R&D for Future Accelerators

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Abstract

Research & development for future accelerators are reviewed. First, I discuss colliding hadron beams, in particular upgrades to the Large Hadron Collider (LHC). This is followed by an overview of new concepts and technologies for lepton ring colliders, with examples taken from VEPP-2000, DAFNE-2, and Super-KEKB. I then turn to recent progress and studies for the multi-TeV Compact Linear Collider (CLIC). Some generic linear-collider research, centered at the KEK Accelerator Test Facility, is described next. Subsequently, I survey the neutrino factory R&D performed in the framework of the US feasibility study IIa, and I also comment on a novel scheme for producing monochromatic neutrinos from an electron-capture beta beam. Finally, I present innovative ideas for a high-energy muon collider and I consider recent experimental progress on laser and plasma acceleration.

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R&D FOR FUTURE ACCELERATORS

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Research & development for future accelerators are reviewed. First, I discuss colliding hadron beams, in particular upgrades to the Large Hadron Collider (LHC). This is followed by an overview of new concepts and technologies for lepton ring colliders, with examples taken from VEPP-2000, DAFNE-2, and Super-KEKB. I then turn to recent progress and studies for the multi-TeV Compact Linear Collider (CLIC). Some generic linear-collider research, centered at the KEK Accelerator Test Facility, is described next. Subsequently, I survey the neutrino factory R&D performed in the framework of the US feasibility study IIa, and I also comment on a novel scheme for producing monochromatic neutrinos from an electron-capture beta beam. Finally, I present innovative ideas for a high-energy muon collider and I consider recent experimental progress on laser and plasma acceleration.

1 Introduction

The past 40 years have seen a remarkable increase in the energy of colliding particle beams, which is illustrated in Fig. 1. This progress in acceleration technology has paved the way for many fundamental discoveries in particle physics. With the advent of the Large Hadron Collider (LHC) in 2007, the steep improvement is set to continue. Upgrades of the LHC are already considered, first, around 2014, in luminosity and after 2020 also in energy. Later perhaps a Very Large Hadron Collider (VLHC) could become the ultimate hadron collider. In parallel, the lepton colliders have followed a similar trend. The final incarnation of the Large Electron Positron Ring (LEP-2) presumably marks the maximum energy which will ever be reached by storage-ring electron-positron colliders. For the future, three novel types of lepton colliders are, therefore, proposed, which in different ways overcome the fundamental obstacle of synchrotron radiation. Two of them are linear colliders, with the design extrapolated over many orders of magnitude from the only linear collider ever in operation, namely the Stanford Linear Collider (SLC). The International Linear Collider (ILC) uses superconducting accelerating structures and is limited to a maximum

beam energy of 500 GeV. The Compact Linear Collider (CLIC) is based on two-beam acceleration with an ultimate beam energy of 2.5 TeV. In the longer-distant future, a muon ring collider may conceivably reach beam energies of 10 TeV. The dates indicated in Fig. 1 for the various future colliders represent subjective guesses based on the current state of planning and development, optimistically assuming that all proposed projects will be realized. Beyond the muon collider, several evolving advanced acceleration techniques, e.g., ones utilizing lasers or plasmas, offer the exciting prospect of pushing the high-energy frontier even further.

2 Hadron Colliders

Presently two hadron colliders are in operation — the Tevatron and RHIC. A third, the LHC, is scheduled to start in 2007. The R&D at the Tevatron is limited to electron cooling in the recycler ring and to beam-beam compensation using a pair of electron lenses. At the time of writing, a first successful cooling of unbunched antiprotons in the recycler ring has been reported, with an electron beam energy of 4.3 MeV, which constitutes a world record¹. The beam-beam compensation is on a promising track as well, with a successful demonstration of beam-lifetime improvement

Figure 1. Schematic of collider energy as a function of year. Shown are the beam energies of hadron ring colliders (blue rhombi), including an intrepid extrapolation into the future, those of electron-positron colliders (pink squares) as well as hypothetical points for future electron-positron linear colliders (red squares) and a high-energy muon collider (green triangles). Only data points before 2005 are certain.

in 2004, by a single lens². RHIC pursues an ambitious extension plan. Studies for an upgrade of the LHC have begun.

