Unit 2
Overview of Superconducting Magnets for Particle Accelerators

Steve Gourlay and Soren Prestemon
Lawrence Berkeley National Laboratory (LBNL)

Introduction

- General aspects of large scale applications of superconducting technology

- Origins of superconducting magnets for accelerators
  - Particle physics legacy

- Role of magnets as accelerator components

- Magnet parameters in the context of accelerator performance
  - Example: 40mm SSC Dipole

Applications

- Two general categories
  - **Enables new technology (no conventional alternative)**
  - **Replaces existing technology (better, cheaper)**
    (Can I make money with this?)

The Challenges for Large Scale 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

Enabling Technology: Materials

Application/performance engineering ⟺ material properties and

- There are several thousand materials known to be superconductors

. . . .but only a few have been considered for practical applications

"Low" and "High"

Temperature Superconductors

Nb-Ti	Bi-2212
Nb_3Sn	Bi-2223
Nb_3Al	YBCO

MgB_2

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

From this . . . to

this . . .

80 Years

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

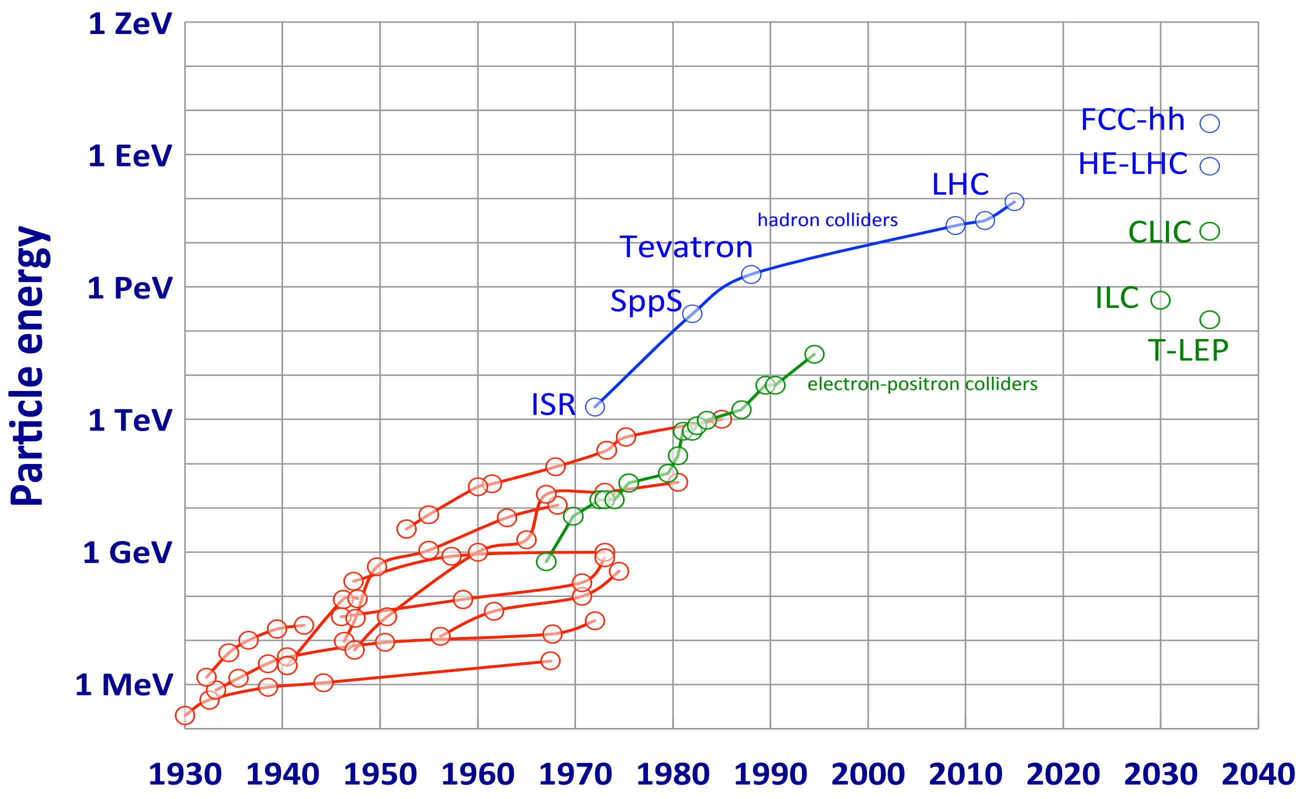
And superconducting magnets have been an essential key to continued progress

Two modes of operation

- The beam of particles produced by an accelerator can be directed at a stationary target. Some of the energy carried by each electron or proton is transformed into new matter according to Einstein's relation $E = mc^2$. The incident particle carries a great deal of momentum which has to be shared among the final particles that are produced. As a result, only a small fraction of the energy is actually available for production of new particles.

- To circumvent this problem, a new type of accelerator called a collider was developed. In a collider, the collisions occur between two beams moving in opposite directions. The momentum in one of the beams is just opposite the momentum in the other. Since the sum of the momenta is zero, none needs to be carried away after the collision and all the energy is available for particle production.

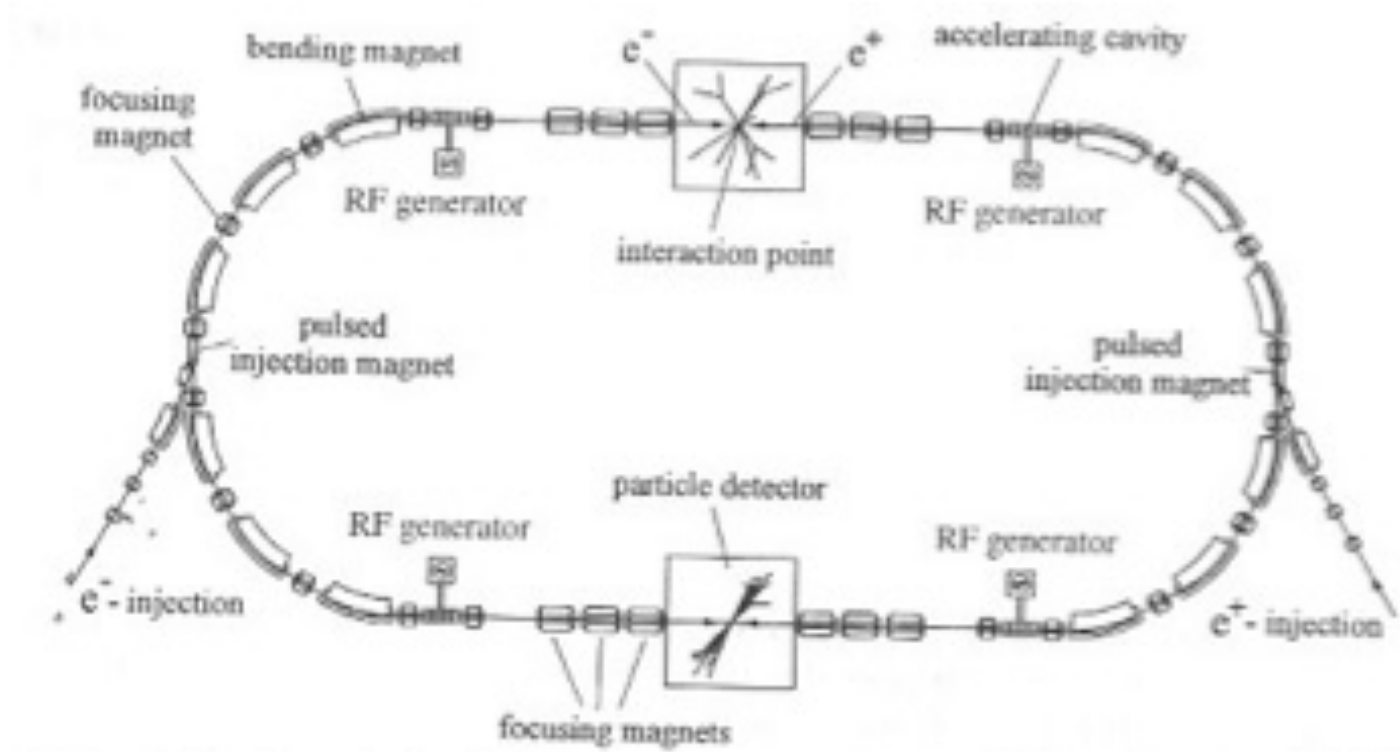
An Historic Need for High Field



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

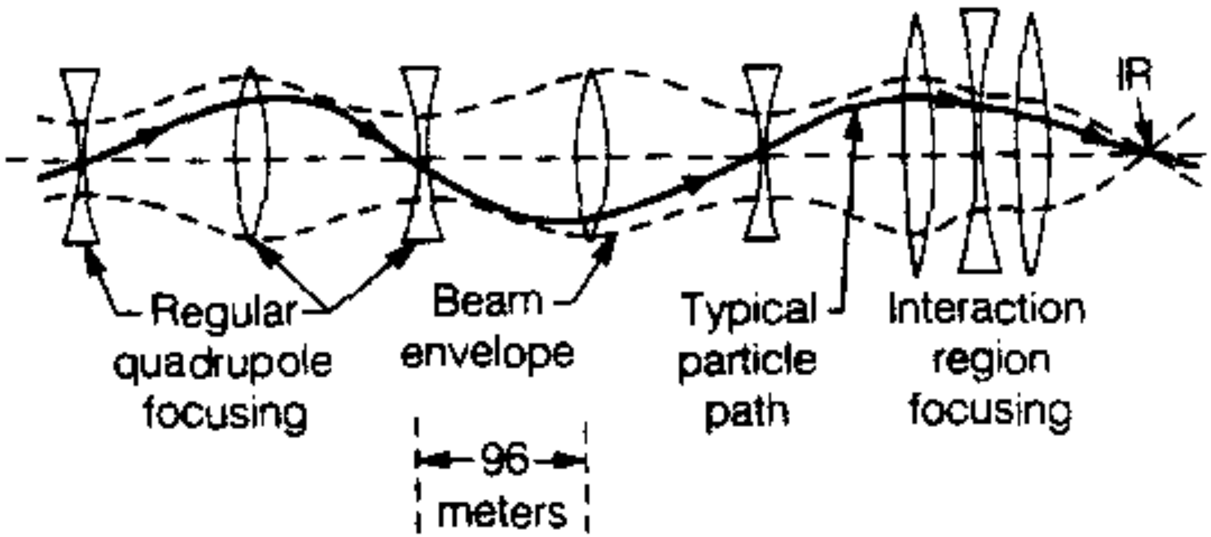
Colliders Win:
Example of a Particle Collider



The Physics of Particle Accelerators, K. Wille

SSC Bending and Focusing Layout

Focusing magnets are alternately focusing and defocusing (opposite in each plane) By alternating the sense of the focusing magnets, the beams can be focused simultaneously in both directions. Principle of “Strong focusing.” A big, big deal!



