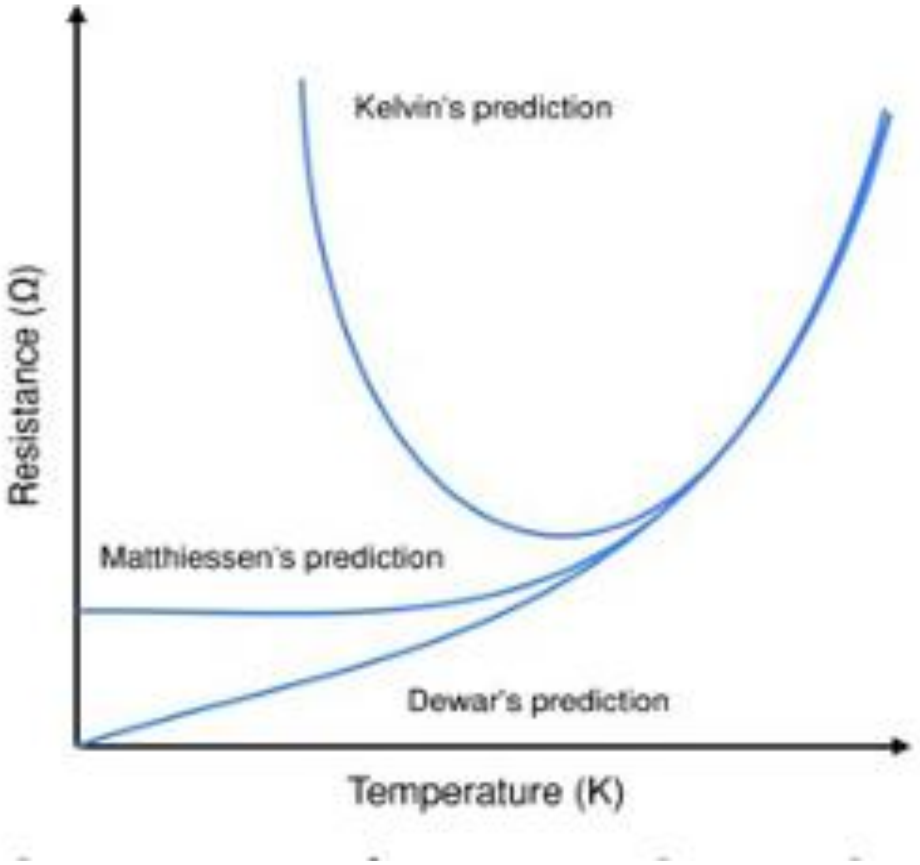
Applications of Superconductivity

Larger and stronger magnets for Big Science:
Colliders, detectors and more…

Erwin Bielert

A little bit of history…



Dewar: all vibrations stop at zero Kelvin and thus electrons can move through the atomic lattice without resistance

Matthiessen: resistance is dominated by impurities and dislocations inside the atomic lattice and therefore resistance should be finite at low temperatures and towards zero Kelvin

Kelvin: all movement stops, also the electrons, therefore, no current can be present, which is represented as an infinitely large resistance

Fundamental physics questions require the need for new technologies:
How do we reach such low temperatures?!

A little bit of history… continued

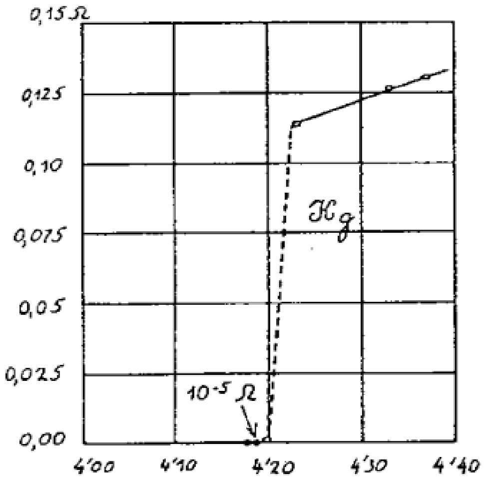
1877: liquefaction of air by Cailletet (FR) and independently Pictet (CH)

1883: liquefaction of oxygen by Wroblewski and Olszewski (PL)

1898: liquefaction of hydrogen by Dewar (UK)

1908: liquefaction of helium by Kamerlingh Onnes (NL)

1911: resistance measurement of Mercury cooled by liquid helium



Some Nobel prizes…

1913, Heike Kamerlingh Onnes:

"for his investigations on the properties of matter at low temperatures that led, inter alia, to the production of liquid helium"

1962, Lev Landau:

"for his pioneering theories for condensed matter, especially liquid helium"

1972, John Bardeen, Leon Cooper and John Robert Schriefer:

"for their jointly developed theory of superconductivity, usually called the BCS theory"

1973, Leo Esaki and Ivar Glaever, jointly with Brian Josephson:

"for their experimental discoveries regarding tunneling phenomena in semiconductors and superconductors respectively" *and* "For his theoretical predictions of the properties of a super current through a tunnel barrier, in particular those phenomena that are generally known as the Josephson effects"

1987, Georg Bednorz and Alexander Mueller:

"for their important break-through in the discovery of superconductivity in ceramic materials"

2003, Alexi Abrikosov, Vitaly Ginzburg and Anthony Leggett:

"for pioneering contributions to the theory of superconductors and superfluids".

The dream… and the reality

A dream was born: let’s make a 10 T magnet!

<u>1912:</u> first superconducting Lead coil


1st Pb wire coil 1912

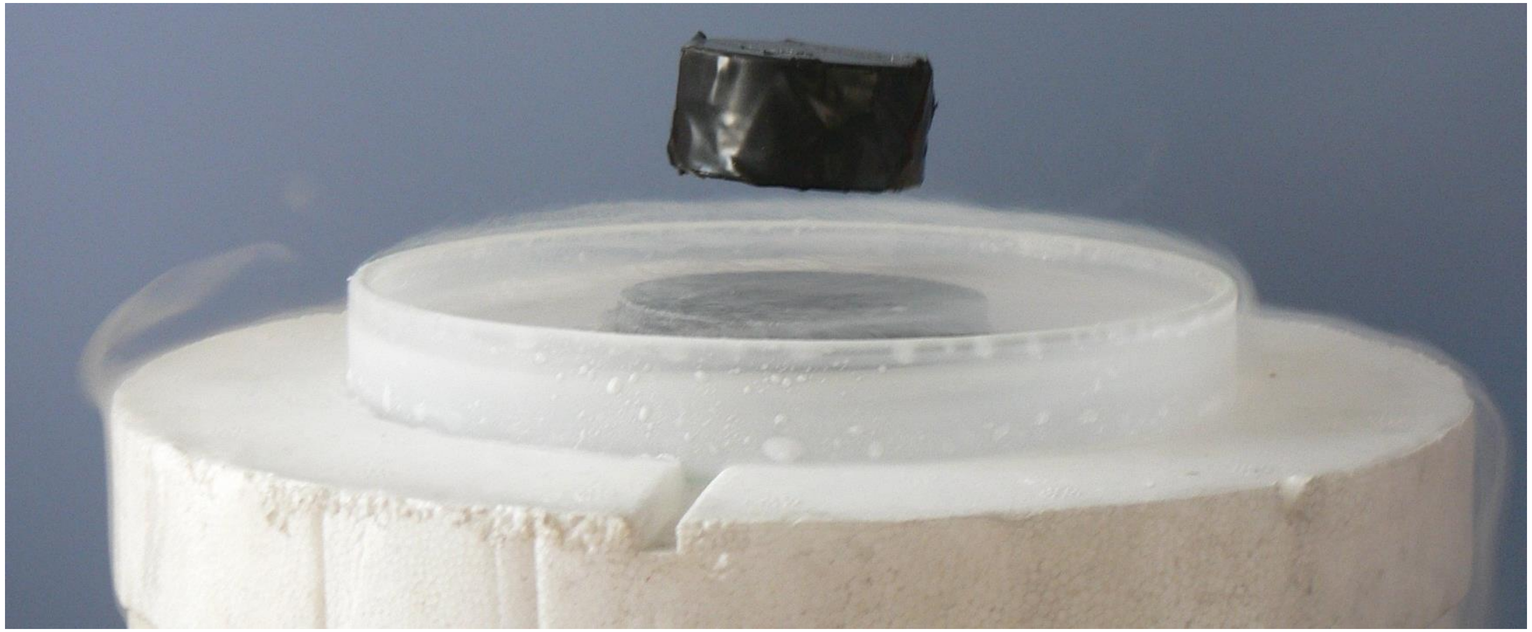
“The 10 T magnet project was stopped when it was observed that superconductivity in Hg and Pb was destroyed by the presence of an external magnetic field as small as 500 Gauss (0.05 T)”

It took about 50 years to understand why it was not possible to make strong superconducting magnets. Only in the 1960s the first real superconducting coils were available.

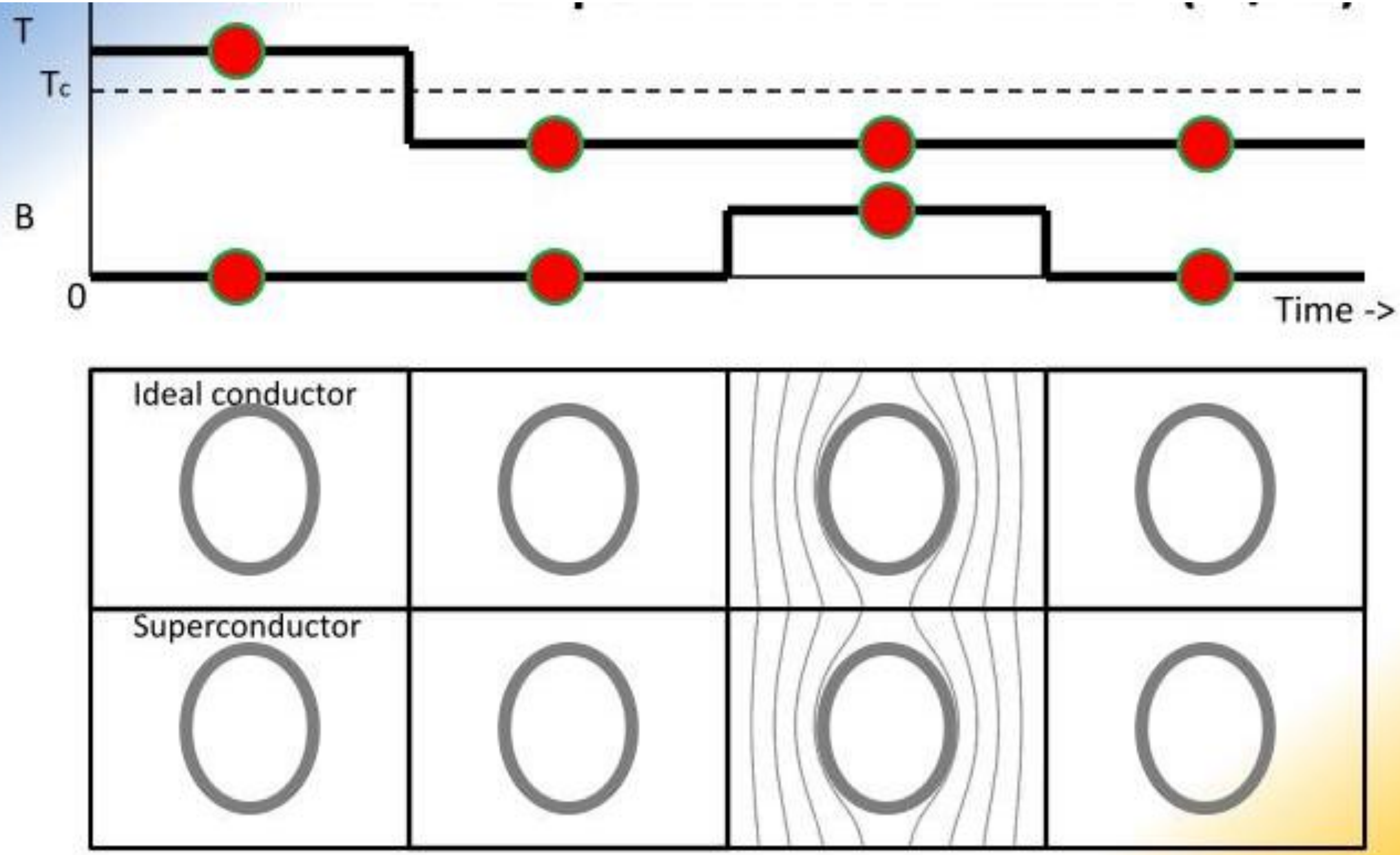
Meissner – Ochsenfeld effect

Perfect diamagnetism due to the fact that persistent screening currents flow at the surface of the superconductor as to oppose the externally applied magnetic field: i.e. in the bulk of the material there is no magnetic field, the field is expulsed.
Note that diamagnetism in normal metals rather has to do with orbital spin of electrons.

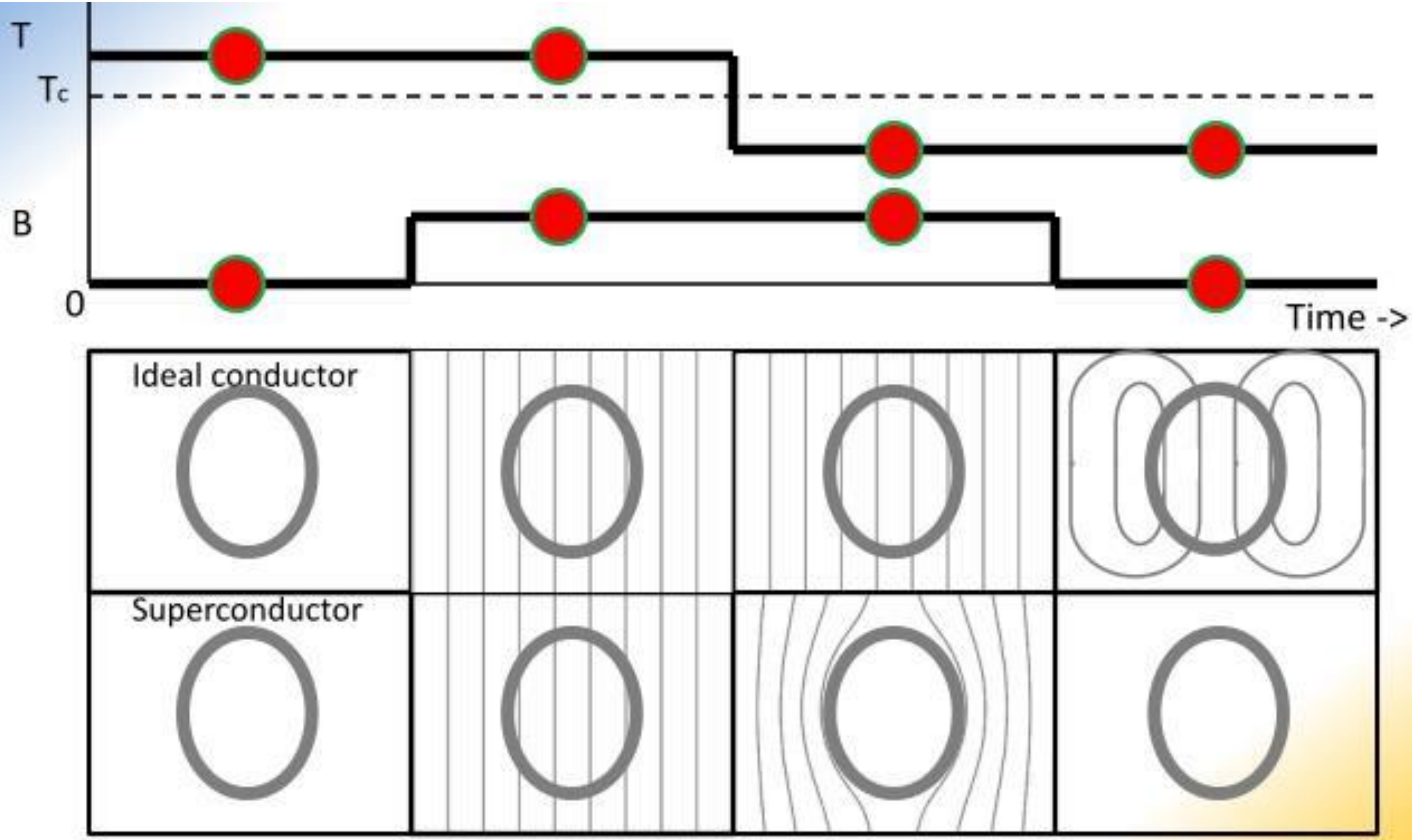
Perfect conductors without any resistance, would also prevent any *change* of magnetic flux due to ordinary electromagnetic induction, but for superconductors there is more going on…



