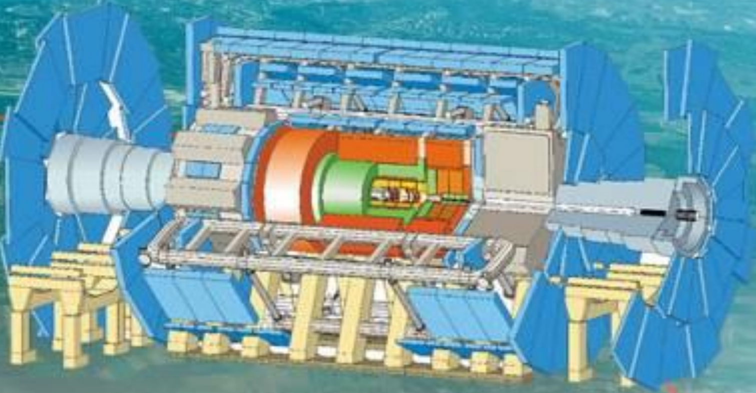
Superconducting Magnets for Big Science

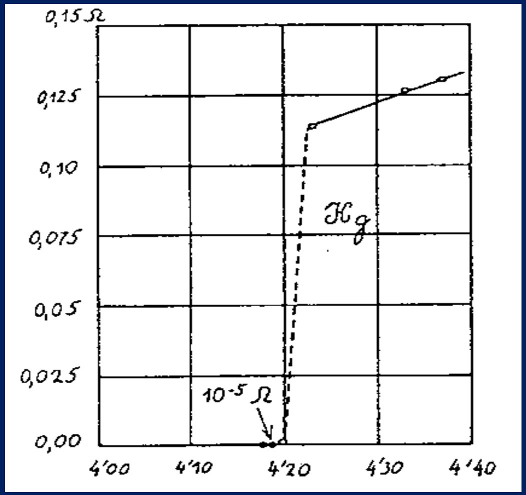
- the Future Circular Collider, their Detectors and more -



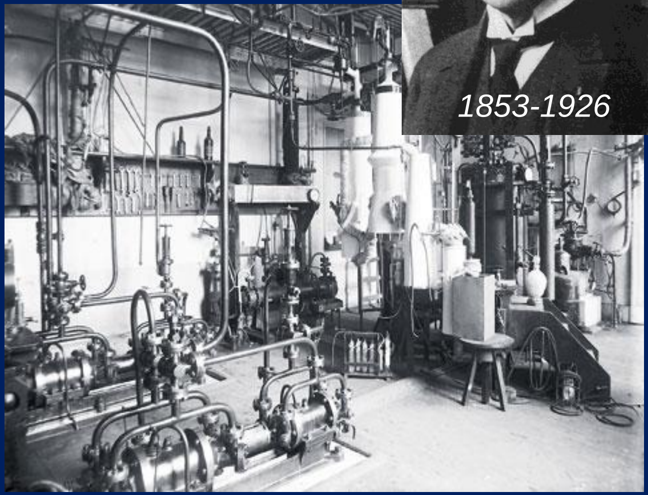
Herman ten Kate

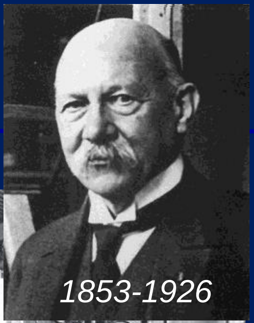
CERN & University of Twente

Leiden 1911 Heike Kamerlingh Onnes



Discovered ***superconductivity*** in Mercury and Lead, and had **a vision to build a 10 T magnet**





1853-1926

1st Pb wire coil 1912

"The 10 T magnet project was stopped when it was observed that superconductivity in Hg and Pb was destroyed by the presence of an external magnetic field as small as 500 Gauss" (0.05 T).

Ambitious goal of making the first superconducting magnet fell flat, and it took ~50 years to understand why → 1960s

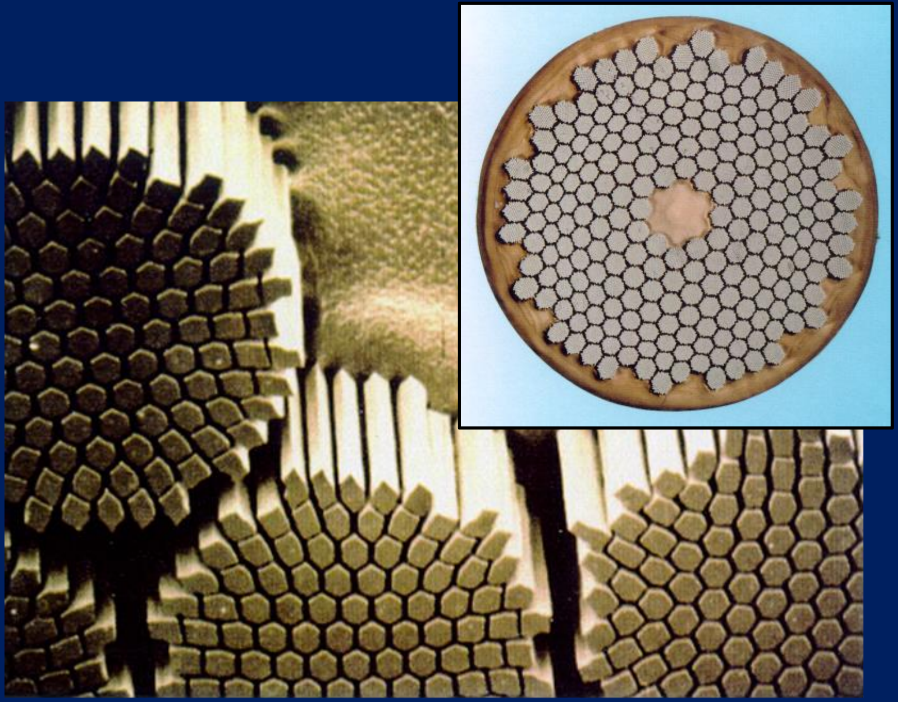
Raising Critical Current & Understanding Stability

50 years of research was needed to understand the basics of superconductors and to make the first practical wires for 100-500 A!

Recipe: Pick the right superconductor, NbTi, study the micro structure and fill the superconductor with pinning centers in a pattern that matches the flux line lattice **---> high critical current in thin filaments**

Precipitates in alloys

Microstructure of Nb-Ti

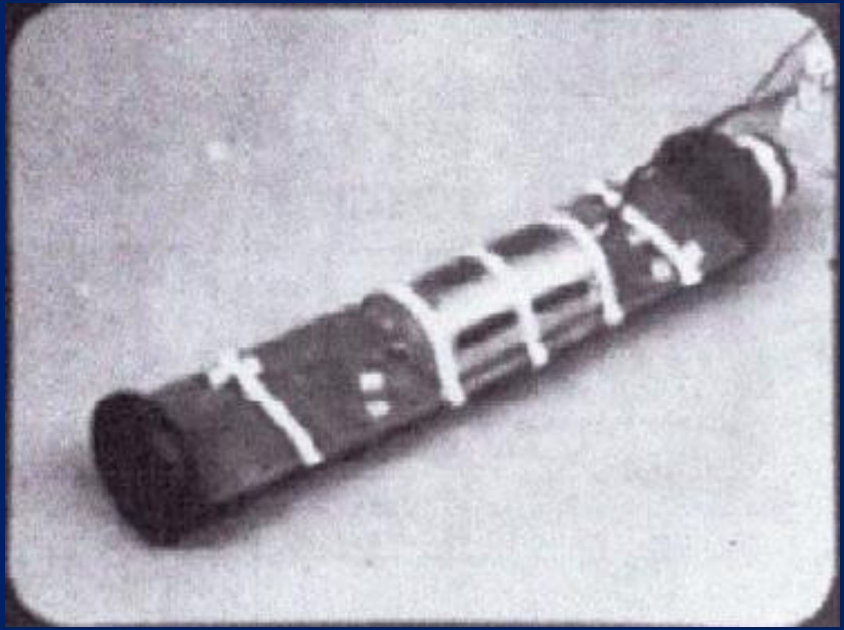


Fine NbTi filaments in a wire

First real superconducting magnets

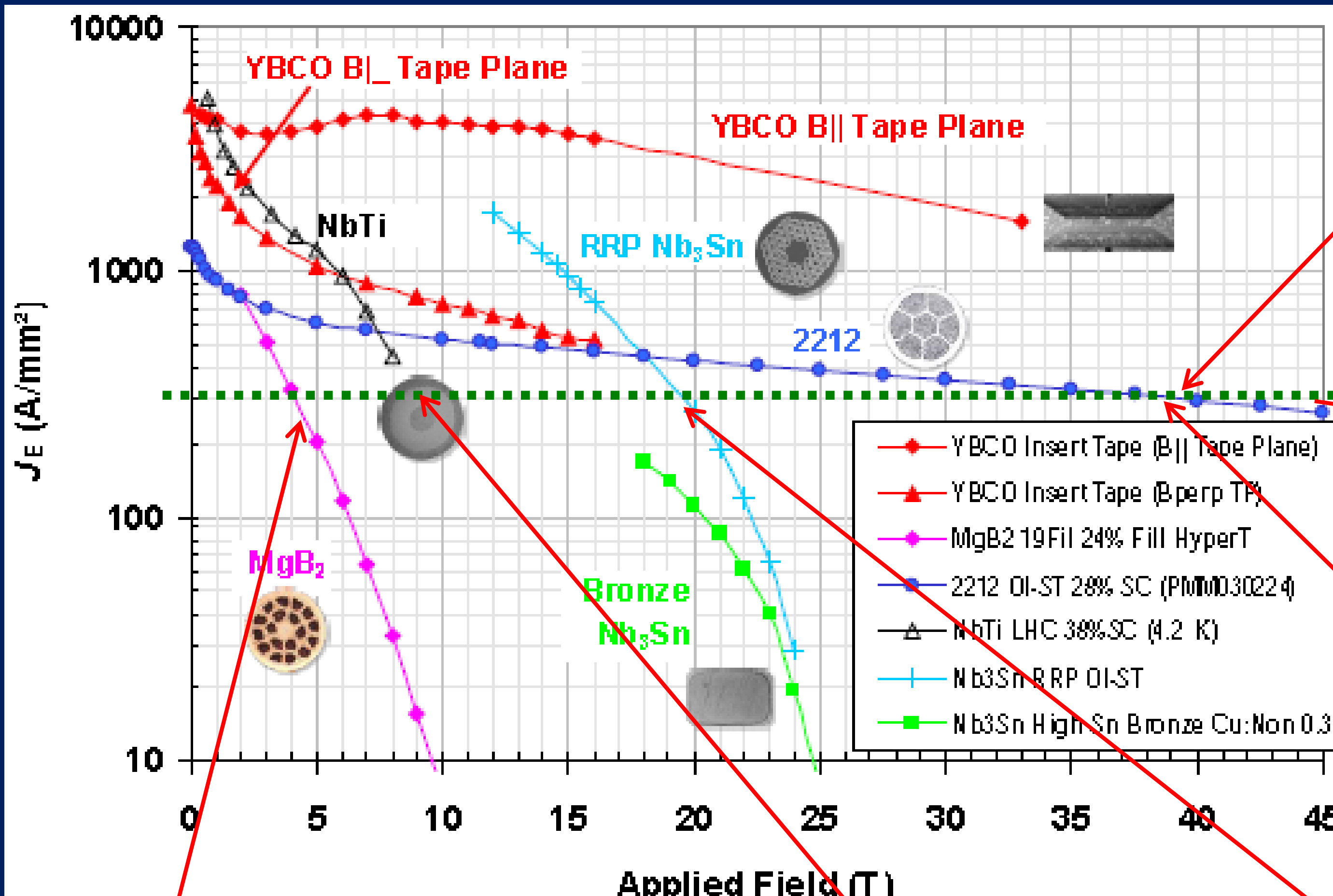
It took 50 to 60 years for making a first showable coil.....

1961: 1.5 T @ 1.5 K coil with Mo3Re wire (Kunzler e.a., Bell Labs)



1971: first NbTi magnet Oxford Instruments

Modern Superconductors : practical for magnets



ReBCO for DC magnets of 17 - 40 T , expensive, cost must come down for large scale use

Minimum practical current density

BSCCO-2212 for DC magnets of 17-40 T provided cost reduced

MgB_2 not for high field magnets but for niche market 1-5 T, 4-20 K

NbTi, still the workhorse for 1-9 T at 2-4 K

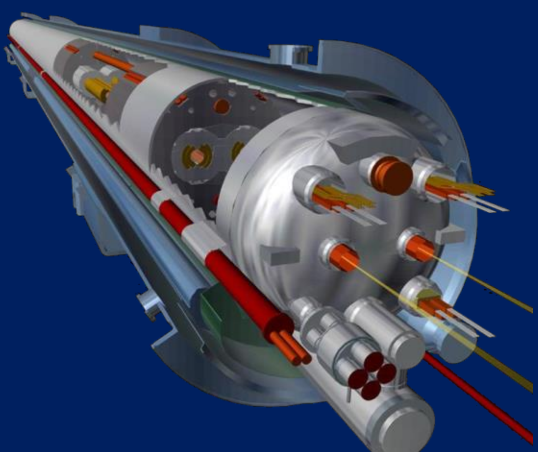
Nb_3Sn for magnets of 9-20 T

Safe Magnet Current scales with volume of magnet,
----> quest for high current cables

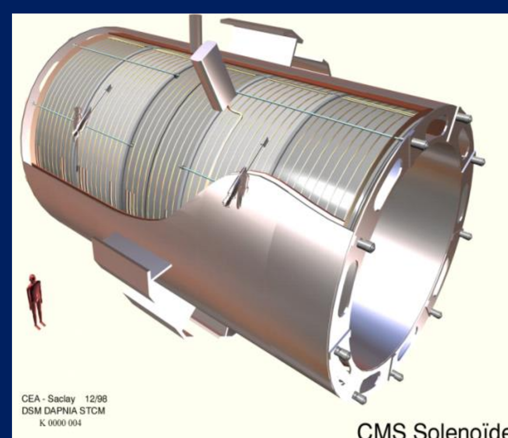
0.0001 m^3 HF insert model
~ **200 A**

2 m^3 MRI magnet
200-800 A @ 1-3 T, ~10 MJ

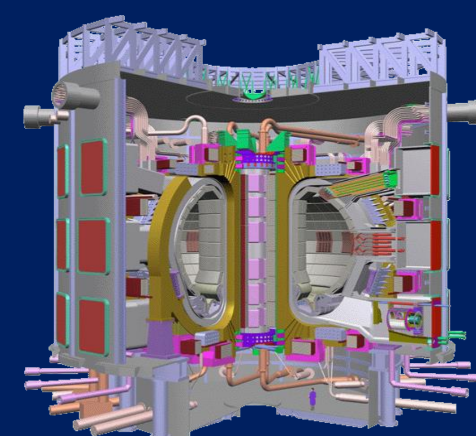
25 m^3 ATLAS solenoid
8 kA @ 2T, 40 MJ



50m^3 LHC dipole
12 kA @ 8.3 T



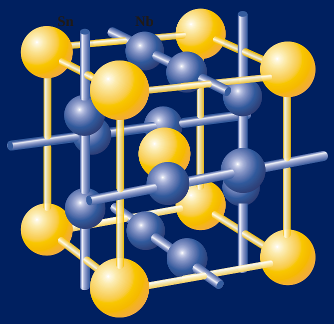
400 m^3 HEF detector magnet
20 kA @ 4 T, 2.6 GJ



1000 m^3 ITER magnets
40-70 kA @ 10-13T , 50 GJ

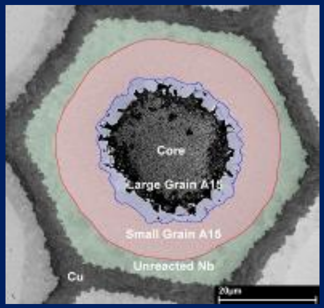
The Challenge: Engineering from Material to Magnet

Lattice



50 nm

Filament



20 µm

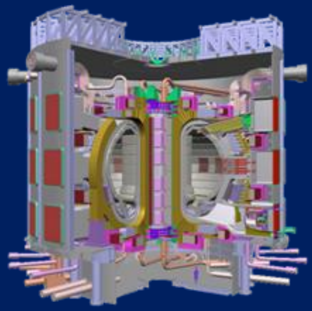
Wire

1 mm

Cable

50 mm

Magnet



35 meter

How to make performing multi-kA conductors that guarantee magnets to operate safely, reliably, showing no degradation ?

