Overview of Magnets for Particle Accelerators

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Fermilab Summer Students School

Context for Magnets

Particle Accelerators are Enabling Technology for Many Areas of Science, Starting with High Energy/Nuclear Physics

80 Years

From this . . . to

this . . .

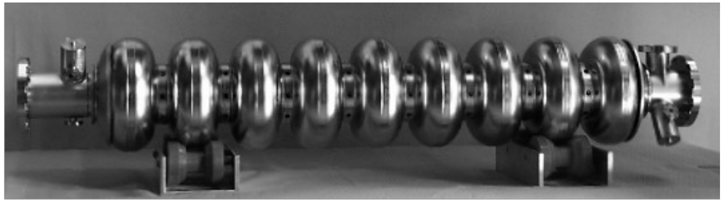
The LHC: 27 km collider

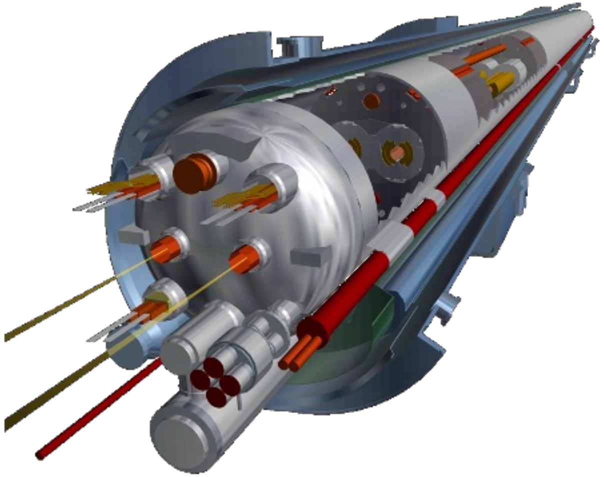
By recreating conditions in the early universe, particle accelerators have been the main drivers for progress in high energy physics

And superconducting magnets have been an essential key to continued progress

Accelerator Building Blocks

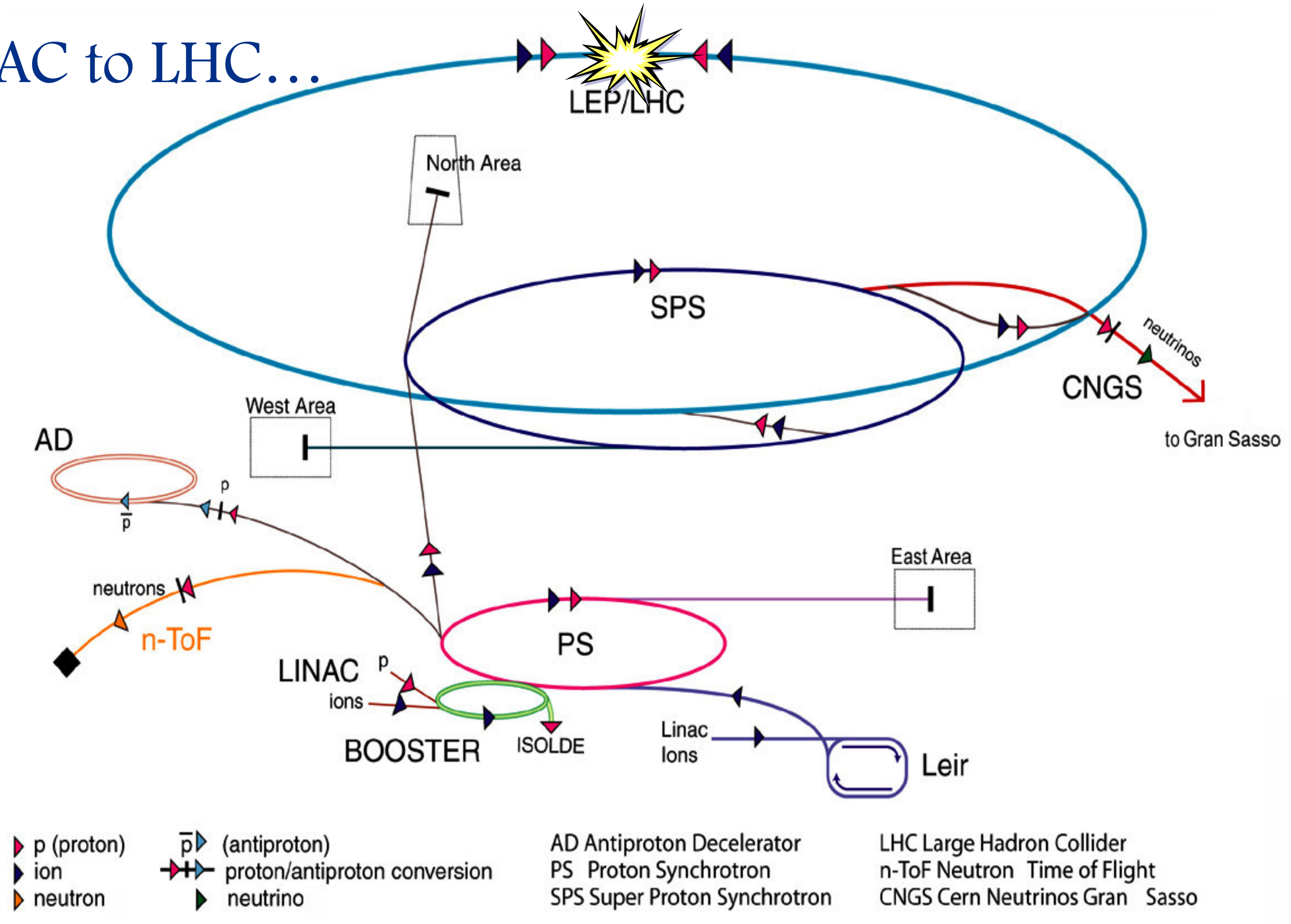
- A Source (electrons, protons, ions)
- Accelerating Structure
  - RF Systems (Normal or Superconducting)
- Arc Magnets (Superconducting)
  - Dipoles (bending)
    - E_{beam} (GeV) = 0.3 $B(T)$ R(m)
  - Quadrupoles (focusing)
  - Higher-order (correction)
- Damping Rings (Linacs)
  - Beam cooling
- Interaction Region (IR) Quadrupoles
  - Final focusing (luminosity)



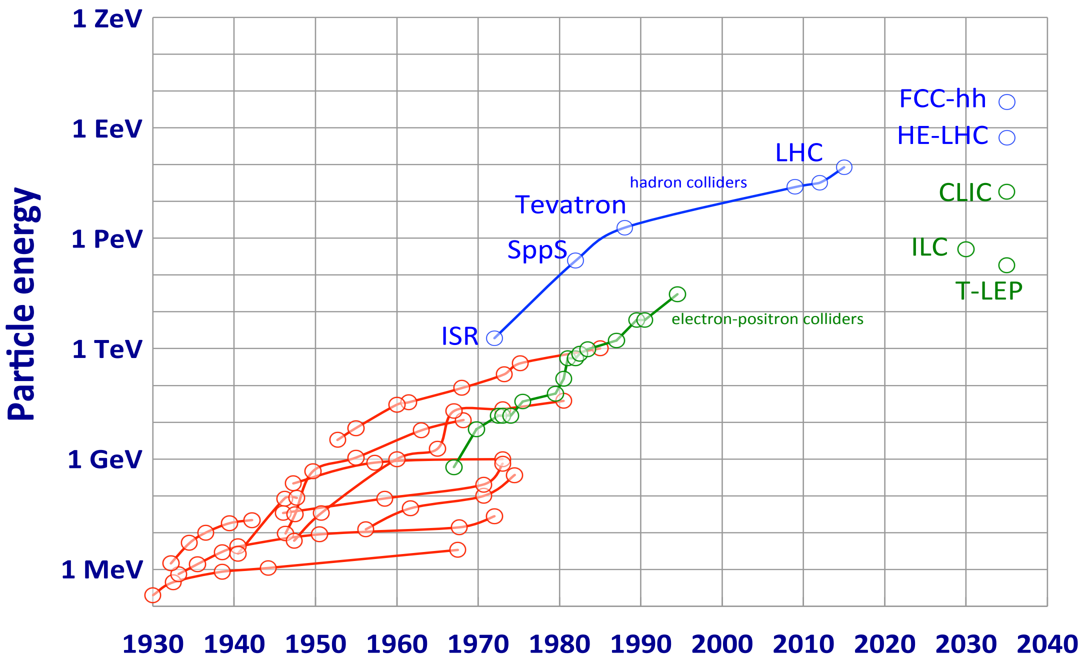


CERN Accelerator Complex

From LINAC to LHC…



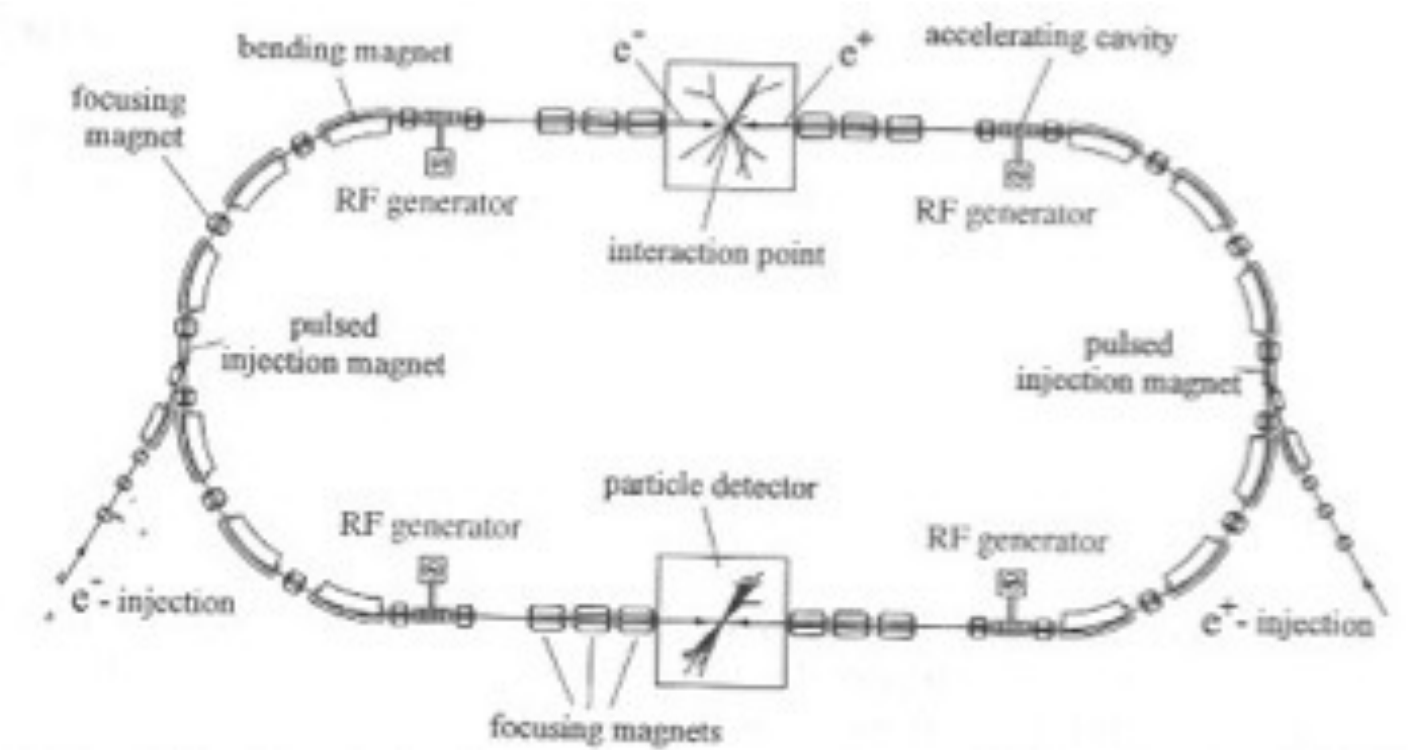
An Historic Need for High Field



Livingston plot of particle energy (in the laboratory reference frame, fixed target equivalent), where blue refers to hadron colliders and green to lepton colliders.

