SPACE CHARGE EFFECT OF THE HIGH INTENSITY PROTON BEAM DURING THE RESONANCE EXTRACTION FOR THE MU2E EXPERIMENT AT FERMILAB*

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Abstract

The proposed Mu2e experiment to search for direct $\mu \rightarrow e$ conversion at Fermilab plans slow, resonant extraction of a beam with 3×10^{12} protons from the Debuncher ring. Space charge of this high intensity beam is a critical factor, since it induces significant betatron tune spread and consequently affects resonance extraction processes, such as spill uniformity and beam losses. This study shows the multi-particle simulation results in the early stages of resonance extraction and spill uniformity in the presence of 2D and 3D space charge effects.

INTRODUCTION

The Mu2e experiment will search for charged lepton flavor violation by measuring the ratio of the coherent neutrino-less conversion in the field of a nucleus of a negatively charged muon into an electron to the muon capture process [1]. To do this, high intensity protons will be extracted from Fermilab's Debuncher ring using slow resonant extraction method and will be delivered to the production target through an external beamline.

These high intensity beams, normally $2 - 3 \times 10^{12}$ protons per bunch, will be critical during the extraction. This study will show the simulation results of third-integer resonance extraction using Synergia2. Mainly, we will investigate how space charge affects the beam dynamics and consequently the spill rate and beam losses.

In the first section, we will present how the third-integer resonance extractions will be excited and controlled. The simulation parameters and methods will be addressed in Section 2. Finally, particle tracking simulation results with and without space charge effects will be shown.

THIRD INTEGER RESONANCE EXTRACTION IN THE DEBUNCHER

Since the Debuncher ring has 3-fold symmetry, as shown in Figure 1, and its operating tune, $\nu_x \approx 9.765$, is close to $29/3$, third-integer resonance has been mainly considered to extract the particles from the ring. The half-integer extraction is still under consideration, however, this paper presents the study of the third-integer extraction exclusively.

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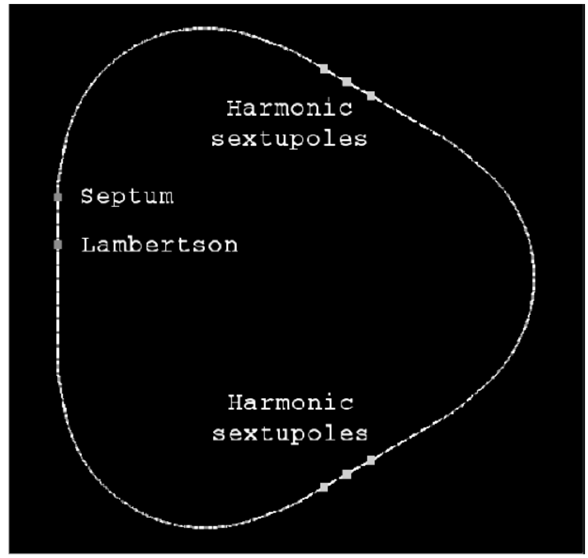


Figure 1: Locations of the septum, Lambertson, and harmonics sextupoles in the Debuncher ring.

In order to adjust the machine tune during the extraction, three existing trim quadrupoles in the middle of the straight sections are operated as a harmonic circuit. The harmonic sextupoles formed by two orthogonal groups of three sextupoles are located in two straight sections. This harmonic sextupole circuit excites the third-integer resonance. These two harmonic circuits, composed of quadrupoles and sextupoles, are ramped to control the spill during the operation. In Synergia2 simulations, the sextupole fields are ramped for the first 100 turns, then are kept constant at the final setting values. After the sextupole-field rampings, the quadrupole fields are ramped to spill protons resonantly with a reasonable rate.

Two "knobs" of the harmonics sextupole circuits control the amplitude and phase of the resonance coupling constant, g,

$$g = \frac{i}{6\sqrt{2}} \frac{1}{4\pi} \sum \frac{B''l}{B\rho} \beta_1^{3/2}(\theta)\, e^{-i3(\psi_1(\theta) - \Delta\nu\cdot\theta)} \qquad (1)$$

The phase of g, which determines the orientation of the separatrix in the phase space, is set to enhance the efficiency of the extraction. The detailed mechanism for controlling the harmonic circuit is addressed in reference [2].

