ACCELERATOR PHYSICS AND TECHNOLOGY – EPISODE I

Ezio Todesco
CERN, Technology Department
Magnet Superconductors and Cryostat Group
The science of superconducting magnets is a exciting, fancy and dirty mixture of **physics, engineering, and chemistry**

- Chemistry and material science: the quest for **superconducting materials** with better performances
- Quantum physics: the key mechanisms of **superconductivity**
- Classical electrodynamics: **magnet design**
- Mechanical engineering: **support structures**
- Electrical engineering: powering of the magnets and their **protection**
- Cryogenics: keep them **cool** …

The **cost** optimization also plays a relevant role
- Keep them **cheap** …
FOREWORD

An example of the variety of the issues to be taken into account

- The field of the LHC dipoles (8.3 T) is related to the critical field of Niobium-Titanium (Nb-Ti), which is determined by the microscopic quantum properties of the material.

Quantized fluxoids penetrating a superconductor used in accelerator magnets

A 15m truck unloading a 27 tons LHC dipole

- The length of the LHC dipoles (15 m) has been determined by the maximal dimensions of (regular) trucks allowed on European roads.

- This makes the subject complex, challenging and complete for the formation of a (young) physicist or engineer.
Foreword

- The size of our objects
  - Length of an high energy physics accelerator: ~Km

RHIC ring at BNL, Long Island, US

Main ring at Fermilab, Chicago, US
FOREWORD

The size of our objects

- Length of an accelerator magnet: ~10 m
- Diameter of an accelerator magnet: ~m
- Beam pipe size of an accelerator magnet: ~cm

https://www.youtube.com/watch?v=KKFnsFFdPh8

Unloading a 27 tons dipole

Dipoles in the LHC tunnel, Geneva, CH

A stack of LHC dipoles, CERN, Geneva, CH
CONTENTS

The synchrotron and its magnets

How to generate magnetic fields

What superconductivity gives
Electro-magnetic field accelerates particles

Magnetic field steers the particles in a closed (~circular) orbit to drive particles through the same accelerating structure several times

- Most of the accelerator bends, a small part increases the energy

- As the particle is accelerated, its energy increases and the magnetic field is increased ("synchro") to keep the particles on the same orbit

What are the limitations to increase the energy?

- Proton machines: the maximum field of the dipoles (LHC, Tevatron, SPS …)
- Electron machines: the synchrotron radiation due to bending trajectories (LEP)
REMINDER: THE SYNCHROTRON AND ITS MAGNETS

- **The arcs**: bending the beam → energy

  ![Diagram of an arc with poles labeled N and S](image1.png)
  ![Diagram of a dipole magnet](image2.png)

  **Dipoles** for bending  **Quadrupoles** for focusing
  Sextupoles, octupoles … for correcting

- **Long straight sections (LSS)** → luminosity

  - **Interaction regions** (IR) housing the experiments
    - Solenoids (detector magnets) acting as spectrometers
    - **Quadrupole triplet** to squeeze the beams in collision
  - **Regions for other services**
    - Beam injection and dump (dipole kickers)
    - Accelerating structure (RF cavities) and beam cleaning (collimators)

  ![Schematic view of a synchrotron](image3.png)

  ![Lay-out of the LHC](image4.png)
REMINDER: THE SYNCHROTRON AND ITS MAGNETS

Why do we need many km to get a few TeV?

Dynamics ruled by Lorentz force

\[ \vec{F} = e\vec{v} \times \vec{B} \]

\[ \vec{p} = m\gamma\vec{v} \]

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

\[ \frac{d\vec{v}}{dt} = \frac{\nu^2}{\rho} \]

\[ F = evB \]

\[ \vec{F} = \frac{d}{dt} p = m \frac{d}{dt} (\gamma v) \sim m\gamma \frac{d}{dt} v \]

\[ eB = m\gamma \frac{v}{\rho} = \frac{p}{\rho} \]

\[ F = m\gamma \left| \frac{d\vec{v}}{dt} \right| = m\gamma \frac{\nu^2}{\rho} \]

\[ p = eB\rho \]

\[ E[GeV] = 0.3 \times B[T] \times \rho[m] \]
In many textbooks the gamma is attached to the mass to create the concept of relativistic mass

\[ \vec{p} = m \gamma \vec{v} \]

\[ \gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \]

\[ m_R = m \gamma \]

So momentum equation is as in Newton
So we «understand» that speed of light cannot be reached because particle mass go to infinity

It is a rather misleading concept
We lose mass invariance …
Einstein did not like it
I would suggest avoid using it

It is not good to introduce the concept of the mass of a moving body for which no clear definition can be given. It is better to introduce no other mass concept than the ’rest mass’ \( m \).
Instead of introducing \( M \) it is better to mention the expression for the momentum and energy of a body in motion.

