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EXPLORING SPACE CHARGE MITIGATION WITH EIGENPAINTING AT THE SNS*

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Abstract

Building on recent work developing the method of eigenpainting to preferentially fill one non-planar mode of coupled optics in the Spallation Neutron Soruce ring via phase space paining, we present plans for future experiments. Our plans focus on experimentally producing several beam distributions prepared in non-planar modes, including gaussian, hollow, and Danilov (a special case of the KV). We lay out plans for experiments in the SNS, describe the available hardware, and propose a new technique for probing space charge in non-planar modes.

INTRODUCTION

A major challenge to the operation of high-intensity hadron accelerators is the effect of space charge on beam dynamics. Dependent on the details of the distribution of particles, space charge is generally non-linear, complicating the design, and operation of high-power accelerators. Perturbative treatments predict nonlinear particle-core resonances which drive particles from dense inner regions of phase space to a sparsely populated "halo" surrounding the beam [1]. Non-perturbative treatments reveal collective instabilities which can dramatically change the distribution, leading to growth in effective phase space volume [2]. Finally, in circular accelerators, space charge introduces a frequency spread in the beam which can effectively broaden single-particle resonance stopbands driven by nonlinear external forces [3]. All these effects can contribute to beam degradation and loss at high intensities. The standard limiting figure for beam loss in high power accelerators is 1 W/m, less than 1 part per million for MW scale machines such as the Spallation Neutron Source. Such stringent limits require a deep understanding of space charge dynamics to plan and operate the next generation of high-power accelerators.

One standard technique to increase the intensity of an accelerator complex is to increase the energy before injection, due to the advantageous scaling of space charge effects with energy. However, this is expensive, and other techniques have also been proposed to mitigate space charge effects, including controlling the shape of the distribution to manage the space charge force. Here we consider non-planar beam distributions as method of mitigating space charge.

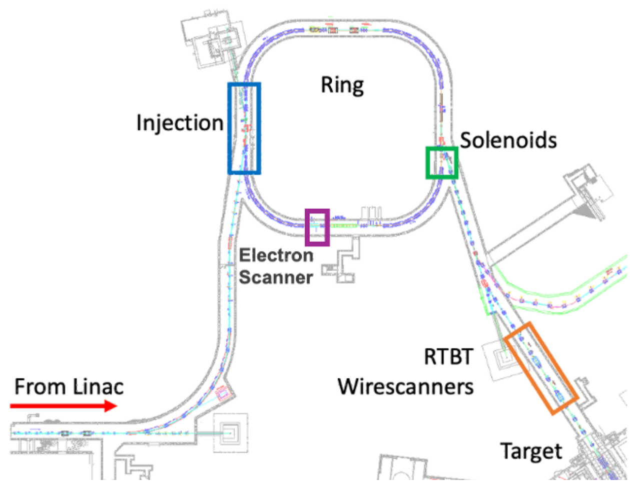

Figure 1: The SNS ring with location of key diagnostics and insertions indicated.

Exploiting the fact that transverse motion takes place in 4D phase space, but space charge only depends on the distribution in the x-y plane, non-planar modes maintain beam brightness, while reducing the effects of space charge. Additional mitigation is gained by phase-space painting—precisely placing small "beamlets" into the ring in a controlled way to construct a desired distribution. As of recent upgrades to the ring optics to allow non-planar beams, SNS is the only facility capable of both supporting non-planar beams, and phase space painting with control of position and angle in both transverse planes. In previous work we have developed a technique to paint exclusively into a single non-planar mode we call 'eigenpainting'. Eigenpainting offers direct control over the full four-dimensional phase space density in a fully-coupled ring, offering new ways to mitigate collective effects during accumulation. Compared to other methods of space charge mitigation painting non-planar beams may offer a cost-effective solution based on standard optics that could be retrofitted at existing facilities with minor disturbance to existing programs.

In addition to other applications non-planar modes have been proposed as a mitigation for space charge [4, 5]. However, no one has undertaken a systematic, experimental study of this method in a high-intensity hadron ring. This is largely due to the lack of available facilities. SNS is currently the only high-intensity ring equipped with both a flexible phase space painting system, and the optics necessary to produce non-planar modes. Figure 1 shows the layout of the ring and downstream Ring to Target Beam Transport (RTBT) line

