BEAM DYNAMICS STUDIES OF H- BEAM CHOPPING IN A LEBT FOR PROJECT X*

Qing Ji#, David Grote, John Staples, Thomas Schenkel, Andrew Lambert, and Derun Li
Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

Abstract

Project X is proposed as a high intensity proton facility at Fermilab to support a world-leading program in neutrino and flavor physics over the next several decades. The front-end consists of an H^- ion source, low-energy beam transport (LEBT), and 162.5 MHz CW Radio-Frequency-Quadrupole (RFQ) accelerator. The LEBT design, currently under study at LBNL, would comprise two solenoids, a dipole magnet and a chopper. The LEBT chopper is designed to achieve 1 MHz beam chopping of a partially neutralized 30 keV, 5 mA H- beam. Preliminary simulation studies show that chopping the beam before the second solenoid is more efficient in terms of chopper bias voltages. However, the space charge neutralization will be lost along the beam after the chopper and through the second solenoid. A beam dynamics study, using WARP 3D (a Particle-in-cell simulation code), has been carried out to investigate both the time dependence of the partial neutralization in the segment after the chopper, as well as the emittance growth. Beam emittances have been measured at various chopping repetition rates. The experimental results can be used to benchmark future transport simulations.

INTRODUCTION

Project X is a multi-functional high intensity proton facility being proposed by Fermilab to support the intensity frontier of future high energy physics programs in the US [1]. As a critical centrepiece of the technology development R&D program toward the success of Project X, Project X Injector Experiment (PXIE) is aimed at studying, building and validating the concept for the Project X front-end, thereby minimizing a primary technical risk element within the reference design. The PXIE system will have a DC H^- ion source (up to 10 mA cw H^- production), a solenoid-based low energy beam transport (LEBT) system, a 162.5-MHz 2.1-MeV CW radio-frequency quadruple (RFQ), MEBT with wideband choppers and two SC cryomodules to accelerate beam to 30 MeV.

Solenoid-based LEBTs do not spark, can withstand uncontrolled beam losses, and transport high current, space-charge neutralized ion beams [2]. But solenoid-based LEBTs are typically longer then electrostatic LEBTs. When the beam is chopped, e.g. at MHz frequencies, the space charge neutralization will be partially lost along the chopper, which causes beam emittance growth and mismatch into the RFQ and these detrimental effects are aggravated for longer LEBTs.. Hence, it is crucial to understand the time- dependent beam dynamics, in particular beam matching into the RFQ after the LEBT chopper where the beam transitions from nearly neutralized to un-neutralized.

WARP 3D is a particle-in-cell code, developed to achieve end-to-end 3D self-consistent time-dependent simulations of beams [3-5]. The WARP code includes a variety of physical models that make it useful for a broad range of research in plasma physics and computational electrodynamics. It can model acceleration, focusing and compression along accelerators, particle loss at walls, particle interaction with desorbed gas and electrons, neutralization from plasma etc. We used WARP 3D to study beam dynamics in the PXIE LEBT and chopper.

ION SOURCE AND LEBT

H- Ion Source

A filament-discharge H^- ion source was chosen as the PXIE baseline ion source. The ion source has been tested and confirmed to deliver 10 mA DC H^- beam without using any Cs [6]. The normalized rms emittance for the 10 mA beam was measured to be less than 0.2 π mm mrad [7]. As the filament is a consumable component in the ion source, there is a limited time of operation before filament replacement is necessary. The filament lifetimes are approximately 350 and 500 hours for 5 mA and 10 mA operating levels, respectively. A LEBT design with two ion sources and a switching magnet has been proposed to significantly shorten the beam downtime due to ion source service cycles.

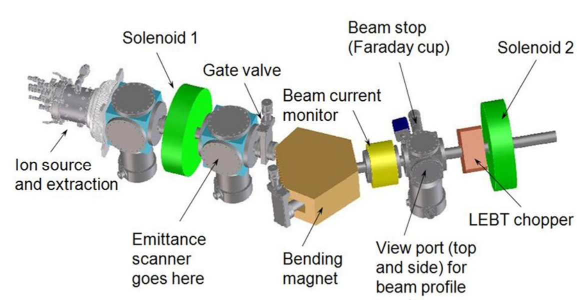


Figure 1: Schematic drawing of a two-solenoid LEBT proposed to PXIE.

