
Accelerator Technology Test-Beds and Test Beams

Conveners: W. Gai, G. Hoffstaetter, M. Hogan, V. Shiltsev

35.1 Executive Summary

The charge to the CSS-2013 Frontier Capabilities Working Group 6, “Accelerator Technology Test-Beds and Test Beams” was to assess the situation with and identify the needs in the accelerator R&D facilities for high energy particle physics. Of particular interest are HEP accelerators at the Energy Frontier (hadron and lepton colliders), and at the Intensity Frontier (linacs and rings). In February 2013, WG6 organized a workshop on “Frontier Capabilities: Accelerator Technology Test Beds and Test Beams” at the University of Chicago. This workshop covered four major topics:

1. R&D beam facilities for future Energy Frontier machines: required R&D and (beam) facilities needed
2. R&D beam facilities for Intensity Frontier machines: required R&D and (beam) facilities needed
3. Technology developments: required R&D and (no beam) facilities needed
4. Detector R&D and required Test Beam facilities

43 participants had discussed the needs of almost two dozen HEP facilities — existing, planned and future ones. All presentations and summaries are available at the conference website [1].

Among the most common questions concerning future HEP accelerators are:

- What is the potential of SCRF R&D for high energy physics?
- What are limits of conventional linacs and synchrotrons? with SC structures? with room temperature structures?
- What is the potential for cost reduction technologies for “conventional” accelerators?
- What limits beam current and brightness in linacs and rings? Would new cooling techniques help?
- How can plasma and laser based accelerators make a difference? What is the opportunity for a low energy collider demo with plasma optics?
- What are the R&D road maps for these technologies?
- What are opportunities at exiting facilities for test beams for detector development?
- What are opportunities at exiting facilities for test beams for accelerator development?

Our finding and recommendations are structured below along several major thrusts:

- Energy Frontier Hadron Colliders [LHC and upgrades, VLHC]
- Energy Frontier Lepton Colliders [ILC, CLIC, Muon Collider, VLLC]
- Intensity Frontier Accelerators [Project X, Daedalus, Neutrino Factory]
- Accelerator Technology Test Facilities [SCRF, SC Magnets, etc]
- Proof-of-Principle Tests for Far Future HEP Accelerators [plasma wakefield accelerators, etc]

35.1.1 Energy Frontier hadron colliders

Hadron colliders dominated HEP landscape for several decades and expect to continue the domination over many more years of the LHC operation. Several energy frontier hadron colliders are under consideration now, including upgrade of LHC luminosity to $5 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, upgrade of the LHC energy to some 33 TeV cme, and design of the VLHC in a 80–100 km or longer tunnel.

35.1.1.1 Issues

The most important accelerator issues for these machines are in the areas of:

Technology: superconducting magnets which are the crucial determinants of the cost and energy and performance reach of these collider. Of great challenge are Nb₃Sn 15 T arc dipoles and possible HTS superconductors such as YBCO and Bi-2212 capable to support dipole fields well above 20 T. For the VLHC, cheaper lower-field magnets and innovative low-cost tunneling technologies are of utmost importance to conclude on colliders financial feasibility. Technologies of the CW SC crab-cavities and higher power beam dumps need to be developed.

Beam Dynamics: Many of challenges are associated with expected few GJ of beam energy in the higher energy colliders and synchrotron radiation affecting beam dynamics and machine design and operation. That will require R&D on efficient collimation and control, vacuum chamber design and development of the photon stops to protect the superconducting magnets and other equipment.

Injectors: production and acceleration of high intensity low emittance proton beams will require modern particle sources, SC linacs and fast synchrotrons, as well as reliable control of losses in space-charge dominated beams.

35.1.1.2 Required R&D facilities

Many of the above listed technology developments can be carried out at the existing SC magnet and RF test facilities supported by OHEP GARD program and by LARP at the US National Labs, as well as at similar facilities overseas, first of all at CERN. Some of these facilities might need to be upgraded to accommodate the R&D needs of specific projects (cable tests, transmission line magnet tests, etc). Many beam dynamics studies on collimation and coherent instabilities can be performed at the LHC and its injectors and at Fermilab's Main Injector and Booster and RHIC. Essentially all Project X R&D activities and facilities will

directly address many issues related to hadron colliders injectors. Several promising novel accelerator schemes like resonance free integrable optics, space charge compensation with electron devices and optical stochastic cooling - will require dedicated test accelerators, and the IOTA ring (Integrable Optics Test Accelerator) at the Advanced Superconducting Test Accelerator (ASTA) facility at Fermilab offers a perfect match for the task.

35.1.2 Energy Frontier lepton and gamma colliders

A list of facilities on the horizon begins with electron-positron Linear colliders including the International Linear Collider that has recently delivered a Technical Design Report. The list continues with other concepts that are technically promising for various reasons but are progressively less mature in terms of collider design.

- Linear collider type e^+e^-
- Circular e^+e^-
- Photon collider
- Muon colliders
- Plasma based accelerators (beam and laser driven)
- Dielectric accelerators (beam and laser driven)
- Crystal based linear collider

Linear collider designs benefit from the extensive design and prototyping work that has been done, key technologies are in hand after large investment for R&D and there exist well-organized international collaborations led respectively by the ILC GDE and CLIC Collaboration. Primary challenge of any linear collider type system is the high cost but specific challenges remain for the final focus system and the positron source. These issues are being addressed at dedicated facilities including FLASH at DESY, ASTA at FNAL and the ATF2 at KEK. A CLIC type system has additional challenges to develop and industrialize the accelerating structures and major components. These questions are being actively addressed at the facilities above as well as CsrTA, ATF2 and CTF3.

At lower energies, with sufficiently large diameter, circular colliders can potentially provide higher luminosity while drawing on a base of mature technology with rich experience. Primary challenges for rings are the large synchrotron power, beamstrahlung and large momentum acceptance required. These problems are being addressed in large part at existing rings, light sources and beam test facilities at listed in Section 35.2.2.2.

Photon collider designs allow access to the CP property of the Higgs and they can study the Higgs at a lower beam energy with a high degree of polarization without the need for positrons and ancillary systems. Primary challenges for photon colliders relate to generating sufficient photon flux that require as yet undeveloped high-power lasers as well as new IR region designs as described in Section 35.2.2.2. Appropriate laser technology is being developed within the international consortiums and at LLNL in the U.S.

A muon collider scales well to high energies given the relatively large mass of the muons that allows for tight bends and compact accelerator geometry. The primary challenge for muons is creating and cooling them to sufficient phase space density to allow for sufficient luminosity. The Muon Accelerator Program is coordinating the R&D into the major issues with experiments primarily at FNAL and RAL.

Plasma Acceleration holds much promise for advancing the energy frontier because it can potentially provide a 1000-fold or more increase in acceleration gradient, reducing a linear collider to a footprint dominated by the final focus and beam delivery systems. The main challenges for plasma accelerators are demonstrating a concept for positron acceleration and demonstrating staged acceleration with the required beam brightness and efficiency. These issues are being addressed through multi-institution collaborations conducting experiments at dedicated and proposed facilities BELLA/BELLA-II at LBNL and FACET/FACET-II at SLAC.

Accelerators built from dielectric materials have been proposed to deliver higher accelerating gradients and allow for a more compact overall accelerator. Challenges for beam driven dielectrics include identifying materials with appropriate breakdown voltage characteristics, identifying optimal structure geometries and the demonstration of staging with the required efficiency. These are being addressed at the AWA at ANL, ATF at BNL and FACET and SLAC. The NLCTA facility at SLAC hosts a dedicated beamline studying the primary issues for laser driven microstructures including damage limits, coupling geometry, staging and phase tolerances.

35.1.2.1 Staging experiment for wakefield accelerators:

One of the major challenges for the wakefield accelerator application is to use many drive beams to accelerate a witness beam to the desired energy with sufficient intensity. This requires the generation of high intensity, multiple drive electron/laser beams. Also, longitudinal shaping of a drive beam can effectively increase the energy transfer efficiency from the drive beam to the witness beam, thus reducing the number of required stages.

Several staging schemes have been investigated:

- **AWA:** Multiple 75 MeV drive beams with a 15 MeV witness beam are available for this test. The test will be done using a deflecting cavity and set of magnets for beam manipulation and transportations. Also a beam shaping experiment will be performed. The wakefield device used here will be dielectric based.
- **FACET:** The facility will investigate multiple drive beam generation and pulse shaping. The experiment will be designed with a short beam transport in mind. The parameters are not fixed yet, but it is one of the major goals for the FACET II.
- **BELLA:** At LBL, there are efforts to synchronize two lasers and accelerate a single electron beam. The experiment will done at sub-GeV level, but nevertheless demonstrate the concept.

There are many other facilities that can be used for staging demonstrations, however, not much effort have been put forth on this.

35.1.3 Intensity Frontier accelerators and secondary beams driven by protons

The short- and medium-term needs of the US Intensity Frontier program will employ Fermilab proton accelerators – a power-upgraded Booster and Main Injector augmented by the “muon campus” rings (g-2, mu2e, nuSTORM, etc). Longer term aspirations require construction of Project-X — a modern SC RF proton linac. That unique world-leading Intensity Frontier facility will be able to deliver,

simultaneously, up to 6 MW of site-wide beam power to multiple experiments, at energies ranging from 233 MeV to 120 GeV, and with flexible beam formats. Project X will support a wide range of experiments based on neutrinos, muons, kaons, nucleons, and nuclei and also can form a basis of the front-end of a future Neutrino Factory. The proposed Daedalus experiment calls for construction of several very high power, 1 to 5 MW, 800 MeV proton cyclotrons.

High power hadron accelerators for the Intensity Frontier have two over-riding design constraints of minimizing beam loss (< 1 Watt/m, or/and $< 1 \times 10^{-4}$ total beam loss), and beam delivery in experiment-specific time formats (from a quasi-CW for rare particle decays to single few ns long bunches).

The key accelerator challenges of the IF accelerators include:

- Producing high current, high-quality and high brightness beams with required bunch structure
- Efficient accelerating high beam currents to high energies
- Required beam manipulations on the bunch-by-bunch base for parallel experiments
- Maintaining beam loss at a level where routine maintenance is possible
- Emittance preservations and minimizing beam halo
- Low-loss extraction of the beams
- Target systems for extreme power densities and extreme radiation environments

35.1.3.1 Required R&D facilities

Essentially all Project X R&D activities at the PXIE facility and beam studies with the SC RF cryomodules at Fermilab's ASTA facility will directly address many issues listed above. Many beam experiments on efficient collimation, coherent instabilities, and novel extraction methods can be performed at Fermilab's Main Injector and Booster, at the ORNLs SNS or at the LHC and its injectors. Studies of promising novel accelerator techniques — such as halo suppression in the integrable optics, space charge compensation with electron devices — can be performed at IOTA ring (Integrable Optics Test Accelerator) at the ASTA facility. A dedicated facility is needed for development and tests of high power targets, though some targetry issues can be explored at existing accelerators. Many tests and technology demonstrations to support the Daedalus experiment design work can be performed at the existing facilities, e.g., INFN-Catania, RIKEN, ORNL, The Best Cyclotron Systems, Vancouver, BC.

35.1.4 High intensity electron accelerators

The Super KEK-B factory is the only HEP machine under construction today. It is an asymmetric-energy and double-ring collider; the beam energy of the positron (LER) is 4 GeV and that of the electron (HER) is 7 GeV. The luminosity gain of 40, with respect to KEKB, can be obtained. Several versions of the super Tau-charm factories have been discussed/proposed; notably, at Novosibirsk and Tor Vergata/Frascati. Approval of these projects construction will largely depend on the physics case, not the accelerator challenges. Another proposed application of the high intensity electron beam at JLABs ERL based FEL machine is that it could be used for a dark matter test. It uses a 1 MW electron beam striking on a windowless target for detecting pair production from a dark photon produced in the collision.

35.1.5 High intensity electron-ion colliders

Although there are not any electron-ion colliders under construction today, there are several projects eRHIC(BNL), ELIC(JLAB), LHeC (CERN). In addition, FAIR in GSI and HIAF in Lanzhou are being proposed. Technical challenges for these machines are: electron cooling of heavy ion beam; low beta insertion and crab crossing. In addition, it is still a challenge to generate an intense polarized electron beam for ERL accelerator. The needed R&D efforts are being conducted at the respective labs.

35.2 Accelerators on and beyond the horizon

Particle accelerators have been widely used for physics research since the early 20th century and have greatly progressed both scientifically and technologically since then. To gain an insight into the physics of elementary particles, one accelerates them to very high kinetic energy, let them impact on other particles, and detect products of the reactions that transform the particles into other particles. It is estimated that in the post-1938 era, accelerator science has influenced almost 1/3 of physicists and physics studies and on average contributed to physics Nobel Prize-winning research every 2.9 years [2]. Colliding beam facilities which produce high-energy collisions (interactions) between particles of approximately oppositely directed beams did pave the way for progress since the 1960s. Recent discussion on the development of the colliders can be found at [3]. Twenty nine colliders reached operational stage between the late 50s and now. The energy of colliders has been increasing over the years, as demonstrated in Fig 35-1. There, the triangles represent maximum CM energy and the start of operation for lepton (usually, e^+e^-) colliders and full circles are for hadron (protons, antiprotons, ions, proton-electron) colliders. One can see that until the early 1990s, the CM energy on average increased by a factor of 10 every decade and, notably, the hadron colliders were 10-20 times more powerful. Since then, following the demands of high energy physics, the paths of the colliders diverged to reach record high energies in the particle reaction. The Large Hadron Collider (LHC) was built at CERN, while new e^+e^- colliders called particle factories were focused on detail exploration of phenomena at much lower energies.

Figure 35-2 demonstrates the impressive progress of luminosities of colliding beam facilities since the invention of the method. Again, the triangles are lepton colliders and full circles are for hadron colliders. One can see that over the last 50 years, the performance of the colliders has improved by more than 6 orders of magnitude and reached record high values of over $10^{34}\text{cm}^{-2}\text{s}^{-1}$. At such luminosity, one can expect to produce, e.g., 100 events over one year of operation (about 10^7 s) if the reaction cross section is 1 picobarn (pb)= 10^{39}cm^2 .

In general, colliders have had 50 glorious past years as not only many important particle discoveries were made at them, but they also initiated a wide range of innovation in accelerator physics and technology which resulted in 100-fold increase in energy (for each hadron and lepton colliding facilities) and 104-106 fold increase of the luminosity. At the same time, it is obvious that the progress in the maximum c.m. energy has drastically slowed down since the early 1990's and the lepton colliders even went backwards in energy to study rare processes — see Fig. 35-1. Moreover, the number of the facilities in operation has dropped from 9 to 5, as indicated in Table 35-1, which lists all operational colliders as of the early 1990's and now (early 2010's) and accounts for the projects under construction or under serious consideration at this time (in parentheses). Our current landscape shows the end of the Tevatron era (The 26 years long ~ 2 TeV c.m. energy proton-antiproton Collider Run ended in September 2011.) and is dominated by the LHC at CERN. The Tevatron, LEP and HERA established the Standard Model (SM) of particle physics. The next generation of colliders is expected to explore it at deeper levels and to eventually lead the exploration of the smallest dimensions beyond the current SM.

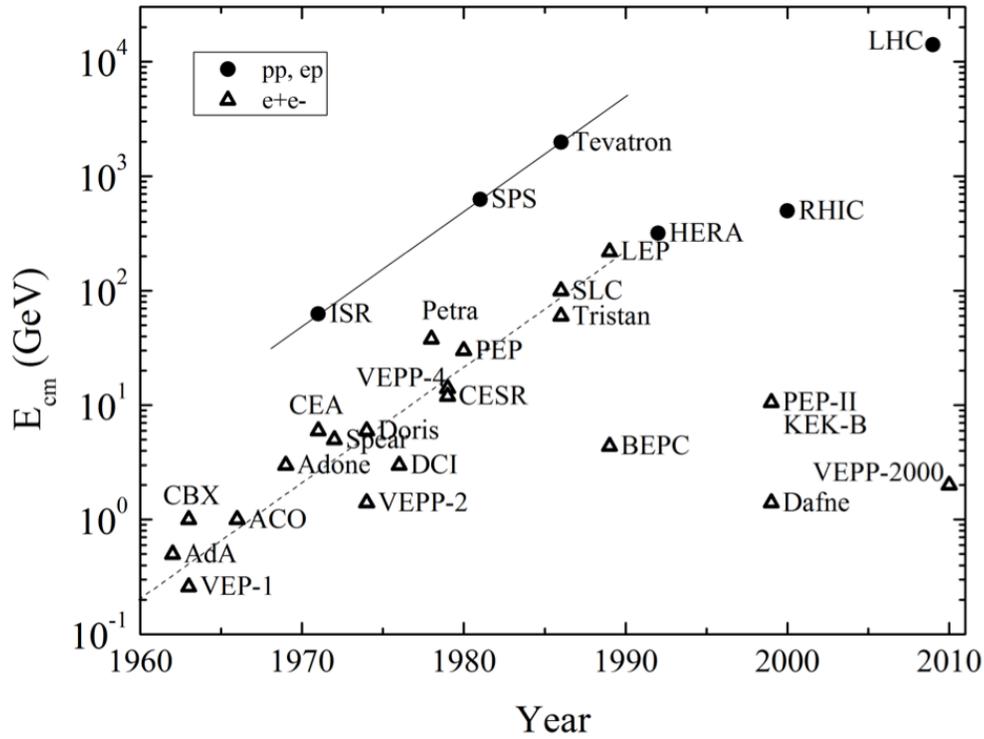


Figure 35-1. Colliders over the decades (from [3]).

