# HIGH INTENSITY LONGITUDINAL DYNAMICS STUDIES FOR HIGHER ENERGY INJECTION INTO THE ISIS SYNCHROTRON

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*Abstract*

ISIS is the world's most productive pulsed neutron and muon source, 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.

Present studies on ISIS upgrades are focussed on a new linac for higher energy injection into the existing ring, potentially increasing beam current through reduction in space charge and optimized injection. Studies assume injection of a chopped beam at 180 MeV and offer the possibility of beam powers in the 0.5 MW regime. A critical aspect of such an upgrade is the longitudinal dynamics, associated RF parameters, space charge levels and stringent requirements on beam loss.

This paper outlines studies optimizing longitudinal parameters including key design requirements such as bunching factor and satisfying the Keil-Schnell-Boussard stability criterion throughout acceleration. Work developing and benchmarking the in-house longitudinal dynamics code used for these studies is also summarized.

## INTRODUCTION

A number of reasonable upgrade routes for ISIS, increasing beam power into the megawatt (MW) regime, are currently under study [1]. The recommended upgrade path increases beam power to ~1 MW by adding a ~3.2 GeV RCS onto the output of the existing 800 MeV ring. A further upgrade would then be to accumulate and accelerate beam in the ~3.2 GeV RCS from a new 800 MeV linac for 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 as well as ensuring reliable future operation. Present studies have focussed on the more challenging option of installing a higher energy (~180 MeV) linac with a new optimised injection system into the present 800 MeV RCS [2, 3]. With a higher injection energy transverse space charge is reduced which could allow for an increase in beam current and hence beam power.

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

At the intensities required for ~0.5 MW operation ($8\times10^{13}$ protons per pulse, ppp) however, the effects of longitudinal space charge and instabilities are more challenging than on the present machine.

## HOFMANN-PEDERSEN DISTRIBUTION

The basic viability of accelerating $8\times10^{13}$ ppp with realistic RF systems and satisfying constraints is demonstrated using an idealised invariant Hofmann-Pedersen (HP) distribution [4] created at main magnet field minimum. Analytical and simulation studies have shown this distribution can be accelerated with no longitudinal loss whilst maintaining beam stability (evaluated using the Keil-Schnell-Boussard (KSB) criterion [5], equation 2).

Two bunches are accelerated on the present machine by first ($h$=2) and second ($h$=4) harmonic RF systems. The second harmonic increases trapping efficiency and improves the bunching factor for more stable beam dynamics. The system is defined by:

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

where $\varphi$ is the RF phase and $\theta$ is the phase between the first and second harmonic waveforms. Acceleration of the HP distribution requires parameters similar to the present machine with peak voltages of 144 and 78 kV per turn for $h$=2 and $h$=4 respectively and $\theta$ sweeping from 0 to -70°. Bunching factors are ~0.4 with a 100% longitudinal emittance per bunch of ~1 eVs. A summary of these results is shown in Figure 1.

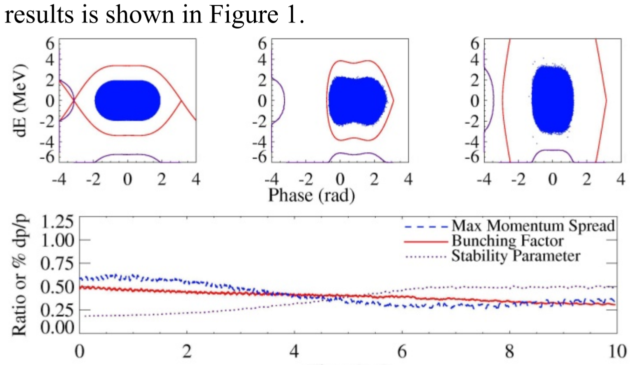


Figure 1: Phase space at 0, 5, 10 ms for $8\times10^{13}$ ppp and evolution of bunching factor, stability parameter (equation 2) and maximum dp/p.

## PAINTED DISTRIBUTION

Realistic painted distributions over hundreds of turns are more challenging to contain and stabilise than the idealised HP case as the result tends to be 'peakier' in the energy plane, with extended tails. However, several plausible painting schemes have been found and two have been pursued in 3D dynamics studies.

