50 years of Superconducting Magnets for Physics Research and Medicine

Herman ten Kate

- Kamerlingh Onnes and magnets
- Understanding superconductors
- From materials to magnets
- Examples of Applications:
  Lab magnets, NMR, MRI, Accelerators, Fusion, Maglev
- Conclusion

EUCAS ISEC ICMC
Superconductivity Centennial Conference

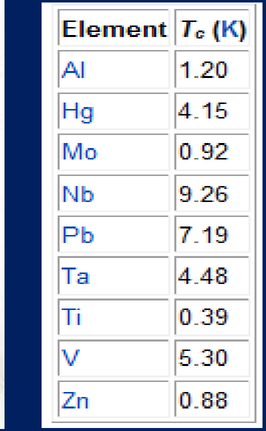
Disappointing first magnets

Kamerlingh Onnes had a vision to build a 100 kGauss magnet

3rd International Congress of Refrigeration, Chicago in 1913

1853-1926

1st Pb wire coil 1912

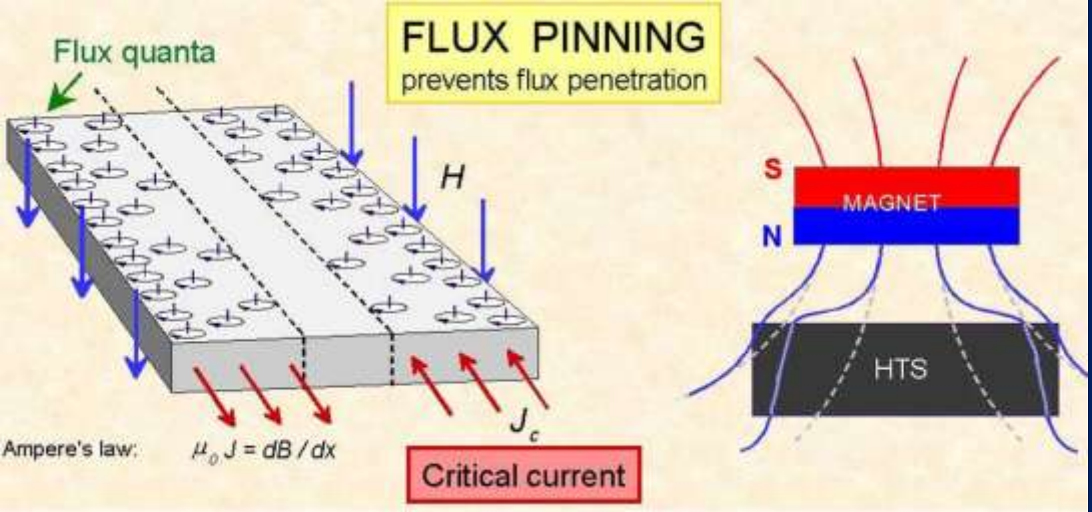


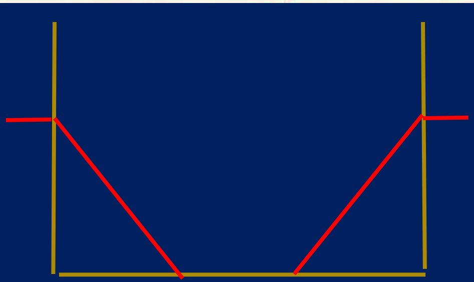
Element	***T*c (K)**
Al	1.20
Hg	4.15
Mo	0.92
Nb	9.26
Pb	7.19
Ta	4.48
Ti	0.39
V	5.30
Zn	0.88

"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 magnets from elements fell flat………, and it took 40 years to understand, 1960s

Flux lines and Flux pinning





Flux quantum Φ_0= h/2e= 2.1x10^{-15} Wb

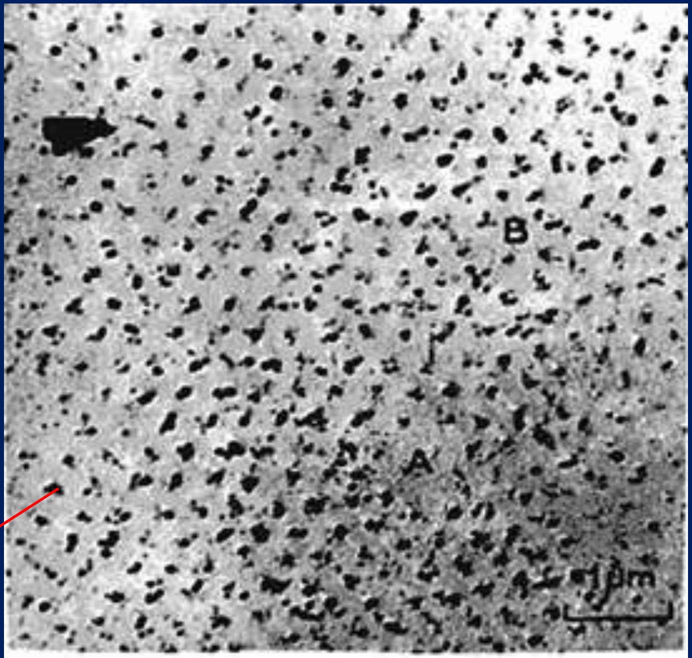


Fig. 2. Flux line lattice on the surface of a lead-4at% indium rod at 1.1°K showing a high density of defects in the flux line lattice (A: Hole. B: Flux line dislocations).

Maxwell: $rot\ B = \mu_o J = Jc$

Need a gradient in B to carry a current

And a very high gradient in a good superconductor for magnet application

Observation of real flux lines in Pb-4at%In in 0.3T magnetic field, clusters of Co particles showing lattice of flux quanta

Essmann & Träuble, 1967

Increase Flux pinning ---> raising Jc

X

Flux lines:

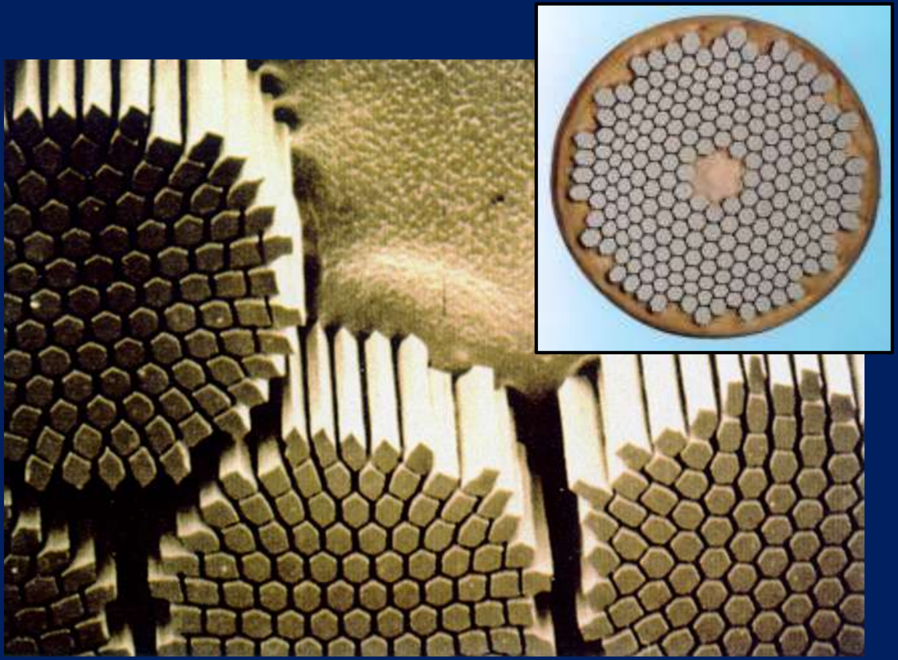
- Are exposed to Lorentz force JxB, need to be pinned, otherwise they move, meaning dB/dt and thus losses, effective resistance!

Recipe:

- Study the micro structure and fill the superconductor with pinning centers in a pattern that matches the flux line lattice -> high critical current

Precipitates in alloys

Microstructure of Nb-Ti



Fine NbTi filaments in a wire

Why to use superconductivity in magnets ?

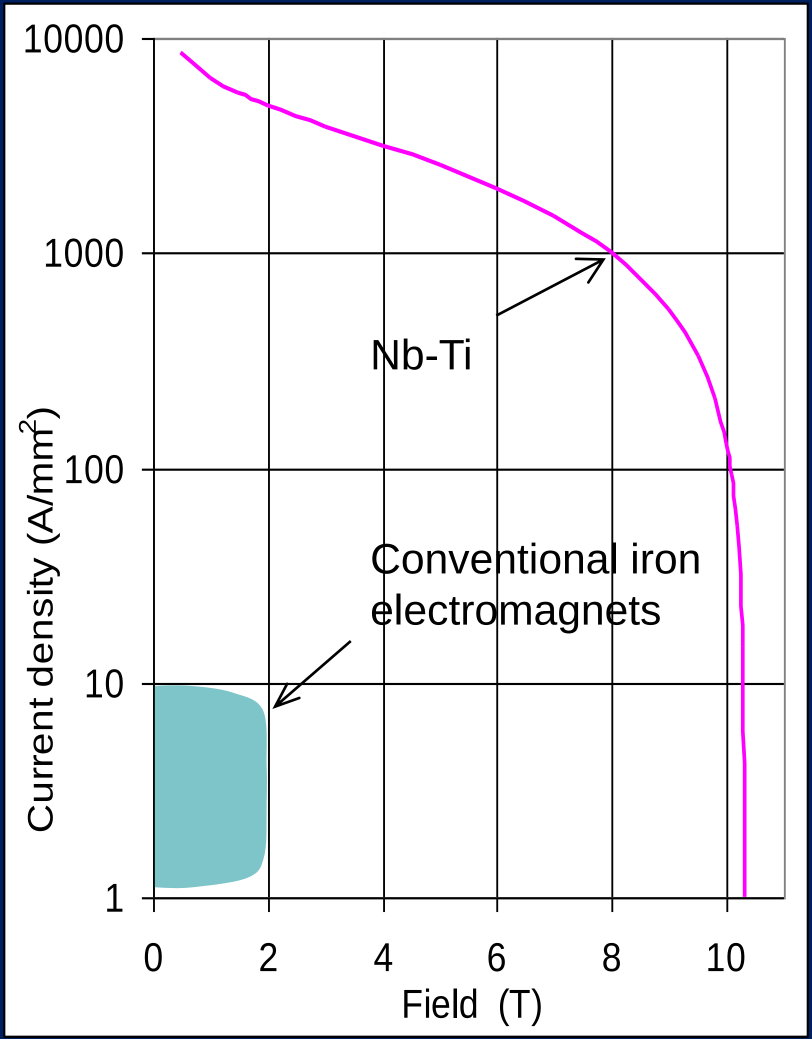
Use of zero resistance

- no power consumption of coil,
  but pay for the refrigeration power
- use high current density, compact

