# Accelerator Frontier Topical Group 2 Report: Accelerators for Neutrinos

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## AF2 Report Intro

This document is a partial draft of the AF2 report for consideration during the summer study meeting. It will be updated with whitepaper input, and input form the summer study meeting.

The Accelerators for Neutrino working group addressed the following points:

- The proton (or other) beam requirements to meet the needs of the neutrino community
- The capability of existing or planned accelerator facilities to satisfy the above requirements, and If not: the necessary upgrades or new facilities.
- Enabling R&D and test facilities necessary to develop upgrades and new facilities.

The proton beam requirements are derived from the neutrino physics input, and these are provided largely by the Artificial Neutrino Sources (NF09) working group of the Neutrino Physics frontier. The existing neutrino beam capabilities (and proton driver beam characteristics) are summarized in Table 1. Table 2 shows planned upgrades or new artificial neutrino beam capabilities.

Separately the worldwide high-power proton beam existing capabilities were assessed, and are summarized in Table 3. Table 4 lists the planned upgrades and ongoing projects for high power proton accelerators. Since the last Snowmass exercise, a number of facilities world-wide now routinely operate at or near the MW level (PSI, SNS, J-PARC, FNAL MI). Furthermore, a number of upgrade projects will soon be online providing > 1MW capability (e.g. the PIP-II, ESS, J-PARC, SNS upgrade).

## AF2 Executive Summary

Neutrinos beams produced from Multi-MW proton accelerators are high-priority efforts within the present plans for discovery research in High Energy Physics, particularly for precisely exploring the three-neutrino oscillation paradigm and directly measuring leptonic CP violation. These beams are produced with high-power proton beams combined with targets and magnetic-horn focusing to produce extremely intense and precisely understood artificial neutrino beams. They are ideally suited for long-baseline neutrino oscillation studies, and have been at the forefront of recent measurements in this field. Several major experiments are presently operating and under development, with more being proposed.

At the same time, Megawatt-Class proton accelerators have become available for multiple purposes (neutrons, neutrinos, rare particle production), and Multi-MW machines are on the horizon, often enabled by superconducting proton linear accelerators. Presently two accelerator complexes provide high-power beams specifically for neutrinos. J-PARC produces 500-600 kW for the T2K experiment, and plans to increase to 1.3 MW in the next several years in anticipation of the T2HK / Hyper-K experiment.

Fermilab produces 800-900 kW for the NOvA experiment, and will increase to 1.2 MW within a decade for the LBNF/DUNE experiment with the PIP-II accelerator.

Fermilab is now studying several accelerator approaches to further double that beam power to 2.4 MW to an enhanced DUNE experiment, fulfilling the vision for the “full scope” of the LBFN/DUNE effort as sanctioned in the previous P5 report. Multiple options have been proposed including additional high duty-factor linear accelerator, and either a synchrotron or storage ring for accumulation of intense beam current required for the experiments. The above proposals aggressively push the envelope of neutrino beams, but are achievable, and even conservative in some of their aspects. These long-baseline neutrino experiments will combine to produce a dramatically more detailed understanding of neutrino oscillations, as well as the first direct measurements of leptonic CP violation. Optimization of the design will depend on the performance of the proposed technologies for LBNF and also the suite of future experiments likely to use the Fermilab accelerator complex, including other neutrino beams, muon experiments, dark sector searches, and a high-power irradiation station. Some of these experiments and a possible future muon collider all require very-low duty factor MW class beams – the chosen must provide the capability to accumulate and highly compress the beam from the linac.



An additional high-power, long-baseline neutrino beam has also been proposed to use a 5MW beam from an upgraded ESS proton accelerator delivered to megaton-scale detectors to measure CP violation. The ESS neutrino Super Beam proposal is instructive in demonstrating some of the challenges, and perhaps ultimate limitations, of pushing to ever higher beam powers. The proton beam must be highly compressed so as to have a low duty factor – order microsecond pulses, to be useful for experiments and be properly focused by pulsed horns. Linac-based beams, with their rather low peak current and high duty factor, must have some ring to accumulate and compress $H^-$ beams to be useful in this way. The 2.5 GeV energy is on the low-end for high-power neutrino beams, where pion production yield is marginally less efficient, and particularly the proton flux on the target station is incredibly high, such that the target station must be split into four separate targets and focusing horns. Higher primary beam energy (when possible) is advantageous for targetry, so higher energy linacs and synchrotrons should continue to be considered to best accommodate multi-MW beams. Ultimately, the complications of high power also indicate that, after this next generation of machines, we may be reaching the limit of conventional, horn-focused neutrino beams. Further advances in neutrino beams may require different approaches than ever higher proton beam powers.

