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BENCHMARKING SIMULATIONS OF SLOW EXTRACTION DRIVEN BY RF TRANSVERSE EXCITATION AT THE CERN PROTON SYNCHROTRON*

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Abstract

Resonant slow extraction is a technique that supplies a continuous beam spill over an extended duration compared to fast single-turn or non-resonant multi-turn methods. By employing transverse excitation to drive circulating particles into resonance, it enables beam delivery to experiments that necessitate long-duration spills.

To accurately and efficiently simulate the extraction process over various timescales, new modelling tools and computing platforms must be explored. By utilising optimised computational hardware such as Graphics Processing Units (GPUs), and next-generation simulation software (such as Xsuite), computation times for simulations can be reduced.

This contribution presents recent developments of resonant slow extraction modelling and benchmarking with a comparison to measurements made at CERN's Proton Synchrotron (PS), focusing on understanding the dynamics of transverse RF excitation and effect on spill quality.

INTRODUCTION

The CERN Proton Synchrotron (PS), alongside providing intermediary acceleration for hadron and ion beams for the CERN accelerator complex, provides beam to many fixed target experiments located at the East Area (EA) experiment facility. The facility consists of the proton (IRRAD) and mixed-field (CHARM) irradiation facilities via a dedicated 24 GeV/c beamline, in addition to a multi-target beamline providing three secondary beams.

Ongoing experiments in these facilities use low-intensity ($<10^6$ ions/spill), high-energy (>100 MeV/u) ion beams to simulate natural phenomena, such as interaction between high-energy cosmic rays and micro-electronics (CHIMERA) [1]. To provide spills on the order of ~100 ms required for these experiments, the slow extraction system in the PS is used.

Where fast extraction methods use strong kicker magnets to extract entire particle bunches from an accelerator over the period of a single turn (~2.1 µs in the PS), slow extraction systems deliver a continuous flux of particles, not bounded by the revolution frequency of the accelerator.

Methods of slow extraction can be divided into resonant and non-resonant categories. Resonant configurations, which will be examined, exploit multipole magnets to create unstable "regions" in phase-space [2].

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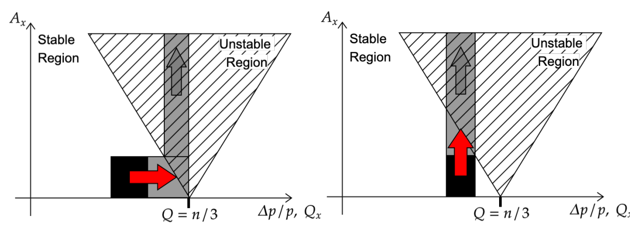
RADIO-FREQUENCY KNOCK OUT

Steinbach diagrams are a useful tool for visualizing the role of stability in slow extraction regimes. They display a particle's betatron amplitude $A_x = \sqrt{\epsilon_x/\pi}$ (with x as the horizontal direction and ϵ_x as the single-particle transverse emittance) as a function of its horizontal betatron tune Q_x (or $\Delta p/p$; the graphs are equivalent).

Fig. 1 demonstrates the two categories of resonant slow extraction: momentum-driven, and amplitude-driven.



(a) Momentum-driven RSX (b) Amplitude-driven RSX

Figure 1: Steinbach diagrams showing two methods of Resonant Slow Extraction (RSX). Black rectangle indicates the circulating beam, grey rectangle represents extracted spill. Red arrow indicates driving either the momentum or amplitude, grey indicates amplitude growth caused by resonance. Shaded area indicates unstable region created by sextupoles.

Momentum-driven RSX can be performed by accelerating particles to change their momentum (in the case of betatron core RSX), or by changing the reference momentum (in the case of Constant-Optics RSX (COSE)), amongst others [3].

Amplitude-driven RSX induces resonant amplitude growth by directly increasing the amplitude of particles (and thus emittance) into the unstable region. This is achieved by "heating" the beam transversely (increasing transverse emittance), allowing particles to diffuse from the beam core towards the unstable phase-space region. This heating can be provided by a non-adiabatic transverse kick, typically operating at frequency modulation around the betatron (horizontal tune) sideband [4]. Driving signals could include "colored" noise, multi-tone frequencies, or a "chirp" (linear frequency sweep) signal [4]. Such signals are generally in the Radio frequency spectrum of EM radiation, and "knock" the particles out of stable ellipses onto separatrices; hence, the term Radio-Frequency Knock-Out (RFKO) describes this form of amplitude-driven RSX [5].

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RFKO at the Proton Synchrotron

RFKO was carried out at the PS in conjunction with the ongoing CHARM High-energy Ions for Micro Electronics Reliability Assurance (CHIMERA) project [6]. The Transverse Feedback (TFB) system, created to damp injection oscillations [7], is used to drive the emittance blow-up required for RFKO. Similar systems are used in the SPS [8], for which the "Qmeter" application is used for control [9]. This application, originally designed for tune measurement, can be used to send a chirp signal to the TFB plates, controlling the frequency range, gain, repetition rate (currently limited to 1 ms or slower), and duty cycle of the signal (in 2^n of number of turns).

