ACCELERATORS: THE FINAL FRONTIER?

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Abstract

Particle Accelerators have been the mainstream tool of nuclear and particle physicists for more than 70 years. Progress has been remarkable, with the beam energies increasing by much more than a million-fold in that time. Progress has been equally remarkable in the development of the so-called “Standard Model of Particle Physics”, which is the result of decades of careful work at accelerators, and which provides a wonderfully precise description of the interaction of the most fundamental building blocks so far discovered, but which is known to be incomplete. Uncovering a deeper layer of nature, and perhaps the “Theory of Everything”, requires ever more challenging accelerators, pushing the frontiers of energy and precision. While the primary motivation for the development of these facilities is scientific – understanding the “attoworld” – there are real benefits to society through the development of these technologies, which are of great importance in other sciences, industry and particularly medicine.

INTRODUCTION

The motivation for high-energy and high-luminosity accelerators for particle physics is to explore the structure of the Universe at its most elemental. The first fundamental particle (the electron) was discovered by JJ Thomson in Cambridge in 1897 and the most recent (the top quark) was discovered at Fermilab in 1994; the 20th century was really the century of the Standard Model of particles and their interactions. The structure of the Standard Model will be described, and some ideas about how to extend the model to address some of its defects will be discussed. New frontier accelerators are needed, both to complete the Standard Model and to search for the new phenomena believed to lie within reach of the next generation of such machines - the Large Hadron Collider (LHC) now nearing completion at CERN, Geneva and the International Linear Collider (ILC). There are other, even more adventurous, ideas for new machines, such as the Muon Collider, and for its possible forerunner, the Neutrino Factor.

Sadly, there is not time to discuss the many other accelerator “frontiers” – the exciting development of other novel neutrino beams (“beta beams”), or in Nuclear Physics (FAIR, SPIRAL2, EURISOL, RIA), or in light sources (FELs and ERLs), or in other branches of particle physics (the “factories” for bottom, charm, τ, g-2, $\mu \rightarrow e$ conversion…). Nor is there time to discuss recent developments in laser-plasma accelerators, and or applications of accelerator technology in cancer therapy.

THE STANDARD MODEL OF PARTICLES AND THEIR INTERACTIONS

Particle Physics is concerned with identifying the most basic constituents of the universe around us, and describing how they interact. Towards the end of the nineteenth century, it was realised that that atoms, then still not universally accepted as physical entities, were probably not fundamental but had internal structure. Much of the twentieth century was devoted to exploring the consequences of this observation.

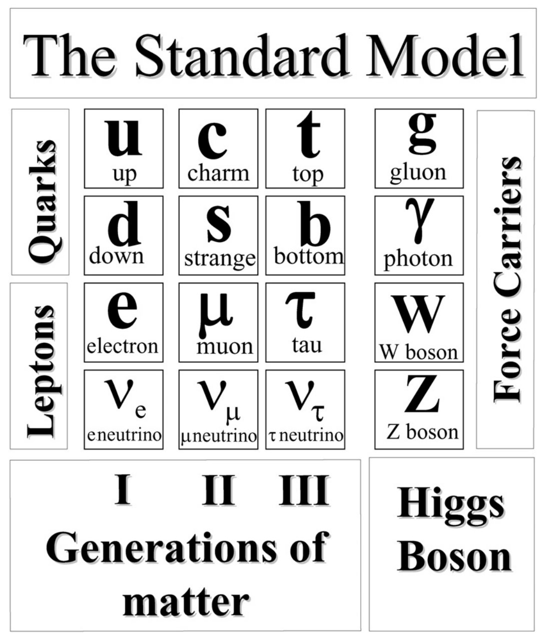

Figure 1: The particles of the Standard Model

The twin pillars of quantum mechanics and relativity led eventually to the development of the Standard Model of Particles and their Interaction, or simply the Standard Model. This describes the sub-atomic (actually, sub-nuclear) domain in terms of twelve constituent particles (six quarks and six leptons, arranged in three families) and their anti-particles, together with five force-carrying particles (the gluon, the photon and W^+, W^- and Z bosons) – see Figure 1. Over the past thirty years, the Standard Model has been subjected to increasingly stringent tests, and has been found to describe an enormous range of phenomena with astonishing precision. Figure 2 shows the mathematical form of the Standard Model at the scale of energies around the W and Z masses ~ of order 100 GeV. While it looks to be very complicated, what is remarkable is that it fits easily on one page. So far, a quantum theory of gravity seems beyond reach, although there are promising lines of enquiry such as string theory.

