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STUDIES FOR MAJOR ISIS UPGRADES VIA CONVENTIONAL RCS AND ACCUMULATOR RING DESIGNS

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Abstract

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK, which provides 0.2 MW of beam power via a 50 Hz, 800 MeV proton RCS. Detailed studies are now under way to find the optimal configuration for a next generation, short pulsed neutron source that will define a major ISIS upgrade, with construction beginning ~2031. Accelerator configurations being considered for the MW beam powers required include designs exploiting FFAG rings as well as conventional accumulator and synchrotron rings. This paper describes work exploring the latter, conventional options, but includes the possibility of pushing further toward intensity limits to reduce facility costs. The scope of planned studies is summarised, looking at optimal exploitation of existing ISIS infrastructure, and incorporating results from recent target studies and user consultations. Results from initial baseline studies for an accumulator ring and RCS located in the existing ISIS synchrotron hall are presented. The injection scheme, foil limits, longitudinal and transverse beam dynamics optimization with related beam loss are outlined, as are results from detailed 3D PIC simulations.

INTRODUCTION

The ISIS Facility has been operating since 1984 and, as the second target station celebrates 10 years of successful operation, it continues to produce world leading science. This paper outlines studies to identify an optimal configuration for a next generation, short pulse facility "ISIS II" that will build upon experience from existing sources, complement and perhaps exceed their capabilities. More specifically, it examines the accelerator options exploiting conventional rapid cycling synchrotrons (RCS) or accumulator rings (AR).

A NEXT GENERATION SOURCE: ISIS II

Main Upgrade Routes and Timescales

A roadmap defining the research, feasibility and design work required to identify and build an optimal ISIS upgrade has been established [1]. This is drawing upon expertise on neutron instruments, moderators, targets and accelerators, and is driven by user requirements.

Upgrade routes can be based on either exploitation of existing ISIS infrastructure, buildings and utilities to reduce costs, or assume relatively unconstrained "green field" options. Here we concentrate on the former, but future studies will also cover the latter to allow a comparative cost assessment.

Planned timescales for the ISIS II roadmap include an R&D, feasibility and design stage which, on completion in 2027, will define the accelerator and target configuration to be built. A full technical design will follow, finishing in 2031, when construction of the facility will begin.

Current studies focus on re-use of the existing synchrotron hall to house a new ring. A new injector is assumed. Presently ISIS supplies two target stations: TS 1 (40 Hz) and TS 2 (10 Hz). An upgrade route is proposed whereby the existing TS 1 is superseded by a new 1 MW TS 3 (40 Hz) and TS 2 would be upgraded to 0.25 MW (10 Hz). In this scenario, TS 1 would be phased out (with the possibility of further development). These schemes imply a new ring design, constrained to fit the ISIS hall, delivering 1.25 MW at 50 Hz, ideally with a potential for higher powers to allow for future upgrades.

Conventional Ring and FFAG Options

All existing short pulse sources make use of conventional RCS or AR, but recent studies suggest FFAG rings may be a persuasive option. Therefore, both conventional and FFAG rings are being studied for ISIS II. Many issues are common to both types of rings, so research will be complementary.

There are numerous advantages for FFAGs, including avoiding fast cycling magnets, the possibility of higher reprates and flexible pulse structures with slip-stacking schemes. However, FFAGs have yet to be demonstrated as viable high power machines and so a proof of principle test ring is planned. This will have a mean radius of about 4 m and be constructed at ISIS using the FETS facility as an injector. The experimental programme for the test ring will finish in 2027, when results will determine if the FFAG is the best option for ISIS II. The designs of both the test FFAG ring and ISIS II FFAG are presently under study [2].

Based on the above, conventional rings are designed for the ISIS hall, i.e. with R≈26 m, and to provide 1.25 MW at 50 Hz. The essential challenge is achieving low total and uncontrolled ring beam loss, at levels of ~0.2 and 0.02% respectively, whilst minimising costs. Exploratory design parameters are presented here, which satisfy *most* requirements for a workable machine. However, these are expected to change as designs evolve.