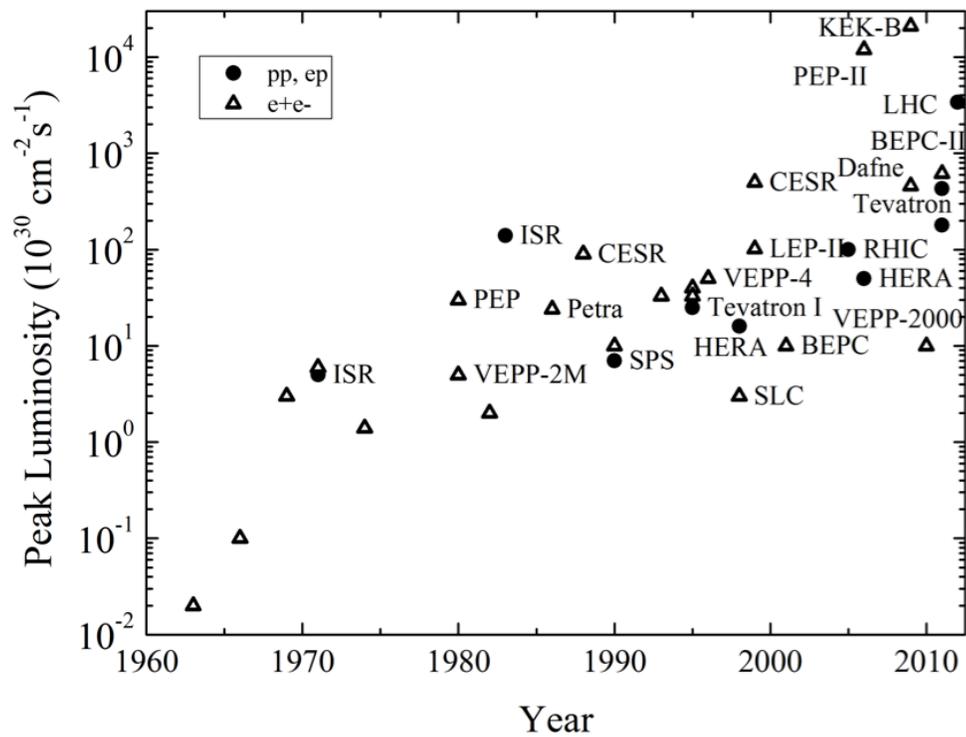


Figure 35-2. Peak luminosities of particle colliders (from [3]).

	early 1990's	early 2010's	2030's
Europe	<i>HERA</i> , (LHC) <i>LEP (Dafne)</i>	LHC (<i>Super-B</i> , HL-LHC) (LHeC , <i>ENC</i>)	HE-LHC <i>CLIC</i> ?
Russia	<i>VEPP-2</i> , <i>VEPP-4</i> (UNK , <i>VLEPP</i>)	<i>VEPP-2000</i> , <i>VEPP-4M</i> (NICA , <i>Tau-Charm</i>)	NICA ? <i>Higgs Factory</i> ?
United States	Tevatron , (SSC) <i>SLC</i> , <i>CESR</i> , (<i>PEP-II</i>)	RHIC (eRHIC , <i>ELIC</i>)	<i>Muon Collider</i> ? <i>PWLA/DLA</i> ?
Asia	<i>Tristan</i> , <i>BEPC</i> (<i>KEK-B</i>)	<i>BEPC</i> (<i>Super-KEKB</i>)	<i>ILC</i> ? <i>Higgs Factory</i> ?
Total	9 (7)	5 (9)	1+ ?

Table 35-1. Past, present and possible future colliders; hadron colliders are in bold, lepton colliders in italic, facilities under construction or in decisive design and planning stage are listed in parentheses.

35.2.1 Energy Frontier hadron colliders

35.2.1.1 LHC upgrades

High luminosity LHC: The LHC luminosity upgrade project HL-LHC will employ novel SC magnet technology based on the Nb₃Sn superconductors for tighter focusing at the interaction points and quintuple the performance of the energy frontier machine by mid-2020s to $5 \times 10^{34} \text{cm}^{-2} \text{s}^{-1}$ with luminosity levelling at 14 TeV c.m. energy in proton-proton collisions and will enable to obtain about 250fb^{-1} of the integrated luminosity per year with ultimate goal of 3000fb^{-1} for both ATLAS and CMS experiments [4].

Higher energy LHC: One of the most feasible opportunities is an energy upgrade of the LHC to 33 TeV c.m. proton-proton collisions. The HE-LHC in the existing LHC tunnel will require 20T dipole magnets which are currently thought possible via combination of the NbTi, Nb₃Sn and HTS (high-temperature superconductor) SC magnet technology. Such a collider could follow the HL-LHC and start operation in the early 2030s. Despite the (presumed) feasibility of the machine, its energy reach is limited to 2.5 times the LHC energy and it is not fully clear yet whether such a (relatively) small energy advance will justify its construction.

VLHC (Proton-proton and electron-positron collider in a 100 km ring at Fermilab): [5] It is believed that a proton-proton (pp) collider in a 100 km ring, with center of mass(CM) Energy of 100 TeV which would have substantial discovery potential for new heavy particles and new physics beyond the Standard Model. The main technological components are the superconducting magnets with required dipole fields in the range of 15-20 T. The main operational challenges are likely to be in providing adequate machine protection to cope with the GJs of beam energy and protecting the superconducting components from the high doses of synchrotron radiation. It is to be noted that a two stage design of the VLHC was considered in 2001 with (a) a low field and (b) a high field magnets, both contained in a 233 km ring. The low field ring used 2T transmission line magnets to reach a beam energy of 20 TeV. The high field ring used 10 T magnets

to reach a beam energy of 87.5 TeV. Advances in technology in the past decade now make it possible to design colliders in a smaller ring.

Concerning the high energy p-p colliders, the remaining R&D topics are in the areas:

Technology: The superconducting magnets are the crucial determinants of cost and energy reach of this collider. A design based on 15 T arc dipoles makes Nb₃Sn the conductor of choice for this application. The use of high temperature superconductors such as YBCO and Bi-2212 is being actively explored to surpass the intrinsic limits of Nb₃Sn. While these materials can in principle support dipole fields well above 20 T, their application in large accelerators presents significant challenges. These options can be considered for possible later upgrades, rather than as a baseline choice for the collider.

Beam Dynamics: Many of challenges associated with this collider are mostly known and much has been learnt from the Tevatron and continuing operation of the LHC. At the same time, the amount of beam energy in the higher energy colliders will be at the level of a few GJ, an order of magnitude higher than in the LHC at design parameters. Synchrotron radiation will also significantly affect beam dynamics and machine design and operation. Damping times will be of the order of an hour and the synchrotron radiation power will be of the order of a MW. Coping with this radiation level and the consequent beam induced pressure rise will require R&D in vacuum chamber design and the development of photon stops to protect the superconducting magnets and other equipment. Accelerator physics experiments which likely to have a significant impact on the design and operation of high energy p-p colliders include:

- A head-on beam-beam compensation experiment at RHIC with electron lenses.
- A long-range beam-beam compensation with current carrying wires planned at the LHC.
- Use of a crab cavity in each IR with a crossing angle.
- A small ring called the Integrable Optics Test Accelerator (IOTA) at the Advanced Superconducting Test Accelerator (ASTA) facility at Fermilab will test the idea of a resonance free lattice. If successful, this will allow reducing the magnet apertures in the arcs and hence significantly reduce cost and in addition make beam operation more stable.
- Application of new cooling techniques such as optical stochastic cooling, coherent electron cooling or improvements in microwave stochastic cooling could lower emittances and lead to higher luminosities.

Injectors: It is envisioned that for a possible high energy p-p collider at Fermilab, Project X linac can be used as a high intensity low emittance 8 GeV proton pre-accelerator to the existing Main Injector which can accelerate beams to 150 GeV. Another injector will be needed to accelerate beam to 4–5 TeV for injection into the collider. One possibility is to reuse the Tevatron ring (circumference = 6.3 km) with 15 T magnets, an alternative would be to build a Fermilab site-filler synchrotron with circumference 16 km and lower field magnets.

35.2.1.2 Summary of the accelerator R&D topics that would utilize test beds and test beams

Below we summarize accelerator R&D topics needed for the next generation high energy hadron colliders and identify relevant R&D facilities:

- New engineering conductors (e.g., small filament HTS) can be carried out at the existing facilities supported by OHEP GARD program
- Magnets with high T_c : can be carried out at the existing facilities supported by OHEP GARD program and by the MAP program
- Collimation: can be carried out at the LHC machines and Fermilabs Main Injector and Booster
- Proton SR heating and vacuum issues [heating studies of cold copper vacuum chambers, how does RRR change, how can be cooled]: R&D can be carried at low energy electron storage rings
- Machine protection and abort dumps: can be carried out at the LHC machines and Fermilabs Main Injector and Booster
- Tuneshift with marginal damping: no experimental R&D test facility needed
- Beam physics in injector chain: space charge dynamics and space charge compensation in low energy proton beams can be studied at IOTA ring of the Fermilabs ASTA facility and later attempted at the LHC injectors or/and Fermilab's Main Injector
- IR design and technology options: while no dedicated facilities are needed, a lot can be learned from the LARP supported HL-LHC design studies and from similar studies for the muon collider design.
- Crab-cavity R&D: the needed SRF test bed will be part of the LARPs "LHC construction project"
- Radiation studies: many existing and planned R&D facilities for the Intensity Frontier accelerators can be utilized

Beam dynamics and control in the collider, halo control, noise and ground motion effects: halo dynamics and control can be studied at IOTA ring of the Fermilabs ASTA facility; certain types of beam studies can be carried out at the LHC, e.g., on hollow beam collimation and bent crystal collimation, and at Fermilab's Main Injector and Recycler; ground motion studies can benefit from continuation of the similar ILC R&D program.

35.2.2 Energy Frontier lepton and gamma colliders

35.2.2.1 Summary of Projects on and beyond the Horizon

A future lepton or photon collider can provide a factory for measurements of the properties of the Higgs with ultimate precision. It would also provide opportunities to probe for and study new physics, both through the production of new particles predicted by models of physics beyond the Standard Model and through the study of indirect effects of new physics on the W and Z bosons, the top quark, and other systems. This section of the report begins by listing the options for such facilities foreseen at this time. The following section lists the technical challenges with realizing these facilities and the corresponding tests programs underway or envisioned to address these issues. A complete list of test facilities and their capabilities is given in the Appendix.

Linear collider type e^+e^- : Advantages of the linear collider type Higgs factories are the extensive design and prototyping work have been done. Key technologies are in hand after large investment for R&D. There exist well-organized international collaborations led respectively by the ILC GDE and CLIC Collaboration (now combined in the Linear Collider Collaboration). A Higgs Factory would be an important step towards higher energy e^+e^- collisions, has polarized beams (e^- 80%, e^+ 30%) and is the front runner (in terms of readiness).

The primary challenge of any linear collider type system is the high cost. Specific challenges for an ILC type design are the Final Focus System and a positron source for a Higgs factory needs 10 Hz operation of the e^- linac for e^+ production, or the use of an unpolarized e^+ beam as a backup scheme. For a CLIC type Higgs Factory, challenges are the development of the accelerating structures, industrialization of major components and going from CDR to TDR. The International Linear Collider (ILC) project Technical Design Report has a summary of supporting R&D done to date. The TDR also includes a list of work that remains to be done. Approximately 22 km of high gradient superconducting linac will be constructed for ILC and the related technology is a central topic of ongoing development aimed at cost reduction. Technical development toward the ILC superconducting linac has unified the global R&D effort and has led to successful cavity industrialization. The large scale deployment of the technology for ILC will lead to further advance in the performance and economics of superconducting RF.

The Compact Linear Collider (CLIC) is a TeV-scale high-luminosity linear e^+e^- collider under development by a 49 institute strong international collaboration. The CLIC-study is hosted by CERN. The machine is based on a novel two-beam acceleration technique providing acceleration gradients at the level of 100 MV/m with normal conducting RF structures. The project can be implemented in energy stages that reuse the existing equipment. At each energy stage the centre-of-mass energy can be tuned to lower values within a range of a factor three and with limited loss on luminosity performance. Stages at ~ 350 GeV, ~ 1.5 TeV and 3 TeV are currently being studied, key parameters of a first and a last stage are given in [6]. The first and second stage use only a single drive-beam generation complex to feed both linacs, while in stage 3 each linac is fed by a separate complex. The initial stage can include a klystron powered part, or be fully klystron based, and therefore an initial klystron based stage is currently also under study.

The CLIC design is based on three key technologies, which have been addressed experimentally:

1. The use of normal-conducting accelerating structures in the main linac with a gradient of 100 MV/m, in order to limit the length of the machine. The RF frequency of 12 GHz and detailed parameters of the structure have been derived from an overall cost optimisation at 3 TeV. Experiments at KEK, SLAC and CERN verified the structure design and established its gradient and breakdown-rate performance.
2. The use of drive beams that run parallel to the colliding beams through a sequence of power extraction and transfer structures, where they produce the short, high-power RF pulses that are transferred into the accelerating structures. These drive beams are generated in a central complex. The drive-beam generation and use has been demonstrated in a dedicated test facility (CTF3) at CERN.
3. The high luminosity that is achieved by the very small beam emittances, which are generated in the damping rings and maintained during the transport to the collision point. These emittances are ensured by appropriate design of the beam lines and tuning techniques, as well as by a precision pre-alignment system and an active stabilisation system that decouples the magnets from the ground motion. Prototypes of both systems have demonstrated performance close to or better than the specifications.

Circular e^+e^- : Advantages of the circular concepts are, at 240 GeV and below, a higher luminosity than a linear collider when the ring size is sufficiently large. Rings draw on a base of mature technology and rich

experience. Some designs can use an existing tunnel and site. Rings can also offer more than one IP. The tunnel of a large ring can be reused as a pp collider in the future.

A challenge for rings is Beamstrahlung limiting beam lifetime. The required lattice need large momentum acceptance and must preserve low emittance. RF and vacuum problems from the large synchrotron radiation generated need to be dealt with. High-energy circular machines efficiently convert wall power to synchrotron radiation power and this will limit the maximum energy reach. Finally, no comprehensive studies have been done; a design study report is needed.

Photon collider: An advantage of photon collider designs is that they allow access to the CP property of the Higgs. Also, they can study the Higgs at a lower beam energy (80 GeV e^- beam to generate a 63 GeV γ beam). Photon colliders can deliver high polarization in the colliding γ beams. There is no need for e^+ beams and the ancillary systems. The smaller linac corresponds to cost savings: 160 GeV e^- linac has a lower cost w.r.t. a 240 GeV linear e^+e^- collider. An additional attractive feature of photon colliders is that they can be added onto a linear e^+e^- collider.

Challenges common to all Photon Collider type designs start with the Physics not being as comprehensive as a 240 GeV e^+e^- collider would be. Background problems have to be mitigated and they require a complex IR design. No comprehensive study has been carried out; a design study report is needed. An ILC based system requires an optical cavity to get the required flux. For a CLIC-based system the laser can piggy-back on the Livermore LIFE fusion project but the project schedule is unknown. A recirculating linac-based concept requires a polarized low emittance e^- gun.

Muon colliders: The block diagrams for a Neutrino Factory and Muon Collider, which are the capabilities being pursued by the U.S. Muon Accelerator Program (MAP), are shown in Fig. 35-3.

Plasma based accelerators – beam driven [7]: Plasma Wakefield Acceleration (PWFA) holds much promise for advancing the energy frontier because it can potentially provide a 1000-fold or more increase in acceleration gradient with excellent power efficiency in respect with standard technologies. The beam-driver technology benefits from the extensive R&D that has been performed for conventional rf linear colliders during the last twenty years, especially ILC and CLIC, with a potential for a comparably lower power consumption and cost. In a pulsed mode, the PWFA scheme could be used to upgrade up to the multi-TeV energy range a facility initially built with ILC technology.

The main challenges for a beam driven plasma accelerator are directly related to the beam acceleration mechanism. The primary issues are fully developing a concept for positron acceleration and demonstrating staged acceleration with the required beam brightness and efficiency.

Plasma based accelerators – laser driven: Laser Plasma Acceleration (LPA), also known as Laser Wakefield Acceleration (LWFA) also holds much promise for advancing the energy frontier because it too can potentially provide a 1000-fold or more increase in acceleration gradient. A future collider will stage together multiple modular and compact 10s GeV class accelerator systems that can be developed independently for a broad range of applications. The LWFA technology also extends naturally to gamma-gamma colliders using the same drive technology and built in synchronization.

The main challenges for a laser driven plasma accelerator are again directly related to the beam acceleration mechanism. The primary issues are fully developing a concept for positron acceleration and demonstrating staged acceleration with the required beam brightness and efficiency. Additionally, development of high

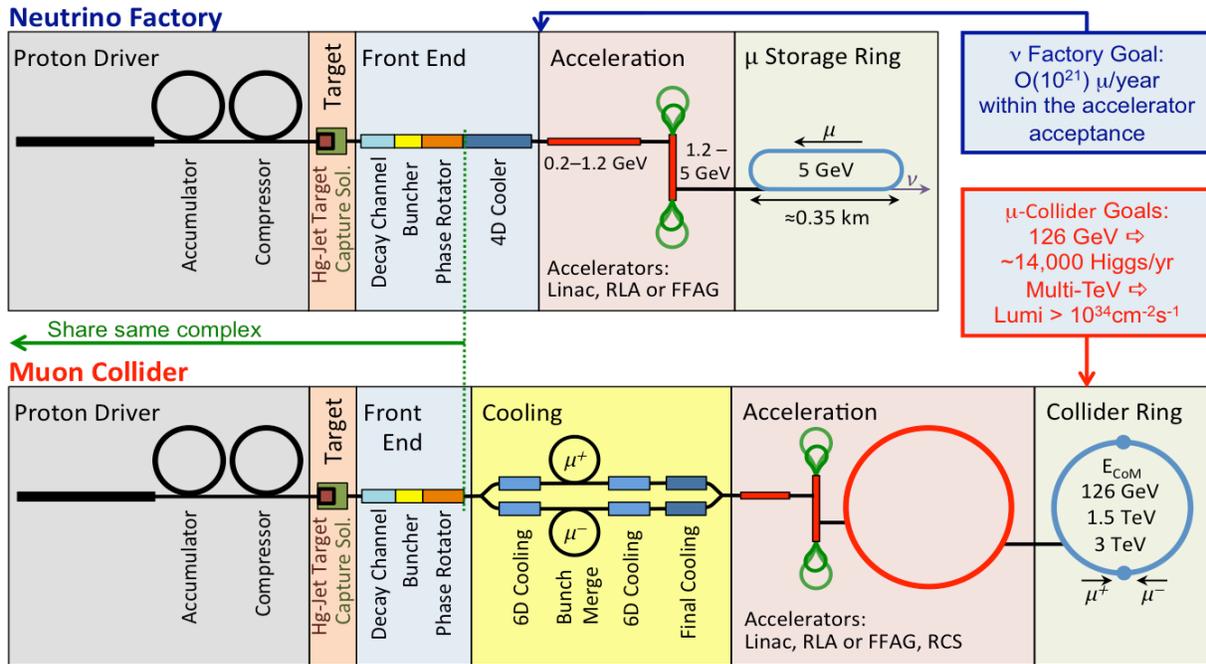


Figure 35-3. Block diagrams showing the performance goals and synergies between a Neutrino Factory and Muon Collider accelerator complex.

average power (multi-kW to tens of kW), high efficiency (10's of percent) laser driver technology is needed but these developments leverage off large investments from outside HEP.

