# HIGH INTENSITY LONGITUDINAL DYNAMICS STUDIES FOR AN ISIS INJECTION UPGRADE

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## *Abstract*

ISIS is the world's most productive pulsed neutron and muon source, located at the Rutherford Appleton Laboratory in the UK. Operation is centred on a loss-limited 50 Hz proton synchrotron which accelerates $3\times10^{13}$ protons per pulse from 70 MeV to 800 MeV, delivering a mean beam power of 0.2 MW.

Recent upgrade studies at ISIS have centred on a new 180 MeV linac for injection into the existing ring offering the possibility of beam powers in the 0.5 MW regime through reduction in space charge and optimised injection. A central and critical aspect of such an upgrade is the longitudinal dynamics including beam stability, associated RF parameters, space charge levels and stringent requirements on beam loss.

This paper outlines possible longitudinal injection schemes for the injection upgrade meeting key design requirements such as minimising halo, maximising the bunching factor and satisfying the Keil-Schnell-Boussard (KSB) stability criterion throughout acceleration. Details of simulation models including calculation of KSB are given together with associated assumptions. Latest results from studies to understand and confirm stability limits on ISIS via simulation and experiment are presented.

## INTRODUCTION

Present ISIS operations centre on an 800 MeV rapid cycling synchrotron (RCS) accelerating $3\times10^{13}$ protons per pulse (ppp) on the 10 ms rising edge of a sinusoidal main magnet field. At the repetition rate of 50 Hz this corresponds to 0.2 MW. A high intensity proton beam is accumulated via charge-exchange injection of a 70 MeV un-chopped $H^-$ beam. Injection begins 0.4 ms prior to main magnet field minimum, lasting ~200 µs (~135 turns). The proton beam is 'adiabatically' trapped in two bunches by the ring dual harmonic RF system. The RF system consists of 10 ferrite tuned cavities with peak design voltages of 160 and 80 kV/turn for the $h$=2 and $h$=4 harmonics respectively.

A range of ISIS upgrade routes, increasing beam power into the megawatt (MW) regime, is under study [1]. The favoured path increases beam power by a factor of ~4 by adding a ~3.2 GeV RCS onto the output of the present 800 MeV synchrotron, providing 1 MW or more. Subsequently the ~3.2 GeV ring can then be adapted for multi-turn charge-exchange injection from a new 800 MeV linac, increasing beam current and delivering 2 – 5 MW beam powers.

However, with a focus on reliability and affordability priority has been given to the replacement of all, or part of, the 70 MeV $H^-$ injector. This could address obsolescence issues with the current linac and ensure more reliable future operation.

Current studies are centred on the option of installing a new, higher energy (~180 MeV) linac with an optimised injection system into the existing 800 MeV synchrotron [2, 3]. Injecting at higher energy reduces space charge and allows for an increase in beam current and hence power. It also enhances the other upgrade routes mentioned.

A critical aspect of the injection upgrade is the longitudinal beam dynamics in the ISIS RCS. Accelerating a substantially higher intensity beam from 180 to 800 MeV whilst satisfying the necessary constraints is non-trivial. The main constraints include painting a suitable beam (1D and 3D); maintaining slow adiabatic changes and avoiding halo generation; maximising the bunching factor; controlling the momentum spread; achieving near zero loss and staying below known instability thresholds whilst keeping the RF system parameters practical.

For the injection upgrade studies a nominal intensity of $8\times10^{13}$ ppp has been assumed, corresponding to ~0.5 MW operation. The effect this increase in beam current has on the longitudinal space charge and associated instabilities is considerably more challenging than on the present machine. Other key aspects of the injection upgrade such as transverse dynamics and injection studies are covered elsewhere [4, 5].

The basic viability of accelerating $8\times10^{13}$ ppp with realistic RF parameters has been reported [6] simulating a dual harmonic idealised, invariant Hofmann-Pedersen [7, 8] distribution created at main magnet field minimum. Two plausible injection schemes have also been presented [6].

In this paper, following further optimisations, three possible longitudinal injection schemes are presented together with simulation results. The implementation of the KSB stability criterion in the longitudinal dynamics code is elaborated and its output compared to results from the present ISIS.

