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PROGRESS ON DESIGN STUDIES FOR THE ISIS II UPGRADE

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Abstract

ISIS, the spallation neutron source at the Rutherford Appleton Laboratory in the UK, uses a 50 Hz, 800 MeV proton RCS to provide a beam power of 0.2 MW, delivered in 0.4 μs long pulses. Detailed studies are now under way for a major upgrade. Accelerator designs using FFAs, conventional accumulator and synchrotron rings are being considered for the required MW beam power. This paper summarises the scope of the different research incorporating results from recent target studies and user consultations. Preliminary results for Fixed Field Alternating gradient (FFA) rings and conventional rings located in the existing ISIS synchrotron hall are presented.

INTRODUCTION

The ISIS Facility has been successfully producing world leading science for 35 years [1]. Studies are now under way to identify an optimal configuration for a next generation, short pulse facility “ISIS II” that will build upon experience from existing sources and consultations with users. A roadmap defining the research, feasibility and design work required to identify and build an optimal ISIS upgrade has been established [2]. The roadmap includes 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. Options for a standalone facility or exploitation of existing ISIS infrastructure, building and utilities to reduce costs will be considered. Current studies focus on reuse of the existing synchrotron hall to house a new ring. Presently ISIS supplies two target stations: TS1 (40 Hz) and TS2 (10 Hz). An upgrade route is proposed whereby the existing TS1 is superseded by a new 1 MW TS3 (40 Hz) and TS2 would be upgraded to 0.25 MW (10 Hz), while TS1 would be either phased out or further developed. These schemes imply a new proton driver design, delivering a 1.2 GeV proton beam with a power of 1.25 MW and a repetition rate of 50 Hz or higher. A new superconducting linac, accelerating particles to 0.4 or 1.2 GeV, is assumed as an injector. Conventional accumulator (AR) and synchrotron (RCS) rings options are first reported here, followed by FFA ring options.

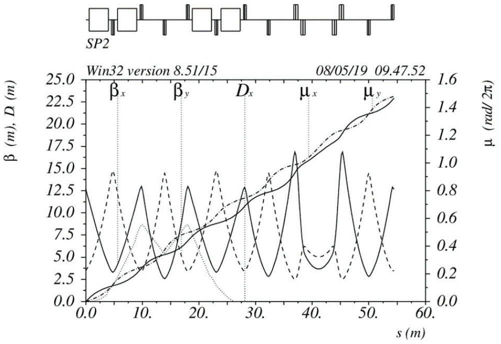

Figure 1: Optics for an RCS lattice option.

RCS AND AR

Ring Options

Design studies are presently focussed on the most constrained case of an RCS with a mean radius of 26 m that would fit in the existing ISIS hall. Solutions for this should then be adaptable to the less demanding accumulator ring option. An outline design for a 0.4 - 1.2 GeV, 50 Hz, 1.25 MW RCS, was summarised in [3]. This indicated essential aspects of the design were feasible, most importantly injection and beam loss (~0.2%). It was noted that two such rings could be stacked in the ISIS hall, giving beam powers of 2.5 MW. Work is now directed at optimising these designs, and in particular, understanding their intensity limitations.

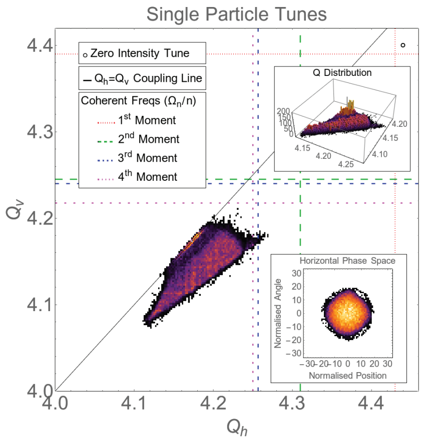

Figure 2: $(Q_\mathrm{h}, Q_\mathrm{v})$, (X_h, X_h') Distributions and Coherent Beam Moments from Set 2D PIC Study.

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Ring Lattice Options, Layout and Design

A range of lattice optics and super-periodicities (SP) are being evaluated. Optics of a promising 3 SP variation based on an achromatic FODO arc and doublet straight is shown in Fig. 1. This avoids the large cell phase advances and beta functions of the previous design [3]. All options include suitable straights and optics for optimised injection, RF, extraction and collimation. Detailed studies are in progress evaluating the effects of randomised magnet errors and misalignments, along with suitable orbit correction schemes. The tunability of the betatron working point is also being explored, with possible benefits for machine flexibility. Non-linear correction and chromaticity control are also being accommodated. Collimation designs are being laid out, with two-stage transverse systems and provision for controlling longitudinal and foil losses. For each candidate lattice, overall performance is being assessed, in addition to critical injection and beam loss requirements.

