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Future High Energy Colliders and Options for the U.S.

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Abstract: The United States has a rich history in high energy particle accelerators and colliders – both lepton and hadron machines, which have enabled several major discoveries in elementary particle physics. To ensure continued progress in the field, U.S. leadership as a key partner in building next generation collider facilities abroad is essential; also critically important is to prepare to host an energy frontier collider in the U.S. once the construction of the LBNF/DUNE project is completed. In this paper, we briefly discuss the ongoing and potential U.S. engagement in proposed collider projects abroad and present a number of future collider options we have studied for hosting an energy frontier collider in the U.S. We also call for initiating an integrated national R&D program in the U.S. now, focused on future colliders.

Keywords: Accelerator Subsystems and Technologies, Colliders

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Contents

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1 Introduction

High energy particle accelerators and colliders [1, 2] have played a central role in the experimental establishment of the Standard Model, enabling discoveries of elementary particles, and extensive studies and precision measurements of their properties. The U.S. has been at the forefront of the field, defining progress in particle physics with major discoveries at U.S. high-energy accelerator facilities, for example, at Brookhaven National Laboratory, Stanford Linear Accelerator Center (SLAC) and Fermi National Accelerator Laboratory (Fermilab): the muon neutrino [3], evidence for the quark model [4, 5], the charm quark [6, 7], the tau lepton [8, 9], the bottom quark [10], the

top quark [11, 12] and the tau neutrino [13]. Fermilab's Tevatron, which operated for well over 25 years, had been the world's most powerful proton/anti-proton accelerator and hadron collider prior to the commissioning of the Large Hadron Collider at CERN. The role of U.S. leadership in advancing accelerator technology in these endeavors has also been indisputable.

After the unfortunate cancellation of the Superconducting Super Collider (SSC) construction project (design $\sqrt{s}$ = 40 TeV) in the U.S. in 1993, the global HEP community came together to build the Large Hadron Collider (LHC) at CERN. With the beginning of operations of the LHC in 2008, Fermilab switched its focus to flagship research at the intensity frontier, and the Tevatron collider ($p\bar{p}$ at $\sqrt{s} \simeq 2$ TeV) was shutdown in 2011. However, using the data collected from the Tevatron Run until the shutdown, the CDF and D0 collaborations were able to find a 3σ evidence [14] for the Higgs boson, produced in association with the weak bosons and decaying to bottom-antibottom quark pairs. The spectacular discovery of the Higgs boson in 2012 by the CMS and ATLAS experiments at the LHC [15, 16], a crowning achievement of the Standard Model and for the collider community, illuminates the path forward.

While the U.S. domestic program pursues the development and execution of neutrino and muon physics projects, the high luminosity upgrade of the LHC (HL-LHC) at CERN would provide a compelling and comprehensive program that includes essential measurements of the Higgs properties. An e^+e^- collider (either linear or circular) can provide the next outstanding opportunity to investigate the properties of the Higgs boson, a unique and special particle in the SM, in detail and with exquisite precision. Beyond an e^+e^- collider for studies of the Higgs, either a very high energy post-LHC proton-proton collider or a multi-TeV muon collider would provide extensive direct reach for new physics beyond the SM.

The U.S. particle physics community came together over the past two years, during its so-called "Snowmass" study, to carry out an extensive study of the status of the field and to develop a vision and plan for the future. This allowed for in-depth studies of these future collider facility options. The Snowmass'21 Implementation Task Force (ITF) evaluated, with input from the proponents, numerous proposed future collider projects for performance, technology readiness, schedule, cost, and environmental impact. In the process, the ITF has developed metrics for uniform comparison of the proposals ranging from Higgs/EW factories to multi-TeV lepton, hadron and ep collider facilities, based on traditional and advanced acceleration technologies – see Ref.[17].

In this paper, we briefly outline global projects under consideration abroad and U.S. engagement in those projects, and discuss in greater detail options for a future high energy collider facility in the U.S.

1.1 Physics Landscape

The Standard Model (SM), developed in the 1960s and 1970s, describes a universe in which fermions, the fundamental constituents of matter, interact via fundamental forces propagated by gauge bosons. The Standard Model has been validated extensively through precision experiments and found to be incredibly successful at describing our world. The discovery of the Higgs boson [15, 16], which was the last missing piece of the Standard Model, was another major triumph.

However, despite the huge success of the SM, there are a number of experimental observations that it fails to explain. It does not fully explain the baryon asymmetry, incorporate the theory of gravitation as described by general relativity, or account for the accelerating expansion of the

Universe as possibly described by dark energy. The model does not contain any viable dark matter particle that possesses all of the required properties deduced from cosmology and astrophysics. It also does not incorporate non-zero neutrino masses and their oscillations. Furthermore, the model suffers from several internal shortcomings, such as the hierarchy problem, where fine-tuned cancellations of large quantum corrections are required in order for the Higgs boson mass to be near the electroweak scale. It is evident that the Standard Model is just an effective theory that appears, so far, to be valid at the energies experimentally accessible today.

For the next two decades, the LHC will remain the highest energy collider in the world. The full LHC dataset is expected to be approximately 3 ab^{-1}. Such a dataset will provide great opportunities for studies of the SM, including detailed characterization of the Higgs boson. Deviations from Standard Model predictions in these measurements can be an indirect evidence of new physics at energy scales higher than those accessible directly. Precision on many of the Higgs boson couplings at the HL-LHC is expected to reach few percent level [18], thus allowing to probe large phase space of new physics. Besides detailed exploration of the SM, the LHC is a discovery machine. The HL-LHC data will greatly extend the sensitivity for new physics, with excellent chances for fundamental discoveries.

However, it is conceivable that the HL-LHC dataset will not be sufficient to discover and fully characterize new physics. Higher collision energies would enable exploration of the laws of Nature at ever-shorter distances, providing a deeper understanding of fundamental particles and fields. Furthermore, both hadron and lepton future colliders [2] enable even more precise measurements of Standard Model parameters, including those in the Higgs sector, which in turn provide deeper insight into the mechanism of electroweak symmetry breaking [19, 20].

It is evident that detailed exploration of the electroweak sector of the Standard Model remains a high priority for the field. This includes precise determination of the nature of the Higgs boson, including measurements of its properties and couplings. In particular, measuring Higgs boson couplings at the sub-percent level allows to constrain a wide range of new physics models or provide first indirect evidence of beyond the SM (BSM) particles or forces [21]. Measurements of the Higgs boson decay rate to invisible particles and its total width are also very important for discovering or constraining BSM physics. Beyond the couplings, measurements of Higgs boson self-interactions allow to fully establish the shape of the Higgs potential and verify if it agrees with the SM predictions. While the Higgs boson remains the centerpiece of the precision physics program, many other rare SM processes continue to attract significant interest. These include studies of lepton flavor universality in B meson decays, flavor changing neutral currents in top decays, $\tau \to 3\mu$ and others [22]. Measurements of the mass and width of the vector bosons, the electroweak mixing angle, and the vector boson scattering amplitudes would further shed light on the underlying structure of the electroweak sector of the SM [23].

Increasing the energy scales accessible at the colliders allows the laws of nature to be probed directly at ever shorter distances, which permits the exploration of underlying principles that may govern the properties of the elementary fields [24]. It may lead to the discovery of new particles or forces that are impossible to produce, or not produced in sufficient numbers, at present colliders. The purest science driver is therefore the exploration of the unknown. Prominent objectives include particle explanations of dark matter, the matter-antimatter asymmetry, probes for the existence of new gauge or space-time symmetries, as well as tests of theories containing multi-TeV resonances.

Furthermore, only higher-energy colliders may probe the key question of whether the particles currently considered elementary are, in fact, composite states at shorter distances. Finally, the future colliders program has certain unique synergies with the neutrino and precision frontiers, which enable a complementary program of physics measurements at neutrino factories and/or fixed-target experiments.

1.2 Existing and proposed facilities

Following the recommendation of the U.S. Particle Physics Project Prioritization Panel (P5) in 2014 [25], a strong program for "Building for Discovery" in the U.S. for neutrino and muon-beam based physics is underway. The major component of the program, the Long Baseline Neutrino Facility (LBNF) to host the Deep Underground Neutrino Experiment (DUNE), is being implemented. A new 800 MeV Superconducting Radio Frequency (SRF) PIP-II (Proton Improvement Plan-II) accelerator under construction, will provide ultra-intense neutrino beams to DUNE. The LBNF/DUNE and PIP-II accelerator projects are expected to be completed by the end of this decade.

The U.S. collider physics community is engaged in physics and upgrades at the LHC, including the HL-LHC program at CERN which will commence later in this decade. The U.S. is engaged in both accelerator upgrades and upgrades of the experiments to ensure maximum physics output from the program.

The Higgs boson discovery at the LHC has led to a greatly renewed interest in the world HEP community towards planning next generation colliders [2]. The need for two categories of colliders is apparent: 1) a Higgs Factory that would enable extensive and precision studies of the Higgs boson; and 2) a post-LHC energy frontier collider, e.g. $\sim$ 100 TeV scale, hadron collider, or $\geq$ 10 TeV muon colloider to advance the energy frontier explorations in search of new physics beyond the Standard Model.

Since the measured Higgs mass is $\sim$ 125 GeV, several proposals for an electron–positron Higgs Factory, have been made in Europe and Asia:

- International Linear Collider (ILC), being considered in Japan [26–28],
- Compact Linear Collider (CLIC) at CERN [29],
- Future Circular Collider (e^+e^-: FCC-ee) [30] to be followed by a hadron collider (FCC-hh) at CERN [31], and
- Circular Electron–Positron Collider (CEPC) to be followed by Super Proton-Proton Collider (SppC) in China [32, 33].

Recently, there has been a significant resurgence of interest in muon colliders, which have also been studied for over two decades. A muon collider could be built as a Higgs Factory at $\sqrt{s}$ of $\sim$ 125 GeV for precision studies of the Higgs properties while multi-TeV muon colliders could provide competitive discovery potential and precision measurements, on par with hadron colliders at several tens of TeV.

Apart from the aforementioned global collider projects under development over the past couple of decades, there are many novel concepts for colliders of modest size and cost, that have emerged in the past couple of years.

1.3 Emerging Concepts and proposals

The energy frontier facilities that address the HEP mission of studying the Higgs boson in detail and with great precision, and for pursuing new physics beyond the HL-LHC reach, include linear e^+e^- colliders, circular (preferably large circumference) e^+e^- storage rings, muon colliders, and high energy hadron colliders. We have mentioned global megaprojects of ILC, FCC, CLIC, CEPC/SppC that have been studied extensively and we will discuss the U.S. engagement in some of these projects very briefly in this paper. With the resurgence of interest in a muon collider, an international muon collider collaboration (IMCC) has been formed based at CERN. The U.S. engagement in IMCC will also be discussed here. In addition to the robust machine proposals mentioned in the previous section, ideas for intermediate scale, modest-cost, compact colliders have emerged recently. These proposals include:

- a novel "Cool Copper Collider (C^3)" linear collider concept (250 GeV to potentially 550 GeV collider can fit on Fermilab site) [34, 35],
- linear colliders based on high gradient SRF (in the accelerating gradient range of 50 MV/m to 90 MV/m; standing wave or travelling wave structures). A center of mass energy reach between 250 and 500 GeV with the facility's central campus within the Fermilab site is possible [36],
- 16-km circumference site-filler circular e^+e^- collider, from Z to the Higgs (90 – 240 GeV), described in Sec. 4,
- muon colliders from Higgs Factory (125 GeV) to a maximum energy of 8 – 10 TeV, in three or four stages, described in Sec. 2.3,
- a proton-proton collider (24 – 27 TeV) in a 16 km circumference site-filler tunnel, described in Sec. 6.

Some of these machine options have been described in detail elsewhere; we briefly outline them here and cite relevant papers. Other proposals we discuss in some detail. We show in Table 1 some of the salient machine and performance parameters for various relevant e^+e^- Higgs factory machine options.

We would like to emphasize that a strong R&D program addressing major challenges for these concepts need to be undertaken to make timely progress. Early emphasis in the R&D could be placed on design/simulation studies including tools development that would have applicability for all of the promising collider concepts. Focused and intense R&D on most promising collider option(s) should be undertaken over the next several years to investigate and address major technological challenges, perform preliminary feasibility studies and produce CDR-level reports before the start of the next U.S. Particle Physics Community Study (next "Snowmass" study). To achieve this goal, we have proposed that an integrated collider R&D program in the U.S. be launched as soon as possible. Synergies with intensity frontier facility requirements, where available, should be taken into consideration while planning the R&D program.

	ILC	CLIC	C^3	HELEN	FCC-ee	CEPC	FNAL Site Filler
Length/Circumference [km]	20.5	11	8	7.5	91	100	16
Collision energy [GeV]	250	380	250	250	240	240	240
Average beam current [mA]	0.021	0.015	0.016	0.021	27.	16.7	5.0
Total SR power [MW]	n/a	n/a	n/a	n/a	100	60	100
Total power (MW)	111	110	~ 150	110	290	340	~ 200
Number of IPs	1	1	1	1	4	2	1
Peak $\mathcal{L}$ / IP [10^{34} cm^{-2}s^{-1}]	1.35	1.5	1.3	1.35	5.0	5.0	~ 1.3

Table 1. Comparison of important machine parameters for various e^+e^- Higgs factory options.

2 U.S. Engagement in Global HEP Projects

2.1 International Linear Collider (ILC)

2.1.1 Introduction and status

The International Linear Collider has been the prime candidate for a Higgs Factory since the discovery of the Higgs boson. Since then, it has been under consideration to be hosted in Japan. The collider facility will be about 20.5 kilometers in total length. ILC will accelerate beams of electrons and positrons to 125 GeV each in two superconducting RF linacs, and collide them at the center of the machine where detector(s) will record the data from the collisions, see e.g., [26–28].

Operating at 250 GeV, the ILC (referred to as ILC250) will provide for copious production of the Higgs boson along with a Z boson via the process $e^+e^- \rightarrow ZH$. The baseline design instantaneous luminosity of the ILC250 is 1.35×10^{34} cm^{-2}s^{-1}. There are proposals to upgrade to higher luminosity (up to 8.1×10^{34} cm^{-2}s^{-1}) [37] and with beam polarization (80% for electrons and 30% for positrons), the effective luminosity would be about 2.0×10^{35} cm^{-2}s^{-1} . With some modest investment, the ILC will be upgradeable to higher collision energies up to 380 GeV in the future. In principle, upgrades to 500 GeV, 1 TeV, and beyond are possible [28, 38].

The underlying SRF linac technology (originally developed for TESLA collider project [39]) is mature and has been utilized in a number of SRF projects throughout the world, such as free electron laser facilities European XFEL at DESY and LCLS-II at SLAC. The cavity production data (from 831 cavities) for European XFEL show that it is possible to mass-produce cavities with desired gradient and efficiency.

As reported in the ILC TDR [40], during phase II of the R&D program, 94 ± 6% yield has been achieved for cavities that demonstrated accelerating gradients > 28 MV/m and 75 ± 11% for 35 MV/m (ILC specification 31.5 MV/m). This ensemble of cavities has an average gradient of 37.1 MV/m. The yields were demonstrated after re-treating cavities with gradients outside the ILC specification. Laboratories from three regions – America, Asia, and Europe – developed this critical technology over the years. Cryomodules are built globally at DESY, CEA, FNAL, JLAB, KEK, and in China. Cryomodules meeting the ILC gradient specifications have demonstrated operation with beam at Fermilab [41] and KEK [42].

SRF was chosen as the ILC technology in 2005 for multiple reasons, including:

- power-efficient acceleration (beam power to AC power efficiency) with the total AC power of ~110 MW for ILC250,
- relaxed alignment tolerances compared to room-temperature designs due to larger apertures,
- larger vertical beam spot at collision (7.7 nm) than for normal conducting linear colliders,
- feasibility to implement both bunch-train-to-bunch-train and intra-train beam orbit feedback due to long RF pulses and large bunch separation within the train (727 μs and 554 ns, respectively),
- luminosity upgrades via increased beam power,
- energy upgrades with gradient advances in SRF technology.

Other critical items for ILC accelerator technologies are nano-beams for final focus, low-emittance damping rings, and positron production. Accelerator Test Facility 2 (ATF2) was built at KEK in 2008 as a test-bench for the ILC final focus scheme. The primary goals were to achieve a 37 nm vertical beam size at the interaction point (IP), and to demonstrate beam stabilization at the nm level. After scaling for the beam energies from 1.3 GeV (ATF2) to 250 GeV, the 37 nm beam size corresponds to the TDR design value of 5.7 nm at 250 GeV beam energy. The goal has been reached within 10%, validating the final focus design. Experiments at CESR-TA (CESR Test Accelerator) at Cornell have demonstrated confidence in the ILC damping ring parameters.

The baseline machine parameters remain stable since the publication of the Technical Design Report (TDR) in 2013 [40, 43] with some recent updates [27, 28, 44]. The ILC cost was evaluated in 2012 for the TDR using a detailed, bottoms-up approach. It has been reevaluated since then for the 250 GeV Higgs Factory. The overall construction cost of ILC250 is estimated to be in the range of 4.8 – 5.3 BILCU (Billions of ILC Units, 1 ILCU is approximately 1 US$), excluding labor and detectors. The labor is evaluated at 10,000 person-years, and the detectors cost at 0.7 BILCU plus 2,200 person-years. Much R&D, in recent years, has also been focused towards cost-reduction for the machine.

