EXPERIMENTAL STUDIES OF RANDOM ERROR EFFECTS IN HIGH-INTENSITY ACCELERATORS USING THE PAUL TRAP SIMULATOR EXPERIMENT (PTSX) *

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Abstract

Understanding the effects of random errors in machine components such as quadrupole magnets and RF cavities is essential for the optimum design and stable operation of high-intensity accelerators. The effects of random errors have been studied theoretically, but systematic experimental studies have been somewhat limited due to the lack of dedicated experimental facilities. In this paper, based on the physics analogy between intense beam propagation through a periodic focusing quadrupole magnet system and pure ion plasma confinement in a linear Paul trap, experimental studies of random error effects have been performed using the Paul Trap Simulator Experiment (PTSX). It is shown that random errors in the quadrupole focusing strength continuously produce a non-thermal tail of trapped ions, and increases the rms radius and the transverse emittance approximately linearly with the duration of the noise. This result is consistent with 2D WARP particle-in-cell (PIC) simulations. In particular, it is observed that random error effect can be further enhanced in the presence of beam mismatch.

INTRODUCTION

Random errors in machine components such as quadrupole magnets and RF cavities in high-intensity accelerators can provide a free energy source for emittance growth and beam degradation, particularly over long propagation distances. In high-intensity accelerators, the action of nonlinear space-charge force plays an important role in the thermalization of such free energy [1]. From various multi-particle simulations with both space-charge and random machine-error effects, considerable progress has been made, but systematic experimental studies have been somewhat limited due to the lack of dedicated experimental facilities. In this paper, we present a unique experimental approach to study random error effect on the beam with moderate nonlinear space-charge force using the Paul Trap Simulator Experiment (PTSX) device [2]. The PTSX device is a compact laboratory facility that investigates intense beam dynamics by taking advantage of the similarity between the dynamics of an intense beam propagating through a periodic focusing quadrupole magnetic field, and a one-component nonneutral plasma confined in an oscillating quadrupole electric field [3]. By slightly modifying the voltage amplitude of the PTSX electrodes in every half-focusing period, we can simulate the effects of randomly distributed quadrupole focusing gradient errors in the actual beam transport channel.

EXPERIMENTAL SETUP

The PTSX device, cesium ion source, and radially scanning charge collector have been described in detail elsewhere [4] and only a brief summary is given here. The PTSX device is a linear Paul trap constructed from a 2.8 m-long, r_w = 10 cm-radius, gold-plated stainless steel cylinder. The cylinder is divided into two 40 cm-long end cylinders and a $2L = 2$ m-long central cylinder. All cylinders are azimuthally divided into four 90° sectors so that when an oscillating voltage is applied with alternating polarity on adjacent segments, the resulting electric field becomes an oscillating quadruple field near the trap axis. This quadrupole electric field exerts a ponderomotive force that confines the pure ion plasma radially. To trap the plasma axially, the two end electrodes are biased to a constant positive voltage. The cesium ion source is located on the trap axis near the center of one of the end short-electrode sets so that ion injection is not affected by the fringe fields. The charge collector is mounted on a linear motion feedthrough at the other end of the short electrode set, and moves in the transverse direction along a null of the applied potential in order to minimize the perturbation on the quadrupole potential configuration during the profile measurement.

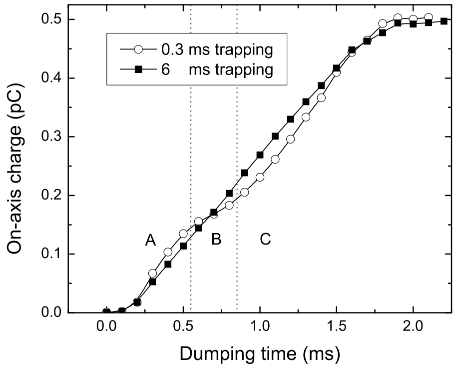

Figure 1: The slope of the on-axis charge versus dumping time curve corresponds to the on-axis beam current. If the trapping time is too short (e.g., 0.3 ms case), the axial nonuniformity induced during ion injection is not fully smoothed out (see different slopes in regions A, B, and C).

