The role of technology in high-energy research

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ABSTRACT

A brief survey of the activities of CERN is presented, and examples of technological problems occurring in the performance of high-energy physics experiments are given. The main fields discussed are: acceleration, production of particles, detectors, and data handling.

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I will attempt to explain why, how, and where advanced technology is used at CERN. In order to do this, let us first summarize the main work of the Laboratory (Fig. 1):

Protons are accelerated in the CERN Proton Synchrotron (CPS) up to an energy of 28 GeV and directed onto targets, where part of their energy is converted into matter in the form of particles which are viewed by various types of detectors that produce data. The data are then analysed in order to obtain knowledge which is fed back to the experiments in many ways. For instance, within a matter of hours information is acquired which enables the physicists to improve the conditions of their experiment and achieve better results. Other data, after

*) Adapted from tape recording.
longer analysis, might influence the particular theory under investigation. If this is the case, the experimental equipment might then have to be modified or replaced in order to test the new aspects of the theory.

As an illustration of the "raw materials" with which CERN physicists are dealing, let us look at a typical particle of 10 GeV energy, which has a diameter of approximately $10^{-15}$ m, travels at a speed of about 500,000 km/sec, and usually lives for between $10^{-8}$ and $10^{-28}$ sec. There are only two "tools" which can be used with these "raw materials", namely electric and magnetic fields. Even very strong electric fields have only a slight influence on very energetic particles. Magnetic fields can only have a curving effect, e.g. a field of 10 kG acting on a 10 GeV particle will produce a radius of curvature in its track of 35 m.

This brief introduction already illustrates some of the technological requirements of research into elementary particles: firstly, very high electric fields; secondly, very high magnetic fields; thirdly, as a logical extension of the second requirement, superconducting and hence cryogenic techniques; fourthly, pulsed fields in order to cope with the particles' extremely short lifetime and high velocity; and lastly, high vacuum in order to ensure "clean" experimental conditions.

1. **ACCELERATION**

A short description of what happens in the CPS will help towards understanding the acceleration process.

Protons pass from the hydrogen source to the pre-injector (Fig. 2). There they are subjected to an accelerating voltage of 550 kV over a length of 10-12 cm. They then enter the linear accelerator (Linac, Fig. 3) where they are further accelerated to 50 MeV by a technique

![Diagram](image)

**Fig. 2**

- **a)** The proton source, in which the protons are extracted from a hydrogen plasma, and the pre-injector
- **b)** Section through the pre-injector:
  1. anode (+550 kV);
  2. extraction electrode (490 kV);
  3. intermediate electrode (275 kV);
  4. cathode;
  5. focusing lenses;
  6. source;
  7. cathode of source;
  8. magnet.
a) View of the first two accelerating cavities of the Linac with their covers removed, looking towards the source. Down the middle run the drift tubes in which the protons are shielded from the electric field during the accelerating phase.

b) Simplified diagram of one of the three accelerating cavities of the Linac. The length and spacing of the drift tubes increase steadily, in such a way that a particle will be subjected to an accelerating field between tubes; for example, at A, then shielded from the field during the decelerating phase A', all the way down the cavity.

Fig. 3

similar to that used by a surf-rider. The protons are pushed forward by a series of electromagnetic waves through three cavities having a total power of 7 MW. They are protected from the decelerating effect which occurs between the waves by means of drift tubes. The manufacturing tolerance imposed on the length of the tubes is less than 50 μm.

The protons are then transferred at one-third of the speed of light to the PS where they are subjected to an accelerating technique which is similar to that used in the Linac but on a much larger scale (Fig. 4). There are many problems to be overcome in the design of a machine such as the PS. For instance, in order to avoid beam losses through unwanted oscillations, the positioning of the magnets had to be accurate to within 0.1 mm, and the reference system of the 200 m diameter machine was surveyed to an accuracy of 0.015 mm. Another problem is that of focusing: magnetic lenses are used to reduce the cross-section of the beam to a minimum. During acceleration, the inwards centrifugal force on a particle has to be increased in order to keep the beam on an equilibrium orbit. This is achieved by raising the current in the magnets in relation to the frequency of the RF cavities, which is tracked very precisely to the magnet current by means of a feedback loop. During a typical 28 GeV acceleration cycle (Fig. 5) lasting two seconds, the power supplied to the magnets reaches a peak of over 50 MW.

