Next Generation Superconducting Magnets for Future Accelerators

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FAS Lecture Series

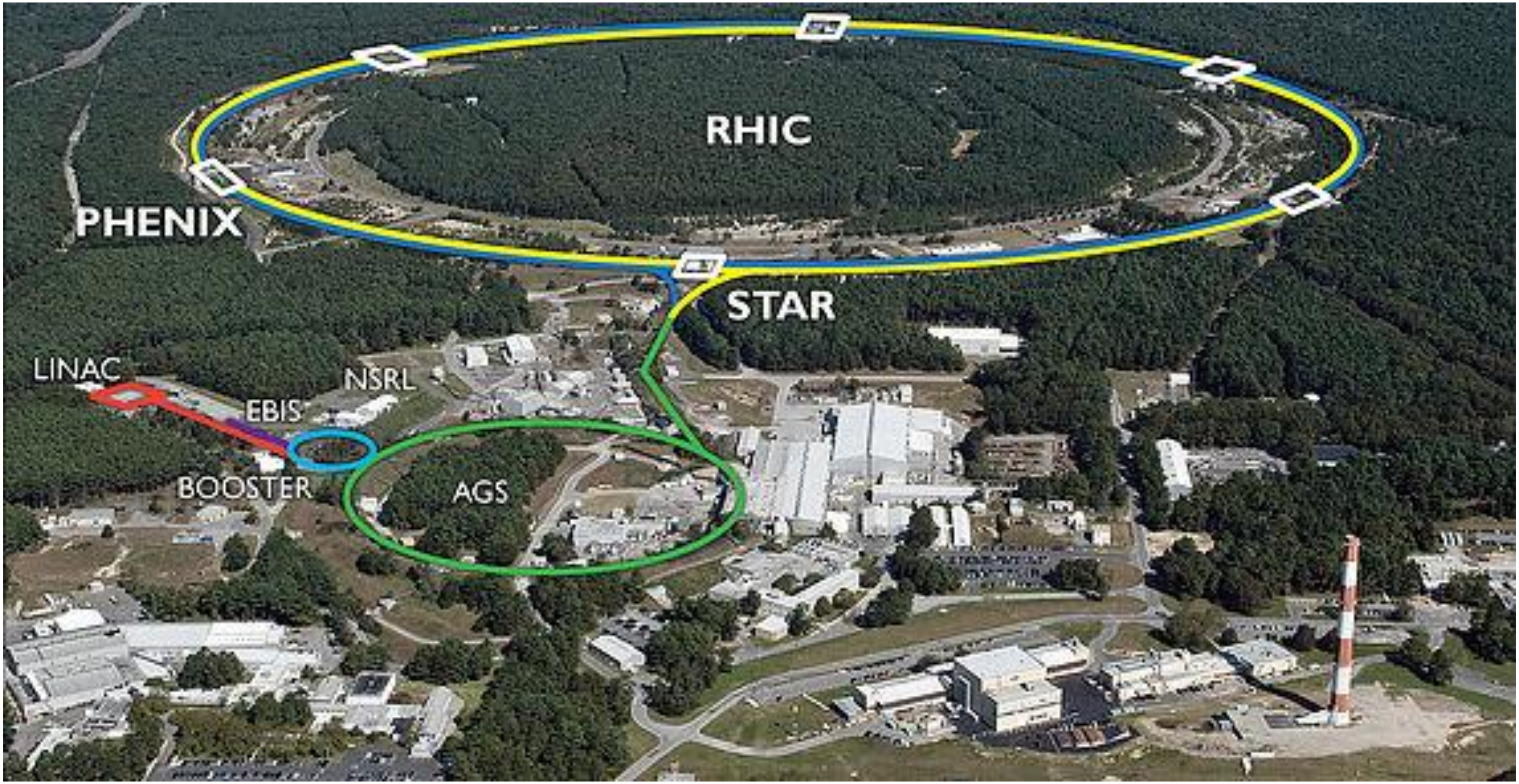
Contents

- Superconducting magnets in accelerators
- Present technology
- Future prospects
  - Need for developing new designs and technologies
- Opportunity for graduate students
- Summary

Superconducting Magnets in Accelerators

- After the discovery of the Higgs Boson at CERN, the scientific community is looking for the next generation higher energy collider
- Superconducting magnets are the key components
- The panel instituted by the US Dept. of Energy has recommended an aggressive R&D to develop higher field, lower cost magnets
- Superconducting magnets define the foot-print of the machine
    - ❑ Higher field means smaller size
- They fill most of the tunnel. They are the cost driver
- In fact, often the superconducting magnets is the enabling technology for many discoveries in high energy and nuclear physics
- Next generation accelerators need next generation magnets

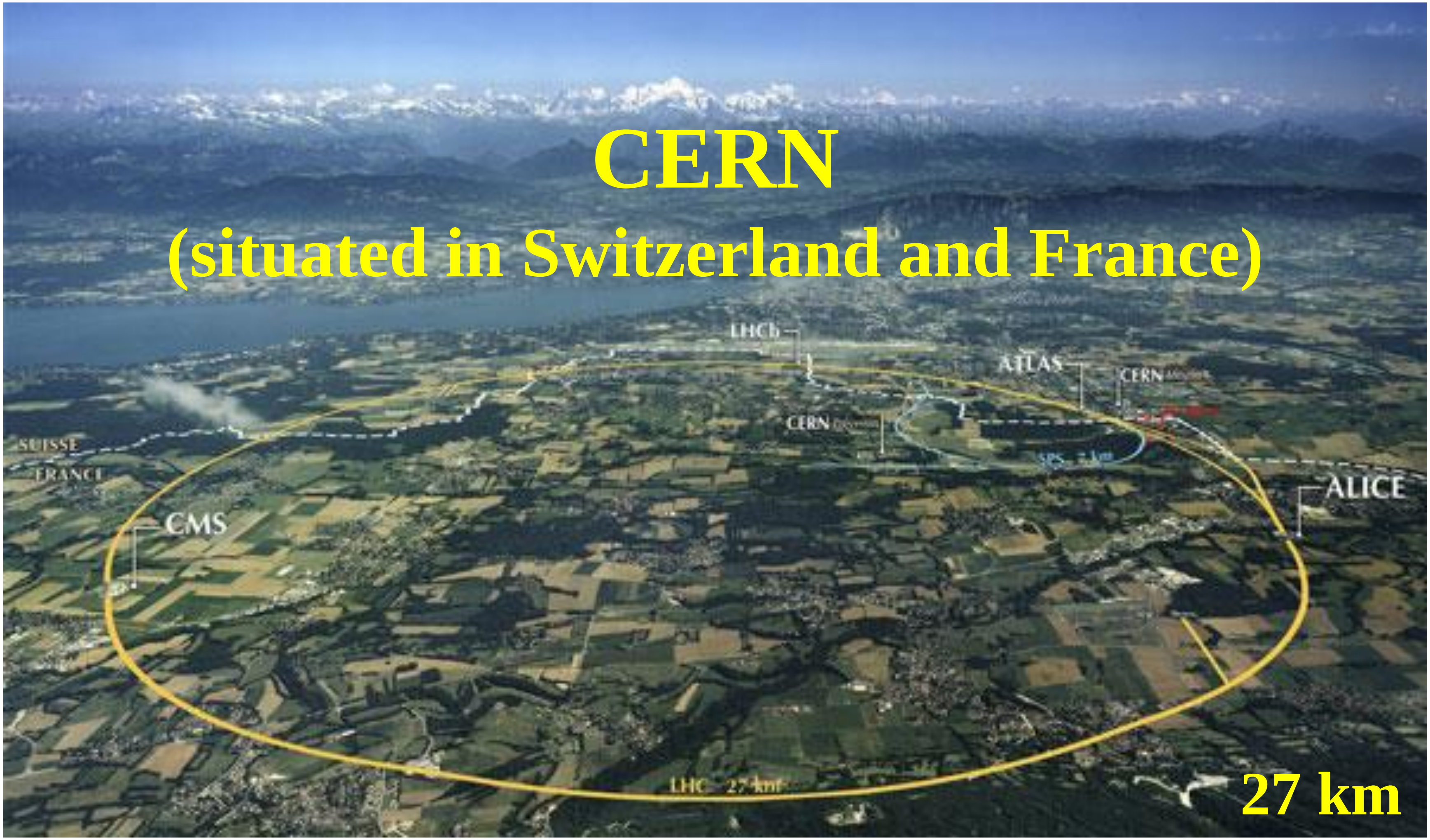
Relativistic Heavy Ion Collider



3.8 km circular tunnel - mostly filled with magnets

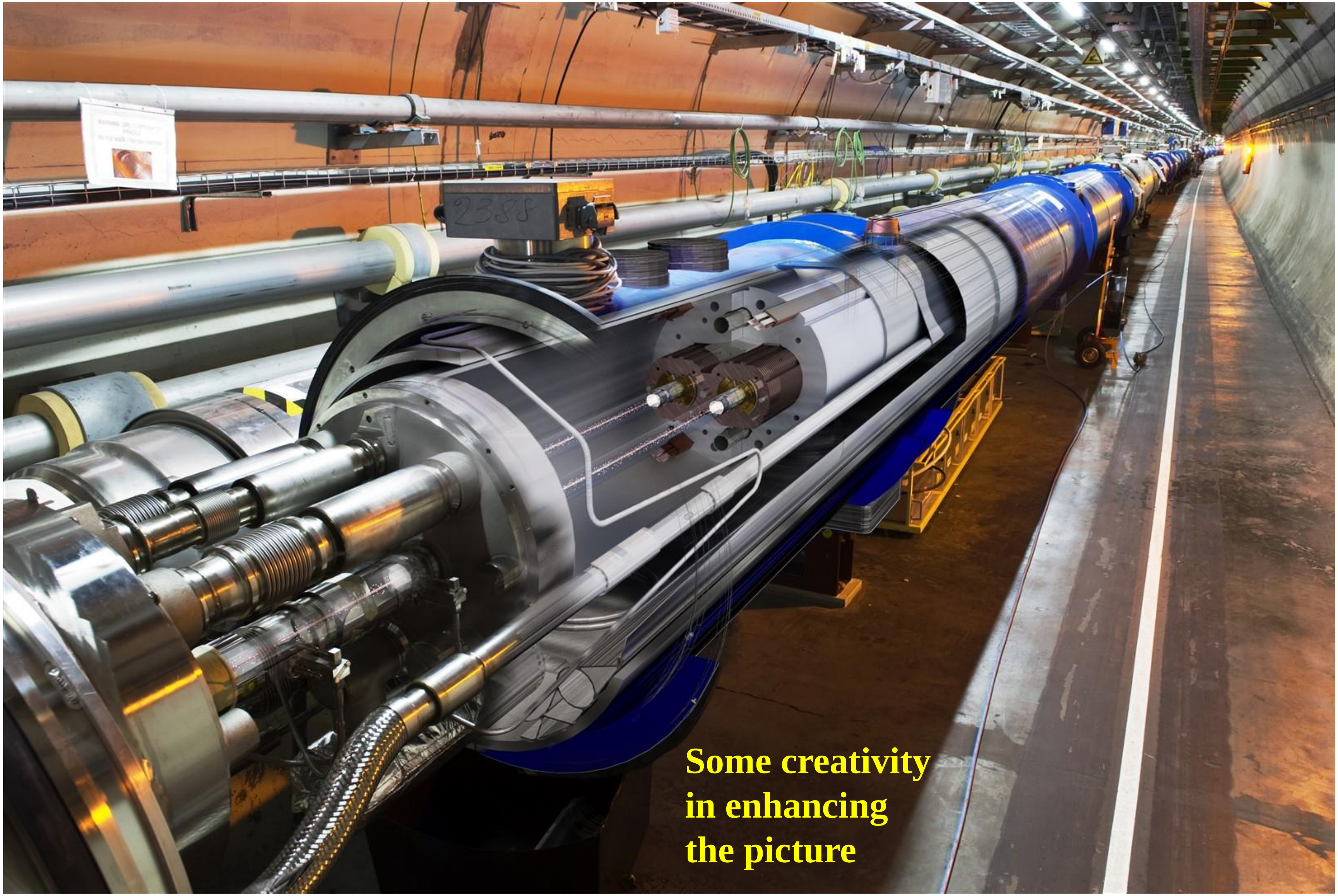
Superconducting Magnets inside the RHIC Tunnel

