The Eloisatron

Thomas Taylor

CERN
Frontier High Energy Physics in the laboratory. The long march of hadron colliders

It started with the ISR (Intersecting Storage Rings, 30 + 30 GeV) This was audacious. Many scientists doubted it would work, and would have preferred a classical fixed target accelerator

• 1965 – V. Weisskopf gets approval to build the CERN ISR (Kjell Johnsen appointed project leader)
• 1971 – start of operation

Many discoveries could have been made, but crucially most of the experiments were not prepared to see tracks at large angles...

The collider was to be a test bed for accelerator physics, and eventually for detector physics in the collider environment
Potential of hadron colliders for discovery physics

While the experimental physics community was concentrated on the upcoming 300 GeV fixed target machines at CERN and Fermilab, and plans were being laid for similar superconducting machines, some far-sighted physicists had understood the greater potential of ISR-type machines...

Notably A. Zichichi dreamt of a very large superconducting collider (e.g. in the largest circle that would fit in Sicily) which he called the Eloisatron (ELN)

and thus started the adventure!
The early steps towards the ELN project

\[ \Rightarrow \textbf{Impact} \text{ on science & technology of accelerators} \]

- 1976 - International School of Accelerator Physics at Erice

\textit{Identify a need: create \textit{Accelerator Schools} at CERN and in the US}

\[ \Rightarrow \text{dawn of education in accelerator science} \]

- 1981 – \textit{HERA Project} presented to the INFN Council

\textit{Crucial insight: Involve \textit{industrial labs} very early in the R&D}

- 1985 – Start construction in Italy of prototype magnets for HERA
- 1988 - Complete construction of the HERA magnets

\[ \Rightarrow \text{understand industry can play a key role in magnet R&D} \]
From new ideas to reality

We can’t just wait for new, better ideas to solve our problems...

• Experience tells us

  ⇒ *it takes a long time to transform an idea into practice*

Relevant example

• Superconducting high-field magnets, first proposed in 1961 following a breakthrough in conductor technology, did not become a reality for high energy accelerators until 1986 (Tevatron and ISR low-beta). *It took 25 years...*

• The success of the LHC serves as a *demonstrator for the ELN concept* that can be built upon
• Full-scale ELOISATRON PROJECT

- Phase 1 - Conceptual Design Report (*Kjell Johnson*)
- Phase 2 - R&D in fundamental technologies
- Phase 3 - Construction of long superconducting magnets
  - 1985 - Start model magnet work for LHC (10% ELN !)
  - By 1992 feasibility of LHC magnets was demonstrated
  - 2008 – LHC operational

• The ELOISATRON (ELN) relies on *extrapolation from known technologies, + we hope,*
  - new acceleration techniques
  - new technologies (e.g. *high temperature superconductors*)
These are monitored for inclusion in the full-scale project
From 1996 to 2016

⇒ ELOISATRON Project Design Workshops

• 1991, 1992 - ELN conceptual design workshop 1 & 2
  ❖ Showed how \textit{feedback systems can be scaled up to cater for to 100 TeV protons}
  ❖ Assessed possibility of \textit{increasing the luminosity of ELN by a factor of 100}

⇒ \textit{no fundamental obstacle for a 200 TeV collider at }10^{35}\textit{ cm}^{-2}\textit{s}^{-1}

• 1995, 1999 - ELN workshops held on magnets beyond the LHC
  ❖ \textit{Inspired the US-led multi-lab study of Very Large Hadron Collider (VLHC) (1999-2001)}
  ❖ \textit{Identified direction for a significant improvement in SC material properties}
SUPERCOLLIDERS AND SUPERDETECTORS

ELOISATRON
Main Ring: 100 TeV, 300–400 km
Scintillating Fibre Tracker

BOOSTER 8 TeV

Superconducting coils
Vacuum chamber
High conductivity beam tube

Editors: W. A. Barletta and H. Leutz
World Scientific

SUPERCONDUCTING MATERIALS FOR HIGH ENERGY COLLIDERS

in memory of T. Ypsilantis

Editors
L. Cifarelli and L. Maritato
World Scientific
Key insights in the original ELN plan - and continue to guide the studies (A. Zichichi, The Superworld II)

• “Authentic innovations stem from the discovery of Fundamental Laws of Nature”

