

FUTURE HIGH POWER PROTON DRIVERS FOR NEUTRINO BEAMS*

C. Plostinar, M. Eshraqi, B. Gålnander, European Spallation Source ERIC (ESS), Lund, Sweden
 V. Lebedev, Fermi National Accelerator Laboratory (Fermilab), Batavia, IL, USA
 C. Prior, Science and Technology Facilities Council, Rutherford Appleton Laboratory,
 ISIS Department (STFC/RAL/ISIS), Harwell, UK
 Y. Sato, High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
 J. Tang, Institute of High Energy Physics (IHEP), Beijing, China

Abstract

Over the last two decades, significant efforts were made through several international studies to identify and develop technical solutions for potential Neutrino Factories and Superbeam Facilities. With many questions now settled, as well as clearer R&D needs, various proposals are being made for future facilities in China, Europe, Japan and North America. These include both developing and adapting existing machines as well as green-field solutions. In this paper, we review the major accelerator programmes aimed at delivering high-power proton beams for neutrino physics.

INTRODUCTION

The global development of the next generation of high power proton accelerators is driven by an extensive range of applications. Systematic reviews [1,2] of current efforts have identified potential uses ranging from spallation neutron sources, accelerator driven subcritical reactors and transmutation of nuclear waste to material irradiation facilities, radioactive ion beams, production of tritium or secondary beams (neutrino/muon/kaon factories). The power capabilities of various machines is illustrated in Figure 1, where the trend towards higher power can be seen for most future projects.

For the neutrino physics programme, a systematic approach to defining an optimal, baseline design for a future neutrino complex, was made by the International Scoping Study of a Future Neutrino Factory and Superbeam Facility (ISS-NF) [3] as well as the EUROnu project [4]. Within ISS-NF, the Accelerator Working Group (AWG) [5] addressed multiple issues, including the proton driver for a neutrino factory and defined the required beam power, the optimum beam energy, repetition rate, bunch length as well as the preferred hardware configuration (linac, synchrotron, FFAs). The resulting Neutrino Factory baseline as defined by ISS-NF can be seen in Figure 2.

ISS-NF, was followed by the IDS-NF (The International Design Study for the Neutrino Factory) [6], which built on the previous findings to develop baseline concepts for each part of the facility. For the proton driver, specific proposals were made at CERN, Fermilab and RAL that included both green-field solutions as well developing and adapting existing facilities. At CERN, a superconducting proton linac (SPL) was studied, with an energy of 5 GeV and a beam

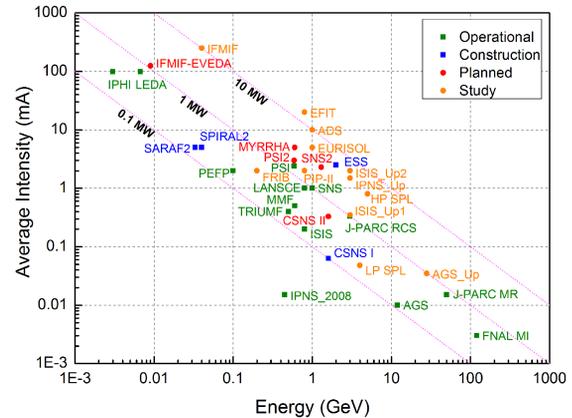


Figure 1: Average beam power of several major accelerator projects. Compiled in part from [2, 7] and with data from E. Laface (private communication).

power of 4 MW [8]. A similar approach was taken by Fermilab, where ProjectX aimed to deliver beam powers up to 3 MW using a CW linac driver with the option for future staged upgrades [9]. Finally at RAL, a multi-MW machine was analysed that could also be used as a driver for ISIS Spallation Neutron Source. Designs including superconducting linacs, RCS and FFAs were under consideration [10, 11].

While valuable knowledge was gained from these design and R&D efforts, the go ahead for construction was never given. However, the need for high power proton beams for neutrino physics remains and we will further review the current major proposals.