Table 1: Beam and Machine Parameters

	Value	Units
Beam Intensity	3×10^{12}	protons
Beam Energy	8	GeV
$B\rho$	29.650	T-m
Bunch Length (rms)	40	nsec
Initial Emittance	20	π mm-mrad
Debuncher Circumference	505.283	m
Harmonic Number	4	
RF Frequency	2.36	MHz
RF Voltage	32	kV
Septum Gap	0.016	m
Septum Wire Width	100	μ m

SIMULATIONS

Table 1 shows the machine and beam parameters of the Debuncher for the Mu2e experiment. An 8 GeV proton beam is injected into the Debuncher ring. Although two scenarios have been considered for the Mu2e experiment, this study shows the results of the "Hybrid A" scenario, which transfer and deliver the beam of 3×10^{12} protons in 167 msec through the ring to the production target [3]. An RF cavity is located in one of the straight sections, and is operated with $h = 4$, $f_{RF} = 2.36$ MHz and $V_{RF} = 32$ kV.

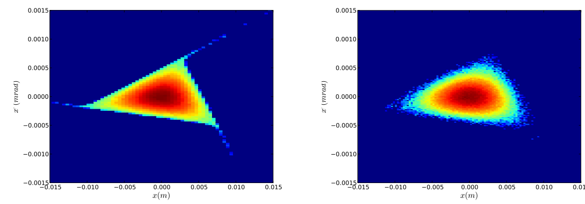
The strengths of the harmonic sextupoles are determined by using initial conditions of tune and emittance of the injected beam,

$$|g| = \frac{|\Delta|}{\sqrt{2\sqrt{3}\epsilon}}, \tag{2}$$

where Δ is the difference between the linear horizontal tune and the resonant tune, and ϵ is the emittance of the central stable region. The ramping rate of the harmonic quadrupoles corresponds with the spill rate of the particles.

Various factors, such as the wire thickness of an electrostatic septum, the betatron function at the septum, and the phase advance between the septum and Lambertson, are also important for the efficiency of the slow extraction. The septum and the Lambertson are located in the straight section where the harmonic sextupole circuit is not installed. The location of septum is chosen where the betatron function is close to the maximum and the dispersion is zero.

Synergia2 is the parallel code composed of several modules, such as linear/non-linear optics, space charge, and impedance etc [4]. In order to track multi-particles, a map-based single particle tracking suite, CHEF is used. Space charge effects for open boundary conditions are calculated self-consistently with 2D/3D Poisson suite, Sphyraena, which uses the Hockney's algorithm with the integrated Green's function method. In this study, 32^3 grid cells form the window of interest. Simulations were performed with 327,680 macroparticles; 240 space charge kicks were applied for every turn.



(a) Without Space Charge Effects (b) With Space Charge Effects

Figure 2: Phase space of the third order resonance extraction in the Debuncher ring.

PHASE SPACE AND BEAM LOSSES

Since the Mu2e experiment requires high intensity beams, space charge effects significantly affect the beam dynamics during the extraction process. Figure 2 shows the comparison of the phase space without and with space charge effects when the sextupoles are fully ramped. Space charge effects distort the separatrix geometry.

Due to the high intensity of the beam, the self-defocusing space charge fields induce the tune shift within the core of the beam. Previous studies showed that the extraction is more efficient when the machine tune is set below the resonance value due to the space charge [2, 5]. Based on these studies, we have found the optimal point of the bare tune as $(\nu_x, \nu_y) = (9.66, 9.78)$.

