Chapter 1

Introduction

1.1 History of particle accelerators

1.1.1 Early accelerators

The history of particle accelerators started around the 1870s when Crookes applied a potential difference between two electrodes in a vacuum tube: Cathode rays were observed and they would latter be identified as accelerated electrons [?]. Later Rutherford proposed to use α particles to probe the the inner structure of matter [?] and Geiger and Marsden carried out the experiment on a gold foil in 1908 [?]. For the first time a probe had been used to study subatomic matter. In 1917, by bombarding nitrogen with α particle Rutherford demonstrated that it was possible to transmute an atom by sending a high energy particles onto it [?, ?].

The next step was to find how to accelerate the probe to higher energies. In 1920 Wideröe proposed to use an alternating current in a coil to accelerate electrons by electromagnetic induction, however this was limited by the defocusing induced by the magnetic field. Instead he decided to use radiofrequence (RF) voltages and demonstrated that ions could be accelerated in such way [?]. This idea inspired Lawrence who decided to build a device in which the particles would still be accelerated by RF voltages but a large magnetic field would bend the particles in a circular trajectory between two accelerations. This device became known as a cyclotron and with such design Lawrence accelerated protons to an energy of 1.22 MeV in 1931. This earned him the Nobel Prize in Physics in 1939.

At the same time Cockcroft and Walton used a high voltage generator (now known as a Cockcroft-Walton generator) to accelerate protons up to an energy of 700 keV. With these protons they succeeded in transmuting lithium into helium [?, ?]. They received the Nobel Prize in Physics in 1951 for this work.

All these researches where halted by the outbreak of the second world war (WWII) but some of the technologies needed for accelerators were developed for other applications. For example, the generation of RF waves was boosted by the invention in 1937 of the klystron by the Varian brothers and by its development as a power source for radars during the war.

1.1.2 Accelerators after WWII

After the war significant efforts were devoted to research in Nuclear Physics and this relied heavily on accelerators. In France the research carried at the University of Paris needed more space to build larger devices and in 1956 they were relocated south of Paris, in the Orsay area, where a 1 GeV linear accelerator and a cyclotron were built. The Linear Accelerator Laboratory (*Laboratoire de l'Accélérateur Linéaire*, LAL) was created around this 1-GeV linear accelerator [**?**].

The European Organisation for Nuclear Research (CERN, formerly *Conseil Européen de la Recherche Nucléaire*) was founded in 1954 to pool european research in Nuclear Physics. Several proton accelerators and storage rings were built at CERN, including the Proton Synchrotron (1959) and the Intersecting Storage Ring (the first proton-proton collider, in 1971).

In 1960 Touschek proposed a ring device, AdA (*Anello di Accumulazione*, accumulation ring in italian) in which electrons and positrons could be injected with the aim of colliding them. In the first attempt, in Frascati, the linac did not deliver a sufficiently energetic beam to allow the production and storage of enough particles to allow the observation of collisions. AdA was then brought to LAL and tested with the LAL linac. These tests were successful and in 1964 the first electron-positron collisions were observed, opening a new era, the colliders era, in High Energy Physics (HEP) research.

AdA was soon followed by other colliders, VEP-1 (e^-e^- collider) and VEPP-2 (e^-e^+ collider) in Novosibirsk [**?**], the Princeton-Stanford storage ring experiment and, in Orsay, the Orsay Collider Ring (*Anneau de Collision d'Orsay*, ACO).

The next four decades would see a large number of lepton colliders built, the largest being the CERN's Large Electron Positron collider (LEP) that achieved a center-of-mass energy of more than 209 GeV, the highest center-of-mass energy achieved for e^-e^+ collisions to date.

All these progresses with accelerators and colliders have driven discoveries in Particle Physics and shaped our understanding of elementary Particle Physics, leading to several Nobel Prizes and a very accurate validation of the Standard Model of Particle Physics, culminating with the discovery of the Higgs boson in 2012.

Figure 1.1 gives a non-exhaustive list of colliders, their energy and operation dates, showing the tremendous progress made in the field over that past century (such plot is called a “Linvingston plot”). The trend has been to a fast increase of the centre-of-mass energy of the lepton colliders with the energy tripling every six years from 1960 until 1995. Fewer hadron colliders have been built because they are significantly more expensive, but for them it is possible to see that the energy was doubling every six years.

This increase in energy required the colliders’ circumference to increase even faster: as shown on figure 1.2 from 1963 to 1989 they doubled in size every two year, from 3 m to 27 km!

