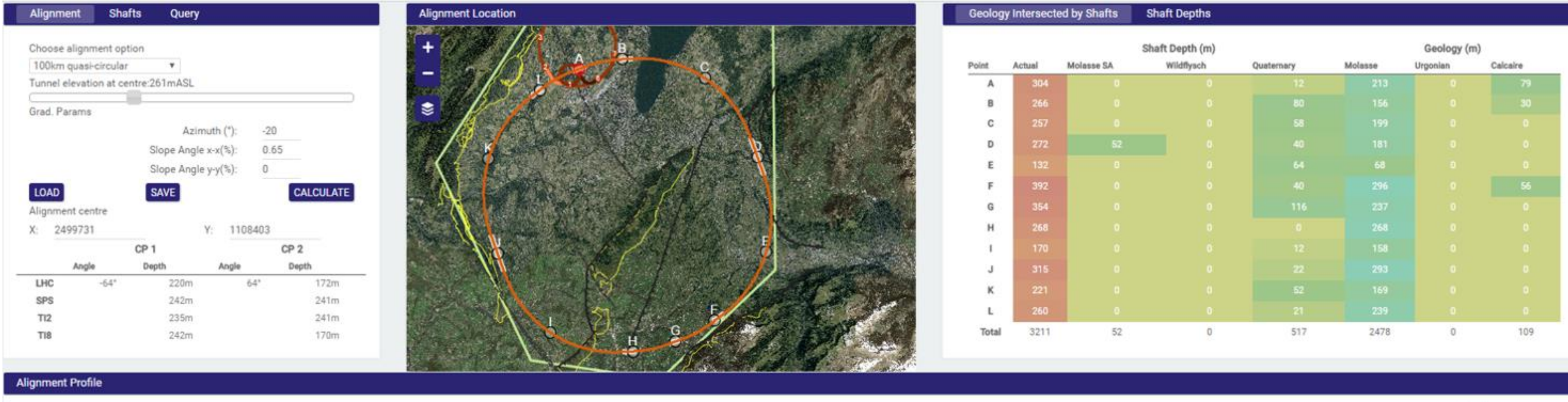
Geology Intersected by Shafts | Shaft Depths

	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

Alignment Profile



Progress on site investigations



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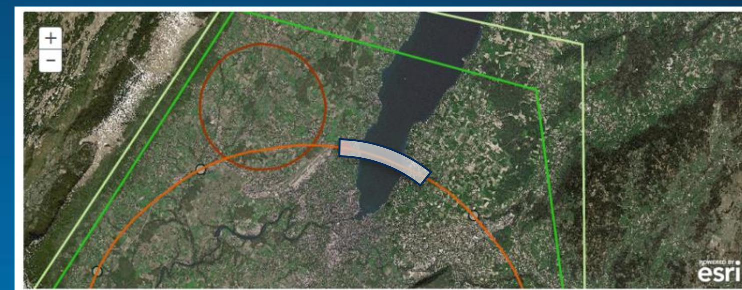
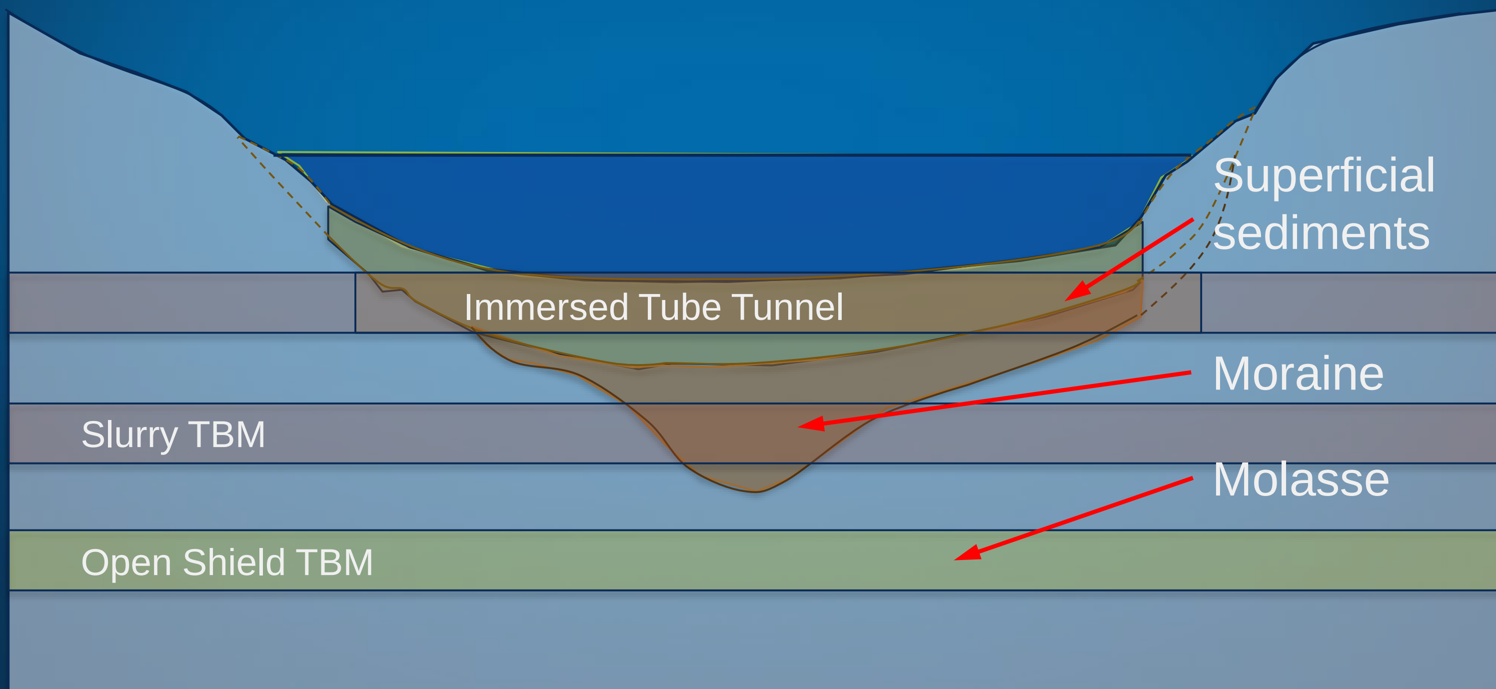
L	260	0	0	21	239	0	0
Total	3211	52	0	517	2478	0	109

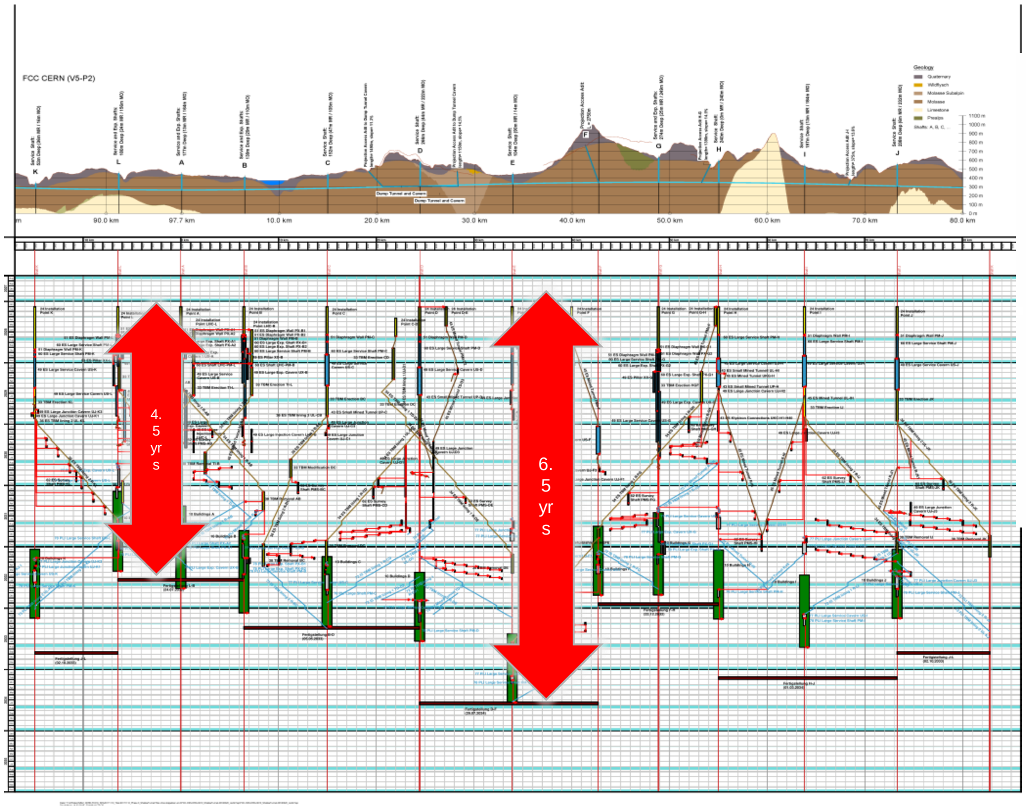
- 90 – 100 km fits geological situation well
- LHC suitable as potential injector
- The 100 km version, intersecting LHC, is the baseline and studied in more detail