Consequences

- lower running cost enabling up new commercial possibilities
- high current density
  --> smaller, lighter, cheaper, reduced capital cost
- higher magnetic fields feasible
  --> new research possibilities, new physics in high magnetic field

Steady magnetic field >2T
in volumes of >1L

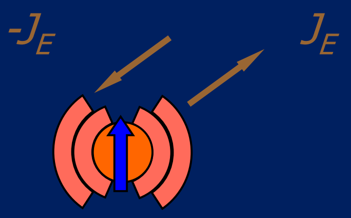


High current density - dipoles

Magnetic field produced by an ideal dipole is:

$$B = \mu_o J_e \frac{t}{2}$$

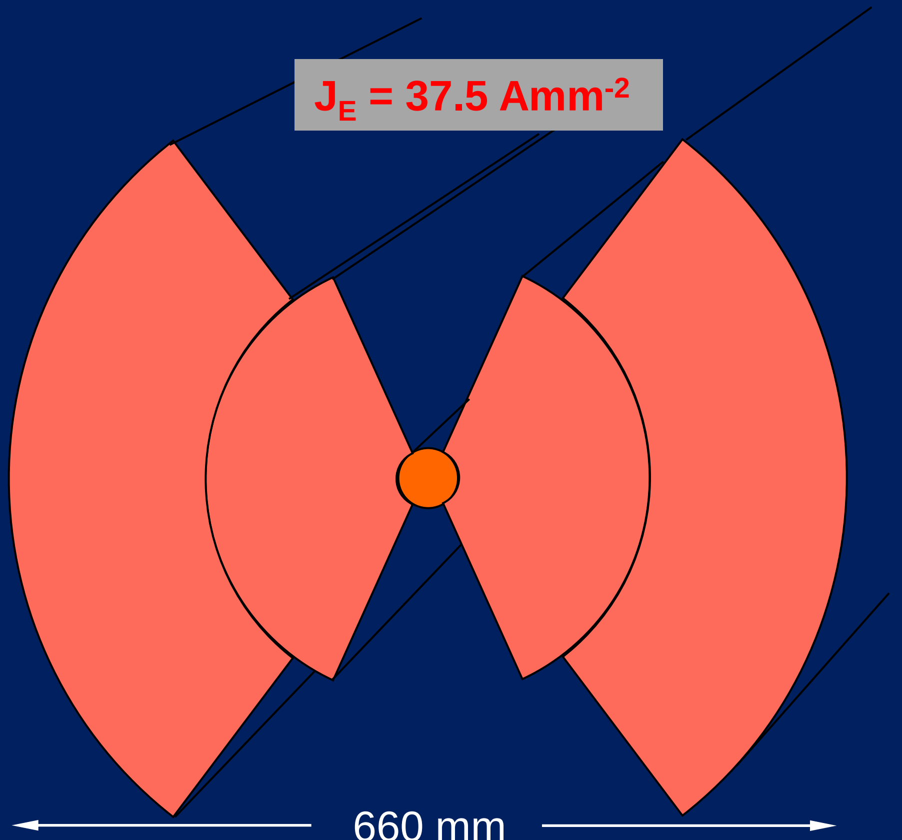
LHC dipole case



J_E = 375 Amm^{-2}

120 mm

950 kA-turns



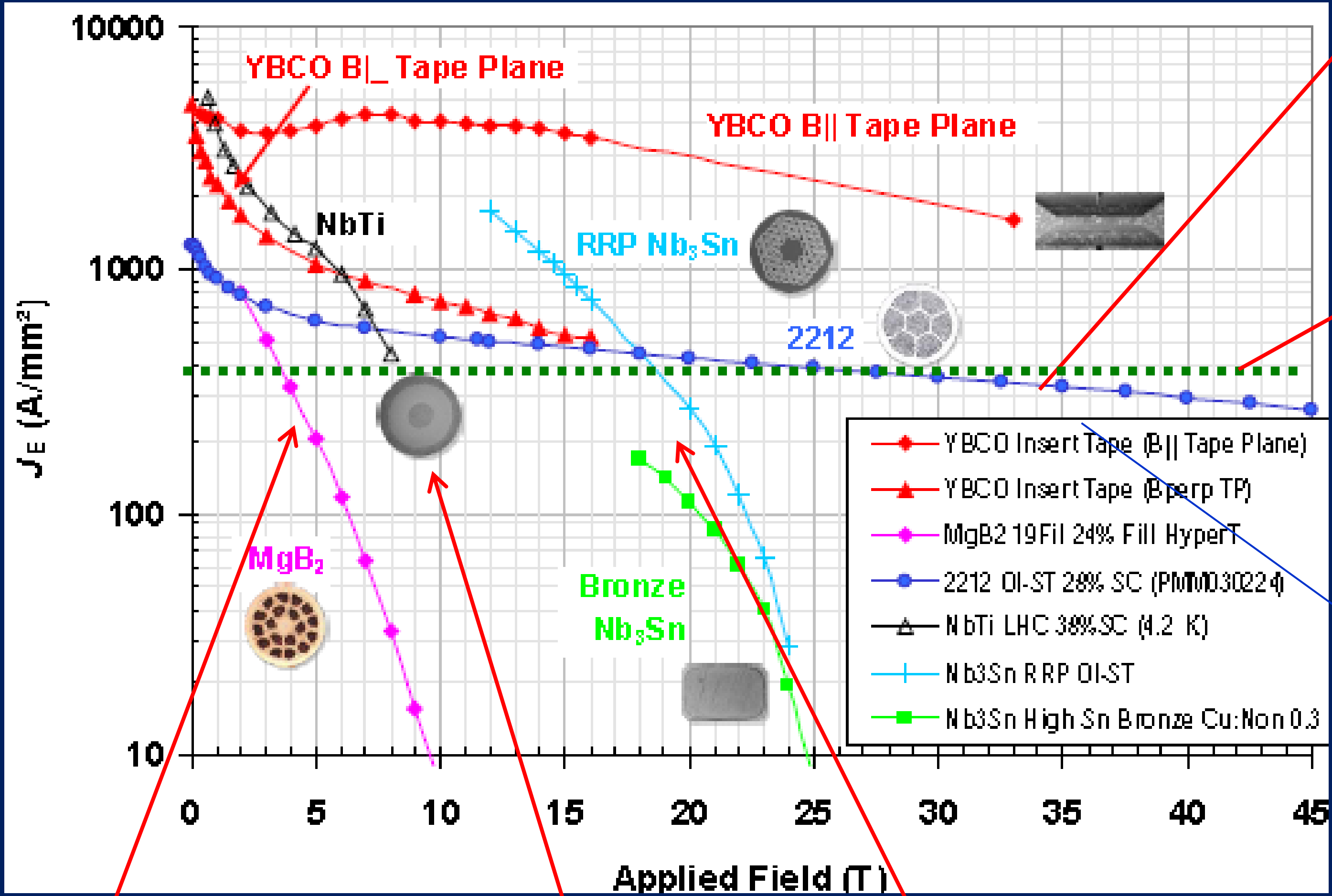
J_E = 37.5 Amm^{-2}

660 mm

9500 kA-turns

---> An LHC dipole is not be possible with normal conductors

Superconductors for magnets



Y123 in a magnet, not in // field !

Minimum practical current density

B2211 may do better than Y123 when anisotropy is considered

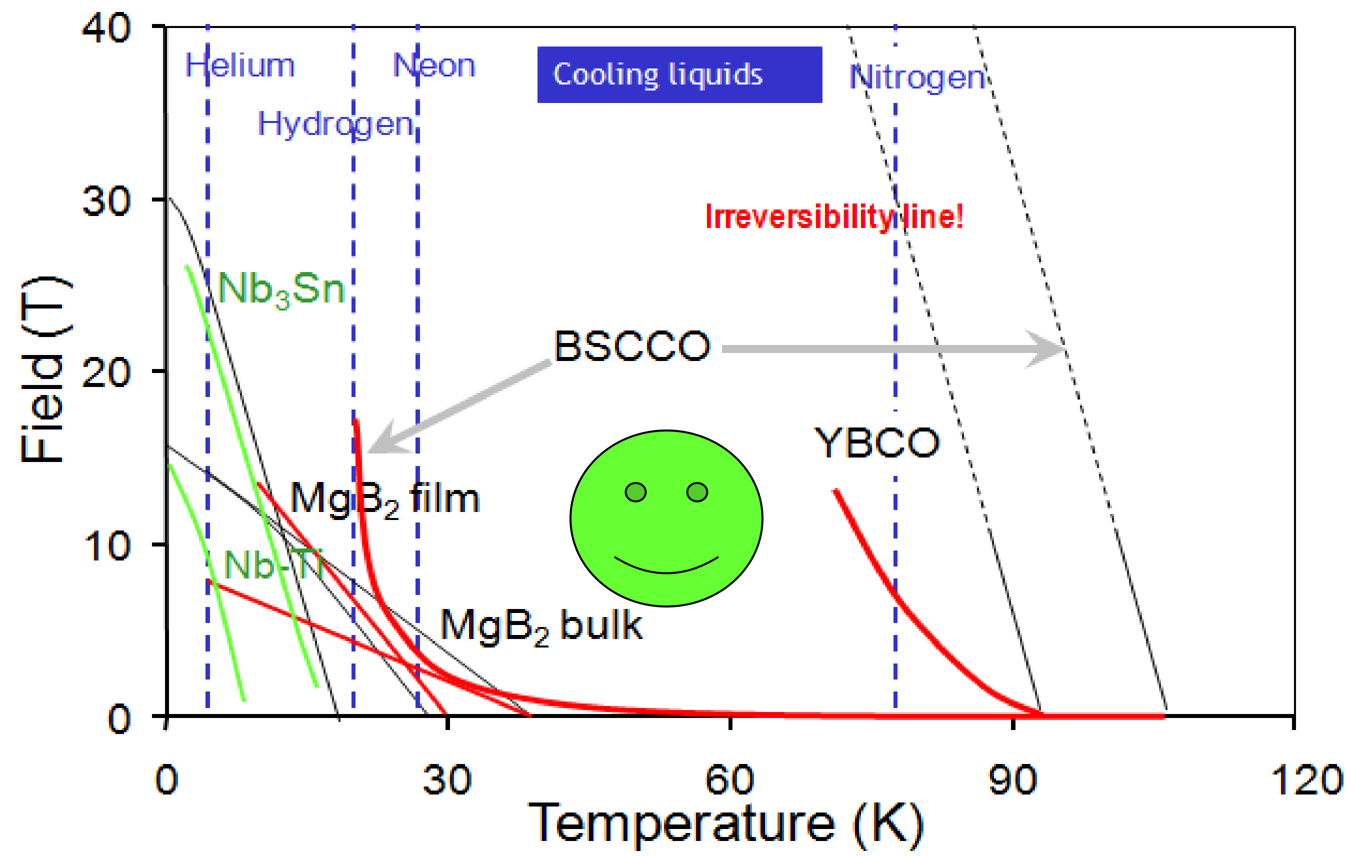
MgB$_2$ not for high field magnets but niche market 1-5T, 4-20K

NbTi
for high field up to 9 T and 4 K and 11T at 1.8 K

Nb$_3$Sn
for any magnets of 9-20T

B2212 or Y123
for DC magnets of 17-40T provided cost comes down

The unique opportunity of YBCO……if…..