If the efforts led by Japan continue, it is anticipated that after a couple of years of transition period with very modest investment in the most critical, high priority activities, an approximately four-year Pre-Lab will be organized that would prepare the project for the beginning of construction.

2.1.2 U.S. engagement

The U.S. institutions have been involved in the development of the SRF TESLA technology from the very beginning, making important contributions. In fact, the first TESLA collider workshop was held in the USA, at Cornell University [45] in 1990. In addition to SRF, the U.S. laboratories have participated in almost all other aspects of the ILC development: electron and positron sources, RF power distribution, damping rings, beam delivery system, beam dynamics, instrumentation, detector R&D. Fermilab, in particular, contributed to developing fundamental RF power couplers, cavity frequency tuners, the 1.3 GHz cryomodule design, design of the 3.9 GHz cryomodule and all its components, etc.

In recent years, the U.S. community has been engaged in collaboration with Japan in the framework of the ILC Cost Reduction R&D Program and more generally in updating ILC plans

via participation in the ILC International Development Team (IDT) [46]. New surface treatment processes were developed at Fermilab for the cavity preparation process, allowing the cavities to achieve higher accelerating gradients while improving the quality factors at the same time. Applying these new treatments to ILC would provide opportunities to i) improve the efficiency of ILC250, ii) upgrade the luminosity, and iii) upgrade the energy of collisions as described in [37]. The anticipated savings from the ILC Cost Reduction R&D is $\sim 10\%$. In addition to the cavity R&D, Fermilab scientists and engineers are involved in updating designs of the ILC cryomodule and some components and in efforts to harmonize pressure vessel codes across the three regions. Fermilab, JLAB and Old Dominion University are developing new SRF crab cavities for ILC.

As of this writing, the plan for the U.S. community is to continue engagement in preparations for the ILC in Japan.

2.2 Future Circular Collider (FCC)

2.2.1 Introduction and status

The proposed circular collider FCC-ee is a well-studied e^+e^- machine to be located surrounding CERN and Geneva. The double-ring collider would operate at center of mass energies ranging from the Z-pole (91 GeV) to $t\bar{t}$ (365 GeV). The present optimized main tunnel length is about 90.7 km. Bunched beams (with $\sim$ ampere current) maintained by SRF cavities would circulate in the two rings, one per beam, and collide in up to four interaction regions. The projected luminosity per IP ranges from 1.8×10^{36} cm^{-2}s^{-1} at the Z to 1.25×10^{34} cm^{-2}s^{-1} at the $t\bar{t}$ within the limit of 50 MW of synchrotron radiation power loss per beam. A full-energy injector ring located in the same tunnel would top-up the beam currents in the collider rings. In addition to the new ring, the injector chain would reuse significant parts of the present CERN infrastructure. A CDR has been written in 2018 [30] and recently updated to a 4-IP lattice. Significant design efforts and R&D have been completed including lattice, magnets, IR, site, and staging. The crucial future technical R&D will concentrate on developing the 11.3 GV SRF systems (at 400 MHz and 800 MHz) for collider rings and 11.3 GV 800 MHz SRF system for the booster ring, which would include higher order mode (HOM) damped cavities and highly efficient RF klystrons.

Though technically the project is nearly ready to proceed, it needs to wait for the HL-LHC operational program to be completed leading to a start date for the FCC-ee physics program in late 2040s. Its construction cost is projected by the proponents to be about 10.5 BCHF (European accounting) and an additional 1.1 BCHF for the RF needed to go to the $t\bar{t}$ energy. The FCC collaboration is carrying out extensive R&D and prototyping effort. To the project's advantage, circular e^+e^- colliders overall have a half-century long history of success including CESR and PEP-II in the U.S. and LEP/LEP2 at CERN. Multi-ampere beams have been demonstrated at PEP-II and KEKB in Japan. The SuperKEKB collider in Tsukuba, now in operation, will demonstrate in the next few years nearly all the required accelerator physics techniques for the FCC-ee, as will the future electron ring for the electron-ion collider (EIC) at Brookhaven National Laboratory.

Among the main challenges for FCC-ee are: i) the peak luminosity within the given synchrotron radiation power limit P_{SR} drops at higher beam energies approximately as $L \propto P_{SR}/E^3$; ii) a crab waist collision scheme with a large crossing angle, high bunch charges and mm-level vertical beta functions need solid verification; iii) SRF cavities with strong HOM damping required to support

multi-ampere beams need to be developed and tested; iv) overall cost and total facility site power reduction strategies need to be fully explored.

Following the execution of the FCC-ee physics program, in a way similar to the hands-off between LEP/LEP2 and LHC, the FCC-ee tunnel can be dedicated to a hadron collider called FCC-hh [31]. FCC-hh can provide proton–proton collisions with a center-of-mass energy of $\sim$ 100 TeV, instantaneous luminosity ranging from 5×10^{34} cm^{-2}s^{-1} to 30×10^{34} cm^{-2}s^{-1} and an integrated luminosity of $\sim$ 20 ab^{-1} in each of the two main experiments for 25 years of operation.

The collider would use the existing CERN accelerator complex as injector facility at $\sim$ 3.3 TeV from the LHC and, with a filling factor of 0.8, would require dipole fields just below 16 Tesla to keep the nominal beams on the circular orbit.

Many technical systems and operational concepts for FCC-hh can be scaled up from HL-LHC but will require, in some cases, additional R&D. Particular technological challenges arise from the higher total energy in the beam (20 times that of LHC), the much increased collision debris in the experiments (40 times that of HL-LHC) and far higher levels of synchrotron radiation in the arcs (200 times that of LHC).

2.2.2 U.S. engagement

The U.S. HEP community has long-term, very productive and close ties with the CERN collider program. In general, our community supports the main recommendations of the 2019 European Particle Physics Strategy Update (EPPSU 2019) [20] to consider exploration of Higgs physics, and Higgs factory as the highest priority for particle physics after completion of the LHC program. The U.S. is ramping up its engagement in the efforts on Future Circular Colliders (FCC) at CERN, while the European community, led by CERN, is carrying out technical and financial feasibility studies for FCC-ee. A U.S. DOE-CERN agreement was signed in December 2020 to formalize collaborations in the FCC efforts, and various US contributions to the FCC-ee project are being considered by the US community. There is significant expertise available in the U.S. in the area of accelerator design and corresponding R&D, and it would be beneficial to engage early with organization of the FCC-ee related effort.

Apart from the pioneering R&D on the high Q_0 SRF and high field (HF) magnets that are needed for the FCC-ee, and FCC-hh, respectively, new U.S.-CERN collaborative efforts on tunneling issues, civil engineering, accelerator design, beam physics, etc. are developing. Some of the design and beam physics topics for FCC-ee are also synergistic with other e^+e^- machines. Examples of common topics include studies of the machine-detector interface, beam collimation, and tuning of linear and non-linear optics. Supported topics would be a mix of theory, simulation, and hardware development and experiments. Working groups in the U.S. for engagement in accelerator and detector studies are being put in place.

2.3 Muon Collider

2.3.1 Introduction

A colliding beam facility based on muons has a number of advantages [47] when compared to e^+e^- and pp machines. First, since the muon is a lepton, all of the beam energy is available in the collision. Second, since the muon is roughly 200 times heavier than the electron and thus emits

around 10^9 times less synchrotron radiation than an electron beam of the same energy, it is possible to produce multi-TeV collisions in a Fermilab-sized circular collider. The large muon mass also enhances the direct "s-channel" Higgs-production rate by a factor of around 40,000 compared to that in electron–positron colliders, making it possible to scan the center-of-mass energy to measure the Higgs-boson line shape directly and to search for closely spaced new physics states. Finally, high-energy muon colliders are the most efficient machines in terms of power per luminosity. While the above arguments are highly appealing, there are several challenges with muons. First, muons are obtained from decay of pions made by higher energy protons impinging on a target. The proton source must provide very high intensity beams, and very efficient capture of pions is required. Second, muons have very large emittance and must be cooled quickly before they decay. Given their short lifetime, ionization cooling [48] is the only viable option. Moreover, conventional synchrotron accelerators are too slow and recirculating accelerators and/or pulsed synchrotrons must be considered. Because they decay while stored in the collider, muons irradiate the ring and detectors with decay electrons. Shielding is essential and backgrounds will be high.

2.3.2 Muon Collider History

The concept of a muon collider is not new. Muon storage rings were mentioned in the literature in 1965 [49] and concepts for a muon collider and for the required muon cooling were developed in the 1970s and 1980s. A muon collider collaboration was formed in the U.S. in the 1990s which delivered a design report in 1999 [50]. In 2000, the Neutrino Factory and Muon Collider Collaboration (NFMCC) was formed [51] which set out to perform a multi-year R&D program aimed at validating the critical design concepts for the Neutrino Factory (NF) and the Muon Collider (MC). The Muon Accelerator Program (MAP) [52] was a follow-on (approved in 2011) program to the NFMCC and was tasked to assess the feasibility of the technologies required for the construction of the NF and the MC. At the conclusion of MAP the program had achieved a number of significant milestones:

1. Full development of the principal elements of the NF and the MC [52] (see Figure 1).
2. End-to-End simulation of cooling for the MC [53].
3. Demonstration of a mercury-jet target capable of 8 MW operation [54].
4. Operation of a high-gradient 805 MHz RF cavity in high magnetic field [55].
5. First demonstration of muon ionization cooling (MICE [56]).

Although MAP was terminated in 2016, work continued on documenting the program's results and has provided a "jumping-off" point for the recently formed International Muon Collider Collaboration (Sec. 2.3.3).

2.3.3 International Muon Collider Collaboration

The 2019 update of the European Strategy for Particle Physics identified muon colliders as a highly promising path to reaching very high center-of-mass energies in leptonic collisions. These machines therefore combine excellent new physics discovery potential with high precision capabilities. In

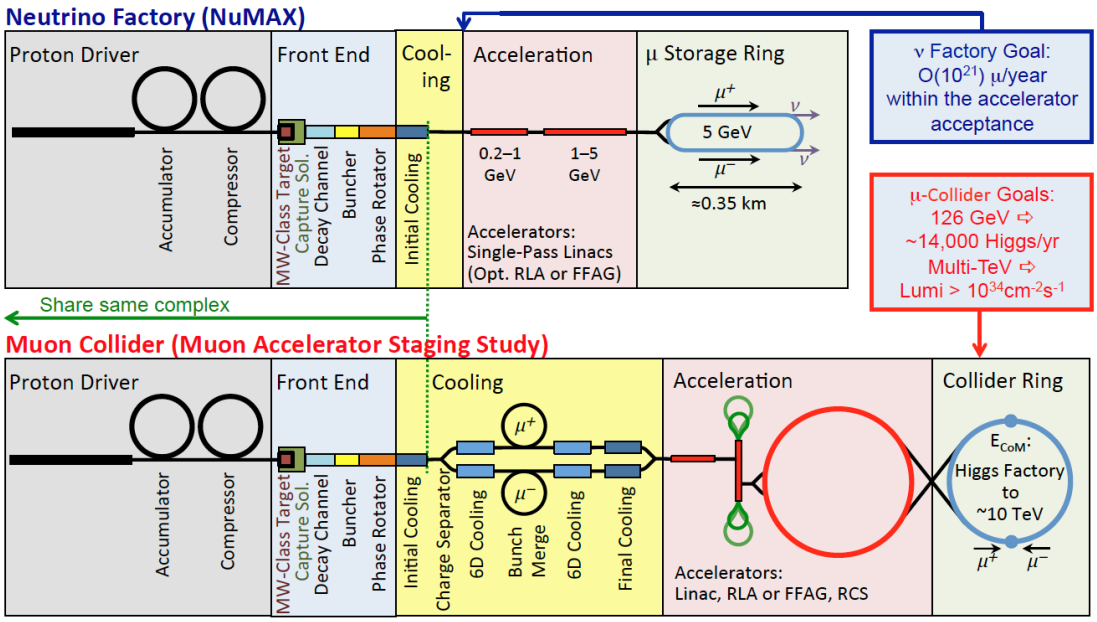

Figure 1. Schematic diagrams showing the principal elements of a Neutrino Factory and a Muon Collider.

response to these findings, the European Laboratory Directors Group (LDG) formed a muon beam panel and charged it with delivering input to the European Accelerator R&D Roadmap covering the development and evaluation of a muon collider option. In parallel, CERN initiated formation of a new International Muon Collider Collaboration (IMCC) to assess feasibility of building a high energy muon collider, identify critical challenges, and develop an R&D program aimed to address them. The effort includes development of the machine-detector interface (MDI), detector concepts, and an evaluation of the physics potential.

The collaboration is hosted by CERN. The near-term goal is to establish by the next European Strategy for Particle Physics Update whether an investment into a full Conceptual Design Report and a demonstrator are scientifically justified. Depending on the outcome of this study and the decisions made at the next EPPSU, the design can be further optimised and a demonstration program can be executed in the following years. The latter contains one or more test facilities as well as the development and testing of individual components and potentially dedicated beam tests. The resulting conceptual design will demonstrate the possibility to technically commit to the collider. In this case a technical design phase will follow to prepare for the approval and ultimate implementation of the collider.

The design strategy taken by IMCC relies heavily on the concepts developed by the MAP collaboration [57]. In the baseline design, muons are produced in decays of pions that are produced by colliding a multi-megawatt proton beam onto a target. The muons are then cooled to the emittances necessary to achieve target luminosities, rapidly accelerated to the desired energies in order to minimize the number of muon decays, and injected into a collider ring with two interaction points. IMCC envisions a staged approach with the first stage collider operating at the center-of-

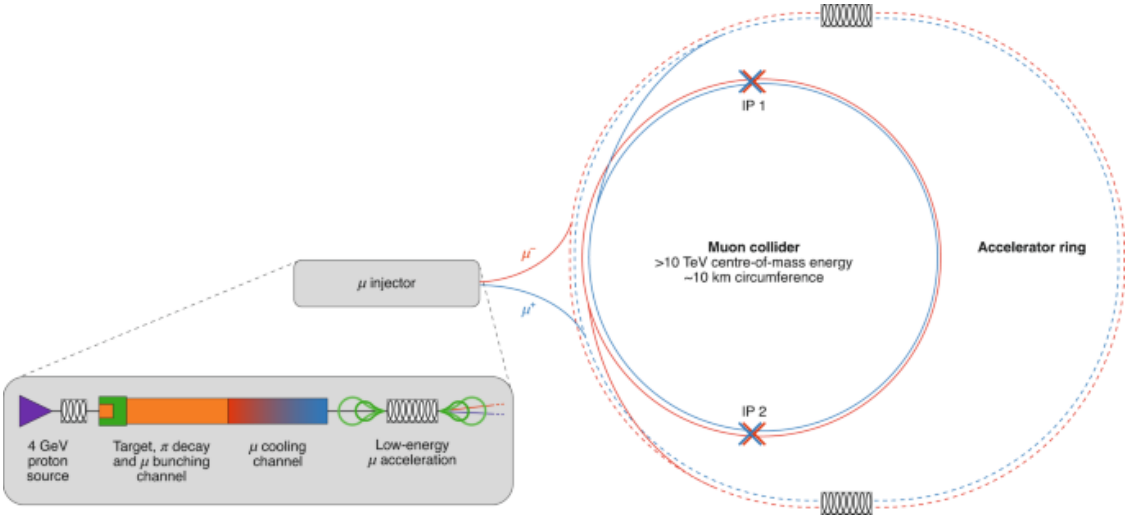

Figure 2. Schematic layout of 10 TeV-class muon collider complex being studied within the International Muon Collider Collaboration. From https://muoncollider.web.cern.ch/

mass energy of 3 TeV and the second stage at 10+ TeV (Figure 2). Integrated luminosity targets per interaction point are 1 ab^{-1} and 10 ab^{-1}, respectively. Staging allows for demonstration of performance at the lower energy and also facilitates stretching out the construction time, while executing a vibrant physics program. The front end and most of the cooling chain in the accelerator complex are common to the two stages. An alternative approach (LEMMA), which uses positrons to produce muon pairs at threshold, was also considered but had difficulties with achieving a high muon beam current and hence the necessary luminosity.

The IMCC held four "community meetings" in 2020 and 2021 to develop the scope and the plan of work to be done between now and the next ESPPU. R&D objectives have been identified in several key areas, including muon production and cooling, neutrino induced radiation mitigation, MDI studies and optimization, and the high energy complex. Technologically, the design imposes challenging requirements on the high power targets where short proton bunch length and frequency may compromise the target's lifetime and integrity, on the high-field solenoidal magnets used in the production, collection and cooling of the muons, as well as on the specs of fast-ramping and fixed-field magnets used in the accelerator and collider rings. The ionization cooling system is a novel concept and requires careful studies for optimal integration of the absorber and RF stations inside of high magnetic fields. Successful demonstration of a partial muon cooling system is therefore crucial for the design verification. This test facility can be located at any laboratory that can provide a proton beam of needed power. Currently rough dimensions of the facility have been identified and siting at CERN is being explored. Sec. 5.5 describes how such a facility can be hosted at Fermilab.