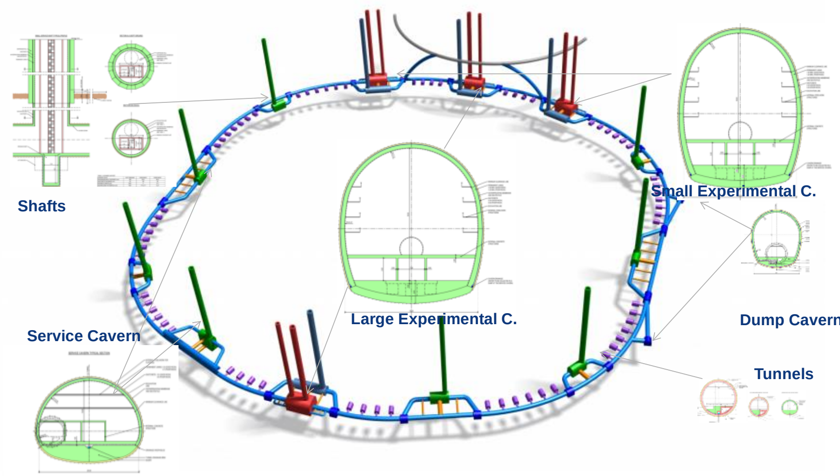
Tunnelling options for crossing the lake





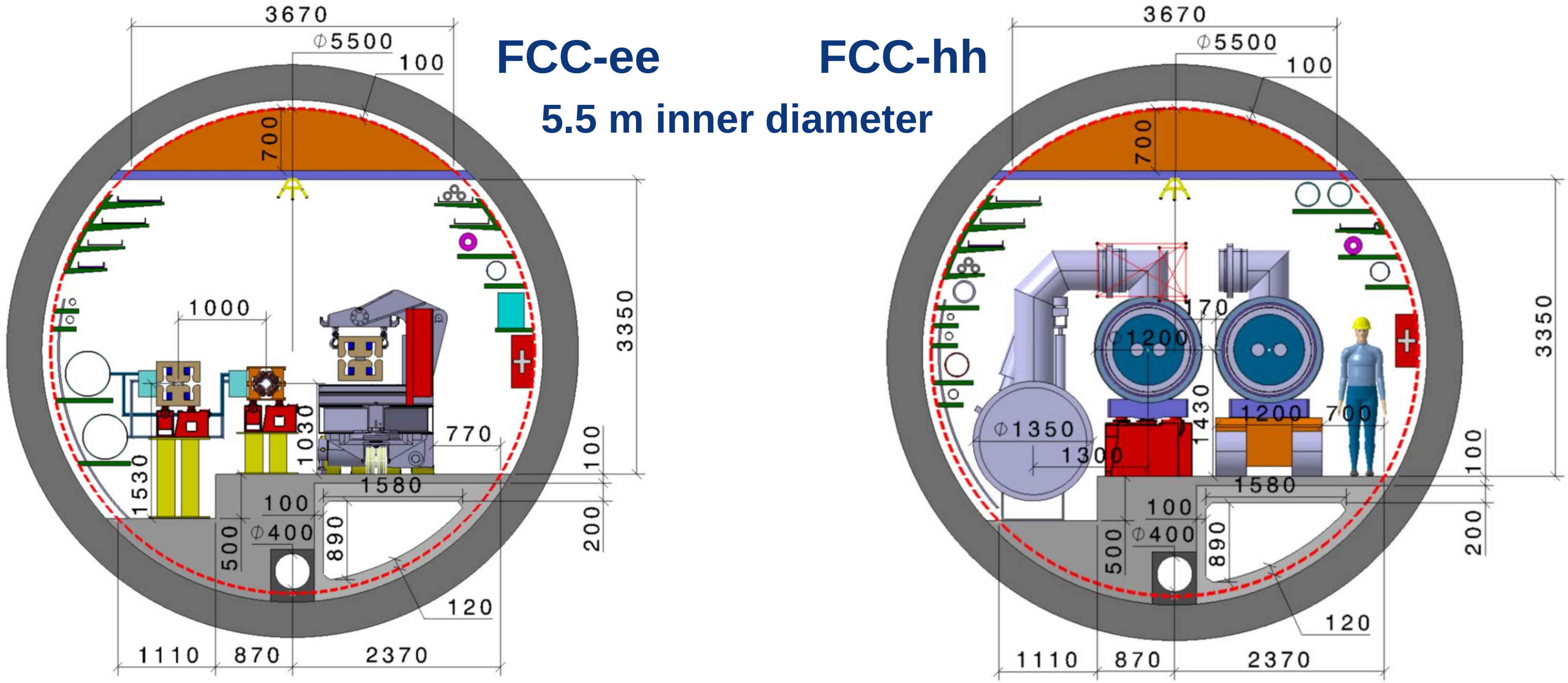
CE schedule studies





- **Total construction duration 7 years**
- **First sectors ready after 4.5 years**

FCC – tunnel integration in arcs



Hadron collider parameters

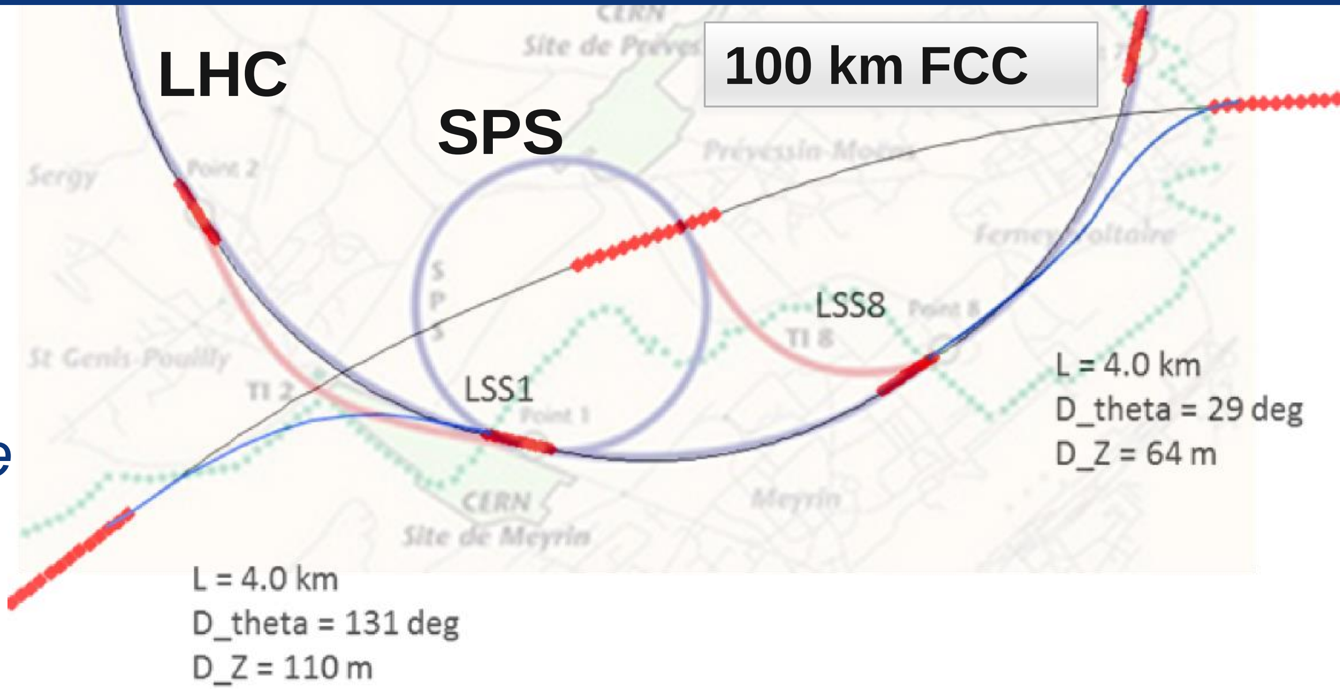
parameter	FCC-hh		HE-LHC*	(HL) LHC
collision energy cms [TeV]	100		27	14
dipole field [T]	16		16	8.3
circumference [km]	100		27	27
# IP	2 main & 2		2 & 2	2 & 2
beam current [A]	0.5		1.12	(1.12) 0.58
bunch intensity [10^{11}]	1	1 (0.2)	2.2	(2.2) 1.15
bunch spacing [ns]	25	25 (5)	25	25
beta* [m]	1.1	0.3	0.25	(0.15) 0.55
luminosity/IP [10^{34} $cm^{-2}s^{-1}$]	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

*tentative

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**

Key Technologies

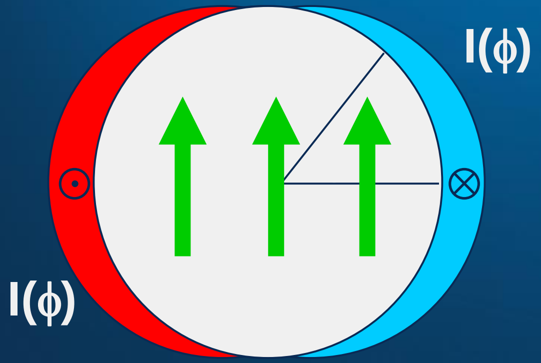
- 16 T superconducting magnets
- Synchrotron radiation
- Affordable & reliable cryogenics
- Superconducting RF cavities
- RF power sources
- Reliability & availability concepts

