# HIGH INTENSITY STUDIES ON THE ISIS SYNCHROTRON, INCLUDING KEY FACTORS FOR UPGRADES AND THE EFFECTS OF HALF INTEGER RESONANCE

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*Abstract*

ISIS is the spallation neutron source at the Rutherford Appleton Laboratory in the UK. Operation centres on a high intensity proton synchrotron, accelerating $3\times10^{13}$ ppp from 70-800 MeV, at a rep. rate of 50 Hz. Studies are under way looking at many aspects of high intensity behaviour with a view to increasing operational intensity, identifying optimal upgrade routes and understanding more about fundamental intensity limitations. Present work is assessing the possibility of increasing beam power by raising injection energy into the existing ring (to ~180 MeV), with a new optimised injector. Progress on calculations and simulations for the main high intensity topics is presented, including: space charge and emittance evolution in the transverse and longitudinal planes, beam stability, and injection optimisation. Of particular interest is the space charge limit imposed by half integer resonance, for which the latest experimental and simulation results are reviewed.

## HIGH INTENSITY STUDIES AT ISIS

### *Present ISIS Status and Operations*

Following the commissioning of the ISIS second target station in 2008, the ISIS accelerators now supply beam for two neutron target stations [1]. Beam power is being increased to accommodate the new users, and central to this is the high intensity optimisation of the ring, particularly the dual harmonic RF (DHRF) system and associated beam dynamics. Typical operational beam intensities are now 220-230 µA with well controlled losses (~5%). As machine performance is better understood, intensities should approach 240 µA.

The ISIS synchrotron has a circumference of 163 m, composed of 10 superperiods. It accelerates $\sim3\times10^{13}$ ppp (protons per pulse) from 70-800 MeV, on the 10 ms rising edge of the sinusoidal main magnet field. At a repetition rate of 50 Hz this corresponds to an average beam power of ~0.2 MW. Charge-exchange injection takes place over 130 turns, with painting over both transverse acceptances, which are collimated at about 300 π mm mr. Nominal tunes are $Q_{h,v}$=(4.31, 3.83), but these are varied during the cycle using trim quadrupoles. Peak incoherent tune shifts due to space charge are estimated at $\Delta Q_{inc}\approx-0.4$. The beam is essentially unbunched at injection, and is 'adiabatically' captured by the DHRF system. Two bunches are accelerated by the $h$=2, 4 systems, with peak design voltages of 160 and 80 kV/turn respectively. The $h$=2 frequency sweep is 1.3-3.1 MHz. The second harmonic system increases trapping efficiency and improves the bunching factor. The machine operates below transition ($\gamma_t$=5.034) and with natural chromaticities ($\xi_h\approx\xi_v\approx-1.4$). Three fast kickers extract the beam in a single turn, via a vertical septum magnet.

High intensity rings studies address three main areas: increasing intensity for present operations, studying higher intensity potential for the existing ring with a new injector, and assessing options for adding a new ring aiming at ≥1 MW beam powers. Underpinning this work is a programme of code development, experiments and diagnostics improvements to allow study of beam loss mechanisms. Many of the concerns for future upgrades coincide with those for current operations.

### *ISIS Injection and Megawatt Upgrades*

The age and associated risk of breakdown are motivating plans to replace large sections of the ISIS 70 MeV linac. Such a replacement could be combined with an overall upgrade to the injector and injection system into the existing ISIS ring. If the injection energy were to be increased (~180 MeV), and injection optimised, there is the prospect of substantially increased beam power (perhaps ~0.5 MW). Although there are numerous potential problems with such a scheme, it could offer a high value upgrade path. Increases in beam power may also carry through to later upgrades. This option is the subject of current studies and is discussed below.

For beam powers in the megawatt regime, ISIS upgrades would make use of an additional 3.2 GeV RCS. Direct injection from the present 800 MeV ring would provide beam powers of ~1 MW. The 3.2 GeV ring could then be adapted for multi-turn charge-exchange injection from a new 800 MeV linac, and provide beam powers of 2-5 MW. Appropriate designs have been described in [2] and will be studied in more detail in due course.