Beam Dynamics Work

To achieve the required beam loss levels of <0.2% detailed studies of the beam dynamics are required. 2D PIC simulations with the in-house Set code [4] have been used to investigate transverse behaviour of the above lattice around the working point of $(Q_\mathrm{h}, Q_\mathrm{v}) = (4.44, 4.40)$. Figure 2 shows the tune plane for a test run with a 1% mismatched waterbag beam over 100 turns, at design intensities ($\sim 1.3 \times 10^{14}$ protons per pulse), with space charge and representative quadrupole error driving terms included. These simulations help characterise expected loss mechanisms: coupling effects are evident ($2Q_\mathrm{h} - 2Q_\mathrm{v} = 0$) as is octupole structure due to a coherent space charge driving term ($4Q_\mathrm{h} = 17$). Understanding these effects is critical to detailed control of the beam during injection painting. 3D ORBIT and Set simulations, with tools to study particle motion in 6D are also being developed to allow the effects of bunching and synchrotron motion on injection and transverse loss to be quantified. Forthcoming studies will consider instabilities as well as options for higher repetition rates in accumulator rings.

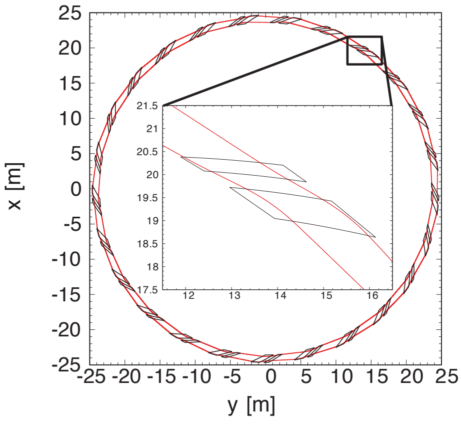

Figure 3: Spiral FFA ISIS upgrade lattice with 25 cells with closed orbits of injection and extraction momenta.

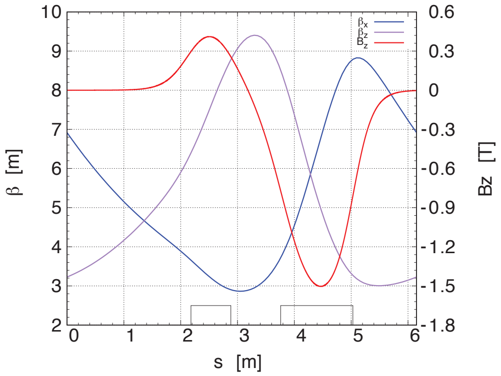

Figure 4: Vertical magnetic field on the median plane and beta functions of the DF spiral cell at extraction energy (1.2 GeV).

FFA RINGS

Proton drivers for neutron production have been based so far either on RCS or full energy linacs with an accumulator ring. However, FFAs have several advantages as a proton driver of a spallation neutron source. First, their energy efficiency can be high, since DC magnets can easily be designed with superconducting technology or permanent magnets. Secondly, they can deliver high average beam current, because the acceleration pattern is not constrained by the magnetic field ramping speed as it is in synchrotrons, but is solely determined by the RF voltage and frequency. Thirdly, the possible high repetition rate from an FFA accelerator could be used to deliver pulsed beams to multiple target stations at different rates so that neutrons could be generated with a variety of time structures. An FFA test ring is proposed to confirm these features experimentally and to build engineering experience, using the 3 MeV beam from RAL's R&D injector, FETS [5].

Two FFA options are currently considered for the ISIS-II ring lattice. The first one is a horizontal orbit excursion FFA based on the DF spiral design [6] and the second is an FFA in which the orbit moves vertically (vFFA) [7–9]. The latter is more challenging because this kind of machine has never been built before.

DF Spiral FFA Option

Designing a lattice with logarithmic spiral FFA magnets gives a constant edge focussing independent of the beam momentum and eliminates reverse bending magnets compared to radial sector FFAs. Spiral FFAs thus have a smaller circumference, but the possibility of adjusting focussing in the transverse plane is very limited. The field gradient of the main magnets could be changed if pole-face winding coils are used. However, this would only allow adjustment of the transverse tune in a very confined range, which could be a problem for the initial commissioning, especially for high current proton accelerators where the tune depends on the beam current.