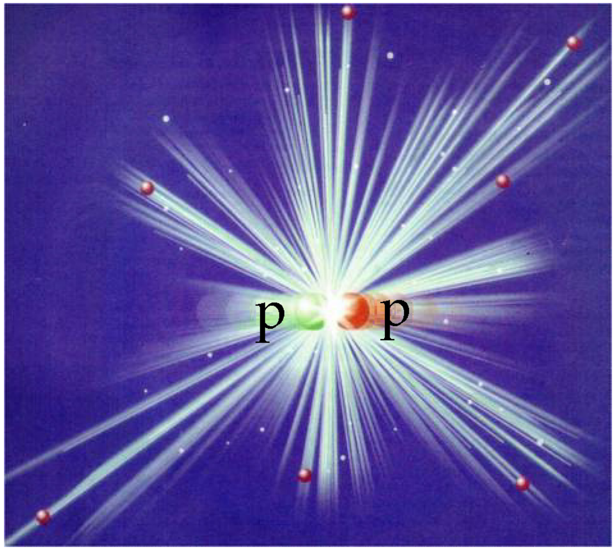
A standard cell is typically a quadrupole followed by several dipoles, then a quadrupole of the opposite focusing characteristic from the first and another set of bending magnets equal in length to the first. Referred to as a FODO cell.

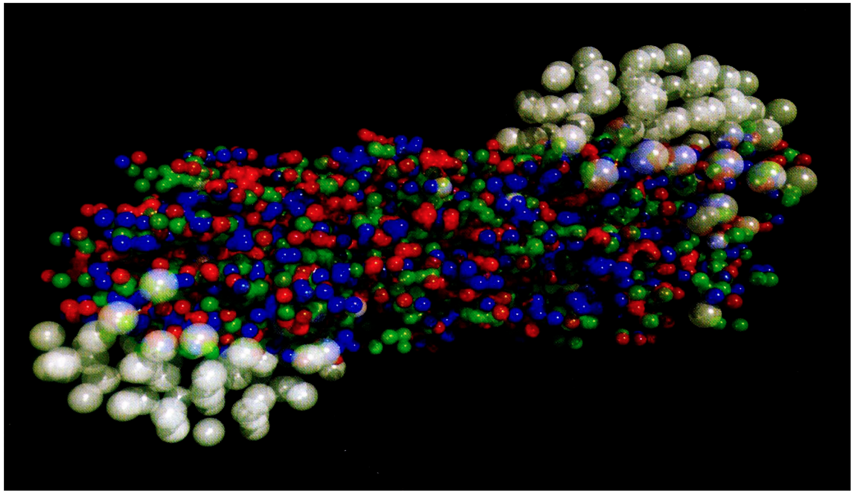
A complete closed ring of cells is called the “lattice.”

SSC Conceptual Design Report, http://inspirehep.net/record/229226/files/ssc-sr-2020.pdf

…back to the Big Bang

- Trip back toward the Big Bang: $t_{\mu s} \cong 1/E^2_{Gev}$
- $t \cong 1$ ps for single particle creation?
- $t \cong 1$ μs for collective phenomena QGS (Quark-Gluon Soup)



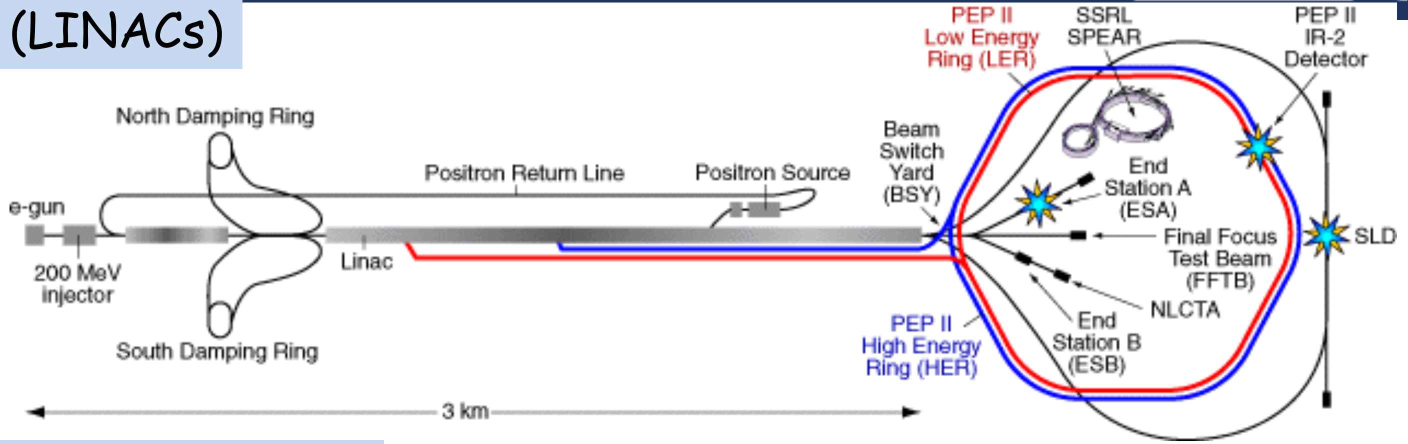


But we are left with the task of explaining how the rich complexity that developed in the ensuing 13.7 billion years came about…

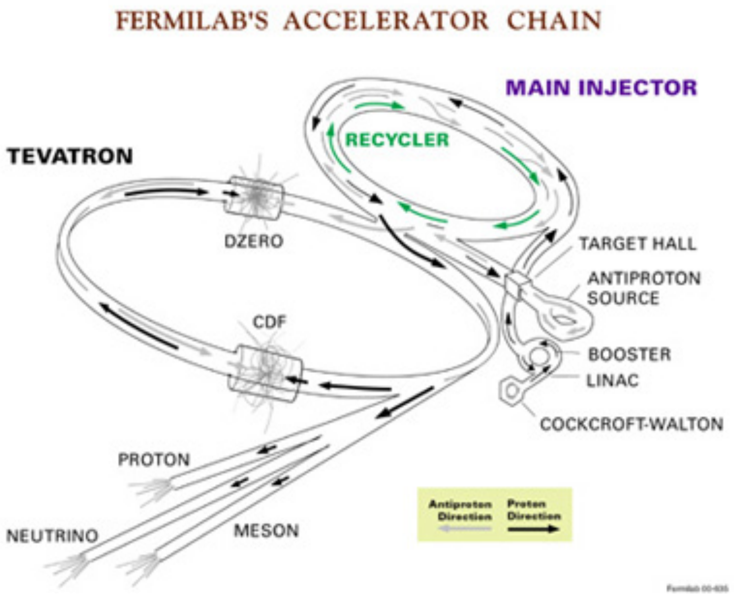
Which is a much more complex task!

Examples of accelerators

Linear accelerator (LINACs)

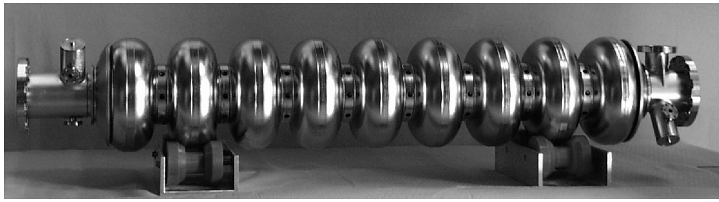


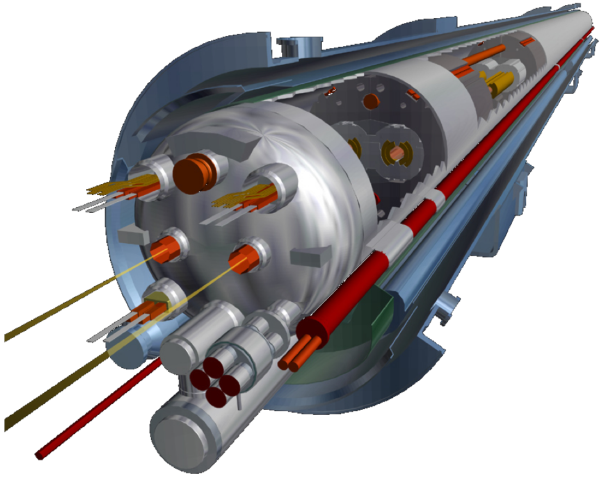
Circular accelerator (synchrotron)



