FUTURE ACCELERATORS, MUON COLLIDERS, AND NEUTRINO FACTORIES

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1 Introduction

Particle physics is driven by five great topics. Neutrino oscillations and masses are now at the fore. The standard model with extensions to supersymmetry and a Higgs to generate mass explains much of the field. The origins of CP violation are not understood. The possibility of extra dimensions has raised tantalizing new questions. A fifth topic lurking in the background is the possibility of something totally different. Many of the questions raised by these topics require powerful new accelerators. It is not an overstatement to say that for some of the issues, the accelerator is almost the experiment. Indeed some of the questions require machines beyond our present capability.

As this volume attests, there are parts of the particle physics program that have been significantly advanced without the use of accelerators such as the subject of neutrino oscillations and many aspects of the particle-cosmology interface. At this stage in the development of physics, both approaches are needed and important.

This chapter first reviews the status of the great accelerator facilities now in operation or coming on within the decade. Next, midrange possibilities are discussed including linear colliders with the adjunct possibility of gamma-gamma colliders, muon colliders, with precursor neutrino factories, and very large hadron colliders. Finally visionary possibilities are considered including plasma and laser accelerators.

2 Now and the immediate future

The upgraded Fermilab Tevatron started operation in the spring of 2001. The machine now operates with 36 colliding bunches rather than the 6 bunches used in the past. This has been made possible by the new Main Injector which takes the pre-Tevatron accelerator out of the Tevatron tunnel. This move also reduces backgrounds at the collider detectors. The Tevatron energy has been pushed closer to 1 TeV by lowering the magnet temperature and by selecting and rearranging magnets. The integrated luminosity goal for the first 2 years of running is 2 fb^{-1} with a peak luminosity up to $2x10^{32}$ $cm^{-2}s^{-1}$. At some point the machine will switch to 103 bunch operation. A second four year running period is planned with the luminosity ranging up to $5x10^{32}$ $cm^{-2}s^{-1}$. This could produce a total integrated luminosity of 15 fb^{-1}. With this luminosity there is a fair opportunity to discover supersymmetry and a low mass Higgs.

The Fermilab Tevatron is shown schematically in Figure 1. The complex is a bestiary of different types of accelerators. The venerable Cockcroft-Walton accelerates protons (actually negative hydrogen ions) in a DC electrical field. The linac uses a series of RF cavities to accelerate them up to 400 MeV. From there the hydrogen ions are stripped and the protons injected into the Booster. The Booster is an aging rapid-cycling, combined-function accelerator. From the Booster the protons travel to the new Main Injector where they are accelerated to 150 GeV. Main Injector protons are used to make antiprotons and feed protons and antiprotons to the Tevatron.

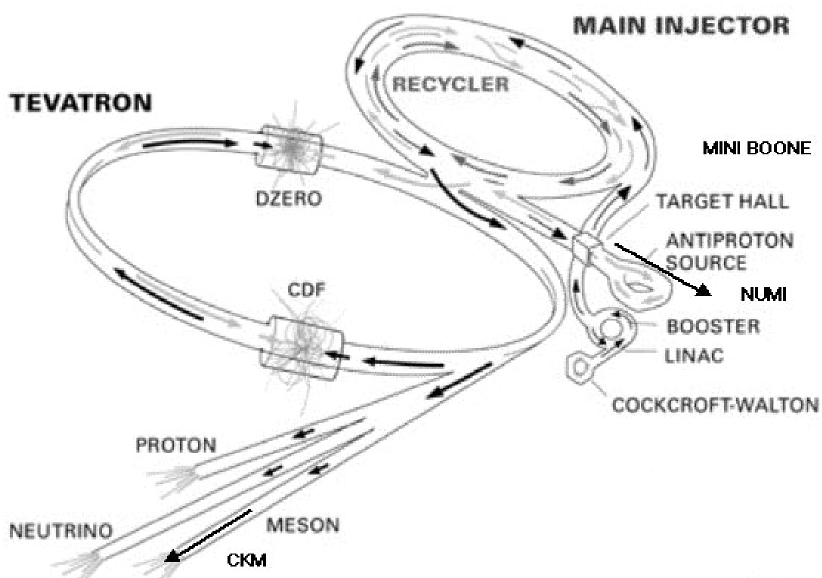

Figure 1: Tevatron schematic.

The antiprotons are accumulated in three storage rings, first the debuncher, then the accumulator. Together these two rings are the antiproton source shown in the figure. Post store antiprotons can be saved in the new Recycler in the Main Injector tunnel. The core parts of the physics program, the collider experiments, are located in the

Tevatron tunnel. The collider detectors, CDF and D0, have been completely re-equipped to take care of the higher rates. The Main Injector protons will also be used to support a fixed target program including kaon and neutrino physics. One part of the program, NuMI (Neutrinos at the Main Injector) is particularly interesting to the non-accelerator particle astrophysics community. NuMI will send a neutrino beam 735 km to a large, underground detector located at Soudan in Minnesota. A second lower energy neutrino experiment, MiniBooNE will soon be underway. The MiniBooNE neutrino beam is fed by protons from the Booster.

Mid-decade the new Large Hadron Collider (LHC) will come into operation at CERN in the old LEP tunnel. The LHC beam energy will be 7 TeV, 7 times the Tevatron. The peak luminosity will be 10^{34} $cm^{-2}s^{-1}$ or 20 times the peak luminosity at the Tevatron. Many brands of SUSY and the Higgs should be observable there. The LHC is truly a marvelous accelerator. In fact, its existence raises the bar for future projects since they must be able to probe beyond the range of the LHC. This will be no easy challenge.