However, these trends required more and more construction time between two machines (and also more money) and it is now clear that the next generation colliders will not follow these trends, neither in energy nor in circumference[1]. This breakdown in the trend has led many scientists to say that at the energy frontier accelerator technology has probably reached its limit.

It is important to note that although higher energies open the door to discoveries in Particle Physics, it is not the only driver for discoveries. Lower energy machines such as KEKB and PEPII have also made important discoveries while being far from the energy frontier. In that case the discovery became possible because the accelerator operated with intense beam and therefore delivered a very high luminosity (the intensity frontier) allowing physicists to collect very large amounts of data.

1.2 Applications of accelerators beyond HEP

Although the development of the most impressive accelerators has been driven by High-Energy Physics, these accelerators are only a small fraction of the 17 000 accelerators operating worldwide and of the more than 650 in France[2].

As early as 1938 Lawrence, together with Chaikoff, decided to study how his cyclotron could be used for medical research. He showed that it could produce isotopes with therapeutic applications. After the war, in 1954, cyclotrons were also used to develop proton therapy (in which a beam of protons is used to kill a cancer tumor). Today cyclotrons producing medical isotopes can be purchased ”off-the-shelf” from specialized companies. There are about 60 proton therapy facilities in the world, the main limitation to their development being their cost. They use a proton beam of a few hundred MeV.

Radiotherapy offers a cheaper alternative to proton therapy. It uses a short linac (about 1 m) to accelerate electrons to about 20 MeV and send them on a tungsten target where

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[1] If the 100-km circumference Future Circular Collider (FCC) currently being designed, is built before 2032 with at least 50 TeV per beam it will still follow the trend for hadron colliders’ energy but not for circumference.

[2] In the case of electron accelerators we do not consider cathode ray tubes such as old television sets but only accelerators where the particles reach an energy of at least 1 MeV.