Large Hadron Collider (LHC)



Credits: Many pictures in this presentation are taken from web, a large number from CERN

Superconducting Magnets inside the LHC Tunnel



Major Accelerator Projects in Past with Superconducting Magnets

Machine	Location	Energy	Circumference	Status
Tevatron	Fermilab, USA	900 GeV (p) X 900 GeV (p-)	6.3 km	Commisioned: 1983
HERA	DESY, Germany	820 GeV (p) X 30 GeV (e)	6.4 km	Commisioned: 1990
~~**SSC**~~	~~SSCL, USA~~	~~20 TeV (p) X 20 TeV (p)~~	~~87 km~~	~~Cancelled: 1993~~
~~**UNK**~~	~~IHEP, Russia~~	~~3 TeV~~	~~21 km~~	~~Suspended~~
RHIC	BNL, USA	100 GeV/amu X 100 GeV/amu (proton: 250GeV X 250 GeV)	3.8 km	Commisioned: 2000
LHC	CERN, Europe	7 TeV (p) X 7 TeV (p)	27 km	Commissioned: 2008

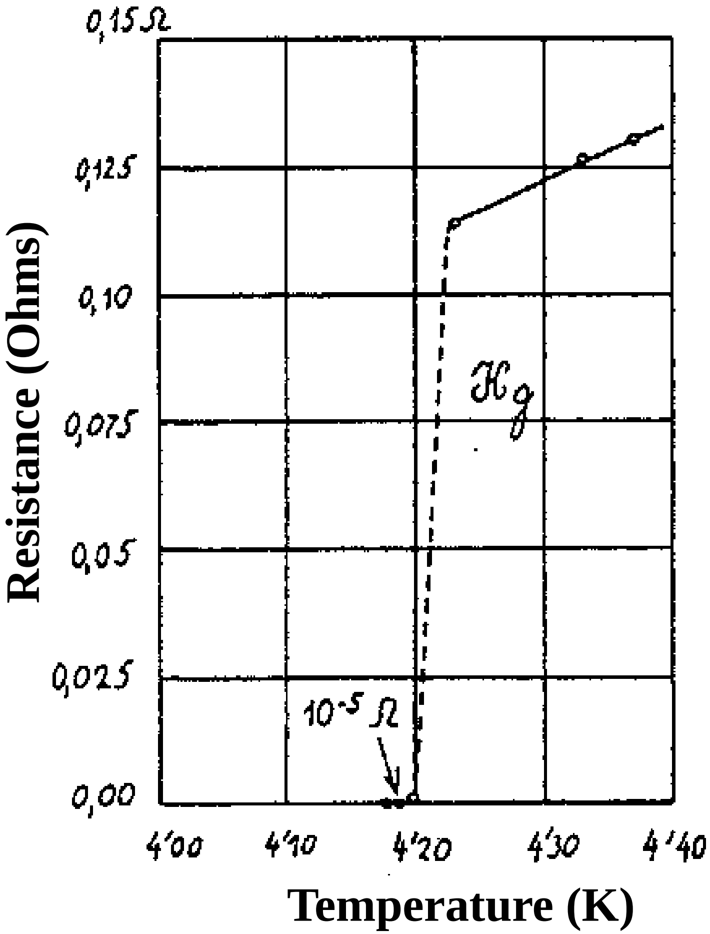
	Dipoles				Quadrupoles			
Machine	B(T)	Aper(mm)	Length(m)	Number	Grad(T/m)	Aper(mm)	Length(m)	Number
Tevatron	4	76.2	6.1	774	76	88.9	1.7	216
HERA	4.68	75	8.8	416	91.2	75	1.9	256
~~**SSC**~~	~~6.7~~	~~50~~	~~15~~	~~7944~~	~~194~~	~~40~~	~~5.7~~	~~1696~~
~~**UNK**~~	~~5~~	~~70~~	~~5.8~~	~~2168~~	~~70~~	~~70~~	~~3~~	~~322~~
RHIC	3.5	80	9.7	264	71	80	1.1	276
LHC	8.3	56	14.3	1232	223	56	3.1	386

Next generation colliders need 16-20 T magnets in 80-100 km tunnel

Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS)

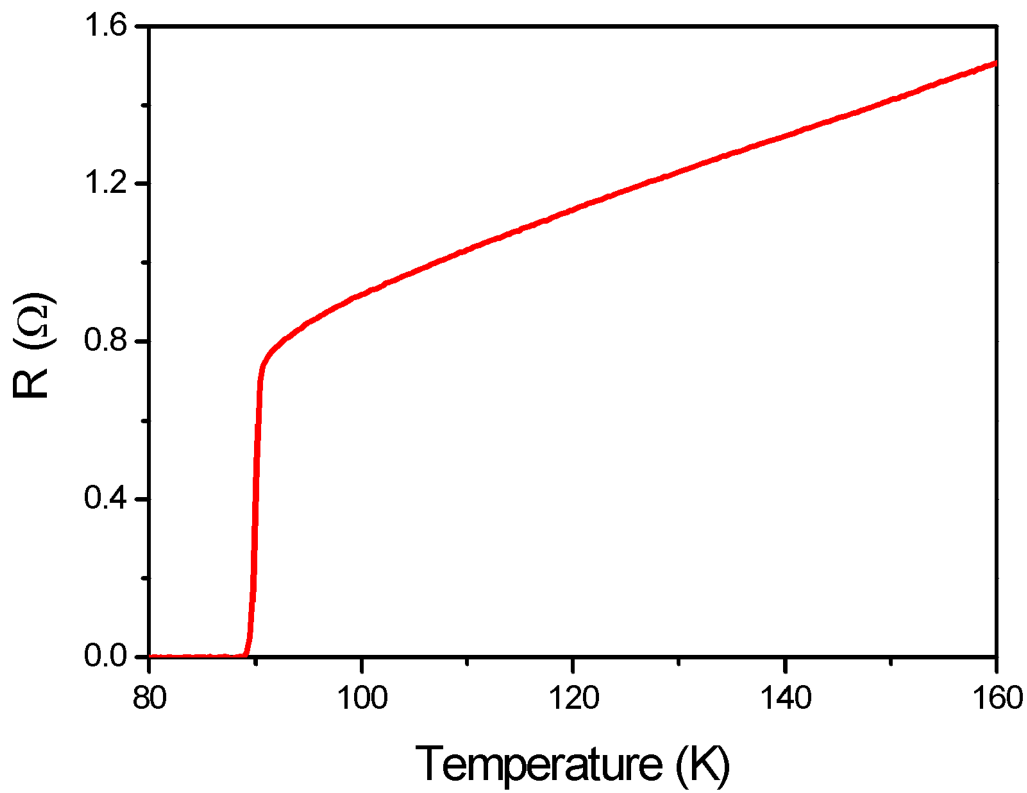
Low Temperature Superconductor Onnes (1911)

Resistance of Mercury falls suddenly below meas. accuracy at very low (4.2)



High Temperature Superconductors (1986)

They loose their resistance at NOT so low temperatures (Liquid Nitrogen)!



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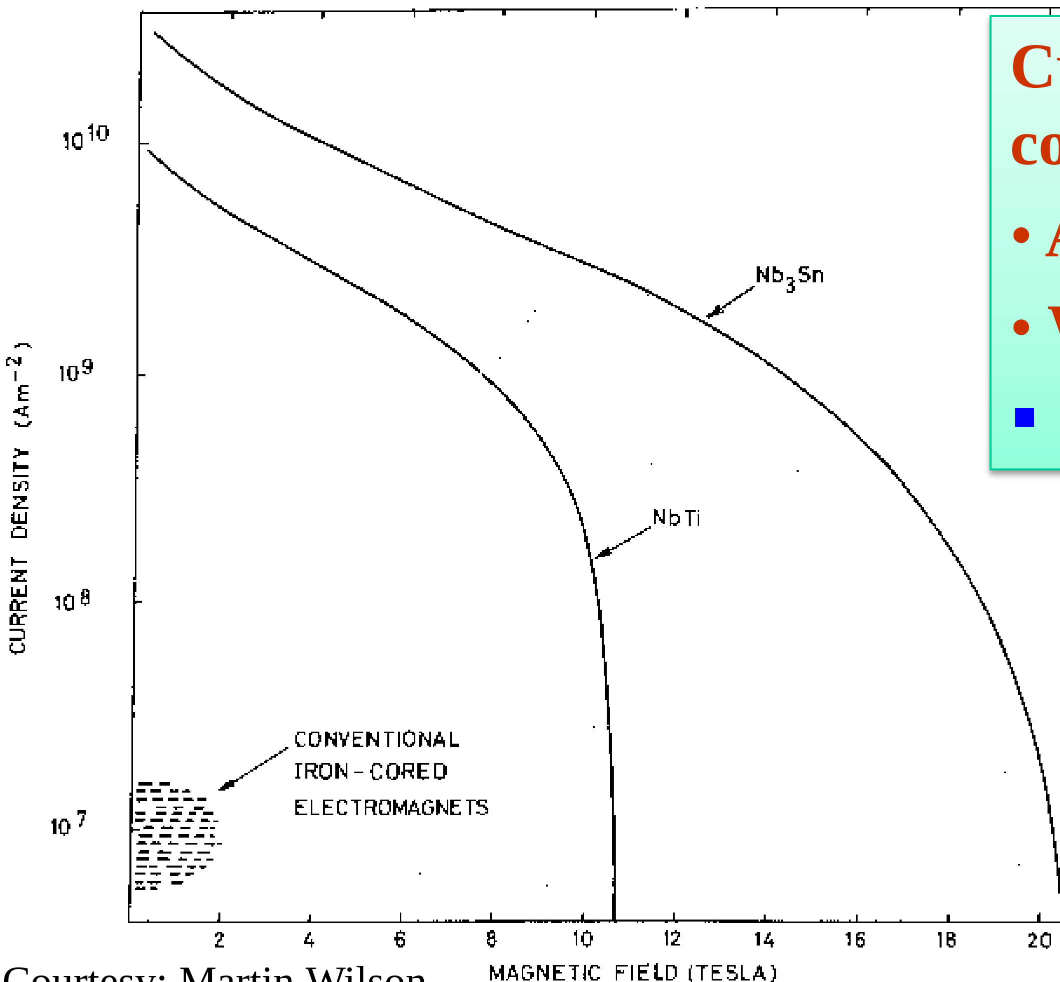
Why Use Superconducting Electro-magnets in Accelerators?



