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# ACCELERATORS: ENGINES FOR TRAVERSING A LARGE AND OFTEN DIFFICULT LANDSCAPE\*

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\*Dedicated, with fond memories, to Dieter Moehl and Andre Lebedev

## *Abstract*

The many applications of accelerators are presented, with pictures and comments, upon the machines and the results obtained with them. Attention is then given to possible future applications, and some remarks are made on the future development of accelerators. In short, the presentation should serve as an introduction to the Conference itself where there shall be many – wonderfully detailed – contributions to all of this.

## INTRODUCTION

In this paper I will try to show – all in only five pages – the breadth of accelerator types and, more importantly, the many uses (applications) of particle accelerators. For a number of decades, starting in about 1930, accelerators were used primarily for nuclear and then high-energy physics. This wasn't exclusively true, for even in the 1930's Lawrence was employing his cyclotrons for medical purposes, but it was almost exclusively true.

However, now-a-days accelerators are widely used for many different purposes. Essentially all these accelerators are of a type particularly chosen for the application and specially designed to the particular use. This short report can't possibly go into the details --- which is the heart of the subject (and the topic of many contributions at this Conference) – but can only show the general sweep and extent of these applications. Nevertheless, it should prove interesting, especially to the many deep into the details of some particular application, to look broadly and see how extensive is the range of application of particle accelerators.

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## TYPES OF ACCELERATORS

There are some 30,000 accelerators in the world and these are of the six major types, or small modifications of these types. That is there are electrostatic machines, cyclotrons, linacs, betatrons, synchrotrons or colliders. We are all rather familiar with modern versions of these machines, but perhaps not many of us have looked back at their humble beginnings. In Fig. 1 is shown the very beginning; namely the first electrostatic machine that was able to fulfill Rutherford's dream, which was to achieve artificial radioactivity.

Looking to the future – and surely – the future will contain ever-more of the types mentioned; there may well be two very different accelerators. The first is an accelerator of muons. True, this may be a linac or a synchrotron at its heart, and culminate in a collider, but the handling of the short lifetime muon would seem to justify considering this a new type of accelerator. Muons are diffusely produced in hadron collisions, so they must be captured and “cooled” into a beam; a non-trivial task. A section of the proposed 2D cooling channel is incorporated in the experimental demonstration of cooling: Muon Ionization Cooling Experiment (MICE). This is an international collaboration and is underway at the Rutherford-Appleton Laboratories.

The second is the use of lasers and plasmas as accelerators. Effort in this direction has gone on for decades, and 1 GeV of acceleration has been achieved, but much still remains to be accomplished before the method produces a practical accelerator. Two methods are under particular study; a wakefield accelerator at SLAC and a laser/plasma accelerator at LBNL. Of course there is activity in many other places.

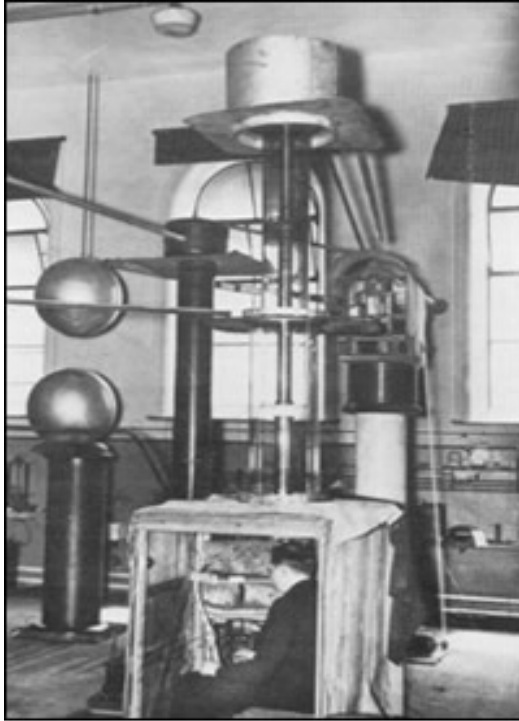


Figure 1: The first electrostatic accelerator. The original Cockcroft-Walton installation at Cavendish Laboratory in Cambridge. Walton is sitting in the observation cubicle (experimental area) immediately below the acceleration tube.

## APPLICATIONS OF ACCELERATORS

In the remainder of this paper – the largest part of the paper – I will describe the various applications; i.e., uses of accelerators. The first to consider, are the uses in basic science that was, of course, the original driving force that led to the development and ever-improvement of accelerators. However, as we shall note, there are really a great many diverse uses for the very many accelerators in the world.

