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ISIS MEGAWATT UPGRADE PLANS

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Abstract

The ISIS spallation neutron source has been running successfully for more than 15 years and at 160 kW remains the most powerful source of its kind in the world. With machines due to operate at or near the megawatt level under construction in the United States and Japan and expected to come on line within the next decade, advances in Europe have not progressed at the same rate. A positive decision on the European Spallation Source (ESS) looks unlikely and one is led to consider the feasibility of alternative options. An ISIS upgrade is one such possibility. The current installation of a radio frequency quadrupole (RFQ) in the linac and a dual harmonic RF system in the synchrotron should lead to an increase in intensity of up to 50%, but plans are also under way to increase the beam power to 1 MW with the possibility of going to 4-5 MW in the longer term. The 1 MW option is based on an increase in energy to 3 GeV by means of a second synchrotron using ISIS as a booster. Details of the new ring and studies of the accelerating system are given in this paper. The ring also has the option of accelerating to 8 GeV at reduced frequency and this could be used as a test bed for the nanosecond bunch compression needed for the proton driver for a neutrino factory (NF). The cost of these proposals is relatively modest compared with a completely new facility. In the longer term, a combination of two such rings with a new synchrotron booster (replacing the existing ISIS) would give several options, for example: 4 MW for neutrons, or 2 MW for neutrons plus 2 MW for neutrino/muon studies, or 4 MW for a neutrino facility.

INTRODUCTION

Based on a 70 MeV linac and an 800 MeV synchrotron, ISIS is an extremely robust, reliable and stable machine. An impressive amount of high quality research has followed since its inception and there have been many important developments over a range of subjects including both physical and biological sciences. Operational experience and technological progress have provided valuable guidance for studies towards future accelerator-based neutron sources. ISIS is increasingly seen as a benchmark not only for neutron production but also as a high power proton accelerator. Many of the ideas behind its design have had a bearing on the US spallation neutron source (SNS) and the Japanese high intensity accelerator facility (J-PARC), and it has had a major influence on plans for a multi-megawatt spallation source in Europe, ESS. While the demand for neutrons in Europe remains strong, a decision over construction of ESS seems increasingly remote. A development of ISIS into a versatile, high power, high intenstity proton driver (ISIS2), therefore seems attractive, and would provide options for a range of fixed-target studies. The proposed upgrade would be in three phases, during each of which ISIS could continue to operate, with changeover made only as construction is completed.

1. Phase 1 involves the construction of a 1 MW proton synchrotron, operating either at 3 GeV and 50 Hz or at 8 GeV and 16.7 Hz, with injection directly from the existing 800 MeV beam from ISIS. The 3 GeV option would provide beam for a 1 MW spallation neutron source, and in 8 GeV mode the machine could be used for bunch compression tests, studies of a pion target and experiments with a prototype muon front-end system, all essential ingredients of a neutrino factory design.

2. Phase 2 sees development of the new synchrotron to 2.5 MW with a new injector comprising a 180 MeV linac and two 1.2 GeV, 50 Hz booster synchrotrons, replacing the ISIS linac and synchrotron.

3. In Phase 3, a second high energy synchrotron would be added, stacked above the first, with both operating at 25 Hz. An energy of $\sim$3 GeV would be used for an enhanced neutron source and acceleration would be to 6 GeV for a 5 MW neutrino factor driver.

PHASE 1: THE NEW SYNCHROTRON

The ISIS synchrotron has a mean radius of 26 m and accelerates two bunches at harmonic number h=2 to an energy of 800 MeV. Installation of a dual harmonic RF system is expected to improve the bunching factor so that pulses of 3.75×10^{13} protons can be accelerated onto the target at a frequency of 50 Hz. Beyond this, the machine is space-charge limited and the simplest way to increase the beam power is through an increase in energy. Bucket to bucket transfer is therefore proposed into a new synchrotron with mean radius 78 m (three times that of ISIS) with h=6, followed by an (approximately) fourfold increase in energy to the MW level of beam power. Since only one third of the circumference is occupied by beam, the peak current remains the same, the average current is reduced by a factor of three, space charge forces are unaltered but, owing to the increased radius, the betatron tune shifts and spreads are trebled. These are allowed for in the design. Similarly beam scrapers are included in the injection line for assumed (unnormalised) transverse input emittances of 19 π mm.mr (rms), 95 π mm.mr (99%) and 125 π mm.mr (100%).