Today, the only superconductor enabling 1-20 T magnets to work at 40-60 K, free of He, conduction cooled, very stable

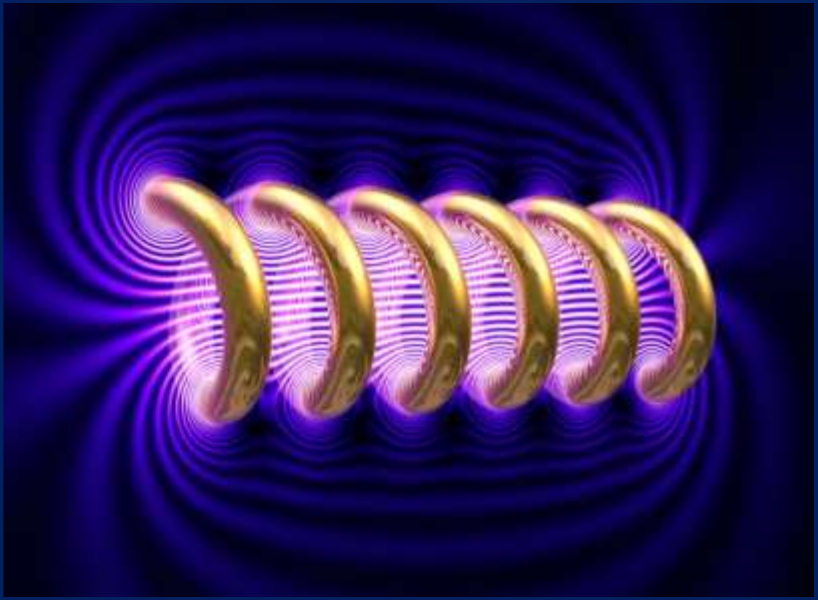
But how to make large high field magnets from 200 A tapes and how to get the material cost down from ~200 to ~5 €/kAm……

Why magnets require High Current and Cables

Magnetic field and stored energy

$B \propto N.I$ $E \propto B^2.Volume$

Inductance $L \propto N^2$



- Need safe survival from a quench
- Energy dump within short time before conductor burns out

--->Thus low N, high current I

Also $I_{safe} \propto J.E/V_d$, kV-range for V_d , with usual current densities this leads to 10-100 kA

- Given strand currents of typically 100 to 500A, we need for large scale magnets multi strand cables of 20-1000 strands,

  No escape!

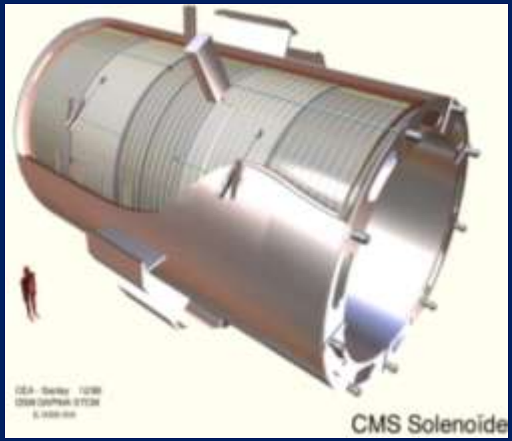
Scaling $I_{safe} \propto J \times B^2 \times Volume$

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

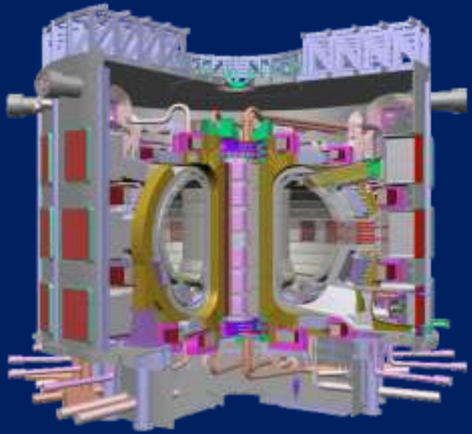
2 m^3 MRI magnet
200-800 A @ 1-3 T, ~10 MJ

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

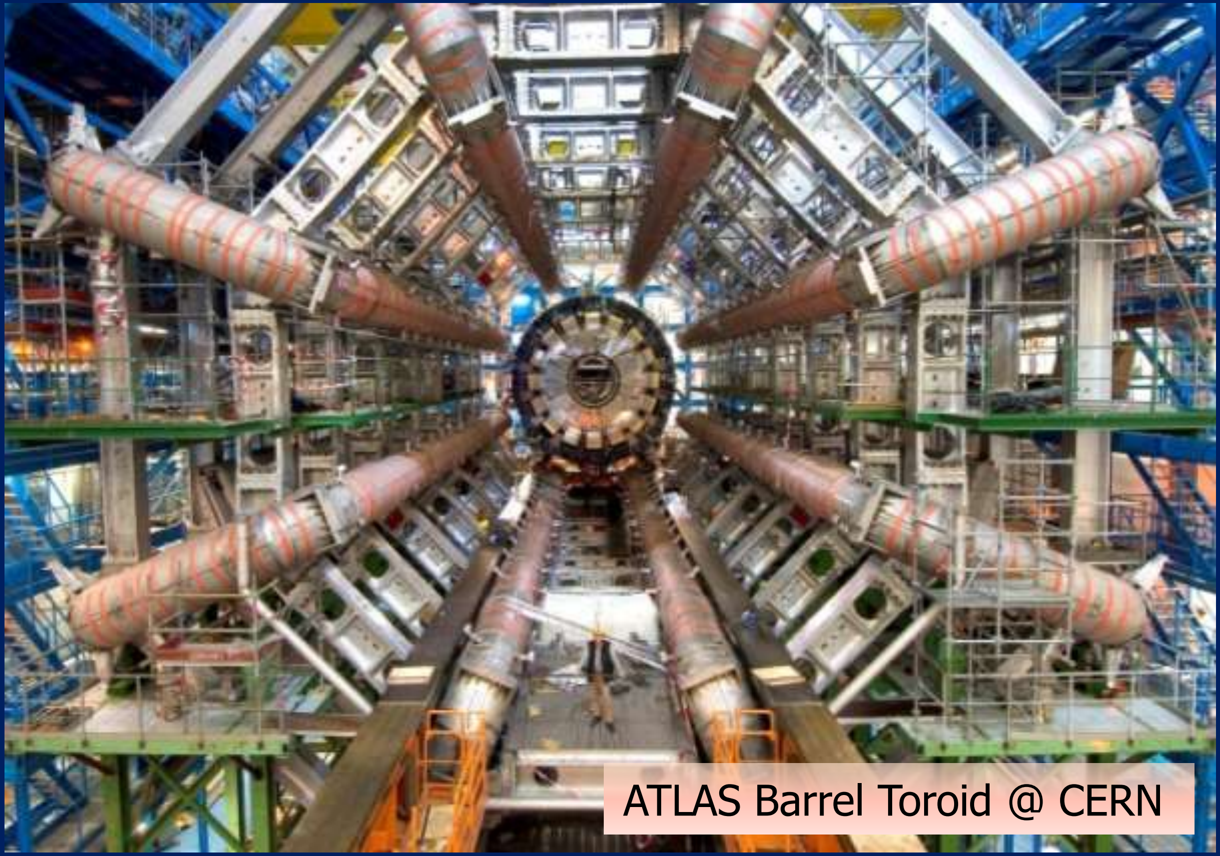
High current conductors are requested

200 A HTS tape

no

65000 A@5T Al-NbTi/Cu

yes



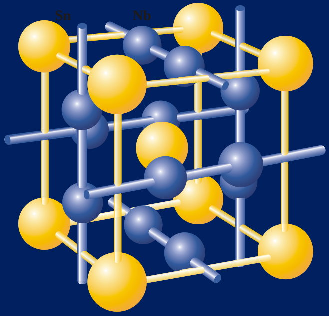
ATLAS Barrel Toroid @ CERN

One cannot build large scale magnets from single NbTi-Nb_3Sn-B2212-Y123 wires or tapes

We need superconductors that can be cabled and survive a quench!

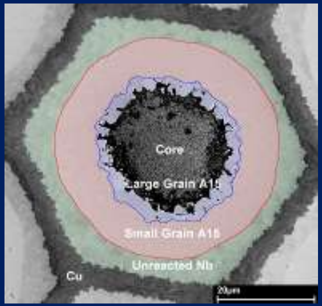
From material to magnet

Lattice



50 nm

Filament

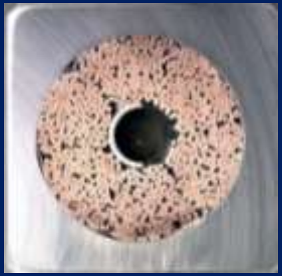


20 µm

Wire

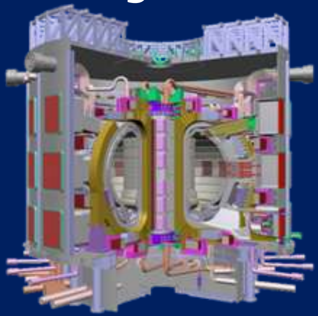
1 mm

Cable



50 mm

Magnet



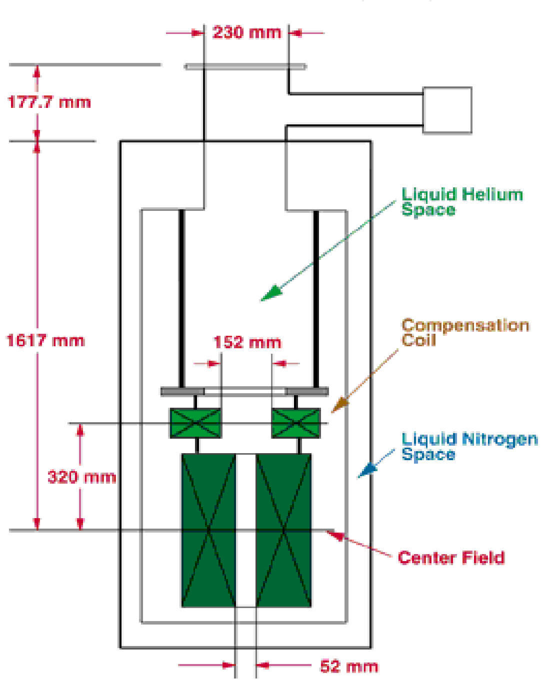
35 meter

How to make performing multi-kA conductors that guarantee the magnet not to quench or degrade ?