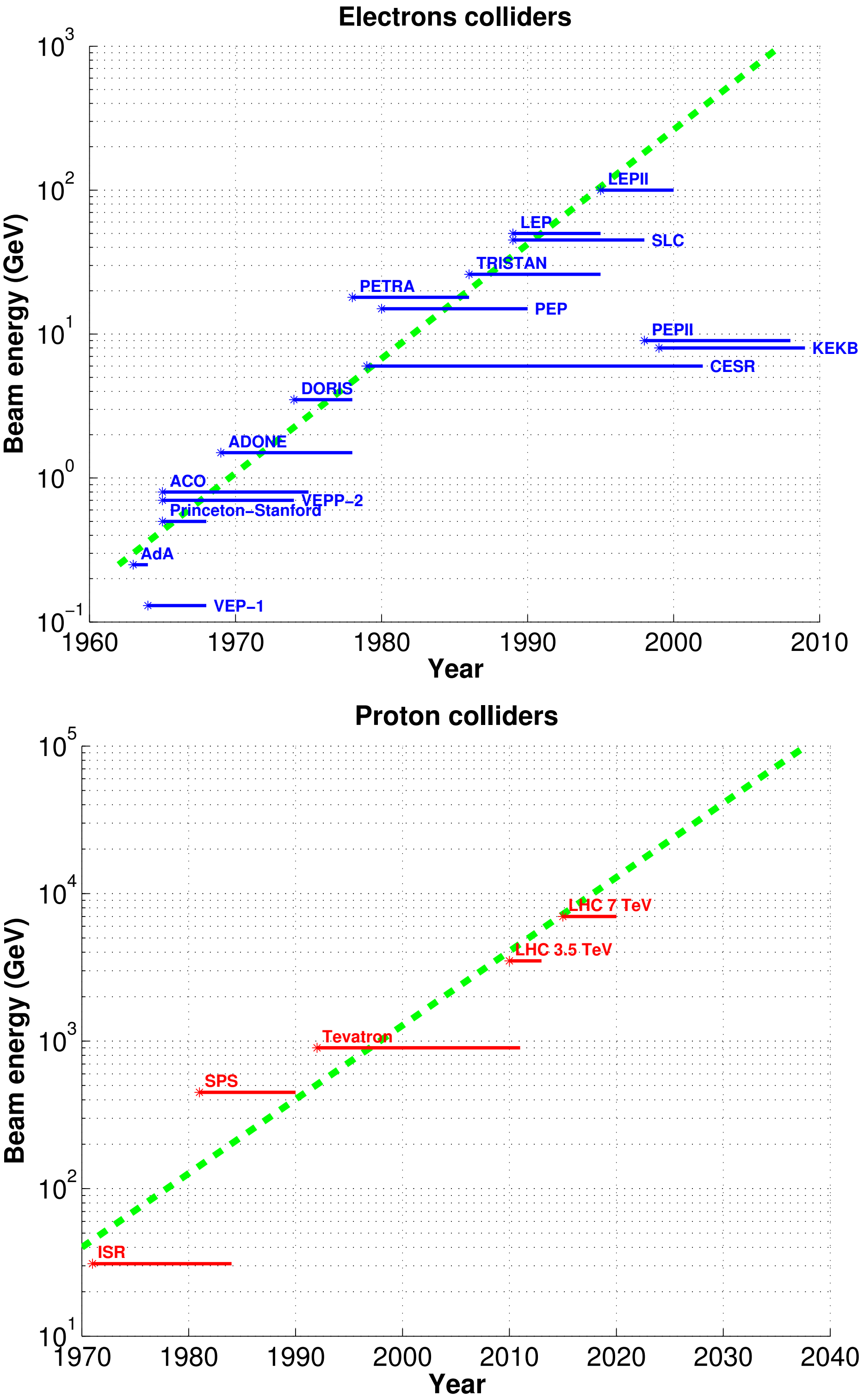

Figure 1.1: Non-exhaustive chart showing the energy of colliders versus their operating years. The upper plot is for electron-positron (or electron-electron) colliders, the lower plot is for hadron colliders. The green lines gives a possible trend (energy tripling every six years for lepton colliders, energy doubling every six years for hadron colliders). The planned ILC, a 1 TeV electron-positron collider, will not follow that trend as it was not operational by 2010 and to follow the protons' colliders trend the FCC, a 50 TeV proton collider, should be operational by 2032.

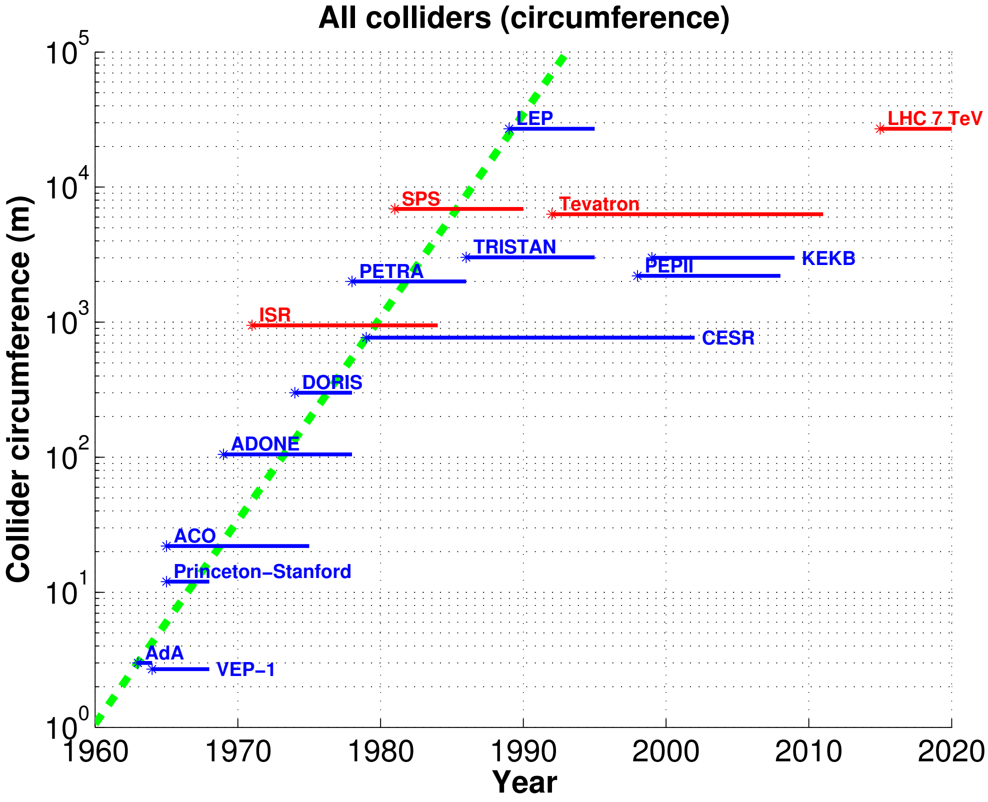

Figure 1.2: Non-exhaustive chart showing the circumference of colliders versus their operating years. Lepton colliders are in blue and hadron colliders are in red. The green line gives a possible trend (circumference doubling every two years). To follow this trend colliders reaching 100 km should have been operational before year 2000, which was not the case.

they produce X-rays. There are several thousands radiotherapy accelerators installed worldwide (and about 600 in France).