2.1 RHIC Upgrade

The expanded RHIC complex is illustrated in Fig. 2. It consists of two parts. First, the RHIC luminosity will be increased by a factor of 10, primarily by a pioneering scheme of high-energy bunched-beam electron cooling, which requires a 54-MeV electron beam³. Second, an additional electron beam accelerated in a recirculating linac and stored in a 5–10 GeV static ring will collide with the ion beams stored in RHIC. The upgraded RHIC will explore QCD at high energy and high temperature (strongly coupled quark gluon plasma), as well as QCD at low x (colour glass condensate), and the origin of nuclear spin.

2.2 LHC Upgrade

In 2001 two CERN task forces investigated the physics potential⁴ and accelerator aspects⁵ of an LHC upgrade. Presently,

Figure 2. Schematic of the upgraded RHIC complex, with high-energy electron cooling and additional ion-electron collisions (bottom right and top, in green).

the European CARE-HHH Network⁶ and the US DOE US LARP programme⁷ are jointly studying ways of increasing the LHC luminosity by a factor of 10, from the nominal value of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ to $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at two interaction points (IPs) by about 2014^{8,9}. A factor two increase in luminosity can be achieved by a reduction of the IP beta functions $\beta_{x,y}^*$. The remaining factor of five may be obtained by raising the beam current: The baseline upgrade scheme foresees decreasing the bunch spacing from 25 ns to either 15 or 10 ns, at the ultimate bunch population of $N_b \approx 1.7 \times 10^{11}$ protons⁸. An alternative scheme would collide fewer, but longer and more intense bunches ($N_b \approx 6 \times 10^{11}$), and operate with a large Piwinski angle $\phi \equiv \theta_c \sigma_z / (2\sigma^*) \approx 3$, where σ_z denotes the bunch length, θ_c the full crossing angle, and σ^* the rms beam size⁸. An upgrade of the LHC injectors for higher energy and reduced LHC turnaround time is under consideration, and for a later stage the increase of the LHC beam energy itself.

Two reasons call for an upgrade of the LHC after about 6 years of operation. They are illustrated in Fig. 3, due to J. Strait¹⁰. The figure illustrates two possible evolutions of peak luminosity as a function of the year, as well as the corresponding integrated luminosity and the run-time needed to halve the statistical error of experimental measure-

ments. Both scenarios assume an LHC start up in 2007, and that 10% of the design luminosity is reached in 2008, and 100% in 2011¹¹. In one case, the luminosity is taken to be constant from then on, in the other it continues to increase linearly until the so-called ultimate luminosity (2.3 times the nominal) would be reached by 2016. The radiation damage limit of the LHC low- β quadrupoles is estimated at an integrated luminosity of 600–700 fb^{-1} ¹³. As the figure shows, this value would be exceeded in 2014 or 2016 depending on the scenario. The additional runtime required to halve the statistical error rises more steeply. It would exceed 7 years by 2011 or 2013, respectively. In view of the life expectancy of the interaction-region magnets and the forecast for the statistical-error halving time, it is reasonable to plan a machine luminosity upgrade based on new low- β IR magnets before about 2014.

Figure 3. Time to halve the statistical error (green curves), integrated luminosity (blue curves), and peak luminosity (red curves) for two different scenarios compatible with the baseline LHC: (1) the luminosity is raised to the nominal value by 2011 and then stays constant, (2) it continues to increase linearly, reaching the ultimate value by 2016. The assumed radiation damage limit of the IR magnets is 700 fb^{-1} ¹⁰ [J. Strait].

Figures 4 and 5 illustrate various options for the IR configuration of an upgraded LHC^{11,12}. Either quadrupoles or dipoles are the first magnetic elements closest to the main collision points. Placing

the quadrupoles in front (Fig. 4) reduces the chromaticity, while “dipoles first” (Fig. 5) leads to a rapid separation of the two beams and minimizes the number of long-range collision points. In the dipoles-first scheme, collision debris is swept into the magnet, and for this reason the US-LARP program studies the design of open-midplane s.c. dipoles. In addition, the two LHC beams could be collided either with a small crossing angle, necessitating long-range beam-beam compensation, e.g., using current-carrying wires, or with a large crossing angle, requiring crab cavities, much shorter bunches, or operation in a regime of large Piwinski angle.

Figure 4. IR ‘baseline’ schemes for the LHC upgrade with minimum crossing angle and possibly long-range beam-beam compensation (left) or with large crossing angle and possibly crab cavities (right); see also¹².