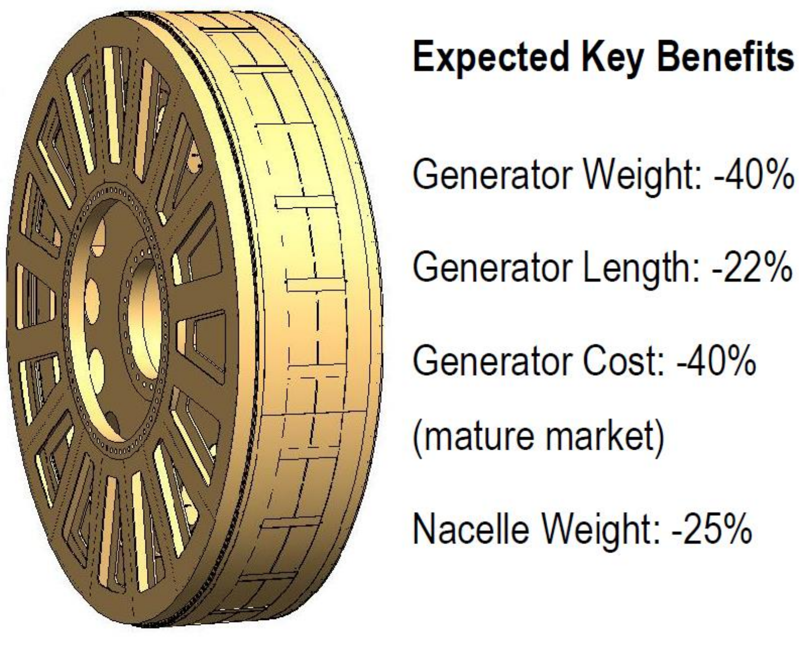
----> We need to understand and control the entire chain.

A front line magnet can perform only with the best possible conductor made from optimized superconducting material.

Applications? Example 1: Wind turbines

- A *first-in-the-world* demonstration medio 2019 of a really superconducting wind turbine using ReBCO superconductor!
- 3.6 MW, 128 m span with ReBCO superconducting coils in the rotor.

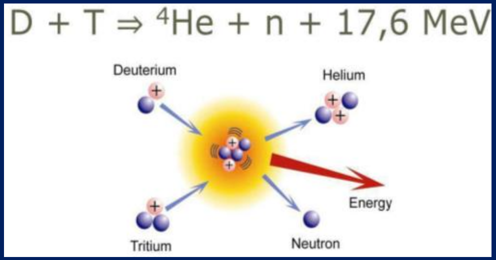
Fig. 1: Envision GC-1 turbine (E128-3.6 MW) installed Thyborøn, Denmark. EcoSwing will replace pink parts by an HTS generator and an innovative power converter.

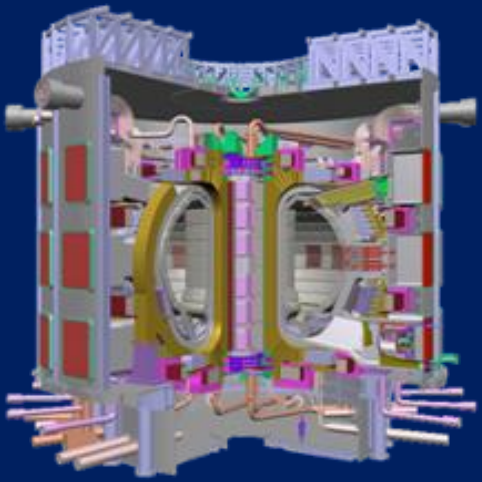


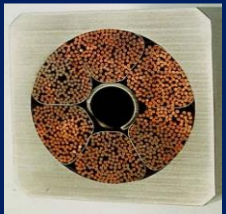
A EU Horizon 2020 project by Envision, ECO5, Jeumont, Delta, Theva, SHI, DNV GL Energy, Fraunhofer Institute & University of Twente.

Applications? Example 2: Nuclear fusion

- Superconducting magnet system for plasma drive and confinement: ITER, designed for 500 MW net energy, a unique 1e demonstration device in Europe.
  - University of Twente is a reference test-lab for the development of superconductors for such magnets.
  - Not only for ITER, but practically for all fusion projects on this planet.







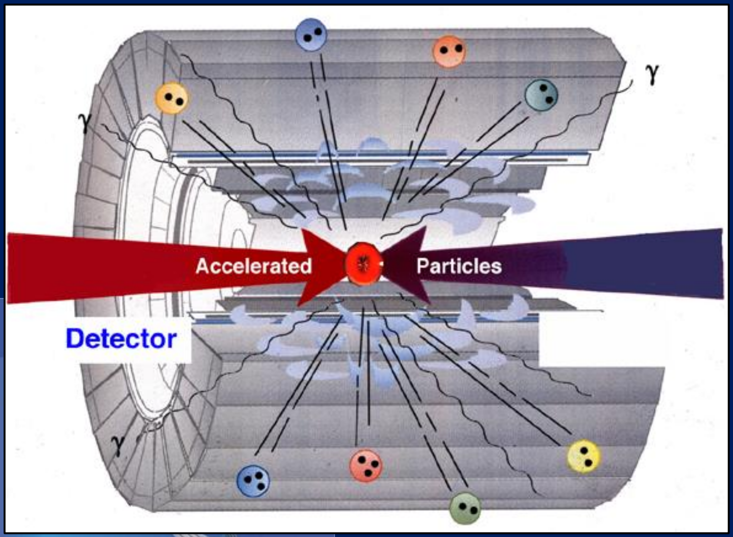
ITER construction in Cadarache, Frankrijk

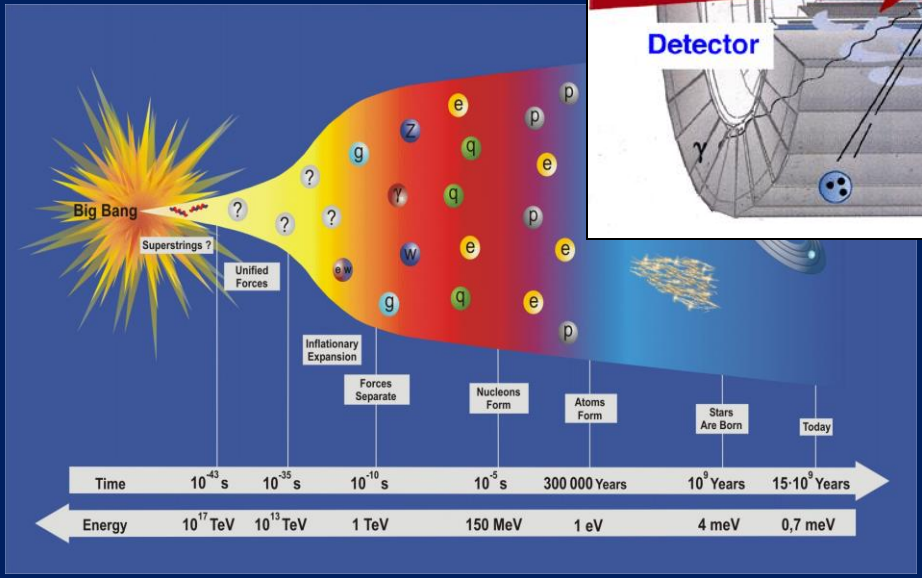
ITER machine

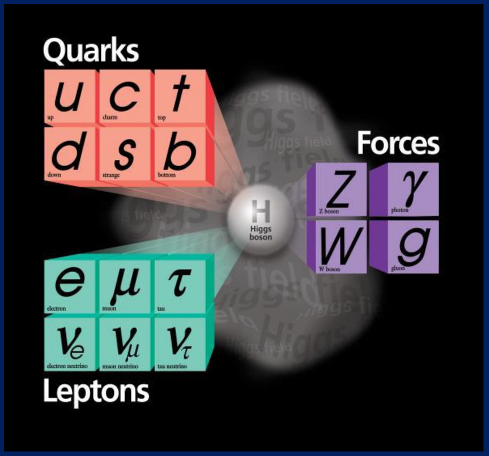
ITER superconductors

Applications? Example 3: Particle Accelerators

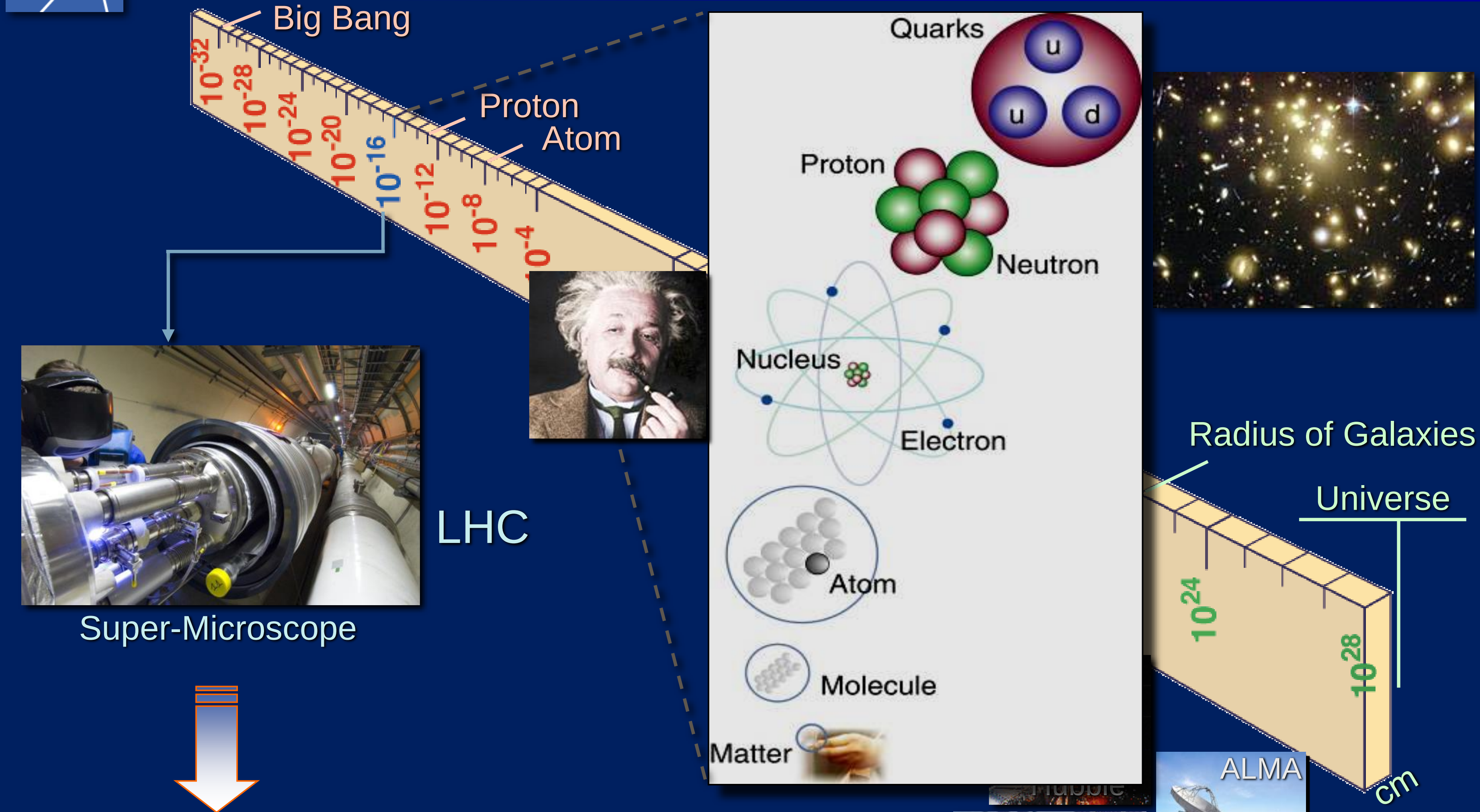
- CERN's core activity: production of new particles by bringing into collision protons/electrons by which energy is transformed into showers of new particles …….and thus also generating the unknown we are looking for………





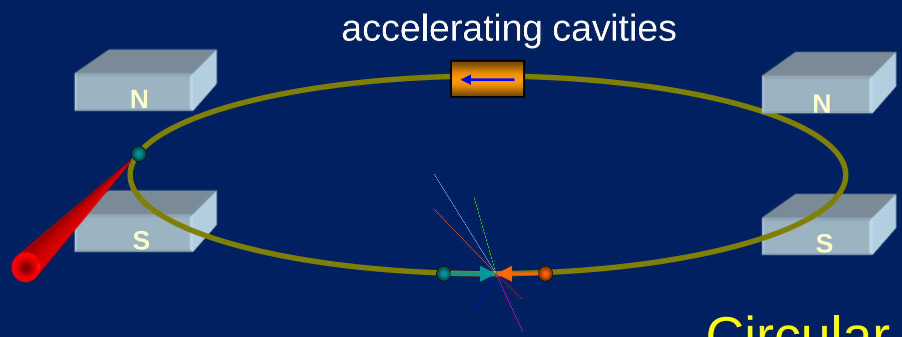


Zoom: High Energy & Astro Physics Tools



Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

Tool box: Circular - versus Linear Collider



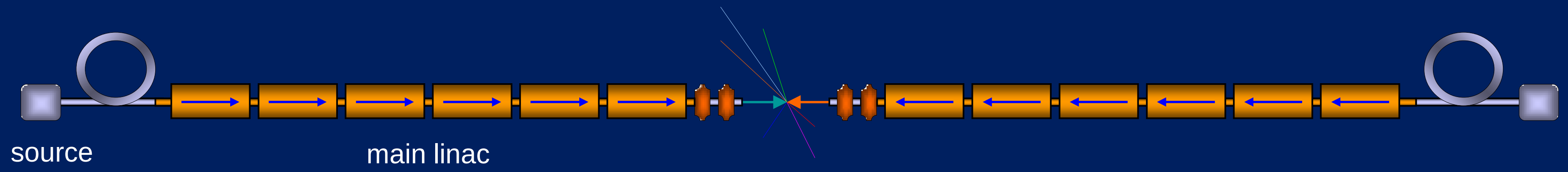
Collision energy:

$E_{TeV} \cong 0.3\ B_T\ R_{km}$

9 T & 4.6 km ⇒ 14 TeV

Circular Collider

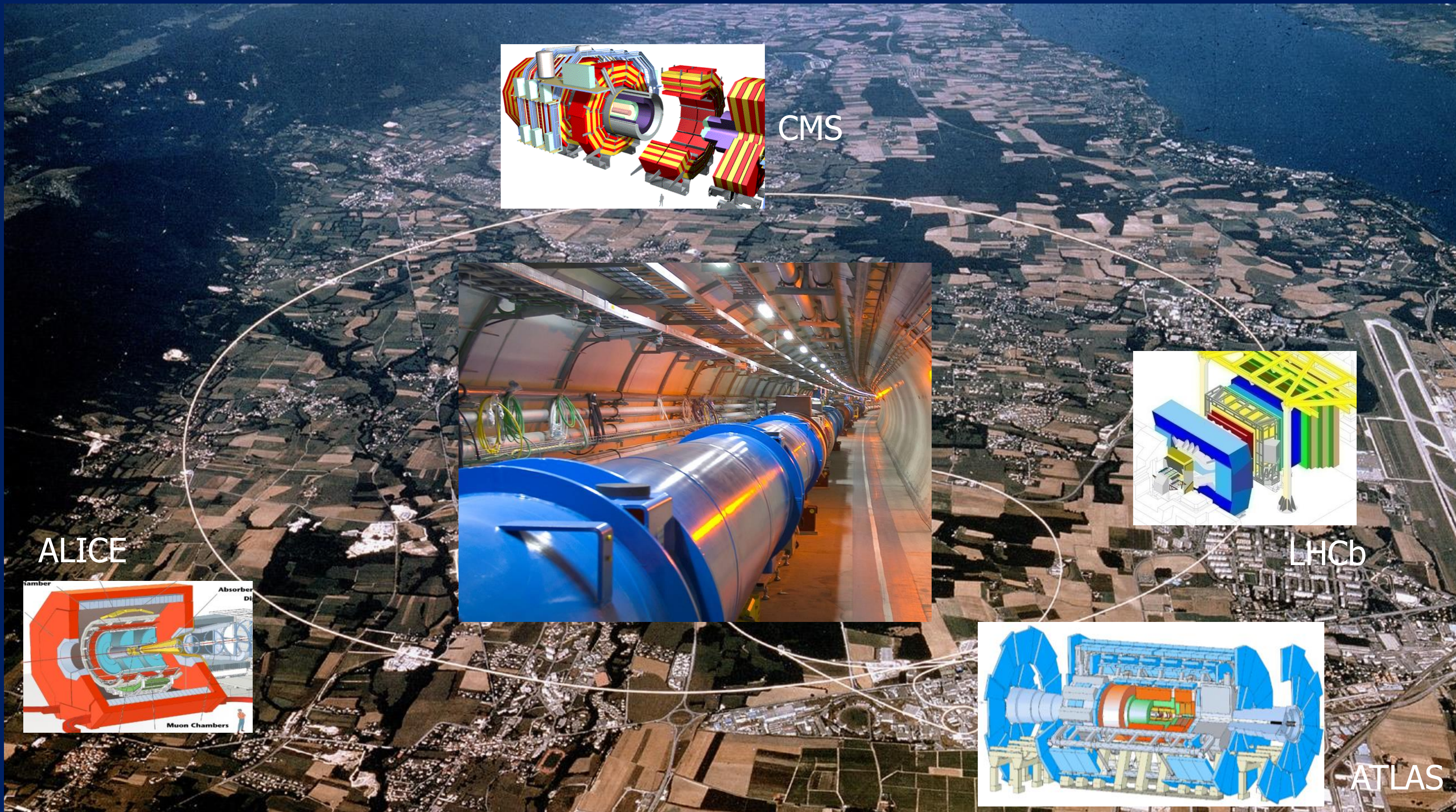
Many magnets & few cavities → need strong magnetic field for smaller ring
High energy → high synchrotron radiation losses ($\propto E^4/R$)
High bunch repetition rate → high luminosity



Linear Collider

Few magnets & many cavities → need efficient RF power production
Higher gradient → shorter linac
Single pass → need small cross-section for high luminosity

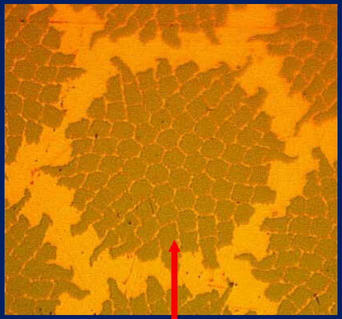
Higgs search at the Large Hadron Collider

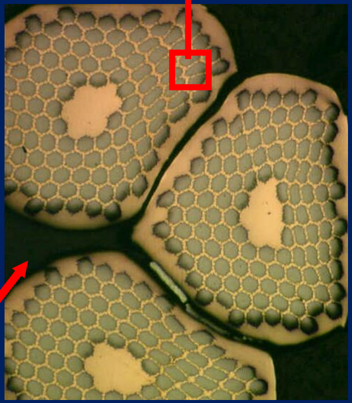


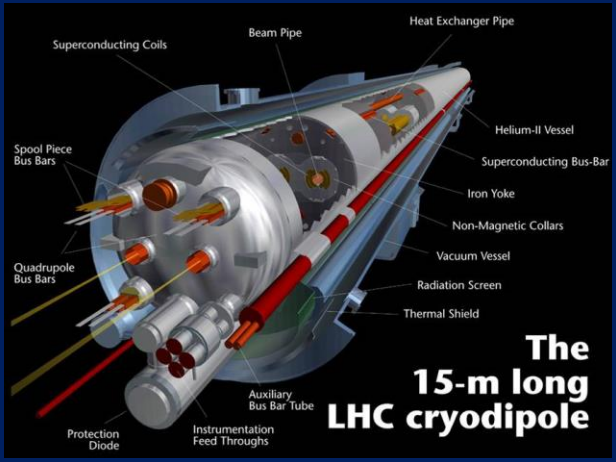
14 TeV proton-proton collider, more than 9000 superconducting magnets

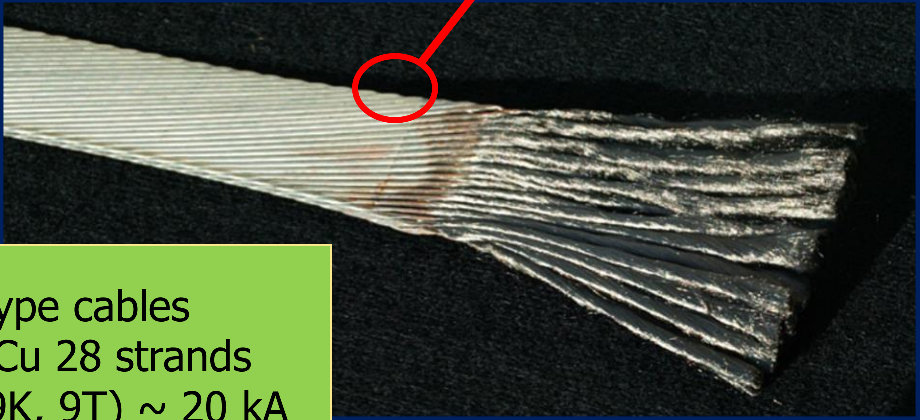
by far the largest superconducting system in operation

LHC: 8 T dipole magnets in a 23 km tunnel





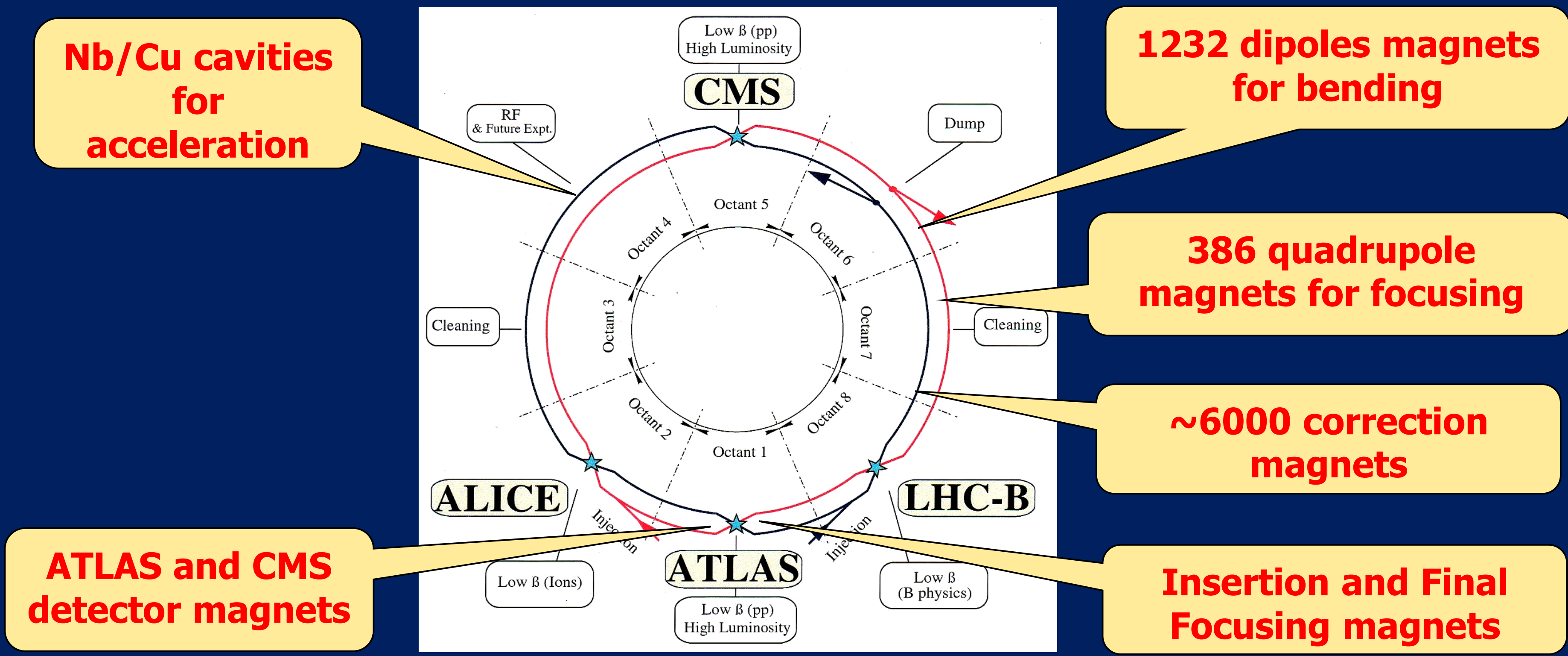




LHC type cables
NbTi/Cu 28 strands
I_c (1.9K, 9T) ~ 20 kA

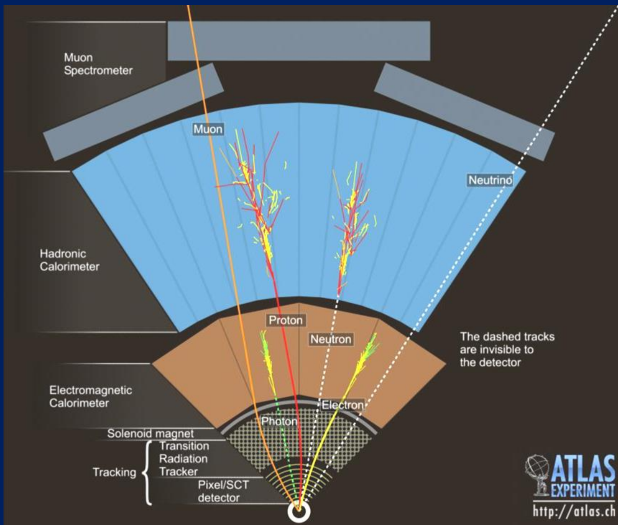
Superconductors & High Energy Physics

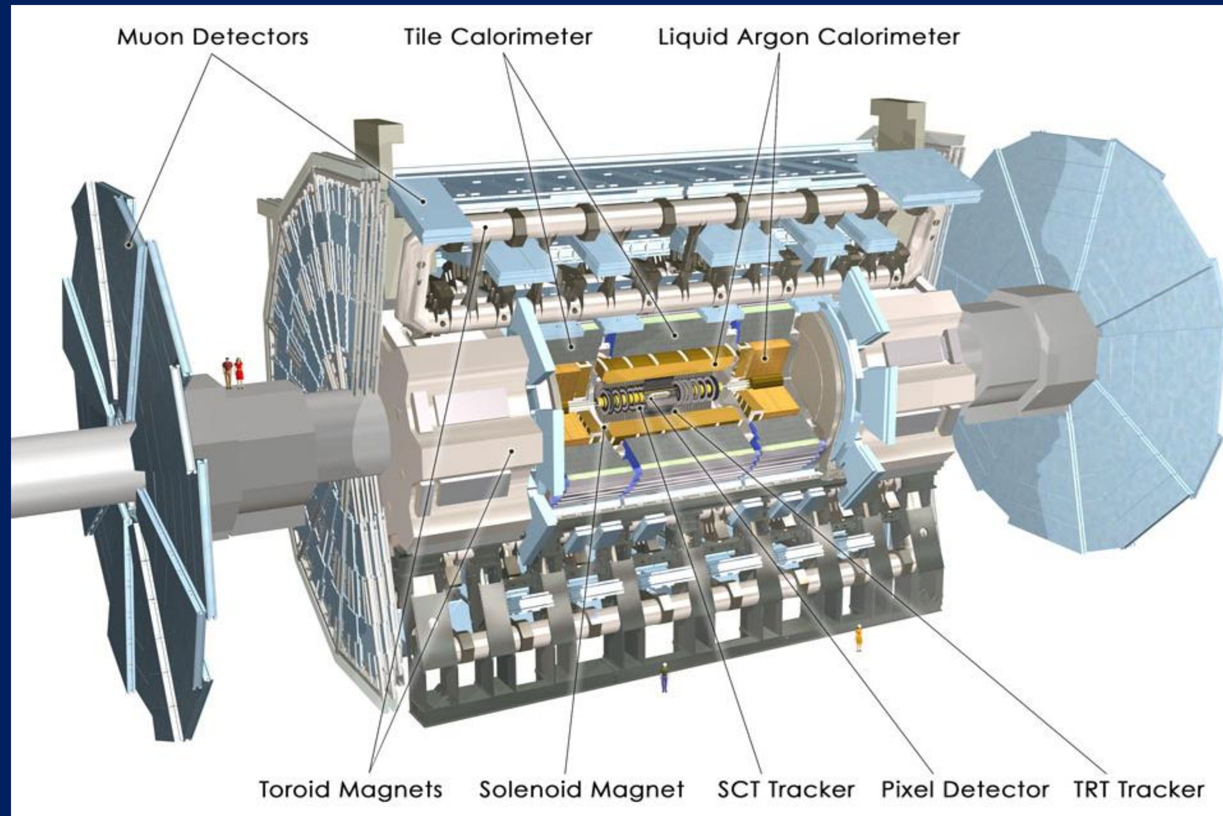
The Large Hadron Collider could not be realized without exclusive use of superconductivity and high quality magnets.

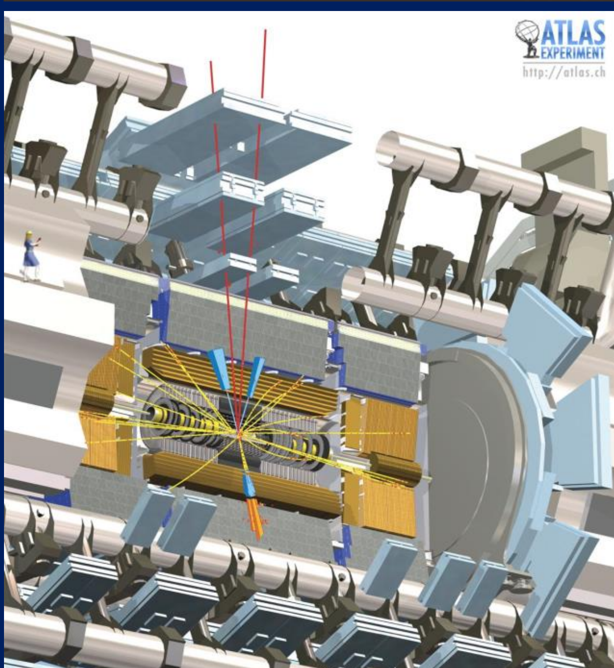


No Higgs without Superconductivity!