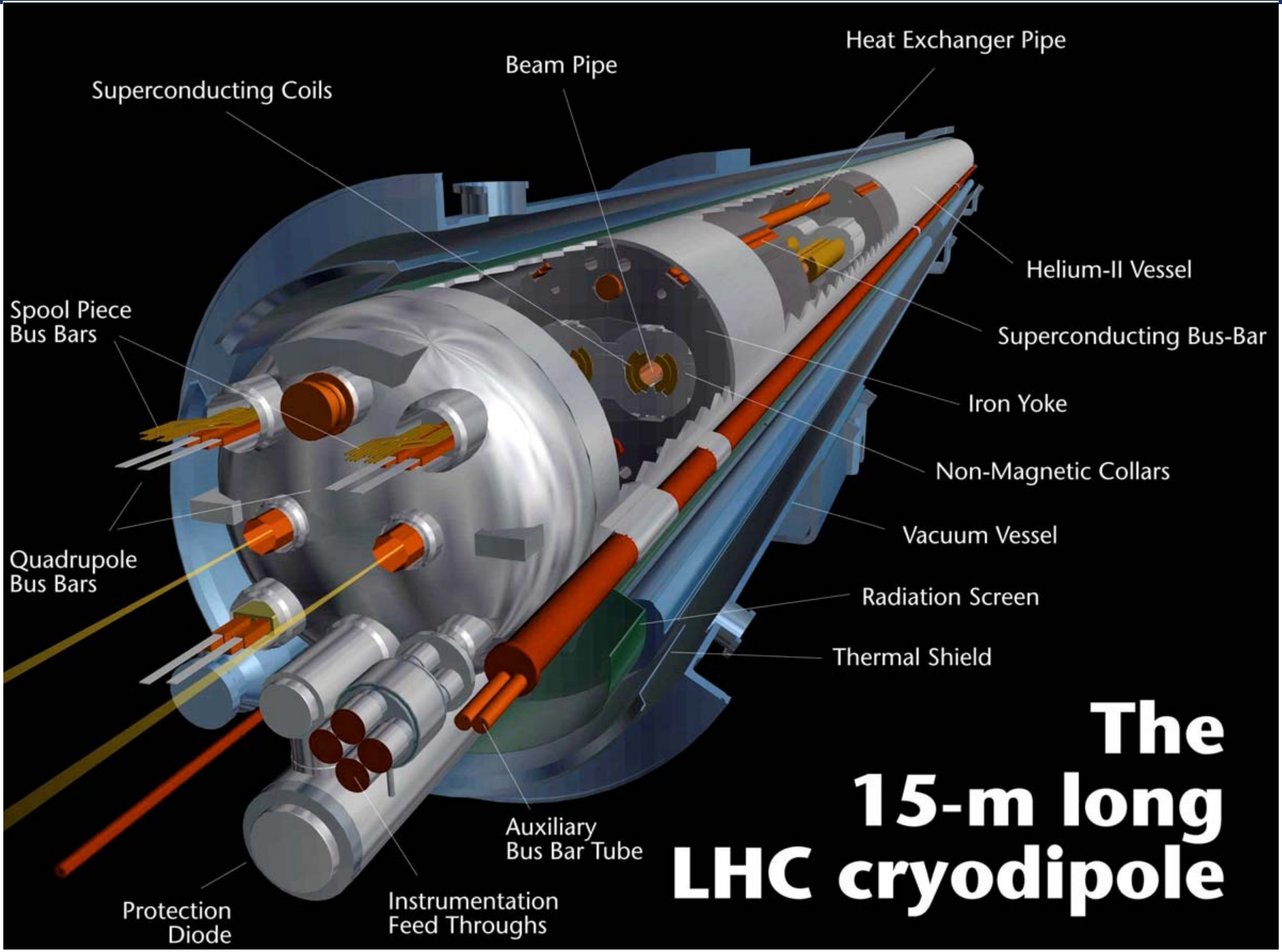
Accelerator Building Blocks

- 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)



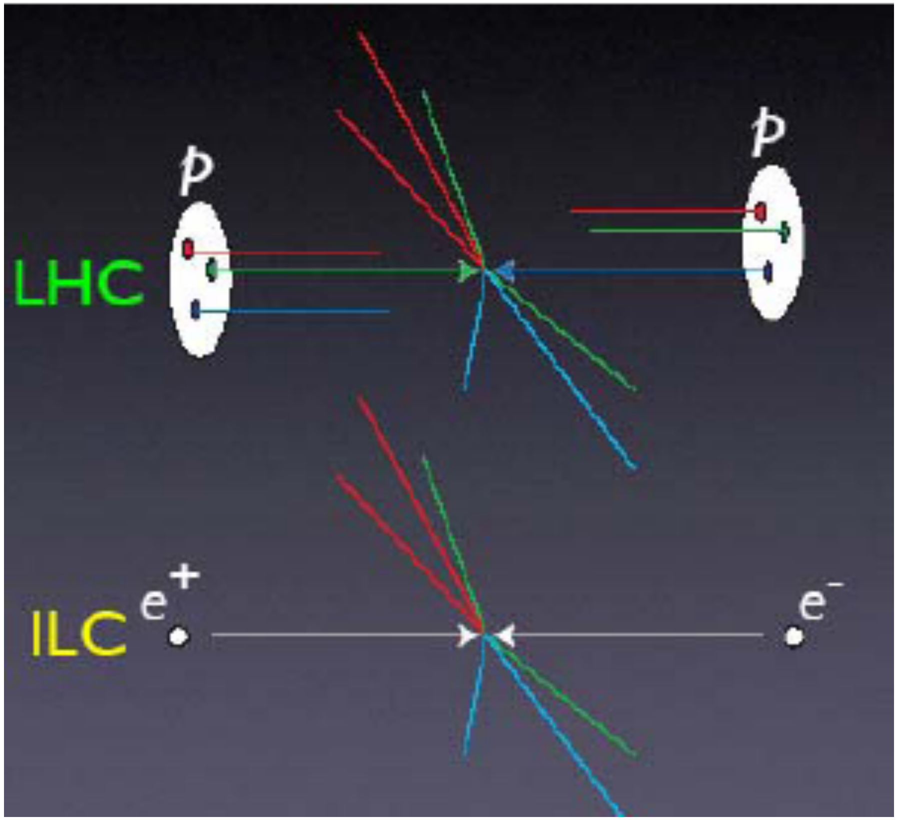


Anatomy of a Superconducting Magnet



Projectiles

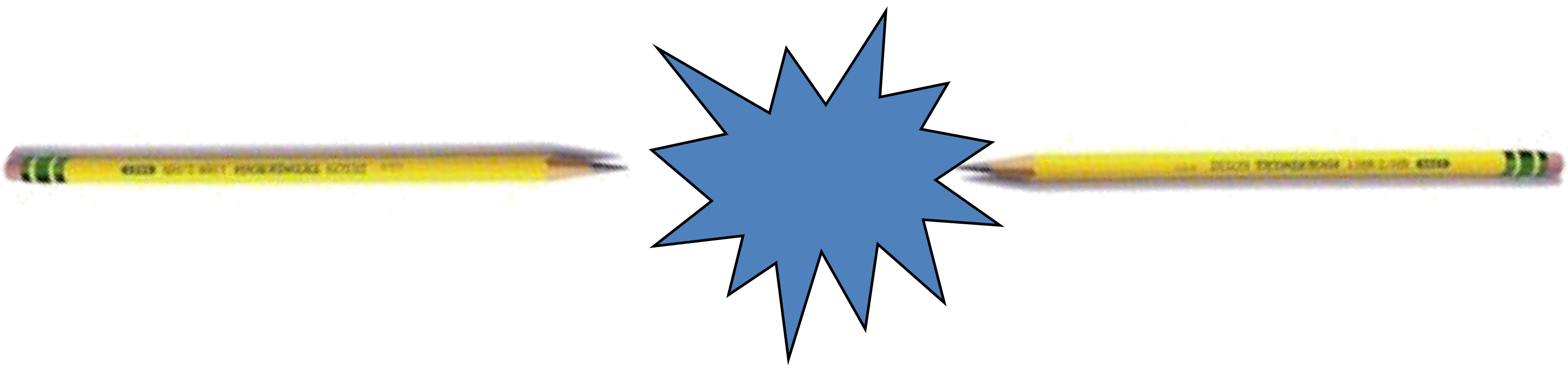
- Hadrons
  - Protons/anti-protons
    - Bags of quarks and gluons
      - **~ 1/7 of beam energy**
- Leptons
  - Electrons/positrons (muons)
    - Elementary particles
    - Well-defined -
      - **Energy**
      - **Angular momentum**
    - Uses full CoM energy
    - Produces particles democratically
    - Fully reconstructed events



Need higher energy to produce heavier particles ($E=mc^2$)

Relatively straightforward . . .

The Latest Accelerator Concept



Particle Production

To adequately study a particle, a significant number need to be produced and measured by the experiment

Interaction probability is characterized by the cross section

σ (unit of area) 1 barn = 10^{-24} cm^2

Production cross section ~ $1/mass^2$

As energy goes up we need more interactions to find the interesting stuff!

Luminosity

Total interaction rate (R) depends on the geometry, density and energy of the beams.

All characteristics are combined into one quantity defined as luminosity.

$\mathcal{L}$ = interaction rate per unit cross section

Accelerator

Production Rate $R = \sigma \mathcal{L}$

Physics

For gaussian beam (in x and y) where N_b = number of protons per bunch, σ_g = width of gaussian and S_b = bunch spacing

$$\mathcal{L} = Nb^2 c/4\pi\sigma_g{}^2 S_b$$

Luminosity is increased by stronger focusing – higher gradient quadrupoles in the interaction regions

Performance Metrics

ENERGY

- Physics reach
  - Mass of Higgs 125 GeV
  - New goal: TeV-scale in CM
- EM fields
  - Electrostatic
  - Radio Frequency Cavities
    - Normal and Superconducting
- Mostly an issue of cost

LUMINOSITY

- Event rate
- Must increase with energy
- $\int \mathcal{L}\, dt$
- Challenge for accelerator and experiments

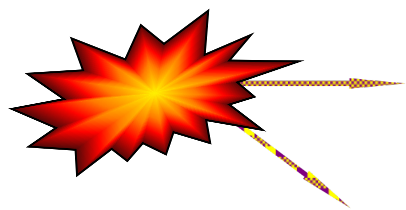
What do we need to make progress?