To get some idea of how the Standard Model works, let us consider a very simple process – $e^+e^- \rightarrow \mu^+\mu^-$. At high energies (where the masses of the electron and muon can be neglected) but well below the Z-mass (where other terms must be included), this process involves just a single term – the one labelled "[$\gamma\ell^+\ell^-$]". After a few pages (!) of Dirac algebra, the answer for the cross-section for this process is given by

$$\sigma = 4\pi\alpha^2/3s \qquad (1)$$

– what could be simpler?

The Standard Model Effective Lagrangean

$$
\begin{array}{rl}
\mathcal{L}_{\text{(Standard Model)}} & = \\
[W^\pm] & - \frac{1}{2}(\partial_\mu W_\nu - \partial_\nu W_\mu)(\partial^\mu W^{\dagger\nu} - \partial^\nu W^{\dagger\mu}) + M_W^2 W_\mu W^{\dagger\mu} \\
[\text{Photon}] & - \frac{1}{4} F^A_{\mu\nu} F^{A\mu\nu} \\
[Z^o] & - F^Z_{\mu\nu} F^{Z\mu\nu} + \frac{1}{2} M_Z^2 Z_\mu Z^\mu \\
[\ell, \nu_\ell] & + i\overline{L_\ell}\, \partial\!\!\!/ L_\ell + i\overline{R_\ell}\, \partial\!\!\!/ R_\ell - m_\ell \bar{\ell}\ell \\
[W\ell\nu] & - \frac{g}{\sqrt{2}} \overline{L_\ell}(\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/) L_\ell \\
[\gamma\ell^+\ell^-] & + e_{e/m} \bar{\ell} A\!\!\!/ \ell \\
[Z\ell^+\ell^-, Z\nu\bar{\nu}] & - \frac{g}{\cos\theta_W} \overline{L_\ell} \left(\frac{\tau_3}{2} \cos^2\theta_W + \frac{1}{2}\sin^2\theta_W \right) Z\!\!\!/ L_\ell - \frac{g \sin^2\theta_W}{\cos\theta_W} \overline{R_\ell} Z\!\!\!/ R_\ell \\
[\text{H}] & + \frac{1}{2}\partial_\mu H \partial^\mu H - \frac{1}{2}\mu^2 H^2 - \frac{1}{2}\lambda\mu H^3 - \frac{1}{8}\lambda^2 H^4 \\
[\text{HH\&H } W^+W^-] & + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda} H \right) \left(2W_\mu W^{\dagger\mu} \right) \\
[\text{HH\&H } ZZ] & + \frac{g^2}{8}\left(H^2 + \frac{2\mu}{\lambda} H \right) \left(\frac{1}{\cos^2\theta_W} Z_\mu Z^\mu \right) \\
[\text{H } \ell^+\ell^-] & - m_\ell \sqrt{\sqrt{2} G_F}\, \bar{\ell}\ell H \\
[\text{quark } \gamma] & + Q \bar{q} A\!\!\!/ q \\
[\text{quark Z}] & - \frac{g}{\cos\theta_W} \overline{L_q} \left(\frac{\tau_3}{2}\cos^2\theta_W + \frac{\sin^2\theta_W}{2} \right) Z\!\!\!/ L_q \\
[\text{quark W}] & - \frac{g}{\sqrt{2}} \overline{\mathcal{U}} V_{\text{CKM}} (\tau_+ W\!\!\!\!/ + \tau_- W\!\!\!\!/) \mathcal{D} \\
[\text{quark H}] & - m_q \sqrt{\sqrt{2} G_F}\, \bar{q} q H \\
[\text{gluons}] & - \frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} \\
[\text{quarks}] & + \overline{\mathcal{U}}(i\partial\!\!\!/ - m_\mathcal{U})\mathcal{U} + \overline{\mathcal{D}}(i\partial\!\!\!/ - m_\mathcal{D})\mathcal{D} \\
[\text{quark gluon}] & + igT^a \left(\overline{\mathcal{U}} A\!\!\!/^a \mathcal{U} + \overline{\mathcal{D}} A\!\!\!/^a \mathcal{D} \right) \\
[\text{ 3 gluons}] & + \frac{g}{2} \left(\partial_\mu A^a_\nu - \partial_\nu A^a_\mu \right) f^{abc} A^{b\mu} A^{c\nu} \\
[\text{4 gluons}] & - \frac{g^2}{4} f^{abc} f^{axy} A^b_\mu A^c_\nu A^{x\mu} A^{y\nu}
\end{array}
$$

