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Neutrino Factory Proton Driver: preferred scenarios and remaining issues

C.R. Prior[*]
STFC Rutherford Appleton Laboratory, Harwell Science & Innovation Campus, Chilton, Oxfordshire OX11 0QX, UK
E-mail: chris.prior@stfc.ac.uk

The International Scoping Study (ISS) and its successor, the International Design Study (IDS-NF), have identified a preferred scenario for the accelerator complex of a Neutrino Factory based on a 50 Hz, 4 MW driver generating pulses of ∼3 proton bunches at an energy in the range 5–10 GeV. A model matching these requirements was produced during the ISS, but, this apart, work on developing existing facilities around the world will fail to meet the IDS-NF parameters without substantial modifications. There are however considerable synergies between Neutrino Factory (NF) drivers and the proton accelerators used for spallation neutron sources, and the NF study can benefit from the associated R&D. This paper outlines the main areas of research in high intensity proton accelerators, as well as addressing the remaining issue peculiar only to NF - that of nanosecond bunch compression. The merit of pursuing a green-field NF design rather than concentrating on adapting the IDS-NF scenario to use current proton driver plans, at for example Fermilab or CERN, remains to be assessed.

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[*] Speaker.

1. Introduction

Following many years of concentrated study of high intensity pulsed proton accelerators, the proton driver is arguably the most advanced aspect of the Neutrino Factory. Much of the activity has focussed on advanced neutron sources generating beams of 1-5 MW at energies up to 3.5 GeV. These provide many of the basic requirements of a proton driver for a Neutrino Factory. NF additionally requires short bunches (1-3 ns rms) and a (slightly) higher beam energy, both of which can be achieved with the addition of one or more extra rings. Stand-alone NF drivers benefit greatly from synergies with earlier studies where, for example, successes at J-PARC [1] and SNS [2] indicate that most of the main problems have been resolved.

While it may turn out to be the case that a Neutrino Factory is built on a green-field site, it is much more likely to be at a national laboratory through development of existing infrastructure. The idealised parameters from the International Scoping Study [3] may ultimately serve only for guidance, and compromise will be necessary in the final NF scenario. Thus, whereas some ideas may seem most appropriate for the proton driver at the present time, factors such as the energy, pulse structure and repetition rate are likely to be different in reality.

The fundamental choice lies between:

(i) drivers that carry out acceleration to the final proton energy in a linac, then accumulate and compress the beam in separate storage rings; and

(ii) drivers based on one or more synchrotrons and/or FFAGs following limited acceleration in a linac.

The US Studies II and IIa did not specifically identify the driver; however the European study carried out at CERN used a design based on the SPL (superconducting proton linac) [4], corresponding to the first category above. The Project-X study at Fermilab [5] incorporates an 8 GeV linac generating a neutrino superbeam, so would nominally be in (i) but could feed into a recycler ring or the main injector and fall into category (ii). Specific studies under (ii) include the many designs at RAL using a 200 MeV linac to feed a synchrotron-based booster for beam accumulation followed by one or more synchrotrons or an FFAG for main acceleration. The J-PARC accelerator complex at Tokai-mura in Japan, with 3 GeV and 50 GeV rings would also be in (ii). To date, the 10 GeV synchrotron+FFAG model at RAL comes closest to meeting the specific requirements of IDS-NF (see Figure 1).

2. Main Design Issues

The main issues for the proton driver are the accumulation of sufficient beam to deliver 4 MW of power to the pion production target in bunches of 1-3 ns rms duration. The beam power is given by $P = NeEf$ where N is the total number of protons per pulse, f is the driver repetition rate and E is the kinetic energy. ISS suggested a repetition rate $f \sim 50$ Hz, so at an energy of 10 GeV (in the middle of the range 5–15 GeV recommended by ISS), there would need to be 5×10^{13} protons in the ring. Split between n bunches, and assuming a parabolic line density (for which the bunching factor is $\frac{2}{3}$ and the bunch length is $2\sqrt{5}$ times its rms length), each bunch would carry a peak current of

$$\hat{I} = \frac{3Ne}{4\sqrt{5}n\tau} = \frac{1.677}{n}\,\mathrm{kA}$$

at $\tau = 1$ ns rms compression, i.e. of the order of kiloAmps.