Figure 3 shows the tune spread of the beam at 1000 turn after the sextupole field ramps. Laslett's tune shift for the round beam is given by

$$\Delta\nu_x = \frac{3 r_p N_{tot}}{2\pi\gamma^2\epsilon_N F_B}, \tag{3}$$

where r_p is the classical proton radius, N_{tot} is the total number of particles, ϵ_N is the normalized emittance, and F_B is the bunching factor [6]. With the careful consideration of the Gaussian beam distribution, this formula pre-

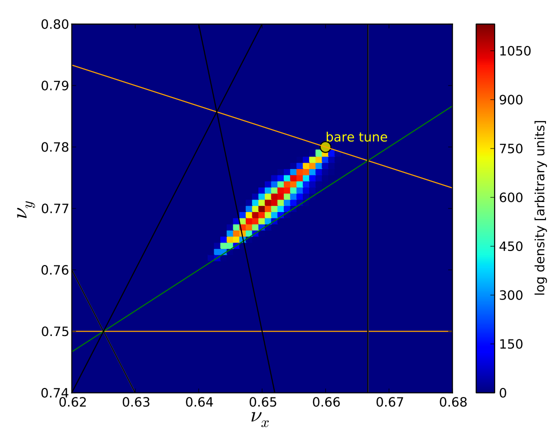


Figure 3: Tune spread plot calculated at 1000 turn after the sextupole field rampings

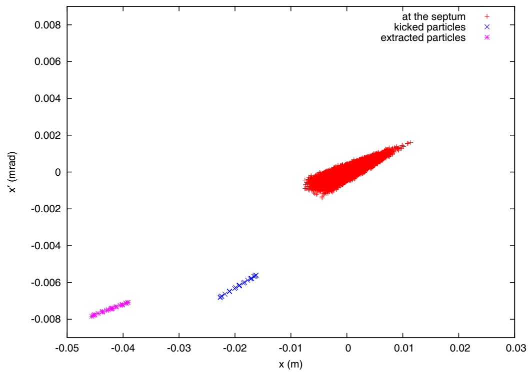


Figure 4: Phase space (red) at the septum with kicked (at the septum:blue) and extracted (at the Lambertson:pink) particles

dicts the tune shift of 0.020, while the simulation result is about 0.018.

Particles are resonantly extracted from the separatrix and are kicked at the electrostatic septum. Synergia2 simulations predict that only few percent of particles hit the septum wire and others are extracted at the Lambertson magnet. And beam losses at other beamline elements are relatively small. The phase space of the beam measured at the septum is shown in Figure 4. Particles are kicked at the septum with the strength of 2 mrad kick (Blue). The Lambertson magnet is put on the 1-cell downstream of the septum to keep extracted particles (Pink) apart from the circulating beam and kicked particles.

Figure 5 presents the beam loss with and without space charge effects. Here, the beam loss includes extracted and wire-hit particles. These calculations were done with the same ramping rate of the harmonic quadrupole circuit. The sextupole field ramps affects large fraction of beam losses due to the reshape of the distribution for both cases. One can see uniform spills of particles after the reshape of the separatrix, while space charge effects decrease the initial spill rate. Results also show that the 2D solver is sufficient to calculate space charge effects.

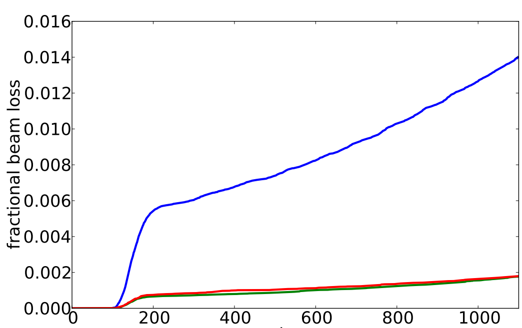


Figure 5: Fractional beam loss: without space charge effects(blue); with 2D space charge effects(green); with 3D space charge effects(red)

CONCLUSION

We have presented the results of the third-integer resonance extraction in early stage for the Mu2e experiment in the presence of space charge effects. In order to track particles and to calculate self-consistent space charge effects, Synergia2 was used, which is capable of parallel computing. The space charge tune shift was computed and was reasonable value compared with the analytical calculation. Locations of the septum and Lambertson were chosen so that particles are kicked and extracted efficiently. The spill rates for with and without space charge effects were uniform, but should be improved for the early stage after the sextupole field ramping.

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