excluding GRAVITY

Figure 2: The "Standard Model"

Intrinsic to the model, however, is one as-yet undiscovered particle – the Higgs boson – without which the model fails at a very fundamental level – none of the particles (quarks, charged leptons, W and Z) have mass; such a Universe would be a very dreary place indeed.

Despite this enormous success, the Standard Model is known to be incomplete, and must itself be derived from an even more fundamental theory. Some of the motivation for physics "beyond the Standard Model" comes from the model itself – while it is very successful in describing the physics universe, its basic structure is unexplained. Further clues that there is a more fundamental theory come from astronomy and cosmology – it seems that the Standard Model accounts for only about 5% of the energy content of the universe, and that other forms of matter ("Dark Matter") and energy ("Dark Energy") are all pervasive. There is thus an increasing interest in astroparticle physics, which uses particle physics techniques and high-energy cosmic rays to study astrophysical phenomena, providing valuable insights to both particle physicists and astronomers.

THE ACCELERATORS …

… at the Energy Frontier

In order to find clues to the physics beyond the Standard Model, and to discover the Higgs boson (if it exists) or what replaces it (if it does not), new accelerators are required, with either higher energy or higher intensity, or both. The "Energy Frontier" machines are these days all colliders, since the days of the Intersecting Storage rings at CERN in the 1970s. The highest energy machine currently operating is the Tevatron at Fermilab (2 TeV in the centre of mass), but this will soon be overtaken by the Large Hadron Collider at CERN at 14 TeV. The other crucial parameter which determines the discovery potential is the *Luminosity* (L) of the machine. The number of events in the experiment is simply the "integrated luminosity" (luminosity × time) multiplied by the cross-section, calculated in a similar way to equation (1). Figure 3 shows typical LHC cross-sections for some important processes. The conclusion is that the LHC has to operate at very high luminosity 10^{33}-10^{34} cm^2s^{-1} – one to two orders of magnitude higher than at the Tevatron – a significant challenge.

