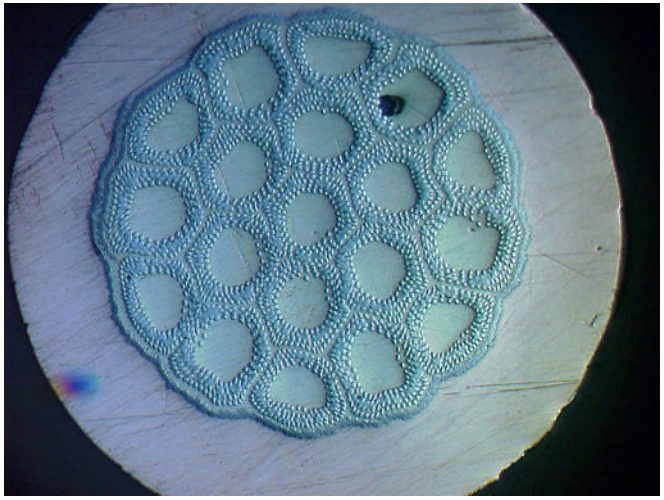
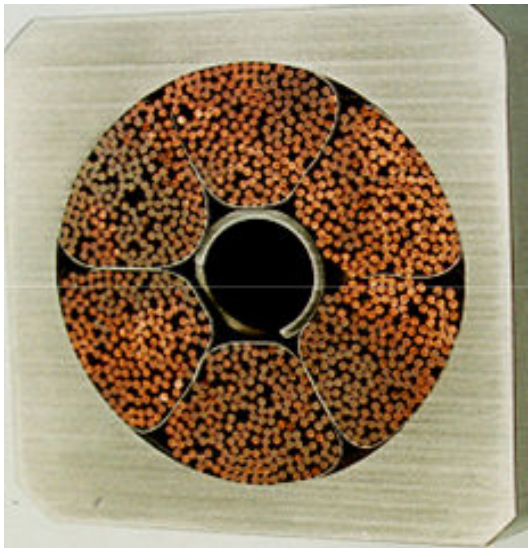
Superconducting Magnets for Fusion Application





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October 8, 2009
Accelerator Physics and Technology Seminars, FNAL

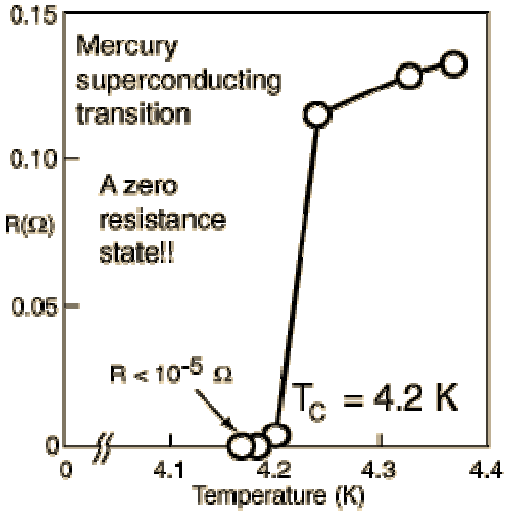
Outline

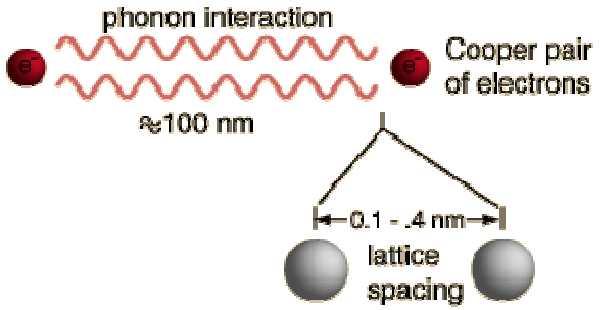
- Introduction
- Superconductivity and its applications
- High energy physics
- Fusion
- Mechanical behavior of cable in conduit conductors
- Conclusions

What is superconductivity?

A material is said to be superconductive if it has the ability of conducting electricity WITHOUT the loss of energy…basically you carry current for FREE!

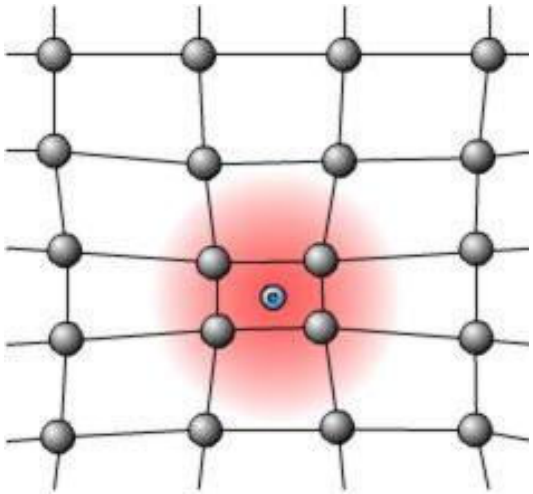
In 1908
H. Kamerlingh Onnes successfully liquified helium.
In 1911 he studied the low temperature resistivity of mercury and…
He got the Nobel price in 1913 for it.

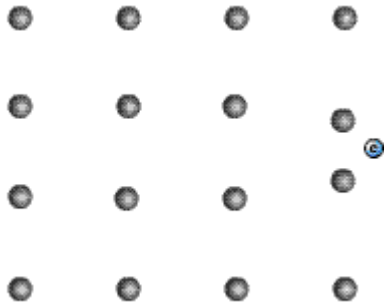




In 1957 the BCS theory was developed and explained superconductivity through a macroscopic collective quantum mechanic effect.

Here's a SIMPLIFIED explanation…





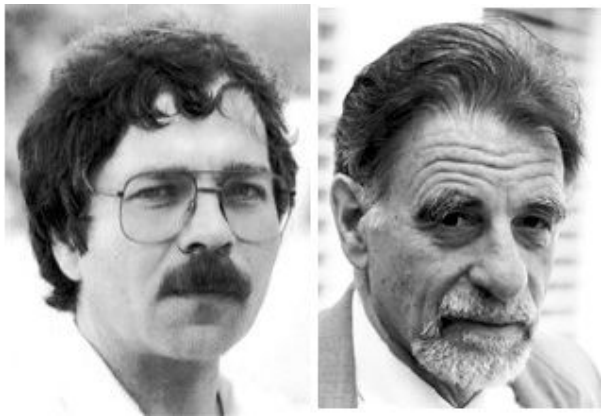
Requirement is to have
LOW TEMPERATURES

What does BCS theory get you?

Bardeen Cooper Schrieffer

Nobel price in physics 1972

In 1986 Bednorz and Muller discovered **superconductivity at high temperatures** in layered materials comprising copper oxide planes and…
…they got the Nobel price for it in 1987.

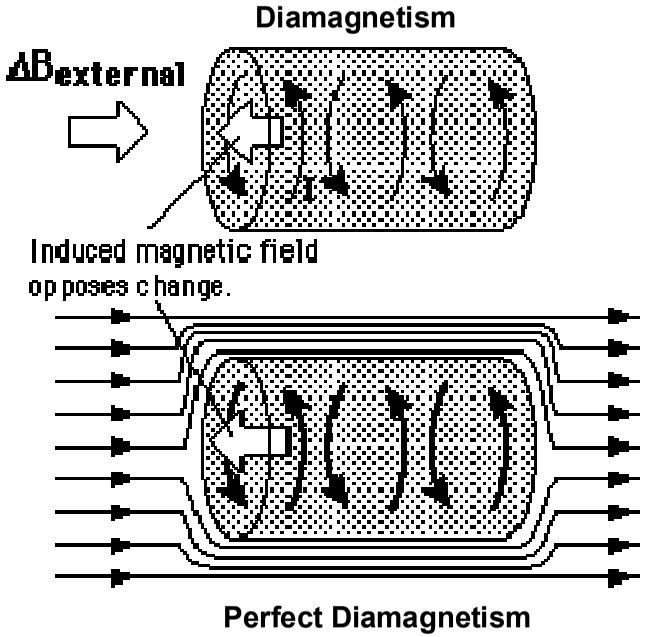


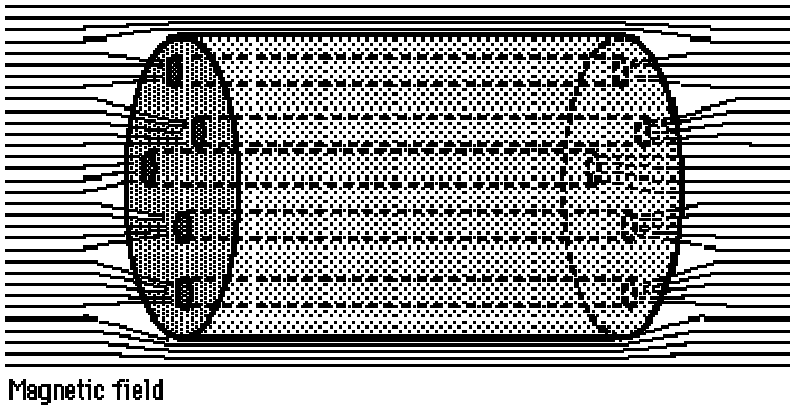
Bednorz Muller

Nobel price in physics 1987

Type of superconductors

There are two types of superconducting materials:





Type I (pure metals):
perfect diamagnetism

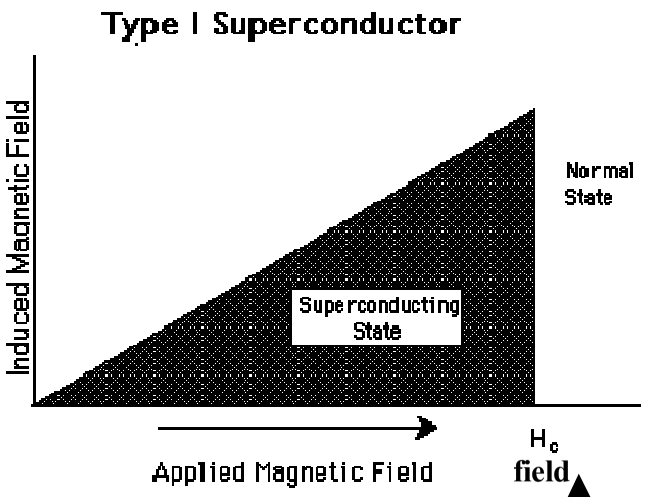
Type II (composite materials):
mixed state and allow partial penetration

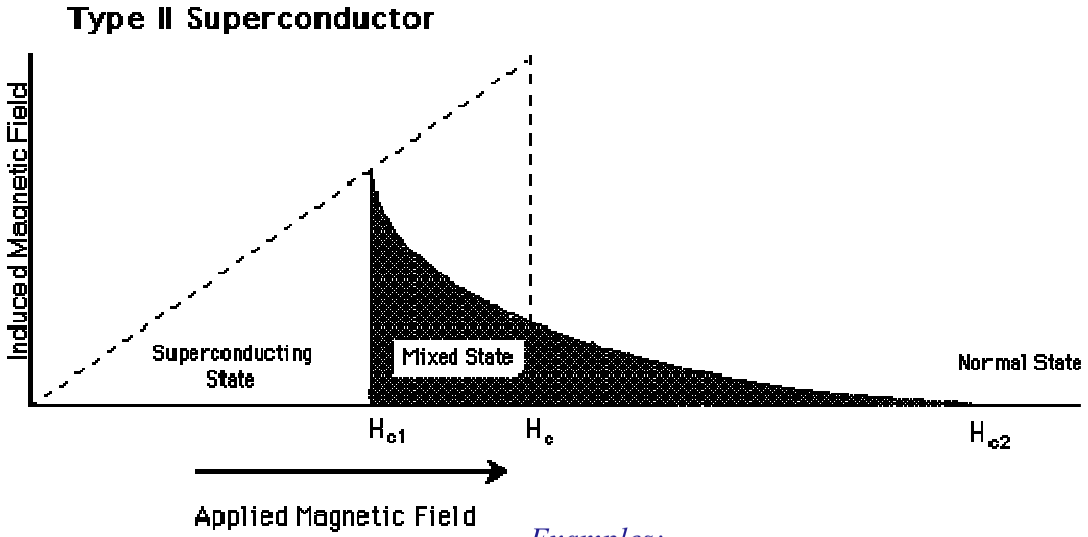
Critical Field

An electric current in a wire creates magnetic field. Superconductors are well suited for making strong electromagnets (no loss and high currents).
BUT if an "external" field applied to a single strand is too high, it will cause the transition from superconducting to resistive state.

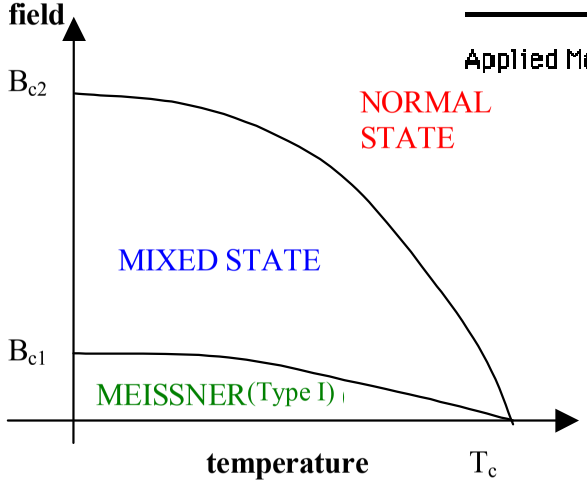
Type I superconductor withstand very low magnetic field (< 0.1 T).

Practical materials for electromagnets are only *Type II* superconductors (critical field up to 30 T).