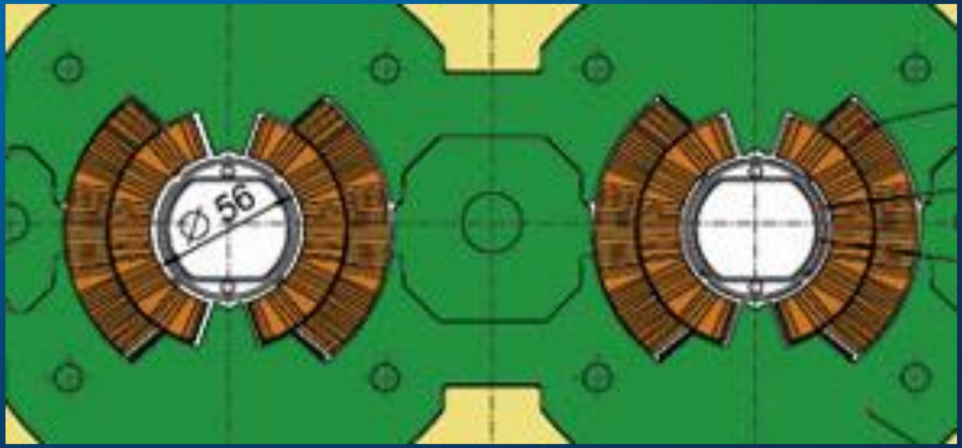
High –field SC dipoles

- **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

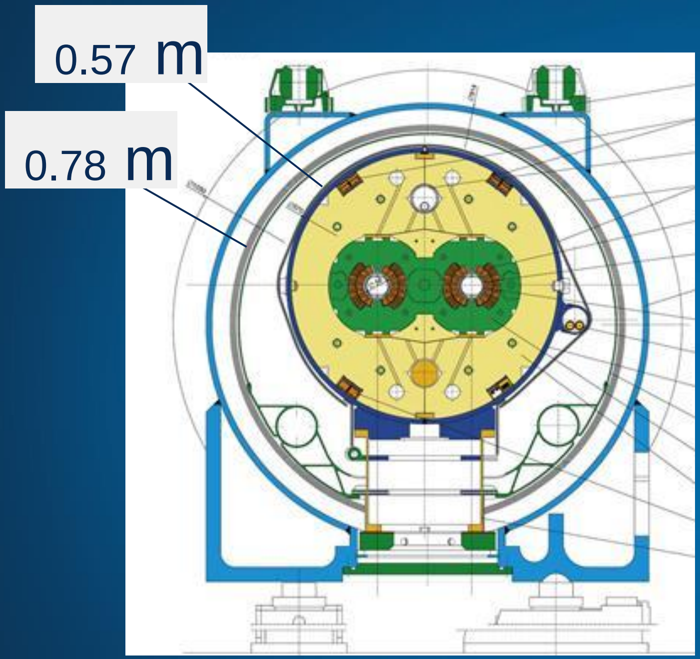
- **Ideal coil geometry for dipolar fields:**
  - Azimuthal current distribution **$I(\phi) = I_0\cos(\phi)$ Dipol**, ($I_0\cos(2\phi)$ Quadrupol)
  - 2 horizontally displaced circles

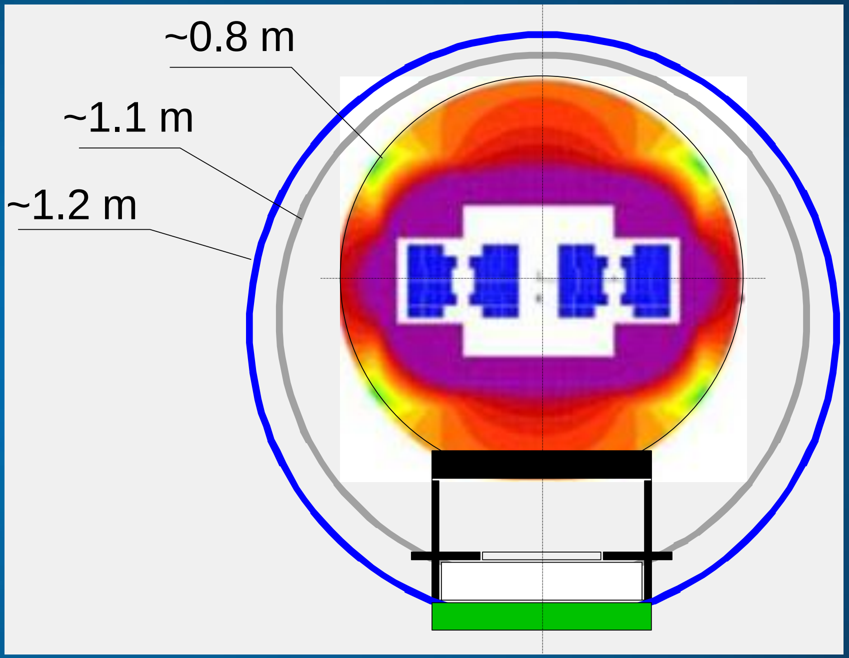
Cross section





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

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

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

LHC

Bore diameter: 56 mm

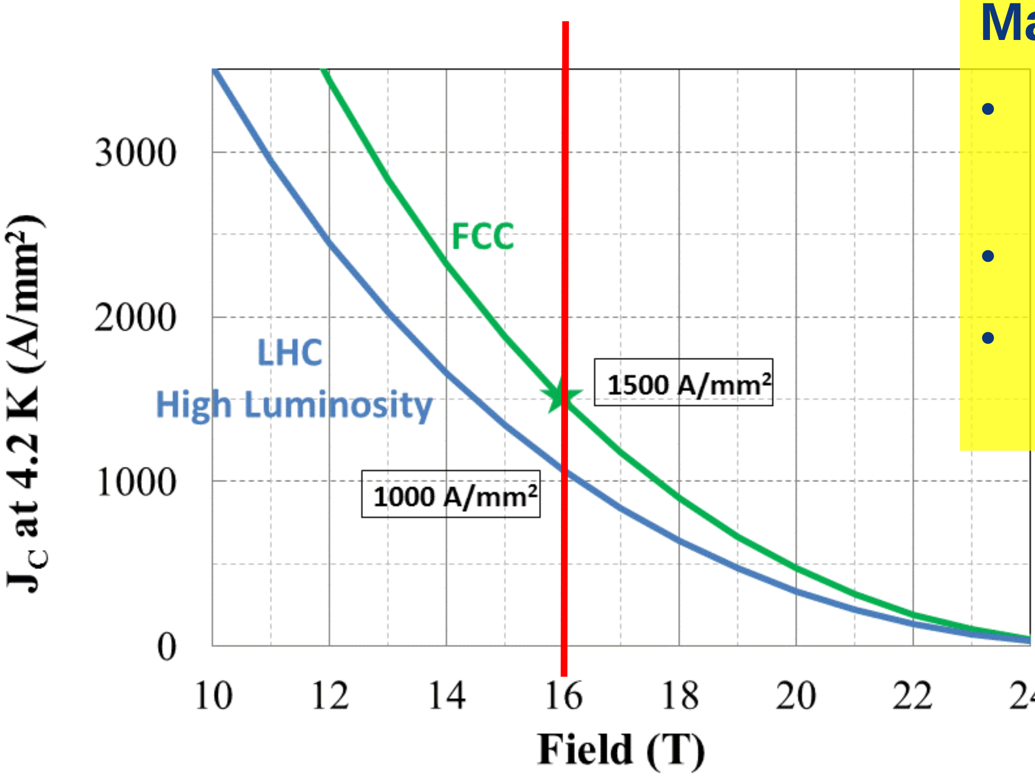
Dipoles: $1232\ units, 14.3\ m\ long, 8.3\ T \Leftrightarrow \int Bdl{\sim}0.15\ MTm$

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

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

Nb_3Sn conductor program

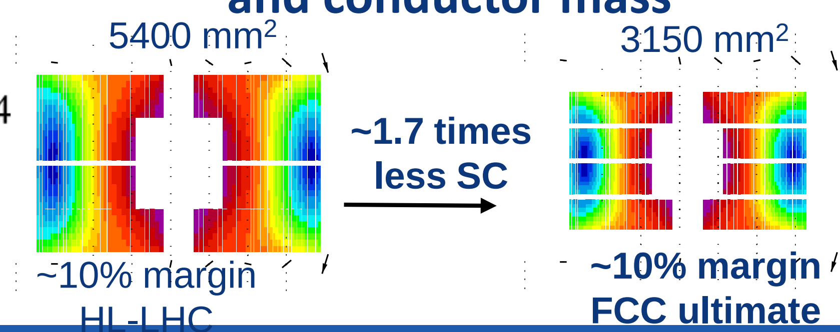
Nb_3Sn is one of the major cost & performance factors



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**

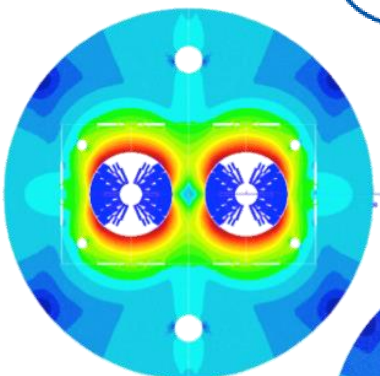
Impact on coil section and conductor mass