Figure 2 shows a cross section of the superconducting LHC dipole. It is a very complicated device. The magnet has a two-in-one geometry. Both of the counter-rotating beams are contained in one magnet structure. The coils need state of the art wire to achieve the high fields that are required. Non-magnetic collars are used to hold the coils in place. An iron yoke, outside the collars contains and boosts the fields. Outside that is a 1.9 ˚K cryogenic system for the superconductors.

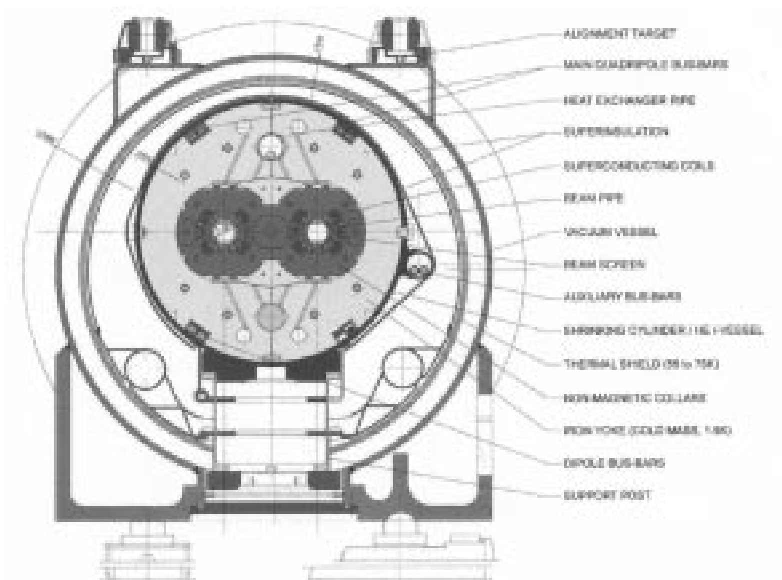

Figure 2: LHC magnet cross section.

As of June, 2001 CERN reported that almost 60% of the magnet system was under contract and the project was on schedule. In the fall of 2001 concerns developed about cost overruns. Two large colliding detectors are also under construction. Parenthetically, CERN is also building a neutrino beam to Gran Sasso using the older SPS accelerator.

The sophisticated ensembles of machines at CERN and Fermilab represent the highest state of accelerator science and art. (The textbook by Edwards and Syphers [1] and the Tigner-Chao handbook [2] contain useful information on accelerator science and engineering.) These accelerators rely on a number of individual components and systems. A breakthrough in any one of the areas could result in an important advance in the field. Characteristically a large accelerator system requires an ion source (antiproton accumulators and positron sources are special cases of ion sources). In some cases these may provide polarized beams. The Cockcroft-Walton is the Fermilab ion source. The particles must be accelerated. In most cases this is done with radio frequency (RF) cavities. Linacs are just a series of RF cavities strung together. Conventional cavities (including superconducting models) can reach accelerating gradients of 50-100 MeV/m. A breakthrough here would be important but unexpected. Bending magnets are required for circular machines. These are now limited by the available superconductors to peak fields on the order of 10 Tesla. A breakthrough in this area could have a profound impact but might be hampered by material strength. Focusing must be provided in addition to bending. Focusing is particularly important near colliding beam points where the beam must be as small as possible. Again the technology has been pushed to the edge. The larger process of colliding the beams is also a key to operation. Finally, an accelerator needs an enclosure. Planned accelerators typically have tunnels extending tens of kilometers. At least in the US, this represents a real practical problem because the accelerator must go below many homes and businesses. The development of future accelerator systems requires progress on all these fronts. In addition cost minimization is extremely important.

3 The next decade (2010-2019)

Looking beyond the LHC three interesting possibilities for accelerators have emerged. At the top of the list is the linear collider, colliding beams of electrons and positrons. A second possibility is the so-called muon collider. This is like an electron-positron collider in principle but the practical realization is completely different. Third is a logical extension of the LHC, the obviously-named, Very Large Hadron Collider or VLHC. The electron-positron collider can also be operated as a gamma-gamma collider. The muons needed for a muon collider can also be used to make a neutrino factory.

Each of these three possibilities has its physics advocates. Higgs signatures on the linear collider are clean. Indeed, CERN's LEP (an e^+e^- collider but not a linear collider) saw some evidence of a Higgs signature that was later discounted [3]. On the other hand the cross section for Higgs production on a muon collider goes as $(m_\mu/m_e)^2$ so that all other things being equal the production rate would be 40,000 times larger on a muon collider. Physics advocates for a very large hadron collider argue that it is the natural extension of the LHC.

At present ideas for the linear colliders are closest to execution. It seems possible that a project will get underway somewhere in the next 2-4 years. A muon collider is challenging. More likely is that a precursor muon factory will be tried. A VLHC is straightforward but very costly. There is also concern about starting a VLHC before early LHC results are in.