## HIGH INTENSITY ISSUES FOR INJECTION UPGRADES

A set of *working parameters* is assumed for the injection upgrade study: whether these are optimal, or the proposed intensities are practical, is to be determined. The starting point is a new 180 MeV injector, with chopped beam injection into the present ring. A suitable linac design has been established [2], which defines the injected beam parameters. *Provisional* working values for intensity are $8\times10^{13}$ ppp, corresponding to 0.5 MW. Other (flexible) working assumptions are: acceleration from 180-800 MeV, a sinusoidal main magnet field, injection from the outside of the ring, increased extraction acceptance, and an unchanged rep rate of 50 Hz.

There are numerous practical and beam dynamics issues to be addressed. Practical issues include: a design for a new 180 MeV injection straight, increased activation associated with higher energy loss, loss control, managing foil derived losses, extraction loss, and RF beam loading. These are currently under study [3], with workable solutions looking likely in most areas. Beam dynamics concerns are principally focused on losses related to space charge, instabilities and achieving optimal injection: these are discussed further below.

### Transverse Dynamics Considerations

The main concerns for transverse dynamics are losses associated with space charge and instabilities. Here we address what are expected to be the main mechanisms, but systematic checks for others are under way.

The increase in injection energy gives a reduction in the space charge force as typically characterised by the incoherent tune shift (1), scaling by a factor $\beta^2\gamma^3$. On the present machine space charge peaks during trapping (80 MeV), whilst on the upgrade it peaks at injection (180 MeV). This gives a scaling factor of 2.6, all other parameters being constant, which multiplies the current operational beam power of ~0.2 MW to suggest the upgrade working value of 0.5 MW.

$$\Delta Q_{inc} = \frac{r_p N}{2\pi\beta^2\gamma^3\varepsilon}\frac{1}{B} \qquad (1)$$

Equation (1): the incoherent tune shift for a KV beam, with $r_p$ proton radius, $N$ intensity, $\varepsilon=4\varepsilon_{rms}$, $\beta,\gamma$ are relativistic parameters, $B$ bunching factor. Additional scaling is required for peak shifts of non-KV beams [4].

The change of injection energy also has some potentially less beneficial implications. Transverse emittance damping from 180-800 MeV reduces by 0.6 relative to 70-800 MeV (assuming conserved $\varepsilon^*=\beta\gamma\varepsilon$). This could imply a significant reduction in useful acceptance at injection, if the same extracted emittance is to be preserved. This would substantially reduce $\varepsilon$ when space charge peaks, thus reducing the gains assumed above. However, it is expected that upgrades to the ISIS extraction system could allow for acceptances near those of the ring collimated limits (~300 π mm mr), thus removing this restriction. More detailed checks of the ring and extraction acceptances are under way. Bunching factor is also critical, optimised via the DHRF system, see below.

While space charge is reduced substantially by the injection energy increase, growth rates of important instabilities can be expected to scale most strongly with intensity. The vertical head-tail instability, driven by the resistive-wall impedance, is the most obvious problem already observed on ISIS [5]. At present intensities this instability is avoided by setting $Q_v$ lower, away from $Q_v$=4. This solution will probably not be effective at 2.6 times the intensity, with similarly scaling growth rates. Pushing $Q$'s down further will excite half integer loss: Figure 1. Solutions being considered are damping systems and moving $Q_v$< 3.5. However, simulation studies (below) suggest there may be a structure resonance near this lower working point.

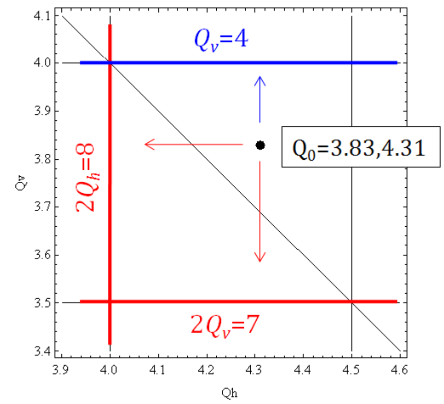


Figure 1: The ISIS Working Point and Main Resonances.

Other potential instabilities and resonances are being assessed. Electron cloud effects are a potential problem, although not yet seen on ISIS: electron monitors are being installed to explore this further. Wideband damping systems are a possible solution. The effects of different transverse painting schemes on halo generation and stability are also under study.