When charged particles are accelerated (longitudinally or radially) they emit radiation. When the acceleration occurs radially it is called “Synchrotron radiation”. Such radiation was first observed in 1946. It is potentially very bright and can reach wavelengths that can hardly be reached by other means, giving it a large number of applications in material science, chemistry and biology. It can, for example, be used to determine the elemental composition of a sample, its crystalline structure or the presence of structural defects. Synchrotron radiation light sources typically use a storage ring with a beam of a few GeV electrons. There are about fifty storage rings used as synchrotron radiation light sources installed in the world, including two in France, one near Orsay called “Synchrotron SOLEIL” and one in Grenoble called ESRF (*European Synchrotron Radiation Facility*) [**?**].

The production of synchrotron radiation can be significantly enhanced by stimulated emission creating a Free Electron Laser (FEL). There are more than a dozen FEL in operation in the world. Unlike storage ring based synchrotron radiation light sources, FEL typically use only a linac to accelerate the electrons. Depending on the wavelength to be reached the length of this linac can be a few tens meters (for infrared) to several kilometers (for hard X-rays). In Orsay there is one FEL called CLIO (*Centre Laser Infrarouge d'Orsay*). It was built jointly by LAL and another laboratory called LURE.

High energy protons sent on a neutron rich nucleus will trigger a process called spallation during which several neutrons are emitted. These neutrons can penetrate deeply in matter and can be used to probe the proton density of a sample. There are about half a dozen spallation sources operating in the world. In addition the neutrons produced during spallation can be used to trigger nuclear reactions in fissile materials. This property is being used in Accelerator Driven Systems (ADS), a new kind of nuclear reactors where the chain reaction is subcritical and the extra neutrons needed to sustain the reactor operations are brought by spallation from an accelerator. ADS are still in the design phase, but they are seen as a possible solution to burn nuclear waste.

Accelerator based on Van de Graaff generator with a charge exchange mechanism in the high voltage terminal are called “Tandem”. They are still heavily used for research in Nuclear Physics, but also in a variety of other domains such as radiocarbon dating (as done by the LMC14 near Orsay), sample analysis or even to study old artefacts as is done by the AGLAE accelerator under the Louvres museum in Paris.

All these applications mean that there is a market for turn-key accelerators and most of the accelerators installed worldwide have been built by the industry. Most of the accelerator R&D today is focussed on improving accelerators for HEP, Nuclear Physics and light sources.

1.3 Accelerators today and state of the art

The largest accelerator today, both in size and in energy per particle is the Large Hadron Collider (LHC) located near Geneva. In proton-proton collisions mode it accelerates beam to 6.5 TeV (to be upgraded to 7 TeV) and in ion-ion collision mode it accelerates $^{208}Pb^{82+}$ ions up to an energy of 2.8 TeV per nucleon. To minimize its power consumption it operates using superconducting accelerating cavities and superconducting magnets. The LHC has replaced the Large Electron-Positron collider (LEP) that was the largest electron-positron collider in the world with an energy of more than 100 GeV per beam. The LEP had superconducting accelerating cavities but normal conducting magnets. Its energy per beam was limited by the loss due to the emission of synchrotron radiation in each bend of the accelerator.

After the shutdown of LEP and another lepton collider of slightly lower energy at SLAC (Stanford Linear Accelerator Center), the SLAC Linear Collider (SLC), the highest energy available for an electron-positron collider decreased significantly with the B factories (PEPII and KEKB) being the highest energy accelerator (asymmetric collisions of 9 GeV electrons on 3.1 GeV positrons for PEPII and 8 GeV electrons on 3.5 GeV positrons for KEKB). This drop in energy can be explained by the large size and power consumption required to build a lepton collider with an energy of the order of 100 GeV per beam or more. PEPII and KEKB have now been shutdown and replaced by SuperKEKB in Japan.

To prepare the next generation colliders several test facilities have being built across the world, focussing on some of the R&D steps required to build the next collider. Among them, I worked at the Accelerator Test Facilty (ATF) at KEK that uses a 1.3 GeV ring and aimed to demonstrate the damping of the beam for a warm technology collider. The ATF has been upgraded into the ATF2 that aims to solve issues related to the beam focussing at the interaction point and to associated instrumentation.