3.1 Linear colliders

The ultimate requirement for e^+e^- colliders to be linear machines rather than circular machines has been understood for many years [4]. This arises because synchrotron radiation in a circular machine rises rapidly with increasing energy. The first and only linear collider built so far was the Stanford Linear Collider (SLC) at SLAC. This 50 on 50 GeV collider came into full operation after LEP. It was a challenging machine to build because of the very small beam sizes required at the collision point to achieve useful luminosity. In one way SLC was better than the circular e^+e^- LEP at CERN because it could use polarized electrons. If there had been no LEP, SLC would have been considered a spectacular success.

To be useful for new physics the total energy of a linear collider must be in the 500-1000 GeV range and the luminosity must be $O(10^{34}\ /\mathrm{cm}^2\mathrm{s})$. Achieving this luminosity requires extremely high beam power and small beam cross sections. These are conflicting requirements which must be solved by the designs. Even with high luminosity, some are skeptical of a linear collider's ability to do frontier physics [5]. Butler [6] has looked at whether a linear collider will have enough integrated luminosity to address a full physics program. He divides the operation into three modes; "sit" (on one energy), "span" (operate at the full energy), and "scan" (look for thresholds). He concludes that a full program can be carried out. With 300 fb^{-1} integrated luminosity a 250 fb cross section will give on the order of 75K Higgs bosons in a year's running.

Four groups are pursuing linear collider designs. Japan (JLC [7]) and SLAC (NLC [8]) have been working on warm RF cavity designs operating at 11.3 GHz. DESY has a superconducting project called TESLA. It would operate at a frequency of 1.3 GHz. DESY completed the design report for TESLA in the spring of 2001 [9]. The most ambitious linear collider project is the Compact Linear Collider or CLIC [10] project at CERN. This is a so-called two-beam accelerator where an intense beam in one accelerator drives the 33 GHZ RF system in the second accelerator. This arrangement can produce an extremely high accelerating gradient but requires four linear accelerators rather than two. A prototype has been operated and has accelerated a probe beam by 60 MeV [11]. The CLIC approach is often

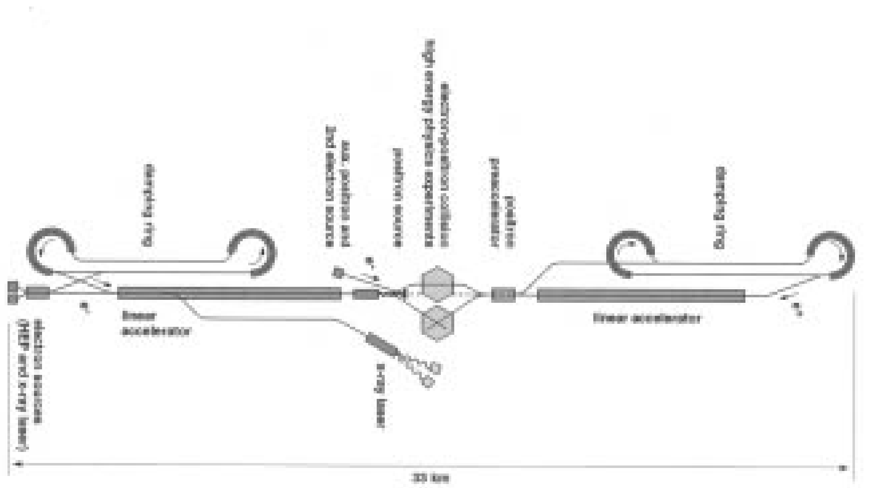

Figure 3-TESLA layout.

suggested as an upgrade path for an initial linear collider. The question of which if any of these linear collider facilities will be built is perhaps the most pressing open program topic in high energy physics.

The footprint for TESLA is shown in Figure 3. The complex is 33 kM long. At present the RF gradient is about 25 MV/m. DESY hopes that future developments such as electro-polishing will increase the gradient. Damping rings are required to achieve the small emittance. The so-called dog bone damping rings in TESLA are more extensive than the NLC rings because of the longer pulse trains possible with the superconducting RF. The straight sections of the rings are contained in the main linac tunnel. The damping rings also require wigglers to cut the damping time. Recent developments of flat beams at the Fermilab A0 test facility may moderate the requirements for the electron damping ring [12]. In general TESLA beam cross section and stability requirements are less challenging than for NLC and JLC because of the lower RF frequency.

The footprint for NLC is about the same as TESLA. The warm NLC RF system would be able to deliver 50 MV/m. Some people argue that warm RF systems are better understood than superconducting ones. Several sites for NLC have been suggested including locations in Illinois and California. It is estimated that 2 years more of R&D are required to prepare a design report for NLC.

Another interesting possibility available with a linear collider is to construct a gamma-gamma collider. One physics channel this could study is the partial decay width of the Higgs into $\lambda\lambda$. High energy gamma rays are produced by Compton backscattering (Figure 4), that is by colliding the electron beam with an intense laser beam. The eλ collision produces a spectrum of high energy gamma rays with a peak energy of 0.8 of the electron energy moving in a cone with an angle 1/λ in the direction of the initial electron. About 10^9 laser photons are needed to make one gamma ray. This factor is proportional to the square of the laser photon wavelength divided by the classical radius of the electron. A terawatt laser with an average power of tens of kilowatts is required. Note that separate systems are needed to handle the electron and positron beams. While the lasers are large, they are not impossible.

