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Future Directions of Accelerator-Based NP and HEP Facilities

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Abstract. Progress in particle and nuclear physics has been closely connected to the progress in accelerator technologies - a connection that is highly beneficial to both fields. This paper presents a review of the present and future facilities and accelerator technologies that will push the frontiers of high-energy particle interactions and high intensity secondary particle beams.

Keywords: Particle Physics, Nuclear Physics, Facilities

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ACCELERATORS AND PARTICLE PHYSICS

Progress in accelerator technology is motivated by and has driven advances in both particle and nuclear physics. This started with Ernest Lawrence's first cyclotron built in 1932 and small enough to fit in one's hand and continues with today's Large Hadron Collider with a circumference of 27 km (Fig. 1). This paper reviews the present status and future directions of particle accelerators for particle and nuclear physics with a special emphasis on enabling advanced accelerator technologies. I apologize in advance for not being able to cover all existing and planned accelerator projects.

Most accelerators developed for nuclear and particle physics have dual-use and important spin-offs. An important example is the intense synchrotron radiation radiated by circulating electrons in high energy accelerators. Although a major limitation to the acceleration of electrons to very high energy it was quickly realized that the synchrotron radiation can be used for material research. Whereas initially accelerators would be used for both particle physics and material research in dual-use facilities, most facilities are now mainly dedicated to either of these pursuits. With the advent of ever larger accelerators dual-use might again be possible as is planned for the future SuperB facility in Italy,

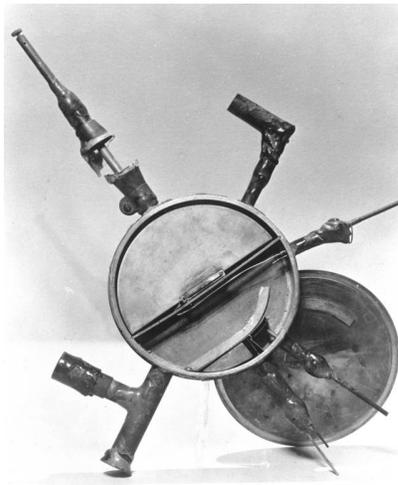


FIGURE 1. Accelerators used for nuclear and particle physics spanned an enormous range of scales from Ernest Lawrence's cyclotron that fit into one's hand to the 27 km circumference Large Hadron Collider at CERN

and could also be the case for the proposed 20 GeV Energy Recovery Linac (ERL) of a future Electron Ion Collider at RHIC. A 20 GeV ERL could drive a very powerful X-ray Free Electron Laser (FEL).

A second example is the application of high beam power proton drivers that were developed for the production of secondary beams of either unstable particles (pions, muons, kaons, radioactive isotopes) or particles that don't readily exist for beam production (neutrons, neutrinos, anti-protons). Such high power beam drivers are now used for the production of intense neutron radiation again for material research. Another important application would be for nuclear waste transmutation or as drivers for subcritical reactors. Although again present facilities are mainly dedicated to their purpose the recently completed J-PARC facility produces neutrino and kaon beams as well as feeds a 1 MW spallation neutron source. Also, the planned 3 GeV high power proton beam of the Project-X at Fermilab could be used for nuclear waste transmutation studies.

Throughout the history of accelerator-based particle physics, efficient reuse of accelerator investments has been very beneficial. This is probably most effectively demonstrated at CERN where an accelerator complex, serving high energy and nuclear physics, was built up over the last five decades. Future accelerator-based particle physics will increasingly rely on large investments in machines and could benefit from using existing facilities, possible dual-use applications and, where possible, cross-use for nuclear and high energy physics.

FACILITIES FOR SECONDARY BEAM PRODUCTION USING FIXED TARGETS

The production of secondary beams includes stable beams such as neutron, neutrino, and anti-proton beams as well as beams of unstable particles such as muon and kaon beams and beams of radioactive isotopes. The facilities consist of a "driver" producing high intensity beams of stable particles impinging on a high power production target.

The main accelerator challenges and issues include high intensity beam sources, low energy beam transport with high levels of space charge, acceleration with high beam loading in the rf cavities, cooling and radiation damage of high power production targets and, in the case of heavy ion drivers, radiation damage of ion strippers.

