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OVERVIEW OF PROTON DRIVERS FOR NEUTRINO SUPER BEAMS AND NEUTRINO FACTORIES*

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Abstract

There has been a world-wide interest in Proton Drivers in the past decade. Numerous design proposals have been presented in Asia, Europe and North America, ranging from low energy rapid cycling synchrotrons, normal or superconducting linacs to high energy slow cycling synchrotrons and FFAGs. One thing in common is that all these machines provide MW beam power and are used primarily for neutrino experiments. This paper gives an overview of these activities. In the last section the author expresses his personal opinion on the future of this field.

INTRODUCTION

A Proton Driver is a high average power, modest energy proton facility. It offers an interesting future physics program in the high-energy physics field, for example, neutrino super beams for long baseline and off-axis experiments, neutrino factory and muon collider.

The term "Proton Driver" was originated from the neutrino factory and muon collider studies in late '90s. Strictly speaking, it not only needs to provide high beam power (~ MW) on the production target, but also should generate very short beam pulses (~ ns) in the multi-GeV (> 4 GeV) energy range in order to maximize the capture efficiency of muon beams in the decay channel and to produce equal number of μ^+ and μ^- particles (when carbon target is used). But nowadays "Proton Driver" has been used in a loose sense, including any MW-class proton sources that are to be used for neutrino physics studies. This paper will give an overview of these machines, some under construction and most on the drawing board, including J-PARC, BNL AGS upgrade, RAL FFAG, CERN SPL, Fermilab superconducting rf (SCRF) linac and Fermilab Main Injector (MI) upgrade. Table 1 lists the parameters of these machines.

Table 1: Proton Driver Parameters

Machine	Energy (GeV)	Rep rate (Hz)	Power (MW)
J-PARC	50	0.3	0.75
BNL AGS upgrade	28	2.5	1
RAL FFAG	10	50	4
CERN SPL	3.5	50	5
Fermilab SCRF linac	8	2.5	0.5
Fermilab MI upgrade	120	0.67	1

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It should be pointed out that neutrinos in a neutrino super beam and that from a neutrino factory have fundamental differences. The former are the conventional neutrinos, namely, the product from pion decay, whereas the latter are the decay product of muons, which themselves are from pion decay, as illustrated in Figure 1.

Figure 1: Protons hitting the target generate pions (both π^+ and π^-), which decay to a muon and a neutrino. In a neutrino factory, these muons are stored in a ring and decay to neutrinos and other particles.

PRESENT STATUS

Asia

J-PARC is currently under construction. Its 50 GeV synchrotron will be able to deliver 0.75 MW proton beams on a neutrino production target for the T2K experiment. The operation is scheduled to start in 2009. Figure 2 shows the T2K long baseline from J-PARC in JAEA (former JAERI), Tokai to an underground 50k-ton water Cherenkov detector in Kamiokande. The distance is 295 km.

Figure 2: T2K long baseline.

America

Fermilab Main Injector is presently delivering 120 GeV proton beams on the NuMI target for neutrino experiment. The beam power is about 0.3 MW. There is also a SNuMI (Super NuMI) study with the goal to increase the beam power to 0.7-1 MW [1]. Figure 3 shows the NuMI long baseline from the Main Injector in Fermilab, Chicago to

an underground 5k-ton steel detector in Soudan, Minnesota. The distance is 735 km.

Figure 3: NuMI long baseline.

In the meantime, Fermilab has proposed an off-axis neutrino experiment called NOvA, which will use the same NuMI beamline but with a new 25k-ton liquid scintillator surface detector located at Ash River, Minnesota, about 825 km from MI. Fermilab is also joining force with BNL for more ambitious very long baseline neutrino experiments that would use large underground detectors in Homestake or Henderson in Colorado. However, DOE recently decided to cancel the planned CD-1 (Critical Decision-1) review of the Proton Driver in order to give way to the International Linear Collider (ILC). This was consistent with the priority list proposed in the EPP2010 report [2]. It is not clear at this moment what new time table will be set for the Proton Driver in the U.S.

Europe

CNGS will start operation in the summer of 2006. Figure 4 shows the long baseline from SPS at CERN to two 600-ton liquid argon underground detectors in Gran Sasso.

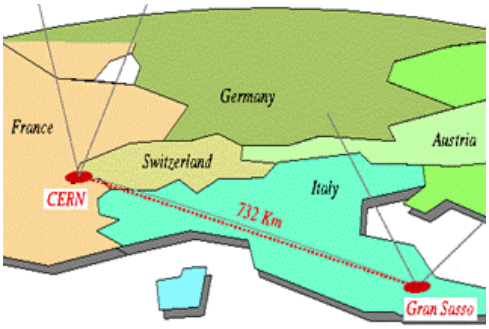

Figure 4: CNGS long baseline.