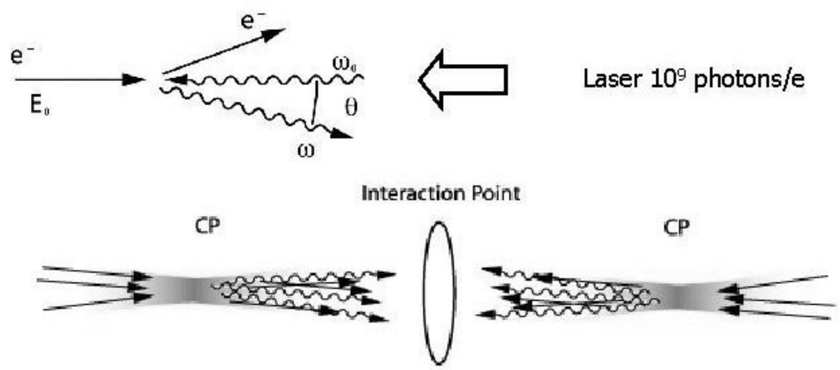

Figure 4: Gamma-gamma collider process.

Finally, all the linear collider designs contemplate use of the facilities to provide powerful free electron lasers based on self amplified spontaneous emission (SASE). SASE was first proposed at SLAC. The brilliance is typically 10^8 times current light sources. An FEL based on a linear collider will produce 1 Å x-rays with a pulse length of 100 fs. Figure 5 taken from the TESLA design report [13] illustrates the SASE mechanism.

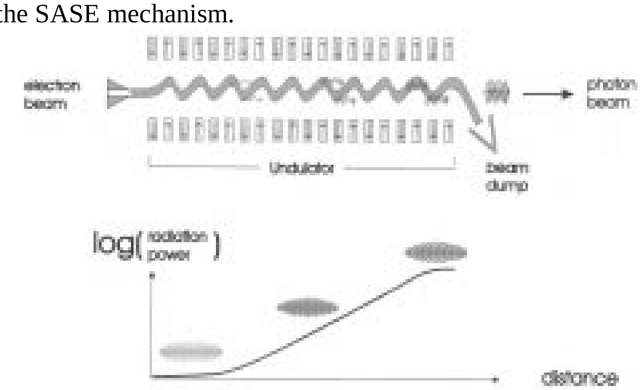

Figure 5: TESLA FEL-SASE mechanism.

The small cross section, high current electron beam emits synchrotron radiation in the undulator. Resonances develop in the longitudinal charge density modulation for the correct energy and undulator period. These resonances result in micro bunching. The number of photons grows exponentially to give lasing. The TESLA Test Facility has already demonstrated SASE for 80-180 nm wavelengths. A large material science and solid state community is interested in the development of these FELs. Typically these FELs do not use the full energy of an e^+e^- linac.

3.2 Muon colliders

The possibility of building muon storage rings has been around for a long time. Several rings have been built to study the anomalous magnetic moment of the muon. A recent experiment using a muon storage ring at Brookhaven has found a 3 sigma departure for the anomalous muon magnetic moment from straight QED predictions [14]. The problem with muons, in contrast to positrons and anti-protons is that they decay with a lifetime of 2.2 μs. However if long straight sections are added to a muon storage ring these decaying muons result in neutrinos beamed in the direction of the straight sections. There is a second problem in this process. Muons are produced by first making pions and kaons which decay into muons. The maximum transverse momentum of the decay muon is 30 MeV/c so that a 3 GeV muon could have an angular divergence up to 10 mrad. To overcome this, the muon beam must be cooled before it is injected into a storage ring in the same spirit that dampers are required for linear colliders. As will be seen, this a huge challenge.

Muon colliders probably would not have elicited much interest except for the fact that the Higgs cross section is expected to be $(m_\mu/m_e)^2$ or 40,000 times larger than the e^+e^- cross sections. This is enough to cause one to investigate ways to address the large problems. Figure 6 shows a schematic of a muon collider [15]. In this approach protons from a high intensity source are used to produce pions which decay into muons. The muons are captured by a very large, 20 T solenoid. The solenoid is followed by a so-called Siberian snake magnetic beam line which rotates the muon spin and provides momentum selection. Next follows an ionization cooling system where the muons are cycled 20 times through a system where they are slowed and lose both longitudinal and transverse energy and are then accelerated by a linac to regain the longitudinal energy. Because of the short muon lifetime all of this must occur very rapidly. From there they are transferred to re-circulating linacs where they are accelerated to the Tev regime. The beams collide in a smaller ring shown at the bottom of the figure. Note that the accelerating stages typically require large, rapid cycling magnets.

This is not an easy project! The ionization cooling is based on straightforward energy loss and multiple scattering. However cooling takes place in a six-dimension phase space. Every factor of two counts and the details of the tails of the distributions may be important. It is generally felt that a successful, full-scale test of