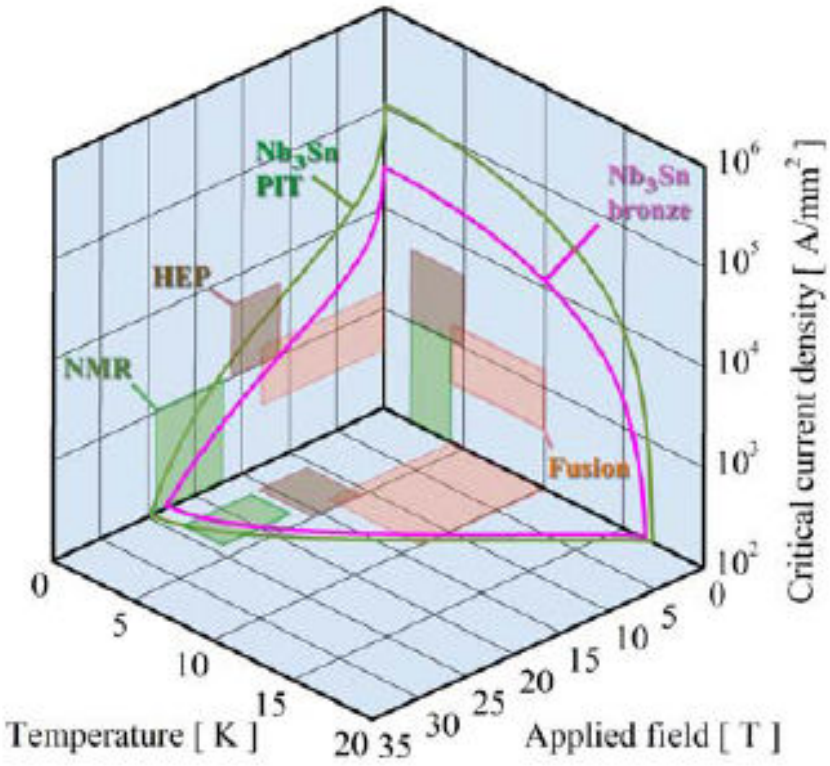
Examples:
Pb
V
Ta
Hg
Sn
In
Ti
Zn



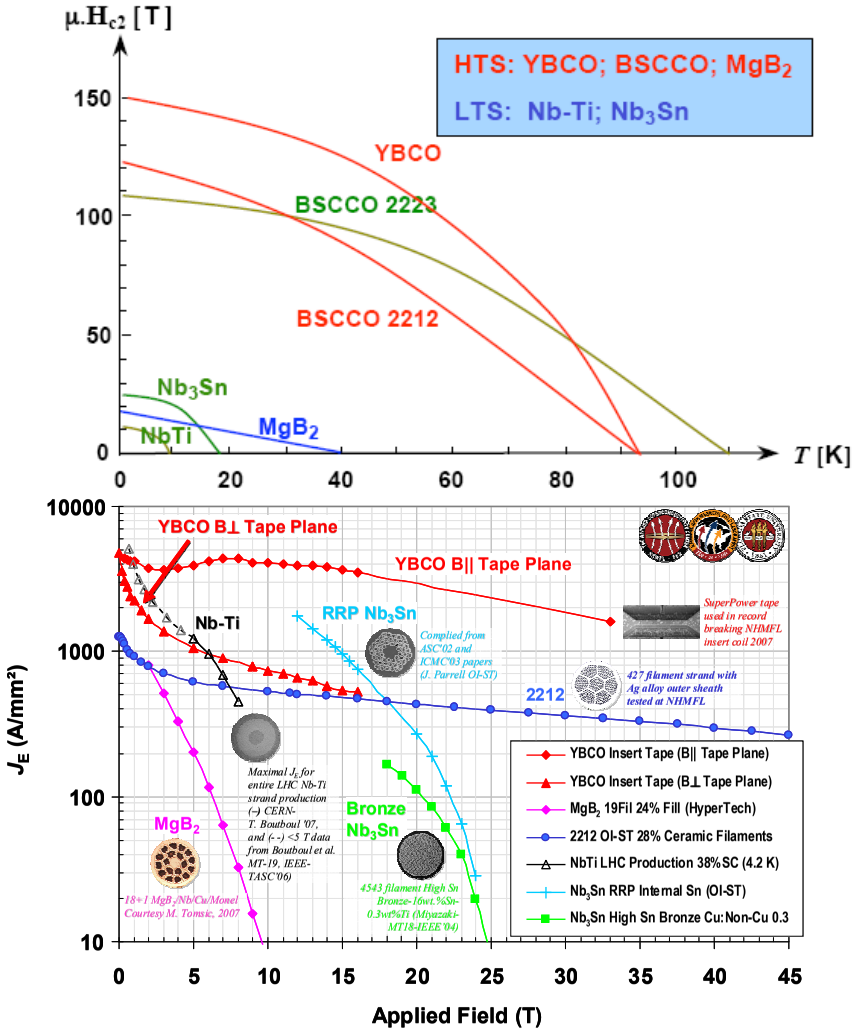
Examples:
NbTi
Nb_3Sn
Nb_3Al
V_3Ga
Nb_3Ga
Ga
Nb
Zn
MgB_2
HTS (YBCO, BSSCO)

J, B, T

A superconductor is characterized by a critical current I_c (or current density J_c), a critical field B_c, a critical temperature T_c.



Depending on the critical temperature superconductors are defined as
Low Temperature Superconductor (LTS)
High Temperature Superconductor (HTS)

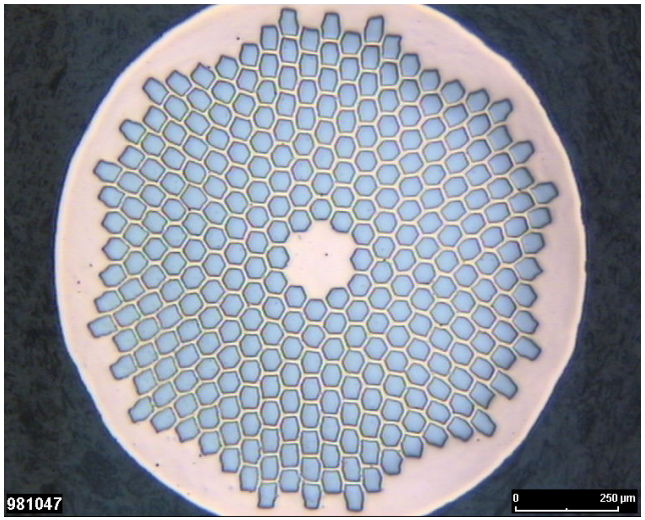


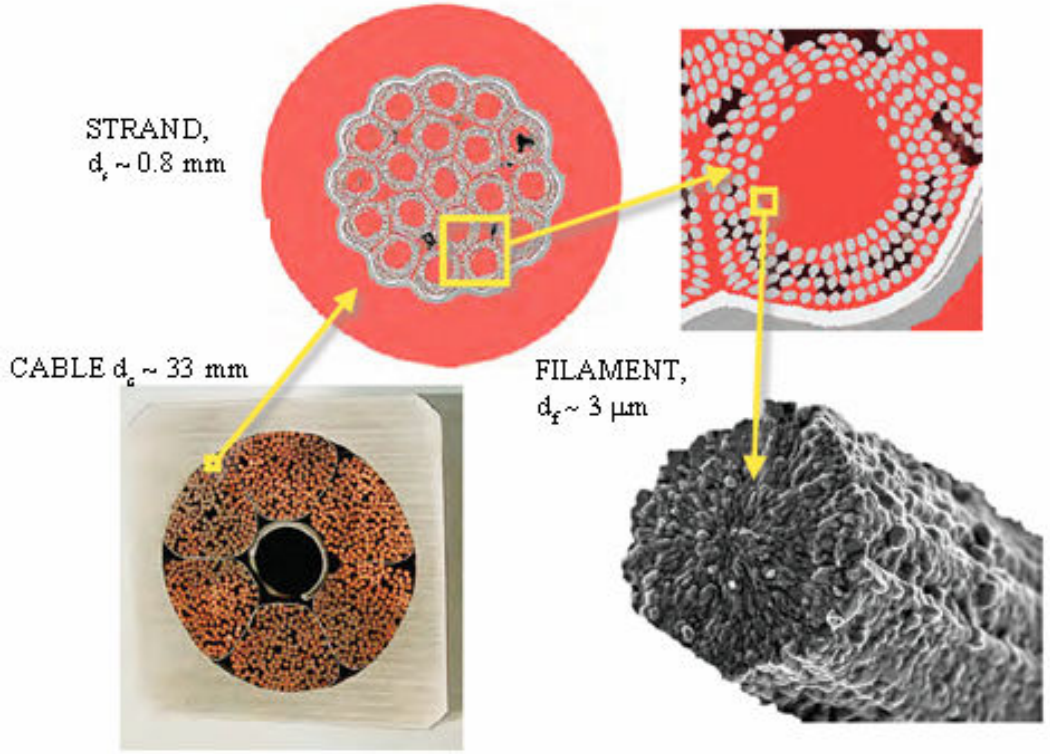
Materials suitable for magnets

Many materials are superconductive but only few of them are ready to be used in superconducting magnets.

NbTi
critical temperature 9.1 K
critical field 10.5 T (@ 4.2 K)

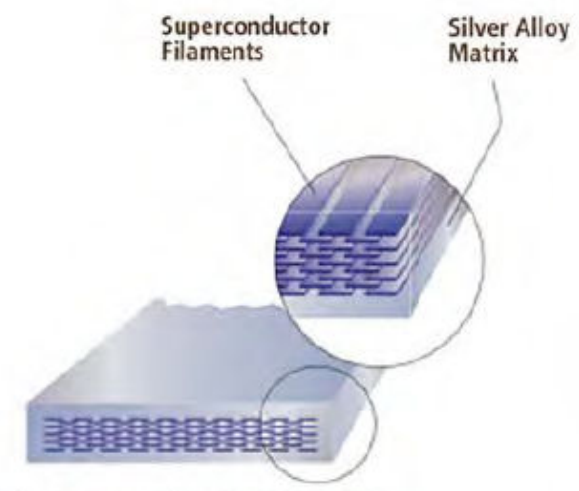
Nb_3Sn (after heat treatment becomes BRITTLE and sensitive to strain)
critical temperature 18.2 K
critical field 24.5 T (@ 4.2 K)



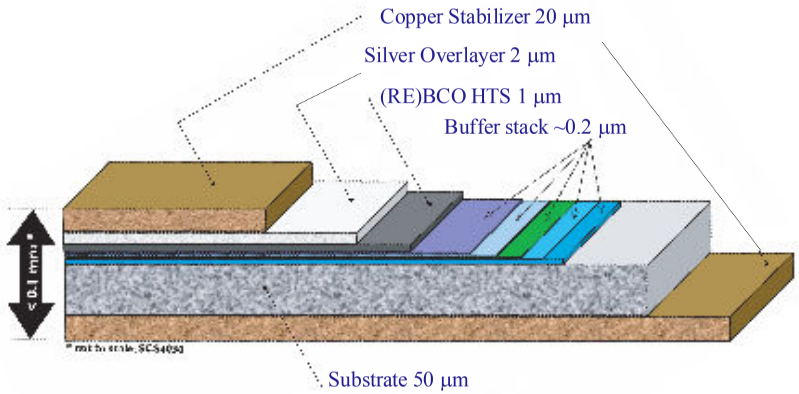


High Temperature Superconductors

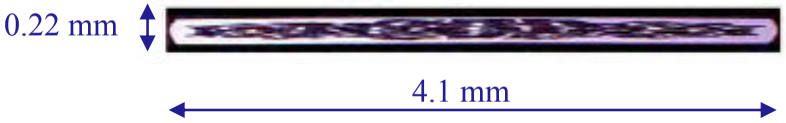
High Temperature Superconductors are materials of interest because they can operate at higher temperature (liquid nitrogen vs. liquid helium).



First Generation (1G) HTS wire
Multi-Filamentary Composite
(Commercially available)



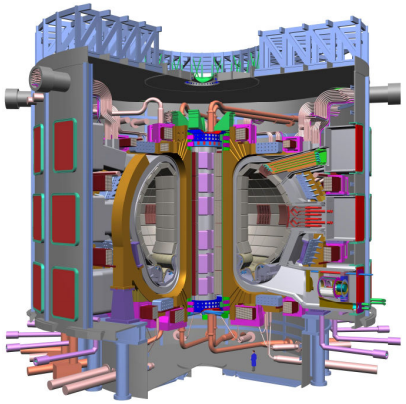
Second Generation (2G) HTS wire
Coated Conductor Composite
(Commercially available AMSC, Superpower)



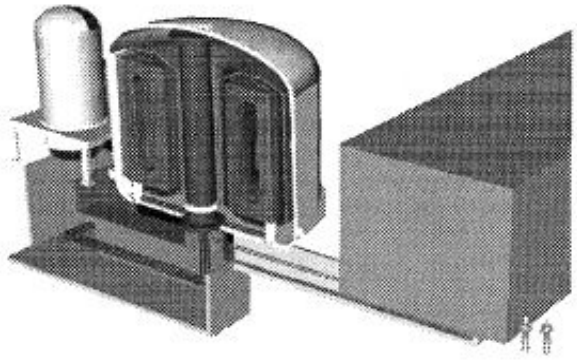
SuperPower

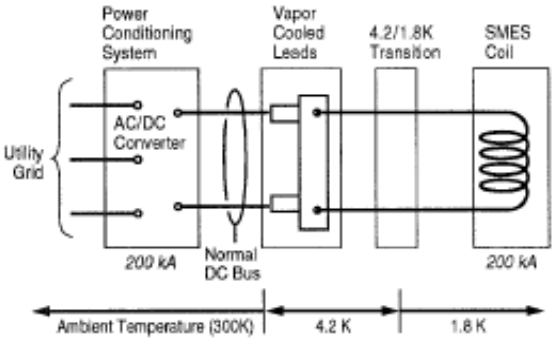
Energy Applications

Fusion Energy

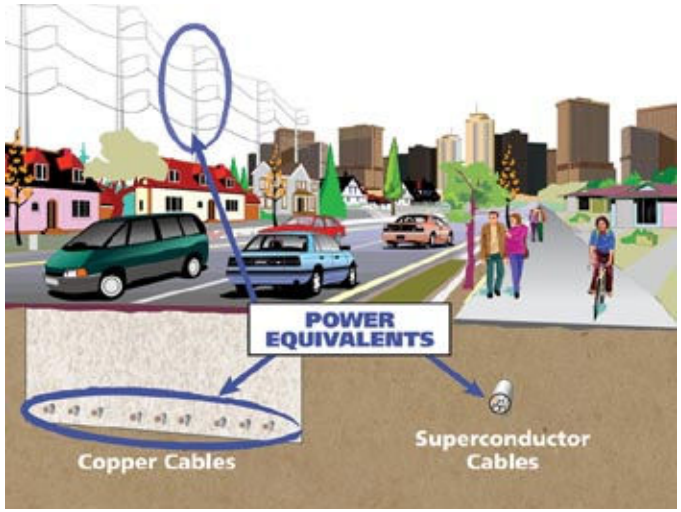


Superconducting Magnetic Energy Storage (SMES)



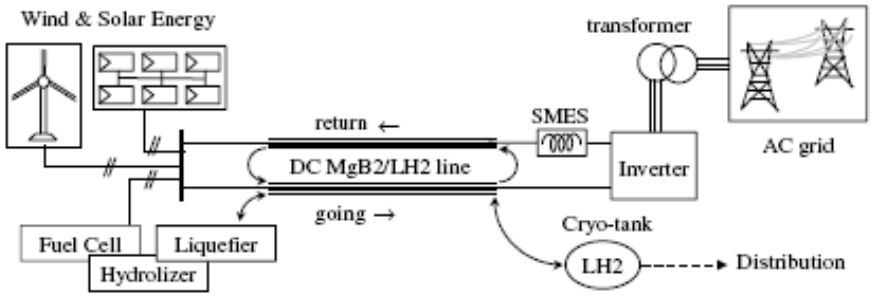


Superconducting Power Transmission Cables



Copper strand 10A/mm^2
Superconductor 600-1200A/mm^2

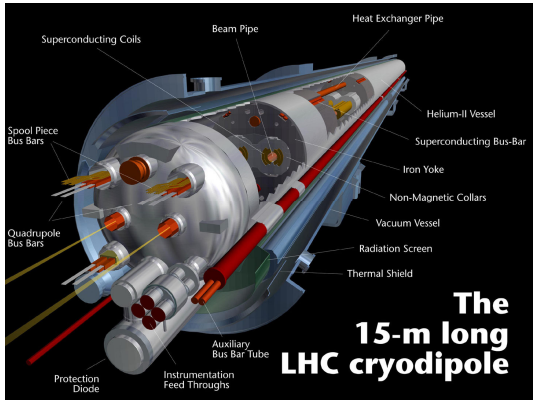
"Super-cable" Hydrogen-Electricity transport