ATLAS Experiment: particle detection







Charge identification and momentum measurement require curved trajectories of collision products, thus magnetic field

Solenoid for inner trackers, Toroids for outer muon tracing (example Higgs event)

ATLAS Superconducting magnet system

1 Barrel Toroid and **2 End Cap Toroids** and **1 Central Solenoid** generate 2 T for the inner detector and ~1 T for the muon detectors

21 m diameter and 25 m long

8300 m^3 volume with field

170 t superconductor

320 t magnets

7000 t detector

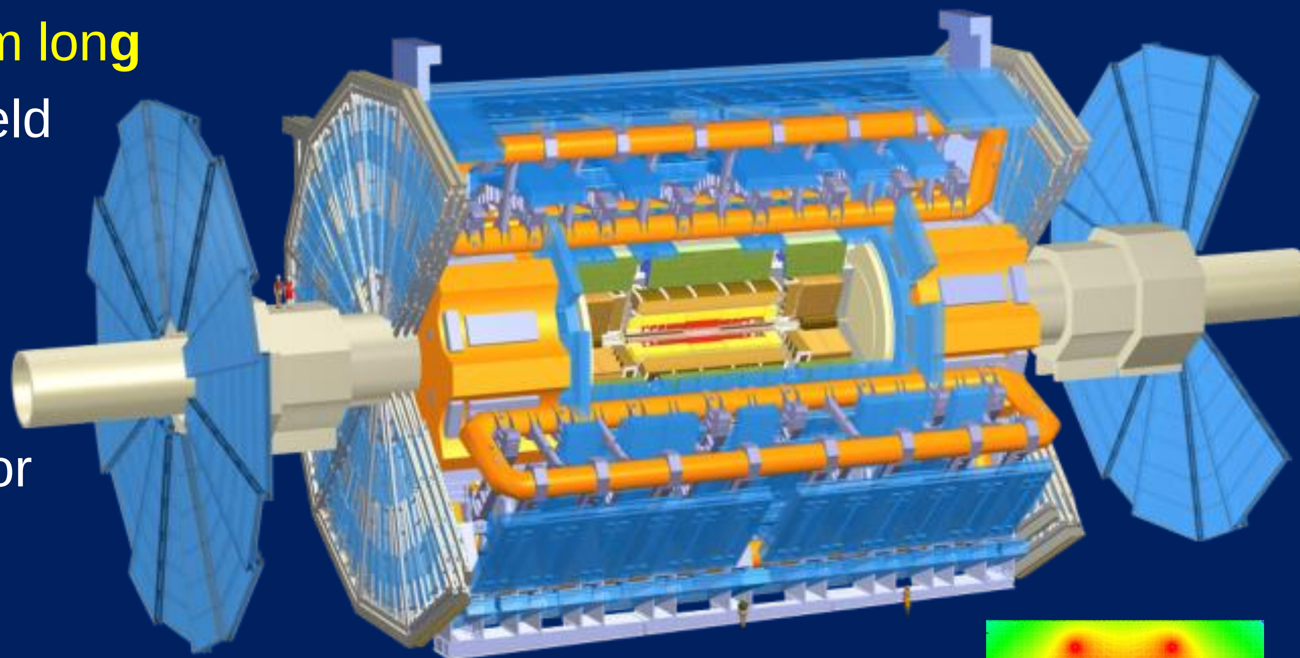
90 km superconductor

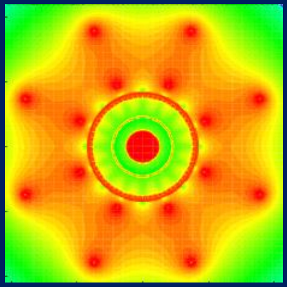
20.4 kA at 4.1 T

1.6 GJ stored energy

4.7 K conduction cooled

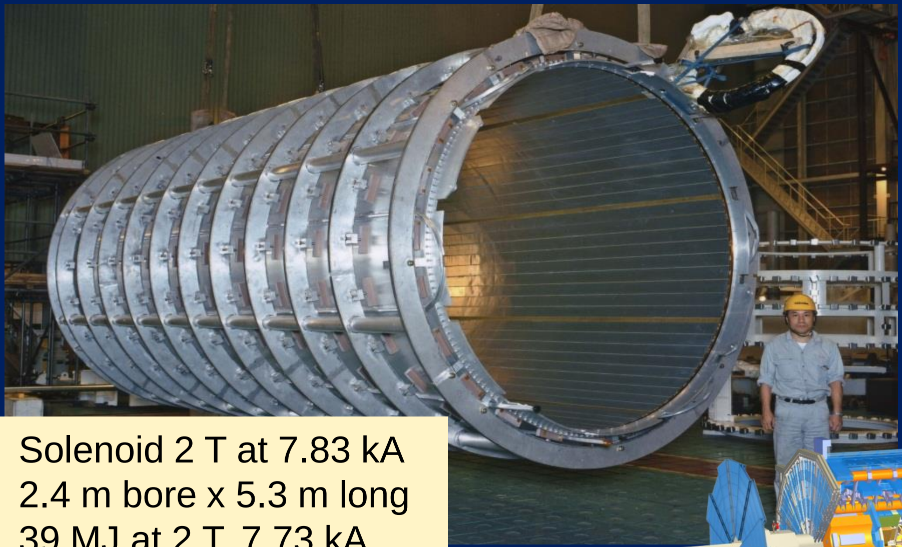
9 yrs of construction 1998-2007





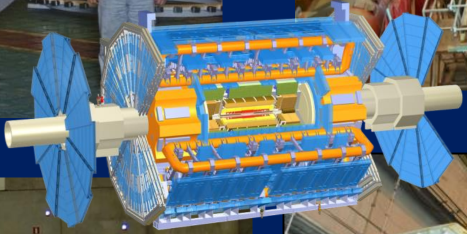
By far the largest trio of toroids ever built !

ATLAS Magnets - integration on surface



Solenoid 2 T at 7.83 kA
2.4 m bore x 5.3 m long
39 MJ at 2 T, 7.73 kA

Barrel Toroid integration



8 25x5 m^2 long/wide coils
1.1 GJ at 4 T, 20.4 kA

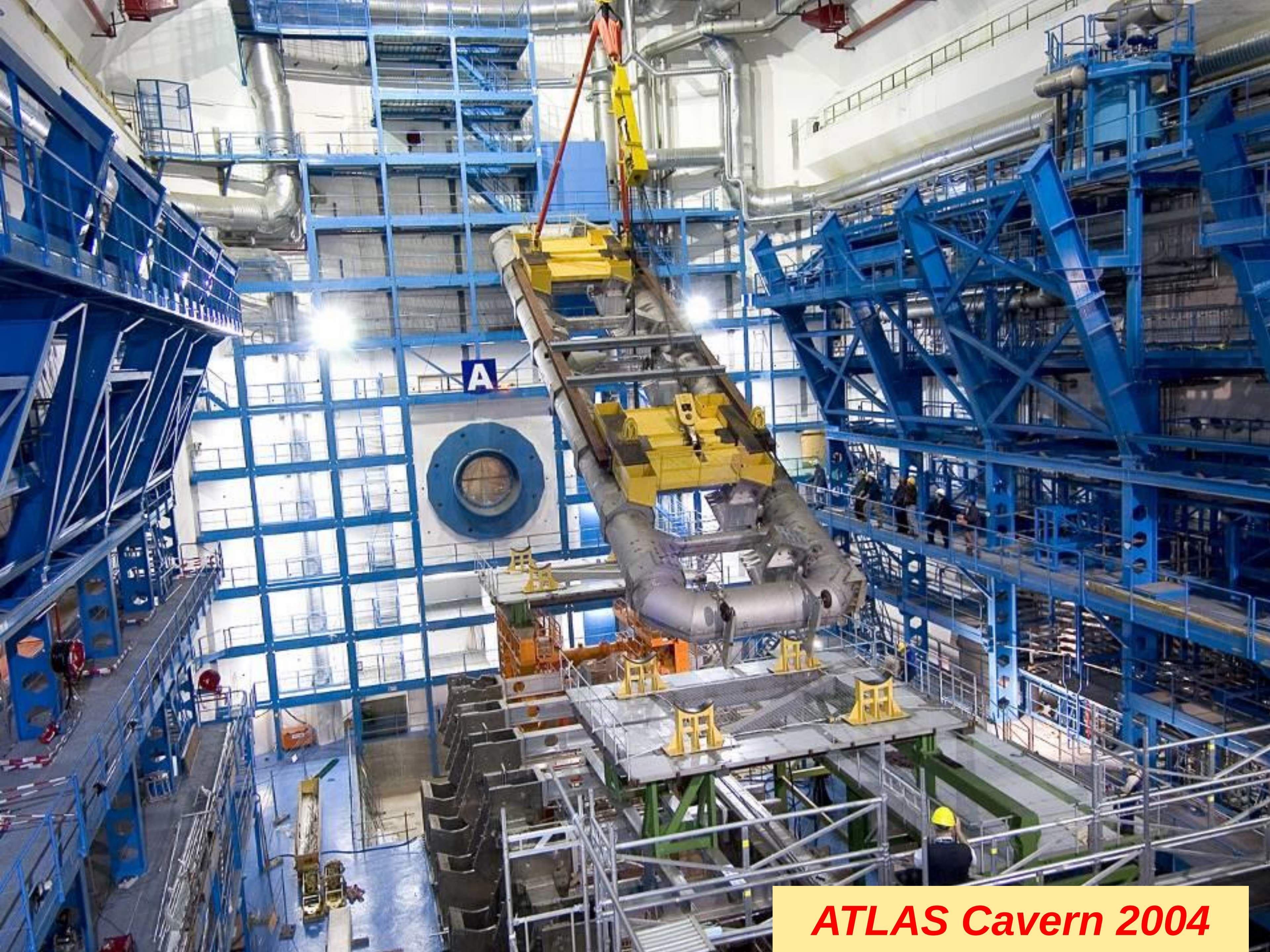
End Cap Toroids
20.4 kA, 4.1 T, 250 MJ
140 t cold mass