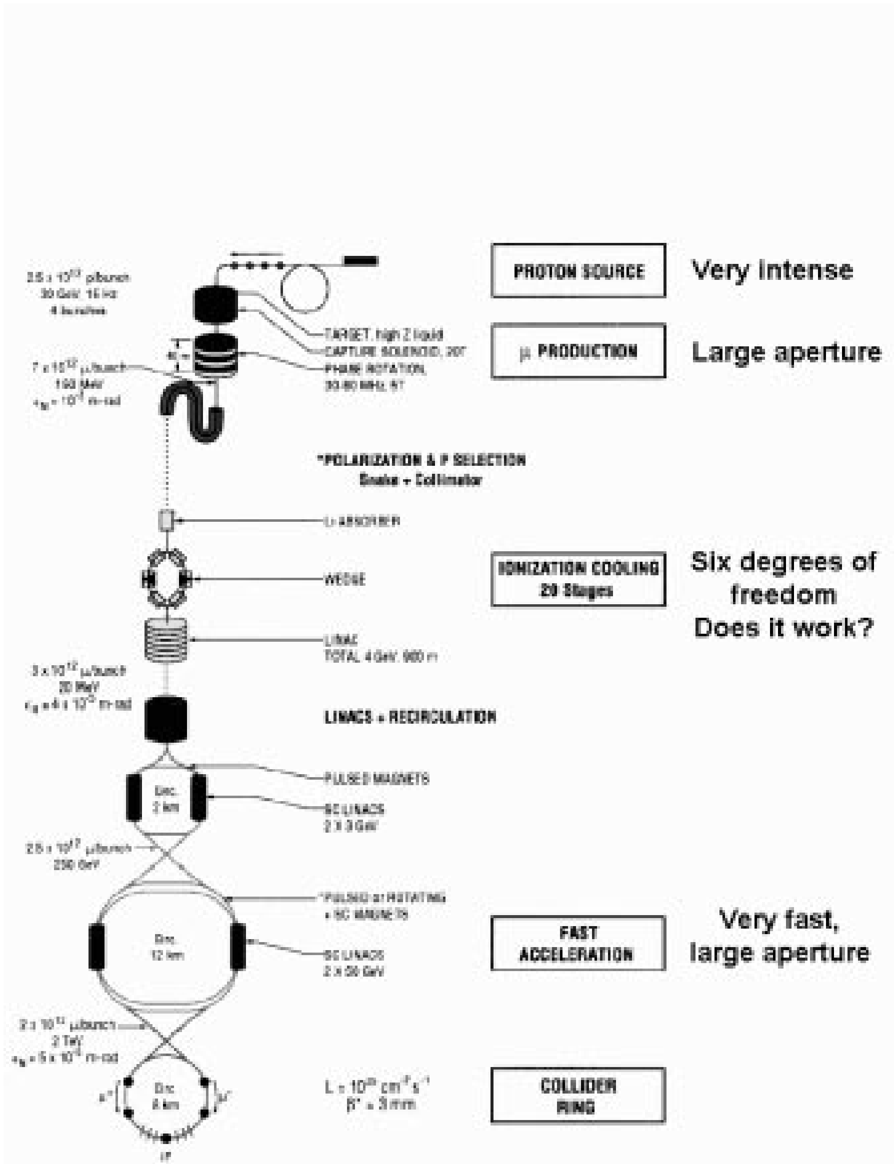

Figure 6: Muon collider schematic.

ionization cooling would be necessary before any real design and building program could start.

The possibility of muon colliders has reawakened consideration of muon storage rings for producing intense neutrino beams. In fact, early investigations of muon colliders showed that some designs resulted in off-site radiation from neutrinos that was unacceptable. Figure 7 shows a neutrino factory that could be fit on the Fermilab site and produce neutrino beams from 50 GeV muons. Even this system is complicated-two re-circulating linacs, a storage ring, ionization cooling, and a powerful proton driver. It is so daunting that the proponents have recently revisited conventional neutrino beam geometries using the proton driver alone. The estimated neutrino beams from a proton driver alone would be 0.1 as intense as a simple neutrino factory.

3.3 Very large hadron colliders

With the mid-decade arrival of the LHC the possibility of an extension to somewhat higher energy has stirred some interest in the US. In part this interest harks back to the abandoned SSC project. From the start cost is recognized as an important consideration. Typically the designers look for inexpensive magnet and deep tunneling technologies. The tunnel challenge is illustrated in a Fermilab design. The tunnel is 233 km in circumference, nearly ten times as long as the LHC tunnel. Going to a large circumference permits the use of super-ferric superconducting magnets that operate at 3 TESLA. T. W. Foster has devised an inventive 2 in 1 geometry for the magnet with only a single conductor. This magnet would undoubtedly be simpler to make than the LHC magnet shown earlier. In a later stage the energy of the complex could be upgraded by going to high field superconducting magnets.

My own view is that such a project is far in the future. LHC will first have to operate. Land acquisition in the US would be difficult even with deep tunneling. And, for the US, the demise of the SSC has left a somber legacy.

4 Visionary possibilities (2020 and beyond)

Is there a way to break out of these complicated accelerating schemes? The path most often suggested is to find ways to get higher accelerating gradients. One suggestion is to use lasers. Tremendous strides have been made in the laser field and the future continues to look promising. In particular so-called table top Terawatt lasers have been developed in the last decade by "chirping" lasers [16].