L. Bottura, CERN

Colliders Win



The Physics of Particle Accelerators, K. Wille

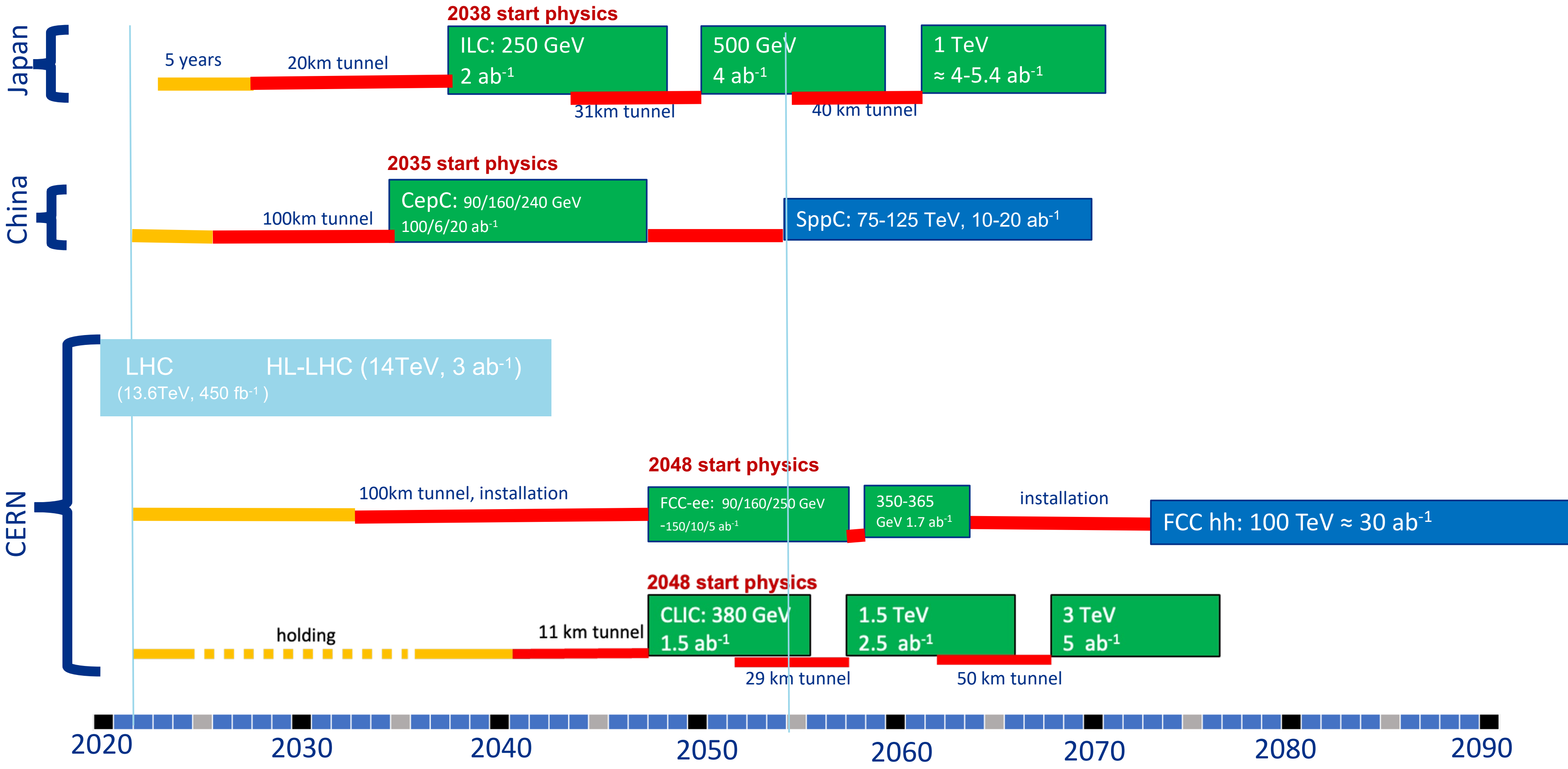
Large-Scale Facilities for Particle Physics are International

- Approximately every ten years, the US has a strategic planning process starting with “Snowmass” and followed by the Particle Physics Project Prioritization Panel (P5).
- Each country/region has their own approach for setting priorities for large physics projects, but they are done in an international context.
  - The EU planning process (European Strategy for Particle Physics) – precedes US and has significant influence.
  - The International Linear Collider in Japan is still on the table.
  - Serious discussions on large-scale facility in China but no decisions yet.

Indicative scenarios of future colliders [considered by ESG]

🟦 Proton collider
🟩 Electron collider
🟧 Muon collider

🟥 Construction/Transformation
🟨 Preparation / R&D



Japan

5 years
20km tunnel
2038 start physics
ILC: 250 GeV
2 ab^{-1}
31km tunnel
500 GeV
4 ab^{-1}
40 km tunnel
1 TeV
≈ 4-5.4 ab^{-1}

China

100km tunnel
2035 start physics
CepC: 90/160/240 GeV
100/6/20 ab^{-1}
SppC: 75-125 TeV, 10-20 ab^{-1}

CERN

LHC
(13.6TeV, 450 fb^{-1})
HL-LHC (14TeV, 3 ab^{-1})

100km tunnel, installation
2048 start physics
FCC-ee: 90/160/250 GeV
-150/10/5 ab^{-1}
350-365
GeV 1.7 ab^{-1}
installation
FCC hh: 100 TeV ≈ 30 ab^{-1}

holding
11 km tunnel
2048 start physics
CLIC: 380 GeV
1.5 ab^{-1}
29 km tunnel
1.5 TeV
2.5 ab^{-1}
50 km tunnel
3 TeV
5 ab^{-1}

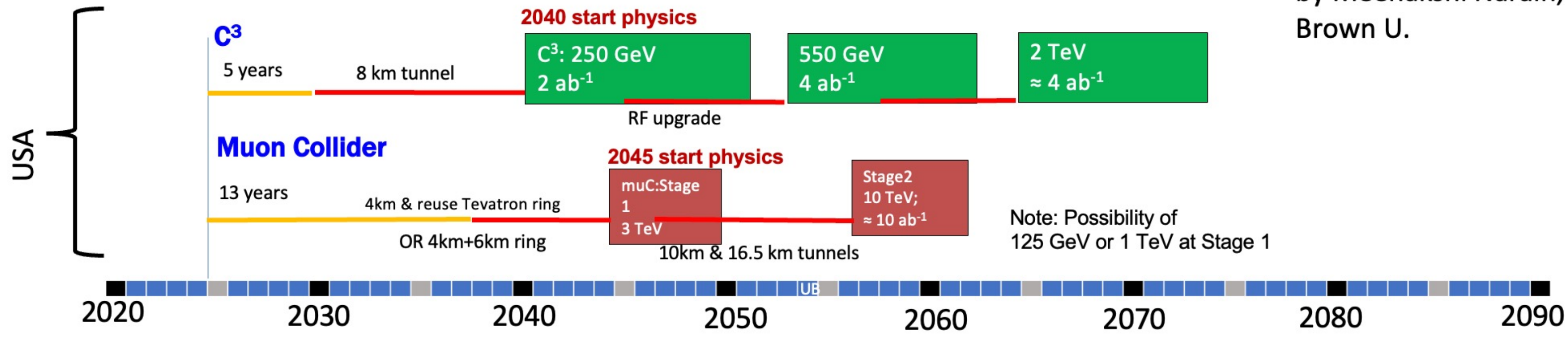
Possible scenarios of future colliders

🟦 Proton collider
🟩 Electron collider
🟥 Muon collider

▬ Construction/Transformation
▬ Preparation / R&D

Original from ESG by UB
Updated July 25, 2022
by Meenakshi Narain,
Brown U.

Proposals emerging from this Snowmass for a US based collider



Note: Possibility of
125 GeV or 1 TeV at Stage 1

- **Timelines technologically limited**
- **Uncertainties to be sorted out**
    - **Successful R&D and feasibility demonstration for C^3 and Muon Collider**
    - **Evaluate C^3 progress in the international context, and consider proposing an ILC/C^3 [ie C^3 used as an upgrade of ILC] or a C^3 only option in the US.**
    - **International Cost Sharing**

- **Consider proposing hosting ILC in the US.**

Many options to choose from.

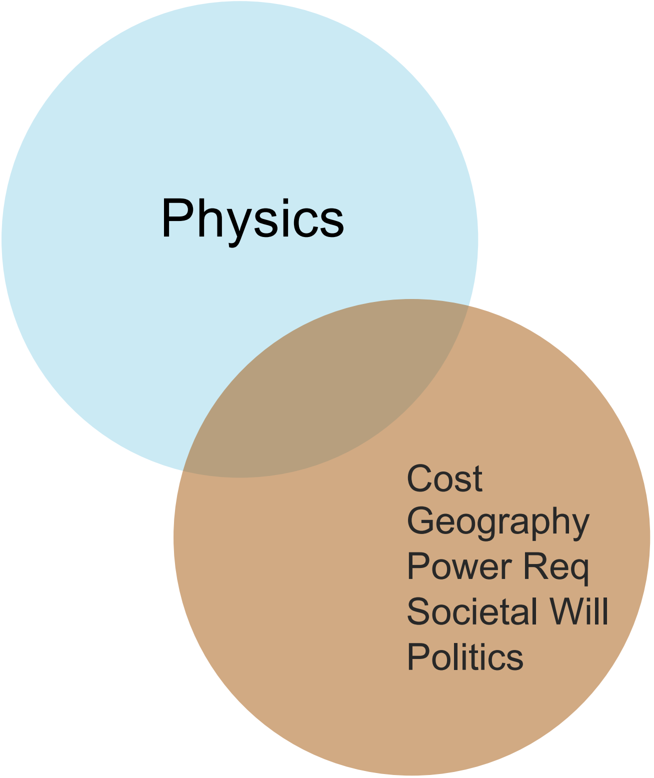
So why can't you just pick one?

Student question at Snowmass Community Summer Study in July 2022.

Well, it's complicated.

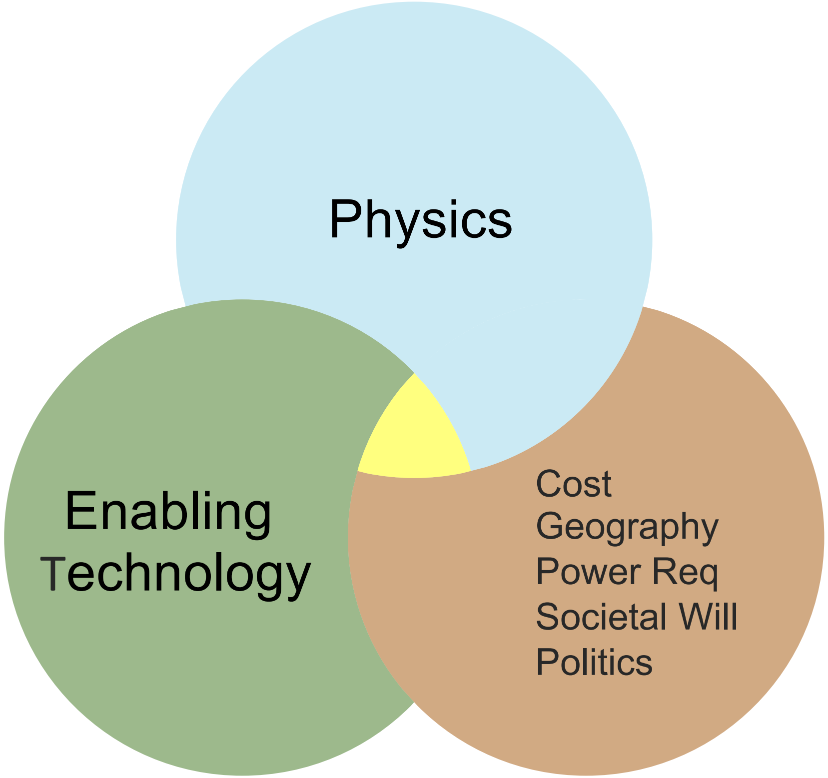
- For discovery potential, physics wants the highest energy possible
- Power consumption and environmental impact
- Footprint is a limitation in most cases
- Societal and political support required
  - coordinated international effort
  - cost
- Technological Limits

Physics



Physics

Cost
Geography
Power Req
Societal Will
Politics



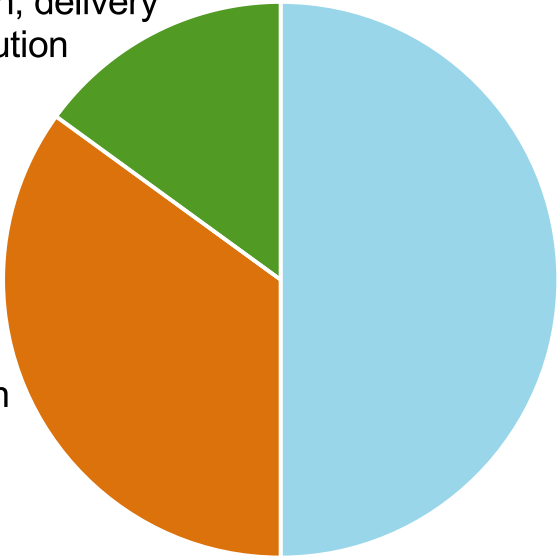
Physics

Enabling Technology

Cost
Geography
Power Req
Societal Will
Politics

Cost of Large Accelerator Facilities

Set by scale (energy, length, power) and technology



Power production, delivery
and distribution
15 +/- 10%

Largely determined by industry

Civil construction
35 +/- 15%

Accelerator components
Magnets and RF Systems
50 +/- 10%

Progress depends on development
of enabling technologies

Energy Will Not Cost Less in the Future!

And here’s a very recent example

“CERN slashes experiment time next year by 20% as energy costs bite” – ***PhysicsWorld.com 10/12/22***

Historical Background

Key historical events

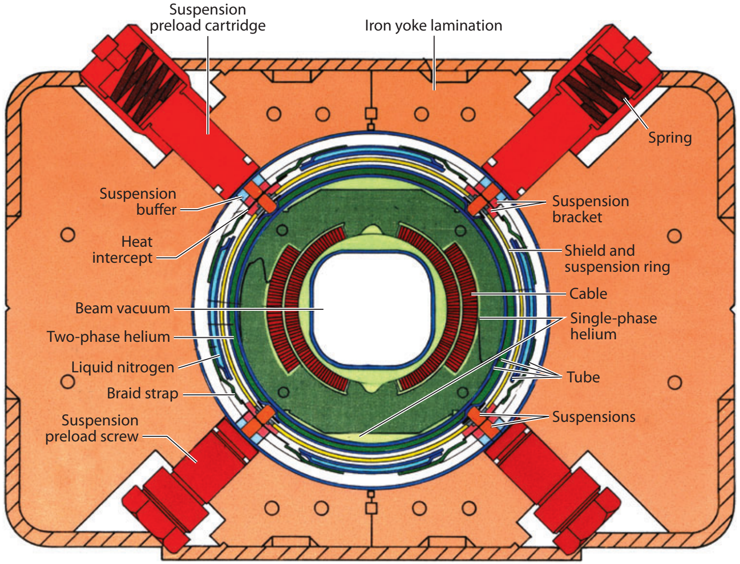
- In the ‘60’s there was considerable discussion of using superconducting magnets for the National Accelerator Laboratory (FNAL), but the technology was considered not yet ready for accelerators
- 1968 BNL Summer Study (200 physicists and engineers for 6 weeks)
  - Strand diameter and flux jumps (Steckley)
  - Twisted filaments
  - Discussion of doubling the energy of the NAL accelerator using SC magnets
- Panel discussion at the 1971 Particle Accelerator Conference was the kick-off of superconducting magnets in accelerators
  - Paper on compact, fully transposed cable produced by Rutherford lab
- World-wide activity ensued but Europeans were at first reluctant (though superconducting quadrupoles were used in the ISR at CERN)

Bill Sampson, BNL
Still going strong!