Other Applications

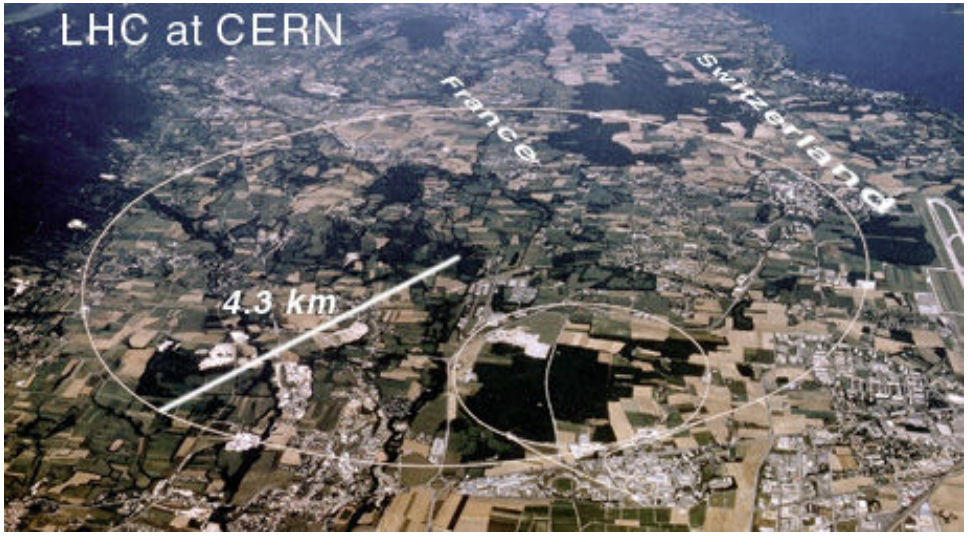
Magnetic Levitation

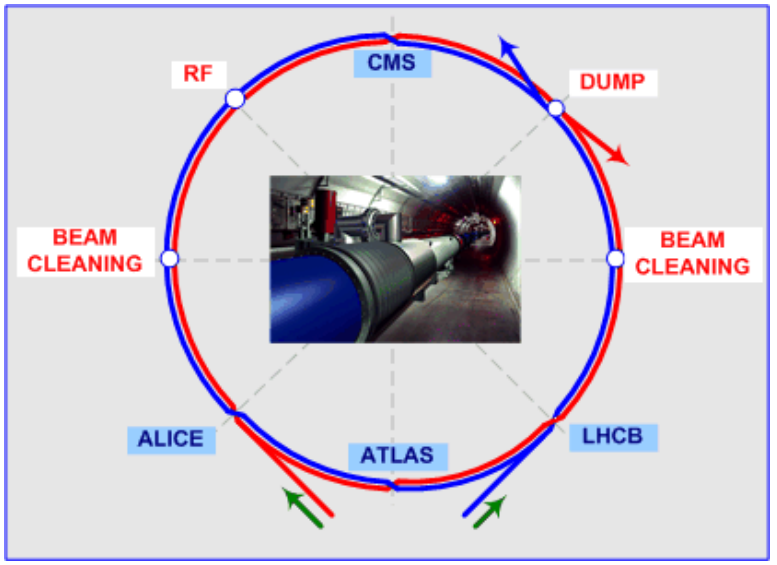
High Energy Physics



Magnetic Resonance Imaging (MRI)

High Energy Physics-LHC





The Large Hadron Collider (LHC) is a 27-kilometer circular collider in which high-energy protons in two counter-rotating beams will be smashed together in search of Higgs bosons and new particles predicted by super-symmetry.

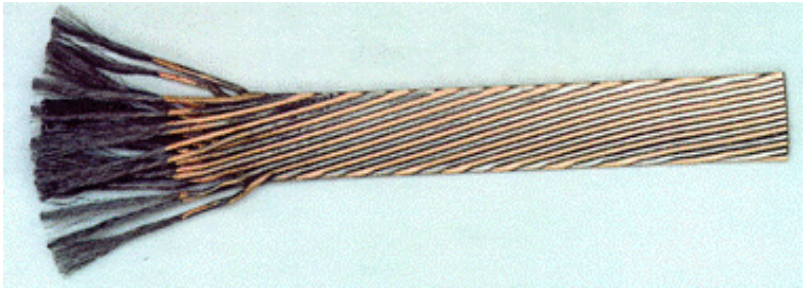
The beams are accelerated and kept circulating using superconducting magnets.

Why superconducting?
Using copper magnets we would need **>1000 MW**
With superconducting magnets "only" **120 MW**
(cryogenic 27.5 MW, experiments 22 MW)

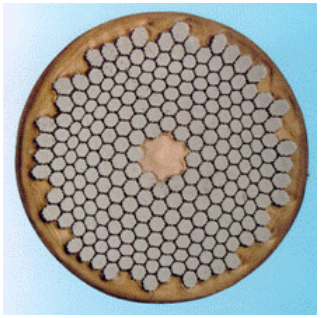
How strong is strong?

1.9 K superconducting dipoles producing a field of 8.3 T - current 11850 A.
The machine has roughly ~5000 magnets
Main magnet components are bending magnets (DIPOLES, 1232 total, 14.3m long, 35 ton in weight)
Quadrupoles are used to focus the beam in the interaction regions
Stored magnetic energy is ~1.3 GJ per sector (8 sectors, total energy stored 11 GJ).

Rutherford cable NbTi



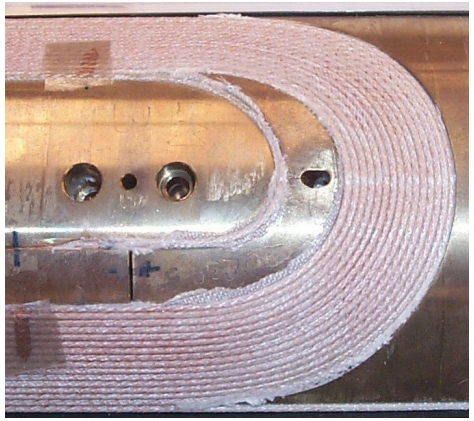
Superconducting strand



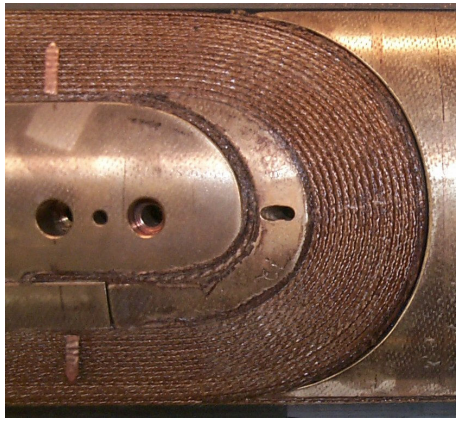
Superconducting filaments

"The combined strands of the superconducting cables for the machine would go around the equator 6.8 times. If you add all the filaments of the strands together they would stretch to the sun and back 5 times with enough left over for a few trips to the moon."

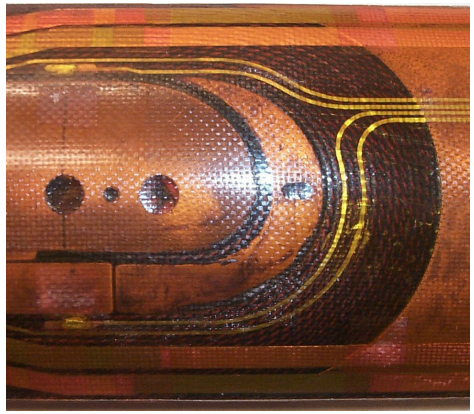
Wind



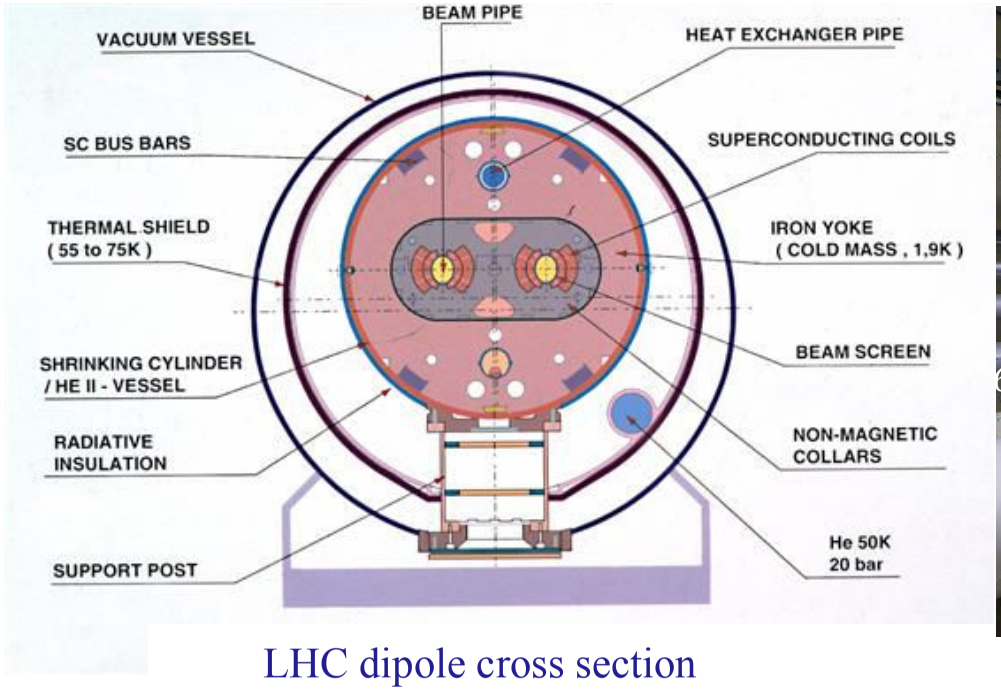
React

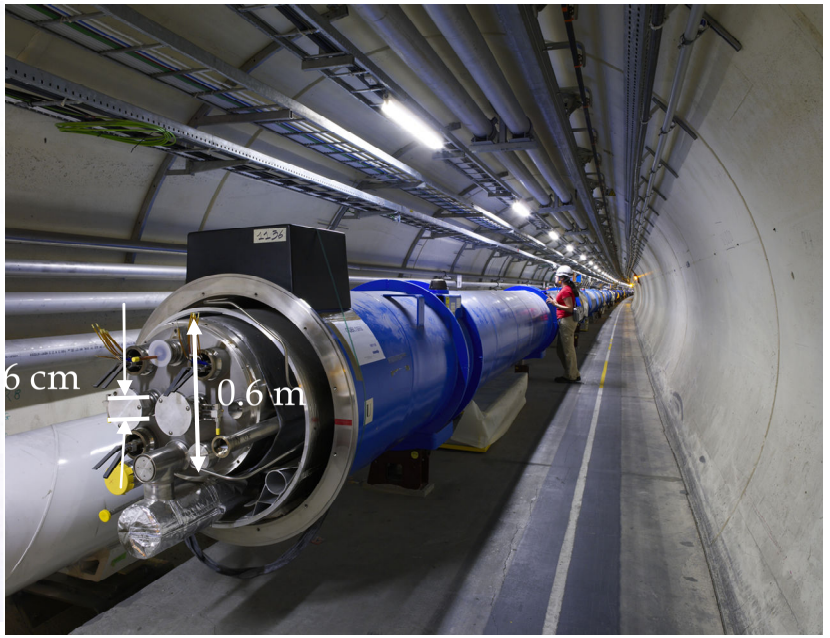


Epoxy impregnation and instrumentation



Cooling of magnets

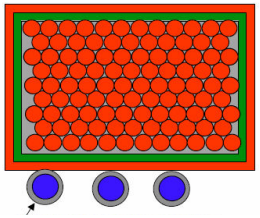




LHC dipole cross section

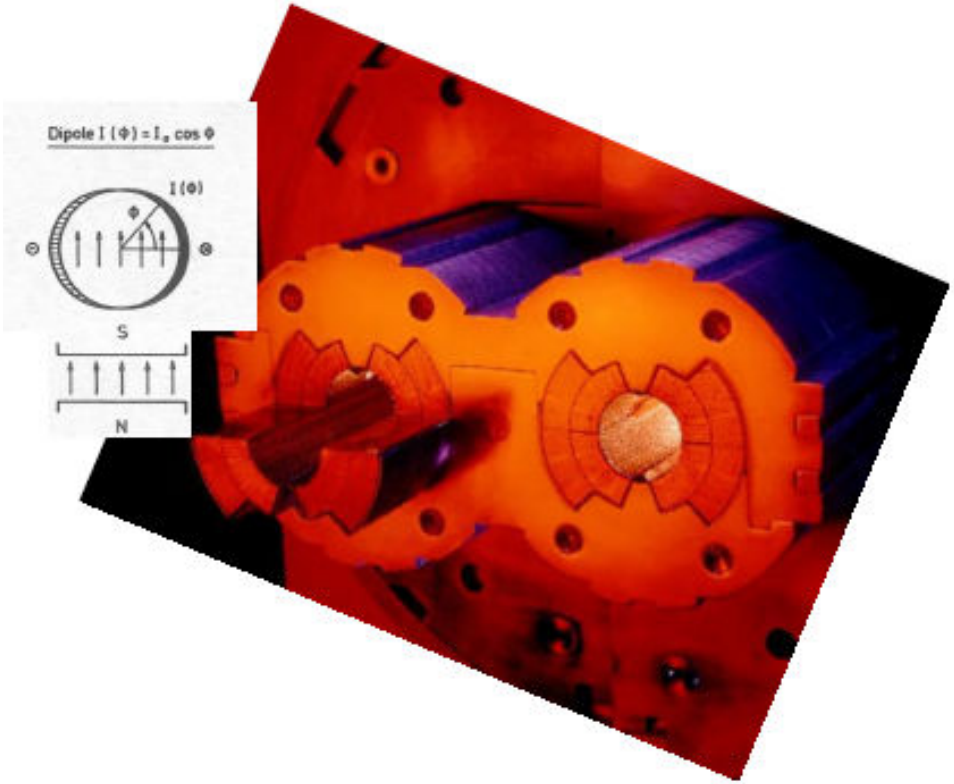
LHC magnets are NbTi and cooled with superfluid helium at 1.9 K (below 2.17 K part of the fluid has "zero" viscosity).

The cables are embedded in epoxy eliminating local coolant (adiabatic winding)
Winding is a single monolithic entity (improve mechanical stability).
The winding is globally cooled by forced-flow cryogen (vs. fusion magnets).

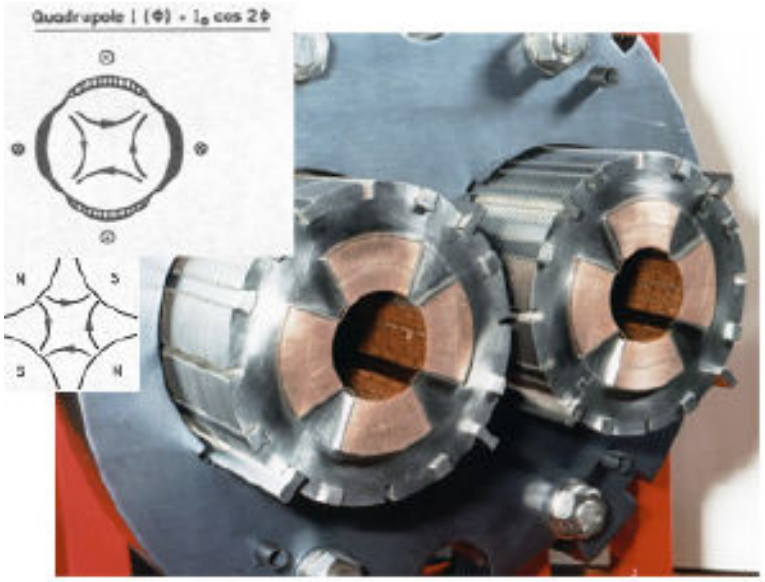


Cryogen forced through pipe

Main Magnets



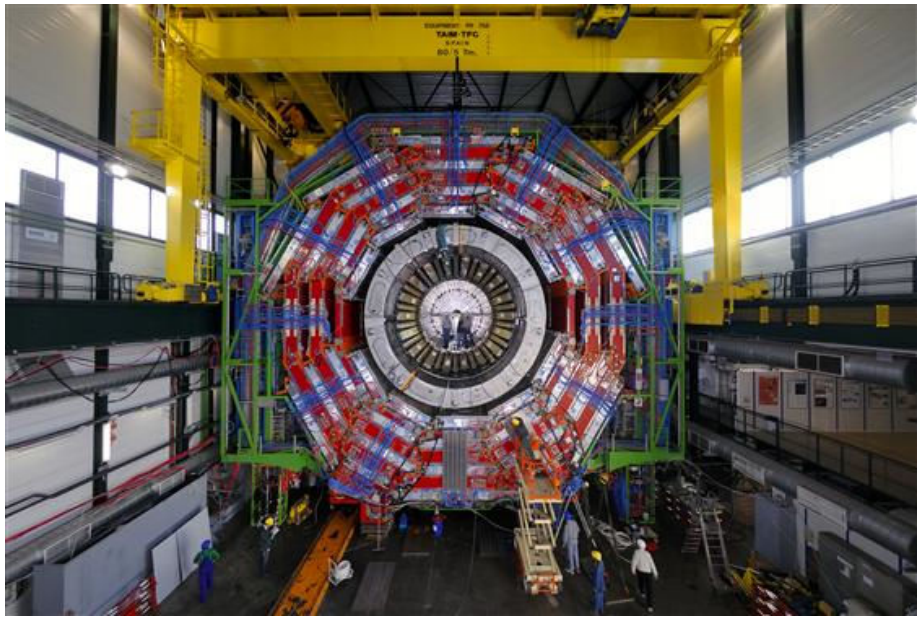
Dipole to bend the beam



Quadrupole to focus the beam at the interaction region

Magnets are designed to reach an ideal single multipole (dipole, quadrupole and so on) to avoid spreading of beam.
In real life we have to deal with harmonics and we want them to be small (0.01% deviation from ideal field) or correct them with geometry changes.