### Transverse Dynamics Simulations

Extensive 2D simulation studies of beam behaviour under expected space charge levels have been undertaken using the code Set [6]. These include the ISIS AG lattice, half integer error terms, closed orbits and the image effects of the rectangular, varying aperture vacuum vessels. These have, so far, identified half integer resonance as the main intensity limiting factor, with a possible image driven structure term near a proposed new working point.

A number of simulations have been used to understand the half integer intensity limit. The main parameters used were: coasting beams of 1-2×$10^{14}$ ppp, in a 4D waterbag distribution, with $\varepsilon_{rmsx}=\varepsilon_{rmsy}$=50 π mm mr, representative half integer stop band widths ($\delta Q_{sb}\approx$0.02, for $2Q_h=8$, $2Q_v=7$) and beam energy of 180 MeV. A nominal working point of $Q_{h,v}$=(4.31, 3.83) was assumed. Beams were rms matched and tracked for 100 turns at various intensities: beam motion and loss were analysed. Development of coherent modes and emittances were studied with collimation limits removed. However, intensity limits were estimated using loss levels (5%) with collimators at realistic apertures. Results for the vertical plane are shown in Figure 2. These show the depression of the coherent envelope mode, with the corresponding increase in its amplitude as resonance is approached. The inset shows characteristic halo formation as the beam blows up.

Simulation results with realistic collimation limits suggest half integer limits occur in the vertical plane first, $2Q_v$=7, at about 1.5×$10^{14}$ ppp; horizontally $2Q_h$=8 at similar, but slightly higher levels. These correspond to $6\times10^{13}$ ppp at a bunching factor of 0.4. Parameters assumed for these simulations are still under study, in particular working points, acceptances and bunching factors. Variations of these may allow higher intensities, e.g. raising the working points. However, as described above, in the vertical plane this is severely constrained by vertical instability near $Q_v$=4. Moving $Q_v$<3.5 is being studied as a possible solution, but the appearance of a possible structure resonance at $3Q_v$=10 described next, may compromise this option.

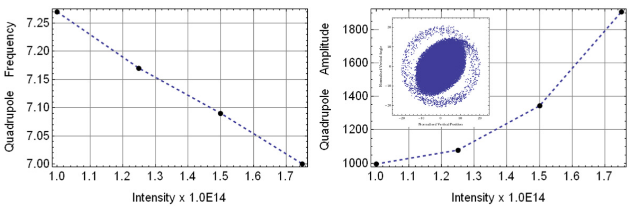


Figure 2: Quadrupole Coherent Frequency and Amplitude vs Intensity; Single particle phase space near resonance.

Simulations at the standard working point, but at higher intensities, suggest an image driven, structure, 3rd order resonance $3Q_v$=10, giving significant loss at $2\times10^{14}$ ppp. At the nominal working point, half integer losses limit intensity first, but if $Q_v$<3.5 it is likely this systematic resonance would be a significant problem. Results from the simulation are shown in Figure 3: again the coherent frequency depresses with intensity, and amplitude grows as resonance is approached. The expected threefold symmetry is seen in particle phase space once the beam redistributes. Further study of the simulation results, and experimental work, will explore this effect further. The 2D simulations above will be extended to include momentum spread and 3D motion in the near future.

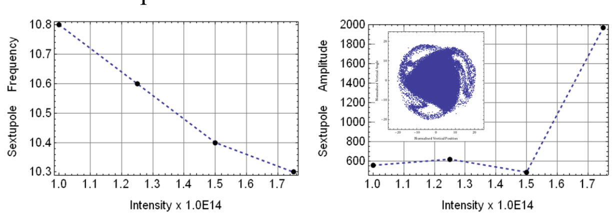


Figure 3: Sextupole Coherent Frequency and Amplitude vs Intensity; Single particle phase space near resonance.