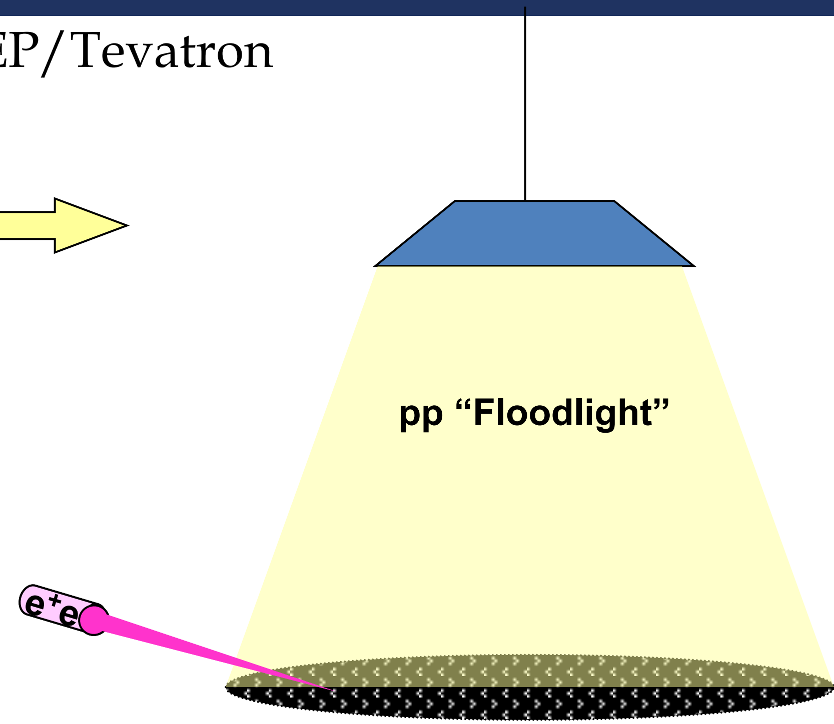
To reach higher energy, i.e., go beyond the LEP/Tevatron energy scale ~100-300 GeV

- The Large Hadron Collider:

  0.1-1.5 TeV

  New phenomena

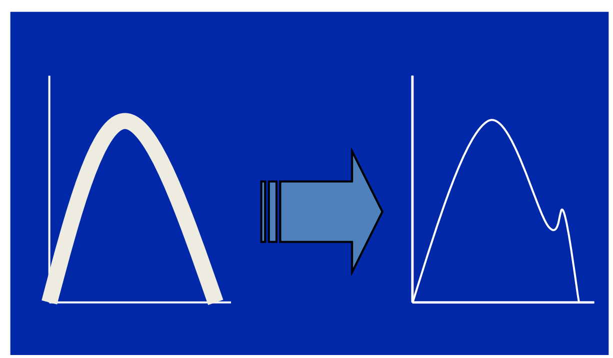




- The Linear Electron-Positron Collider:

  0.2 - 0.5 TeV with more precision

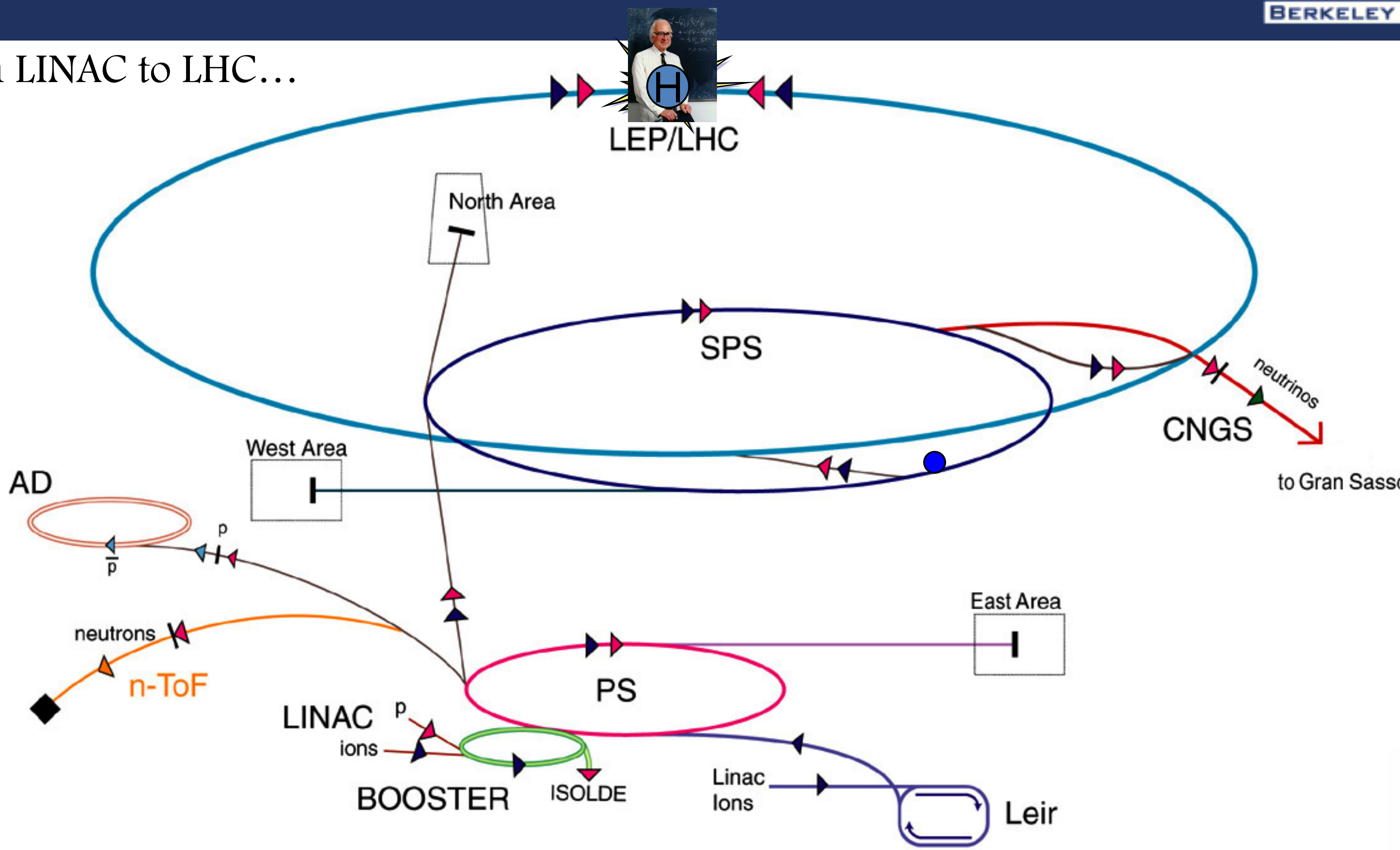
  Known phenomena studied with high precision



The Large Hadron Collider (LHC)

CERN's Particle Accelerator Chain

From LINAC to LHC…



p (proton)
ion
neutron

p̄ (antiproton)
proton/antiproton conversion
neutrino

AD Antiproton Decelerator
PS Proton Synchrotron
SPS Super Proton Synchrotron

LHC Large Hadron Collider
n-ToF Neutron Time of Flight
CNGS Cern Neutrinos Gran Sasso

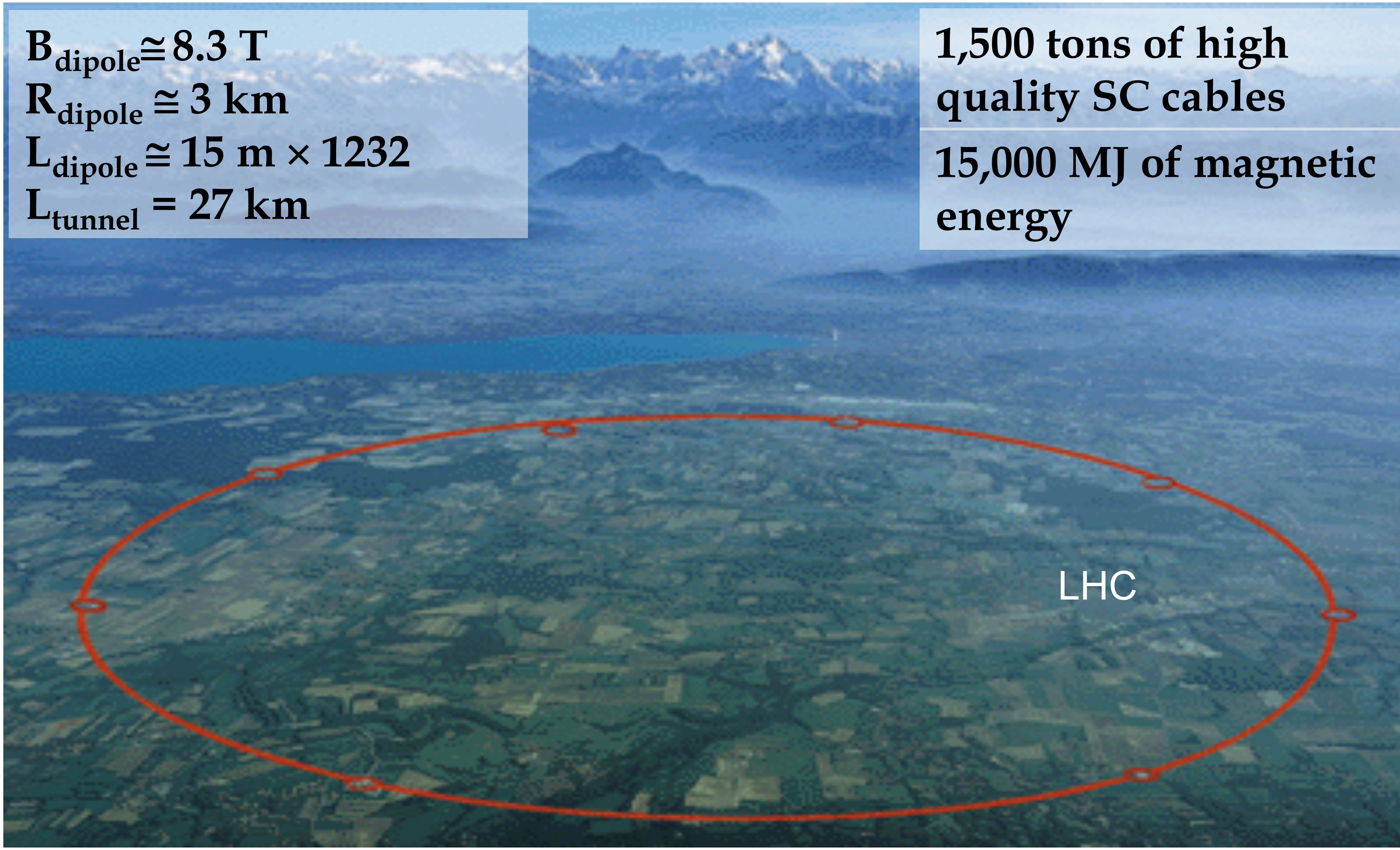
L. Rossi

Largest Application of Superconductivity (so far)