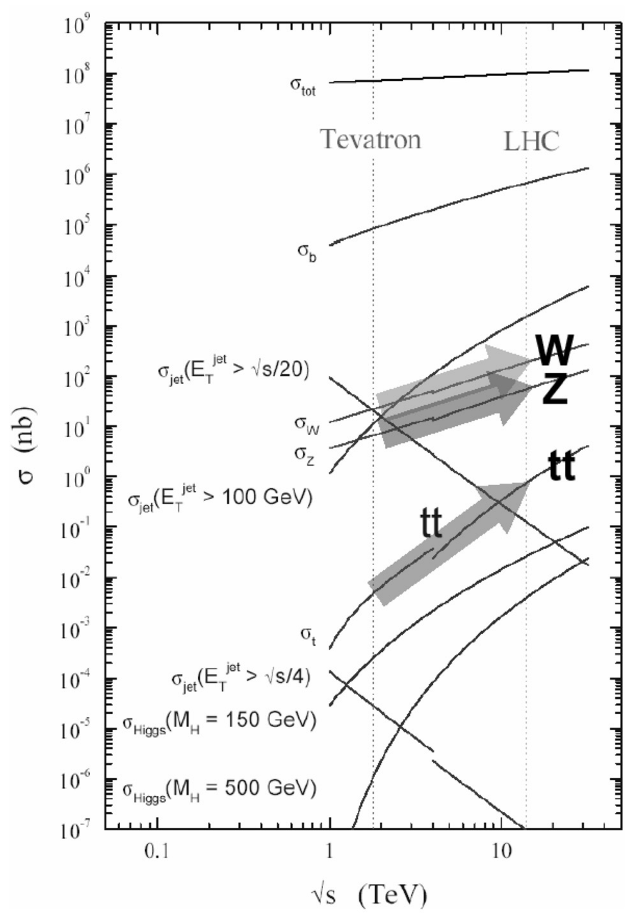

Figure 3: Some typical LHC cross-sections

Of course, Figure 3 shows only the cross-sections for some processes that we know to exist or, like the Higgs, we expect to exist. What about new phenomena? The theorists have been very busy, and very imaginative, in suggesting ways in which the imperfections of the Standard Model can be rectified. Each of these new theories has a mathematical description, like Figure 2, but often much more complicated. Using the techniques used to obtain equation (1) (but much more complicated), it is possible to predict, as a function of the parameters of the new theory, the cross-sections for the production new particles or new phenomena, provided that the energy is high enough – usually more than twice the mass of the new particles (when they must be produced in pairs) but occasionally (like the Higgs) when the energy is sufficient to produce a single particle. In fact, there are good reasons to expect that there is new physics just around the corner. First, one of the deficiencies of the Standard Model is that higher order processes (quantum loops) mean that, as well as the Higgs mechanism giving the particles the masses that they have, the particles acquire other contributions which drag their masses to the next higher scale – say the Grand Unified scale (see below) or the Planck Scale (10^{19} GeV), whichever is the sooner. One way of counteracting this is to suppose that there is a new symmetry (super-symmetry or SUSY) whose role is to ensure that, for each divergent process, there is a second process with the opposite sign which annuls its effect at very high energies. For this to be effective, the masses of the super-symmetric particles cannot be too high, say less than about 1 TeV. A second motivation for believing in super-symmetry, or at least something new at the TeV scale, is the concept of Grand Unification (see Figure 4). The three coupling "constants" associated with the three interactions of the Standard Model (the strong force and two interactions which eventually become the electromagnetic and weak forces) vary with energy, and almost – but not quite – meet at very high energy (around 10^{15} GeV). However, if some new ingredient is added to the theory at about a TeV, with similar properties to super-symmetry, then all three forces are unified at around 10^{16} GeV. If super-symmetry does exist, it naturally provides (at least in most implementations) a natural candidate for the Dark Matter that pervades the Universe – the lightest super-symmetric particle or LSP, which has to be stable.

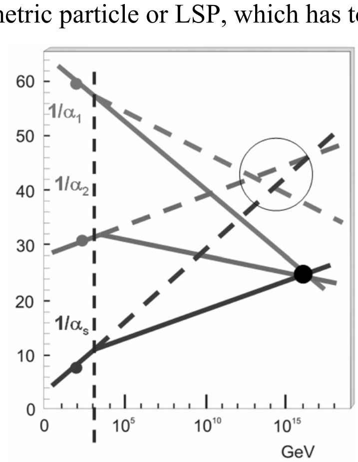

Figure 4: Grand Unification. The dotted lines are the Standard Model expectations, and the solid lines the predictions with supersymmetry at a scale of 1 TeV.

Of course, there are other ideas that perform similar tasks but which have a very different phenomenology. However, *something* should happen at the TeV scale explored by the LHC, and the physicists with their huge detectors (ATLAS and CMS) will see it.

The LHC is a very complicated machine (see Figure 5), and both the accelerator and the detectors are pushing technology to the limits.

