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Mu2e RESONANT EXTRACTION REGULATION SYSTEM SIMULATION IN DELIVERY RING

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Abstract

Mu2e is an upcoming experiment at Fermilab that relies on the slowly extracted 8 GeV proton beam from the Delivery Ring. The experiment imposes strong requirements on the spill uniformity. To address these requirements, the fast spill regulations system is being developed and commissioned. To inform this development and optimize the system performance we are carrying out the detailed simulations of the regulation process. The simulation includes the effect of six harmonic sextupoles that excite the third-integer resonance and three fast ramping quadrupoles that drive the horizontal tune to 29/3. The components of spill regulation system are designed to mitigate long-term drifts in the beam, ensuring stable operation over extended timescales, as well as addresses rapid variations within single spill. In this study, we review the regulation system design, simulation of the slow regulation, and the fast regulation PID regulation to curtail random variations in the extraction rate that could occur within a single spill.

RESONANT EXTRACTION FOR Mu2e

Mu2e is an upcoming experiment at Fermilab that is designed to look for charged lepton flavor violation thorugh direct neutrino-less decay of muon to electron. To create the muons for the experiment, 8 GeV kinetic energy protons are to be bombarded to a muon production target. In order to suppress several background physics processes, Mu2e demands pulses muon beam, which is achieved by creating pulsed proton beam using resonantly extracted 8 GeV proton from Fermilab's Delivery Ring (DR). The 3rd integer resonant extraction is achieved in the machine by using 6 harmonic sextpoles that excite the third-integer resonance and three fast ramping quadrupoles that drive the machine tune close to a third-integer resonance. The goal is to inject 1e12 proton from the Fermilab Recycler Ring into the DR and resonantly extract the beam over 43 ms (which is about 25,000 turns). Other beam parameters can be found in Table 1.

SPILL REGULATION SYSTEM (SRS)

Mu2e imposes strict requirements on the intensity of the spill, quantified by spill duty factor, defined by

$$\mathrm{SDF} = \frac{1}{1+\sigma^2} \tag{1}$$

where σ is the standard deviation in the extraction rate. Mu2e requires an SDF of 60% or higher. To help achieve

Table 1: Some Key Beam Parameters Pertinent to Resonant Extraction

Parameter	Value
Beam kinetic energy	8 GeV
Spill Duration	43 ms
Number of spills per super cycle	8
Number of bunches per spill	1
Initial proton intensity	10^{12} protons
# of protons extracted per turn	$< 4 \times 10^7$ protons
Time between proton micropulses	1.695 µs
Normalized Emittance (95 %) ϵ_x	16 π·mm·mrad
Spill Duty Factor (SDF)	> 60 %
Reset time between spills	5 ms

this SDF, a spill regulation system [1] is in place to ensure extraction uniformity. The Spill Regulation System primarily consists of three components: slow spill profile regulation, fast random ripple regulation and Harmonic ripple content suppressor.

In this paper, we shall go into the details of the slow regulation algorithm [2], look at particle tracking results for the fast regulation, and discuss future directions of potentially extending this framework to implementing Radio Frequency Knock-out (RFKO).

Slow Regulation

Some of the main characteristics of the beam, such as its horizontal size, injection emittance, beam steering error, etc., could vary slowly over time due to many factors. Apart from this, a slow drift in the accelerator components could reflect in the spill intensity profile as a low frequency deviation from the ideal spill rate. Given such a short spill time, this slow variation in the spill rate could be possibly span across multiple spill durations. A regulation loop is thus needed to keep the overall profile of the spill intensity as close to the ideal as possible, and this would be done using the Slow Regulation Loop (SRL).

The Slow Regulation Loop would not concern itself about any random fluctuations in the spill rate that could occur just within one spill, nor does it care about the high frequency noise components, either arising from the magnet power supplies or other wise, that could fluctuate the spill intensity within one spill.

In order to avoid correcting the random fluctuations in the spill rate that may occur just within one spill (but not repeat in the subsequent spills), the Slow Regulation Loop would work over *many* spills. The exact number of spills to average the spill rate data over could vary depending on the actual operation of the spill. But the main goal of the Slow

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Regulation Loop is to 'zero-in' on the ideal power supply ramp of the tune-ramping quadrupoles that would result in an *ideal* spill rate (in the absence of any instantaneous fast noises in the accelerator system).

Fast Regulation Loop

Within a given spill, the extraction rate could fluctuate randomly because of high frequency noise components in the power supply or random jitters in the accelerator components. To mitigate this, a fast regulation loop is designed to provide feedback corrections within a single spill.