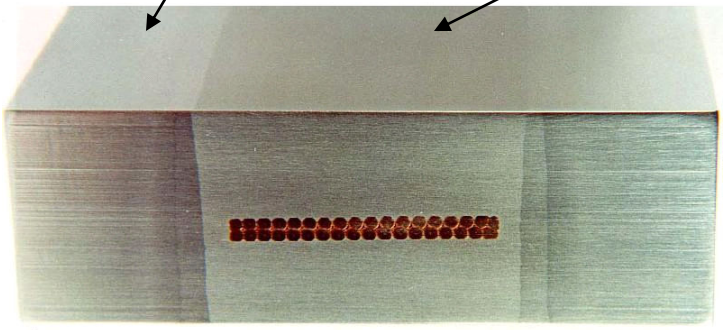
CMS detector

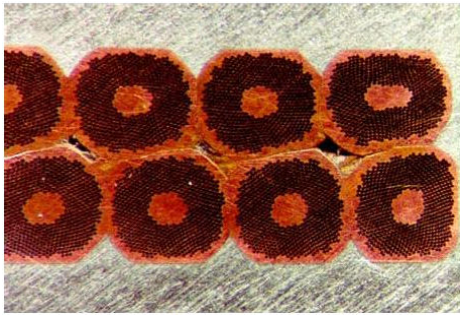


CMS detector

Cables used in CMS solenoid (cryostable)

Aluminum alloy reinforcement Aluminum stabilizer

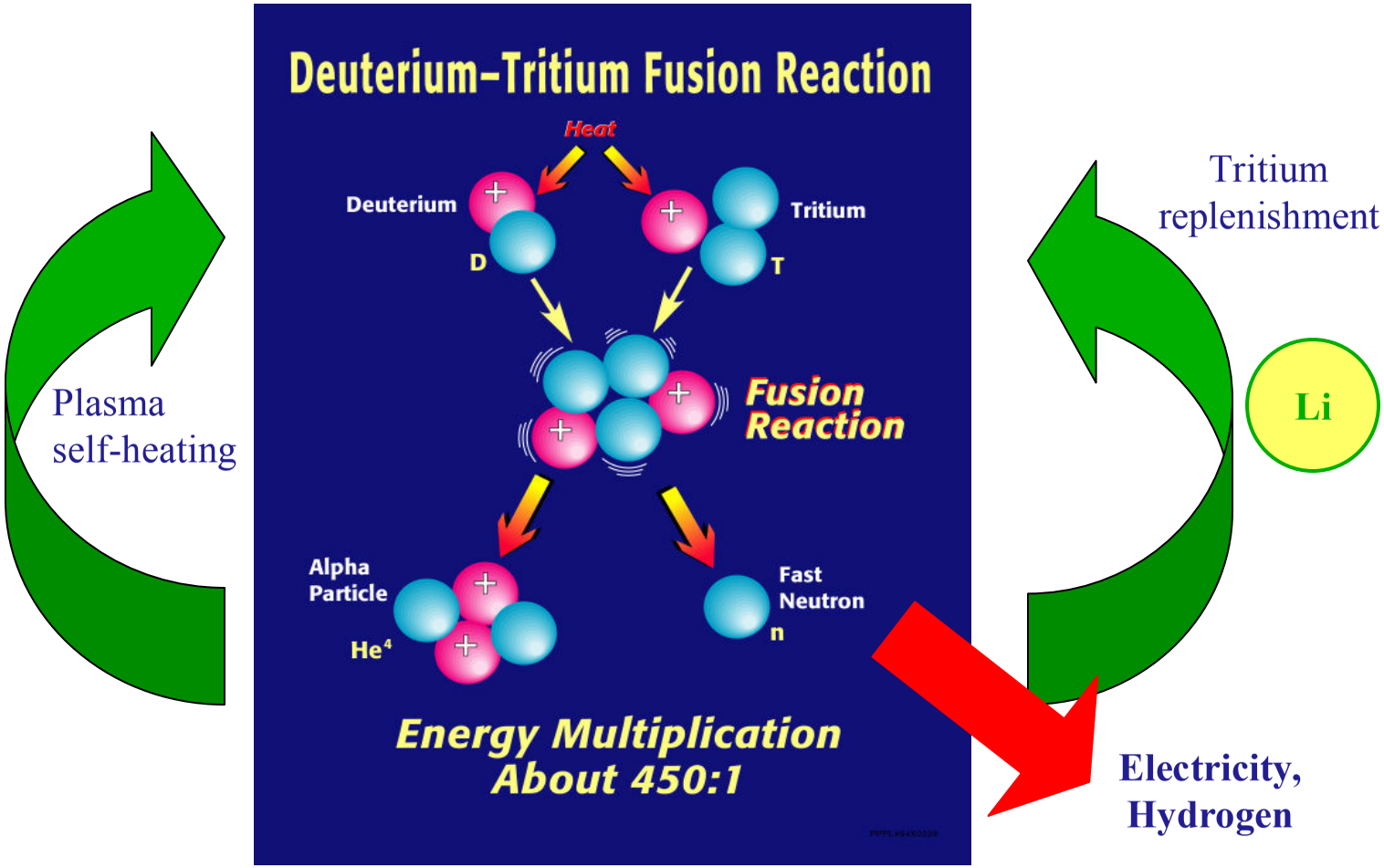




Conductor needs to absorb a lot of heat and produces lower field (~4-5T) so less superconducting strands are used in aluminum stabilizer (local coolant).

What about fusion?

Fusion and plasma physics are at the core of nature's most intriguing self driven systems.
Examples? The sun confines hot plasma (gravitational and magnetic confinements).
Producing power using fusion reactions has been the great promise of the last **50 years…**
How many more do we have to wait?

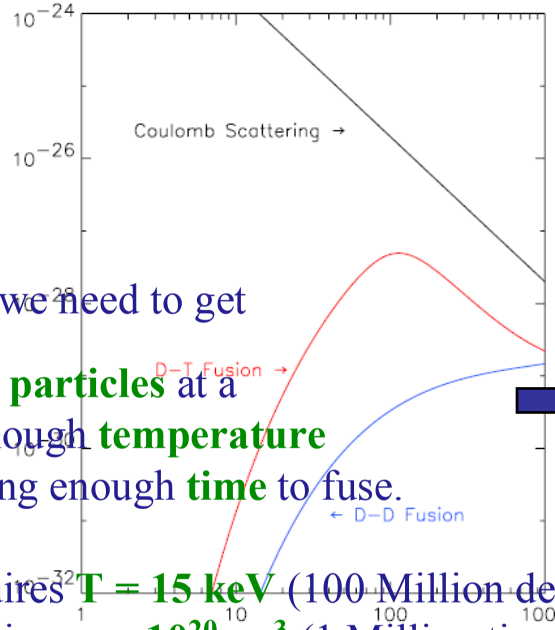


Problem: Coulomb Barrier

Like charges repel each other

Problem 1: Particles must have enough energy to overcome the coulomb barrier.
Therefore: very hot (100 *Million* Degrees) Plasma

Problem 2: In physics terms: $\sigma_{Coul} >> \sigma_{fusion}$ Thermal distribution



For fusion we need to get

a. enough **particles** at a
b. high enough **temperature**
c. for a long enough **time** to fuse.

→ $p\tau > 8$ *atm-sec*

Fusion requires **T = 15 keV** (100 Million degrees).
Fusion requires **n = 10^{20} m^{-3}** (1 Million times less dense than air).

This means we need **τ = 1 – 10 sec** → **Confinement**

How do we confine very hot particles

Hot plasmas like to spread out. How can they be confined? We can't put it in a container but…

- Gravitational Confinement:

  Stars do it this way so we need star-size plasma.

- Inertial confinement:

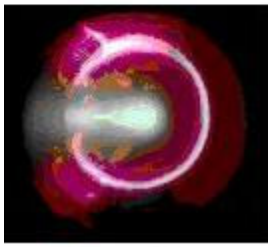
  Get enough fusion fuel hot enough and close enough together that the reaction is done before it has time to spread out.

- Magnetic Confinement:

  The leading scheme for energy production. Take advantage of charged particles tendency to cling to magnetic field lines.

Gravitational Confinement

Inertial Confinement



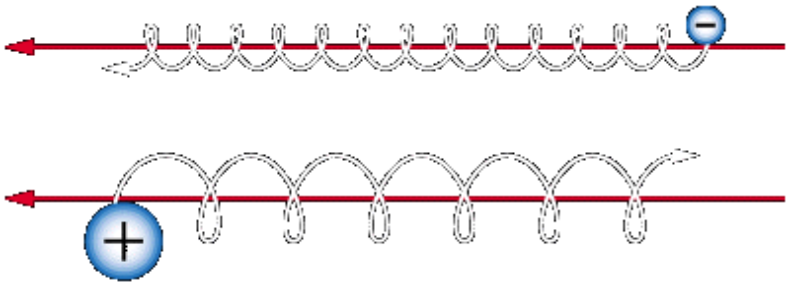
Magnetic Confinement

Magnetic confinement

Recall **cyclotron orbits**

a. Good confinement perpendicular to **B** circular orbits perpendicular to the field with gyro-radius $r_l = v_\perp/\Omega$, where $\Omega = qB/mc$

b. No confinement parallel to **B**



Uniform Field → *Incomplete confinement!*

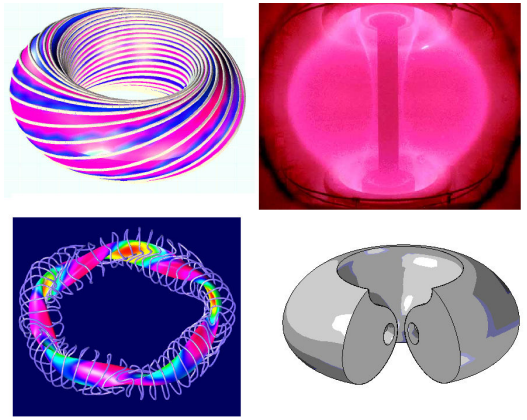
The Answer:

"Donuts. Is there anything they can't do?"

-Homer Simpson

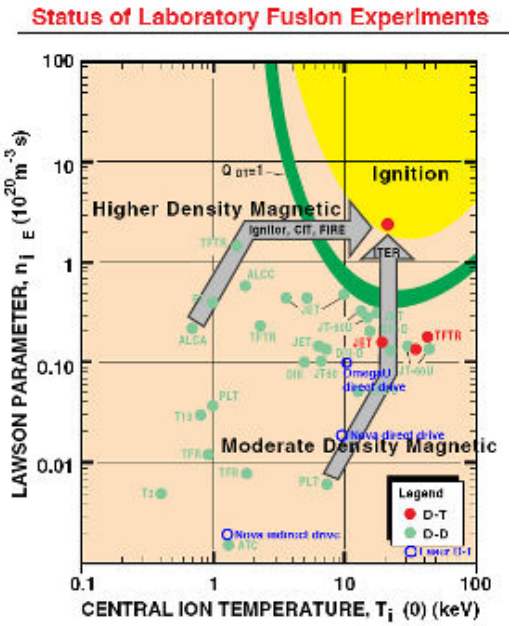
Tokamak: The most successful configuration to date.
Spherical Torus: Some advantages over tokamak but less developed.

Stellarator: More stable, but has not demonstrated confinement of a tokamak.
Dipole: Promising but tricky



What do we need to make fusion power?

We need to contain a high temperature, T, high density, n, plasma for a long enough time, τ, to achieve ignition ($Power_{out} >> Power_{in}$)
Why is it so difficult to achieve in the lab? It works large scale…



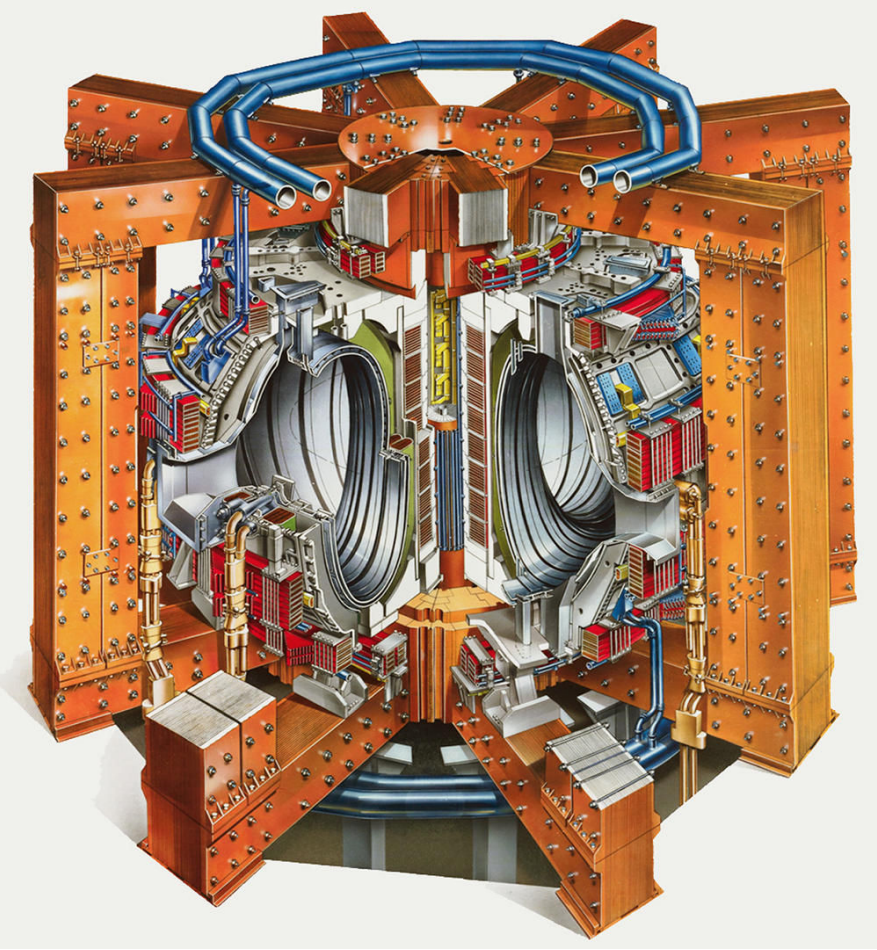
We only need τ ~ 1-10 s but τ increases with the size of the machine ($$$) and…