Other accelerator-based neutrino approaches are underway for other searches within neutrino physics. Several forms of “decay-at-rest” neutrino sources (often from high-power spallation neutron sources) have detected coherent neutrino interactions, and offer potential approaches to sterile neutrino oscillations and dark sector searches. Additional opportunities exist in further exploiting the timing and kinematics of beams to gain additional experimental reach. Hadron colliders have been found to be significant sources of neutrinos, and proposals are being developed to detect them at the LHC and future colliders. The neutrino factory concept (and its related proposals) remains an option for further precision in long- and short- baseline neutrino physics.

The R&D needed for many of these next generation solutions vary widely. Superconducting proton linear accelerators have been a prominent tool to generate high power proton beams, but these beams must be compressed and formatted to short beam pulses that neutrino beam experiments require. Thus, development into higher-current linac H- beams, H- injection, and high-current accumulation are essential. There is still often an advantage in particle production to higher energies (>10 GeV), and the issues of high-power targetry are partially ameliorated to even higher energy (CNGS used 400 GeV), so high-power synchrotrons are likely to remain an essential tool. New concepts such as FFAs, integrable optics, and recirculating linear accelerators could provide advantages to future machines. High current broadband or highly tunable RF is needed for synchrotrons and accumulator rings. Instabilities and loss control techniques are vital to all of the above machines as losses of << 1% can become prohibitive to operations, such that the machine's performance is limited more by efficiency than maximum current or energy.

## White papers summary

A number of white papers were contributed to this working group, and we include a summary of their content here.

High energy collisions at the High-Luminosity Large Hadron Collider (LHC) produce a large number of particles along the beam collision axis, outside of the acceptance of existing LHC experiments. In particular, the highest energy neutrino beams from an artificial source emerge from each of the collision points. The proposed Forward Physics Facility (FPF), to be located approximately 600 m from the ATLAS experiment along the beam collision axis and shielded by concrete and rock, will host a suite of experiments to probe Standard Model (SM) processes and search for physics beyond the Standard Model (BSM). The facility could operate parasitically to the high luminosity experiments without requiring any modification to the LHC machine or its mode of operation. The considered beam and machine parameters are those expected for the LHC after its High Luminosity Upgrade [FPF]

The LHC Injector complex has undergone a major upgrade in view of delivering the beams with the high brightness (an increase of the bunch population by a factor 2 and a reduction of the emittance by almost 50% with respect to the nominal values are expected) required for the High Luminosity LHC. The main modifications include:

- A new 160 MeV H- linac replacing the 50 MeV proton linac and a new H stripping and injection in the PS Booster
- Increased extraction kinetic energy (from 1.4 to 2 GeV) from the PS Booster to the PS
- New injection system to cope with the higher injection energy in the PS together with a reduction of the longitudinal impedance of the main RF system and a new longitudinal feedback system
- Impedance reduction and RF power upgrade for the SPS

One year after the completion of the upgrade work and the recommissioning phase the injector chain is on track (and even ahead of schedule) for demonstrating the expected beam parameters for the LHC beams. The hardware upgrades are expected to benefit also the performance of the accelerators for the production of the high intensity beams serving a wide range of fixed target experiments (e.g. in the ISOLDE, Neutron Time of Flight, PS East Area and SPS North Areas). Simulation and experimental studies have started and have already allowed to increase the intensity of some of the fixed target beams while maintaining low level of beam losses, some more are planned to explore further the intensity reach of the accelerator chain. Future proposals for neutrino physics, hidden sector searches, rare kaon decays, lepton flavor violation searches could benefit of these intensity increase [CERNAcc].