In this work, we shall give an overview of the slow regulation algorithm that results in a uniform spill. Followed by which we present a preliminary result of fast regulation loop using PID quadrupole regulation.

SIMULATION PARAMETERS

The first step in simulating the spill regulation is to find the ideal tune ramp curve that would result in a coarse uniform extraction rate.

The inputs to the tracking simulation are the number of particles: N_{part}, the total number of turns over which resonant extraction happens: N_{turns}, the total number of bins in one spill duration: N_{bin}, an initial (unoptimized) tune-ramp curve $\nu_x(n)$, and Slow Regulation Loop algorithm parameters that would iterate over the tune ramp over many spills.

For the purposes of this study, an initial proton distribution was prepared with a mean value of 0 and a standard deviation 1.65 mm and the extraction septa position at 12 mm from beam center. An input distribution of ≈132,000 particles was prepared, clearing the high-amplitude halo tail that may get extracted in the first few hundred turns (Fig. 1.).

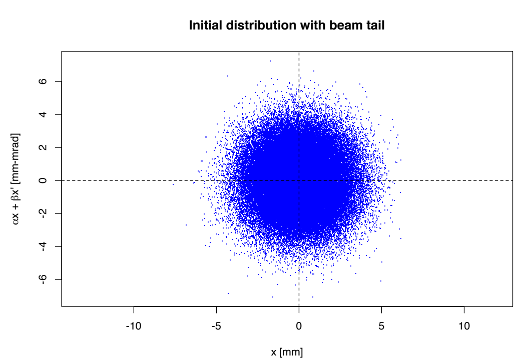

Figure 1: The red colored distribution is the same distribution in blue after clearing all the halo by performing resonant extraction at a constant tune of $\nu_x = 9.650$.

The kinetic energy of the beam in the simulation is assumed to be 8 GeV, and the total energy is 8.938 GeV. The average path length around the DR was assumed to be approximately 505.2 meters, the total spill time T_{spill} to be 43 ms. With a kinetic energy of 8 GeV for the protons, this gives us the total number of turns per spill time as ≈ 25,371 turns. The maximum bandwidth of the SRS is 10 KHz. In the simulation, this fact is reflected through binning the spill into n_{bin} number of bins. Even though the ideal n_{bin} is 430, simulations were done with 108 bins to be computationally efficient.

SLOW REGULATION WORKFLOW

For the purpose of validating various Slow Regulation adaptive learning algorithms, we input a tune curve that is purely linear, running from $\nu_x = 9.650$ to 9.666 from the start to the end of one spill duration. (The tune-ramping curve is synonymous with the quad current ramp as the current in the fast-ramping quads directly affect the tune.)

To keep track of the particles' coordinates in the phase space, the simulation creates two arrays, one for X and another for X'. In addition to these, the simulation creates a 2D array, one dimension to keep track of the particle's identity and the other to keep track of the number of turns traversed by the particle. The count of this 2D array for the whole of the simulation would thus be $N_{\text{part}} \times N_{\text{turns}}$. The tracking simulation assumes a single sextupole at the proper location with respect to the septum. We use a single 'virtual' sextupole strength $S_0 = 500$ T/m^2 to simulate the effect of the six dedicated harmonic sextupoles in the real lattice of the Delivery Ring to excite the third integer resonance.

The electrostatic septum foil plane is assumed to be located 12 mm from the beam center. Any particle whose X value goes higher than this value will not circulate further in the beam lattice. The simulation also assumes an admittance value of 40π mm-mrad for the lattice; any particle that strays outside this circle of radius 40π is counted as lost and not extracted. The code assumes a simplified model of the Delivery Ring, where by it is divided into two parts. The first part would be consist the segment between the injection point of the particles and the sextupole. The second segment consists of propagating the particle from the sextupole to the injection point. After the beam traverses through these linear elements, we apply the non-linear effect of the sextupole with strength S_0.

Since ≈ 132,000 particles were tracked, this was done at NERSC Perlmutter cluster by batch operations, where the particles were divided into individual cores and run independently (we can do this as we are not simulating space charge force or any inter-particle intensity dependent effects). After each cores complete their jobs, a separate bash script combines the output and integrates to find the total number of particles extracted at each turn, which is then used to optimize the tune curve for the next spill. This is iteratively done until the tune ramp give a coarse uniform extraction rate with 5% error tolerance in the extraction rate. We see in Fig. 2 that the error in extraction rate has converged almost perfectly to the required spill error fraction with ±5% tolerance.