## INJECTION SCHEMES

Several parameters are available to optimise longitudinal painting over injection. These include the flexibility inherent in dual harmonic RF defined by Equation 1, allowing manipulation in phase space with first and second harmonic voltages ($V_{h=2}$, $V_{h=4}$) and the phase between them ($\theta$).

$$V = V_{h=2}\sin\varphi - V_{h=4}\sin(2\varphi+\theta)\,, \tag{1}$$

where $\varphi$ is the RF phase.

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Designs for the new injector include the option of an energy ramp which can be combined with ring RF steering to paint the energy of the beam. There is also a choice of injection periods: painting over the falling main magnet field (as currently employed on ISIS), on the rising field or symmetrically about field minimum. A number of painting schemes have been identified using different combinations of these parameters that satisfy the longitudinal constraints.

Working parameters for the output of the 180 MeV injector [9] include a beam current of 43 mA, a 70% chopping duty cycle and an adjustable momentum spread of between $\pm 0.3 - 1.0\times10^{-3}$. With these values a beam of $8\times10^{13}$ ppp requires ~500 turns of 3.84 rad ($h$=2, RF phase) chopped beam.

Outlined below are three plausible injection schemes that showcase some of the longitudinal painting techniques available. For all simulations the maximum injected momentum spread available from the injector design, $1.0\times10^{-3}$, is used. RF voltages and phases through acceleration (>1 ms) have been kept the same for each case. These values are within current ISIS RF system design limits, although the additional beam loading at higher intensities may require hardware upgrades. Options for dealing with the additional beam loading are currently under study.

## *Injection Scheme One*

This scheme injects over the falling edge of the main magnet field (-0.5 – 0 ms). The injection energy is linearly ramped from 182.4 to 181.4 MeV over the injection period and the RF frequency is swept non-linearly to give a steer over the range -0.47 – 0.43 MeV relative to the synchronous energy. This combination paints the beam from the centre of the RF bucket to 1.35 MeV off axis.

RF volts are held constant over the injection period at 72 and 57.6 kV per turn, for $h$=2 and $h$=4 respectively, and $\theta$ is varied to maximise the bunching factor. A summary of simulation results for this scheme from the end of injection to 10 ms is shown in Figures 1 and 2.

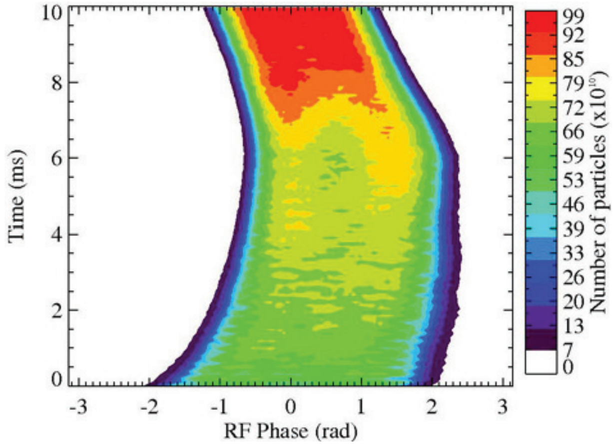

Figure 1: Longitudinal profile evolution from 0 – 10 ms for injection scheme one.

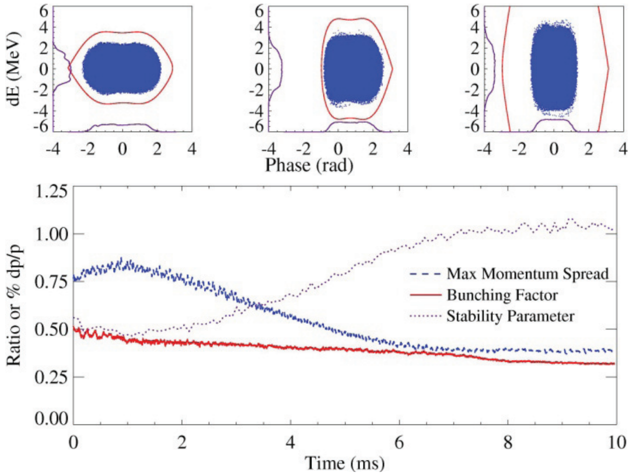

Figure 2: Phase space at the end of injection, 5 and 10 ms and evolution of bunching factor, stability parameter (Eq. 2) and maximum dp/p for injection scheme one.