Al (Mac) McInturff, retired BNL, FNAL, SSC, LBNL, TAMU

The rise of the application of superconductivity for accelerators was triggered by the success of the Tevatron

- 774 dipoles and 216 quadrupoles
  - Nb-Ti at 4.2K
  - Field corresponding to 1 TeV was 4.4T
  - Warm iron yoke
  - Collared coils
  - Rutherford cable used for the first time in a full-scale magnet
  - Relatively high ramp rate – 100mT/s
- Considerable influence on future projects – HERA at DESY, RHIC, SSC (almost) and the LHC
- Unexpected benefit
  - Development of a conductor industry



The Tevatron (Energy Doubler/Saver)

- The first synchrotron ever constructed using superconducting magnets
  - Approximately ten-year development program (1972 – 1983)
  - Originally intended to support the fixed-target operation
  - Reached 980 GeV
  - Proton-antiproton collisions in 1985 and that became the main focus

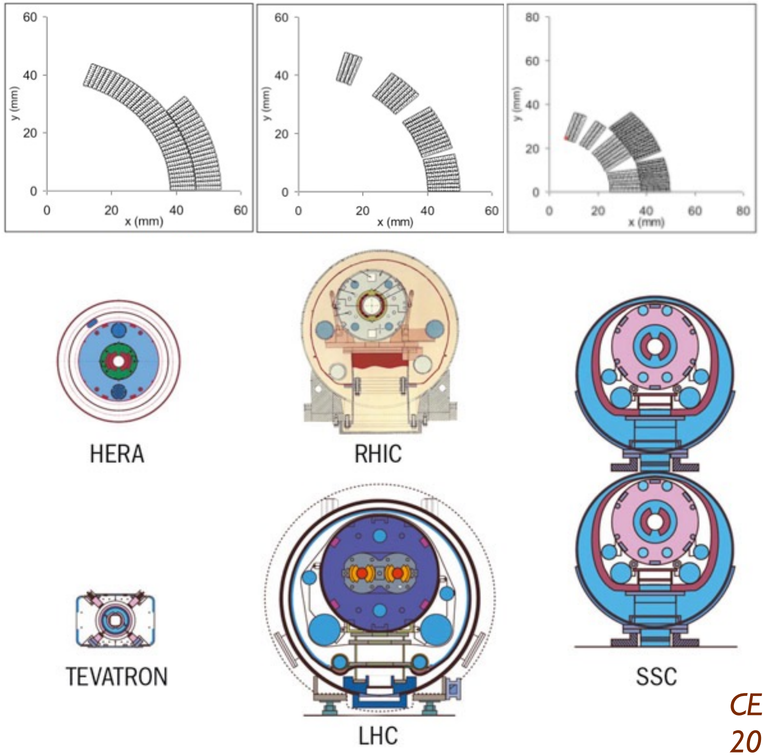
The Challenges for Large Scale Magnet Applications

In general . . .

- Requires cryogenic systems
  - Complexity and cost (Requires power to keep things cold!)
- Mechanical properties
  - Can you make a wire or cable?
  - Brittle (in many cases)
  - Strain sensitive (in many cases)
- Electrical properties
  - Doesn’t always stay superconducting!
  - And other application-specific issues
- Cost
  - Materials
  - Infrastructure
  - Engineering

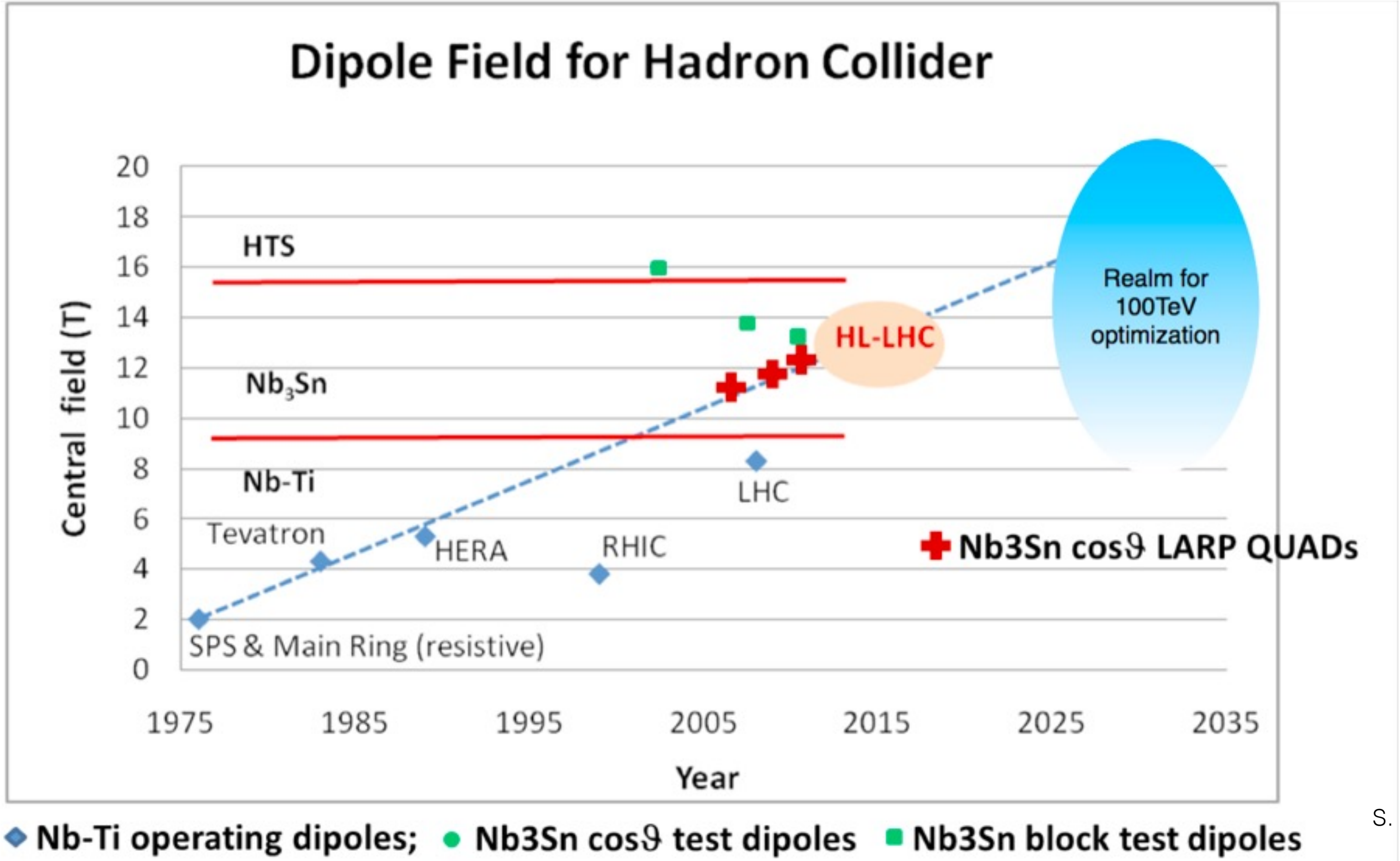
The upshot: Never use superconductivity unless there is no better option

Magnet Evolution – no real revolution, just a lot of work



CERN Courier, Oct. 2011

Progress towards higher field accelerator magnets



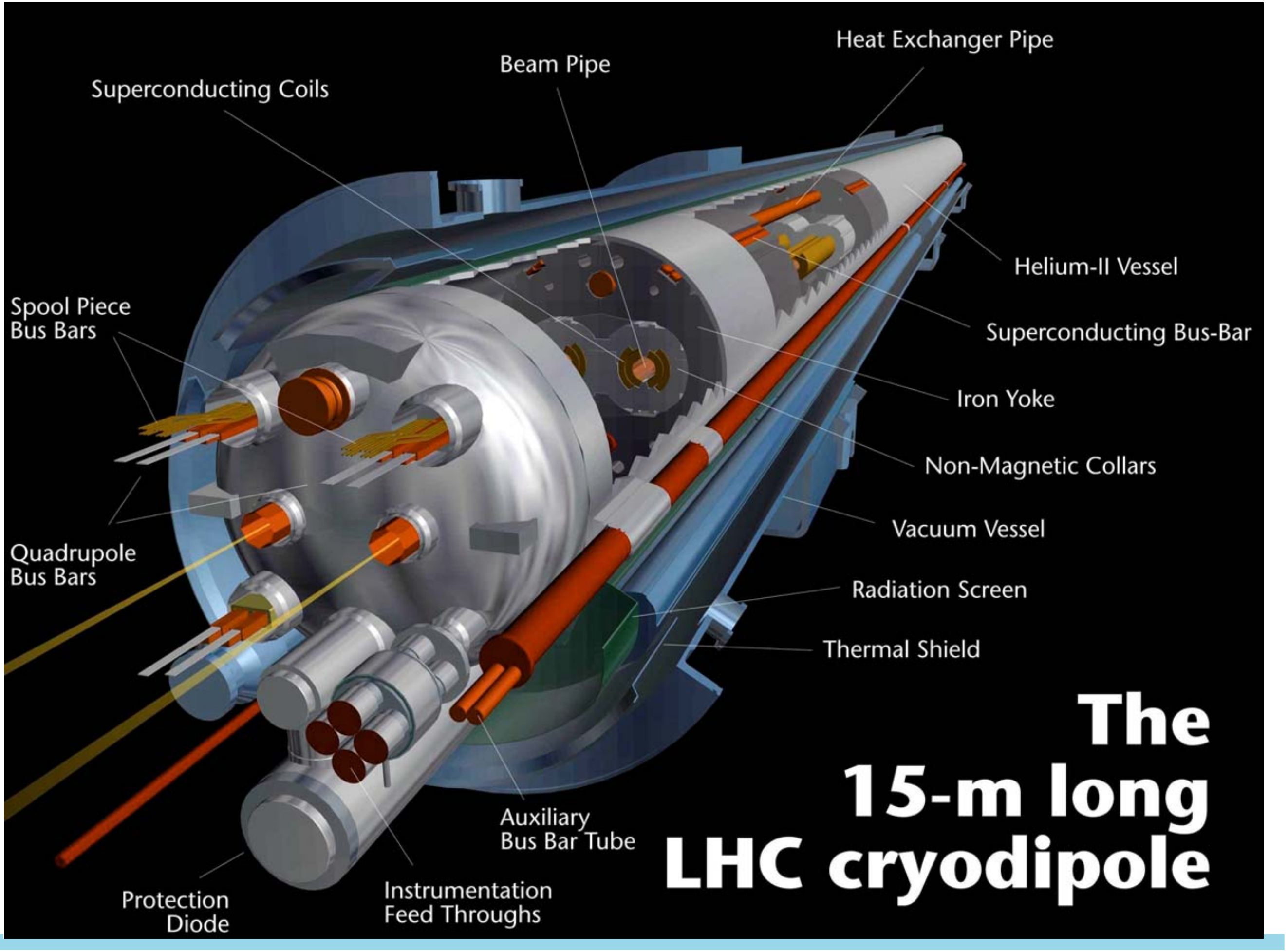
S. Prestemon, LBNL

Practical accelerator magnet technology has culminated in the LHC dipole

- Drew heavily on previous concepts
  - Collars
  - Cold-iron yoke (proposed for ISABELLE at BNL, used by HERA)
  - Two-in-one yoke design (ISABELLE)
  - Profited from the fairly recent performance improvement (X2) in Nb-Ti
  - Large-scale use of superfluid He

  - Has not quite reached goal of 8.3T operation for all magnets

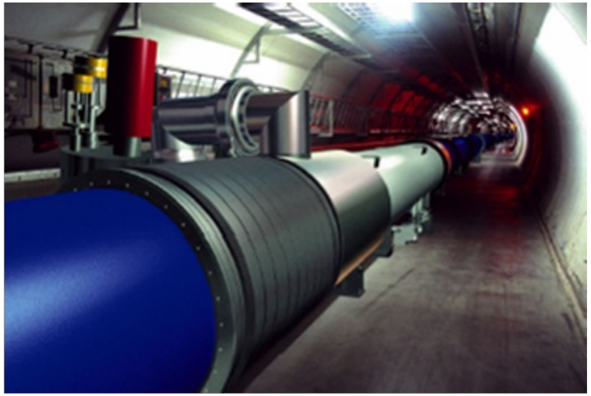
Anatomy of a Superconducting Magnet



The 15-m long LHC cryodipole

Fun Facts!
Stored energy of LHC beam 350 MJoules

- Kinetic energy
  - 1 small aircraft carrier of 104 tons at 30 kph
  - 450 automobiles of 2 tons going 100 kph
- Chemical energy
  - 80 kg of TNT
  - 70 kg of (Swiss?) chocolate
- Thermal Energy
  - Melt 500 kg of copper
  - Raise 1 cubic meter of water 85C: a ton of tea



