A COMMON PROTON DRIVER FOR A NEUTRINO FACTORY AND A SPALLATION NEUTRON SOURCE BASED ON MEGAWATT UPGRADES TO ISIS

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Abstract

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. Potential upgrades of the ISIS accelerators to provide beam powers of 2 – 5 MW in the few GeV energy range could be envisaged as the starting point for a proton driver shared between a short pulse spallation neutron source and the Neutrino Factory (NF). The concept of sharing a proton driver between other facilities and the Neutrino Factory is an attractive, cost-effective solution which is already being studied in site-specific cases at CERN [1] and FNAL [2]. Although in the RAL case the requirements for the Neutrino Factory baseline proton energy and time structure are different from those for a spallation neutron source, an additional RCS or FFAG booster bridging the gap in proton energy and performing appropriate bunch compression seems feasible.

INTRODUCTION

The Rutherford Appleton Laboratory (RAL) is home to ISIS, the world's most productive spallation neutron source. ISIS has two neutron producing target stations (TS-1 and TS-2), driven at 40 Hz and 10 Hz respectively by a 50 Hz, 800 MeV proton beam from a rapid cycling synchrotron (RCS), which is fed by a 70 MeV H^- drift tube linac (DTL) [3].

A detailed comparison of reasonable upgrade routes for ISIS that will provide a major increase in beam power has been carried out in order to identify optimal upgrades. Designs are to be developed primarily for an optimised neutron facility, and will include the provision of an appropriate proton beam to the existing TS-2 target station. This forms part of the on-going research programme into high intensity proton beams at ISIS [4, 5], based on understanding, optimising and upgrading the existing ISIS RCS, and putative new upgrade synchrotrons at ISIS. Development and experimental testing of simulation codes is under way using the SNS code ORBIT [6] and also with the in-house code SET [7]. The latter is presently being expanded to cover 3-D particle motion, exploiting the parallel computing facilities available at RAL. The aim is to adapt models being verified on the present ISIS synchrotron to proposed new running régimes.

ISIS MEGAWATT UPGRADES

The recommended first stage of the upgrade path is to replace parts or all of the ISIS 70 MeV H^- injector. Replacement with a new or partly new linac of the same energy could address obsolescence issues with the present linac, and ensure reliable operation for the foreseeable future. The more exciting but more challenging option is to install a higher energy linac (up to ≈ 180 MeV), with a new optimised injection system into the present ring. This could give a substantial increase in beam power (≤ 0.5 MW), but there are numerous issues to be considered, and these are currently being worked on [8].

The next stage is a new ≈ 3.2 GeV RCS that can be employed to increase the energy of the existing ISIS beam to provide powers of ≈ 1 MW. This new RCS would require a new building, along with a new ≈ 1 MW target station. There are a number of possible candidates for the ≈ 3.2 GeV, 50 Hz RCS, but studies are presently focused on a 3.2 GeV doublet-triplet design with five superperiods (5SP) and a 3.2 GeV triplet design with four superperiods (4SP), both of which will include features required for fast injection directly from the existing ISIS RCS, together with the option for optimised multi-turn injection from a new 800 MeV H^- linac [9].

The final upgrade stage is to accumulate and accelerate beam in the ≈ 3.2 GeV RCS from a new 800 MeV linac for 2 – 5 MW beams [10]. It should be noted that a significant collimation section or 'achromat'' would be required after the linac to provide a suitably stable beam for injection into the RCS. These upgrades to the ISIS facility are shown in figure 1.

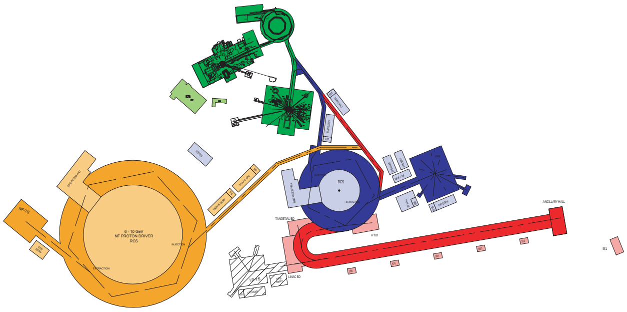

Figure 1: Conceptual layout of the NF proton driver with ISIS (green), ≈ 3.2 GeV RCS (blue), 800 MeV linac (red) and dedicated NF booster (orange). As shown the footprint lies wholly within the RAL site boundary.

Studies and simulations will assess the key loss mechanisms that will impose intensity limitations. Important factors include injection, RF systems, instabilities, loss control and longitudinal and transverse space charge.

