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TOMOGRAPHIC LONGITUDINAL PHASE SPACE RECONSTRUCTION OF BUNCH COMPRESSION AT ISIS

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Abstract

ISIS is an 800 MeV, high intensity, rapid-cycling synchrotron (RCS) used as a driver for a spallation neutron and muon spectroscopy (μSR) facility. The intensity-limited beam and RCS operation at ISIS poses significant challenges, with non-adiabatic acceleration and space charge forces resulting in distortions to the Hamiltonian longitudinal dynamics. Effective modelling of the machine and benchmarking of models with beam measurements is essential both to improving machine performance, and to the development of the proposed ISIS II facility. The tomographic principle is a well-established tool for the reconstruction of the longitudinal phase space (LPS) of synchrotron beams. Is it operationally desirable for the ISIS accelerator to provide longitudinally compressed proton beams for μSR instrumentation. A new bunch compression scheme has been developed and validated using tomography. A reconstruction of the LPS of the ISIS high-intensity proton beam is presented, along with accompanying benchmarking measurements and beam physics simulations.

INTRODUCTION

Despite the primary scientific output of the ISIS facility making use of spallation neutrons, ISIS also boasts a significant muon exploitation program [1]. Neutron and muon science is enabled by the ISIS accelerators, comprising a 70 MeV injector linac, and an 800 MeV RCS. The accelerators deliver high intensity proton beams, up to 3×10^{13} protons per pulse (ppp), to two target stations at a combined repetition rate of 50 Hz [2]. The energy gain of the beam follows the rising edge of the 50 Hz sinusoidal main dipole field, with acceleration facilitated by six fundamental (1RF) radio-frequency (RF) systems ($h = 2$), and four 2^{nd}-harmonic (2RF) RF systems ($h = 4$) [3]. Each of the RF systems comprise 2 gaps.

Charge-exchange injection facilitates generation of this high-brightness beam, wherein a continuous 70 MeV H^- beam is injected into the RCS along the falling edge of the main magnet sinusoid for a duration of 200-240 μs through a carbon stripping foil to form a proton beam [4]. Over the injection period, the beam phase space is painted actively in the vertical plane with a dedicated magnet, and dispersively in the horizontal plane due to the constant beam energy but decreasing main dipole field [5].

An intermediate graphite target is situated on the beam transfer line to Target Station 1 which is used to produce muon beams for muon spectroscopy (μSR) [1, 6]. Unlike the neutron instruments, which do not have requirements on the longitudinal distribution of the driver beam, the muon

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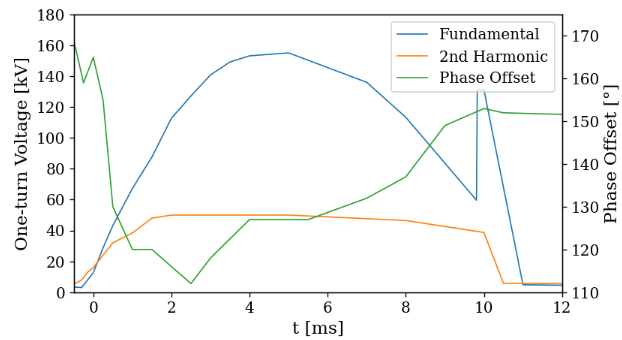

Figure 1: Typical RF voltage and phase offset program used for bunch rotation. The phase offset is in units of degrees of the 2RF.

experiments are improved by shorter bunch lengths ($\lesssim 60$ ns full width half maximum (FWHM), where an uncompressed bunch length is typically in the range of 60-80 ns depending on the operational state of the machine). This improvement has motivated the development of bunch compression schemes using the synchrotron RF systems to manipulate the longitudinal phase space (LPS) of the proton beam in the synchrotron. This paper presents a possible new bunch compression scheme with simulations and measurements.

BUNCH COMPRESSION

Historically, a bunch rotation scheme has been successfully employed for delivery of compressed proton beams on ISIS. LPS rotation comprises two stages. Firstly, the beam is elongated by a steady reduction of the 1RF peak voltage from the uncompressed operational values. This is followed by a rapid increase in the 1RF voltage just prior to extraction (Fig. 1), causing the bunch LPS to rotate at the synchrotron frequency resulting in bunch compression (Fig. 2). This scheme requires careful timing of the RF voltage profile, to ensure that the synchrotron extract kicker magnets fire at the point of minimum bunch length.

Extraction timing occurs within a 350 μs window, and the exact extraction point is established on a pulse-by-pulse basis through synchronisation between neutron instrument choppers and the synchrotron RF. As such, a degree of pulse-to-pulse fluctuation in the extracted bunch length is to be expected. Minimisation of this jitter would aid in maintaining consistent data resolution in μSR measurements.