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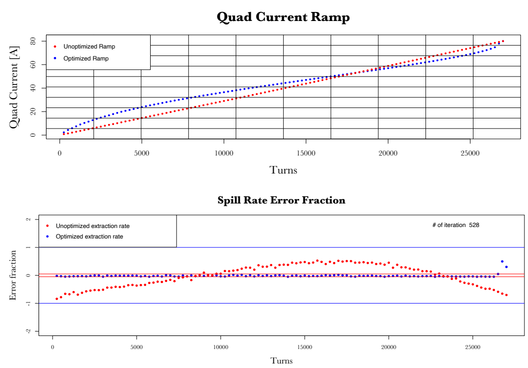

Figure 2: The Slow Regulation Loop adaptively learning to make the coarse ideal extraction rate.

FAST QUADRUPOLE REGULATION

The same beam simulation parameters for the slow regulation simulations were used to simulate the fast regulation but significant alterations were made to the workflow. The spill is divided into 108 bins and upon starting the simulation, all of the ≈132,000 particles are divided and sent to 128 cores and are tracked for 250 turns. After this, the tracking code outputs the state of each particles whether they are extracted or not. The tracking code also outputs the coordinates of the unextracted particle at the last (250th) turn. Then, a second script combines the output from all the 128 cores and computes the total number of particles extracted for the first bin. The error signal is calculated by finding the difference between $e(n) = N_{ext.} - N_{ideal}$, where n is the bin number. Based on this error, a PID loop outputs a control signal, given by $u(n) = K_p e(n) + K_i \Sigma_1^N e(n) + K_d(e(n) - e(n-1))$. This control signal is then added to the next bin's tune value in the ramp and the tracking code is called again. This is done iteratively until the end of the spill, i.e., all 108 bins.

Noise Introduction

In simulation, the variation in the extraction rate is introduced directly in the tune ramp profile. In this sense, whatever jitters or noises in the real-world lattice is modelled as the ripple in the tune of the particle once around the ring (we assume the sextupole strength to be constant).

FAST REGULATION RESULT

Since the error rate is in raw particle count (≈ 100s of particles), the PID gain tested are very small. With initial gain parameters of $K_p = 0.00001$, $K_d = K_i = 0.00000001$, we see in Fig. 3 that the PID is able to regulate the fast noise in the ripple. We see that the SDF has improved and the higher peaks are tamed by the PID regulation.

Future Directions and RFKO

Next immediate steps include optimizing the PID gains to get the best PID quadrupole regulation. The subsequent step after that would be to explore radio-frequency knockout (RFKO) [3] as a fast regulator. RFKO is a technique by which the circulating beam is subjected to a transverse kick

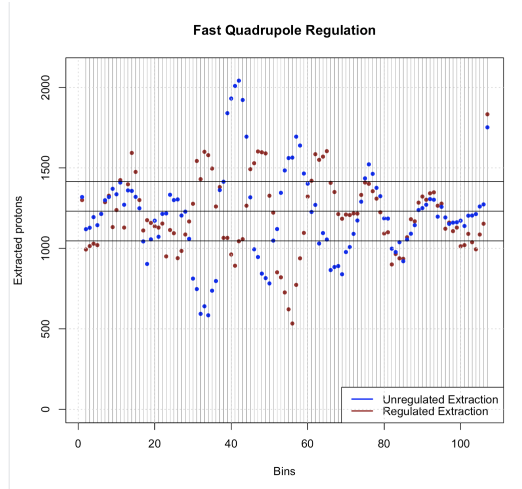

Figure 3: Fast Quadrupole regulation by PID feedback loop.

every time the beam arrives at the RFKO station. When the beam gets the transverse RF kicks over multiple turns, the beam distribution in the phase space heats up. The RFKO frequency should sweep the betatron frequency band of the circulating beam, and along with the intensity of its kick, could help regulate the fast noised extraction rate within a single spill.

$$k_{RFKO} = A(n)[\sin(2\pi f(n) + \phi)] \tag{2}$$

where k_{RFKO} is the kick given to particle, n is turn number, $f(n)$ is the modulated RFKO frequency to ensure all particles eventually *feel* the kick, ϕ is the phase, and $A(n)$ is the amplitude of the kick controlled by a separate feedback PID loop every turn. Our next steps are to compare multiple RFKO frequency modulation schemes with best-in-class PID quadrupole regulation and identify the optimal fast regulator for Mu2e resonant extraction scheme.

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