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

- An under developed area of research, but essential to avoid surprises and degraded magnet performance
- Striking examples exist of missing understanding putting large projects at risk

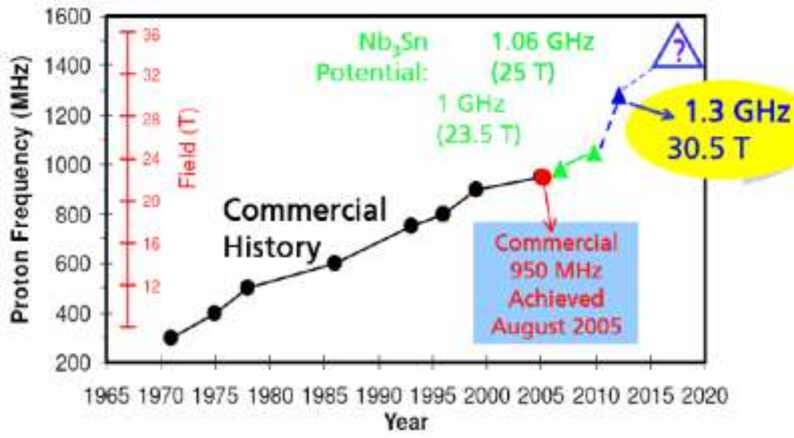
Application 1 : Lab magnets and NMR



Market of laboratory magnets in many variants up to 20 T at 1.9 K

NMR spectroscopy magnets up to ~ 22 T, 950 MHz

Pushing up to 30 T using HTS



New high field magnets as user facilities

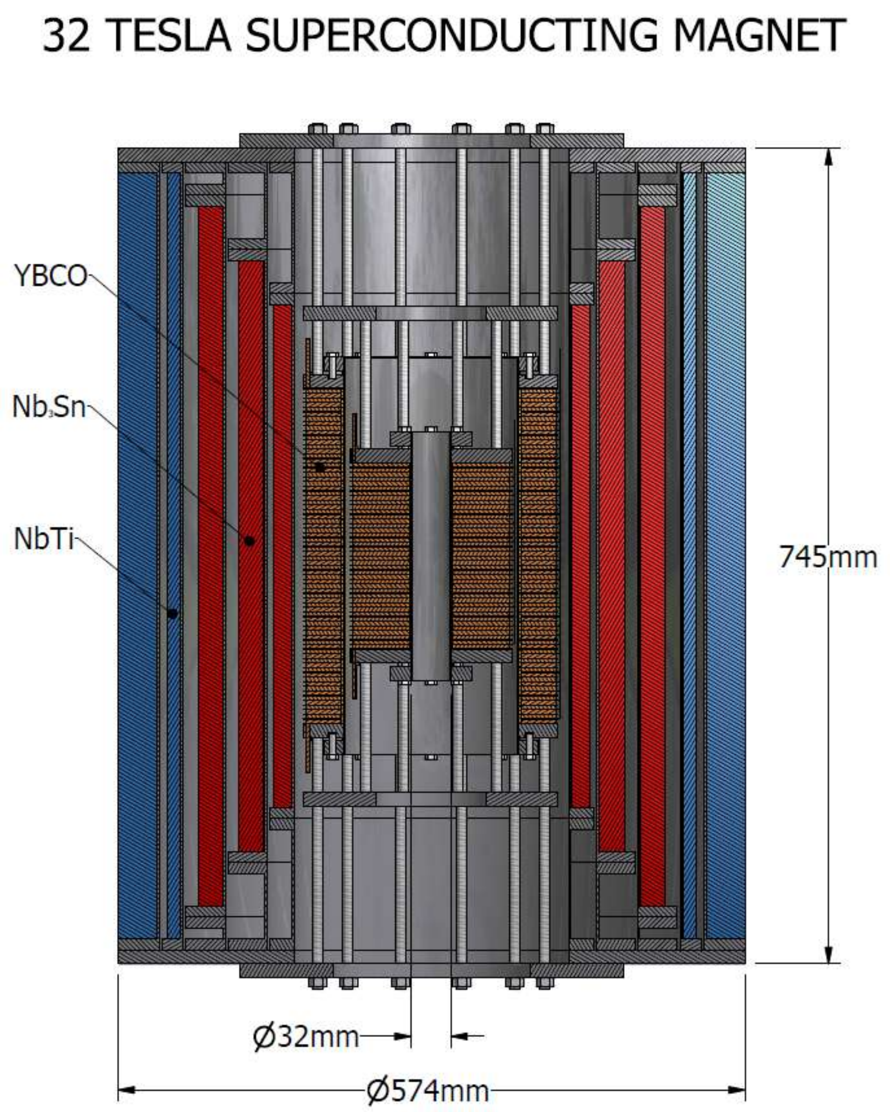
Beyond 20 T systems become too expensive for single labs and we move to user facilities

A new and unique fully superconducting 32 T magnet user facility, YBCO insert pancake coils

A nested HTS coil in an existing twin outsert of NbTi/Nb3Sn

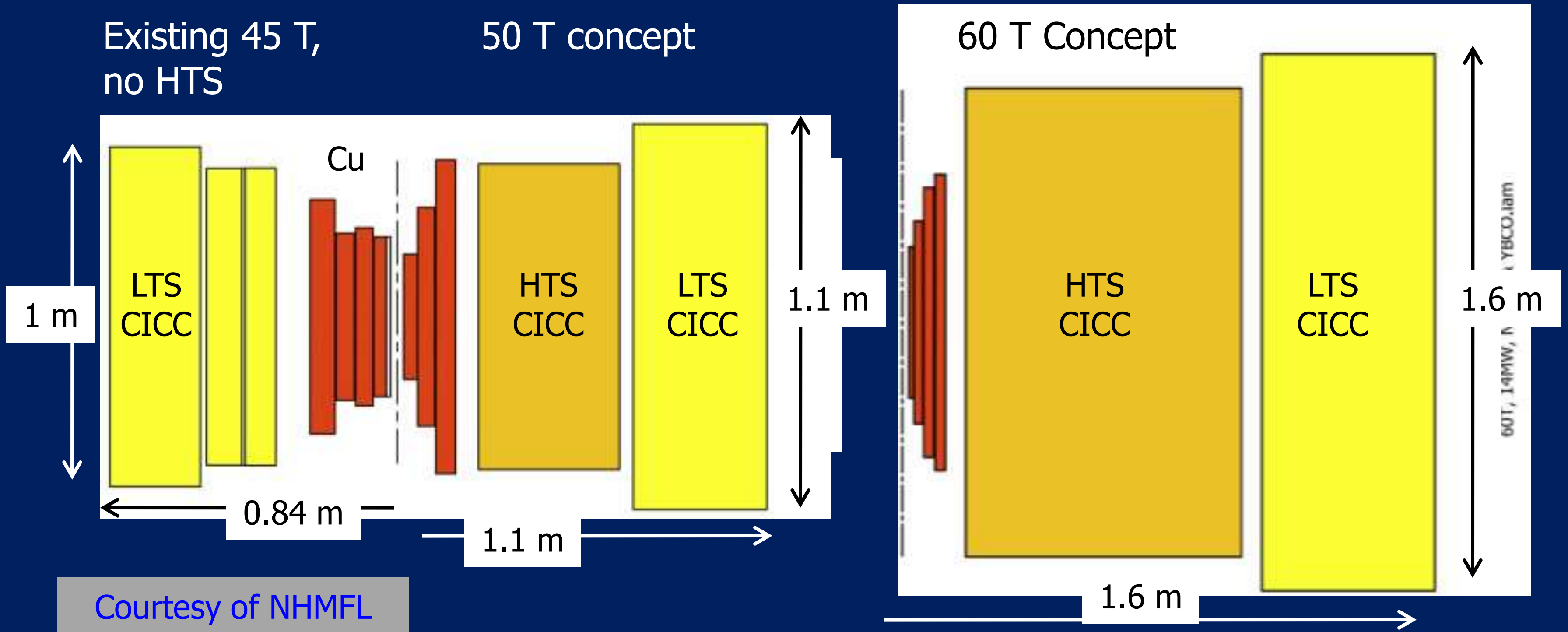
- 172 A, 619 H, 9 MJ
- Under Construction at the NHMFL, test in 2013

✓ When successful, a real breakthrough



Courtesy of NHMFL-Tallahassee

Another challenge : towards a 60 T Hybrid

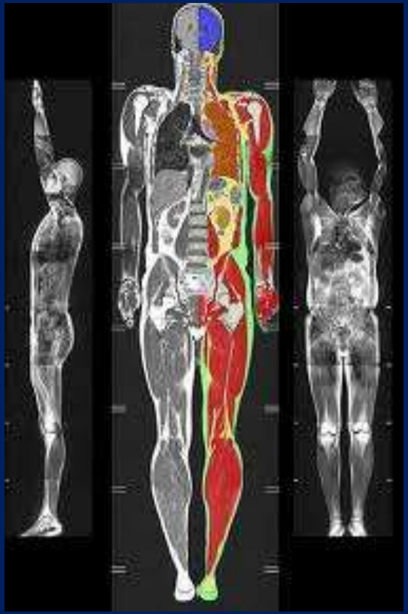


Courtesy of NHMFL

	Units	45 T	60 T	50 T
Insert Power	MW	30	14	14
Outsert Field	T	14.2	43	28
Stored Energy	MJ	100	1100	230
Cold Mass	tons	10	95	24
Outer Dia	m	1.6	3.2	2.2
Length	m	1	1.6	1.1

Important initiative to push the HTS technology forward and solve practical coil construction problems