The beam power of drivers has steadily increased due to a number of recent technological advances. Linear accelerators using superconducting rf cavities allowed for high repetition rate or CW beam production (SNS, FRIB, Project-X). Liquid metal targets are used to minimize radiation and shock damage (SNS, J-PARC). Liquid metal film or high density gas ion strippers allow for higher intensity heavy ion driver (FRIB). Rf cavities loaded with FineMet allows for much higher rf field in low frequency rf cavities and are used in compact Rapid Cycling Synchrotrons (J-PARC). Finally non-scaling Fixed Field Alternating Gradient (FFAG) designs make it possible to build compact drivers with a repetition rate of up to 1 kHz.

Many high power beam drivers exist in the world today. They can be classified into drivers with a short pulse (SP) that use a synchrotron or an accumulator ring and long pulse (LP) drivers, including CW drivers, that use a cyclotron or a linac. Note that the record beam power of 1.3 MW is held by the 590 MeV ring cyclotron at PSI, Switzerland [1]. Further power increases are planned at PSI that will maintain its leading status for years to come.

Several new high power beam drivers have recently been completed, are under construction or are being planned:

- The J-PARC facility in Tokai, Japan, is a 30 GeV proton driver using a Booster and Main ring with FineMet loaded rf cavities. The J-PARC Main Ring is also the first synchrotron with an imaginary transition energy, which avoids the potential instabilities during transition energy crossing. J-PARC has delivered 30 GeV proton beams with 120 kW on the neutrino production target. The design goal is 750 kW. The J-PARC operation was interrupted in March 2011 by a large earthquake off the coast of Japan causing substantial damage to the facility. Amazingly, the facility will be repaired and resume operation at the beginning of 2012 [2].
- Construction is starting for the Facility for Rare Isotope Beams (FRIB), a 0.2 GeV/n, 400 kW heavy ion driver that will produce beams of radioactive isotopes through fragmentation of uranium beam on a high power target [3]. This will be the first installation of a large, CW srf linac for hadron beams. It requires cavities for non-relativistic particle with a high quality factor (Q) to minimize the cryogenic cooling power. The heavy ion beams are produced partially stripped and then pass through an ion stripper as they gain energy. The ion stripper for the high intensity beams will be implemented either with a liquid metal film or a high pressure gas target.
- GSI near Darmstadt, Germany, is planning to expand its facility with a 30 GeV proton-equivalent heavy ion driver plus multiple accumulation and storage rings [4]. The new 30 GeV synchrotron will be using fast cycling super ferric magnets and will be optimized for the acceleration and storage of high intensity, partially stripped uranium ions. Construction is planned to start in 2011.

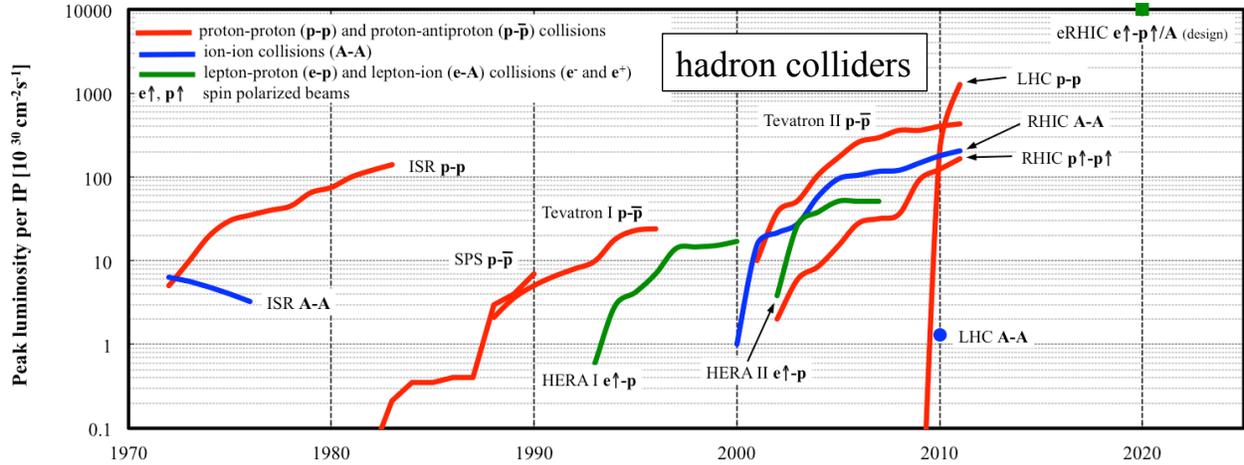


FIGURE 2. History of the peak luminosity of hadron and lepton-hadron colliders [6]