## *Longitudinal Dynamics*

The first stage of assessing the longitudinal dynamics was ensuring beams of $8\times10^{13}$ ppp could be accelerated with realistic RF systems, and satisfying basic beam dynamics requirements. The requirements are: control of space charge, beam stability, maximum bunching factor, momentum spread and pulse length control. Analytical and simulation studies with the idealised Hofmann-Pedersen distribution [7] indicate that stable acceleration of $8\times10^{13}$ ppp should be possible with a dual harmonic RF system defined by:

$$V = V_1 \sin\varphi - V_2 \sin(2\varphi + \theta) \tag{2}$$

Parameters are similar to the present machine, with two bunches and RF harmonic numbers $h$=2, 4. Peak volts of $V_1$=160 and $V_2$=80 kV/turn are required, with $\theta$ sweeping 0 to -70°. The $h$=2 frequency sweep is 2.0-3.1 MHz, and each bunch occupies an emittance of ~1 eV s. Particle simulations using the Hofmann-Pedersen distribution confirm the satisfactory evolution of parameters, controlled bunch lengths and emittances. In particular, bunching factors are ~0.4 and the ratio of induced to applied focusing accelerating voltage is <0.4, preventing appearance of the microwave instability [7], Figure 4.

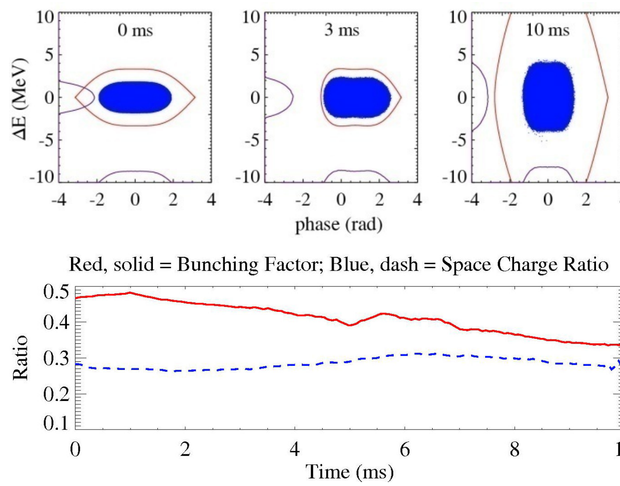


Figure 4: Acceleration of test distribution at 0, 3, 10 ms, at $8\times10^{13}$ ppp, with corresponding evolution of space charge ratio and bunching factor.

Studies now need to demonstrate stable acceleration of more realistic distributions, as generated by injection painting. Trials are currently looking at injection symmetrically around the minimum of the main magnet field, with appropriate RF steering, momentum ramping and manipulation of DHRF parameters to maximise bunching factor. Initial results are promising, with losses <1%, bunching and space charge factors approaching plausible values. However, achieving the intensities proposed is challenging.

## *High Intensity Challenges*

The work above highlights some of the significant issues in the transverse and longitudinal planes. Studies next need to incorporate the effects of realistic 3D painting and likely implications for stability and losses. While the chopped injected beam should offer substantial benefits compared to unbunched trapping of the present machine, control of beam distributions and space charge will be critical. Simulation studies of injection with space charge will help predict beam growth and loss. Many aspects of the proposed upgrade look plausible, but there is important work to be done on some major issues. It remains to be seen if the suggested powers of 0.5 MW will be achievable.

# EXPERIMENTS ON ISIS

## *Storage Ring Mode Experiments*

Experiments putting the ISIS ring into storage ring mode (SRM) are useful for studying aspects of key loss mechanisms. With the RF off, and the main magnet field on a constant DC, observation of a "steady state" coasting beam gives valuable information on instabilities and space charge effects.

## *Instabilities of Coasting Beams*

In normal RCS operation, the resistive-wall impedance can drive a vertical head-tail instability [5], which may be a major intensity limitation in proposed upgrades. It is therefore useful to learn more about vertical stability and impedances using coasting beam experiments.

Once the machine is in SRM, at nominal $Q$ values, ($Q_v \approx 3.8$) the first effect seen as intensities approach $3\times10^{12}$ ppp is beam loss associated with vertical beam growth. This is indicated on profile monitors and position monitors. The latter show strong coherent motion at the lowest betatron side band frequency $(Q_v\text{-}4)\omega_0 = q\omega_0$: the amplitude of this is seen to grow exponentially (growth time ~1 ms), Figure 5. Growth times increase quickly as $Q_v \to 4$, and with intensity. The beam rapidly stabilises as $Q_v$ is lowered. Interestingly, it can be seen on Figure 5, that once beam loss is induced (after 5 ms), other, higher modes appear on the spectrum.