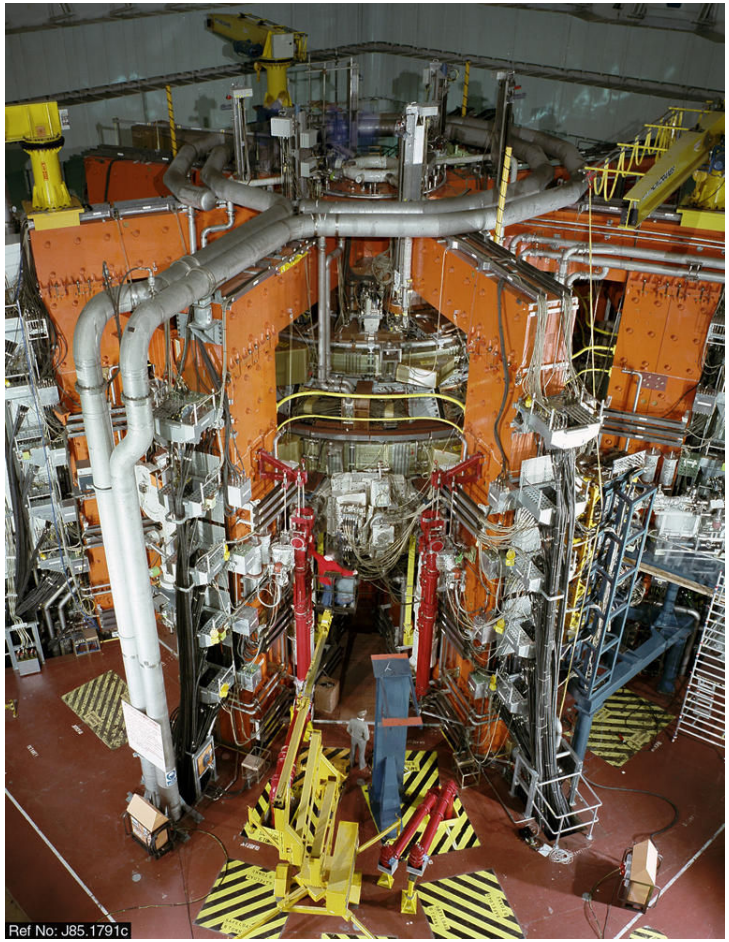
"Confining plasma is like holding jello with rubber bands"

Fusion power density in sun ~ 300 W/m^3,
In a burning plasma experiment ~10 MW/m^3
Physics (equilibrium, stability, transport) and engineering challenges

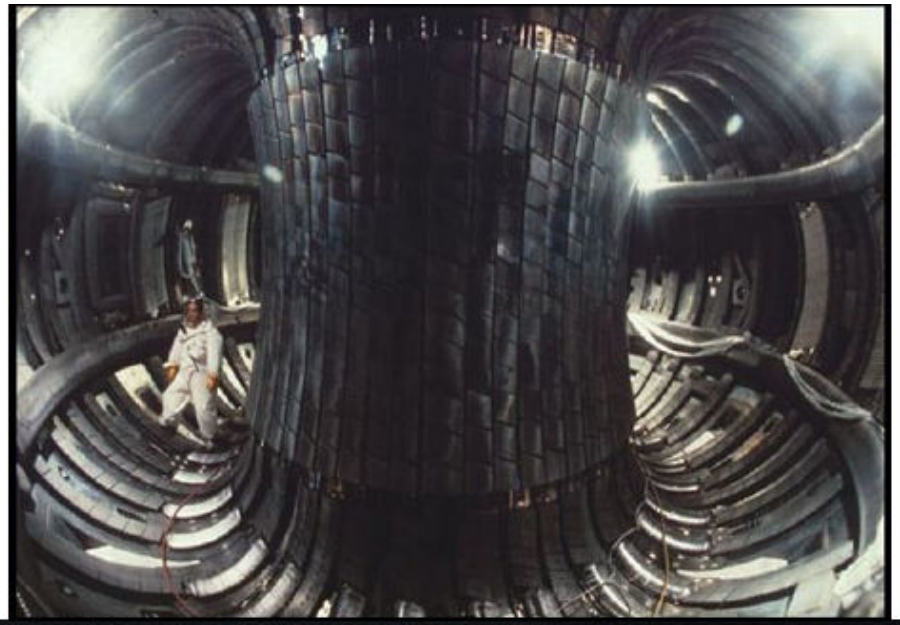
Existing experiments: Joint European Torus

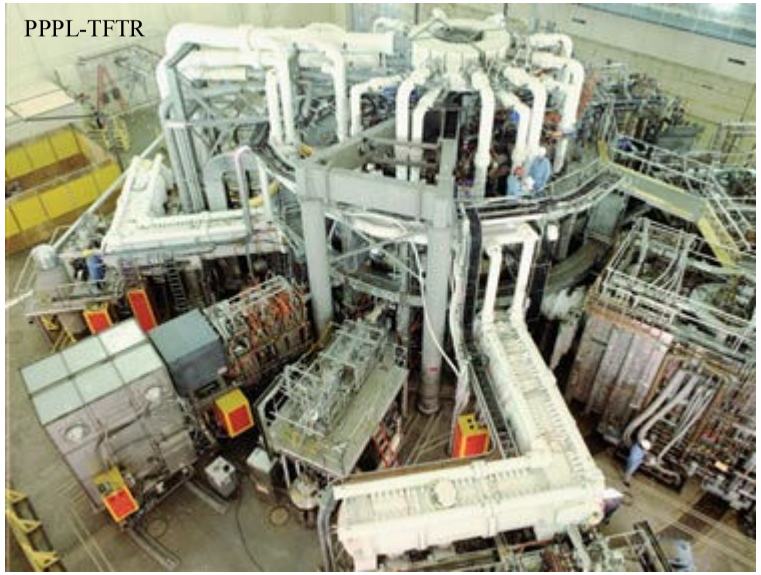
- Water-cooled copper tokamak
- World's largest fusion device

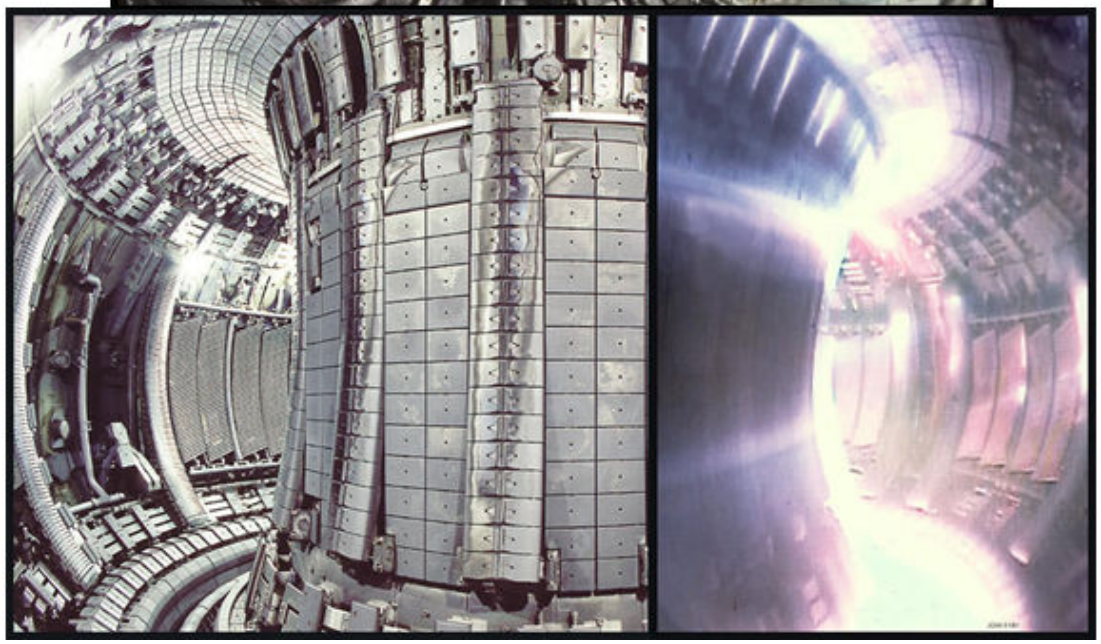




JET, PPPL, MIT

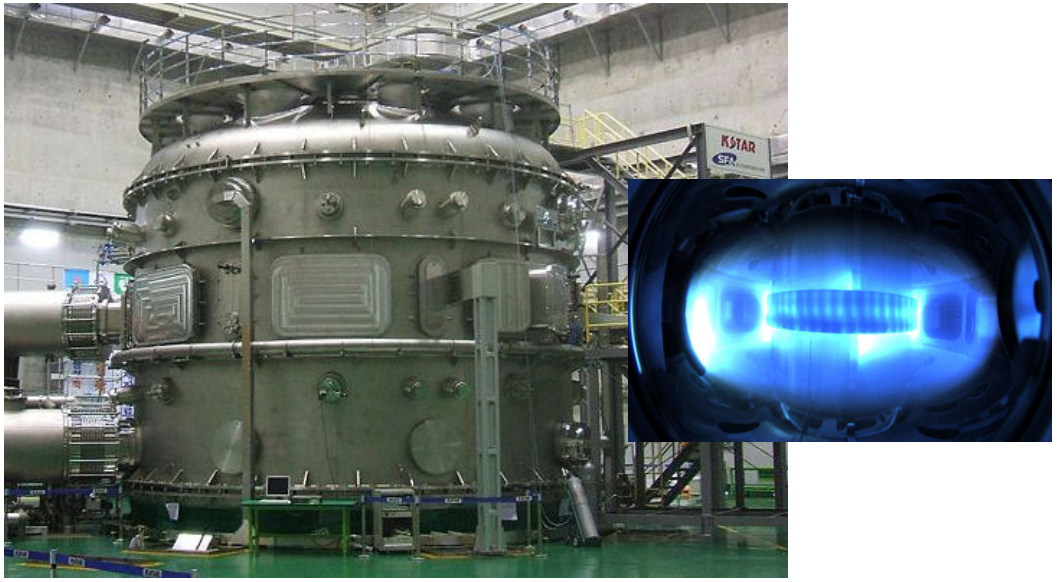






Why not superconducting then?

KSTAR Tokamak



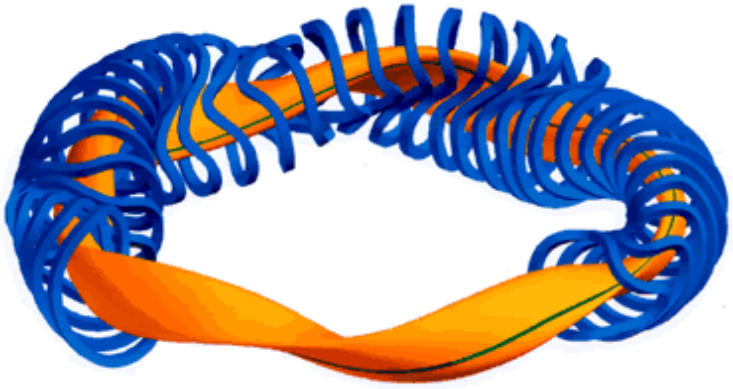
- Toroidal Field Coils - Nb_3Sn CICC with Incoloy Alloy 908 Jacket 35.2 kA 7.2 T (max field)
- Central Solenoid - Nb_3Sn CICC with Incoloy Alloy 908 Jacket 25 kA
- Poloidal Field Coils - NbTi CICC with modified 316LN Jacket
- 20 tons of Nb_3Sn is largest production run since ITER EDA Model Coils

EAST Tokamak

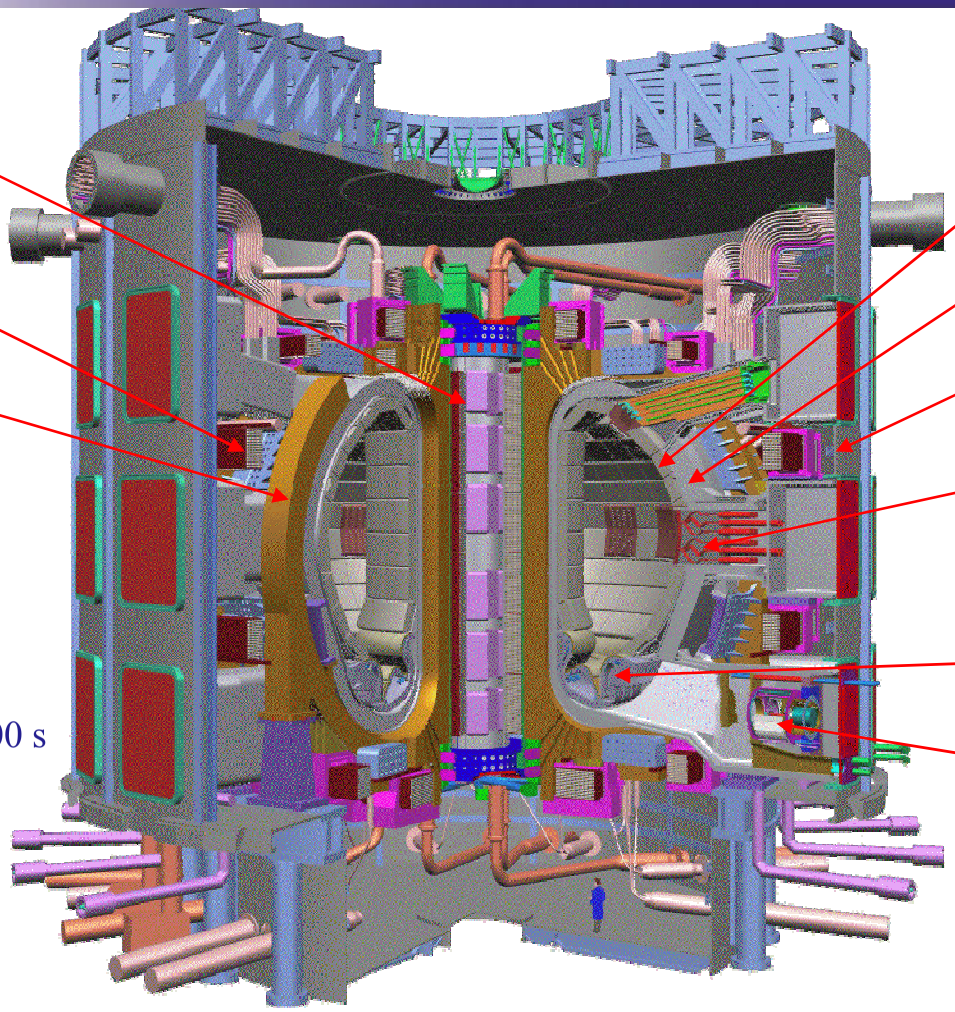
- Magnets are NbTi CICC with SS Jacket
- Operating temperature is 3.8 K
- TF 14.3 kA at 5.8 T (max field)
- CS plasma initiation cycle 14.5 kA 4.3 T (max field)
- Fast discharge at 6.8 T/s

Alternative design Stellarator

In a stellarator we use a single coil system with no longitudinal net-current in the plasma and hence without a transformer (continuous operation and inherent stability).



The future promise…ITER



Central Solenoid
Nb_3Sn, 6 modules

Poloidal Field Coil
Nb-Ti, 6

Toroidal Field Coil
Nb_3Sn, 18, wedged

Blanket Module
440 modules

Vacuum Vessel
9 sectors

Cryostat
24 m high x 28 m dia.