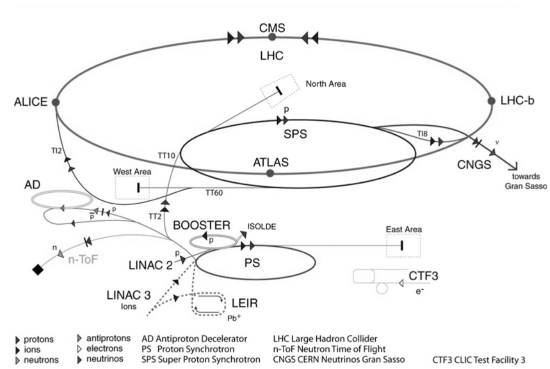

Figure 5: The LHC complex

Proton-(anti)proton machines like the Tevatron and the LHC are extremely good at looking new particles over a very wide range of masses, because the fundamental collisions take place between "partons" (bits of the proton, essentially quarks and gluons) which share the proton's energy. However, this advantage becomes a *disadvantage* when trying to make precision measurements of the particle properties, which is essential to understanding the details of any new theory – the initial state is not all that well known, there are large backgrounds from other processes, there may be lots of missing energy and unseen particles. The W and Z particles were discovered at the CERN proton-antiproton collider (the SppS), but the precision measurements of their properties was made at electron-positron colliders (LEP and the SLC). So, once the results of the LHC are known, a new high-energy electron-positron collider will be needed to explore the new physics – the International Linear Collider (ILC).

The ILC needs to reach a total energy of at least 500 GeV (250 GeV per beam) to cover the physics reach of the LHC, and will probably needs to be capable of reaching 1 TeV, and have a luminosity of at least 10^{34} cm^2s^{-1}. Following the choice of superconducting RF technology for the main linac in August 2004, a world-wide collaborative programme (the Global Design Effort or GDE) produced a Reference Design Report (RDR) in February 2007. Although there are still many technical challenges to be resolved, the principal parameters of the machine are now known, and work has started on an Engineering Design Report, to be ready in 2010 when the first results from the LHC are available. The layout of the machine is shown in Figure 6. If a site can be selected and funding agreed, construction could start as early as 2012, with first beam in 2019 or 2020. However, there are considerable political issues to be resolved before construction could start, so that this "technically driven" schedule will almost certainly slip, probably by several years. Concurrent running with an upgraded LHC would be highly desirable scientifically. Work is just beginning on defining the specifications for the two detectors that will share, in a "push-pull" arrangement, the single intersection region.

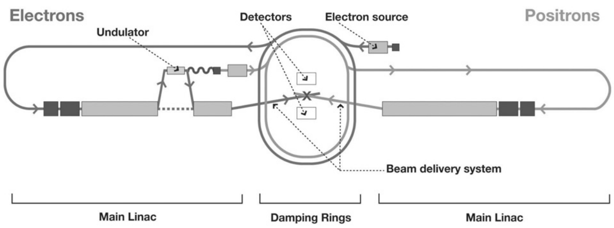

Figure 6: ILC Layout in the Reference Design Report

The advantage of an electron-positron collider over a proton-proton collider covering the roughly same energy region (i.e. the same discovery potential) is that the initial state is well known, and the final state can usually be well-reconstructed. In general, therefore, there is a better resolution on, for example, the masses of new particles, and a much lower background when calculating production cross-sections, which is also important in testing the theoretical predictions. Finally, the ability to "tag" the characteristics of one of a pair of particles produced in a collision means that often the characteristics of the other are well-predicted, and so it is possible, for example, to measure, say, absolute branching fractions or relative branching ratios, which provide further constraints upon models. On the other hand, in order to be able to reap the benefits, it is usually necessary to know with reasonable precision, at least the masses of the new particles, so that the total energy can be adjusted to maximize the production cross-sections.