$B_{dipole} \cong 8.3$ T
$R_{dipole} \cong 3$ km
$L_{dipole} \cong 15$ m $\times$ 1232
$L_{tunnel} = 27$ km

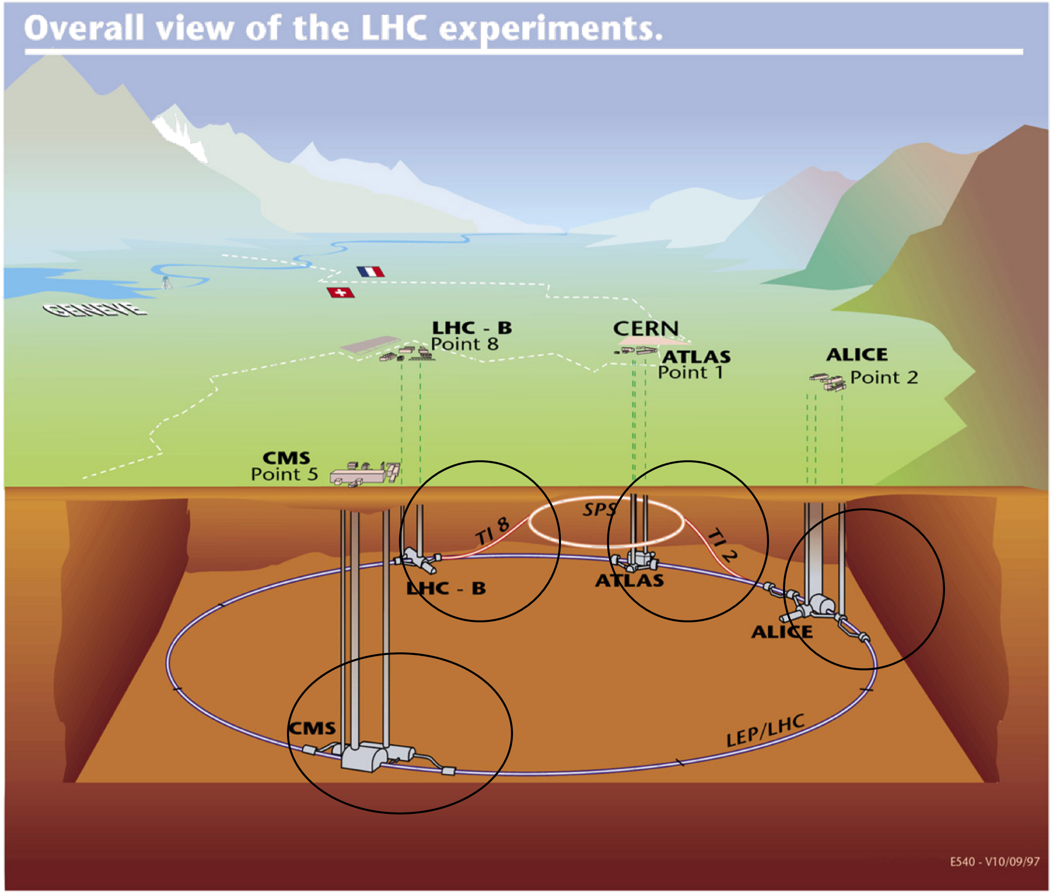
1,500 tons of high quality SC cables

15,000 MJ of magnetic energy



The LHC

The Large Hadron Collider (LHC) is the most powerful instrument ever built to investigate particle properties.



- Four **underground caverns** to house the huge detectors
- The **highest energy** of any accelerator in the world
- Unprecedented **beam intensity**
- 25 km of magnets operating at **1.9 K**

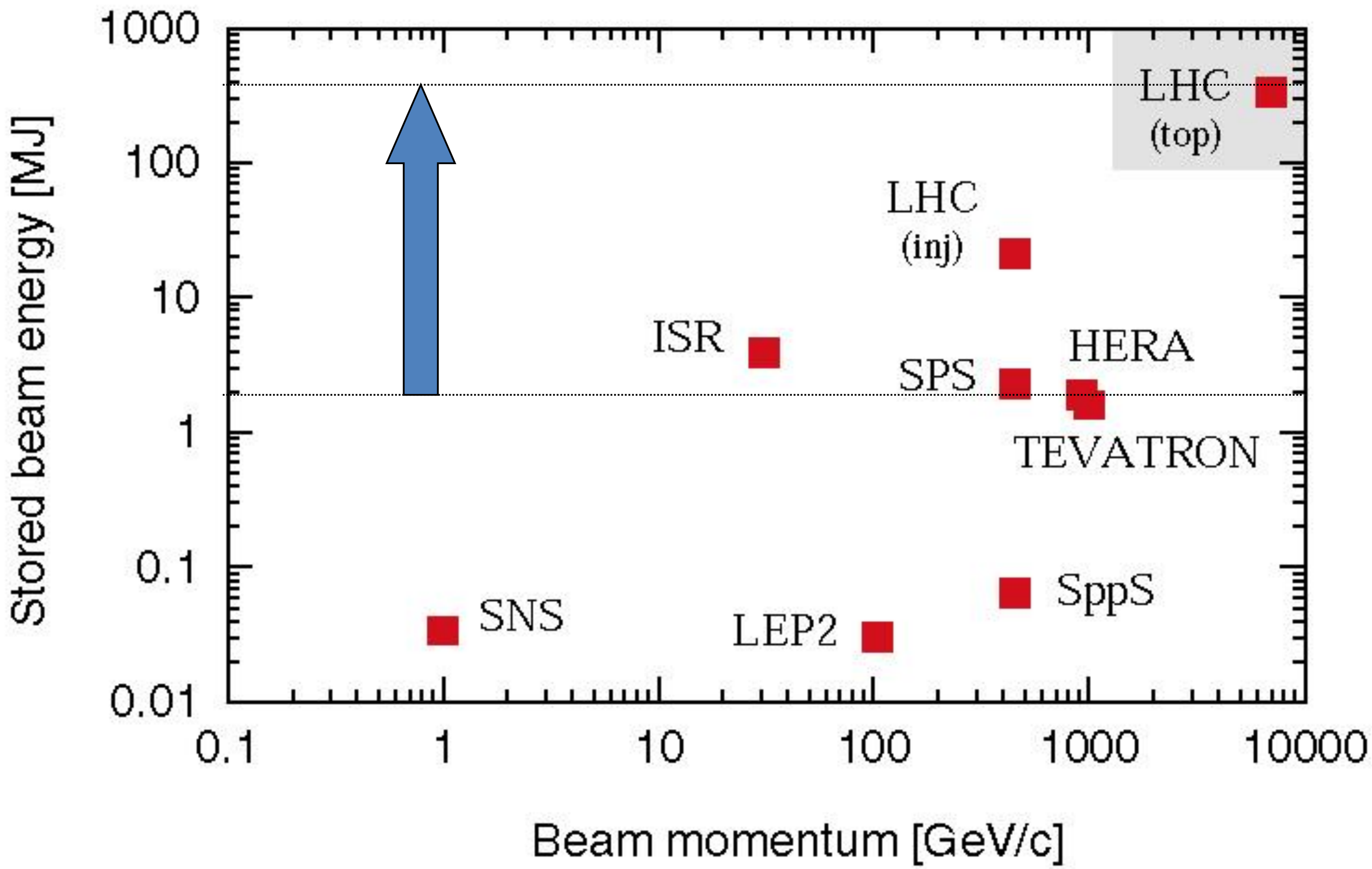
What is a TeV?

- 1 eV = (1.602 X 10^{-19}C)(1V) = 1.602 X 10^{-19} J
- 1 MeV = 1.602 X 10^{-13} J
- 1 GeV = 1.602 X 10^{-10} J

- 1 TeV is the energy required to raise 1 g about 16 micron against gravity or power a 100 W light bulb 1.6 ns

- Accelerators typically have 10^{10} – 10^{12} particles in a single bunch with an instantaneous power of Terawatts

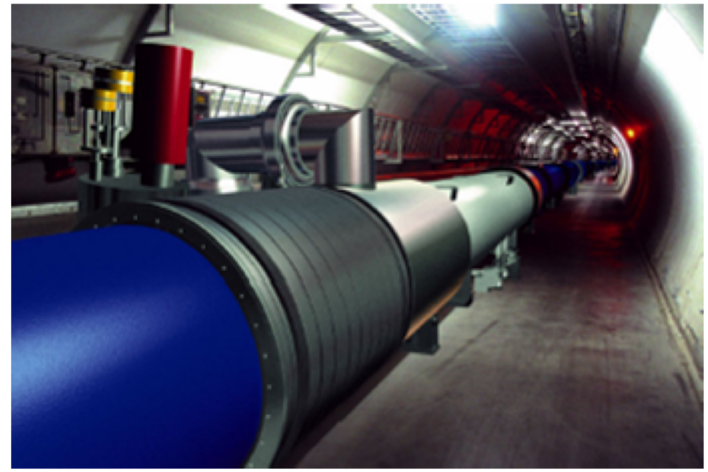
- Cosmic rays have been observed with energies of 300 EeV or 3 X 10^{8} TeV!