• “It is not wise to sit around waiting for new ideas”

• Recognize that it takes a time to transform ideas into reality
  ❖ 25 years from practical superconductivity to the Tevatron

• Do not build a new Laboratory if the work can be done within existing structures
  ❖ Failure of the US SSC demonstrates the wisdom of this advice

• Involve Industry in the implementation of the project
  ❖ Labs cannot build tens of kilometres of components

Italy has engaged significant intellectual resources in HEP
Key technological insights in ELN project

(A. Zichichi, The Superworld II – 1990)

- We know how to build a proton synchrotron for 100 TeV

- We have had to learn how to build an adequate detector
  - Hermeticity is important.
  - Radiation hardness is important...

  ➢ This led to the successful LAA project

- Maximize the potential of the facility:
  Build a large tunnel (300 km ... ) !

- Minimize the magnet & vacuum challenges. Minimize costs

- Devote parallel effort to experiments & accelerator

  ➢ Focused engineering development + innovative R&D
In che modo Antonino Zichichi ha ottenuto dal governo italiano 30 miliardi per realizzare un suo progetto con il Cern di Ginevra? Ecco i retroscena dell'operazione.
Detector challenges ⇒ need for R&D (Measure all detectable particles over as much solid angle as possible)

- Minimize reducible backgrounds from misidentified particles
- Enable data-taking in high luminosity environment
- Large track multiplicity, many uninteresting events per crossing
- Radiation damage degrades sensor efficiency & increases noise
  - Total exposure of sensors to radiation scales with integrated luminosity & falls off with distance from collision point
- For undetectable particles (e.g. neutrinos & Dark Matter) the momentum has to be extracted from the data
  - Record all visible momentum; impose conservation
Present perspective:
ELN => decades of forefront particle physics

• Large interest worldwide in a 100-TeV-class pp collider
  ❖ E.g. the present CERN Future Circular Collider study

• A new collider should be a large advance beyond LHC
  ❖ Probably the last big tunnel ...
  ❖ Up to about 100 TeV per beam

• Discovery potential far surpasses that of $e^+e^-$ colliders
  ❖ Much higher energy, plus high luminosity
  ❖ The best way to the next energy scale
  (But building an $e^+e^-$ collider on the way could make sense...)
The importance of the ELN studies is acknowledged worldwide

- USA (SSC 87 km; VLHC, 233 km),
- Japan (TRISTAN-II, 94 km),
- Europe (CERN FCC, 100 km)
- China (CCC, 100 km)
Previous studies in Italy (ELOISATRON 300km), USA (SSC 87km, VLHC 233km), Japan (TRISTAN-II 94km)

ex. ELOISATRON

Supercolliders
Superdetectors: Proceedings of the 19th and 25th Workshops of the INFN Eloisatron Project

ex. SSC

The closest to ELN was clearly the VLHC

- Serious study in early 2000s
- Accelerator to be hosted by Fermilab (existing infrastructure)
- Proposed a phased approach (to get the longest possible tunnel)
- Addressed the total cost issue in a professional way
  - Homed in on a 233 km long tunnel

- Note that while tunnel cost is proportional to length, Magnet cost increases fast with field strength (and requires expensive technology to pass certain thresholds)
Determining the design parameters

What sets the discovery potential of colliders?

1. Beam Energy $E$
   - Determines the energy scale of phenomena to be studied

2. Luminosity $\mathcal{L}$ (collision rate)
   - Determines the rate of producing of “interesting” events
   - We should scale $\mathcal{L}$ as $E^2$ to maximize discovery potential

$Luminosity$ $is$ $proportion$ $to$ $the$ $beam$ $power$ ($I_{\text{beam}} \times E_{\text{beam}}$)

3. Detector efficiency
“Higher energy is always better”

(A. Zichichi ... and many others ...)

What is the cost / benefit for

- Higher energy
- Higher luminosity
- What is the Energy vs Luminosity tradeoff?