During the November 2022 ion run, a Lead ion cycle ($^{208}_{82}Pb^{54+}$), was injected from the Low Energy Ion Ring (LEIR), and accelerated in the PS to begin the RFKO RSX process. The betatron tune was parked close to the third integer, and the TFB system activated to provide transverse heating. Described in Fig. 2, the East Area extraction system includes extraction dipoles in section 53 to 67 which provide a large transverse deflection, changing the closed orbit from its nominal trajectory (solid line) to a bumped trajectory (dashed). After several hundred turns, particles

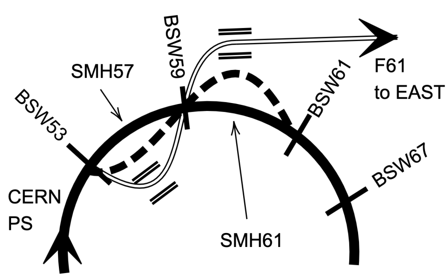

Figure 2: The slow extraction system of the PS to EA, showing nominal trajectory (solid line), bumped trajectory to meet septum (dashed), and extracted trajectory (double-lined). Marked are the two magnetic septa (SMH57, 61, double-lined), and extraction kicker magnets from BSW57.53 to 57.61.

reach the magnetic septum (SMH57), which consists of the blade (4 mm thick), and a window (30 mm thick). SMH57 imparts a kick to the beam within its window, causing those particles to follow the extraction trajectory (double-lined), before reaching the final extraction septum at section 61, and subsequently stripped to Pb^{82+} at the vacuum window.

RFKO in Simulation

RFKO simulations were conducted using Xsuite [10], a set of Python packages for multiparticle accelerator simulations. It improves upon other simulation tools used at CERN (MAD-X, Sixtrack, etc) by enabling GPU-accelerated computation, while remaining backwards-compatible with MAD-X lattice files.

Fig. 3 shows a flowchart for the simulation process. Lattice files from CERN's common optics repository [11] were processed with MAD-X and imported to Xsuite. Table 1 tabulates the values of key parameters used in simulations.

Table 1: Values Used for Simulations

Quantity	Value
Particle	Proton
Normalized Emittance ε_x	1.5 mm mrad
Relative Chromaticity ξ_x	-0.5
Momentum	5.392 GeV/c
Momentum Spread dp/p	0
Revolution Frequency f_{rev}	473.13 kHz

Xsuite's recently added custom "Exciter" beam element models a time-dependent thin multipole. Using `SciPy` [12] to generate a chirp signal, the exciter element can impart a normalised multipole kick at arbitrary excitation frequencies, independent of the revolution frequency.

By setting an aperture limit corresponding to the radial and transverse coordinates of the SMH57 septum, particles lost to the aperture can be considered extracted. Recording the particles loss $cts./turn$ provides a simulated spill signal.

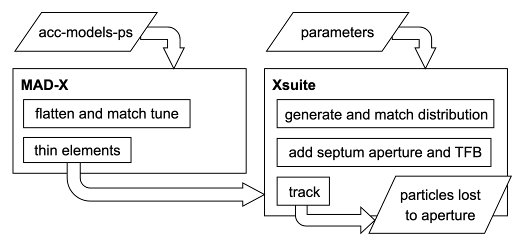

Figure 3: Flowchart describing the simulation process

Fig. 4 shows a successful RFKO simulation as a per-turn phase-space plot at the septum. The TFB system diffusively heats the particle distribution, causing emittance blow-up, visible in the growing central ellipse. As emittance and amplitude increase, particles enter the unstable region (shown in Fig. 1). Particles then move along the separatrices, transverse position increasing in 3-turn steps until they are lost to the aperture and considered extracted. This three-turn position change, ΔX_3, is known as "spiral step". The inset in Fig. 4 shows an enlarged view of the extracted beam phase-space profile, with the spiral step indicated by the maximum negative transverse displacement achieved before extraction.

BENCHMARKING

Fig. 5 shows FFTs of the driving and spill signals from machine measurements (left) and simulations (right). These plots compare the extracted spill/loss signal with the driving TFB/kicker signal, effectively comparing the "output" and "input" signals in frequency space. The signal used was a frequency-modulated chirp, from .3–.35 fractions of the time taken for one revolution, shown in Fig. 6. These chirps lasted for a set number of turns, and were repeated at a frequency marked at the red line, which is prominent in both the TFB/exciter and spill/loss frequency plots.

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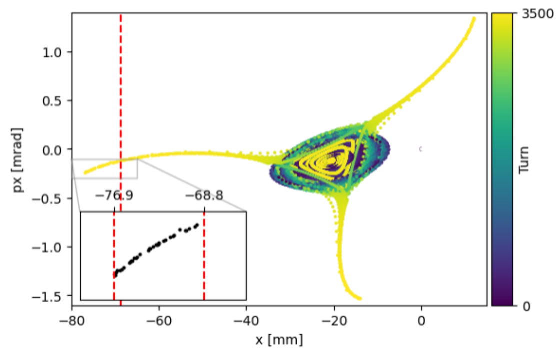

Figure 4: Phase-space distribution of an RFKO simulation at the septum location, plotting all particles for 3500 turns (approx. 7.353 ms in lab time). Colour scale indicates turn number. Inset shows spiral step of $\Delta X_3 \approx 8.1$mm.