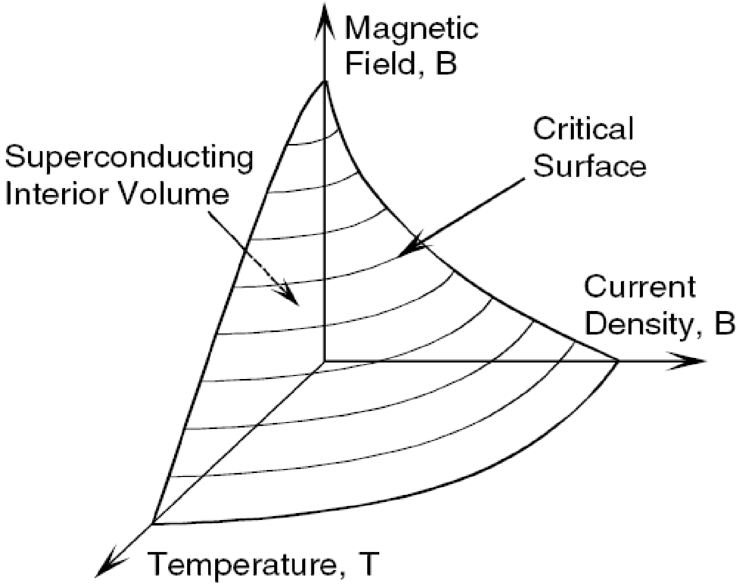
Courtesy of S. Peggs

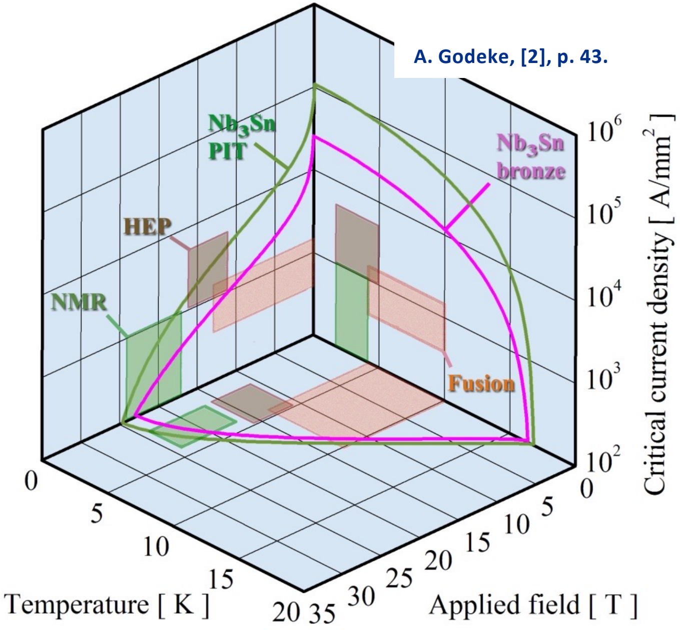
Conductors for Accelerator Magnets

- Conductor ultimately determines magnet performance
  - You can’t do any better than the virgin conductor
  - But . . . you can do worse!
- With few exceptions all accelerator magnets use Rutherford-style cables
  - Multi-strand/high current – can use shorter strand lengths, fewer turns (lower inductance)
  - High current density
  - Precise dimensions – controlled conductor placement (field quality)
  - Current redistribution – stability
  - Twisting to reduce interstrand coupling currents (field quality)

Superconducting materials - Critical surface

- The critical surface defines the boundaries between the superconducting state and the normal conducting state in the space defined by temperature, magnetic field, and current densities.
- The surface, determined experimentally, can be fit with parameterization curves.



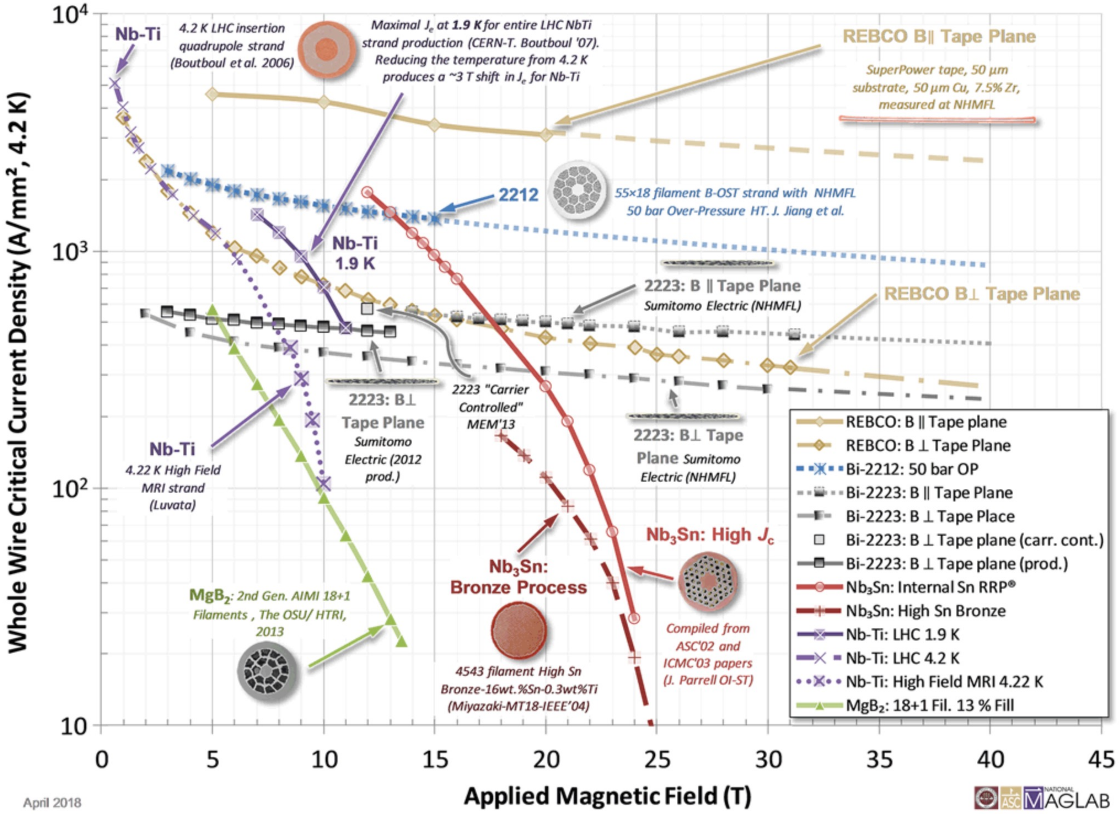

A. Godeke, [2], p. 43.

Current conductor landscape

- Nb_3Sn has been around for many years
  - Still possible improvements – J_c, high C_p
    - Work on increasing heat capacity of strands
    - Artificial Pinning Centers (X. Xu et al, MDP/FNAL)
  - Demonstrate technology for large-scale accelerator deployment
    - Substantial CERN program to develop industrial capacity
- Fe-based could be game-changer
  - Worth pursuing?
  - Potentially lower cost but performance not there yet

- Bi-2212 has clear niche applications
  - Several desirable properties
  - Expensive and cost reduction path not so clear
  - Powder supply chain?
- REBCO
  - Fusion can drive capacity and has substantially lowered cost of some architectures.
  - Prohibitively expensive, expensive, or OK?
  - R&D to improve performance – and make into a magnet conductor

Engineering current density (J_e) vs field

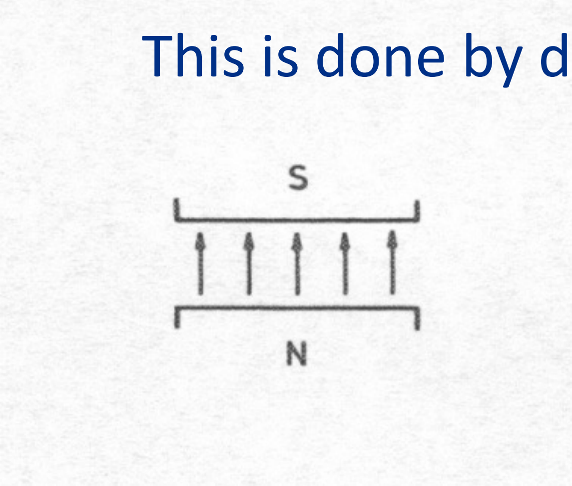


Whole wire critical current density (J_e) of accelerator magnet conductors as a function of external magnetic field. Courtesy of Peter J. Lee, Applied Superconductivity Center, Florida State University and the National High Magnetic Field Laboratory https://nationalmaglab.org/magnet-development/applied-superconductivity-center/plots

Keeping particles on track: dipoles

The magnet that we need should provide a constant (over the beam region) magnetic field, to be increased with time to follow the particle acceleration

This is done by dipoles

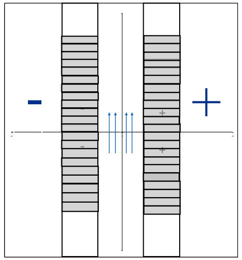


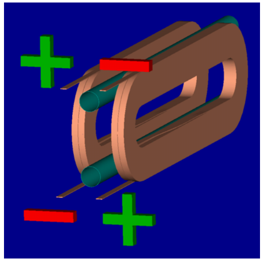
$$\begin{cases} B_y = B_1 \\ B_x = 0 \end{cases}$$

E. Todesco, CERN

Start with ideal case for dipole field

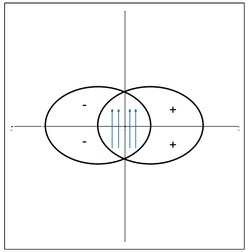
- Uniform current walls
  - Easy to wind but the height is infinite
  - Practical implementation requires . . .
    - High aspect ratio
    - Modification of ends





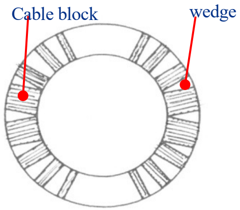
BNL “Common Coil”

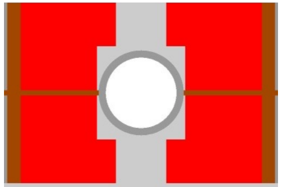
- Intersecting Ellipses
  - Non-circular aperture
  - Requires internal support structure



- Cosθ current distribution
  - Circular aperture, self-supporting
  - Reasonably easy to reproduce in practical configurations

A practical winding with one layer and wedges
[from M. N. Wilson, pg. 33]





Block Coil Implementation
LBNL “HD-2”

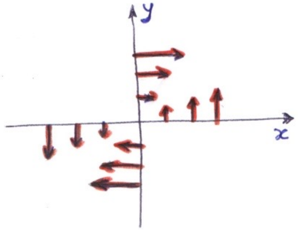
Keeping particles on track: quadrupoles

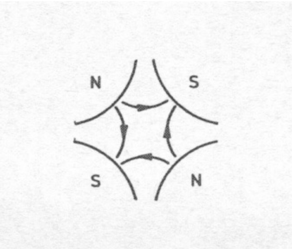
As the particle can deviate from the orbit, one needs a linear force to bring it back

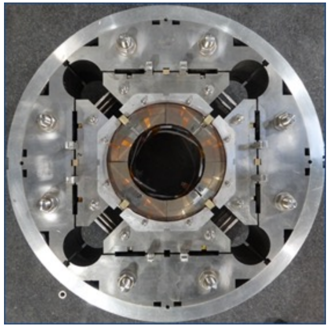
Quadrupoles provide a field which is proportional to the transverse deviation from the orbit, acting like a spring

Prescription for stable oscillations is that distance between quadrupoles is less than twice their focal length

$$\begin{cases} B_y = Gx \\ B_x = Gy \end{cases}$$







E. Todesco, CERN

Keeping particles on track: Higher order correctors

No such thing as a “perfect” field so we need to correct or compensate to achieve stable beam

Harmonic content
- Allowed (by symmetry)
- Un-allowed (tolerances and fabrication errors)

Sextupoles
- Chromaticity (momentum dependent focusing) compensation
    - Momentum dependent correction to account for “off momentum” particles ($\Delta p/p$)

Octupoles (and up to 14-pole)
    - Correct for unwanted field errors

Accelerator magnet field quality

- Field components expressed as

$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1}$$

EU notation

- Coefficients (b_n and a_n) are normalized with the main field component (B_1 for dipoles, B_2 for Quadrupoles)
- Dimensionless coefficients defined WRT reference radius
  - R_f = 2/3 of coil diameter (typically) and given in units of 10^{-4}
- The coefficients b_n, a_n are called normalized multipoles
  - b_n are the normal, a_n are the skew components

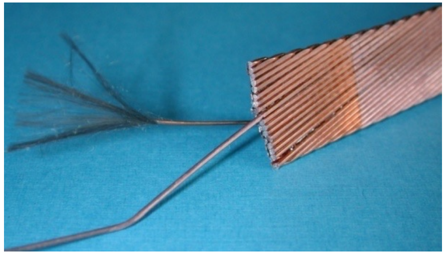
$$b_2^{US} = b_3^{EU}$$

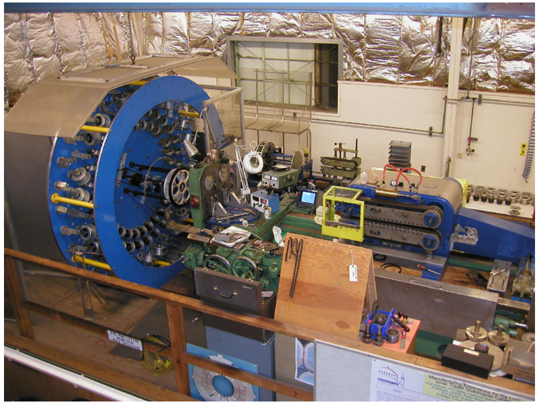
- Note that unfortunately US and EU are different