LEBT

In Figure 1 we show a LEBT beamline (approximately 1.3 meters long), consisting of a two-solenoid magnetic lens system and chopper, which is being evaluated for

*Work supported by the Office of Science, Department of Energy under the contract number DE-AC02-05CH11231.
#qji@lbl.gov

ISBN 978-3-95450-118-2

PXIE. Beam diagnostics such as an online emittance scanner, DC current transformer for online beam monitoring, and a Faraday cup as a beam stop have been proposed to be added along the beamline. A LEBT chopper, placed in front of the second solenoid, has been designed to achieve a 1 MHz beam chopping rate for a partially neutralized 30 keV, 5 mA H^- beam.

LEBT BEAM DYNAMICS

In contrast to electrostatic lenses, which have been used in compact LEBTs [8], magnetic solenoid lenses are inherently spark-free but typically longer, so it is more important to compensate the space charge of the ion beam by particles of the opposite charge, usually created by ion impact ionization of the residual gas in the beamline. The LEBT chopper will provide up to 1MHz chopper capability with rise/fall times of less than 50 nsec. Typical space charge re-neutralization times are on the order of 50 µs at background pressure of 10^{-6} Torr [9], much slower than the beam pulse. Partial space charge neutralization will be lost along the beam in the chopper and possibly through the second solenoid. It is crucial to understand the time-dependent beam transport, in particular beam matching and emittance growth.

Particle Interactions with Background Gas

In the LEBT, energetic H^- ions collide with background residual H_2, creating positive ions and electrons that interact further with the H^- beam and the background H_2. The charge state balance resulting from these collisional processes, listed as follows, impacts H^- beam transport [10].

$H^- + H_2 \rightarrow H + H_2 + e$ (detachment), (1)

$e + H_2 \rightarrow H_2^+ + e$ (ionization), (2)

$H^- + H_2 \rightarrow H^- + H_2^+ + e$ (ionization), (3)

$H^- + H \rightarrow 2H + e$ (detachment), (4)

$e + H \rightarrow H^+ + 2e$ (ionization), (5)

$H- + H \rightarrow H + H^-$ (charge exchange), (6)

Time-Dependent Beam Transport Simulation Using WARP 3D

In order to include particle interactions with the background gas, WARP 3D is being further developed to model charge exchange, electron detachment, and ionization processes that occur during the beam transport. Currently, reactions (1)-(3) have been implemented in the code, using cross sections obtained from various references and databases [11-13].

Figure 2 shows a snapshot of the particles transported through a chopper and a solenoid simulated by WARP 3D. The white dots represent H^-, blue are H_2^+, and red are electrons. Preliminary results show an emittance increase of 20% along the x-axis.

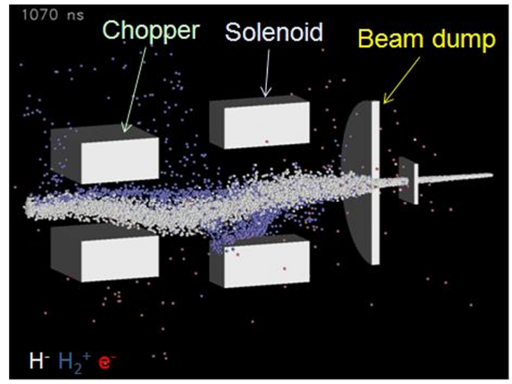


Figure 2: WARP 3D time-dependent simulations of chopper beam dynamics in the LEBT.

BENCHMARK EXPERIMENT

We have measured the emittance of a pulsed H^- beam for a series of pulsing conditions (pulse lengths and repetition rates) in order to benchmark the LEBT chopper simulations. As shown in Figure 3, the H^- ion beam is extracted from the ion source, pulsed by a parallel-plate chopper, and focused by a solenoid lens. In the present study, the background pressure was 6×10^{-6} Torr, and the ion beam energy was set to 16 keV. Simulations predict that there is a beam waist located between the solenoid and the scanner.

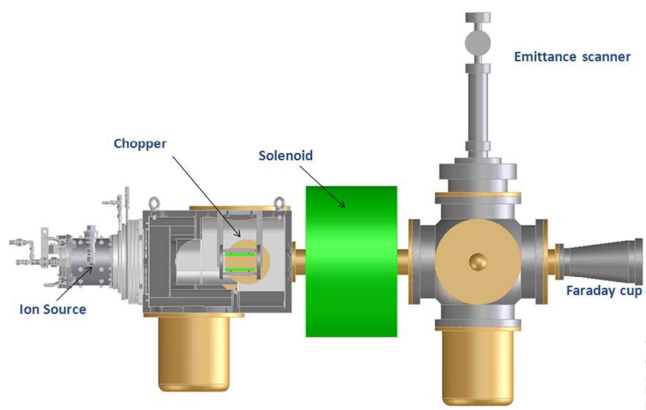


Figure 3: Benchmarking experiment setup.