I also performed experiments at the Facility for Advanced aCcelerators Experimental Tests (FACET) at SLAC. It uses two third of the SLC linac to provide experimenters with a 20 GeV electron beam to study beam driven plasma acceleration and the associated diagnostics.

I also participated in experiments at two tests facilities at the Frascati National Laboratory (LNF): the Beam Test Facility (BTF), a 500 MeV extraction from the LNF linac and SPARC (*Sorgente Pulsata Auto-amplificata di Radiazione Coerente*, Pulsed and Self-Amplified Radiation Source) which is made of a linac delivering a 200 MeV electron beam.

Apart from the LHC, high energy ions collisions can also be obtained a the Relativistic Heavy Ions Collider (RHIC) located at Brookhaven and that can deliver beams of a large number of ions species with energies between 3.85 GeV and 100 GeV per nucleon. In France heavy ions can also be studied (but not collided) at the GANIL (*Grand*

Accélérateur National d'Ions Lourds, National Large Accelerator of Heavy Ions) and its newest facility, SPIRAL2 (*Système de Production d'Ions Radioactifs Accélérés en Ligne*, Production Facility for Radioactive Ions Accelerated Inline).

1.4 Future Accelerators

Progress in HEP and Nuclear Physics will require more powerful accelerators. The next generation of accelerators is likely to be conventional, but advanced concept or completely new designs need to be studied for the long term.

1.4.1 Conventional accelerators

The LHC is working well and has already made impressive discoveries but further discoveries will require more and more data[3]. Once a sufficient amount of data will have been collected in the present configuration, upgrades will be required (luminosity and possibly energy)[4]. At the moment there is no machine approved and funded to extend the physics reach beyond the LHC. The two main contenders are the International Linear Collider (ILC) and the Future Circular Collider (FCC).

The ILC would be a linac with a length of up to 40 km using superconducting accelerating cavities to accelerate electrons and positrons up to an energy of 250 GeV, 500 GeV or 1 TeV (depending on the results of LHC's run 2). The use of a linac has the advantage of minimizing the energy loss due to synchrotron radiation, but it requires fresh particles to be produced and accelerated for each collision. The most likely location to build it would be Japan. One of the key element for the ILC is the gradient that can be achieved in the superconducting accelerating cavities. This gradient is limited by several factors. At high fields the cavity may suddenly loose its superconducting behavior and ”quench” (return to a normal conducting behavior). There may also be irregularities on the metallic surfaces which will trigger breakdowns at high fields. Most of these problems can be addressed by conditioning the cavities but there will still be a maximum accelerating field that can be achieved for any given cavity. The lower the electromagnetic wavelength the higher the maximum field will be. For L-band (1.3 GHz) superconducting cavities for the ILC the design gradient is about 35 MV/m whereas for X-band (12 GHz) normal conducting cavities gradients beyond 100 MV/m have been achieved. Despite a lower gradient superconducting cavities have been chosen for the ILC as their power consumption is much lower. A linear collider based on warm X-band cavities is also being studied under the name Compact LInear Collider (CLIC).

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[3] For most studies the discovery potential evolves with the square root of the amount of data collected, so doubling the amount of data collected increases only the discovery potential by a factor 1.4.

[4] The High Luminosity LHC (HL-LHC) is already approved and due to start beyond 2025.

The FCC would be a ring with a circumference of 100 km. It is foreseen as a machine that would first collide leptons (FCC-ee) with 45 GeV to 200 GeV per beam and then protons (FCC-hh) with about 50 TeV per beam. In both cases the machine will use superconducting accelerating cavities and the FCC-hh will also use superconducting magnet. It is proposed to built it near CERN. There is also a Chinese project similar to FCC-ee called CEPC-SPPC.

One of the key features of future colliders is that they will have to use cold (superconducting) technology that is much more efficient than warm technology. This choice is less obvious with smaller accelerators as the cost and complexity overhead of an helium cooling plant are not always offset by the power gain.

1.4.2 Energy Recovery Linacs

A key advantage of a ring-based collider over a linac is that particles can be recycled a large number of times and they are therefore more efficient. However rings have their own limitations such as a limited size at the focal point to avoid disruptive beam-beam effect and the emittance increase due to collective effects. For synchrotron radiation sources rings have the drawback of producing longer particle bunches as they fill their RF bucket and therefore the light pulse produced are also longer (typically several picoseconds).