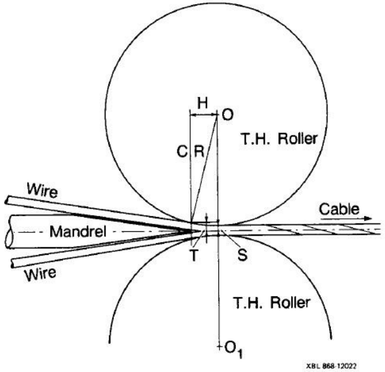
Rutherford cables

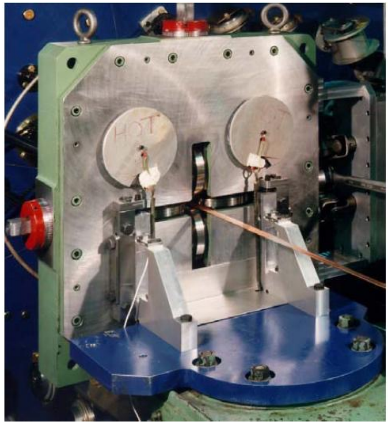
- Cable cross-section is rectangular or trapezoidal
- Packing Fraction (PF) ranges from 85% - 92%
  - Too much compaction – damage to filaments
  - Too little compaction – mechanically unstable

$$PF_{cable} = \frac{N_{wire} \pi d_{wire}^2}{4 w_{cable} t_{cable} \cos \psi_{cable}}$$



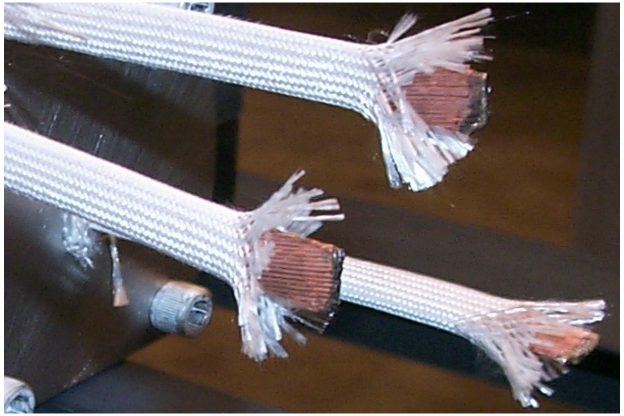






Current density

- Start with J_c of Superconductor
  - Nb-Ti ~ 3,000 A/mm^2 @ 5T and 4.2K
  - Nb_3Sn ~ 3,000 A/mm^2 @ 12T and 4.2K
- Add copper/non-Superconductor
  - Typically ~50%
- Cable compaction ~88%
- Insulation – order of 100 microns (X2) compared to ~2 mm
- Filling factor = $(N_{wire} A_{sc})/A_{ins\_cable}$
- Engineering current density defined as $J_e = \kappa J_c$
  - Typically on the order of 1,000 A/mm^2

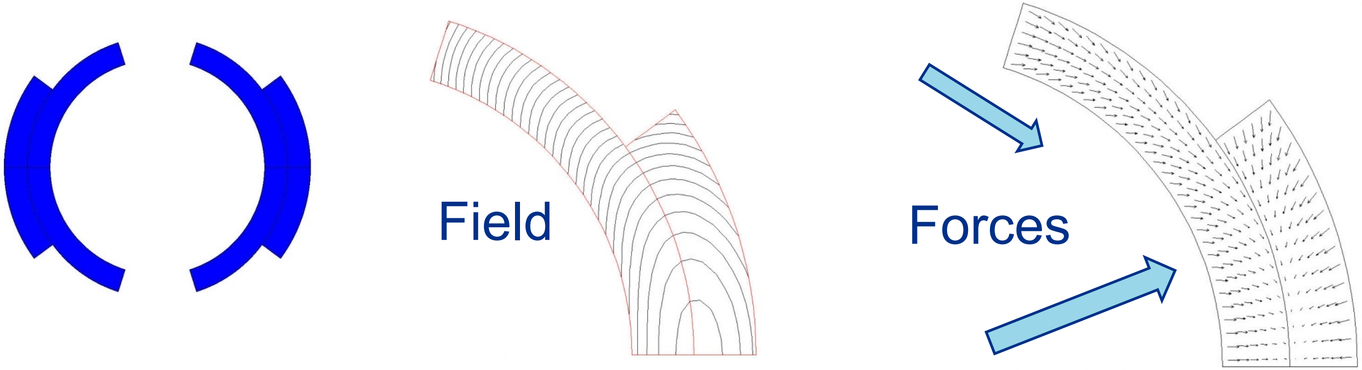


Mechanics

Forces, Stresses and Structures

Lorentz forces in dipoles

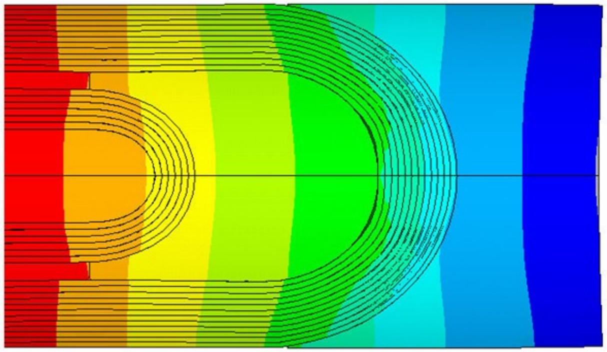
- Coils are subjected to large forces due to high current densities and high fields
  - Must prevent coil motion/deformation
    - Field quality good to ~ 1 part in 10^4 (conductor positioning to 25 microns)
    - Restrict motion to prevent conductor going normal (“Quench”)

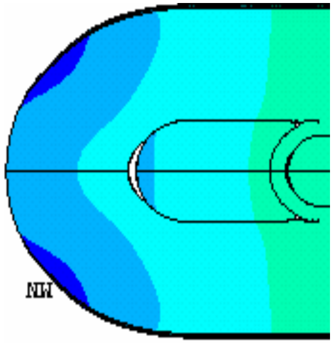


- Forces are outward in radial direction and towards the mid plane in the azimuthal direction

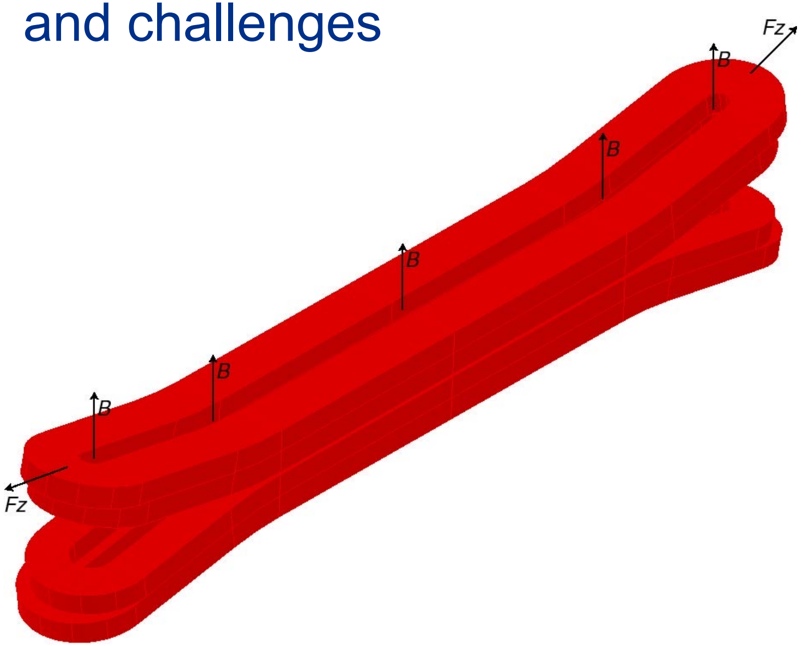
Ends – the hard part

- Lorentz forces creates an axial tension, pushing the coil ends outward (not unlike a solenoid)





Source of many design decisions and challenges



Forces

- The magnetic pressure, p_m acting on the winding surface element is given by

$$p_m = \frac{B_0^2}{2\mu_0}$$

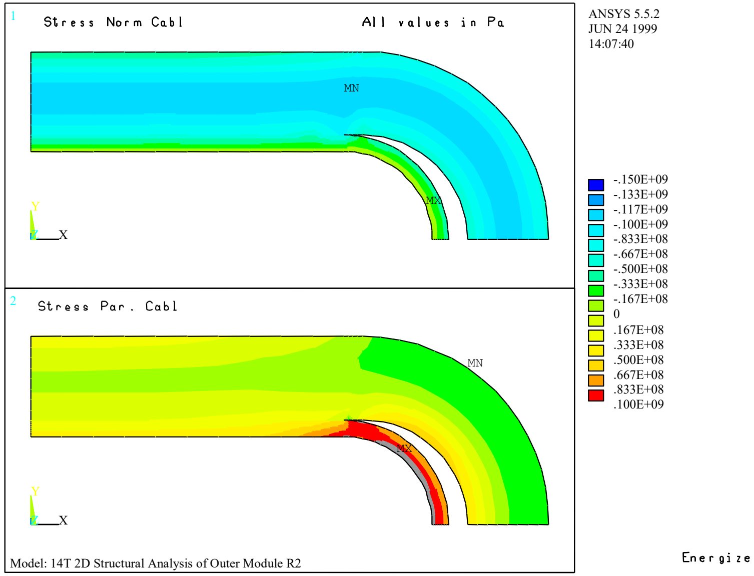
similar to the pressure of a gas acting on its container

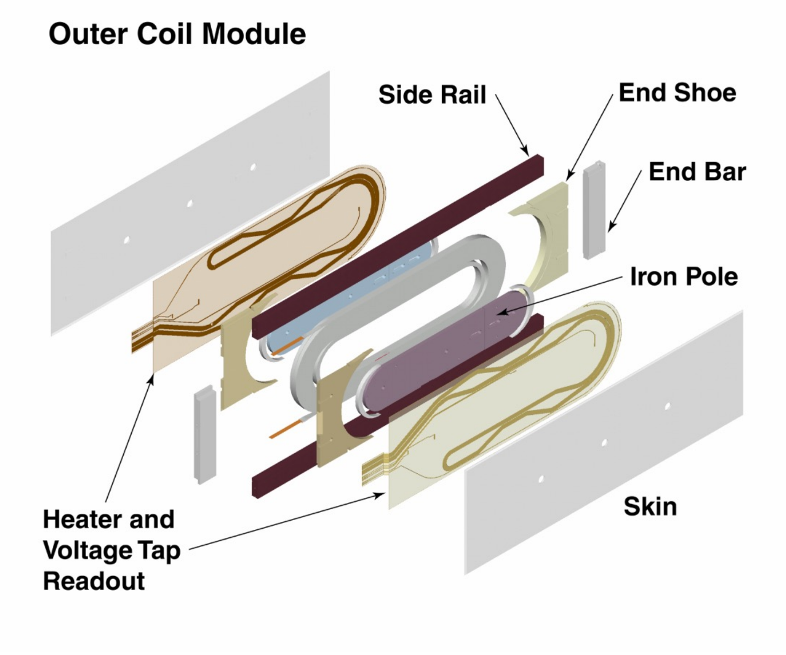
- In the example to follow we have 12 T

so . . . $p_m = (12^2)/(2\cdot 4\,\pi \times 10^{-7}) = 5.7 \times 10^7$ Pa = 555 atm

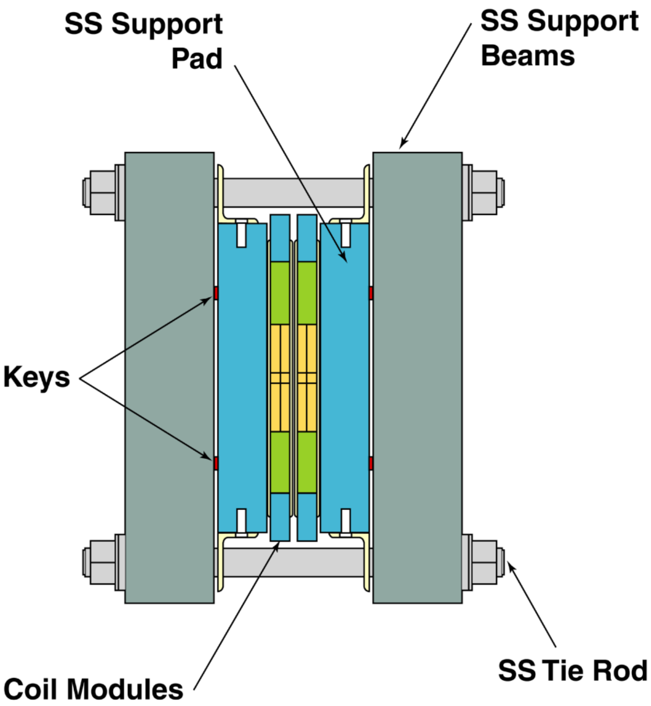
Racetrack coil test (RT-1)