Figure 5. Alternative IR schemes for the LHC upgrade with dipole first for small (left) or large crossing angle (right). The right layout needs to either operate with large Piwinski angle or employ crab cavities; see also¹².

A possible injector upgrade consists of refurbishing the PS, and replacing the SPS with two new rings, a first ring using normal conducting or super-ferric magnets and accel-

erating to 150 GeV and a second fast cycling superconducting ring, raising the LHC injection energy to 1 TeV¹⁴. The higher injection energy will alleviate dynamic effects in the LHC and should significantly reduce the LHC turnaround time. In addition, beams with larger normalized emittance and higher intensity can be injected at the higher energy. Finally, the increased injection energy can be the first step of an energy upgrade for the LHC.

The LHC beam energy is determined by the main dipole field, which nominally is 8.39 T corresponding to 7 TeV beam energy. A proof-of-principle magnet based on Nb₃Sn s.c. material at LBNL has reached 16 T a few years ago, with a 10-mm aperture¹⁵. The European NED activity¹⁶ aims to develop a large-aperture (up to 88 mm), 15-T dipole-magnet model. A 24-T block-coil dipole for an LHC energy tripler is also being developed by Texas A&M University¹⁷. It employs high-Tc superconductor (Bi-2212) in the inner high-field windings and Ti₃Sn for the outer low-field windings. The magnet layout is illustrated in Fig. 6 and its small coil area is emphasized in Fig. 7.

Figure 6. Schematic of a dual-pipe 24-T block dipole magnet with Bi-2212 in inner high field windings (green) and Nb₃Sn in outer low field windings (red)¹⁷.

3 Electron-Positron Ring Colliders

Among the e^+e^- colliders, several high-luminosity factories will explore innovative beam-manipulation techniques. Though

Figure 7. Magnet coil area vs. field strength for different s.c. dipoles, showing a reduced size for the proposed block-dipole magnets of the LHC energy tripler¹⁷.

BEPC-II, CESR-c and PEP-II are contributing to this effort, below we can only present a few selected highlights from VEPP-2000, DAFNE, and Super-KEKB.

3.1 VEPP-2000

VEPP-2000 will fill the missing-data gap for hadron production in the range of 1.4–2.0 GeV c.m. energies. The start of operation is foreseen for 2007. VEPP-2000 will collide round beams focused by s.c. 13-T solenoids. The round beam collisions offer two distinctive advantages: (1) for the same particle density (tune shift), the luminosity doubles, (2) the transverse particle motion becomes 1-dimensional, introducing an additional integral of motion, which, according to simulations, should allow about 3 times higher tune shifts than flat beams¹⁸. The VEPP-2000 luminosity scales with ξ^2 . Its design value is $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$.

3.2 DAFNE-2

The upgrade of DAFNE, DAFNE-2, will study discrete symmetries in the neutral kaon system, and perform the most sensitive test of CPT invariance. For DAFNE-2, a new concept of “strong rf focusing” has been proposed, where the bunch length and momentum spread vary around the ring¹⁹. At the collision point, the bunch length assumes a

minimum, so that the beta function can be squeezed to a small value. Over the rest of the ring a long bunch length is desirable, since this improves the beam lifetime and mitigates impedance effects. The strong rf focusing is realized by a higher rf voltage and by tailoring the local momentum compaction around the ring. It has recently been shown that such a scheme can be realized without a synchrotron tune near the half integer. An experiment of strong rf focusing at DAFNE is foreseen for 2007, with the installation of a 10-MV 1.3-GHz multi-cell s.c. rf cavity²⁰.

3.3 Super-KEKB

KEKB and its upgrade, Super-KEKB, represent the luminosity frontier. Super-KEKB will provide definitive answers on new physics beyond the standard model in the heavy-flavor sector. With a peak luminosity of $1.58 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, KEBB presently holds the record luminosity of any collider. The goal of Super-KEKB is a luminosity of $4 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, which would make it a truly unique facility, as illustrated in Fig. 8. The luminosity can be expressed as

$$L = \frac{\gamma_{\pm}}{2er_e} \left(1 + \frac{\sigma_y^*}{\sigma_x^*} \right) \frac{I_{\pm}\xi_{\pm}}{\beta_y^*} \left(\frac{R_L}{R_y} \right), \quad (1)$$