New experimental proposals require high-intensity beams for “monitored” neutrino beams in which the neutrino flavor and energy is tagged. In addition to a high proton intensity low-noise slow extraction is required to minimize pile-up and therefore reconstruction inefficiency. New techniques to generate pulsed slow-extracted beams have been also proposed to boost the neutrino flux with the help of magnetic horns pulsed at regular intervals and in coincidence with the extraction bursts or to provide a time structure employed at the neutrino detector to reduce cosmic-induced background [NUBET, NUTAG]. It appears though that beam line designs with slowly pulsed elements can also be conceived and are therefore compatible with a slow extraction over the time scale of seconds not requiring the use of magnetic horns.

A high-intensity, intermediate-energy (O(GeV)) linac coupled with an accumulator ring to compress the long linac pulse are proposed as multi-MW proton drivers for neutrino experiments for the measurement of $\delta_{CP}$ at the second neutrino oscillation peak and/or for feeding muon storage rings for neutrino physics or as test-stand for future muon colliders. A conceptual study for the upgrade of the ESS 2 GeV proton linac under construction at Lund (Sweden) has been performed. This would require an energy increase of the linac from 2 to 2.5 GeV, a new H-source with currents exceeding 60 mA and associated front-end acceleration stage, doubling the repetition rate of the linac from 14 to 28 Hz, an accumulator ring compressing the linac pulse from 0.8 ms to 1.2 us. Particularly challenging are the $H^-$ stripping and injection system that could benefit of possible development of laser stripping, beam loss control possibly requiring a collimation system in the accumulator ring, and the target station consisting of four high power targets in the present design each of them surrounded by a pulsed magnetic horn [ESS].

The case for a Neutrino Factory (NF) [NF] was presented, namely it provides unique capabilities that complement ongoing superbeam experiments and provides new physics, and it could be used to follow-up any observed anomalies. The NF complements a muon factory, and shares the proton driver. The accelerator needs include muon production (multi-GeV/multi-MW p-driver, target muon source), capture (decay channel + bunch + phase rotate) and cooling (6-D cooling of muon beams + muon storage ring) and are all challenges. A recirculation linac (15 GeV) and decay ring is proposed.

The IsoDar community [Isodar] provided a comprehensive list of references on work since the last Snowmass. Isodar is proposed to be built near a South Korean detector (associated with the underground mine/lab Yemilab).

A paper on synergies with non-proliferation efforts [Arms] recognizes the synergy possibilities for neutrino detector development between HEP and NNSA (non-proliferation applications). Detector technology overlaps, but nothing to do directly with accelerators.

A summary of a workshop on cyclotrons and Fixed Field Accelerators [Cyclotron_FAA] was prepared. Cyclotron PIC simulation efforts have improved, and identified optimizations of field, RF cavity shapes, and collimation proposals provide clean beams. Studies of low energy (60 MeV) $H_2^+$ accelerators identified clean beams with sufficiently low populations of vibrational excited states from the source. Also, a concept for a single stage 1 GeV cyclotron using $H_2^+$, and use of a magnetic inflector for injection were presented. Previously identified concepts such as vertical extension FFA and RFQ injection are still on going. Some conceptual developments in the past years on injection (RFQ, inflectors), improved acceleration (optimizations of field, RF cavity shapes, collimation), and improved extraction (new stripping schemes). Improvements in PIC modeling capabilities. In general, the higher energy concepts are supported by simulations, but need some experimental demonstration at least at intermediate range of design parameters.

## R&D Areas

The experimental proposals for neutrino physics, as well as the searches for the Hidden Sector and the study of rare decays all require high intensity beams and pose several challenges in the design of accelerators and their components.

Minimization of beam losses is critical to minimize damage to components and allow maintenance in case of failure keeping downtime and radiation doses to personnel as low as possible. This requires the understanding of loss mechanisms (e.g. space charge effects and halo generation mechanisms) and the implementation of these effects in simulation codes with the aim of providing a realistic model of the evolution of the beam observables (intensity, profile, etc.) profiting of the progress in High Performance Computing and algorithms. As an example, the modelling of diffusion processes is critical for the design of efficient collimation systems to protect the accelerator from uncontrolled losses. The simulation effort should be accompanied by developments of advanced diagnostics with high dynamic range to accurately characterize the beam properties (e.g. beam transverse and longitudinal distribution and in particular beam halo) to benchmark simulations and for protection and tuning purposes.