2.3.4 U.S. Contributions to IMCC

Despite strong interest and expertise, U.S. participation in IMCC has been mainly limited to the work done in the context of the recent Snowmass process. As mentioned above, the design strategy taken by IMCC relies heavily on the concepts developed by the MAP collaboration. The European

muon beam panel included two representatives (including the co-chair) from the U.S., and a large number of scientists helped to organize the IMCC working group activities. U.S. scientists made key contributions to most areas of the IMCC design development and planning, including magnets, RF cavities, muon production and cooling, muon acceleration, beam dynamics, machine-detector interface, and the high-energy complex. Besides the accelerator design, the Energy and Theory Frontier communities in the U.S. provided strong contributions in the areas of physics studies and detector design.

2.3.5 Snowmass Muon Collider Forum

In light of renewed interest in muon colliders within the United States particle physics community, the Snowmass Energy, Theory and Accelerator Frontiers created a Muon Collider Forum. The Forum [58] met on a monthly basis and has invited several experts to give their perspective and to educate the broader community about the physics potential and technical feasibility of such a collider. In addition, it facilitated interactions between the particle physics community and accelerator experts and organized related workshops. The Muon Collider Forum Summary Report [59] describes the motivation for a muon collider, identifies primary R&D needs, highlights areas where the U.S. can provide critical contributions to the global efforts and presents Fermilab as one of the options for hosting a Muon Collider in the future.

Future U.S. contributions to the global Muon Collider R&D roadmap are contingent on the outcome of the ongoing P5 process. However, discussions within the Snowmass Muon Collider Forum identified key areas of interest and expertise, assuming that P5 will support a revival of the Muon Collider R&D program. The areas that have been identified include design of the proton driver (in synergy with the PIP-II accelerator), targetry (in synergy with future Fermilab neutrino and precision muon programs), muon cooling design and optimization, accelerator lattice design, high-field magnet development (in synergy with the Magnet Development Program), beam acceleration using superconducting RF technology, and mitigation of the neutrino induced radiation. In addition to accelerator R&D, strong efforts in refining the physics case and in conducting R&D for muon collider detectors, will be necessary.

3 Linear e^+e^- colliders at Fermilab

3.1 C^3 proposal

The Cool Copper Collider (C^3), proposed in Ref. [34] is based on a cold normal conducting RF (NCRF) C-band technology, which promises dramatic improvement in efficiency and breakdown rate compared to those previously achieved. High accelerating gradient of 70 – 120 MV/m allows to reach HZ production energies with a relatively small facility that could, for example, be located at the Fermilab site. An ~ 8-km long 250 GeV Higgs Factory (with a relatively inexpensive upgrade to 550 GeV within the same footprint) has a luminosity of 1.3×10^{34} cm^{-2}s^{-1} (2.4×10^{34} cm^{-2}s^{-1} at 550 GeV) [34, 35]. The estimated site power is ~150 MW at 250 GeV and ~175 MW at 550 GeV. In principle, C^3 is potentially extendable to 3 TeV by simple extension of the linac while keeping the accelerating gradient at 120 MV/m.

The key technology of C^3 is a structure distributing power to each accelerating cell in parallel from a common RF manifold. This allows optimization for cell efficiency (shunt impedance) while

controlling peak surface electric and magnetic fields. Operation at ~ 80 K with liquid nitrogen cooling improves the material strength, reduces the breakdown rate, and allows higher accelerating gradients. First proof-of-principle experiments demonstrated operation up to 150 MV/m with expected robust operation up to 120 MV/m. Further R&D in a few key areas is required (e.g., scaling modular units; developing cryogenic, cryomodule and alignment systems; integration of wakefield detuning/damping scheme into the structure design) [60]. Main challenges for C^3 include alignment and jitter. The main linac will require 5-micron structure alignment, which would be achieved by a combination of mechanical pre-alignment and beam-based alignment. A demonstration facility is proposed to support critical R&D topics [61].

While RF sources and modulators capable of powering the 250 GeV C^3 are commercially available, the RF source is the key cost driver for the overall cost of the machine. R&D on reducing the RF source cost is of critical importance. The plan is to leverage significant recent developments in performance of high-power RF sources (e.g., by HEIKA collaboration [62]). It will require significant industrialization efforts after the technology demonstration.

The 8-km long C^3 footprint allows achieving 250 GeV center-of-mass energy with an accelerating gradient of 70 MV/m (assumed linac filling factor is 90%). This gradient is cost-optimal for the current large-volume RF source unit cost of ~ \$7.5/peak-kW. Raising the gradient to 120 MV/m would increase the energy to 550 GeV within the same footprint (a full suite of cryomodules needed for the 550 GeV operation would be installed during the 250 GeV construction, but not all of them would be powered up.) This upgrade will benefit from the development of new RF sources and/or RF pulse compression scheme. Large portions of the accelerator complex are similar to other linear colliders: beam delivery system (BDS) and interaction region (IR) can be modified from the ILC design (currently C^3 assumes a 3 km BDS for the 550 GeV center-of-mass energy); damping rings and injectors can be optimized with CLIC as a baseline. Costing studies so far used other linear collider estimates as inputs. The total capital cost is estimated at 3.7 BILCU. The technically-driven timeline includes 2 years for a pre-demo stage, 5 years for the technology demonstration, 3 years for a string test, and 8-10 years of construction and commissioning time.

Considering Fermilab site as a potential location for C^3, the 8-km footprint currently proposed to upgrade to 550 GeV, can be accommodated with about 5 km of the footprint inside the laboratory site and extending the facility under the ComEd power company's easement to the north of the Lab site (North – South (N–S) orientation). This option is shown in Figure 3. It is possible to have the machine footprint up to 12 km in this orientation and siting option, keeping the interaction region of the collider within the Lab campus. This siting location, was, in fact, one of the options studied for the ILC at Fermilab. Using the full 12 km length can provide upgrade paths to 750 GeV collision energy or higher.

Perhaps, further optimization of the final focus or operating structures at higher accelerating gradients could let the 250 GeV machine and for energy upgrade up to 550 GeV fit within the boundaries of the laboratory, i.e., with a footprint of 7 km or less, using North East – South West (NE–SW) orientation (see Figure 4). Structure tests have been able to achieve 155 MV/m at both C-band and X-band distributed coupling structures [63, 64]. The possibility of operating the main linac at this higher gradient is planned to be investigated during the proposed C^3 Demo phase.

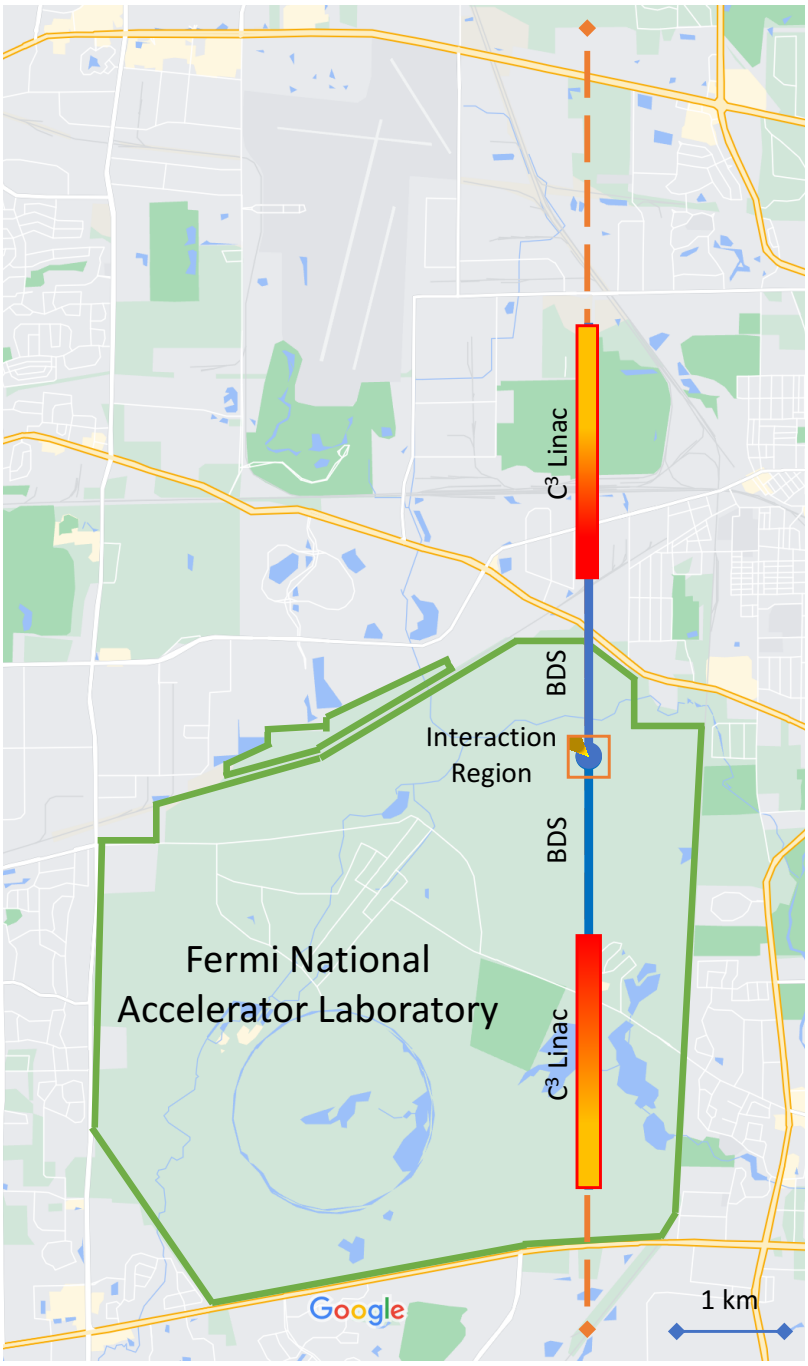

Figure 3. The 8-km footprint consisting of 5 km inside the Lab site and extending the facility under the Common Wealth Edison power company's easement, considered for C^3 and HELEN.

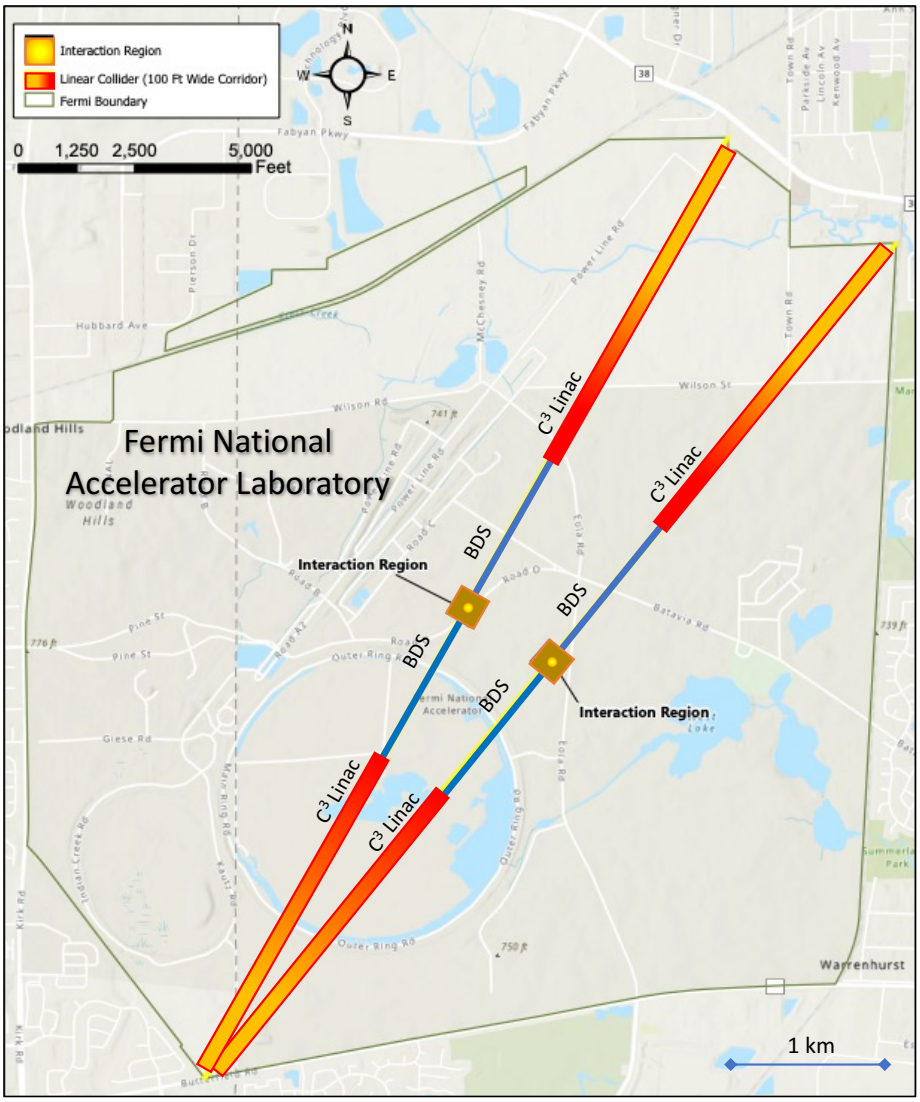

Figure 4. Possible locations for a 7-km footprint linear collider on Fermilab site considered for C^3.

3.2 HELEN – A linear collider based on advanced SRF

Since the ILC SRF linac parameters were baselined in 2013 [40, 43], the community has made advances in further developing the technology. Three possible paths have been identified that could lead to a more compact SRF linear collider, the Higgs-Energy LEptoN (HELEN) collider [36, 65]. The options are listed here in the order of their maturity:

- With recent advances in surface treatments of niobium SRF cavities and development of more efficient standing wave structure geometries, it is anticipated that cavities can reach 50 – 60 MV/m. With just 2–3 years of intensive R&D, one can anticipate demonstration of such gradients in 9-cell SRF cavities. Assuming that cavities with operating gradient of 55 MV/m can be manufactured with sufficient yield, a 250-GeV linear collider will be 9.4-km long and will fit within the 12 km footprint in the N–S orientation at Fermilab similar to that shown in

Figure 5. The maximum energy that could potentially be reached by fully occupying 12 km is 350 GeV.

- A newly optimized traveling wave (TW) SRF structure can potentially reach an accelerating gradient of $\sim$ 70 MV/m. We consider this option as a baseline for HELEN. At 250 GeV, the collider length is 7.5 km and it will comfortably fit within the 12-km N–S corridor as shown in Figure 5. If we can move the IR further North, then it would be possible to upgrade the HELEN collider energy to 500 GeV while still fitting within the 12 km footprint available.

- If the 90 MV/m gradient potential for Nb_3Sn cavities with Q of 1×10^{10} at 4.2 K (based on extrapolations from high power pulsed measurements) can be realized, then the 250-GeV collider would fit entirely on the Fermilab site along one of NE–SW diagonals as shown in Figure 4. Alternatively, it can be built along the N–S line which offers possibility of energy upgrades.

Utilizing one of the three options, one could design and build a linear collider Higgs Factory that partially lies within the Fermilab site, particularly the interaction region and experiments. The baseline luminosity of HELEN would be similar to that of the ILC, i.e., 1.35×10^{34} cm^{-2}s^{-1} at 250 GeV and 1.8×10^{34} cm^{-2}s^{-1} at 500 GeV. The R&D program and a demonstrator test facility that would be needed to realize such a collider are described in subsequent sections and in [36, 65]. As HELEN collider in many ways is similar to ILC, its luminosity can be upgraded using approaches developed for ILC.

3.3 ILC in the U.S.

Another proposal that continues to be extremely viable is the construction of ILC in the U.S. ILC has been characterized as a "shovel-ready" project, with well-established technical design and with world-class accelerators like the European XFEL acting as large-scale demonstrations of key SRF systems. As described above, U.S. scientists are involved in international collaborative efforts to realize the ILC in Japan. However, if ILC in Japan is not realized, constructing ILC in the U.S. could be an attractive option. There are existing international technical coordination teams already working together from different regions across the world, discussing the next steps for ILC leading up to construction. Funding agencies are already engaged. If ILC in Japan does not proceed, enthusiasm from the U.S. HEP community could motivate funding agencies to develop plans to support construction domestically, with international contributions built on well established collaborations and frameworks. Experience from construction of the LCLS-II / LCLS-II-HE accelerator involving SLAC, Fermilab, and JLab could help alleviate typical concerns of ballooning costs and schedules from projects with less well-established technologies. This includes critical expertise of and confidence in technical vendors (such as those for SRF cavities and RF power couplers) to help build confidence that cost and schedule estimates are realistic. For these reasons, the U.S. is well positioned to take on a host role for the ILC. The sites previously considered to host the ILC at Fermilab are shown in Figure 6.