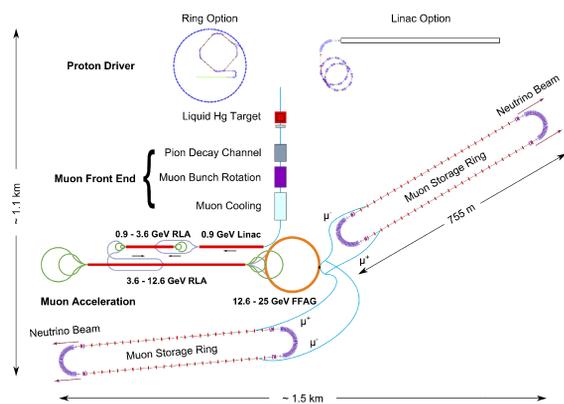


Figure 2: A possible layout for a neutrino factory as defined by the ISS-NF.

* ESSnuSB has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 7774.

Content from this work may be used under the terms of the CC BY 3.0 licence (© 2019). Any distribution of this work must maintain attribution to the author(s), title of the work, publisher, and DOI

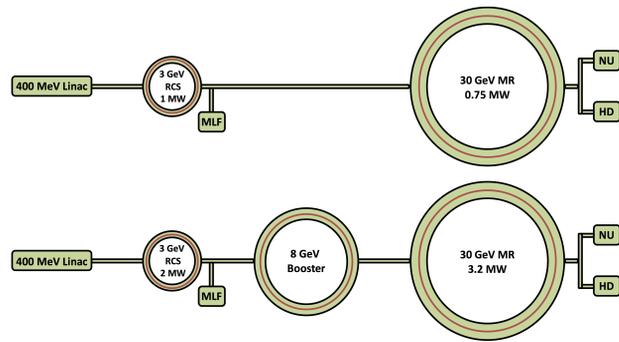


Figure 3: Current J-PARC accelerator chain (top) and a long term power upgrade scenario for neutrino physics (bottom).

ACTIVITIES IN JAPAN

J-PARC in Japan, is one of the most successful multidisciplinary facilities in the world. It consists of a 400 MeV normal conducting linac, a 3 GeV RCS and a 30 GeV Main Ring (MR). The design power is 1 MW in the RCS and 0.75 MW in the MR. The RCS provides the beam for the Materials and Life Science Experimental Facility (MLF), while the beam from the MR is used for the Hadron Facility (HD) and neutrino physics (the T2K experiment - beam to Kamioka). Recently, J-PARC has made significant progress in achieving the design beam power specifications. In the RCS, 530 kW is now routinely delivered for user operation while operation at 1 MW was also demonstrated. Plans for incremental upgrades up to 1.5 MW are being made in preparation for the addition of a second neutron target station [12].

In the MR, stable operation at 500 kW was also achieved, with a 2.48 s cycle time and an intensity of 2.5×10^{14} protons per pulse. A medium term power upgrade to 1.3 MW is also being planned. This will require significant hardware upgrades of the main magnet PS, RF system, ring collimators, injection and fast extraction systems, etc., but will allow faster cycling at 1.16 s and higher intensity operation at 3.3×10^{14} protons per pulse. When completed, this upgrade will be able to provide the most powerful proton beam for neutrino physics in the world [13].

For long term upgrades other options are being investigated. One proposal is to add an intermediate 8 GeV booster synchrotron between the RCS and the MR. This new machine, in combination with an upgrade of the RCS to 2 MW would allow beam powers of up to 3.2 MW in the MR, or could become a new multi-MW source itself [14]. A schematic drawing of this potential upgrade can be seen in Figure 3.

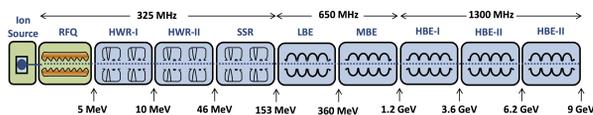


Figure 4: Schematic layout of the high power proton linac proposed at KEK for future neutrino physics experiments.

Plans for a high power proton driver are also being made at KEK. The proposal is to utilise the KEKB tunnel to build a 9 GeV proton linac after SuperKEKB will come to the end of its planned operational life. The new linac will be employing superconducting cavities and making use of the technology already developed for the ILC. The tunnel has a fourfold configuration with four straight sections and four arc sections. The accelerating structures will be placed in the straight sections, with the energy ramping to 1.2, 3.3, 6.2 and finally 9 GeV as illustrated in Figure 4. Operating at 100 mA and 1% duty cycle, the new machine could provide 9 MW beams for neutrino experiments at Kamioka [15].

