Research and Technology: Essential Interplay

Illustrated with examples from CERN

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CERN
Introduction

• CERN was founded in 1954 to provide a world-class laboratory in Europe for high energy physics

• First accelerators at CERN:
  – Synchrocyclotron (SC) (1957)
  – Proton synchrotron (PS) (1960)

• The world’s first hadron collider:
  – Intersecting storage rings (ISR) (1971)

• Followed by:
  – Super proton synchrotron (SPS) (1974)
  – p-pbar collider (SppS) (1984) and other antiproton accelerators
  – Large electron positron collider (LEP) (1987)
  – Large hadron collider (LHC) (2008)
Succeeding accelerators use accumulated infrastructure

Constant interplay between Research and Technology

• Requirements of the experiments pushed technical innovation
• Technical innovation enabled experimentalists to envision better experiments
• Ambiance fosters frequent discussions between experimentalists and accelerator scientists
• Presence of well-equipped and staffed workshops

Strong shared loyalty to the Organization
The synchrocyclotron (SC)

- This was a relatively conventional type of accelerator, that had been developed in the US and Europe to reach higher energies (up to 300 MeV) than were possible with a standard cyclotron (up to 200 MeV). The objective was to enable CERN to start experiments as quickly as possible. It delivered protons to targets to provide:
  - Abundant supply of mesons
    - Kaon studies
  - Abundant supply of muons
    - The first g-2 experiment
  - World-class experimental physics results in the first 5 years!
Dick Garwin writes: “In our CERN g-2 experiment, team members as individuals “owned” and were primarily responsible for individual portions of the experiment. Thus, Nino Zichichi assumed responsibility for producing the magnetic field of the desired shape, measuring it, and providing quantifiable data for the magnetic field, all on the short timescale commensurate with rapid progress. This was achieved as a result of the design of the 6-m magnet (86 tons) with removable upper and lower steel pole faces of 50-mm thickness, and the decision not to machine the pole faces to obtain the desired magnetic field, but to provide a magnetic buildup of the poles by the application of flat Armco steel shim stock of various thicknesses, secured by Scotch tape and ultimately held down in the vacuum by copper lids secured by brass screws into the pole faces. A large portion of the paper and the effort is devoted to details of this work, which resulted in the desired magnetic field profile over the 6-m length...”
Francis Farley, Hans Sens, Georges Charpak, Theo Muller, Antonino Zichichi with the 6-meter g-2 magnet
The Summary of the 16 June 1965 publication of this experiment in Il Nuovo Cimento reads,

“The anomalous part of the gyromagnetic ratio, \( a \equiv \frac{1}{2} (g-2) \) of the muon has been measured by determining the precession \( \vartheta = a \omega_0 \bar{B} t \) for 100 MeV/c muons as a function of storage time \( t \) in a known static magnetic field of the form \( B = B_0 (1 + ay + by^2 + cy^3 + dy^4) \). The result is \( a_{\text{exp}} = (1162 \pm 5) \cdot 10^{-6} \) compared with the theoretical value \( a_{\text{th}} = \frac{\alpha}{2\pi} + 0.76\alpha^2 / \pi^2 = 1165 \cdot 10^{-6} \). This agreement shows that the muon obeys standard quantum electrodynamics down to distances \( \sim 0.1 \) fermi. Details are given of the methods used to store muons for \( \sim 10^3 \) turns in the field, and of measuring techniques and precautions necessary to achieve the final accuracy…..”

The proton synchrotron (PS)

The original plan was to build a 10 GeV weak focusing synchrotron. Design studies were interrupted following the publication by Courant and Snyder of the theory of strong focusing. Design was changed to a 25 GeV strong focusing synchrotron. *(Could such a rapid change happen today?...)*

- The new machine required very **precise magnetic field**:
  - use **punched laminations** and **poleface windings**
- Acceleration and beam extraction brought many challenges to the PS team: new ideas....