3.4 Test demonstrator for e^+e^- Linear Collider

IOTA/FAST is an R&D Facility for Accelerator Science and Technology at Fermilab. It has two components: an Integrable Optics Test Accelerator (IOTA), 150 MeV electron / 2.5 MeV proton

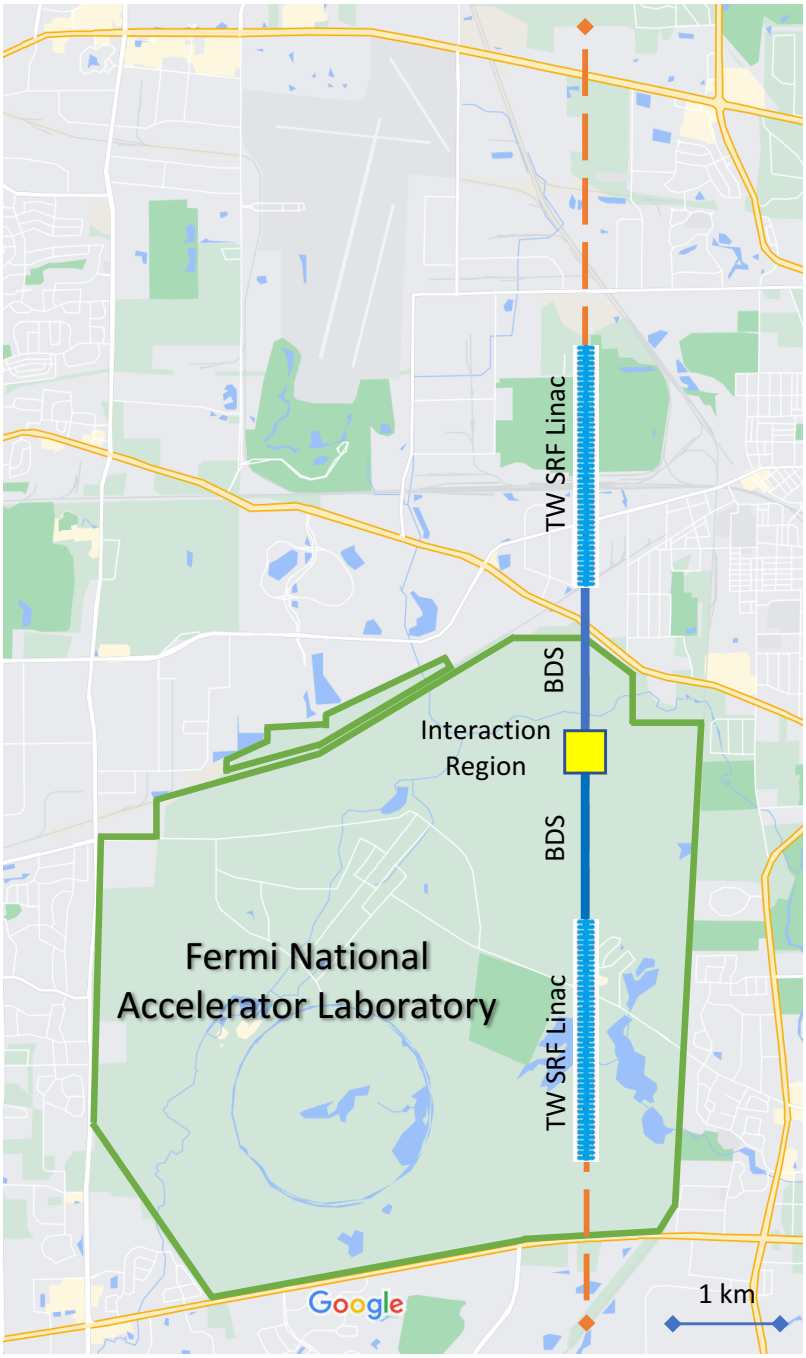

Figure 5. Possible siting of the 250 GeV HELEN collider at Fermilab. The Traveling Wave SRF option is shown. The orange dashed line indicates a 12-km stretch that might be available for a future upgrade of HELEN to 500 GeV.

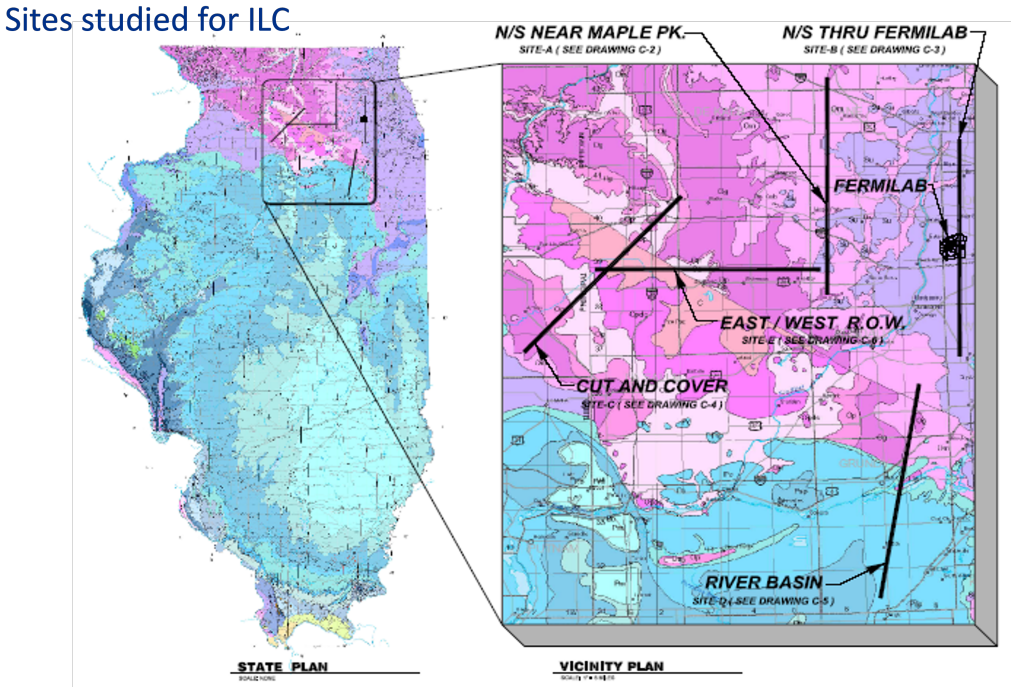

Figure 6. Potential siting options considered in the past for ILC at Fermilab.

storage ring [66], with a dedicated proton injector and a FAST SRF linac. The 300-MeV FAST linac serves as an injector of electrons for IOTA and provides beam to dedicated experiments with linac beam.

Besides a 8-cavity ILC-style SRF cryomodule, the electron linac includes a 5-MeV RF photoinjector of a DESY/PITZ design, a 25-m long low-energy ($\leq$ 50 MeV) beam line with 2 SRF capture cavities, and a $\sim$ 100-m long high-energy beam line. Both beam lines are equipped with high-precision beam instrumentation.

Originally, the ILC-style FAST SRF linac was envisioned as a demonstration facility to test and operate a full ILC "RF unit" with ILC beam intensity. The RF unit consists of 2 cryomodules driven by a single 10 MW klystron. However, only one cryomodule was installed at FAST. The ILC beam intensity is a $\sim$ 1 ms long train of $\sim 3,000$ bunches (3 MHz bunch repetition frequency) with a charge of 3.2 nC per bunch. The bunch train repetition rate is 5 Hz, and the r.m.s. bunch length is 300 μm. The FAST linac was the first to demonstrate the performance of a large-scale SRF system with average beam accelerating gradient matching the ILC specification of 31.5 MV/m [41].

FAST can serve as a demonstrator facility for all linear colliders R&D mentioned in this paper. Its high-energy beam line has plenty of space to accommodate additional test cryomodules. Here is a brief explanation on how FAST can be used for technology demonstrator tests in the two linear collider scenarios:

- While some upgrades to the laser and low level RF systems are needed for stable operation with full ILC bunch trains, the facility is uniquely positioned as a demonstrator for the proposed HELEN collider, which shares the beam parameters with ILC. New SRF cryomodule(s)

could either replace the existing CM2 cryomodule or be added to the high-energy beam line. Additional RF system(s) will have to be installed in the latter case.

- C^3 demonstrator cryomodules and associated high-power RF equipment can easily fit into the high-energy beam line tunnel. The facility has a dedicated cryogenic system, which includes a 5,800 gallons ($> 26,000$ liters) LN_2 tank, with a capacity exceeding the C^3 demonstrator requirements [61]. At first, FAST can be used for cryogenic RF testing of the C^3 cryomodules with and without beam. However, the present FAST injector cannot provide the beam with C^3 specifications, and an upgrade with S-band injector would be required for a full-scale beam demonstration.

4 An electron-positron circular collider as a Higgs Factory at Fermilab

4.1 Design Overview

Here we discuss the design of an e^+e^- circular collider to fit within the Fermilab campus. Figure 7 shows a bird's eye view of the laboratory site. The red circle denotes the designated location of the proposed 16 km ring which could work as Higgs factory at 120 GeV beam energy. The present description is primarily based on preliminary studies presented at a workshop on Accelerators for a Higgs Factory in 2012 [67], and updated in 2021. At 45.6 GeV beam energy the ring could work as a Z factory collider. These studies had used expressions developed earlier in 2001 for a very large lepton collider in a proposed 233 km long tunnel at Fermilab [68].

4.2 Design of the Higgs and Z factories

The design principles of the Higgs factory e^+e^- circular collider operating at a center of mass energy of 240 GeV is largely determined by the tolerable levels of the synchrotron radiation power, P_{SR}. The beam current I and luminosity $\mathcal{L}$ in this high energy regime are given by

$$I = \frac{e\rho}{2C_\gamma E^4} P_{SR}, \quad C_\gamma = \frac{4\pi}{3}\frac{r_e}{(m_e c^2)^3} = 8.86 \times 10^{-5} \ [\mathrm{m/GeV^3}] \tag{4.1}$$

$$\mathcal{L}\gamma^3 = \frac{3}{16\pi r_e^2 (m_e c^2)} \left[\rho \frac{\xi_y SR}{\beta_y^*} H(\beta_y^*, \sigma_z)\right] \tag{4.2}$$

The luminosity equation shows that at a given energy, the luminosity is determined by the factors in square brackets. In addition to P_{SR}, these are the bend radius ρ, the vertical beam-beam parameter ξ_y, the vertical beta function β_y^* and $H(\beta_y^*, \sigma_z) \leq 1$ is the hourglass factor, which is a measure of the overlap between colliding bunches at the collision point. We have assumed head-on collisions between the beams which is a valid assumption with a small number of bunches in each beam.

After fixing the maximum synchrotron radiation power to 50 MW per beam, the luminosity of the Higgs factory at Fermilab was maximized by the following choices, some of which are enforced by the limited circumference.

- A single Interaction Point: This has several accelerator physics advantages which include:
  - a larger bending radius ρ in the arc cells

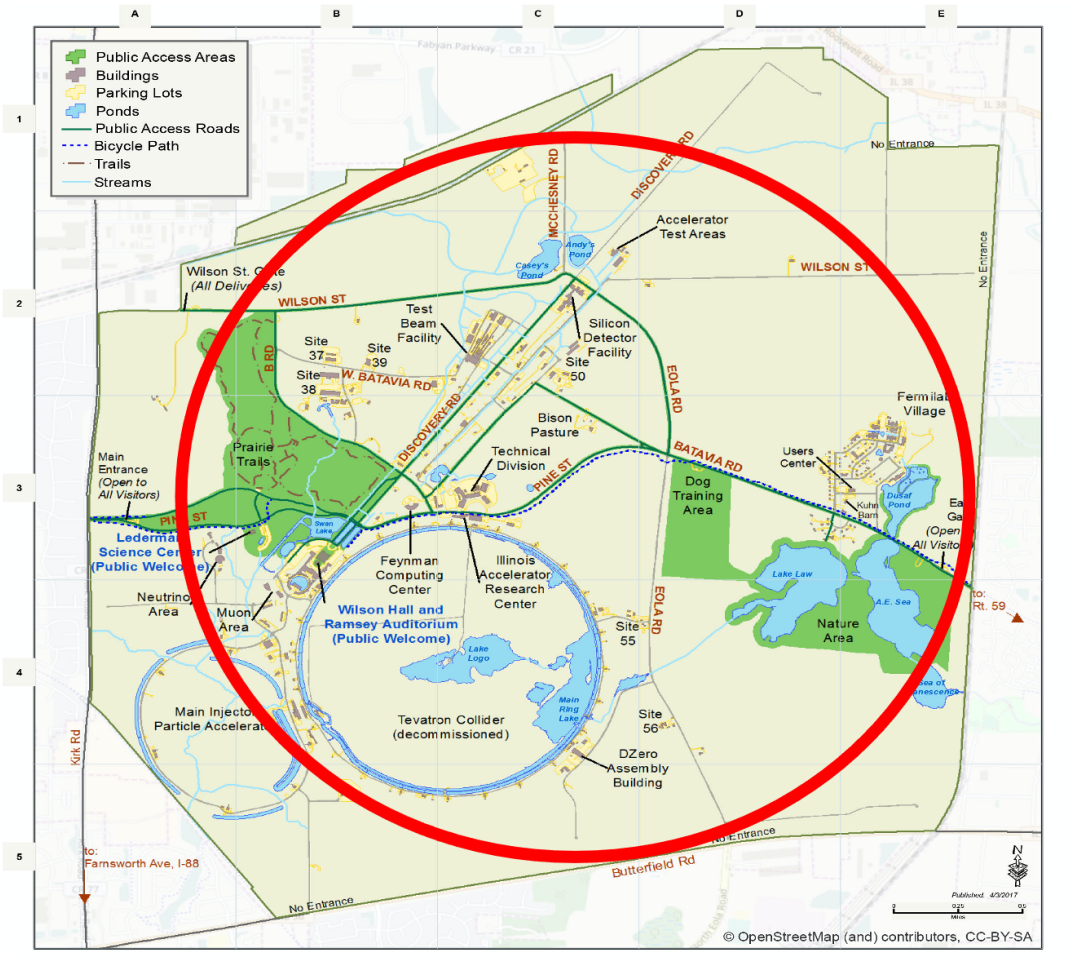

Figure 7. The proposed collider ring (red circle) on Fermilab site.

- total beam-beam effects (tune shift, beamsstrahlung, Bhabha scattering) are minimized;
- the IR chromaticity is reduced which will increase the momentum acceptance and consequently the beam lifetime.

- Very small vertical beam size at the IP (0.2 μm).
- Large number of particles distributed into two bunches for maximizing the luminosity. The single bunch intensity must respect limits set by the Transverse Mode Coupling Instability (TMCI) and by the allowable beam-beam tune shift.
- Head-on collisions for operational simplicity and cost reduction.

The Z factory which will operate at a lower center of mass energy of 92 GeV is not necessarily limited by the synchrotron radiation power so it can operate at the beam-beam limit. The luminosity at this limit is given by

$$\mathcal{L} = \frac{\pi}{r_e^2} N_B f_{rev} \left(\frac{\kappa \beta_x^*}{(\beta_y^*)^3} \right)^{1/2} (\gamma \xi_y)^2 \epsilon_x \tag{4.3}$$

where N_B is the number of bunches, κ is the emittance coupling ratio. In this regime, the luminosity is proportional to the horizontal emittance ϵ_x. This favors increasing ϵ_x either by lowering the phase advance per FODO cell to say 60°, or by external means such as with noise or using wigglers. This regime also requires distributing the beam current over as many possible bunches as possible which lowers the bunch intensity. To avoid parasitic collisions, a crossing angle at the IP may be necessary and a multi-bunch feedback system may be required to avoid instabilities.

	Higgs Factory	Z factory
Circumference [km]	16	16
Beam energy [GeV]	120	45.6
Total synchrotron radiation power [MW]	100	60
Beam current [mA]	5.	140
N [10^{11}]	8.3	1.67
Number of bunches	2	279
β_x^* [m] / β_y^*	0.2 m / 1 mm	0.2 m / 1 mm
ϵ_x / ϵ_y [nm]	21 / 0.05	26.1 / 0.065
σ_z [mm]	2.9 (SR)	6.45
b-b tune shift/IP	0.075/0.11	0.032 / 0.045
RF frequency [MHz]	650	650
RF voltage [GEV]	12	0.24
Momentum acceptance (RF) [%]	±3	±9
τ_{bs}[min]	9 - 36	
τ_{Bhabha}[min]	8.7	37
$\mathcal{L}$/IP [10^{34} cm^{-2}s^{-1}]	1.0	6.3
Production cross-section	200 fb	61 nb
Physics Particle production/year	Higgs: 40000	Z: 7.64 $\times 10^{10}$

Table 2. Parameters of the 2012 Fermilab e^+e^- Higgs and Z Factories

Table 2 shows a set of consistent parameters for both the Higgs and Z factories. The particle production estimates assume 2×10^7 sec/year.

- The bunch length, σ_z, quoted in the table results purely from the synchrotron radiation in the arcs. This does not include the slight lengthening ($\sim$ 10%) due to beamsstrahlung and consequently the hourglass factor calculated here could be slightly optimistic.

- The bunch population assumed is well below the expected beam-beam limit and the TMCI threshold. Both these limits may need to be revisited with detailed simulations.

- The arc cells are 90° FODO cells, which could be replaced by the lower emittance ones adopted in modern synchrotron radiation rings.

- The short beam lifetime calls for *top-up injection* which ensures high average luminosity but at the cost of a full energy injector to be housed in the same tunnel.

4.3 Staging options

A staged approach could envisage the use of existing machines and infrastructure as much as possible. At HF2012 some possible injection scenarios were presented. The minimal one involved the use of the Fermilab Booster and Main Injector, in addition to a new 400 MeV linac and a positron accumulator. Besides the technical feasibility, the compatibility with proton operation for neutrino production must be understood. The most ambitious scenarios envisaged a 1 GeV linac, one e^+ accumulator ring and a superconducting RCS.

4.4 Challenges

Beam Dynamics: The IR nonlinear chromaticity correction system must ensure a sufficient dynamic aperture and energy acceptance. This should be achievable with only 1 IP in the ring. Next, simulations of the impact of beamsstrahlung on the bunch parameters must be done. It is possible that the head-on crossing scheme must be changed to a *crab waist* scheme, which requires the beams to cross at an angle. Its feasibility has been proven at DAΦNE and more recently at SuperKEKB. In this case in addition to synchro-betatron resonances, simulations have found two new instabilities: a *3D flip-flop* instability in the presence of beamsstrahlung, and a beam-beam head-tail instability, confirmed by observation at SuperKEKB.