A new compression program has been investigated which employs a gradual ramp in the phase offset between the 1RF and 2RF systems, Θ_{12}, whilst increasing the ratio $\delta = \hat{V}_{2RF}/\hat{V}_{1RF}$, where $\hat{V}$ are the peak one-turn voltages of the ISIS synchrotron RF harmonics (Fig. 3). The ramp in Θ_{12} is linear and commences at 7 ms through the 10 ms ma-

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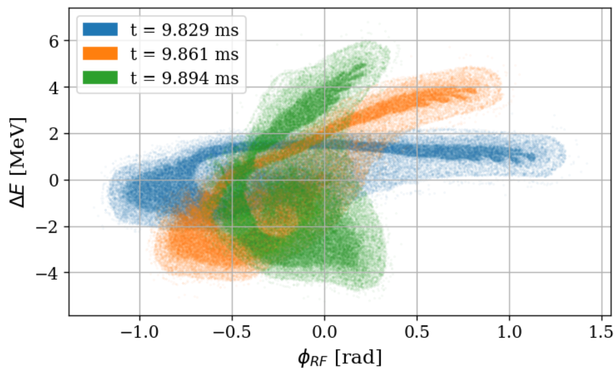

Figure 2: Simulation of LPS rotation dynamics close to extraction, including longitudinal space charge.

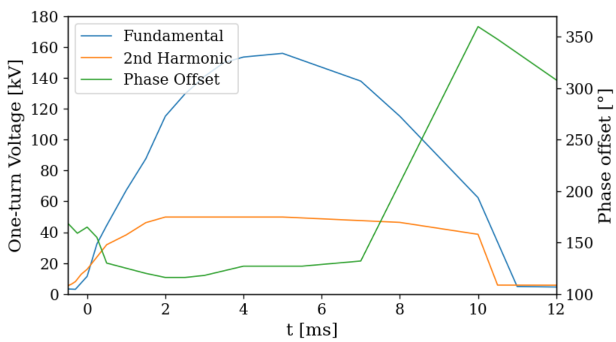

Figure 3: Example of RF voltage and Θ_{12} program used in Θ_{12} ramp bunch compression. The phase offset is in units of degrees of the 2RF.

chine cycle. This is combined with an increase in δ, which produces a highly asymmetric RF bucket. Simulations suggest that the beam is captured around a fixed point of the RF bucket, and is then gradually squeezed to produce a compressed bunch (Fig. 4). This method is expected to stabilise the extracted bunch length in the case where bunch compression is employed, by significantly reducing its dependence on extract timing.

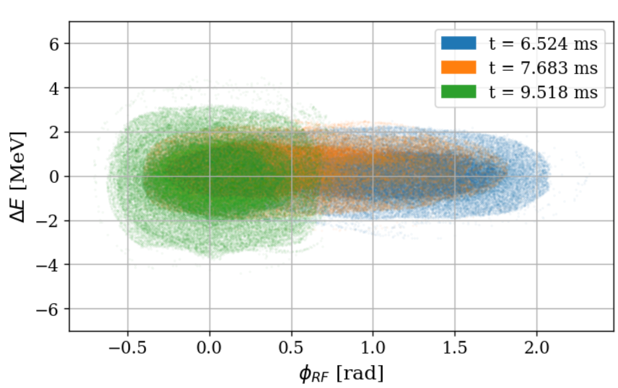

Figure 4: Simulation of Θ_{12} ramp compression from 7 ms onwards, including longitudinal space charge.

TOMOGRAPHY

Tomography is a technique used to reconstruct an N-dimensional image of a system through $(N-1)$-dimensional section cuts, taken across many phases of the system. In the case of LPS reconstruction, it is the inference of the full 2-dimensional phase space from a set of 1-dimensional measurements of the longitudinal bunch distribution [7]. The LPS of a beam in a synchrotron does not act as a rigid rotor, and therefore an element of simulation is required to properly reconstruct the LPS.

The tomograms presented in this paper were generated using a well established tomography code developed at CERN [8]. Originally written in Fortran, it has recently been rewritten as a Python package [9] using C++ as a backend for computationally intensive operations. The RCS operation of ISIS presents some challenges when it comes to tomography; RF voltages and dipole fields are modelled as varying linearly over the frames supplied for reconstruction, but this approximation to the sinusoidal main magnet field of ISIS is only valid for a significantly reduced number of turns. A lack of synchronisation between the RF systems and the diagnostics used for longitudinal profile measurements makes the task of locating the synchronous phase location in the bunch non-trivial. The phase offset between profile data and the RF pickup signal is scanned for every tomogram until a minimum in the discrepancy between the reconstructed and measured longitudinal distributions is found, and is assumed to be the synchronous phase. This is believed to be the dominant source of error in this study.