Courtesy: Martin Wilson

Current density in copper coils of conventional magnets:

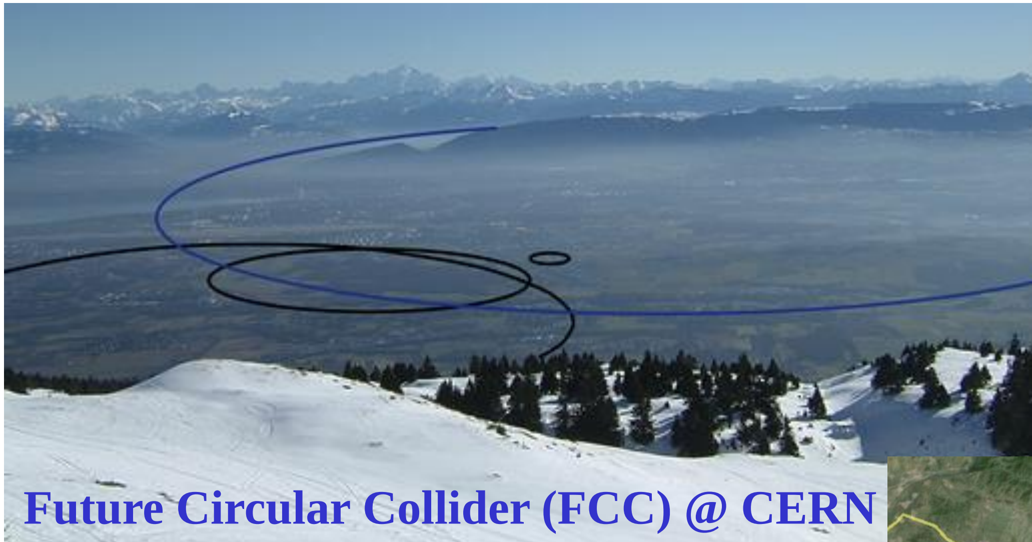
- **Air cooled (max) ~ 1 A/mm^2**
- **Water cooled ~ 2-10 A/mm^2**
- **Typical fields: ~ 1-1.8 T**

High field superconducting magnets (3-8 T) reduce the size of the tunnel, as well as the cost of the operation.

They make high energy colliders realistic.

Proposed field: 16-20 T, Current density >500 A/mm^2

Proposed High Energy Colliders



Future Circular Collider (FCC) @ CERN

Present LHC at CERN

- CoM Energy: 14 TeV
- Tunnel Size: 27 km
- Dipole design field: 8.3 T
- Conductor used: NbTi

Proposals for Future

- CoM Energy: 80 - 100 TeV
- Tunnel Size: 60 - 100 km
- Dipole design field: 15-20 T
- Conductors: Nb_3Sn, HTS

CEPC/SppC in China

Future Circular Collider (FCC)

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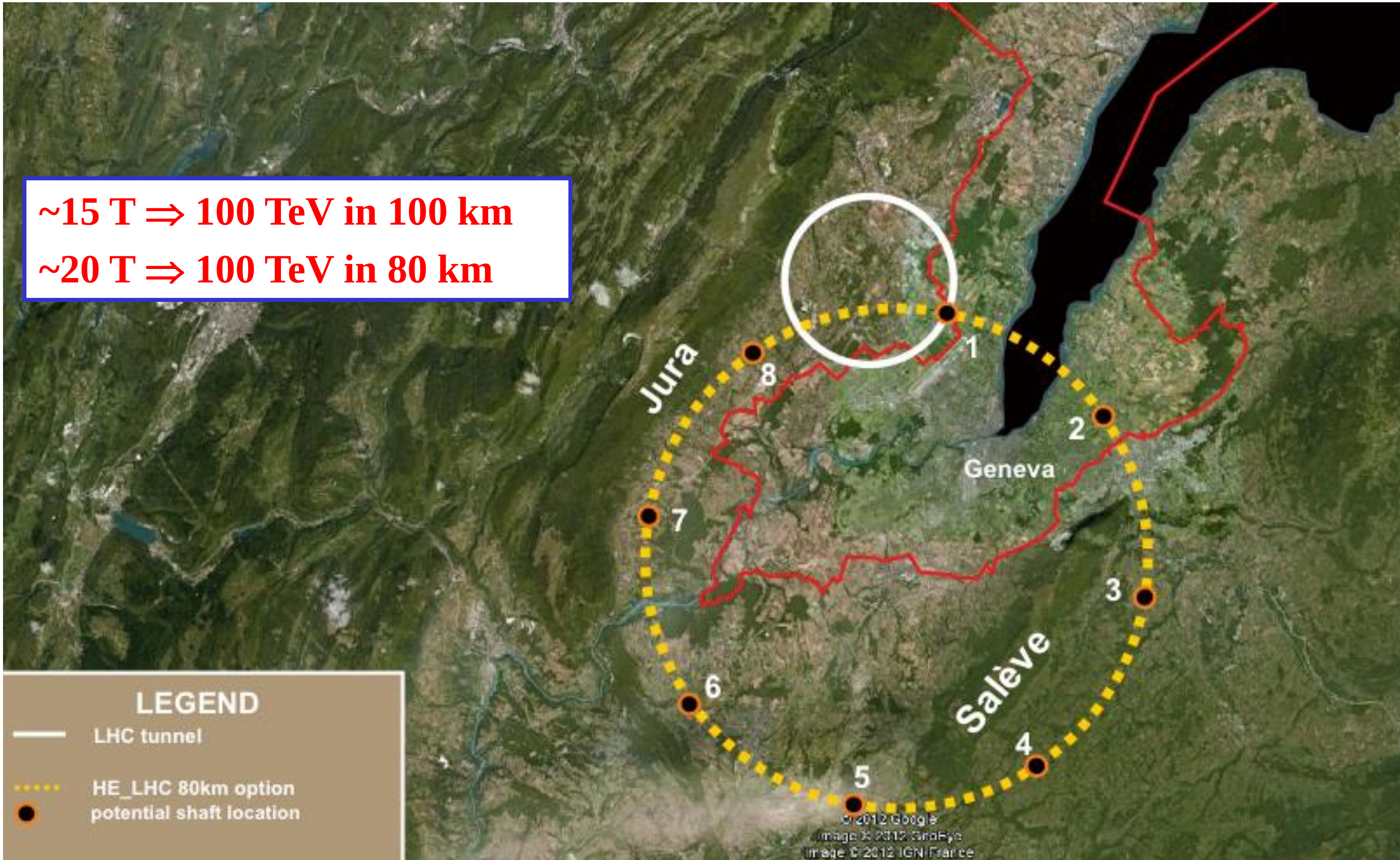
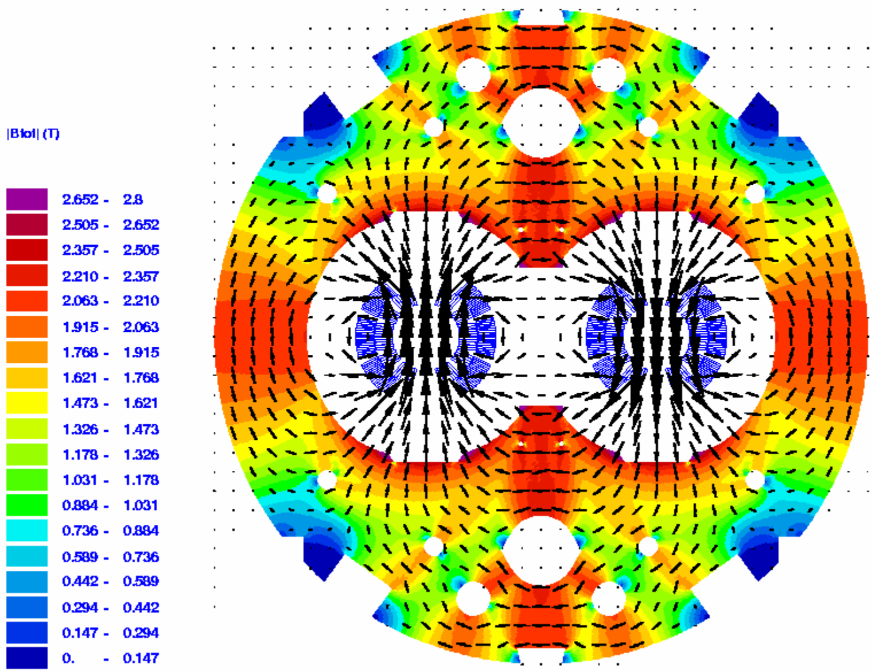
~15 T ⇒ 100 TeV in 100 km

~20 T ⇒ 100 TeV in 80 km



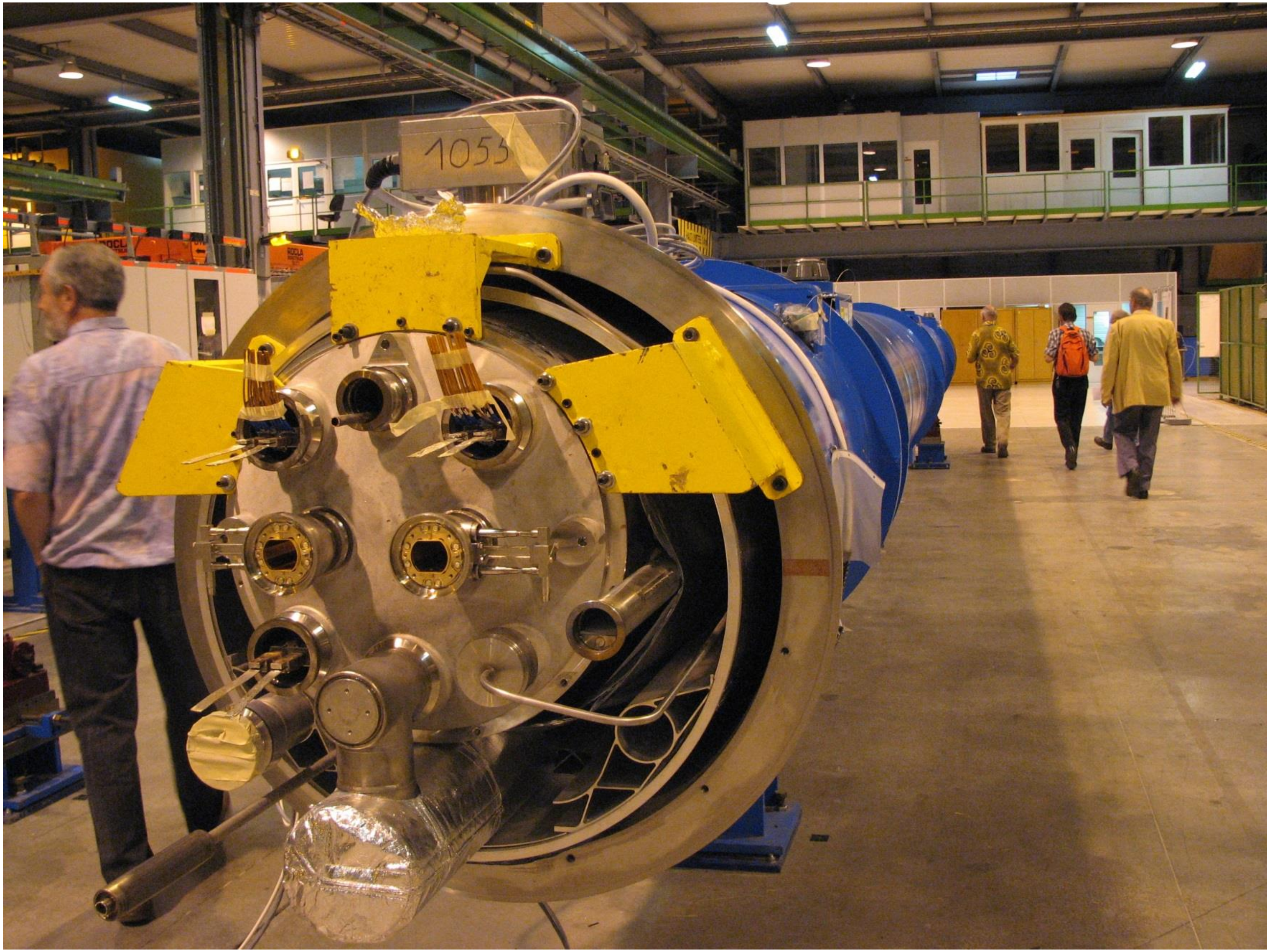
Mechanical and Magnetic Structure of LHC Dipole