Port Plug (IC Heating)
6 heating
3 test blankets

Divertor
54 cassettes

Torus Cryopump
8 units

Fusion Power: 500 MW

Plasma Volume: 840 m^3

$Q \geq 10$

Plasma Inductive Burn Time ≥ 400 s

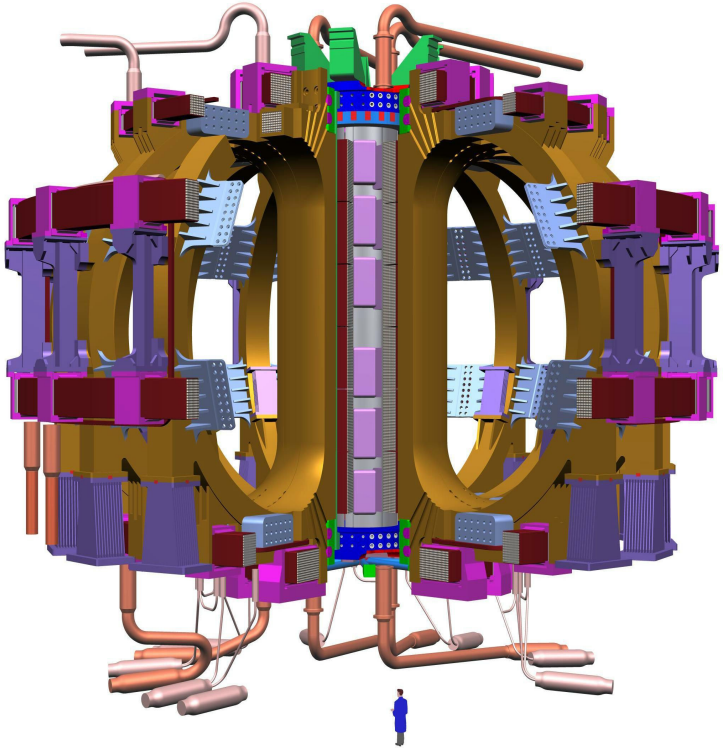
Nominal Plasma Current: 15 MA

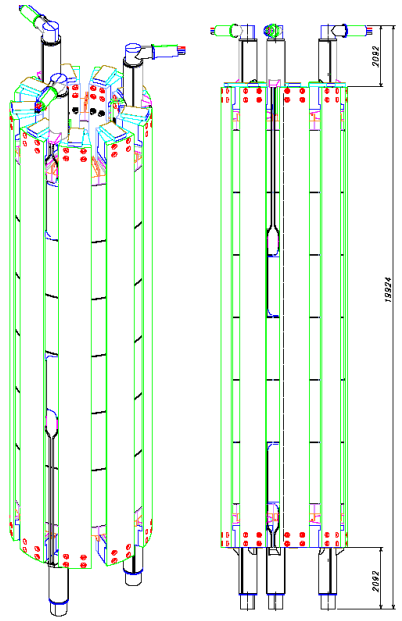
Toroidal field 5.3 T

Typical Temperature: 20 keV

Typical Density: 10^{20} m^{-3}

ITER coil assembly





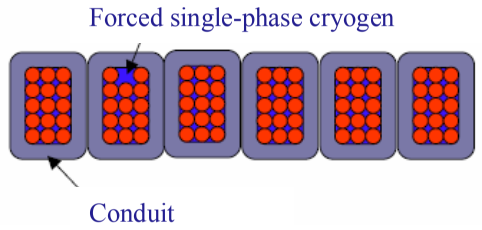
Number of TF coils	18
Magnetic energy in TF coil (GJ)	41
Operating current (kA)	68
Maximum field (T)	11.8
Centering force per TF coil (MN)	403
Vertical force per half TF coil (MN)	205

Number of CS modules	6
Magnetic energy in CS coil (GJ)	21
Operating current (kA)	41.8/46
Maximum field (T)	13.5/12.8

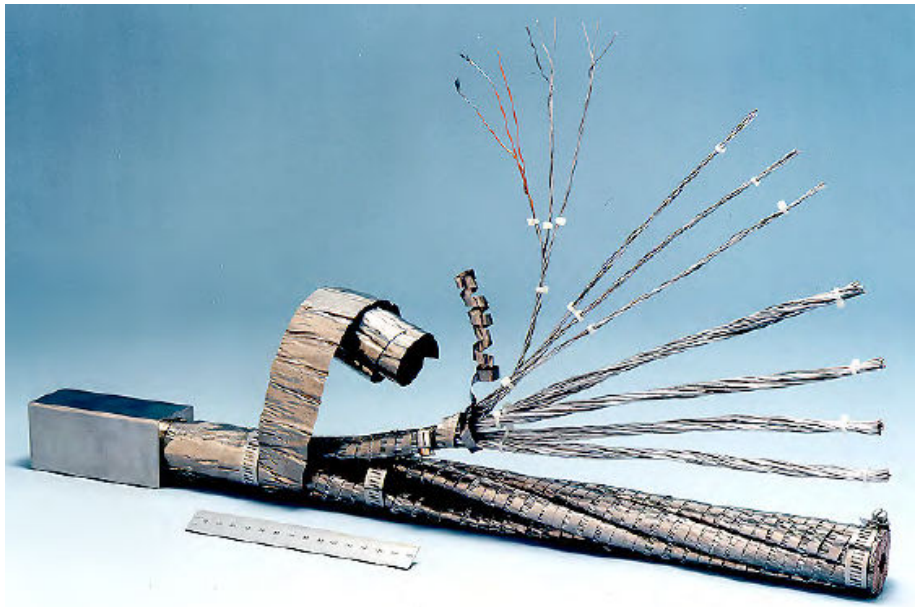
ITER technical basis

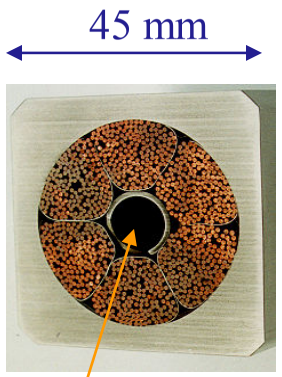
Cable-In-Conduit-Conductor

Fusion magnets are **cryostable** magnets characterized by the presence of local or "near-local" cooling (vs. HEP magnets). Cabled strands of superconductor encased in a conduit (CICC), which provides mechanical strength (R×J×B) large and through which single-phase cryogen (generally helium) is forced to provide cooling to the superconductor.



The cables are wound in stages (for example 3x3x4x5x6).
Performance of Nb3Sn cable is crucial to reach desired **plasma current** and time of **plasma burn.**
Critical effects that could reduce performance: AC losses and **mechanical effects**.



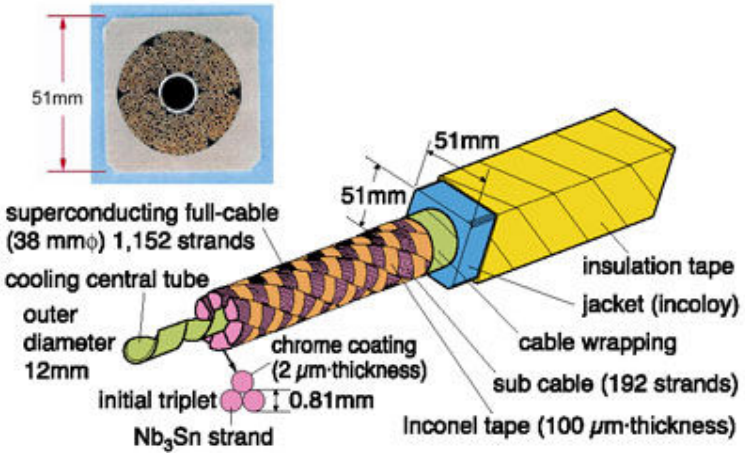


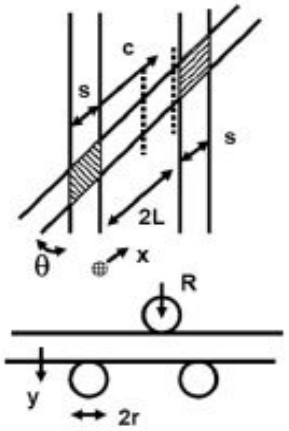
Cooling channel and void fraction ~30%

Mechanical Effects

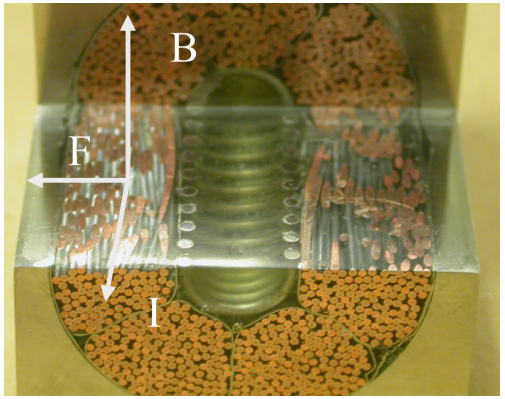
Nb_3Sn superconductor performance is **very sensitive** to strains (vs. NbTi used in HEP).
Various strains appear in a magnet:

- Axial — Thermal mismatch and hoop force
- Bending — Thermal mismatch and Lorentz force
- Transverse — Lorentz force





N. Mitchell, Fusion Eng. and Design,
Vol. 66–68, p. 971–993, 2003.

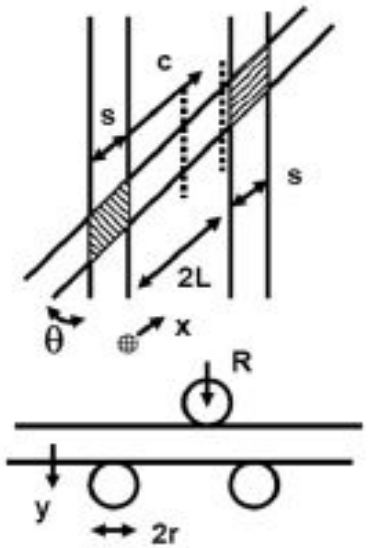


TFMC-CSMC and Bending Model

ITER model coil test results showed **unexpected degradation** in 2000-2003:
50% TFMC
35% CSI, TFI
25% CSMC

N. Martovetsky, Physica C 401 (2004) 22–27.

A **bending** model to explain the degradation has been proposed by N. Mitchell:

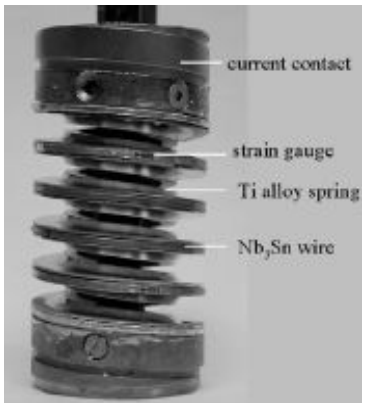


N. Mitchell, Fusion Eng. and Design,
Vol. 66–68, p. 971–993, 2003.

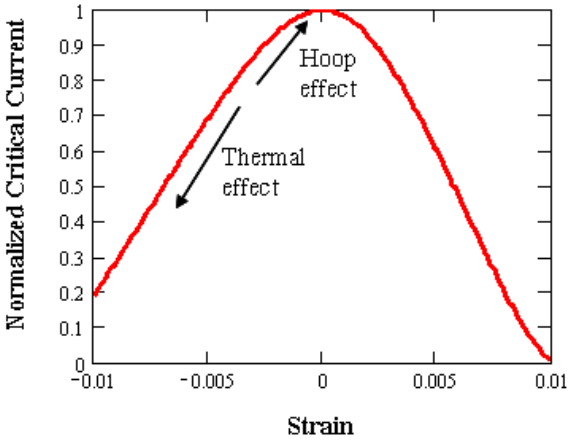
Bending is where most of the experimental work focused in the past few years.
Transverse load effect is considered secondary.

Single Strand Experiments

Uni-axial strain dependence.



D. Uglietti et al.,IEEE Transactions on Applied Superconductivity, v.13, n2, June 2003, p 3544-3547.

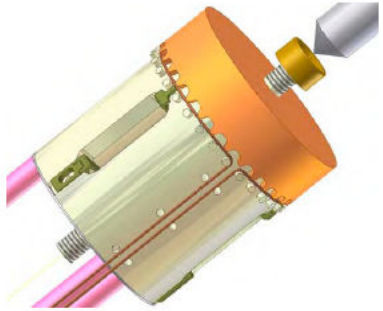


EMPIRICAL scaling laws exist to estimate the degradation caused by the axial strain.

Uncertainty exists in the real axial strain condition of a strand in a cable and this effect alone does not explain the behavior of a full size cable.

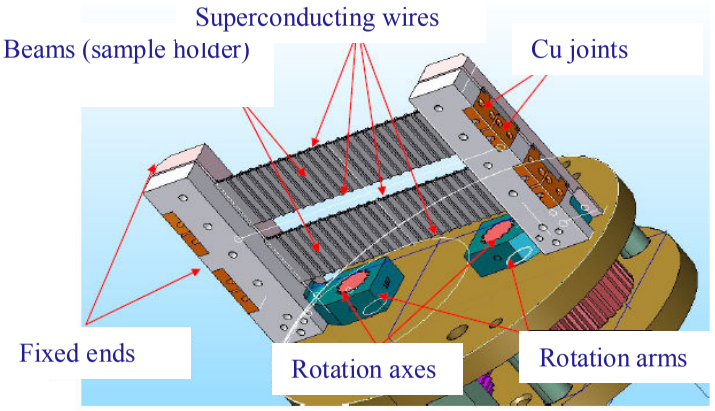
(ITER design values -0.7% for steel jacket, -0.3% for Incoloy Alloy 908®.)

Bending effect.



A Nijhuis

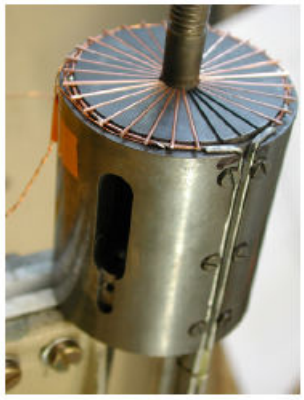
A. Nijhuis et al., Supercond. Sci. Technol. 18, 2005, p. S273-S283.



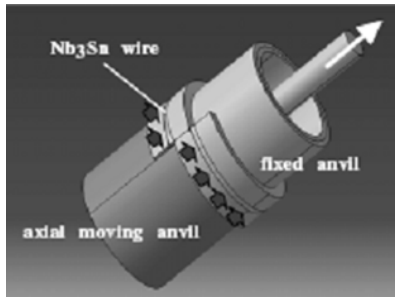
D. L. Harris, M.S. in Mechanical Engineering, Massachusetts Institute of Technology, U.S.A. 2005.

A. Allegritti, University of Bologna, Department of Mechanical Engineering, Italy, 2006.

Transverse load effect.