On the move to the ATLAS site

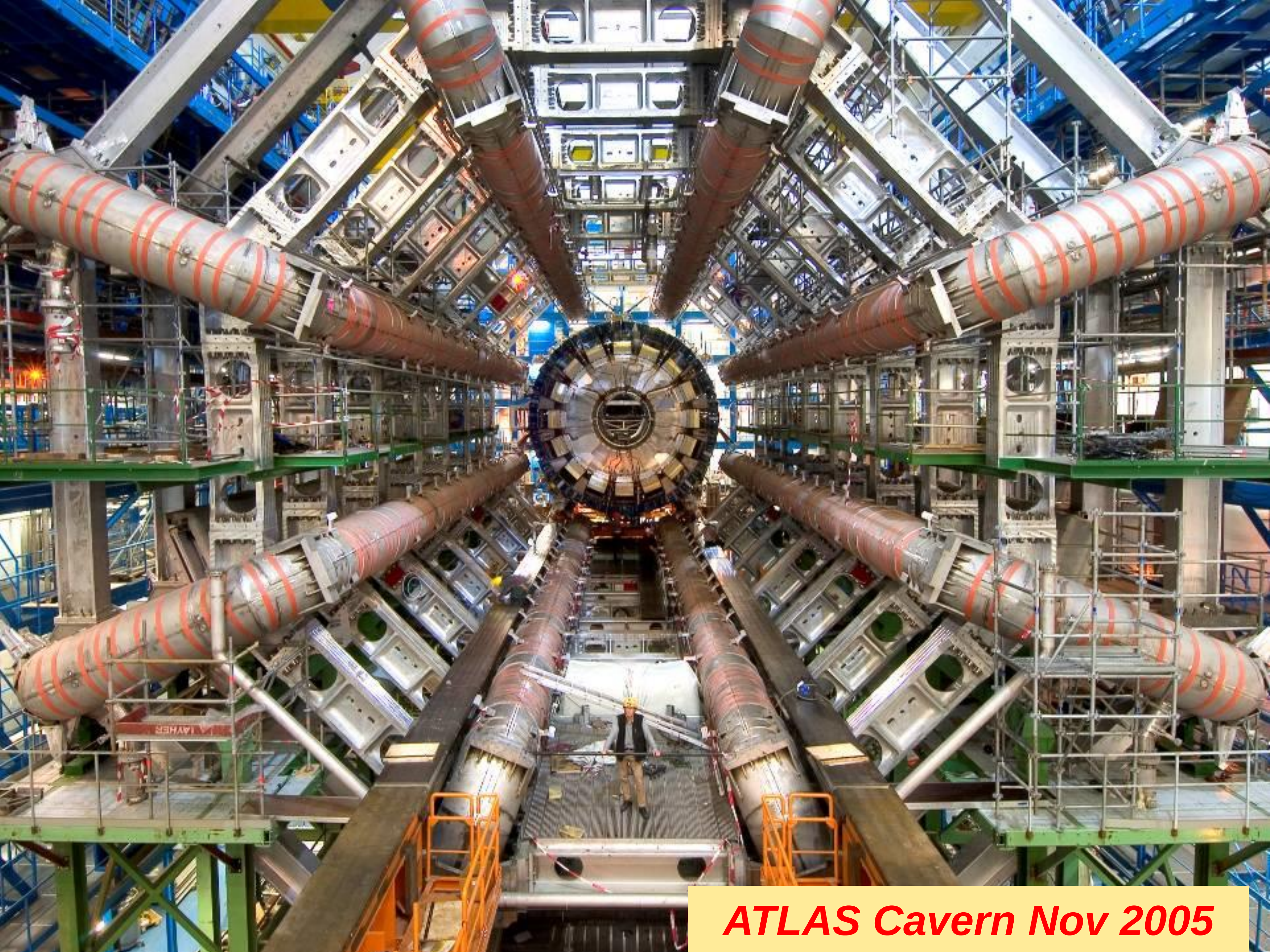
Solenoid insertion

100 tons Barrel Toroid coil

250 tons, 15 m height, 5 m wide

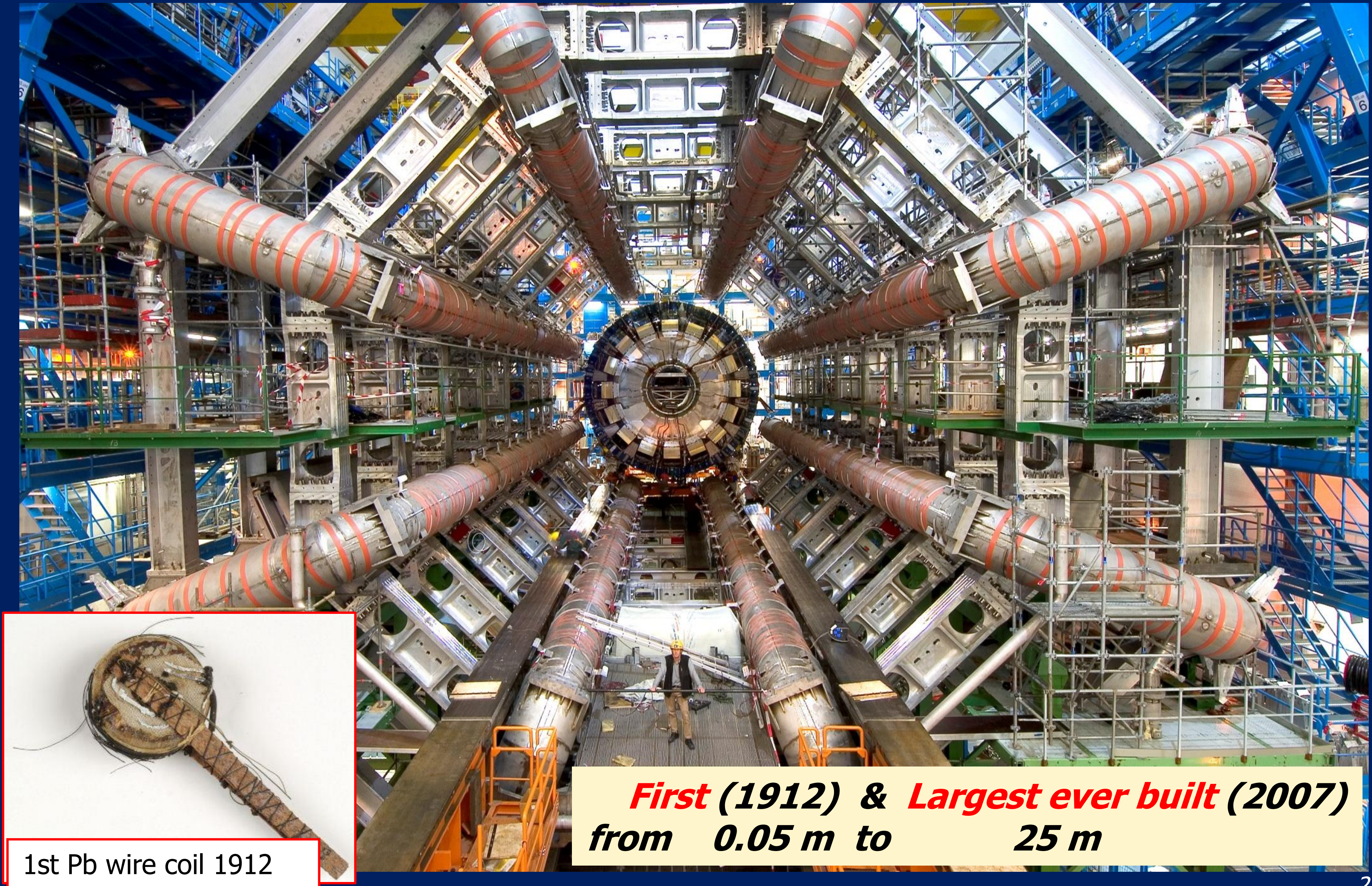


ATLAS Cavern 2004



ATLAS Cavern Nov 2005

Onnes' First Coil and Largest Magnet ever built

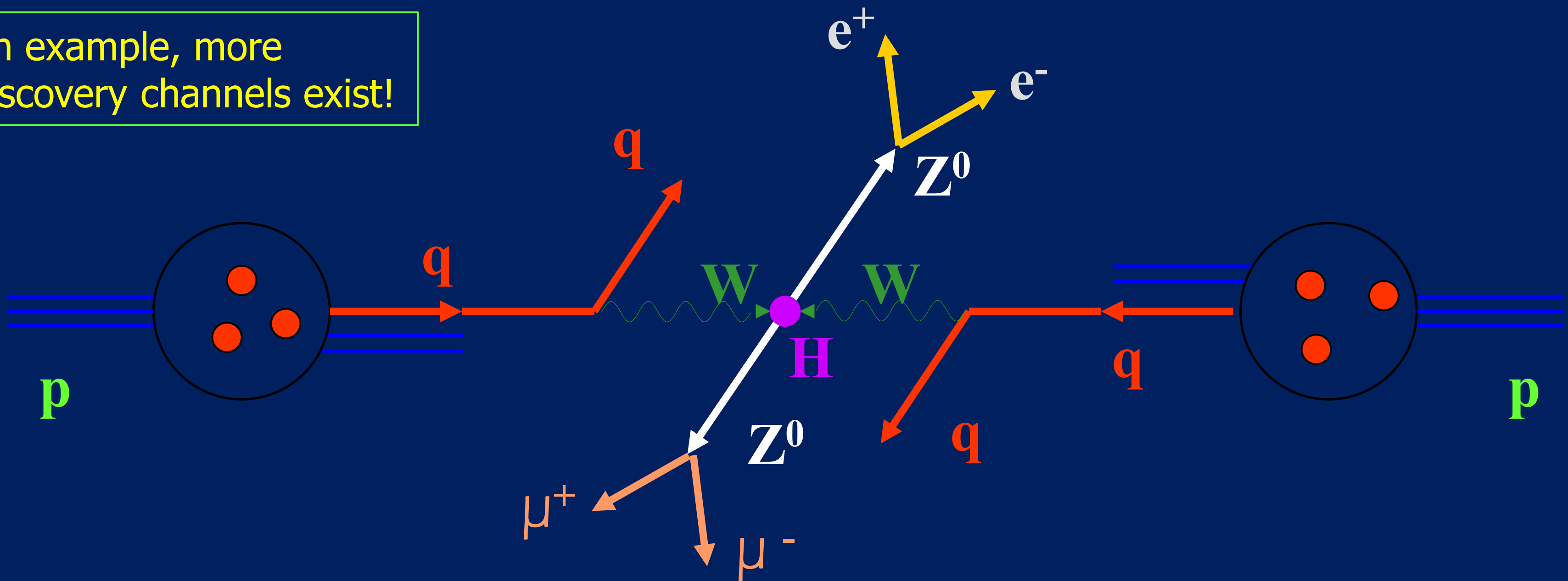


1st Pb wire coil 1912

First ***(1912) & Largest ever built (2007)***
from 0.05 m to 25 m

Finding Higgs in proton-proton collisions

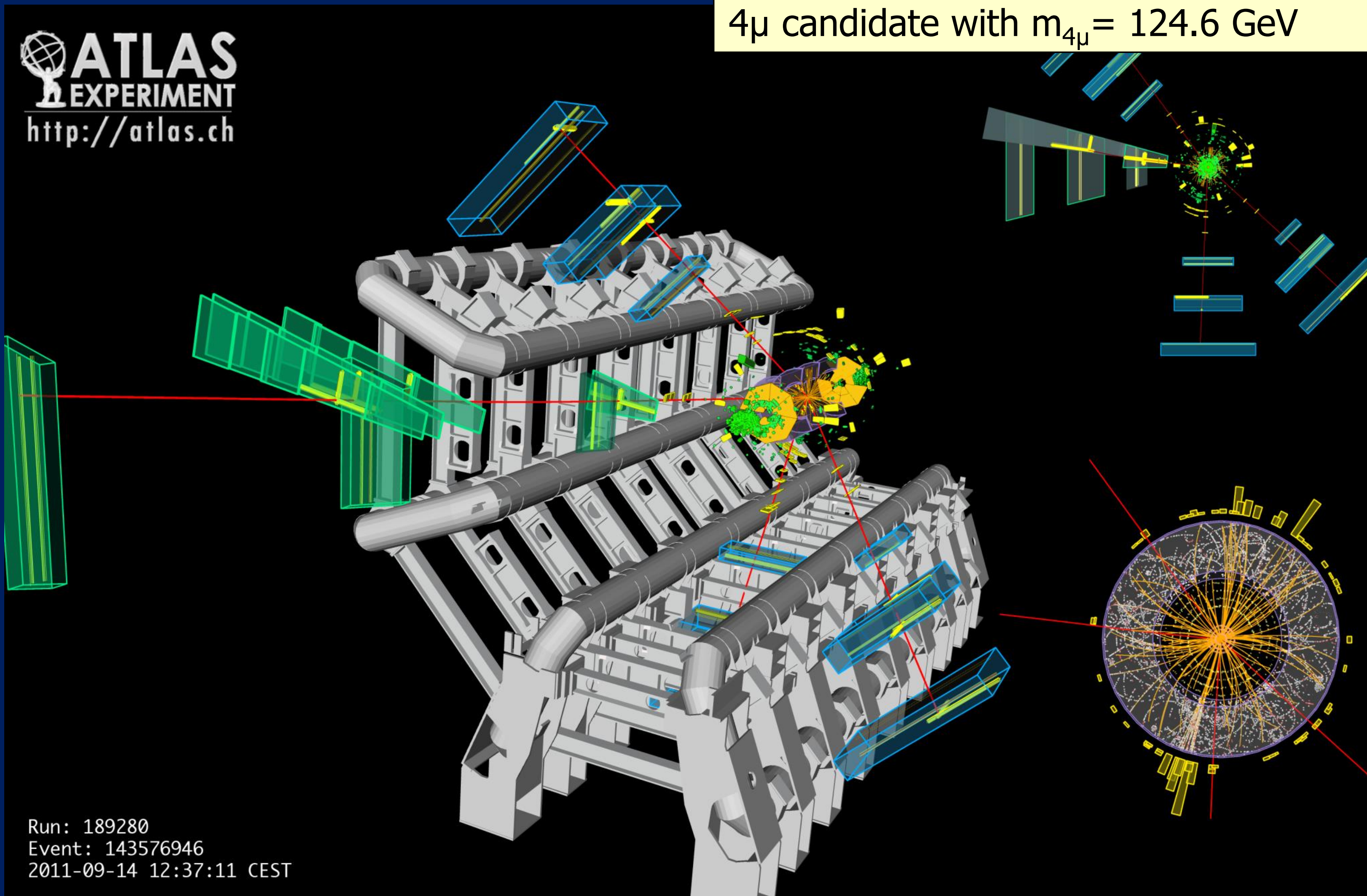
An example, more discovery channels exist!



Higgs events

H → ZZ$^{(*)}$ → 4l (4e, 4μ, 2e2μ)

4μ candidate with $m_{4\mu}$= 124.6 GeV



July 4, 2012

CERN pressconference

It takes time……….Mr Higgs

Volume 13, Number 16 PHYSICAL REVIEW LETTERS 19 October 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

ELSEVIER

Physics Letters B

Volume 716, Issue 1, 17 September 2012, Pages 1–29

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

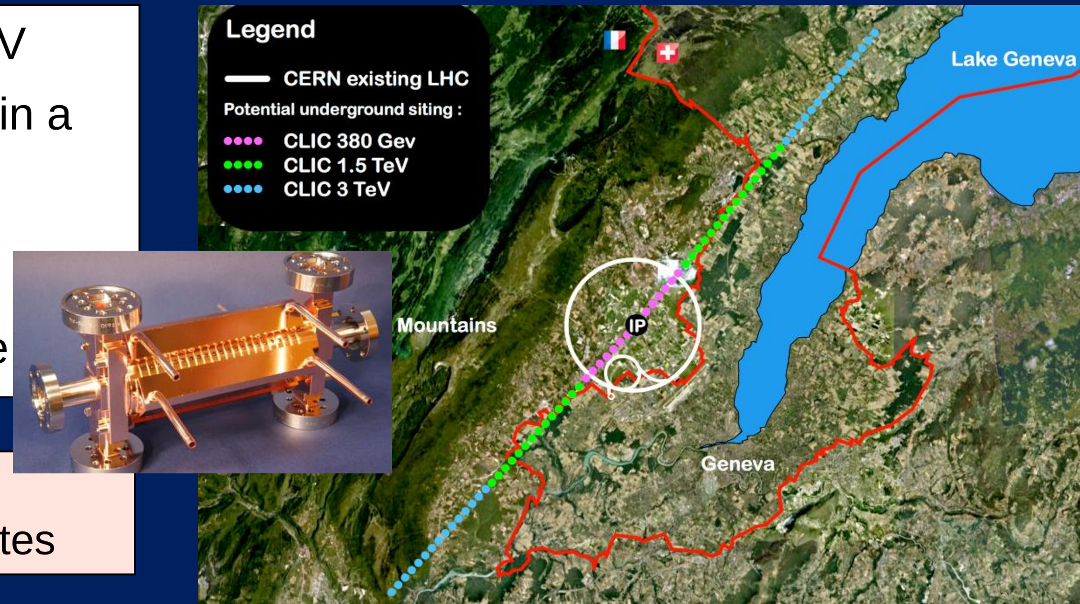
Universally Available

"I certainly had no idea it would happen in my lifetime at the beginning, more than 40 years ago.
I think it shows amazing dedication by the young people involved with these colossal collaborations to persist in this way, on what is a really a very difficult task.
I congratulate them."

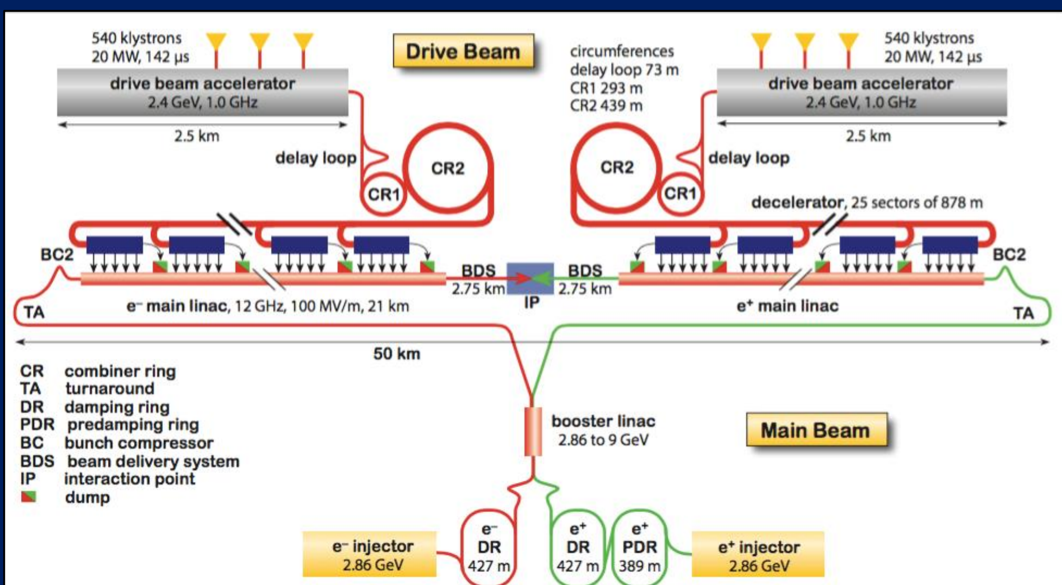
Peter Higgs, July 4th, 2012

Next? 1 - a COMPACT Linear Collider CLIC

- Linear e^+e^- collider for up to 3 TeV
- 100 MV/m accelerating gradient in a compact machine of 50 km
- Based on normal-conducting accelerating structures and a two-beam acceleration scheme



Conceptual Design Report in 2012.
International Collaboration: ~80 Institutes



Challenges:
- Minimize RF breakdown in cavities
- Power transfer drive to main beam
- Reduce power (600 MW@ 3 TeV)
- nm size beams, final focus

But: Almost no superconducting magnets!

Next? 2 - Options for a 100 TeV p-p collider

Collision Energy = 0.6 x B x R

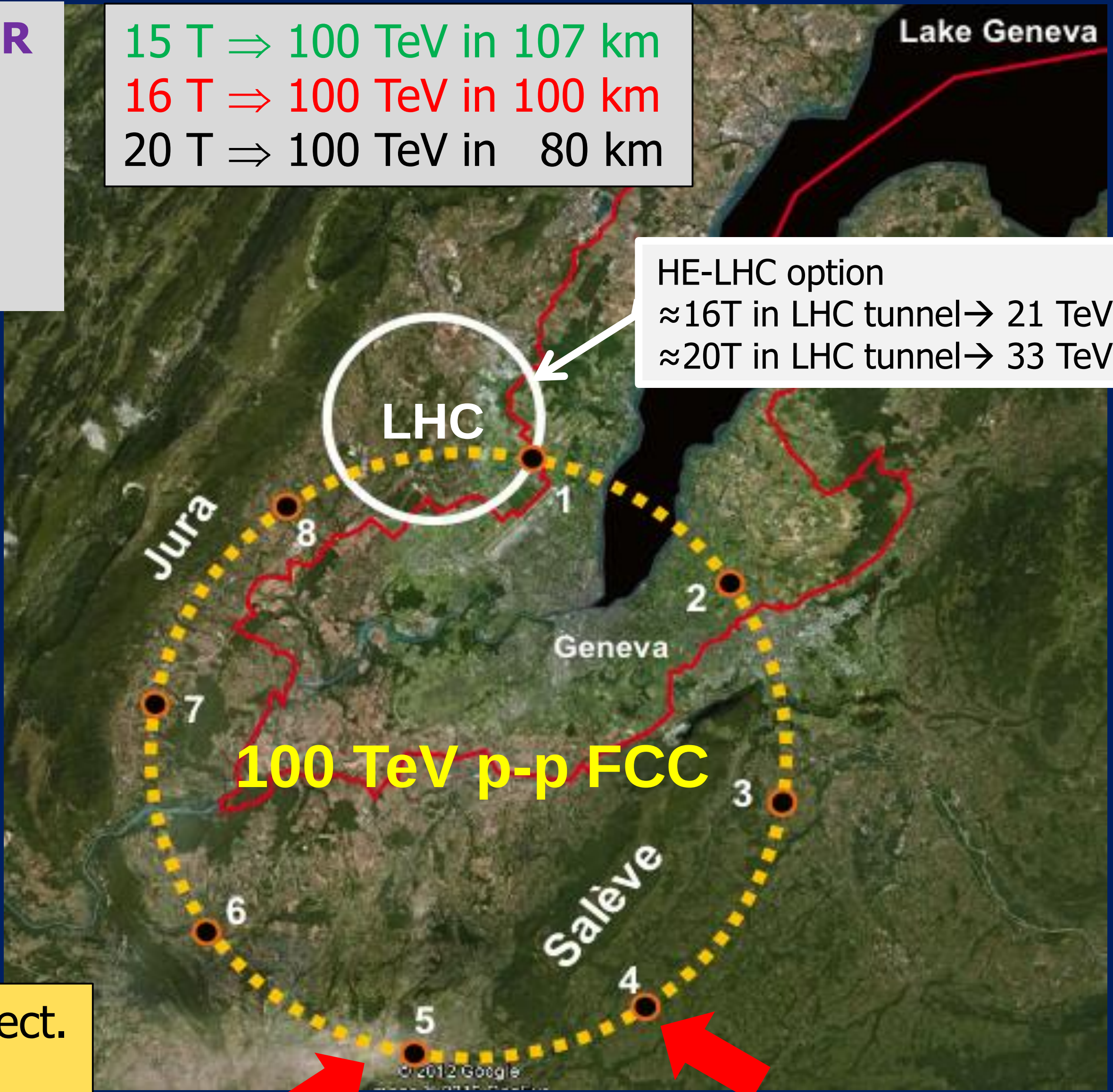
B: 1.9x from NbTi to Nb_3Sn
B: 2.4x from NbTi to HTS
R: 4-5x more magnets

- New ~100 km tunnel in Geneva area
- 100 TeV p-p determines the size
- Options for adding an e+e collider (TLEP) & pe collider (VLHeC)

New CERN-hosted study started in Feb 2014.