where R_L and R_y denote geometric reduction factors, due to crossing angle and hourglass effect, r_e is the classical electron radius, and γ the Lorentz factor. Three improvements will increase the luminosity by more than a factor 20 compared with the present KEBB: (1) The stored beam currents $I_{\pm}$ are raised from 1.27/1.7 A to 4.1/9.4 A, (2) the vertical beta function at the collision point is squeezed from about 6 mm to 3 mm, and (3) the beam-beam tune-shift parameter $\xi_{\pm}$ will be enlarged by a factor of two or three by using crab cavities²¹. These are transversely deflecting dipole-mode cavities, which rotate the bunches at the collision point, so that the particle dynamics becomes equivalent to the one of the head-on case, even though the

bunch centroids cross with an angle. In early 2006, single crab cavities will be installed in both KEBB rings. Simulations predict a resulting large increase in the achievable beam-beam tune-shift parameter.

Figure 8. Peak luminosity of various past and proposed colliders vs. centre-of-mass energy.

A schematic of Super-KEKB is shown in Fig. 9. All elements in color are new. The upgrade notably comprises a new interaction region with a new detector, additional rf stations, new vacuum chambers for both rings including antechambers and novel low-impedance bellows, as well as an exchange of the electron and positron beams between the two rings. Positrons will be stored in the high-energy ring, where they both have a lower current and are more rigid, which is expected to combat the “electron-cloud effect”, i.e., a beam-size blow up due to photoelectrons and secondary electrons. To accelerate the positrons to the higher injection energy (8 GeV instead of 3.5 GeV), their beam size is reduced in a new damping ring, before they are accelerated by a new C-band linac, which replaces the second half of the existing lower-gradient S-band linac.

4 Linear Colliders

Reaching the high-energy frontier in electron-positron collisions requires a linear collider. From initially five proposals (VLEPP, NLC,

Figure 9. Schematic of Super-KEKB, with existing components shown in grey, and new ones in color.

JLC/GLC, TESLA and CLIC), only two have survived, namely the ILC (based on TESLA technology) and CLIC. Since ILC is covered by a separate talk²², we discuss CLIC. Afterwards we present some generic linear-collider R&D of interest to both ILC and CLIC.

4.1 Compact Linear Collider (CLIC)

The physics motivation of CLIC is to probe beyond the standard model and to address, in particular, the origin of mass, the unification of forces, and the origin of flavors. With its centre-of-mass energy reach of 3–5 TeV, CLIC is fully complementary to the LHC. Its physics potential is described in^{23,24,25,26}.

The key features of CLIC are²⁷: (1) a high accelerating gradient, 150 MV/m, which — in view of various limits due to dark-current capture, surface heating, and rf breakdown — requires a high rf frequency, namely 30 GHz; (2) two-beam acceleration, where the energy is stored in a drive beam, which can be transported over long distances with small losses, and the rf power is generated locally from the drive beam, where it is required; and (3) a central injector producing the drive beam, which comprises a fully loaded normal conducting linac with 96% rf-to-beam power-transfer efficiency followed by rf multiplication and power compression.

The overall layout of the CLIC complex for 3-TeV c.m. energy is presented in Fig. 10.

Figure 10. Layout of CLIC for 3 TeV c.m. energy.

The high accelerating gradient of CLIC allows constructing a multi-TeV electron-positron collider with an acceptable length. High-gradient tests of 30-GHz rf structures with molybdenum and tungsten irises exceeded the CLIC design goal of 150 MV/m accelerating gradient and reached a world record of 190 MV/m²⁸ (Fig. 11), but with an rf pulse length of 16 ns only, while the nominal CLIC value is 70 ns. Tests with the nominal pulse length are foreseen at CTF-3 (Fig. 12), presently under construction and commissioning, in the second half of 2005. CTF-3 has already demonstrated two other aspects of the CLIC scheme, namely drive-beam acceleration with full beam loading, shown in Fig. 13, and frequency multiplication²⁹, in Fig. 14.

The two beam acceleration scheme ensures that the main-linac tunnel is simple, without any active elements, which is illustrated in Fig. 15. An additional advantage is that the construction can be staged by simply adding additional structures and corresponding drive beams, each of which accelerates by about 75 GeV/c.