In the long term, U.K. has completed an International Scoping Study of Neutrino Factory. It is expected to submit a proposal to the EU FP7 for funding of an expanded study for another three years. Meanwhile, CERN Council Strategy Study Group will issue a report in July, 2006. It will give direction to the Proton Driver and Neutrino Factory work in Europe.

J-PARC

Figure 5 is a layout of J-PARC. It consists of a 400 MeV linac, a 3 GeV rapid cycling synchrotron (RCS), a 50 GeV synchrotron and several experimental facilities. One of the 50 GeV proton beamlines will be used for neutrino production. The design beam power is 0.75 MW and could be upgraded to 4 MW later. So this machine will be the world's most powerful proton driver in the next decade. Details of J-PARC can be found in [3].

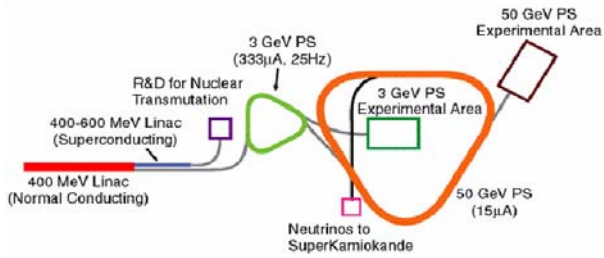

Figure 5: J-PARC layout.

BNL AGS UPGRADE

Figure 6 is a schematic drawing of a plan to increase the AGS beam power from the present 0.1 MW to 1 MW [4]. It has two major upgrades: (1) to build a new 1.2 GeV superconducting linac replacing the present Booster; (2) to increase the AGS repetition rate from present 0.5 to 2.5 Hz.

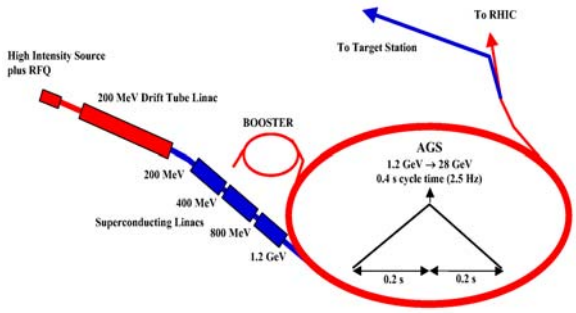

Figure 6: AGS upgrade plan.

RAL FFAG

G. Rees et al. completed a conceptual design of an FFAG machine as a proton driver shown in Figure 7. It consists of a low energy (180 MeV) linac, a 3 GeV rapid cycling synchrotron and a 10 GeV FFAG ring [5]. The FFAG uses radial sector design with reverse bends. But the penalty in circumference increase seems to be acceptable. The ring size is 685.9 m, only modestly larger than a regular 10 GeV synchrotron. Due to the difficulty of injecting H^- particles into FFAG, an RCS is placed between the linac and FFAG. This inevitably puts a limit on the maximum repetition rate of the FFAG, which otherwise could operate in the range of several hundreds hertz up to 1 kHz.

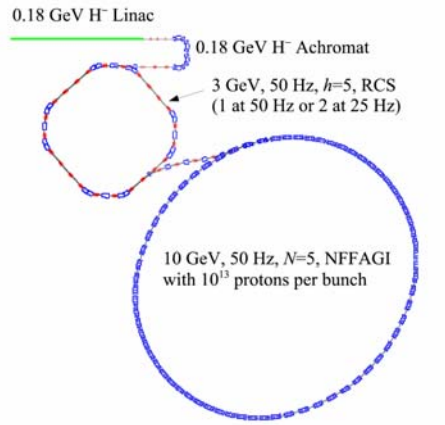

Figure 7: RAL FFAG layout.

CERN SPL

CERN SPL has undergone several design iterations. Table 2 lists the latest parameters [6].

Table 2: CERN SPL Parameters

Beam power	5 MW
Beam energy	3.5 GeV
Repetition rate	50 Hz
Protons per pulse/per second	$0.178/8.92 \times 10^{15}$
Pulse length	0.72 ms
Average pulse current	40 mA
Overall length	450 m
Bunch frequency	352.2 MHz

Compared with earlier designs, the main changes are higher beam energy (it was 2.2 GeV) and shorter machine length (it was 700 m), which are possible thanks to the decision to develop new superconducting rf cavity instead of reusing the LEP cavities. Figure 8 is the layout of SPL. CERN has decided to build the first part up to 180 MeV, which is a normal conducting linac called Linac 4 and will be used as the injector for the LHC. The medium and high energy parts are on the waiting list.