Application 2 : Magnetic Resonance Imaging



Medical NMR, MRI for diagnostics ~ 40000 units installed

It works well due to High Quality NbTi and Persistent Mode

Today standard are 1.5 T but mostly 3 T, actively shielded

- Functional MRI for brain research and treatment
- Real time MRI, filming
- Interventional MRI, surgery

Quest for higher resolutions, higher magnetic field, 7 and 9 T

High-field MRI beyond 3T , 2 examples

9.4 T MRI magnet

90 cm bore and 54 tons

for brain research in combination with PET scanner, to study degeneration processes like Alzheimer and Parkinson decease

Julich Research Center 2009

11.75 T MRI magnet

at the limit of NbTi at 1.8 K

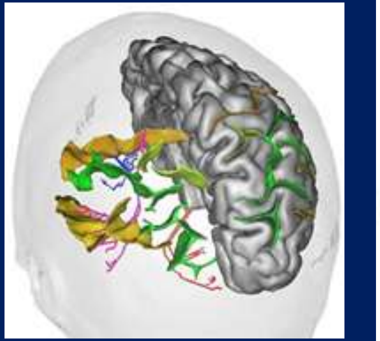
90 cm bore,

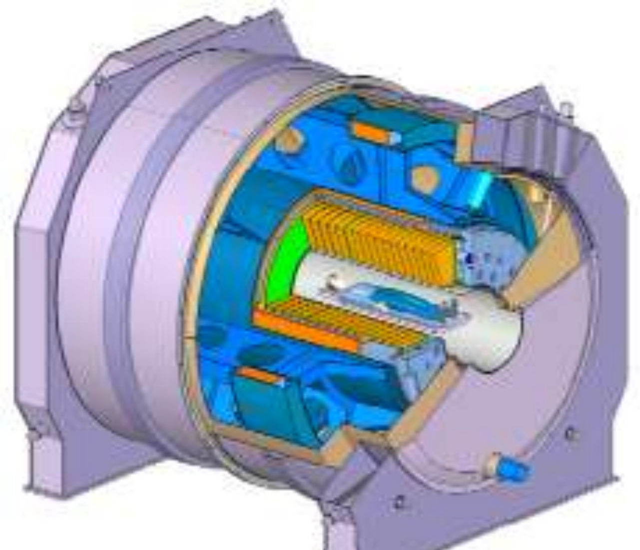
1.48 kA, 338 MJ

5.2 x 5 foot print, 132 tons

Study of central nervous systems "from mice to humans"

Stretching MRI to the limits….





Neurospin Project at CEA-Saclay

3 : Proton Therapy

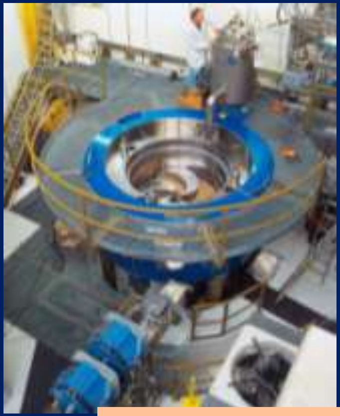
Medical accelerators providing a p beam for tumor treatment

- 28 p-therapy centers in the world
- 8 operational/planned in Europe

2 Options:

- Large scale facility (like Comet)
- Single compact station (future)

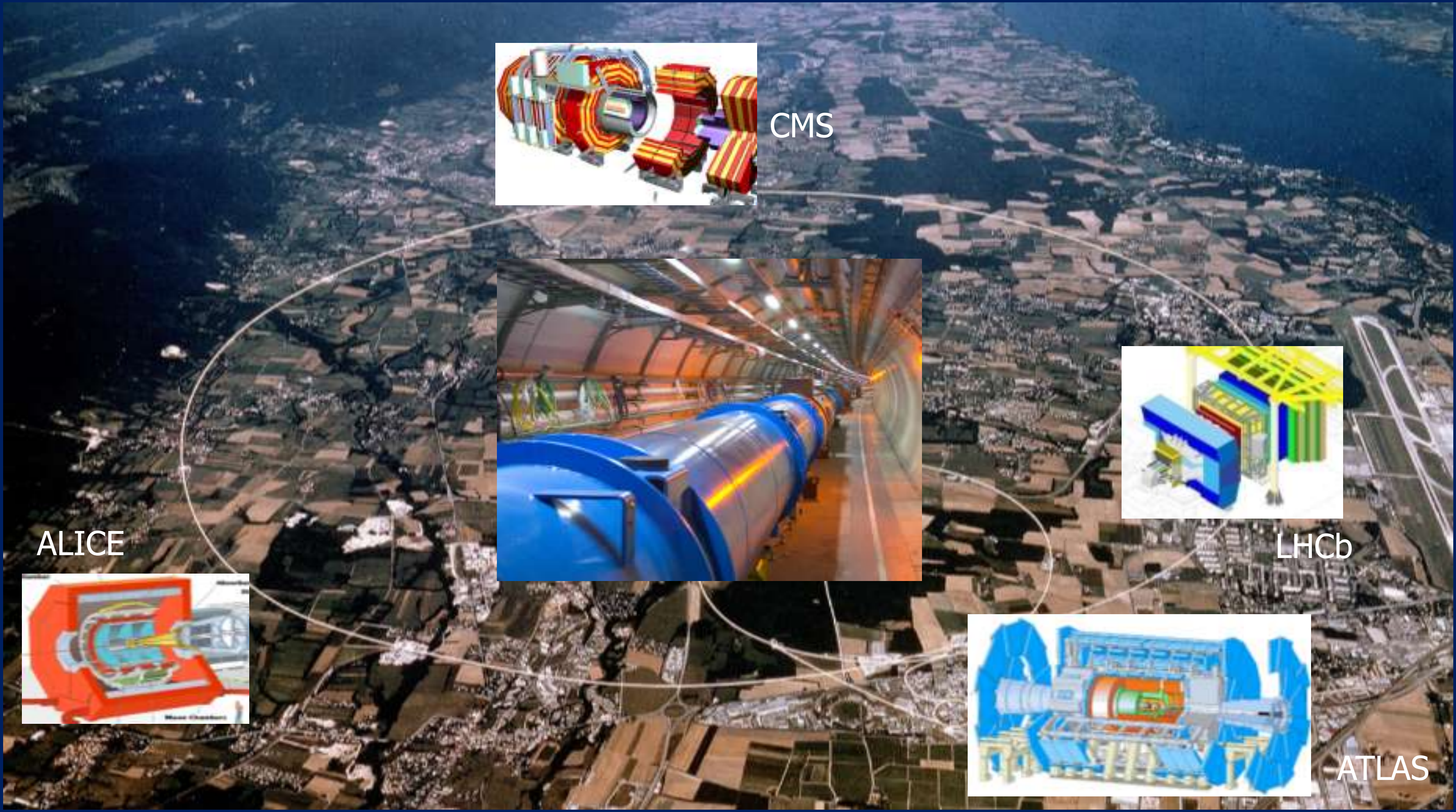
Quest for high-field compact and cost efficient integrated units



Example PSI Switzerland, Comet synchrotron 250 MeV

Needs some time but could become the 2nd large scale medical magnet application of superconductivity

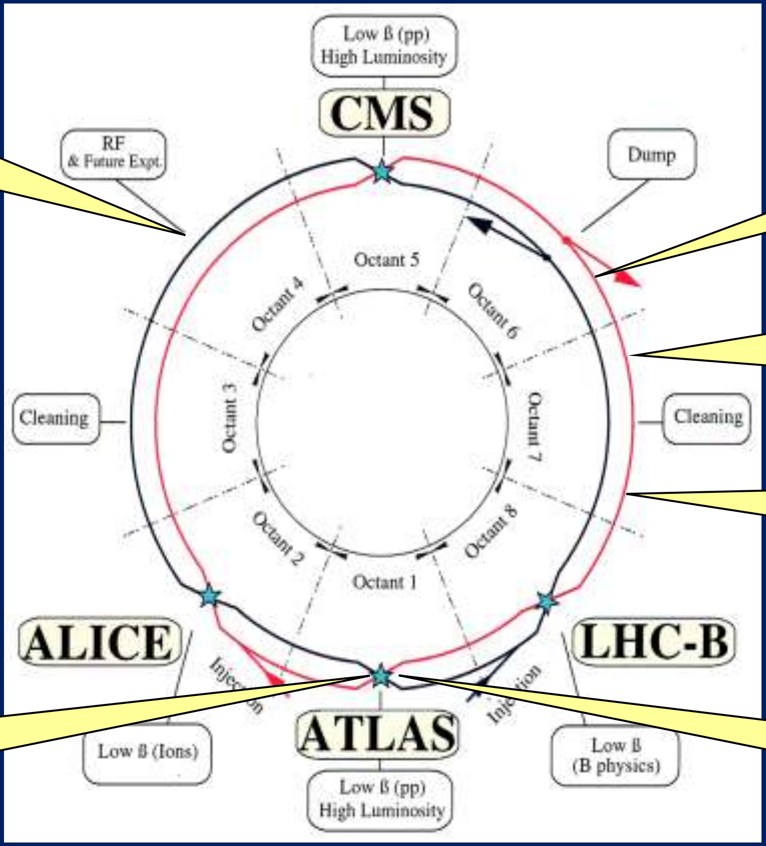
4 : Large Hadron Collider



14 TeV pp collider, a complex with more than 9000 superconducting magnets
by far the largest superconducting system in operation