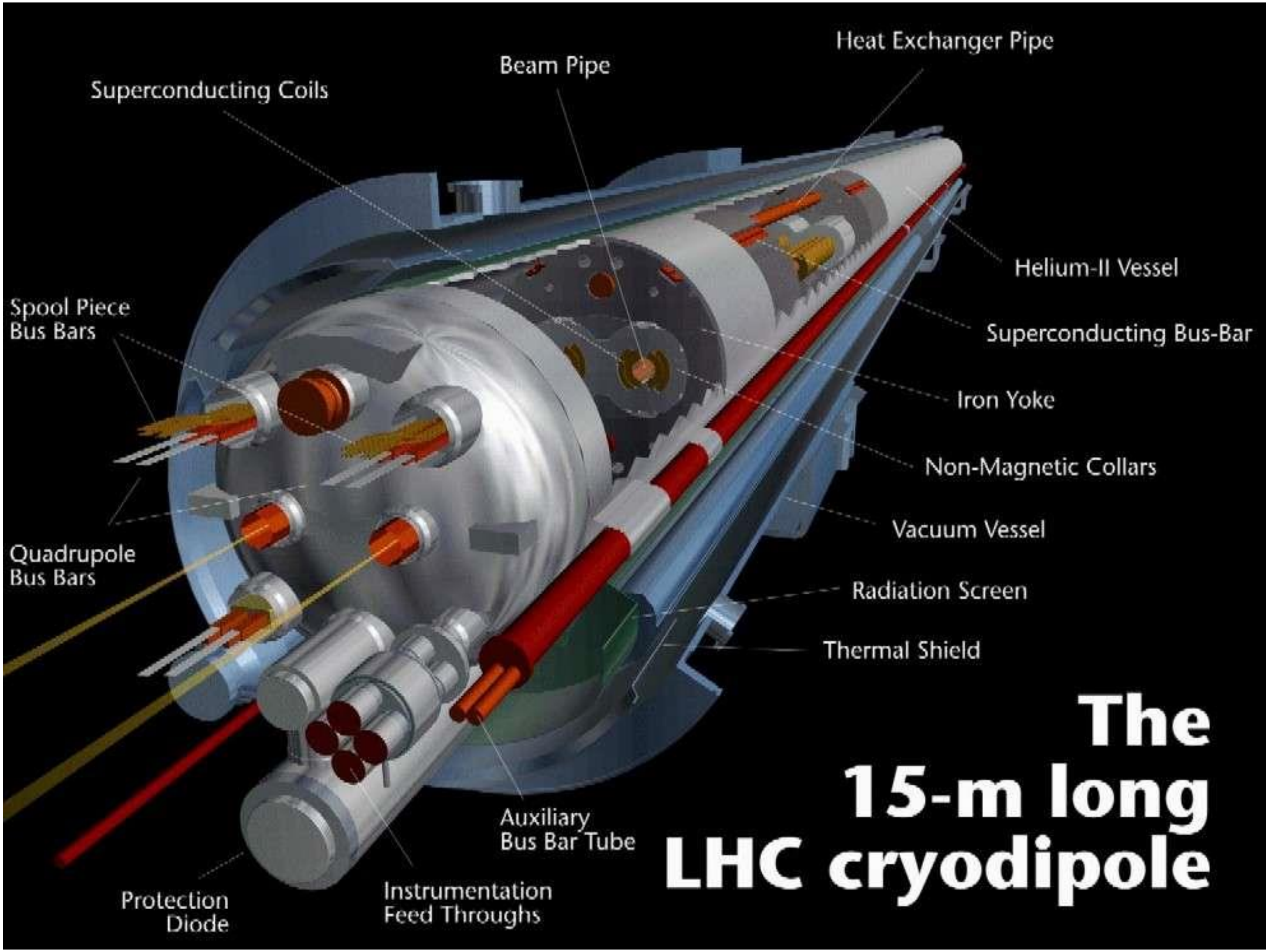
- **Field = 8.3 T**
- **Current = 11.8 kA**
- **Length = 14.3 m**
- **Weight = ~35 tonnes**
- **Number of magnets = 1232**

- **2-in-1 design (2 side by side coils in 1 yoke)**
- **Operating temperature: 1.8 K**
- **Field uniformity: a few parts in 10^4**
- **Stainless collars to hold large forces**
- **Forces on coil: 400 tonnes**
- **Stored energy in ring: 11 GJ**

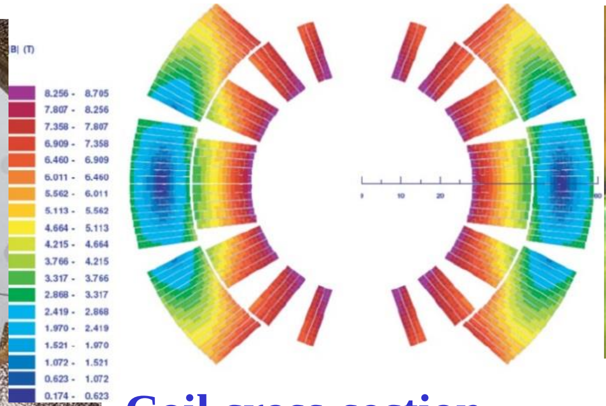
Magnets Used in Accelerators
LHC 2-in-1 Dipole



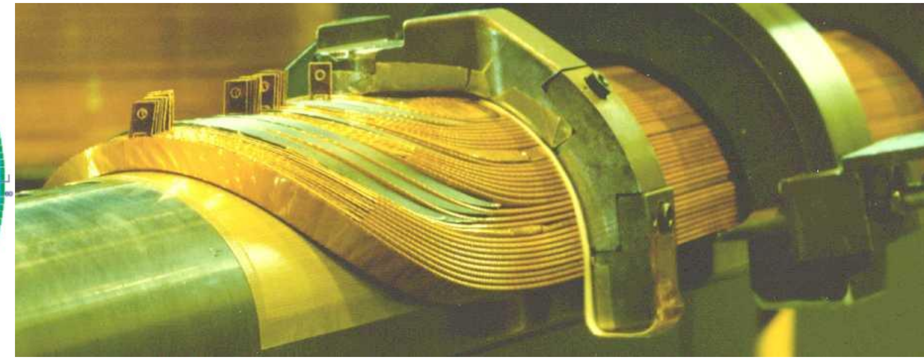
Magnets Used in Accelerators



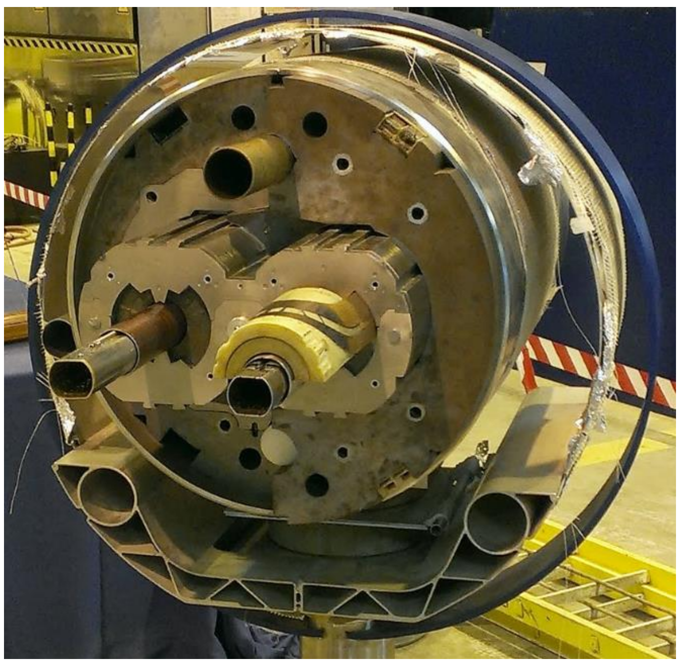
Challenges with Present Magnet Designs and Technology



Coil cross-section



Coil end



- Cosine theta coil geometry with complex ends
- NbTi superconductor is practical up to 8-9 Tesla
- High field dipoles create large Lorentz forces
- Design and technology is in use for many decades - performance and cost unlikely to change much

- **Future colliders need new materials, new designs and perhaps new manufacturing techniques**

A major challenge for the next generation

New Designs and Technology being Developed at BNL

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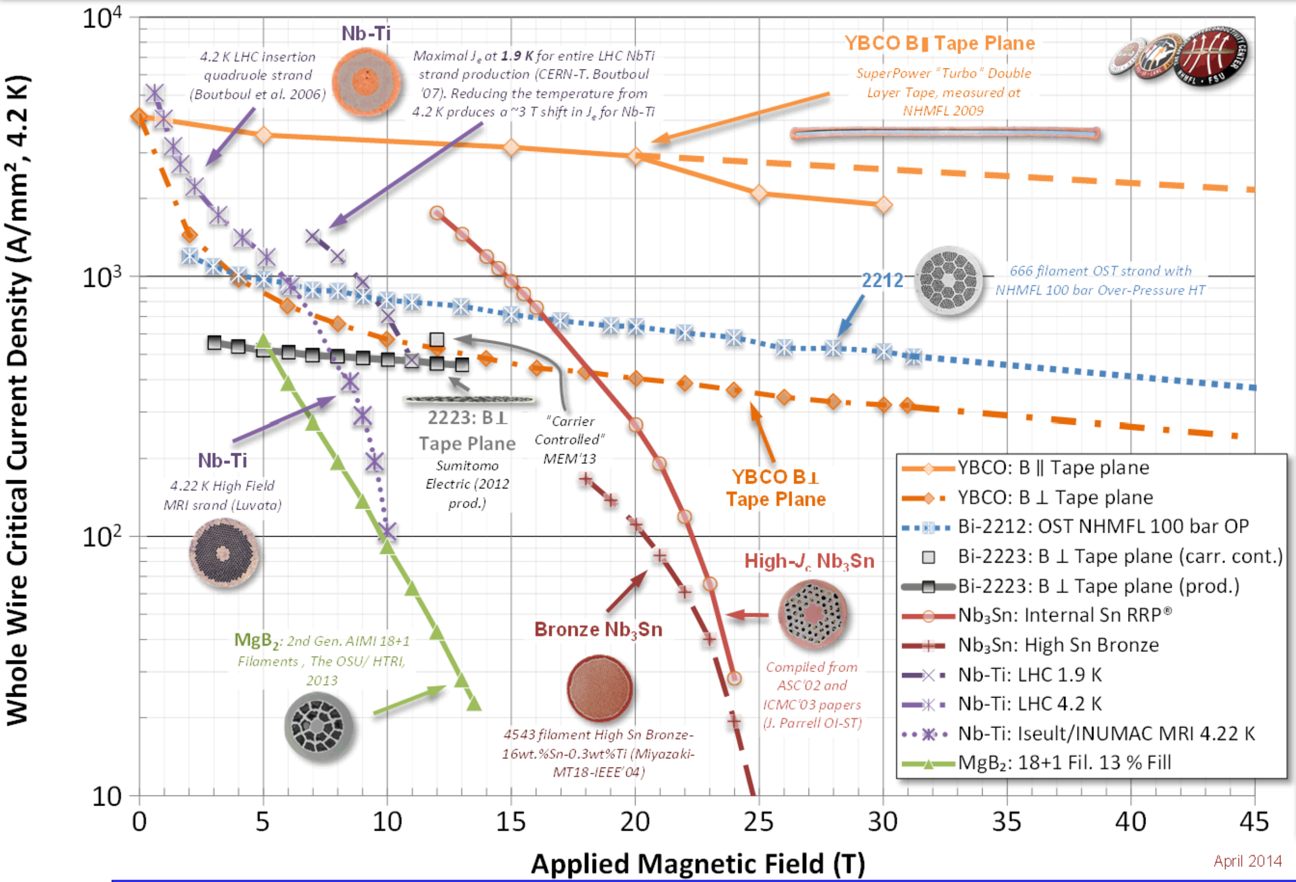
Current Carrying Capacity of Modern Superconductors at 4 K