To avoid high space charge levels that would make the compression so much more difficult, one can increase n and/or τ. ISS attempted to relieve the pressure on the driver by suggesting that if necessary τ could be as large as 3 ns rms without too detrimental an effect on the number of muons reaching the NF storage rings. The peak current can also be reduced by increasing n. However, beam loading issues in the NF muon accelerators require the muon bunch trains to be well spaced, yet the total pulse duration, τ_P, on the liquid mercury target has to be limited to avoid the onset of cavitation. Results from the MERIT experiment suggest the ISS restriction of $\tau_P \leq 40\,\mu$s can be somewhat relaxed, but the acceleration requirements nevertheless indicate $n \leq 3$, and in the case of a muon collider, that $n = 1$.

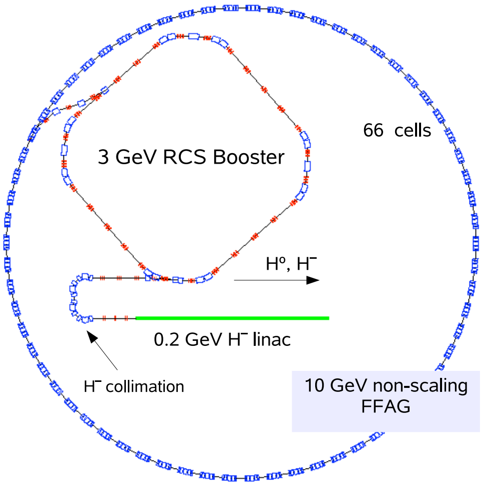

Figure 1: RAL Study of a Proton Driver for a Neutrino Factory

This should be the goal of the driver for a green-field site and the model shown in Figure 1 was specifically designed to that end. It is based on the following fundamental principles:

(i) Beam accumulation and bunch compression have different optical requirements, suggesting different rings for each operation.

(ii) Bunch compression to 1-3 ns can best be achieved if the longitudinal emittance is small and this follows most naturally if injection is at a low energy.

(iii) The whole machine should be designed for very low uncontrolled beam loss. The accepted figure is 1 W/m on average.

A consequence of (ii) is that the driver should preferably comprise a booster for accumulation and initial acceleration, and a main ring for final acceleration and bunch compression. Figure 1 shows an 180 MeV H^- linac injecting via a stripping foil into a 3 GeV synchrotron. The accumulated beam is then accelerated to 10 GeV in a non-linear non-scaling fixed-field alternating gradient (FFAG) accelerator. Since FFAG technology is in its infancy, an alternative has been developed using a conventional synchrotron, though this is expected to be more expensive.

Drivers based on full energy linacs find it harder to meet these requirements. A high harmonic number is needed to obtain a small single-bunch longitudinal emittance, and it is then difficult to obtain the low number n of bunches on the target. However such designs should not be ruled out: most are based on developments of existing infrastructure at national laboratories, and if this is the only way a high power proton driver can be provided, it should not be ignored and the most appropriate form of neutrino facility designed accordingly.

2.1 Fast beam chopping

Low uncontrolled beam loss (allowing hands-on maintenance in the rings) is achieved by preparing the beam in the linac and removing halo prior to ring injection. Chopping the train of linac microbunches at low energy (~ 3 MeV) allows all the protons entering the ring to be trapped in the booster synchrotron buckets (using Figure 1 as illustration) and also creates space between the ring bunches for the rise time of the extraction kickers. The chopper is essentially an electrostatic deflector whose field is switched on in the ~ 3 ns between the micropulses, directing roughly 50 to a beam dump; then is switched off to allow a train of about 120 micropulses to travel on down the linac to the rings. This is carried out h times in every ring revolution period, where h is the booster ring harmonic number. Achieving the necessary rise and fall times for the chopper field, as well as sustaining it throughout the chopping, are major problems, and represent a fundamental area of accelerator R&D. Areas of work include development of the fast beam choppers at SNS and J-PARC, and the testing of novel ideas at RAL and CERN. The RAL scheme uses a tandem device with a fast but unsustainable initial field to deflect only 3 microbunches, but this creates an immediate space for a slower, sustainable field to rise to full intensity. This is part of the Front-End Test Stand (FETS) under construction at ISIS to develop high current H^-ion sources, examine longitudinal bunching in an RFQ and demonstrate clean fast beam chopping.

