ISIS-II UPDATE

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Abstract

ISIS, the spallation Neutron and Muon source at the Rutherford Appleton Laboratory in the UK, uses a 50 Hz, 800 MeV proton rapid cycling synchrotron (RCS) to provide an average beam power of 0.2 MW to its two fixed targets. Whilst demand to answer fundamental questions in materials science is growing, access to neutron research methods is expected to become more limited in Europe as reactor-based sources close [1]. In answer to this, detailed studies for a new major pulsed neutron facility, ISIS-II, are now under way [2, 3]. Fixed-Field Alternating gradient accelerators (FFAs), accumulator rings (ARs) and rapid cycling synchrotrons are being considered to provide the required MW beam power for this new facility. Progress on all three accelerator options will be summarised, and relevant experimental results demonstrating beam stacking at the KURNS FFA will be presented.

INTRODUCTION

The ISIS Neutron and Muon Source at the Rutherford Appleton Laboratory has produced world-leading science for close to 40 years [4]. Despite the anticipated capacity of a new ESS facility [5], the number of neutron instrument-days available in Europe is expected to fall in the coming decade as reactor-based sources close [1]. This will create an increased demand at the remaining sources such as ISIS, and a supply gap in the number of instrument-days available [1, 3]. A new short pulsed facility, “ISIS-II”, has been proposed to address this gap [3], and a roadmap established which includes an R&D, feasibility and design stage that will conclude in 2027 [6]. The new facility will be designed in collaboration with neutron users, but is expected to be driven by a MW-class proton accelerator.

RCS and AR designs build on the experience of existing facilities, whilst the FFA option would be the world’s first high-intensity FFA and requires a demonstrator. For this purpose, the FETS-FFA is currently being developed at the Rutherford Appleton Laboratory and will serve as a testbed for techniques such as low-loss injection and extraction from an FFA [7].

CONVENTIONAL RING DESIGNS

Figure 1: Possible placement of ISIS-II on the RAL site.

The outline design specification is to provide a 1.25 MW proton beam at 1.2 GeV in short, ~1 µs pulses to two targets, one at 40 Hz (1 MW) and a second at 10 Hz (0.25 MW), although these headline figures are yet to be finalised. The key challenge of such a high power machine is in achieving low beam loss levels of ~0.1% such that activation is reduced to a level where hands-on maintenance of components is possible.

Physics designs of conventional rings have been produced [8] for both siting the new ring in the existing ISIS synchrotron hall or building a stand-alone facility (Fig. 1). However, reuse of the ISIS hall, despite potentially providing significant cost savings, imposes constraints on the design and significantly a long break in neutron production at RAL. Therefore, a stand-alone facility is the preferred choice. A further important choice is between a full energy (1.2 GeV) linac and AR or a lower energy (and cheaper) linac and a more complicated (0.4 - 1.2 GeV) RCS. To help understand the feasibility and challenges of these choices, accelerator designs have been studied of an RCS and an AR as a new stand-alone facility at RAL.

Lattice Design

The same lattice design has been utilised for both AR and RCS and is similar to that of SNS [9], but with drift spaces in the arc sections to accommodate the RCS RF requirements. It incorporates 4 superperiods (see Fig. 2), each comprising a four cell FODO achromatic arc and a two cell reverse doublet for the straights. The nominal working point is (Q_x, Q_y)=(6.40, 6.32) and the circumference is 282 m. Charge exchange injection at 400 MeV accumulates 1.3×10^{14} protons over a 600 µs pulse, with beam chopped at the dominant ($h = 2$) ring RF frequency to allow efficient capture.

The beam is painted in both the transverse and longitudinal planes, with the design carefully optimised to form distributions that minimise beam loss and make best use of the acceptances (600 π and 350 π mm mrad for collimated

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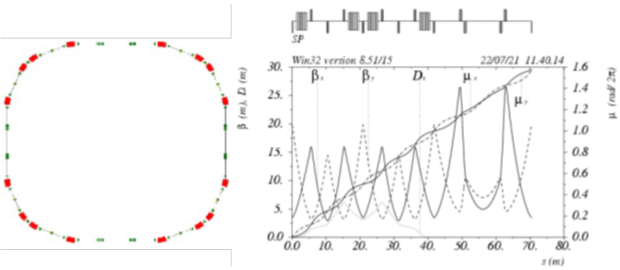

Figure 2: Ring schematic (left) and lattice Twiss parameters, dispersion and phase advance (right).

acceptances of the RCS and AR respectively). Table 1 summarises the main parameters of the stand-alone RCS and AR ISIS-II designs.