ACCUMLATOR RING STUDY

The original ESS studies from 1996 [3] have provided an instructive starting point for designs. These included a 1.334 GeV accumulator ring with R=26 m, and beam powers in the MW regime. This ring was dropped from the ESS study in favour of a larger circumference option to avoid excessive foil re-circulations. New studies, which use the original lattice but have reworked injection and longitudinal dynamics, indicate that ~1.25 MW would be plausible with such a ring. However, in the context of ISIS II, cost

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considerations make RCS designs with a lower energy linac look preferable. A novel feature of the ESS lattice was the highly optimised injection into the dispersive arc and this remains an interesting option.

RCS STUDY

Study Parameters

The main RCS parameters being studied are summarized in Table 1. Other parameters are in the text: all emittances are un-normalised.

Table 1: RCS Working Parameters

Energy Range	0.4 – 1.2 GeV
Intensity	1.3×10^{14} ppp
Repetition Rate	50 Hz
Mean Power	1.25 MW
Circumference (mean R)	163 m (26 m)
No. Super-periods	3
Magnet Excitation	Sinusoidal
Dipole Fields	0.49 – 0.99 T
Gamma Transition	3.78
Peak RF h = (2,4)	(240, 120) kV/turn
RF Frequency (h = 2)	2.62 – 3.30 MHz
Number of Bunches	2

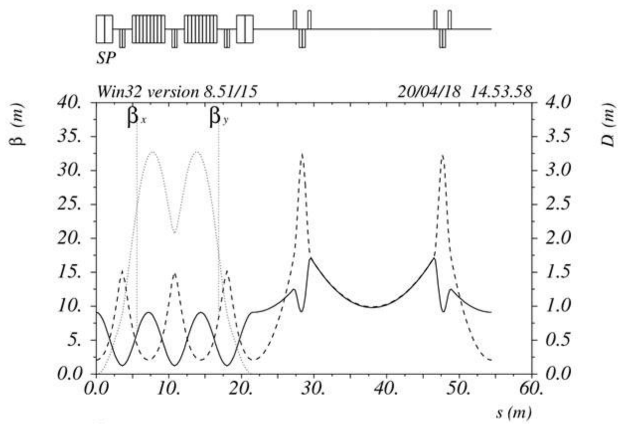

Figure 1: RCS lattice functions.

Ring Lattice

One lattice option under study is shown in Fig. 1. An achromatic arc is constructed from 3 cells with a combined function dipole and a quadrupole which minimises beta functions and peak magnet fields. This is matched into a long dispersion free straight consisting of 2 triplet cells with two 5.50 m and one 16.92 m drift sections. The longer drift space is symmetric about a central beta waist and is long enough to accommodate all injection painting systems: this decouples dynamics from any tune ramping which may be required. Remaining ring drift lengths are sufficient to allow for RF systems, collimation and fast extraction. Beta functions in the central triplet are high, 32 m, but still allow the possibility for large transverse acceptances (~900 π mm mr) whilst keeping practical apertures for the 50 Hz magnets. Variations with a number of working points are being considered: e.g. $(Q_h, Q_v) \approx (4.40, 4.36)$ and split tunes ≈ (4.40, 3.86).

Injection

Ring injection assumes a 0.4 GeV, 58 mA, H^- beam, with a pulse length of 600 µs, or 786 turns, chopped at duty factor 0.6 for direct capture in 2 RF buckets. Injection timing is symmetric about the minimum of the sinusoidal main magnet field.

The 300 µg/cm² carbon foil is displaced by 65 mm in both planes from the circulating axis and is located at the midpoint of a four magnet, symmetric, horizontal orbit bump. A set of similar, faster, programmable painting bumps are also provided in each plane. This allows flexible, independent horizontal, vertical and longitudinal painting.