We analyse the accelerator shown in Terminator-3 [Warner Bros., Columbia Pictures, 2003]

- Estimation of the magnetic field

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

- Energy = 5760 GeV
- Radius \( \sim 30 \) m
- Field = 5760/0.3/30 \( \sim 640 \) T (a lot!)

- Is it possible to have 640 T magnets??
  - Or is it science-fiction?
Relation momentum-magnetic field-orbit radius

- Having 8 T magnets, we need 3 Km curvature radius to have 7 TeV
- If we would have 800 T magnets, 30 m would be enough …
- We will show why 8 T is the present limit for accelerator magnets

\[ E[GeV] = 0.3 \times B[T] \times \rho[m] \]
Reminder: the synchrotron and its magnets

How to generate magnetic fields

What superconductivity gives
A magnetic field is generated by two mechanisms:
- An electrical charge in movement (macroscopic current)
- Coherent alignment of atomic magnetic momentum (ferromagnetic domains)

**Biot-Savart law:** magnetic field generated by a current line is

\[ |B| = \frac{I\mu_0}{2\pi\rho} \]

- Proportional to current
- Inversely proportional to distance
- Perpendicular to current direction and distance
Magnetic field generated by a winding

We compute the central field given by a sector dipole with uniform current density $j$

$$|B| = \frac{I\mu_0}{2\pi \rho} \quad I \to j\rho d\rho d\theta$$

$$B = -4 \frac{j\mu_0}{2\pi} \int_0^r \int_{r+w}^{r+w} \frac{\cos \theta}{\rho} \rho d\rho d\theta = -\frac{2j\mu_0}{\pi} w \sin \alpha$$

Setting $\alpha=60^\circ$ one gets a more uniform field

- $B \propto$ current density (obvious)
- $B \propto$ coil width $w$ (less obvious)
- $B$ is independent of the aperture $r$ (much less obvious)

$$B[T] \approx 7 \times 10^{-4} \ j[A/mm^2] w[mm]$$
Magnetic field generated by a winding of width $w$

\[ B[T] \approx 7 \times 10^{-4} \; j[A/mm^2]w[mm] \]

- The current density in copper for typical wires used in transmission lines is $\sim 5 \; [A/mm^2]$

- Using special techniques for cooling one can arrive up to $\sim 100 \; [A/mm^2]$

- Superconductors allow current densities in the sc material of $\sim 1000 \; [A/mm^2]$
  - Example: LHC dipoles have $j_{sc} = 1500 \; A/mm^2$
    - $j=360 \; A/mm^2$, ($\sim \frac{1}{4}$ of the cable made by sc !)
    - Coil width $w \sim 30 \; mm$, $B \sim 8 \; T$

- There is still a factor 10, and moreover the normal conducting consumes a lot of power ...
Normal conducting magnets for accelerators are made with a copper winding around a ferromagnetic core that greatly enhances the field. This is a very effective and cheap design.

The shape of the pole gives the field homogeneity:
- The limit is given by the iron saturation, i.e. 2 T
- This limit is due to the atomic properties, i.e. it looks like a hard limit

Therefore, superconducting magnets today give a factor ~4 larger field than normal conducting – not so bad anyway …
- LHC with 2 T magnets would be 100 Km long, and it would not fit between the lake and the Jura …
Nikolai Tesla (10 July 1856 - 7 January 1943)
- Born at midnight during an electrical storm in Smiljan near Gospić (now Croatia)
- Son of an orthodox priest
- A national hero in Serbia – but also in the other republics of ex-Yugoslavia

Career
- Polytechnic in Gratz (Austria) and Prague
- Emigrated in the States in 1884
- Electrical engineer
- Inventor of the alternating current induction motor (1887)
- Author of 250 patents

A rather strange character, a lot of legends on him …
Check on the web! (wikipedia, etc …)
Reminder: the synchrotron and its magnets

How to generate magnetic fields

What superconductivity gives
104 years ago, in 1911, Kamerlingh Onnes discovers the superconductivity of mercury

- Below 4.2 K, mercury has a non measurable electric resistance – not very small, but **zero**!
- This discovery has been made possible thanks to his efforts to **liquify Helium**, a major technological advancement needed for the discovery
- 4.2 K is called the **critical temperature**: below it the material is superconductor