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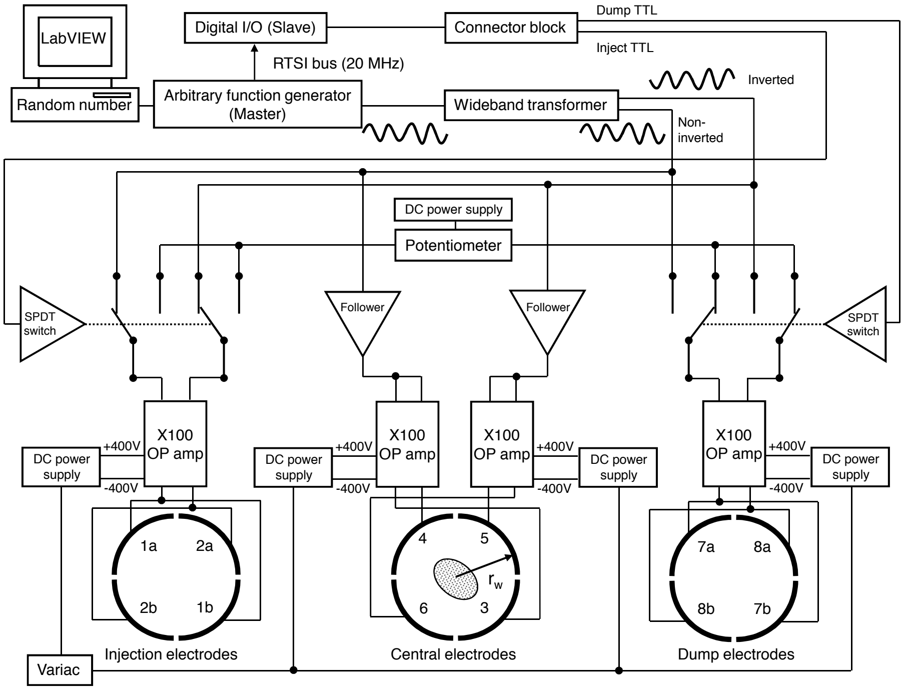

Figure 2: Schematic diagram of the PTSX electrode control system. Random noise is applied through a LabVIEW interface which samples a uniformly-distributed random number, and adjusts voltage waveform in every half-focusing period accordingly.

The PTSX device manipulates the charge bunch using an inject-trap-dump-rest cycle, and the one-component plasmas created in the trap are highly reproducible. In performing the actual experiments on random error effects, however, it is important to minimize any other sources of beam state change that might be comparable to the random error effects. In particular, the ion injection process should be optimized to avoid injection beam mismatch, production of a broad halo due to fast ions, and two-stream interactions. Through the injection scheme described in Ref. [4], we obtain an initial quiescent plasma with number density that is approximately a Gaussian function of radius. After injection is finished, the plasma is allowed to relax for several milliseconds. This relaxation time allows the residual mismatch oscillations to be damped away and the axial density nonuniformity to be smoothed out (Fig. 1). Random noise is applied to the electrodes through a LabVIEW interface which samples a uniformly-distributed random number, and adjusts the voltage waveform in every half-focusing period (see Fig. 2). To apply the arbitrary voltage signal, a National Instruments 5411 Arbitrary Function Generator Card (NI PCI-5411) with a 20 MHz clock rate and a 2 M-sample, 16-bit waveform memory is used. This PCI card has a single analog output connector whose voltage levels are 5 V with 12-bit resolution for nominal 50 Ω load termination. By looping a single waveform many times and linking different waveforms together, a long arbitrary waveform is generated to simulate a wide variety of periodic-focusing quadrupole lattice patterns with machine errors (see, for example, Fig. 3). To create the train of TTL (Transistor-Transistor Logic) pulses that controls the timing of the injecting, trapping, and dumping of the plasma, a National Instruments 6534 Digital I/O Card (NI PCI-6534) is used. We use 3 channels of the PCI card that switch on and off the bias voltages

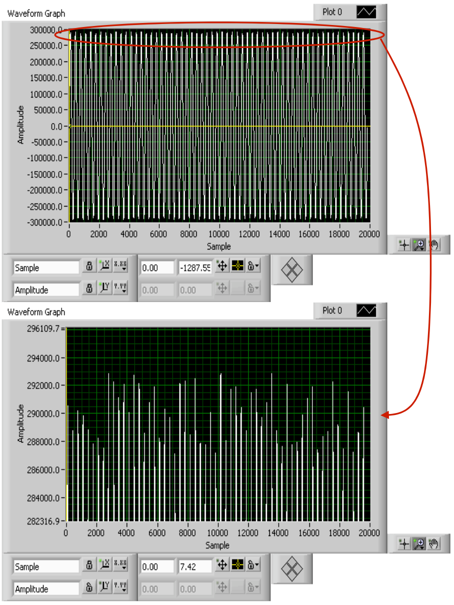

Figure 3: An example of the LabVIEW-generated voltage waveform applied to the PTSX electrodes with slight random errors in the amplitude.

of the injection electrodes, dump electrodes, and emission surface of the ion source. The waveform signal from the arbitrary function generator is split into $+V_0(t)$ and $-V_0(t)$ by a pair of unbalanced wideband transformers and these signals are sent to a set of solid-state SPDT (Single Pole Double Throw) switches. Based on the TTL pattern from the digital I/O card, the switches allow the end electrodes to receive either the DC voltage $+\hat{V}$ for trapping, or $\pm V_0(t)$ for injecting and dumping the plasma. The signals are then sent to high-voltage operational amplifiers (Apex Microtechnology PA94) with ± 400 V supply voltages. The system can apply signals up to $V_0 = 400$ V and $f_0 = 100$ kHz to the PTSX electrodes.