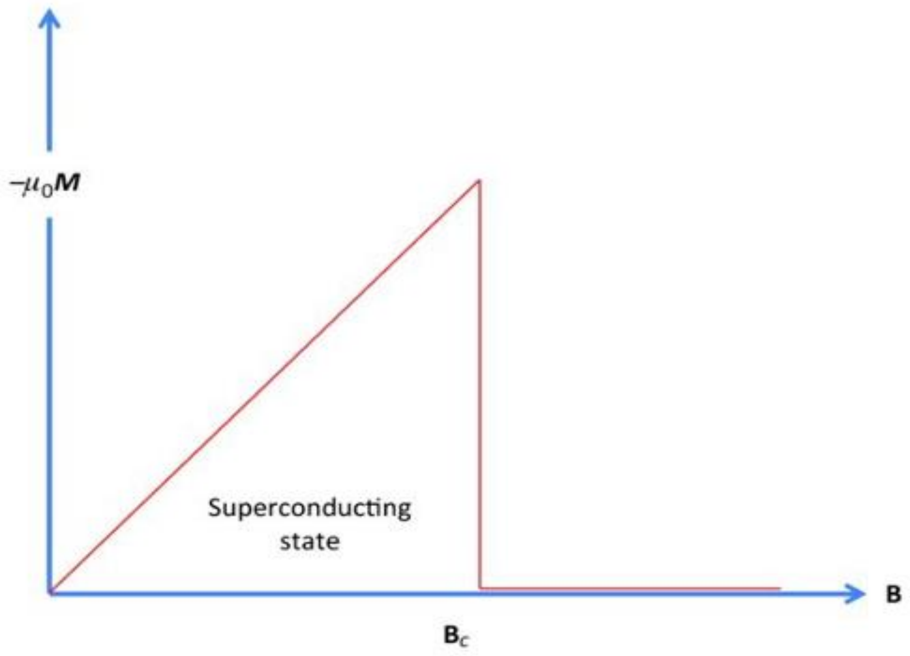
Meissner – Ochsenfeld effect

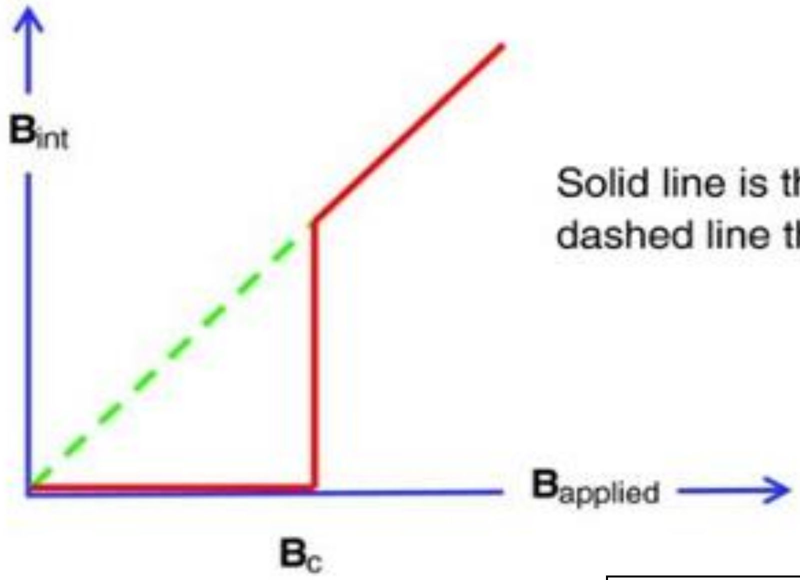


Meissner – Ochsenfeld effect



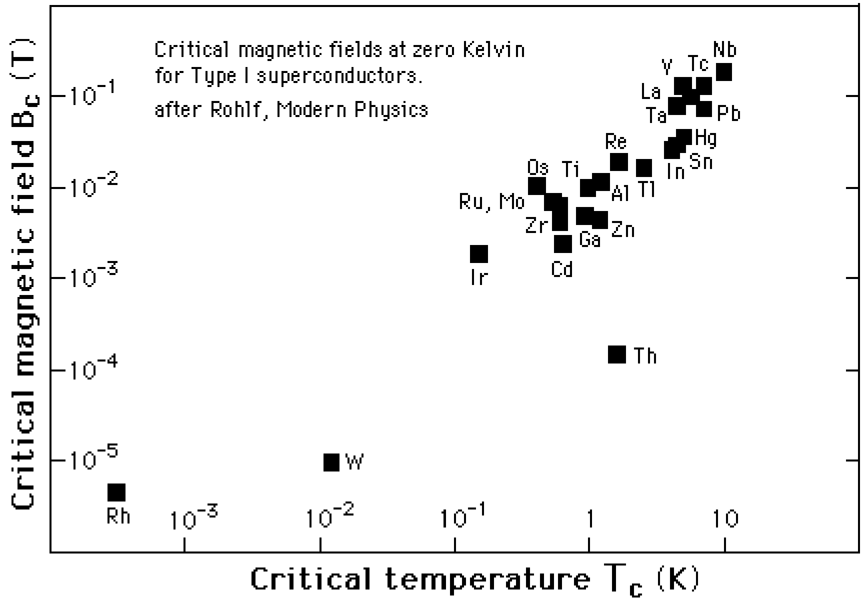
Critical field



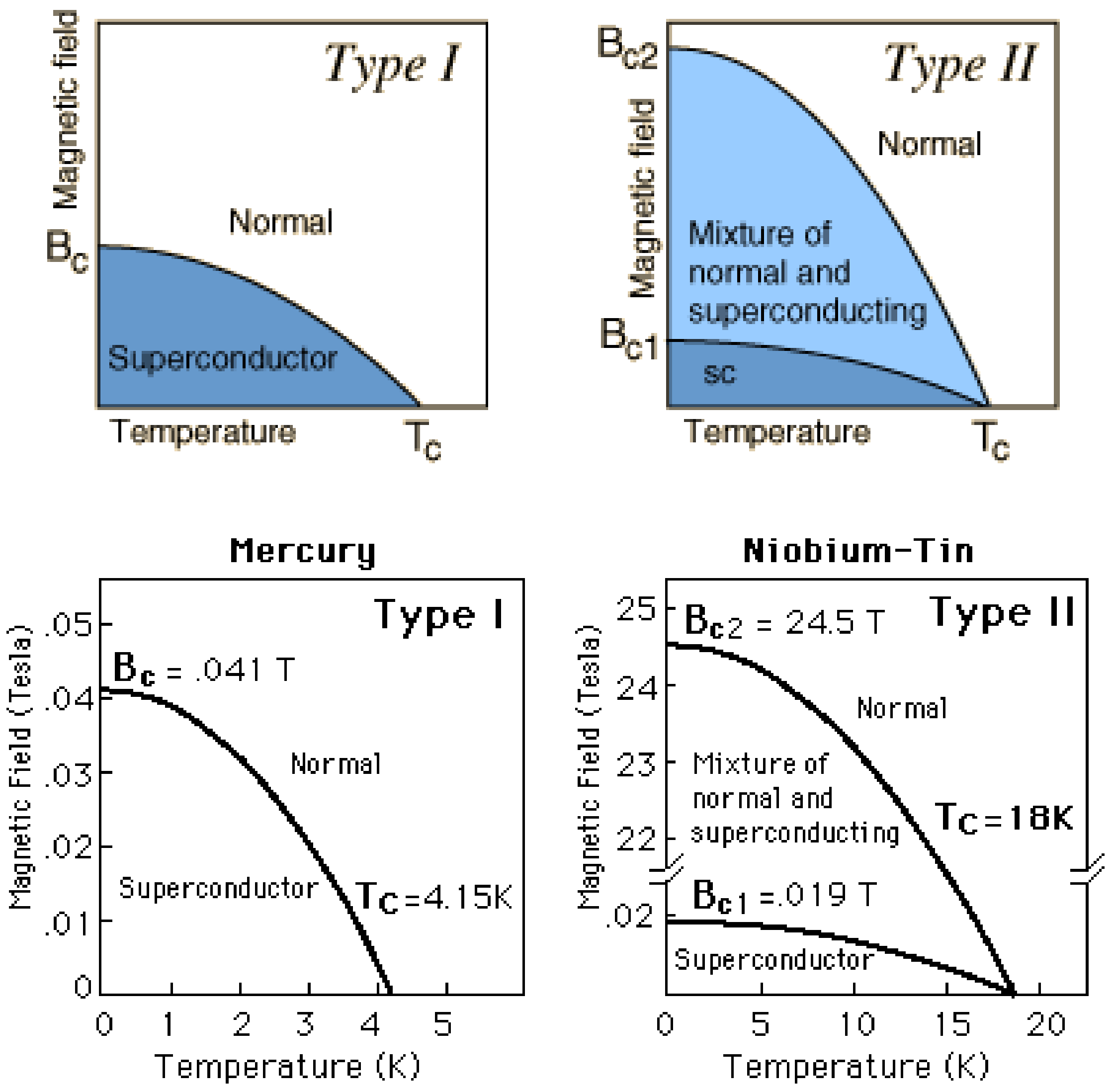


Solid line is the superconductor and the dashed line the *normal* metal

1st Pb wire coil 1912

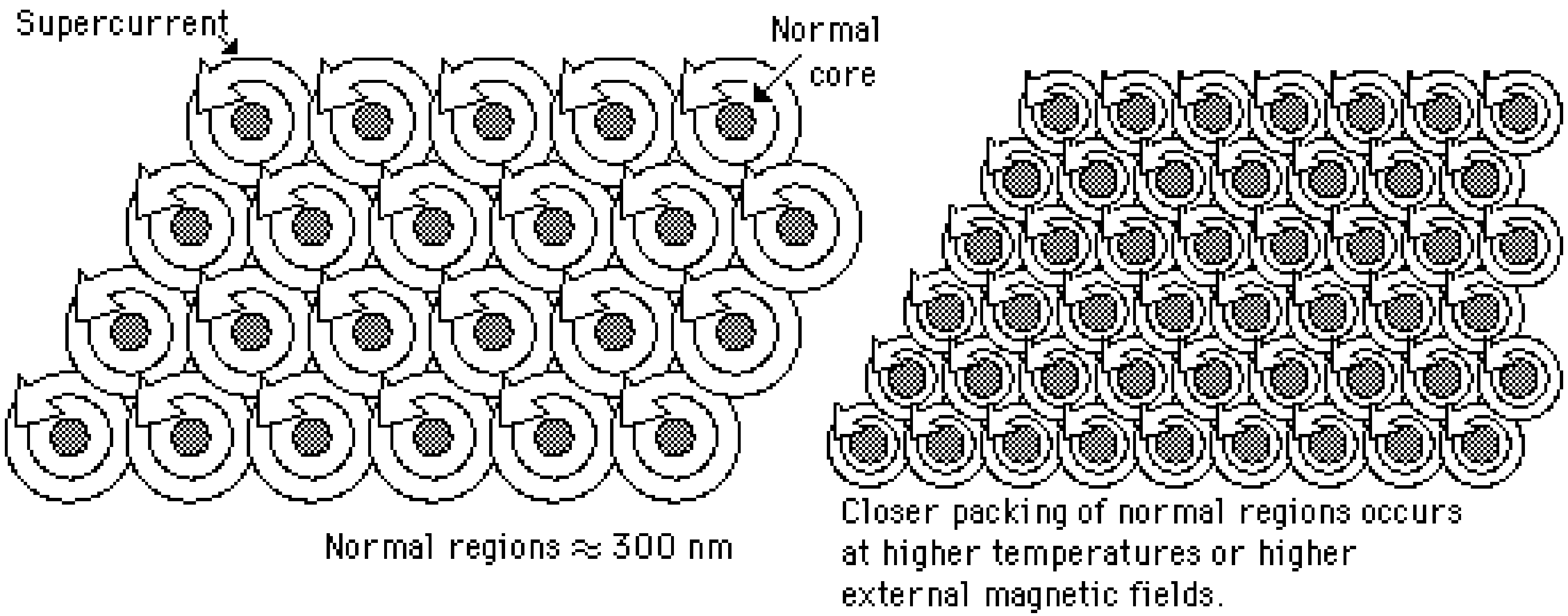


Type I and Type II superconductors



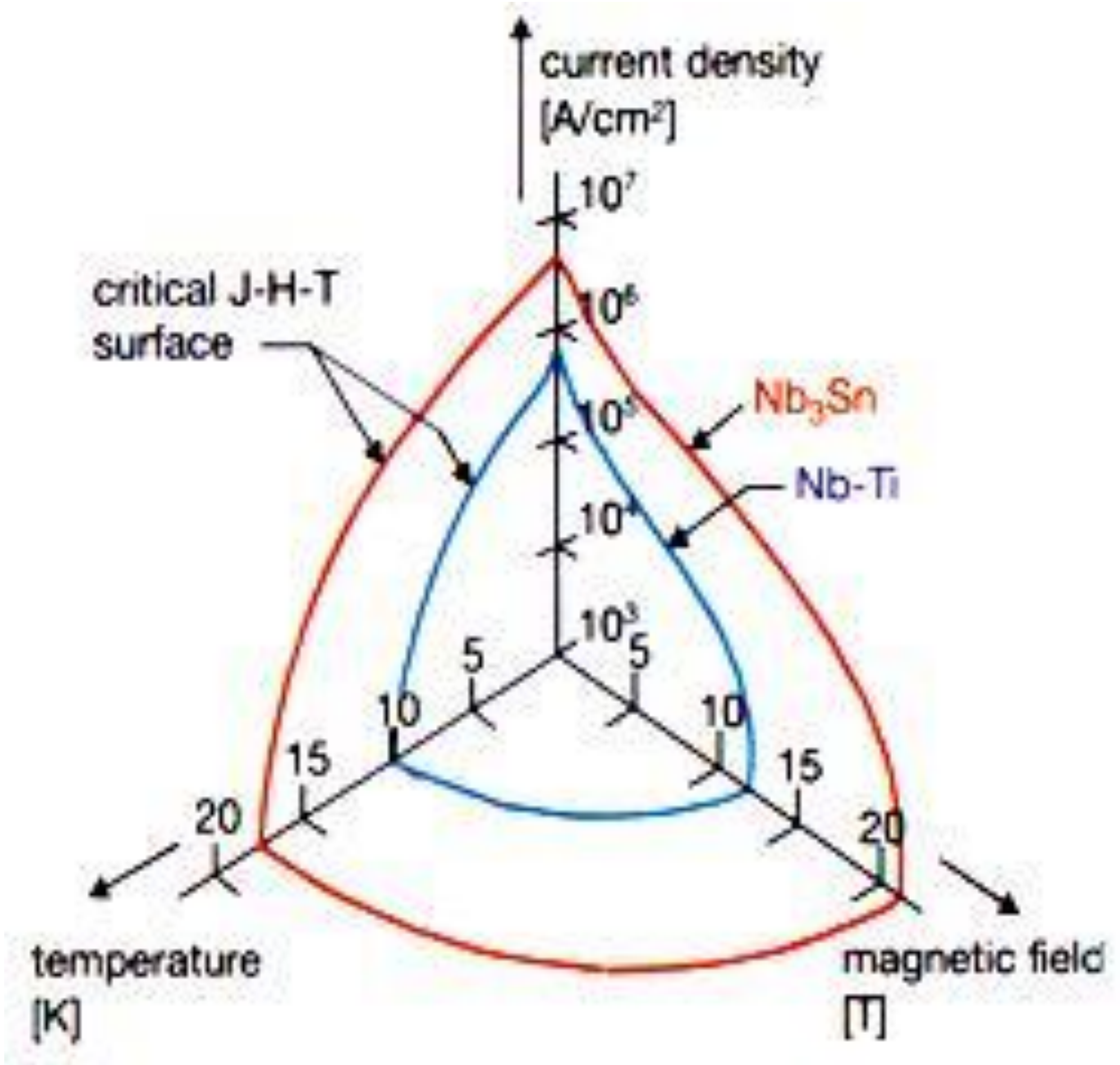
$$B_c \approx B_c(0)\left[1-\left(\frac{T}{T_c}\right)^2\right]$$

Flux pinning

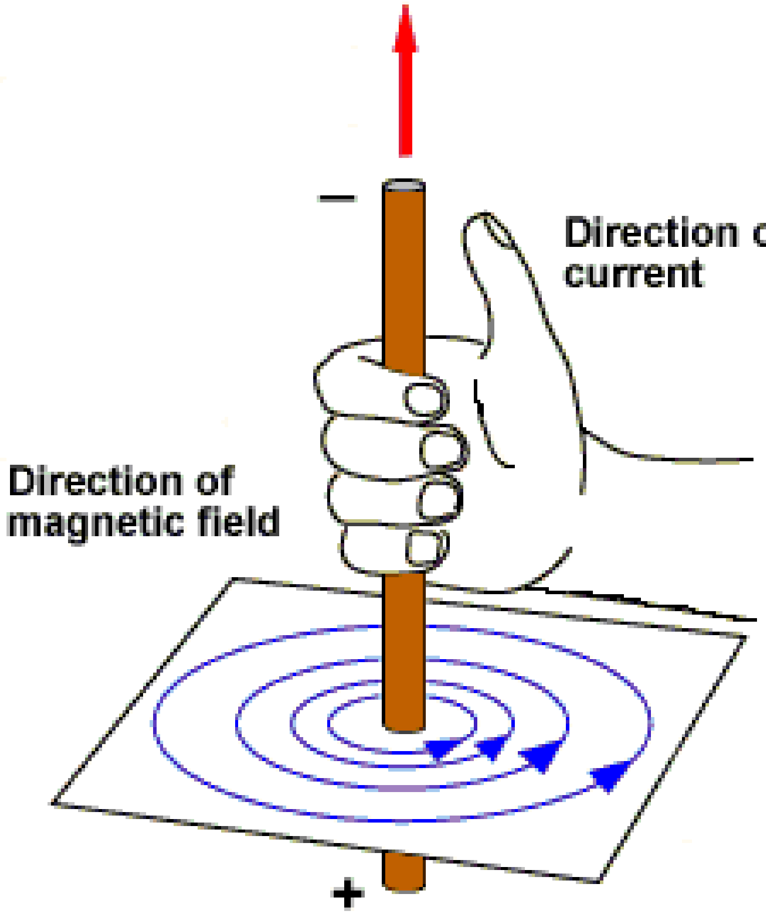


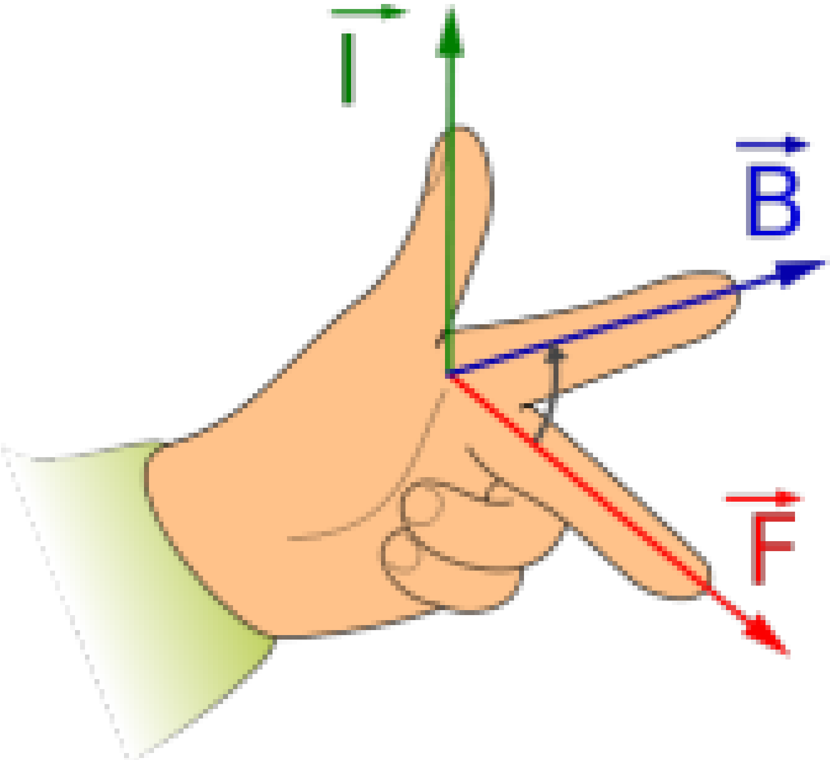
Vortices can move under the action of forces, flux creep and even flux jumps might occur. Due to a better understanding at the microscopic level, pinning centers can be introduced. Material science is of utmost importance for the development of future superconductors.