ACTIVITIES IN CHINA

In China, perhaps the most ambitious proposal is the MOMENT facility (MuOn-decay MEdium baseline NeuTrino beam facility). It aims to produce muon-decayed neutrinos of unprecedented flux intensity for leptonic CP violation phase measurements. The machine proposed is a CW superconducting linac, with a nominal design energy of 1.5 GeV and beam current of 10 mA, delivering a beam power of 15 MW [16]. A schematic accelerator layout can be seen in Figure 5.

The linac will adopt the machine configuration currently under development as part of the China ADS programme (CADS), thus benefiting from the large ongoing R&D efforts. Indeed, the first phase of the CADS has seen the successful development of two separate 10 MeV injectors by IMP and IHEP. Recently, 25 MeV CW operation at 2 mA was achieved using a front end with an RFQ, HWRs and Spoke cryomodules. The next phase of the CADS project will see the beam energy increased to 500 MeV, delivering 2.5 MW at 5 mA in CW mode [17].

Also in China, CSNS (China Spallation Neutron Source) has recently started user operation. The machine consists of an 80 MeV linac and a 1.6 GeV RCS, delivering a power of 100 kW. In the next phase, a linac energy upgrade to 250 MeV would allow a higher average beam current in the RCS and an output beam power of 500 kW. CSNS is mainly intended for multidisciplinary research based on neutron scattering techniques, but future neutrino experiments are also under consideration. One proposal is the addition of a post-acceleration system to CSNS for a Superbeam facility. By using 10% of the CSNS beam, a system with a 20 GeV booster ring, followed by an accumulator ring and a 128 GeV main ring, could deliver beams in the 4 MW range [18].

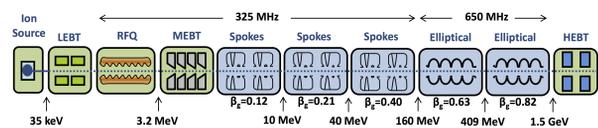


Figure 5: Schematic layout of the proton driver proposed for the MOMENT facility employing the CADS linac configuration.

ACTIVITIES IN EUROPE

In Europe, perhaps the largest effort to develop proton drivers for future neutrino physics is currently associated with the ESS Neutrino Superbeam project (ESSnuSB). ESS is a neutron spallation source presently under construction in Lund, Sweden. When completed, it will deliver a 2 GeV, 2.86 ms, 62.5 mA beam at 14 Hz using a normal conducting front end up to 90 MeV and superconducting spoke and elliptical cell cryomodules up to the final energy (Figure 6). This equates with an average beam power of 5 MW, making ESS the most powerful proton source in the world [19]. Although the main purpose of ESS is to deliver beam for the neutron community, the large beam power in the accelerator, makes it the ideal candidate as a driver for a future neutrino facility.

The ESSnuSB project is studying the possibility to add an accumulator ring and a neutrino target that would be using the ESS linac as the injector. To avoid reducing the beam power to the neutron users, the proposal is to double the power in the linac to 10 MW, by accelerating both protons and H^- , with the proton beam to be sent to the neutron target, while the H^- beam to be injected in the accumulator ring via charge-exchange injection. This upgrade could potentially also benefit the ESS users by opening up the possibility of short pulse operation for neutron production, but would require the addition of a new neutron target station.

Doubling the beam power in the linac is not trivial. By adding the H^- pulse structure the duty cycle will be increased from 4% to 8%. This will require an upgrade of the RF system, a new linac front end capable of delivering both H^- and protons as well as a careful reexamination of the beam dynamics in the linac to reduce beam losses in particular from intra-beam stripping associated with H^- acceleration. The baseline ESSnuSB is therefore proposing operating the upgraded ESS proton and H^- linac at a reduced current (50 mA), but a higher energy (2.5 GeV), by installing more superconducting accelerating structures in the HEBT area of ESS [20]. A schematic layout of the baseline 5 MW ESS linac as well as the future ESSnuSB 10 MW linac upgrade can be seen in Figure 6.