The fundamental problem with the electric field produced by a laser is that the field is oscillating very rapidly so that it is difficult to couple it to a particle beam. The potentials and problems of laser acceleration were covered in a classic review by Palmer [17] written before the invention of chirped lasers. One way acceleration

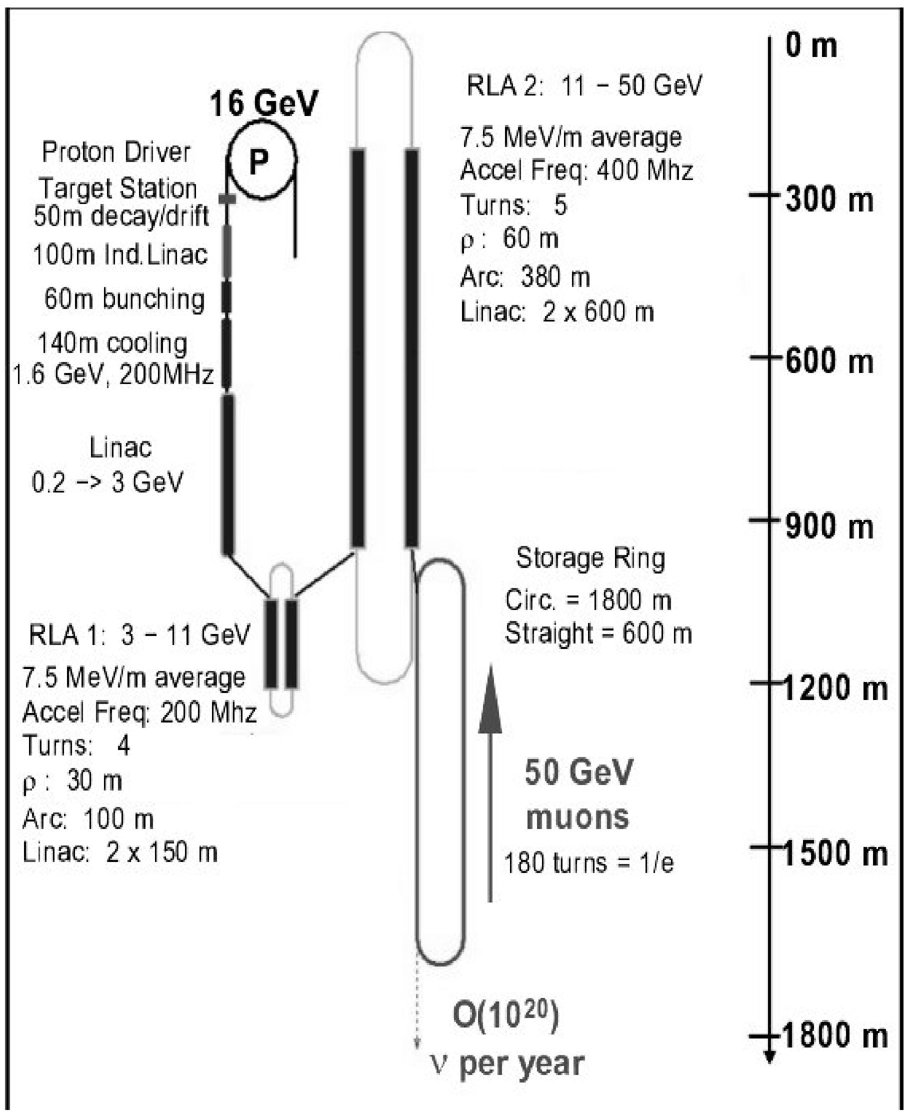

Figure 7: Schematic of a possible Fermilab neutrino factory.

could be achieved is through the use of an inverse free electron laser (IFEL). This is the inverse of the Free Electron Laser where a beam of x-rays is produced by an electron beam. In an IFEL an electron beam is accelerated transversely and longitudinally by a laser. A step on the path toward a coupled IFEL has recently been taken at the STELLA [18] experiment at the Brookhaven Accelerator Test Facility (ATF). That facility employs two coupled wigglers driven by 24 MW of laser power in the first stage and 300 MW in the second. The facility has been used to demonstrate electron beam rephasing in the second wiggler. So far there has not been an attempt to accelerate the linac beam.

A second acceleration possibility is to use plasmas. Pretty good plasmas oscillations can be generated with both lasers and charged particle beams. It is here that the most progress has been made. Good introductions are contained in articles by Dawson [19] and Tajima and Dawson [20]. Esarey and his collaborators [21] have prepared a useful up-to-date review.

4.1 Plasma wakefield acceleration

A metaphor for plasma wakefield acceleration is shown in Figure 8. The power boat in the lower left is moving through a fluid, the river in this case. It creates a moving wave behind it. The surfer is riding the wave. Notice that no rope connects the surfer to the boat, he is riding the wave. If the boat accelerates, the surfer will accelerate meanwhile moving slightly down the wave.

Figure 8: Wake field surfer metaphor for plasma wakefield acceleration (courtesy S. and L. Carrigan).

There are lots of ways the surfer can fall including the results of turbulence, drifting too far down the wake, and improper phasing, that is getting too far up toward the crest. In a plasma accelerator the fluid is typically ionized electrons in a gas. The plasma wave driver is a charged particle beam or a laser rather than a boat. The surfer is a “witness” beam of particles accelerated by waves in the charged particle plasma. These plasmas can generate high accelerating gradients. The “non-relativistic wavebreaking" field for a plasma is G (V/cm) = 0.96 $(n_0)^{1/2}$ where n_0 is the electron density. For $n_0 = 10^{18}/cm^3$ (a possible plasma density in a gas) the accelerating gradient is G = 1 GV/cm. This should be compared to a good RF cavity gradient of 0.0005 GV/cm.