Dielectric accelerators – beam driven [8]: Ultra-high gradients and ultra-high power rf are preferred for future high energy collider designs, but due to rf breakdown, they are difficult to implement with rf pulse lengths ($>200\text{ns}$) that are currently used in many designs. Recent scaling arguments show that the rf breakdown threshold improves with decreasing rf pulse length so it is desirable to find a way to run at short pulse length with good efficiency. A dielectric-based two-beam accelerator scheme using short rf pulses may sustain a high gradient ($>250\text{ MV/m}$) with the generation of a fast rise time ($<3\text{ ns}$), high power ($>1\text{ GW}$), short rf pulse ($\sim 20\text{ ns}$ flat top) in the dielectric wakefield power extractor. Approximately 7% overall efficiency may be achievable.

Challenges for beam driven dielectrics include identifying materials with appropriate breakdown voltage characteristics, identifying optimal structure geometries that provide the required accelerating gradient but are not limited by beam break-up from transverse wakefields, demonstration of staging and the required efficiency.

Dielectric accelerators – laser driven: The acceleration of charged particles in a dielectric microstructure powered by an infrared laser (colloquially dubbed an “accelerator on a chip”) is a promising new area of study that has garnered increasing interest in recent years due to its potential for realizing compact and inexpensive integrated accelerator systems using nanofabrication. The first observation of high-gradient ($> 250\text{ MV/m}$) acceleration in a micron-scale DLA driven by an infrared laser has recently been achieved at SLAC [9]. To our knowledge, this is the first such demonstration at optical wavelengths using

relativistic particles and with accelerating fields of this magnitude. At Max Planck Institute for Quantum Optics (MPQ), synchronous acceleration has recently been demonstrated at sub-relativistic particle energies, a development that is important for making compatible integrated systems for particle injection at speed-of-light velocities [10]. Both of these important new results indicate considerable promise for this exciting area of research. These dielectric laser-driven accelerators (DLAs) can support accelerating fields one to two orders of magnitude higher than RF cavity-based accelerators, and leverage well-established industrial fabrication capabilities with the commercial availability of tabletop lasers, potentially reducing both cost and footprint. Power estimates for the DLA scenario are comparable with conventional RF technology, assuming that similar power efficiency (near 100%) for guided wave systems can be achieved, 40% wall plug laser efficiencies (feasible with solid state Thulium fiber laser systems [11] and 40% laser to electron beam coupling, consistent with published calculations [12].

Crystal Based Linear Collider: The density of charge carriers (conduction electrons) in solids, $n_0 \sim 10^{22}\text{--}10^{23}/\text{cm}^3$, is significantly higher than what was considered above in plasmas. Correspondingly, longitudinal fields of up to 100 GeV/cm or 10 TV/m are possible[13]. The new effects at higher densities are due to intense energy radiation in high fields and increased scattering rates, which result in fast pitch-angle diffusion over distances of $l_d \sim 1 \text{ m}\cdot\text{E} [\text{TeV}]$. The latter leads to particles escaping from the driving field. Thus, it was suggested that particles be accelerated in solids along major crystallographic directions. This provides a channeling effect in combination with low emittance, determined by the Ångström-scale aperture of the atomic “tubes.” Channeling with nanotubes is also being discussed. Positively charged particles are channeled more robustly, as they are repelled from ions and thus experience weaker scattering. Radiation emission due to betatron oscillations between the atomic planes is thought to be the major source of energy dissipation. The maximum beam energies are limited to about 0.3 TeV for positrons, 104 TeV for muons and 106 TeV for protons [14]. X-ray lasers can efficiently excite solid plasma and accelerate particles inside a crystal channel waveguide, though ultimate acceleration gradients $\sim 10 \text{ TeV/m}$ might require relativistic intensities, exceeding those conceivable for x-rays as of today. Moreover, only disposable crystal accelerators, e.g., in the form of fibers or films, are possible at such high externally excited fields, which would exceed the ionization thresholds and destroy the periodic atomic structure of the crystal so that acceleration will take place only in a short time before full dissociation of the lattice. For the laser and plasma fields of about 1 GV/cm= 0.1 TV/m or less, reusable crystal accelerators can probably be built which can survive multiple pulses. Side injection of powerful x-ray pulses into continuous a fiber of 0.1–10 km length allows one to avoid multiple staging issues intrinsic to other methods and to reach 10–1000 TeV energies. Imperfections like crystal dislocations must be kept under control and unintended crystal curvatures must be kept less than the inverse “critical” radius $R_c \sim 2 [\text{m}]\cdot\text{E} [\text{TeV}]$, so that the channeling conditions remain. Despite a lot of promise, the concept of the crystal based linear muon collider is in its infancy and requires substantial experimental and theoretical studies [3].

35.2.2.2 Needed R&D and corresponding facilities

For subjects where there are a large number of facilities, the table format is used. For others where the work is carried out primarily at a single facility, a bulleted list is used.

Linear e^+e^- colliders: To prepare for the ILC, test facilities in each region have built and are building linacs with ILC technology. The European XFEL is the largest of these and will be completed in 2015. FLASH, the VUV FEL at DESY, was completed in 2005 and will continue to be used for beam tests. In the US ASTA at Fermilab and in Japan STF at KEK will be used to develop and test ILC SRF linac technology in direct, component-by-component fashion. Cryomodule integration, high level RF and beam operation

development will be done at each of these test facilities. Positron target engineering and testing has also been identified as needing further work and full-scale test apparatus has been constructed at LLNL to carry out the most important aspects of this effort.

Related system parameters have been benchmarked in CTF3, in advanced light sources, in the ATF(2) and CsrTA, and in other setups. For example, the beam-based correction method foreseen for the main linac has been experimentally verified in FACET at SLAC, the damping ring vertical emittance has been demonstrated at PSI. Further development goals are defined and a work-program has been implemented across the collaboration for 2013-2018.

One important element is that a re-baselining of the CLIC energy stages is underway. Cost and power studies will follow; in addition to being key elements for the stage and design optimization additional technical developments can lead to important reductions.

Important technical studies will further address stability and alignment, timing and phasing, stray fields and dynamic vacuum including collective effects. Other studies will address failure modes and operation issues.

The collaboration will continue to identify and carry out system tests and priorities are the measurements in CTF3, ATF and related to the CLIC injector.

Further X-band structure development and tests are high priorities as well as constructing integrated modules where a number of central functional elements are included and need to be optimized. Initial site studies have already been carried out and preliminary footprints have been identified for an initial machine as well as an ultimate 3 TeV layout, and these studies will continue.

The relevance and importance of an initial stage largely focused on Higgs measurements will depend on the overall physics scenario at the time and the status of these measurements at other machines. The collision energies available at stage 2 and 3 are unique to CLIC, and provide potentially direct access to Beyond the Standard Model phenomena and also improved access to some important Higgs measurements. A staged implementation of CLIC along the lines described would open the door to an impressive long-term and timely physics programme at the energy frontier, beyond the LHC programme. The machine is therefore considered an important option for a post-LHC facility at CERN.

A summary of R&D facilities for future linear e^+e^- colliders is given in Table 35-2.

Circular e^+e^- colliders: A summary of R&D facilities for future circular e^+e^- colliders is given in Table 35-3.

Photon colliders: A summary of R&D facilities for photon colliders is given in Table 35-4.

Muon colliders: Critical path R&D items important to the performance of muon colliders include:

- Development of a high power target station which is ultimately capable of handling ≥ 4 MW of power. Liquid-metal jet technology has been shown, in the MERIT experiment, to be capable of handling the necessary beam power [15]. While the complete engineering design of a multi-MW target station, including a high field capture solenoid (nominally 20 T hybrid normal and superconducting magnet with ~ 3 GJ stored energy) is challenging, target stations with similar specifications are required for other planned facilities (e.g., spallation sources). Our expectation is that the engineering challenges can be successfully addressed over the course of the next decade. In particular, we expect that the general

Type	R&D	Goal	Facility
ILC	Optimization for 250 GeV E_{CM}	Cost effectiveness	LLC, XFEL
	Final Focusing System	37 nm vertical size	ATF2
		Collision point stability	ATF2
	High gradient 1.3 GHz 9-cell cavity	$E_{acc} > 35$ MeV/m	DESY, IHEP, JLab, KEK
	Beam loading effect	31.5 MeV/m w ILC beam	LLC, XFEL, ASTA
	e^+ production with 125 GeV e^- beam	Yield rate > 1	ANL, LLNL, KEK
	longer undulator (150 to 230 m)		
	10 Hz e^- linac new undulator with shorter period (11.5 to 8-9 mm)		
CLIC	Power efficiency		CTF3
	Optimization for 250 GeV E_{CM}	Cost effectiveness	CTF3
	Accelerating structure	100 MeV/m in a complete unit	CTF3
NLC-type X band	New RF sources, better cavity design, new energy-efficient modulators	Cost effectiveness, energy efficiency	CTF3, SLAC, KEK

Table 35-2. R&D facilities for linear e^+e^- colliders.

Type	R&D	Goal	Facility
All	Forming a study group	Produce a design report	Fermilab, SLAC, CERN, SLS ESRF, DAFNE, Diamond SuperKEK-B, IHEP
	Lattice design in the arc and IR	Large η (2-6%), small ϵ	Fermilab, SLAC, CERN, IHEP, IOTA (?)
	RF coupler, 1.3 GHz	50 kW CW	ARIEL, IHEP
	RF coupling, 650 MHz (700 MHz)	200 kW CW	ASTA, SLAC, IHEP, (CERN)
	HOM damper		ASTA, SLAC, IHEP
	Vacuum	Cooling	Fermilab, SLAC
		Radio activation with MeV γ s	?
	Wall plug efficiency	50%	ILC, CLIC, Proj X, CERN
	Radiation shielding		KEK-B
	Beam-beam	Limit for multiple IPs	CERN
	Top-up injector	Ramp speed	CESR (5 GeV/0.1s) SRF ?
	Collective effects	Stabilities	Fermilab, SLAC, IHEP

Table 35-3. R&D facilities for circular e^+e^- colliders.

Type	R&D	Goal	Facility
All type	Forming a study group	Produce a design report	Fermilab, SLAC, CERN, KEK, JLab
	IR optics	Feasible design	KEK, JLab KEK, JLab
	Removal of spent electrons		ASTA
	Inverse Compton scattering		ASTA, SLAC, KEK
	High average power laser		LLNL, LBNL, LANL, ELI SPARC-X, FERMI, IRIDE
ILC-based	Optical cavity		SLAC, KEK
CLIC-based and SLC-type	50 Hz high power laser		LLNL (LIFE), ELI
SAPPHIRE	FEL design		SLAC

Table 35-4. *R&D facilities for photon colliders.*

R&D plan on high power targetry being pursued by the RADIATE Collaboration will provide enabling R&D and engineering studies for these capabilities. In the meantime, a muon accelerator complex can begin producing world-class physics with the proton beam powers that will become available with Project X Stage II. This starting point is a 1 MW proton beam at 3 GeV.

- Muon cooling is required in order to achieve the beam parameters for a high performance NF and for all MC designs under consideration. An ionization cooling channel requires the operation of RF cavities in tesla-scale magnetic fields. Promising recent results from the MuCool Test Area (MTA) at Fermilab point towards solutions to the breakdown problems of RF cavities operating in this environment [16, 17, 18]. These advances, along with technology concepts developed over the past decade, are expected to allow MAP to establish a baseline 6D cooling design on the 2-year timescale [19, 20, 21]. In addition, the Muon Ionization Cooling Experiment (MICE) is expected to begin producing relevant results in the same time frame [22]. In the longer term, demonstration of 6D ionization cooling systems could be pursued with muon beams that could be provided by the nuSTORM (neutrinos from Stored Muons) ring [23].
- High intensity, low energy beams (~ 200 MeV/c, optimal for muon ionization cooling) are susceptible to a range of potential collective effects. Evaluating the likely impact of these effects on the muon beams required for NF and MC applications, through simulation and experiment, is an important deliverable of the MAP feasibility assessment.
- For the MC, muon decays in the ring impact both the magnet and shielding design for the collider itself as well as backgrounds in the detector. Detector backgrounds have been shown to be manageable via pixelated detectors with good time resolution [24]. Thus, this issue appears to present no impediment to moving forward with full detector studies and machinedetector interface design efforts.

A thorough evaluation of these issues is crucial for an informed community decision on muon accelerator facilities. An important element of the MAP plan is a staging path for physics-producing facilities that enables the demonstration of critical concept for subsequent facilities. This will allow a well-informed decision process moving forward.

In addition to the above list of critical R&D issues described above, there are a number of thrusts in the development of key technologies that should also be mentioned:

- The 6D cooling channel will require very high field solenoid magnets, having fields that may reach 30 T. Development of High Temperature Superconductor (HTS) technologies is a major technology thrust. This effort benefits from the synergies for development of high field user solenoids at facilities such as the National High Magnetic Field Laboratory (NHMFL) at Florida State University.
- In general, the development of very high field accelerator magnets with high field quality can improve the performance of a muon collider. Development of such magnets using both low temperature superconductor (LTS) and HTS technologies is of importance to the research program and shares synergies with other accelerator development (in particular for the high energy upgrade option of the Large Hadron Collider) and has potentially significant benefits beyond the field.
- Acceleration schemes for short-lived muon beams presents particular challenges. In order to utilize RF systems efficiently, it requires ring or recirculating linac designs which can operate over wide energy ranges. This drives interest by MAP in advanced accelerator designs such as Fixed Field Alternating Gradient (FFAG) machines, as being explored by the EMMA Experiment [25] at Daresbury Laboratory in the UK, and Recirculating Linear Accelerators (RLA), which could be demonstrated with the JEMMRLA [26] test accelerator that has been proposed by Jefferson Laboratory in the US. To attain the TeV-scale energies required by muon colliders, Rapid Cycling Synchrotrons (RCS) are the present technology choice. These machines will require rapid cycling magnets that can operate with ~ 2 T peak fields at frequencies up to 400 Hz. These magnets are under active development [27, 28].
- The accelerator chains also require Superconducting RF cavities based on Ni on Cu fabrication techniques. Techniques to fabricate such cavities with good Q behavior are presently under development.

Plasma accelerators — beam driven: Challenges:

- A concept of positron acceleration with high beam brightness (required for collider operation) still has to be developed.
- High beam loading with both electrons and positrons (required for high efficiency),
- Beam acceleration with small energy spreads (required for high luminosity and narrow luminosity spectrum),
- Preservation of small electron beam emittances (required to achieve luminosity), mitigation of effects resulting from plasma ion motion,
- Preservation of small positron beam emittances (required to achieve luminosity), suppression of effects resulting from plasma electrons collapse,
- Average bunch repetition rates in the 10s of kHz (required to achieve luminosity), Synchronization of multiple plasma stages,
- Optical beam matching between plasma acceleration stages and from plasma to beam delivery systems.
- Halo control, collimation, final focus, etc., will be like in other linear colliders

Facilities: An ambitious test facility, FACET, operated as a user facility at SLAC and taking advantage of the dense electron and positron bunches provided by the 22 GeV linac is ideal to directly address with a targeted experimental program a number of critical issues listed above over the next four years. Desire to address the remaining issues has led to a concept for a follow on facility dedicated to studying beam-driven plasma wakefield acceleration called FACET-II aiming for a feasibility demonstration within a decade. An extensive design and simulation effort must proceed in parallel with the FACET experimental effort to both support the experimental program and to fully develop the PWFA-LC design concepts.

Plasma accelerators — laser driven: Challenges:

- A comprehensive experimental, theoretical and computation program would include the following: 10 GeV level beams from a single LPA stage (e.g., BELLA experiment),
- Staging: demonstrate staged LPAs at 5 GeV+5 GeV,
- Beam loading studies including phase space manipulation techniques for longitudinal shaping of bunches to optimize efficiency,
- Tailored plasma channels to mitigate dephasing and near-hollow plasma channels to mitigate emittance growth from scattering,
- Positron capture and acceleration in LPA,
- Novel methods for electron beam cooling via plasma-wave-based radiation generation
- Survival of spin polarization in LPA,
- Emittance preservation through longitudinal plasma shaping with large number of accelerating sections and transverse laser beam mode control,
- Development of compact high gradient plasma based final focus concepts (e.g., adiabatic plasma lens) to reduce length from kms to tens-hundreds of meters,
- Development of high average power (multi-kW to tens of kW), high efficiency (10s of percent) laser driver technology,
- Demonstration of high average power LPA (multi-kW) and high repetition rate of plasma cell.