## *Injection Scheme Two*

The second scheme injects symmetrically about the main magnet field minimum (-0.25 – 0.25 ms) with a constant injection energy of 181 MeV. A non-linear RF steer is used to paint the beam in energy from the centre of the RF bucket to 1.44 MeV off axis.

RF volts are held constant at 72 and 57.6 kV per turn for $h$=2 and $h$=4 respectively, and $\theta$ is varied to maximise the bunching factor through injection as in injection scheme one. The simulation results of this injection scheme are summarised in Figures 3 and 4.

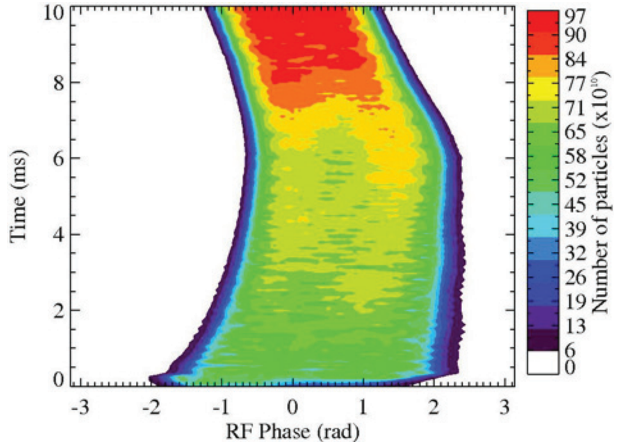

Figure 3: Longitudinal profile evolution from 0 – 10 ms for injection scheme two.

## *Injection Scheme Three*

The third injection scheme paints the beam over the rising edge of the main magnet field (0 – 0.5 ms). The injection energy is linearly ramped over this period from 181 – 182 MeV and the RF frequency is non-linearly ramped resulting in a steer of 1.05 – -0.9 MeV relative to the synchronous energy. The combined effect of this leads to a half sinusoid painting scheme in energy beginning and ending at bucket centre and reaching 0.95 MeV off axis at 0.25 ms.

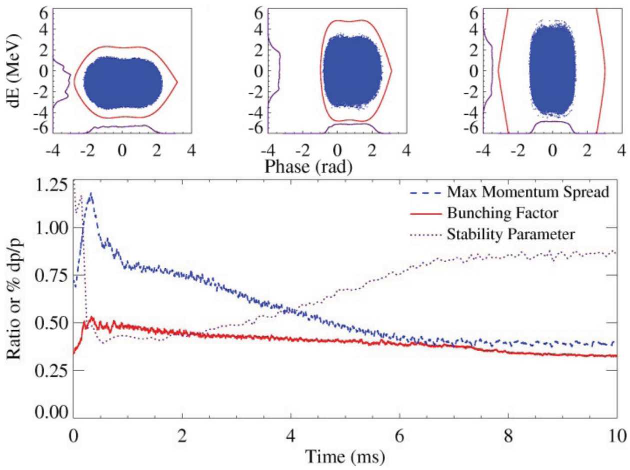

Figure 4: Phase space at the end of injection, 5 and 10 ms and evolution of bunching factor, stability parameter (Eq. 2) and maximum dp/p for injection scheme two.

RF volts are held constant at 72 and 57.6 kV per turn for $h$=2 and $h$=4 respectively and $\theta$ is swept from -1.05 – 0 rad with respect to that required for a 'flat' bucket. This injects the beam into an asymmetric bucket spreading the beam quickly in energy. A summary of simulation results for this scheme is shown in Figures 5 and 6.

### *Comparison of Painting Schemes*

All three painting schemes have their equivalents in the three defined injection periods: over the falling or rising edge of the main magnet field and symmetrically about field minimum. These designs are reasonable working longitudinal solutions for the injection upgrade scenario meeting all the necessary constraints including lossless acceleration, good bunching factors and plausible stability parameters.