The synchrotron lattice is based on a racetrack design with superperiodicity two and integer Q_h in the arcs in order to obtain dispersion-free straight sections. Adequate space must be provided for the main and trim magnets and the RF systems, and the straight sections must be sufficiently long to meet the demands of injection, extraction and beam loss collection. Analysis of various models [1] has identified the best option as having 22 cells per superperiod (15 in the arcs, 7 in the straights) with phase shifts per cell close to 96° horizontally and 60° vertically. Arc and betatron tunes are then $(Q_h, Q_v) = (4.0, 2.5)$ and (11.7,7.2) respectively. Trim quadrupoles can be used to raise Q_v so as to avoid the resonances $2Q_v = 14$ and $4Q_v = 28$ under space charge conditions. Chromaticity correcting sextupoles have been evaluated and have been found to give a large dynamic aperture corresponding to a normalised emittance of about 600 π mm.mr. Sector dipoles, 5.97 m in length, are preferred to parallel edge units to avoid ripples in the vertical β-function (*c.f.* [2]). Short (1.08 m) central dipoles are included to limit the field to $B \sim 1.44$ T at 8 GeV and assist with dispersion control. The main quadrupoles have field gradients $\lesssim 9.8$ T/m at top energy. The overall dimensions of the lattice, which is shown in Figure 1, are 184 m horizontally × 107 m vertically. The optical parameters are shown in Figure 2.

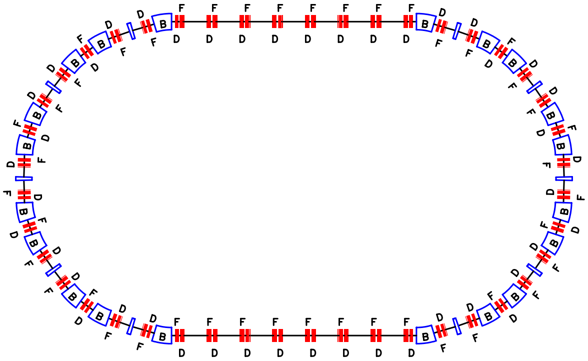

Figure 1: 8 GeV ISIS upgrade synchrotron

The accelerating cycle uses a magnetic dipole field of the form

$$B(t) = B_0 - B_1 \cos 2\pi f t + B_2 \sin 4\pi f t.$$

Choosing the higher harmonic amplitude $B_2 = B_1/4\sqrt{2}$ minimises the maximum value of $\dot{B}$ during the cycle and studies show that this leads to a reduction in total RF voltage, $\hat{V}$, in the ring by about 30%. Operation at $f = 50$ Hz, taking the full ISIS pulse from 0.8 to 3 GeV in just under 12 ms, requires $B_0 = 0.4276$ T, $B_1 = 0.1810$ T and $\hat{V} \sim 570$ kV. Parameters for the cycle are listed in Table 1 and some results from longitudinal simulations are shown in Figure 3. The input beam in these calculations has been taken from ISIS modelling using the dual harmonic RF system currently being implemented and detailed in [3]. The final bunches are 71.5 ns in duration with a momentum spread of $\pm 3 \times 10^{-3}$. In this mode of operation, the machine would be used as a source of spallation neutrons. However, the possibility exists of operating at $f = 16.7$ Hz and accelerating only one pulse in three from ISIS (the others being discarded) to 8 GeV over 30 ms. The aim would be experimental tests of bunch compression to ~1 ns (rms), which is one of the requirements of a proton driver for a neutrino factory. Pion target tests could also be undertaken along with investigations of a prototype pion decay/muon capture channel.

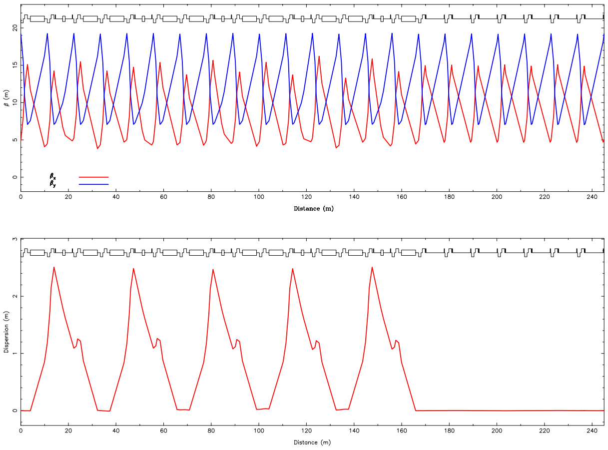

Figure 2: 8 GeV synchrotron optical parameters

Table 1: Acceleration cycle to 3 GeV

Time (ms)	B (T)	$\dot{B}$	Energy (GeV)	Volts (kV)
-0.95	0.237	0.0	0.8	86.6
0.0	0.247	20.10	0.85	422.4
2.0	0.312	39.63	1.21	571.1
5.0	0.428	36.75	1.87	495.2
7.0	0.504	39.78	2.31	516.3
9.0	0.581	33.83	2.77	432.5
10.95	0.619	0.0	3.0	130.0

PHASE 2: THE NEW INJECTOR

In Phase 2, the synchrotron would be upgraded to deliver 2.5 MW of beam power, and a new injector would be developed. ISIS as we know it today would be decommissioned. The dual role of a neutron facility with applications to neutrino factory development would be maintained.