Other challenges include: proper positioning of rf cavities in the ring to avoid saw-tooth orbits due to energy droop, management of the synchrotron radiation power load (15 kW/m for both beams) with a large photon critical energy (2 MeV), HOM heating in presence of large bunch population in short bunches etc. These issues were deemed to be manageable for the similar LEP3/TLEP.

4.5 Upgrade options

We consider the luminosity reach of a larger collider based at Fermilab. Fig. 8 shows the luminosity per IP and the total number of Higgs produced from all IPs as the circumference increases from 16 km to 50 km. We assume that the number of IPs can be increased from 1 to 2 for circumferences greater than 20 km. Over this range, the luminosity per IP increases in the same ratio as the increase in circumference. At the larger sizes, it is possible to optimize the design for higher intensities than the values shown in this figure. As a possible future upgrade, the site filler ring could serve as an injector for a larger collider.

4.6 Large Crossing Angle Option

Introducing a crossing angle reduces both the luminosity and beam-beam tune shifts if no optics changes are made. The lowered beam-beam tune shifts however allows the possibility of further reducing the beta functions at the IP to increase the luminosity while keeping the beam-beam tune shifts within allowed limits. Specifically in an e^+e^- collider where $\beta_y^* \ll \beta_x^*$, a crossing angle in the horizontal plane allows a scheme where β_x^* is reduced sufficiently to increase the luminosity beyond values without a crossing angle. This has been investigated in recent designs of colliders such as SuperKEKB, FCC-ee etc.

Here we consider this scheme for the Fermilab site filler. We include both the crossing angle and the hourglass effects on the luminosity and the beam-beam tune shifts. Analytic expressions for the combined effects do not appear to be available in the literature; instead they are approximated

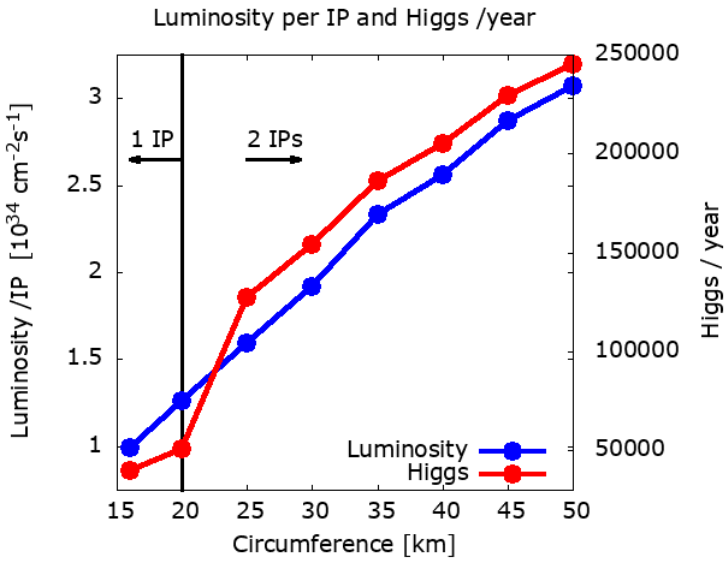

Figure 8. Luminosity per IP and the total number of Higgs per year produced from all IPs as a function of the circumference.

as acting independently. We have developed the exact expressions for both the luminosity and beam-beam tune shifts with the combined effects in [69]. Here we apply these formulae to this collider.

The first plot in Figure 9 show the luminosity as a function of the so called Piwinski angle parameter $\Phi = \tan(\theta_C/2)\sigma_z/\sigma_x^*$ for four values of β_x^*. This shows that the luminosity is relatively flat upto $\Phi \sim 0.5$ which corresponds to $\theta_C = 21$ mrad or 69 times the beam divergence, a relatively large value. The second plot shows the luminosity as a function of Φ and β_x^* over the ranges $0 \leq \Phi \leq 5$ and $0.01[m] \leq \beta_x^* \leq 0.20[m]$ respectively. This plot shows that the luminosity varies slowly as a function of Φ over $0 \leq \Phi \leq 0.5$, more rapidly from $0.5 \leq \Phi \leq 2$ and then is relatively flat over $2 \leq \Phi \leq 5$. Decreasing β_x^* from 0.2 m to 0.01 m increases the luminosity to nearly 4×10^{34} cm^{-2} s^{-1} for $0 \leq \Phi \leq 0.5$. However, the vertical tune shift at these parameters is very large at ~ 0.25, as the next figure shows.

The top plot in Figure 10 shows the vertical tune shift as a function of β_x^* at constant $\Phi = 0.5$ for different cases showing the relative impact of the crossing angle and hourglass effects. It is clear that the hourglass effect is dominant in determining the vertical tune shift. The bottom plots in this figure show the horizontal and vertical tune shifts as functions of β_x^* and Φ with both effects included. The horizontal tune shift ξ_x varies more strongly with the crossing angle and is mostly independent of β_x^*. The vertical tune shift on the other hand, varies strongly with β_x^* and slowly with Φ. Assuming that tune shifts of ~ 0.12 are dynamically sustainable and the increased chromaticity can be corrected, this suggests that β_x^* could be lowered to values in the range $0.025 \leq \beta_x^* \leq 0.05$m with $\beta_y^* = 0.001$ m. These would increase luminosity to the range $(2 - 2.5) \times 10^{34}$ cm^{-2}s^{-1}.

We can be more aggressive by lowering β_y^* further. The plots in Figure 11 show that with $\beta_x^* \leq 0.01$ m, $\beta_y^* = 0.0005$m, $\Phi < 2$, the vertical beam-beam tune shift $\xi_y \leq 0.14$ and the luminosity increases to $\sim 4 \times 10^{34}$ cm^{-2}s^{-1}. The major challenge at these parameters will be to

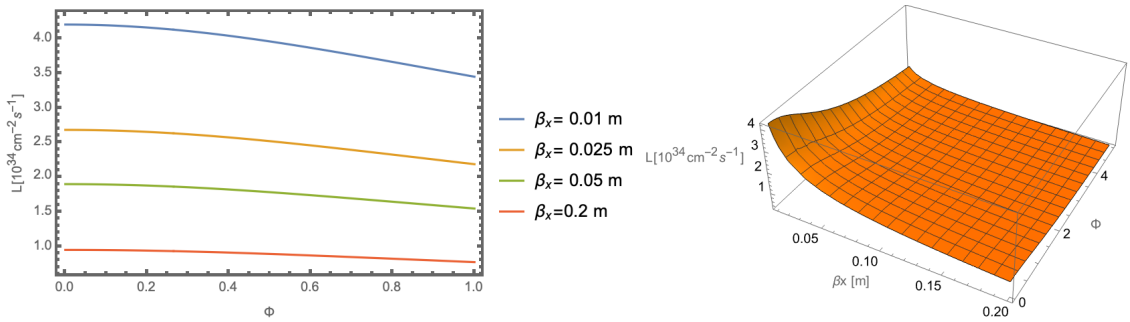

Figure 9. (Left): Luminosity as a function of the Piwinski angle Φ for four values of β_x*. (Right): Luminosity as a function of Φ and β_x^*. β_y^* is constant at 1mm in both figures.

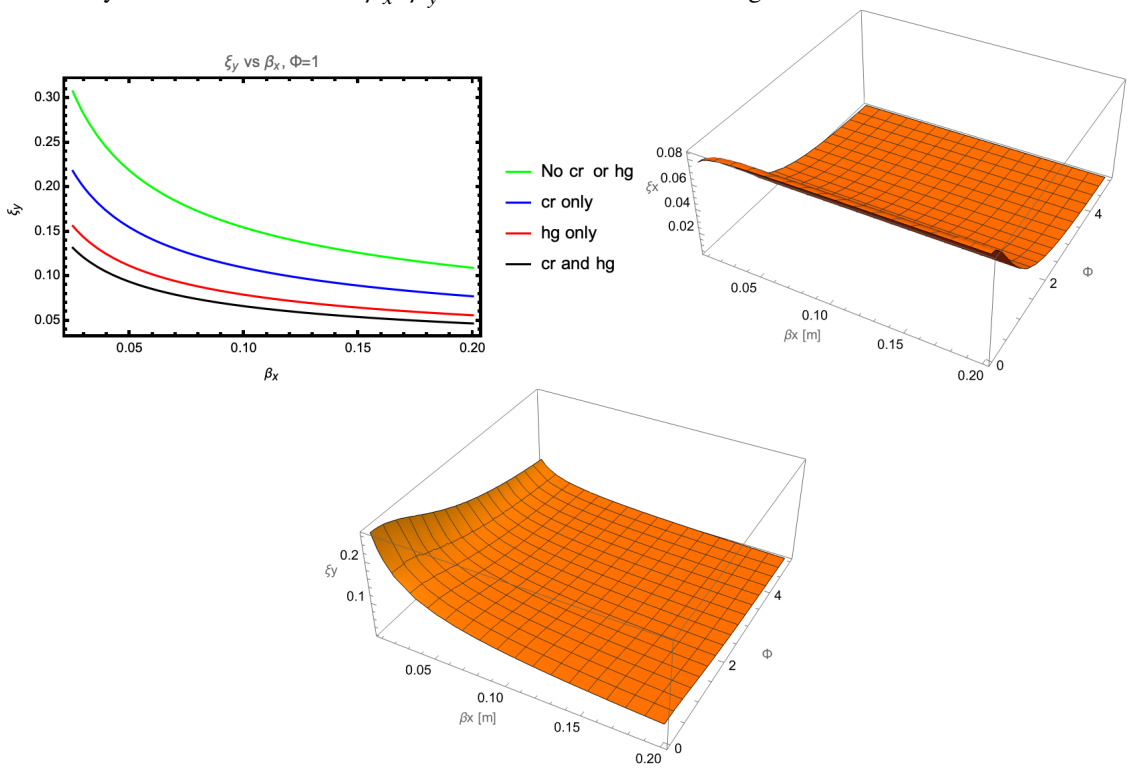

Figure 10. Top: Vertical beam-beam tune shift ξ_y as a function of β_x^* for different cases; no crossing angle (Cr) and no hourglass (Hg), only the crossing angle, only the hourglass and with both effects. $\Phi = 0.5$ in all cases. Bottom: Horizontal and vertical tune shifts as functions of of Φ and β_x^*. β_y^* is constant at 1mm in all figures.

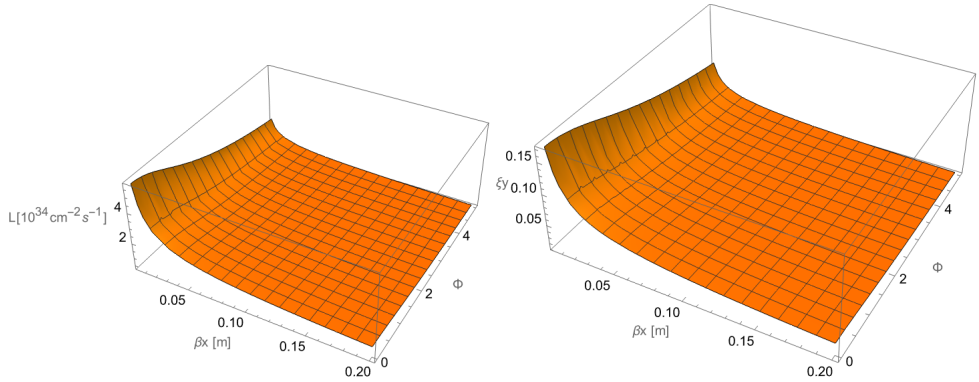

Figure 11. Luminosity and ξ_y as functions of β_x^* and Φ at $\beta_y^* = 0.5$mm.

control the linear and non-linear IR chromaticities at these values of β_x^*, β_y^*.

5 Muon collider options at Fermilab

5.1 Conceptual design

The idea of building a Muon Collider as a potential site filler for Fermilab dates back to the early 2000s. The focus then was a 4 TeV machine. Recently, the required parameter space towards a 6 – 10 TeV MC site filler has been identified and a first design concept has been developed. A schematic layout of this configuration is shown in Figure 12. Parameter sets for the primary collider energy options considered here are derived from the MAP and IMCC studies and are summarized in Table 3.

The idea is to start with a future PIP-II upgrade as a proton driver. This could well align with recent proposals for a Fermilab booster upgrade [70] or extension of the PIP-II linac [71, 72]. The target will operate at around 8 GeV with a 5 – 10 Hz repetition rate and a beam power around 2 MW, although this requirement can be reduced if more cooling is achieved. 6D muon cooling can be achieved with a rectilinear channel first, followed by a solenoidal 6D cooling channel using NC RF at 325 MHz and 650 MHz [73]. Muon acceleration is achieved in three stages: (1) A linac (up to 5 GeV) first that is followed by a Recirculating Linear Accelerator (RLA) (up to 65 GeV). This energy would be sufficient for a Higgs Factory [74]. (2) A set of two Rapid Cycling Synchrotrons (RCSs) that can potentially fit into the Tevatron ring tunnel and are capable of delivering an energy up to 1.5 TeV. (3) A final RCS that has a radius of 2.65 km (site filler) and can bring the energy up to 5 TeV. Acceleration will be conducted with superconducting RF cavities at frequencies of 650 MHz and 1300 MHz. Based on extrapolations from Ref. [75] the 10 TeV collider ring is expected to have a radius of 1.65 km. It is important to emphasize that given the 3 accelerator stages, staging is possible and operations at 125 GeV, 600 GeV (for the top quark Yukawa measurement), and 2 – 3 TeV can be envisioned as intermediate stages. Figure 12 shows a schematic view of the collider for the different stages.

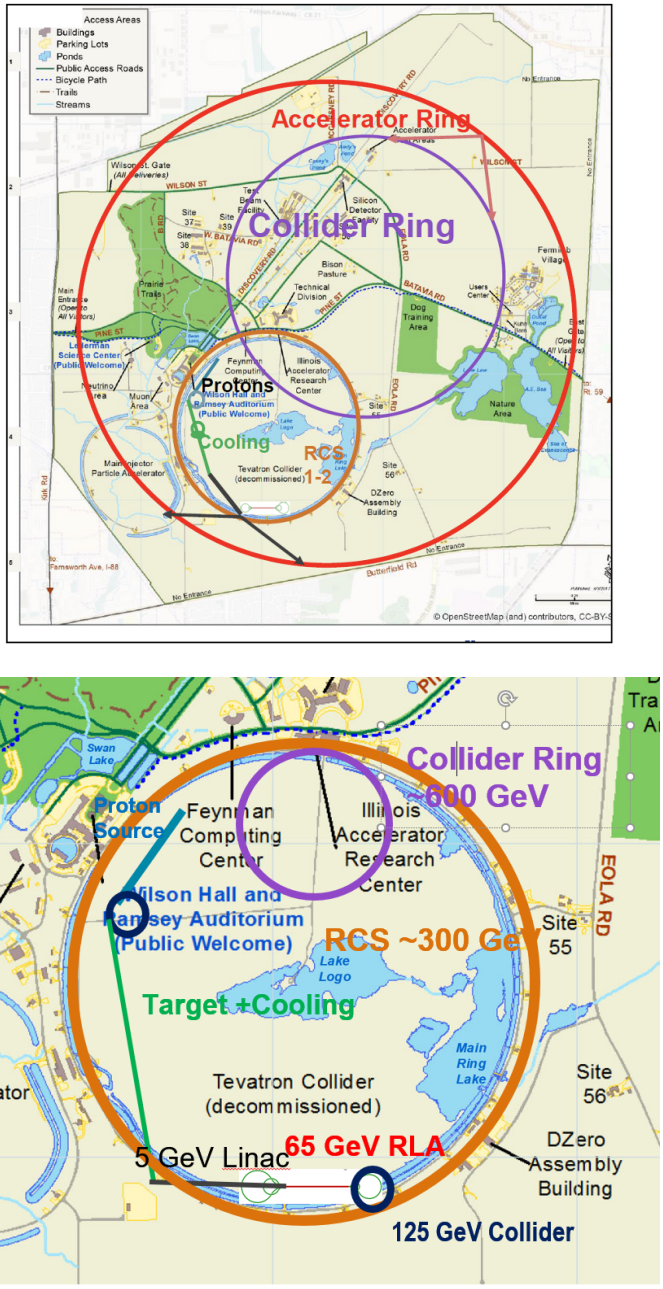

Figure 12. A schematic view of the Fermilab site and the layout of the proposed collider complex for the Muon Collider site-filler (top) and a zoomed-in version showing the 125 and 600 GeV staging options (bottom).

Parameter	Unit	Higgs Factory	3 TeV	10 TeV
COM Beam Energy	TeV	0.126	3	10
Collider Ring Circumference	km	0.3	4.5	10
Interaction Regions		1	2	2
Est. Integ. Luminosity	$ab^{-}1$/year	0.002	0.4	4
Peak Luminosity	10^{34} cm^{-2} s^{-1}	0.01	1.8	20
Repetition rate	Hz	15	5	5
Time between collisions	μs	1	15	33
Bunch length, rms	mm	63	5	1.5
IP beam size σ^*, rms	μm	75	3	0.9
Emittance (trans), rms	mm-mrad	200	25	25
β function at IP	cm	1.7	0.5	0.15
RF Frequency	MHz	325/1300	325/1300	325/1300
Bunches per beam		1	1	1
Plug power	MW	~ 200	~ 230	~ 300
Muons per bunch	10^{12}	4	2.2	1.8
Average field in ring	T	4.4	7	10.5

Table 3. A summary of parameters for the primary muon collider options considered for a Muon Collider at Fermilab.