For machine measurements, spill signals were measured using N2 gas scintillators [13] as they have been found to perform better at lower intensities than secondary emission monitors [1]. The driving signal was measured via an OASIS oscilloscope connected to the TFB plates [14].

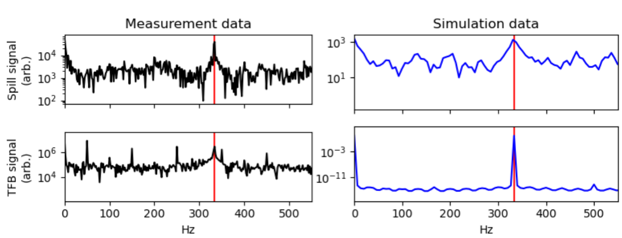

Figure 5: Examples of measured (left) and simulated (right) signals of particle extraction spill (top) and TFB kicker (bottom) in frequency domain (calculated via FFT [12]). Red line indicates chirp repetition rate.

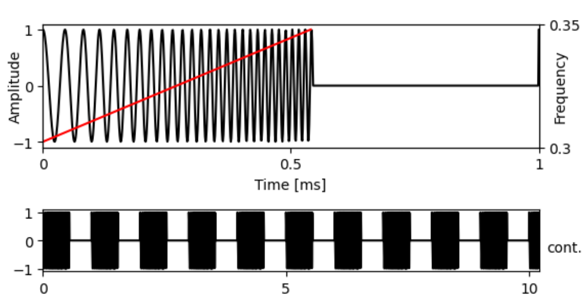

Figure 6: Time-domain plot of chirp signal used in amplitude (black) and frequency (red). Frequency in multiples of f_{rev} revolution frequency, amplitude in arbitrary units.

Previous works characterising slow extraction have utilised fixed-amplitude frequency response functions, which describe how the frequency characteristics of the chirp signal propagate to the spill signal. One prominent feature is a "low-pass filter" effect, where low-frequency current ripples (e.g., chirp repetition rate) propagate to the extraction frequencies more than higher frequencies [15], with a pronounced cut-off frequency [16]. To compare the accuracy of the simulation's frequency characteristics, this low-pass filter effect will be compared between simulations and machine data.

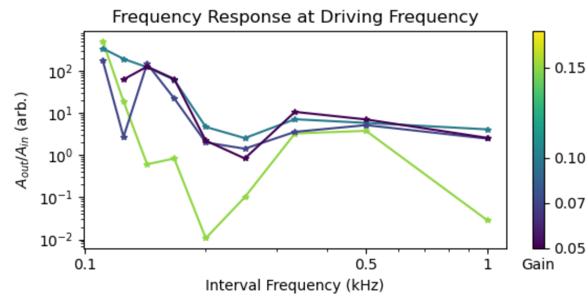

Figure 7: Fixed-amplitude frequency response for RFKO carried out at the PS. Figure plots output amplitude of the chirp interval frequency normalised by the input amplitude as a function of the interval frequency. Data shows characteristic "low-pass filter" effect, but unexpectedly shows response rises for higher frequencies after minimum at 250 Hz

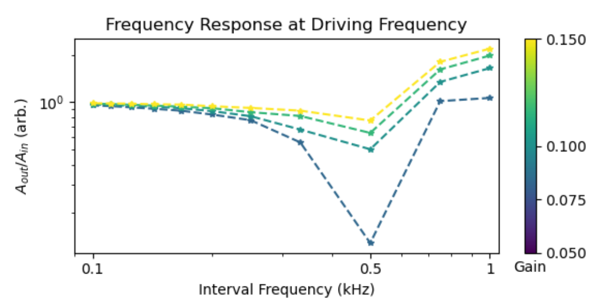

Figure 8: Simulated fixed-amplitude frequency response for RFKO carried on the PS model. Data shows characteristic "low-pass filter" effect with a minimum response at 0.5 kHz, which again rises as frequency increases.

SUMMARY

Frequency response measurements were produced for both machine (Fig. 7) and simulation (Fig. 8) data, comparing the relative "output" amplitude in frequency domain at the chirp repetition rate to the TFB kicker's "input" amplitude. The spill signals from the RFKO simulations performed show accurate characteristics in the frequency domain, with the predicted low-pass filter effect pronounced in both simulations and measurements. Simulations show a cut-off frequency higher than measurements, likely due to the non-linearities introduced by the Pole-Face Winding (PFW) magnets [6]. Future work will instead rely on the Low Energy Quadrupoles (LEQ) for tune control.

Future experiments also will explore simulation performance for different TFB signals, such as higher chirp rates or coloured noise, using new function generators in the PS TFB system. This system, set-up and tested during the November 2022 ion run, will provide experimental results later this year.

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