EXPERIMENTAL RESULTS

Uniform white noise

The evolution of the average transverse emittance is estimated from the radial profile measurements for a given noise amplitude and duration [5]. Consistent with the WARP 2D particle-in-cell (PIC) simulations, we observe a continuous emittance growth which is approximately linear with the duration of the noise (Fig. 4). This implies the conversion of free energy available from the noise-induced envelope oscillations into emittance growth (i.e., temperature increase) through the nonliner space-charge force.

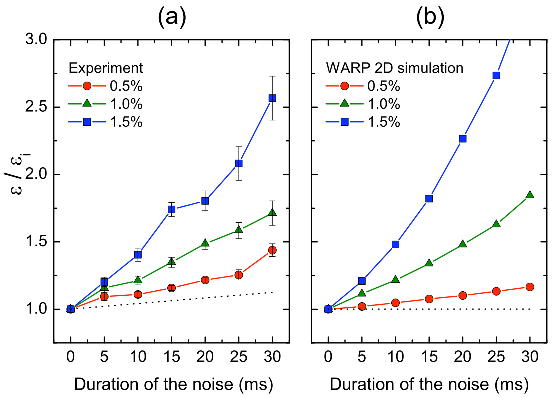

Figure 4: The emittance growth is estimated from (a) radial profile measurements, and (b) WARP 2D PIC simulations. The dotted lines indicate the background emittance growth in the absence of the applied noise [5].

Gaussian colored noise

Although colored noise itself is less detrimental than white noise, it can enhance halo formation when combined with collective mode excitations [6]. Initial experiments in Fig. 5 demonstrate that the PTSX device can generate colored noise with collective mode excitations, and detect small combined effect between them. Here, the collective modes are excited by instantaneously increasing the voltage amplitude by 1.5 times, and switching back to the original value after one focusing period.

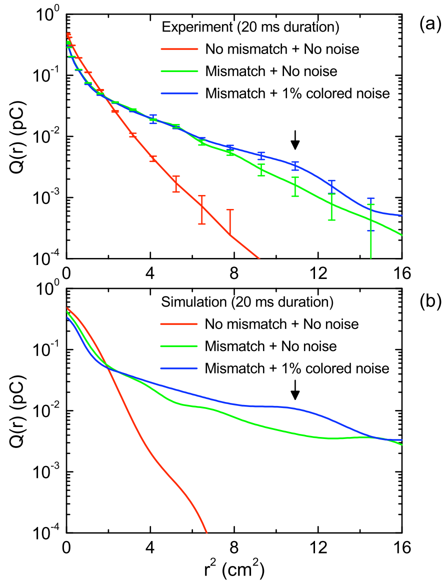

Figure 5: Radial profiles are either (a) measured in the experiments, or (b) obtained from the PIC simulations. Three different external perturbation scenarios are considered: no perturbation (red curves); instantaneous mismatch only (green curves); and both instantaneous mismatch, and colored noise (blue curves) [6].

CONCLUSIONS

In this study, we have demonstrated that random error effects in high-intensity accelerators can be effectively studied in a compact laboratory setup by making use of the transverse beam dynamics equivalence between an alternating-gradient focusing system and a linear Paul trap system. By generating various lattice patterns with white noise, colored noise, or periodic (cyclic) perturbations, we are able to significantly improve our basic understanding of random-error-induced effects in high-intensity accelerators.

REFERENCES

[1] R. C. Davidson and H. Qin, *Physics of Intense Charged Particle Beams in High Energy Accelerators* (World Scientific, Singapore, 2001).

[2] E. P. Gilson, R. C. Davidson, P. C. Efthimion, and R. Majeski, Phys. Rev. Lett. **92**, 155002 (2004).

[3] R. C. Davidson, H. Qin, and G. Shvets, Phys. Plasmas **7**, 1020 (2000).

[4] M. Chung, Ph.D. thesis, Princeton University, Princeton, NJ (2008).

[5] M. Chung, E. P. Gilson, R. C. Davidson, P. C. Efthimion, and R. Majeski, Phys. Rev. Lett. **102**, 145003 (2009).

[6] M. Chung, E. P. Gilson, R. C. Davidson, P. C. Efthimion, and R. Majeski, Phys. Rev. ST Accel. Beams **12**, submitted (2009).