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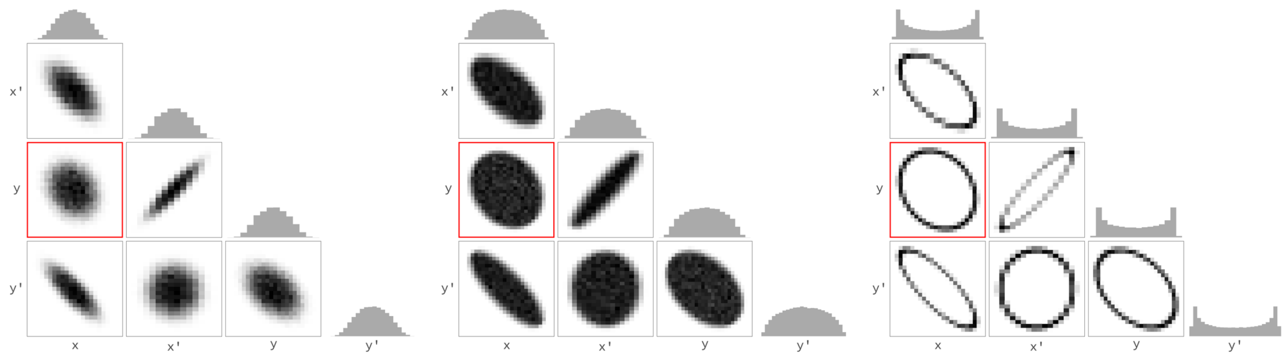

(a) Gaussian (b) Danilov (c) Hollow

Figure 2: Schematic representation of three distributions painted into a non-planar mode. The x-y plane is indicated by a red frame.

with key insertions and diagnostics required for this program described here. Both the hardware, and expertise to provide the community with valuable information for evaluating this space charge mitigation technique are available at SNS.

Building on an on-going program [6–8] to demonstrate painting of a special case of the Kapchinskij-Vladimirskij (KV) [9] distribution we call the Danilov distribution [10], we present future plans to explore the dynamics of non-planar beams in a high-intensity ring. The Danilov can be realized as one uniformly filled non-planar mode of coupled ring, making it an ideal goal for the eigenpainting method, but not the only option.

DESCRIPTION OF PLANNED EXPERIMENTAL PROGRAM

Painting Non-Planar Distributions

Beyond recent work to develop the eigenpainting method, we plan to experimentally explore the physics of painting non-planar beams for space charge mitigation. We will prepare several non-planar distributions, Gaussian, hollow, and Danilov, and compare the beam evolution to standard non-coupled SNS optics. The model of the ring in PyORBIT [11], an SNS-developed particle-in-cell code, has been thoroughly tested against data from operations and experiment, and agrees quite well with observations. However, benchmarking these unique experiments will provide valuable information on the beam dynamics, and performance of the code under non-standard operating scenarios. Figure 2 shows how schematically how each of these distributions appear when painted into a single non-planar mode.

To set up non-planar modes we rely on solenoids installed in the SNS ring to break the degeneracy of the ring lattice set with equal tunes. It would be of interest to use a traditional round-to-flat transformer [12] to study the effects of the transition from round (non-planar) to flat beams on emittance growth over many passes as one might experience in a collider. However, given the space constraints in the SNS, the solenoid + equal tune method was easier to implement.

Once non-planar modes have been established, we can inject into the modes by finding the 4D coordinates associated with the eigenmode, $\mathbf{v}_1$, for which the linear model of the ring provides a sufficient starting point. This process has been described elsewhere [8]. Injection can be further refined empirically by minimizing the oscillation in the second mode, $\mathbf{v}_2$, which has a tune ν_2. Eight kicker magnets allow a four-bump in each plane with variable position and angle of the closed orbit at the location of the foil to inject beam into one mode. We paint into the distribution by varying the amplitude of the four-bump as a function of time during the injection cycle holding the relationship between the coordinates fixed. By varying only the amplitude of the bump which injects into a single mode, we simply change the betatron amplitude of the beam injected into that mode holding the phase fixed. By modifying the time evolution of the amplitude, we can paint into a variety of transverse distributions. Three interesting distributions we plan to explore are: gaussian, Danilov, and hollow non-planar beams. By virtue of painting into a single mode, all these distributions will have an elliptical envelope in any projection.

Evaluating Painted Beams

We will use well-established techniques to characterize these beams, including 4D tomography using wirescanners in the Ring to Target Beam Transport (RTBT) line [13, 14], the SNS target imaging system [15], BPMs for tuning, and an electron profile scanner in the SNS ring [16].

Tomographic reconstruction provides a powerful insight into the time evolution of such distributions. To reconstruct the beam it must be extracted from the ring after some number of turns for wirescans. The pulse-to-pulse stability of beam in such scenarios is very good [7]. Once a reconstruction is complete, the number of turns the beam is stored before extaction can be extended, and another reconstruction produced. Comparing these reconstructions done after various numbers of turns provides 4D picture of the time evolution of the beam in the ring. This technique is time-consuming, but the technique is well-established and will provide valuable insight into the dynamics of these beams in the ring.