If energies higher than a TeV or so are required, the superconducting RF technology of the ILC is no longer viable – the length of the linacs is about 30km per TeV, which is prohibitively expensive above 1 TeV. An alternative approach is the Compact Linear Collider or CLIC technology, which uses a novel two-beam acceleration technique (see Figure 7). A low energy, high-current drive beam is decelerated, and the energy transferred to the main linac and used to accelerate the main beam. This can in principle deliver very high accelerating gradients, and it was hoped to be able to produce gradients as high as 150 MV/m at a frequency of 30GHz (to be compared with the superconducting rf parameters of around 32 MV/m at 1.3GHz) but the breakdown rate in the accelerating structures is too high for stable operation, and so recently the specification has been changed to a target of 100 MV/m at a frequency of 12 GHz. Many of the other challenges – the damping rings and beam delivery system for example – are similar to that for the ILC, but the bunch structure is very different. The ILC has very long bunch trains, with 2670 bunches separated by ~150 nsec, whereas the CLIC bunch structure has ~300 bunches separated by only 0.3 nsec. The CLIC technology is being developed by part of a broad collaboration at the CLIC Test Facility at CERN (CTF3).

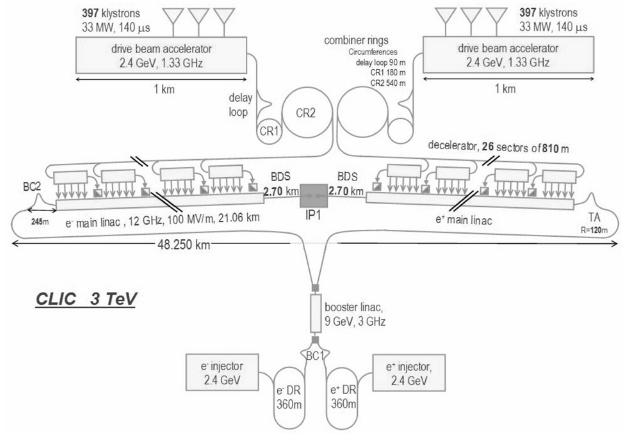

Figure 7: Layout of CLIC

Another approach to clean interactions is the "Muon Collider", where the challenges are, to say the least, significantly greater. The muon is some 200 times heavier than the electron and so synchrotron radiation is not an issue, leading to compact circular machines, which could fit easily within existing accelerator laboratories such as Fermilab or CERN. But of course, there is a price to pay for this new freedom – the muon lifetime is only 2.2μsec, and the muons are produced in tertiary beams with a wide range of energies and angles. The muon collider is then a very complex machine (see Figure 8) with several challenging stages – a multi-GeV, multi-MW proton driver, incident upon (probably) a mercury-jet target embedded in a strong solenoidal magnet, followed by sections to collect, bunch, cool, accelerate and store. None of these technologies is yet mature and so many people believe that an important step along the way to a muon collider is the *Neutrino Factory,* which is an accelerator …

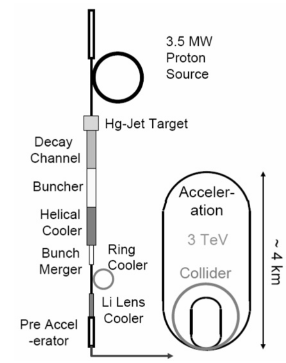

Figure 8: Layout of a Muon Collider

... at the Precision Frontier

There are a number of accelerator facilities that are required to study the Standard Model predictions with much greater precision, in order to look for cracks and inconsistencies that will yield important clues to the physics beyond (and underneath) the Standard Model. These are often referred to as *factories* because their role is to produce as many of a given type of particle as possible. The great success of the two B-factories at KEK and SLAC have shown the value of such facilities – both machines have far exceeded their design luminosities, and there are ambitious plans to go still further, with luminosities in the range of 10^{35}-10^{36} cm^2s^{-1}. There are other ideas for tau, charm and ϕ factories, all of which face technical challenges to be overcome. There is also, in my view, a scientific need for at least one more generation of muon g-2 experiment, to explore whether the hint of a discrepancy between the measured value and the theoretical predictions (currently at about 3 σ) from the most recent experiment is real or not.