Table 1: Key Parameters for Conventional Ring ISIS-II Designs

	RCS	AR
Kinetic energy (GeV)	0.4 - 1.2	1.2
Intensity (protons per pulse)	1.3×10^{14}	1.3×10^{14}
Repetition rate (Hz)	50	50
Circumference (m)	282	282
Number of superperiods	4	4
Magnet Excitation	Sinusoidal	DC
Dipole fields (T)	0.42 - 0.89	0.89
Nominal betatron tunes (Q_x, Q_y)	(6.40, 6.32)	(6.40, 6.32)
Gamma transition, γ_t	5.2	5.2
Peak RF volts h =(2,4) (kV/turn)	(300, 150)	(50, 28)
RF frequency, h = 2 (MHz)	1.52 - 1.91	1.91
Acceptances: collimation, aperture (π mm mrad) ($\Delta p/p \pm 0.01$)	600, 750	350, 500
Natural chromaticity ξ_x, ξ_y	-11.49, -9.62	-11.49, -9.62
Momentum compaction, α_c	0.036	0.036
Number of injected turns	455	573

Design Elements

Both RCS and AR designs include detailed studies into longitudinal and transverse beam dynamics, combined 3D beam dynamics, charge-exchange foils and injection straight, correction magnets, collimation, extraction system and instabilities [8]. Each machine has its own challenges in meeting the demanding physics specification. For example, the RCS injects at lower energy and has larger space charge effects whilst the AR, with injection at higher energy, requires a thicker injection foil leading to more foil heating.

Detailed PIC simulations using PyORBIT [10] have been performed of injection and trapping with full 6D dynamics, space charge, magnet multipole errors and chromatic correction. Probing the beam extremes with virtual scrapers shows the beam acceptance for 0.1% loss is 585 π and 250 π mm mrad for RCS and AR respectively, in close agreement to initial estimates. Longitudinal distributions are well-controlled through acceleration, however transverse emittance growth continues longer than expected and is the subject of further study.

Further Work

The ISIS-II RCS and AR feasibility designs have identified good solutions within conventional technology limits for a stand-alone facility. However, more detailed simulations investigating beam loss below the 0.1% level are essential for reaching, optimising and exceeding current state-of-the-art designs. Studies are ongoing into loss mechanisms and the production of more realistic models with appropriate magnet errors and impedances, benchmarked on the current ISIS synchrotron [11]. Furthermore, operating in a sustainable manner is increasingly a priority on ISIS and for the design of ISIS-II. Incorporating full lifetime carbon costs is now under consideration and will inform the next iteration of designs.

FFA DESIGN

For a future accelerator based facility, sustainability and stable operation are factors that will be given more weight. An FFA is expected to have an advantage in that respect.

A proposal of an FFA accelerator as a high intensity proton driver or as a spallation neutron driver is not new [12]. Long before conventional ring options were established, an FFA was considered as a credible option. Unfortunately, it was hard to convince people to choose this option because there was no FFA constructed other than a small proof of principle machine. Nowadays a couple of FFA accelerators are running for a variety of applications. Flexibility of the output energy and wide momentum acceptance are among unique features an FFA can provide easily. The applications the existing FFAs are dedicated to, however, do not require high intensity, either in average or at peak. The experimental validation of high intensity acceleration in an FFA, more specifically the same level of space charge tune shift as in RCS or AR has not been achieved.

FETS-FFA

To narrow the gap, a project was started to design and construct a prototype high intensity FFA at RAL downstream of Front End Test Stand (FETS). We call it FETS-FFA. FETS-FFA takes the 3 MeV H- beams from FETS linac and accelerates it up to 12 MeV. The momentum ratio of 2 is the same as that of ISIS-II. We aim at achieving space charge tune shift of -0.3 at injection to demonstrate the high intensity operation.