5.2 Recent Technology Advancements

There have been several technological accomplishments over the last decade or so. Below we highlight some of them:

- **Liquid Mercury targets:** The MERIT experiment [76] provided a proof-of-principle demonstration of a target system based on a free mercury jet inside a 15-T solenoid and showed that it is capable of sustaining proton beam powers of up to 4 MW.

- **NC RF in 3 T field:** The experiment conducted at Fermilab MTA facility [55] demonstrated stable high-vacuum, normal-conducting RF cavity operation at gradients of 50 MV/m in an external magnetic field of 3 T, through the use of beryllium cavity elements. A high-pressure hydrogen gas filled RF (HPRF) cavity was also demonstrated with intense beams in a multi-Tesla solenoid field at MTA. [77]. Cooling simulations show that the HPRF cavity can be used in various ionization cooling schemes [78].

- **Rapid cycling magnets:** A High Temperature Superconductor (HTS) based fast cycling prototype accelerator magnet was demonstrated to operate up to about a 300 T/s ramping rate with some 0.5 T field in the magnet gap [79, 80].

- **Ionization cooling:** Demonstration of ionization cooling by the Muon Ionization Cooling Experiment (MICE) at Rutherford Appleton Laboratory (RAL) [56].

- **Lattice design:** Self-consistent lattice designs of the various subsystems have been produced. These include the front-end and cooling systems [81], acceleration scenarios [82], and collider rings up to 6 TeV [73].

5.3 Future R&D needs and synergies

- **Proton driver:** Fermilab's PIP-II program will be capable of delivering beam powers up to 1.2 MW. Several proposals are under development for either extending the linac or combining the existing linac with an RCS to increase the beam power to 2 MW or higher. The Spallation Neutron Source (SNS) [83] and European Spallation Source (ESS) [84] MW proton accelerators can be upgraded and extended to demonstrate the generation of a nanosecond-scale beams with very high charge (10^{15}) proton pulses that need to be used for the generation of the initial muon pulses for a muon collider.

- **Target:** Fermilab has an active target development program, including targets for Mu2e-II (100 kW), AMF (1 MW), and LBNF (1.2-2.4 MW). The Mu2e-II geometry is a simpler version of the MC target system, with targets within high field large-bore solenoids. The field strength of Mu2e-II solenoids is lower and the target length is shorter than the MC target system. However, making the Mu2e-II target system is still extremely challenging. Fermilab also hosts RaDIATE collaboration that explores targets for LBNF at 2.4 MW operation. The Fermilab research for MC can collaborate with the Mu2e-II target group and with RaDIATE to synergetically develop the target technology for the MC.

- **Cooling:** Improving the cooling performance is a primary goal of the cooling design R&D. Depending upon the future target system, decay, bunching, and phase rotation (called the "front end"), the following 6D cooling channel must be optimized. Improving cooling can significantly relax the beam requirements, reducing the primary proton beam power, the beam induced background at the collider detector, and the neutrino flux. Research on integration of AI techniques can aid in making the channels shorter and perhaps identify new parameters for improved cooling. Different cooling schemes such as the Parametric resonance Ionization Cooling (PIC) scheme for cooling to ultra low emittances [85] or the FOFO Snake [86] for cooling both muons simultaneously could be explored.

- **Acceleration:** An RCS will require the operation of high-gradient RF cavities. While 1300 MHz SRF at 35 MV/m has been demonstrated for ILC cavities, 50 MV/m would be desired for a site filler. RCS accelerators will also require fast cycling magnets at rates of 500–1000 T/s with peak fields of up to 4 T. These high ramp rates have been already demonstrated using normal conducting magnets, but design of an efficient power supply system for these magnets is needed. Fermilab has also demonstrated 290 T/s using HTS magnets albeit at a lower peak field (0.6 T). While an RLA scheme for acceleration to 65 GeV has been shown, more design studies are needed to demonstrate RCS acceleration towards TeV energies. FFAs could also be studied for fast muon acceleration.

- **Magnet:** MAP considered ionization cooling designs with solenoidal magnetic fields of up to 30 T. Commercial MRI magnets are now available at 29 T and the record field demonstrated is 32 T with bores similar to those needed for cooling; these could be extended to MC parameters. The collider ring requires 16 T arc dipoles with a 15 cm bore. The US MDP program will have 120 mm, 12 – 15 T dipole demonstrators with Nb_3Sn coils within the next 3 – 4 years.

- **RF cavities:** Demonstrations of the performance of RF cavities in magnetic fields are crucial. 50 MV/m at 3 T has been demonstrated at the MTA. Normal Conducting RF cavities operating at LN_2 temperature could have potential to reach high RF gradient in stronger magnetic fields than the past demonstration. Further tests are needed to establish performance at the parameters of cooling scenarios. Integrating RF cavities with cooling magnets is a crucial engineering challenge. High power RF sources need to be developed.

5.4 Higgs factory considerations

A muon collider Higgs factory continues to be of interest to the community, especially if none of the e^+e^- options are realized. Such a machine can substantially improve the measurement precision of most Higgs boson couplings when compared to HL-LHC. It can also be complementary to e^+e^- by providing very precise and model independent measurements of the Higgs boson total width, mass, and the muon Yukawa coupling. There is considerable overlap between the accelerator complex required for a 125 GeV Higgs factory with that required for a multi-TeV machine. Based on MAP studies, the proton driver, the front-end, and the 6D muon cooling system can be shared with a Collider. As a result, a Higgs Factory can serve as an acceleration demonstrator for subsequent higher energy stages. Moreover, acceleration will be based on more established methods, such as the use of RLAs, and the Collider Ring circumference will be only $\sim$ 300 m. The final 6D cooling system, which trades off increased longitudinal emittance to obtain smaller transverse emittance as required for a TeV-scale MC, is not needed for the Higgs factory.

5.5 Fermilab site option for demonstrator

A critical component of the R&D for a muon collider is a late-stage 6D cooling demonstrator. This was true during MAP and now is a central component of the IMCC. Within the IMCC, a great deal of work has been done to define the proposed demonstrator facility. The IMCC is taking a modular approach to the facility where initially a minimum configuration is deployed and over time upgrades are implemented that deliver additional capability. The demonstrator facility components as defined by the IMCC are indicated in Figure 13. The facility includes up to a $\simeq$ 100 kW target station (upgradable to higher power), a pion momentum selection section, collimation and a demonstration cooling section. The facility will be designed with flexibility in mind so that different cooling lattices can be tested. Given the envisioned configuration of the facility, it could support HEP experiments. Branching off from the target station, the facility could support nuSTORM [87] and/or ENUBET[88]. Figure 14 shows how a demo facility could be used to feed nuSTORM.

The IMCC design assumes siting at CERN where protons are extracted from the PS using land close to the TTf10 line. However, there are multiple possibilities to site the ionization cooling demonstrator at Fermilab. For example, it could be placed at the Muon Campus by re-purposing a lot of its current components and using the 8 GeV booster beam via the Recycler to AP0. This siting option would take advantage of the existing tunnel, part of the beamline, instrumentation and the infrastructure at the Muon Campus. Alternatively, the demo could be put on the SBN beamline and utilize the 8 GeV beam directly from the booster. The nuSTORM siting plan at Fermilab [89] using 120 GeV Main Injector proton beam is yet another option, but this energy is much higher than the desirable proton energy for a muon collider.

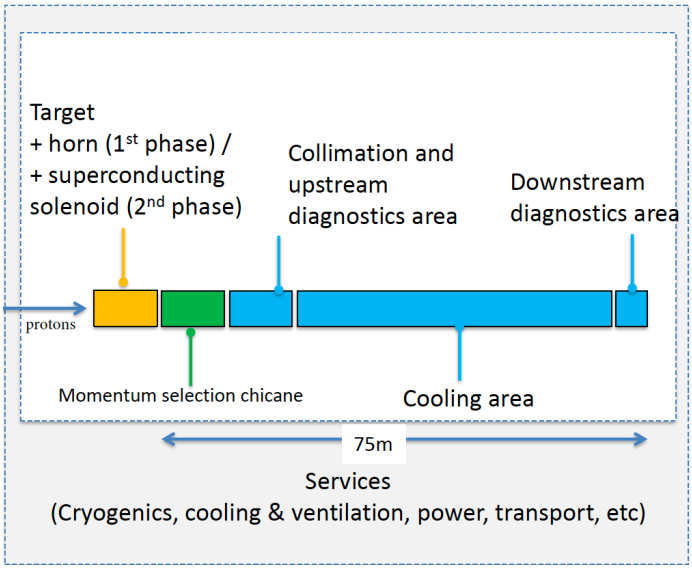

Figure 13. Components of a demonstrator facility for the Muon Collider

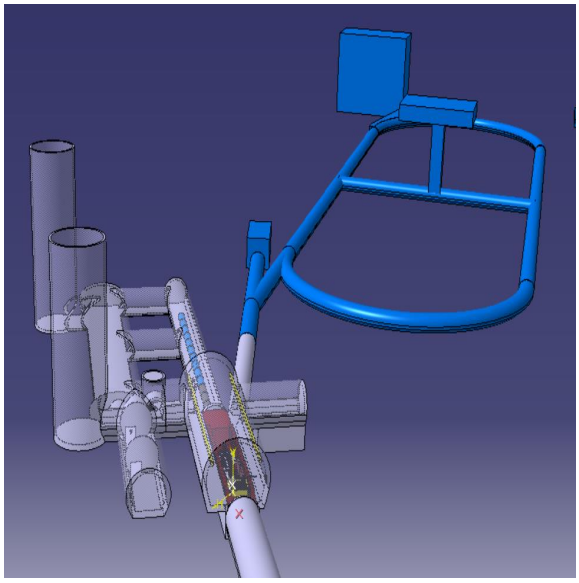

Figure 14. Schematic of the demo facility providing muons to nuSTORM.

6 A proton-proton collider at Fermilab

We consider here the possibility of building a proton-proton collider to fit on the Fermilab campus to operate at energies about twice that of the LHC . The Tevatron and its injector complex can serve as the entire injector chain for this collider. Given the compact circumference of 16 km, this will require dipole fields of unprecedented strength. Simply scaling from the LHC circumference and dipole field strength shows that dipole fields around 28 T would be required to reach energies

close to 28 TeV in the Fermilab site filler. This is far beyond the scale of fields envisaged in the design of other future pp colliders such as the FCC-hh and the SppC. Nevertheless, we will proceed with the bold (and likely foolhardy) assumption that such magnets can be built with the required accelerator quality and in a cost effective and timely manner. With this major issue swept under the rug, we discuss the accelerator physics of this collider. Some of these issues were considered in the preliminary design of a 100km ring collider at Fermilab [90].

6.1 Design of the pp collider

The design of the arc lattice requires, among other choices, selecting the cell length and dipole length. A longer dipole generally leads to lower magnetic fields but is limited from above to ~ 15 m for logistical reasons. We chose a dipole length of 12 m and a cell length of 76 m which result in dipole fields at the lower end of the range. The design of the interaction region (IR) is more complex and will be done when necessary. The parameters of this collider discussed below are obtained without an IR design.

Due to the large number of bunches required to attain high luminosities in this collider, crossing angles need to be introduced at the interaction points to avoid parasitic collisions. Assuming a crossing angle θ_c in the horizontal plane, the luminosity $\mathcal{L}$ and beam-beam tune shifts (ξ_x, ξ_y) are given by

$$\mathcal{L} = \frac{f_{rev} n_b N_p^2}{4\pi\sigma_x^*\sigma_y^*} R(\theta_c) \tag{6.1}$$

$$\xi_x = \frac{r_p N_p \beta_x^* R(\theta_c)^2}{2\pi\gamma\sigma_x^*(\sigma_x^* + R(\theta_c)\sigma_y^*)}, \quad \xi_y = \frac{r_p N_p \beta_y^* R(\theta_c)^2}{2\pi\gamma\sigma_y^*(\sigma_x^* + R(\theta_c)\sigma_y^*)} \tag{6.2}$$

$$R(\theta_c) = \frac{1}{\sqrt{1 + (\theta_c\sigma_z/(2\sigma_x^*))^2}} \tag{6.3}$$

Here n_b is the number of bunches, N_p is the bunch intensity, σ_x^*, σ_y^* are the rms transverse sizes at the IP, $R(\theta_c) \leq 1$ is the reduction factor due to the crossing angle and σ_z is the rms bunch length. The bunch intensity decreases during a luminosity store with the loss rate given by

$$\frac{d}{dt} N_p = -n_{IP}\sigma_{tot}^{pp}\frac{\mathcal{L}}{n_b} \tag{6.4}$$

Here n_{IP} is the number of IPs and σ_{tot}^{pp} is the total pp cross-section. At the high energies of this collider, synchrotron radiation has a dominant effect on the beam dynamics as is discussed below. The emittance damping is modeled simply as an exponential decay $\epsilon_\perp(t) = \epsilon_0 \exp[-t/\tau]$ where τ is the emittance damping time and ϵ_0 is the initial emittance.

Design Assumptions:

- The arc lattice is based on FODO cells, 90° phase advance per cell.
- Two insertions for experiments, with a total length of 2.6 km for all the straight sections.
- The beam separation at the long-range interactions in the drift space before the first IR quadrupole is 12σ, larger than the separation of 9.5σ in the LHC.

- The maximum beam-beam tune shift in any plane from all IPs is 0.025, based on Tevatron experience.

- The crossing angle is in the horizontal plane at one IP and in the vertical plane at the other IP.

	E_{CM} = 24 TeV	E_{CM} = 27 TeV	HE-LHC	FCC-hh
Circumference [km]	16	16	26.7	97.8
Beam energy [TeV]	12	13.5	13.5	50
Number of IPs	2	2	2	4
Main dipole field [T]	24.4	27.4	16	16
Number of bunches	1600	1600	2808	10600
Harmonic number	21348	21348	35640	130680
Bunch spacing [ns]	25	25	25	25
rms emittance $\epsilon_\perp$ [mm-mrad]	1.5	1.5	2.5	2.1
rms bunch length σ_z [cm]	3.7	3.6	8	8
β_x^*, β_y^* [m]	0.5, 0.5	0.5, 0.5	0.45, 0.45	1.1, 1.1
Beam current [mA]	446	333	1120	500
Particles/bunch N [10^{11}]	0.93	0.69	2.2	1.0
Beam energy [GJ]	0.29	0.24		
Crossing angle [μrad]	184	173		
Initial b-b tune shifts/IP (ξ_x, ξ_y)	(0.0066, 0.0072)	(0.005, 0.0054)	0.005	0.005
Max. b-b tune shift from 2 IPs	0.024	0.025		
Trans. emittance damping time [hrs]	1.8	1.3		
Critical energy of synch. rad. [keV]	0.377	0.537		
Synch. rad. power/ beam [MW]	0.043	0.051	0.1	2.4
Density of synch. rad in arc [W/m]	4.2	5.1		
Initial $\mathcal{L}$/IP [10^{34} cm^{-2}s^{-1}]	3.2	2.0		
Peak $\mathcal{L}$/IP [10^{34} cm^{-2}s^{-1}]	3.5	2.85	15.0	5.0
Number of events/crossing	80	50	800	170
Initial beam lifetime from burn-off [h]	6.4	7.6	3.0	17.0
Debris power into IR magnets [kW]	6.2	4.4		

Table 4. A set of parameters each for the pp collider at 24 and 27 TeV in the Fermilab site filler compared with the baseline parameters for the HE-LHC and FCC-hh colliders [2].

Table 4 shows the parameters at two center of mass energies of 24 TeV and 27 TeV and compared to the HE-LHC and FCC-hh collider options at CERN.

- The transverse emittance damping time is on the scale of an hour. This damping time ~ 1 hr is much less than the emittance growth due to intra-beam scattering and will have some beneficial effects. The small beam size will not require cooling and should also help against instabilities.

- Synchrotron radiation power at 44 kW is an order of magnitude larger than in the LHC but two orders of magnitude less than in the FCC-hh. Consequently, the problem of removing the synchrotron radiation will be challenging but perhaps manageable.

- The critical energy of synchrotron radiation is also about an order of magnitude larger than the critical energy of 43 eV in the LHC. This will significantly impact the production of electrons by photo-absorption at the beam pipe and other surfaces. Electron cloud generation and associated instabilities will need significant mitigation efforts. Nevertheless, this problem will be less severe than in the FCC-hh.

- Debris power into the IR magnets is $\sim 4 - 6$ times the value in the LHC. This should be manageable with improvements in the design of absorbers and machine protection systems in the IR.

- The number of interactions per crossing increase $\sim 2 - 3$ fold from the 32 events in the LHC, but is much less than in the FCC-hh.