The scientific motivation for these machines is to look for evidence that the Standard Model fails. However, in the neutrino sector, we already know that the Standard Model has failed – the phenomenon of neutrino oscillations requires that at least two of the neutrinos have mass, and this cannot be accommodated in the Standard Model, essentially because the neutrinos are left-handed particles and have only weak (and gravitational) interactions. However, because the neutrinos are electrically neutral, there are other mass-generating mechanisms available that are not possible for charged particles. But the real interest in studying neutrinos with much higher intensity and higher quality beams is the possibility that neutrinos and anti-neutrinos might be subtly different, and through a process known as lepto-genesis, drive the baryon asymmetry of the Universe (the observation that the Universe today seems to contain only matter and not equal amounts of matter and anti-matter). The Neutrino Factory needs to produce $>10^{21}$ muons per year, and store them in decay rings aimed at detectors thousands of kilometres away. To achieve this, all of the components of the Muon Collider in Figure 8 are needed, except that the amount of cooling is 4 orders of magnitude smaller, since the beams do not have to be brought into collision. There is a vigorous ongoing world-wide R&D programme looking into the various technologies required, and the Neutrino Factory, if built, will be the demonstrator for the Muon Collider, as well as producing important physics in its own right – an almost perfect match.

OTHER ACCELERATOR FRONTIERS

There is not space in this short review to cover the many exciting advances in accelerator technology for light sources, spallation sources, free electron lasers, energy recovery linacs, or linear non-scaling fixed-field alternating gradient accelerators (which could be useful for anything from the neutrino factory to cancer therapy). What is welcome is the increasing recognition of the synergies between the various accelerator-based sciences – the damping rings for the ILC look to be very similar in specification to a 3rd generation synchrotron light source, and the relationship between the energy frontier electron linacs and XFELs is obvious – the SLAC linac is being converted into the Linac Coherent Light Source (LCLS), and FLASH and the X-FEL at DESY use the same superconducting technology as the ILC. Indeed, further uses of this technology are being identified, most recently in "Project X" at Fermilab, which envisages an advanced high-power *proton* linac using ILC technology.

Nor is there time to discuss the dramatic developments over the last three or four years in laser-plasma acceleration, for both electrons and ions. Beams of electrons and ions of several hundred MeV have been generated in a few mm of plasma. While the emittance of the beams is still large, and the stability of the accelerated beams is still poor, enormous progress is being made. While these will probably *not* lead to the TeV accelerators of the future (for limitations of power, if for no other reason) they are likely to find many applications in the MeV to GeV range as compact electron and ion sources for a variety of applications.

SUMMARY

The motivation for developing accelerators as we know them, from Röntgen's X-ray machine in 1895 and Thomson's electron accelerator in 1897 to the LHC in 2008, has traditionally been to pursue our understanding of the Universe around us – what it is made of and how it works. However, from the very beginning, these discoveries made an immediate impact in other sciences and more widely – it is well known that Röntgen X-rayed his wife's hand and saw the bone structure shortly after their discovery. It is less well-known that X-rays were used successfully to treat cancer *before* 1900! (Of course, they were less aware of the hazards then – that came later.) There is no reason to suppose that future developments in accelerator technology will have any less impact on the other sciences and society.

So, Particle Accelerators have an exciting future. There is a renewed interest in frontier accelerator R&D around the world. In particle physics we have the LHC, the Linear Collider ILC and/or CLIC), possibly a muon collider and maybe its forerunner the Neutrino Factory and other "precision frontier" machines like the super B factories. In other sciences, there are many developments in Light Sources, FELs, spallation sources, advanced radioactive ion accelerators (RIA, FAIR, HIE-ISOLDE, EURISOL …). In society, accelerators continue to find a variety of uses, from industry to medicine – indeed one of the most exciting developments is the use of proton and light ion (Charged Particle) therapy for the treatment of cancer – more than 50,000 patients world-wide have been treated in this way, and such facilities are becoming increasingly common in the major medical centres.

And finally, they are *fun too!*

REFERENCES

[1] B. Jones and G. McKenna, private communication. See also the University of Alabama at Birmingham Comprehensive Cancer Center, where it is stated that "as early as 1897, scientists were discovering that x-rays could be used for therapeutic as well as diagnostic purposes."