- Project X is a future upgrade of the Fermilab proton facilities. A 3 GeV, 1 mA superconducting linac would provide 3 MW beam power to a number of kaon and muon production targets [5]. A pulsed 5 GeV extension of the superconducting linac would bring the energy up to the injection energy of the Main Injector. After acceleration in the Main Injector to an energy between 60 and 120 GeV a beam power of 2 MW for neutrino production can then be reached. The facility can also be upgraded to serve as a high intensity muon source for a future muon collider. The Project X linacs would be the largest CW and pulsed superconducting linacs.
- The Continuous Electron Beam Accelerator Facility (CEBAF) at JLab is the world's highest energy electron driver, operating reliably at 6 GeV and with a total beam power of 1 MW. Adding an additional 1 GeV of CW superconducting linac sections brings the final energy of the recirculating linac to 12 GeV after 5.5 revolutions[7]. The upgrade is expected to be complete in 2014.

COLLIDING BEAM FACILITIES

Symmetric colliders

Colliding beam facilities are using two counter-rotating or counter-traveling beams with collisions at one or more locations. Colliding beam facilities can reach the highest particle interaction energies. The main challenges are the beam-beam interactions, the direct space charge effect of one beam on the other, the stability and lifetime of the stored beams caused by electron clouds, Intra-Beam Scattering (IBS) and also noise as well as beam polarization preservation at some colliders.

Technological advances have contributed to a very rapid increase of the luminosity, or collision rate, of colliders. Fig. 2 shows a compilation of the luminosity evolution of the major hadron and lepton-hadron colliders and Fig. 3 shows the history of peak luminosity at electron-positron colliders. Superconducting magnets made it possible to accelerate and store very high energy beams. Special surface coating both effectively suppressed the formation of electron clouds as well as increased the pumping speed, particularly in the long, small beam pipes. The luminosity depends strongly on the brightness of the beams and high energy stochastic cooling was developed to counteract IBS during a store and preserve the initial beam brightness. It is also important to preserve the beam quality during the acceleration period and newly developed beam feedback techniques improved the beam control dramatically. For polarized proton beams Siberian snakes are deployed to overcome depolarizing resonances.

The luminosity of colliders naturally increases linearly with the beam energy since adiabatic damping increase the beam brightness without also increasing the beam-beam interactions. Equation [1] shows the luminosity normalized by the Lorentz energy factor γ :

$$\frac{L}{\gamma} = \frac{1}{4\pi} \frac{N_b}{\epsilon_n} \frac{N_b}{\tau_b} \frac{R}{\beta^*} \quad (1)$$

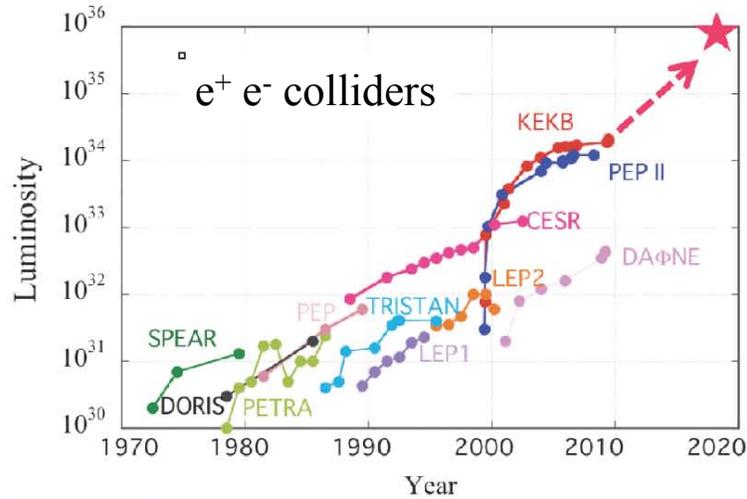


FIGURE 3. History of the peak luminosity of electron-positron colliders [8]

where N_b is the bunch intensity, ϵ_n is the normalized rms beam emittance, τ_b is the bunch spacing, R is the fractural overlap of the two colliding bunches, and β^* is the lattice beta function at the interaction point. The three factors in Equation [1] represent the limitations on the achievable luminosity: N_b/ϵ_n is the bunch brightness that is limited by the maximum level of beam-beam interaction ($< \sim 7 \times 10^{14} \text{ cm}^{-2} \text{ s}^{-1}$ for 2 IPs), N_b/τ_b is the stored beam current limited by both electron cloud formation and beam stability (both forms of beam wake field effects) ($< \sim 1 \text{ A}$), and R/β^* represents geometrical limitations due to limited bunch overlap, hour glass effect and triplet aperture ($< \sim 0.03 \text{ cm}^{-1}$).