Superconductivity and HE Physics

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



Nb/Cu cavities for acceleration

1232 dipoles magnets for bending

386 quadrupole magnets for focusing

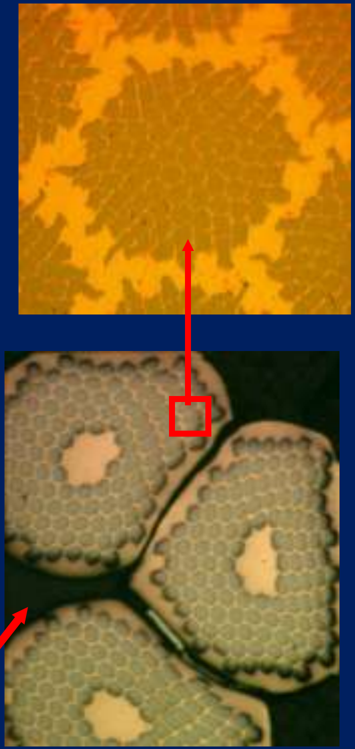
~6000 correction magnets

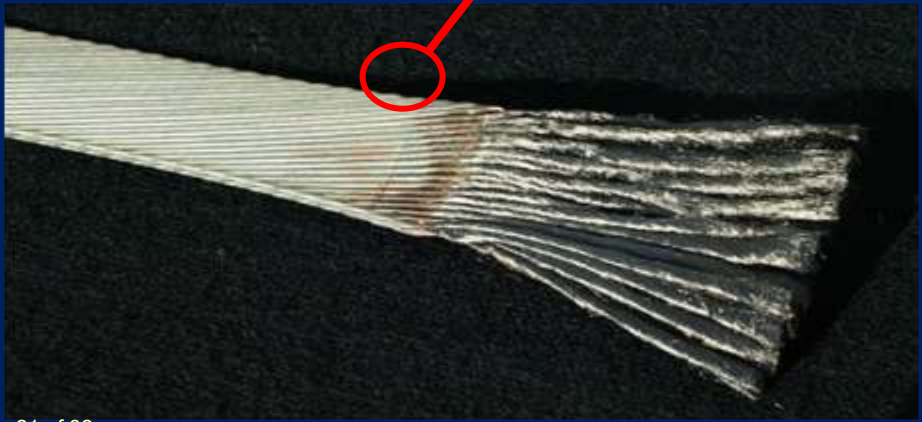
ATLAS and CMS detector magnets

Insertion and Final Focusing magnets

No Higgs without Superconductivity………

LHC : 7000 km of 12 kA NbTi/Cu cable





LHC type I cables
NbTi/Cu 28 strands
15.1 mm wide
I_c (1.9K, 9T) ~ 20 kA
filament size ~ 5 μm

LHC upgrade plans 2020-2040

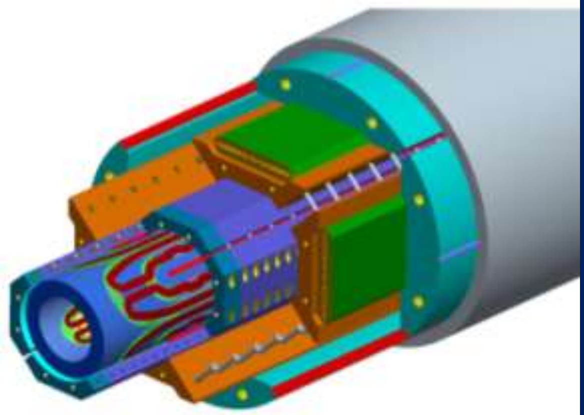
HL-LHC: Boosting the luminosity

>5x10^{34}/cm^2s^1 in 2022

- Nb_3Sn preferred technology

  Some 20-30 11T class dipoles and final focusing quadrupoles are needed

- Modest number, still very challenging

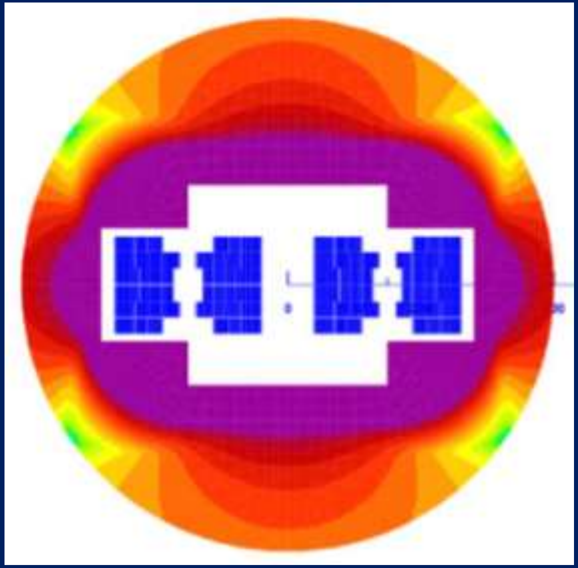


Many models made by the US-LARP program

HE-LHC: doubling or tripling the collision energy in the LHC tunnel, >2035

Rule: E [TeV] ~ 0.3 x B [T] x R [km]

- Option 1: New generation of 15-16 T class Nb_3Sn dipole and quadrupole magnets
- Option 2: Develop a hybrid NbTi-Nb_3Sn-HTS dipole magnet for 20-25T
- Very challenging and good stimulus for R&D



Design of 20 T dipole

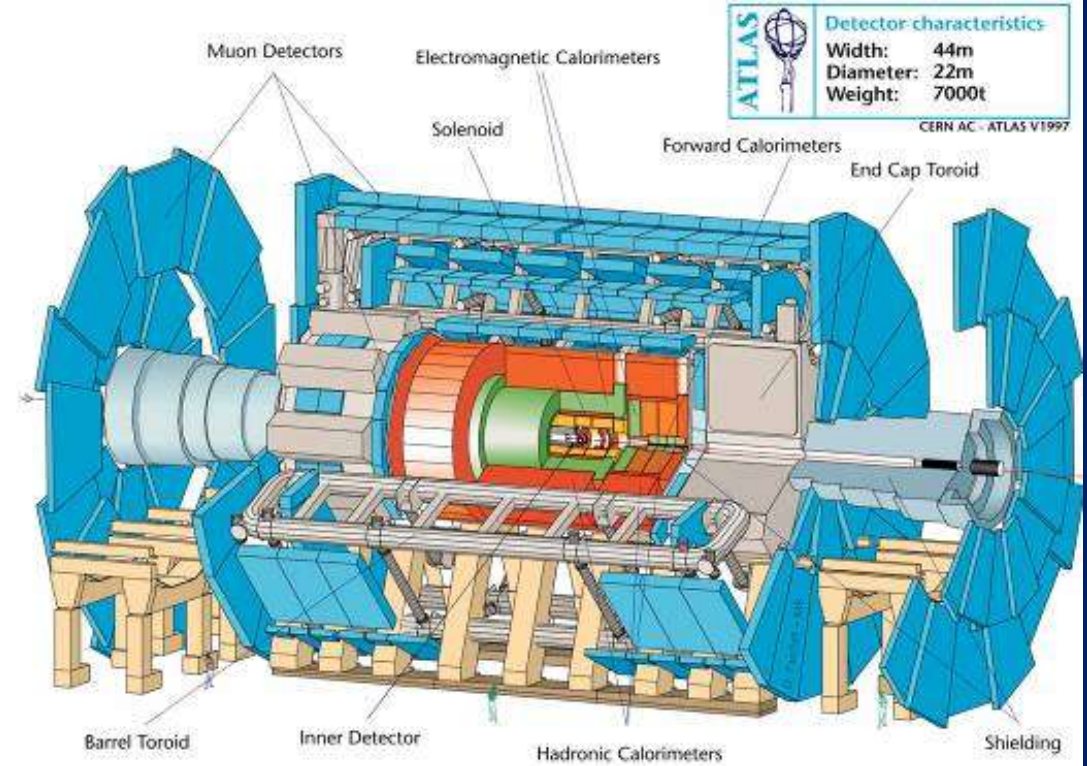
5 : HEF Detector magnets, ATLAS

A Barrel Toroid, two End Cap Toroids and a Central Solenoid
provide 2 T for the inner detector ~1 T for the muon detectors in blue

20 m diam. x 25 m length
1000 m^3 with field

170 t, 90 km superconductor
700 t cold mass
1320 t magnets

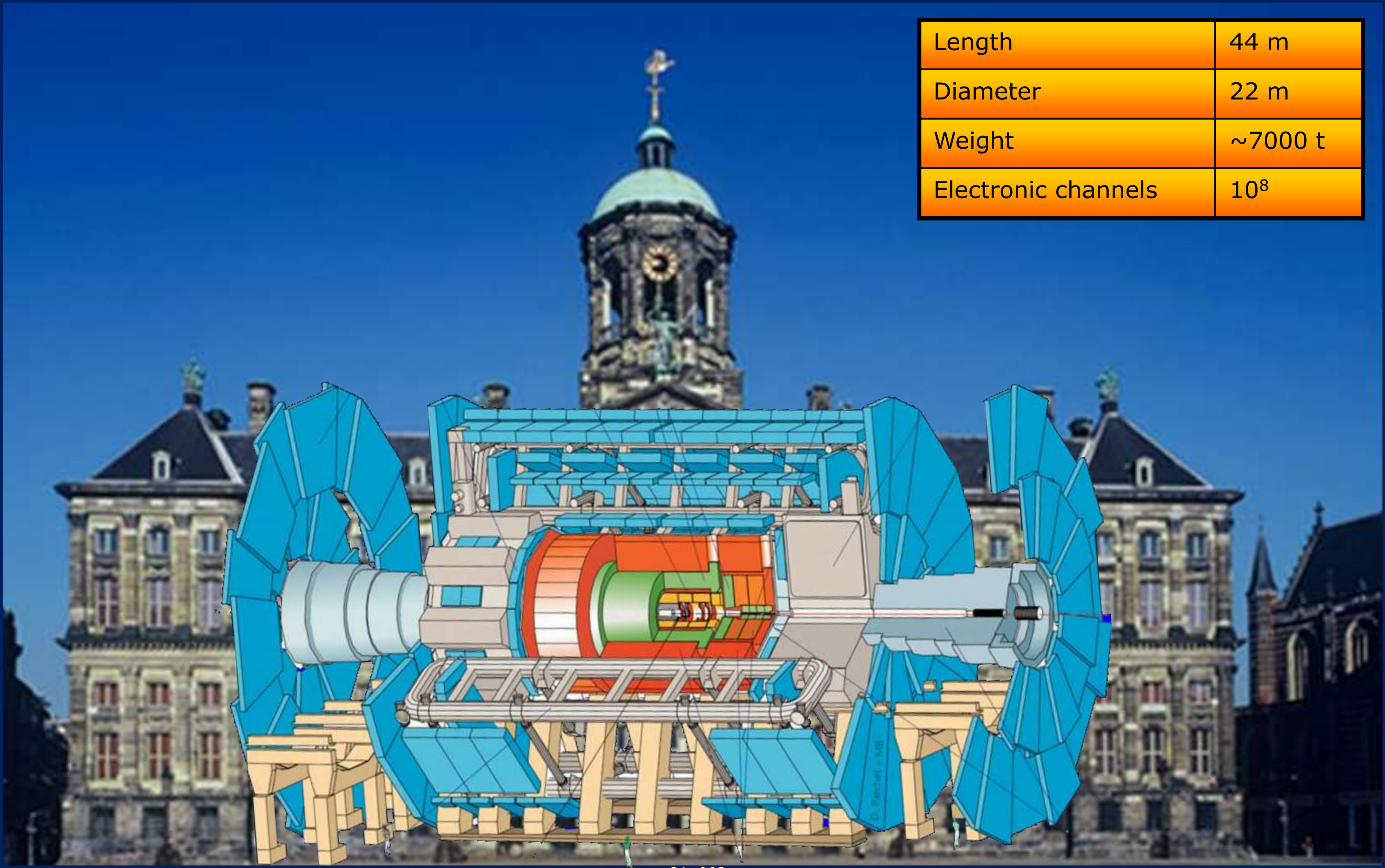
20.4 kA at 4.1 T
1.5 GJ stored energy
4.7 K conduction cooled