Present and future high-intensity circular machines demand for $H^-$ low-energy front-ends to maximize the beam brightness and minimize losses (e.g. ESSnuSB, ….). High intensity $H^-$ sources are required and understanding and simulation of the $H^-$ formation process and beam dynamics at very low energy to optimize the source extraction and low-energy beam transfer to the first accelerating element (typically RFQs) are critical. This domain could profit of the synergy with similar developments required for thermonuclear fusion (e.g. ITER). In addition, reliability issues might be encountered for the stripping foils normally used for the injection process when operating at very high intensities. Progress has been made in the design of alternative laser stripping schemes [SNS] but no operating high-intensity machine is yet routinely using laser stripping for $H^-$ injection and further research and development should be pursued.

Handling multi-megawatt beams as those proposed for future neutrino beams or for the proton drivers for future muon colliders demand for extremely robust targets able to stand enormous thermal and mechanical stresses ideally over long periods and with minimum maintenance. This requires significant research and development in the choice of the materials and the engineering design and demand a careful study of failure and maintenance/repair/replacement scenarios. The latter can greatly benefit of the progress of robotics and should be considered early in the conception phase to guarantee low down-time during operation and safe and affordable disposal of the irradiated material at the end of the lifetime of a project. Similar considerations apply for beam dumps and for the target of the so-called beam dump experiments where the targets and their shielding are supposed to contain a significant fraction of the hadronic cascade, though at lower beam power.

Future neutrino experiments could benefit of tagged neutrino beams [ENUBET][NuTAG] generated by the decay of momentum selected pion or kaon decays and for which the flavor, helicity and energy of each tagged neutrino is determined by accurately measuring the properties of charged particles generated in the decays producing the neutrinos. Although relying on state-of-the-art tracking devices required for the High Luminosity LHC Detector upgrades capable of operating at high particle fluxes, slow proton beam extraction (over time scales of few seconds) are required to minimize pile-up. For the same reason the ripple of the extracted beam intensity needs to be minimized. The refinement of extraction techniques aiming at reducing the sensitivity to unavoidable noise (e.g. those coming from the mains) is important and could benefit other accelerator applications (e.g. medical applications like hadron therapy).

Given the high beam power, maximization of the efficiency of future accelerators is mandatory to guarantee the sustainability and affordability of the research conducted with these machines in view of reducing the carbon footprint and contain the operation costs, particularly in the present international context of increasing energy prizes. Development of efficient energy storage concepts for pulsed accelerators, high efficiency RF sources, superconducting solutions for accelerating cavities and magnet, recovery of waste heat are just a few possible examples of the areas of research to be strengthened.