Each scheme outlined above paints the beam using a different combination of RF steering, injection energy ramps and dual harmonic RF $\theta$ sweeps. Those involving an injection energy ramp will require extra hardware in the injection line to provide the beam energy control as well as to vary the strengths of magnets downstream to match to the new beam energy.

Figure 2 shows that scheme one operates close to the stability limit with the stability parameter (Eq. 2) peaking just above 1. Schemes two and three, however, have a peak stability parameter of approximately 0.87 and 0.99 respectively. These values have a degree of uncertainty as the stability parameter includes some assumptions about the transverse distribution. These assumptions are outlined in the next section. As noted later ISIS presently exceeds the stability criterion with no observed instability [10].

With fewer hardware requirements and room for manoeuvre with the stability parameter, and therefore painting parameters, injection scheme two appears best longitudinally. However, the flexibility possible with an injection energy ramp is desirable and transverse dynamics also places several constraints on what is possible longitudinally. Therefore these injection schemes are being investigated and further optimised using 3D dynamics simulations [2].

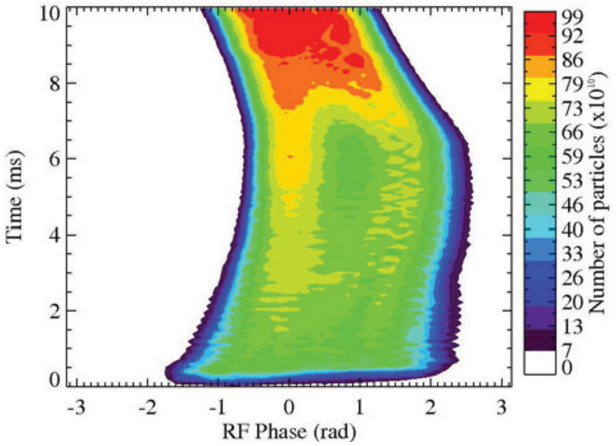

Figure 5: Longitudinal profile evolution from 0 – 10 ms for injection scheme three.

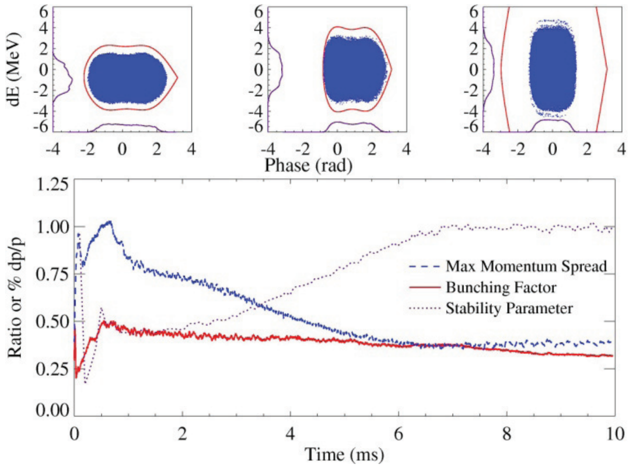

Figure 6: Phase space at the end of injection, 5 and 10 ms and evolution of bunching factor, stability parameter (Eq. 2) and maximum dp/p for injection scheme three.

## LONGITUDINAL DYNAMICS CODE

A stand-alone Particle-In-Cell (PIC) longitudinal tracking code has been written to study longitudinal particle dynamics in ISIS and its proposed upgrades [11]. The code incorporates two space charge calculation routines, one using a Discrete Fourier Transform and the other a difference algorithm, and numerical checks for beam stability using the KSB stability criterion [12]. The implementation of this criterion in the code has been outlined previously [6], however this paper will elaborate on the assumptions required.