A design to combine the advantages of both has been proposed under the name “Energy Recovery Linac” (ERL) [**?**]. In an ERL the particles travel in a closed orbit but after one turn they arrive 180° out of phase in the accelerating cavity and are therefore decelerated. Their energy is transferred back as electromagnetic waves in the cavity and a fresh bunch of particles is injected just behind. This fresh bunch will therefore be accelerated by the energy deposited by the previous bunch. This design has been seen as very promising for FELs but designs of colliders using the ERL principle start to be discussed [**?**].

1.4.3 Plasma Accelerators

As discussed above conventional accelerating cavities are limited by RF breakdown and the risk of loosing superconductivity at high gradients. One solution to achieve higher accelerating gradients is to use the ponderomotive force created by a beam in a plasma. Such driver beam can be either a laser pulse or a bunch of charged particles.

The acceleration mechanism in plasma acceleration will be discussed in section **??** (page **??**).

Laser driven plasma acceleration

Electrons Laser driven plasma acceleration of electrons has been proposed by Tajima and Dawson in 1979 [?]. This acceleration occurs when a high power (at least several tens of TeraWatt) ultra-short (< 50 fs) laser pulse is sent in a low pressure gas volume (either a gas jet or gas confined in a capillary or cell). The laser field ionises the gas, creating a plasma in which a very intense electromagnetic wave propagates and accelerates electrons. The electrons can either be injected externally (from a conventional injector) or be taken from the plasma (this is called self-injection). The most impressive results so far have been obtained with self-injection but this require sufficient laser intensity to create wave-breaking in the plasma that will trap the electrons.

The first demonstration of laser-driven plasma acceleration was obtained by the UCLA group in 1994 [?] when they accelerated an externally injected beam of 2.1 MeV to 9.1 MeV. Another early result was obtained in France in 1998, also with external injection and an electron beam energy gain of 1.6 MeV [?]. A significant breakthrough was made in 2004 when "quasi-monoenergetic" beams of about 100 MeV [?, ?, ?] and two years later a GeV beam was produced [?]. More recently beams of more than 4 GeV have been demonstrated [?] and higher energies have been reported during conferences. These results use the so called "bubble regime" in which the laser pulse is so intense that it creates a region behind it that is fully depleted from plasma electrons. It is in this region that some electrons are captured and accelerated.

A detailed review of developments in laser-driven plasma accelerators can be found in [?] and the energy reached by some of these experiments as function of the year is shown on figure 1.3.

The impressive results obtained in the bubble regime had overshadowed other regimes of acceleration. However in the past few years there has been renewed interest for other scheme such as the quasi-linear regime with external injection. In this regime the laser pulse is not intense enough to trigger self-injection and therefore the electrons have to be injected externally. Several experiments using externally injected electrons from a conventional accelerator have been proposed recently (FLAME at Frascati [?], REGAE and SINBAD [?] at DESY, ESCULAP at LAL [?])

This regime can also be used to reach higher energies by adding several acceleration stages one after the other. The first experimental tests of this technique have been published recently [?].

Although large energies have been reached, the beam stability is not as good as it is in conventional accelerators and therefore significant research is still needed before these accelerators can be used as colliders or even as drivers for a FEL. The charge accelerated are also rather small (1 pC to 10 pC). A design for a laser-plasma linear collider has nevertheless been proposed [?].

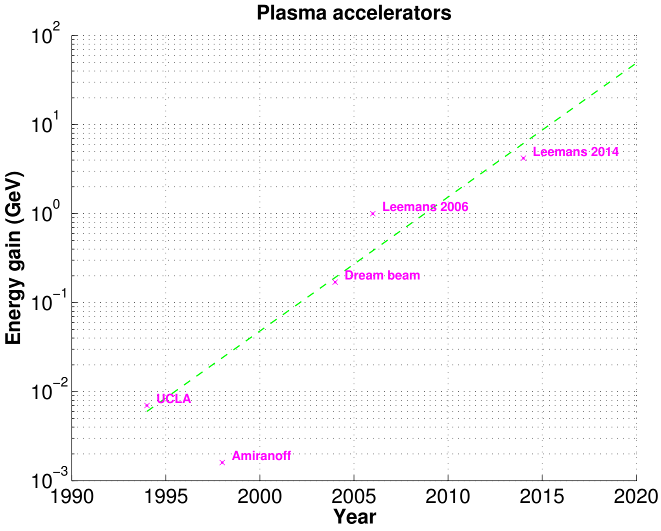

Figure 1.3: Non-exhaustive chart showing the electron energy reached in laser-driven plasma acceleration experiments versus the experiment year. The green line corresponds to an energy doubling every two years. It is important to stress that the data from this figure show the maximum energy reached, not the energy at which a stable beam was produced, as in figure 1.1, therefore the two figures cannot be compared directly.