**Problem: How to produce a usable beam of neutrinos?**

A new device was invented at CERN: a **magnetic horn**

Using this device the kaons and pions produced in the interaction of the energetic proton beam with the protons in the target were focused before decaying into muons, electrons and neutrinos
Magnetic horn  
(S. van der Meer, 1961)

Toroidal field focuses the pions/kaons produced in the target
Power: 12 kV capacitor discharge (200 µs pulse of up to 400 kA)
Environment: high level of induced radioactivity
Schematic layout of the neutrino source for beam to CNGS
Thanks to the magnetic horn, the experiment with the Gargamelle bubble chamber ⇒ evidence for neutral currents (1973)

A neutral current event in Gargamelle. The neutrino beam enters from the left. All three tracks from the collision vertex undergo either very large angle scattering or interaction, proving that no muon is produced. (photo CERN)
The PS measurement of the anomalous magnetic moment of the muon (g-2), continued the tradition started at the SC:

- 2\textsuperscript{nd} muon g-2 experiment (1967-1970) – 5 m diameter storage ring -> accuracy of 3 parts in 10\(^4\)
- 3\textsuperscript{rd} muon g-2 experiment (1972-76) – 7 m diameter storage ring -> accuracy of 1 part in 10\(^5\)

Today, higher order QED calculations, including weak and hadronic corrections, predict g-2 with an accuracy of 1 part in 10\(^6\)
- Experiments today push to achieve even higher accuracy

\textit{NB: a discrepancy between the theoretical and experimental value would be a “smoking gun” for new physics}
Intersecting Storage Rings (ISR)

• Higher centre-of-mass energies are clearly possible if beams are collided head-on

• This was first pointed out by Rolf Wideröe in the 1940s. It was not pursued then for fear that the interaction rate would be too low

• Successful experiments were conducted with beam of electrons in the US, Italy and CERN in the 1960s

• Protons would provide far higher energy of interaction: this was the goal of the ISR – the first hadron collider.
Intersecting Storage Rings (ISR)

- The ISR (1971-1982) was to be the test bed for many of the ideas to be exploited later on
  - Ultra-high vacuum technology
  - Application of superconducting magnets in an accelerator
  - Method for determining luminosity (van der Meer scan)
  - Roman pots
  - Gaseous detectors
  - Stochastic cooling
  - Precision calorimetry
  - $4\pi$ detector architecture

- By this time CERN had built up and trained staff that was able and motivated to innovate on a grand scale
Ultra-high vacuum technology

• **Measurement**
  How to measure UHV? Ionization gauge.
  Bayard-Alpert (1950) to $10^{-9}$ Pa
  State-of-the-art ⇒ not possible at the required level
  Improved understanding ⇒ **new design that achieves** $10^{-10}$ Pa

• **Cryogenic vacuum pumping**
  Need $10^{-10}$ Pa at the interaction points to control background
  Cold surface pumps all gases except $\text{H}_2$. Need to shield radiation from room temperature surfaces. This was demonstrated.
    ⇒ **The beginnings of effective UHV cryo-pumping**
Bayard-Alpert pressure gauge, with illustration of x-ray effect

It was found that contrary to Alpert’s theory, the diameter of the collector could be reduced from 0.1 mm to 0.025 mm, thus improving the range.

External collector type (Helmer) for measuring pressures down to $10^{-12}$ Pa

(To reduce filament temperature)
A cryopumping tank was developed and later used for the H₂ jet target experiment in the ISR, and for a cyclotron at the Hahn Meitner Institute in Berlin.

**Cryopumping** ⇒ very high pumping speed and low ultimate pressure. It was the best pumping technique at the end of the 1970s – until the advent of
- large commercial **turbomolecular pumps**
- **getter pumping** (either Titanium sublimation or Non-Evaporable Getters) reduced the interest of the technique (complicated due to use of liquid helium).