2.2 Beam Accumulation

Prior to injection, halo is removed from the beam in an achromatic arc incorporating transverse (horizontal and vertical) beam scrapers and foils. The arc is designed with a high normalised horizontal dispersion ($D/\sqrt{\beta} \gtrsim 5\,\mathrm{m}^{\frac{1}{2}}$) for removal of longitudinal beam halo. Thus cleaned, accumulation of the chopped beam is achieved via charge-exchange injection using a carbon or diamond stripping foil. Orbit bump magnets are used to ‘paint’ transverse phase space. SNS and J-PARC use both horizontal and vertical bumps in a dispersion-free region, whereas the RAL designs inject into a low-field dipole and use energy ramping of the incoming beam to create the horizontal ring emittance. The painting is carefully designed so as to minimise the number of times the re-circulating proton beam passes through the foil, avoiding excessive foil temperatures and maximising lifetime. Beam dumps are needed for partially stripped H^0 and unstripped H^-ions. With a properly designed system, the main source of loss is scattering in the foil, which is of the order of 0.01%. Injection takes place over ~ 100 turns in a synchrotron-based system (such J-PARC) but can be over more than 1000 turns in a linac+accumulator ring scenario (such as SNS).

The main issues are foil temperatures and lifetime, beam loss through scattering, electron collection, the handling of unstripped H^- and H^0, and a general understanding of the complex beam dynamics issues. All of these are under study but in particular work to check the feasibility of an alternative charge exchange injection system based on resonant laser stripping is being carried out at J-PARC and SNS.

2.3 Bunch compression

Bunch compression, which is a particular feature of the NF proton driver and not a requirement for spallation neutron sources, was considered in detail at a workshop at Brookhaven in 1999 [6] following experiments that had been carried out on the AGS. In scenarios that have a separate ring solely for compression, bunch shortening is achieved through high rf voltages and longitudinal phase space rotation. The CERN NF study used 7-8 MV, for example[1]. Drivers designed directly for NF have their parameters chosen with nanosecond bunch compression specifically in mind. Thus the RAL models not only create beam with small longitudinal emittance but have lattices whose transition energy is only very slightly above the top energy in the ring. The beam does not cross transition but is progressively frozen in phase in the final stage of acceleration. Provided the energy is high enough (and 10 GeV is suitable) adiabatic bunch compression is achieved, possibly enhanced through the addition of a modest amount of rf at higher frequency. As the emittance is small, the energy spread is low and higher-order optical corrections may not be necessary. Compression in the FFAG driver of Figure 1 uses only 0.885 MV per turn at $h = 24$ for compression to 3.3 ns rms and is improved to 1.9 ns rms with a higher harmonic component. An alternative design, which may be more acceptable since it uses a second synchrotron in place of the untried FFAG, has 1.3 MV per turn for 3 ns rms.

3. Summary

The main areas of concern for a proton driver for NF are therefore all being covered through theoretical and experimental development, with the exception on the bunch compression which is restricted to modelling studies. The BNL experiments of compression pre-date the current set of NF parameters and it would be interesting to repeat them in the light of recent developments. The question as to whether it is better to concentrate on a green-field proton driver design or to adapt the NF scenario to fit in with upgrades to existing infra-structure needs to be addressed. In this context, it may be worth noting that the proton bunches from a spallation neutron facility are likely to have too large a longitudinal emittance for compression to the 1–3 ns rms needed for NF.

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[1] The required voltage depends inversely on the fourth power of the bunch length.