Figure 15 shows the evolution of the luminosity and the beam-beam tune shifts over a 6 hr store. The time dependence arises both from particle losses from burn off and the emittance decay from radiation damping. The luminosity increases for about 2 hrs before decreasing to about 10% of the initial luminosity after 6 hrs. This plot suggests that each store time should not exceed ~ 4 hours. The emittance reduction has a stronger impact on the beam-beam tune shifts; e.g., at 27 TeV ξ_x increases by a factor of 2 while ξ_y increases by nearly a factor of 4. This large increase in the beam-beam tune shift poses a major limit on the achievable luminosity. The emittance change in these calculations ignores emittance growth mechanisms such as intra-beam scattering which has a growth time ~ 6 hrs, thus the increase in beam-beam tune shift is somewhat exaggerated.

Beam-beam compensation with electron lenses would be effective in reducing the head-on tune shift and increasing the luminosity.

6.2 Challenges

Clearly the largest challenge is to design and build dipole magnets with fields at and above 24 T together with the required field quality. The next major challenge is to keep the cost of the collider, with all components, to be within reasonable limits. All other issues are relatively insignificant compared to these two.

<u>Accelerator Physics Challenges</u>:

- Machine protection: Very high beam energy and magnetic energy, need improved & sophisticated collimation

- Novel diagnostics for halo control and beam loss, monitoring radiation damage, photon absorbers to protect cold magnets and equipment

- High synchrotron radiation: Impact on components, cryogenic system, radiation hard electronics, electron cloud

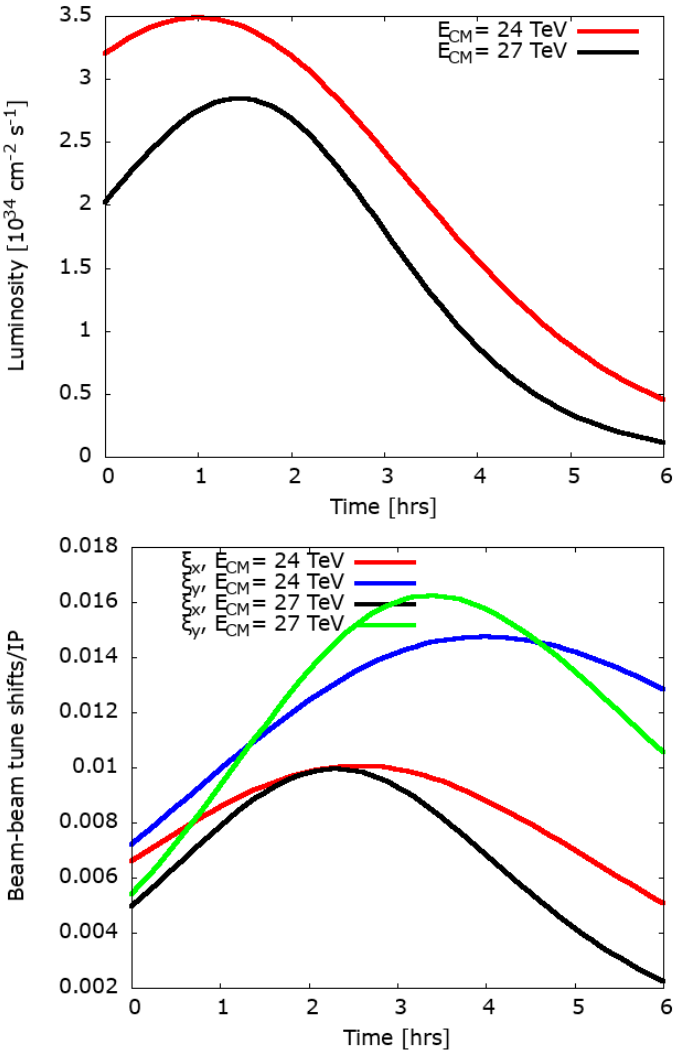

Figure 15. Evolution of the luminosity (top) and the beam-beam tune shifts with a crossing angle in the horizontal plane (bottom) at center of mass energies 24 TeV and 27 TeV.

- Beam dynamics: electron cloud effects, compensation of beam-beam interactions (head-on and long-range), instabilities during injection and the ramp, dynamic aperture, ...

6.3 Upgrade options

Compensation of the head-on beam-beam tune shift with electron lenses would increase the luminosity, as mentioned above. Crab cavities would restore head-on collisions and also raise luminosity. After a few years of operation, it should be possible to increase luminosity by standard methods such as lowering β^*, reducing the crossing angle etc. Finally, this collider can serve as an injector to a collider operating at the 100 TeV energy scale.

7 Technology R&D Directions

7.1 Introduction

As the requirements for colliders continue to grow, the need for investment in accelerator and detector technology research and development becomes more critical. "Brute force" approaches to colliders – by making extremely large rings or long linear tunnels – are possible, but only feasible up to a point. Investments in R&D can pay off multiple fold. For example, developing stronger superconducting magnets would benefit not only hadron colliders, but a muon collider as well; or high gradient / high Q SRF cavities will find applications across several fields from HEP to nuclear physics, to FELs, to industrial accelerators. R&D time frames are difficult to predict, and in some cases, there are large advances that can be leveraged quickly. A recent example was the development of nitrogen doping for SRF cavities, bringing an increase in quality factors by a factor of ~ 3 [91]. This was crucial for the feasibility of the LCLS-II accelerator, that began production of SRF cavities using nitrogen doping less than 5 years after its invention. In this section we describe some promising directions and give approximate time frames, with the caveat that time frames have both positive and negative error bars.

7.2 Magnet R&D

The circular nature of some of the colliders under consideration, such as muon colliders and high energy proton colliders (FCC-hh or SppC) naturally drives the focus to the study and development of advanced magnets in various configurations (dipoles and quadrupoles, solenoids, fast ramping magnets, etc) and at high field levels, normally enabled by the use of superconducting technology. In addition, the number of magnets – in some cases highly specialized, one-of-a-kind elements, in others, several hundreds or thousands of cost-efficient and reproducible magnets – drive considerations on the best way to produce such magnets for the machines described in this paper.

Superconducting magnets (dipoles and quadrupoles) based on Nb_3Sn technology have been demonstrated up to $\sim$ 15 T (single units). Hybrid solenoids using Nb-Ti, Nb_3Sn and high-temperature superconductor (HTS) tape technology have been demonstrated up to 32 T. All the magnets mentioned above are produced in national laboratories in single quantities or in "boutique" operations in quantities of a few dozens, such as for the Nb_3Sn focusing magnet production for the Hi-Lumi Project at the LHC that is currently underway.

A muon collider based on fast ramping magnets for muon acceleration would require the magnets shown in Table 5. A high energy hadron collider would require the magnets shown in Table 6.

In the muon collider, individual solenoids at very high magnetic field (32 T and above) may not necessarily need to be all superconducting in nature and partially resistive (albeit power-hungry) solutions can be considered for those in the high radiation environment of the production target. On the other hand, the cooling channel and all the remaining magnets in the muon collider and very high energy hadron collider have to rely on superconducting technologies. The above considerations are exposing the two main challenges in addressing the feasibility of such future colliders in the next decade.

Industrialization challenge: When needed quantities are in the "hundreds/thousands of units", industrialization is a must to maintain the necessary cost control and ensure uniformity of deliver-

Table 5. Approximate fields and quantities of magnets for a Muon Collider

Magnet type	Field	Quantity
Production target VHF solenoid	$\sim 20 - 2$ T	Several
Cooling channel EHF solenoids	$\sim 40+$ T	Dozens
Cooling channel HF solenoids	$\sim 4 - 19$ T	Hundreds
Fast ramping magnets	$\Delta B \sim 2$ T and $dB/dt \sim 1000$ T/s	Few hundreds
MR high field dipoles	$\sim 8 - 16$ T	Few hundreds
IR high field quadrupole	$\sim 15 - 16$ T	Dozens

Table 6. Approximate fields and quantities of magnets for a very high energy hadron collider

Magnet type	Field	Quantity
MR high field dipoles	$\sim 14 - 16$ T	Few thousands
IR high field quadrupoles	$\sim 15 - 16$ T	Dozens

ables. This aspect was already identified as a challenge for Magnet R&D in the 2014 P5 report [25]. This challenge applies to several beam-line magnetic elements listed above (Main Ring dipoles, fast-ramping magnets, cooling solenoids, etc) and the approach has to involve laboratories and universities in the R&D and prototyping phases, but needs to demonstrate a feasible technology transfer and an appropriate industrialization process for the pre-series and series production phases.

Field level challenge: When a high or very high magnetic field level is necessary to ensure the technical success of machine elements and yet the number of units is small (focusing IR magnets, a few dozens of very high field solenoids, etc.) an approach based on the involvement of laboratories or universities from R&D to final production can be entertained given the inherent difficulties and inefficiencies in technology transfer of high field magnet applications.

7.2.1 HTS, LTS/HTS magnets

R&D efforts on superconducting magnets have been energized, especially in Europe, following the 2019 update of the European Strategy for Particle Physics and the identification of FCC-ee, FCC-hh, and muon colliders as viable options for future machines.

In the U.S., the GARD[1]-supported nation-wide Magnet Development Program (MDP) is pursuing generic R&D with four primary goals: explore the performance limits of Nb_3Sn accelerator magnets, develop and demonstrate an HTS accelerator magnet with a self-field of 5 T or greater (to use in a hybrid configuration with a Nb_3Sn magnet), investigate fundamental aspects of magnet design and technology, and pursue Nb_3Sn and HTS conductor R&D.

At Fermilab, the above mentioned generic MDP efforts are materializing in a series of specific thrusts with the following elements related to future muon or hadron colliders:

- Stress-managed cos-theta (SMCT) coils developed for Nb_3Sn and Bi2212 16+ T magnets [92].

[1]GARD is the General Accelerator R&D program sponsored by the U.S. DOE Office of HEP.

- Development of new technology (HTS, REBCO SC based, COMB) [93] for 18+ T hybrid magnets.
- 20 T hybrid design studies for LTS[2] magnets [94].
- Development of Nb_3Sn APC (artificial pinning centers) wires with higher stability and critical current (J_c) at or above FCC specs [95] and development of high-C_p wires with good drawability.
- Research on coil assembly materials, such as conductor and coil insulation, and high-toughness resins.
- Development of fiber optics technology as cryogenic strain gauges and temperature sensors.
- Development of a capacitor-based device (QCD) to improve training behavior in Nb_3Sn superconducting magnets and usage of AI [96] to detect the quench precursors and other state of the art magnet diagnostics tools.

The previous and other generic magnet R&D efforts are described in a 2021 Snowmass white paper submitted by the MDP Collaboration [97].

7.2.2 Fast-ramping magnet R&D

Next generation HEP facilities such as muon colliders, future circular colliders, and high-intensity proton synchrotrons for neutrino research demand substantially faster cycles of beam acceleration than available at present. To date, the highest ramping rates achieved in operational superconducting accelerator magnets based on LTS (Nb-Ti) are about 4 T/s, a limitation caused by a very narrow allowable operational temperature margin.

Fast-ramping HTS-based magnets offer a cost-effective solution for many future particle accelerators mentioned above but especially for the acceleration of short-lived particles such as muons. The AC losses in the fast-ramping accelerator magnet are due to power losses in both the magnet energizing conductor and the magnetic core. The power losses in the magnetic core can be reduced by using as thin as practically possible laminations. The power losses in the conductor can be reduced by minimizing both its mass and exposure area to the ramping magnetic field descending from the core. The use of superconductors significantly reduces the magnet cable mass and size, and as a result also the size and mass of the magnetic core. Very importantly, however, the HTS conductor can be set to operate at 5 K, well below its critical temperature of e.g., 30 K, providing in this way a wide operational temperature margin and facilitating temperature-based quench detection and protection systems. A prototype HTS-based accelerator magnet of 0.5 m length and two beam gaps of 100 mm (hor.) $\times$ 10 mm (vert.) was successfully tested [79]. Preparations are now underway to increase this test magnet B field to 0.9 T and the ramping rates up to (500 – 600) T/s.

Future goals in the next 2 years include upgrading the present HTS test magnet to 2 T or higher B field and dB/dt rates up to 500 – 1000 T/s. In the longer term (3 – 6 years), goals should include the design, construction and power test of a long prototype magnet as required for the muon accelerator and the initiation of a possible industrialization process [98].

[2] Low Temperature Superconductor

7.2.3 LEAF Program

In order to transition from the generic R&D effort described above to meeting the industrialization and field level challenges described in the introduction to this section, an effort based on the magnets' leading edge technology, yet driven to demonstrate the feasibility of future colliders, is essential.

Historically, the development and demonstration of maturity of Nb_3Sn technology for application in Hi-Lumi LHC was made possible by a 15 year-long (2003 – 2018) DOE investment in a U.S. national program of directed R&D (called the LHC Accelerator Research Program) working in combination with generic and complementary R&D efforts.

In the same spirit, the proposed Leading-Edge technology And Feasibility-directed (LEAF) program is foreseen to be a decade-long effort to be concluded on the time-scale of ~2034 – 2035. The LEAF Program describes the hand-off from the generic magnet R&D effort to a feasibility-directed approach entertaining a more directed design and development effort and, where necessary, a down selection and industrialization effort for large quantity production. The LEAF Program is described in a white paper submitted to the 2021 Snowmass process [99]. The main elements of the LEAF program can be summarized as follows:

- Design and development of magnets addressing specific elements for the colliders under consideration (field and field quality, aperture, operation, radiation environment, interfaces with experiments, etc.).
- Support for industrial production and usage of advanced superconductors (LTS and HTS).
- Scaling of magnet lengths (fast-ramping magnets, main ring, and IR magnets, ...).
- Synergetic collaboration for high field solenoid development with other offices in DOE or with NSF.
- Industrialization and cost reduction through next generation design for Nb_3Sn magnets [100].

7.3 RF R&D

Advanced RF systems are central to a large number of proposals for future HEP facilities. This includes future colliders like ILC, FCC-ee, CEPC, CLIC, C^3, HELEN, FCC-hh, SppC, and muon colliders, as well as drivers for intensity frontier experiments like LBNF/DUNE. It also includes some smaller-scale experiments such as axion haloscopes. The needs for RF R&D are not only in the area of increasing gradient – other important areas to improve include cavity quality factors, RF source power efficiency and cost, and RF control systems. Mitigating issues related to short- and long-range wakefield effects is important, especially for high-intensity machines.

A decade-long roadmap for RF R&D was developed under the framework of the DOE GARD program in 2017 [101]. The roadmap was worked out by a team of leading researchers in the field from various national labs and universities, both domestic and international. The roadmap reflects the most promising research directions for advances that enable future experimental high energy physics programs. While much progress has been made since that time, most of the topics remain valid. However, the roadmap should be updated and extended into the next decade according to the needs of future HEP machines.

In this section, we divide R&D topics into SRF cavities, normal conducting RF (NCRF) cavities, and companion topics.

7.3.1 SRF for future colliders

SRF cavities are used to accelerate beams in some of the most advanced worldwide accelerator facilities, including for HEP (such as the LHC and PIP-II), basic energy sciences (European XFEL, LCLS-II, SNS, ESS) and nuclear physics (CEBAF, FRIB, future EIC). SRF R&D over the years has led to performance improvements that have enabled new applications which previously had not been feasible. Continued investment in SRF R&D can help to increase the scientific reach of colliders in different ways.

Increasing accelerating gradients, while maintaining high quality factors, is a key research direction. Higher gradients allow linear accelerator tunnels to be shorter and use fewer components to reach a given energy. This helps to enable both linear colliders (e.g., ILC and its upgrades and HELEN) and pulsed drivers for machines like muon colliders and intensity frontier experiments. Promising R&D directions are being pursued for increasing gradient, including new superconducting materials, travelling wave cavities, new cell shapes for standing wave structures, cleanroom robotics to reduce field emission, layered superconductor structures, and new impurity doping treatments, as well as more fundamental explorations of the limits of RF superconductivity, such as the use of "slow surface" materials that could prevent dissipation from magnetic flux penetration. For examples of SRF R&D directions, see references [102–108]. There are many exciting ideas to pursue.

Increasing the quality factors of SRF cavities is another key research direction. Higher quality factors reduce RF dissipation to the liquid helium. This can reduce the cryogenic plant size (which can have a substantial impact for continuous wave RF accelerators like FCC-ee and CEPC), or allow pulsed accelerators to operate with higher duty factor. Promising directions that are being pursued include new superconducting materials, new impurity doping treatments, and expulsion of magnetic flux to minimize trapped flux dissipation.

A very important issue for high-intensity machines (e.g., FCC-ee and CEPC) is to mitigate effects of higher-order mode (HOM) impedances of SRF cavities on stability of beam motion. Developing HOM-damped SRF cavities (sometimes called single-mode cavities) and components to couple out and absorb HOM power is an important R&D topic for these machines, see e.g., [109].

7.3.2 NCRF for future colliders

The main challenge in NCRF for future linear colliders is developing high-gradient structures with an acceptable breakdown rate and adequate mitigation of wakefield effects. The CLIC team has developed and demonstrated a room-temperature X-band structure stably operating at $\sim$ 70 MV/m. Further improvements in gradient has been possible by cooling down copper structures to cryogenic temperatures, which strengthens the material and improves the breakdown rate. C^3 follows this path with developing novel C-band structures [34, 35]. However, there are still many R&D issues to address, which are described in [60, 61].

NCRF for a muon collider faces a very specific challenge of operating high-gradient cavities in high magnetic field of the muon cooling channel. Some R&D has been done in the past, but more

is required to find an optimal combination of the cavity frequency, geometry, material, operating temperature and pressure.

7.3.3 Companion R&D topics

RF cavities require RF power sources, for which two areas of R&D can be beneficial: cost and efficiency. Improving RF power source efficiency can be especially beneficial for accelerators that have high AC power requirements, which may be dominated by the RF system demand.