Besides being a facility for physics research, the ISR was a test bench for solutions which could be adopted for a larger accelerator using superconducting magnets. To evaluate “cold bore” behaviour, a cryostat containing a 1.3 m long vacuum chamber cooled to from 2K to 200K was installed in the ISR. Different gases were condensed on the chamber surfaces while beams up to 40 A were circulating. The vacuum remained stable in severe conditions thanks to the large pumping speed provided by cryopumping.

This experience gained provided the confidence to propose and to use large scale **cryopumping at the LHC (18 km of cold sectors)**.
Superconducting low-beta insertion (to enhance luminosity)

1972. **Practical superconductivity** young, but obviously important

**Good application:** a low-beta insertion (to improve luminosity)

*Also to learn about how to use it for the future...*

- **Basic concepts developed.** Mock-ups built and tested
- Understanding of mechanical and electrical constraints
- Understanding of cryogenic constraints
- **Magnets designed** and **ordered from industry**

Magnets integrated into the collider. **Good experience!**

*Team trained for future applications...*
Superconducting quadrupole for ISR high luminosity insertion

- Aluminium shrink rings
- Steel yoke quadrants
- Stainless steel tube: inner wall of helium vessel and support for correction coils

Roman arch
Cryogenics for the ISR low-beta insertion

Measuring luminosity. The van der Meer scan

Important to **maximize**, and to **measure** the luminosity of the interaction.
Roman pots

Bellows

Detectors

Machine vacuum chamber

Beam

TOP VIEW

SIDE VIEW

9 m

A

D

C

B

side view

view along beam
Multi-Wire Proportional Chamber (MWPC)

Charpak (left) and collaborators with an early large MWPC

Filled with “magic gas”, charge multiplication can reach $10^6$

G. Charpak, 1968
Schematic of frequently used calorimeter readout techniques:
(a) Plates of scintillator optically coupled to a photomultiplier. (In modern instruments more compact readout methods of the scintillator light are used);
(b) Ionization charge produced in an electron-transporting medium (e.g. liquefied argon) is collected at electrodes that also function as the absorber plates.
When the ISR was built it was expected that most of the interesting physics would be in the forward direction, and the largest facility was the split field magnet: no analyzing magnetic field for particles with large $p_t$. Huge mistake!

Mid 1970s: working group set up to optimize a magnetic facility. Two designs: solenoid, air-cored toroid, both superconducting. NB: emphasis was put on accessibility for installing detector. CERN authorities rejected SC option (expensive, delay).

Alternative design was quickly developed. Field of the resistive magnet was reduced but accessibility better addressed. Field shaping: problem of reduced field was mitigated.

The magnet was adapted to use with the SC low-beta insertion. It took just 2 years to go from first sketches to installation.

When the ISR was closed (to save money for LEP construction), the magnet was moved to serve the Obelisk experiment (LEAR).
The Super Proton Synchrotron (SPS)

- Not everyone was confident that the ISR would perform as required, and there was a simultaneous drive for a larger fixed target synchrotron, similar to that being built at Fermilab. The approval process had been mired in discussions about the site (the original idea being to locate it away from Geneva). John Adams played the card of re-using the CERN infrastructure to break the deadlock, and the machine was built in a deep tunnel (rather than cut-and-fill, like the ISR and the 300 GeV machine at Fermilab). Innovations included:
  - Developing techniques for **accurate underground alignment**
  - Introduction of **distributed control systems**, and touch screens in the control room
  - Kaon beams and the discovery of direct CP violation
  - Bubble chamber technology at its apogee
  - **Liquid krypton calorimetry**
  - Development and use of **polarized targets**
- As in the case of the ISR, the fact that CERN had built up and trained staff that was able and motivated to solve problems (and innovate) was essential.
The Proton-Antiproton Collider

- Simon van der Meer and colleagues had been experimenting with **stochastic cooling** (an idea originating in Russia) at the ISR, and developing amplifiers with sufficient bandwidth. With the possibility of shrinking the dimensions of a beam of antiprotons, Carlo Rubbia seized upon the idea to propose a p-pbar collider at the SPS. This was to be done in parallel with the LEP effort, as being a fast way to establish the existence of the Z and W bosons that were being predicted by the **Standard Model**. This would not have been possible without the thorough understanding of the technique, and the development of the necessary equipment using the latest wide-band technology. Two large experiments UA1 and UA2 were designed and installed in the SPS.