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| | | Secondary beam | | | | | Primary beam | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | Primary Physics Goal | Particle | Purity | Energy [GeV] | Spatial characteristics | Timing | Particle | Energy [GeV] | Power [MW] | Timing | Ref. |
| NuMI/NOvA Upgrade | $\nu_\mu$ LBLO | $\nu_\mu$, $\overline{\nu_\mu}$ | | 2 | Pulsed-horn forward beam | Low Duty Factor | p | 120 | 0.9 – 1.0 | 10 $\mu$s every 1.2 s | NF145 |
| BNB/SBN | $\nu_\mu$ SBLO | $\nu_\mu$, $\overline{\nu_\mu}$ | | 0 – 4 | Pulsed-horn forward beam | Low Duty Factor | p | 8 | 0.04 | 1.5 $\mu$s @ 5 Hz | NF145 |
| T2K Upgrade | $\nu_\mu$ LBLO | $\nu_\mu$, $\overline{\nu_\mu}$ | | 2 | Pulsed-horn forward beam | Low Duty Factor | p | 30 | 1.3 | 5 $\mu$s every 1 s | NF187 |
| LBNF/DUNE | $\nu_\mu$ LBLO | $\nu_\mu$, $\overline{\nu_\mu}$ | | 0.5–4 | Pulsed-horn forward beam | Low Duty Factor | p | 60 – 120 | 1.2 | 10 $\mu$s every 1.2 s | DUNE TDR |
| LBNF/DUNE Upgrade | CP viol. | $\nu_\mu$, $\overline{\nu_\mu}$ | | 0.5–4 | Pulsed-horn forward beam | Low Duty Factor | p | 60 – 120 | 2.4 | 10 $\mu$s every 1.2 s | AF092, DUNE TDR |
| LBNF/DUNE Timing Upgrade | CP viol. | $\nu_\mu$, $\overline{\nu_\mu}$ | | 0.5–4 | Pulsed-horn forward beam | Low Duty Factor | p | 60 – 120 | 1.2 | <200 ps bunches | NF116 |
| LBNF/DUNE Low Energy Upgrade | CP viol., solar oscillation parameters | $\nu_\mu$, $\overline{\nu_\mu}$ | | 0–4 | Pulsed-horn forward beam | Dual BNB/MI timing | p | 8 / 120 | ? | Dual BNB/MI timing | AF092, DUNE TDR |
| LBNF/DUNE High Energy Upgrade | $\nu_\tau$ appearance: unitarity, NSI | $\nu_\mu$ | | 0.5–10 | Pulsed-horn forward beam | Low Duty Factor | p | 120 | >1.2 | Low Duty Factor | AF092, DUNE TDR |
| FASER2/ FASER$\nu$2 | $\nu$ interaction, Dark matter | $\nu_e$, $\overline{\nu_e}$, $\nu_\mu$, $\overline{\nu_\mu}$, $\nu_\tau$, $\overline{\nu_\tau}$ | | 1-7000 | Secondary beams emerging from collider IP | 25 ns structure | p | 7000 | | 25 ns structure | EF038 |
| ORNL SNS | Sterile $\nu$, BSM, coherent interactions | $\nu_e$, $\nu_\mu$, $\overline{\nu_\mu}$ | 99% [1] | 0–0.052 | High-purity $\pi$ decay at rest | ≈400 ns width for prompt $\pi$ decay, 2.2 µs for $\mu$ decay @ 60 Hz | p | 1–1.3 | 1.4–2.0 (FTS), eventually 1.8 FTS+0.6 STS | 400 ns @ 60 Hz | NF108, NF095, NF111, NF067, NF161 |
| LANL PSR | Sterile $\nu$, BSM, coherent interactions | $\nu_e$, $\nu_\mu$, $\overline{\nu_\mu}$ | 0–0.052 | Pulsed Beam Dump | 280 ns pulses @ 20 Hz | p | 0.8 | 0.08 | | 280 ns pulses @ 20 Hz | |
| JPARC SNS | Sterile $\nu$, BSM, coherent interactions | $\nu_e$, $\nu_\mu$, $\overline{\nu_\mu}$ | | 0–0.053–0.236 | Pulsed Beam dump | $2\times$ 100 ns pulses @ 25 Hz | p | 3 | 0.75–1 | $2\times$ 100 ns pulses @ 25 Hz | NF128 |

Table 1: Existing neutrino beams or under construction/upgrade. For the latter requirements are presented. BNB=(FNAL) Booster Neutrino Beam, BSM=Beyond the Standard Model, FTS=First Target Station, HE=High Energy, LBLO=Long Baseline Oscillations, SBLO-Short Baseline Oscillations, MI=(FNAL) Main Injector, LE=Low Energy, NSI=Non-Standard Neutrino Interactions, STS=Second Target Station. Table from Neutrino Frontier (L. Fields).