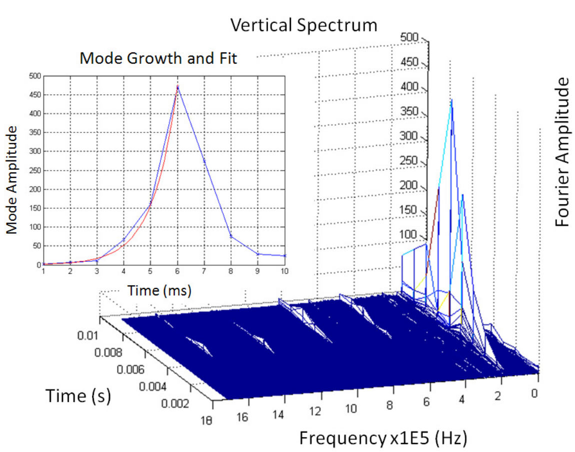


Figure 5: Vertical Dipole Spectrum vs Time.

Observations correspond reasonably well with expectations from basic theory. The transverse frequency shift for a coasting beam (without Landau damping) and the low frequency estimate for transverse resistive-wall impedance are [8]

$$\Delta\omega = i\frac{ec}{4\pi Q\gamma E_0} Z_T I; \quad \mathrm{Re}[Z_{Trw}] \approx \frac{2cR}{b^3 \sigma\omega d} \qquad (3)$$

The associated growth rate is $\tau^{-1} = -\mathrm{Im}[\Delta\omega]$, and so instability corresponds to a real negative impedance. Parameters are standard, with $R$ the machine radius, $b$ the circular pipe aperture, $\sigma$ conductivity, $d$ the skin depth, $I$ beam current. The impedance becomes large for small $\omega$, predicting large growth rates for the low frequency betatron sidebands. That is, where $\omega=(Q+n)\omega_0=q\omega_0$, and $q$ is the fractional part of $Q$; the impedance is negative when $Q$ is below the integer ($q<0$). This explains the dominance of the low frequency sideband, and dependence of growth rate on $Q$ as observed. This estimate (not including the varying, rectangular vessels of ISIS) suggests values of $\mathrm{Re}[Z_{Trw}]$~50 kΩ/m at $Q_v$=3.83. Use of measured growth rates and equation (3) implies corresponding estimates of $\mathrm{Re}[Z_{Trw}]$~200 kΩ/m, with a factor 4 variation with beam size ($\varepsilon_{rmsy}$~20-50 π mm mr). Observed growth rates are thus higher than predictions.

The measurements and experimental techniques above will now allow much more detailed study of impedances. Measurements of frequency shifts and growth rates as a function of $Q$ and $I$ will give information on real and imaginary components of the impedance $Z_T$. This will be useful for RCS mode optimisation, and has also allowed stabilisation of beams for space charge experiments. Similar studies of longitudinal stability are planned.

## *Half Integer Resonance with Coasting Beams*

The action of the half integer resonance under space charge is thought to be a main loss mechanism on ISIS. Studying the loss process under DC conditions allows complications of longitudinal motion to be removed, and the basic process to be studied.

With the ISIS ring in SRM, injection painting can be adjusted to provide a range of beam emittances and intensities suitable for studying envelope resonance. Selecting roughly equal emittances in both planes, $\varepsilon_{rms}\approx20\pm4$ π mm mr, and intensities of $1\times10^{13}$ ppp gives envelope tune shifts of ≈0.3±0.04. These can be found from the round beam, large tune split formulae for envelope frequencies [4]

$$\begin{aligned}\omega_x^2 &= 4Q_{0x}^2 - 5Q_{0x}\Delta Q_{inc,x} \\ \omega_y^2 &= 4Q_{0y}^2 - 5Q_{0x}\Delta Q_{inc,x}\end{aligned} \qquad (4)$$

where $\Delta Q_{inc}$ is defined in equation (1), and $Q_0$'s are zero intensity values. Expected shifts are plotted in Figure 6.

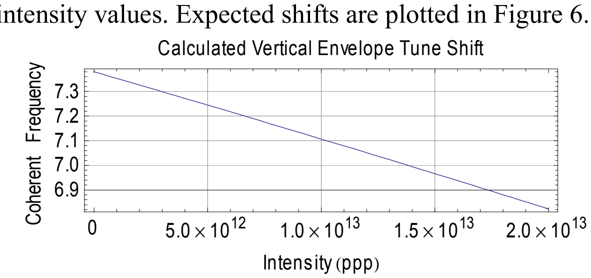


Figure 6: Calculated Envelope Frequency Shift.