Figure 4 shows the emittance plots of beams chopped with rates from 5 kHz to 1 MHz, where the Pulse repetition rates were adjusted so that the duty factor was kept constant at 50% for all pulse conditions. As shown in Figure 5, the normalized emittance values of a pulsed beams vary only very little (+/-10%). However, the Twiss parameter alpha increases with increasing beam pulsing frequency and approaches zero with increases in the repetition rate, indicating that the beam waist moves downstream towards the emittance scanner.

ISBN 978-3-95450-118-2

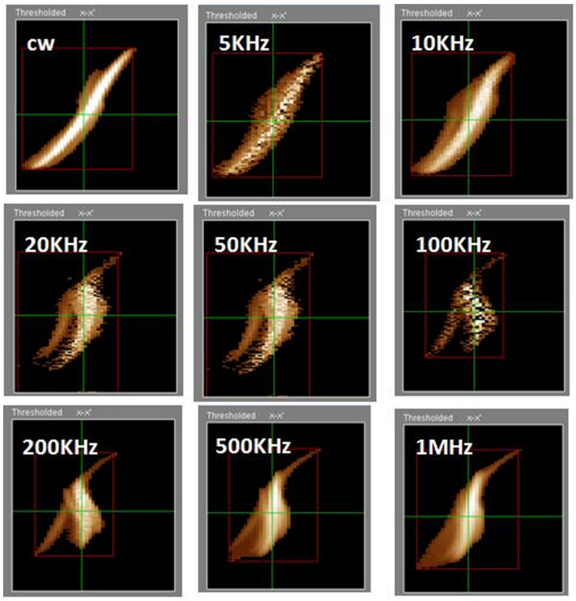
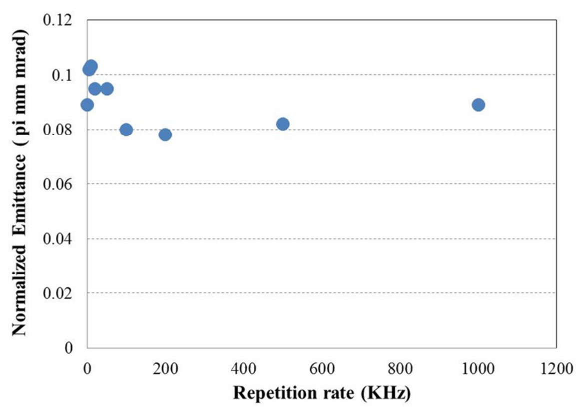
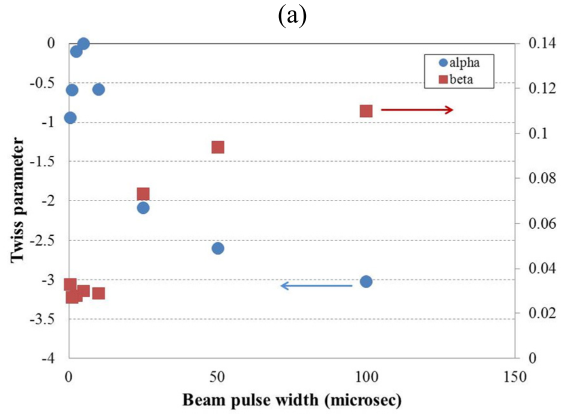


Figure 4: Emittance plots of 3.5 mA, 16 keV H$^-$ beam, chopped at 50% duty factor, and repetition rate from CW to 1 MHz.



(a)



(b)

Figure 5: (a) Normalized rms emittance as a function of pulse repetition rate. (b) Twiss parameters of the pulsed H$^-$ beam as a function of beam pulse width.

The typical space charge neutralization time is on the order of 50 μsec [8]. Partial space charge neutralization will be lost when the chopper voltage is ON. As the repetition rate increases above about 10 kHz, the beam pulse width becomes shorter than the space charge neutralization time. There is not enough time for the space charge compensation to build up again during a short beam pulse before the chopper is turned ON again. Therefore, under the same focusing force, the beam is more divergent and the waist of the beam envelope moves downstream.