The Proton Synchrotron not only serves for "direct" high-energy physics experiments but it is also used as injector to the Intersecting Storage Rings and will feed a 10 GeV beam to the Super Proton Synchrotron (now under construction), where by further acceleration a maximum energy of 400 GeV will be obtained.
Fig. 4 Three-dimensional view of the ring

Fig. 5 A typical cycle of the PS

1. change of magnetic field in the main magnets with time, which is identical in shape to
2. the energy of the synchronous particles;
3. voltage applied to main magnet terminals;
4. frequency to which the RF cavities are tuned.
2. PRODUCTION OF PARTICLES

Particles can be produced in different ways. For instance, the proton beam may be directed onto internal targets. However, owing to the high beam intensities now reached in the PS, these targets are liable to produce a high level of radioactivity which could damage vulnerable parts of the accelerator. An alternative method is to extract the protons from the machine and direct them onto external targets.

The extraction of a 28 GeV beam circulating in the PS at a rate of 2 μsec/turn obviously poses very considerable technological difficulties. Two techniques are used at CERN: firstly, fast ejection whereby selected bunches of protons are kicked out of the ring by a special magnet operating in approximately 0.1 μsec; secondly, slow ejection whereby the beam is gradually shaved during 300 msec (this corresponds to about 150,000 turns).

Whatever the method used, the secondary beams have to arrive at the right time, at the right place, at the right energy, and in the right number.

There exist a great variety of secondary beams originating from the PS (Fig. 6). One area to which such a beam is directed is the South-East Hall, which houses a neutrino facility. In order to produce neutrinos, the extracted proton beam is focused onto a beryllium target, 1 cm in diameter and 1 m in length, situated inside a magnetic horn. The kaons and pions emerging from the target are very strongly focused by means of 400 kA pulses of 100 μsec duration. These particles decay into muons and neutrinos which then pass through steel shielding where the muons are stopped, leaving the neutrinos to continue on their way to the Gargamelle bubble chamber.

Another secondary beam is ejected from the PS to the Intersecting Storage Rings (ISR). The principle behind the ISR can be explained by using the analogy of the fly and the hand.
described earlier by Dr. Hine. The stationary fly represents the proton at rest. As the proton is accelerated, then, according to the theory of relativistic mechanics, not only its speed but also its inertia increases, and so the fly becomes a moving hand. At the ISR two hands are clapped together, and their energy is entirely used up in the collision, whereas at the PS only a part of the proton's energy is absorbed in the collision with the stationary target. One of the reasons why very high energy collisions are necessary is that only they can produce the heavy particles in which the physicists are particularly interested.

In order to make the head-on collisions sufficiently frequent and to allow the physicists enough time to carry out their research, the beams have to be very intense and have to be kept circulating for several days. This poses considerable technological problems. Firstly, a vacuum of at least $10^{-11}$ Torr has to be maintained throughout the rings, which have a total length of approximately 2 km. Secondly, the manufacturing tolerances imposed on the magnets are about ten times greater than those at the PS. The pole faces have been built to an accuracy of 0.01 mm to achieve the precise field configuration required. Lastly, the magnet power supplies have to be capable of supplying currents of 4000 A with an extremely high stability for hours or even days.

3. DETECTORS

CERN makes extensive use of bubble chambers for particle detection. The principle behind the bubble chamber is the following: it contains a liquid which is brought to its boiling point by suddenly reducing the pressure inside the vessel; during the very short period in which the liquid should be boiling but has not yet had time to do so, a charged particle passing through the chamber will cause the liquid to boil, and the bubbles will mark the position of its track. Bubble chambers have grown very considerably in size and complexity in the 20 years since the appearance of the first Glaser chamber, which had a volume of a few cm$^3$. For instance Gargamelle, the chamber used for neutrino experiments, is 12 m$^3$ in volume (Fig. 7); such a large useful volume is needed because of the neutrino's low interaction probability. The pressure in the chamber can be reduced from 22 bars to 10 bars in about 20 milliseconds, and a magnetic field of 20,000 gauss is applied to the chamber for the purposes of track analysis.