*Physics studies generate answers to these questions*

- For a 100 TeV scale collider,
  “discovery” luminosity ~ $2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
  - Present knowledge pushes for higher energy
    *collider energy wins rapidly at higher masses*

- Dark Matter *may* relate to physics at *lower masses & smaller coupling*
  - *high luminosity is more important in this case*
The importance of Superconductivity

A superconductor is an element, intermetallic alloy or compound that conducts electricity without resistance below a certain temperature

Superconductivity is a macroscopic quantum phenomenon which many materials exhibit at cryogenic temperatures

The intrinsic performance advantages of superconductors ⇒ *overcome technological barriers in accelerators and detectors*
Non-superconductive Metal

Superconductor

Current Density, J
Critical Surface
Superconducting Interior Volume
Magnetic Field, B
Temperature, T
Superconductivity is big business

2016 - Global market $ 3.4 billion (of which more than 90% of the $ 3.3 Billion for magnets is for MRI)

Three main practical types are manufactured:

<table>
<thead>
<tr>
<th>material</th>
<th>cost factor</th>
<th>Max field</th>
<th>Tc</th>
<th>main use</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nb-Ti alloy</td>
<td>1</td>
<td>$\sim$ 10 T</td>
<td>$\sim$ 10 K</td>
<td>MRI magnets</td>
</tr>
<tr>
<td>Nb$_3$Sn compound</td>
<td>$\sim$ 8</td>
<td>$\sim$ 20 T</td>
<td>$\sim$ 18 K</td>
<td>NMR, ITER</td>
</tr>
<tr>
<td>HTS (BSCCO, REBCO)</td>
<td>$\sim$ 20</td>
<td>$\sim$ 30 T</td>
<td>$\sim$ 100 K</td>
<td>Devices</td>
</tr>
</tbody>
</table>

Also, interesting for low-field applications:

- MgB$_2$ compound $\sim$ 3 $\sim$ 3 T $\sim$ 39 K power cables

Not yet commercially available, but potentially interesting:

- Fe-based pnictides low ? $\sim$ 25 T ? $\sim$ 55 K ? Being studied
Niobium-titanium alloy (Nb-Ti) ⇒ workhorse material for magnets

Thoroughly studied at RAL in late 1960s and early 1970s for application to accelerators (GESSS collaboration)

- Fine filaments
- Twisting
- Copper matrix
- Assembly into flat cables ("Rutherford cables", for high current magnet applications)

This sophisticated composite material came about thanks to the drive for high energy accelerators. It was taken up for MRI magnets, which created a huge demand and drove down the cost – which was subsequently important to drive down the cost of magnets for accelerators and detectors...
Nb-Ti conductor is available and affordable thanks to the success of the MRI magnet industry
Superconductivity and the LHC dipole magnet
LHC Nb-Ti
Rutherford cable
  36 strands
  0.825 mm diameter
  6500 filaments
  6 micron diameter
1200 t of SC
7500 km cable
FCC Nb$_3$Sn
8000 t of SC
(cf. ITER 600 t)
Magnets for next generation proton colliders

• For a 100 TeV centre-of-mass machine
  - 270 km ⇒ 4.5 T
  - 100 km ⇒ 16 T

(These are field levels at which all dipoles must operate reliably, and therefore less than the highest test field)

NB: the LHC dipoles are wound with Nb-Ti and to operate at ~ 8 T they must be cooled with superfluid helium at < 2 K. They are industrialized, but expensive (about ½ total cost of the collider ring)

• 16 T magnets (proposed for the 100 km FCC) require better Nb$_3$Sn than that presently produced
  ⇒ *an intensive R&D programme addresses this issue*
Nb-Ti also has excellent mechanical properties
(Luck is a useful ally!)

- The material had been used in the aircraft industry for *rivets*
- Processing is relatively easy
- Easy to wind magnet coils

But there are *drawbacks*

- *Cost of niobium* (like silver) limits potential for cost reduction
- *Not appropriate for very high fields*

⇒ This has driven the need to use \( \text{Nb}_3\text{Sn} \) for accelerators

But \( \text{Nb}_3\text{Sn} \) is *brittle and expensive*, and there is not a large scale application... It is presently the subject of *R&D* for accelerators. In the meantime only Nb-Ti is really affordable...
The machine should be designed with the highest possible luminosity & energy.
Components that limit energy & luminosity

• **Main ring**
  - *Dipoles* - bend beam around circular orbit
  - *Beam dumps* - protects machine and detectors
  - *Cooling system* - removes waste heat at cryogenic temperatures

• **Interaction Regions and detectors**
  - *Quadrupoles* to focus beam
  - *Detector* (via radiation damage)
Alternative design strategies for ELN