Critical surface



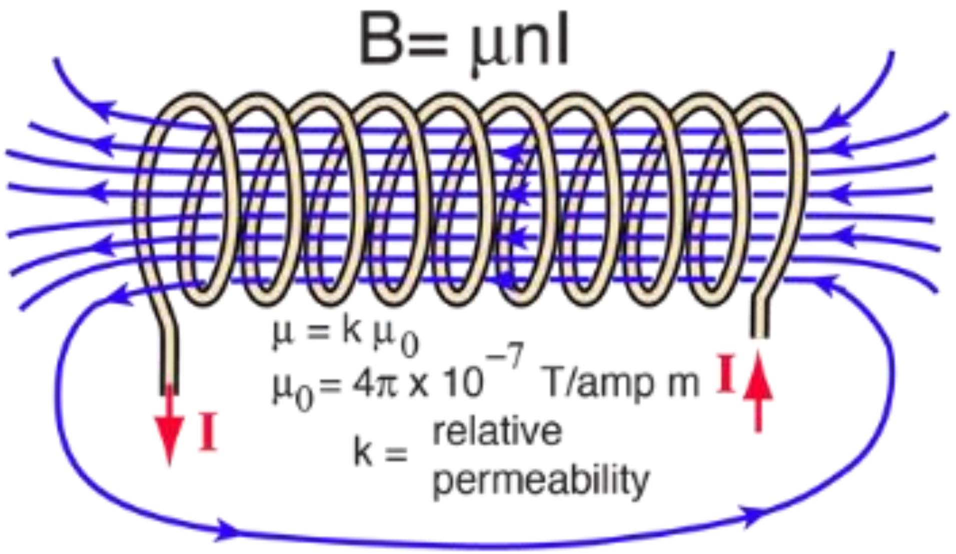
Oersted, Ampère, Biot-Savart





Magnetic field goes down with increased distance from current source… to have high magnetic fields, currents need to be close!

Superconducting magnets: why bother at all?



Magnetic field scales with number of turns, current and permeability.

The ingredients for a strong magnet are clear: Many turns with high current and a iron core.

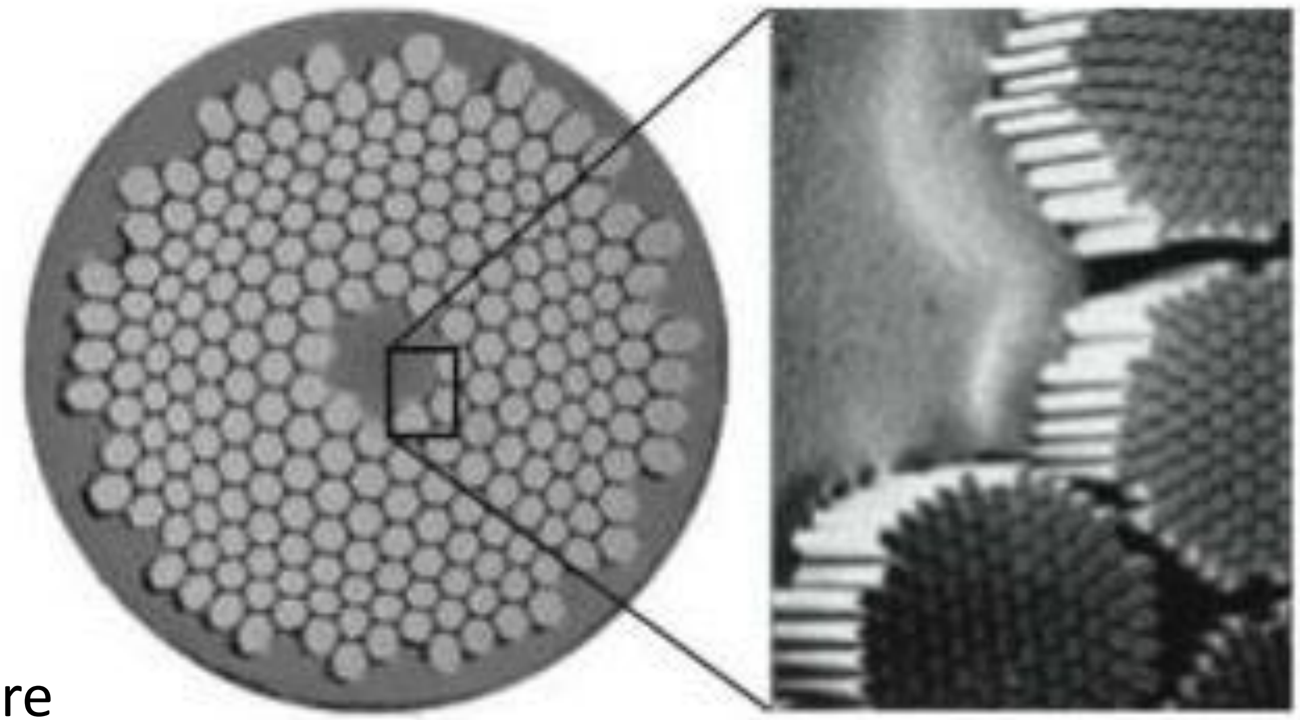
Problems and difficulties:

- Iron saturates
- Current causes Ohmic heating (V=IR, P=VI)

Practical limitation of normal conducting, water cooled magnets is 2 T.

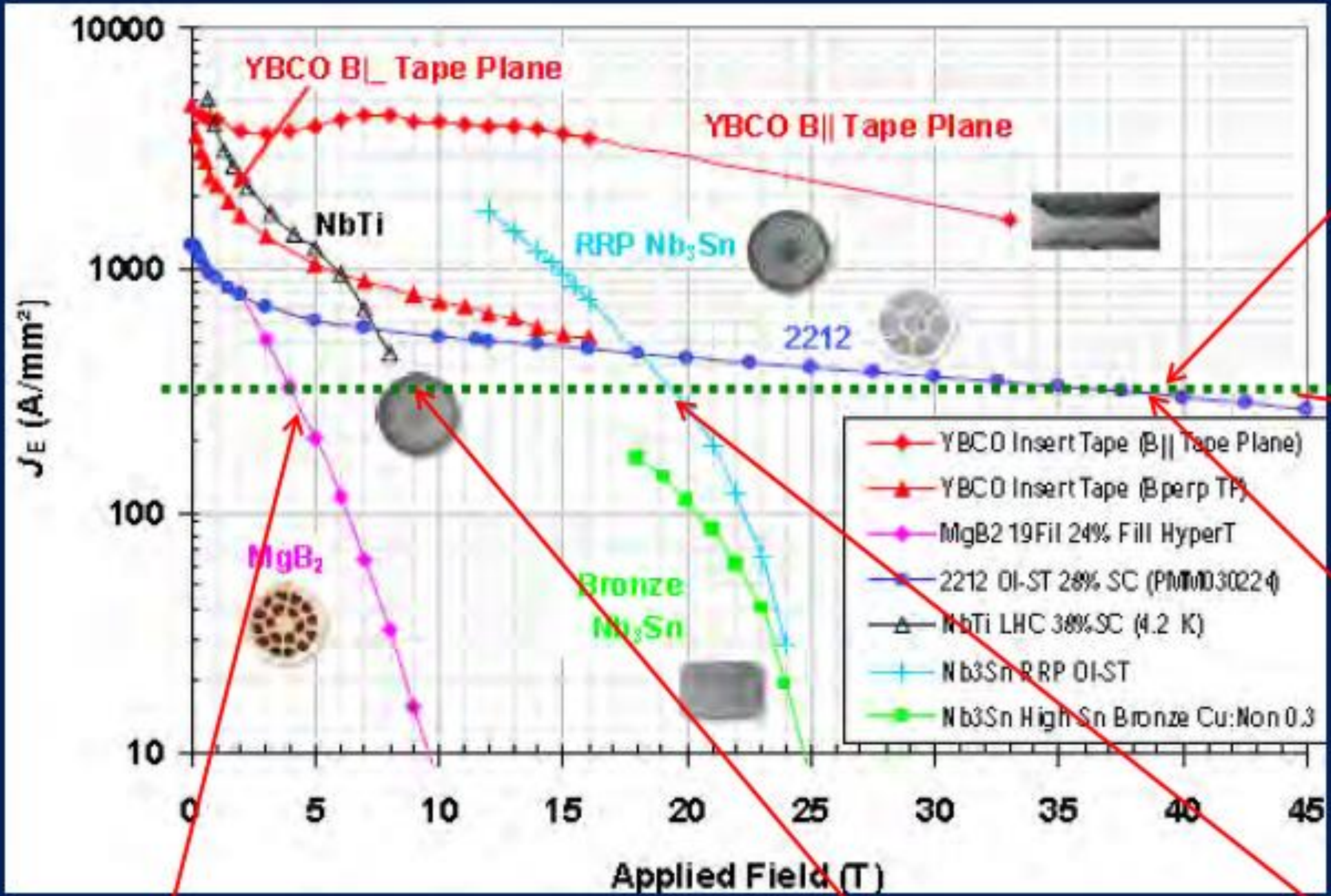
Recipe for increased current densities

Precipitates in alloys, microstructure of Nb-Ti



Thin filaments in a wire

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

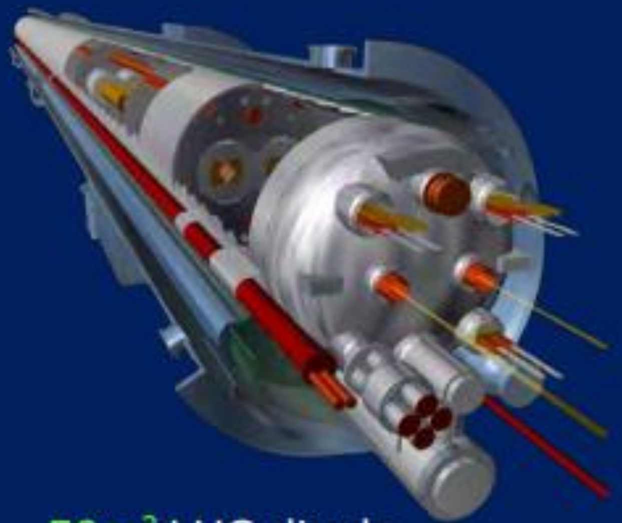
Nb_3Sn for magnets of 9-20 T

Scaling of current with volume: huge currents!

0.0001 m³ HF insert model
~ **200 A**

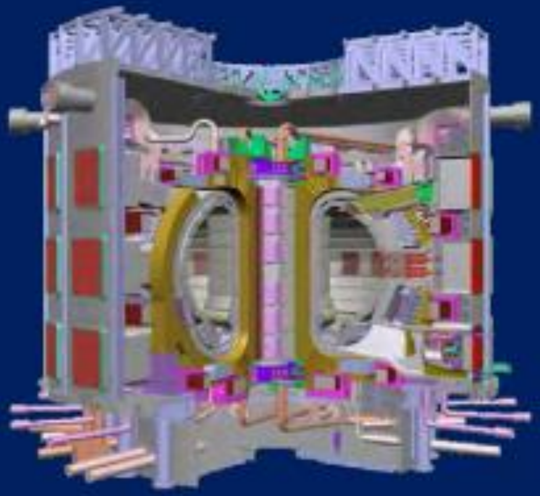
2 m³ MRI magnet
200-800 A @ 1-3 T, ~10 MJ

25 m³ ATLAS solenoid
8 kA @ 2T, 40 MJ



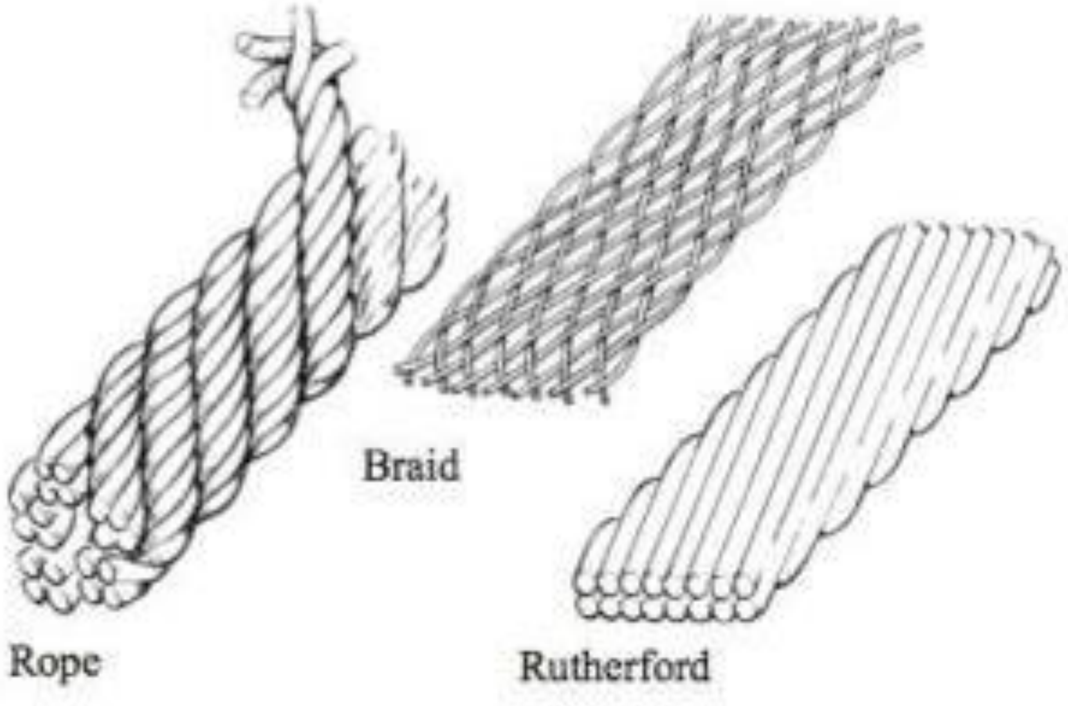
50m³ LHC dipole
12 kA @ 8.3 T

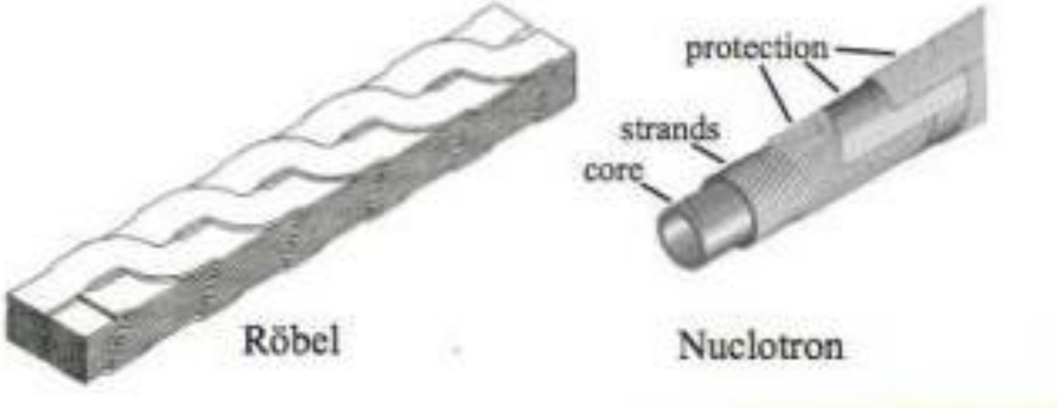
400 m³ HEF detector magnet
20 kA @ 4 T, 2.6 GJ



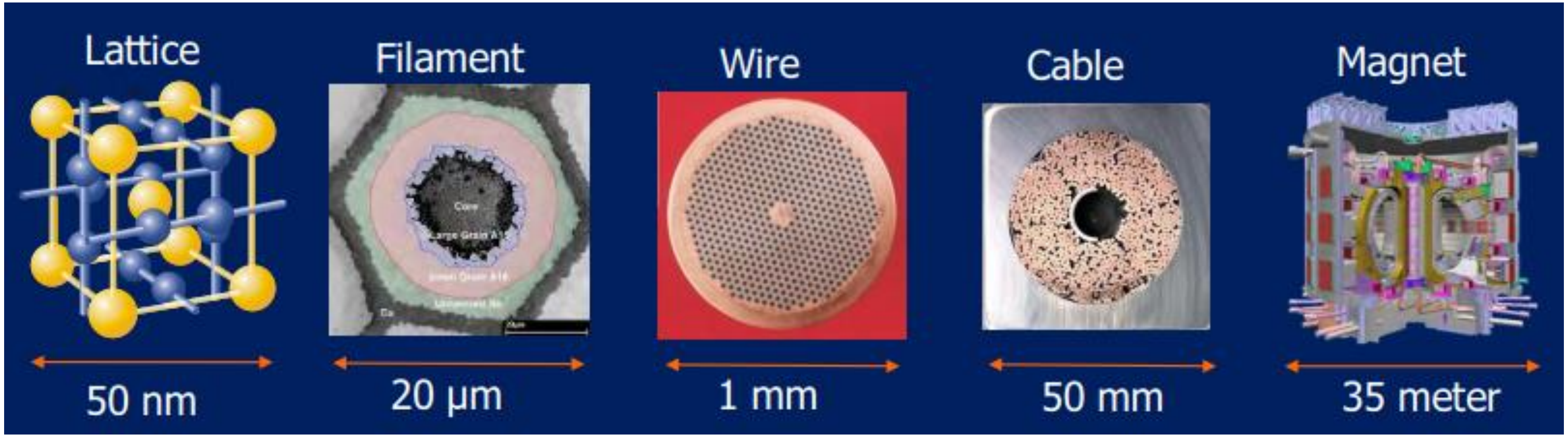
1000 m³ ITER magnets
40-70 kA @ 10-13T , 50 GJ

Large current asks for cables rather than wires





Understanding the chain



A magnet can only meet high standards, if the cable used to wind the coils is of the best quality imaginable. But the cable will only perform correctly if the wires are designed properly and this goes all the way down to the most fundamental understanding of the superconducting material itself.