Fig. 7 Body of the Gargamelle Bubble Chamber

Fig. 8 Set-up for an experiment in the Intersecting Storage Rings
Whereas Gargamelle is filled with either propane or freon for neutrino physics, liquid-hydrogen fillings are normally used in chambers where proton interactions are to be investigated. For instance, the Big European Bubble Chamber (BEBC) contains 40 m$^3$ of liquid hydrogen to which a field of up to 35 kG is applied by two superconducting coils operating at $-255^\circ$C. Owing to the very high magnetic field, a force of approximately 9000 tons is exerted between the two coils, and this enormous force has to be compensated lest the position of the coils is altered and track measurement efficiency impaired.

Apart from bubble chambers, CERN also makes wide use of electronic detectors such as scintillation counters, spark chambers, etc. The set-up for an experiment usually takes on quite a complex appearance, as can be seen in Fig. 8.

4. DATA HANDLING

Whereas data from electronic detectors are produced in a form which is relatively easy to handle, information from bubble chambers is recorded on film and calls for very sophisticated analysing devices. Both the position and radius of curvature of the tracks have to be measured with extremely high precision and the results then transferred to magnetic tape. In addition, the device has to be designed to avoid misinterpretations, which is not an easy task. In order to meet these requirements, CERN has developed various instruments; for example, ERASME, which can be used to analyse film mainly from BEBC and which allows a high degree of operator intervention. Some of the specialized hardware developed at CERN is capable of operating up to 100 times more quickly than the present-day computers. As an example of the amount of information to be handled by these devices, Table 7 shows the total data.

### Table 7

<table>
<thead>
<tr>
<th>Beam</th>
<th>Pictures taken</th>
<th>Laboratories</th>
<th>Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu^-$</td>
<td>11.2 GeV/c</td>
<td>380,000</td>
<td>Bologna, Florence, Genova, Milan</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>8.25 GeV/c</td>
<td>220,000</td>
<td>Athens (Demokritos and University), Liverpool, Vienna</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>11 GeV/c</td>
<td>71,000</td>
<td>Strasbourg, Tel Aviv</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>14.3 GeV/c</td>
<td>393,000</td>
<td>Ecole polytechnique, Rutherford Laboratory, Saclay</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>24 GeV/c</td>
<td>142,000</td>
<td>Bonn, Hamburg, Munich</td>
</tr>
<tr>
<td>$\mu^-$</td>
<td>16 GeV/c</td>
<td>257,000</td>
<td>Aachen, Berlin, CERN, Imperial College London, Vienna, Westfield College London</td>
</tr>
<tr>
<td>$\mu^+$</td>
<td>16 GeV/c</td>
<td>265,000</td>
<td>Aachen, Bonn, CERN, Heidelberg, Cracow, Warsaw</td>
</tr>
<tr>
<td>$k_\pi$</td>
<td>0.88 GeV/c</td>
<td>352,000</td>
<td>Imperial College London, Rutherford Laboratory</td>
</tr>
<tr>
<td>$k_\pi$</td>
<td>1.04 GeV/c</td>
<td>352,000</td>
<td></td>
</tr>
<tr>
<td>$k_\pi$</td>
<td>0.5 GeV/c</td>
<td>520,000</td>
<td>Glasgow, Pisa, Rutherford Laboratory</td>
</tr>
</tbody>
</table>
produced by the 2 m hydrogen bubble chamber in a typical year. The reduction of these data into a meaningful form is obviously a very difficult task, which is undertaken partly at CERN and partly in the Member States.

5. CONCLUSION

CERN is a place where physicists from throughout Europe find the facilities and the assistance to carry out extremely sophisticated experiments using very advanced technologies. The main object of their study is that of elementary particles, the smallest physical objects we can think of and whose behaviour reveals the deepest laws of nature which are probably also the most universal.