### *Keil-Schnell-Boussard Criterion*

Experimental observations and numerical calculations of the dispersion relation have led to the Keil-Schnell criterion for the longitudinal stability of coasting beams. In the case of a bunched beam the modified Keil-Schnell-Boussard criterion (KSB) is used where beam current and energy spread are expressed as a function of RF phase. The criterion can be used at each longitudinal 'slice' to determine the stability along the bunch. A rearranged form of the criterion, as implemented in the code, is shown in Equation 2 as a 'stability parameter' where stability is indicated if its value is less than unity.

$$\frac{|Z|}{n}\frac{1}{F}\frac{e\beta^2}{E|\eta|}\frac{I(\varphi)}{[\Delta E(\varphi)/E]^2} \leq 1 \ , \tag{2}$$

where $Z$ is the impedance; $n$, the mode number; $F$, a form factor; $E$, the total beam energy; $\beta$ and $\eta$ are the usual relativistic factors; $I(\varphi)$, the beam current as a function of RF phase; $\Delta E(\varphi)/E$, the full width at half maximum energy spread of the beam as a function of RF phase.

The code outputs the stability parameter for each longitudinal slice and an average value over the length of the bunch. This enables detailed study of longitudinal stability along the bunch and as a function of time through the acceleration cycle.

### *Form Factor, F*

The KSB criterion includes a form factor, $F$, dependent on the longitudinal distribution function. This is calculated from the threshold for unstable oscillations using the dispersion integral [13].

Assuming a simplified circular stability limit in ($U'$,$V'$) space, $F$ is close to unity for most reasonable, smooth, coasting beam distributions, without sharp edges. This assumption may also hold for bunched beams if the bunch length is much greater than its transverse extent. However, for sharp-edged distributions the form factor can become very small or zero and the full stability diagram must be used. In this study a form factor of unity has been assumed throughout.

### *Space Charge Impedance, $Z_{sc}$*

The impedance in the KSB criterion is assumed to be dominated by the space charge impedance (Eq. 3),

$$Z_{sc} = \frac{gZ_0}{2\beta\gamma^2}, \tag{3}$$

where $Z_0$ is the impedance of free space and $\beta$ and $\gamma$ are the usual relativistic factors. This is dependent on the transverse distribution through the geometric factor, $g$. The code implements the $g$ factor assuming a circular, uniform beam in a concentric circular beam pipe given by Equation 4.

$$g = \ 1 + 2\ln\frac{b}{a} \ , \tag{4}$$

where $b$ and $a$ are the vacuum pipe diameter and 100% beam width respectively.

In the ISIS specific case (and its proposed injection upgrade) careful consideration of the $g$ factor is required to take into account non-uniform transverse distributions and more importantly the rectangular, profiled ISIS vacuum vessel, Figure 7. This was designed to reduce the impact of space charge by keeping the ratio $b/a$ low and approximately constant. Numerical solution is required to evaluate the space charge potential in this case, although there are some semi-analytic solutions for uniform rectangular beams in rectangular beam pipes [14].

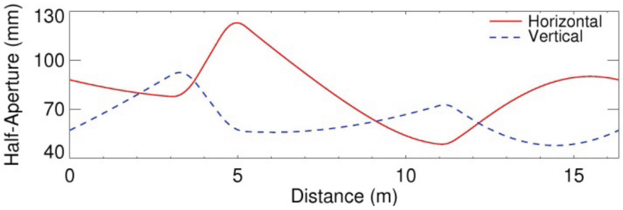

Figure 7: Horizontal and vertical half apertures over one superperiod of the ISIS synchrotron.

Assuming reasonable values for the transverse beam size on ISIS the $g$ factor has been calculated for a uniform rectangular beam in a rectangular vacuum vessel to be around 1 (±0.5 depending on the beam size). An overestimated $g$ factor has been used in this study (1.45) to take into account these errors. Therefore the stability parameters in Figures 2, 4, 6 and 9 are likely to be an overestimate of the true figure in regards to the $g$ factor.

## ISIS STABILITY SIMULATIONS

Using reasonable approximations of the current working parameters, longitudinal dynamics simulations have been performed for present ISIS operations. Figures 8 and 9 summarise these results including the stability parameter (Eq. 2) over the acceleration cycle (note the change in scale).