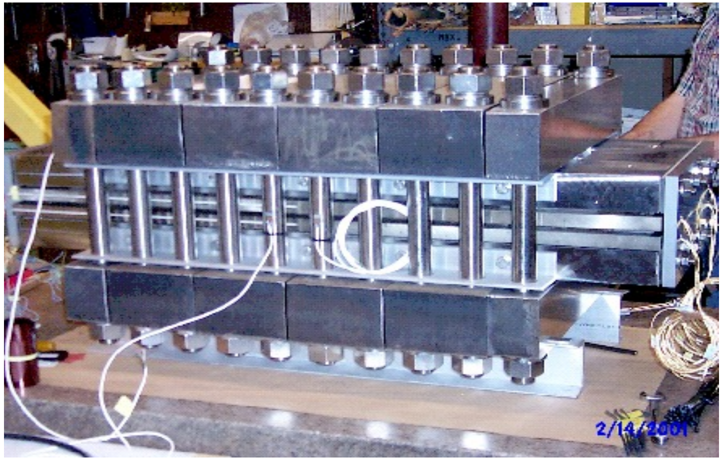
- Two simple racetrack coils
  - 50 cm long
  - 12 Tesla



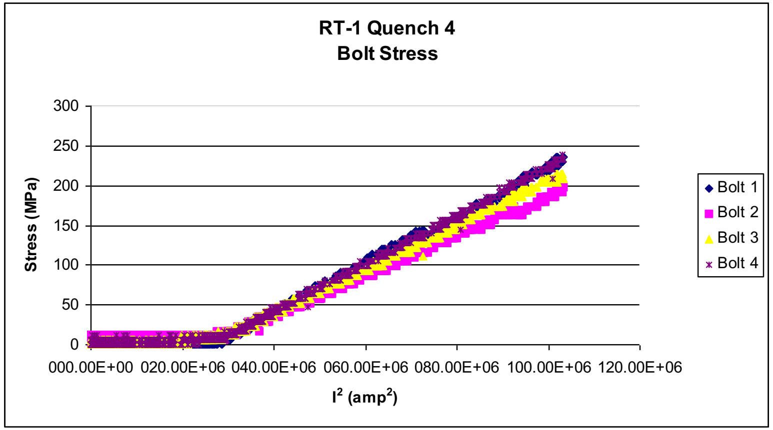


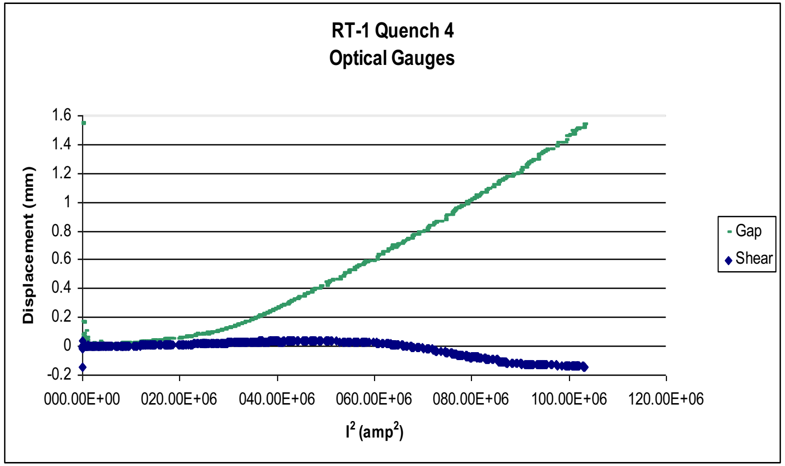
Support Structure

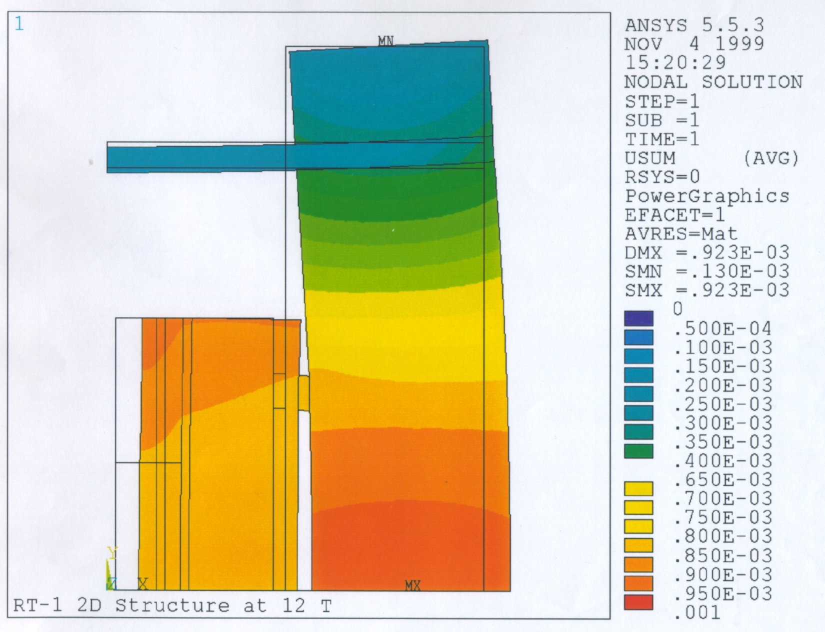




Test Results


RT-1 Quench 4
Bolt Stress


RT-1 Quench 4
Optical Gauges

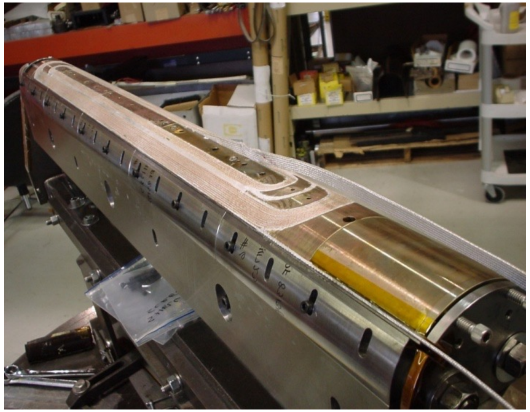


Fabrication

Coil Fabrication

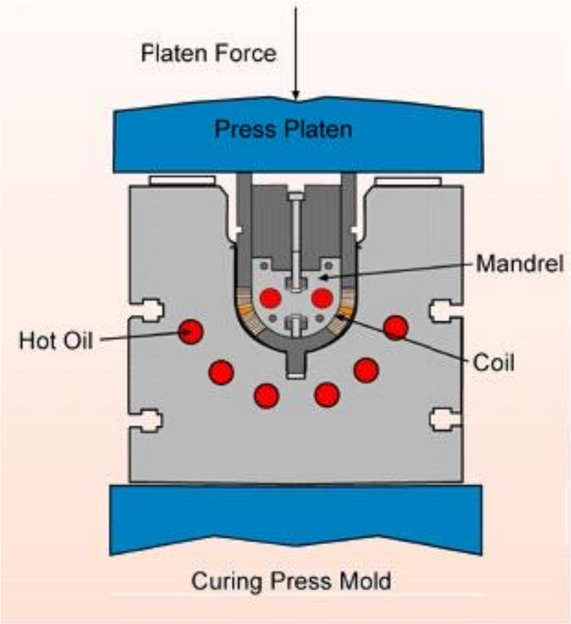
Nb-Ti (dominates use now) but now the focus is on Nb_3Sn for higher fields

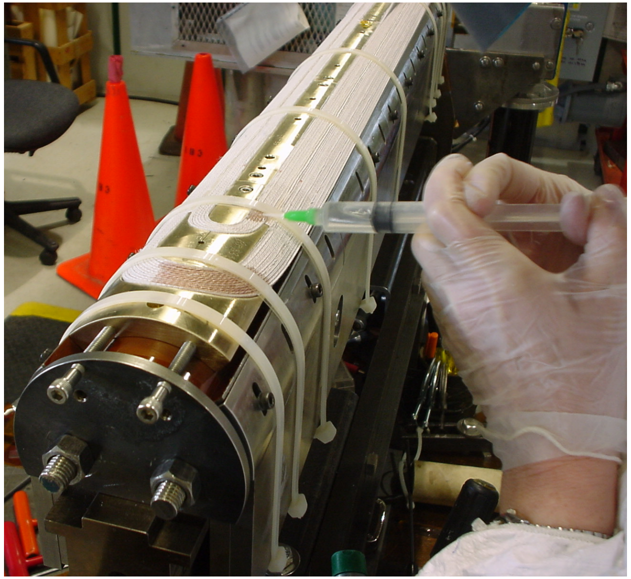
- Winding
  - Virtually the same process for both materials
  - Start with insulated cable
    - Nb-Ti – 1 or 2 layers of polyimide wrap
    - Nb_3Sn – S-2 glass "sock" – really not insulator but matrix for later epoxy impregnation



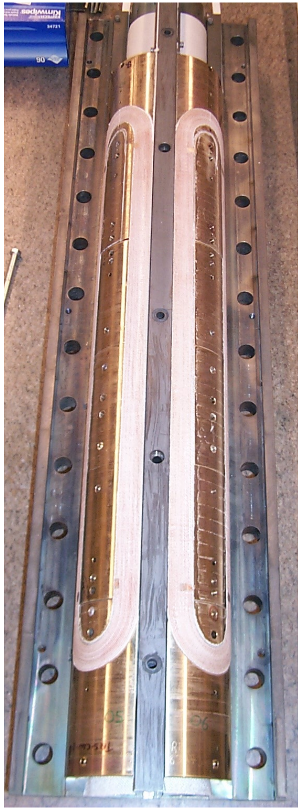
Coil Fabrication

- Curing/Reaction
  - Nb-Ti coils “cured” in fixture to set dimension and aid handling
  - Nb_3Sn coils “cured” with ceramic binder and reacted (650 – 700 ^{0}C)



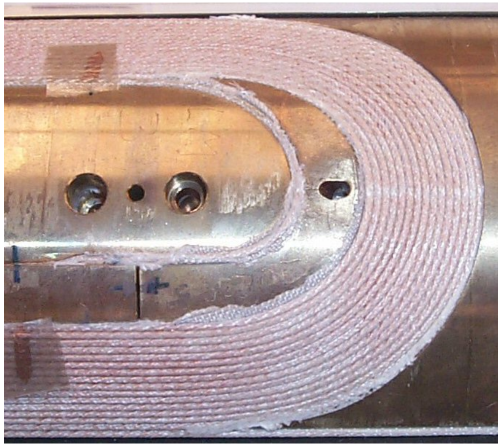


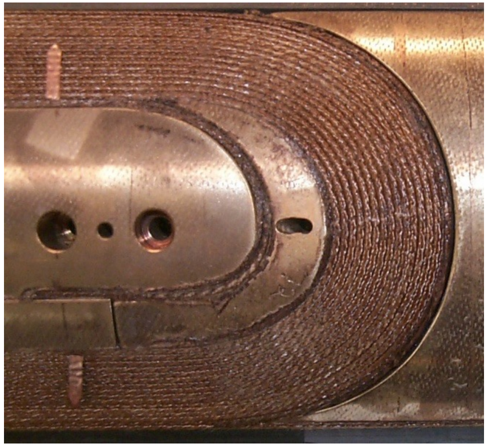
Reaction fixture for Nb_3Sn coils

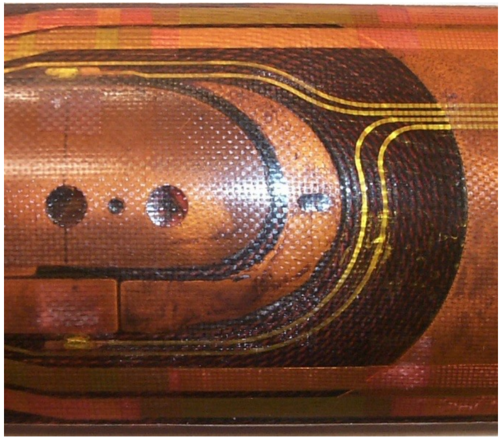


Coil Fabrication

- Epoxy impregnation of Nb_3Sn Coils
  - In US CTD-101 is used for impregnation (looking at alternatives)
  - Two-fold purpose -
    - Provide insulation
    - Distribute load between strands to reduce stress points



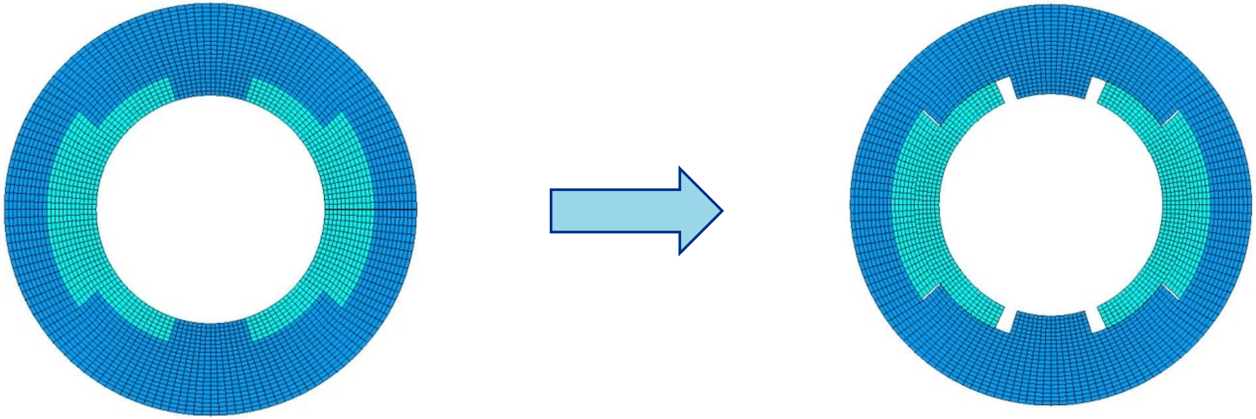




Structures and Pre-Stress

- Due to character of Lorentz forces, a simple rigid structure is not sufficient.