There are three challenges in the physics design. Firstly, the optics should have enough flexibility so that horizontal and vertical tune will be almost equal and both are below 90 degree phase advance per unit cell. The operation of SNS and J-PARC empirically proves that this operation point gives the minimum beam loss. The first choice of tune in a high intensity FFA is set to satisfy the same condition. The FD (or DF) spiral lattice has been proposed which has the flexibility of optics without sacrificing the ratio of average and bending radius [13]. The spiral angle of the magnets reduces the requirement of a D magnet (reverse bending) to increase vertical tune.

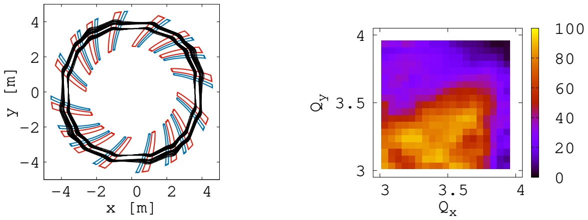

Figure 3: (left) Top view of 4-fold symmetry lattice. Orbits at injection and extraction energy are also shown. There are several orbits corresponding to different operation points in the tune rage from 3 to 4 in H and V. (right) Dynamic aperture of 4-fold symmetry lattice. Colour scale indicates dynamic aperture in π mm mrad (normalised). Q_x=4 and Q_y=4 are the lines where 4^{th} order systematic multipole exists.

Secondly, injection and extraction must be tightly controlled, and enough space must be provided for those systems. An FFA lattice usually has high symmetry consisting of a simple unit cell, but that divide the available straight section into equal distances, which may not be long enough. By introducing 8 different types of magnets or 4 families of FD doublet magnets, we introduce a superperiod structure with 4-fold symmetry. Four out of 16 straight sections increase the length by about 50% where injection and extraction system are installed. The top view of the lattice with injection and extraction orbits at different operating points is shown in Fig. 3 (left).

Finally, transverse emittance must be reasonably large to decrease space charge tune shift with the fixed number of protons. Because all orders of multipoles intrinsically exist in an FFA magnet, the dynamic aperture is a concern. Tune shift with amplitude in the vertical direction due to the octupole component of the fringe field is a primary source of aperture limitation. By optimising parameters such as spiral angle and the distance between 4 families of FD doublet, a normalised dynamic aperture of almost 100 π mm mrad has been achieved (Fig. 3 (right)). Since the nominal emittance after painting is set to be 10 π mm mrad, collimator acceptance is 20 π mm mrad and the physical aperture is set around 40 to 80 π mm mrad, a dynamics aperture of 100 π mm mrad is comfortable.

Table 2 shows the main parameters of 4-fold symmetry FETS-FFA design.

BEAM STACKING

The term beam stacking refers to a number of methods aimed at producing high intensity beams composed of several lower intensity beams [14]. Momentum stacking is one such technique, where previously accelerated bunches coast whilst additional bunches are injected, accelerated and debunched [15]. The resulting stack of coasting beams could then be captured with a suitable RF bucket.

Table 2: Parameters of 4-fold Symmetry FDspiral FFA

	value	unit
Kinetic energy	3 to 12	MeV
Number of superperiod	4	
Number of cell per superperiod	4	
Spiral angle ξ	30	degree
Radius at injection	3.6	m
Geometry of $B_f B_d$ doublet magnet		
B_f magnet	0.2*2π/16	rad
B_d magnet	0.1*2π/16	rad
Space between B_f and B_d magnets	0.1*2π/16	rad
Fringe field model		
$G(s) = 1/\left[1 + \exp\left(c_{10}\frac{s}{\lambda/\cos\xi}\right)\right]$		
defined at 4.0 m		
s: path along azimuthal angle		
c_{10}: Enge coefficient	3.91	
λ: corresponds to the full gap	0.140	m
Nominal superperiod tune	(0.8525, 0.8475)	
Nominal ring tune	(3.41, 3.39)	
Field index k	7.4561	

Momentum stacking has several potential applications at ISIS-II, and is being studied for the FFA and AR designs (momentum stacking is not possible in a standard RCS due to the AC magnet excitation). In both cases, stacking would allow bunches to be extracted at a slower rate than they were injected; making customised user-cycle conditions a possibility. In the FFA case, it could also overcome the intensity limitation due to space charge at injection, and is thus of considerable interest.