As gradients increase, it is important to perform R&D on corresponding improvements in auxiliary systems that will need to be modified in order to take full advantage of the higher gradients. These include high-power RF distribution, resonance control systems, RF power couplers, and methods to mitigate field emission.

7.4 High Power Targetry R&D

A High-Power Target (HPT) system is a critical beam element to accomplish future High Energy Physics experiments. Future neutrino facilities, like LBNF and J-PARC, propose 1 – 3 MW proton beams delivered to a target for neutrino production [110, 111]. The beam power range is comparable to a muon collider and neutrino factory, which propose 2 – 5 MW proton beams [112]. On the other hand, the European Particle Physics community has been investigating a 100 TeV center-of-mass energy hadron collider FCC-hh [113]. The HPT technology R&D is also beneficial to the FCC-hh which requires radiation hardened beam elements: beam collimators, beam dampers, beam window, and beam instrumentation that will need to tolerate a radiation dose equivalent to a MW of beam power. Even though the FCC-hh does not have a target system in the complex, HPT R&D is needed. The current HEP target technology tolerates a beam power up to 1 MW. The goal of the proposed R&D extends their capability well beyond 1 MW beams.

7.4.1 Material science R&D

To maximize the yield of secondary and tertiary particles coming from a target system, the typical length of the target is a few interaction lengths. A hot spot appears in every beam cycle at a depth of one interaction length in the target. Such a high cycle thermal stress and radiation damage make the target lifetime short. The RaDIATE collaboration was formed to research a radiation tolerant material for HEP solid targets [114, 115]. The Post Irradiation Experiment (PIE) and Displacement Per Atom (DPA) cross-section experiment are proposed at Fermilab, BNL, and CERN to extend the fundamental radiological material science in HEP energy regimes. Graphite is currently the most popular material for a neutrino target. It recovers from a mechanical strain because it can be annealed at high temperature caused by the energy deposition of the beam.

State of the art technology in nano-science is capable of investigating radiation damage at the atomic scale. A recent study suggests that a compound material, such as Ti-6Al-4V [116] or a high-entropy compound [117] have radiation resistance by controlling the crystal phase change and irradiation temperature. A nano-fiber target is another possible technology to mitigate propagating thermal shock [118]. Another possible solution is the use of liquid or granular materials which potentially mitigate the instantaneous thermal stress issue.

The Muon Accelerator Program (MAP) investigated a mercury jet target. The concept was experimentally demonstrated at instantaneous power up to 8 MW. However, because mercury is

harmful to the environment, and since the SNS and J-PARC report cavitation damage in a mercury target vessel, mercury targets are not favored. A flowing granular Tungsten pion production target is proposed to avoid the issues of a mercury target. Finely powedered Tungsten is injected into a beam interaction volume by using a He gas jet. Such fluidized powder target introduces new challenges, however. These include: achieving reliable circulation and continuous stable horizontal dense phase flow, managing heat dissipation, mitigating radiation damage and erosion of the containing pipework and beam windows, as well as ensuring reliable diagnostics and controls for the powder handling processes.

7.4.2 Simulation tools for HEP target design

Producing a precise hadronic interaction model in simulation is crucial for designing a target system and reducing systematic uncertainty in experiments. To this end, the experimental data (from NA61 and EMPHATIC) will be used to optimize simulation code (GEANT4, MARS and FLUKA). Present target design is typically a monolithic shape made by stacking either identical thin rods or blocks. An optimal HEP target could have a varied cross section and material property along the target length to have better mechanical strength and secondary/tertiary yields. Artificial Intelligence (AI) and Machine Learning (ML) can be applied to optimize the design of target systems. Utilizing a national High Performance Computing (HPC) facility supported by DOE is likely needed to obtain the high statistics needed for such simulation studies.

7.4.3 Pion capture channel R&D

The pion capture channel should be addressed in the target system R&D. The target is immersed in a solenoidal magnet to direct captured pions at the target to the downstream beam line. The field strength is adiabatically reduced along the beam path length to induce a beam focusing. A peak field strength at the target is 15–20 T and the strength goes down to 2 T in 10–20 meters at the end of the pion capture channel. A high pion yield and high capture efficiencies in this scheme have been successfully demonstrated in simulation. To mitigate the radiation issue, the solenoid coil in a high radiation area uses a hybrid structure: an inner coil that is normal conducting and an outer superconducting coil are used, and a thick radiation shielding layer is inserted between the two coils. However, there is not yet an engineering design developed to remove the heat from the channel in a short time. It is unknown how long these solenoid coils, especially an electric insulator in the coil, can survive in such extreme environments. Besides, no practical design for a primary proton beam dump exists. A detailed engineering study and demonstration tests are needed.

A magnetic horn focusing channel is considered as an alternate option. This is widely used for a neutrino target system. It has been demonstrated with a 900 kW beam operation. This technology is mature and can be extended to accept multi-MW beam power. An idea of making a FODO cell by combining multiple horns is considered to capture and focus both charged particles. The present design goals are to validate the concept and to improve pion yield and capture efficiencies in the horn scheme.

7.5 Detectors R&D for future colliders

Detector R&D needs for future colliders have been studied and summarized very recently in 2019 by the DOE Basic Research Needs For High Energy Physics Detector Research and Development

report [119] as well as by the 2021 ECFA Detector Research and Development Roadmap [120]. Main findings from these two articles have been summarized here.

7.5.1 Tracking

The main workhorse for Inner Tracking Systems are silicon detectors. The most important R&D directions in this area are to achieve full integration of sensing and microelectronics, e.g. in monolithic pixelated CMOS sensors; the development of 4D capabilities for picosecond timing; radiation hardness to extreme fluences of up to 5×10^{18} n_eq/cm^2, including exploration of alternative materials; and the development of 3D-interconnect technologies; ultra-low mass support structures and cooling systems, going hand-in-hand with low-power and optical/wireless readout capabilities. To scale up to ever larger systems, especially for silicon-based calorimeters, R&D is needed into large wafer sizes and new, lower cost materials, such as graphene or GaAs. Testing infrastructure, such as irradiation and testbeam facilities that can reach the relevant energies and fluences, are crucial ingredients to the success of this ambitious R&D program. Close collaboration with industry partners is becoming more and more important in order to benefit from ongoing advances in telecommunication and to keep the cost from becoming prohibitive.

7.5.2 Calorimetry

Radiation-hard calorimeters with enhanced electromagnetic energy and timing resolution are to be developed for experiments at future colliders. They also need to be high-granularity calorimeters with multi-dimensional readout for optimized use of particle flow methods, while being able to operate in extreme environments of not only high radiation, but also high data rates and pile-up. For silicon-based calorimeters the passive space needs to be reduced by developing larger wafers, smaller guardrings, and suitable mechanical structures. It would be important to design thicker sensors with active gain to increase the signal yield, especially for use at electron-positron and muon colliders. Investments in new technologies, such as CMOS-based sensors and digital SiPMs, as well as new materials, such as GaAs, have to be made. To enable very large area detectors, new advances in interconnects need to be made, such as anisotropic conductive films or PCBs made of new materials with the same CTE as silicon. Larger scale industrialization for these detectors will be needed, in particular for hadron colliders. The challenges for calorimeters based on liquid noble gases lie in developing high readout granularity for pileup mitigation and particle-flow reconstruction, picosecond timing information, and the minimization of passive material in front of the calorimeter: calorimeter weighing hundreds of tons needs to be supported by low-mass cryostats. For calorimeters with light-based readout the R&D challenges are related to the development of novel Silicon Photomultipliers (SiPMs) with large spectral sensitivity and high-bandwidth semiconductors for higher radiation tolerance, as well as digital SiPMs. The development of novel crystal and liquid scintillator technologies are crucial.

7.5.3 Gaseous Detectors

The main gaseous detector types are GEM, Micromegas, μ-RWELL, RPC and RICH. Time and spatial resolutions in these detectors need to be improved along with long-term stability and radiation hardness. Tracking with dE/dx and dN/dx capabilities in large volumes with very low material budget and different readout schemes have to be developed. Detectors for very large areas with

high-rate capability that use environmentally friendly gas systems would be critical in the future. For Inner Tracking applications, the detectors need to be ultra-lightweight. Given the large areas needed, the cost needs to be driven down, perhaps through industrialization. These detectors can be used for Muon Systems, inner tracking Detectors, including particle identification (PID), as well as calorimeters and pre-shower Detectors.

7.5.4 Photon Detection and PID

For these applications, we need to develop photosensors for extreme radiation environments, in particular for hadron colliders. The leading technology for this are SiPMs, for which low noise, fast-timing capable and inherently radiation-hard versions will have to be developed. R&D should go into developing RICH and imaging detectors with low mass and high-resolution timing capabilities in order to enable particle ID. Also needed are compact high-performance time-of-flight detectors for particle ID.

7.5.5 Electronics and Data Processing

New technologies have to evolve to deal with greatly increased data density, such as high data rate ASICs and systems, and new link technologies, such as optical fibers, wireless, wireline, and free-space optics to communicate between detector layers for increased on-detector data reduction. Power consumption and readout efficiency need to be improved; new technologies to increase the intelligence on the detector, i.e., to process data close to the detector have be advanced. This involves front-end programmability, configurability and modularity; intelligent power management and advanced data reduction techniques using AI/ML. Readout technologies need to be on par with new developments in 4D and 5D detector techniques. For example, high-performance sampling ADCs and TDCs, as well as high-precision timing distribution need to be developed. Again, it is to be emphasized that all these need to work in extreme radiation environments, especially for future hadron and muon colliders. Commercial developments are advancing at a record pace in the area of readout electronics and data processing. HEP R&D needs to be able to keep up with these developments to profit from industry standards and cheaper processes.

7.5.6 Collider Detector R&D at Fermilab

The Fermilab Detector R&D program currently supports a wide range of R&D topics in the area of collider physics. One main research focus is on the development of silicon sensors and ASICs with special interest in picosecond timing and 3D-integration. R&D is also being performed on extruded, molded and 3D-printed scintillators with special emphasis on light-yield and radiation hardness. We are working on thermally improved carbon fiber composites for light-weight support structures. One area of our R&D is focused on radiation-hard and B-field-hard DC-DC converters. In the area of new materials we are performing long-term “Blue Sky” R&D involving GaAs and Graphene. GaAs with In quantum dots is a potential new material for photon-collecting ultra-light tracking or calorimetry detectors. Graphene, or other large-bandgap materials, have the potential to replace silicon for large-area, low-mass, cost-effective tracking detectors. Furthermore, we are developing novel readout links based on silicon photonics, and we are working towards intelligent, self-calibrating detectors using AI/ML.

Picosecond Timing R&D is one of the current two high-priority directions of the Fermilab R&D program. This is being approached by a combination of sensor R&D, ASIC R&D, Systems engineering and facility development. On the sensor side we are working on different LGAD designs as well as the principle of small pixels that could potentially deliver 5D information (position, timing and direction). Future R&D plans include an expanded picosecond timing R&D program as well as increased R&D for on-detector AI/ML. Long-term Blue Sky R&D efforts will continue.

Two extremely important components in Fermilab's successful collider detector program are the Fermilab Test Beam Facility (FTBF) and the Irradiation Test Area (ITA). It is crucial that these facilities continue to be supported and improved in the future. A proposal for new test beam and high-intensity irradiation facilities at Fermilab are described in [121]. These will be designed to enable detector R&D for future colliders.

7.6 Software and Computing Infrastructure

While the HEP field plans for future experimental facilities, newly established and emerging computing technologies are changing the way we do particle physics. The break down of Dennard Scaling (independence on the number of transistors of the power/volume used by silicon devices) and Moore's Law (transistor density doubling every two years), as well as the flattening of the clock speed curve, have brought a paradigm shift in computing architectures. New systems follow a heterogeneous model with multi-core machines using co-processors (e.g., GPUs) and complex memory configurations. Simultaneously, AI/ML has evolved from an emerging technology to a main stream tool which has permeated every aspect of particle physics, triggering the development of specialized hardware and algorithms adaptations to HEP-specific problems. Quantum computing is today an emerging technology that promises a potentially revolutionary impact on science in general and particle physics in particular. The challenge comes from environmental noise affecting the quantum state, known as quantum decoherence. At the moment, the quantum computing field is at the noisy intermediate-scale quantum (NISQ) era, with a rapid development of software for quantum computers. The HEP field should prepare for the possibility that fault tolerance (post-noisy era) is achieved in about a decade.

Given technology breakthroughs potentially occurring in the timescale of future colliders, defining computing models today for experiments operating at these facilities is premature. Even much shorter timescales such as those associated with the HL-LHC experiments, expected to start in 2029, make software and computing planning a difficult task. What is clear is the need to invest sustainably on R&D to understand the potential applications of these technologies to HEP, integrate the resulting tools, and adapt or re-engineer the computing and software ecosystems. (The Snowmass 2021-2022 Computational Frontier report [122] offers a summary of the US community computing challenges assessment and recommendations. An overview of the computational challenges of the HL-LHC program is presented in Ref. [123].)

While rapidly evolving technologies call for investment in R&D, computing needs for physics studies and accelerator and detector R&D in the next few years are easier to predict and should be pursued without delay. Teams with expertise in accelerator and detector simulation modeling tools focused on future colliders need to be strengthened and provided with resources within HEP laboratories and university groups. Software infrastructure commensurate with the requirements to run compute intensive simulations based on beam and detector modeling toolkits must be developed,

and effort spent to incorporate the necessary features to provide user-friendly interfaces and accurate predictions.

Simulation tools must be able to model accelerator components and beam transport conditions unique to each of the proposed collider accelerators. They are of fundamental importance in the design and optimization of these components, as well as the actual configurations of R&D experiments performed to address technology challenges. For example, in the case of the Muon Collider, extensive simulation would be needed to improve target and cooling channel designs and to analyze the data from the associated demonstrator experiments. Event generators must be capable of modeling hard collisions and processes potentially occurring at the energies at which future colliders would be operated. Detector simulation tookits, such as Geant4 [124–126], must be improved to be able to model the complex geometries of future detectors and the physics interactions inside the detectors. Reconstruction algorithms should be developed to extract the physics information made available by novel detector technologies and features. Even if the computing demands of future colliders were smaller than those of HL-LHC, software tools must be adapted to support prospect studies and R&D activities. The improvement, maintenance, and support of existing common software tools are essential and complementary to the investment in their adaptation or re-engineering to take advantage of the opportunities presented by evolving computing platforms and facilities, including super-computing centers demanding effective use of hardware compute accelerators.

A long-term commitment to build and sustain expertise is critical, given that the utilization of the above-mentioned computing infrastructure and the execution of the software development projects require skills and expertise which are currently scarce and in high demand. Continuity and predictability are essential to build competent and productive teams to provide software and computing support for future collider efforts where the US plans to play a leading role.

Concretely, in order to maximize the U.S. impact on future colliders R&D in the next few years, including accelerator and detector efforts, the community would potentially pursue the modernization of future colliders software infrastructure for both accelerator and detector studies. This should include common software tools, common data formats, automatic scaling of columnar analysis in analysis facilities, all in the context of a highly-concurrent software framework supporting multi-threading and the use of co-processors such as GPUs and FPGAs. Accelerator and particle physicists, as well as computing professionals, need to partner to create this computing ecosystem aimed at increasing the efficiency and impact of U.S. contributions to all existing future collider concept efforts.

8 Summary and Conclusions

There is significant interest in the U.S. HEP community to make progress towards the construction of a global collider, to pursue precision Higgs physics and to search for new physics beyond the standard model. There are several proposed candidates which have been extensively studied globally and they are in various stages of readiness. In addition to engaging in colliders proposed to be hosted abroad, there is great interest to explore options to host a collider in the U.S. following the LBNF/DUNE project completion. We have discussed U.S. engagement in global projects proposed in Japan and at CERN, and collider options for hosting in the U.S.

Of all the candidates on the table for an e^+e^- Higgs factory, the ILC is the most mature and "shovel ready" project for construction. If the ILC does not get approval to move forward in Japan soon, and if the FCC-ee project (or any e^+e^- Higgs factory) does not proceed at CERN, the ILC could be considered to be built in the U.S., perhaps at or near Fermilab. In this paper, we have also discussed a few other novel, timely, cost effective, compact Higgs factory options that are suitable for the Fermilab site. These linear e^+e^- collider options are highly promising and technology R&D for them should be pursued vigorously. We also considered a staged muon collider from a 125 GeV Higgs to multi-TeV (up to $\geq$ 10 TeV) energy range. There is immense interest in a muon collider beacuse of its promise of both precision and discovery potential, and synergies with other particle physics (charged flavor violation and neutrino physics) programs; the Accelerator Complex Evolution plans at Fermilab also strongly facilitate a future muon collider complex. Finally, preliminary studies for a compact site-filler hadron collider has also been presented.

We have discussed critical technology R&D and demonstrator projects for C^3 linear collider and the muon collider. To make progress towards a decision on the selection of one of the collider options for the U.S. by the end of this decade as well as to facilitate strong engagement with future collider efforts abroad, an integrated national future colliders R&D program has been proposed. If supported, this program would enable required design studies and focused R&D to address major challenges for feasibility demonstrations. It would also position the U.S. as a key player in future collider facilities abroad and help advance the potential collider options for the U.S. to the next stage of conceptual and technical design development.

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