- “Pre-stress” is required to prevent conductor from losing contact with the structure



- Due to uncertainties, some margin is allowed, ~ 20 MPa

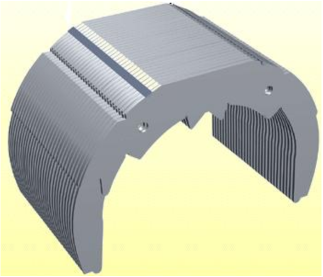
Support Structure

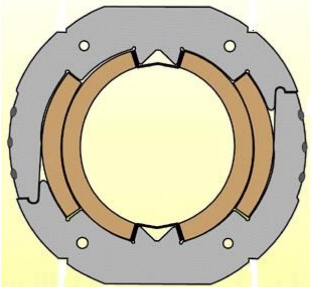
- Provides
  - Precise positioning and alignment
    - Prevents changes in coil shape that could affect field quality
  - Pre-stress and prevents movement under Lorentz loading
    - Conductor displacement that could release frictional energy

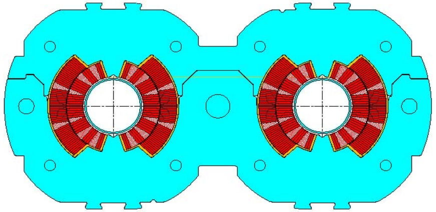
- But must prevent over-stressing the coil
  - Insulation damage at about 150-200 MPa
  - Possible conductor degradation of Nb_3Sn magnets at 150 – 200 MPa.
  - Yielding of structural components

Collars

- First introduced in the Tevatron
  - Since used in most accelerator magnets





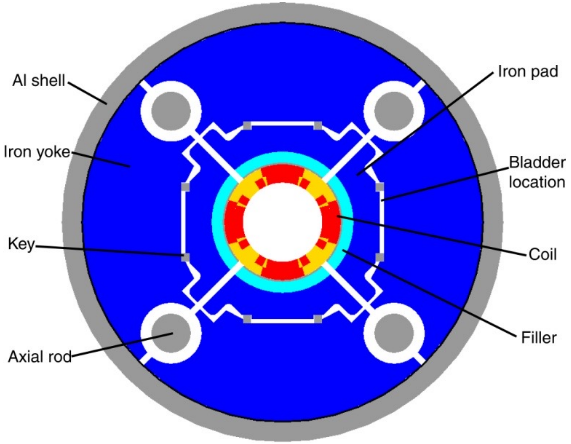


LHC

  - Provide some or all of the pre-stress
  - Precise cavity (~ 20 microns)
  - Composed of Al or stainless steel laminations

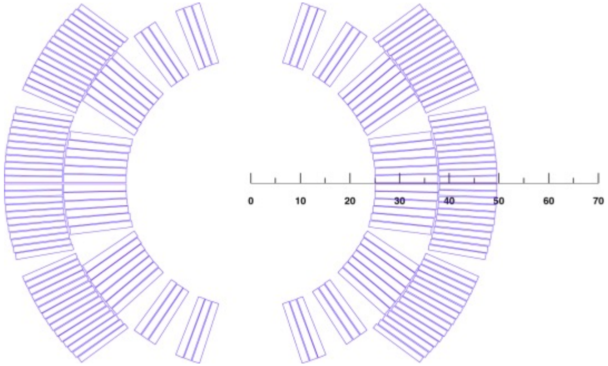
Final Assembly

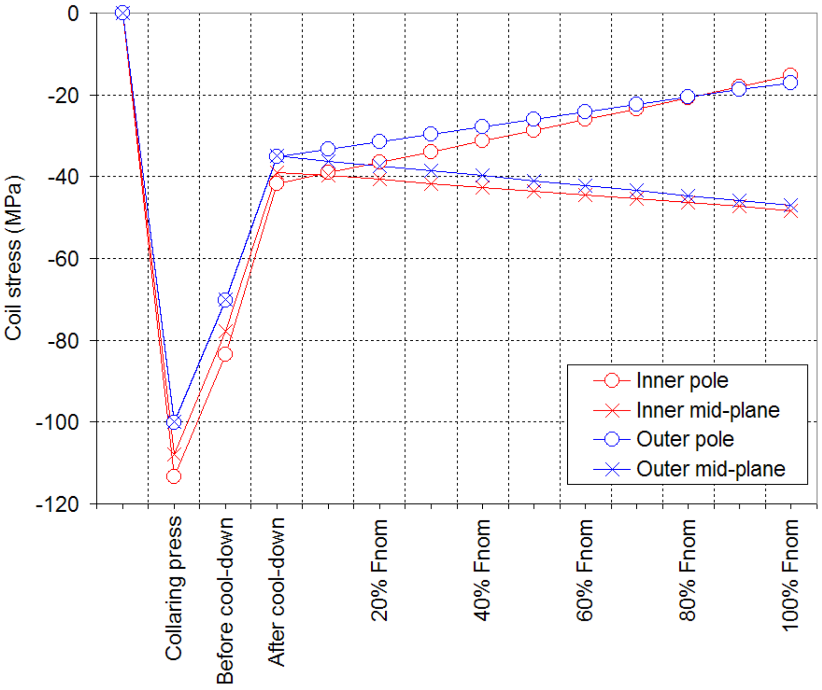
- Iron yoke
  - Shields and enhances field
  - In some cases provides additional preload
- “Skin” or shell
  - Yoke is contained within two welded half-shells of stainless steel (the “skin”) or a shrinking cylinder of aluminum
    - Outer shell contributes to coil rigidity and provides helium containment
- End support or loading
  - Thick plates provide axial support



Classic Example (SSC Dipole)

- Goal
  - Load but don't overload the coil with enough pre-stress to keep coil in contact with structure at full field

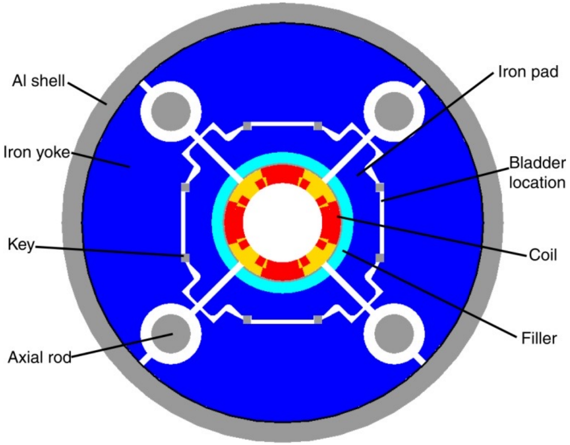


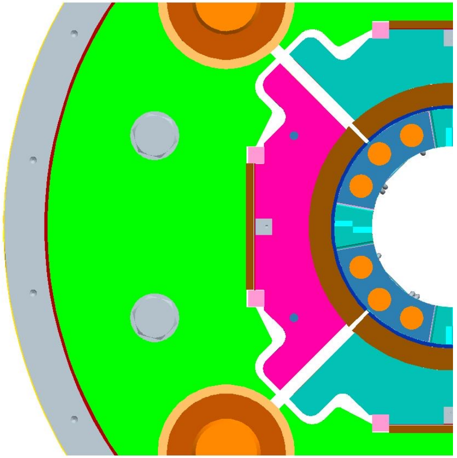


  - What if you need more?
  - And high field magnets will need a lot more . . .

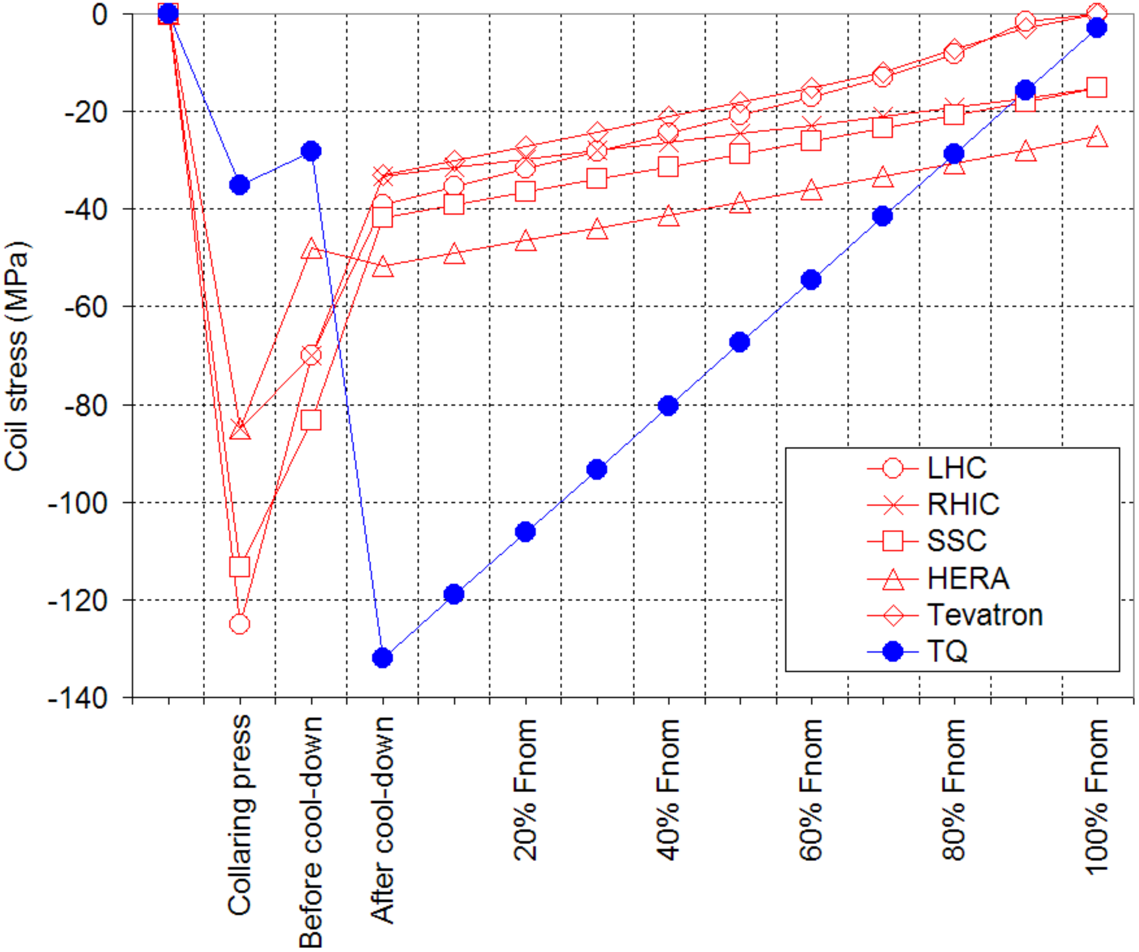
Key and Bladder (LARP/LBNL TQS Quad)

- Four pads or collars transfer load to coils
- Yoke is contained by aluminum shell
- Preload provided by inflating bladders and held via keys
- Coil pre-stress increases during cooldown due to the high thermal contraction of the aluminum shell.





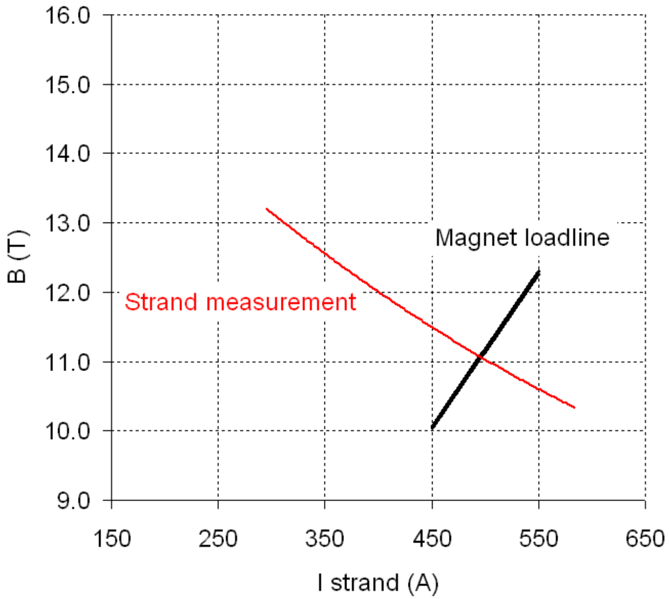
Comparison

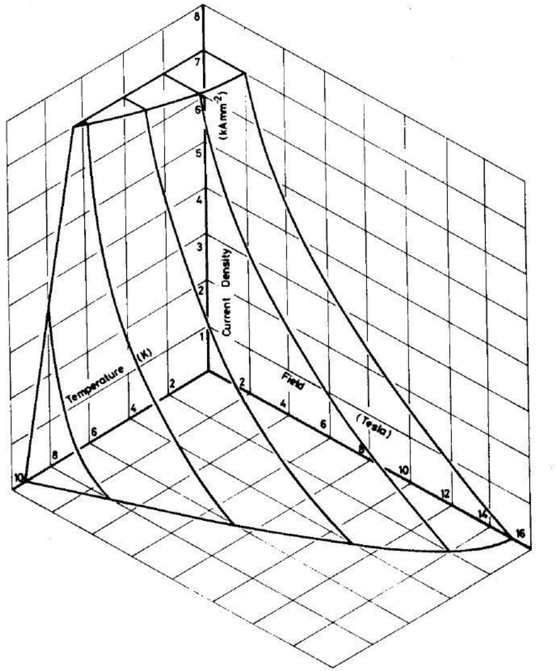


Coil stress (MPa)
0
-20
-40
-60
-80
-100
-120
-140
Collaring press
Before cool-down
After cool-down
20% Fnom
40% Fnom
60% Fnom
80% Fnom
100% Fnom
LHC
RHIC
SSC
HERA
Tevatron
TQ