Ions High-power, ultra-short laser pulses can also be used to accelerate ions. The laser pulse has to be sent on a thin solid target and the acceleration mechanism is different, it is called Target Normal Sheath Acceleration (TNSA). According to TNSA, when the laser pulse hits the target its energy is transferred to the electrons of the target. These electrons then propagates in the target and exit it. As they exit the electrons pull out some protons and ions with them and give them some of their energy. Proton beams of 58 MeV [**?**] have been reported with a very broad energy spectrum. This is much less than what was reported for electrons but still very promising. A detailed review of laser-driven ion acceleration can be found in [**?**].

Beam driven plasma acceleration

The energy required to create the accelerating field in the plasma can also be taken from a bunch of charged particles. SLAC has performed several experiments demonstrating this possibility. In 2007 an experiment at the Final Focus Test Beam (FFTB) reported energy doubling of a few electrons from a 42 GeV beam [**?**]. More recently FACET at SLAC has seen several progress in that area: acceleration of a higher charge using 2 separate bunches [**?**], acceleration of positrons [**?**],... However here the energy gain is strongly dependent on the energy of the drive beam. A similar experiment at much lower energy is being planned at SPARC_LAB in Frascati [**?**].

Another limitation of electron driven plasma acceleration is that the energy gained by one electron has to be taken from another electron that is decelerated by the same amount. To overcome this limitation the AWAKE collaboration [?] proposes to use a proton beam extracted from the SPS at CERN and use it to accelerate electrons. Their simulations show that they could accelerate the electrons to several hundred GeVs. They have recently reported during conferences significant progress toward this goal [?].

Dielectric acceleration

Another technique to transfer energy from a high power laser to a beam uses a dielectric insulator. In the case it is directly the electromagnetic field of the optical waves that creates the accelerating field. In such accelerators the electrons are naturally bunched at the optical wavelength [?]. Although the gradients achieved so far are lower than in plasma acceleration this technique offers the possibility of miniaturisation of the accelerator with gradients still higher than with a conventional accelerator. In some case a dielectric material can be used to replace the plasma in beam driven plasma acceleration. Given the small size of such accelerators which could be realized almost entirely on a silicium chip, this is sometimes dubbed “accelerator-on-a-chip”.

1.5 Diagnostics for accelerators

The operation of accelerators would not be possible without diagnostics giving real time information to the operator on the status of the beam inside the accelerator. Diagnostics use either the fact that charged particles radiates a field (or emit radiation) while travelling or that they deposit energy when interacting with matter. Diagnostics relying on the radiating field include Beam Position Monitor (BPMs), Beam Current Monitors but also more advanced diagnostics such as transition radiation monitors or Smith-Purcell monitors. They usually do not interfere much with the beam. Diagnostics that required energy to be deposited often destroy the beam. They include Faraday cups, wire-scanners and fluorescent screens.

Some beam parameters can be difficult to measure and will require some beam preparation before their measurement. The most common example is the measurement of the beam energy that requires first the beam to be deflected with a spectrometer magnet of known field before its position can be measured with a screen or a BPM. Deflecting cavities and pepper-pots are part of this category.

A significant part of my career has been devoted to developing new diagnostics that allow measurement in cases where other diagnostics would fail either because the beam is too intense (for example in the case of laser-wire discussed in chapter **??**) or because it is not stable enough (for example with high-energy pepper-pots discussed in chapter **??** or Smith-Purcell monitor, chapter **??**).

Before being used in new facilities these diagnostics had to be tested at conventional accelerators with known characteristics. I have had the pleasure to use several accelerators for that purpose: the Accelerator Test Facility at KEK, the Beam Test Facility at INFN Frascati, the booster to main ring line at the DIAMOND synchrotron, the linac at the SOLEIL synchrotron, the LINAC2 at CERN, FACET at SLAC, the diagnostic line at SPARC at INFN Frascati and the CLIO Linac. Each accelerator has its own specificities as far as beam characteristics are concerned but also the procedures to install a new equipment, vacuum procedures, safety procedures,... This makes each test a new adventure.

1.6 Lasers

Several of the projects I have worked on involved lasers and it is therefore useful to discuss recent progress with lasers and their applications to particle accelerators.