The injector would comprise a 180 MeV H$^-$ linac feeding two 1.2 GeV, 50 Hz booster synchrotrons. The choice

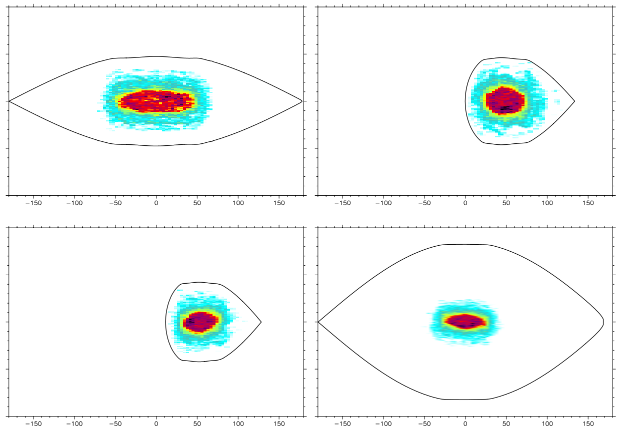

Figure 3: Longitudinal phase space simulation of acceleration to 3 GeV for ISIS2 as a spallation neutron source.

of a low energy linac is based on the need for a small longitudinal emittance (∼1 eV.s) to facilitate final bunch compression [4]. The linac is an extension of the design developed for the ESS [5] and comprises a 60 mA H^- ion source, a 280 MHz RFQ, a 2.5 MeV fast beam chopper and a drift tube linac. Beam chopping is necessary to ensure very low levels of particle loss at ring injection and facilitate clean extraction. For both the new linac and ESS, chopping is achieved by deflecting 30% of the train of micro-bunches to a water-cooled collector by means of an electric field. The field has to rise in the inter-bunch gap, which, being of the order of 2 ns, presents severe technological difficulties. A novel two-stage chopper design has been chosen in which two or three microbunches are initially deflected to a collector with voltages $\sim \pm 2$ kV, so creating a larger gap and easing the rise-time requirements for the much stronger deflection of the remaining beam. A prototype is in the early stages of construction and the design is described in [6].

The transfer line to the rings contains a 180° achromatic arc with both positive and negative bends to create a high normalised dispersion $D/\sqrt{\beta_h}$ for momentum collimation within a relatively compact space. Horizontal and vertical betatron collimation will be included, along with momentum ramping cavities for injection painting.

The 1.2 GeV synchrotrons have mean radius 39 m (half the radius of the main synchrotron) and three bunches of protons would be accumulated in each. The rings would be filled one after the other, and all six bunches would then be transferred to the main ring for final acceleration. Using booster synchrotrons allows the task of accumulating the high intensity proton beam to be separated from the NF final compression, which is carried out in the main ring and is addressed with altogether different lattice requirements. H^- injection into the booster rings is by charge exchange through a carbon, or possibly aluminium oxide, stripping foil at a point in the latttice where the normalised dispersion is ~ 1.6. This allows simultaneous longitudinal and horizontal transverse phase space painting in order to help reduce space charge effects. Longitudinal injection will start into a decelerating bucket and end in an accelerating bucket, with the voltages carefully controlled throughout the cycle to maintain losses at the 10^{-4} level. The principles for these rings are similar to those described in [7].

For a compact site layout, the booster synchrotrons could be stacked one above the other and would ideally fit inside the main synchrotron.

PHASE 3: ADDITION OF A SECOND SYNCHROTRON

The final phase of development would see the addition of a second main synchrotron, stacked vertically above the ring built in Phase I, and operating at 25 Hz. The two booster synchrotrons would be filled one immediately after the other, each with 3 bunches of $\sim 1.7 \times 10^{13}$ protons at 50 Hz. Extraction from the two rings needs to be at the same energy, so would be on the falling edge of the B-field from the first ring and the rising edge in the second. All six bunches would be transferred to one of the main synchrotrons; the process would then be repeated to fill the second. After acceleration, extraction would take place on alternate cycles so as to recover the 50 Hz frequency at the target. Of several possible options, a top energy of $\sim$ 3 GeV could be used for a spallation neutron source; at 6 GeV, bunch compression could be carried out for a 5 MW NF proton driver; or one could use the output from each ring for multiple purposes, one ring for neutrino studies, the other for neutrons, for example.

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