MEASUREMENTS

Turn-by-turn longitudinal bunch profile measurements were made of the ISIS beam using a beam position monitor (BPM) in the RCS. ISIS BPMs are split-cylinder capacitative monitors [10], from which both transverse and longitudinal information of the beam can be obtained. The summed voltage on the BPM electrodes provides a measure of the instantaneous beam current in the monitor [11]. BPM data is digitized with an NI PXI at a rate of 0.5 GHz [12], which is then re-binned into 720 bins-per-turn for fast rendering of operational visualisation software.

Tomographic reconstruction of the LPS evolution was carried out for both compression methods. In the case of the bunch rotation method, the rapid change in the synchronous phase due to the 1RF voltage increase further limits the number of frames that is usable for a given LPS reconstruction. Alongside this, the quality of the LPS reconstruction close to extraction is made more challenging as the reconstruction point cannot be centrally located in the set of profile measurements used. Despite this, LPS rotation and compression can be seen in the tomograms (Fig. 5) and the reconstructed longitudinal profiles differ from those measured by ~1-2 % except for those profiles close to extraction. The shape of the LPS's shown in Fig. 5 differ significantly from their equivalents generated in simulation (Fig. 2).

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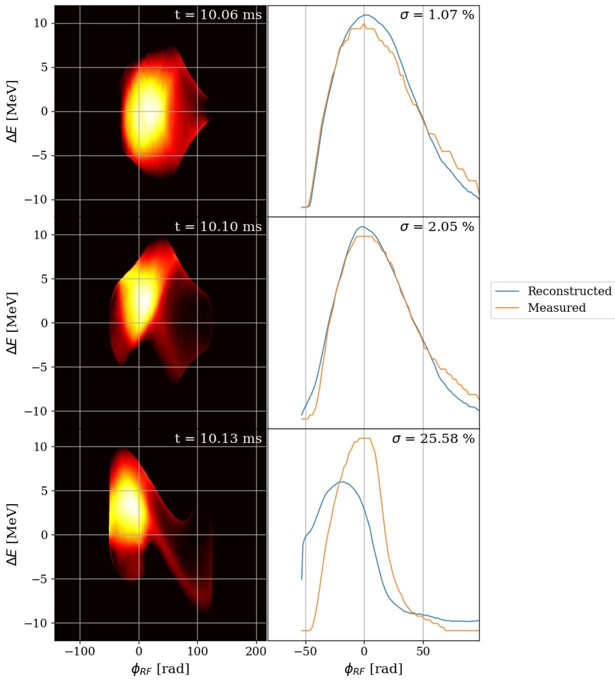

Figure 5: Tomographic reconstruction of LPS in bunch rotation mode, and corresponding comparison between the measured and reconstructed bunch profiles. Rotation of the beam core is observed, although a poor fit is achieved in the LPS at extraction (bottom).

The ramp gradients for Θ_{12} were scanned in order to determine the maximal compression ramp. Tomographic reconstruction of this method clearly shows the compression of the bunch (Fig. 6), and reconstructed bunch profiles from tomography agree very well with the measured profiles ($\sigma < 1$ %). The minimum extracted bunch length measured for this compression method was 57.5 ns, achieving a desirable bunch length for μSR experiments albeit with considerably less compression than seen in the bunch rotation scheme. Nevertheless, the expected improvement to the stability of the extracted bunch length provides a clear use-case for this scheme. Increased beam losses associated with the Θ_{12} ramp were observed, potentially due to the increased energy spread of the beam, necessitating additional tuning, should this method be adopted. A comparison of the simulated and calculated beam energy spread (from tomography) shows a considerable overestimation in the case of the latter (Fig. 4 and Fig. 6), which is thought to be due to the constant value for Θ_{12} assumed by the code.

CONCLUSION

An alternative method of proton bunch compression for μSR experiments has been demonstrated to be viable, achieving bunch lengths of <60 ns with the promise of improved extracted bunch length stability due to a weaker dependence on extract timing. LPS reconstruction through tomography has shown promise as a diagnostic tool for development of longitudinal bunch manipulation methods, achieving deviations between reconstructed and measured longitudinal profiles of <1 % in some cases. However, some limitations stemming from the RCS mode of operation in ISIS have been highlighted. In the case of bunch rotation, allowing the bunch to over-rotate will allow for better reconstruction of the LPS at minimum bunch length. In the case of Θ_{12} ramp compression, modifying the tomography code to incorporate a linear variation in Θ_{12} may prove fruitful in improving agreement in the beam energy spread from simulations and tomograms.