NbTi has been used in all existing high energy circular colliders built to date

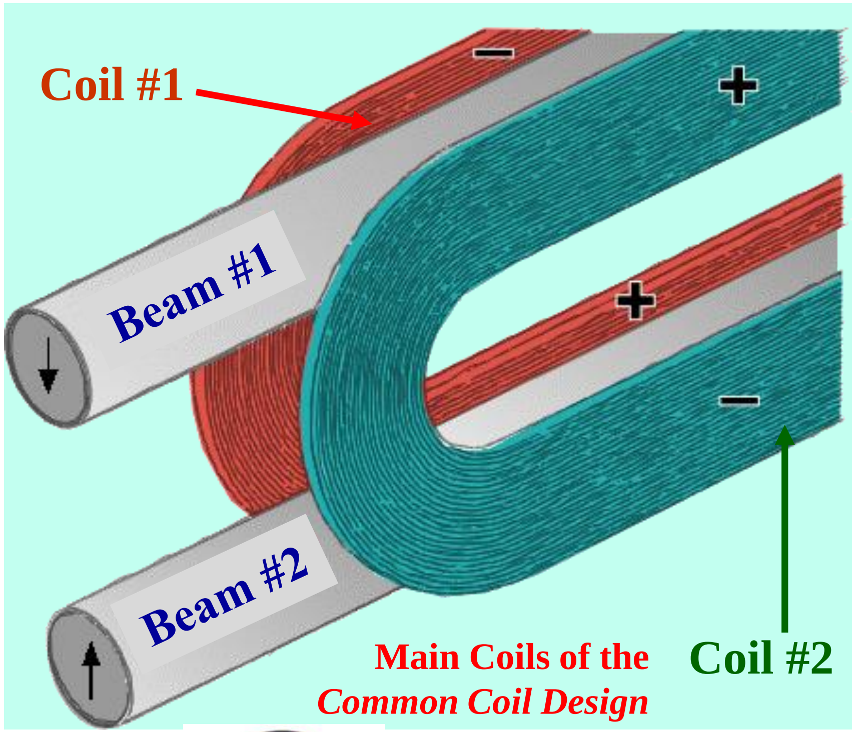


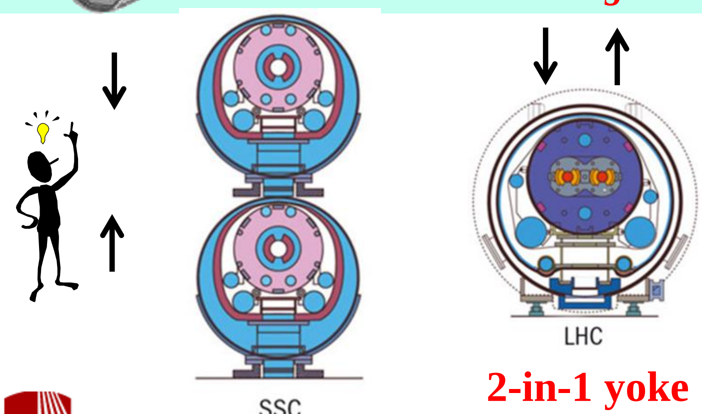
High field magnets need superconductors with large current carrying capacity at high fields – unfortunately NbTi, which is relatively ductile, doesn't.

However, Nb_3Sn and YBCO, Bi2231 & Bi223 (HTS) are brittle.

Interestingly, High Temperature Superconductors (HTS) are also high field Superconductors (HFS)

Common Coil Design (The Basic Concept)





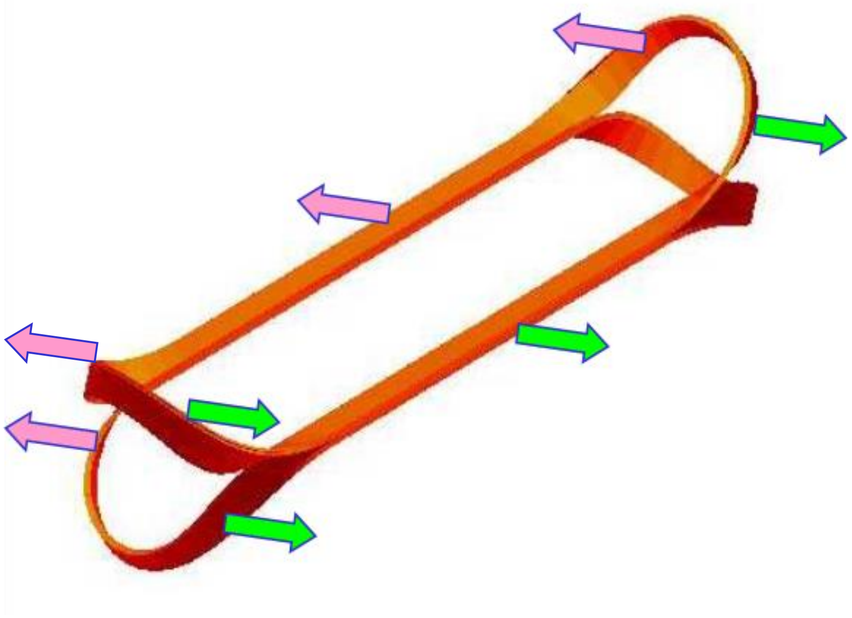
2-in-1 yoke

- **Simple 2-d coil geometry for colliders**
- **Fewer coils (about half) as the same coils are common between the two apertures (2-in-1 geometry for both iron and coils)**
- **Conductor friendly with large bend radii (determined by the spacing between two apertures) without complex 3-d ends**
- **Minimum requirements on expensive tooling and labor**
- **Potential for producing lower cost, more reliable high field magnets**
- **Efficient and rapid turn around magnet R&D due to simpler and modular design**

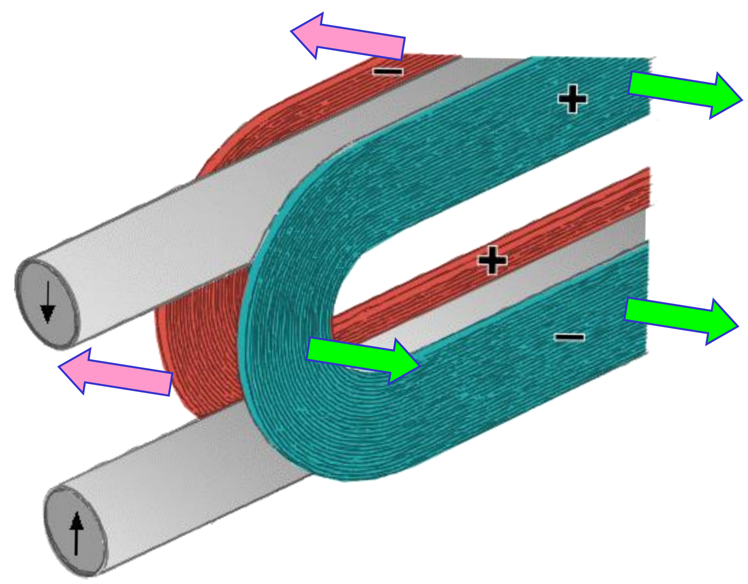
Advantage of Common Coil Design in High Field Magnet Structure

A key technical and cost issue in high field magnets is structure

In most designs, large forces put excessive stress/strain on the conductor in the end region



In a common coil design, coils move as a whole - much smaller stress/strain on the conductor in the end region

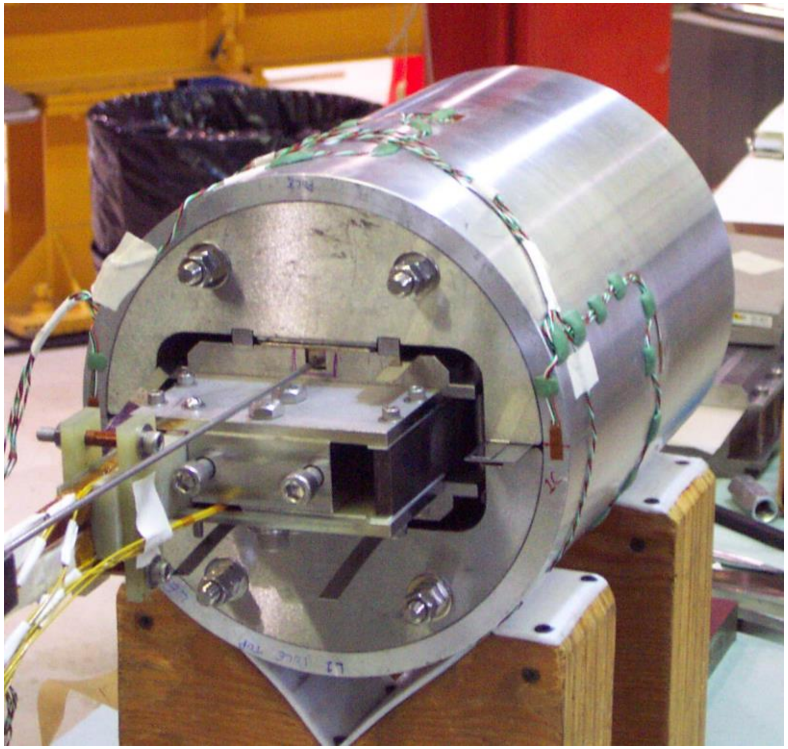


Expect lower cost due to less structure and better performance due to less strain

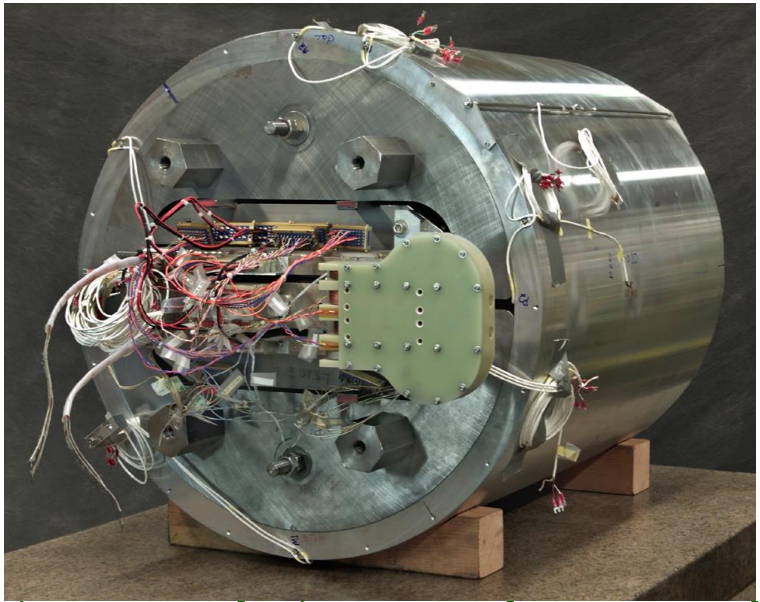
Common Coil Magnets Built at BNL, FNAL, LBNL

BNL

FNAL



LBNL



What Remains to be Done?