Facilities:

All issues mentioned above are foreseen to be addressed in the present BELLA and envisaged future facilities (BELLA II) at LBNL during the next decade or two. The present experimental program at LBNL includes research using the 1 PW BELLA laser system (40 J, 35 fs, 1 Hz), with the main goal of demonstrating high quality electron beams at 10 GeV using a meter-scale plasma channel. Other experiments at LBNL include the staging of two LPA modules at the 1 GeV level and a development of novel laser-triggered electron injection methods to improve the electron beam quality. To proceed with a comprehensive R&D research program on LPAs, LBNL has plans to develop a world leading national high peak and average power laser user facility, BELLA II, that would consist of multiple high power laser systems operating at high repetition rates, multiple beam lines and multiple shielded experimental areas. This national facility would be able to support a large number of users and feed several experiments simultaneously.

The development of high average power, high peak power laser technology underpinning the development of the LPAs requires new investments in the following key R&D milestones (for details see [29]):

- 5 – 10 year time frame:
 - 3 kW (3 J @ 1 kHz) laser for driving 1 GeV LPA at 1 kHz
 - Laser beam shaping for emittance control through mode shaping
 - Laser beam combining concepts
 - Novel fiber laser technology
- 10-20 years time frame:
 - 30-300 kW average power, short pulse laser technology
 - High repetition rate plasma structures (>10 kHz)

Dielectric accelerators — beam driven: Challenges:

The main challenges involved with the short pulse high gradient accelerator design include high power RF extraction devices that capable of > 1 GW at 20 ns pulse length, high gradient accelerating structures to sustain 300 MV/m at 20 ns pulse length, beam transport, and staging. There are many other physics engineering issues, such as stable beam propagation (BBU control), structure heating and mass structure productions, are to be addressed in the future.

Facilities:

The Argonne Wakefield Accelerator (AWA) facility has been constructed as a test bed for this type of short pulse high gradient accelerators. It maintains the worlds two highest charge RF photoinjectors, both capable of 100 nC per bunch. The drive RF photoinjector beamline generates a 75 MeV, GW-class drive bunch train of variable pulse length and the witness RF photoinjector produces a 15 MeV, high-quality 1nC@1m witness bunch. The switchyard between two beamlines allows concomitant experiments: (a) RF power generation; (b) two beam acceleration; (c) staging; (d) collinear wakefield acceleration. Many tests to understand optimal structure materials and geometry are developed at the Brookhaven Accelerator Test Facility (BNL ATF) where the structures are probed with low intensity beams to verify which modes are excited. Structure designs can then be tested at and above breakdown threshold at the FACET Facility at SLAC using the high peak-current low emittance beams to test structures with small apertures and $> \text{GeV/m}$ fields.

Dielectric accelerators — laser driven: Challenges:

To develop DLA into a useable technology for discovery science, test facilities need to address critical challenges on several fronts: (1) understanding IR laser damage limits of semiconductor materials at picosecond pulse lengths, (2) development of high (near 100%) efficiency power coupling schemes, (3) integrated designs with multiple stages of acceleration, and (4) understanding phase stability issues related to temperature and nonlinear high-field effects in dielectrics.

Facilities:

Subsets of these challenges are being addressed at a number of institutions, including SLAC, Stanford, UCLA, MPQ, and Purdue. Development of a multi-staged DLA prototype scalable to high energy on a 5-year time scale will require strong collaborations between university and laboratory groups that can attract some of the brightest researchers in the field of beam physics and synthesize expertise in accelerators, lasers, and nanofabrication methods. Appropriate investment in these facilities will allow the continued development of DLA and other advanced acceleration concepts, and will provide opportunities for students, post-docs, and scientists from institutions across the world to engage in ground-breaking experimental, theoretical, and computational work at the cutting edge of accelerator research.

Crystal based linear collider: This is very novel and not well studied concept. Its theoretical feasibility should get assessed.

Challenges:

There several new effects at higher densities are due to intense energy radiation and scattering while particles are accelerated in along major crystallographic directions — stronger for electrons, weaker for muons and protons. Acceleration inside CNTs (carbon nanotubes) can offer some advantages in that regard. Feasibility of the wave excitation by X-ray lasers or modulated drive beams needs careful exploration. Any methods to combine multiple microbeams into one bunch can provide significant increase in the luminosity reach.

Facilities:

The first proof-of-principle experiments with CNTs and/or crystals can be performed with high brightness electron beams available at ASTA (FNAL) and FACET (SLAC).

35.2.3 High Intensity Secondary Beams Driven by Protons

This topic includes intense neutrino beams and intense neutron, muon, and kaon beams.

Operation, upgrade and development of accelerators for Intensity Frontier face formidable challenges in order to satisfy both the near-term and long-term Particle Physics program. The near-term US domestic program continuing throughout this decade includes the long-baseline neutrino experiments and a muon program focused on precision/rare processes. It requires:

- Double the beam power capability of the Booster
- Double the beam power capability of the Main Injector (MI)
- Build-out the muon campus infrastructure and capability based on the 8 GeV proton source.

The long-term needs of the US Intensity Frontier community are expected to be based on the following experiments:

- long-baseline neutrino experiments to unravel neutrino sector, CP-violation, etc.
- rare and precision measurements of muons, kaons, neutrons to probe mass-scales beyond LHC

Both types of experiments will require MW-class beams. Construction of the Project-X — a modern and flexible multi-MW proton linac — is expected to address these challenges.

Project X is a high intensity proton facility that will support a world-leading Intensity Frontier research program over the next several decades. When compared to other facilities in the planning stages elsewhere in the world Project X is completely unique in its ability to deliver, simultaneously, up to 6 MW of site-wide beam power to multiple experiments, at energies ranging from 233 MeV to 120 GeV, and with flexible beam formats. Project X will support a wide range of experiments based on neutrinos, muons, kaons, nucleons, and nuclei. In addition, Project X will lay the foundation for the long-term development of a Neutrino Factory and/or Muon Collider. A complete concept for Project X has been developed and is documented in the Project X Reference Design Report [30]. The 2013 HEPAP Facilities Subpanel has assessed the science

capabilities of Project X as “absolutely central” and the state of development as “ready for construction”. The proposed DAE δ ALUS experiment calls for construction of several very high power 1 to 5 MW 800 MeV proton cyclotrons. High power hadron accelerators for the Intensity Frontier have two over-riding design constraints :

- Minimizing beam loss (typical beam loss requirements for a MW proton beam: <1 Watt/m, or/and $<1 \times 10^{-4}$ total beam loss)
- Proper beam structure (the required formats significantly vary from experiment to experiment, from quasi-CW for rare particle decays to a single ~ 2 ns long bunch for MC/NF)

The key challenges to satisfy these constrains include:

- Producing high current, high-quality and high brightness beams with required bunch structure
- Accelerating high beam currents to high energy with (1) high-duty factors required for high resolution experiments, and (2) very low duty factors for neutrino experiments.
- Running multiple experiments in parallel (quasi-simultaneously) required means for beam manipulations on the bunch-by-bunch base.
- Transporting high power beams while maintaining beam loss at a level where routine maintenance is possible
- Acceleration of beams from keVs to GeVs preserving emittance and minimizing amplitude growth for large-amplitude particles (“beam halo”)
- Low-loss extraction of the beams
- Target systems capable of handling extreme power densities and extreme radiation environments
- Producing intense, high-quality beams of secondary particles (muons, kaons, ...)

35.2.3.1 Summary of the accelerator R&D topics that would utilize a test beds and test beams

Below we outline the directions of the accelerator R&D needed to address the above challenges. The specific Project X R&D needs are addressed elsewhere [30].

1. High Intensity beam sources: Radio-frequency quadrupoles (RFQs) are the injector technology of choice at present; the state of the art performance of 100 mA CW demonstrated at LANL/LEDA with 6.7 MeV output energy. Is there an alternative technology which could compete with conventional technology?
2. Beam dynamics issues with high intensity beams in existing accelerators (e-cloud, impedances/instabilities):
 - RF systems (how to provide RF power for beam acceleration with many-fold higher beam current when the beam induced voltage greatly exceeds RF voltage?)
 - Space Charge issues (need to understand the Space Charge losses with the higher intensity slipped stacked bunches; the need collimators; realistic Space Charge simulations with predictive power that we can compare with data)

- Electron-Cloud (most effective coating and scrubbing; in situ SEY measurements, micro-wave measurements in, eg MI)
 - Transition Crossing (evaluation need of a γ_t jump in MI, transition crossing in Booster)
 - Injection issues (investigation of painting scenarios and other potential mitigation schemes — such as use of laser assisted stripping and R&D on rotating injection foil technology — Ultra Nano Crystalline Diamond (UNCD) technology, rotating graphene foil technology)
 - Loss Control (the need and design of the most efficient collimation schemes)
3. Advanced simulation/modeling capabilities for high-intensity beams:
- Theory of coherent motion of coasting and bunched beams needs to be further studied in various approximations with several complimentary approaches. Characterization of the loss mechanisms will have significant impact on the entire field of high-intensity accelerators it is fundamental to loss minimization and control.
 - Development of a (flexible) beam dynamics framework with fully 3D PIC capabilities (eg on base of SYNERGIA) which will include space-charge and impedance capabilities, both single and multi-bunch effects, single-particle physics with full dynamics and which could run on desktops, clusters and supercomputers
 - Further development of Energy Deposition modeling tools (eg MARS).
 - Transfer knowledge from theory and modeling to general R&D (support of the IF-related experiments in existing accelerators and beam test facilities, eg ASTA) further into the projects.
4. Beam-stripping and beam-chopping with laser-based methods:
- The conventional approach to accumulating high proton intensities in a ring is to use multi-turn charge-exchange injection of H⁻ beams, but it is very challenging to apply to >MW class beams, esp. CW beams.
 - Novel laser stripping idea from Danilov et. al. has been demonstrated, but scaling to realistic accelerator parameters is needed.
 - Laser chopping offers very attractive way to form the required beam current structures, and needs to be explored in realistic beam environment
5. Targetry and collimation:
- Enhanced modeling of beam energy deposition, secondary particle production and collection, radiation damage (DPA), transmutation products (gas production), and residual dose.
 - Advanced simulation of target material (non-linear) response using FEA codes including fracture and/or phase change.
 - Explore/determine radiation damage effects in candidate target and collimator materials at accelerator target facility operating parameters (RaDIATE Collaboration: Radiation Damage In Accelerator Target Environments).
 - Verification and benchmarking of above mentioned simulation tools and material properties through dedicated testing at beam facilities and autopsy of existing materials.
 - Explore and compare high heat flux cooling methods through analysis and testing.
 - Develop novel target and beam window concepts for use in proposed facilities
 - Develop target facility conceptual designs taking into account full life-cycle and radiation protection issues (remote handling, radioactive component disposal, tritium mitigation, etc.)

- Develop diagnostics for use in high radiation environments
 - Continue to engage in the high power targetry community to leverage the collaborative expertise and knowledge base to address the challenges of the High Intensity Frontier.
6. New ideas for clean slow extraction:
- Slow spills of high intensity beams are needed in particle physics, but beam loss limits intensity. Are there novel ways to cleanly achieve slow spills of high intensity beams?
 - (Resonant extraction, can it be extended to higher orders? Can crystals be used for high-power proton extraction? Can electron beams be used to extract protons? Absolutely novel ideas - Lasers? High brightness electron beams??)
7. Revolutionary ideas for Intensity Frontier accelerators
- Integrable Optics promises significant advance for low-loss operation of the IF facilities and must be tested at IOTA (at Fermilabs ASTA facility)
 - Space-charge compensation with either electron columns or electron lenses also has shown effective gains for high intensity beams (due to improved emittance and loss control in high intensity beams) and also needs to be tested at IOTA/ASTA.
8. Advanced Instrumentation
- Instrumentation for precise halo (and emittance) measurement and connection to simulation in a reliable way
 - Novel diagnostics needed for in-depth understanding of intra-bunch and multi-bunch dynamics (position, modes, tunes, chromaticities, etc.)

35.2.3.2 Summary of desirable facilities and their properties

The facilities where the above listed R&D can/will be carried out include existing accelerators (Fermilabs Booster, Recycler and Main Injector, CERN proton accelerators) and the ASTA facility (see [31] for a detailed plan of the ASTA thrusts and experiments). Radiation damage studies for high power targetry may need dedicated facilities for required irradiations and examinations, such as BLIP at BNL for high energy proton irradiations or the proposed UK triple-beam facility, TRITON, for low energy ion irradiations. Verification studies for high power targetry will need dedicated areas at beam facilities capable of delivering intense beam pulses on heavily instrumented test samples, such as HiRadMat at CERN. Some targetry issues can be explored at existing accelerators or facilities under construction (at Fermilab and BNL, SNS, FRIB and ESS, etc) or benefit from synergetic programs on the Accelerator Driven Systems. Many tests and technology demonstrations to support the Deadalus experiment design work can be performed at the existing facilities e.g., INFN-Catania, RIKEN, ORNL, The Best Cyclotron Systems, Vancouver, BC.

It is to be noted that the Project X collaboration is engaged in a comprehensive development program aimed at mitigating technical and cost risks associated with construction and operations. Critical element of the Project X R&D program is PXIE — Project X Injector Experiment at Fermilab — as one of key components [32].

35.2.4 High Intensity Electron and Photon Beams

This section mainly concerns Super-B [33] and Tau-Charm factories [34, 35] and a proposed Darklight high intensity photon project.

The SuperKEKB project requires a positron-electron collider with a peak luminosity of $8 \times 10^{35} \text{cm}^{-2}\text{s}^{-1}$. This luminosity is 40 times that of the KEKB B-factory, which operated for 11 years up to 2010. SuperKEKB is an asymmetric-energy and double-ring collider; the beam energy of the positron (LER) is 4 GeV and that of the electron (HER) is 7 GeV. An extremely small beta function at the interaction point (IP) and a low emittance are necessary. In addition, in order to achieve the target luminosity, a large horizontal crossing angle between the two colliding beams is adopted, as is a bunch length much longer than the beta function at the IP. This method is called the nano-beam scheme. The beam-beam parameter is assumed to be similar to KEKB, the beta function at the IP is 1/20, and the beam currents are twice those of KEKB in the nano-beam scheme. Consequently, the luminosity gain of 40 with respect to KEKB can be obtained.

The Novosibirsk Super Tau-Charm factory is a proposed machine with the following major specifications: Beam energy from 1.0 to 2.5 GeV, Luminosity $\sim 10^{35}$ at 2 GeV with longitudinal polarization of electrons at the IP. The machine will operate with no energy asymmetry and without energy monochromatization; energy calibration is obtained with Compton backscattering. Key features of the proposed machine are: It is a two-rings machine with crab waist collisions, a small beta function at the IP ($\beta_y \sim 800 \mu\text{m}$). A superconducting wiggler is used to keep the same damping and emittance in the whole energy range. It has 5 Siberian Snakes. A draft version of CDR has been completed. Documents for the project application to Russian Government are under preparation.

The DarkLight project at JLAB is a proposed facility that utilizes ERL-based FEL technology to generate a photon power of up to 1 MW. To achieve these beam powers, an Energy-Recovery Linac (ERL) is needed. With this facility, a possible dark-matter detection in a narrow resonance mode might be possible.

35.2.5 Electron-Ion Colliders

35.2.5.1 Summary of the Projects on the horizon

Currently, several projects eRHIC, ELIC, LHeC and possible FAIR in Darmstadt and HIAF in Lanzhou.

35.2.5.2 Electron-Ion colliders projects around the world

Several designs of future electron-ion colliders have been under consideration in recent years. All of them are based at an existing accelerator facility. Table 35-5 lists the electron-ion collider designs and the corresponding facilities.

The last report on the Electron-Nucleon Collider (ENC) at FAIR facility is from 2011 and it seems that the accelerator design has been frozen since that time.

A new electron-ion collider, called EIC@HIAF, has recently been proposed in Lanzhou, China, as part of a planned Heavy Ion Accelerator Facility (HIAF). No details of the accelerator design have been released, so far, besides that the first stage would be 3 GeV electrons on 12 GeV protons with a luminosity of 10^{32} –

	Ring-Ring			Linac-Ring	
	ENC	MEIC	LHeC RR	LHeC LR	eRHIC
CM Energy (GeV)	14	15 – 65 (150)	1300	1300 (2000)	30–70 (175)
hline based at	HESR FAIR (GSI)	CEBAF (JLab)	LHC (CERN)	LHC (CERN)	RHIC (BNL)

Table 35-5. *Electron-Ion Colliders. Center-of-mass energies are shown for electron-proton operation.*

$10^{33}\text{cm}^{-2}\text{s}^{-1}$, while the second stage assumes 10 GeV electrons on 100 GeV protons with a luminosity of $10^{35}\text{cm}^{-2}\text{s}^{-1}$.

35.2.5.3 Accelerator R&D items that will require test beds and test beams

Cooling of hadron beams: Small transverse and longitudinal emittances of the hadron beam greatly reduce the required electron beam intensity. In the designs with medium hadron energy this calls for the application of powerful cooling techniques:

- Coherent electron cooling: This novel cooling technique is under development for eRHIC. A proof-of-principle experiment is planned for 2015.
- Electron cooling: An electron cooler based on a high-current re-circulator ring fed by an ERL is under development for MEIC. Tests are planned for 2016.

Low β^* interaction region: IR designs face the issues of strong focusing of beams at the collision point and fast separation of beams after the collision. The synchrotron radiation fan produced by electrons in the IR magnets has to be kept away from hitting the pipe inside or in the vicinity of the detectors and in superconducting magnets. The requirements imposed by the detector integration have to be satisfied and chromatic corrections have to be accomplished while maintaining an acceptable dynamic aperture.

Crab-crossing: Crab-cavities have to be used in the designs with a large crossing angle to maximize the luminosity. Corresponding R&D includes designing and prototyping the superconducting crab-cavities and the study of the beam dynamics in the presence of crab crossing.

High beam power ERL and high beam current SRF cavities: This topic includes the SRF cavities able to operate with high average and peak beam currents, providing effective damping of high-order modes, the cryomodule design and the issues related with containing the high beam power.

The R&D ERL facility at BNL aims to explore CW operation of an ERL with an average current of up to 0.3 A.

Preserving e^- beam polarization in ring-ring schemes: The spin matching and the harmonic correction techniques have to be investigated to minimize the beam depolarization due to synchrotron radiation, especially in the presence of spin rotators and solenoidal detector magnets.