1. **Medium field design** (4 - 7 T magnets) with Nb-Ti
   - Extensive engineering experience is at hand
   - Large tunnel & large stored beam energy
   - Some luminosity enhancement from radiation damping

2. **High field magnet design** (~ 15 T for Nb$_3$Sn, ~ 20 T for HTS)
   - Highest possible energy in given size tunnel
   - **Greater technical risk and greater cost**
   - Maximizes effect of synchrotron radiation (good and bad)

3. **Staged approach**
   - Get the longest tunnel
   - Phase 1 with cheap-as-possible Nb-Ti magnets!
   - Invest in conductor R&D for 3 – 4 times E in Phase 2

• ELN magnets should ideally cost less than half per T-m than LHC
Vacuum/cryo systems are sophisticated and expensive – *Scaling from LHC is not an option*

- $\mathcal{L} \sim 2 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1} \Rightarrow 5 – 25 \text{ W/m}$ (depending on the circumference of the collider)

- Practical limits for cryogenic beam pipes are being studied

- CERN is designing beam screens for high field options
  - This leads to increases in magnet aperture and overall cost

*Managing synchrotron radiation power is increasingly challenging as $P_{\text{sr}} > 5 \text{ W/m}$*
LHC beam screen

Studies of beam screens for FCC

The challenge of machine protection

- ELN-type proton colliders have **enormous stored energy** in both magnets & beams compared with the LHC
  - Needs many more machine sectors to keep dipole energy per sector similar (energy per dipole is up to 50 MJ (12 kg of TNT))
  - Needs many more beam abort lines to keep energy per abort line similar (distributed energy deposition is a special case)

- At 100 TeV per beam and \( \mathcal{L} = 10^{35} \text{ cm}^{-2}\text{s}^{-1} \), \( P_{\text{debris}} = 180 \text{ kW/side} \)

- Before shielding, *dose in the vicinity of Q1* \( \approx 4 \times 10^8 \text{ Gy/year} \)

*For luminosity = \( 10^{35} \text{ cm}^{-2}\text{s}^{-1} \)*

<table>
<thead>
<tr>
<th></th>
<th>( E_{\text{cm}} ) (TeV)</th>
<th>( C_{\text{cce}} ) (km)</th>
<th>Energy/beams (GJ)</th>
<th>Energy/dipoles (GJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC</td>
<td>14</td>
<td>27</td>
<td>( \sim 2 \times 0.4 ) 11</td>
<td>11</td>
</tr>
<tr>
<td>FCC</td>
<td>100</td>
<td>100</td>
<td>( \sim 2 \times 9 ) \sim 180</td>
<td>( \sim 180 )</td>
</tr>
<tr>
<td>ELN</td>
<td>100 ( \rightarrow ) 300</td>
<td>300</td>
<td>( \sim 2 \times 30 ) \sim 60</td>
<td>( \sim 60 )</td>
</tr>
</tbody>
</table>
Proposed ELN project
leverages existing CERN efforts

v Project objective: Facilitate progress toward a 100+ TeV collider
v Project duration: 4-years
v Project priorities in work program:
Ø Develop robust machine protection strategies
  • Recent studies point to significant non-local energy deposition
Ø Facilitate serious engineering of high field magnets with a greatly reduced cost
Ø R&D to make detectors compatible with ELN luminosities
v Project director: W. Barletta (MIT)
Ø With assistance of Project Steering Committee
v Project personnel: Two post-doctoral fellows
Ø Home institutions in Italy
“Go big or go home”

• There are no insurmountable technical obstacles to realizing a high luminosity, 100 TeV class proton collider

• Contribute to research in technologies critical for accelerator & detector

• Closely follow ongoing FCC study

• However, there are several good reasons for choosing to build a much larger ring (200 - 300 km) than that considered for the CERN FCC (100 km)

• Radiation damage is a serious issue

• A 300 km synchrotron could reach up to $E_{cm} = 0.5 \text{ PeV} \ldots$

• How to remove synchrotron radiation from the beam tube?
Acknowledgment

I wish to acknowledge the input of my friend

*Bill Barletta*

Who has been long been close to the progress of the Eloisatron, and crucially played a major role in the design study of the VLHC
Thank you for your attention