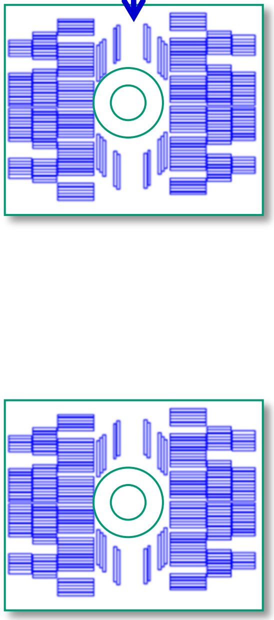
The basic design concept with field up to ~13 T field has been demonstrated

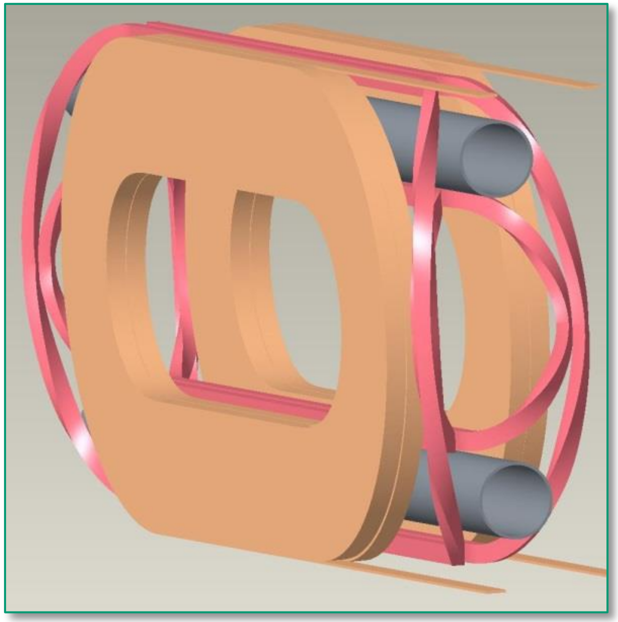
- **However, accelerator type dipoles with proper field quality are yet to be demonstrated**
  - **Requires additional coils and more complex structure**
- **Magnet designs with the desired field (15-20 T), field quality (a few parts in 10,000) and required aperture (~50 mm)**
  - **Magnetic & mechanical design plus demonstration**

Accelerator-type Field Quality and Structure for Common Coil Dipole

- Require "pole coils" which must clear beam tube in the ends

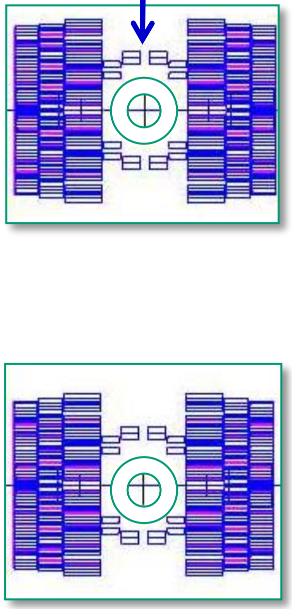
(a) Pole coils like midplane coils of cosine theta dipoles (easy bend)

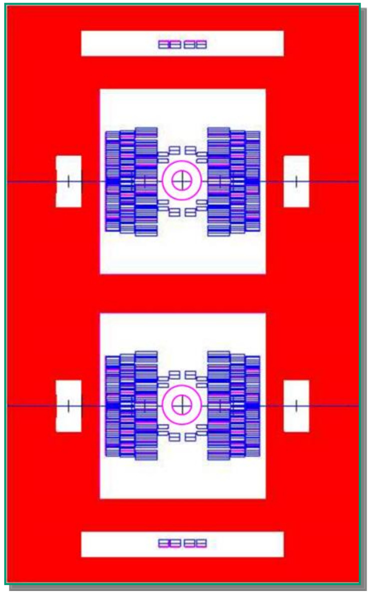




OR

(b) Simpler configuration of pole coils (waste some conductor)

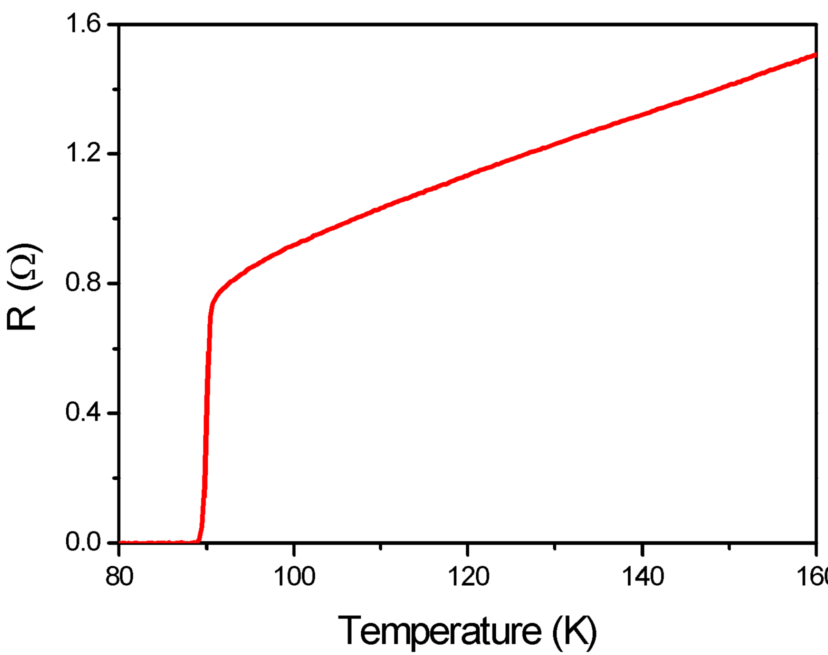




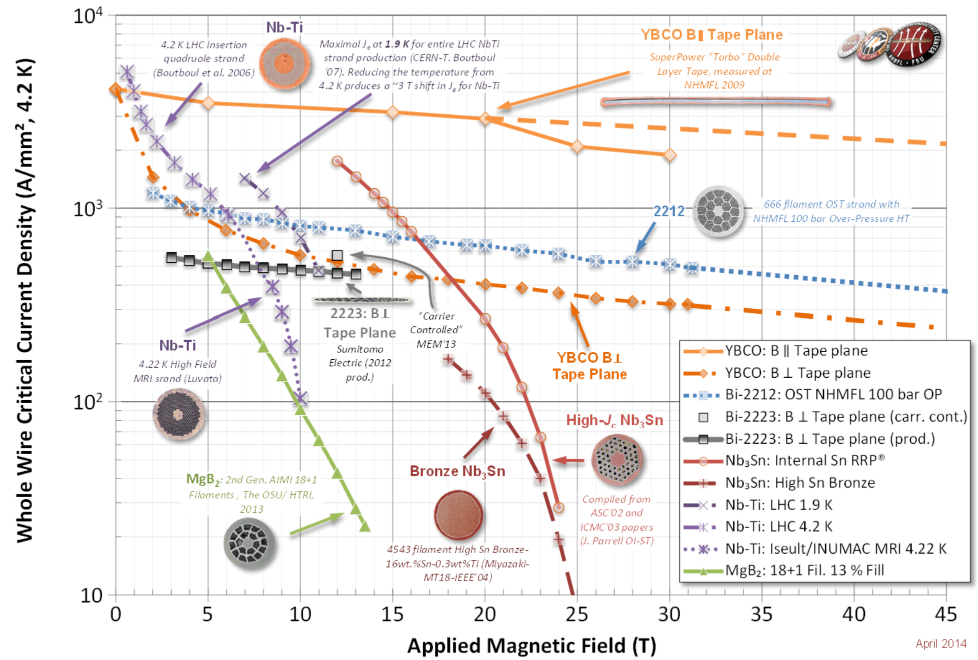
We have funding available to work on this exciting opportunity which can potentially bring a new magnet design in future machines

High Temperature Superconductor (HTS) or High Field Superconductors (HFS)

High Temperature Superconductors



High Field Superconductors



<u>HTS available from industry</u>:

- **Bismuth strontium calcium copper oxide (BSCCO): Bi2213, Bi2212 – 1G**
- **Yttrium barium copper oxide (YBCO) – 2G**
  - ❑ **Also ReBCO (Re: Rare Earth)**

New Possibilities with HTS in Superconducting Magnet Technology

HTS can function at high temperature

- That makes helium free superconducting magnets operating at high temperature possible as never before (20 K or More)

HTS can carry substantial currents at high fields

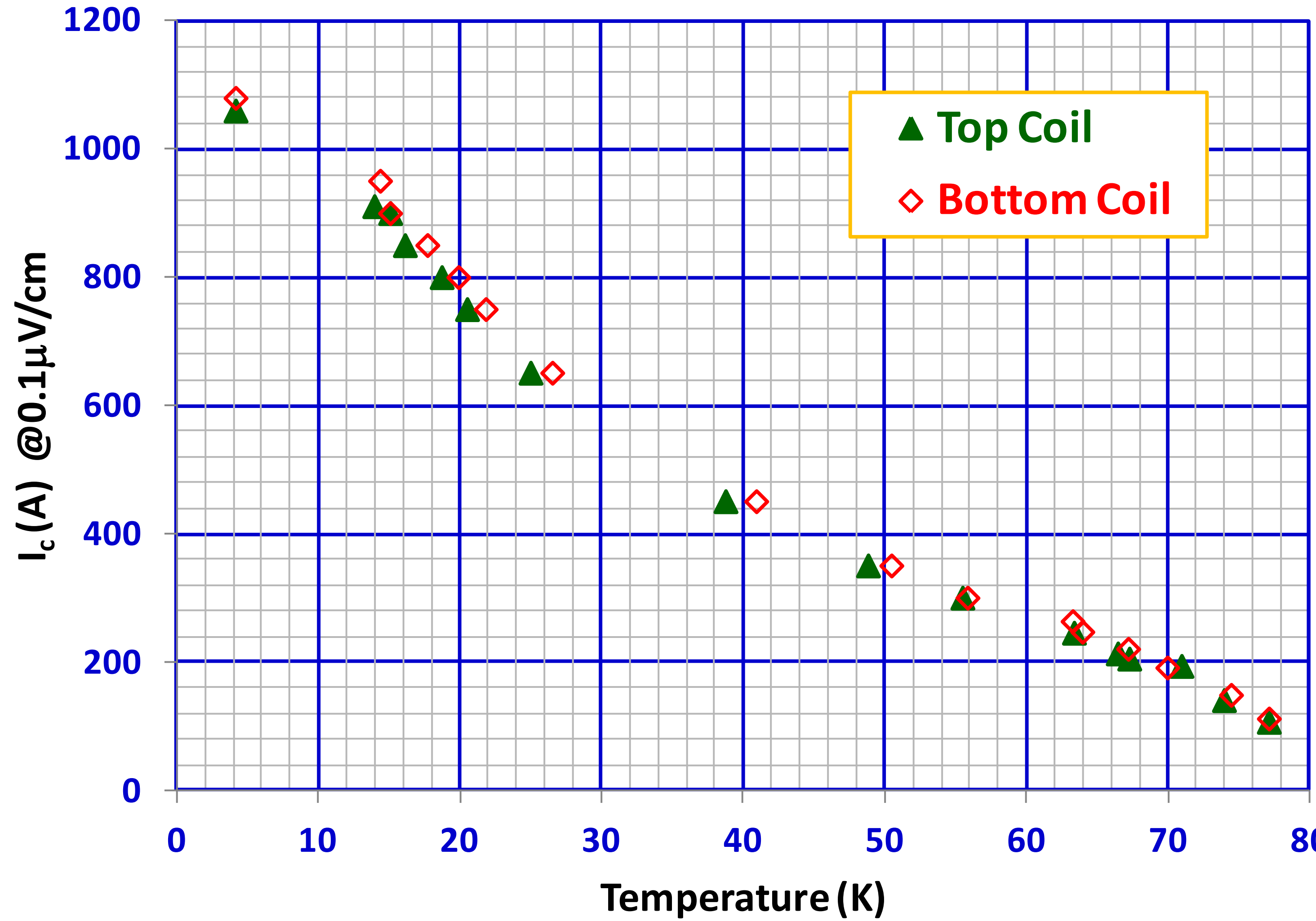
- That makes very high field superconducting magnets possible as never before (20 T or more)

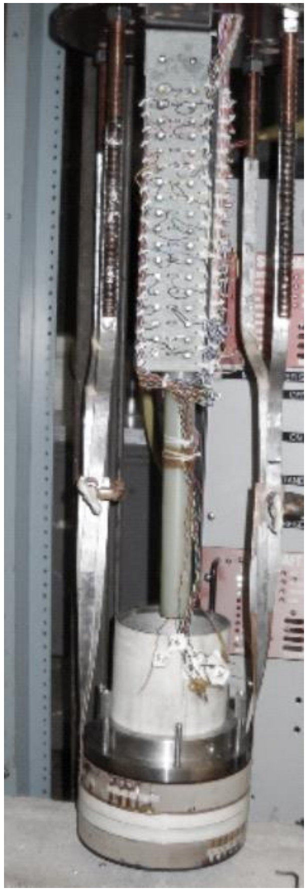
➢ **Even one of above is sufficient to revolutionize the field**

- Here we have two ! !