High current polarized electron source: The linac-ring designs utilize the high-current polarized electron source, with the average current ranging from 6 mA (LHeC LR) to 50 mA (eRHIC).

Considered approaches: Gatling gun or large size cathode gun to produce up to 50 mA current.

Proton and light ion polarization: This includes the preservation of the beam polarization at the acceleration, the polarization orientation control at the interaction points and the precise polarization measurement. Study of polarization survival in the novel figure-8 shaped ring used in the MEIC design, which allows for the acceleration of polarized deuterons.

For both MEIC and eRHIC, the production, the acceleration and the polarimetry of polarized He3 ions is being explored.

Beam-beam effects in the linac-ring scheme: The linac-ring scheme introduces non-standard beam-beam effects, which have to be explored to understand the limits on the luminosity and the beam parameters. The effects include the electron beam disruption, the hadron beam kink instability and the effect of the electron beam parameter fluctuation on the hadron beam.

Intense positron beam in the linac-ring scheme: The goal is to achieve the luminosity of e^+ -ion collisions acceptable for physics experiments. Considered techniques: advanced targets for the e^+ production, the use of powerful gamma beam source, and the schemes for positron beam recycling, cooling and reuse.

Matching electron and hadron bunch frequencies at different hadron energies: For hadrons that are not ultra-relativistic the change of the hadron energy considerably affects the hadron revolution frequency. Special provisions have to be made in these collider designs to match the bunch frequencies of hadrons and electrons at different hadron energies. This could include a variable circumference for the electron or hadron accelerators.

35.3 Accelerator technologies

35.3.1 SRF, NCRF, and power sources

Contacts: Rongli Geng, Sami Tantawi/Derun Li, Curt Hovater

35.3.1.1 SRF test facilities

Superconducting radio-frequency (SRF) cavities have been studied since 1964 and have been developed to a successful accelerator technology for nuclear physics in heavy ion linacs and electron linacs, for synchrotrons and recirculating linear accelerators in light sources, for linacs of spallation neutron sources, and in storage rings and for a linear collider in HEP. Nevertheless, SRF is still a technology that has potential for improvement and needs much R&D for its planned applications.

A large-scale linear electron-positron collider (the International Linear Collider) would require more than 10,000 cavities and their ancillary components. While large advances have been made, these components

have to operate at the limits of what is currently possible and R&D is still needed to make these system reliable and their construction reproducible.

US laboratories with major SRF programs are at Fermilab and Jefferson Lab, Argonne National Laboratory, Cornell University, and Michigan State University.

Research needs depend on the accelerator application of SRF: The highest gradients are needed for pulsed SRF accelerators, for example at a linear collider. The lowest wall losses and therefore the highest quality factors are needed for continuous-wave accelerators at medium voltages at projects such as Project X, Jefferson Labs CEBAF and its FEL. Active research areas include improved cavity construction techniques, such as surface treatments for conventionally deep-drawn niobium cavities; hydroforming and spinning niobium to create seamless cavities; combining niobium with copper for cost-effectiveness by coating copper with thin niobium layers by sputtering, electron resonance coating, arc deposition, spun explosion or atomic layer deposition; electroplating copper on a thin hydroformed niobium; and experimenting with new superconducting materials such as Nb_3Sn , MgB_2 , and multi-layers. And shape optimizations for cavities in any application are sought to improve their performance parameters.

Components of the accelerator cryostat go beyond the accelerating cavity and further R&D is under way on optimal higher-order mode absorbers, on low microphonics and low cavity detuning, efficient cryogenics system and cryogenic distribution in cryostats, the use of cooling loops to cool niobium-on-copper cavities. Constructing a full cryostat with the best components itself is an R&D topic.

For high-energy physics, projects that rely on SRF research include Project X, the muon collider and the linear collider. And there are synergies with programs for nuclear physics, including the FRIB facility, Jefferson Labs accelerator projects, and Brookhavens RHIC and eRHIC facilities. And further synergies with light source and neutron facilities, within the US these are Oak Ridges SNS, Brookhavens NSLS-II and Argonnes APS, the US Navy FEL and ERL.

SRF research also provides good opportunities for student training. Examples for such training efforts are Cornells SRF group and its energy-recovery linac research program and MSU, where students contribute to the NSCL program and in SRF for FRIB. Many breakthroughs in accelerator science and technology have been made at universities with on-campus machines with the involvement of students.

35.3.1.2 NCRF test facilities and power sources

Normal-conducting radio-frequency cavities have been widely used in accelerators for half a decade. Remaining unanswered questions in that realm are related extreme regimes of operation, such as very high gradients, operation in strong magnetic fields or with high pressure gas inside, or cavities operating at very high frequencies. Major test facilities where these issues are being addressed are CTF3 at CERN, NLCTA at SLAC and MTA at Fermilab.

35.3.2 SC magnets

Contact: Soren Prestemon

Development of superconducting accelerator magnets for the Tevatron was a success story with many spin-offs and with a large influence on subsequent accelerators. In the 1980s it provided a useful superconducting

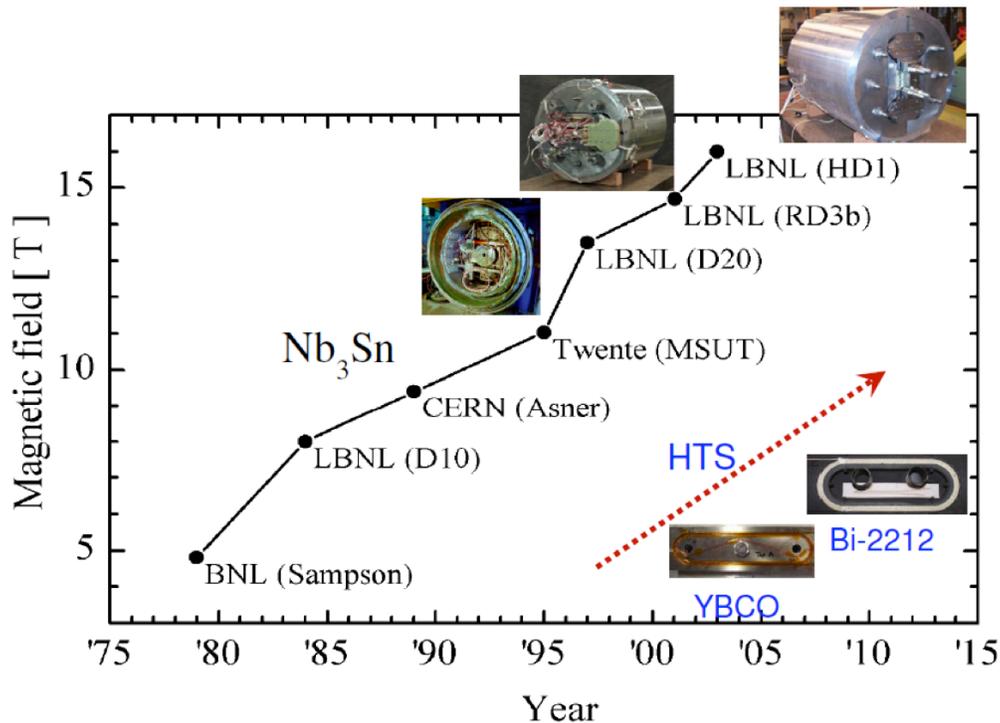


Figure 35-4. Growth in magnetic field over development period (technological tests) from [40].

cable technology that led to the widespread commercial production of magnetic resonance imaging (MRI) magnets, a several billion dollar per year industry with about 50% in the US.

To date, the vast majority of superconducting magnets (both for accelerators and for MRI systems) have been based on niobium titanium (NbTi) superconductor, the technology developed for the Tevatron. The next generation of accelerators, particularly planned upgrades to the Large Hadron Collider (LHC) at CERN, will require higher magnetic fields than can be supported by NbTi conductor. Nb₃Sn, which has a higher critical field than NbTi, is the conductor of choice for this next generation of magnets. A proof-of-principle high-field magnet, D20, was fabricated at Lawrence Berkeley National Laboratory (LBNL) in 1997 and reached a field of 13.5 T at a temperature of 1.8 K [36]. However, this magnet was fabricated using a brute force approach based on low-performance conductor. In the next several years, improvements in cable quality (see below) and fabrication techniques allowed further increases in field. Successor magnets, RD-3b (2001) [37] and HD-1 (2003) [38] reached 14.7 T and ~16 T, respectively, using improved conductor, albeit in simplified test configurations with no usable bore. A more recent dipole magnet, HD-2 (2009) [39] was more realistic, in the sense of allowing clearance for a beam pipe, and nonetheless reached 14.5 T. Further optimization and testing are under way, with the goal of reaching the full potential of this design, namely 15 T at 4.5 K or 17 T at 1.9 K. Overall progress is illustrated in Fig. 35-4.

Required improvements for SC wires include raising the critical current density (J_c) to enable compact windings, reducing the effective filament size to reduce higher-order multipoles in the magnetic field and to minimize AC losses, and increasing the cryogenic conductivity of the strand matrix to maximize stability. To address these development needs, HEP organized the Conductor Development Group (CDG) in 2002 and funded it (see Table 35-6) with \$500,000 per annum in its initial years. The great majority of these funds

were used to pay for development of an engineering conductor in US industry. The CDG is managed by LBNL with an advisory group whose members come from magnet groups at each of the national laboratories and from university grantees whose research supports conductor development. Advanced material from the program has been used to leverage magnet development in the HEP base program as well as in the LHC Accelerator Research Program (LARP). In complementary fashion, measurements and performance data from these customer programs are fed back to the industrial conductor developers via the CDG. The CDG benefits from economy of scale and helps to ensure that Nb₃Sn makes the transition to a practical engineering material. As is obvious from Table 35-6, the investments in both time and money are substantial.

Year	CDG	LARP	Core Program
2002	500		7291
2003	500		6800
2004	500	163	6416
2005	500	606	7139
2006	200	2909	7223
2007	390	2782	7229
2008	296	3020	6961
2009	396	3171	6790
2010	1020	3367	6022
2011	585	3124	5972

Table 35-6. *CDG and magnet development core program funding, in \$K.*

Figure 35-5 shows the improvement in J_c during the early years of the CDG. The success of the program is indicated by the rapid rise in performance at 4.2 K and 20 T, from 275 A/cm² in 2000 to 525 A/cm² in 2005.

Similarly, Fig. 35-6 illustrates the decrease in effective filament diameter, going from 70 μm in 2001 to 50 μm in 2006. Reducing the filament diameter even further, to 40 μm , is a current development goal. The cryogenic conductivity of the strand matrix, as measured by the residual resistivity ratio (RRR), has also been improved, but performance optimization requires balancing between improved RRR and improved J_c . For fields beyond those obtainable with Nb₃Sn, high-temperature superconductor (HTS) materials offer promise and are now being studied. A corresponding effort focused on conductor improvements has gotten under way.

From the above brief summary, two things are clear: The time scale from initial development of accelerator technologies to their commercialization can be lengthy, sometimes decades; having a substantial market, as in the case of MRI development, can drastically reduce this interval.

The investment required to ready an accelerator technology for commercialization can also be substantial, and must often be borne by government-supported accelerator R&D institutions. The Conductor Development Group, funded by HEP and managed by Lawrence Berkeley National Laboratory, funded the development of a new superconductor in American industry, particularly the development of compact cyclotrons for medical therapy and higher-field and -frequency MRI systems.

Brookhaven National Laboratory carried out a successful collaborative development of cryogenic and high-critical-temperature superconducting wire and cables, acting as an experimental magnet fabrication facility and as the test center of the industrial partners.

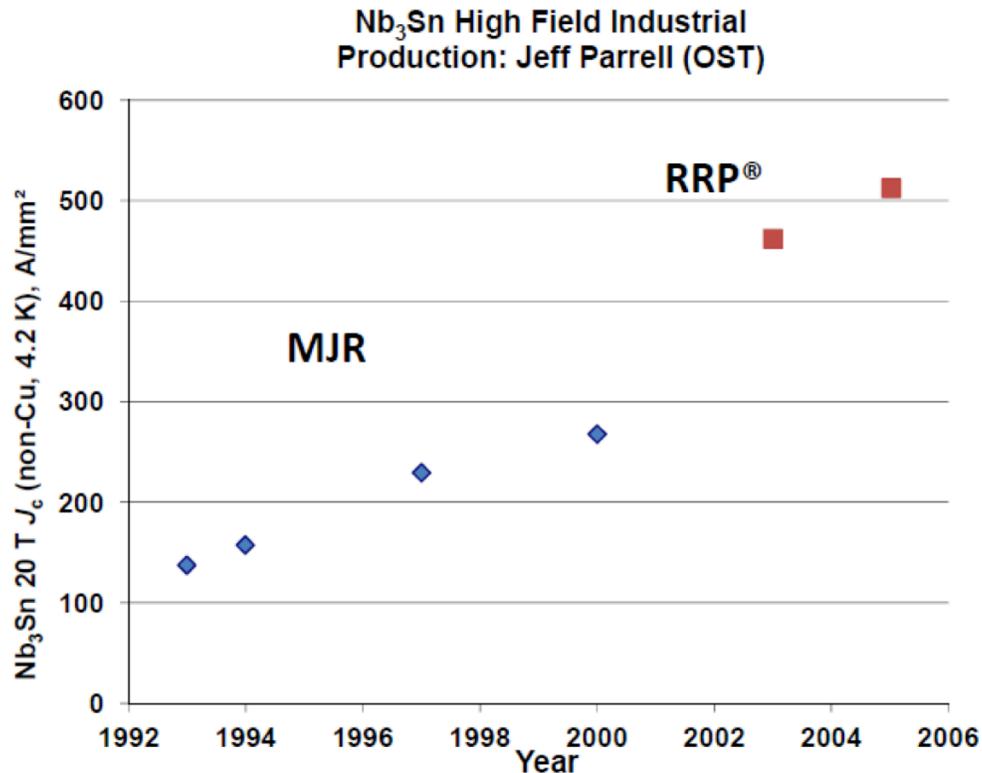


Figure 35-5. Growth in J_c resulting from CDG effort.

Discovery sciences will drive accelerator R&D and will have a broad impact in the coming years. This is especially true in the areas of superconducting radio-frequency acceleration, superconducting magnets and particle sources.

Demonstration and technical projects for SRF advancements abound. For high-energy physics, these include the proposed Project X, muon collider, and linear collider. For nuclear physics, they include MSUs FRIB facility, Jefferson Labs accelerator projects, and Brookhavens RHIC and eRHIC facilities. Oak Ridges SNS, Brookhavens NSLS-II and Argonnes APS all have a hand in advancing basic energy science. The US Navy FEL and ERL and the commercial projects of AES and Niowave are examples of projects that lie outside the national lab system but that are nevertheless beneficial for SRF.

The country also has multiple programs for the advancement of superconducting magnet technology. The US contribution to CERNs Large Hadron Collider involves cutting-edge technology in these magnets. The countrys light sources are developing superconducting undulators. Superconducting magnet technology can also be demonstrated in an electron-ion collider. The advancements in this area could be immediately industrialized for MRI technologies and medical cyclotrons.

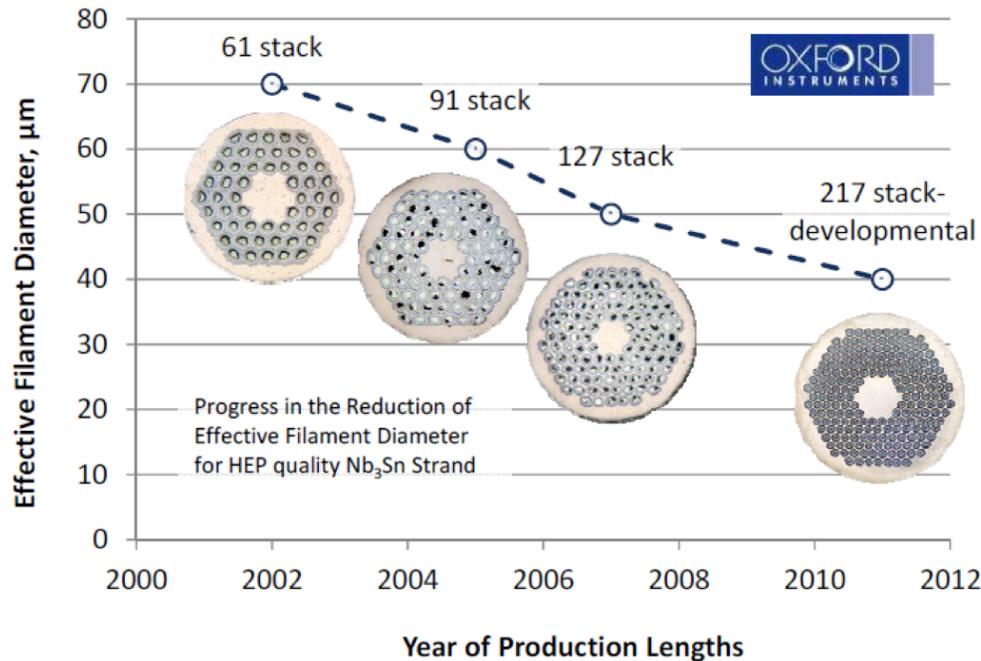


Figure 35-6. Decrease over time of effective filament diameter in Nb_3Sn strands.

35.3.3 Target tests

Test facilities that incorporate beam for targets are generally home grown to address the specific problems that are plaguing a specific facility or project (with radiation damage R&D being an exception). For example in 1999, the AP-0 (p-bar production facility) was used to conduct target tests for NuMI using 120 GeV Main Injector beam. This facility has since been re-configured and is unavailable to host other tests. FRIB has used accelerators in Israel and Russia to test their targets.