Applications: wind turbines

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.

Expected Key Benefits

Generator Weight: -40%

Generator Length: -22%

Generator Cost: -40% (mature market)

Nacelle Weight: -25%

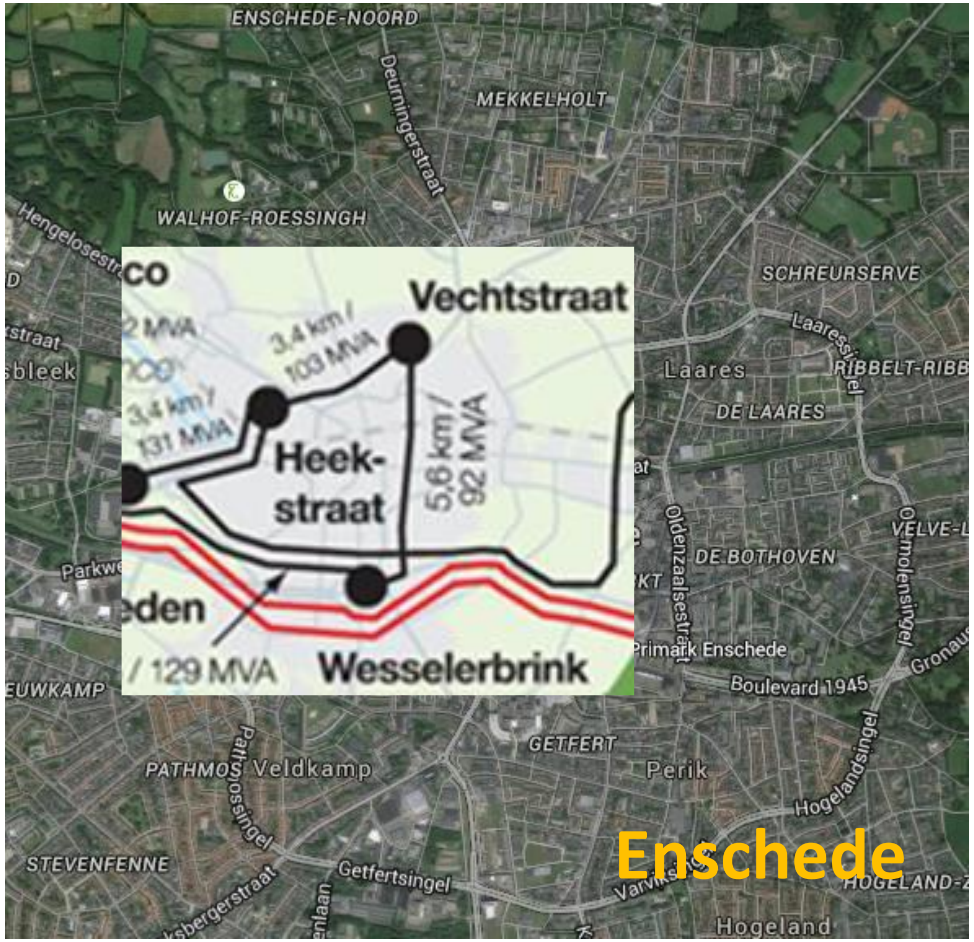
A EU Horizon 2020 project by Envision, ECO5, Jeumont, Delta, Theva, SHI, DNV GL Energy, Fraunhofer Institute & University of Twente.

Applications: power lines

Coordinated by TenneT (Dutch TSO)

- 3.4 km long
- 64 / 110 kV; 150MVA

- Feasibility
- Cost-effectiveness
- Reliability & reparability

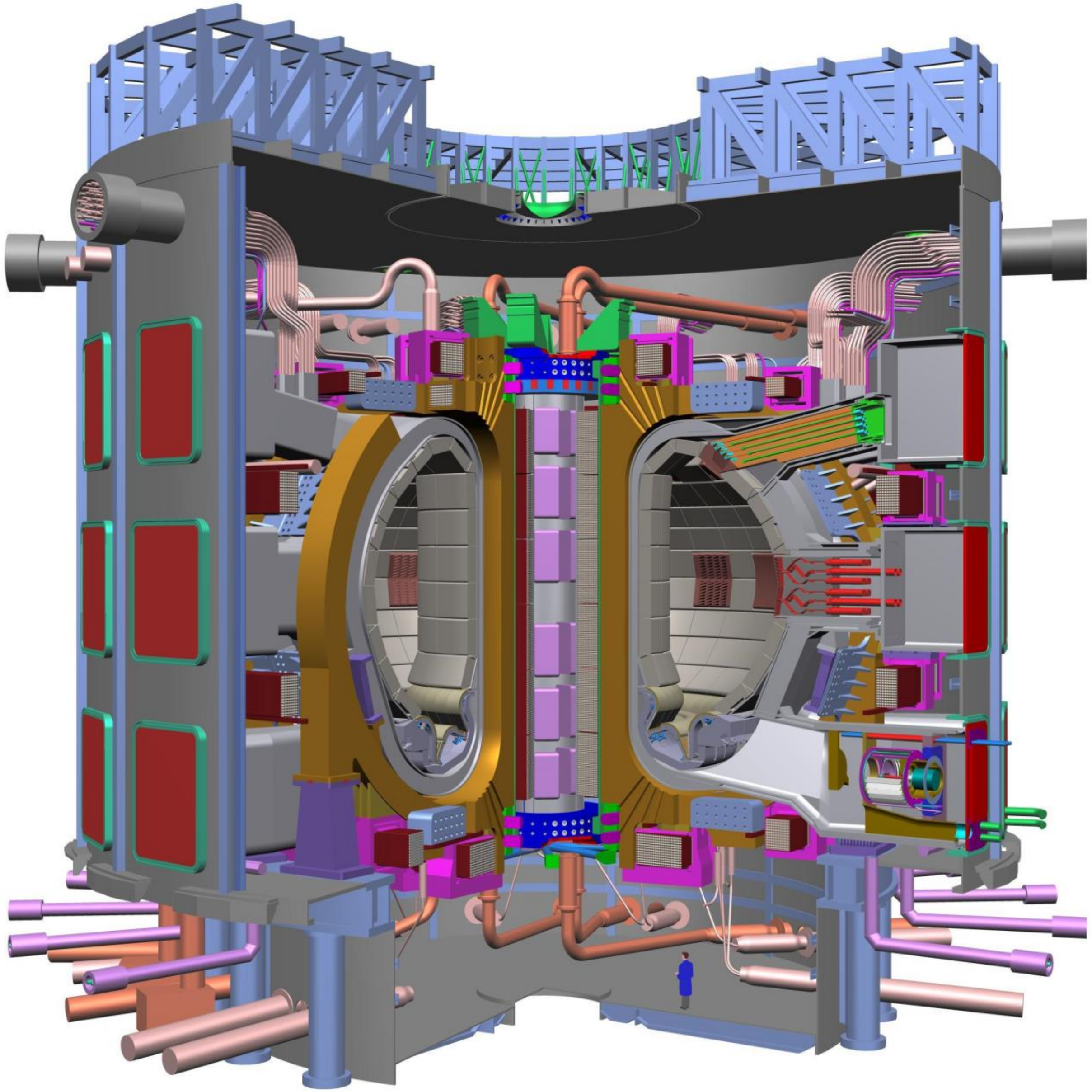


Gesponsord door RvO
Agentschap van het NL Ministerie van Economische Zaken en Klimaat

UNIVERSITY OF TWENTE.

Applications: nuclear fusion

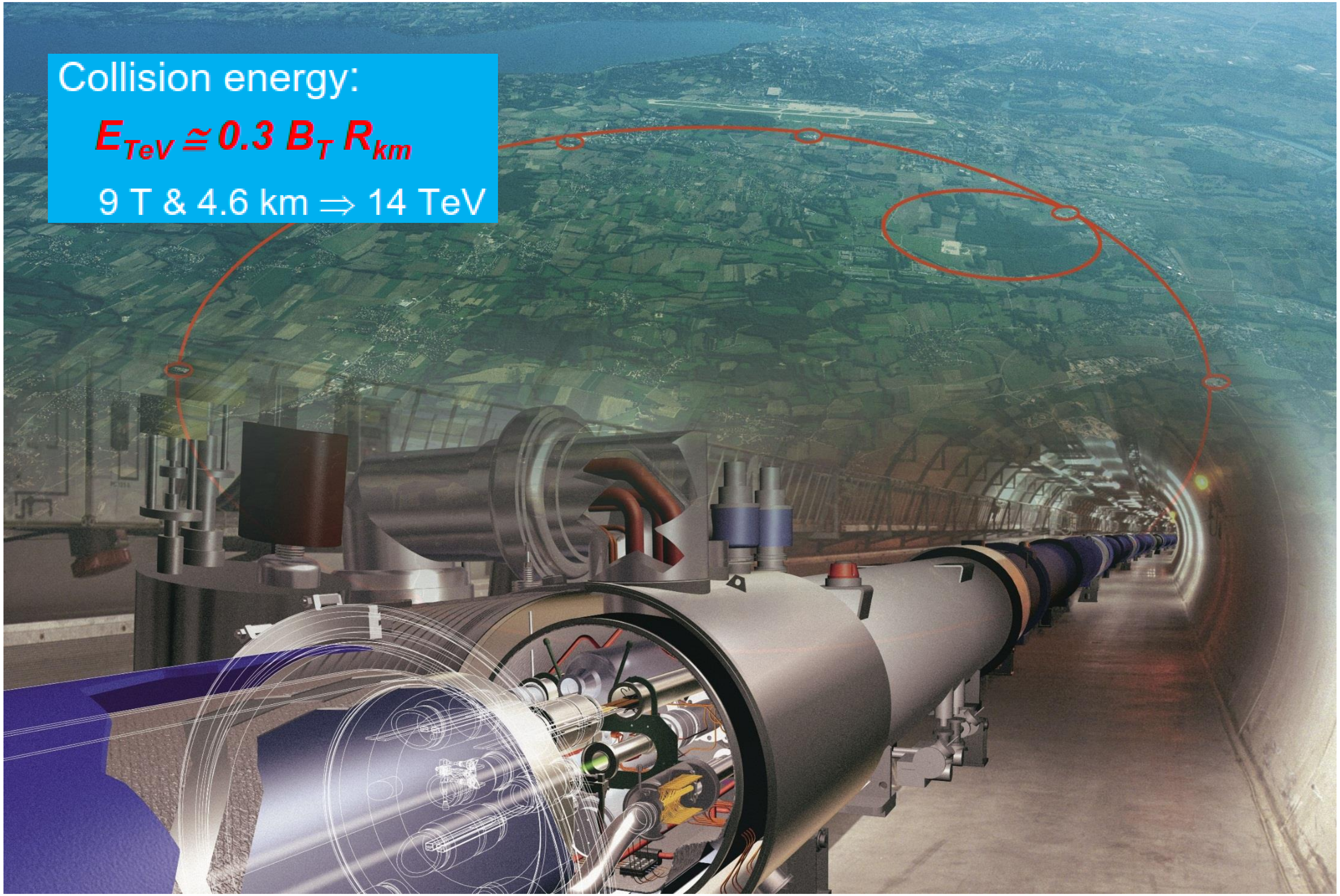
Caderache, France: building site



Applications: MRI

Largest market for superconducting material

Applications: accelerators



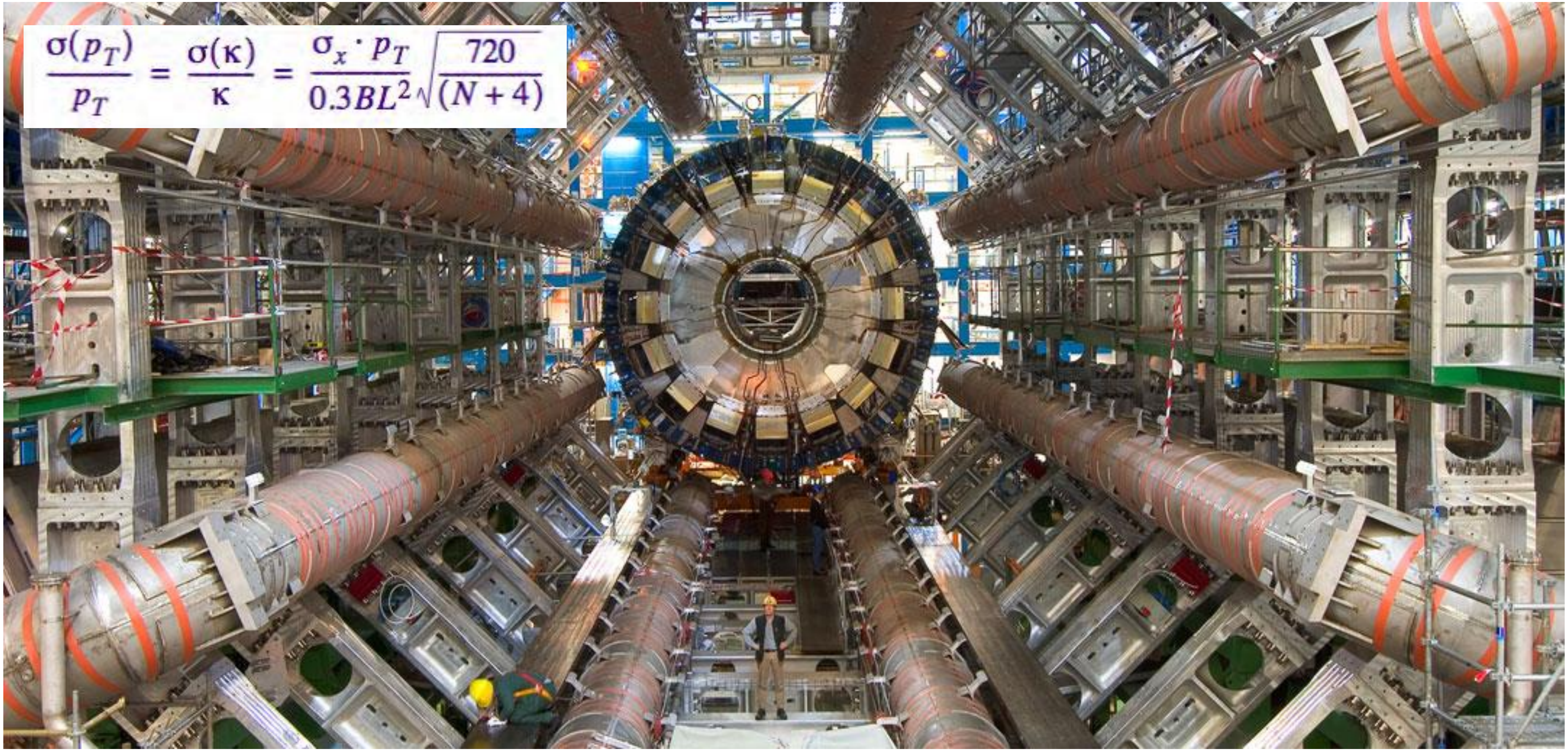
Collision energy:

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

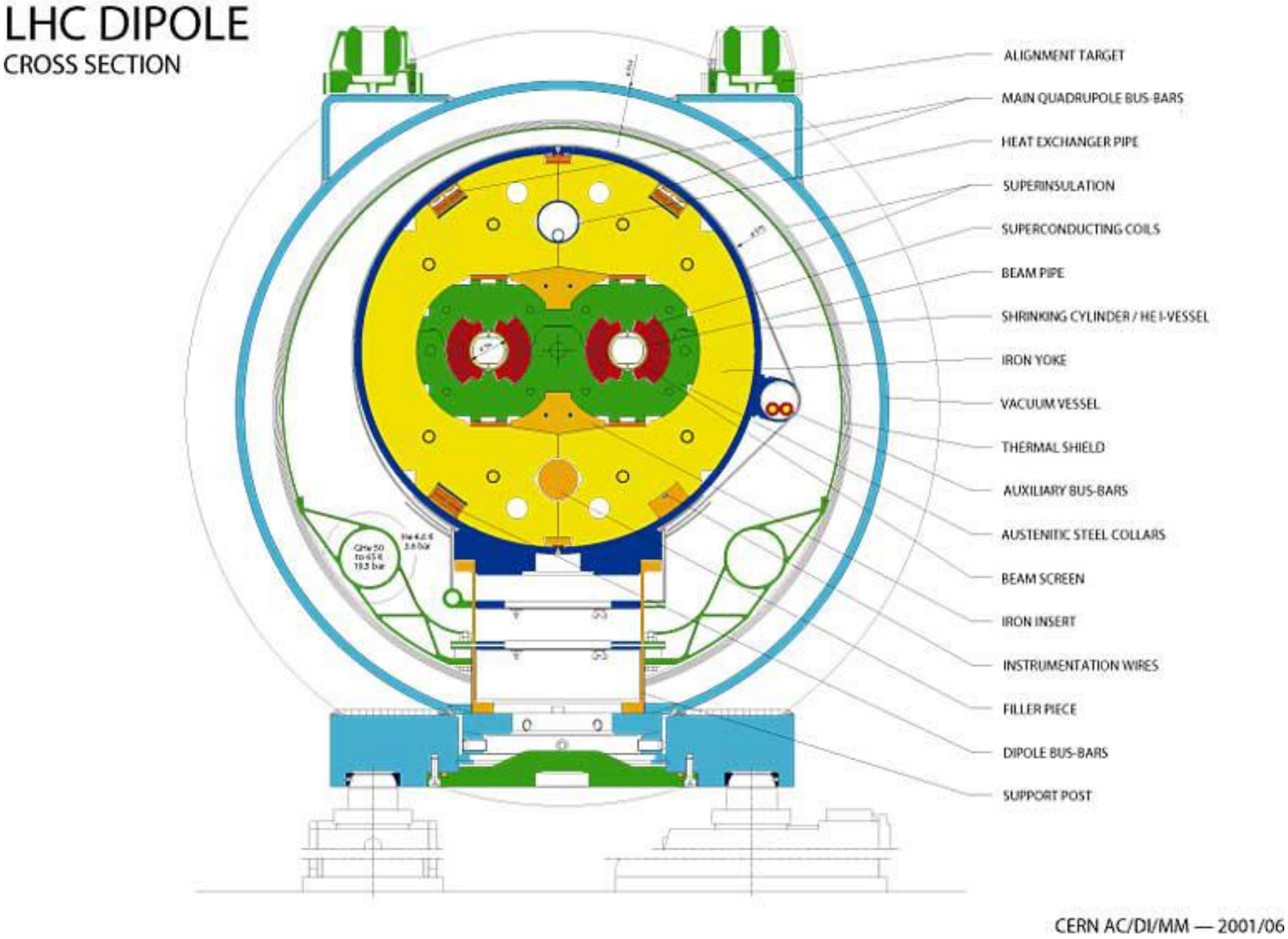
9 T & 4.6 km $\Rightarrow$ 14 TeV

Applications: detectors

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

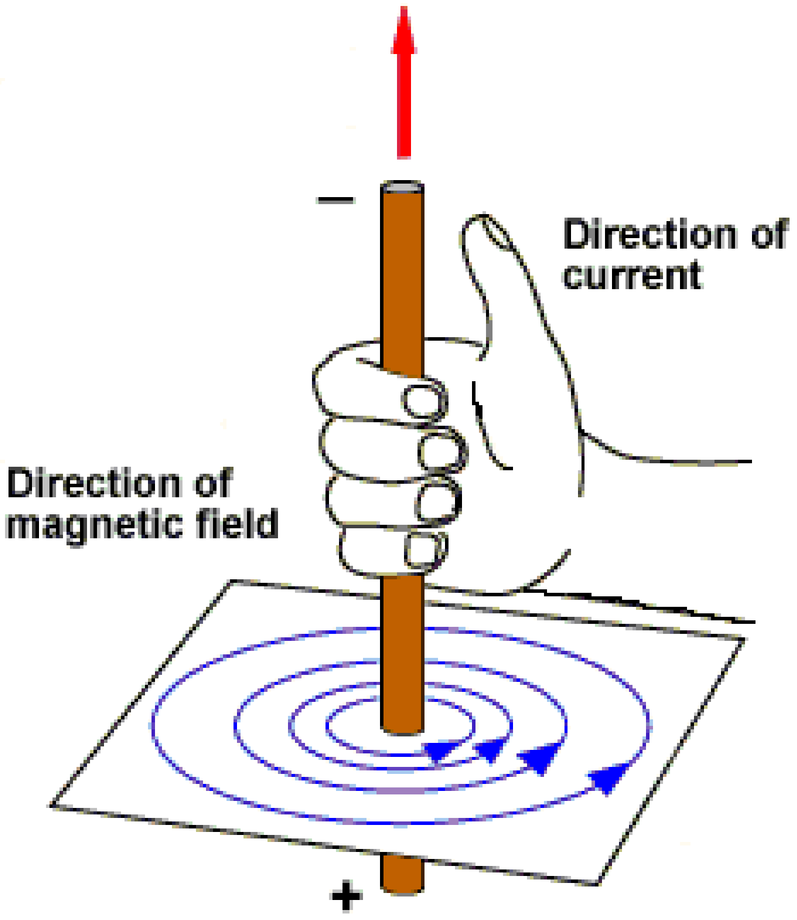


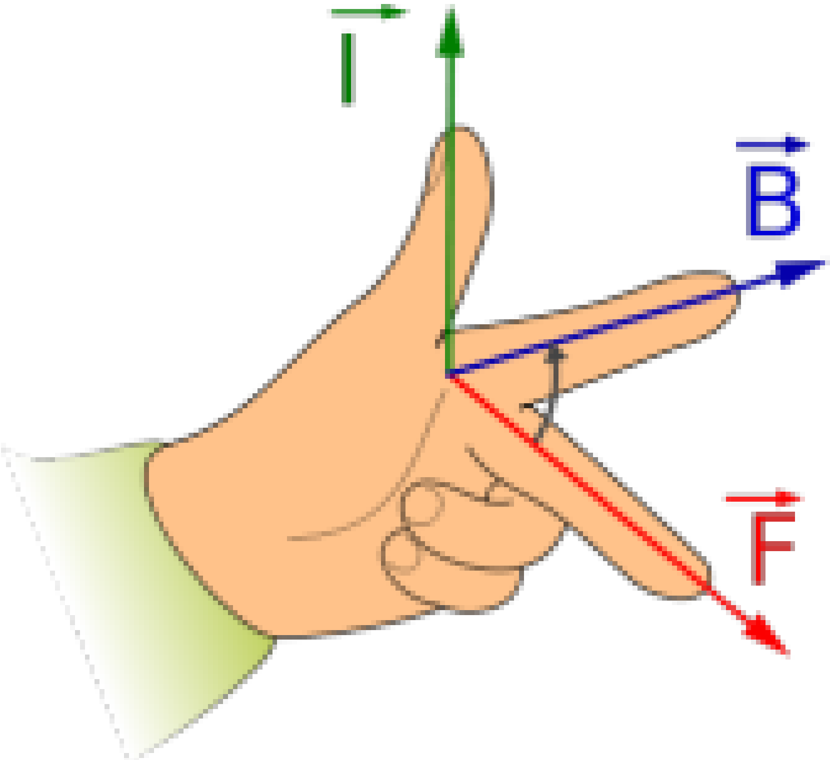
LHC magnets



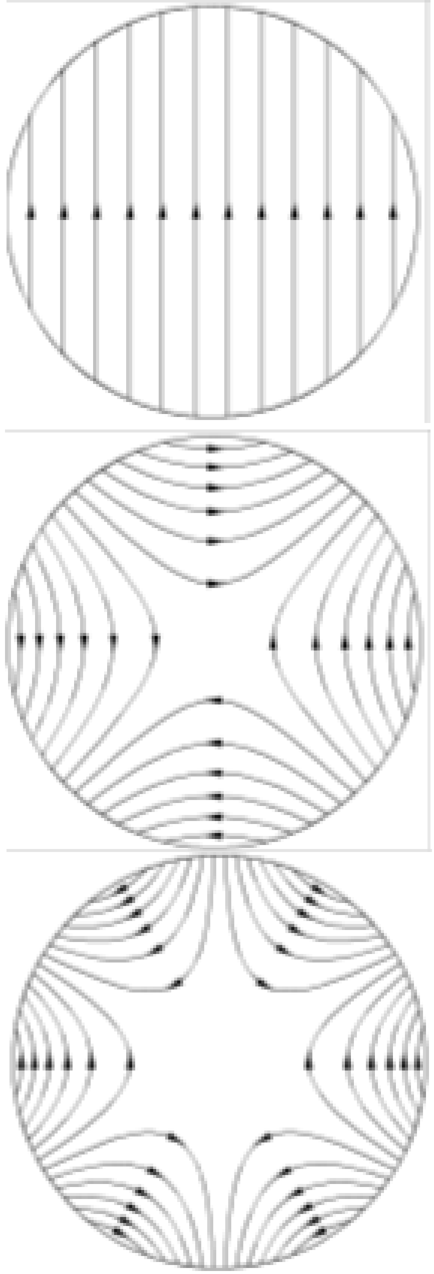
LHC DIPOLE
CROSS SECTION
ALIGNMENT TARGET
MAIN QUADRUPOLE BUS-BARS
HEAT EXCHANGER PIPE
SUPERINSULATION
SUPERCONDUCTING COILS
BEAM PIPE
SHRINKING CYLINDER / HE I-VESSEL
IRON YOKE
VACUUM VESSEL
THERMAL SHIELD
AUXILIARY BUS-BARS
AUSTENITIC STEEL COLLARS
BEAM SCREEN
IRON INSERT
INSTRUMENTATION WIRES
FILLER PIECE
DIPOLE BUS-BARS
SUPPORT POST
CERN AC/DI/MM — 2001/06