A number of parameters are available to optimise longitudinal painting over injection. Designs for the new injector include the possibility of an energy ramp which can be combined with RF steering to paint the beam in energy. Dual harmonic RF allows further manipulation in phase space with first and second harmonic voltages and the phase between them. There is also a choice in painting over the falling main magnet field, as is currently used on ISIS, on the rising field or symmetrically about field minimum.

Current studies have focussed on the symmetric option, into a dual harmonic RF bucket. Working parameters for the output of the 180 MeV linac include a beam current of 43 mA, a 70% chopping duty cycle and an adjustable momentum spread of between $\pm 0.3 - 1.0{\times}10^{-3}$. To accumulate $8{\times}10^{13}$ ppp requires ~500 turns of 220° ($h$=2, RF phase) chopped beam.

RF voltages throughout acceleration (>1 ms) have been kept the same as in the HP case described above and are within current RF system design limits, although the additional beam loading at higher intensities may require hardware upgrades.

### *Injection Scheme One*

This scheme linearly ramps the injection energy from 180 to 181 MeV over the injection period (-0.25 to 0.25 ms) and the RF frequency is swept to give a steer from -0.7 to 0.0 MeV relative to the synchronous energy. RF volts are kept constant at 72 and 43 kV per turn for $h$=2 and $h$=4 respectively, and $\theta$ is utilised to keep a stationary bucket throughout injection. A summary of simulation results for this scheme from injection through to extraction is shown in Figure 2. Simulations utilise the maximum momentum spread available (dp/p = $1.0{\times}10^{-3}$) from the linac design.

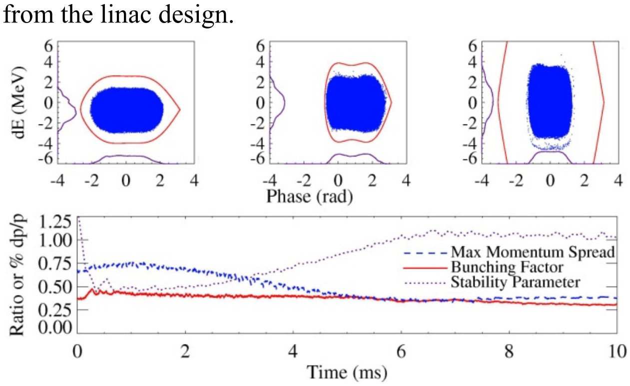


Figure 2: Phase space at 0, 5, 10 ms for $8{\times}10^{13}$ ppp and evolution of bunching factor, stability parameter (equation 2) and maximum dp/p for scheme one.

### *Injection Scheme Two*

The second scheme keeps the injection energy constant at 180 MeV over the injection period, together with a constant RF steer of -0.65 MeV. RF volts are held at 72 and 57.6 kV per turn for $h$=2 and $h$=4 respectively, and $\theta$ is swept from -60° to 0° with respect to that for a stationary bucket. This entails injecting the beam into an asymmetric bucket. A summary of the simulation results for this scheme is shown in Figure 3, using an injected momentum spread of $1.0{\times}10^{-3}$.

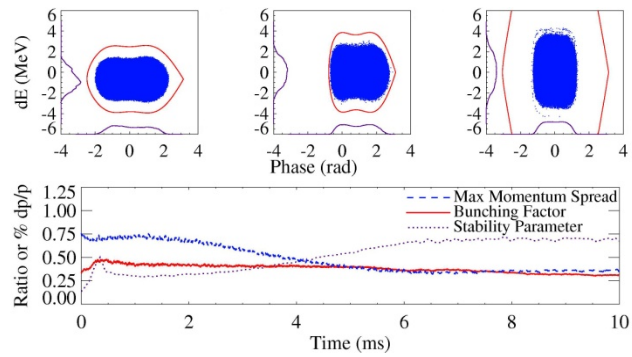


Figure 3: Phase space at 0, 5, 10 ms for $8{\times}10^{13}$ ppp and evolution of bunching factor, stability parameter (equation 2) and maximum dp/p for scheme two.

### *Comparison of Painting Schemes*

Both painting schemes are reasonable working longitudinal solutions for the injection upgrade with lossless acceleration, good bunching factors and plausible stability parameters. Scheme one predominantly paints the beam using RF steering and injection energy ramping whereas scheme two utilises an asymmetric RF bucket early in injection to provide painting.

Scheme two makes use of a high ratio between second harmonic and fundamental RF voltages. This provides two clear stable fixed points for particles to oscillate around and prevents an undesirable 'peaky' distribution, and low bunching factor, early on. Together with the asymmetric bucket this spreads the beam out quickly in energy and reduces the stability factor considerably due to its dependence on the energy spread.