For radiation damage R&D, low energy ion beams are often used to irradiate samples. Suitable beam facilities exist at many Universities and Labs almost too numerous to list. These facilities are not HEP related, but nuclear physics and/or nuclear energy related. A draw-back to this irradiation source is "poisoning" of the samples with the ion beam, inability to create gas through transmutation (high in the case of high energy proton irradiation), and shallow depth of penetration. Dual beam facilities exist to simultaneously implant gas ions at the same time. A (possibly the only) high energy proton irradiation program in the US is the RaDIATE collaboration which now uses BLIP at BNL for irradiations and the BNL hot cells for PIE. RaDIATE will expand to use materials irradiated in service (from different Labs) with PIE at PNNL, Oxford, and BNL. There are many US labs capable of doing the PIE, some of them have access to ion beam irradiation facilities, such as LANL and PNNL.

Finally, a number of studies can be done using non-beam facilities. Tests like thermal shock can be replicated with electrical pulses in thin wires or lasers. High heat flux tests can be done in any thermal science lab. The HPT Workshop to be held at Fermilab in May 2014 will address some of these issues.

35.3.3.1 High-power proton targets

To convert protons into muons for Neutrino Factory or a Muon Collider, targets capable of withstanding the 45MW mean power of the proton driver are required. E.g., current neutrino factory designs call for a 4 MW (mean power) proton beam of 515 GeV energy impinging on a heavy element target. The beam is pulsed at 50 Hz with $\sim 240 \mu\text{s}$ long macro-pulses consisting of three micro-pulses of $\sim 1\text{--}3$ ns length (rms). The target is heated by ~ 1 MW (average) and the target station shielding absorbs the remaining ~ 3 MW of secondary particle power. The high power density makes cooling a single static target difficult and the high energy density per pulse gives rise to a severe thermal shock effect. At present several target solutions are proposed: (a) a mercury jet target which removes the heat by flowing. The target is blasted apart by each beam pulse but reforms before the next pulse, thereby overcoming the thermal shock problem; (b) a solid tungsten rod, 1–2 cm diameter and ~ 17 cm long, which is replaced every 1/50 of a second by either a chain or wheel mechanism; c) a solid target of small spheres to overcome the thermal shock problems, cooled by flowing helium or water.; d) a fluidised tungsten powder jet ($\sim 50\%$ density), which does not suffer from shock because of its granulated nature. The UK target group focusses on the solid target, with another group at RAL working on the powder jet (website coming soon). The main IDS study, predominantly in the US, studies the mercury jet, which is currently the baseline option.

Many of the above issues are being subject of the R&D work by the RADIATE collaboration: <http://www-radiate.fnal.gov/>.

35.3.3.2 Positron production

Most of the positron production issues, related tests and facilities have been discussed in the ILC/CLIC sections above; see Section 35.2.2.

35.4 Required proof-of-principle system tests

Accelerators beyond the horizon have a large number of R&D topics that have yet to be addressed. Instead of attacking all items, it is important to address first those techniques without which the accelerator could not function. If these technologies cannot be proven to work, R&D on other topics will not be worth while. In this section we try to specify the most important tests of systems that have to work in order to make further R&D on the associated accelerator reasonable.

35.4.1 Multi-MW proton drivers

High intensity proton sources within the current era are capable of delivering of order 1 MW beam power onto a secondary particle production target. These sources are used to support research in particle physics, nuclear physics, and materials science. Applications in the future will require beam powers of roughly an order of magnitude higher. Two examples include (1) proton drivers for muon-based particle physics facilities (Neutrino Factory and Muon Collider); and (2) proton drivers for nuclear energy applications including materials studies, nuclear waste transmutation, and/or energy generation, the latter two referred to collectively as Accelerator Driven Systems (ADS).

35.4.1.1 Muon-based particle physics facilities

A Neutrino Factory or Muon Collider requires a Proton Driver with the following general characteristics to supply the required numbers of muons:

Beam Energy	3–15	GeV
Beam Power	1–4	MW
Pulse Rate	10–50	Hz
Pulse Length	<10	μ sec
Bunches/Pulse	2–5	
Bunch Length (rms)	2–3	nsec

The energy and beam power are well matched to concepts for superconducting-linac-based proton facilities and their upgrades (see, for example, Project X [30]). However, such facilities inherently feature beam duty factors ranging from 5-100% while the Muon Facilities require a Proton Driver with duty factors of typically 10^{-4} or less. Transformation of the beam delivered from a linac into the beam format required for a Muon Facility is likely to require the introduction of two rings at the end of the linac – an accumulator ring to reduce the inherent duty factor by transforming the long linac pulse into a short pulse (given by the circumference of the accumulator); and a compressor ring to shorten the bunches into the 2–3 nsec range. The primary technical issues in these rings have to do with mitigation of space-charge (both transverse and longitudinal), and the multi-turn H^- injection required into the accumulator. In principle these issues can be addressed through computer modeling, although a demonstration of the extremely high longitudinal densities required would be advisable to benchmark simulation codes, given that the extrapolation goes significantly beyond current experience.

An even greater challenge than the rings is the targeting – delivery of up to 4 MW of beam power onto a production target at very low duty factor is a significant extrapolation beyond current experience. These issues also exist in the current era program and should be addressed through a comprehensive development program aimed at multi-MW targets for a variety of applications.

35.4.1.2 Nuclear Energy Applications

Advanced nuclear energy systems have the potential to deliver significant improvements in sustainability, safety, reliability and proliferation-resistance relative to the conventional, Generation II nuclear power systems. National needs in Advanced Nuclear Energy Systems have been articulated in a number of recent reports [40, 41]. Many of these needs rely on materials development that could be driven by a high power proton linac coupled with a flexible target station for neutron generation. Examples include irradiation testing of fast reactor structural materials, integral testing of fast reactor fuel rodlets, separate-effects testing of fission reactor fuel materials, and irradiation testing of fusion structural materials. A preliminary concept for a target facility based on the Project X linac has been developed and is described in [42].

Since the early 1990s, Accelerator Driven Systems — subcritical assemblies driven by high power proton accelerators through a spallation target which is neutronically coupled to the core — have been proposed for addressing certain missions in advanced nuclear fuel cycles. Research into this area is currently centered outside the US, in Europe and Asia. Active programs aimed at low power demonstration projects are currently being pursued in Belgium [43] and China [44]. Similar programs are in the planning stages in Japan, South Korea, India, and Russia. All these programs are focused on both waste transmutation

and power generation. In 2010 the DOE Office of Science established a Working Group that produced a whitepaper [45] outlining opportunities and R&D challenges. The following comments are based on that whitepaper.

The principal advantages that accelerator-driven sub-critical systems have relative to critical reactors are twofold: greater flexibility with respect to fuel composition, and potentially enhanced safety. Accelerator driven systems are ideally suited to burning fuels which are problematic from the standpoint of critical reactor operation, namely, fuels that would degrade neutronic characteristics of the critical core to unacceptable levels due to small delayed neutron fractions and short neutron lifetimes, such as ^{233}U and minor actinide fuel. Additionally, ADS allows the use of non-fissile fuels (e.g., Th) without the incorporation of U or Pu into fresh fuel. The enhanced safety of ADS is due to the fact that once the accelerator is turned off, the system shuts down. If the margin to criticality is sufficiently large, reactivity-induced transients can never result in a super-critical accident with potentially severe consequences. Power control in accelerator-driven systems is achieved through the control of the beam current, a feature which can be utilized for fuel burnup compensation.

An ADS consists of a high-power proton accelerator, a heavy-metal spallation target that produces neutrons when bombarded by the high-power beam, and a sub-critical core that is neutronicly coupled to the spallation target. To achieve good neutronic coupling the target is usually placed at the center of a cylindrical core. The core consists of nuclear fuel, which may be liquid (e.g., molten salt) or solid as in conventional nuclear reactors. ADS technology has evolved considerably over the last two decades, including several key advances that make ADS a viable technology which is ready to proceed to the demonstration stage:

- The construction, commissioning, and operation of a high-power continuous wave front-end system that meets the beam current performance required for up to 100 mA ADS accelerator system (the Low-Energy Demonstration Accelerator (LEDA) at Los Alamos)
- The construction, commissioning and MW-level operation with acceptable beam loss rates of a modern linear accelerator based on independently-phased superconducting accelerating structures (the Spallation Neutron Source at ORNL)
- The construction and deployment of a wide variety of pulsed and continuous-wave superconducting accelerating structures for proton/ion acceleration over a wide range in particle velocities, which is a key ingredient to achieving high reliability operation
- The high-power beam test of a liquid Pb-Bi eutectic spallation target loop at the Paul Scherrer Institute in Switzerland (the MEGAPIE project), and the operation of a MW-class liquid metal spallation target system at SNS

Perhaps more important, recent analyses of subcritical reactor response to beam interruptions reveal greater tolerance to and therefore more relaxed requirements for beam trips, which had been a key criticism of previous ADS concepts.

An ADS facility capable of transmutation of waste and/or generation of electricity on a commercial scale requires a proton accelerator operating at 1–2 GeV, with a beam power of 10–20 MW. The primary accelerator technology and accelerator physics issues related to such a facility include the development and demonstration of very high reliability accelerator operation through automated fault recovery, deployment of specialized diagnostic and control systems, accelerator-target coupling studies, and beamloss control and mitigation. A current generation MW-class proton accelerator can provide critical input on reliability and diagnostics issues, while an optimized Target Station at such an accelerator would provide the flexibility for supporting key R&D with an emphasis on spallation neutron target and transmutation studies [46]. The focus at such

a Target Station would be on developing, demonstrating and verifying several critical aspects of neutron spallation target systems for ADS:

- Lead-bismuth target R&D including oxygen control, cleanup chemistry, safety in in-beam conditions
- Development and testing of windowless concepts
- Materials irradiation studies relevant to the ADS environment
- Characterization of neutron yield, spectra, spatial distributions, etc.

35.4.2 Multi-stage wake-field based accelerator

35.4.2.1 Staging plan

In order to achieve a high energy collision, a scheme that can accelerate a witness beam to higher energies is required and needs to be demonstrated. This can be obtained by using either a staging technique or a high transformer ratio, or even a combination of the technologies. In order to demonstrate staging techniques for a collider application, several key issues need to be addressed.

Efficient drive beam generation for both power and bunch parameters. The drive beam (both laser and electron beam) must have a visible path toward order of ~ 10 MW.

Develop a scheme that can effectively deliver the drive beam, which uses minimal spaces and demonstrates sufficient timing control. Must be extendable from two stages to multi-stages (> 3). This technology would require precision time and energy control of the drive beams

Stages can be reduced if a higher transformer ration (> 2) acceleration scheme can be used. This requires beam shaping (triangular longitudinal beam shape) technique development and transportation.

Common requirements for the staging tests are: 1) generation of at least two separable drive beam (or bunch train) in time and space. 2) A witness beam to probe the wakefields by the drive beam in structures.

Several facilities will be available to test the staging and beam shaping concepts (see appendix for details):

- Argonne wakefield accelerator (AWA): Attempts will be made to generate realistic drive beam for the Argonne Flexible Linear Collider applications. With its 75 MeV drive beam and flexible drive beam timing structure, a staging experiment is planned. This will require a deflecting cavity to separate the drive beam and inject it into different stages. The planned staging experiment will be done with dielectric wakefield structures. In addition, a staging technique for two parallel beam acceleration scheme can be studied. Another subject is to make a longitudinal shaped bunch through a process called emittance exchange, this will demonstrate the viability of the high transformer ratio scheme.
- FACET at SLAC: A staging experiment is being planned at FACET II, the facility proposed to follow FACET, which will have a demonstration of staged, high-brightness beam acceleration as one of its primary goals. This will elucidate many of the technical issues inherent in realizing a wakefield acceleration-based linear collider.

The path towards high-energy physics applications of LPAs will involve hundreds of 10 Gev-class stages to achieve energy that satisfy interaction point requirements on beam-beam interaction. The lasers driving

each stage will need to be synchronized at a fraction of the plasma wavelength (which is ~ 100 m). The particle beam must be coupled between stages, while allowing space for extraction of the drive pulse from the last stage/insertion of the drive pulse for the next stage. This space should be as short as possible to preserve geometric gradient. Lasers allow short coupling space because they can be turned at right angles by plasma mirrors in short ($\sim 10\%$ Lacc) distances. To preserve emittance, radial expansion of the beam must be controlled: for collider scale emittances ballistic expansion will be small for plasma mirror coupling distances which may reduce or eliminate the need for focusing optics between stages. Experiments to demonstrate staging are being conducted now at the half GeV energy scale. Following this, multistage experiments with multi-GeV and low emittance beams will be needed to evaluate beam transport and emittance preservation including coupling and scattering contributions. In the longer run, near-hollow plasma channels may be incorporated to mitigate emittance growth from scattering.

There may be other facilities that could be used to demonstrate staging concepts for laser and beam driven wakefield accelerators.

35.4.3 Muon accelerators

Technology development of critical importance to the performance of a muon collider and/or neutrino factories includes [47]: (1) development of a high power target station including a high field capture solenoid (nominally 20 T hybrid normal and superconducting magnet with about 3 GJ stored energy) that is ultimately capable of handling more than 4 MW of power; (2) SC magnets and NC RF components of the cooling section for the muon six-dimensional phase space volume reduction by six orders of magnitude to achieve the beam parameters required for the muon collider designs; (3) development of very large aperture, superconducting dipole magnets with heavy inserts to protect the superconductors from the decay products of the stored muons in the collide; (4) development of rapid cycling synchrotron or FFAG rings for fast acceleration. Many of these tests are already subjects of the present US Muon Accelerator Program (MAP) technology feasibility study.

35.5 Appendix: Existing test-beam facilities

35.5.1 APEX LBNL

Contact: Fernando Sannibale <FSannibale@lbl.gov>

The APEX is a R&D project at the Lawrence Berkeley National Laboratory that focuses in the fabrication and test of a high-brightness, high-repetition-rate photo-injector system, essential to a class of future light sources based on free electron lasers (FEL). The APEX project core consists of a continuous wave (CW) VHF-frequency (186 MHz) normal-conducting photo-electron gun, and extends that system to provide higher energy beams at which the emittance is not dominated by space-charge effects, and is in a condition ready to inject into a linac for further acceleration.

APEX is organized in 3 phases. In Phase 0, already successfully commissioned (PRST-AB 15, 103501, 2012), the VHF gun is followed by a beamline with the diagnostic required for characterizing photocathodes. In Phase I, presently under installation, a complete electron beam diagnostics suite with 6D phase space characterization capability is added to gun. In Phase II a 30 MeV pulsed linac is added to allow beam

characterization in negligible space-charge force regime. The main APEX beam parameters are shown in the Table 35-7.

Initial operation (Phase 0/Phase I/ Phase II)	2011/2013/2015*
Beam energy (Phase 0/Phase I/ Phase II)	<0.8/<0.8/<30 MeV
Particle type	electrons
Charge per bunch	from few pC to ~ 0.5 nC
Phase 0 and I repetition rate (CW operation with equally spaced bunches pulsed operation possible)	from 10 Hz to 1 MHz
Phase II repetition rate (pulsed operation)	up to 10 Hz
Normalized beam emittance	from $\sim 10^{-7}$ (low charge) to 10^{-6} m
Bunch length (FWHM) charge dependent	from ~ 500 fs to ~ 50 ps
Electric field at the cathode	~ 20 MV/m
Gun vacuum pressure (at nominal RF power)	10^{-9} – 10^{-10} Torr

Table 35-7. APEX beam parameters. 2015 operation depends on funding.

APEX has been designed and optimized as a versatile injector with flexibility of operational modes, and complete electron beam phase space diagnostic capability, in which the production of FEL quality beams can be demonstrated and where a wide variety of photocathode types can be tested in a real-world environment. A carefully designed vacuum system in the VHF cavity will allow operation of the photo-gun at the very low pressures required by sensitive semiconductor photocathodes. A laser system with flexibility in photon wavelength, pulse shape, peak and average power, and repetition rate is available to match with a variety of photocathode materials. A vacuum load lock system permits replacement and transport of cathodes without breaking the vacuum.

35.5.2 ARIEL

Contact: Shane Koscielniak <shane@triumf.ca>

The ARIEL facility is for the production of rare isotope beams, primarily for nuclear physics. When complete, circa 2017, there will be two target stations. One station will operate with 500 MeV 200 μ A protons, the other station will operate with 50 MeV 10 mA electrons. The project is staged. In the first stage to be completed 2015, there will be 10 mA of 30 MeV electrons.

Leading toward those ambitions, we have a test facility that will provide 3 mA of 10 MeV electrons. Present status is 10 mA at 100keV to be followed by 300keV in September and 10 MeV in November 2013.

Available energy= up to 10 MeV, particle type= electron, up to 16 pC per bunch, bunch repetition rate =650 MHz, number of bunches per pulse = up to c.w., pulse repetition rate = up to c.w., emittance = 6 μ m r.m.s. normalized, bunch-lengths = sub-millimetre, energy-spread limits $\Delta p/p$ estimated at 10^{-3} r.m.s.