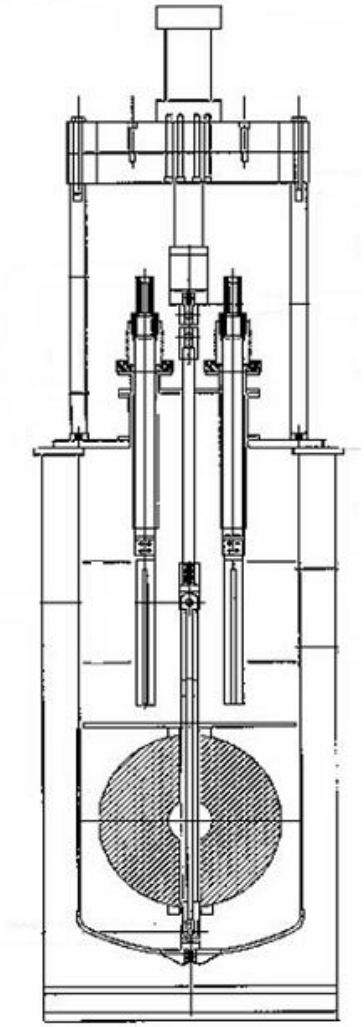


A. Nijhuis et al., Supercond. Sci. Technol. 19, 2006, p. 1089–1096.

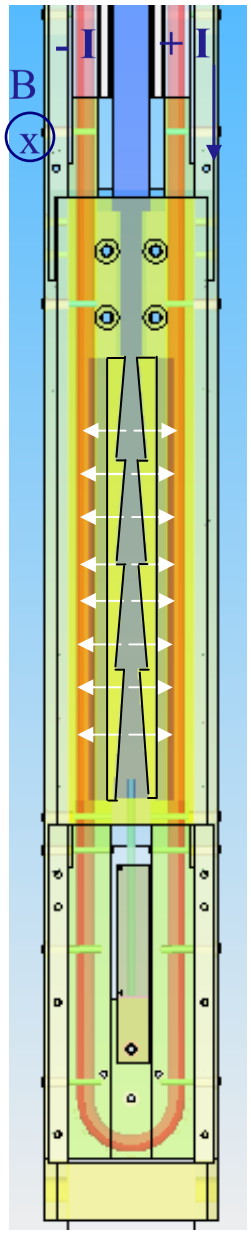


B. Seeber et al., Supercond. Sci. Technol. 20, 2007, p. S184–S188.

Transverse load of sub-cable samples



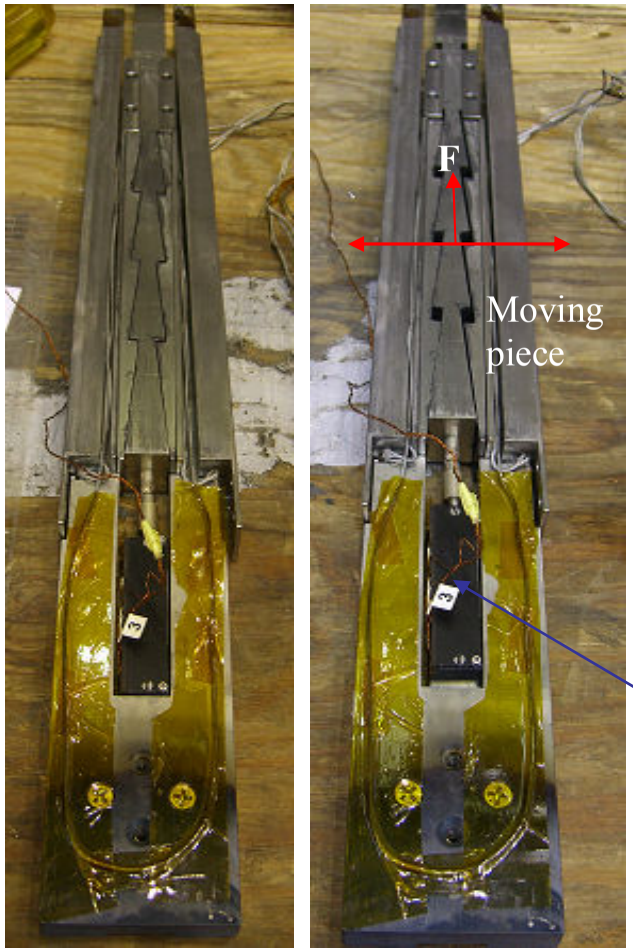
Use split superconducting magnet facility at NHMFL:
30x70 mm radial access port
150 mm axial bore (uniform high field region)
Hairpin type of cable



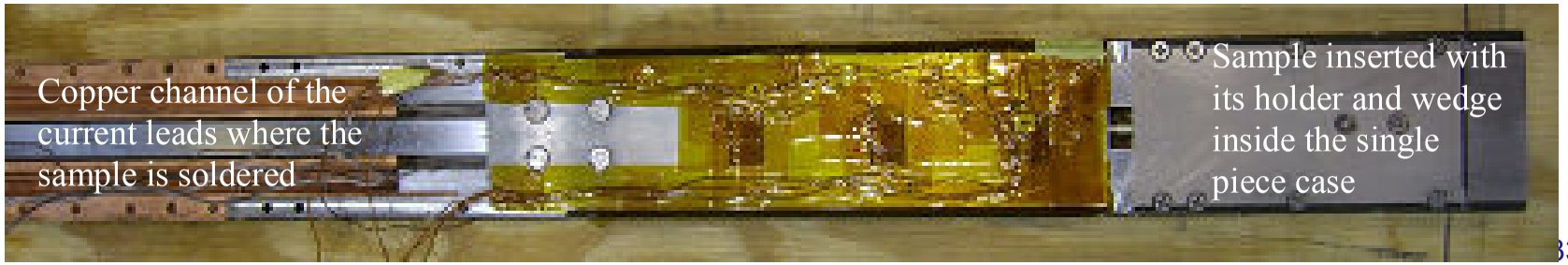
To simulate same loading conditions as ITER cable we need to apply external mechanical load (applied with a moving wedge).
To insure pressure uniformity it is necessary to use a “teeth”-like wedge.
Same structure can be used for **single strand, triplet and 45-strand samples.**
Various cable tests with minor sample holder modifications.

Hairpin Sample

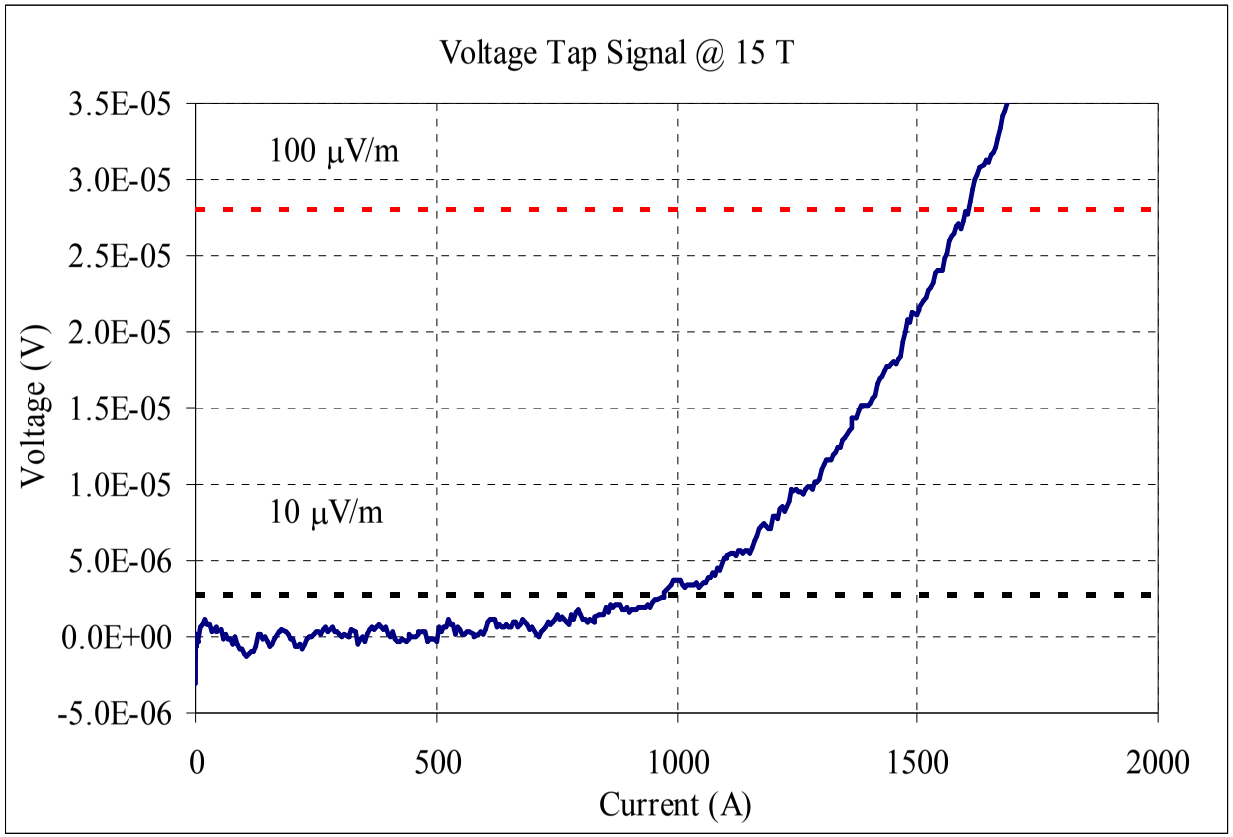
Resting position



Applying load



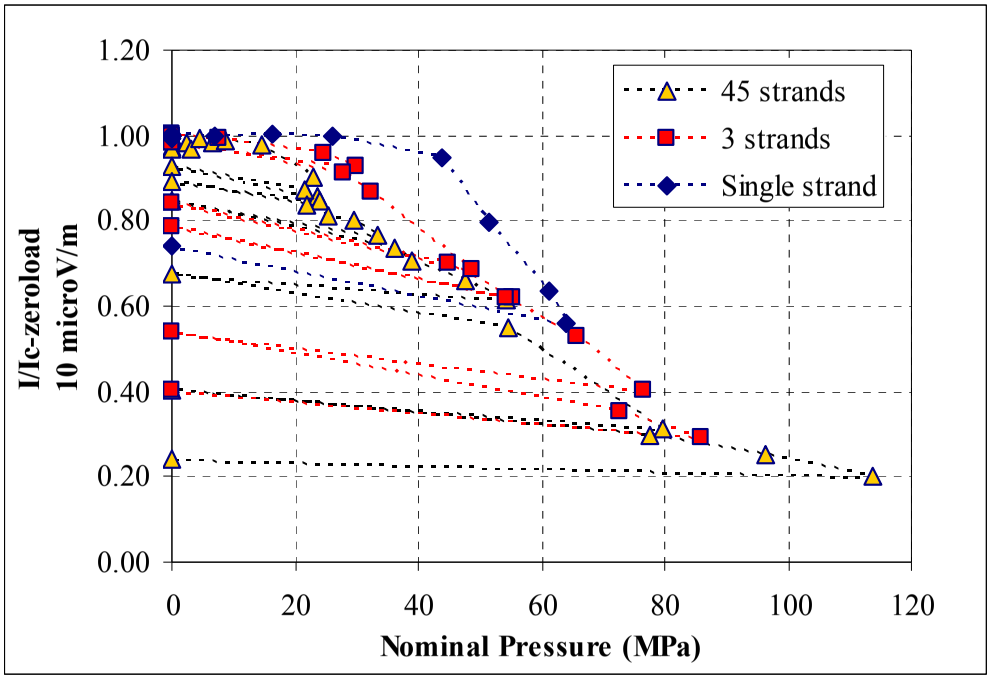
Typical Measurements



Critical current measurements are performed at **4.2 K** and **fixed field**.

Standard critical current criteria of E_{c1}=10 μV/m, E_{c2}=100 μV/m have been used to evaluate critical current.

Some Results



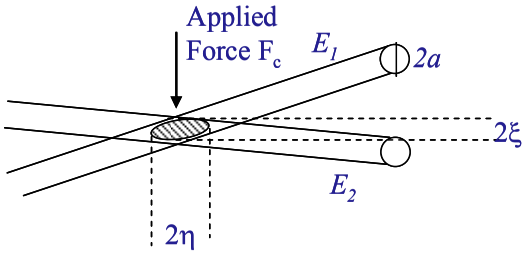
- Single strand and 3-strand cable reached the expected critical current.
- The 45-strand sample showed a 23% initial degradation.
- All samples showed a significant change in critical current as a function of the nominal pressure.
- Degradation data of single strand and 3-strand samples cannot be explained with existing bending models because they do not have significant bending, indicating Lorentz load can effect the behavior of superconductors.

Contact Mechanics and Model

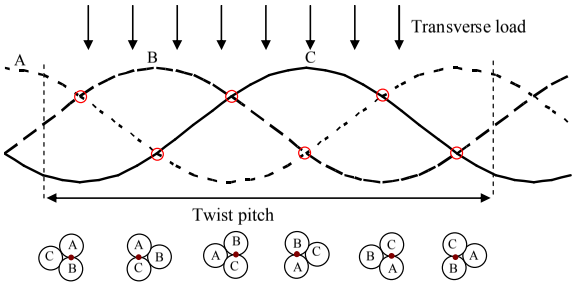
With those data contact mechanics was used to evaluate the effect of local pressure between strands and it was possible to reproduce the results of the 45-strand cable using the 3-strand data.

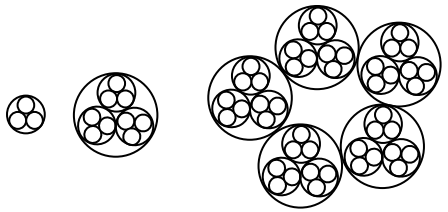
A new model was proposed to evaluate the degradation caused by the transverse Lorentz load effect on full size cables and suggestions on the cable design were made.

Here's a simplified explanation of the model…



In our experiment we applied a known total mechanical load so in order to estimate F_c we need the number of contact points in a cable

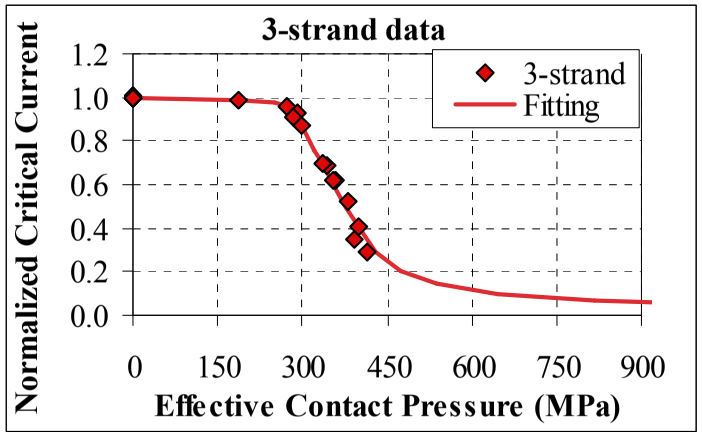


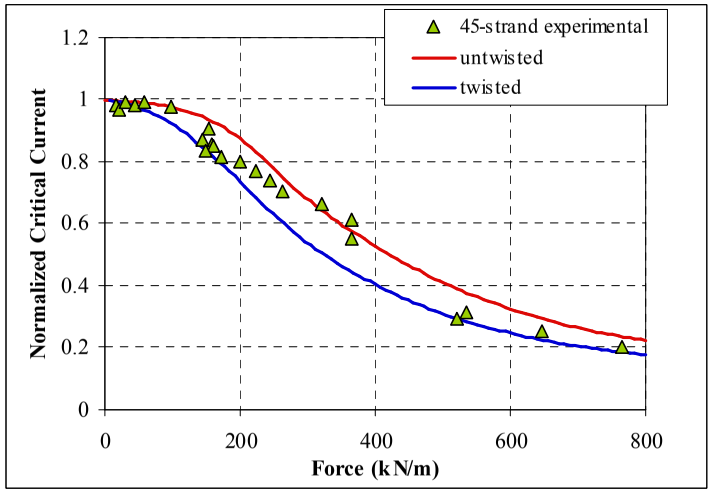


The **total contact points** per unit length for a cable with number of strand $N_s = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot k_5$
(k_i number of bundles, N_i number of contacts in a stage)