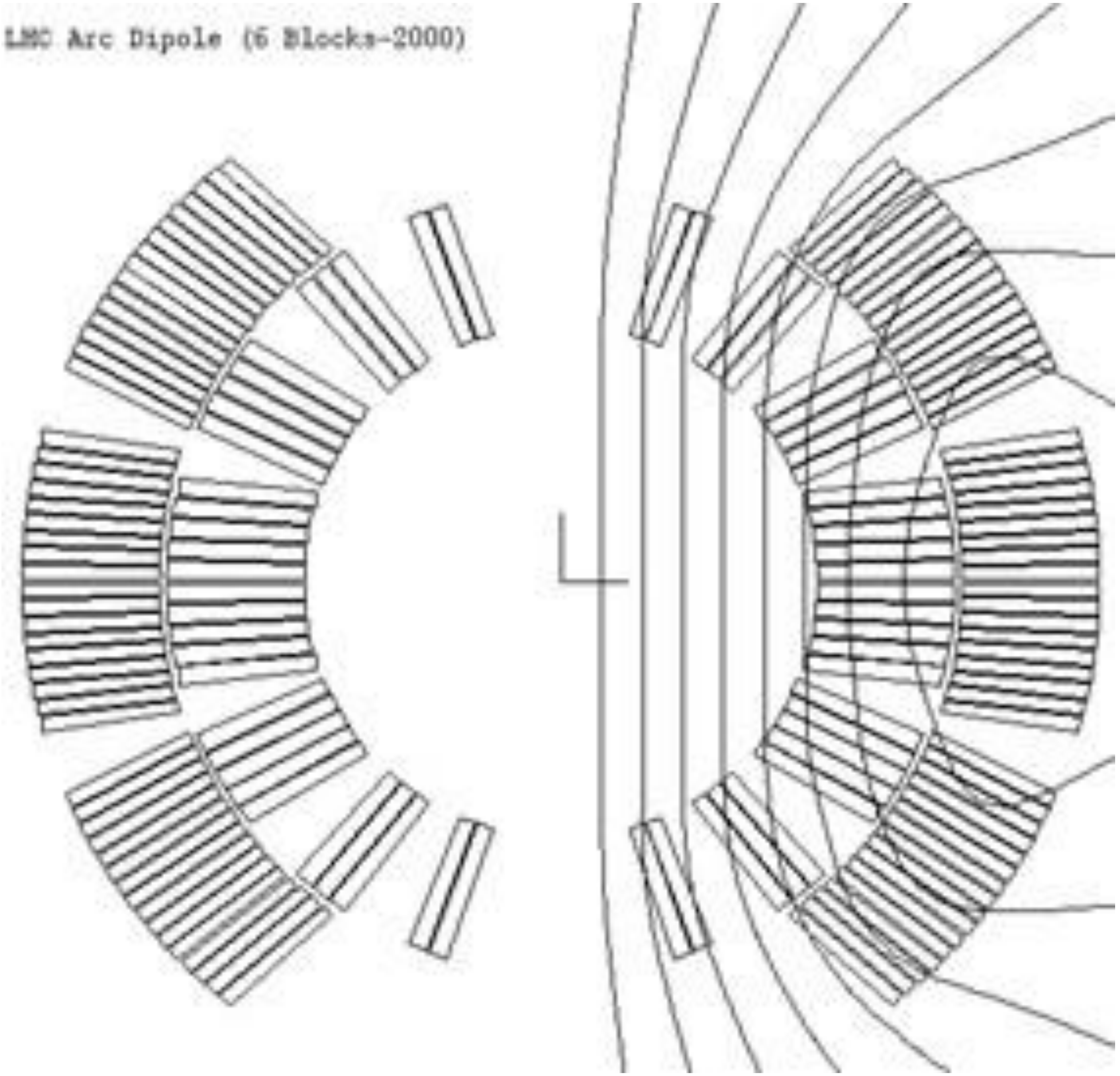
Oersted, Ampère, Biot-Savart



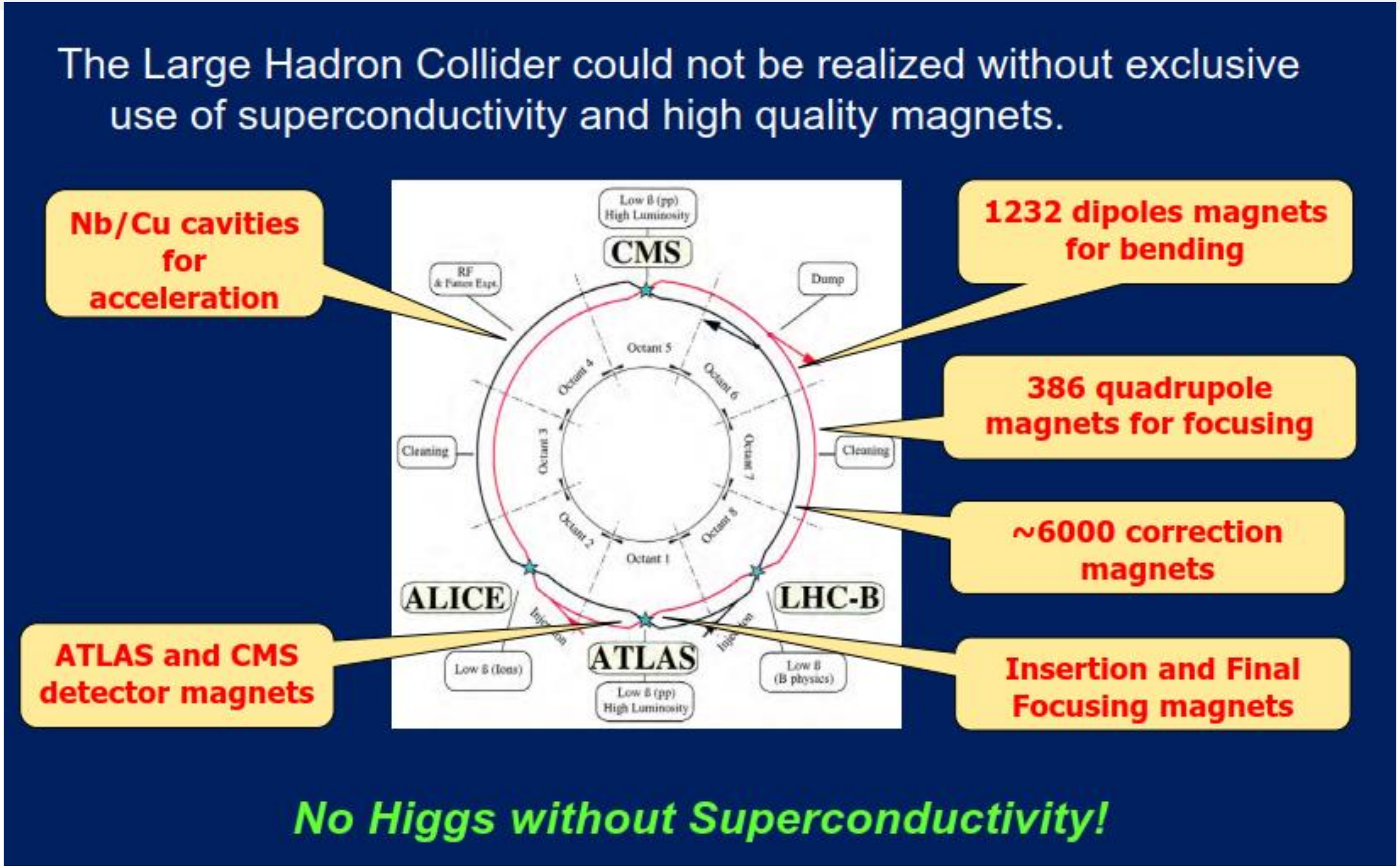


Bending and focussing



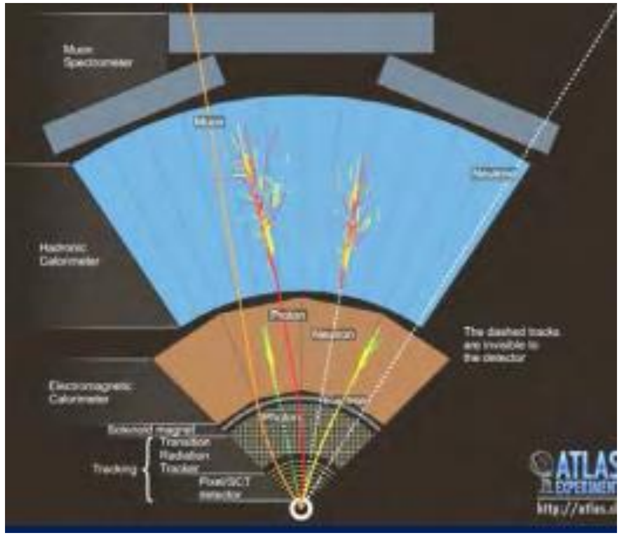


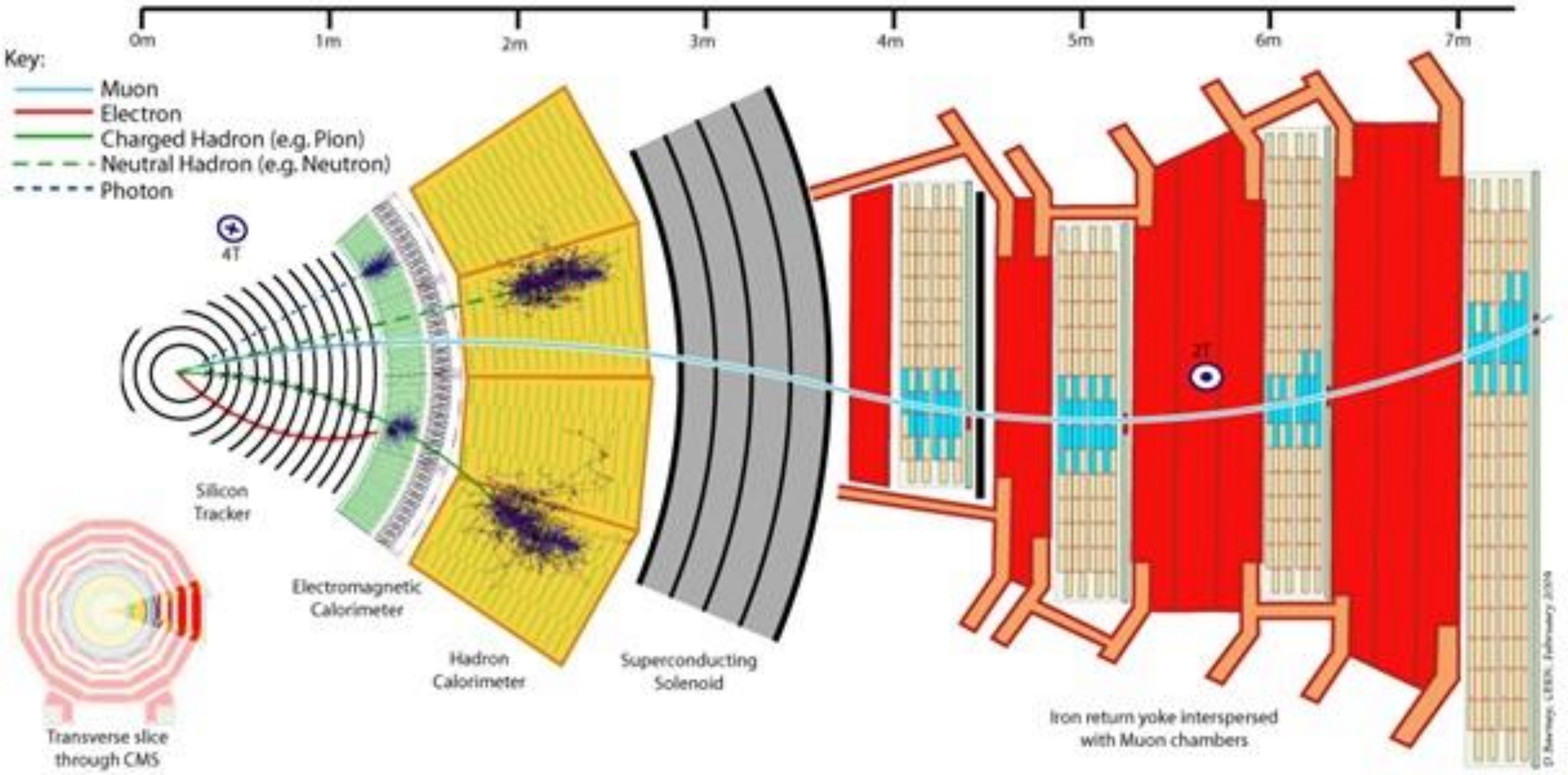
No superconductivity, no Higgs…



Fundamental physics questions require the need for new technologies…

CMS and ATLAS: fundamentally different magnets





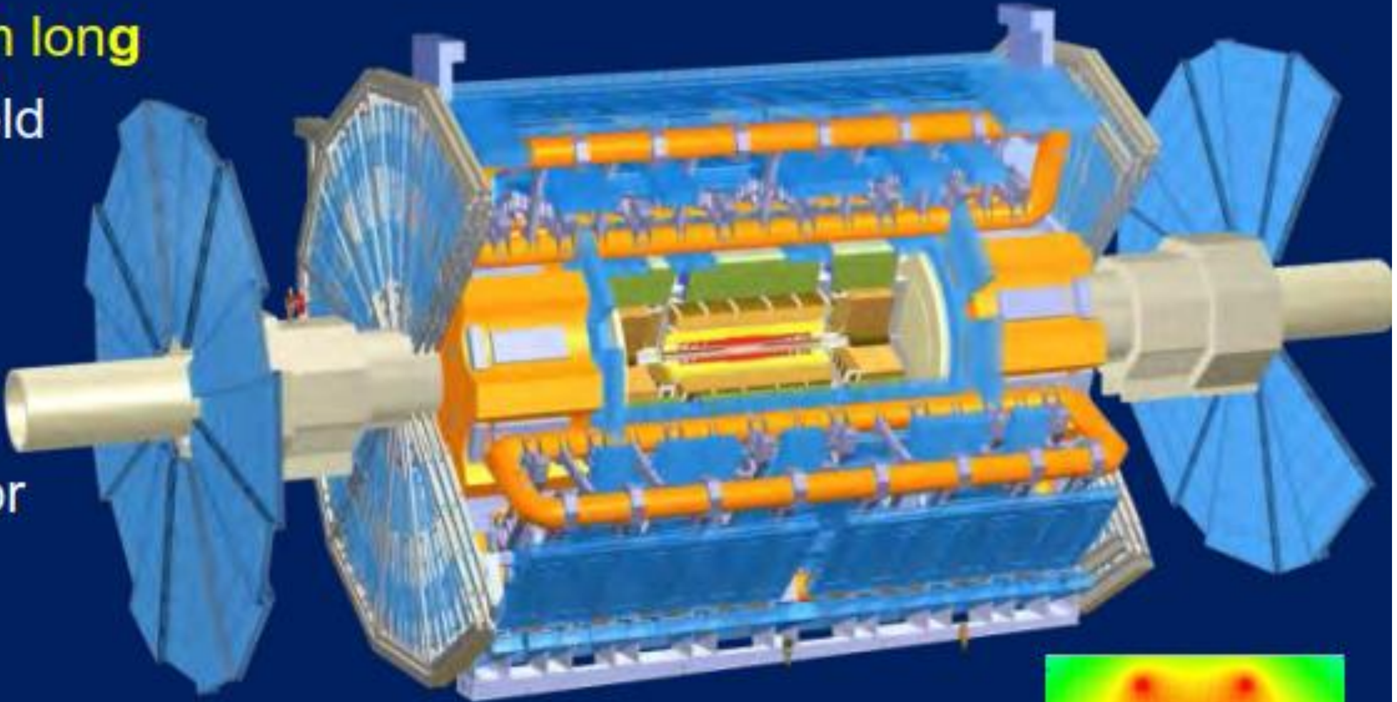
ATLAS: extreme use of superconductors

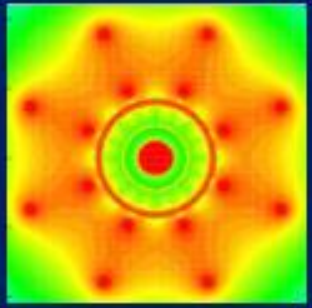
1 Barrel Toroid and 2 End Cap Toroids and 1 Central Solenoid
generate 2 T for the inner detector and ~1 T for the muon detectors

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

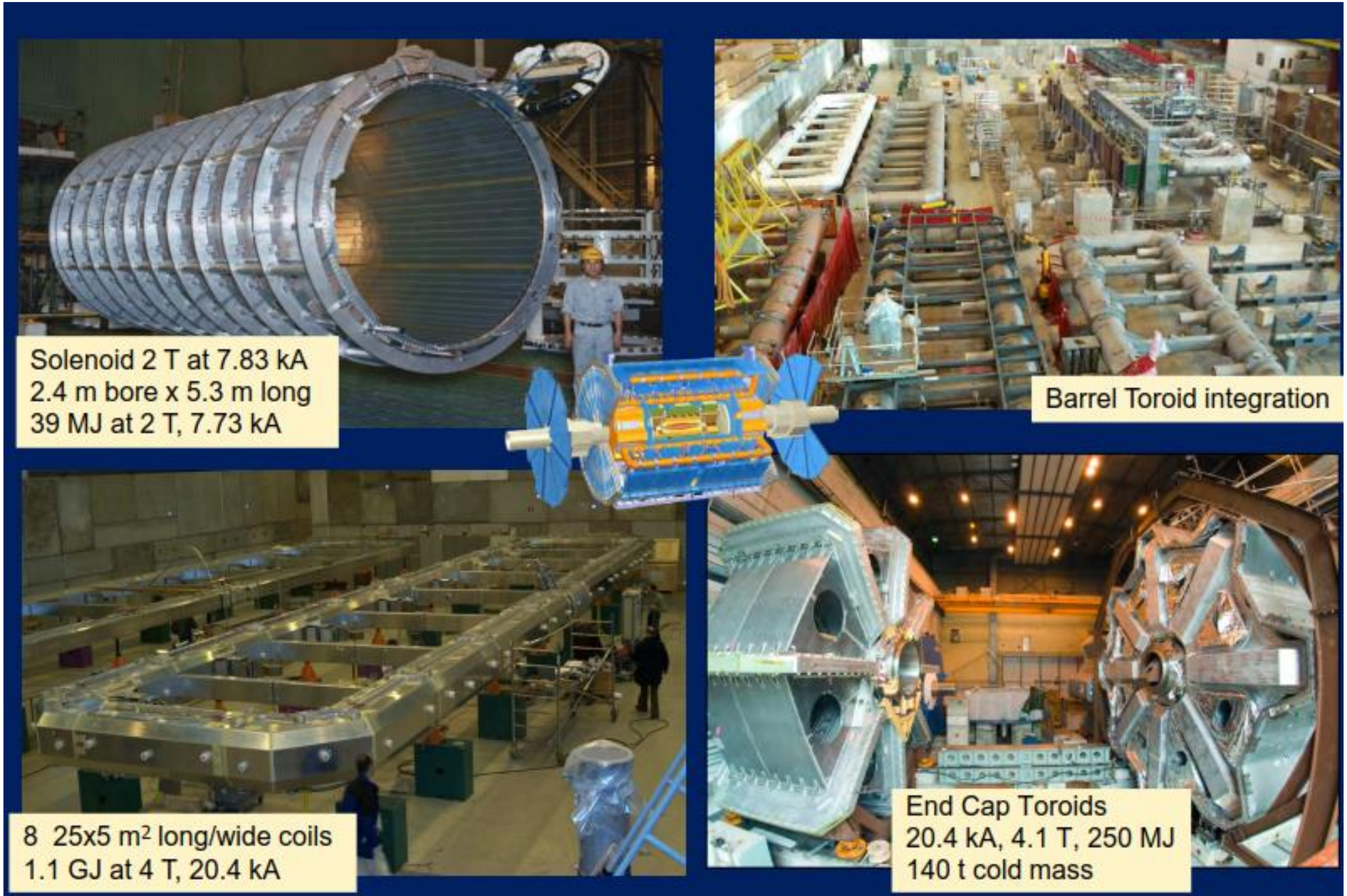
20.4 kA at 4.1 T
1.6 GJ stored energy
4.7 K conduction cooled
9 yrs of construction 1998-2007





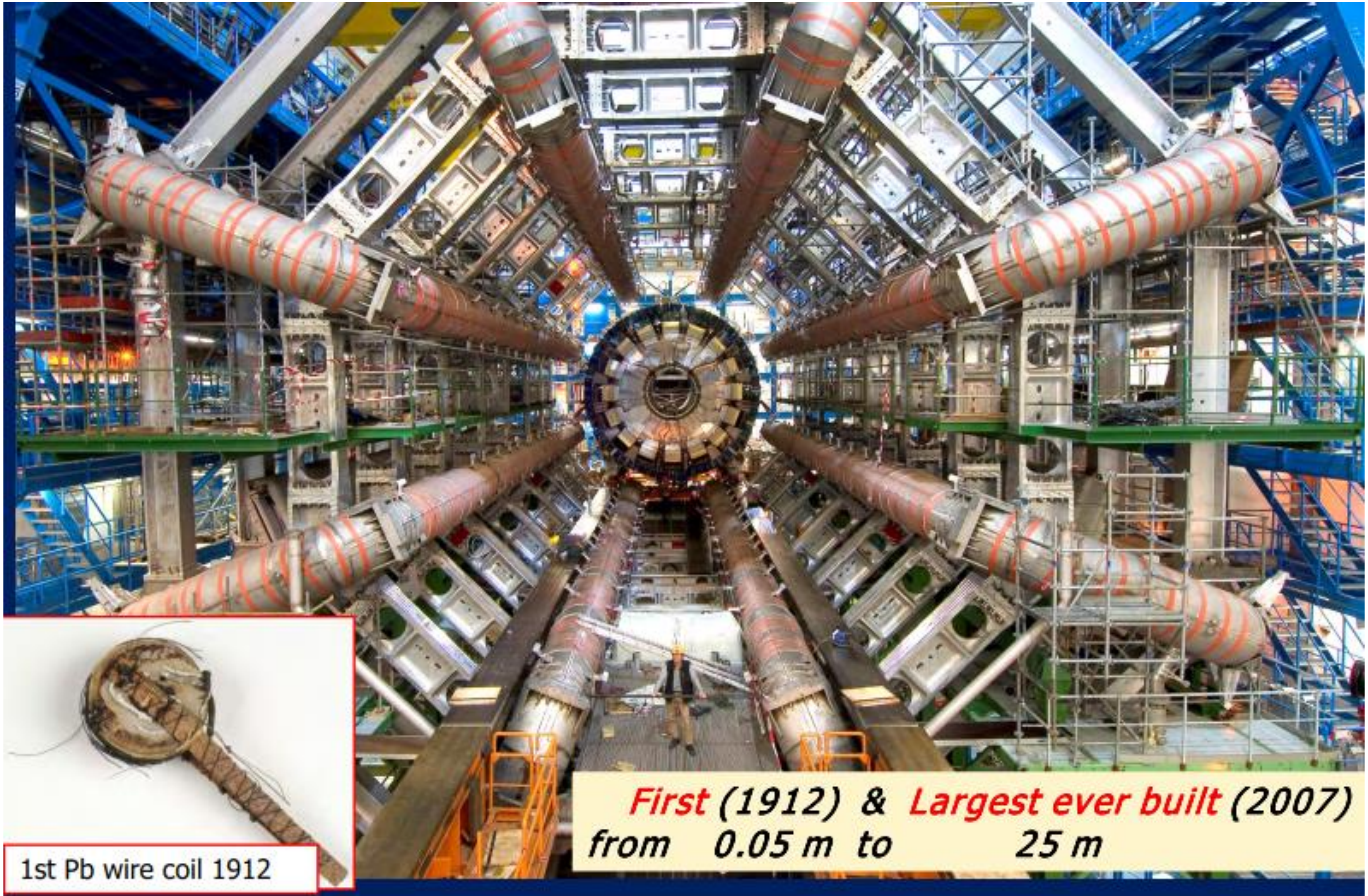
By far the largest trio of toroids ever built !