Quench and Training

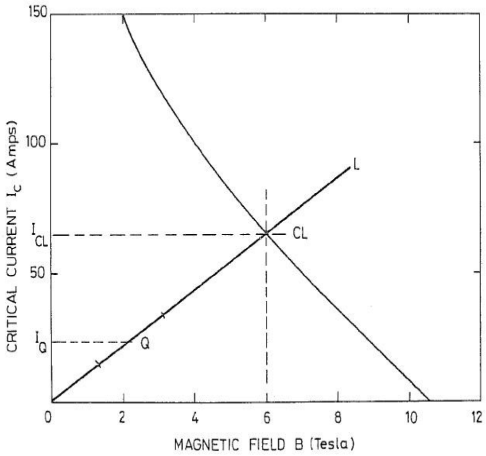
- Magnet operates below the critical surface
  - Continued increase of the current will eventually create a “normal” zone at some location in the magnet
  - Propagation of the normal zone is called a “quench”

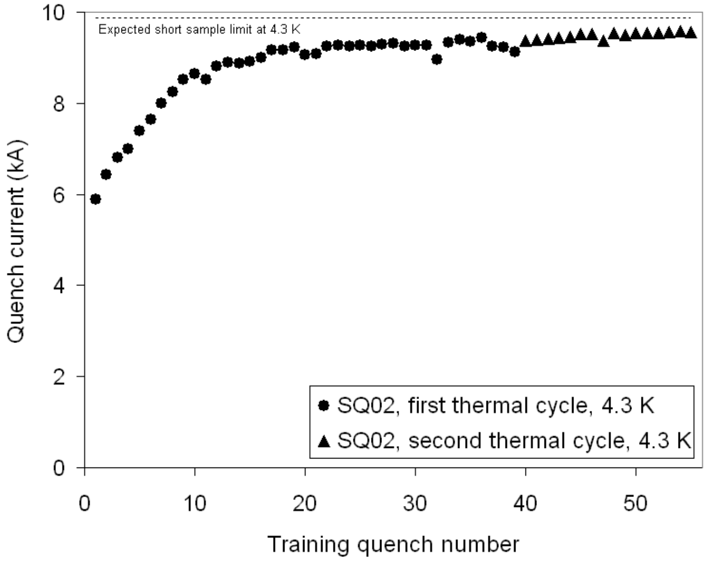




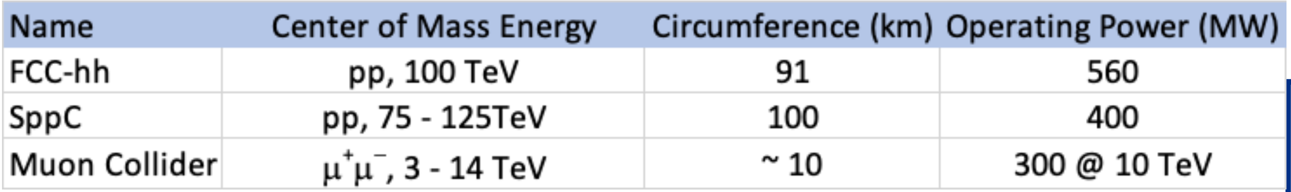
Quench and Training

- Two categories of quench
  - Conductor limited $I_{max} = I_c$ (short sample limit)
    - Increase of I and B
  - or $I_{max} < I_c$ (energy deposited quench)
    - Increase of temperature
  - Successive, increasing quench current is called “training”



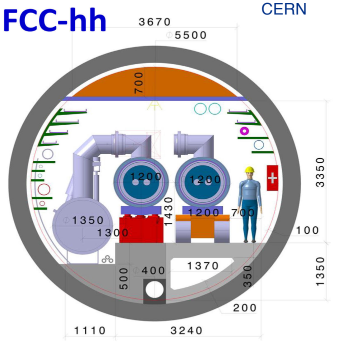


Proposed high energy colliders



Name	Center of Mass Energy	Circumference (km)	Operating Power (MW)
FCC-hh	pp, 100 TeV	91	560
SppC	pp, 75 - 125TeV	100	400
Muon Collider	$\mu^+\mu^-$, 3 - 14 TeV	~ 10	300 @ 10 TeV

FCC-hh

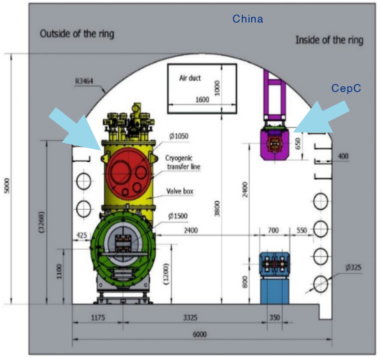


100 TeV, 16 T magnets, 91 km

50mm, Nb_3Sn, HTS?

Staged from e^+e^- collider

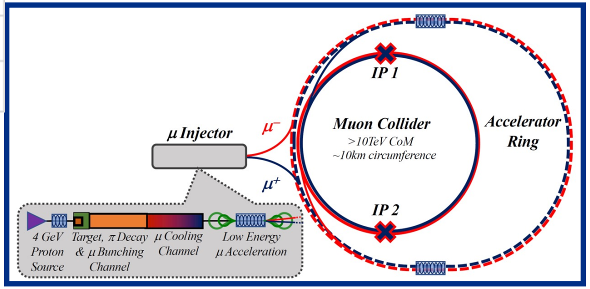
SppC



125 TeV, 20 T magnets, 110 km

50mm, IBS, Nb_3Sn, HTS

Muon Collider



- Large variety of challenging magnets
- Energy reach X7 over pp
- Luminosity/power ratio best among all multi-TeV colliders
- Relatively small footprint and cost

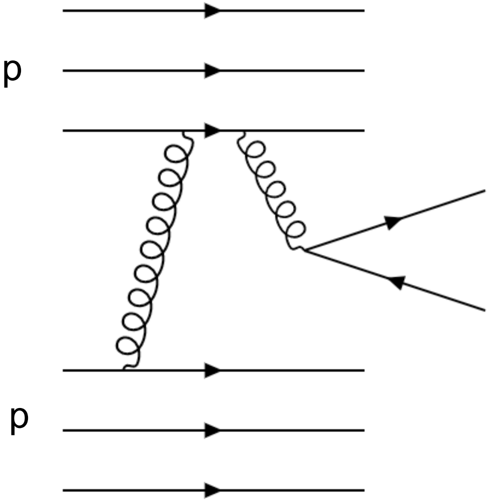
”A Muon Collider Facility for Physics Discovery”, arXiv:2203.08033 [physics.acc-ph]
arXiv:1901.06150v1

The proposed hadron colliders are a challenging extension of the usual formula

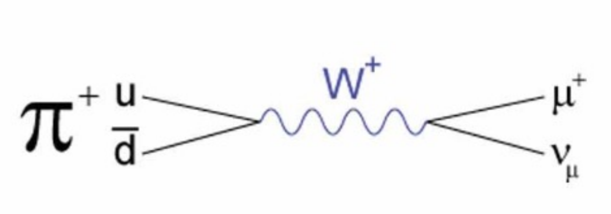
(RF, dipoles, quadrupoles, . . .)

A Muon collider is that and a bit more . . .

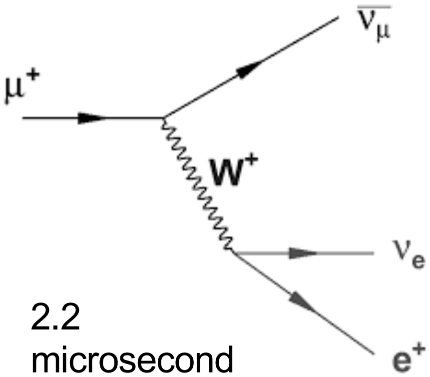
Not a simple task to round-up muons!



Primary proton beam



Pions (plus and minus) decay to muons



2.2 microsecond

Muon lifetime

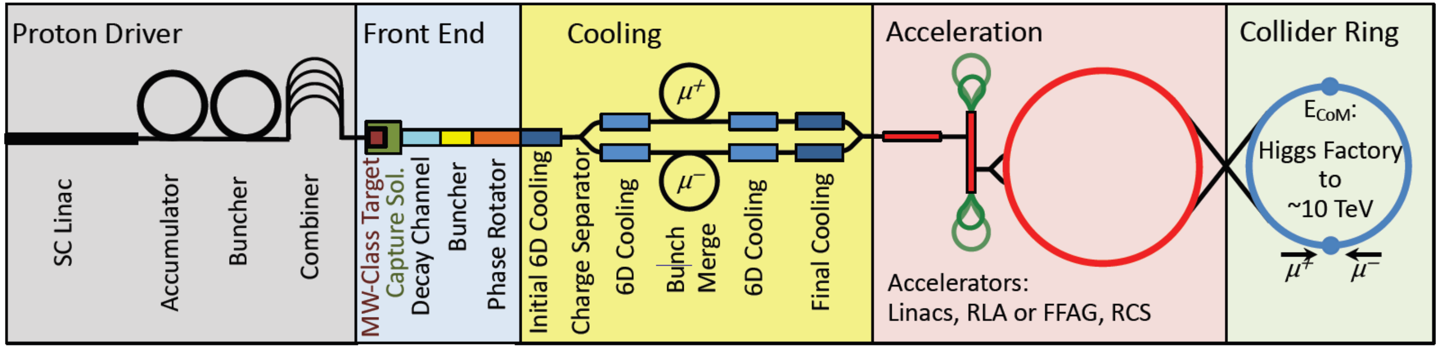
The most exciting magnet challenges: Muon Collider

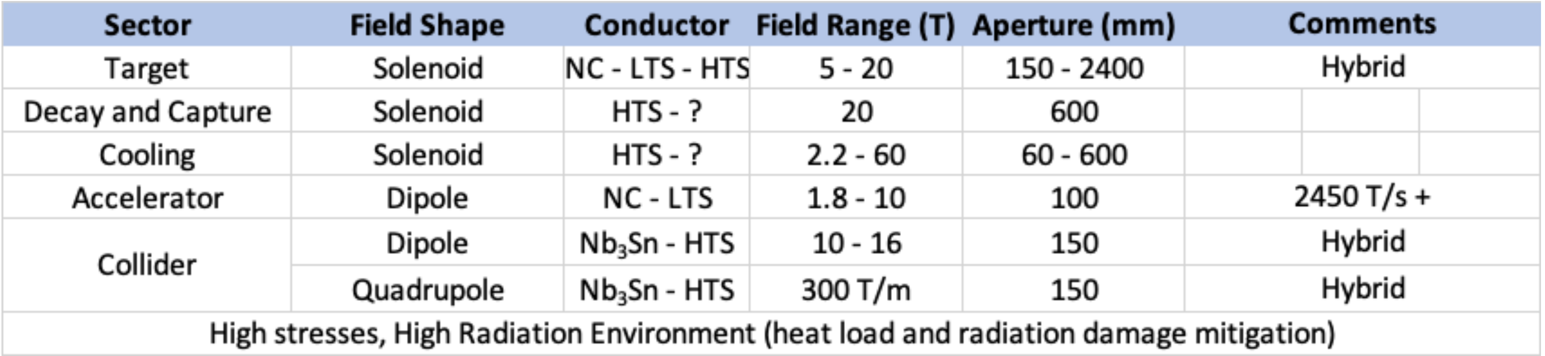
- Capture Solenoid
  - 15 – 20T
  - Meter-scale bore
  - High Radiation environment
- 6-D Cooling Channel
  - Fields from LTS to HTS regime
- Final cooling channel
  - 50mm bore
  - 40 – 60T solenoids
- Acceleration to TeV
  - 400 Hz
  - 1.5T
- Ring dipoles
  - Luminosity proportional to field
    - 10 T – 20 T
  - High radiation environment
    - Especially in Irs
  - Combined function preferred

This is an application where HTS is REQUIRED

Courtesy M. Palmer, BNL

$\mu^+\mu^-$ Collider is an exciting opportunity for the magnet community!





Sector	Field Shape	Conductor	Field Range (T)	Aperture (mm)	Comments
Target	Solenoid	NC - LTS - HTS	5 - 20	150 - 2400	Hybrid
Decay and Capture	Solenoid	HTS - ?	20	600	
Cooling	Solenoid	HTS - ?	2.2 - 60	60 - 600	
Accelerator	Dipole	NC - LTS	1.8 - 10	100	2450 T/s +
Collider	Dipole	Nb_3Sn - HTS	10 - 16	150	Hybrid
	Quadrupole	Nb_3Sn - HTS	300 T/m	150	Hybrid
High stresses, High Radiation Environment (heat load and radiation damage mitigation)					

Thanks to Luca Bottura, CERN

Summarizing magnet needs for potential future colliders

- High field dipoles – up to 17T (and perhaps 20 – 24T)
- Large aperture dipoles with fields up to 13T (or more)
- (Very) fast ramping magnets
- Large aperture, high field solenoids (> 30T)
- Large aperture interaction region quadrupoles

High radiation environment
  Damage
  Heat deposition

Manage stress

To summarize: There is good news and bad news for the magnet community

- Good news
  - International interest in next generation colliders
  - World-wide magnet R&D effort is ramping up
  - A greater variety of potentially game-changing materials
  - Better tools and more experience

- And the bad news
  - R&D effort is not large enough (yet)
  - Goals may be too ambitious?
  - The R&D approach is too evolutionary – need irreverent thinking!

Final Comment

Fingers Crossed:

An exciting and challenging future for the younger generation!