A laser creates a plasma wake field in the following way. The laser transverse E field accelerates the electrons transversely with a time varying field with a frequency λ. The laser B field can then push these forward (and also backwards). This sets up a wave in the plasma with a frequency λ_p given by

$$\omega_p = \left(4\pi n_0 e^2 / m_e\right)^{1/2} \tag{1}$$

where m_e is the electron mass. This plasma wave will give rise to an acceleration gradient of

$$G = m_e c \omega_p / e\,. \tag{2}$$

This gives the gradient mentioned earlier. A transverse wake field is also created that can provide focusing. The plasma wave has a phase velocity of

$$v_p = c\left(1 - \omega_p^2 / \omega^2\right)^{1/2}. \tag{3}$$

For $\lambda >> \lambda_p$ the phase velocity approaches c. The best wake is generated when the photon packet is half the plasma wavelength. For that case

$$E_{\max} \cong 2 m_e c^2 \omega^2 / \omega_p^2\,. \tag{4}$$

The length of the acceleration process is determined by the smallest of the dephasing length, pump depletion length, or the depth of field if the plasma is laser driven. The use of a so-called optical channel can help. Figure 9 (taken from Figure 3 in Sprangle et al.) illustrates the characteristic field strengths available from a laser driven plasma. The case shows a highly relativistic plasma, that is a case where the driving power of the laser is large enough to produce relativistic electron motion. For this case the laser pulse length is 0.3 cm. The pulse moves from right to

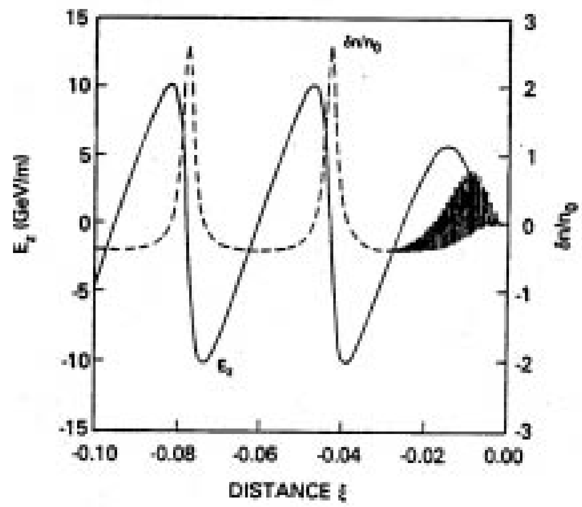

Figure 9: Plasma acceleration fields (from Esarey, et al.)

left. The dark, fast oscillations in the figure are due to the laser with frequency λ. The plasma density is $n_0 = 10^{16}/cm^3$. The gradient rises to 10 GeV/m. A lower intensity plasma would produce a more sinusoidal plasma wave.

Four types of plasma accelerators have been discussed. The laser wakefield accelerator (LWFA) is driven by a short laser pulse where $L \sim \lambda_p$. The laser power needed is typically 10^{18} W/cm^2. Self modulated laser wakefield accelerators (smLWFA) use an even higher power, slightly longer pulse to get a self-modulated instability along the axis. This type of acceleration has been studied recently at Rutherford [22]. Using the Vulcan laser which can produce 50 TW laser pulses to give 10^{19} W/cm^2, they have been able to get $4*10^{11}$ electrons/shot with energies greater than 10 MeV. Another laser-driven plasma accelerator [23], the plasma beat wave accelerator (PBWA), has been studied at UCLA. Two lasers with a frequency difference near the plasma frequency are used. They must be finely tuned to the plasma frequency. This type of accelerator uses long, lower power laser pulses. The UCLA system has accelerated some particles from a 2 MeV electron beam up to 28 MeV using a 0.2 TW CO_2 laser. This is equivalent to an accelerating gradient of 2.2 GeV/m. Finally electron beams are also used to drive a plasma. These are called plasma wakefield accelerators (PWFA). They are similar in spirit to the laser wakefield accelerator. The short, powerful electron pulse drives the plasma to create a more energetic, low power witness beam. These devises have a so-called transformer ratio, the ratio of the witness beam energy to the drive beam. $E_{wit} < 2^* E_{drv}$ unless the drive beam is shaped or one drives the plasma in to a so-called blowout regime where the plasma is driven out of the beam hole momentarily.

A recent example of a plasma wakefield accelerator is SLAC experiment E157 which has been set up in the SLAC Final Focus Test Beam [24]. They use a 30 GeV electron beam with $2*10^{10}$ e in a 0.65 mm long bunch. The head of the bunch sets up a plasma wave in a Li gas plasma. The tail of the bunch can then be accelerated. The configuration used up until now produces both accelerated and decelerated particles in the beam. Barov and Rosenzweig [25] have seen similar results in a plasma at the Fermilab A0 photo-injector. One exciting possibility for the SLAC project is the prospect of using a plasma afterburner as an energy doubler for the SLAC linac [26]. Hose instabilities, positron acceleration, focusing, and plasma source development present interesting challenges for this novel concept.

Plasmas can also be used to focus beams. If the beam diameter is small compared to the plasma wavelength, the azimuthal magnetic field will not be neutralized. The magnetic field will pinch the beam and focus it. An alternative way of looking at this is to note that the slow ions in the plasma attract e^-. Since the complete process is more complicated the focusing also works for e^+. A second team at SLAC has recently looked at this process [27]. They see plasma focusing equivalent to up to $4*10^6$ T/m.