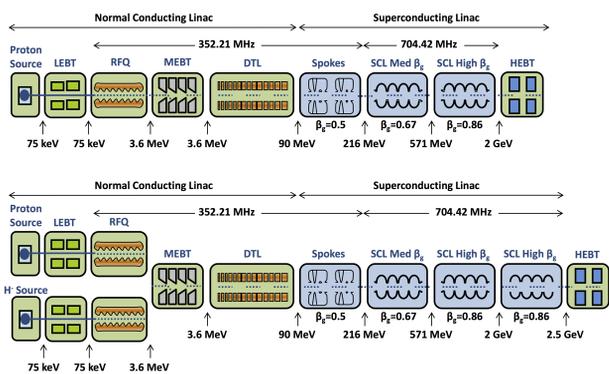


Figure 6: Schematic layout of the ESS proton linac (top) and a potential upgrade for ESSnuSB operation (bottom).

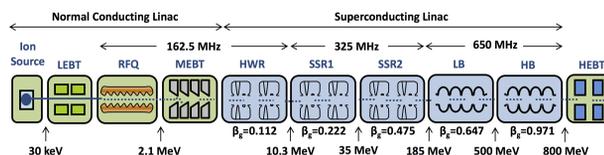


Figure 7: Schematic layout of the PIP-II 800 MeV linac at Fermilab.

ACTIVITIES IN NORTH AMERICA

In North America, plans for providing high power proton beams for neutrino physics are closely connected with the upgrade strategy for Fermilab. To support its long-term science goals, Fermilab aims to achieve MW level beam power through the Proton Improvement Plan II (PIP-II). The main aim is to increase the Main Injector (MI) power from 700 kW currently available for the NuMI/NOvA programme to 1.2 MW at 120 GeV for the start of LBNF/DUNE operation. The Booster power will also be increased from 80 to 160 kW [21, 22].

The main development of PIP-II is a new 800 MeV superconducting H^- linac, which is now under construction. It will be operating in pulsed mode, but capable of CW operation for potential future upgrades. This will replace the current 400 MeV injector. The linac will have a duty cycle of 1.1%, accelerating a peak current of 2 mA, with a normal conducting 2.1 MeV front end (Ion Source, LEBT, RFQ and MEBT), followed by superconducting half-wave resonators, spoke and elliptical cavities up to the final energy. A schematic layout of the new linac can be seen in Figure 7.

A new transfer line from the linac to the Booster will also be required, as well as upgrades of the Booster, Recycler and MI to accommodate higher energy injection into the Booster and higher intensity operation (6.5×10^{12} protons per pulse in the Booster, 7.7×10^{13} in the Recycler and 7.6×10^{13} in the MI). In the long term, achieving more than 2 MW of beam power is possible by increasing the linac energy to 8 GeV and injecting directly into the MI. Another option is to extend the linac energy to 2 GeV and add an intermediate RCS. Upgrading the linac to operate in CW mode would also support MW level beam operation.

CONCLUSIONS

The state of development of proton drivers for future neutrino physics is encouraging. While the ambitious proposals made a decade ago didn't materialise, we're currently seeing concrete developments in several labs with the clear goal of delivering MW level beams in the short and medium term.

Long term plans are also being proposed, with several scenarios aiming to increase the available power to multi-MW level. The superconducting linac route appear to be the preferred option, although circular machines are also being considered. Many of the challenges of running such facilities remain unknown and the experience gained from operating the current high power facilities like J-PARC and SNS will be essential.