Superconductivity has been discovered in **other elements**, with critical temperatures ranging from a few K (low temp. sc) to up to 150 K (high temperature sc)

The behaviour has been modeled later in terms of **quantum mechanics**

- Electron form pairs (**Cooper pairs**) that act as a boson, and “freely” move in the superconductor without resistance
- Several Nobel prizes have been awarded in this field …
1950: Ginzburg and Landau propose a macroscopic theory (GL) for superconductivity
   - Nobel prize in 2003 to Ginzburg, Abrikosov, Leggett

1957: Bardeen, Cooper, and Schrieffer publish microscopic theory (BCS) of Cooper-pair formation in low-temperature superconductors
   - Nobel prize in 1972

1986: Bednorz and Muller discover superconductivity at high temperatures in layered materials having copper oxide planes
   - Nobel prize in 1986 (a fast one …)
The quest for the Holy Graal of superconductivity at higher temperatures

- LTS: Low Temperature Superconductors (below 30 K)
- HTS: High Temperature Superconductors (above 30 K)

Two main applications: **power lines and magnets** – radically different

- Power lines: no field or absent field, possibly high T to simplify cooling
- Magnets: have “enough” current density able to stay in large field, working at low T is not a problem

Courtesy from J. Schwartz, CERN academic training 2012
https://indico.cern.ch/conferenceDisplay.py?confId=158073
Superconductivity

For making magnets, our Holy Graal is having ability to survive magnetic fields

- Type I superconductors: they expel magnetic field (example: Hg)
  - They cannot be used for building magnets

- Type II superconductors: they do not expel magnetic field (example: Nb-Ti)
  - The magnetic field penetrates locally in very tiny quantized vortex
    \[ \phi_0 = \frac{h}{2e} \]
  - The current acts on the fluxoids with a Lorentz force that must be balanced, otherwise they start to move, dissipate, and the superconductivity is lost
  - The more current density, the less magnetic field, and viceversa \(\rightarrow\) concept of critical surface

First image of flux penetration, U. Essmann and H. Trauble
Max-Planck Institute, Stuttgart
The magnetic field penetrates locally in very tiny quantized vortex

The current acts on the fluxoids with a Lorentz force that must be balanced, otherwise they start to move, dissipate, and the superconductivity is lost.

The sc material is built to have a strong pinning force to counteract fluxoid motion.

Pinning centers are generated with imperfections in the lattice.

This is sometimes done with doping.

It is a very delicate and fascinating cooking …

The material is superconductor as long as $B$, $j$, and temperature stay below the critical surface.

- The maximum current density $\sim 10,000$ A/mm$^2$, but this at zero field and zero temperature.
- In a magnet, the winding has a current density to create a magnetic field → the magnetic field is also in the winding → this reduces the current density.

Operational temperature

- The lowest the better … but not at 0 K!
  - Specific heats go to zero
- Many machines run at 4.2 K (liquid He)
- LHC has been the first accelerator to operate at 1.9 K (after Tore Supra tokamak)
  - Superfluid helium! (second purely quantum effect on which LHC technology relies daily)
Critical current density vs. field for different materials (semilog scale) at 4.2 K

- To remember: more critical current density, less field

Critical current density in the superconductor versus field for different materials at 4.2 K [P. J. Lee, et al]
SUMMARY

- Principles of magnets
  - Why superconducting magnets are very effective
  - The mechanisms behind superconductivity
- Superconductivity is based on couples and relies on defects
  - And gives many Nobel prizes …
- Some features of the design
- Coming soon
  - Why 8 T is the present limit for Nb-Ti
  - Why Ms. Terminator sticks on the T3 accelerator dipoles
  - Going to larger fields: other materials
REFERENCES

Books

- For superconductivity, check the last chapter of 3rd volume of Feynmann lectures!

Review paper

T. Taylor, L. Rossi, P. Lebrun, L. Bottura who gave the lectures in 2004-6, 2010-11, from which I took material and ideas

P. Ferracin and S. Prestemon for the material prepared for the US Particle Accelerator School

www.wikipedia.org for most of the pictures of the scientists

Google Earth for the images of accelerators in the world

The Nikolai Tesla museum of Belgrade, for brochures, images, and information, and the anonymous guard I met in August 2002

Warner Bros. and Columbia Pictures for some images of Terminator-3: the rise of machines, by J. Mostow