| | | Secondary beam | | | | | Primary beam | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Project | Primary Physics Goal | Particle | Purity | Energy [GeV] | Spatial characteristics | Timing | Particle | Energy [GeV] | Power [MW] | Timing | Ref. |
| PIP2-BD (PIP-II Beam Dump Experiment) | Dark matter and Sterile $\nu$ search | $\nu_e$, $\nu_\mu$, $\overline{\nu_\mu}$, BSM | | $\mathcal{O}(0.01–1)$ | Beam dump | Low duty factor | p | $\mathcal{O}(1)$ | 0.1–1 | Low duty factor | AF092, AF185, RF099, [2] |
| SBN-BD (SBN Beam Dump Experiment) | Dark matter and Sterile $\nu$ search | $\nu_e$, $\nu_\mu$, $\overline{\nu_\mu}$, BSM | | $\mathcal{O}(0.01–1)$ | Beam dump | Low duty factor | p | 8 | 0.1–1 | Low duty factor | AF092, RF084, [2] |
| IsoDAR | Sterile $\nu$ search, BSM | $\overline{\nu_e}$ | 100% | 0.000–0.015 | Beam dump | CW | p | 0.06 | 0.6 | CW | AF092, RF084 |
| ESS$\nu$SB | CP viol. | $\nu_\mu$ | | 2–2.5 | Pulsed Horn Forward Beam | 14 Hz | p ($H^-$) | 2.5 | 5 | 1.3 µs duration | NF062 |
| ESS$\nu$SB-LE$\nu$STORM | cross sections, sterile $\nu$ | $\nu_\mu$, $\nu_e$ | 50% /50% | 0.4 | | 14 Hz | p ($H^-$) | 2.5 | 5 | 1.3 µs duration | NF062 |
| TeV Muon collider | BSM, energy frontier discoveries | $\mu^+/\mu^-$ | | 0.2 | high-efficiency collection system | 5–15 Hz | p ($H^-$) | 4–8 | 2–4 | 1–12×1–2 ns bunches | AF081 |
| $\nu$STORM | Sterile $\nu$ search | $\nu_e$,$\overline{\nu_e}$, $\nu_\mu$,$\overline{\nu_\mu}$ | Precise mix | 1–4 | Relativistic $\mu$ decay | | p | 100 | 0.156 | 10 µs every 3.6 s | NF067. Requires $\mu$ storage ring |
| Moment | LBLO | $\nu_e$,$\overline{\nu_e}$, $\nu_\mu$,$\overline{\nu_\mu}$ | | 0-0.6 | Solenoid capture and decay channel | CW | p | 1.5 | 15 | CW | IPAC18, C. Meng et al |
| ENUBET | $\nu$ cross sections, sterile $\nu$ using a beam with well known normalization | charged $\pi$, K | K is 5/10% of $\pi$ | 4-9 | after collimation and focusing $\mathcal{O}(10 \times 10)$ cm$^2$ | $\mathcal{O}(10^{10}–10^{11})$ $\pi^+$/K$^+$ over 2–4 s or a sequence of $\mathcal{O}(1)$ ms bursts with ≈10 Hz for horn focusing | p | 30–120–400 | >0.1 | $\mathcal{O}(10^{13})$ p.o.t. over 2–4 s or a sequence of $\mathcal{O}(1)$ ms bursts with ≈10 Hz for horn focusing | [3] |

Table 2: New requirements. BSM=Beyond the Standard Model. Table from Neutrino Frontier (L. Fields).