- The skills available at CERN thanks to training with previous projects, together with the team spirit, enabled the organization to rise to the occasion. The final result was the discovery of the bosons, leading to the Nobel prize for Carlo Rubbia and Simon van der Meer.
Stochastic Cooling

Principle

Pick-up measures horizontal error. Kicker corrects angle

Spaced by \( \frac{1}{4} \lambda_{\beta} + \frac{1}{2} n \lambda_{\beta} \)

Repeat for vertical error

Amplifier must be wideband

\( a \) See “Stochastic cooling for beginners“ by D. Möhl
Stochastic Cooling

Slot-type PU and kicker.
(TEM transmission lines above and below)

Beam circulates at the centre of the chamber

Signal wavelength $\gg$ slot separation
Phase velocity in transmission line = particle velocity ($\approx c$)

The antiproton collector (AC) was built to boost accumulation rate
To shrink beam fast in AC (to fit in AA) use plunging electrodes
Large electron positron collider (LEP)

- LEP 1: Study Z in detail
- LEP 2: Study W in detail, and look for Higgs

- Developments
  - Non-evaporable getter (NEG) pumping
  - Economical low field magnets
  - Superconducting RF cavities
  - Ring imaging Cherenkov (RICH)
  - BGO
Diagram showing the CERN accelerators at the time of LEP and how they were used to produce the high energy beams circulating in the collider.
Non-evaporable getters (NEG)

Cross-section of the LEP dipole chamber with the getter pump. 1: extruded Al profile, 2: cooling channels, 3: lead shielding for synchrotron radiation, 4: ceramic insulators, 5: pumping slots.
Low field magnets
Superconducting RF cavities

sputtering configuration
RICH at DELPHI
Silicon vertex detectors

The Z-strips are wire bonded to diagonal readout strips at the edge of the detector.
Large Hadron Collider (LHC)

- LEP tunnel was excavated with the idea of eventually re-using it for protons.
- Studies for the machine and the experiments started in the early 1980s, in parallel with construction work on LEP.
- Due to competition with the SSC, but having much smaller radius, emphasis was on high luminosity and high field.
Superconducting dipoles

Powerful Precise and Many
Field lines and direction in the apertures

Transverse electromagnetic forces on the coils

Flat cable with copper etched away to show superconducting filaments

Superconducting strand

Nb-Ti filaments within a strand
LHC cryogenics

Cooling with superfluid helium at 1.8 K
HTS current leads

• Use new technology to save cryo power
• Large number of current leads required to feed power from warm power converters to cold magnets. (3 MA to transfer)
• Ideal application for HTS (discovered in 1987)
• 3 types designed with large production in mind (i.e. using techniques adapted for quality control in industry)
• 64 rated 13 kA, 500 rated 6 kA, 600 rated 0.6 kA
• Prototypes made in CERN workshops
• Produced (to build-to-print specification) in BINP and industry
• Tested via contracts in Italy and UK
HTS section of a 13 kA lead. The stacks of BSCCO 2223 are soldered to a stainless steel support tube with brazed copper terminals.

Detail showing the joint between HTS stacks and Nb-Ti wires (leading to the cold busbar system) at the cold end of the 13 kA lead.
Detector magnets for the LHC

Superconductors for large detector magnets have converged to cabled Nb-Ti in Cu matrix, co-extruded with pure Al for stabilization.
For the winding of the powerful CMS magnet, designed for operation at 4 T, the high-purity Al used to stabilize the superconductor was not strong enough to withstand the stress on the conductor with the magnet at full field (4 T). It was proposed to surround the pure Al / Nb-Ti insert with Al alloy, and co-extrude simultaneously. This would have required heating to > 500°C degrade the superconductor.