ISIS has 20 programmable trim quadrupoles, which allow application of harmonic quadrupole driving terms (i.e. $2Q_v$=7) and independent adjustment of the machine $Q$ values. Profile monitors, with suitable corrections for space charge [9], provide measurements of emittance, and spectra from position monitors allow measurements of coherent, dipole $Q$ values. The latter are used to deduce zero intensity envelope tunes.

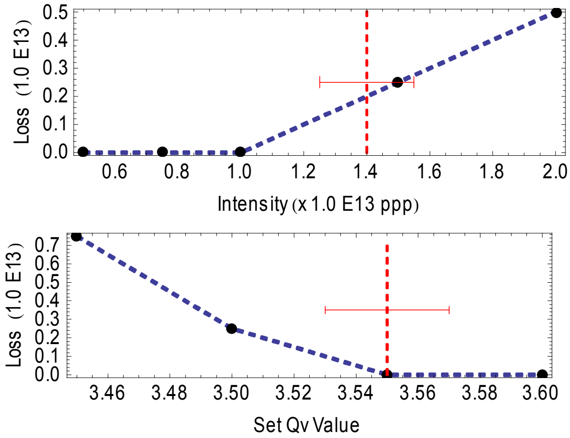


Figure 7: Loss vs Intensity and Loss vs Q, Vertical red line is the predicted envelope resonance.

By varying intensity and $Q$ values it is possible to see if loss occurs where envelope resonance is predicted from equation (4). Two experiments are summarised in Figure 7: fixed $Q_v$ (3.60) and variation of intensity; fixed intensity ($1.0\times10^{13}$ ppp) and variation of $Q_v$. The red line shows the calculated location of envelope resonance, with estimated uncertainty.

Results indicate large losses, and reduction in possible circulating beam intensity, coincident with predicted coherent envelope resonance. These experiments are a useful first step in observing and manipulating the half integer resonance, but more work is required to establish unequivocal measurement. Scheduled calibration work on profile monitors will reduce the main uncertainty, that in the emittances. In the long term, it is hoped that refined beam control and profile measurement will allow observation of parametric halo. In addition, quadrupole kickers and monitors are planned, which should allow direct excitation and observation of the envelope modes. Such observations will be valuable for verification of theory and codes.

### *Some Measurements from RCS Mode*

The resistive-wall, head-tail instability is a key issue for injection upgrades, and may be important for current operations as intensities increase. At the moment, however, beam is stabilised by lowering $Q_v$. Detailed studies of this instability were undertaken 18 years ago during initial ISIS operations [5]; work is now starting to pick this up again. Interestingly, the $m$=1 mode is observed, not the $m$=2 as predicted by theory [5, 8]. Recent measurements of the head-tail motion have been taken in RCS mode at 210 μA, induced by raising $Q_v$: Figure 8 shows vertical motion of the two ISIS bunches. Manipulation of DHRF parameters was seen to affect the motion. Interaction between head-tail stability and longitudinal motion made possible with DHRF are an interesting avenue of study. There are also plans to install strip line monitors and kickers which could form part of a damping system.

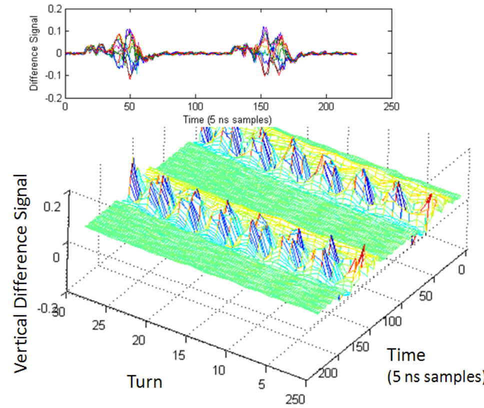


Figure 8: Vertical Head-Tail Motion in RCS Mode.

## SUMMARY & PLANS

Study of many aspects of high intensity beam behaviour are under way at ISIS, as required by operational and upgrade requirements. Beam dynamics study, code development, experimental work and diagnostics developments are all essential to this work, and essential for improved and consistent ISIS performance. Present and proposed upgrades demand an ever improving understanding of the ISIS ring.

## ACKNOWLEDGMENTS

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