ATLAS subsystems



Transport of ATLAS magnets

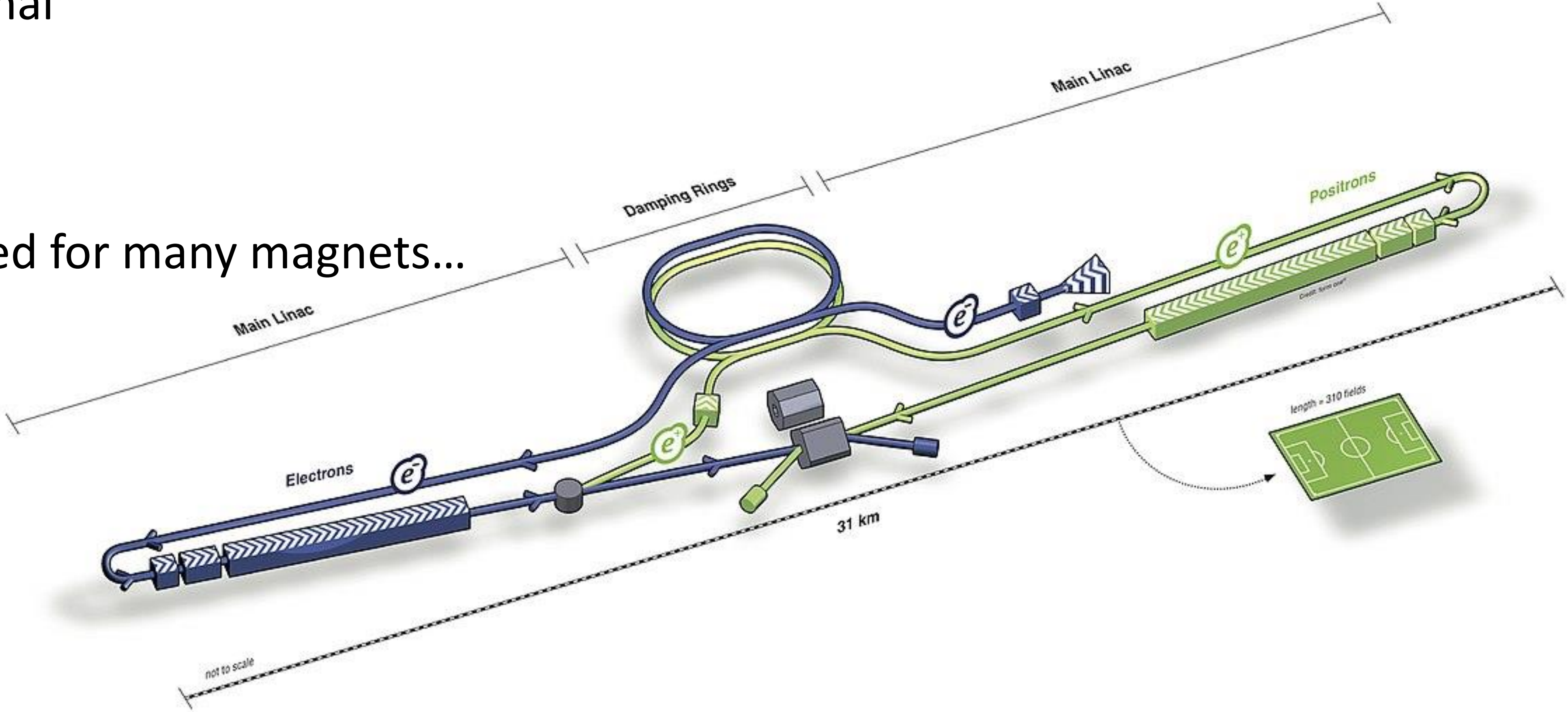
Applications: MRI



Possible accelerators of the future

ILC in Japan:
International
Linear
Collider

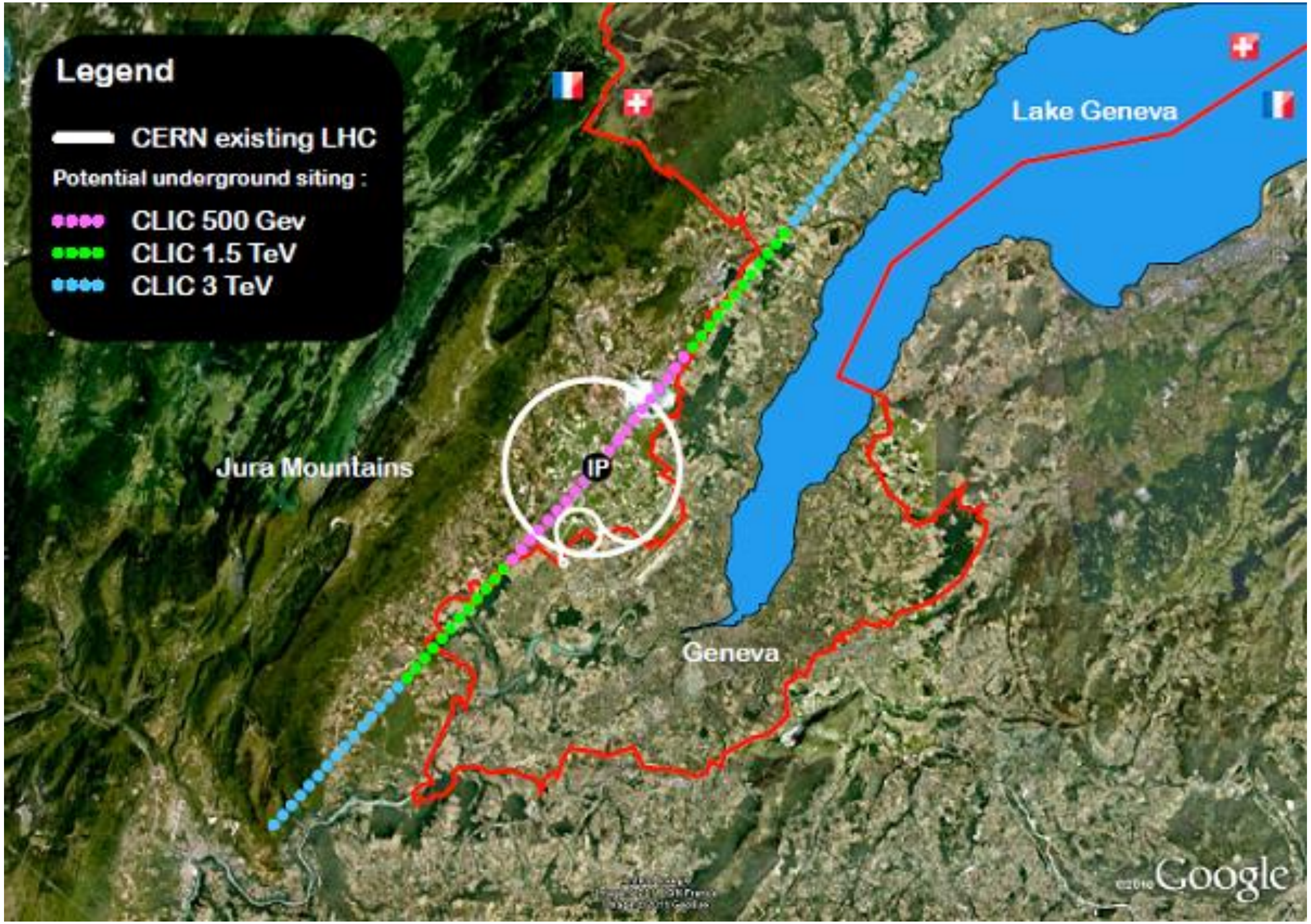
But no need for many magnets…



Possible accelerators of the future

<u>CLIC:</u>
Compact
LInear
Collider

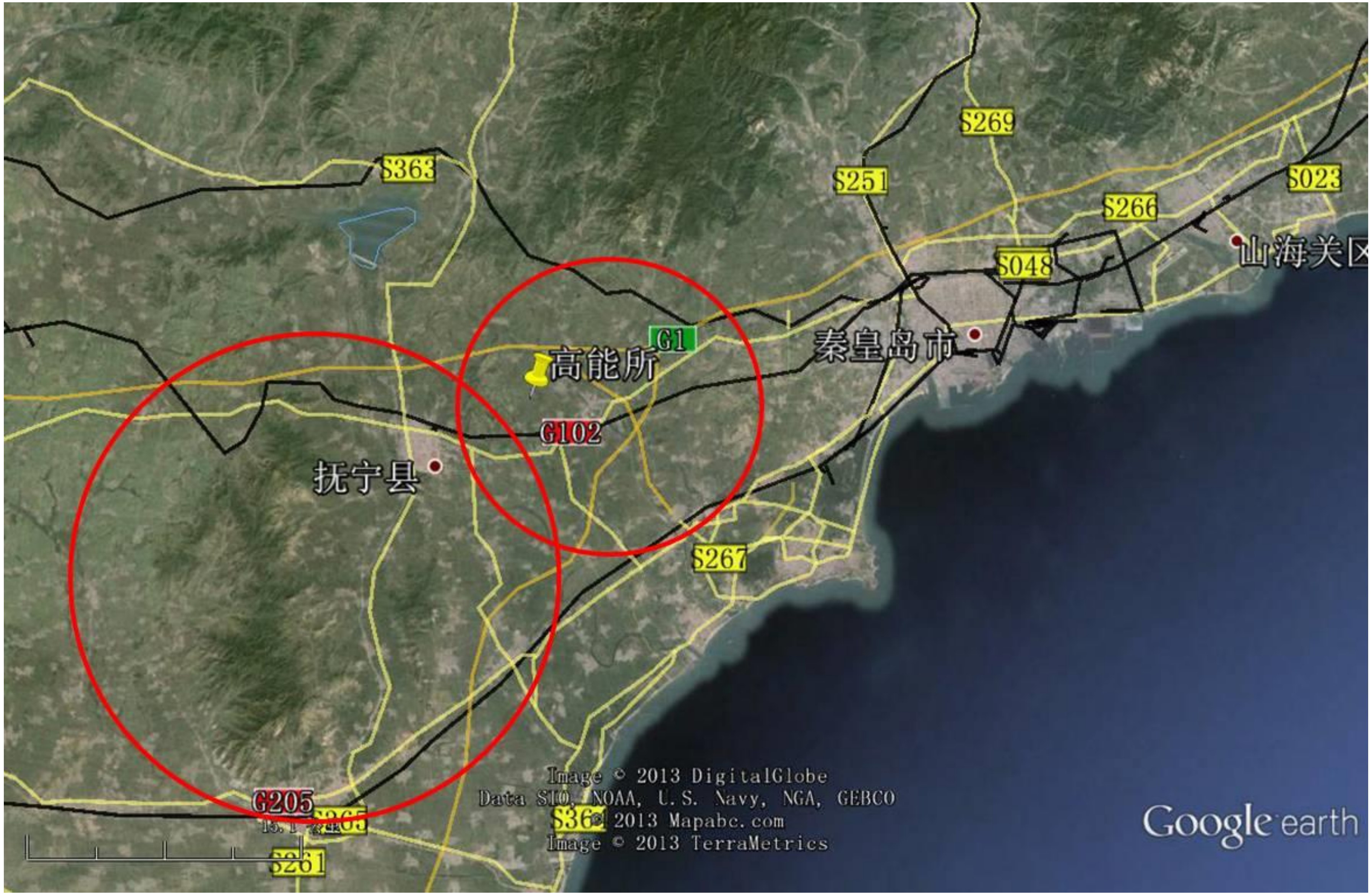
Yet again:
not many magnets required…



Possible accelerators of the future

<u>CepC/SppC in China:</u>
Circular
Electron
Proton
Collider

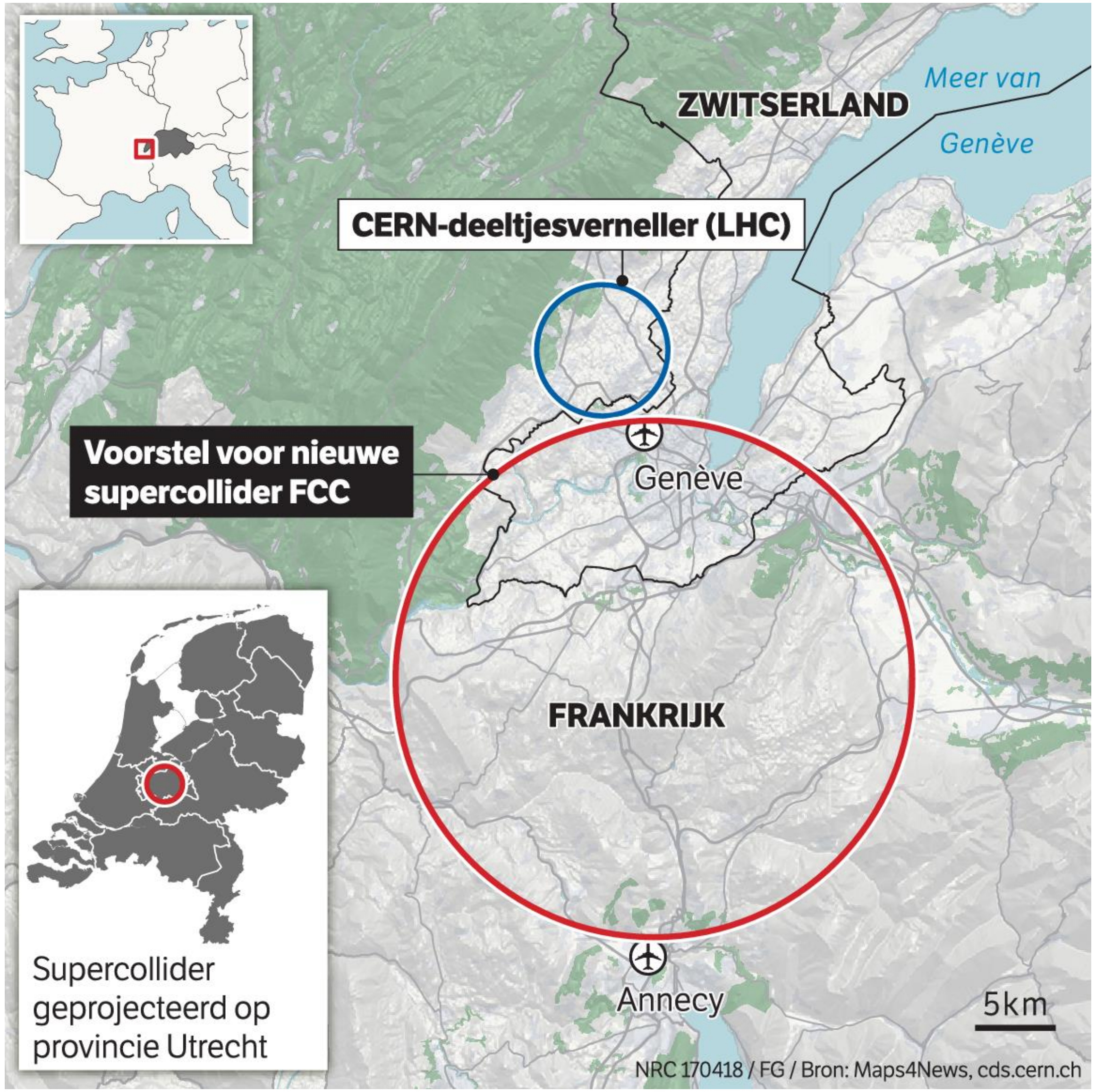
Super
Proton
Proton
Collider



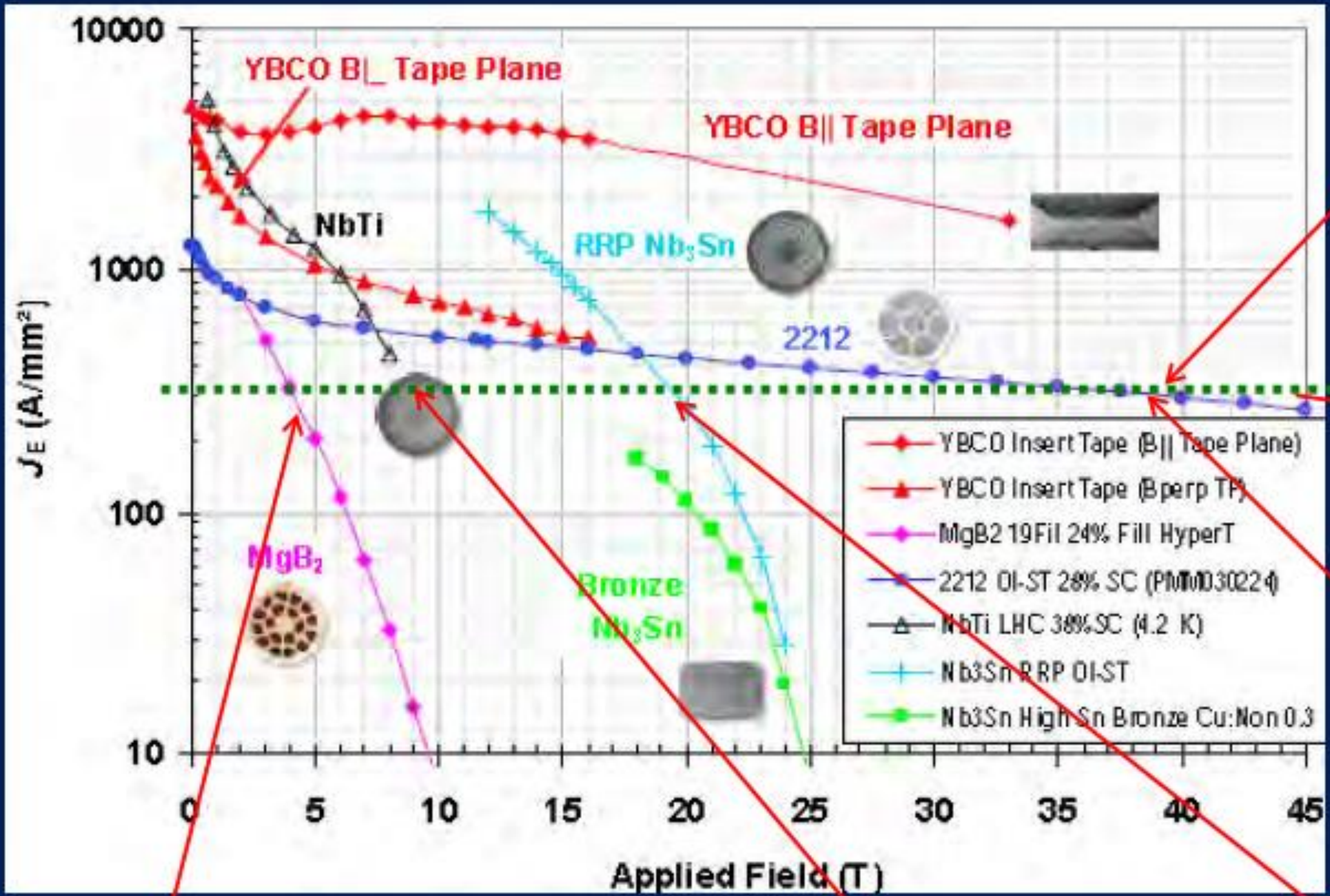
Possible accelerators of the future

FCC:
Future
Circular
Collider

100 TeV c.o.m.
100 km circumference
16 T magnets -> how?



Remember this one?



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

Minimum practical current density

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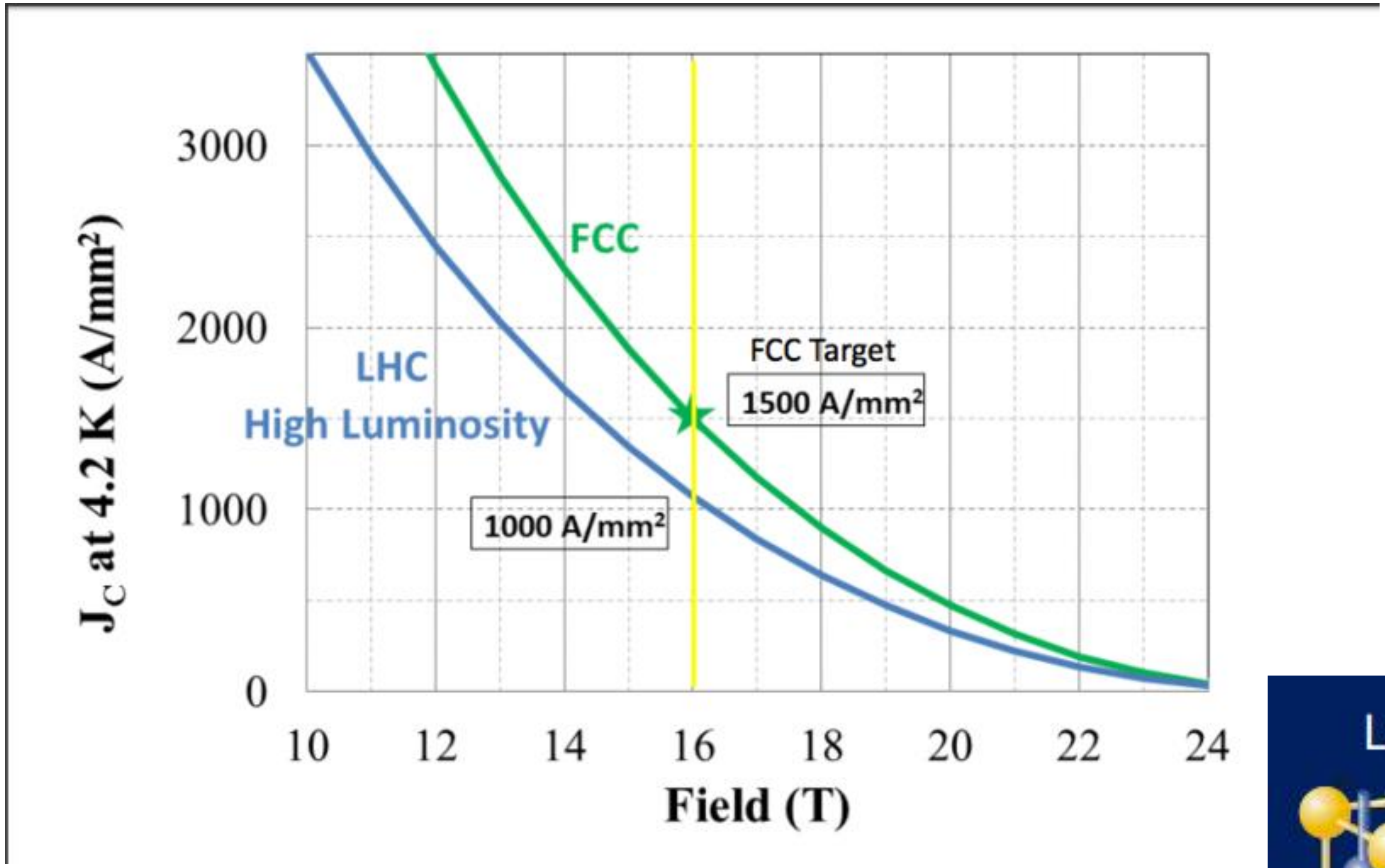
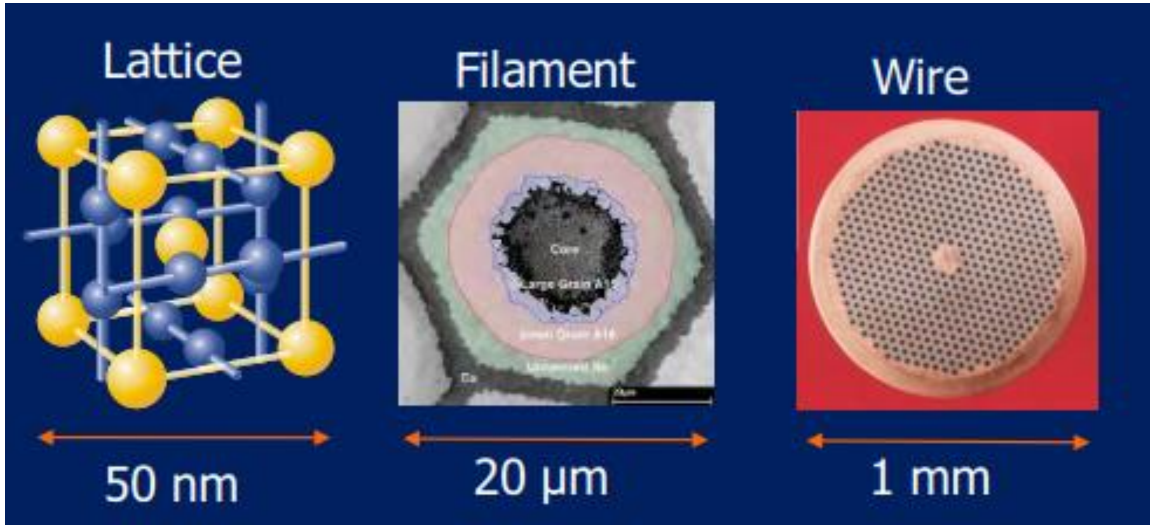
Nb_3Sn for magnets of 9-20 T