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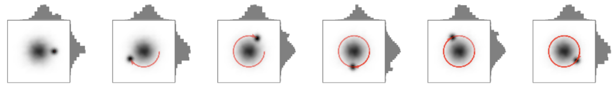
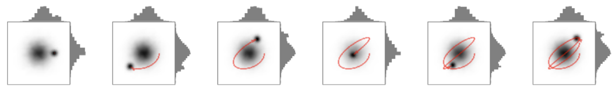


(a) Orbiting



(b) Sampling

Figure 3: Cartoon view of the x-y plane over several turns during proposed particle-core experiments in core orbiting, and core sampling configurations.

Injection Techniques for Studying Space Charge

We also have plans to develop a new experimental technique based on “particle-core” techniques in simulation to directly measure the impact of space charge. Relying on the flexibility of the SNS Low-Energy Beam Transport (LEBT) chopper, we can control the timing of injection of mini-pulses, or single revolutions, of beam into the ring. Typically the chopper notches the extraction gap into DC beam coming from the H^- ion source before the Radio-Frequency Quadrupole (RFQ). For 1000 turns of injection into the ring, which has a roughly 1 ms revolution period, the chopper will remove anywhere from 20-70 % of the beam at a frequency locked to the ring RF frequency to provide an extraction gap. The beam between each gap is referred to as a 'mini-pulse', the 'macro-pulse' being the full 1 ms beam, and ‘micro-pulses‘ being the bunches formed by the 402.5 MHz RF of the RFQ. By injecting one pulse at a much later time, as indicated by the red test 'particle' in the top panel of Fig. 4, we can explore the interaction of this test pulse as it decoheres in the presence of the 'core' which has been given some time to filament. During the time delay between core and test particle injections, the kickers will be varied to provide a precise injection of the test pulse relative to the core.

Because of the circular orbits obtained in the x-y plane when injecting into a single mode, the test particle can be made to orbit the core, or injecting into a combination of both modes, to sample the core as betatron motion carries the beam through the x-y plane. The two panels of Fig. 3 demonstrate the trajectory of the late beam when injected over a stable core. In panel 3a, the core and the test bunch are injected exclusively into mode 1, with the test bunch at a larger amplitude than the maximum extent of the core. The test bunch orbits the core. In panel 3b, the test beam is injected into both modes 1 and 2 with some non-zero amplitude, while the core fills only mode 1. During the resulting evolution the test bunch samples the core of the beam in the x-y plane providing a probe of the space charge. Beam profiles can be monitored turn-by-turn with the ring electron scanner, and the distribution reconstructed in 4D in the RTBT, as described above.

This technique of delayed injection has been demonstrated in the SNS, as shown in the bottom panel of Fig. 4, which

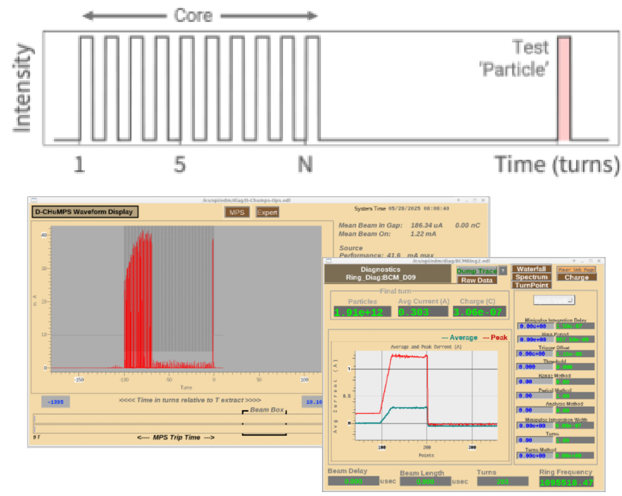


Figure 4: Schematic view of chopped beam (top) and diagnostics screens from a demonstration(bottom) showing chopped beam current, and resulting beam current in the ring (inset).

shows the beam current just after the RFQ in the Medium Energy Beam Transport (MEBT) line, with the peak and average beam current in the ring for the same accumulation cycle in the inset. The late addition of beam can clearly be seen in both the MEBT current, and the ring current. For this demonstration standard uncoupled production optics and kicker settings were used.

The complete particle-core technique has not yet been tested in either simulation or experiment with the non-planar modes. While the core-particle configuration is certainly achievable in the SNS, the insight to be gained in the face of limitations from dynamic range of diagnostics, tomographic reconstruction, and magnitude of the effect on the test bunch are yet to be confirmed. However, this offers a unique bench marking opportunity for space charge models.

CONCLUSION

Having developed a method for eigenpainting a beam into a ring with non-planar optics, we are developing plans to further explore the dynamics of non-planar beams in a high-intensity ring. This program will focus on well-established techniques, as well as develop a novel injection technique to probe space charge in non-planar beams. Observations will be benchmark against simulation to gain a deeper understanding of space charge, and improve the fidelity of PIC simulations of high-intensity beams in non-standard scenarios.

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