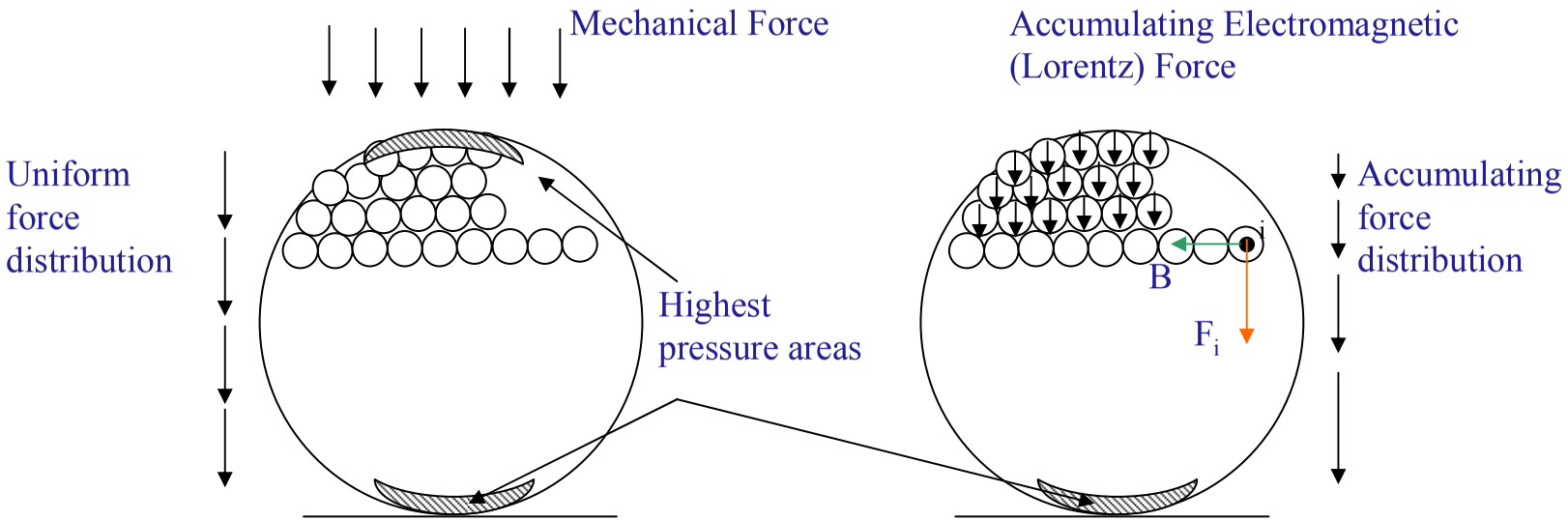
$$N_T = k_2 \cdot k_3 \cdot k_4 \cdot k_5 \cdot N_1 + k_3 \cdot k_4 \cdot k_5 \cdot N_2 + k_4 \cdot k_5 \cdot N_3 + k_5 \cdot N_4 + N_5$$

Model results

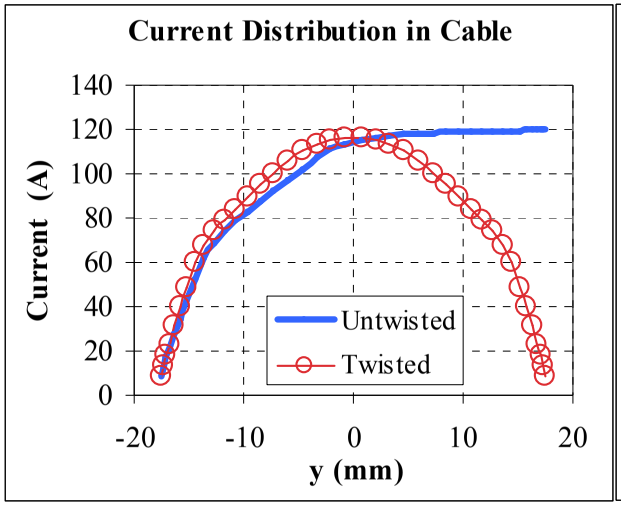


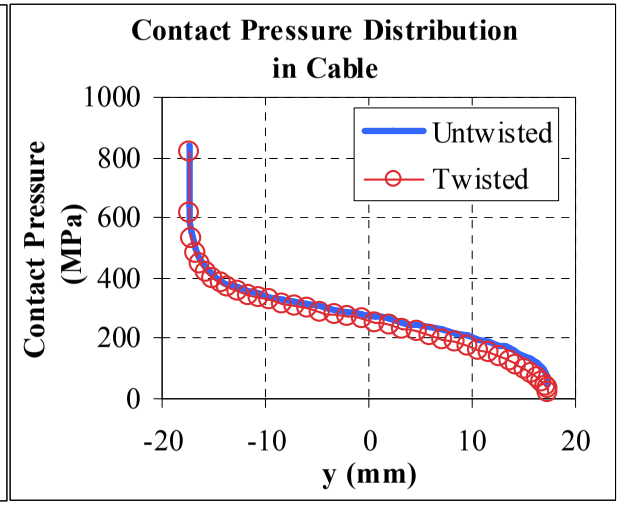


"can we predict the behavior of a cable from its smallest stage behavior (3-strand sample)?"

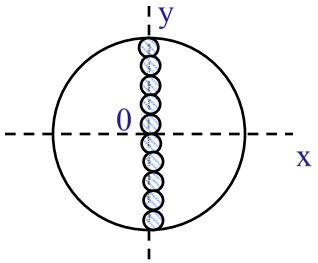


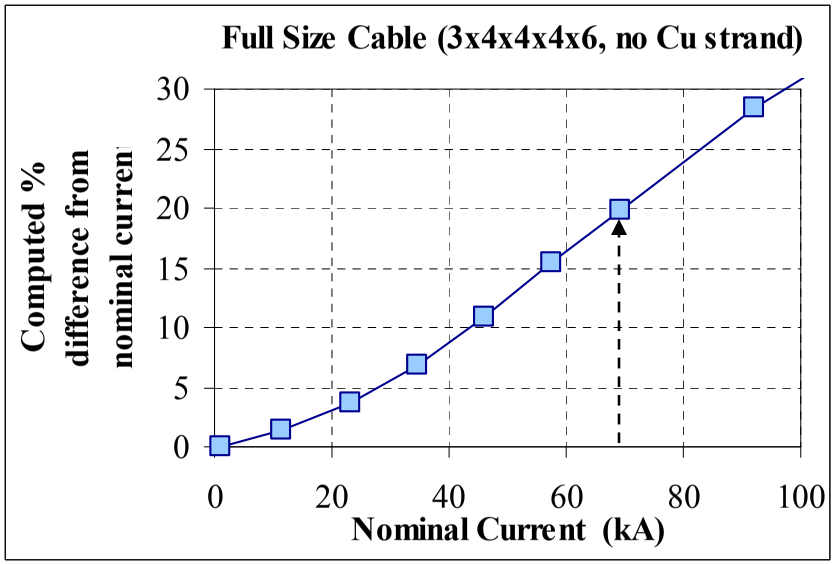
Model Results





Full size cable 3x4x4x4x6 (1152 strands).

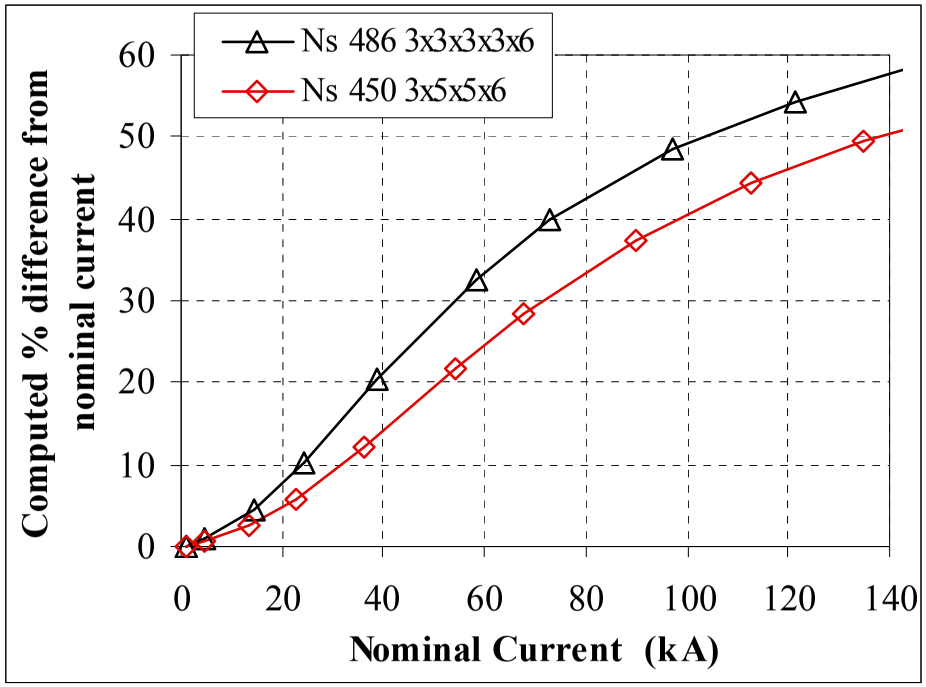




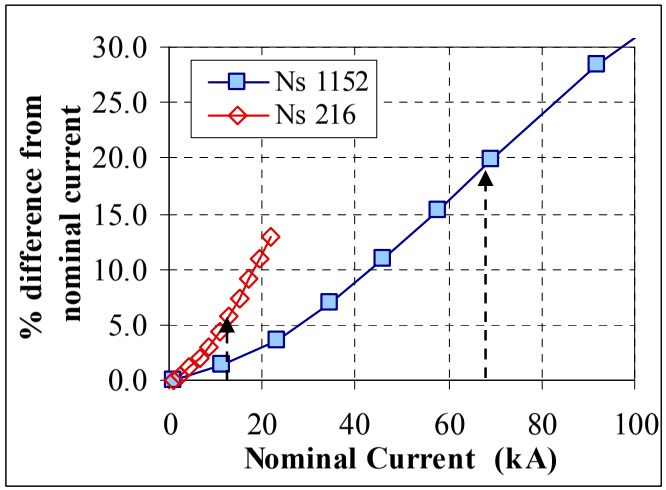
The model results show that for a full size cable with the original cable pattern proposed for the TF coil in ITER (cabling pattern 3x4x4x4x6 and twist pitches 65, 90, 150, 270, 430 mm), the Lorentz load could affect for up to 20% of degradation at operation current of 68 kA.

Axial and bending strains caused by thermal contraction and Lorentz load are additional sources of degradation.

Parametric Studies



The cabling pattern affects the performance of a cable.
A cabling pattern **3x3x3x3x6** shows a 10% larger degradation than a cabling pattern **3x5x5x6** (first pattern less number of contacts).



If the **6 petals** of the last stage are **independently supported** the total Lorentz is reduced.
The degradation in this configuration would be 6% at 11.3 kA instead of the 20% at 68 kA for the standard design.

Research needs

Despite the amount of work done in the past few years the mechanical behavior of CICC is **not** well understood.

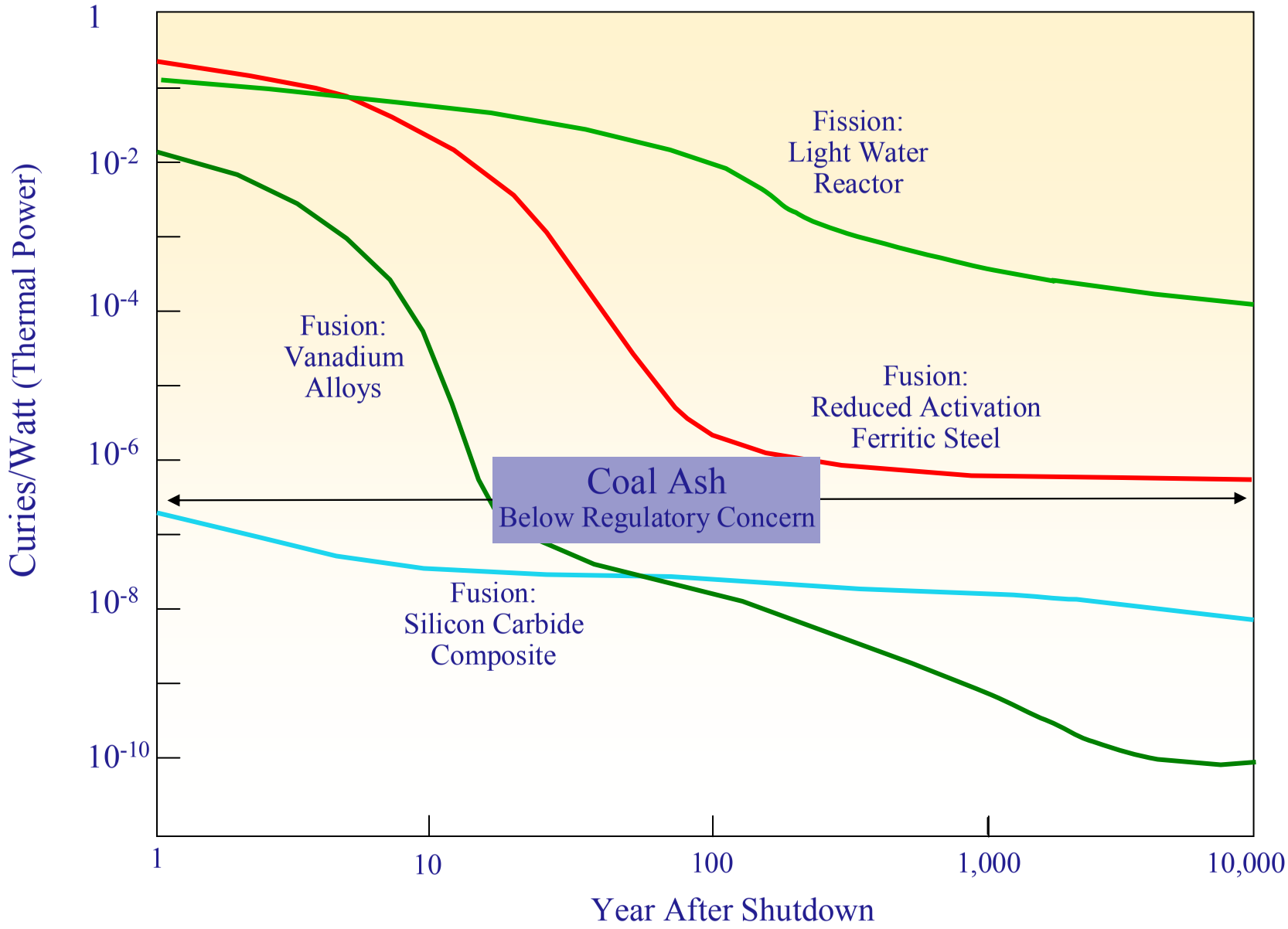
More detailed measurements of the **mechanical properties** of superconducting strands and cables are necessary to implement finite element simulations and to understand the detailed strain mechanisms under loading conditions.

A better understanding of **superconducting magnets limitations** to predict their behaviors, and more efforts in improving their designs are of vital importance to the end goal of operating fusion machine reliably.

HEP is also thinking about the LHC upgrade and Nb_3Sn conductor will be used to obtain higher fields. Understanding the mechanical properties of this material has become of vital importance for this community too.

THANK YOU

Fusion is an Attractive Energy Source

- Abundant fuel, available to all nations
  - Deuterium and lithium easily available for thousands of years
- Environmental advantages
  - No carbon emissions, short-lived radioactivity
- Can't explode, resistant to terrorist attack
  - Small quantity of fuel in the chamber, chamber breach stops reaction
- Low risk of nuclear materials proliferation
  - No fissile or fertile nuclear materials required
- Compact power source relative to solar, wind and biomass
  - Modest land usage
- Not subject to daily, seasonal or regional weather variation
  - No large-scale energy storage or long distance transmission
- Can produce *electricity or hydrogen*
  - Other potential uses:
    - desalination of water
    - deactivation of reactor waste

Comparison of Fission and Fusion
Radioactivity After Shutdown