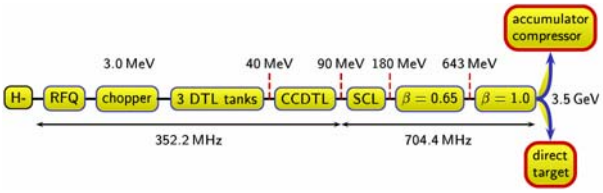

Figure 8: CERN SPL layout.

In the meantime, the SPL team has been carrying out a productive R&D plan. One interesting item is a fast chopper with rise and fall time around 1 ns. Such a chopper will find applications in a number of other high intensity proton machines, such as the SNS and J-PARC. Figure 9 shows the chopper and pulse measurement.

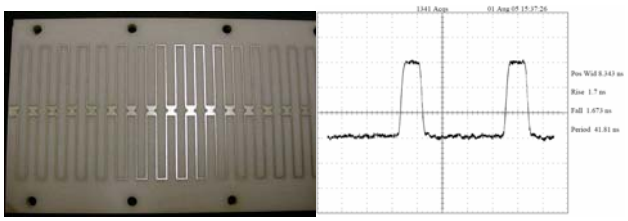

Figure 9: CERN SPL fast chopper.

FERMILAB SCRF LINAC

Fermilab started proton driver designs as early as in 1998. Several design reports were published [7-9]. Early versions include both a synchrotron-based design and a linac-based design. In 2005 Fermilab management decided to choose the linac-based design because of its synergy to the ILC. This design uses superconducting rf technology to accelerate H^- particles to 8 GeV before injecting them into the Main Injector. This new linac would replace the present 400 MeV linac and 8 GeV Booster. The parameters are listed in Table 3. Figure 10 is a layout.

Table 3: Fermilab SCRF Linac Parameters

Beam power	0.5 MW
Beam energy	8 GeV
Particle type	H^- , electrons
Repetition rate	2.5 Hz
Protons per pulse/per hour	1.5×10^{14} / 5.4×10^{18}
Pulse length	3 ms
Average pulse current	8 mA
Active length	671 m
RF frequency	325/1300 MHz

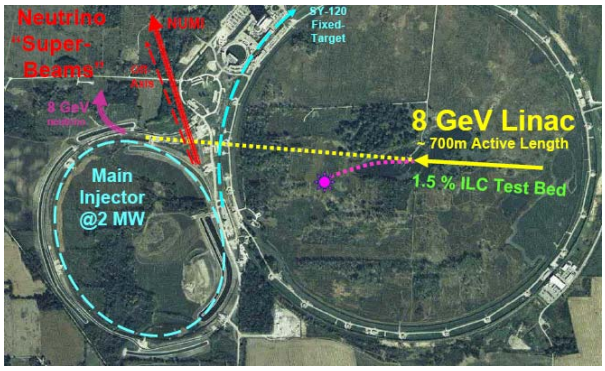

Figure 10: Fermilab 8 GeV SCRF linac layout.

One advantage of using a linac rather than a synchrotron as an injector for the Main Injector is that the maximum beam energy of the MI can vary between 40 and 120 GeV while maintaining the beam power at approximately the same level. This is because the injection time is negligible so the cycle time of the MI is

proportional to the beam energy. (Note: This can also be done when a synchrotron is used if one would use the Recycler in the MI tunnel as an accumulator, see next section.) This is a useful feature for the neutrino experiments, which often require variation of proton energy in order to obtain the desired neutrino energy spectrum.

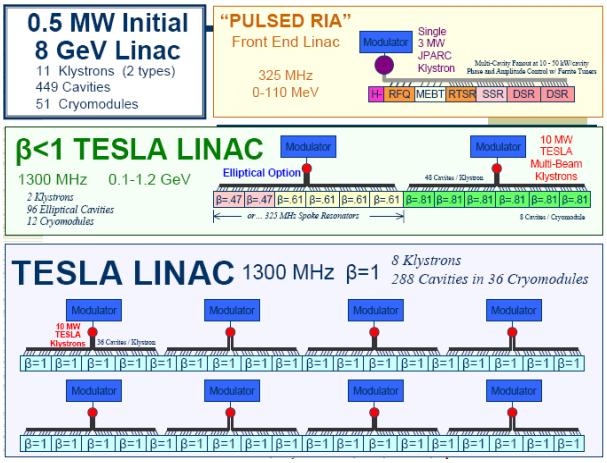

Figure 11: Schematic drawing of Fermilab SCRF linac.