Experimental Demonstration at the KURNS FFA

To gain experience with momentum stacking in an FFA, an experiment to stack two beams in the KURNS FFA has been carried out. The procedure was to inject and accelerate beam-1 to its final energy before debunching it adiabatically, then to repeat this process for beam-2 but with a different final energy. The longitudinal Schottky signal was acquired on an electrostatic pickup [16] to measure the revolution frequency distribution of the two coasting beams. Beams were circulated for more than 10^5 turns after the RF amplitude reached zero before coasting-beam data was acquired; see approximate timings and RF amplitudes in Fig. 4. Signals were acquired using an SA-220F5 low-noise amplifier, an 80 MHz low-pass filter and an oscilloscope sampling at 500 MSa/s.

Figure 5 shows power spectral density (PSD) for three cases, around the 8th harmonic of the revolution frequency; PSD was estimated with the Welch method [17]. With one injected beam, a single Schottky peak was observed above the noise of the beam-off signal. When a second beam was stacked at a lower energy, an additional peak was observed at a lower frequency and with a similar amplitude to that of the beam-1 only case. This confirms that stacking has been achieved in the KURNS FFA; however, with two beams injected, the amplitude of the beam-1 peak was approximately halved, indicating beam-loss during the beam-2 acceleration process. The driving mechanism is now under investiga-

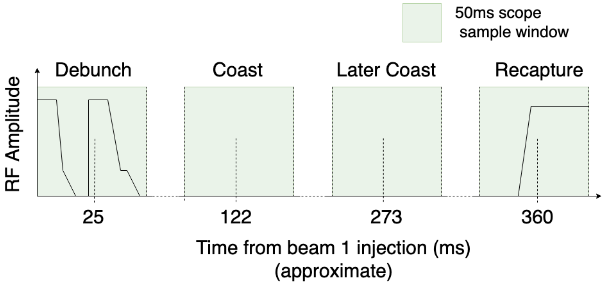

Figure 4: Schematic of RF amplitude versus time, to demonstrate the intended acceleration and debunching procedures and indicate approximate timings. Signal acquisition windows are also shown.

tion, but "RF knockout" [18] is one possible explanation, for which several mitigation techniques have been developed [19, 20]. Follow-up experiments to test these methods are also being developed.

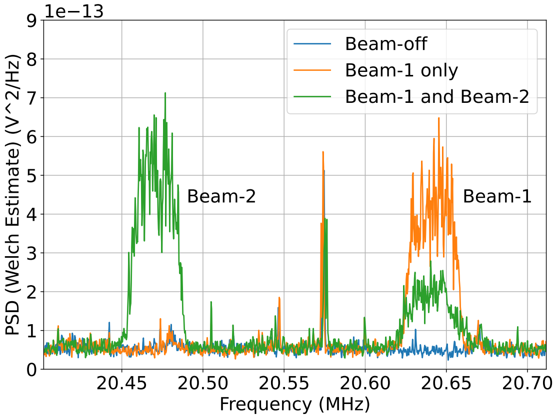

Figure 5: PSD estimate of longitudinal Schottky signals at the 8th revolution harmonic; computed with the Welch method.

CONCLUSION

ISIS-II is a proposed short pulse neutron source to address the upcoming gap in available neutron instrument-days in Europe. Extensive research into RCS, AR and FFA machines capable of providing the necessary beam power is now under way. A lattice for a stand-alone conventional ring has been presented, whose design has been influenced by existing high-intensity accelerator facilities. Since no existing high-intensity FFA-based facilities are currently in operation, the FETS-FFA will act as a demonstrator to guide the development of an ISIS-II FFA design. Beam stacking is being considered to enable a flexible extraction rate in the AR and FFA machines and to alleviate space-charge tune shifts at injection in an FFA. An experiment has successfully demonstrated stacking at the KURNS FFA, and the observed losses are now being investigated.

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