While progress has been interesting, particularly since the development of chirped terawatt lasers a decade ago, there is still much to be accomplished. One of the next steps is to couple two stages of plasmas to get coupled acceleration. Apart from needing multistage acceleration to get high energy, one first has to understand phasing multiple plasma systems. The Neptune accelerator at UCLA is a step toward this goal. Another ultimate requirement is good wall plug efficiency. Power from the electrical mains needs to be turned into beam power. The wall plug efficiency for a normal linac is on the order of 25%. At present laser power conversion (not wall plug power) to plasma power is about 0.01%. Ogata and Nakajima [28] estimate this might be raised to 10%. Finally, particle physics applications of plasma acceleration requires high luminosity. This means emittance must be small and bunch charges must be large. Little work has been done on this so far.

4.2 Solid State Plasma Accelerators

As noted above the plasma acceleration gradient is proportional to the square root of the plasma density. An interesting possibility is to use solids instead of gases as the plasma medium. The plasma density could be up to ten thousand times higher leading to gradients of 100 GV/cm. On the other hand, solids result in high multiple scattering and intense particle beams can be extremely hard on solids.

In the last several years a number of groups have observed energetic electrons and ions coming from foils struck by powerful laser beams. At Livermore [29], a pedawatt laser with a power density of $3*10^{20}$ W/cm^2 has produced protons of up to

58 MeV on the downstream side of a foil. These ions are probably accelerated by a sheath of hot electrons evaporated off the downstream side of the foil. Other, somewhat similar effects have been observed at Michigan [30] and Rutherford [31]. It is quite unlikely that these experiments demonstrate solid state plasma acceleration! Instead, charge inbalances at the solid surface or other boundary effects produce the acceleration.

Concepts for solid state acceleration have been developed in some detail by Chen and Noble [32]. A particular feature of their approach is the use of particle channeling to enhance the process. Particle channeling [33] occurs when a charged particle moves close to a crystal plane or axis in a single crystal. Ultimately, particles are dechanneled due to multiple scattering. For positive particles channeling can reduce energy loss and multiple scattering and possibly provide some focusing. Dechanneling is stronger for negative particles. Ruth, Huang, and Chen [34] have also shown that for very aggressive acceleration channeling radiation can result in impressive radiation damping, effectively cooling the beam. (Channeling radiation from oscillations between crystal planes is similar to synchrotron radiation [35].)

Solid state acceleration requires that an electronic plasma must be established in the solid. Since the plasma density is high in a solid, the plasma oscillation frequency is also high because it is proportional to the square root of the plasma density. The electronic plasma decays in femto-seconds. Normally the plasma oscillations in solids are small. For the Chen-Noble concept plasma densities are in the regime of 10^{22}-10^{24}/cm^3 and the plasma frequency is in the $5*10^{16}$-$5*10^{17}$/s regime. This corresponds to ultraviolet light. The stored energy is $4*10^8$-$4*10^{10}$ J/cm^3. This is much, much higher than the specific heat of vaporization. For a gradient of 1 GeV/cm a power density of 10^{18} W/cm^3 is required. This corresponds to a laser driver focusing 1 Joule on a 10 micron spot for 1 ps. In practice, the pulse would have to be much shorter. Fracture occurs at energy densities 100,000 times smaller.

Clearly these are heroic challenges so there are big problems associated with solid state acceleration. The intense laser or particle beams needed as drivers will destroy the material. However, for femto-second lasers the crystal lattice might survive long enough to accelerate the beam. Daunting as the large laser power densities are, the extremely high gradients and the potential for radiative damping are interesting.

At the Fermilab NICADD Photoinjector Laboratory at A0 [36] we have addressed one step on the path to solid state channeling accelerators. This is whether channeling itself will survive as the beam densities are raised toward those required for acceleration. For example, the very high power density and the associated plasma could ruin the lattice before the bunch passed all the way through the crystal. Past experiments have been at least a factor of 10^8 away from this regime in bunch charge. The Fermilab A0 photoinjector delivers a very high bunch charge, up to 10 nC/bunch. It is capable of reaching 50-100 times further than earlier experiments. This is a step but still a factor of a million away from the interesting regime.

Our Fermilab-Darmstadt collaboration [37] has looked at channeling radiation at A0. The experiment has demonstrated that the channeling radiation yield is constant over the bunch charge range from $2*10^{-4}$ to 10 nC. Comparison to an earlier experiment at Darmstadt shows the yield is constant over a range of 10^{10}. The A0 result demonstrates that channeling continues to work at some of the highest bunch charges currently available.

One way to extend these measurements would be to go to much higher beam energies where the beam spot size would be smaller and shorter. At SLAC with a 30 GeV beam it might be possible to get beam spot diameters 50 times smaller and extend the reach by factors of thousands. The actual experiment would be considerably different than the Fermilab-Darmstadt one.

5 Summary

The next two decades look bright for particle physics. The Tevatron will operate with a luminosity that has a chance of discovering supersymmetry and maybe even a Higgs. The LHC will come on in the middle of the decade and should easily be able to find a Higgs. That facility will be a fine resource until well past 2020. Sometime after 2010 a linear collider will probably be built. We do not know where and we do not know whether it will use conventional or superconducting cavities. It will be expensive and require full-scale international cooperation. That complex will almost surely include the possibility of an FEL and maybe a gamma-gamma collider. Somewhere in the next decades one or more existing or planned facilities may be retooled to function as neutrino factories. Beyond these machines the future is cloudy. A VLHC is extremely expensive. A muon collider is technically challenging and also expensive.

Can exotic devices like plasma accelerators enter the picture and offer a new path to the energy frontier? Some progress has been made but much more information is needed. They may turn out to be impractical or the rate of progress may be too slow. Only time will tell.

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