### *High-Energy and Nuclear Physics*

In high-energy physics the leading machine is shown in Fig. 2, which is a view of the LHC at CERN, where the Higgs was discovered just this year. Fig. 3 is an overview of RHIC at Brookhaven, the largest machine for nuclear physics, where many interesting things are being seen in relativistic heavy ion collisions.

Of course these needs are not ending, and effort is already going into improving the luminosity – and even thinking of increasing the energy – of the LHC, and also the development of electron collisions with ions at RHIC. I don't have

space to describe the many neutrino experiments that are searching for effects beyond the Standard Model. Nor can I describe the work on anti-hydrogen and on many other aspects of pure science.



Figure 2: The Large Hadron Collider (LHC), where the Higgs was just discovered.



Figure 3: The Relativistic Heavy Ion Collider (RHIC).

### *Synchrotron Radiation Source*

Sources of synchrotron radiation, electron storage rings and free electron lasers (FEL), have become vital research tools in surface science, chemistry, biology and drug design for medicine. There are more than 100 dedicated facilities, serving about 100,000 scientists in more than 20 different countries. In Fig. 4 is shown the large European Synchrotron Radiation Facility. Even larger facilities exist in the US and in Japan, while ever-better ones are under construction. The present generation (4<sup>th</sup>) of sources includes FELs such as the SLAC Facility shown in Fig. 5. This facility produces coherent radiation at 1.5 Angstroms (0.15 nm). FELs are now under construction, or already operating, in a range of wavelengths and in a number of different countries.



Figure 4: The European Synchrotron Radiation Facility (ESRF). The doors were open for users in 1994.



Figure 5: The SLAC site showing the LCLS, a 1.5 Angstrom Free Electron Laser (FEL).

### Spallation Neutron Sources

Spallation sources are a complement to synchrotron sources. A number of smaller machines have been in existence for some time. The first of the large new machines, linac based, is the Spallation Neutron Source at Oak Ridge, which is shown in Fig. 6. A similar facility is at JPARC in Japan, and ones are under construction in China and in Sweden (a European Project), while the cyclotron based Swiss facility (SINQ) is quite competitive. Typically, 1 GeV protons are used to spall a nucleus and produce 30 neutrons. The neutrons are used to study magnetism, high-temperature superconductors, biological structures, etc.



Figure 6: A view of The Spallation Neutron Source (SNS).

### Isotope Production and Cancer Therapy

Although reactors are the primary source of isotopes for short-lived isotopes medical imaging, near-by accelerators play an important role in production of isotopes (that are not the daughters of a longer lived mother).

A very important role is in the X-Ray treatment and the external particle beam treatment of cancer. Almost every major hospital has an accelerator produced – rotating on a gantry – source of X-Rays. In fact there are more than 15,000 of these devices installed. A typical treatment facility is shown in Fig. 7. Because there are distinct medical advantages to treatment with heavy particles an ever-increasing number of facilities have been constructed and are, already, treating patients. Ion beams, up to carbon, are even more effective (i.e., less peripheral damage associated with killing a tumor) and facilities with ions are operating in Japan since 1994 and more recently in Europe.



Figure 7: The Varian Medical System for treating a patient with x-ray produced by a high-energy electron beam.

## National Security

As far as I know the first use of accelerators in National Defense was during WWII. The Americans had a betatron at Los Alamos to help in designing the first atomic bomb and the British used a betatron to X-Ray Nazi un-exploded bombs dropped on England. (It is interesting that the betatron, just after the war was converted into the very first demonstration of a synchrotron.) Also, of course, it was on the Berkeley 184 inch cyclotron that electromagnetic separation of uranium was developed. This then led to more than 1,000 Calutrons through which passed all the material used in the Hiroshima bomb.

In recent years, accelerators are still used to study nuclear bomb implosions as shown in Fig. 8. Of more pressing concern, is securing borders against terrorist actions. This has become a very large industry, with many companies producing scanners of many different types. See Fig 9.



Figure 8: The Dual Axis Radiological Hydrodynamics Test Facility (DARHT).



Figure 9: A rail cargo scanner.

## Energy and Environment

Accelerators are used just a bit in conventional energy production from fossil fuels; namely accelerated neutrons are employed in down-hole well logging. However the primary use of accelerators is in the nuclear production of energy.

The use in fission is still in the future. Nevertheless there has been considerable work, in many different countries, on accelerator driven reactors. Besides being safer, but still having many possible fault paths, the degree of burn up (percentage of uranium) can be larger, thorium can be used as a fuel (with many advantages) and, perhaps most importantly, waste isolation from the environment can be reduced from a few hundred thousand years to only a few hundred years. Nevertheless the idea is still at the concept stage.