With these parameters at their limiting value the maximum normalized luminosity is $10 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This is to be compared to the achieved normalized luminosities at the large hadron colliders: The Tevatron achieved $L/\gamma = 0.41 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ in pbar-p collisions. RHIC has so far achieved $L/\gamma = 0.56 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ and has a luminosity upgrade goal of $L/\gamma = 1.9 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. The LHC at CERN has quickly reached a record value of $L/\gamma = 0.94 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$ with a design value of $L/\gamma = 1.3 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. Further luminosity upgrades with an increased triplet aperture has the goal of achieving $L/\gamma = 6.7 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This final number is approaching the limiting value.

Note that the ISR with its 30 GeV beam energy actually reached a normalized luminosity of $L/\gamma = 4.7 \times 10^{30} \text{ cm}^{-2} \text{ s}^{-1}$. This was achieved with high intensity, debunched proton beams. This points the way to overcome the limitation mentioned above. The ISR was the first example of collisions of long bunches with a large crossing angle. This situation is referred to as collisions with a large Piwinski angle or factor, which is the ratio of the beam crossing angle and the bunch aspect ratio ($\sigma_{trans}/\sigma_{long}$). In this situation the overlap region, and consequently the beam-beam interaction, is reduced by the Piwinski factor. This allows for either increasing the beam intensity or reducing the beam emittance [9][10]. In the first case the luminosity increases but might still be limited by the maximum possible beam current. In the second case, as shown schematically in Fig. 4, the luminosity remains unchanged, but the smaller

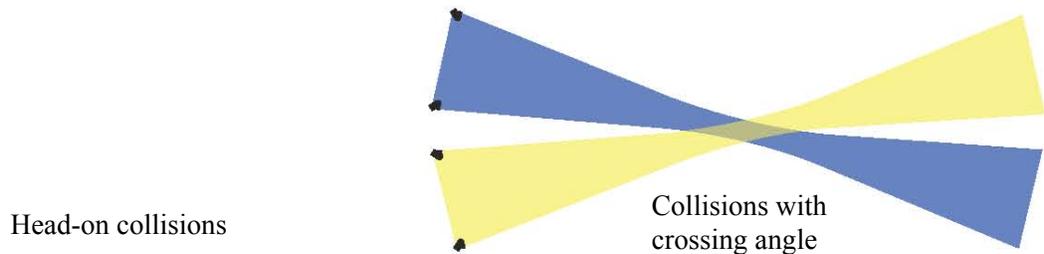


FIGURE 4. Bunch overlap for head-on collisions and collisions with large crossing angle and reduced emittance.

interaction region length and the smaller beam emittance now allows for a reduction, by the same Piwinski factor, of the beta-star. This now leads to an increase in luminosity by the Piwinski factor and the luminosity can exceed the limits referred to above.

Reducing the beam emittance requires a beam cooling process. For electron-positron colliders synchrotron radiation provides such a cooling process and can lead to almost a factor of 100 increase in luminosity. This approach is being planned for the next generation B factories at KEK and in Italy. Fast cooling of hadron beams could be provided by the new concept of "coherent electron cooling" to be tested soon at RHIC [11]. Using such strong beam cooling the RHIC luminosity could be increased by as much as a factor of ten.

There are three hadron colliders operational today:

- The Tevatron at Fermilab consists of a single 6.3 km long superconducting magnet ring that can accelerate protons and anti-protons to 980 GeV each. It was the first accelerator using superconducting magnets and held the energy record of about 2 TeV until it was recently surpassed by the LHC. The collider reached a peak luminosity of $4.3 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ using the most intense anti-proton source. The anti-proton source reach this spectacular level of performance using high power stochastic cooling and the first high energy (8 GeV) electron cooling, which was essential to reach the high beam brightness required for the high luminosity. By the time of the scheduled shut-down of the Tevatron (September 30, 2011) it will have accumulated 12fb^{-1} for each of its two detectors D0 and CDF [12].
- The Relativistic Heavy Ion Collider (RHIC) at Brookhaven started operation in 2000 and consists of two independent 3.8 km long superconducting rings. RHIC has a very high level of flexibility and collides heavy ion (gold) beams with an energy of up to 100 GeV/n and a peak luminosity of $5 \times 10^{27} \text{cm}^{-2} \text{s}^{-1}$, polarized proton beams with an energy of up to 250 GeV and peak luminosity of $1.5 \times 10^{32} \text{cm}^{-2} \text{s}^{-1}$ as well as different species at equal beam energy. Accelerator innovations at RHIC include transition energy crossing with a slow ramping superconducting ring, polarized proton beam acceleration using Siberian snakes, and, recently, high energy bunched beam stochastic cooling to counteract intra-beam scattering. The latter is part of an on-going luminosity upgrade program that also includes the installation of electron-beam lenses to compensate head-on beam-beam interactions [13]. This upgrade program will be completed by 2014.
- The Large Hadron Collider (LHC) at CERN is the latest hadron collider coming on-line. It consists of a single 27 km long ring of 2-in-1 superconducting magnets. The design beam energy is 7 TeV for protons with a design luminosity of $1 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$. The design beam energy for heavy ions (lead) is 2.8 TeV/n. After starting up in 2010 the LHC quickly reached very high luminosities ($3.5 \times 10^{33} \text{cm}^{-2} \text{s}^{-1}$ as of the writing of this paper) at a beam energy of 3.5 TeV, half of the design energy due to limitations of the superconducting wire splices in the interconnects between the dipole magnets [14]. LHC operation will continue through 2012 accumulating up to 10fb^{-1} of proton-proton collisions and an additional Pb-Pb and possible a p-Pb run. This is planned to be followed by an extended shut-down to repair the superconducting wire splices to prepare for operation at the design energy. The LHC is the first accelerator using the magnetically coupled 2-in-1 magnets. The very high energy proton beams also emit significant synchrotron radiation, that requires separately cooled beam screens inside the cold-bore magnets, and the high total stored beam energy requires extremely low losses and an elaborate collimation system.

Plans are already being made for a luminosity upgrade to $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$, five times the design luminosity [15]. This could be achieved with a reduced beta-star, requiring larger bore final focus triplets, increased bunch intensity, and increased crossing angle to reduce the effect of long range parasitic collisions. The latter will require crab cavities to maintain the collision overlap region. Installation of this upgrade is planned for 2021 - 2022.

Electron-positron colliders have reached very high luminosities mainly due to synchrotron radiation that both reduces the beam emittance and stabilizes high intensity beams. Both high luminosity B factories (PEP II at SLAC and KEK B at KEK) have reached more than $10^{34} \text{cm}^{-2} \text{s}^{-1}$ luminosity far exceeded their design values. New proposals for next generation B factories [8], under construction at KEK and approved for construction near Rome, Italy [16], are aiming for luminosities close to $10^{36} \text{cm}^{-2} \text{s}^{-1}$ using strongly cooled "nano-beams" colliding with a large Piwinski factor as described above.

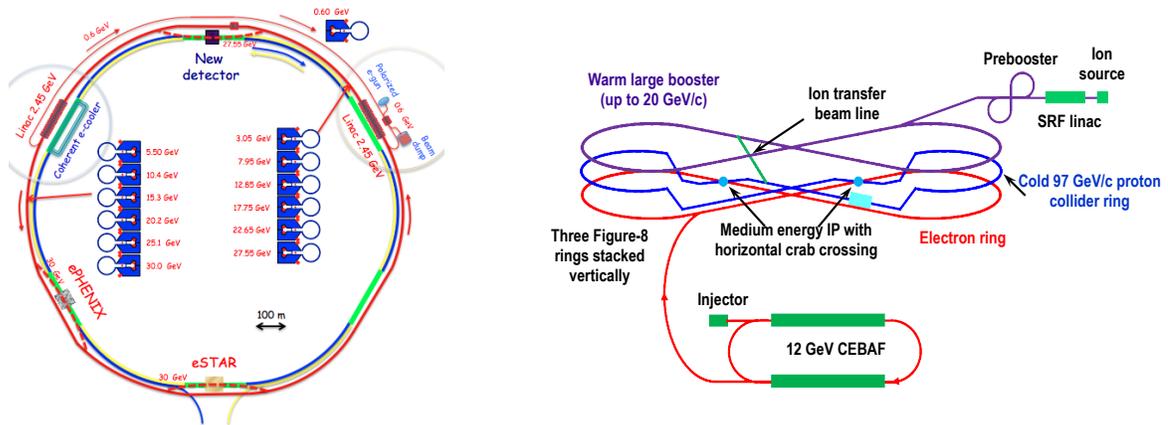


FIGURE 5. The two proposals for an Electron Ion Collider in the U.S. are eRHIC at BNL (left) and MEIC at JLab (right).