1.6.1 Recent progress with Lasers

Since the first experimental realization of a laser (acronym for Light Amplification by Stimulated Emission of Radiation) in 1960 the development of lasers has been very fast. In a laser, atoms from a suitable medium are pumped to a higher energy level so that a population inversion is created. The spontaneous emission of a photon by one of these atoms will provoke massive stimulated emission by the other atoms of the amplification medium. Mirrors are often used to form a cavity in which the photons recirculate, increasing the photon yield at each pass. Damage in the amplification medium limits the maximum power that can be reached in a laser. Until the 1980's this prevented the production of short pulses since in such pulses the power can be very large. This changed after the demonstration of chirped pulse amplification (CPA) in which a laser pulse is stretched by a grating before being amplified and then recompressed.

The spread of CPA has led to high-power ultra-short laser pulses such as those used in laser-plasma acceleration. Today terawatt lasers producing sub-picoseconds pulses are not restricted to laser laboratories but can be purchased commercially and leading manufacturers (including at least two french companies) are not afraid of offering for sale petawatt class laser (however the price is of the order of several million euros making it a not-so-common purchase). These high-power lasers typically use titane sapphire (Ti:Sa) as amplification medium as it has a wide amplification bandwidth, which is important for CPA. Although they can be purchased commercially, it is important to note that, like accelerators, such lasers require significant maintenance to operate them on a daily basis and very few of them are designed to operate round-the-clock like an accelerator.

The availability of petawatt class lasers at an affordable cost has led to progress in physics and in particular in laser-plasma acceleration. In the UK I have had the opportunity to work on the ASTRA-Gemini petawatt laser just after its commissioning. In France I have had the opportunity to do research both on Laserix and UHI-100, which are two laser from the hundred-TW class.

The laser community is now working on more ambitious lasers with a target power of about 10 PW per beam. This is the aim of the APOLLON laser currently being developed near Orsay, but also of the ELI-NP laser to be installed in Magurele (Romania).

For applications that do not require ultra-short pulses but only picosecond pulses, other amplification materials than Ti:Sa are available. Nd:YAG (neodymium-dopped yttrium aluminum garnet, $Nd : Y_3Al_5O_{12}$) and Nd:YLD (neodymium-dopped yttrium lithium fluoride) offer better efficiency and are easier to pump (but they have a much narrower amplification bandwidth).

The telecom industry has made an extensive use of laser to transport information over long distances. This has led to the development of erbium-doped fibers lasers. Fiber lasers have the advantage of producing radiation that is already in a fiber and therefore it does not have to be coupled in a fiber (an operation that is always source of losses). The beam quality in a fiber is usually much better than in solid-state lasers and because all elements of the laser are spliced together there is no risk of misalignment. As the fiber has a large outer surface heat load management is also easier.

The advantages of Erbium-doped fiber lasers have encouraged research in other amplification media, leading to the apparition among others of Ytterbium-doped fiber lasers. Ytterbium is much more resistant to high power than Erbium and this has led to the development of high-power fiber lasers. This power yield has been increased further by specially designed fiber components that allow chirping (and de-chirping) of these narrow band laser pulses, allowing CPA with fiber lasers. The high quality of the beam produced by these lasers has also made them a good choice as seed oscillators for high power amplification. Two experiments on which I worked, Laser-Wire and MightyLasers, used fibers lasers as oscillator and in the case of MightyLaser the full laser chain was made of fibers.

1.6.2 Applications of Lasers in Accelerators

Lasers can enhance the performances of accelerators in several ways. At the source of an electron accelerator, a laser can be used to produce the electrons by photoelectric effect instead of thermionic effect. This has the advantage of producing a bunch of electrons with a lower emittance and allows the production of pulses shorter than can be achieved with a pre-buncher and a buncher. This mechanism is used in several photo-injectors around the world, including PHIL at LAL. In the case of ion sources, a laser can be used to selectively ionise one atom to a desired charge state with a better efficiency than with other mechanism. Resonant Ionization Laser Ion Source (RILIS) is a common method to produce radioactive ions and it used in several facilities such as ISOLDE at CERN , ISAC at TRIUMF, REGLIS at SPIRAL2 and at IPN Orsay in the RIALTO line.

Further down the accelerator, the alignement of the components is important to preserve the emittance along the linac. Laser based alignement techniques are now a common procedure in almost all accelerators.

Compton scattering of laser photons on the electrons (or ions) of the accelerator, can be used either as a diagnostics (as is done in the Laser-Wire project) or as a source of intense X-rays or gamma-rays (as is done in the MightyLaser, ThomX and ELI-NP-GS projects).

1.7 Undefined references

chap:plasmaAccelerationMecanism chap:laser-wire chap:pepper-pot chap:SP laser-synch

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