16 T dipole options under consideration

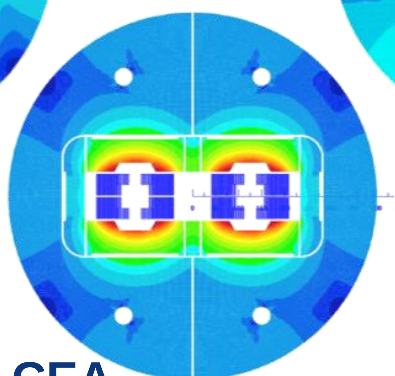
EuroCirCol
A key to New Physics

Cos-theta



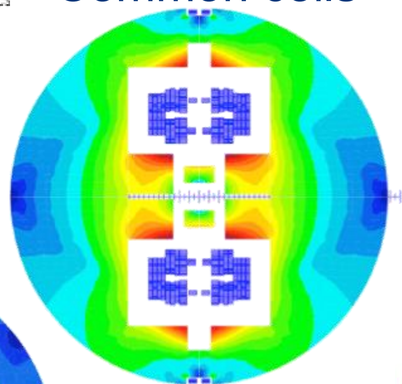
INFN

Blocks



CEA

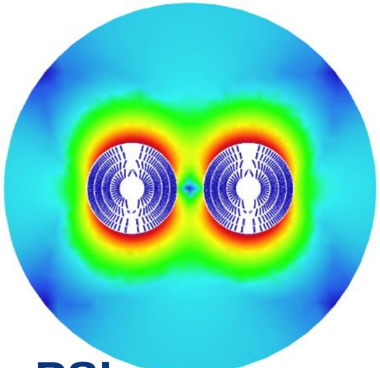
Common coils



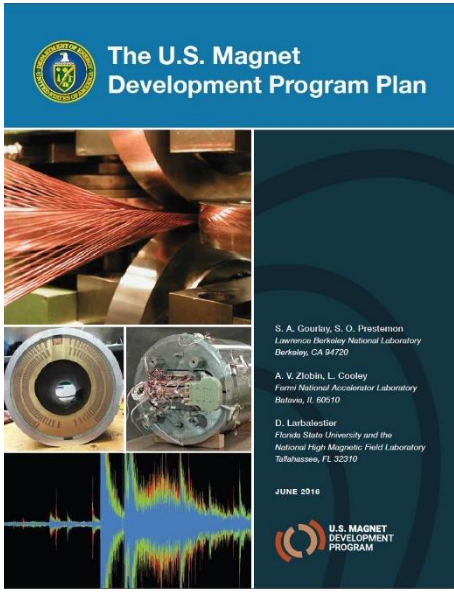
CIEMAT

Swiss contribution

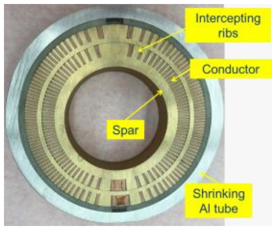
Canted Cos-theta



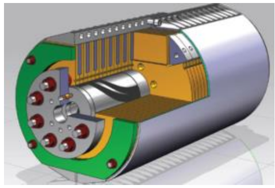
PSI



LBNL



FNAL

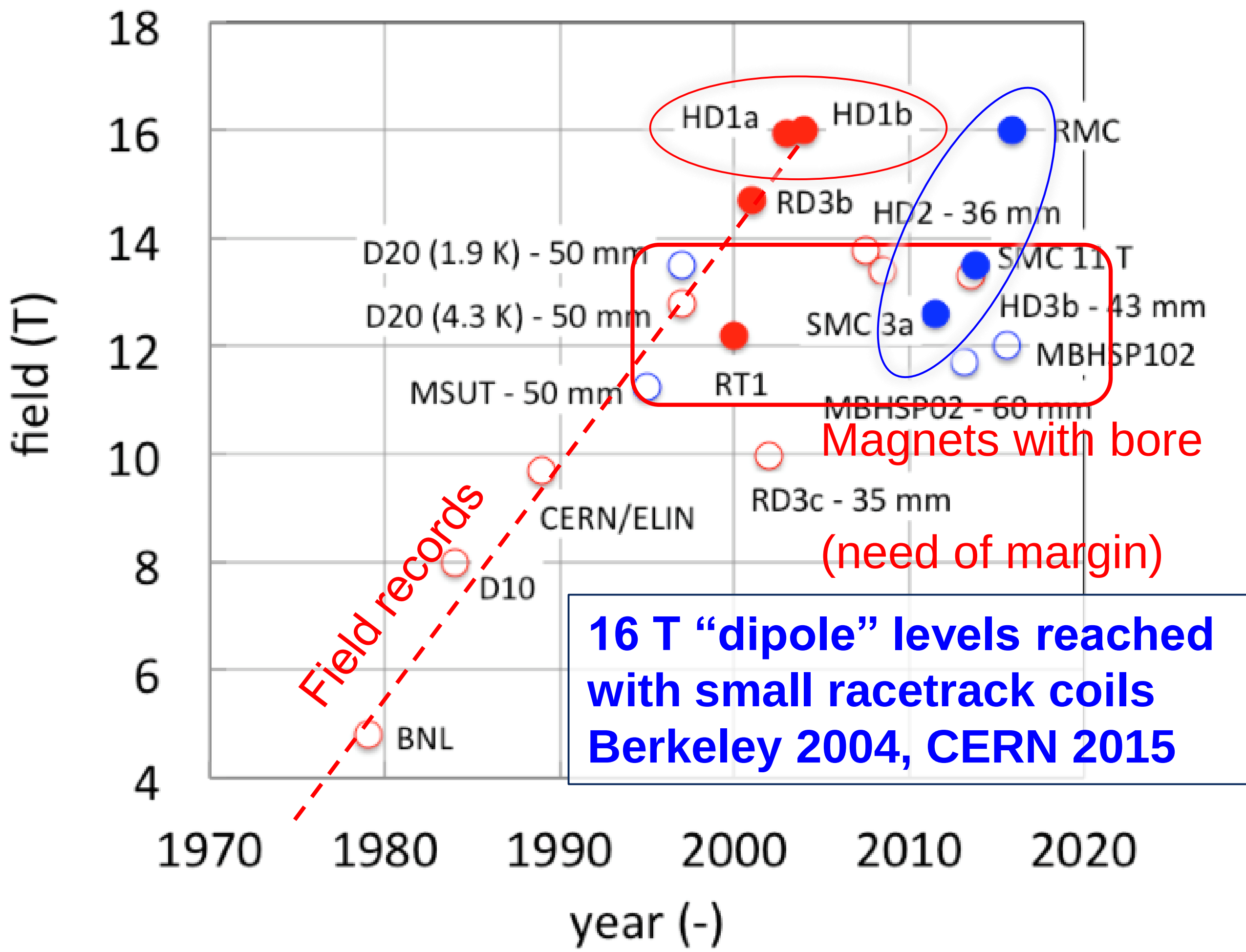


Short model magnets (1.5 m lengths) from 2018 – 2022

Russian 16 T magnet program launched by BINP recently.

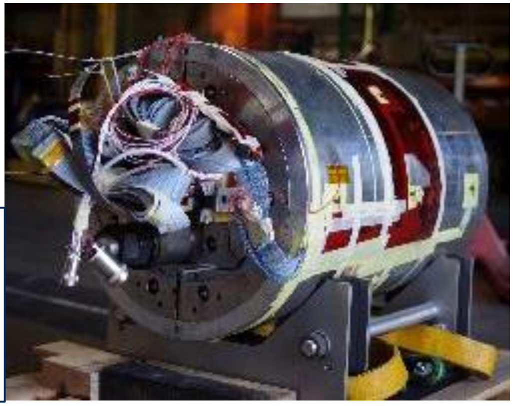
Towards 16T magnets

Record fields for SC magnets in “dipole” configuration



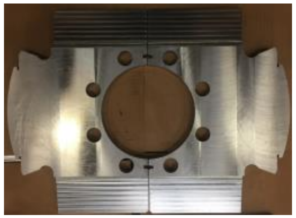
16 T “dipole” levels reached with small racetrack coils Berkeley 2004, CERN 2015