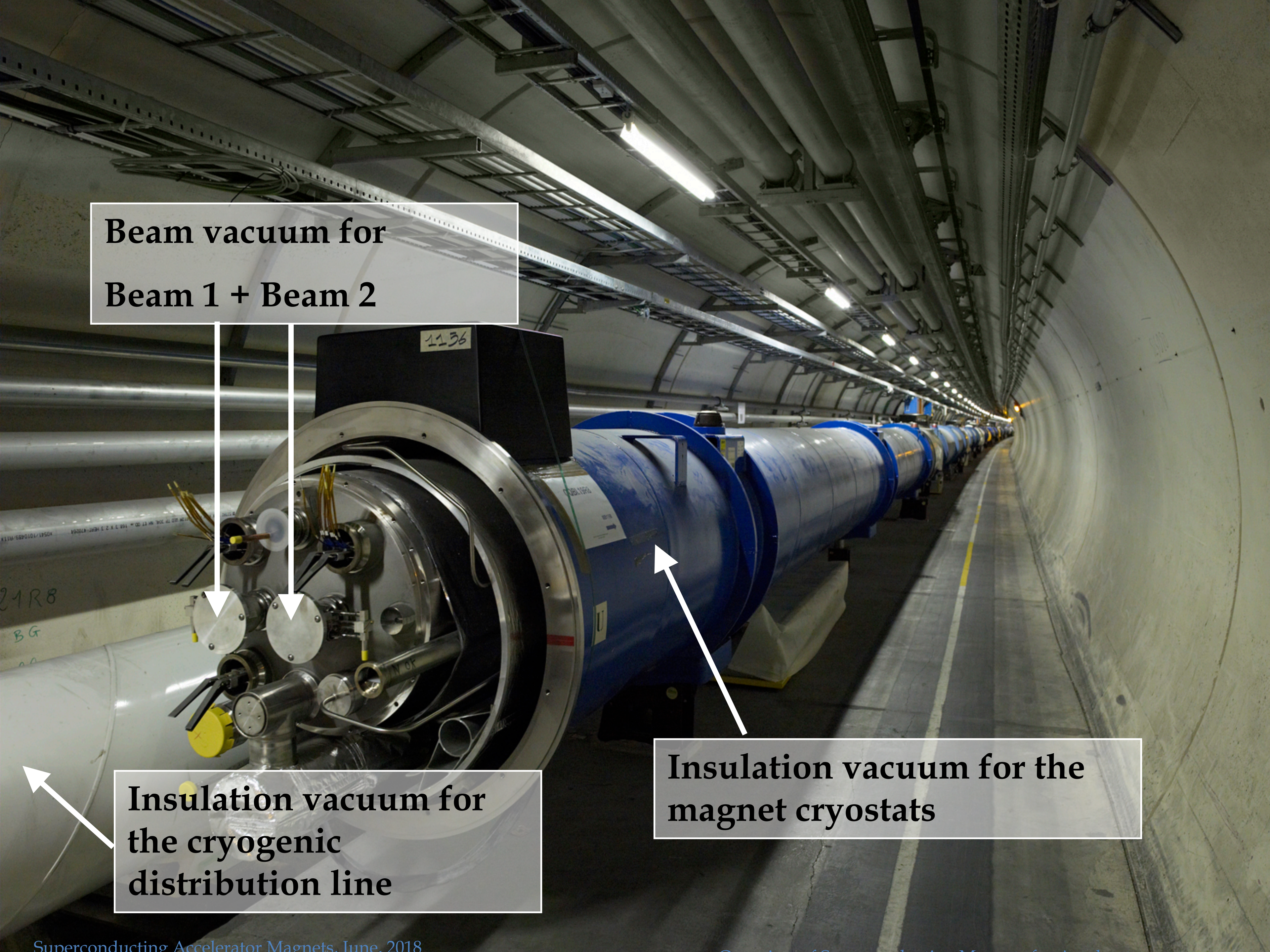
The LHC beam energy is 350 MJ. Lethal to hardware even at injection.

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


Beam vacuum for
Beam 1 + Beam 2
Insulation vacuum for the magnet cryostats
Insulation vacuum for the cryogenic distribution line

Cooldown of First Sector (4625 t over 3.3 km)

Unloading of LHe & LN_2

600 kW precooling to 80 K with LN_2 (up to ~5 tons/h)

Cooldown of Sector 7-8

- From RT to 80K: Precooling with LN_2 1200 tons of LN_2 (64 trucks of 20 tons)
- From 80K to 4.5K: Cooldown with He turbines 4700 tons of material to be cooled
- From 4.2K to 1.9K: Cold compressors (15 mbar) More than 15 tons of helium inventory

Goal is total of 4 weeks

Circular Colliders

- Circular colliders – extremely long (and potentially complex) closed path length.
- Trajectories of individual particles in a beam always have some angular divergence and without constant steering and correction would hit the wall of the vacuum chamber.
- Requires the use of electromagnetic fields (**E** and **B**)
- Lorentz Force $\mathbf{F} = e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) = d\mathbf{p}/dt = d(m\mathbf{v})/dt$

Note: At relativistic velocities E and B have the same effect if E = cB

So B = 1 Tesla is equivalent to $E = 3 \times 10^8$ V/m

Principles of a Synchrotron

- Electro-magnetic field accelerates particles

$$\vec{F} = e\vec{E}$$

- Magnetic field steers the particles in a ~circular orbit

$$\vec{F} = e\vec{v} \times \vec{B} \qquad\qquad p = eB\rho$$

  - Driving particles in the same accelerating structure several times
  - Particle accelerated $\rightarrow$ energy increased $\rightarrow$ magnetic field increased ("synchro") to keep the particles on the same orbit of curvature ρ

$$p = eB\rho$$

Constant

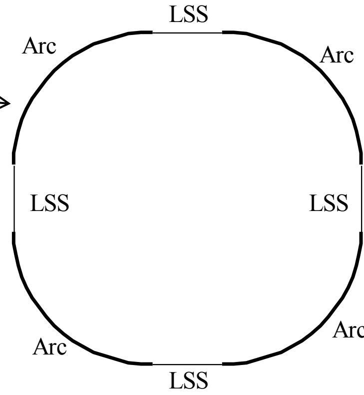
- Limits to the increase in energy
  - The maximum field of the dipoles (proton machines)
    - This is why high field magnets are important to get high energies!
  - The synchrotron radiation due to bending trajectories (electron machines)

E. Todesco, CERN

Principles of a Synchrotron

$$\vec{F} = e\vec{v} \times \vec{B}$$

$$p = eB\rho$$

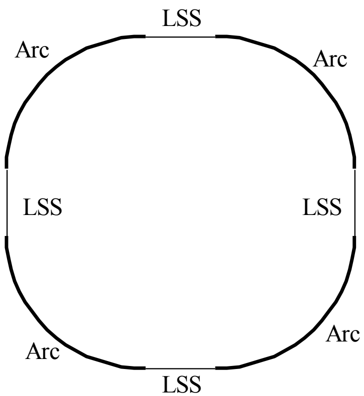


$$\vec{F} = e\vec{E}$$

- Colliders: two beams with opposite momentum collide
  - This doubles the energy but with hadrons about 1/7 available
  - One pipe if particles collide with their antiparticles (LEP, Tevatron)
  - Otherwise, two pipes (ISR, RHIC, HERA, LHC)

E. Todesco, CERN

Principles of a Synchrotron



A schematic view of a synchrotron

- The arcs: region where the beam is bent
  - Dipoles for bending
  - Quadrupoles for focusing
  - Correctors
- Long straight sections (LSS)
  - Interaction regions (IR) where the experiments are housed
    - Quadrupoles for strong focusing in interaction point
    - Dipoles for beam crossing in two-ring machines
  - Regions for other services
    - Beam injection (dipole kickers)
    - Accelerating structure (RF cavities)
    - Beam dump (dipole kickers)
    - Beam cleaning (collimators)

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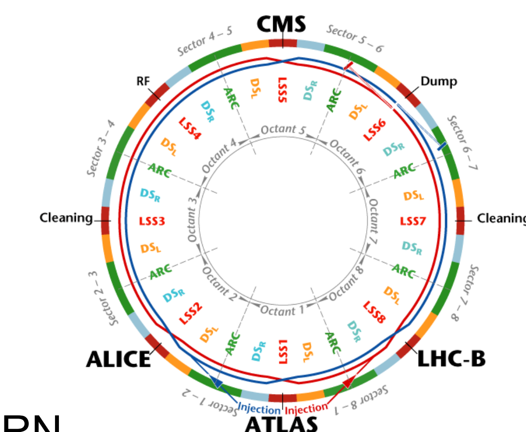
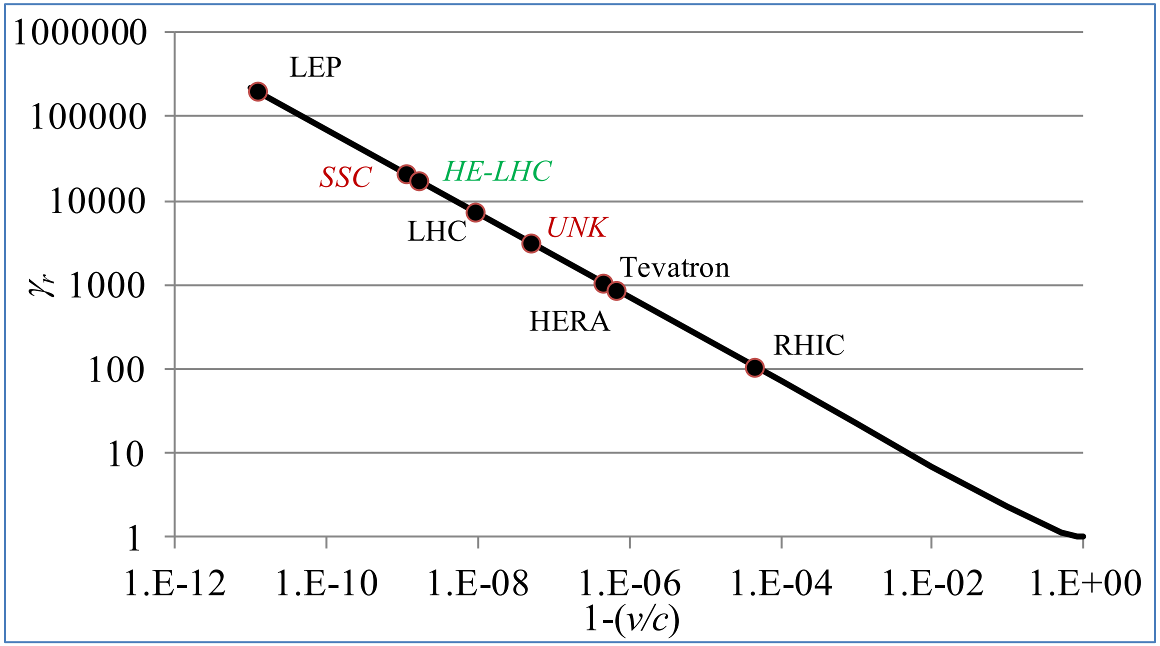


The lay-out of the LHC

- What are the ranges of velocity obtained in particle accelerators?
  - From 10^{-4} to within 10^{-11} of the speed of light !