35.5.3 ASTA

Contact: Vladimir Shiltsev <shiltsev@fnal.gov>

The Advanced Superconducting Test Accelerator (ASTA) currently under construction/commissioning at Fermilab will enable a broad range of beam-based experiments to study fundamental limitations to beam intensity and to develop transformative approaches to particle-beam generation, acceleration and manipulation. ASTA incorporates a superconducting radiofrequency (SRF) linac coupled to a photoinjector and small-circumference storage ring capable of storing electrons or protons. ASTA will establish a unique resource for R&D towards Intensity and Energy Frontier facilities and a test-bed for SRF accelerators and high-brightness beam applications. ASTA will have 3 experimental areas each capable to host a number of experiments: Exp Area #1 with 50 MeV e^- out of a photoinjector (commissioning began in 2013); Exp Area #2 with 300-800 MeV e^- after acceleration in 1.3 GHz SC RF cryomodules (the final energy will depend on resources available, anticipated readiness of the beam through the 1st CM end of CY2014) and Exp Area #3 with a 40-m circumference IOTA ring operating initially with 50-150 MeV e^- which can later operate with 2.5 MeV protons (ring construction to be ended in 2015). The unique features of ASTA include: (1) a high repetition-rate of 3 MHz / 1 ms long pulses of 300 bunches, (2) one of the highest peak and average brightness within the U.S. (ILC beam parameters, e.g 3.2 nC bunch charge and 2-5 μm rms emittance), (3) a GeV-scale beam energy, (4) an extremely stable beam, (5) the availability of SRF and high-quality beams together, and (6) a storage ring capable of supporting a broad range of ring-based advanced beam dynamics experiments. These unique features will foster a broad program in advanced accelerator R&D which cannot be carried out elsewhere. See the full ASTA proposal [31] and [48]. Main beam parameters for the ASTA experimental areas 1 and 2 are given in Table 35-8.

parameter	nominal value	range	units
Energy (exp. area 1)	50	[5, 50]	MeV
Energy (exp. area 2)	~ 300 (stage 1)	[50,580]	MeV
Bunch charge Q	3.2	[0;02, 20]	nC
Bunch frequency	3		MHz
Macropulse duration τ	1	≤ 1	ms
Macropulse frequency f	5	[0.5, 5]	Hz
num. bunch per macro N_b	3000	[1, 3000]	
trans. emittance ϵ_{\perp}	$\simeq 2.11Q^{0.69}$	[0.1, 100]	μm
long. emittance ϵ_{\parallel}	$\sim 30.05Q^{0.84}$	[5,500]	μm
peak current \hat{I}	~ 3	≤ 10	kA

Table 35-8. ASTA beam parameters.

35.5.4 ATF

Contact: Ilan Ben-Zvi <benzvi@bnl.gov>

The Accelerator Test Facility (ATF) has been serving the Department of Energy Accelerator Stewardship mission for over two decades (Since 1992). In its operations as a user facility it served a large community from academia, National Laboratories, small business and international users. It provides unique facilities

such as high-brightness electron beams and high-power lasers synchronized to the electron beams in three beam lines. The ATF serves as training ground for post-docs and graduate students in accelerator science, with 28 PhD and MSc granted so far.

The electron beam energy is 25 to 80 MeV (100 MeV upgrade in progress), 10^8 to 10^{10} electrons per bunch, 1-3 Hz pulse repetition rate, emittance of the order of 1 micron (depending on charge), bunch length 8 ps to 100 fs. The CO₂ laser is synchronized with the electron beam, at a peak power of 2 TW (current) and 100 TW upgrade in progress. The ATF has a large assortment of beam line interaction chambers and beam instrumentation to support its rich users program.

35.5.5 ATF-2

Contact: Glen White <whitegr@SLAC.Stanford.EDU>

ATF2 is a rebuilt extraction line and test final focus system, extending from the ATF damping ring at KEK. First beam through the new beam line was established through to the main dump in December 2008. The facility comprises a multibunch-capable RF gun (with up to 20 bunches, spaced by 2.8 ns per pulse), a 1.3 GeV electron linac, a damping ring, and a test beam line for an ILC final focus system (the ATF2). The nominal electron beam has an energy of 1.3 GeV, charge of up to $1E10$ e/bunch, and pulse repetition rate of 3.12 Hz. Multi-train mode of operation is also possible with 3 trains of 1-20 bunches stored sequentially in the DR and then simultaneously extracted at a third of the normal pulse repetition rate. The extracted bunch parameters depend upon the bunch charge and pulse profile in use, but typically are in the range 6-10mm bunch length, 1.5-2nm.rad x 10-20pm.rad emittances, 0.06-0.08% energy spread. Beam operation is scheduled for 21 weeks per year, interlaced by regular maintenance and shutdown periods in the summer and in the winter. A large number of accelerator scientists from SLAC, LBNL, FNAL, JAI, CI, DESY, CERN, UCL, LLNL, IHEP, PAL, IFIC, LAL, LAPP, and others in addition to KEK and Japanese institutes have participated in research programs at the ATF. ATF2 is a multi-program facility focusing on beam diagnostic R&D for future linear colliders and the validation of the local-chromaticity correction final focus scheme envisioned for ILC and CLIC [49].

35.5.6 AWA

Contact: Wei Gai <wg@hep.anl.gov>

The AWA facility is optimized for the purpose of investigating the most promising Advanced Acceleration Concepts such as two-beam and collinear dielectric wakefield acceleration. For this reason, it contains both a 75 MeV drive beam (the worlds highest charge rf photoinjector at >100 nC) and a separate 15 MeV witness beam. When the drive gun is optimized for two-beam, dielectric wakefield acceleration it is capable of generating single bunches in excess of $> 6 \times 10^{11}$ particles per microbunch with peak current >20 kAmps and long bunch trains of up to 32 electron bunches (25 nsec duration) and 6×10^{12} particles per train. Conversely, the AWA facility is also capable of exploring advanced acceleration schemes that require low charge, low emittance beams since it is based on a 1.5 cell rf photoinjector and can reach the typical, state-of-the-art parameters such as normalized emittance of 1 μm and 1 nC.

35.5.7 BNL Cathode lab

Contact: Ilan Ben-Zvi <benzvi@bnl.gov>

BNL cathode lab carries out a comprehensive program on critical aspects of the production of the electron beams needed for future user facilities. The program has pioneered in situ and in operando diagnostics for alkali antimonide growth and diamond amplified photocathodes. The focus is on development of photocathodes for high repetition rate Free Electron Lasers (FELs) and Energy Recovery Linacs (ERLs), including testing SRF photoguns. Teams from BNL, LBNL and Stony Brook University (SBU) collaborate in this research program, and coordinate their work over a range of topics. The work leverages a robust infrastructure of existing facilities, making extensive use of synchrotron radiation materials science techniques, such as powder- and single-crystal diffraction, x-ray fluorescence, EXAFS and variable energy XPS. Use of these techniques brings understanding of these complex materials to a new level. In addition, we make use of the excellent analytical facilities at nanomaterial centers, where we have access to state of the art UHV XPS, SPM, SEM and scanning Auger microscopy. The program at BNL also includes the development of high-current polarized electron guns through the use of funneling (AKA Gatling Gun).

35.5.8 BNL-ERL

Contact: Ilan Ben-Zvi <benzvi@bnl.gov>

The BNL R&D ERL is aimed at CW operation with 300 mA at 20 MeV (but designed to be capable of 500 mA). One of its main features is a superconducting laser-photocathode RF gun powered by a 1 MW CW klystron and equipped with a load-lock system for inserting high-quantum-efficiency photocathodes. This SRF gun offers high-brightness electron beams at an unprecedented pulse repetition rate and average power. The objective of constructing and operating this ERL is to serve as a platform for R&D into very high current linacs, in particular issues of halo generation and control, Higher-Order Mode (HOM) issues, coherent emissions for the beam and high-brightness, high-power beam generation and preservation. For all these issues the current is important, but the machine energy can be rather low. Following its completion, we plan to use it for various applications, such as generating THz radiation and high-power X-rays through the Compton scattering of laser light off its electron beam. The ERL is now in commissioning stage, with current from the gun due in 2013 and beam in the ERL due in 2014.

35.5.9 CESR-TA

Contact: David Rubin <david.rubin@cornell.edu>

CESR-TA was established in 2008 as a test facility for exploring physics of low emittance electron and positron beams in storage rings for colliders and light sources. The facility has the capability to store trains of electron or positron bunches with spacing of as few as 4ns. The 768m circumference storage ring is instrumented with 100 high bandwidth precision beam position monitors with turn by turn and bunch by bunch capability. A pair of x-ray beam size monitors is use for measurement of the vertical size of electron and positron bunches respectively with few micron precision. Like the beam position monitor system, it is capable of turn by turn, single pass measurements of individual bunches in a train. A pair of visible synchrotron light interferometers is used for bunch by bunch measurement of horizontal beam size. The ring is further instrumented with dozens of special detectors to measure the growth of the electron cloud. Twelve

superconducting 2.1T damping wigglers increase the damping decrement by an order of magnitude so that the machine can operate as a truly wiggler dominated ring. The ring can operate over an energy range from 1.5 to 5.6 GeV with total current up to 300mA in each beam and 1011 particles/bunch. The storage ring control system is closely integrated with sophisticated modeling and analysis software enabling efficient measurement and correction of optical errors and emittance tuning. The ring routinely operates with sub 10pm-rad vertical emittance, 2-3nm-rad horizontal emittance, 1cm bunch length, and 0.08% energy spread, depending on energy and lattice. In facility has been a laboratory for developing beam instrumentation that has subsequently enabled studies of electron cloud growth and mitigation, electron cloud induced instabilities and emittance dilution, intra-beam scattering, and emittance tuning techniques.

35.5.10 Cornell ERL test beam

Contact: Bruce Dunham <bmd29@cornell.edu>

The Cornell ERL prototype electron injector saw first beam in 2008, and was funded to prove out the technologies necessary to build a high-average power, ultra-low emittance injector needed for a 5 GeV ERL light source. The injector must provide 77 pC per bunch at a 1300 MHz rate, equivalent to an average current of 100 mA. This injector has 500 kW of available RF power, thus can provide 100 mA at 5 MeV, or a lower current at higher energies (up to 13 MeV). To generate intense, bright x-ray beams, a normalized (rms) emittance of $<0.3 \mu\text{m}$ is necessary. A DC photocathode gun followed by a superconducting booster module was designed and built to meet these requirements.

Two drive lasers are available, one operating at 50 MHz and the other at the full 1300 MHz rep rate. Either can be chopped using a Pockels cell, meaning a wide- range of pulse structures and repetition rates can be generated. The 1300 MHz fiber laser has enough power at 520 nm to produce 100 mA for cathodes with quantum efficiencies as low as 1%.

Numerous measurements have been carried out with this injector in order to prove out the simulations and demonstrate that the requirements can be met. So far, a maximum current of 75 mA (at 1300 MHz) has been reached, with cathode lifetimes exceeding 2.5 days ($1/e$). Emittance values well below $1 \mu\text{m}$ (normalized, rms) have been measured after a prototype merger section, and match the simulations very closely. The bunch length is typically ~ 2 ps rms, but can be varied between ~ 100 fs to 10 ps at the expense of emittance and/or energy spread. Note that nearly all of the ERL machine parameters have been realized, so the numbers here are not just simulations but based on real measurements. A flexible load-lock system allows most any type of photocathode to be used, making this injector an ideal facility for developing and testing cathodes to meet the demanding needs of many accelerators. The high-average power beams also provide an excellent way to test new high-power diagnostics, study halo generation and elimination, ion formation physics, just to name a few possibilities. We are also preparing to test the HOM mode structure of a full ERL-type SRF cavity, and could in principle test any RF cavity with beam (as long as the resonant frequency is commensurate with 1300 MHz).

35.5.11 Cornell ERL-SRF with beam test lab

Contact: Matthias Liepe <mul2@cornell.edu>

This facility allows for testing the performance of SRF cavities with beam, including beam based HOM measurements (Q and R/Q), and high CW beam current operation (up to 75 mA). The cavity under study

is placed into a test cryomodule located downstream of a short SRF booster section in the Cornell ERL prototype injector. Beam current modulation with variable frequency is used to selectively excite HOMs, and transverse motion of the beam leaving the cavity under test allows for determining R/Q and Q of the given excited HOM.

Available beam parameters during SRF cavity beam test are

Year established	2013
Available energies	Up to 14 MeV; typically 5 MeV. Maximum energy limited by RF power available in the SRF booster (~ 500 kW)
Available particle types	electrons
Particles per bunch	up to $\sim 3 \times 10^8$ at 1.3 GHz bunch rep rate (~ 70 mA cw beam) up to 1×10^9 at lower rep-rates
Bunch repetition rate	50 MHz and 1300 MHz available
Number of bunches per pulse	flexible, up to CW operation
Pulse repetition rate	flexible, up to CW operation
Emittance	< 0.5 mm mrad at 77 pC
Bunch-length	2 to 3 ps
Energy-spread	$< 1 \times 10^{-3}$

35.5.12 CSU ABL

Contact: Biedron <biedron@enr.colostate.edu>

Presently, the research team has a 6-MeV, L-band electron beam linear accelerator, spare klystron, and high power THz FEL resonator system. These components and the three lasers described below will be housed and operated in the newly constructed Advanced Beam Laboratory (ABL). The accelerator and lasers will be moved to the new facility in 2013 and first beam is expected in 2014. Upon first beam, the electron beam energy of the accelerator will be 6 MeV, but upgrades are planned. The accelerator has a demonstrated performance of 3 nC per bunch with a maximum bunch repetition rate in burst mode of 81.25 MHz, a pulse duration of 15 microseconds and a burst repetition rate of 10 Hz. The number of bunches per burst is roughly 1200. Simple 10-Hz operation with a single bunch is also achievable and depends on the desired end experiment. The linac has achieved emittances of 1.2 μm with lower bunch charges, can achieve minimum bunch-lengths minimum of 40 fs with metal cathodes and regularly achieved energy-spreads of 0.4%. The ABL will also be equipped with high peak power laser systems. The first high power laser is a 100-150 Terawatt Ti:Sapphire laser system (800 nm). Its energy before compression is 13 Joules, its repetition rate is presently up to 5 Hz. There is ongoing research that will push this to 0.5 Petawatt. A second high power laser will also be co-located with the linear accelerator. A 1-J, 5-picosecond, 100-Hz repetition rate diode-pumped laser (100 W average power) is operating at 1.03 micrometers. This is the highest repetition rate diode-pumped chirped-pulse-amplification laser in the world. This can be scaled in repetition rate and pulse energy. Finally, a third laser, the driver for the photocathode in the linear accelerator will also be in the new building. It can generate 10-W of average power at 800 nm and 1 W of average power at 256 nm. The pulse duration is down to 40 fs (FWHM). In addition to the accelerator and lasers and peripherals. The

team has a microwave measurements laboratory to measure RF devices. CSU also has an electromagnet and permanent magnet measurement facility. Further, the group has materials laboratories to fabricate and test optics for several high-average power lasers and photon sources of a myriad of sources from the IR to the EUV-X. Finally, the group is developing high-power tunable lasers and associated optics in the IR in the 1-2+ micron regime. This co-location of the accelerator and laser beams is advantageous for both the creation of better accelerators and better lasers (coherent radiators included).

35.5.13 Daresbury test beams

Contact: Peter McIntosh <peter.mcintosh@stfc.ac.uk>

ALICE (Accelerators and Lasers In Combined Experiments) is a multifunctional ERL based R&D facility that operates in various regimes, both energy recovery and non-energy recovery, depending on the project undertaken. Originally implemented as the Energy Recovery Linac Prototype (ERLP) facility in 2007, it has been utilized to develop a number of scientific programmes which include; IR-FEL lasing and its application for scanning near field optical microscopy, generation and applications of coherent broadband THz radiation for life sciences and solid state physics, Compton-backscatter processes, studies of the first non-scaling FFAG EMMA for which ALICE serves as an injector, demonstration of new SRF acceleration systems and fundamental accelerator physics research.

The ALICE beam parameters are:

Beam energy	10–35 MeV
Particle types	electrons
Bunch repetition rate	81.25 MHz
Bunches per pulse	8125
Pulse repetition rate	20 Hz
Bunch length	<1 ps
Bunch charge	20 - 100 pC

EMMA (Electron Model for Many Applications) is a non-scaling FFAG (Fixed Field, Alternating Gradient) accelerator and is currently under operation at Daresbury Laboratory. It is the first time to demonstrate this type of accelerator. EMMA takes electron bunches from ALICE at 10 MeV and passes them around a ring with a circumference of just 16.6 m consisting of 84 quadrupole magnets that both focus and bend the beam and 19 RF cavities to accelerate the beam before extraction. Injection and extraction into and from EMMA are achieved via a system of two kickers and a septum in both cases. The EMMA injection line was commissioned with beam in March 2010, the first beam injected into the EMMA ring and transported to the end of four sectors in June 2010. In August 2010 the complete EMMA ring installation was complete and electrons were transported through multiple turns of the ring - the first for a non-scaling FFAG lattice. By the end of 2011, acceleration was achieved in the "serpentine channel" - thus proving the principle behind this novel type of accelerator for the first time.

The EMMA beam parameters are:

Beam energy	10–20 MeV
Particle types	electrons
Bunch repetition rate	1–20 Hz
Bunches per pulse	1
Pulse repetition rate	1–20 Hz
Bunch length	<1 ps
Bunch charge	16–32 pC

VELA is a high performance, modular injector facility capable of delivering a highly stable, highly customisable, short pulse, high quality electron beam to a series of test enclosures. VELA is being established as a highly accessible tool, both for commercial and academic users. A unique feature of the facility is that users can access both sides of the wall i.e. the two user enclosures are accessible for exploitation of the beam, and the accelerator itself is accessible for testing of new accelerator components. The potential user community is therefore very broad, including those who wish to use the high-precision pulsed electron beams (or pulsed x-rays produced via conversion targets) for testing or imaging of samples, and developers of accelerator components, controls and beam diagnostics. The VELA facility comprises an S-Band Photo-injector, which is capable of delivering up to 250 pC of bunch charge at 6 MeV, with micron level beam emittance performance. The copper photo-cathode is driven by a Coherent Inc. UV laser which delivers a pseudo-Gaussian profile of 1 mm FWHM at the cathode. RF power is delivered to the RF Gun via a Thales TH2157A, 10 MW klystron which is powered by a Scandinova K2 modulator, all of which is housed on the VELA injector enclosure roof. The electron beam is then transported through a beam diagnostics line comprising wall current monitor, pepper pot, YAG screens, Faraday Cup and slit/strip line BPMs, with a transverse deflecting cavity (TDC), before exiting into the two experimental enclosures.