- Extremely challenging project.
- ✓ Options shall be explored……

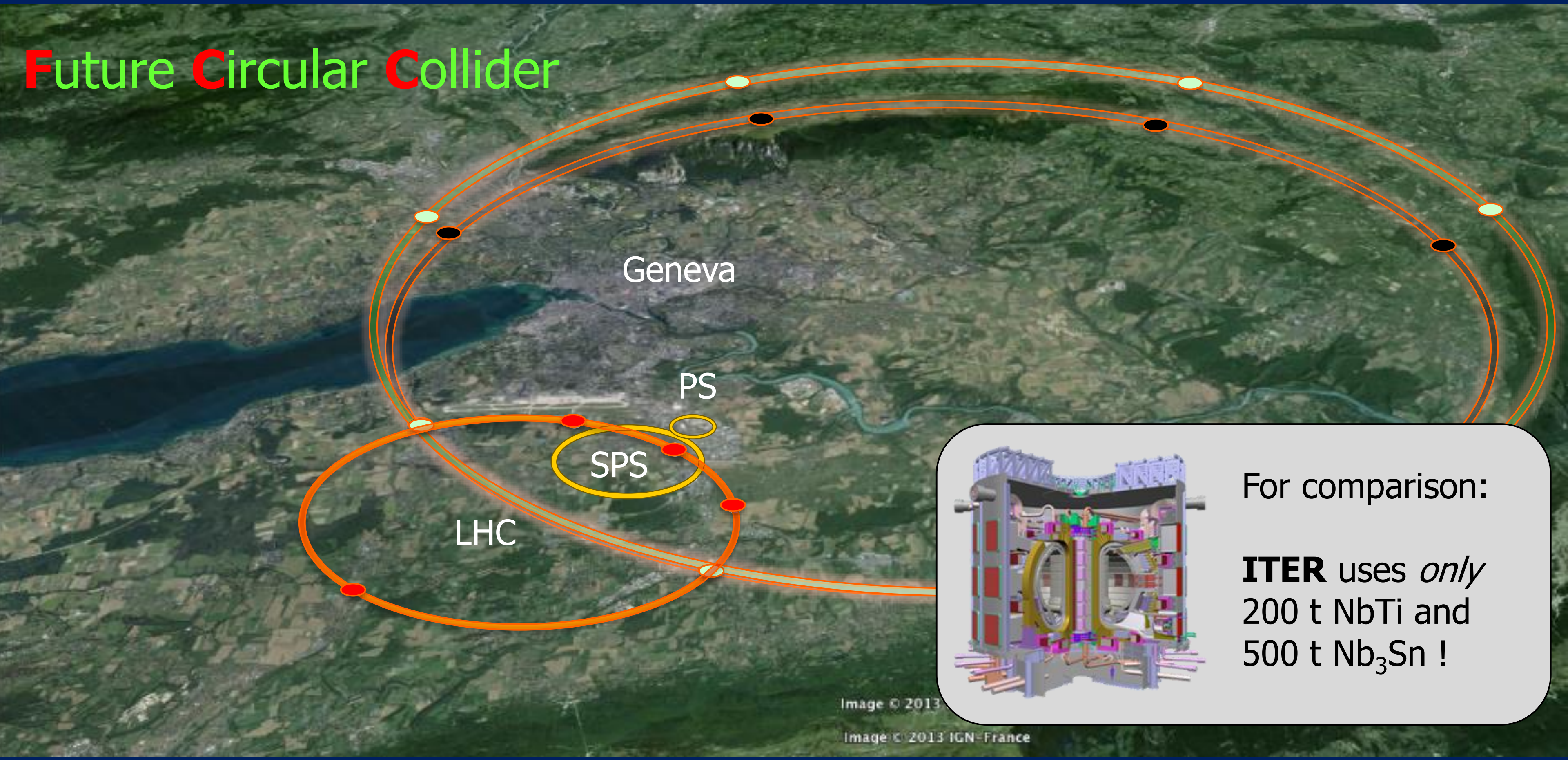
15 T ⇒ 100 TeV in 107 km
16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



HE-LHC option
≈16T in LHC tunnel→ 21 TeV
≈20T in LHC tunnel→ 33 TeV

Detectors in 350-400 m deep caverns !

Superconductors and FCC options

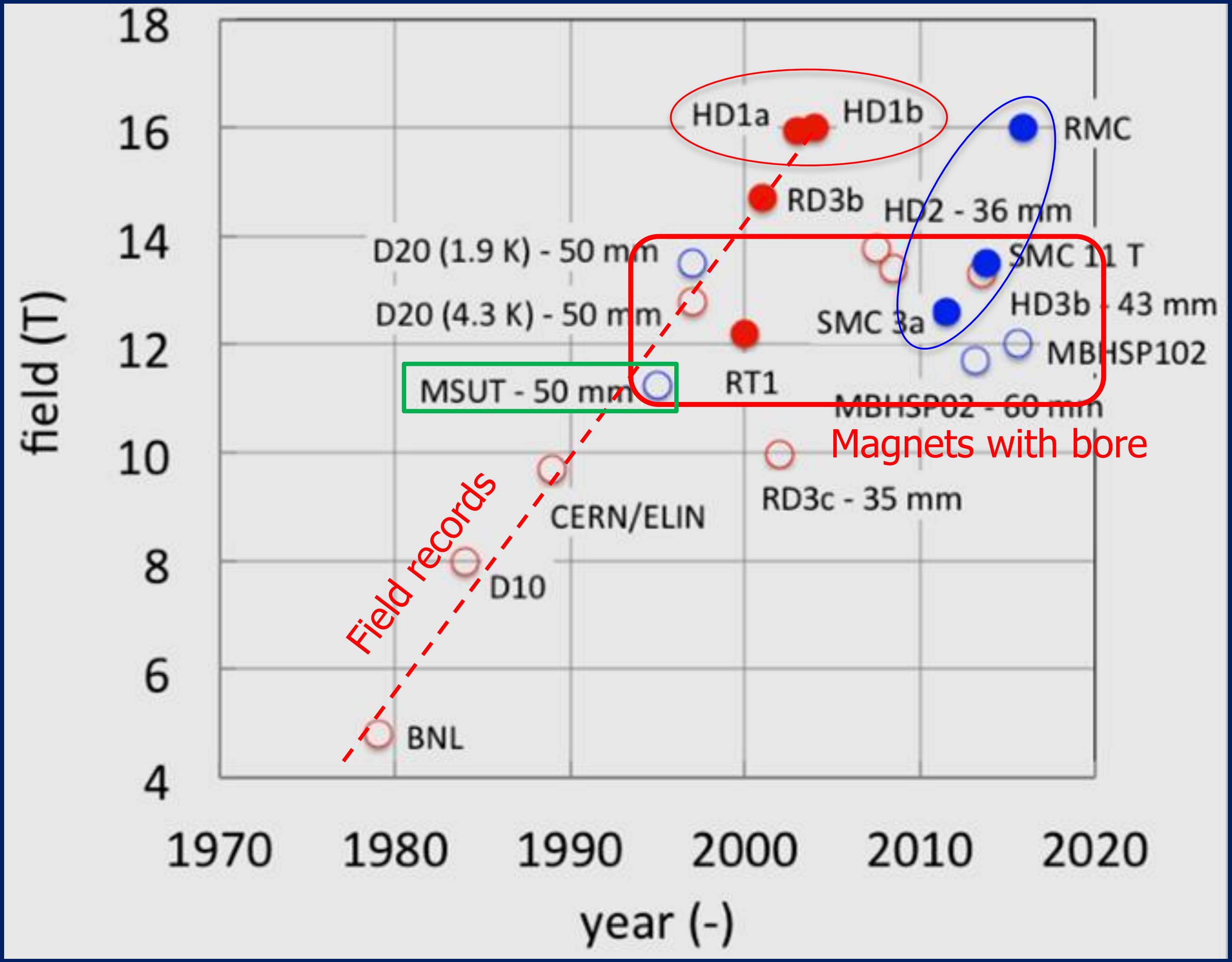


For comparison:

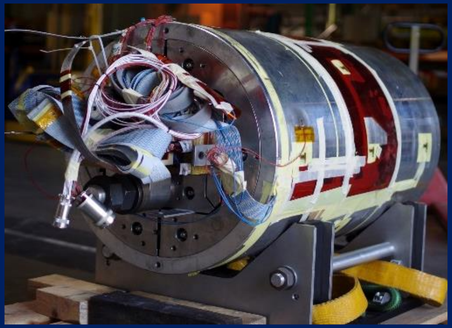
ITER uses *only*
200 t NbTi and
500 t Nb_3Sn !

LHC	HE-LHC	FCC-hh	FCC-hh
27 km, **8.3 T**	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV	33 TeV	100 TeV	100 TeV
1300 t NbTi	3000 t LTS	9000 t LTS	6000 t Nb_3Sn
0.2 t HTS	700 t HTS	2000 t HTS	3000 t Nb-Ti

Highest magnetic field - In dipole magnets



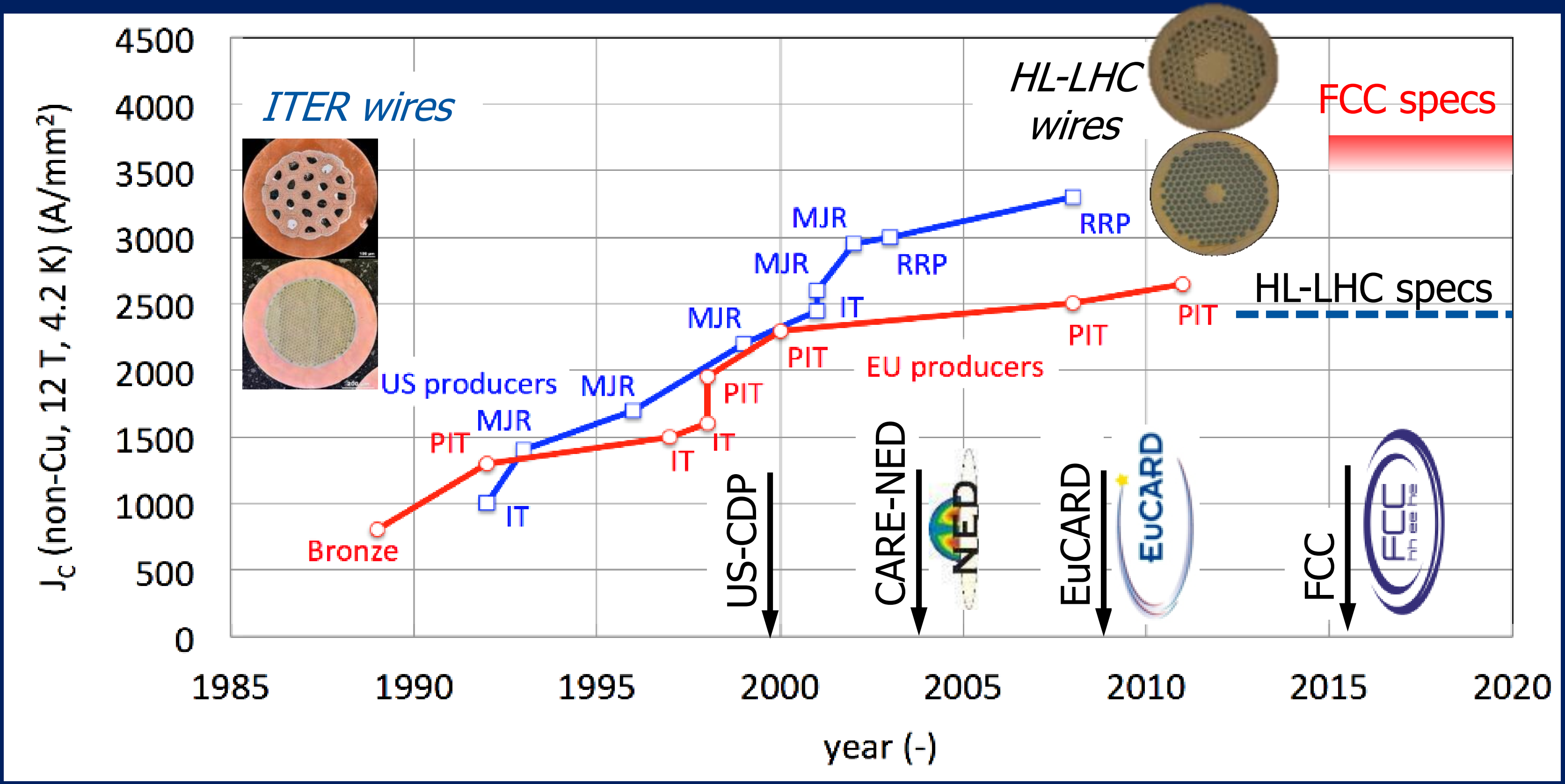
LBNL HD1 magnet



CERN RMC

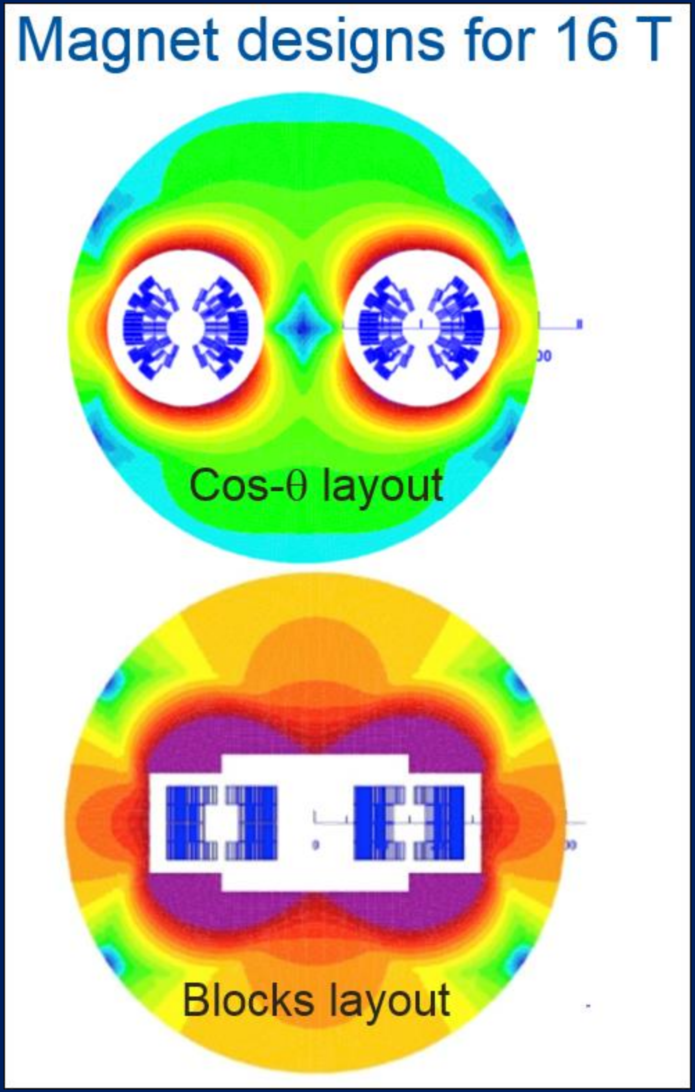
Steady progress towards 16 T class dipole magnets enabling the FCC hh