Table 1: Scenarios for bunch sharing between an upgraded ISIS and the NF, assuming bunches will be transferred from the ≈ 3.2 GeV RCS at 50 Hz with a total power of 4 – 5 MW and that 4 MW is required for the NF target

≈ 3.2 GeV RCS design	Power at 3.2 GeV (MW)	Total number of bunches	Bunch spacing (ns)	Protons per bunch ($\times 10^{13}$)	Number of bunches to ISIS	Power to ISIS (MW)	Number of bunches to NF	NF booster energy (GeV)
4SP	5	5	280	3.9	2	2	3	4.3
4SP	5	5	280	3.9	3	3	2	6.4
5SP	5	9	140	2.2	6	3.33	3	7.7
5SP	4	9	140	1.76	6	2.66	3	9.6

COMMON PROTON DRIVER

In a common proton driver for a neutron source and the NF, based on a 2 – 5 MW ISIS upgrade with an 800 MeV linac and a ≈ 3.2 GeV RCS, both facilities have the same ion source, RFQ, MEBT, linac, H^- injection and acceleration to ≈ 3.2 GeV. Bunches of protons are shared between the two facilities at ≈ 3.2 GeV, and a dedicated RCS or FFAG booster must then accelerate the NF bunches to meet the requirements for the NF baseline (4 MW and 5 – 15 GeV). Taking the optimistic case of a total power of 4 – 5 MW at ≈ 3.2 GeV, some possible bunch sharing scenarios are outlined in table 1.

Assuming that at least half of the power at ≈ 3.2 GeV should be delivered to the neutron source, both the 4SP and 5SP ≈ 3.2 GeV RCS designs could meet the power and energy needs of the NF (although for the 4SP design only two bunches are delivered rather than the NF baseline of three). It would appear that the 5SP design is most suitable, as it meets all the requirements of the NF baseline and provides more beam power to the neutron source, but its merits need to be established by thorough beam dynamics studies. In order to give some flexibility in case the total power at ≈ 3.2 GeV is somewhat less than 5 MW, 6.4 – 10.3 GeV RCS and FFAG booster designs are to be considered. Figure 1 shows the conceptual layout of the common proton driver.

Based on the time structure and longitudinal dynamics of the ISIS upgrade ≈ 3.2 GeV RCS, only a further RCS or an FFAG can be considered as a booster ring to reach the required NF baseline. Preliminary RCS designs [11] have concentrated on achieving the necessary acceleration and bunch compression with present-day, cost-effective RCS technology, *e.g.* dipole magnets with a maximum field of 1.2 T, an RF system similar to that used at ISIS [12] and long straight sections for injection, extraction, RF and collimation. An RCS design with harmonic number 17 and 4 MW total beam power, based on injection from the 5SP 3.2 GeV ISIS upgrade RCS (the last entry in table 1), has been investigated. This case dictates a rather large final proton energy of 9.6 GeV, but allows delivery of the required beam parameters to both facilities with minimal impact on the neutron source performance. The RCS has six superperiods with six FDF triplet cells each, uses only three quadrupole families and allows for a flexible choice of gamma transition. The main RCS parameters for this design are summarised in table 2 and the optical functions are shown in figure 2.

Table 2: Parameters of the dedicated NF booster RCS ring with injection at 3.2 GeV and extraction at 9.6 GeV

Parameter	
Number of superperiods	6
Circumference (m)	694.352
Harmonic number	17
RF frequency (MHz)	7.208 – 7.315
Maximum dipole field (T)	1.2
Tune	8.72 (h), 7.82 (v)
Long straight section length (m)	14
Gamma transition	13.37 (flexible)
RF voltage per turn (MV)	≈ 3.7

Although the preliminary lattice design has been produced a great deal of work remains to be done to produce a full conceptual scenario.

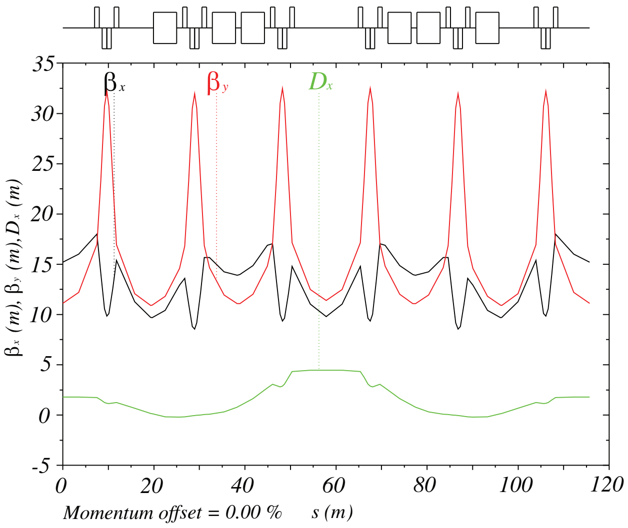

Figure 2: Optical functions in the dedicated NF booster RCS ring for 3.2 – 9.6 GeV.

FFAG options are yet to be explored, and would be based on technology which remains to be fully tested, but in principle would offer the advantage of allowing all the bunches to be extracted to the NF target with the same energy (unlike the RCS where the 160 µs sequential extraction delay required by the NF baseline would give time for the main magnet field to vary between bunches).