The alternative was to solder or weld Al alloy flanges to the pre-extruded insert – a process that became the subject of a development in collaboration with ETHZ. Working together with industry it was found that by using electron-beam welding the process was both feasible and practical and resulted in a superconductor degradation of less than 5 %.
ATLAS toroidal magnet system
Magnet for LHCb
ALICE forward dipole
Data handling and communication

• Computing clusters and data storage
• Local area networks
• WWW
Future prospects

• LHC luminosity upgrade
• CLIC
• FCC
• ......
Luminosity upgrade

- Lifetime of the IR quadrupoles is limited due to accumulation of radiation damage to insulation
- Take advantage of replacement by improving performance by a factor of 10
  - Large aperture Nb$_3$Sn quadrupole
  - Crab cavities
  - Superconducting links
SC quadrupoles with Nb$_3$Sn coils

Nb$_3$Sn is a better superconductor than Nb-Ti, but it pose many challenges, the most severe being that it must be formed via a solid-state reaction, which requires long heat treatment at 650 °C in a controlled atmosphere, after which it is extremely brittle.

The aim is to reach a critical current density of 1500 A/mm$^2$ at a field of 14 - 15 T (for Nb-Ti this is only achieved at 7 - 8 T)
Cross-section of a HL-LHC quadrupole. Bore diameter is 150 mm
A new protection system for superconducting magnets called coupling-loss induced quench system (CLIQ) has been recently developed at CERN. Recent tests on Nb-Ti coils have shown that CLIQ is a valid, efficient, and promising method for the protection superconducting magnets with high magnetic field.

The protection of new-generation Nb$_3$Sn accelerator magnets is even more challenging due to the much higher stored energy per unit volume and to the significantly larger enthalpy needed to initiate and propagate a normal zone in such coils.

Now, the CLIQ system will tested for the first time on a Nb$_3$Sn magnet in the CERN magnet test facility, in order to investigate its performance in practice, and hopefully validate the method for this type of superconducting magnet.
This innovative system can rapidly transfer large portions of superconductors in coil windings to the normal state by introducing a high coupling loss (hence heat) in the copper matrix of the superconductor.

This is accomplished by introducing a series of fast oscillations in the transport current of the coils, which in turn provoke high local magnetic-field changes.

CLIQ offers a more robust electrical design, easier implementation and repair, a faster, more global quench initiation, resulting in a substantially lower hot-spot temperature after a quench.
**MgB$_2$ cable for cold power transfer**

Magnesium diboride (MgB$_2$) round wire has been developed in a collaboration with industry. This can be cabled for transferring multi kA currents for connecting magnets to distant power converters.
Test of a 20 kA cable made using magnesium diboride superconductor, critical temperature 39 K.

The cryostat is semi-flexible (developed from concept first developed for the ISR), for ease of installation.

Use at CERN for the LHC high luminosity upgrade.

Also chosen by IASS, Potsdam, for application to power transmission

http://home.cern/about/updates/2014/04/world-record-current-superconductor
Further to the CERN initiative, MgB$_2$ superconducting technology was also seized upon by Carlo Rubbia, at the time scientific director of the Institute for Advanced Sustainability Studies (IASS) in Potsdam, Germany, for an innovative transmission line for long-distance transport of green power.

MgB$_2$ superconducting cable cooled by liquid hydrogen has been proposed for use in underground power transmission lines, with periodically spaced cryogenic cooling stations.

A collaboration agreement between CERN and IASS was signed in March 2012 with the objective of proving the feasibility of the technology. The development was aimed at testing a 20 kA DC line operated at 20 K (-253 °C), also conveniently close to the CERN requirement for powering the magnets.

The result of the tests demonstrated that such high-current cables can be operated at and above the temperature of liquid hydrogen, and that the basic related technology is now proven.
Compact Linear Collider (CLIC)

Since the mid-1990s CERN has been working on an original concept (due to W. Schnell) for a compact linear e+e- collider, potentially capable of achieving higher energies than a classical linac of the same length.