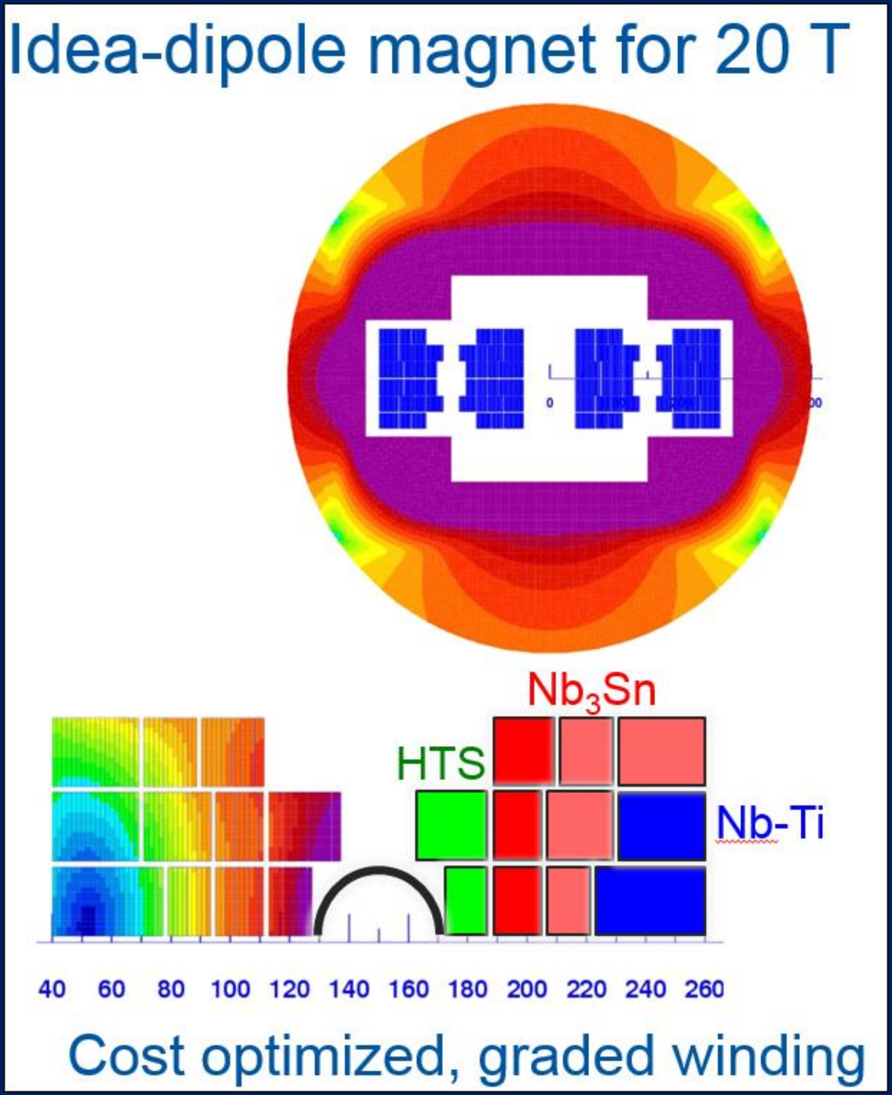
Remarkable progress - Superconductors for 16 T



- Steady increase in current density,
  from 500 to 3500 A/mm² in 30 years!
- **Magnet records follow progress in superconductors with increasing current density!**

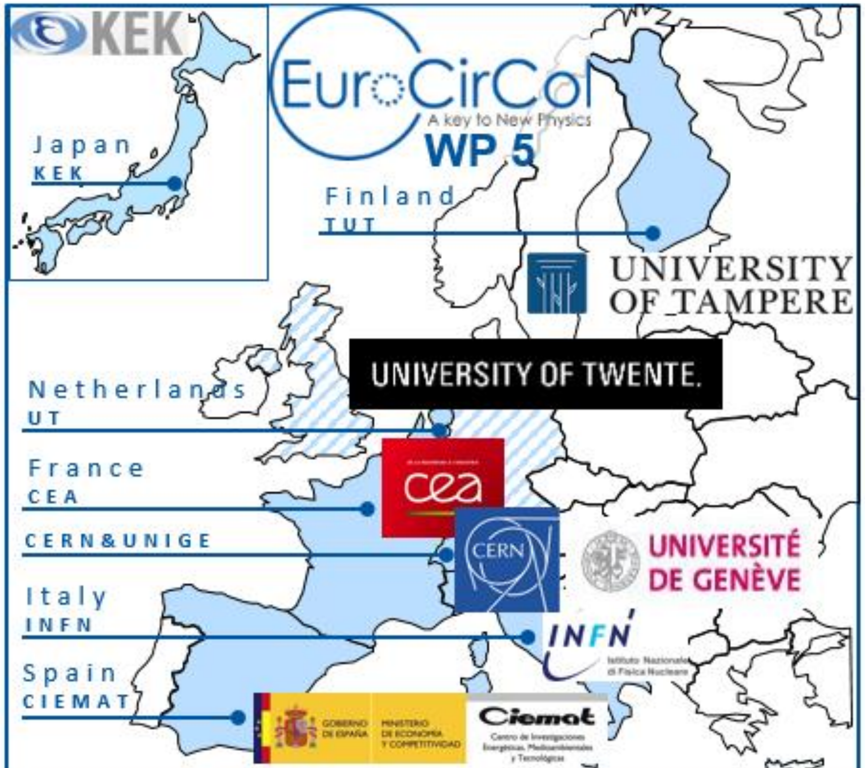
Magnet Design & Engineering for 16 & 20 T



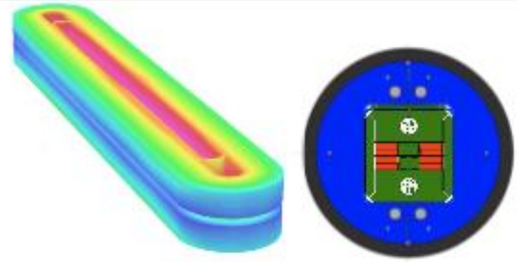


CERN - EU collaboration for 16 T in 2018

CERN/EU program



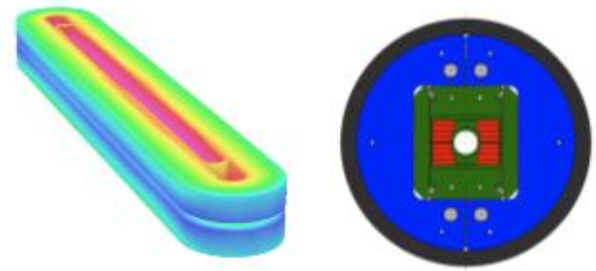
Design a 16 T accelerator-quality model dipole magnet, operating at 4.5 K by 2018 !



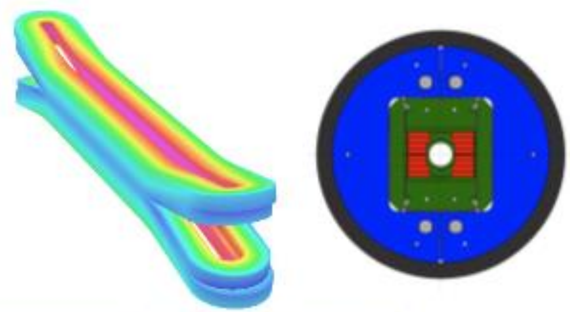
2016

Extended Racetrack 16 T Model Coil

2017



Racetrack Model Magnet, 16 T in 50 mm



2018

Demonstrator Magnet

100 km Nb_3Sn wire for short models

FCC detector magnets - Sizing

What determines the size of the generic “4π“ detector and magnetic field?

Radial thickness

is the summation of:

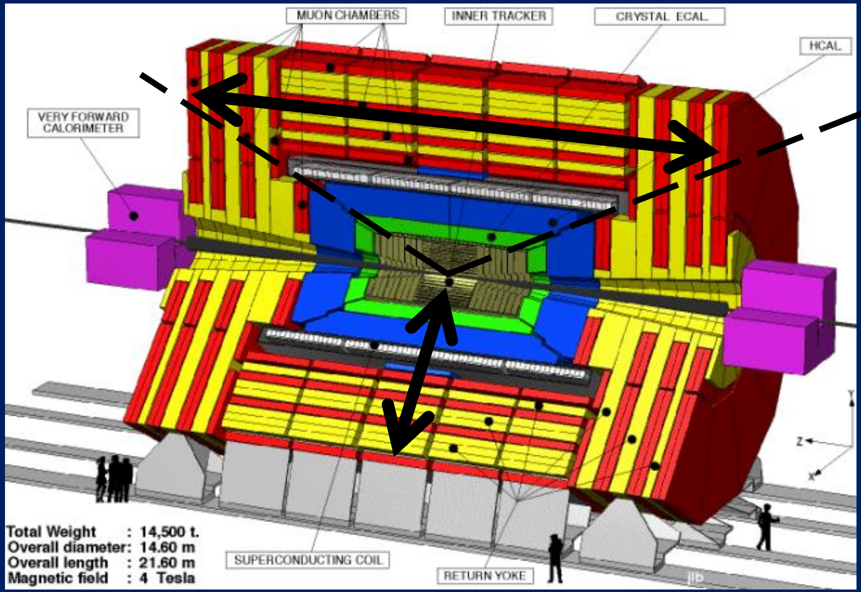
tracking length inner detector

+ thickness of the solenoid

+ radial build of the calorimeters

+ tracking length for muons

+ thickness of shielding iron yoke



Axial length

is the summation of:

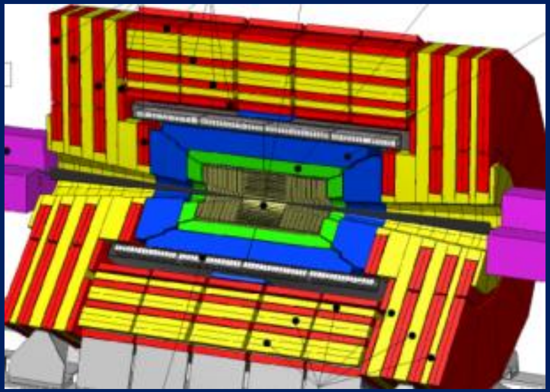
“catch angle” in forward directions sizing the length of the solenoid

+ thickness of iron shielding.

Detector magnets - Design drivers

Bending power: 100 TeV = 7 x 14 TeV

$$\frac{\sigma(p_T)}{p_T} = \frac{\sigma(\kappa)}{\kappa} = \frac{\sigma_x \cdot p_T}{0.3BL^2}\sqrt{\frac{720}{(N+4)}}$$



For same tracking resolution

BL^2/σ has to be increased by factor 7!

> For same σ, need increase magnetic field in solenoid up to 6 T

Also need low-angle coverage in forward direction

> Add a dipole, toroid or solenoid in forward direction

And HCAL depth from 10 to 12 λ (iron), radial thickness 2.5 - 3.0 m!

> Free bore of solenoid increases to 5 to 6 m and length accordingly.

ECAL to cover low angles, move out, from 5 to 15 m, system gets longer.

Thus: higher magnetic field, larger bore, longer system.

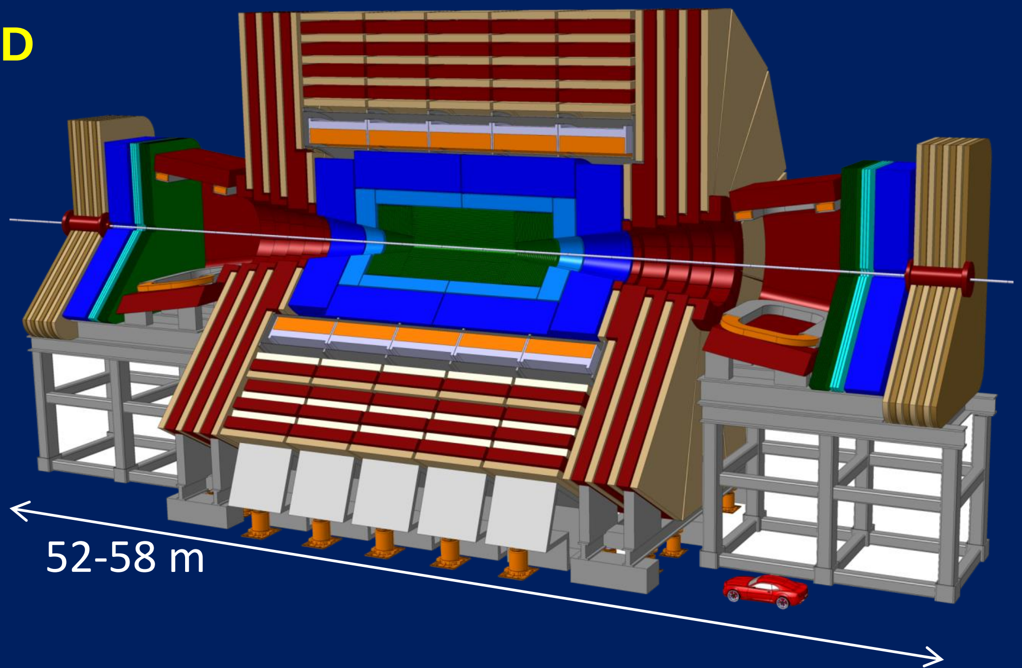
FCC-hh - Solenoid with iron yoke – heavy!

6 T in 12 m bore, 23 m long, 28 m OD

- Stored energy 54 GJ,
- 6.3 T peak magnetic field.

Yoke size and weight?

- 100% shielding requires 6.3 m thick iron (10 mT at 22 m)
- 15 m^3, 120 kt (≈ 600 M€).



Huge mass, serious consequences for cavern floor, installation, not elegant.