Lepton-hadron colliders

There is renewed interest in a electron-ion collider, four years after the very successful electron-proton HERA facility at DESY ended operation. The two new proposals in the U.S. (Fig. 5) focus on the collision of polarized electrons with polarized protons at very high luminosity to measure the gluon spin structure at low x and electrons colliding with heavy ions for high-resolution imaging of gluon-dominated matter.

eRHIC at BNL would add a 5 - 30 GeV electron accelerator, based on an Energy Recovery Linac (ERL) with 6 recirculating passes inside the existing RHIC tunnel, to collide with the existing RHIC beams (250 GeV polarized protons and 100 GeV/n heavy ions) [17]. With the ERL the electron bunches would collide with the ion bunches only once and would allow for a very large disruption from the beam-beam interaction, which results in luminosities of up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. Because of the single pass nature of the collider a very intense (50 mA) polarized electron gun is required, which is a factor of 10 beyond the state-of-the-art. To reach the high luminosity the ion beam will also have to be strongly cooled using coherent electron cooling as described above. Construction of a first stage, using a 5 GeV electron beam, could be completed by 2024.

The first stage EIC proposal at JLab is called Medium Energy Ion Collider (MEIC) and would add a 3 - 11 GeV electron storage ring, using the present CEBAF as a full energy injector, and a new polarized proton (2- - 100 GeV) and heavy ion (12 - 40 GeV/n) accelerator complex [18]. The high luminosity of up to $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ would be achieved with a very high, 750 MHz bunch frequency as well as strong electron cooling of the ion beams. The whole complex would be layed out in the shape of a figure-8 to preserve beam polarization, including polarized deuteron beams, without needing Siberian snakes. Construction of this first stage could also be completed by 2024. A second stage would include a 20 GeV electron ring and a 250 GeV proton ring.

There is also a proposal to collide a polarized electron beam from a 60 GeV ERL with the high energy LHC proton beam. Such a facility, called LHeC, would focus on continuing the search for lepto-quarks started at HERA.

Towards a 3 TeV parton collision energy

If there is a future collider at the energy frontier it will have to exceed the LHC parton collision energy of about 1.5 TeV by a significant factor. There are presently three options that are pursued with R&D efforts:

- An linear electron-positron collider with up to 1.5 TeV beam energy would reach a 3 TeV parton collision energy. To limit the size and cost of such a facility a very high acceleration gradient is necessary. The International Linear Collider (ILC) collaboration is pursuing 32 MV/m superconducting rf cavities to reach a 250 GeV beam energy upgradable to 500 GeV [19]. Alternatively, the Compact Linear Collider (CLIC) collaboration at CERN is planning to use 100 MV/m normal conducting rf cavities driven by a second low energy high intensity electron beam [20]. A first stage would also reach 250 GeV that could be upgraded to 1.5 TeV beam energy. Although a linear collider is not limited by synchrotron radiation, as are ring colliders, the electrons still radiate as they approach the opposing bunch. This leads to a significant energy spread of the colliding electrons and positrons

and also limits the energy reach of electron-positron colliders to about 3 TeV parton collision energy. Also, linear colliders are necessarily very large and consume a very large amount of electric power.

- High energy muon beams can be stored in a collider ring without excessive energy loss from synchrotron radiation. Using ionization cooling and fast acceleration to 2 TeV a compact, high luminosity $\mu^+ - \mu^-$ collider could be possible starting with a 4 MW proton driver for the production of the muon beam [21]. The decaying muons can produce a significant background problem - even the neutrino radiation fan from the high energy storage ring could result in a radiation dose in uncontrolled areas that exceeds legal limits. However, the muon collider is the only facility that can produce mono-energetic 4 TeV parton collisions.
- Finally doubling the magnetic field of the LHC dipoles would allow for 16.5 on 16.5 TeV proton collisions corresponding to about a 3 TeV parton collision energy. 20 Tesla 2-in-1 superconducting magnets might be possible using a hybrid design of Nb_3Sn , Nb_3Al , and High Temperature Superconductor (HTS) [15]. Doubling the LHC energy would require several additional major upgrades but there are no fundamental issues that would prevent it other than the development of 20 T magnets.

Any of these options are clearly both technically and financially very challenging and are likely to await the full exploitation of the LHC physics potential.

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