A DF spiral lattice, which features normal and reverse bending magnets with a spiral edge angle, is a compromise between machine circumference size and tune flexibility [6]. Table 1 shows the parameters identified for an upgrade lattice for ISIS. The number of cells was chosen as 25 so that a systematic 5th order resonance coincides with an integer. Space charge driven resonances at a quarter integer prohibit an operating tune just above a quarter integer. A cell number that is a multiple of 5 gives the largest resonance-free space between an integer and a quarter integer. Almost equal horizontal and vertical tunes are chosen because it is the empirical best operating point of the most recently built high current accelerators, e.g. SNS and J-PARC. The spiral angle is chosen at around 60 degrees since it is the engineering limit. Figure 3 shows the top view of the DF spiral lattice.

Table 1: Parameters of DF Spiral 1.2 GeV FFA

Kinetic energy	0.4 - 1.2 GeV
Reference radius	24 m
Number of cells	25
Packing factor	0.35
Straight section	3.58 m
Spiral angle	62 deg
k-index	20.6
Ratio Bd/Bf strength	-0.443
Orbit excursion	0.8 m
Cell tune (H, V)	(0.2073, 0.2098)
Ring tune (H, V)	(5.18, 5.24)
Transition gamma	4.6

Figure 4 shows the vertical magnetic field strength along the closed orbit and the beta function at the extraction momentum.

Vertical FFA Option

A vFFA has main magnets whose vertical field strength changes exponentially in the vertical direction ($B_z = B_0 e^{mz}$) with proper restoring forces in transverse directions. This means the equilibrium orbit for different beam momenta shifts vertically. This arrangement has several advantages. First, it results in an orbit radius independent of momentum, like synchrotrons. Second, the horizontal dispersion function and the momentum compaction factor are zero, with infinite transition energy. Third, the scaling property is separated from the geometrical arrangement of the lattice footprint. In principle, the ring could have any shape and it would still be possible to maintain a scaling property as long as the vertical magnetic field satisfies the design shape of scaling magnets. Finally, a rectangular shape for the main magnets and the coil geometry is simpler compared to the spiral magnet. Parameters of the test ring lattice presented above have been examined first (see Table 2). Magnetic fields are expanded from the ideal mid-plane field (the mid-plane for a vFFA is a zero-displaced plane in the horizontal direction) so that the fields satisfy Maxwell's equations. Figure 5 shows the top and side view of the vFFA test ring cell. Figure 6 shows the magnetic field components along the orbit at the extraction momentum.

Table 2: Parameters of Test Ring vFFA

Kinetic energy	3 - 12 MeV
Reference radius	3.9789 m
Number of cells	10
Packing factor	0.32
Straight section	1.0 m (long), 0.5 m (short)
m-index	1.6 m^{-1}
Ratio Bd/Bf strength	-0.47
Orbit excursion	0.4 m
Cell tune (H, V)	(0.19, 0.16)
Transition gamma	infinite

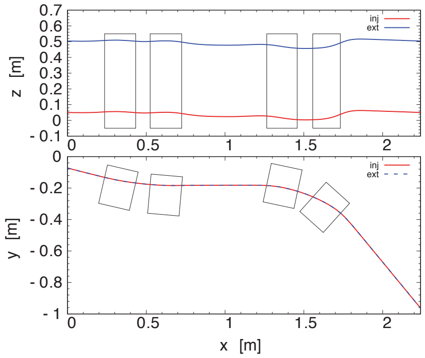

Figure 5: vFFA test ring cell from the side (top part) and from the top (bottom part).

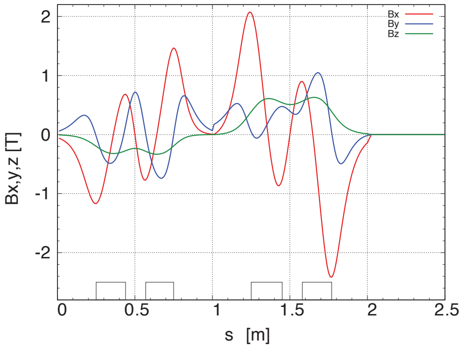

Figure 6: Magnetic field components on the closed orbit in the vFFA test ring cell at extraction momentum.

SUMMARY

A roadmap for research, design and construction of a next generation, short pulse neutron source, ISIS II, has been established. Extensive research is under way to identify the optimal facility and accelerator configuration, including options for FFA as well as conventional RCS and accumulator rings. Designs for the 1.25 MW rings that would fit in the existing ISIS hall are now under detailed study. A test ring to demonstrate experimentally the features of the FFA is planned.

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