FCC target

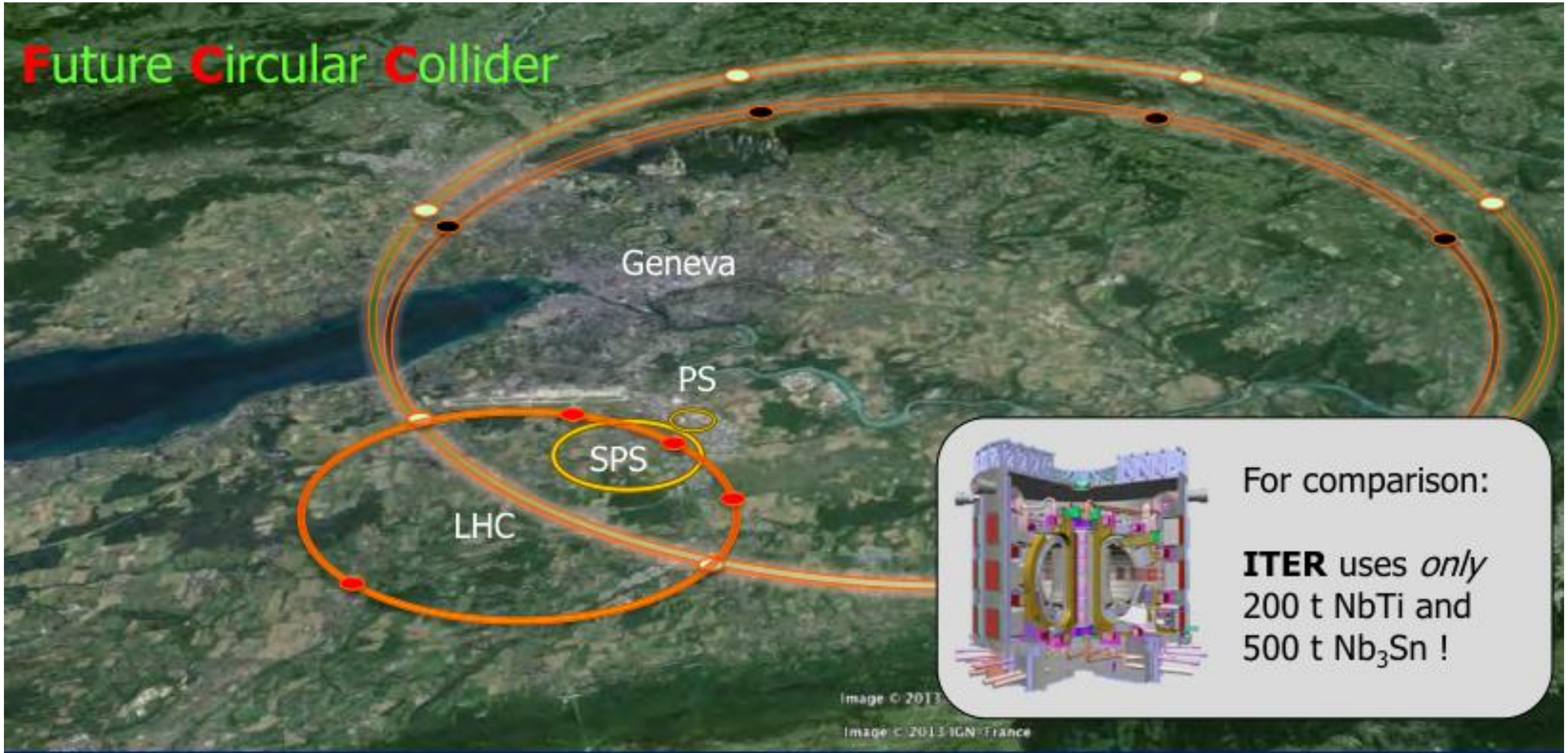


FCC
LHC
High Luminosity
FCC Target
1500 A/mm²
1000 A/mm²
Jc at 4.2 K (A/mm²)
Field (T)
3000
2000
1000
0
10
12
14
16
18
20
22
24



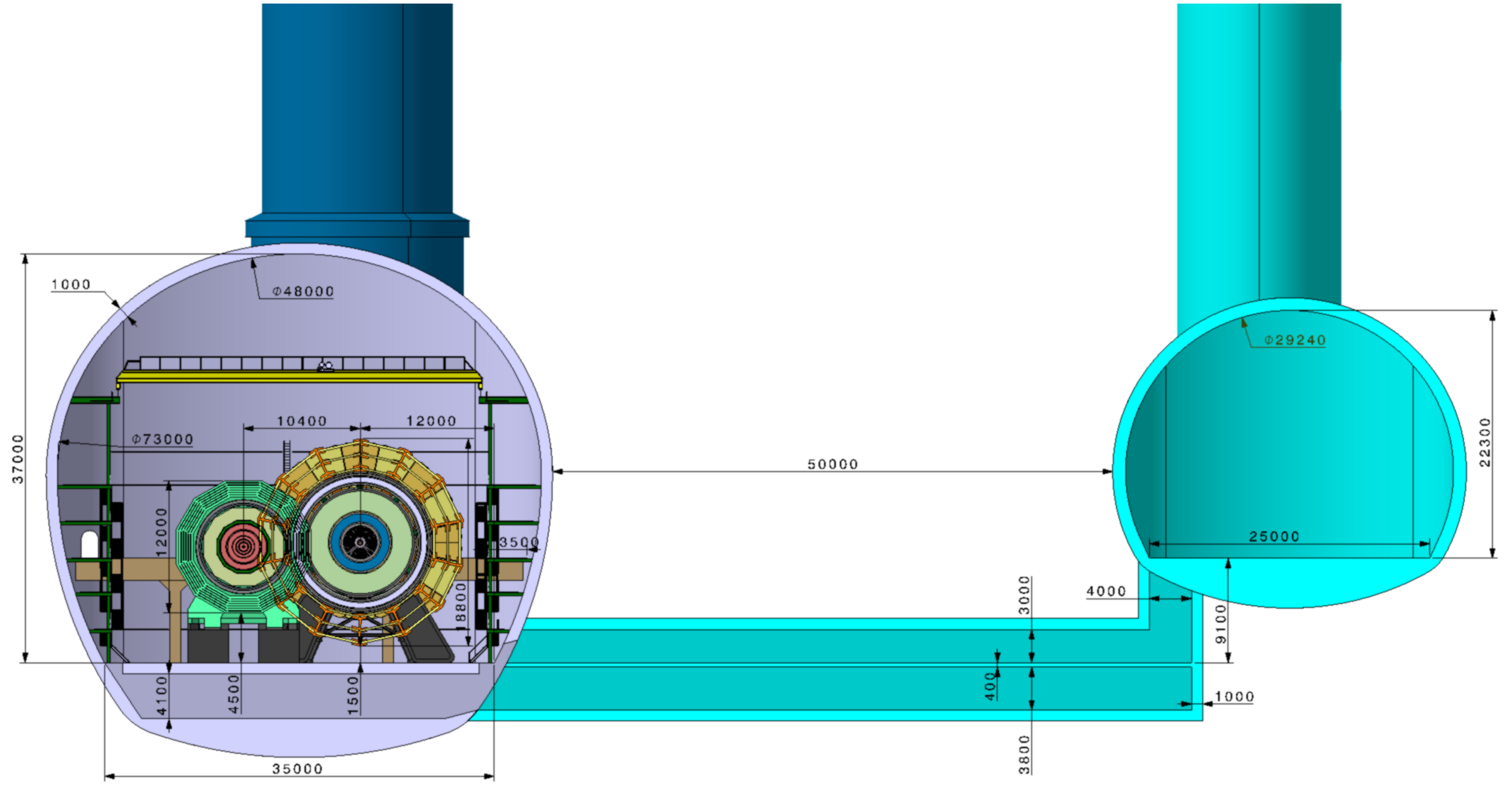
Lattice
Filament
Wire
50 nm
20 μm
1 mm

Upscaling of production

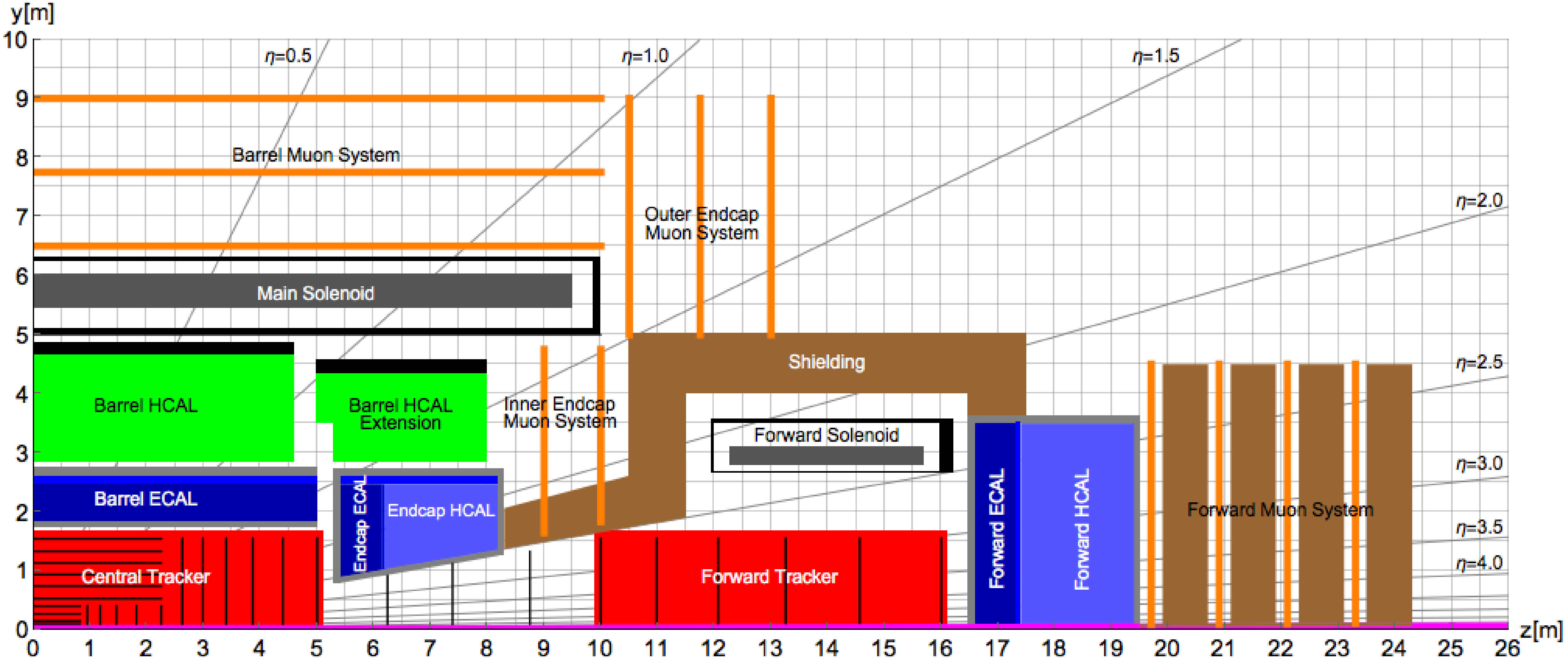


LHC	HE-LHC	FCC-hh	FCC-hh
27 km, **8.3 T**	27 km, **20 T**	80 km, **20 T**	100 km, **16 T**
14 TeV	33 TeV	100 TeV	100 TeV
1300 t NbTi	3000 t LTS	9000 t LTS	6000 t Nb_3Sn
0.2 t HTS	700 t HTS	2000 t HTS	3000 t Nb-Ti

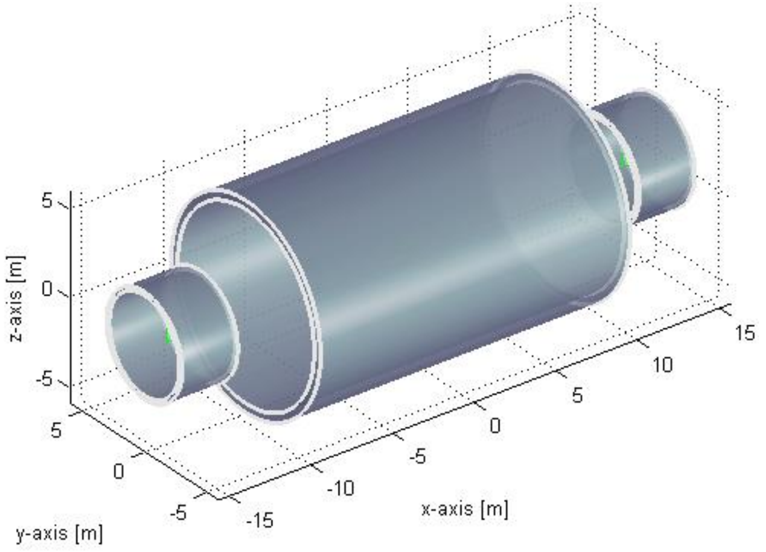
FCC-hh: cavern

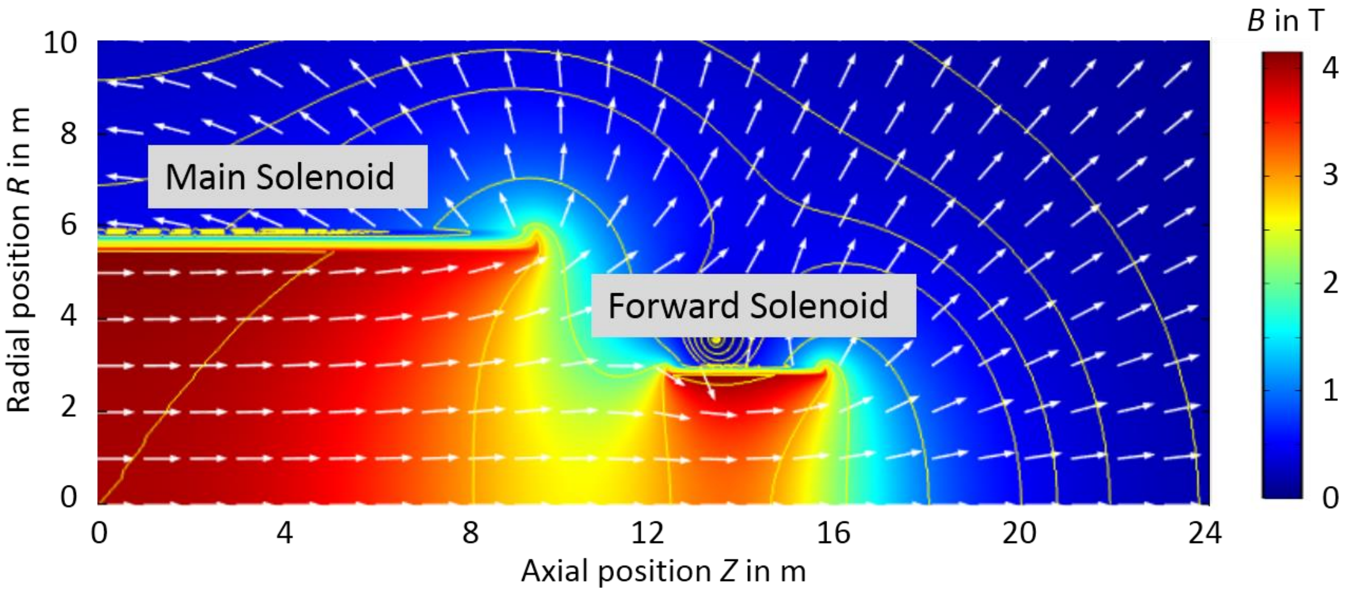


Possible future detector systems: FCC-hh



FCC-hh: baseline





Design:

- Main solenoid with 4 T in a 10 m free bore
- Forward **solenoids**, to **extend** the bending capacity for high eta particles
- Attractive force between solenoids need to be handled with tie rods (60 MN inwards)

Result:

- Relatively simple cold-mass structure, a scaling-up of existing and proven designs
- Stored energy: 13.9 GJ
- Significant stray field in main cavern, since no return yoke, nor shielding coil present (cost reduction)

Possible future detector systems: FCC-hh