10 yrs of construction 97-07

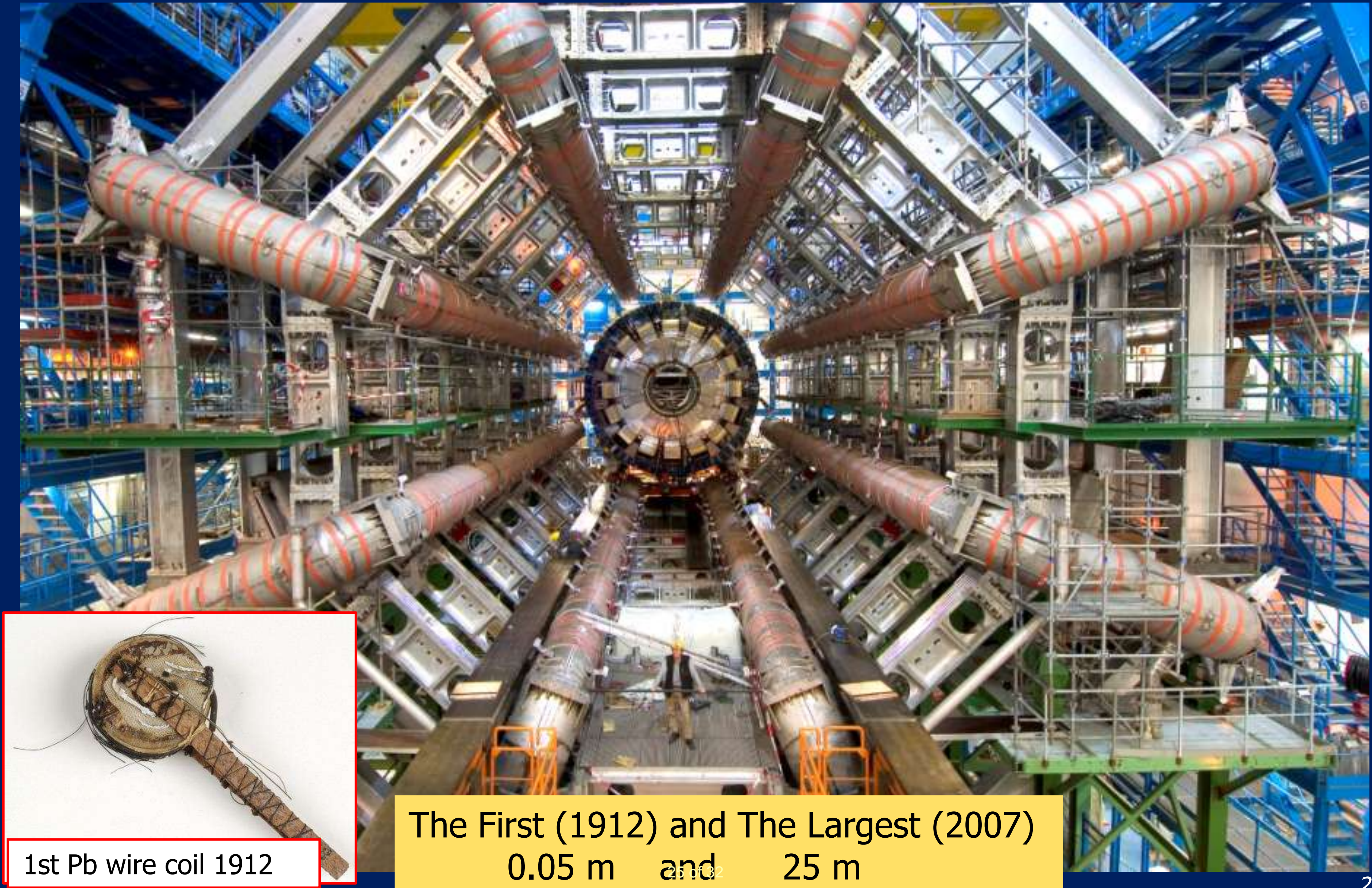
The largest trio of toroids ever built

ATLAS in Amsterdam



Length	44 m
Diameter	22 m
Weight	~7000 t
Electronic channels	10^8

The First and The Largest

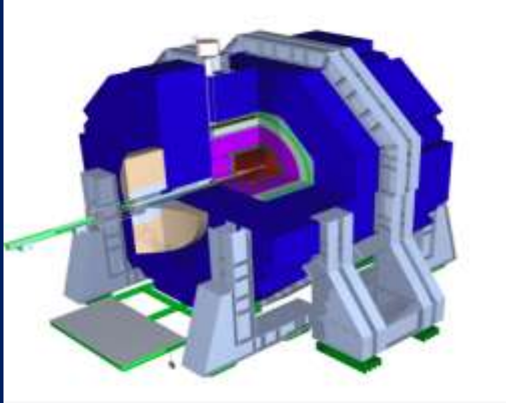


1st Pb wire coil 1912

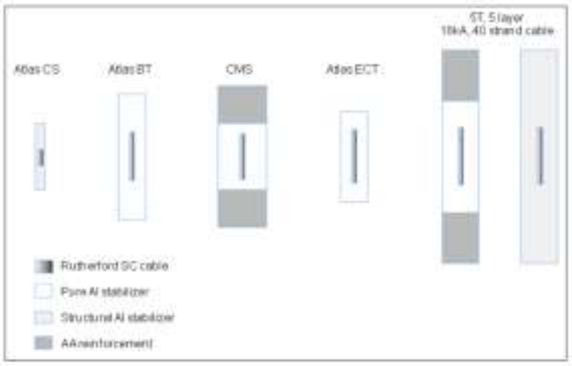
The First (1912) and The Largest (2007)
0.05 m and 25 m

Next generation detector magnets

- Linear Collider (ILC/CLIC) detector magnet design
  show 6 T in a 6 m bore and 6 m length

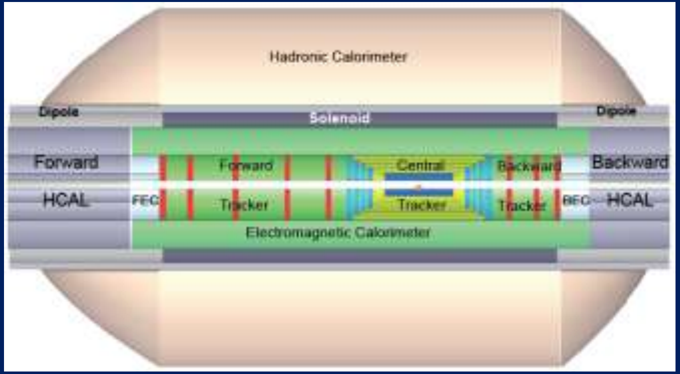


- +2 T requires next generation of reinforced Al stabilized NbTi superconductors

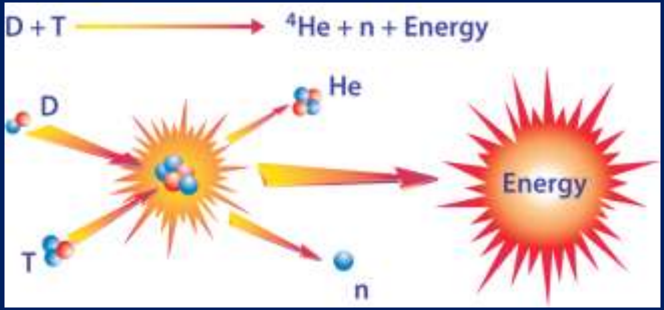


- Alternatively CICC technology may be introduced for large scale detector magnets

- New LHeC detector proposed for proton-election collisions at the LHC medio 2030

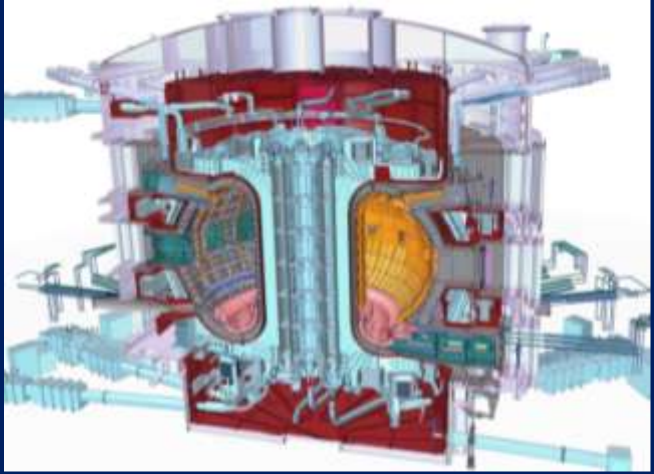


6 : Base load e-power with fusion



Advantages

- Large scale and limitless fuel
- Available all over the world
- No greenhouse gases and safe
- No long-lived radioactive waste



Since 1979, worldwide

- 7 sc tokamaks (213 in total),
- 3-8 T on plasma

Recent superconducting machines:

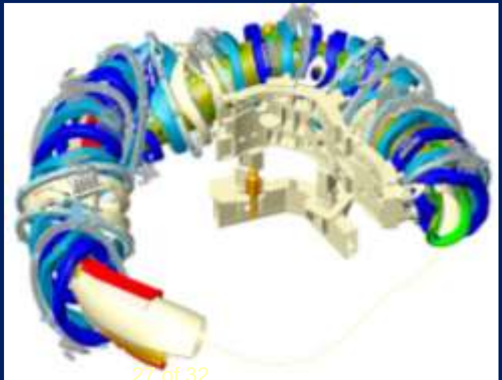
- KSTAR-Korea, EAST-China, SST1-India

2 under construction:

- JT60SA and ITER

and

- 1 Wendelstein type W7X



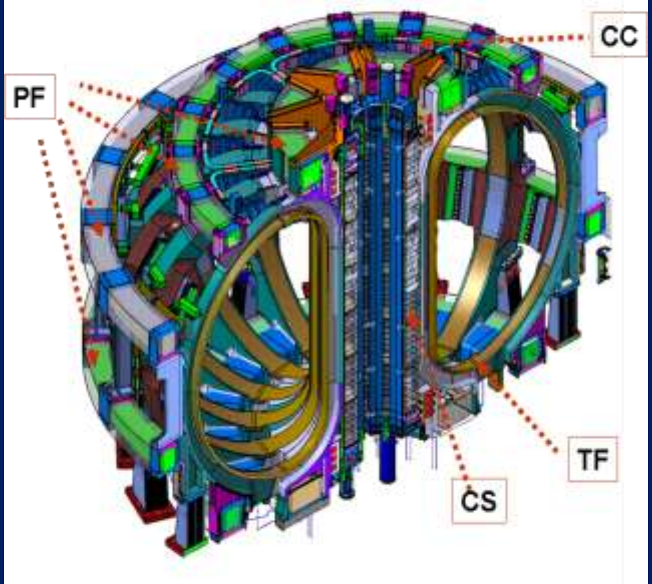
ITER magnet system

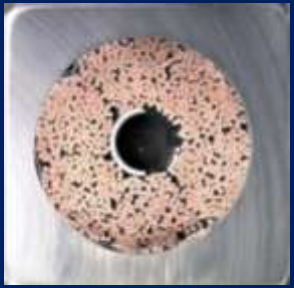
Major plasma radius 6.2 m
840 m^3 plasma and 15 mA current
Fusion power: 500 MW

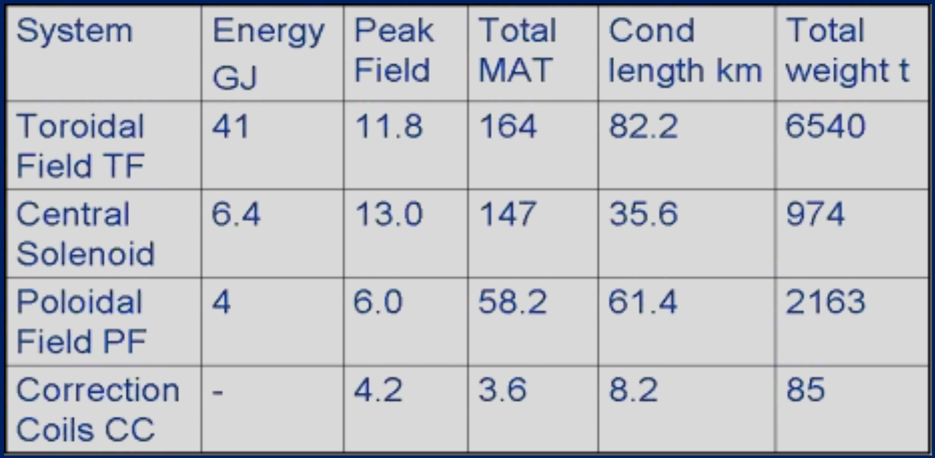
First results medio 2025

ITER: NbTi and Nb_3Sn, no options
DEMO design start soon, still NbTi & Nb_3Sn

May be Bi-2212 or YBCO in production plants when multi-kA cables become available and cost has come down........

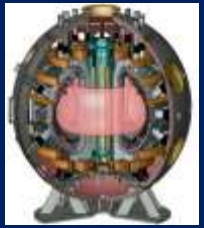






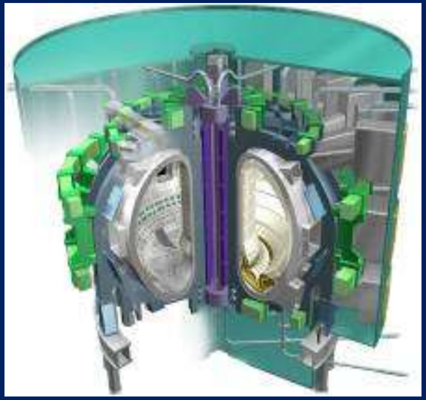
System	Energy GJ	Peak Field	Total MAT	Cond length km	Total weight t
Toroidal Field TF	41	11.8	164	82.2	6540
Central Solenoid	6.4	13.0	147	35.6	974
Poloidal Field PF	4	6.0	58.2	61.4	2163
Correction Coils CC	-	4.2	3.6	8.2	85

Next steps towards a production plant



JT60-SA
Superconducting

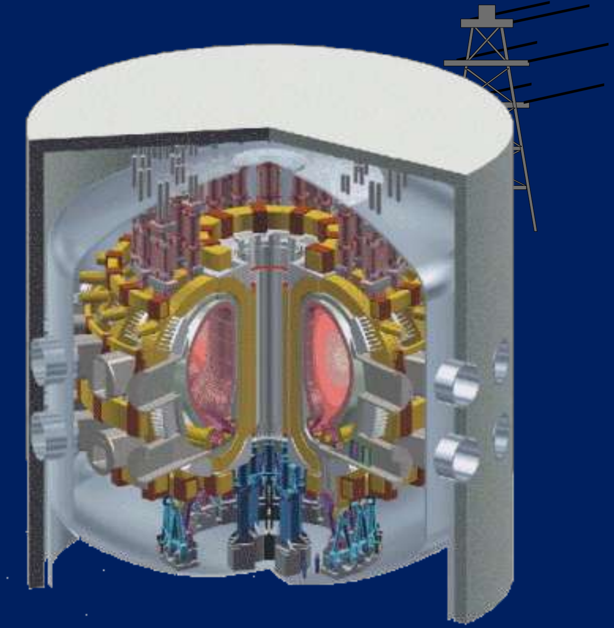
JET ~ 80 m^3
D/T ~16 MW$_{th}$



ITER

800 m^3

~ 500 MW$_{th}$



DEMO

~ 1000 - 3500 m^3

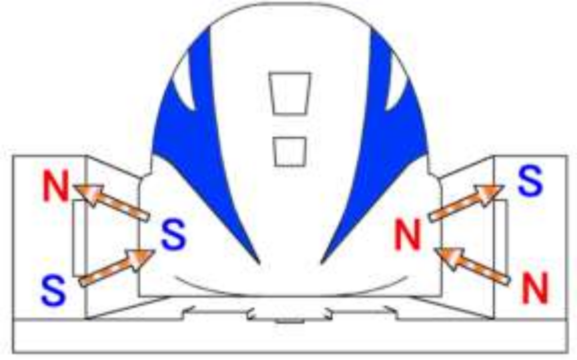
~ 2000 - 4000 MW$_{th}$

We can not afford not to know if it works or not !

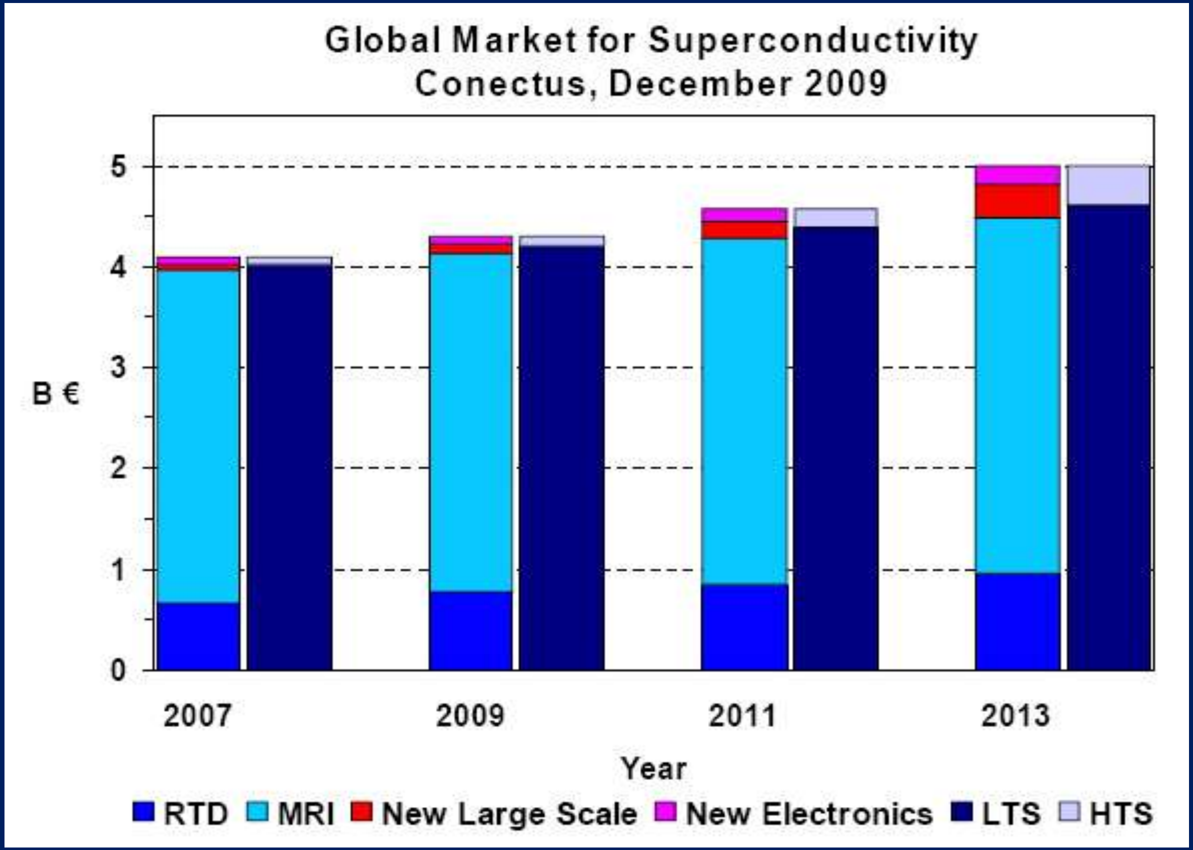
- We are running out of time and have to accelerate
- Utility companies should jump on this and get it done !

7 : Superconducting JR-MAGLEV in Japan

- JR-Maglev since 1969 pushed forward, records at 580 km/h, nominal 500 km/h
- Summer 2011 : Now first passengers track will be built, very important!
- From Tokyo via Nagoya (in 2027) to Osaka (in 2045) in 1h (now 2h25)



Market of superconductors



- ~ 4 B€/yr business, growing
- today dominated by MRI and Research Magnets, including NMR and accelerator magnets, >90 %

  and workhorse superconductors NbTi and Nb_3Sn >90 %

Conclusion

Kamerlingh-Onnes' invention has given us unique new facilities

in Science : High Field labs, NMR, High Energy Physics, Fusion

in Medicine : MRI imaging and medical accelerators

in Transport : Maglev

in much more not presented

Superconductors are very successfully applied where no alternatives are present (magnets >2 T and in a large volume >1 L)

After 25 years of development HTS superconductors are available in km lengths and soon more, still a long way to go, but their properties are shiny and irresistible.....

However, investing in NbTi and Nb_3Sn superconductor and magnet research should not be forgotten, as we need a better technology for the next generation magnets for accelerators and fusion