CLIC aims at colliding nanometre-size beams, for which ground motion and support vibrations are a concern. Using commercially available active stabilization systems, CLIC prototype quadrupoles were stabilized to less

Figure 11. Peak accelerating gradients vs. conditioning time for structures with copper, molybdenum and tungsten irises.

Figure 12. CLIC Test Facility (CTF) 3.

than 0.5-nm above 4 Hz, on the CERN site next to a busy street, which is a factor 2 better than the requirement for the CLIC linac and represents a factor 10 suppression of the ground motion³⁰.

The design optics of the CLIC damping ring provides the exceedingly small target emittances of $\gamma\epsilon_x = 550$ nm, $\gamma\epsilon_y = 3.3$ nm, $(\sigma_z \Delta E_{rms}) = 4725$ eV-m, taking into account the strong effect of intrabeam scattering which far outweighs the quantum excitation from synchrotron radiation³¹. A collaboration with BINP is investigating wiggler-design options for the damping ring. A possible prototype is the permanent wiggler built for the PETRA-3 light source.

Figure 13. Fully loaded operation of the CTF-3 linac, with higher-order mode damping and short fill time.

Figure 14. Bunch frequency multiplication by factors of 2–5 demonstrated in the CTF-3 preliminary phase. Left top plot shows a schematic of the injection into the combiner ring using rf detectors; the right and bottom picture show streak-camera measurements during and after bunch multiplication.

In 2005, the CLIC parameters have been re-optimized³². As a result, the bunch-train length was reduced by almost a factor of 2 to 58 ns, with the same luminosity above 99% of the nominal c.m. energy, which is $3.3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ including the effect of beamstrahlung, and lower detector background.

The CLIC schedule anticipates a complete demonstration of the CLIC feasibility by the end of 2009, at a time when first results from the LHC may offer a clearer picture of the physics ahead.

5 Generic Linear Collider R&D

We briefly describe three items of generic linear-collider R&D centered at the KEK Accelerator Test Facility (ATF).

Figure 15. CLIC tunnel cross section.

5.1 ATF Damping Ring

The ATF is the world's largest linear-collider test facility. It accommodates several sources, an S-band injector linac, a prototype damping ring and an extraction line. The 1.3-GeV ATF ring produces the world's smallest-emittance beams. It has demonstrated single-bunch emittances of $\gamma\epsilon_x \approx 3.5 - 4.3 \mu\text{m}$ and $\gamma\epsilon_y \approx 13 - 18 \text{ nm}$, at $N_b \approx 8 \times 10^9$ electrons per bunch³³; the emittances are highly current dependent due to the strong effect of intrabeam scattering (for comparison, the CLIC design values are $\gamma\epsilon_x \approx 0.45 \mu\text{m}$ and $\gamma\epsilon_y \approx 3 \text{ nm}$, at $N_b \approx 2.6 \times 10^9$). Numerous new beam-diagnostic instruments were developed at the ATF, for monitoring the unprecedentedly small beam size in a storage ring, among which are laser wires, non-invasive diffraction radiation diagnostics, X-ray optics, and interferometry. Damping-ring tuning and correction algorithms were developed, and a young generation of accelerator physicists was trained.

5.2 ATF-2 Final Focus

The ATF-2 is a proposed extension of the ATF extraction line, accommodating a prototype compact final focus³⁴. The ATF-2 final focus is a scaled down version of the NLC, ILC or CLIC final-focus optics, based on a de-

sign principle which has never been put into practice. The ATF-2 final focus will squeeze the extremely low-emittance beam from the ATF damping ring to a spot size of 30 nm with less than 5% orbit jitter. The ATF-2 will also test nm-resolution beam position monitors, various advanced spot-size monitors, as well as feedback and stabilization schemes. Figure 16 presents the ATF layout including the ATF-2 extension.

Figure 16. Layout of ATF/ATF-2 facility with the existing ATF damping ring on the right, and the planned ATF-2 final focus on the top left.

5.3 Polarized Positron Source

A possible scheme of producing highly polarized positron or electron beams is laser Compton back-scattering of a circularly polarized laser off an unpolarized electron beam. The resulting X-ray photons are polarized and their polarization is inherited by the higher-energy component of pairs created when the X-rays impinge on a thin tungsten target. In pioneering experiments at the ATF, about 10^4 positrons were produced per pulse with a measured average polarization of about 75%³⁵. A recent improvement of this scheme, for ILC or CLIC, is the proposal to accumulate the positrons in a dedicated accumulator ring, or in the main damping ring, and, e.g., to combine many small bunches from the Compton-ring source to form one nominal bunch³⁶. The accumulation greatly relaxes the requirements on the laser pulse energy.