In Figure 11, the front end (up to 110 MeV) is similar to the design of Rare Isotope Accelerator (RIA) being pursued by ANL and Michigan State University. It includes an H^- source, an RFQ and several superconducting spoke cavities. The rf frequency is 325 MHz, a quarter of the TESLA frequency (1.3 GHz).

The low energy part (0.1 – 1.2 GeV) is similar to the SNS, consisting of 3 different types of superconducting cavities: β = 0.47, 0.61 and 0.81, respectively. But the rf frequency is different (SNS: 805 MHz). A major difference from the SNS, however, is the number of cavities per klystron. SNS uses 81 klystrons (550 kW each) to drive 81 superconducting cavities. This works fine but is expensive. In order to lower the construction cost of this 8 GeV linac, the design uses small number of large klystrons (10 MW each), with each klystron driving multiple cavities. For this to work, one must be able to control the phase and amplitude of each individual cavity. This control can be achieved by employing fast ferrite phase shifter on each cavity. Such kind of phase shifter was made and used before, but at much lower power rating. An aggressive R&D has been going on to develop new phase shifter to meet the proton driver requirement. The prototype of two different types of shifter – waveguide type and co-axial type – were fabricated and high-power tested. The results are promising.

The high energy part (1.2 – 8 GeV) is identical to the TESLA design. Because the ILC has adopted the TESLA superconducting rf technology, this proton driver can be used as an engineering test bed of the ILC. This was the main reason of the Fermilab management decision to go for an SCRF linac in the Proton Driver proposal.

One important question when using a linac to accelerate H^- particles to 8 GeV is how to transport and strip these ions. This is a non-trivial question because the highest energy of an H^- beam is only 1 GeV (in SNS) at this time. To increase it by an order of magnitude involves many fundamental physics issues [10]. As an example, one can take a look at the blackbody radiation stripping of H^- particles [11]. At low energy, this effect is negligible. At 8 GeV, however, the Doppler shift of the thermal photon energy spectrum leads to significant overlapping with the photodetachment cross section spectrum, as illustrated in Figure 12. This means these thermal photons from the blackbody radiation of the beam pipe would strip H^- to H^0 with certain probability. Figure 13 is the calculation of this probability as a function of H^- ion energy and of temperature, respectively. It is seen that both dependences are strong.

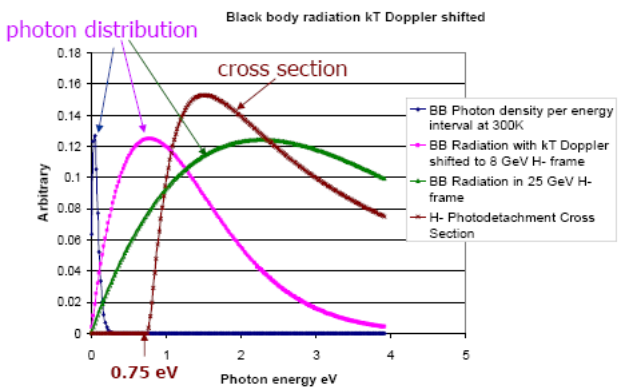

Figure 12: Illustration of blackbody radiation stripping of H^- ions –photon distribution due to Doppler shift and overlapping with the photodetachment cross section.

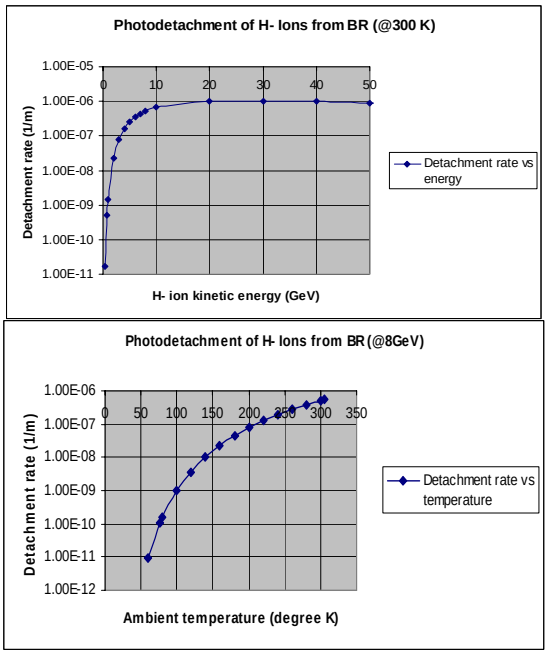

Figure 13: Top – energy dependence of blackbody radiation stripping; bottom – temperature dependence.