$$\vec{p} \equiv m\gamma_r \vec{v}$$

$$\gamma_r \equiv \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$E = m\gamma_r c^2$$

$$\gamma_r = \frac{E}{mc^2}$$

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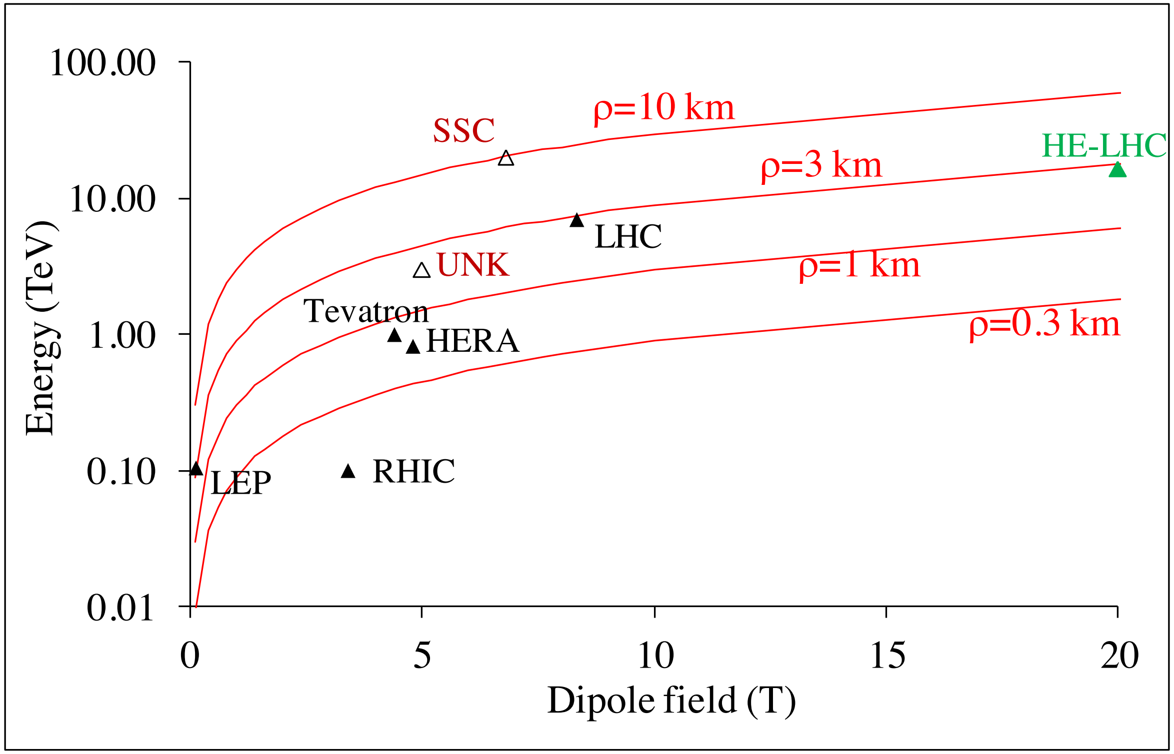
Energy vs Field

- Relationship of energy-magnetic field-orbit radius

$$E[GeV] = 0.3 \times B[T] \times \rho[m]$$



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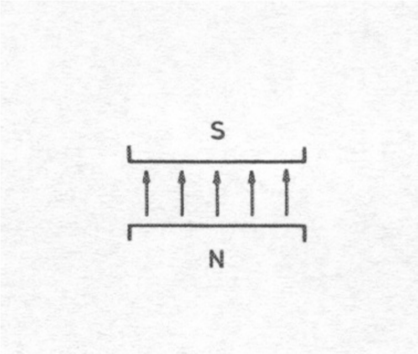
Keeping Particles on Track: Dipoles

- 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



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

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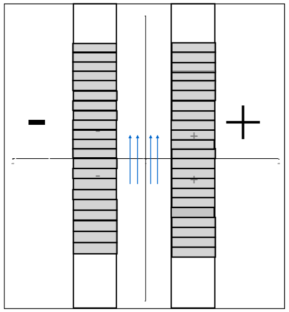
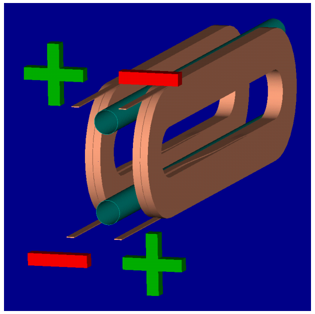
Start with Ideal Case for Dipole Field

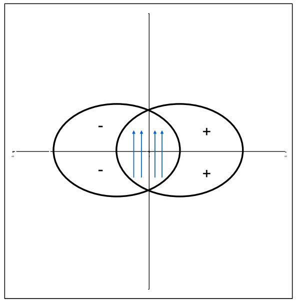
- Uniform current walls
  - Easy to wind but the height is infinite
  - Practical implementation requires . . .
    - High aspect ratio
    - Modification of ends





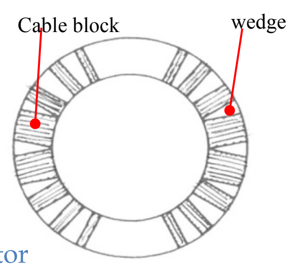
BNL “Common Coil”

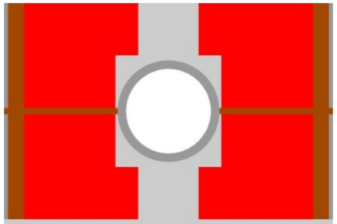
- Intersecting Ellipses
  - Non-circular aperture
  - Requires internal support structure



- 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]

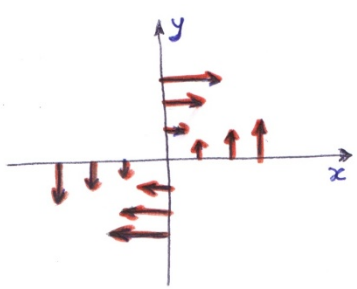


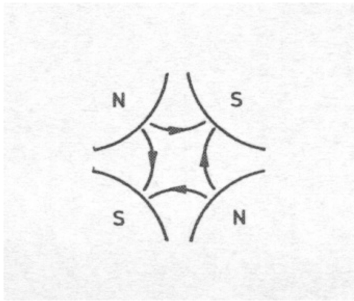


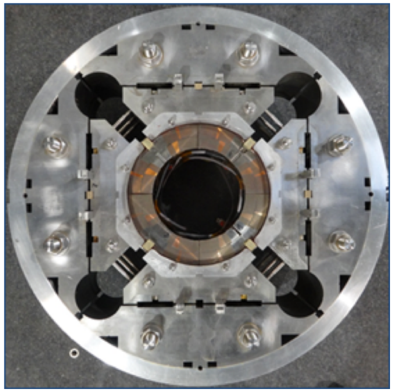
Block Coil Implementation
LBNL “HD-2”

- 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

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







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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

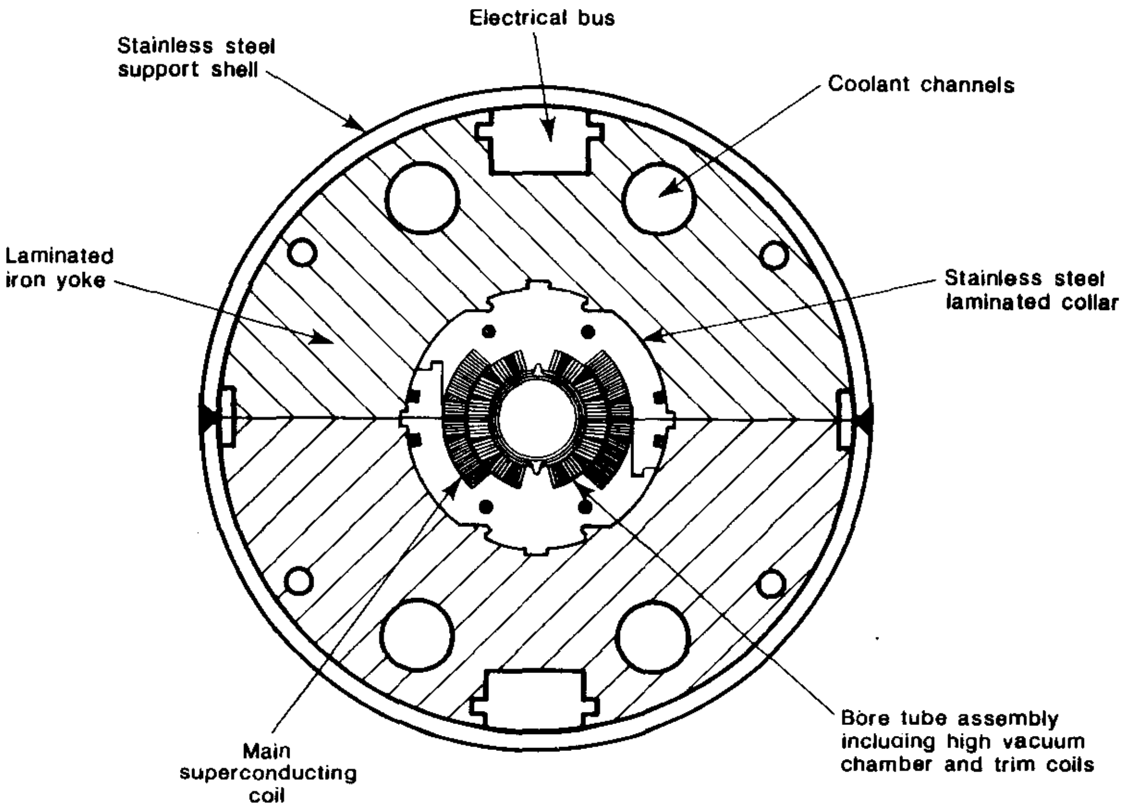
$$B_y + iB_x = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left(\frac{x+iy}{R_{ref}} \right)^{n-1} \qquad \text{EU notation}$$