6 Neutrino Beams

Neutrino beams can be produced by smashing proton superbeams on a target, by muon decay in a future muon storage ring (ν factory), and by β decay or inverse β decay of unstable isotopes. We discuss the latter two options.

6.1 Neutrino Factory

The physics goals of the neutrino factory are the measurement of the θ_{13} mixing angle, determining the neutrino mass hierarchy, and detecting the CP violating phase δ in the neutrino sector. The target intensity of neutrinos required is a few 10^{20} per year. All neutrino-factory designs so far are based on existing sites with appropriately adapted accelerator infrastructure, like CERN (3.5 GeV s.c. proton linac), FNAL (6 GeV s.c. proton linac), BNL (AGS upgrade), J-PARC (50 GeV RCS), or RAL. In 1999-2001 two US feasibility studies were conducted for the FNAL and BNL sites. As part of the 2003 APS Study on the Physics of Neutrinos, the design of the second feasibility study was re-optimized for cost reduction. The outcome is known as feasibility study IIa and was presented at this conference³⁷.

The ν factory proposed here consists of a high-power proton source (24-GeV BNL AGS upgrade), a target (mercury jet in 20-T solenoid), first a bunching and then a phase-rotation section, cooling (solid LiH absorbers, closed cavity apertures), fast acceleration (comprising a s.c. linac, a recirculating linac, 'RLA', and two non-scaling fixed-field alternating gradient synchrotrons or 'FFAGs'), and a storage decay ring. Figure 17 illustrates the muon acceleration.

Crucial demonstration experiments relate to the three areas of targetry, muon cooling, and acceleration: (1) A mercury jet target with 20 m/s speed will be tested in a 15-T solenoid at the CERN nTOF beamline (experiment "nTOF11"). The instantaneous

Figure 17. Layout of neutrino-factory muon acceleration for feasibility³⁷.

power deposition of 180 J/g in this experiment corresponds to that from a 4-MW proton driver. (2) The first phase of on ionization cooling experiment, "MICE"³⁸, has been approved for construction at RAL. It comprises the assembly of two solenoid tracking spectrometers, which will be cross-calibrated using a muon beam. In a second phase it is foreseen to install one lattice cell of a cooling channel between these spectrometers. The expected emittance reduction is of order 10%. At MICE various absorbers and lattice optics can be tested and compared. (3) The "non-scaling" FFAG is a novel approach, entailing unconventional beam dynamics; building a scaled-down electron-beam model of a non-scaling FFAG is under discussion.

6.2 Beta and Electron-Capture Beams

The physics goals of β or electron-capture beam facilities are similar to those of the ν factories. The main difference is that the neutrinos are produced by the beta decay or inverse beta decay of unstable nuclei instead of muon decay. This type of neutrino beam has recently become more attractive thanks to the discovery of nuclei that decay fast through atomic electron capture, like ^{150}Dy or ^{148}Gd ³⁹, which provides the fascinating possibility to create mono-energetic neutrino beams. The energy of the emitted neutrinos is Lorentz boosted, e.g., in the forward direction $E_\nu = 2\gamma E_0$, where E_0 is the emission energy in the rest frame. It is assumed that 10^{18} neutrinos can be obtained per year, for example, at EURISOL.

Figure 18 shows the schematic of a proposed “CERN to Frejus” (130 km) electron-capture neutrino beam facility. Such a project would greatly profit from an LHC injector upgrade, e.g., from a Super-SPS.

Figure 18. CERN part of a “CERN to Frejus” electron-capture neutrino beam facility³⁹.

7 Muon Collider

A collaboration of Muons Inc., IIT, FNAL and JLAB is developing innovative schemes for a muon collider. The new ideas include⁴⁰ (1) high-gradient rf cavities filled with pressurized H_2 , which simultaneously capture, bunch rotate and cool the muon beam [no strong interactions, no showers], (2) continuous absorbers for emittance exchange, (3) helical cooling channels consisting of solenoid plus transverse helical dipole and quadrupole fields, (4) parametric-resonance ionization cooling, and (5) reverse emittance exchange. These novel concepts are expected to reduce the 6D emittance by about 8 orders of magnitude, which would produce high luminosity, e.g., $10^{35} \text{ cm}^{-2}\text{s}^{-1}$ at 5 TeV c.m. energy, with 10 bunches of 10^{11} muons each per beam.