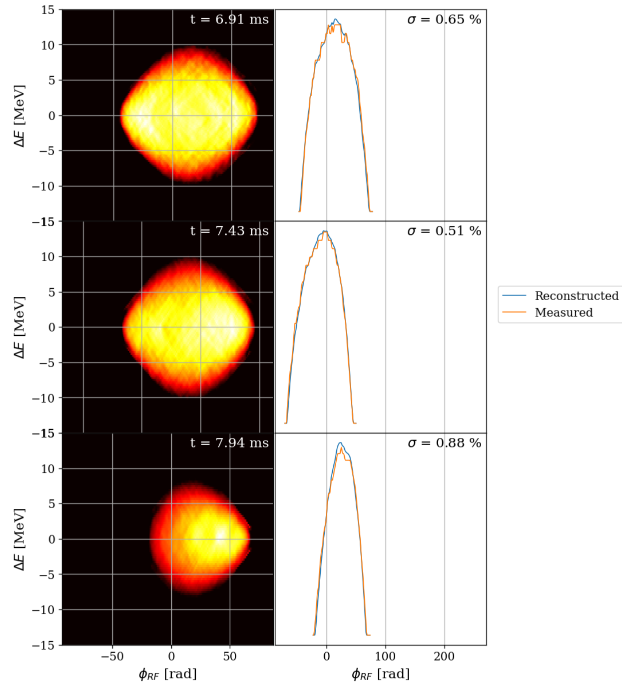

Figure 6: Tomographic reconstruction of LPS in Θ_{12} ramp bunch compression, and corresponding comparison between the measured and reconstructed bunch profiles. A clear compression of the beam is seen, and good agreement is found between reconstructed and measured profiles. However, the energy spread of the compressed beam is expected to be higher in order to preserve the longitudinal emittance, but this is not seen in the reconstructed LPS.

REFERENCES

[1] P. J. C. King *et al.*, "ISIS muons for materials and molecular science studies", *Phys. Scr.*, vol. 88, no. 6, p. 068502, 2013. doi:10.1088/0031-8949/88/06/068502

[2] J. Thomason *et al.*, "Availability and reliability statistics at ISIS and at other high-power proton accelerators", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1053, p. 168338, 2023. doi:10.1016/j.nima.2023.168338

[3] A. Seville *et al.*, "Progress on dual harmonic acceleration on the ISIS synchrotron", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper TUPAN117, pp. 1649–1651.

[4] B. Jones and H. V. Cavanagh, "Progress with carbon stripping foils at ISIS", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-

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May 2018, pp. 1136–1139. doi:10.18429/JACoW-IPAC2018-TUPAL055

[5] B. Jones, D. J. Adams, and C. M. Warsop, "Injection studies on the ISIS synchrotron", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper TUPAN113, pp. 1640–1642.

[6] D. J. S. Findlay, "ISIS, Pulsed neutron and muon source", in *Proc. PAC'07*, Albuquerque, NM, USA, Jun. 2007, paper TUYKI01, pp. 695–699.

[7] S. Hancock, M. Lindroos, E. McIntosh, and M. Metcalf, "Tomographic measurements of longitudinal phase space density", *Comp. Phys. Commun.*, vol. 118, no. 1, pp. 61–70, 1999. doi:10.1016/S0010-4655(99)00194-0

[8] S. Hancock, M. Lindroos, and S. Koscielniak, "Longitudinal phase space tomography with space charge", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 3, p. 124202, 2000. doi:10.1103/PhysRevSTAB.3.124202

[9] C. H. Grindheim and S. Albright, "Longitudinal phase space tomography version 3", CERN, Geneva, Switzerland, Rep. CERN-ACC-Note-2021-0004, 2021. https://cds.cern.ch/record/2750116

[10] C. C. Wilcox *et al.*, "Optimisation of a split plate position monitor for the ISIS proton synchrotron", in *Proc. IBIC'13*, Oxford, UK, Sep. 2013, paper WEPC25, pp. 739–741.

[11] A. Pertica, J. Komppula, D. W. Posthuma de Boer, and R. E. Williamson, "Optimisation of the ISIS proton synchrotron experimental damping system", in *Proc. IBIC'19*, Malmö, Sweden, Sep. 2019, pp. 167–171. doi:10.18429/JACoW-IBIC2019-MOPP031

[12] B. Jones, D. J. Adams, B. G. Pine, H. V. Smith, and C. M. Warsop, "Progress on beam measurement and control systems for the ISIS synchrotron", in *Proc. IPAC'14*, Dresden, Germany, Jun. 2014, pp. 3700–3702. doi:10.18429/JACoW-IPAC2014-THPME181