LBNL HD1



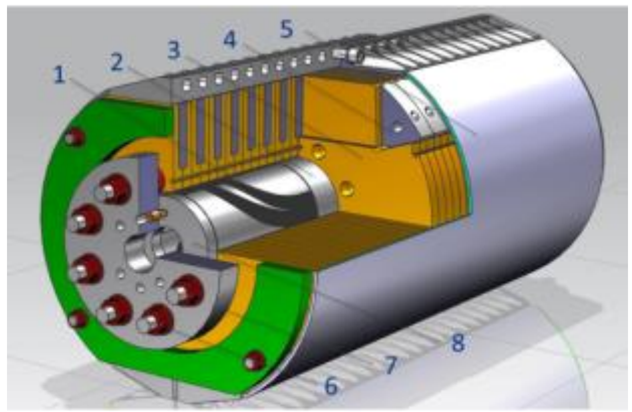
CERN RMC

15 T dipole demonstrator (US-MDP)


Iron Laminations


AL I-Clamps


Fillers



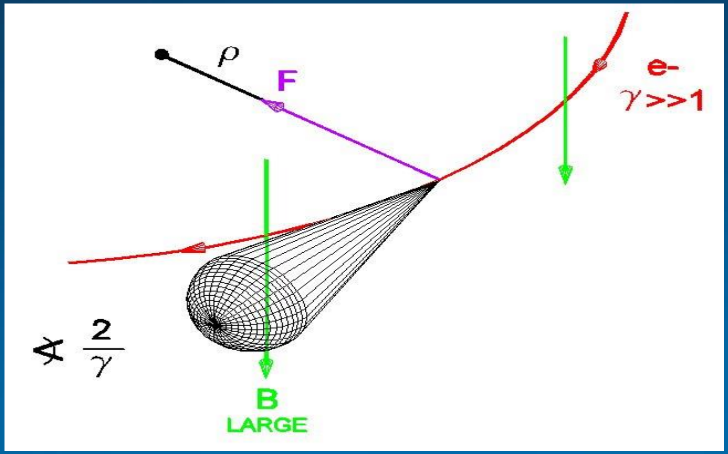

StSt Skin


End Plates


Axial Rods

- **All coil parts, structural components and tooling are available at FNAL**
- **Coil fabrication and the work with mechanical structure are in progress**
- **Magnet reached 14 T in May 2019.**

Synchrotron radiation



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

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

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

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

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

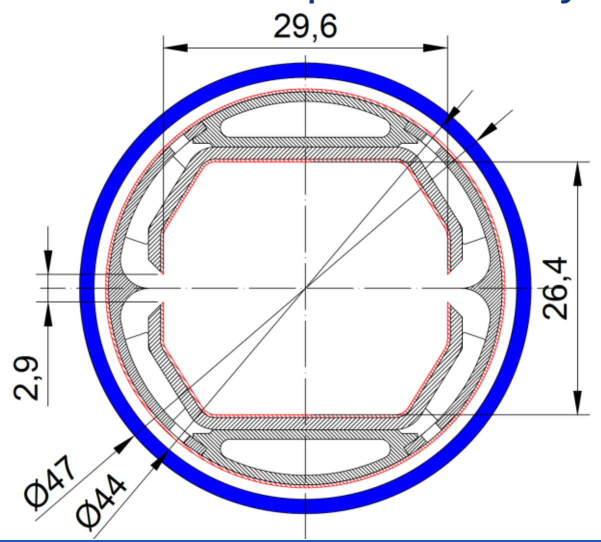
Synchrotron radiation beam screen prototype

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!!!)**

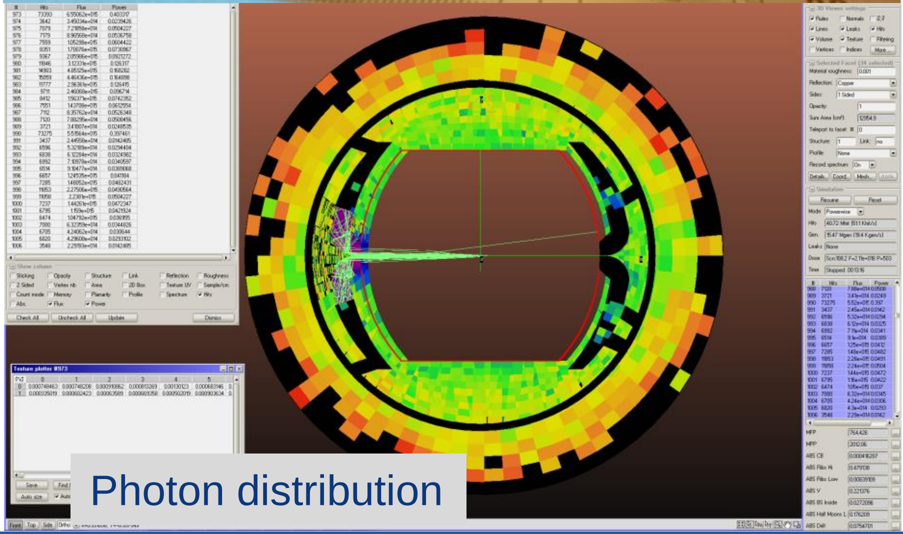
New Beam screen with ante-chamber

- 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

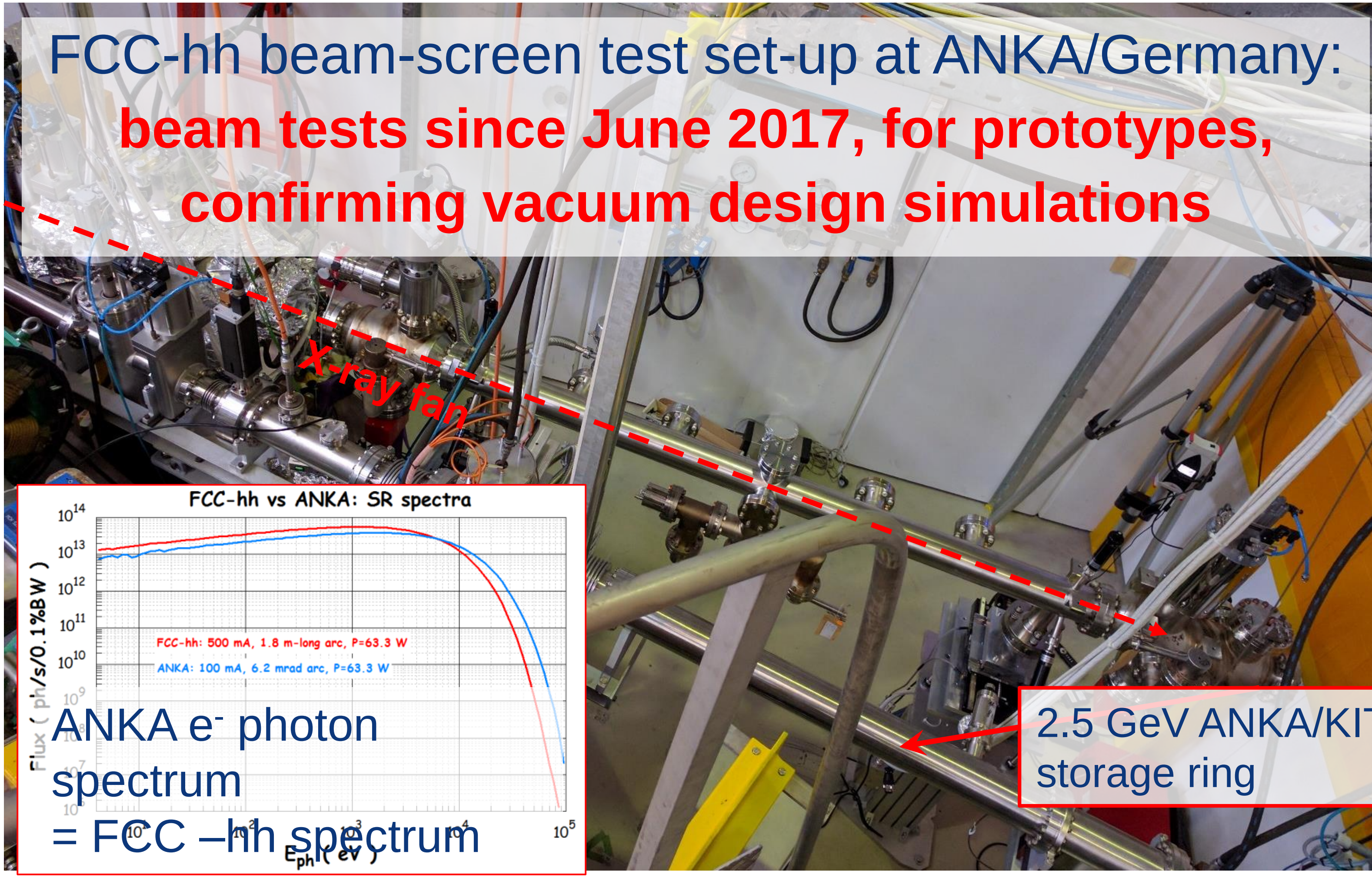


Photon distribution

Beam screen prototype test

FCC-hh beam-screen test set-up at ANKA/Germany:

beam tests since June 2017, for prototypes, confirming vacuum design simulations

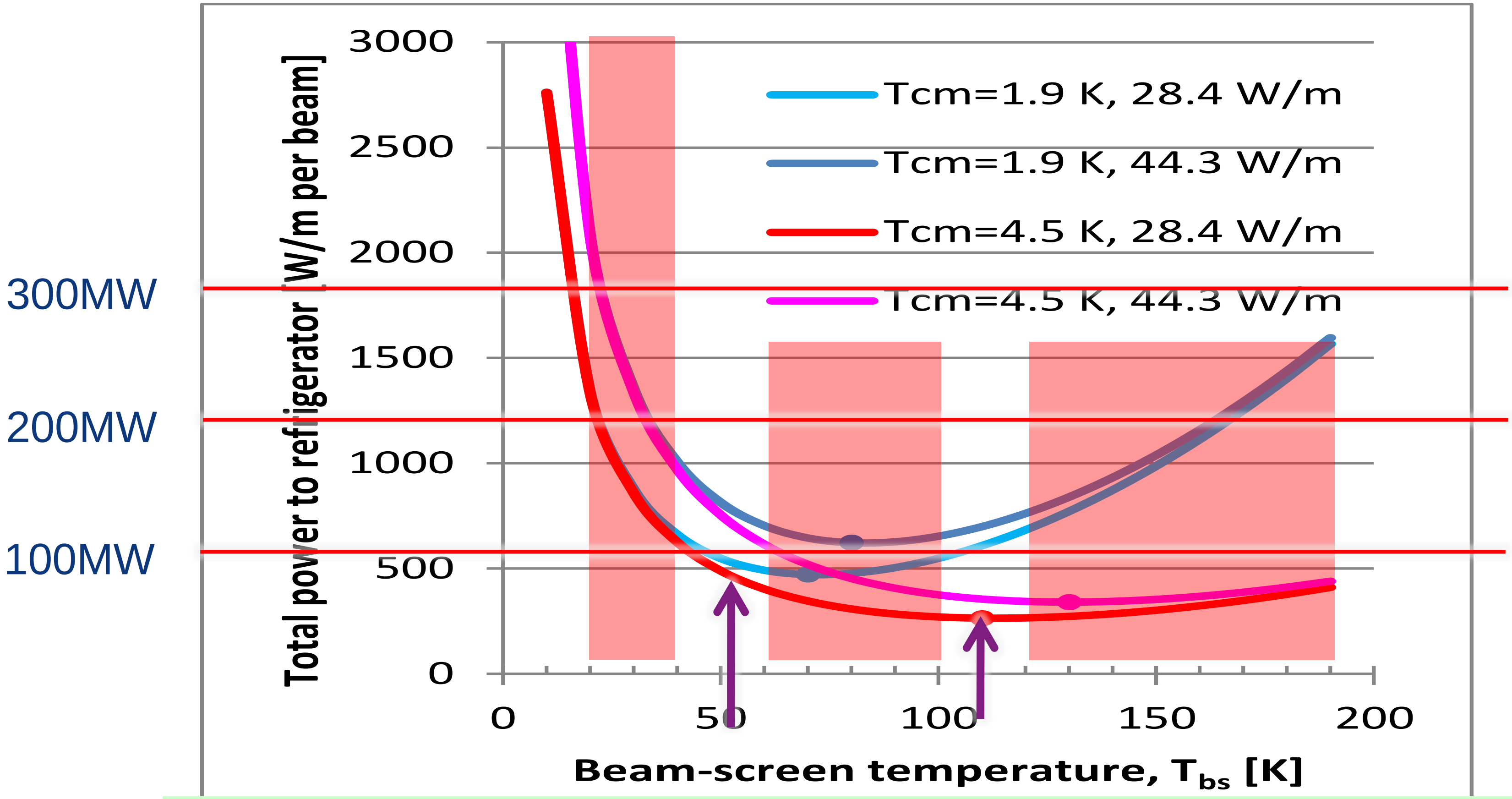


ANKA e^- photon spectrum
= FCC –hh spectrum

2.5 GeV ANKA/KIT storage ring

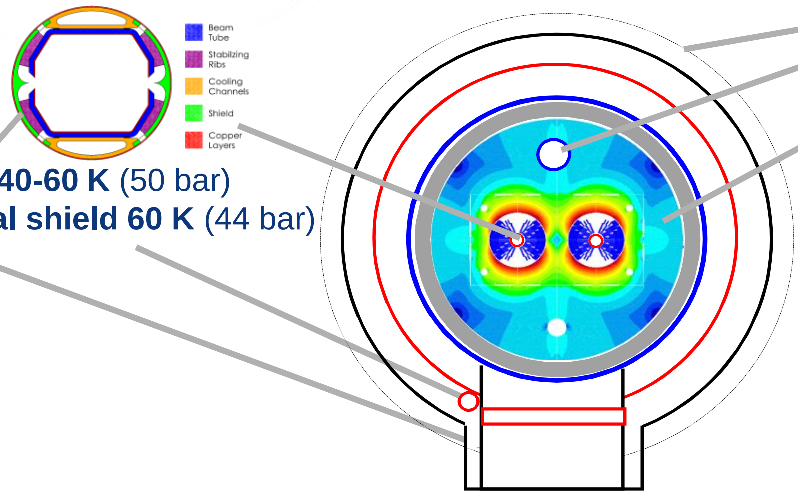
Cryo power for cooling of SR heat

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

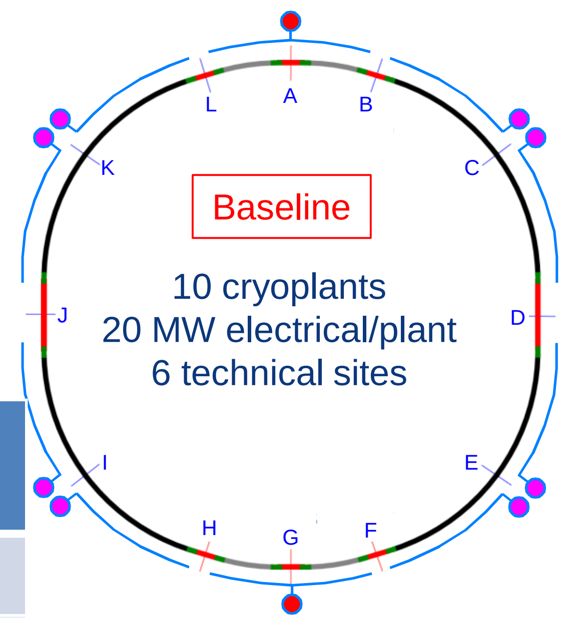


Temperature level	[W/m]
1.9 K, cold mass of magnets • Beam losses • Resistive heating of splices	**1.4**
40-60 K, beam screen, thermal shield • Synchrotron radiation • Beam Image current	**71**

Total load
1 MW equivalent @4.5 K

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

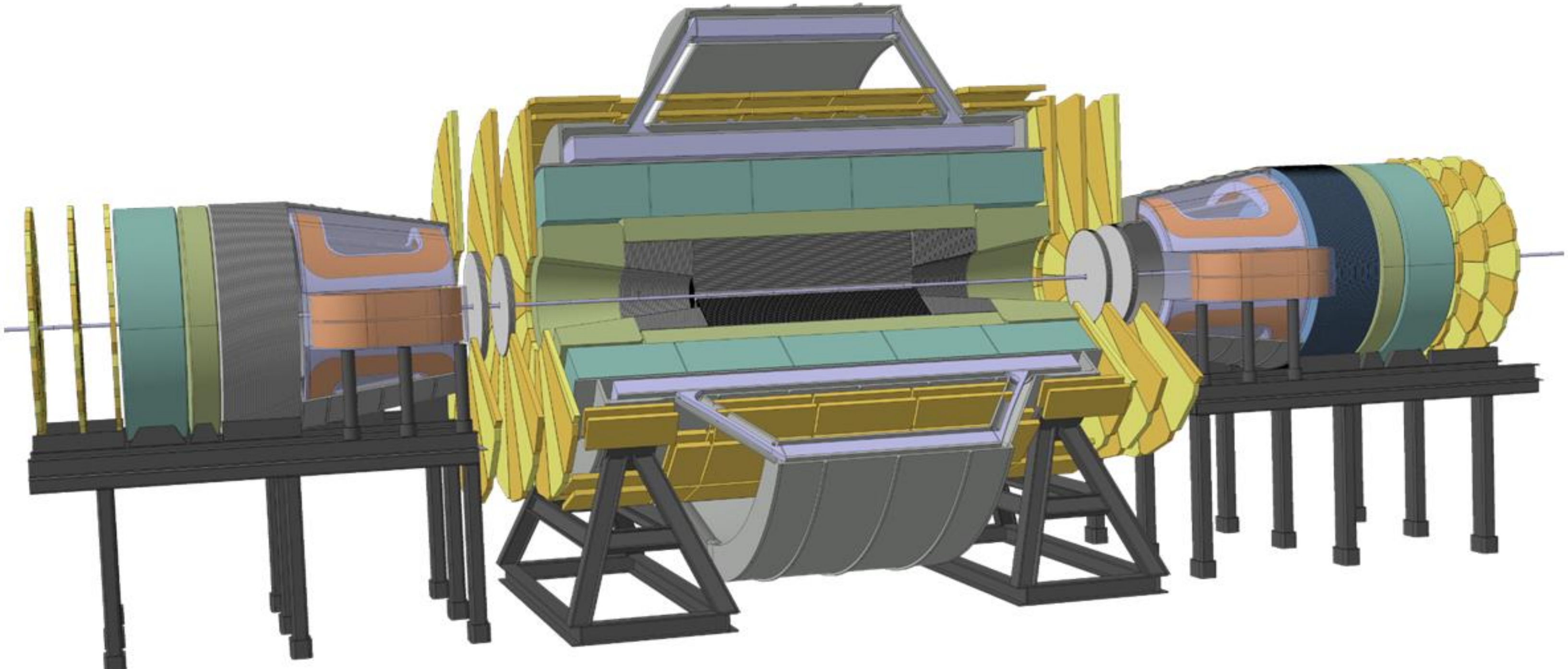
Cryoplants overall layout



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:

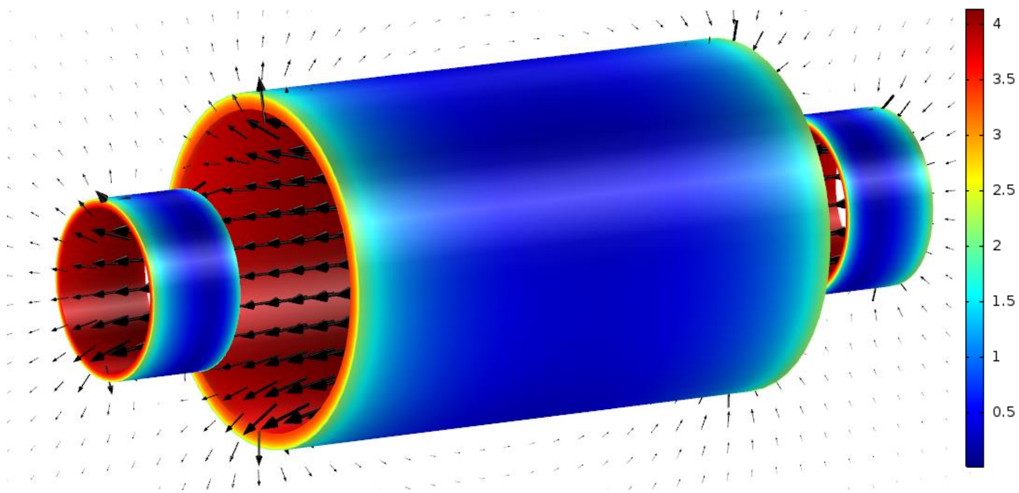


B=6 T, 12 m bore, solenoid with shielding coil and 2 dipoles 10 Tm.

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

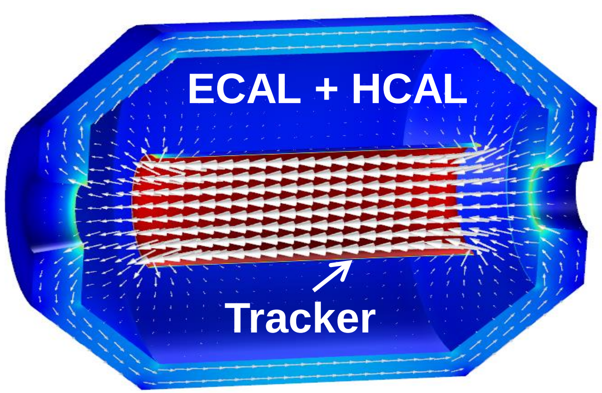
Detector Magnet Studies

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

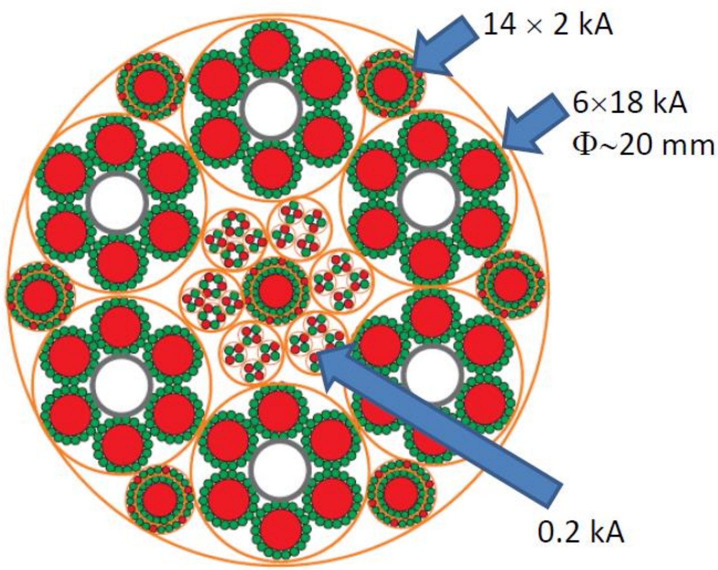


Alternative challenging design:

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!

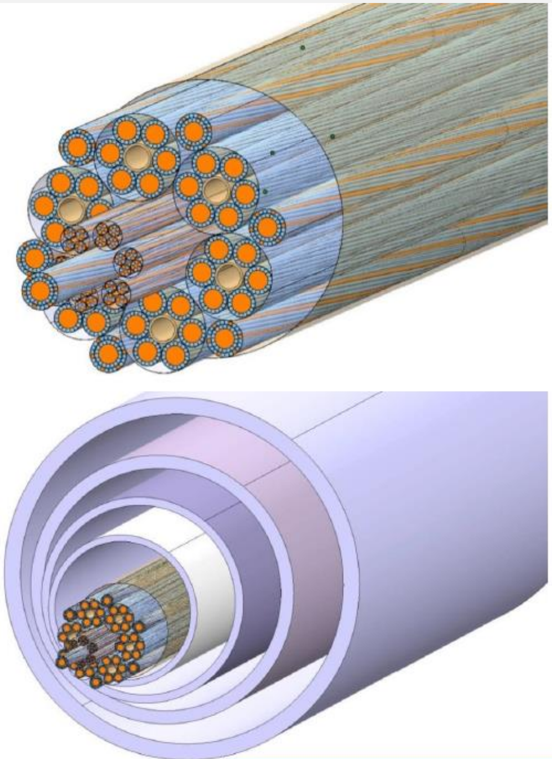
SC links for circuit powering

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

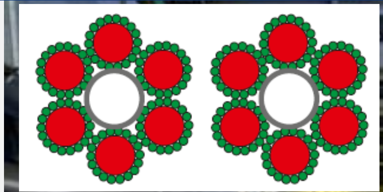


Φext ~ 65 mm
|Itot| ~ 150 kA

Mass ~ 11 kg/m



Φext ~ 220 mm



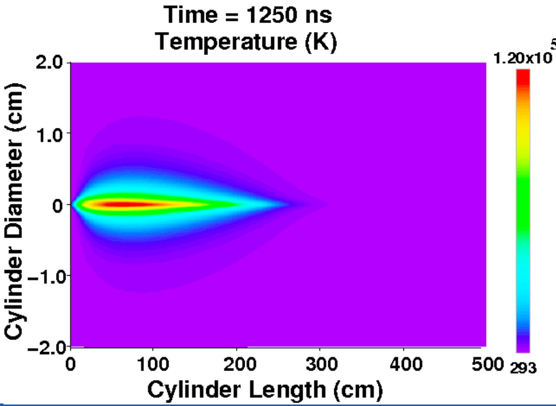
Beam power & machine protection

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.

Damage of a beam with an energy of 2 MJ

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

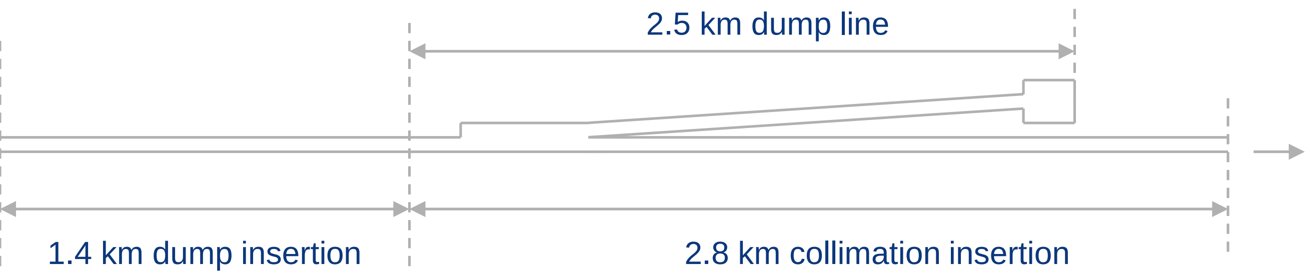


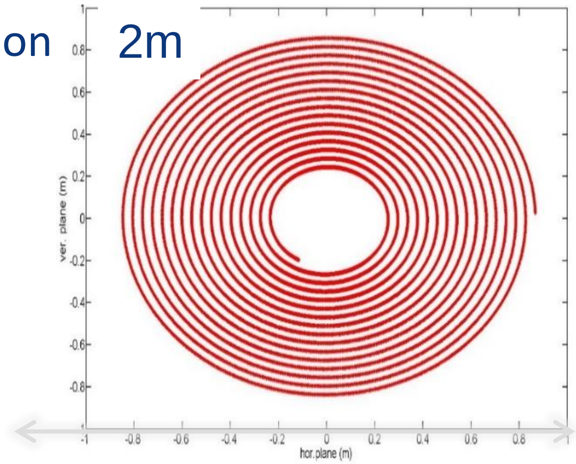
- **Collimation, control of beam losses and radiation effects (shielding) are of prime importance.**
- **Injection, beam transfer and beam dump all critical.**

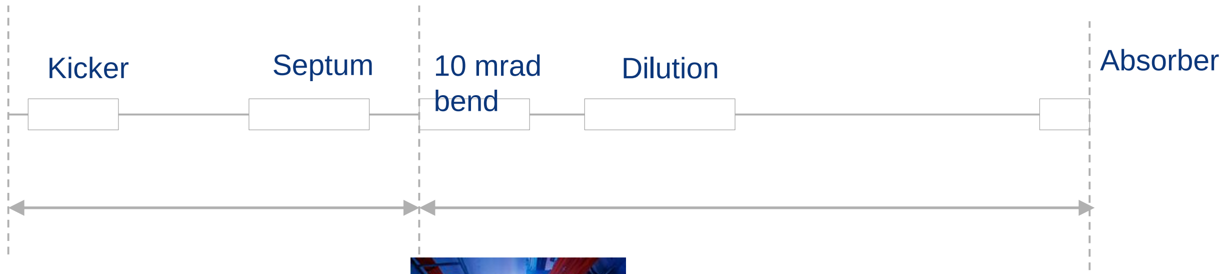
Machine protection issues to be addressed early on!