8 Advanced Acceleration Schemes

Going to even higher energies, beyond several or tens of TeV, will require radically novel concepts. Candidate schemes include laser and plasma acceleration⁴¹.

8.1 Plasma Acceleration

Plasmas can sustain high accelerating gradients of 10–100 GV/m. To produce these fields the plasma must be excited either by a laser or by a drive beam. The resulting plasma wake may be used to accelerate a witness bunch.

One long-standing problem has been the extremely poor beam quality and the large energy spread of electrons accelerated by a laser in a plasma. Recently, three experimental groups accelerated more than 10^9 electrons in a few-mm long plasma interacting with an intense laser pulse to 100–200 MeV with less than 10–20% full energy spread⁴². Planned as the next step is the development of a 1 GeV compact module utilizing a 100 TW laser⁴³. Numerous issues still need to be addressed, however, before a laser-driven plasma can be employed as the primary accelerator in a high-energy collider. Examples are the limited efficiencies of the laser and the plasma, both directly proportional to the collider luminosity.

Closer to a practical application in high-energy physics appears the beam-driven plasma acceleration, which has produced spectacular results in the Final Focus Test Beam (FFTB) line at the end of the SLAC linac. Here, 28.5-GeV bunches of $N_b \approx 2 \times 10^{10}$ electrons, or positrons, with an rms length σ_z of 12–20 μm are sent through a 10-cm Li plasma gas cell of maximum density of 10^{18} cm^{-3} ^{44,45}. In passing the plasma, the bunch excites a large amplitude plasma wave which focuses and accelerates beam particles. For a single bunch, particles in the head of the bunch lose energy, while those at the end of the bunch are accelerated. For the parameter regime of this experiment, the accelerating field scales as $E_z \propto N_b/\sigma_z^2$. Figure 19 shows the energy distribution of a bunch measured by an energy spectrometer without a plasma and when passing through a 10-cm long plasma of $2.8 \times 10^{17} \text{ cm}^{-3}$. The

figure demonstrates that some particles gain more than 2.7 GeV in energy, which corresponds to an accelerating gradient above 27 GV/m. The large energy spread is an artifact of the single-bunch experiment. Future studies will aim at accelerating a second witness bunch travelling at a variable distance behind a short drive bunch.

Figure 19. Single-bunch energy spectra at the end of the SLAC FFTB line without plasma (left), and after traversing a 10-cm long $2.8 \times 10^{17} \text{ cm}^{-3}$ lithium plasma (right)^{44,45}.

8.2 Production of Ultra-Short Bunches

Laser-driven accelerators require the injected bunches to be of femtosecond length. Such bunches can be produced by an inverse free electron laser (IFEL) inducing an energy modulation which is followed by a magnetic chicane for microbunching. In an IFEL, the electron beam travelling through an undulator absorbs energy from a co-propagating laser beam. Experiments by a SLAC-Stanford collaboration have recently demonstrated IFEL operation for a 30-MeV beam at 800 nm laser wavelength over a length of about 6 cm⁴⁶. A peak-to-peak energy mod-

ulation of 50 keV was observed. Adjusting the undulator gap in situ revealed multiple resonances of the IFEL interaction.

8.3 Laser Acceleration

Laser-driven particle acceleration in a structure-loaded vacuum instead of a plasma is also under study. It has some similarities to conventional microwave acceleration. A proof-of-principle experiment has accelerated electrons in a semi-infinite vacuum using 800-nm laser radiation, and it achieved a 40 MV/m peak gradient over a distance of 1000λ ⁴⁷. For net laser acceleration to occur a boundary was proven to be necessary. In the experiment an 8- μm gold-coated Kapton tape was employed. Future applications would use more efficient structures, e.g., ones resembling miniature versions of disk-loaded rf waveguides coupled to a laser.

9 Summary and Conclusion

Ongoing R&D activities for future accelerators are multiple. Exciting results achieved so far and ambitious plans for the future hold great promise for the next decades.

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