| Accelerator | Kin. Energy [GeV] | Particle | Power [MW] | Timing (Pulse length, rep. rate, RF freq.) | Type | Comments |
|---|---|---|---|---|---|---|
| CERN LINAC4 | 0.16 | $H^-$ | 0.0021 | 600 μs @ 0.83 Hz (352 MHz) | Linac | Rep. rate could be increased with some upgrade |
| CERN PSB | 1.4–2 | p | 0.02/0.026 | 2 μs @ 0.83 Hz (4 bunches) | Synch. (4 rings) | |
| CERN PS | 20 | p | 0.027 | 20 ns @ 0.83 Hz (1 bunch) | Synch. | |
| CERN SPS (FX) | 400 | p | 0.57 | 23.1 μs (or 2×10.5 μs @ 0.17 Hz (200 MHz) | Synch. | Could be possibly increased |
| CERN SPS (SX) | 400 | p | 0.36 | ≈ 1 s @ 0.14 Hz (debunched) | Synch. | |
| CERN LHC | 7000 (FT eq.=$1.04 \times 10^8$) | p/p | 36.8 | Hours @ 40 MHz | Collider | The luminosity considered is $2 \times 10^{34}$ $cm^{-2}s^{-1}$ |
| CSNS-Phase I | 1.6 | $H^-$ | 0.1 | 550 ns @ 25 Hz (2.44 MHz, 2 bunches) | Linac (80MeV) +RCS | |
| FNAL Linac | 0.4 | $H^-$ | 0.012 | 50 μs @ 15 Hz (162.5 MHz) | Linac | |
| FNAL Booster | 8 | p | 0.08 | 1.6 μs @ 15 Hz (52.8 MHz) | RCS | |
| FNAL MI | 120 | p | 0.9-1.0 | 9.4 μs @ 0.45 Hz (53.1 MHz) | Synch. | |
| J-PARC linac | 0.4 | $H^-$ | 0.33 | 0.5 ms @ 25 Hz (324/ 972 MHz) | Linac | |
| J-PARC RCS | 3 | p | 0.8 | 1 μs @ 25 Hz (2 bunches) | RCS | |
| J-PARC MR (FX) | 30 | p | 0.52 | 5 μs @ 0.4 Hz (8 bunches) | Synch | |
| J-PARC MR (SX) | 30 | p | 0.05 | 2 s @ 0.19 Hz (debunched) | Synch. | |
| LANSCE area A | 0.8 | $H^-$ | ≈0.8 | 625 μs @ ≤100 Hz (805 MHz) | Linac | Presently inactive. Linac feeding the 805 MHz structure operates at 201.25 MHz |
| LANL Lujan Neutron Science Center | 0.8 | $H^-$ | 0.08–0.1 | 625 μs @ 20 Hz (805 MHz) | Linac + accumulator ring | Spallation neutron source. Target currently being upgraded. Also, Linac feeding the 805 MHz structure operates at 201.25 MHz |
| ISIS | 0.8 | $H^-$ | 0.2 | 0.5 μs @ 40 Hz to TS1 (1.3–6.2 MHz) and 0.5 μs @ 10 Hz to TS2 (1.3–6.2 MHz) | Linac + RCS | 160 kW to TS-1,40 kW to TS-2 |
| PSI | 0.59 | p | 1.4 | CW (50 MHz) | Cyclotron | |
| SNS | 1 | p | 1.4 | 700 ns @ 60 Hz (1 MHz) | Linac+accumulator | |
| TRIUMF | 0.52 | p | 0.2 | CW (23 MHz) | Cyclotron | |

Table 3: Present capabilities (FT=Fixed Target, FX=Fast extraction, h=harmonic number, MI=Main Injector, MR=Main Ring. RCS=Rapid Cycling Synchrotron, Synch.=Synchrotron, SX=Slow Extraction, TS=Target Station). Power is quoted for exclusive operation in a certain mode. The frequency refers to the main bunch repetition frequency. The beam power quoted for the LHC is the power of a fixed target beam with a current corresponding to the number of interactions per second at one LHC IP and having an energy giving a center of mass energy of 14 TeV