Superconducting Magnet Division

HTS Coil Test at BNL

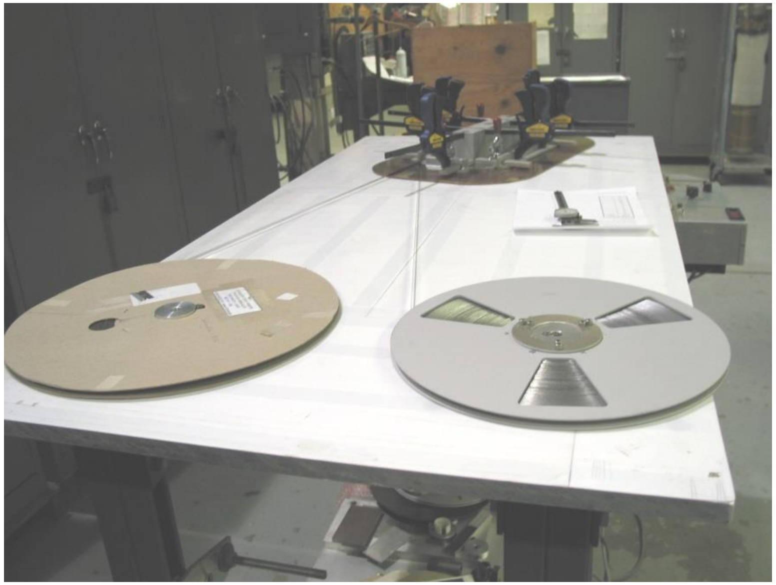




The option of operating over a large range (the benefit of HTS)

Practical Advantage of HTS Magnets
Fast turn-around and Inexpensive R&D

Easy coil winding (table top)



Easy superconducting coil testing (can be done in simple cryostat with LN_2)

One can do experiments in a matter of weeks rather than a matter of years

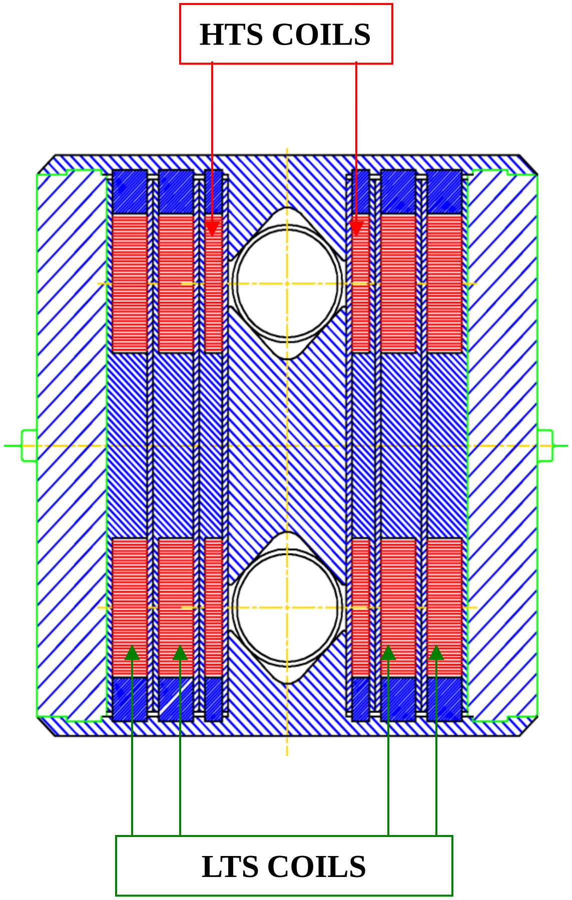
- **Can do a lot of trial and experimental R&D**
- **Fits the time frame of graduate students**

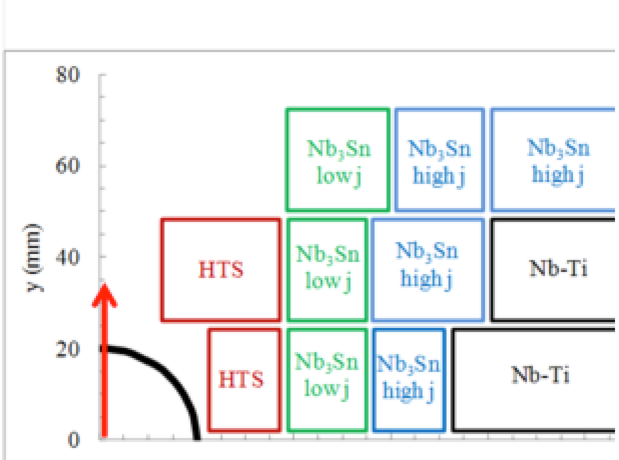
HTS Magnet Program at BNL

- HTS magnet R&D over a wide range:
  - High field, Medium field and low field (high temperature)
  - Many geometries – racetrack, cosine theta, solenoid
- We are currently involved in five HTS magnet programs (in house and in collaboration with others)
- Graduate students would have an opportunity to participate in most of them
- You can also create a new design during the course of your thesis

HTS in LTS/HTS High Field Hybrid Coil Design

HTS Magnet R&D in a Common Coil Hybrid Design



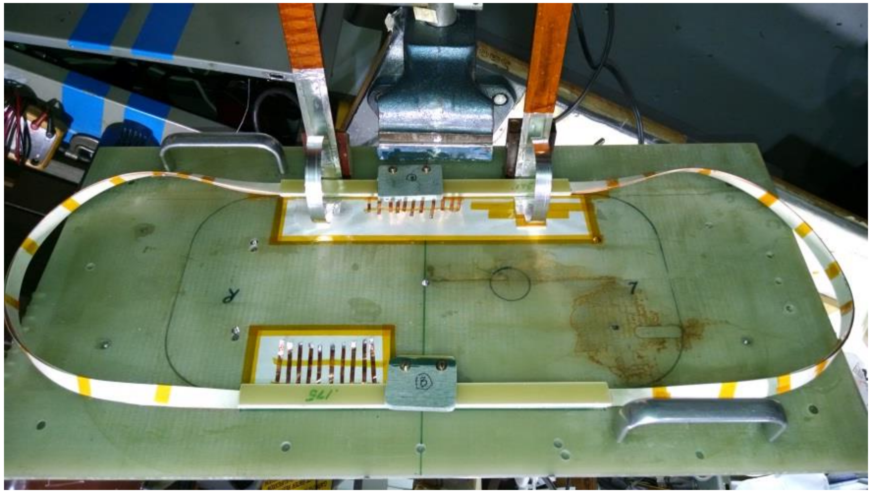


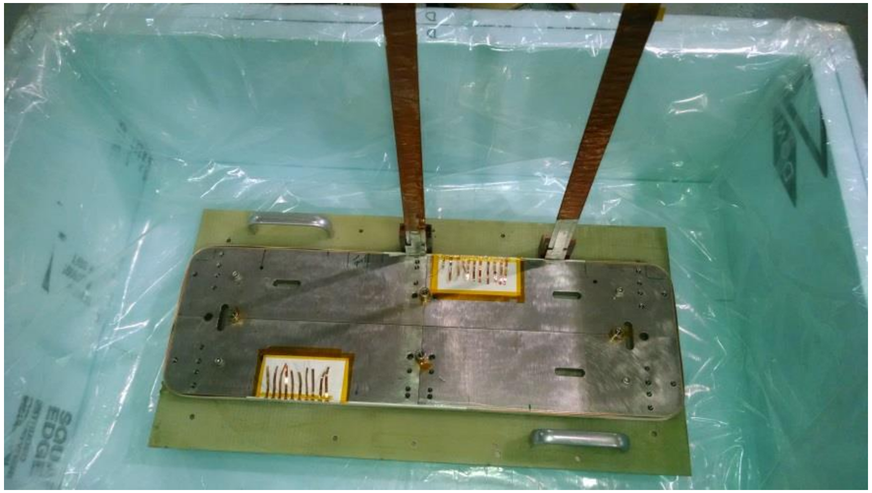
A CERN design

- **Use expensive HTS in the inner coil where field is high and lower cost LTS where field is low**

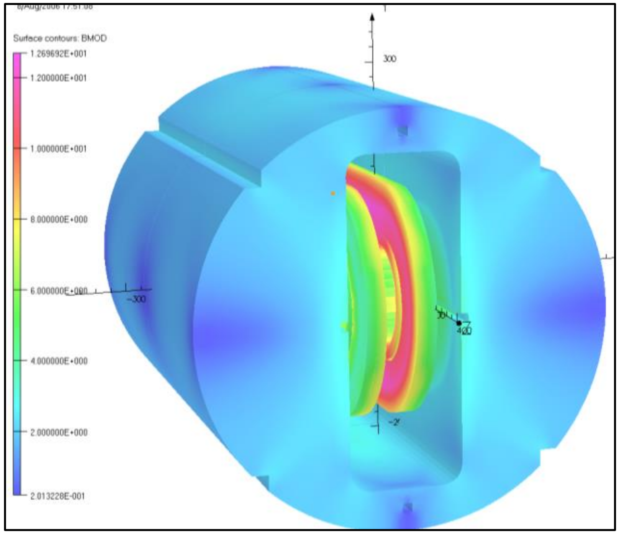
- **Field in outer layers is ~2/3 of that in the 1^{st} layer. Use HTS in the 1^{st} layer (high field region) and LTS in the other layers (low field regions).**

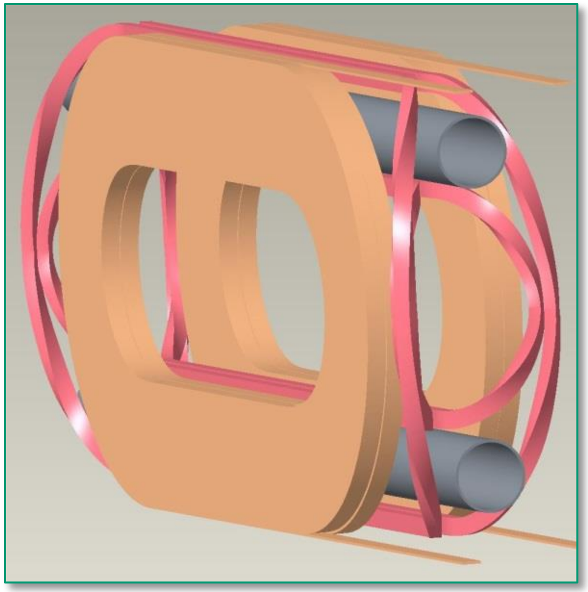
HTS Coil Built and Tested in a Short Period