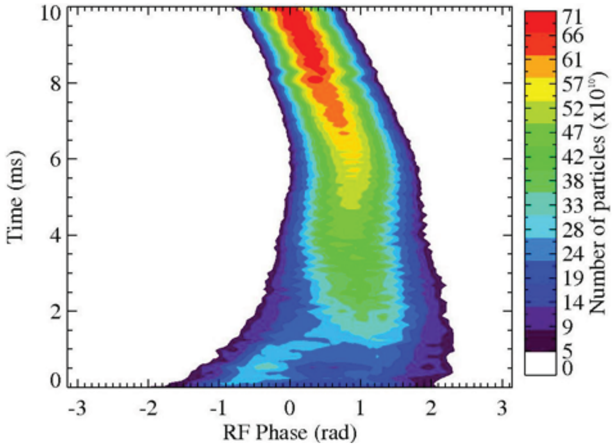

Figure 8: Longitudinal profile evolution from 0 – 10 ms for approximate ISIS working parameters.

Using the assumptions stated above, ISIS operates above the threshold of the KSB stability criterion by a factor of ~6. Previous studies have also shown that ISIS operates above the Keil-Schnell (KS) coasting beam stability threshold during injection [10]. Therefore this suggests that there is a considerable safety margin for stability simulations in ISIS upgrade designs. Fluctuations in the maximum momentum spread prior to 2 ms in Figure 9 are due to controlled particle loss as the RF bunches the continuous beam from the injector.

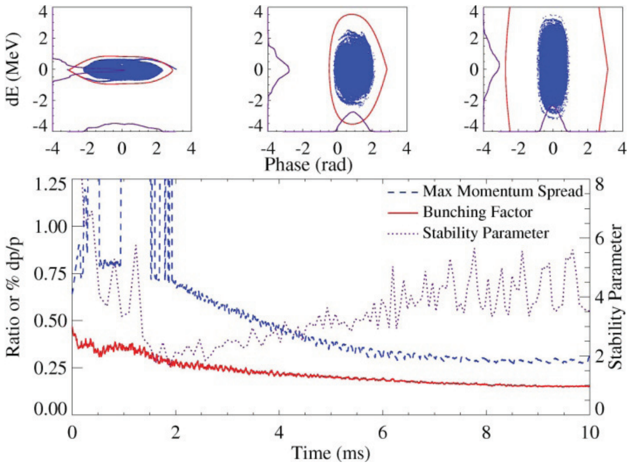

Figure 9: Phase space at the end of injection, 5 and 10 ms and evolution of bunching factor, stability parameter (Eq. 2) and maximum dp/p for approximate ISIS working parameters.

## SUMMARY AND PLANS

Longitudinal dynamics simulations of three plausible injection schemes for the ISIS injection upgrade have been presented. These meet the constraints outlined in the introduction including no longitudinal loss, maximising the bunching factor, controlling the momentum spread and keeping below instability thresholds. Although injection scheme two looks most promising longitudinally, the final design will ideally include some flexibility in longitudinal painting. Further studies using 3D dynamics simulations are being undertaken to explore these, and other, injection options.

An in-house longitudinal beam dynamics code has been further developed to simulate accurately these injection schemes with variable injection energy, RF steering, dual harmonic manipulation and a measure of beam stability. Further additions are planned to account for additional impedances acting on the beam. An in-house parallel 3D PIC tracking code is being produced incorporating the longitudinal code outlined here and the transverse code, Set [4, 15].

Results so far from longitudinal tracking studies suggest the 180 MeV ISIS injection upgrade is realisable, although further research into beam instabilities induced at higher intensities is necessary. Simulations have also shown that ISIS operates above the KSB stability criterion with no observed instability. Therefore beam instability research will also be valuable for the present machine as well as alternative upgrade routes.

An experimental program is planned to induce and measure longitudinal beam instabilities on ISIS. These will include the use of bunched beams in storage ring mode, with the RF on at a fixed frequency and the main magnet field on at a constant DC level, testing the KSB stability criterion. This allows control of the beam energy spread through the RF voltage and as such the stability criterion. Experiments will also be undertaken with coasting beams (storage ring mode with RF off) to test the KS criterion, and in rapid cycling mode (usual ISIS running).

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