| Accelerator | Kin. Energy [GeV] | Particle | Power [MW] | Timing (Pulse length, rep. rate, RF freq.) | Type | Comments/Timescale |
|---|---|---|---|---|---|---|
| BNL BLIP | 0.06–0.2 | $H^-$ | 0.06 | 880 µs @ 6.67 Hz (200 MHz) | Linac | |
| BNL BLIP–BLAIRR | >1 | $H^-$ | 0.25–0.3 | 880 µs @ 6.67 Hz (200 MHz) | Linac | |
| CSNS-Phase II | 1.6 | $H^-$ | >0.5 | 550 ns @ 25 Hz (2.44 MHz, h=2) | Linac+RCS | End of 2028 |
| ESS | 2 | p | 5 | 2.86 ms @ 14 Hz (352 MHz) | Linac | 2023 (projected user operation) |
| ESS$\nu$ | 2.5 | $H^-$/p | 10 | 2.86 ms @ 28 Hz (352 MHz) | Linac with compressor ring | Potential compressor ring upgrade for $\nu$ physics |
| FNAL PIP-II LINAC | 0.8 | $H^-$ | 1.6 | CW (162.5 MHz) | Linac | 2028 |
| FNAL PIP-II Booster | 8 | p | 0.166 | 1.6 µs @ 20 Hz (52.8 MHz) | Linac+RCS | 2028 |
| FNAL PIP-II MI | 120 | p | 1.2 | 9.4 µs @ 0.83 Hz (53.1 MHz) | Linac+RCS+Synch. | 2028 |
| FNAL PIU LE Linac | 1.2–2 | $H^-$ | 2.4–10 | CW (162.5 MHz) | Linac | Upgrade Energy/Current of PIP-II Linac |
| FNAL PIU HE Pulsed Linac | 8–12 | $H^-$ | 0.4–1.2 | 1–10 ms @ 10–20 Hz (162.5 MHz) | Linac | High-Energy Pulsed Extension of PIP-II Linac |
| FNAL PIU HE CW Linac | 8–12 | $H^-$ | > 10 MW | CW (162.5 MHz) | Linac | Upgrade Energy/Current of PIP-II Linac |
| FNAL PIU RCS | 8–12 | p | 0.4–1.2 | 1.6–2.2 µs @ 10–20 Hz (53.1 MHz) | Linac+RCS | Upgrade Energy/Current of PIP-II Linac and new RCS |
| FNAL PIU MI | 120 | p | 2.4–4 | 9.4 µs @ 0.83 Hz (53.1 MHz) | Linac+(RCS)+Synch. | Upgrade Energy/Current of PIP-II Linac, MI, optionally RCS |
| FNAL PAR | 0.8–1.0 | p | 0.1–0.4 | <1 µs @ 100 Hz | Linac+AR | PIP-II + accumulator ring for expts. and injection to Booster |
| FNAL C-PAR | 0.8–1.2 | p | 0.6–1.0 | 4 × 20 ns @ 100 Hz | Linac+AR | PIP-II + compact accumulator ring for expts. |
| IsoDAR | 0.06 GeV/u | $H_2^+$ | 0.6 | CW (32.8 MHz) | Cyclotron | |
| Dae$\delta$alus | 0.8 GeV/u | $H_2^+$ | 3 stations (1+2+5) MW | 1 ms @ 200 Hz (32.8 MHz) | Cyclotron (IsoDAR injector) | 5 emA peak current (10 mA peak protons on target)/ |
| HL–LHC | 7000 | p/p | 92 | Hours @ 40 MHz | Collider | See comment for LHC in Table 3. Luminosity: $5 \times 10^{34}$ cm$^{-2}$s$^{-1}$ |
| ISIS | 0.8 | $H^-$ | 0.5 | 0.5 µs @ 40 Hz to TS3 0.5 µs @ 10 Hz to TS2 | Linac + RCS | 400 kW to TS3, 100 kW to TS2. 2030. |
| ISIS–II | 1.2 | $H^-$ | up to 2.4 | 0.5 µs @ 30 Hz to TS1<br>0.5 µs @ 15 Hz to TS2 | Linac + (RCS or AR or FFA) | Up to 1.6 MW to TS1, up to 800 kW to TS2. 2040. |
| J-PARC RCS | 3 | p | 1 | 1 µs @ 25 Hz (2 bunches) | RCS | 2024 JFY |
| J-PARC MR (FX) | 30 | p | 1.3 | 5 µs @ 0.86 Hz (8 bunches) | Synch | 2028 JFY |
| SNS / PPU upgrade | 1.3 | p | 2.8 | 700 ns @ 60 Hz | Linac+accumulator | Energy increase by 30%, current increase by 50%, 2024 |

Table 4: Planned Upgrades and Facilities (AR=Accumulator Ring, FFA=Fixed-Field Alternating Gradient Accelerator, FT=Fixed Target, FX=Fast extraction, h=harmonic number, JFY=Japanese fiscal Year, MR=Main ring, RCS=Rapid Cycling Synchrotron, Synch.=Synchrotron, SX=Slow Extraction, TS=Target Station). Power is quoted for exclusive operation in a certain mode. The frequency refers to the main bunch repetition frequency. The beam power quoted for the LHC is the power of a fixed target beam with a current corresponding to the number of interactions per second at one LHC IP and having an energy giving a center of mass energy of 14