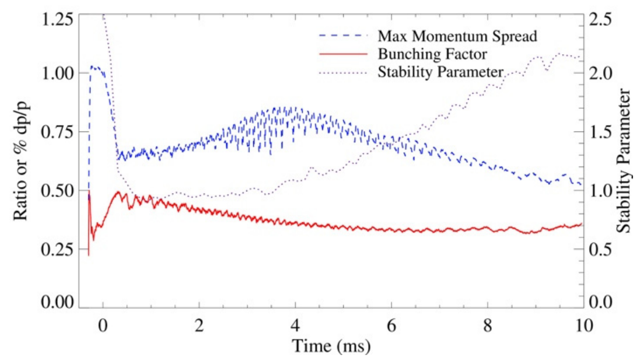

Figure 2: Longitudinal parameters vs time.

A dual harmonic RF system, with h=(2, 4), see Table 1, is required to accelerate the 2 bunches. A sinusoidal, 50 Hz main magnet field is assumed. Ferrite tuned cavities for each harmonic are selected for power efficiency and would be accommodated reasonably in the lattice (requiring ~40 m). A workable longitudinal painting scheme has been devised which exploits ring RF manipulations with fixed injection energy and achieves bunching factors of ~0.3-0.4 with reasonable stability parameters, Fig. 2 [4]. Longitudinal 1D simulations with space charge indicate well controlled bunches with zero loss: further optimisations are being studied.

3D Dynamics and Simulation

Beam dynamics studies use the particle tracking code ORBIT [5]. Physics effects include the use of the '3Dspacecharge' routine, foil scattering and collimation limits as appropriate. Simulations are based on tracking one bunch with 1.5×10^6 macro-particles. The model includes all the details of the longitudinal and transverse painting process, presently the lattice is linear and without errors. In-house PIC codes are also being used for the longitudinal and transverse beam studies.

Transverse Injection Optimisation

Achieving optimal injection is critical for high intensity operation, specifically for controlling foil re-circulations, foil temperatures, beam distributions and any resulting loss. One painting scheme being studied, as defined by the

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painting bumps in both planes, is shown in Fig. 3. The oscillating, correlated bump, that moves the closed orbit away from the foil through injection, has been found to significantly reduce foil re-circulations in numerical optimisations. The centroid of the $\varepsilon_h \approx \varepsilon_v \approx 10\ \pi$ mm mr emmitance injected beam is painted over ring emittances of 200 π mm mr. Simulations indicate an average of 1.4 foil re-circulations, with initial calculations of carbon foil temperatures indicating safe levels of ≈1640 K.

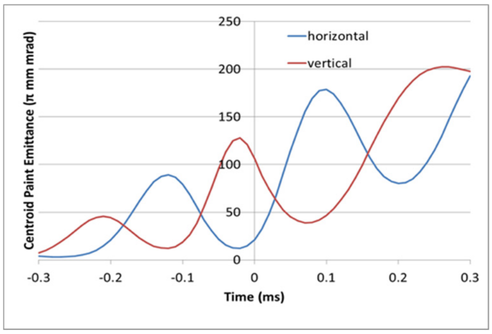

Figure 3: Transverse painting functions.

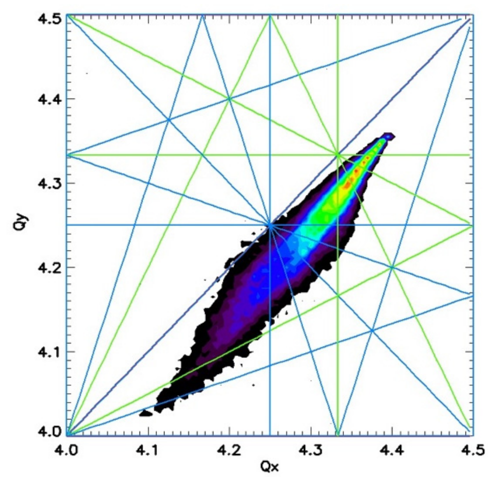

Figure 4: Tune shifts at the end of injection (ORBIT).