Optimised longitudinal muon capture in the muon front end of the NF requires compression of the proton bunch length from the ≈ 100 ns for the neutron source to 1 – 3 ns at the NF target. Several methods have been proposed in order to reach this goal [13], based on either adiabatic compression during acceleration or fast phase rotation at the end of acceleration (or in an additional dedicated compressor ring).

Adiabatic compression during acceleration requires relatively high RF voltage (V) because the bunch length scales as $V^{-1/4}$. Variations of this method apply higher harmonic RF systems or lattices just below transition at the end of compression. Compression by fast phase rotation allows a lower RF gradient, but requires earlier bunch stretching to reduce the momentum spread just before the rotation and does not allow the compressed bunches to be held for many turns. Manipulations close to transition may also be applied in this scheme. Fast phase rotation in an additional dedicated compressor ring, possibly based on the CERN design [2], could provide an alternative solution if RF manipulation in the booster itself proves impractical.

SUMMARY

A common proton driver for neutrons and neutrinos compatible with an ISIS upgrade is an attractive solution to create a cost-effective, multi-user facility, but careful attention must be given to potential conflicts of interest between the neutron and neutrino communities. A conceptual design has been produced, in which it appears to be feasible that the NF baseline can be met, as shown in table 3, although a lot of the detailed beam dynamics remains to be done and no consideration has yet been given to beam transport to the pion-production target.

Table 3: Baseline proton beam parameters at the NF pion-production target compared with expected parameters from a proton driver based on an ISIS MW upgrade at RAL

Parameter	**Baseline**	**RAL**
Beam power (MW)	4	4
Pulse repetition frequency (Hz)	50	50
Proton kinetic energy (GeV)	5 – 15	6.4 – 10.3
Proton rms bunch length (ns)	1 – 3	1 – 3
Number of proton bunches per pulse	3	2 or 3
Sequential extraction delay (µs)	160	160

Bunch compression is clearly of vital importance to the success of a common proton driver and future studies must address longitudinal dynamics and space charge forces in detail.

The site-specific design at RAL is clearly in a preliminary stage, and will require extensive effort on beam dynamics and accelerator engineering (and strategic research and development in a number of key areas) before it can be regarded as viable. The common proton driver could fit onto the RAL site, on land already set aside for large facilities and research expansion, but the complete NF would require the use of part of the Harwell Oxford Campus, where some former UK Atomic Energy Authority (UKAEA) land would need to be decommissioned before any building or tunnelling work could begin. A possible schematic layout of the NF on the Harwell Oxford site is shown in figure 3.

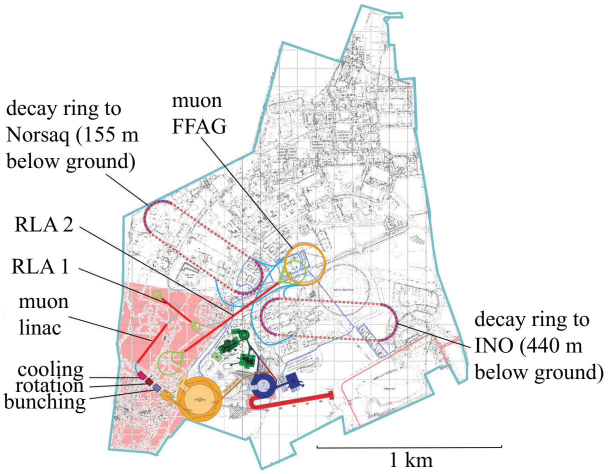

Figure 3: Schematic layout of the NF on the Harwell Oxford site. The components of the proton driver are as shown in figure 1 and the Harwell Oxford site boundary is shown in light blue. The area shown in pink is former UKAEA land which would need to be decommissioned.

REFERENCES

[1] R. Garoby *et al.*, CERN-NEUTRINO-FACTORY-NOTE-157, CERN (2009).
[2] S.D. Holmes, IPAC'10, p.1299 (2010).
[3] D.J.S. Findlay, PAC'07, p.695 (2007).
[4] C.M. Warsop *et al.*, HB2008, p.143 (2008).
[5] C.M. Warsop *et al.*, HB2010, p.619 (2010).
[6] http://neutrons.ornl.gov/APGroup/Codes/orbit.htm.
[7] B.G. Pine and C.M. Warsop, EPAC'08, p.3215 (2008).
[8] C.M. Warsop *et al.*, IPAC'11, WEPS106.
[9] J.W.G. Thomason *et al.*, HB2008, p.434 (2008).
[10] D.C. Plostinar *et al.*, IPAC'11, WEPC041.
[11] J. Pasternak and L.J. Jenner, IPAC'11, WEPS103.
[12] A. Seville *et al.*, EPAC'08, p.349 (2008).
[13] C.R. Prior, Nufact08 (2008).