Scheme one operates close to the stability limit with the stability parameter (see equation 2) peaking just above 1. Scheme two, however, has a peak stability parameter of approximately 0.7. These values have some degree of uncertainty as the form factor $F$ in the stability parameter is distribution dependent. It should also be noted that ISIS exceeds the stability criterion presently with no instability observed.

These are working solutions and further optimizations are in progress together with exploration of different injection schemes over the rising edge of the main magnet field.

## LONGITUDINAL DYNAMICS CODE

A stand-alone Particle-In-Cell (PIC) longitudinal tracking code [6] has been further developed for the study of longitudinal particle dynamics in ISIS and its possible upgrades. Alongside two space charge methods incorporated in the in-house C++ longitudinal tracking code, further developments have been made. Features for injection painting including RF steering and variable injection energy have been included. Dual harmonic acceleration and manipulation has been added to the code together with a HP distribution creation routine.

### *Keil-Schnell-Boussard Criterion*

A major addition to the code has been the inclusion of numerical checks for beam stability using the KSB stability criterion. Experimental observations and numerical calculations of the dispersion relation have led to the Keil-Schnell criterion for longitudinal stability. When applied to a bunched beam, replacing the average current with the peak, it becomes the Keil-Schnell-Boussard (KSB) criterion.

One can use the criterion at each longitudinal 'slice' to determine the stability along the bunch. In doing so one can calculate an average 'stability parameter', a rearranged form of the criterion that indicates stability if the value is less than unity:

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

where $Z$ is the impedance acting on the beam; $n$, the mode number; $F$, the form factor, dependent on the distribution; $E$, the total beam energy; $\beta$ and $\eta$ are the usual relativistic factors; $I(\varphi)$, the beam current as a function of the 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 both the stability parameter for each longitudinal slice and an average value over the bunch. This has enabled detailed study of longitudinal stability for the injection upgrade design and will be useful for future simulations. This parameter is plotted in Figures 1 to 3.

### *Benchmark*

It has been shown that the calculated space charge induced kick matches that from ORBIT [7] and follows theoretical predictions [6]. Further checks have been made on the evolution of HP distributions, conservation of emittance and convergence. Simulation results have also been benchmarked against published results from J-PARC [8] showing good agreement, see Figure 4.

## SUMMARY

Longitudinal aspects of the ISIS injection upgrade project have been studied using the in-house beam dynamics code. Simulation results and analytical calculations have shown that a HP invariant distribution can be accelerated within current ISIS design specifications provided increased beam loading can be addressed. Realistic longitudinal painting schemes have been studied and two possibilities presented with no longitudinal loss and matching the constraints.

Developments of the longitudinal beam dynamics code have been necessary to allow for more accurate simulation of injection dynamics, dual harmonic manipulation of the beam and a measure of beam stability. Further modifications are planned to account for additional impedances.

So far longitudinal results suggest the 180 MeV ISIS injection upgrade is achievable, although further research into beam instabilities at high intensities is necessary. Such research will also be useful on the present machine and towards alternative upgrades to ISIS.

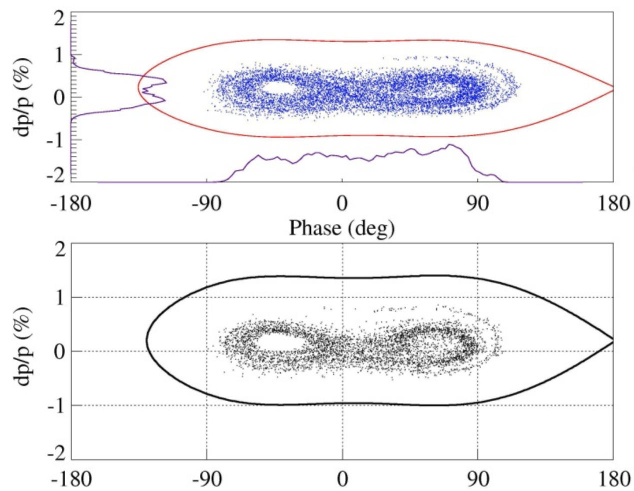


Figure 4: Phase space at the end of J-PARC injection simulated using the ISIS code (top) and the J-PARC code (bottom, [8]).

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