As a matter of fact, the blackbody radiation stripping of 8 GeV H^- ions is so strong that it dominates the stripping

loss in the transport line (much larger than magnetic field and vacuum stripping). A mitigation method is to insert a cryogenic beam screen inside the beam pipe. If gas nitrogen is used to cool the screen to 150 °K, the blackbody stripping could be effectively suppressed.

FERMILAB MI UPGRADE

An 8 GeV SCRF linac is expensive (around 500 millions US dollars). As an intermediate step, Fermilab is investigating possible upgrade of existing accelerator complex after the Tevatron shutdown in 2009. A report on SNuMI project can be found in [1]. Its main components are: (1) to convert the present Recycler to a proton accumulator for eliminating the front porch during injection to the MI and reducing the cycle time; (2) to employ slip stacking or barrier rf stacking technique in the Recycler for increasing proton intensity; (3) to upgrade the magnet power supply and rf for higher repetition rate. Accompanied by improvements in target area and radiation shielding, it is expected to increase the MI power from present 0.3 MW to 0.7–1 MW.

Furthermore, there is a proposal to convert the present anti-proton accumulator to a proton accumulator and take advantage of its large momentum acceptance for momentum stacking [12]. The present Debuncher will be removed. Its tunnel could house a new 8 GeV synchrotron replacing the present Booster. Because of the savings in civil construction and reduced magnet aperture requirement, such a synchrotron (cost around 100 millions US dollars) would be significantly cheaper than an 8 GeV linac. A triangular lattice (Figure 14) was designed for this synchrotron, which could fit nicely in the Debuncher footprint.

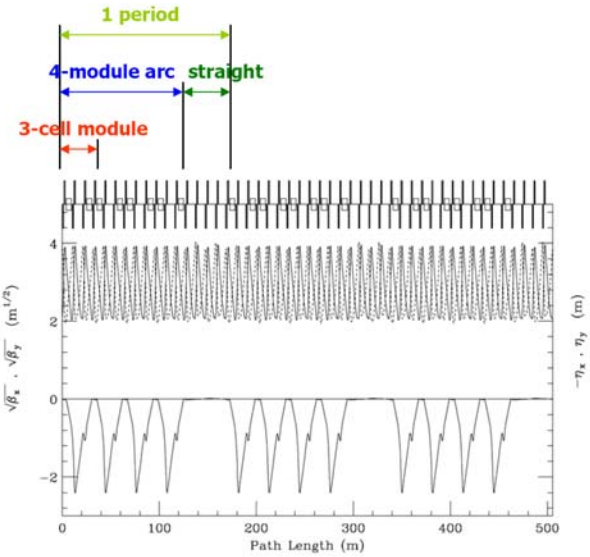

Figure 14: A triangular lattice for a new synchrotron in the Debuncher tunnel.

This lattice has a number of interesting features:

- Simple: only one type of dipole and one type of quadrupole. Focusing and defocusing quadrupoles have the same length.
- No transition crossing: $\gamma_t = 18.6$.
- Zero dispersion straight sections.
- Three super periods with modular structure.
- Small beta-function (16 m) and dispersion (2.4 m).
- Large free space.
- Good optical properties (large dynamic aperture, weak dependence of lattice function on amplitude and momentum).
- Same shape and size of the Debuncher (505 m).

CONCLUSION

High power proton accelerator (HPPA) is an active field around the world. Two of the world's most expensive accelerator projects belong to this category: J-PARC in Japan and SNS in the U.S. Proton Driver is a special application of HPPA in high-energy physics for neutrino super beams and neutrino factories. The recent HEP road map study in the U.S. (EPP2010) and Europe (CERN Council Strategy Study) has put a number of proton driver projects on hold, including CERN SPL, RAL FFAG, BNL AGS upgrade and Fermilab SCRF linac. In the foreseeable future, only J-PARC and MI upgrade are the two proton drivers that will be operational. Meanwhile, interest in HPPA arises rapidly in several world economic power houses such as China, India and Korea. With increasing resources in these countries and declining efforts in the U.S. and Europe, it is conceivable that the leadership in this field will move to Asia in the next decade.

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