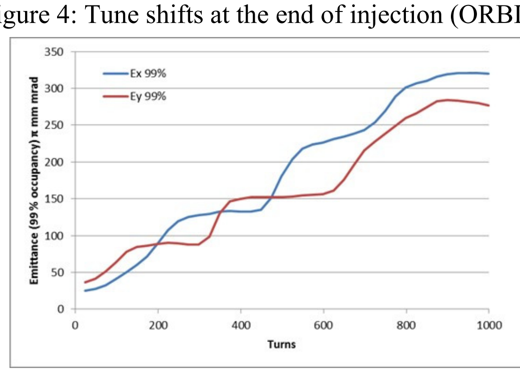

Figure 5: Evolution of 99% emittances vs turn (ORBIT).

Transverse Dynamics and Working Point

Using the injection scheme described above leads to (99%) beam emittances of about 300 π mm mr (with space charge). At the design intensity this corresponds to peak incoherent tune shifts of ~0.3 in both planes. A working point near $(Q_h, Q_v) \approx (4.40, 4.36)$ is presently being assessed, and avoids main low order resonances, the Montague resonance and most systematic terms: see Fig. 4. Detailed studies with space charge have yet to be completed, but initial ORBIT simulations (with no errors) show reasonably controlled emittances at 1.25 MW levels: 99% emittances are within $(\varepsilon_h, \varepsilon_v) = (330, 280)\ \pi$ mm mr, 200 turns after injection, see Fig. 5. A set of ORBIT simulations investigating total loss as a function of collimator acceptance suggest values of around $\varepsilon_h \approx \varepsilon_v \approx 480\ \pi$ mm mr would be required for the ~0.2% losses required: it is expected further optimisations will reduce this.

Key High Intensity R&D

Initial results indicate the basis of a workable design and viable options to increase injection energy and enlarge apertures would help ease loss constraints. However, there are key areas to address, in particular: study of working point with space charge and errors, further injection painting optimisation, 3D simulations of acceleration and studies of coherent instabilities.

Detailed Designs and Developments

The above lattice allows sufficient space for injection, extraction, two-stage collimation systems, correction elements and diagnostics. Once the main high intensity requirements are satisfied, detailed layouts of these systems will be determined e.g. injection straight and magnet design with removal of stripping products, modelling of collimation systems and activation. Direct proton injection using a tilted septum (no foil) is also being studied, and injection over 400 turns is being achieved in simulations with no space charge: more detailed work is needed. Long term options for ISIS upgrades, with beam powers of ~2.5 MW are highly plausible, by stacking two rings vertically in the ISIS hall, using a common injector.

SUMMARY

A roadmap for research, design and construction of a next generation, short pulse neutron source, ISIS II, has been established. Extensive research to identify the optimal facility and accelerator configuration is under way, including options for FFAG and conventional RCS rings. Outline designs for 1.25 MW RCS rings that would fit in the existing ISIS hall are under detailed study and look promising, as do options for powers up to ~2.5 MW.

REFERENCES

[1] J. Thomason *et al.*, ISIS II "Working Group Report", `https://www.isis.stfc.ac.uk/Pages/isis-ii-working-group-report16266.pdf`

[2] S. Machida, "Space Charge Effects in FFAGs", presented at Space Charge 2017, GSI Darmstadt, Germany, Oct. 2017, `https://indico.gsi.de/event/5600/`

[3] "ESS Technical Design Study", ESS, vol. 3, Rep. ESS-96-53-M, 1996.

[4] R. E. Williamson *et al.*, "High Intensity Longitudinal Dynamics Studies for an ISIS Injection Upgrade", in *Proc. HB'12*, pp. 492 – 496.

[5] J. Holmes *et al.*, ORBIT User Manual, ORNL Tech. Note SNS/ORNL/AP/011, 1999.