The idea is to accelerate the bunches by transferring energy from an intense low-energy drive beam, installed parallel to the main beam.

The structure frequency is 12 GHz (X-band), and the aim is for an accelerating gradient of up to 100 MV/m (up to 3 times ILC).

Difficulties reside in the manufacture of the precise cavities, in the alignment, in coupling power from the drive beam, etc. The concept is being evaluated in the CLIC Test Facility (CTF)
drive beam

power-generating structure

main beam

accelerating structure

drive beams
these electron beams provide the RF power to the main accelerators

electron main accelerator
electrons
main beams
detector
positrons
positron main accelerator
return yoke (Fe) with detectors for muon identification

superconducting solenoid, 4 Tesla

Fine-grained (PFA) calorimetry, \(1 + 7.5 \, \Lambda_i\)

main tracker, silicon based (pixels and short strips)

forward region with final beam focusing

ultra low-mass vertex detector with \(\sim 25 \, \mu m\) pixels
Future Circular Collider (FCC)

• The familiar circular synchrotron is well understood and has proved to be a reliable tool for HEP experimentation. Used as a hadron collider it is presently the only proven method of performing experiments at the energy frontier.

• With this in mind CERN is exploring the possibility of installing a machine with magnets twice as strong as those in the LHC in a tunnel of 3 to 4 times the circumference, the aim being to approach centre-of-mass energy of 100 TeV.

• Studies of the terrain show that this should be possible.

• Work is being done to develop Nb$_3$Sn superconductor required for the high-field dipoles, and a model magnets being designed. The magnet system is a major cost driver for such a machine.

• The tunnel could also house an interesting e+e- machine that would rival the ILC.

• A similar machine is being studied in China.
“CERN model”?

• For HEP Institutes (CERN, BINP, FNAL, KEK, etc.) it is relatively easy to set intelligible goals
• Encourage accelerator and experiment personnel to work together to achieve goals
• Lightweight management to foster bottom-up innovation
• Provide laboratory and workshop facilities
• Grow and maintain a competent core team
• Practice intelligent purchasing from industry
• CERN is fortunate in being sited in Geneva, where there is a tradition of hosting international organizations
• CERN is fortunate in having a well thought out convention
• As the major centre for HEP experimentation, CERN bears heavy responsibility to maintain credibility of the domain
Technology transfer

It is a fact that work on accelerators and detectors has generated “useful” fallout, i.e. affecting everyday life far from HEP. This has been documented, and in some way it does offset the high cost to society of the large installations.

This fallout normally occurs through the purchase in industry of equipment based on new concepts or developments that had been modelled (and often prototyped) at CERN and the transfer of knowhow comes from helping the company to fulfil the specification. From the outset, Patenting was not part of the menu.

Unfortunately funding agencies now expect us to take out patents. The returns from licensing do not cover the cost of maintaining a technology transfer group, and the filing/maintenance of patents. The secrecy surrounding them wastes time and resources, and detracts from the team behaviour upon which much of the success of a laboratory like CERN depends.
• The fashion generates a lot of non-productive activity

• A recent article in the Economist newspaper was also highly critical of the process, citing findings from serious studies that society at large does not benefit

• Shareholders of corporations (particularly pharmaceutical) do benefit, but that entails a transfer from the rest of society.
  ➢ Studies have also found that the claim that pharmaceutical companies, for example, need long term patent protection to enable them to finance R&D was not justified
    ❖ (>90 % of the profit goes as “rent” to shareholders, <10 % to R&D)

• Much of the R&D for accelerators and experiments does not generate technology that is directly usable outside the domain
Initiating projects

- The starting (core) team should be small – ideally 2 to 5 persons with complementary primary expertise + sufficient knowledge of other disciplines to contribute to the general optimization.
- Those involved should be prepared to invest real time.
- Project should be fleshed out before forming collaborations.
- Essential collaborations should be set up progressively. *(Remember that collaborations involve coordination overhead)*
- Avoid taking on free-riders.
Thank you for your attention