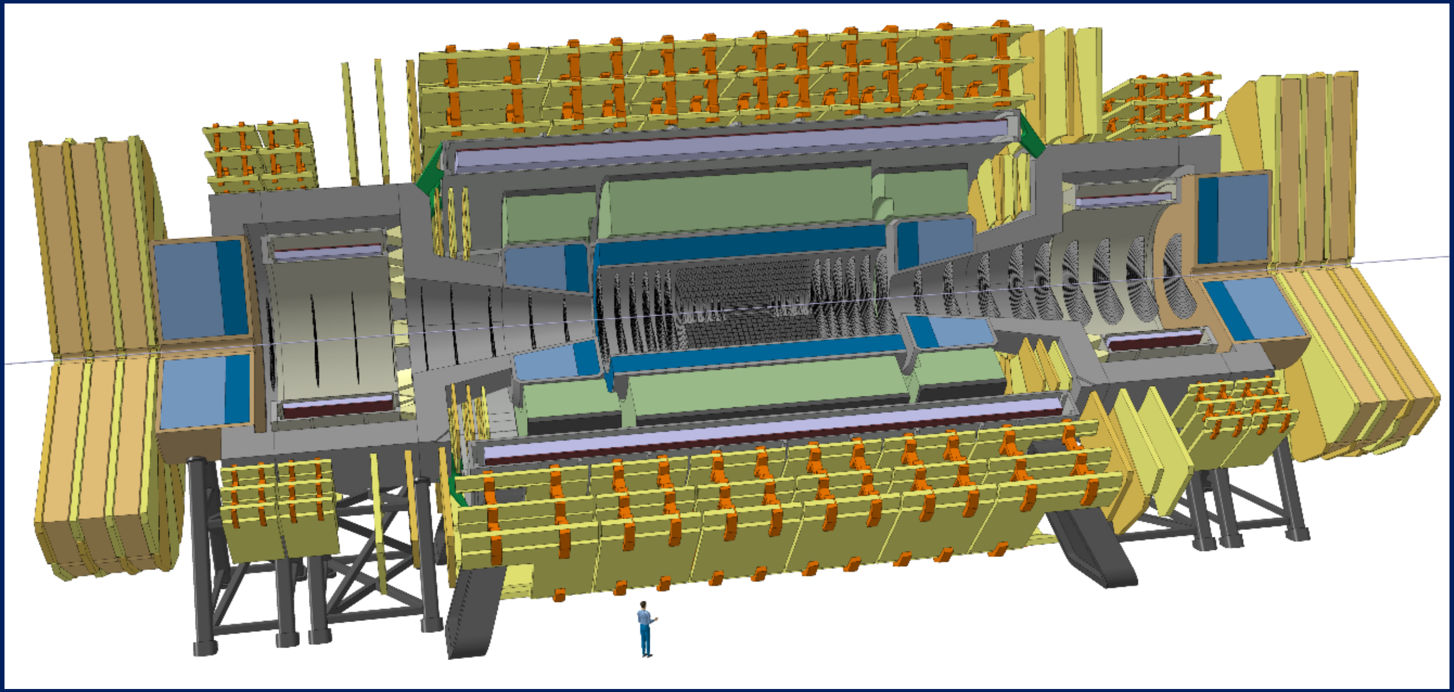
- Can it be less?
- For muon tagging at 1 Tm, yoke thickness of 1 m is fine, still 22 kt
- Then stray field with 2 layers, 1 m iron, 22 kt is 14 mT at 50 m, 300 mT at 30 m.

Fringe field has to be made acceptable, or be reduced by local shielding.

Even so, still a heavy magnet system with some 30 kt overall weight.

Classical solution doesn't work, need innovative design & cost reduction!

FCC-hh novel – Baseline Detector



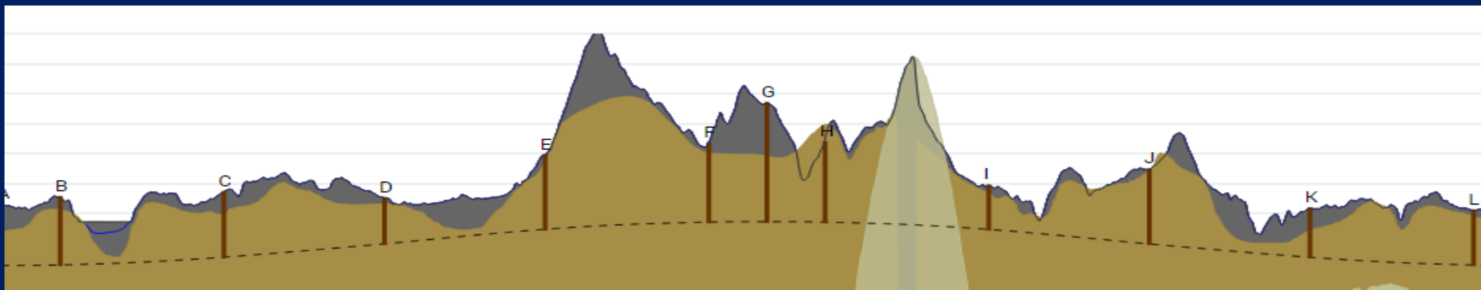
For same resolution BL^2/σ scales with the collision energy leading to much larger detector magnets !

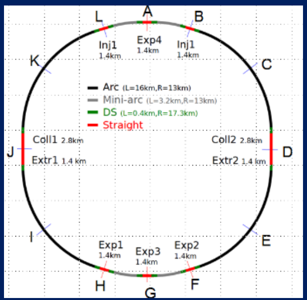
FCC Detector magnets are huge! Systems size of 25 m diameter and 50 m length.

Size scales with collision energy!

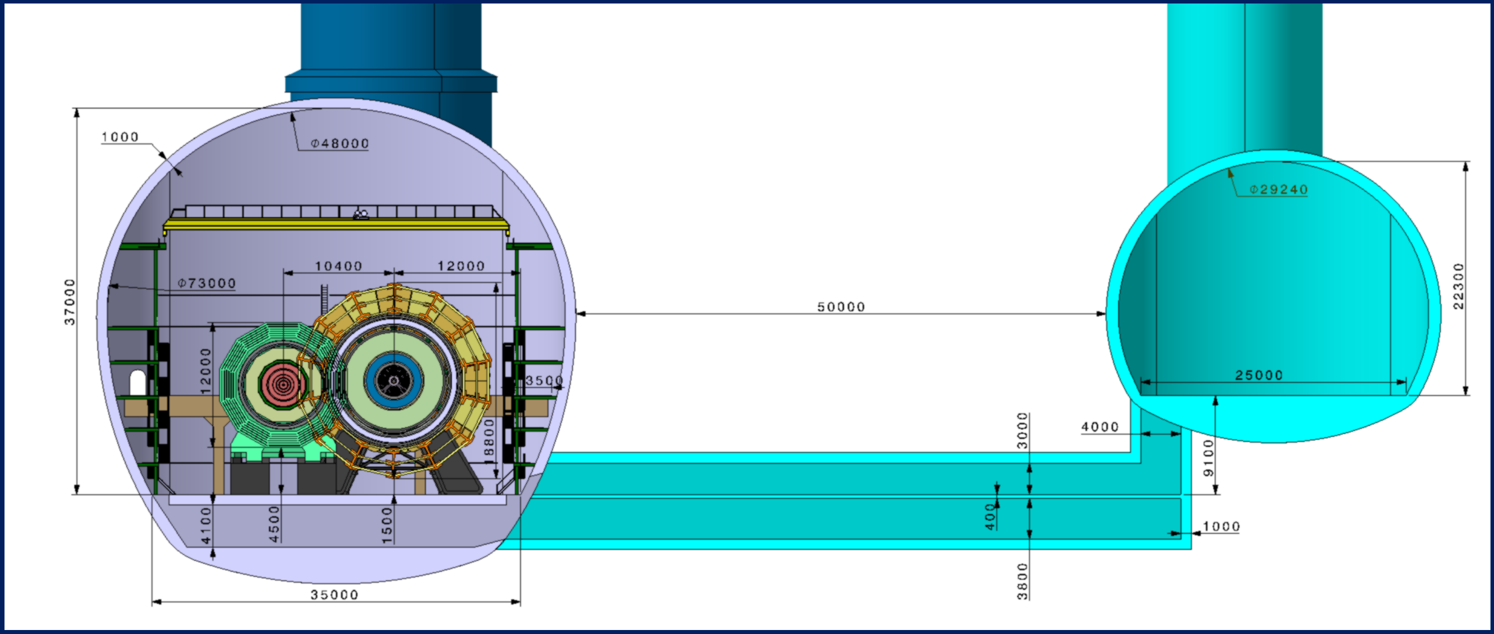
- **Main solenoid with 4 T in a 10 m free bore**
- **Forward solenoids**, to extend the bending capacity for low angle particles
- **Stored energy: 14 GJ**

Cavern - Magnet installation challenges





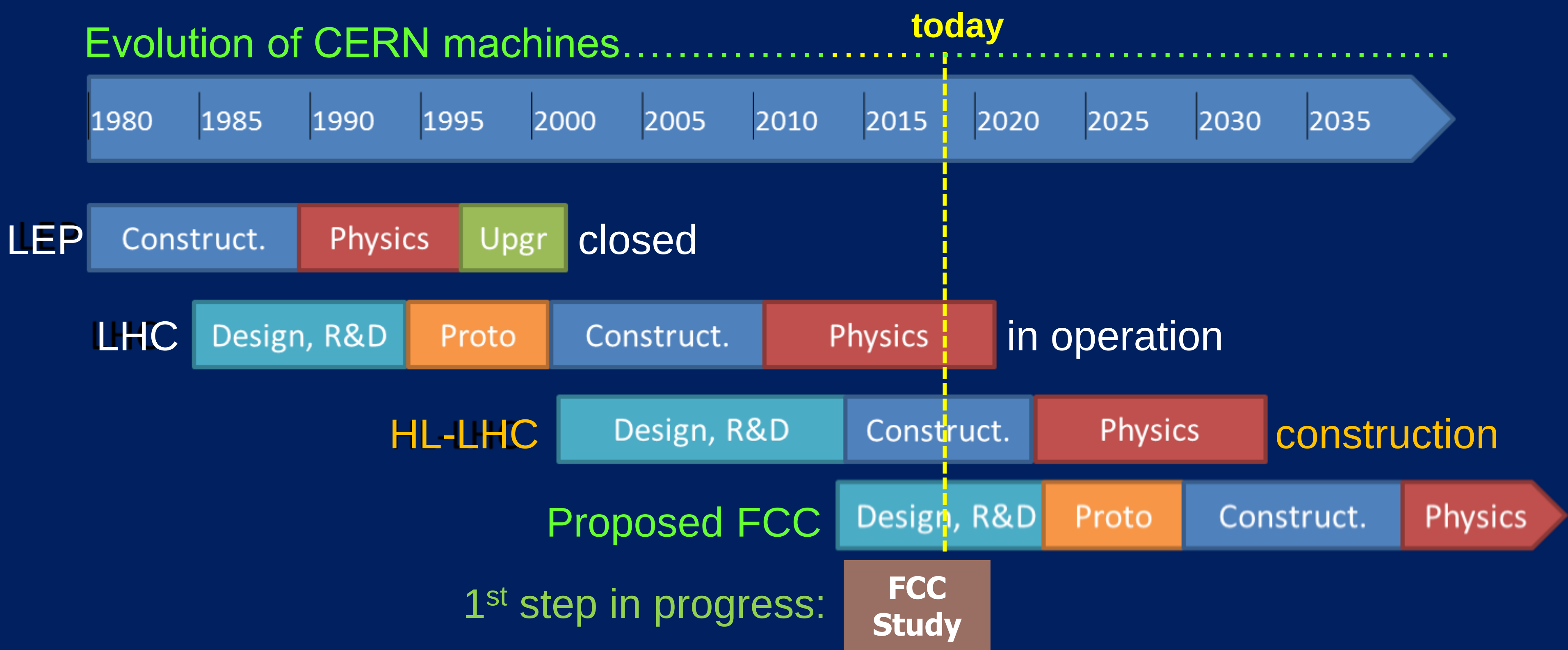
Depth where new tunnel is: detectors in points A-F-G-H at 300 - 400 m below surface



- Installation of a detector in a 400 m deep shaft is not that easy!

It easily takes 30 years……. start now!

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

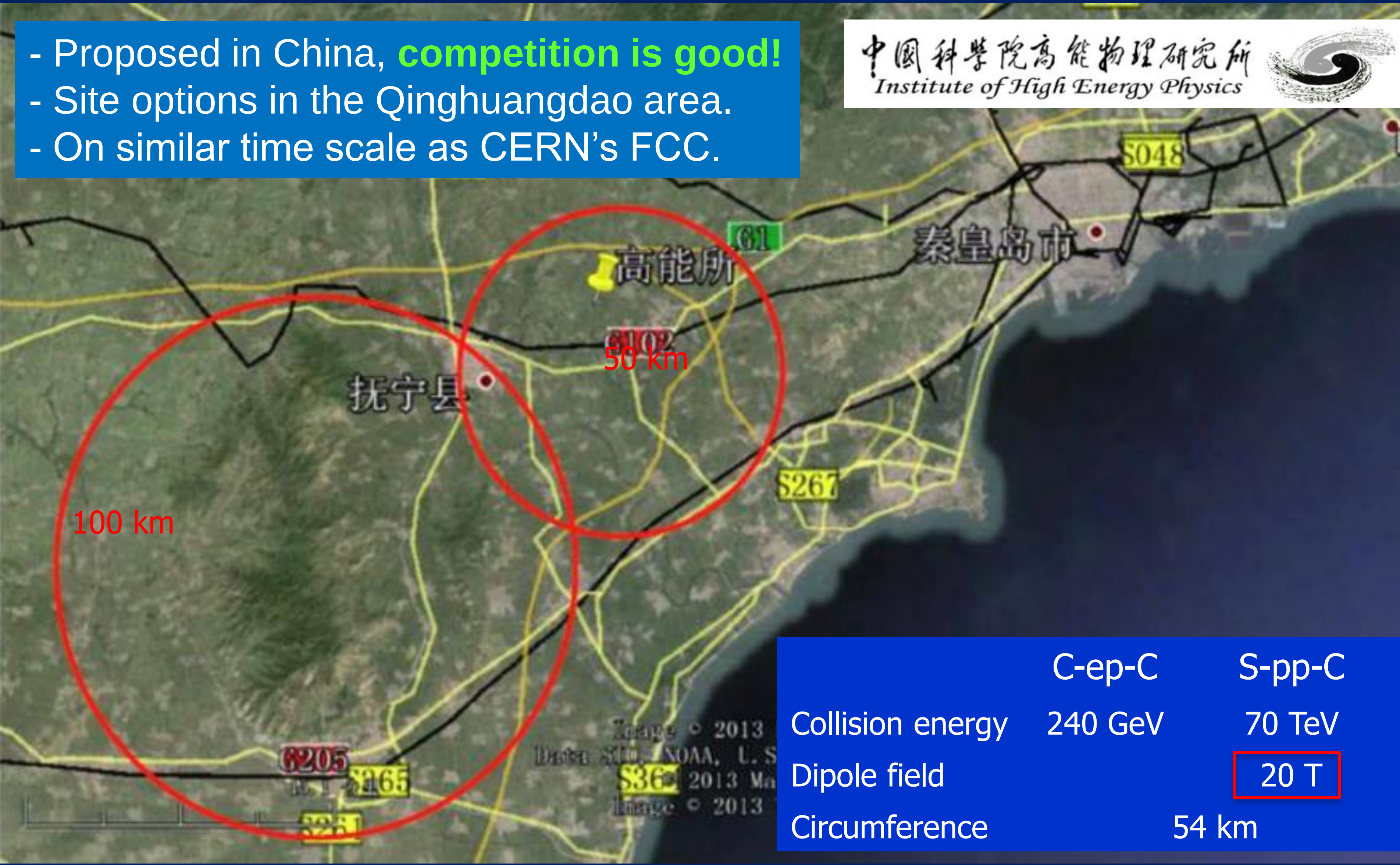


FCC Study: p-p machine to achieve 100 TeV, CDR & Cost Review in 2019

Chinese in China - CepC-SppC ?

- Proposed in China, **competition is good!**
- Site options in the Qinghuangdao area.
- On similar time scale as CERN's FCC.

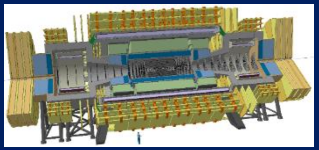
中国科学院高能物理研究所
Institute of High Energy Physics



	C-ep-C	S-pp-C
Collision energy	240 GeV	70 TeV
Dipole field		20 T
Circumference	54 km	

A. Apyan, et al., "CEPC-SPPC Preliminary Conceptual Design Report", IHEP-CEPCPP-DR-2015-01, IHEP-AC-2015-012015.

Conclusion



- CERN is preparing for the upgrade of the present LHC for higher luminosity for which new 11 T class Nb_3Sn dipole and quadrupole magnets are being developed; built and installed in few years.
- This program gives a true boost to magnet R&D and production technology for full-size Nb_3Sn magnets, for the first time in history.
- A design study for a next 100 TeV FCC has started, requiring a large scale production of 16T class Nb_3Sn magnets and the necessary R&D short and long models (including HTS for 20T trials).
- For the detectors, very huge, world's largest magnets with 60 GJ stored energy, need to be developed.
- FCC accelerator and detector magnets require new conductor R&D to get the current densities and stress performance needed, an excellent opportunity for European labs to do highly relevant front line research, and very necessary to let the FCC dream come true….