REFERENCES

- [1] G. H. Rees, “The Development of High Power Hadron Accelerators”, in *Reviews of Accelerator Science and Technology*, Vol. 1, No 43, 2008.
- [2] C. R. Prior, “Overview of High Intensity Accelerator Projects”, in *Proc. HB’10*, Morschach, Switzerland, Sep.-Oct. 2010, paper MOIA02, pp. 6–10.
- [3] C. R. Prior, “Recommendations from the International Scoping Study for a Neutrino Factory”, in *Proc. PAC’07*, Albuquerque, NM, USA, Jun. 2007, paper TUXKI02, pp. 681–685
- [4] R. Edgecock, “High Intensity Neutrino Oscillation Facilities in Europe”, *Phys. Rev. ST Accel. Beams*, vol. 16, pp. 021002.
- [5] The ISS Accelerator Working Group, “Accelerator Design Concept for Future Neutrino Facilities”, *JINST*, vol. 4, pp. P07001.
- [6] K. R. Long, J. K. Pozimski, and J. S. Berg, “The International Design Study for the Neutrino Factory”, in *Proc. IPAC’12*, New Orleans, LA, USA, May 2012, paper MOPPC050, pp. 244–246.
- [7] S. Kim, “SNS Lessons Learned from Design, Integration and Operation”, in *Proceedings of SLHiPP4*, Geneva, Switzerland, 2014.
- [8] F. Gerigk *et al.*, “Conceptual Design of the Low-Power and High-Power SPL”, CERN–2014–007.
- [9] S. Holmes *et al.*, “Project X Reference Design Report”, Fermilab, June 2013.
- [10] C. Prior and G. Rees, “RAL Proton Driver Studies for a Neutrino Factory”, RAL Internal Report, 2011.
- [11] D. C. Plostinar, C. R. Prior, and G. H. Rees, “Conceptual Design of a New 800 MeV H^- Linac for ISIS Megawatt Developments”, in *Proc. IPAC’11*, San Sebastian, Spain, Sep. 2011, paper WEPC041, pp. 2100–2102.
- [12] J. Kamiya and K. Yamamoto, “Operation Status of J-PARC Rapid Cycling Synchrotron”, presented at the IPAC’19, Melbourne, Australia, May 2019, paper TUPTS036, this conference.
- [13] S. Igarashi, “Challenges to Higher Beam Power in J-PARC: Achieved Performance and Future Prospects”, presented at the IPAC’19, Melbourne, Australia, May 2019, paper MOY-PLM1, this conference.
- [14] H. Hotchi *et al.*, “Introducing an 8-GeV Booster Synchrotron between RCS and MR at J-PARC — One Possible Option toward a Multi-MW Output Beam Power from MR”, in *JPS Conf. Proc.*, vol. 8, pp. 012008, 2015. doi:10.7566/JPSCP.8.012008
- [15] T. Maruta *et al.*, “Design Study on the 9 GeV Proton Linac at KEKB Tunnel for the Next Generation Neutrino Experiment”, in *JPS Conf. Proc.*, vol. 8, pp. 011013, 2015.
- [16] J. Cao *et al.*, “MOMENT: a muon-decay medium-baseline neutrino beam facility”, in *Physical Review Special Topics - Accelerators and Beams*, vol. 17, no. 9, 2014.
- [17] Z. Li *et al.*, “Physics design of an accelerator for an accelerator-driven subcritical system”, in *Physical Review Special Topics - Accelerators and Beams*, vol. 16, pp. 080101, 2014.
- [18] Y. Wu and J. Tang, “Post-Acceleration Study for Neutrino Super-beam at CSNS”, in *Chinese Physics C*, vol. 37(9), December 2012.
- [19] R. Garoby *et al.*, “The European Spallation Source Design”, in *Physica Scripta*, vol. 93, pp. 014001, 2018.
- [20] B. Gålnder, M. Eshraqi, C. A. Martins, R. Miyamoto, A. Farricker, and M. Collins, “Status of ESS Linac Upgrade Studies for ESSnuSB”, presented at the IPAC’19, Melbourne, Australia, May 2019, paper MOPTS082, this conference.
- [21] V. Lebedev *et al.*, “The PIP-II Reference Design Report”, Fermilab Internal Report, June 2015.
- [22] S. D. Holmes, P. Derwent, V. A. Lebedev, C. S. Mishra, D. V. Mitchell, and V. P. Yakovlev, “PIP-II Status and Strategy”, in *Proc. IPAC’15*, Richmond, VA, USA, May 2015, pp. 3982–3985. doi:10.18429/JACoW-IPAC2015-THPF116