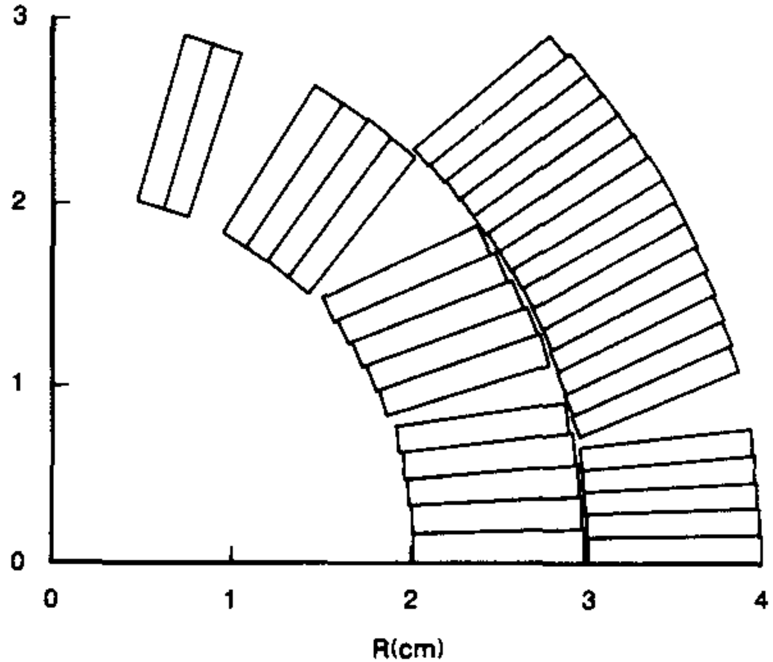
- Coefficients (b_n and a_n) are normalized with the main field component (B_1 for dipoles, B_2 for Quadrupoles)
- Dimensionless coefficients defined WRT reference radius
  - R_f = 2/3 of coil diameter (typically) and given in units of 10^{-4}
- The coefficients b_n, a_n are called normalized multipoles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

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

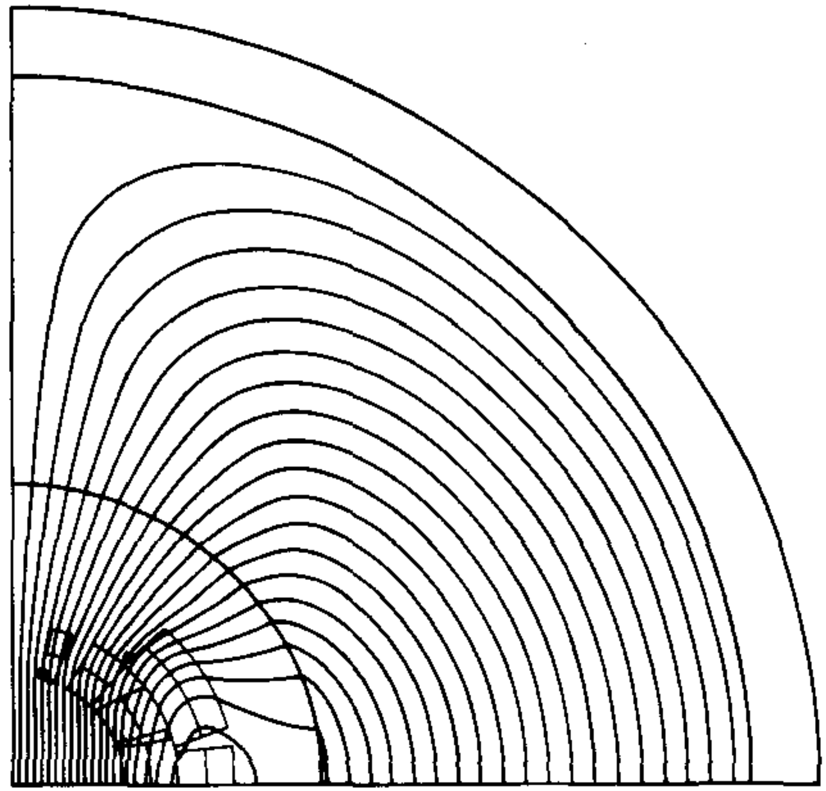
Let's dig into dipoles for a collider

SSC 40mm Dipole





3
2
1
0
0
1
2
3
4
R(cm)



SSC 40mm Dipole Parameters

General

No. of dipoles per ring	3840
Overall length/interface length [m]	17.35/0.8
Magnetic length [m]	16.54
Bore tube inner diameter [cm]	3.226
Mass of conductor [kg]	208
Cold mass [kg]	6759
Central field [T]	6.6
Current [A]	6500
Inductance [mH]	53
Stored energy [MJ]	1.12

The margin in critical current at operating field, J_c/J_O, where J_c is the minimum critical density of the strands before cabling, is 1.25

SSC 40mm Dipole Parameters

- No. of Dipoles per ring
  - Max field, circumference
- Overall length
  - What will fit on a truck
  - Handling and installation
  - Cost (longer, fewer)
- Magnetic length
  - Feature of design (ends)
- Inner diameter
  - See next slides
- Mass of conductor
  - Cost
- Cold mass
  - Cryo
- Central Field
  - Energy, Cost
- Current, Inductance, Stored Energy
  - Magnet protection

Factors Influencing Choice of the Aperture

- Room for beam screen and in some cases shielding
- Field quality required at reference radius
- Alignment
- Beam related: Next slide

- Limits on bore size
  - Larger bore, more
    - Stress
    - Stored energy – powering and protection
    - Conductor (at 50mm a 10% change in bore is a 10% change in the amount of conductor)
  - Smaller bore
    - Room for the beam
    - Manufacturing issues (small bend radii)

SSC 40 – 50mm

Beam-related Aperture Requirements

Several meanings for "aperture"

- **Physical aperture** – inside of the beam pipe
- **Dynamic aperture** – region through which particles may propagate and remain in stable motion. Depends only on the magnetic fields. Could even be larger than the physical aperture!
- **Linear aperture** – smaller region inside dynamic aperture where the beam is normally expected to be. Simple particle trajectories easy to calculate
- Goal is to determine the dependence of the dynamic aperture on the magnet coil diameter and correction system. Lots of work since the trade-offs can greatly affect cost and/or performance.

SSC 40mm Dipole Parameters

Winding

Inner layer	
No. of turns (per coil section)	16
Inner diameter [cm]	4.000
Outer diameter [cm]	5.923
Cable length [m] (for 2 coil sections)	1076
Cable mass [kg] (for 2 coil sections)	100
Maximum field [T]	7.0
Outer layer	
No. of turns (per coil section)	20
Inner diameter [cm]	5.974
Outer diameter [cm]	7.986
Cable length [m] (for 2 coil sections)	1341
Cable mass [kg] (for 2 coil sections)	108
Maximum field [T]	5.6

SSC 40mm Dipole Parameters

Conductor

Inner layer	
Cross section, bare [mm]	9.30×(1.59–1.33)
Keystone [deg.]	1.61
Strand diameter [mm]	0.808
No. of strands	23
Strand twist pitch [per cm]	0.4
Cable twist pitch [per cm]	0.126
Copper-to-superconductor ratio	1.3:1
No. of superconductor filaments	11000
Filament diameter [μm]	5
Outer layer	
Cross section, bare [mm]	9.73×(1.27–1.07)
Keystone [deg.]	1.21
Strand diameter [mm]	0.648
No. of strands	30
Strand twist pitch [per cm]	0.4
Cable twist pitch [per cm]	0.136
Copper-to-superconductor ratio	1.8:1
No. of superconducting filaments	6000
Filament diameter [μm]	5

SSC 40mm Dipole Parameters

- Cable dimensions
  - Inductance, current
  - Mechanical stability
  - Maximize engineering current density (packing fraction)
  - Minimize cabling damage
    - Keystone angle (field quality, coil geometry)
- Strand diameter
  - Cabling
  - Mechanical stability
- Number of strands
  - Along with cable dimensions determines packing fraction
- Twist pitch
  - Quantity of conductor
  - Dynamic effects
- Cu/SC
  - Stability
  - Magnet protection
- Number of filaments
  - Sub-element design
  - Related to Cu/SC and f_d
- Filament diameter
  - Magnetization effects

SSC 40mm Dipole Parameters

Mechanical structure, field properties

Collars

Material	stainless steel, nitrogen hardened
Lamination thickness [mm/in.]	1.52/0.060
Outer diameter [cm]	11.09
Radial thickness, nominal [cm]	1.5

Iron Yoke

Material	low carbon steel
Inner diameter [cm]	11.14
Inner diameter, magnet ends [cm]	17.51
Outer diameter [cm/in.]	26.67/10.5
Lamination thickness [mm/in.]	1.5/0.060
Weight of iron [kg]	5171

Yoke Containment Structure

Material	stainless steel
Outer diameter [cm/in.]	27.62/10.878
Thickness [cm]	0.47
Weight of shell [kg]	540

SSC 40mm Dipole Parameters

Cryostat

Vacuum vessel material	steel
Vacuum vessel outer diameter [cm/in.]	60.96/24.00
Wall thickness [cm]	0.635
Heat shield material	aluminum
80 K heat shield, outer diameter [cm/in.]	45.72/18.00
20 K heat shield, outer diameter [cm/in.]	40.64/16.00
Superinsulation layers, outside 80 K shield	52
Superinsulation layers, outside 20 K shield	13
Cold mass support type	reentrant post
Support materials	F.R.P. unidirectional
Number of supports	5
Support interval [m]	3.5
Load per support [kg]	1352

Heat load, operation cost, cryo system

Choice of operating temperature

Large impact on magnet design, cost and performance

- Cryogenic production and distribution system
- Much more effective cooling at 1.9K
- Conductor performance enhanced by lower operating temperature – less conductor
- 1.9K enables effective cryo-pumping (good vacuum)
  - Nb-Ti – 3T shift of Bc_2
  - Nb_3Sn ~ 1 – 2T (low temperature enhancement has not been fully realized)
  - For FCC study shows that savings in conductor offset extra cost of cryo system at 1.9K.
- Lower heat capacities, more training

SUMMARY

- Explored the balance between machine design goals and magnet technology.
- For most facilities, cost is the main issue
- For some special applications where performance is a necessity, cost is not so important
- The design process is a close collaboration between magnet builders and accelerator physicists

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