In fusion the use of accelerators is very real. For many decades tokamak reactors have had neutral beam drivers. These injectors supply fuel and current for the fusion reactors. Neutral beam injectors are planned for ITER. The other approach to fusion is inertial fusion that requires a driver. A major effort involves the development and use of glass lasers, but there are other approaches such as krypton-fluoride lasers, or pulsed power or heavy ions. It is the later that is of particular interest to our community. One approach is the use of induction acceleration and an artist's view of how such a power plant would look is shown in Fig. 10.

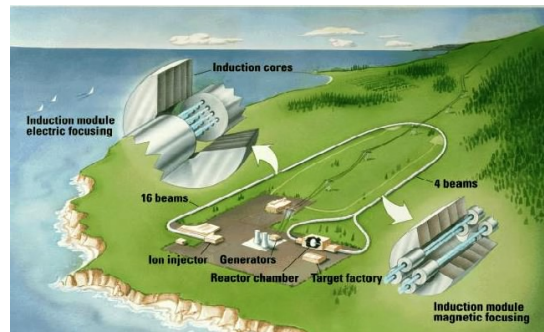


Figure 10: A conceptual view of a heavy ion inertial fusion power plant.

## Industrial Uses

The industrial production of accelerators is a large business (in the range of many B\$/year), but here I want to focus attention upon the use, in industry, of accelerators in the process of producing a commercial product rather than producing an accelerator. To be particular, accelerators are widely used for ion implantation, for electron cutting and welding, for sterilization, for isotope production, for non-destructive testing, and for treating material surfaces. In many of these applications a high current, low voltage (a few MeV) machines are employed.

Fig. 11 shows a facility employed for the coating of cables. Another need for accelerators is for the treating of shrink-wrap. Without accelerator treating we wouldn't have, the ubiquitous, shrink-

wrap. Other uses in industry include the hardening of auto tires, making of biologically compatible components for implantation in humans, and the treatment of material surfaces on furniture. The list goes on and on and one can expect ever-more industrial uses of accelerators.

Finally, in Fig. 12 is shown a very non-industrial use of accelerators. This application surely is surprising to some. I believe we can look forward to many other “surprising applications” in the future.



Figure 11: Electron beam cross-linking of polymers improves heat resistance of coatings for wires and cables.

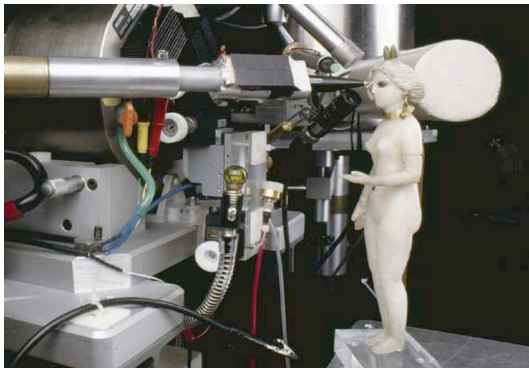


Figure 12: AGLAE, Accélérateur Grand Louvre d'Analyse Élémentaire in Paris, is an accelerator facility devoted to the study and investigation of works of art and archeological artifacts. The proton beam (4 MeV) probes: jewels, ceramics, glass, alloys, coins, statues, paintings and drawings.

## CONCLUSIONS

The variety and capability of accelerators has made them instrumental in a surprisingly large number of endeavors. Their use can be expected to ever-increase.

It is necessary, and possible, to ever-improve accelerators. Since the use of accelerators is broad, in contrast with what it once was (namely almost exclusively for nuclear and high-energy physics), the necessary R&D on accelerators must be supported either from a variety of sources (appropriate to their particular interest) or by one sponsor (but with an understanding of the broad applications of accelerators). In most countries this will require a change in administrative practices.

In the very-long-term accelerators will probably look very different than now they do. (They may, for example, be laser/plasma accelerators or collective accelerators.) It is important that support be given to these activities with the understanding that some will not work (“If we knew what we are doing, it wouldn’t be research.”), but some will revolutionize the field and open up possibilities we can’t even dream about.

## ACKNOWLEDGMENTS

To the tens of thousands of scientists, engineers, and technicians who, working over the last century, in a hundred different places and in about twenty-five different countries, who have made accelerators powerful, diverse, and so capable. Pictures, and the concepts and words that go with them, are from: “Engines of Discovery: Particle Accelerators at Work” by Andrew Sessler and Edmund Wilson, World Scientific, 2012.