The VELA beam parameters are:

Beam energy	4–6 MeV
Particle types	electrons
Bunch repetition rate	1–5 Hz
Bunches per pulse	1
Pulse repetition rate	1–5 Hz
Emittance	1–4 μm
Bunch length	1–10 ps
Energy spread	1–5%
Bunch charge	16–32 pC

FETS: The UK proton accelerator strategy aims to develop a viable high power proton driver with applications including spallation neutrons, the neutrino factory and ADSR. An essential first ingredient, identified as one of the main UK R&D accelerator projects, is the Front End Test Stand (FETS) at the Rutherford Appleton Laboratory (RAL), aimed at producing a high quality, high current, cleanly chopped H-beam. Through its component parts, FETS has triggered development of a high brightness, 60 mA H-ion source, a three-solenoid Low Energy Beam Transport line (LEBT), a 3 MeV four-vane RadioFrequency Quadrupole

(RFQ) and a Medium Energy Beam Transport line (MEBT) with a high speed chopper. The project is well advanced and when operational should be sufficiently versatile to explore a range of operating conditions.

The FETS beam parameters are:

Beam energy	3 MeV
Particle types	H ⁻ ions
Bunch repetition rate	324 MHz
Bunches per pulse	648000
Pulse repetition rate	50 Hz
Emittance	0.3 π mm mrad
Bunch length	variable
Energy spread	<0.001%
Beam current	60 mA

35.5.14 DESY test beams

Contact: Hans Weise <hans.weise@desy.de>

DESY operates FLASH part time for accelerator R&D. What you are probably interested in are HEP related questions. Here we all have seen the 9 mA test program reported in the ILC TDR. The described program is multifaceted and the best candidate to write some paragraph for your Snowmass report is clearly Nick Walker who was coordinating the activities at DESY.

For the European XFEL we have built a number of new test facilities which you may see as technology test beds:

- CMTB Cryomodule Test Bench; single XFEL or FLASH or ILC type module test bench used to perform a full performance test (cryo and RF) incl. recent CW tests
- AMTF Accelerator Module Test Facility
 - three accelerator module test benches similar to CMTB
 - two vertical test stands for parallel testing of 4 cavities each; throughput approx. 2 to 3 times four XFEL (TESLA, ILC) 9-cell cavities per week
- WATF Waveguide Assembly Test Facility;
 - Assembly of waveguide systems tailored to the accelerator module performance as known from the AMTF or CMTB test, i.e. 8 cavity distribution system with selected directional couplers
 - High power test of the assembled WG system; one RF station included
- Modulator and klystron test stand; we still operate at DESY dedicated test stands to perform acceptance tests for klystrons
- At LAL Orsay, a new infrastructure for RF Power Coupler conditioning exists; up to four coupler pairs are conditioned under clean room conditions; throughput 8 couplers per week.

35.5.15 Duke FEL

Contact: Ying Wu <wu@fel.duke.edu>

The Duke Storage Ring has been operational since 1994, with the first operation of the storage ring FEL and generation of Compton gamma-rays in 1996 (the High Intensity Gamma-ray Source, HIGS), followed by several major accelerator upgrades from 2000 to 2012. The available energy is 0.24 to 1.2 GeV; particle type is electron; number of particles per bunch is from 2×10^9 – 2×10^{11} , bunch repetition rate is 178.55 MHz (RF freq.); number of bunches per pulse is from 1 to 64 (RF buckets); pulse repetition rate is CW (multiples of 2.79 MHz, the revolution freq.); emittance limits are about 18 nm-rad horizontal emittance at 1 GeV (natural emittance) and vertical emittance is 2–5% coupling; bunch-lengths limits are from about 70 ps to 500 ps (RMS); energy-spread limits are from 6×10^{-4} to 6×10^{-3} (RMS, relative). Possible R&D projects using the Duke storage ring and related FEL and Compton light source include IBS, beam instability and impedance, gamma-ray diagnostics, and radiation tests.

35.5.16 FTBF

Contact: Aria Soha <FTBF_Co@fnal.gov>

The Fermilab Test Beam Facility (FTBF) consists of 2 beamlines (MTest and MCenter). The facility has been accepting users since 2005. Primary beam is 120 GeV protons, secondary beams of discrete energies of 1–66 GeV, pions, electrons, kaons, or broadband muons, or tertiary beam of discrete energies of 1 GeV–200 MeV: pions, protons, and kaons. 4.2 second-long spills with a 60 second rep-rate can be made up of bunch trains of variable lengths and intensities. Maximum intensity is 600,000 particles/spill. Momentum resolution has been measured to $\sim 3\%$. More details about the facility can be found online [50].

35.5.17 JLAB-ERL

Contact: Georg Neil <neil@jlab.org>

The JLab Energy Recovering Linac was developed for production of high power FEL radiation. In standard operation it provides 150 MeV, 135 pCoul ($8.4E8$ electrons/bunch) continuously at up to 75 MHz for an average current of 10 mA. The machine can also be operated in a macropulse mode with arbitrary macropulse lengths and repetition rates if desired. The normalized emittance is approximately 5.5 microns and the bunch length is 300 fs with an energy spread typically at 0.2%. The beam can be recirculated instead of energy recovered to provide 300 MeV beam at up to 1 mA average current. An upgrade of the energy is underway which will provide 200 MeV (or 400 MeV at reduced current). It has been in operation since 1996 with several upgrades in capability. The facility is in use for FEL studies producing 14 kW CW of IR power and in excess of 1 kW UV power to User labs. It also provides in excess of 100 W broadband THz to User labs. Beam studies underway include high dynamic range diagnostic development, and beam physics of CSR, BBU, wakefield studies, and resistive wall heating. Future plans include searches for Dark Matter for DOE Nuclear Physics and High Energy Physics.

35.5.18 MTA

Contact: Derun Li <DLi@lbl.gov>

The MuCool Test Area (MTA) is a unique accelerator R&D facility, built specifically to test components for a muon ionization cooling channel. It includes a cryoplant (500 watts at 4 K) in a surface building, an underground experimental hall, a beamline to bring a 400-MeV proton beam into the hall, a clean room in the hall for component assembly. The facility can provide 5 MW peak RF power at 201 MHz and 12 MW peak power at 805 MHz. There is a 5-Tesla superconducting solenoid magnet available for RF testing in a strong magnetic field. Moreover, there are diagnostic instrumentation for radiation measurements, and infrastructure for liquid hydrogen. In recent years, the facility has been used mainly for high power NCRF testing in a strong magnetic field that is needed for a muon cooling channel, these tests include both vacuum and high-pressure RF cavities at 805 MHz, and 201-MHz prototype cavity for MuCool/MICE.

35.5.19 Neptune / Pegasus UCLA

Contact: Chan Joshi <cjoshi@ucla.edu>

Neptune Laboratory at UCLA is dedicated to the exploration of advanced accelerator concepts and training of graduate students. It was completed in 1998 and is collaboratively operated by faculty members from both the Electrical Engineering and Physics departments. The Neptune facility currently houses the worlds most powerful CO₂ laser and a state-of-the art photocathode driven electron accelerator. The CO₂ laser produces up to 15 TW peak power, 3ps wide laser pulses that are 18 ps apart within a 150 ps wide macropulse. The electron accelerator has a 4.5 MeV photoinjector gun followed by a short acceletaor section based on the plane wave transformer concept. The accelerator is capable of giving single bunches at 1 Hz with an energy of up to 15 MeV, energy spread of 0.1% and a charge of up to 1 nC. The nominal bunchwidth of a few ps can be further compressed using a magnetic chicane to less than 500 fs. In addition there is a synchronized 100 GW 1 micron laser for diagnostic purposes. Physics explored at Neptune has included beat wave acceleration, IFEL acceleration, shock-wave acceleration of ions, harmonic microbunching of electrons, generation of shaped bunches and other beam dynamics issues in the RF gun and the beam transport line.

35.5.20 NRL Magnicon

Contact: Steven H. Gold <steven.gold@nrl.navy.mil>

The NRL magnicon facility is used for accelerated-related research at 11.4 GHz requiring up to 20 MW of rf power in a 200-ns pulse, or up to 10 MW in a 1-s pulse. The program has been focused on the development of active microwave pulse compressors, in collaboration with Omega-P, Inc. and the Institute of Applied Physics in Nizhny Novgorod, Russia, and on dielectric-loaded accelerating (DLA) structures, in collaboration with Argonne National Laboratory and Euclid Techlabs LLC. In order to carry out planned tests of acceleration in DLA structures, a 11.4 GHz electron accelerator test stand has been developed to produce a test beam. The nominal parameters of the accelerator are 5 MeV at up to 10 mA (~ 1 pC) and 510 Hz. The emittance and energy spread have not been measured. 5×10^6 electrons per bunch.

35.5.21 PXIE

Contact: Valery Lebedev <val@fnal.gov>

The goal of the Project X Injector Experiment (PXIE) is validation of critical technologies required for the Project X R&D program. PXIE should demonstrate operations of Project X front end at full design parameters. Specific goals are:

- Deliver 1 mA average H⁻ current with 80% arbitrary bunch-by-bunch chopping of the beam supplied by the RFQ.
- Demonstrate efficient acceleration with minimal emittance dilution to the PXIE final energy of about 20 MeV.
- Deliver transverse rms normalized emittances below 0.25 mmmrad and the longitudinal rms emittance below 1 keVns with 2108 particles per bunch.

The PXIE will include:

- CW H⁻ source delivering 5 mA at 30 keV
- LEBT with beam pre-chopping
- CW RFQ operating at 162.5 MHz and delivering 5 mA to 2.1 MeV
- MEBT with integrated wide band chopper and beam absorber capable of generating arbitrary bunch patterns at 162.5 MHz, and disposing of up to 5 mA average beam current
- Two low beta superconducting cryomodules based on half-wave (HWR) and spoke (SSR1) resonators operating at 162.5 and 325 MHz, correspondingly, and capable of accelerating 1 mA beam to at least 15 MeV
- HEBT, which includes a beamline with associated beam diagnostics and a 50 kW beam dump. PXIE is part of the Project X R&D program and the development of PXIE will be coordinated from within the Project X organization. The effort will be supported initially by Fermilab, LBNL, ANL, and SLAC with opportunities for collaboration with Indian colleagues who are developing similar systems for their domestic programs. Opportunities to integrate additional collaborators with similar interests will be pursued.

The goal is to complete PXIE in 2016–2019. The spread in the completion dates reflects uncertainty of the expected funding.

35.5.22 SLAC test beams

Contact: Carsten Hast <hast@slac.stanford.edu>

SLAC offers a variety of electron test beams in the energy range from 5 MeV to 23 GeV. All beam lines are managed by the FACET and Test Facilities Division providing a unified user access to SLACs test beams. For all beam lines a formal proposal review process to grant beam time is in place.

ASTA, the Accelerator Structure Test Area, is a small bunker mainly used for the test of RF structures. With the recent addition of an RF gun and a laser system for cathode development work, in principle a low energetic electron beam (5 to a few 10 MeV) is available as well.

NLCTA, the former Next Linear Collider Test Accelerator, is a small X-band accelerator which works between 60 and 220 MeV. Main focus is currently the development of dielectric laser acceleration and the study of various FEL seeding and advanced beam manipulation techniques. Recently this beam line has been altered to allow for medical radiation experiments. The NLCTA houses a second beam line, XTA, the X-Band Test Accelerator, which is a short (6m) X-Band gun and 100 MeV X-Band accelerator, fully equipped with beam manipulation and diagnostics devices.

ESTB, the End Station (A) Test Beam, uses a small percentage of the LCLS electron beam for Linear Collider beam delivery and machine detector interface studies, Radiation Physics experiments, irradiation test and for R&D of detector components or detector systems. About 5 Hz of the LCLS beam can be diverted with kicker magnets to End Station A. Beam energy and bunch charge are predetermined by the LCLS experiments and ESTB has to accept the beam available. Typically LCLS beams are between 3.5 and 14.7 GeV at 150 pC of bunch charge at a repetition rate of 120 Hz. Occasionally LCLS is running at beam energies as low as 2.0 GeV and as high as 16.5 GeV and with only 20 pC or up to 350 pC, in various combinations of beam energy and bunch charge. Recently, for a 4 GeV LCLS beam with an estimated horizontal beam size of 50 to 80 μm in the beam switch yard upstream of the ESTB kickers, we measured a beam sigma of 160 μm in ESA, consistent with expectations.

Besides primary beam, ESTB can produce a very clean secondary electron beam. To generate secondary electrons, single bunches of the LCLS beam are kicked to interact with a copper target. Beam intensities are adjusted with collimators from the full number of particles (10^9) down to one per bunch. A momentum slit in the A-line allows for very precise momentum selection of better than one percent at low energies and approaching a per mill at the highest energies.

FACET, the Facility for ACcelerator Experimental Tests, uses the first two thirds of the SLAC linac. FACET provides high energy density electron and positron (2014) beams with peak currents around 20 kA that are focused down to a 10×10 micron transverse spot size at an energy of up to 23 GeV. A key component of the experimental program at FACET is the second-generation research in plasma wakefield acceleration. Topics include high-gradient electron acceleration with narrow energy spread and preserved emittance, efficiency, high-gradient positron acceleration and radiation generation. This program of FACET research is directed at understanding and establishing plasma wakefield acceleration as a viable particle acceleration technique.

In addition to the plasma wakefield acceleration research, FACET supports a broad user program in accelerator science, materials science, high-energy density physics and other fields of research that can take advantage of these intense beams and the intense fields that are generated. Examples of topics under study include dielectric wakefield acceleration, materials study in extreme conditions, and novel sources of radiation using plasmas, crystals and meta-materials.

FACET's unique high-power beams will provide other important science opportunities, both for high-energy physics and basic energy sciences. In addition to plasma wakefield acceleration research, FACET will support a user facility as part of its science program. User opportunities will include accelerator development for the proposed International Linear Collider, dielectric wakefield accelerators, as well as terahertz radiation and materials science research.

The recent addition of a transvers deflecting cavity allows a precise bunch length measurement, and a notch-collimator system the production of two separate bunchlets, notched out of the single linac bunch. With the commissioning of a 10TW, Ti-Sapphire laser system with 500mJ peak energy for plasma pre-ionization, FACET accelerated for the first time a distinct bunch of electrons in the wake of the ionizing bunch.

Table 35-9 summarizes the most important beam parameters for FACET and test beams at SLAC.

	SLAC ASTA	ESTB	FACET	NLCTA	XTA
Beam type	e^-	e^-	e^- (e^+ 2014)	e^-	e^-
Beam energy (MeV)	5	2,000–15,000	20,000	120	80
(range)			60, 80-120		
Repetition rate (Hz)	60	5	10	10	60
(range)			1–30	1–10	
Bunch intensity (10^8)		20–250 or	200	1.2	
(range)		single particle	50–300	0.06–12	
Bunch length (σ , μm)		300	30	60	
(range)			20-1000		
Beam spot size (σ , μm)		100–200	30	150	
(range)			20-200	100–300	

Table 35-9. *Beam parameters of the SLAC test beams.*

35.5.23 SPARC LAB

Contact: Massimo Ferrario <Massimo.Ferrario@lnf.infn.it>

A new facility named SPARC_LAB (Sources for Plasma Accelerators and Radiation Compton with Lasers and Beams) has been recently launched at the INFN National Laboratories in Frascati, merging the potentialities of the former projects SPARC (2005) and PLASMONX (2007). The test facility is now operating, hosting a 150-200 MeV high brightness electron beam injector, able to operate also in the velocity bunching configuration, which feeds a 12 meters long undulator. Observations of FEL radiation in the SASE, Seeded and HHG modes have been performed from 500 nm down to 40 nm wavelength. SPARC_LAB includes also a 200 TW laser linked to the linac and devoted to explore laser-matter interaction, in particular with regard to laser-plasma acceleration of electrons (and protons) in the self injection and external injection modes. The facility will be also used for particle driven plasma acceleration experiments. A Thomson back-scattering experiment to generate a quasi coherent, monochromatic X-ray radiation up to 100 keV is also in the commissioning phase.

Parameters of the SPARC_LAB facility are:

Year established	2012
Available energies	up to 200 MeV
Available particle types	electrons
Particles per bunch	up to 10^{10}
Bunch repetition rate	10 Hz
Number of bunches per pulse	1
Pulse repetition rate	10 Hz
Emittance limits	<2 mm mrad
Bunch-length limits	200 fs–10 ps
Energy-spread limits	0.1–1%

35.5.24 UMER

Contact: (Rami Kishek <ramiak@umd.edu>)

The University of Maryland Electron Ring (UMER) is a unique facility dedicated to exploring the physics of charged particle beams at the intensity frontier. The facility began operations in 2009. It uses electron beams at nonrelativistic energies (10 keV) to access the physics of space charge directly relevant to low-energy hadron and ion beams, in both rings and linacs. The peak current, emittance, and bunch length are variable and can produce up to 9×10^{10} particles per bunch. A single rectangular bunch is injected at a repetition rate of 10–60 Hz. The emittance is variable from 0.4 to 3.2 m, and bunch length from 15 to 140 ns. The relative energy spread is in the vicinity of 104. As a result, space charge can be made to depress the betatron tunes down to 0.14, enabling scaled examination of a wide range of phenomena (Laslett tune shifts can be made to vary from 0.5 to 5.6). Longitudinal induction focusing is used to counteract the space charge force at the edges of a long rectangular bunch, confining it for 100s of turns.

35.5.25 BELLA

Contact: Wim Leemans <wpleemans@lbl.gov>

35.5.26 Cathode test lab

Contact: Ivan Bazarov <bazarov@cornell.edu>

35.5.27 CTF3 and other CERN test beams

Contact: Roberto Corsini <Roberto.Corsini@cern.ch>

35.5.28 HBESL

Contact: Phillipe Piot <piot@fnal.gov>

35.5.29 JLAB pol-beam test

Contact: Matt Poelker <poelker@jlab.org>

35.5.30 KEK-CERL

Contact: Hiroshi Kawata <hiroshi.kawata@kek.jp>

35.5.31 Korea photo-injector lab

Contact: Jang Han <janghui.han@posttech.ac.kr>

35.5.32 LANL test beam

Contact: Bruce Carlsten <bcarlsten@lanl.gov>

35.5.33 MICE

Contact: Alan Bross <bross@fnal.gov>

35.5.34 MIT

Contact: Richard Temkin <temkin@mit.edu>

35.5.35 U. Texas Austin

Contact: Michael Downer <downer@physics.utexas.edu>

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