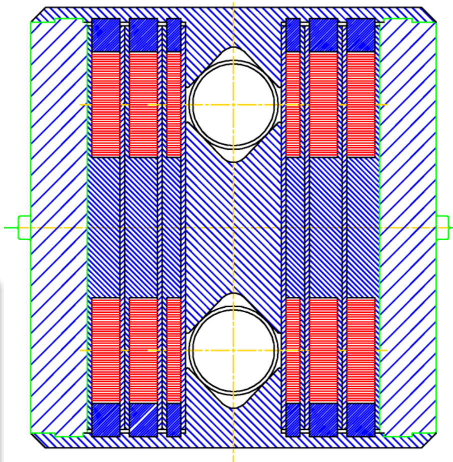




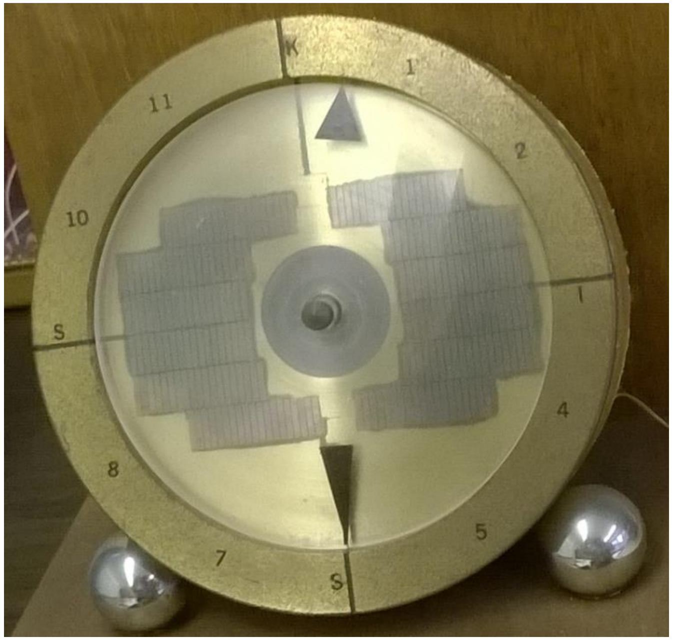
HTS Insert Coil Testing in an Existing Magnet



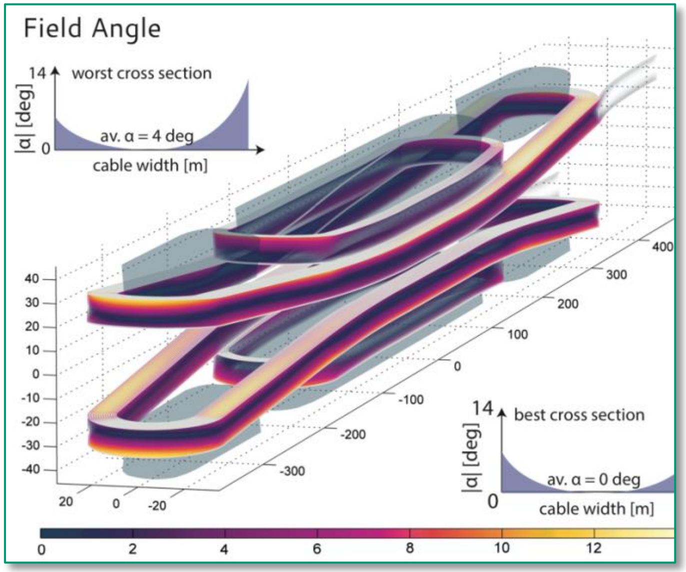




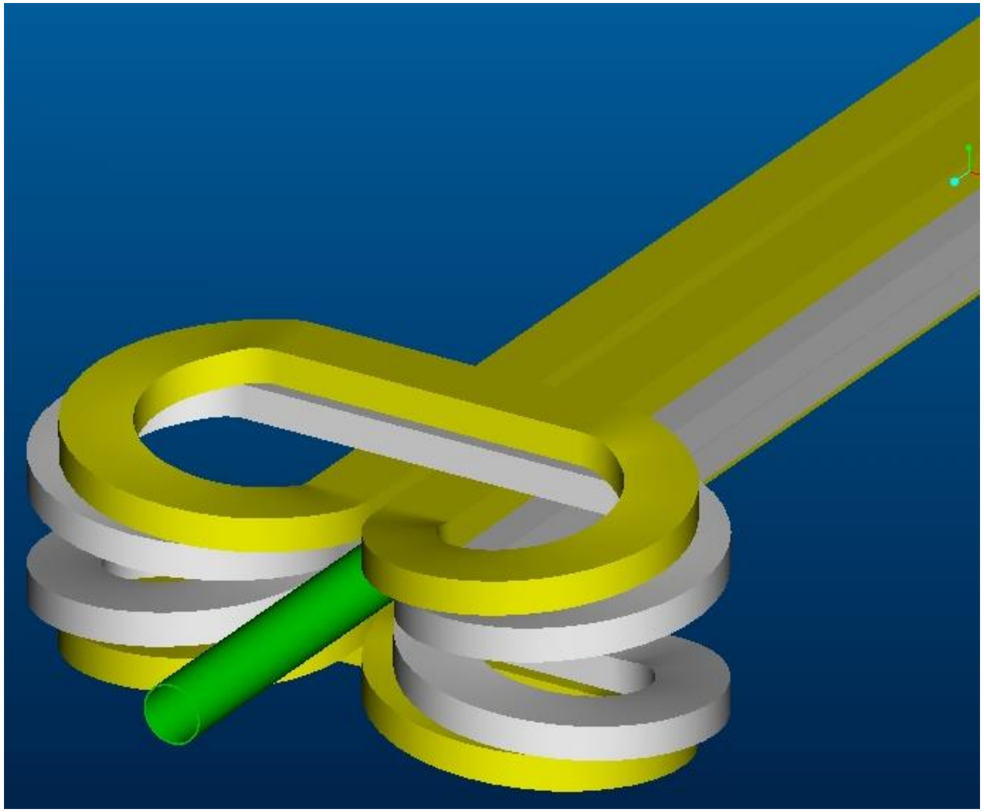
Ends of Single Aperture Block Coil Design with Rutherford Cable



- **Cross-section is simple but the design gets complicated in the end region with lifted ends to clear the tube, long length, reverse bend.**
- **The performance of such magnets often gets limited by the end region**



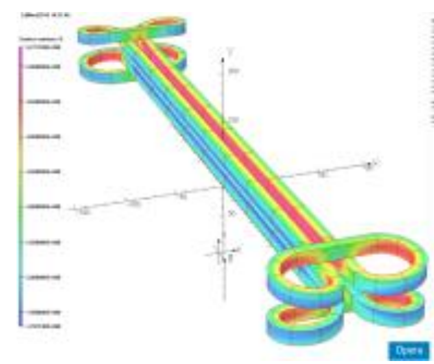
Freeway Overpass/UnderPass Ends



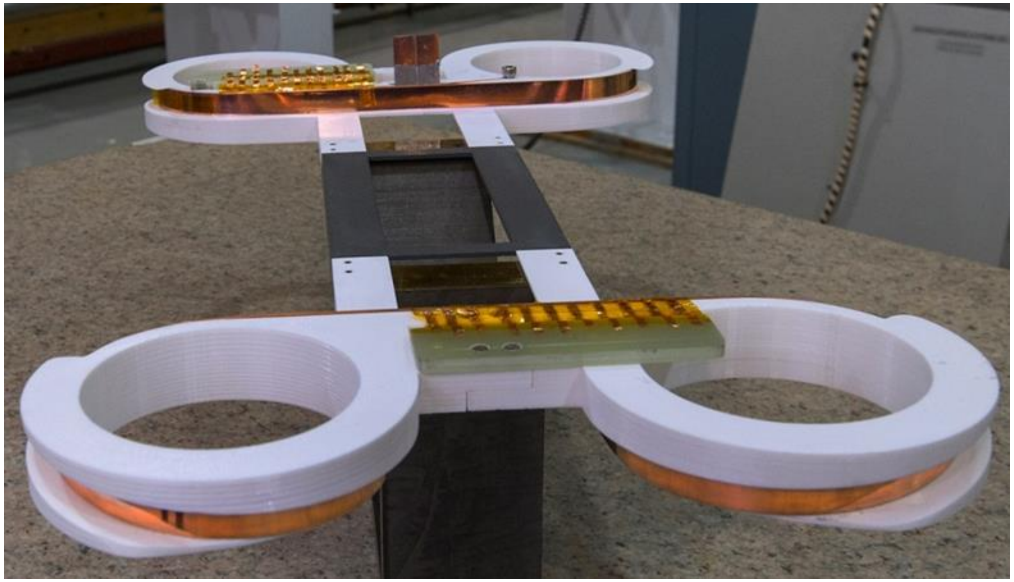
To understand it, imagine driving on high way

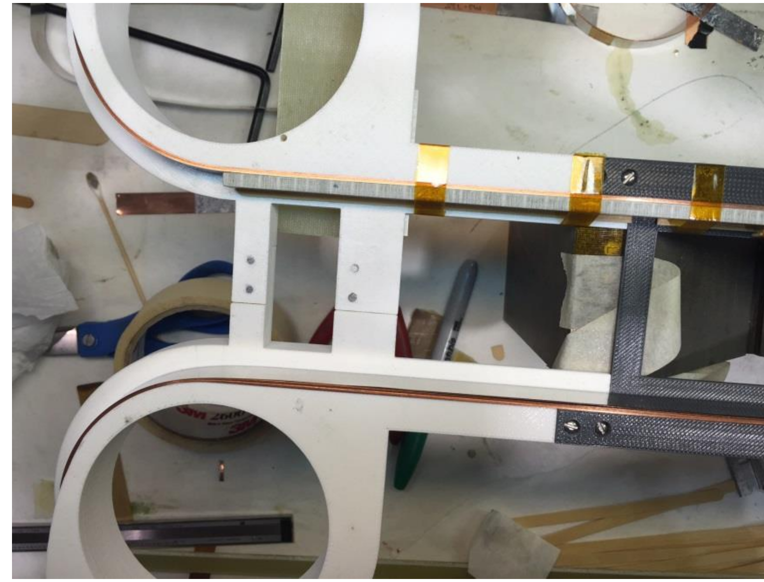
- **No hard-way bend**
- **No reverse bend**
- **Less strain – conductor friendly design**
- **Less axial space**

An Innovative design which could possibly bring a novel solution to an issue spanning over decades



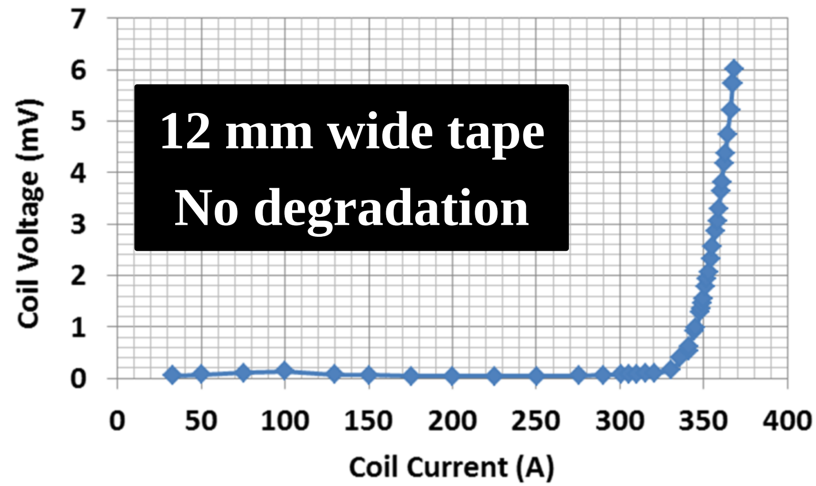
Actual Demonstrations in a Short Period of Time





Courtesy 3d printer

77 K Test Results



SUMMARY

- Next generation high energy colliders offer many challenges and thus also many opportunities where one can make a real difference in the field.
- Such R&D is highly encouraged by the US high energy physics community.
- At BNL we have many ongoing magnet R&D programs where a young scientist can contribute in a variety of ways. I listed only a select few of them after giving general motivation for them. May be you can create a new.
- Graduate students will have an opportunity to contribute to developing the next generation magnet designs and technologies
  - Requires interest in modelling.
- Graduate students can also contribute to HTS coil and magnet technology
  - Requires interest in hands on work and experimental activities.
- One can either choose one of the above two type or alternatively one can also choose one or more magnet design/program and work on both aspects of that.