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!





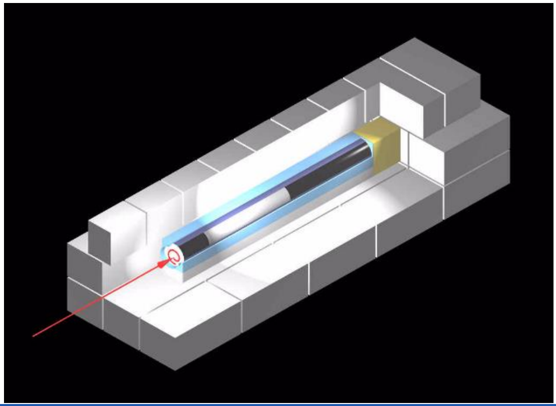


Fluka studies:

- 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



Status of global FCC Collaboration

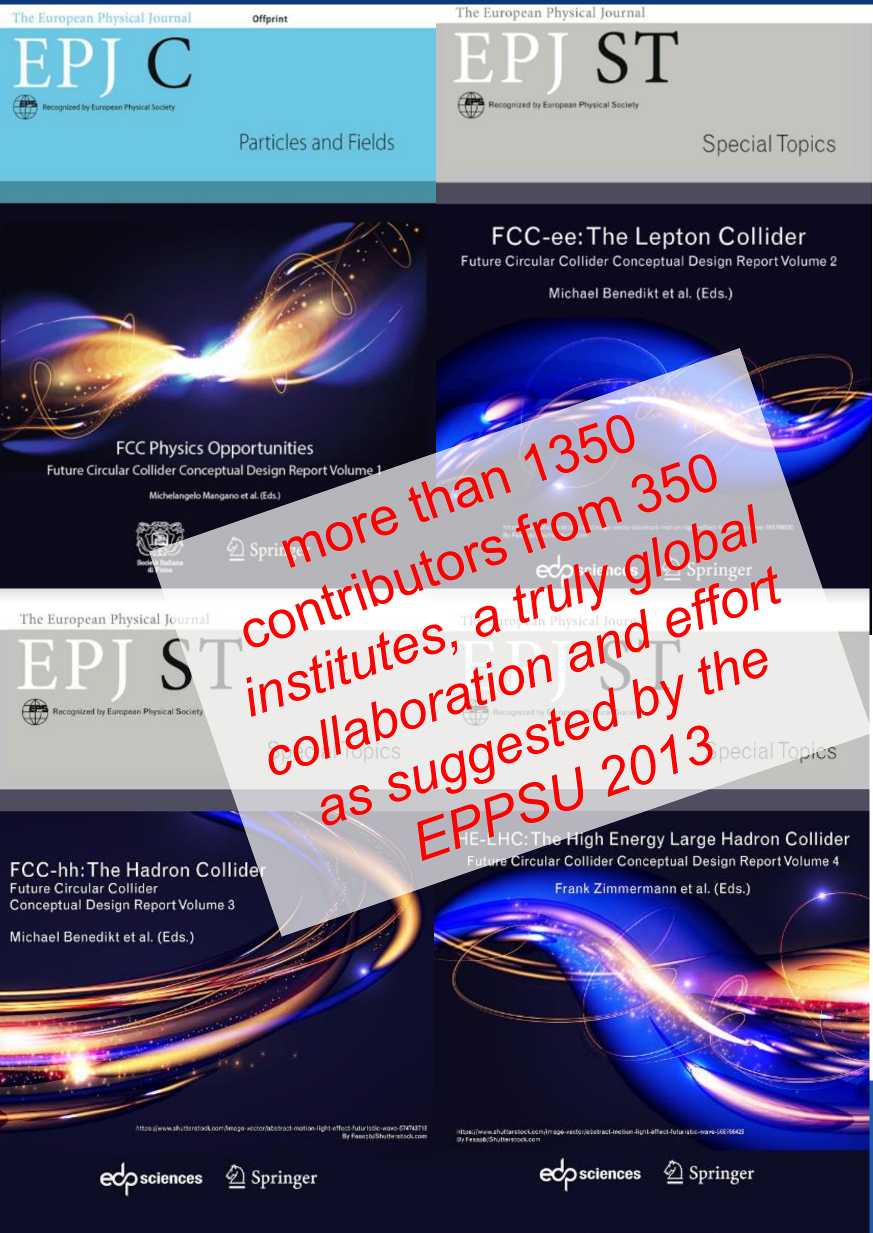
136
Institutes

32
Companies

34
Countries

EC
H2020

Results of FCC Conceptual Design Study



Study Documentation:

4 CDR volumes submitted to EPJ in December 2018.

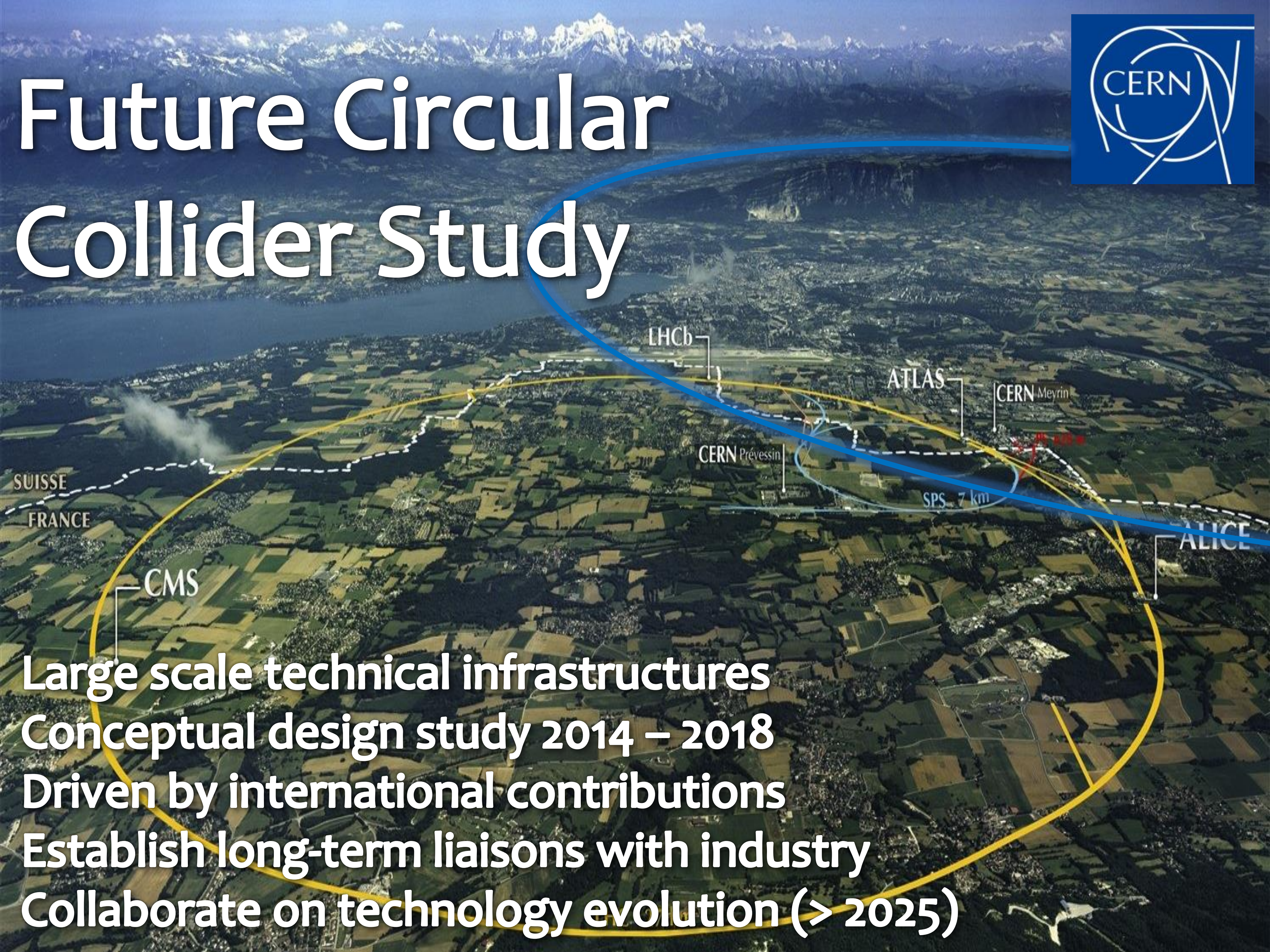
- FCC Physics Opportunities
- FCC-ee
- FCC-hh
- HE-LHC
- Preprints available since 15 January 2019 http://fcc-cdr.web.cern.ch/

CDR presentation during welcome event this evening.

Paper copies can be requested at

- http://get-fcc-cdr.web.cern.ch

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)