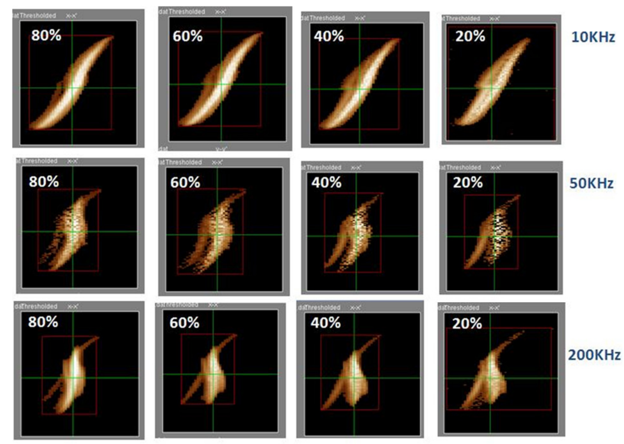
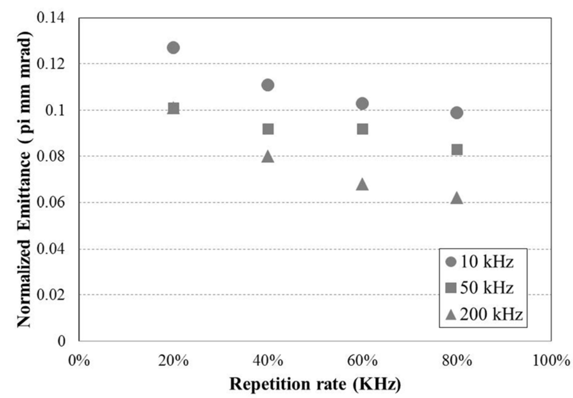
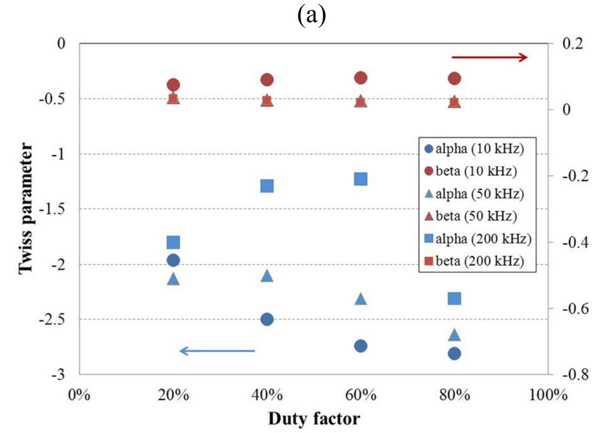


Figure 6: Emittance plots of 3.5 mA, 16 keV H$^-$ beam, chopped at 10 kHz (top), 50 kHz (middle), and 200 kHz (bottom) from 20% to 80% duty factor.



(a)



(b)

Figure 7: (a) Normalized emittance and (b) Twiss parameters of the pulsed H$^-$ beam as a function of pulse duty factor at 10 kHz, 50 kHz, and 200 kHz.

ISBN 978-3-95450-118-2

Figure 6 lists the emittance plots of beam chopped at 10 kHz, 50 kHz, and 200 kHz, respectively. As shown in Figure 7, for a given beam repetition rate, the emittance increases when the pulse duty factor decreases. As discussed above, the Twiss parameter alpha approaches zero when the duty factor (beam pulse width) decreases. This is less effective at higher and higher repetition rate. For different chopping conditions, the LEBT lens parameters need to be adjusted to rematch the beam entering into RFQ.

SUMMARY

Time-dependent WARP 3D simulations of particle interactions, such as electron detachment, charge exchange, electron impact ionization, and H^- ionization in a solenoid-based LEBT have been carried out. Preliminary simulation results show that the beam emittance increases by approximately 20% from the chopper to the entrance of the RFQ when the beam is pulsed at 1 MHz and 20% duty factor. Emittances of an H^- beam chopped at various repetition rates and duty factors have been measured experimentally. The data can be used for benchmarking further simulations in the near future.

ACKNOWLEDGMENT

The authors would like to thank Steve Wilde, Jim Galvin, and Will Waldron for their technical support; thank Amy Sy and Dr. Arun Persaud for their help in WARP 3D input files.

REFERENCES

[1] S. D. Holmes et al., "Project X Functional Requirements Specification", IPAC'2012, New Orleans, U.S.A., WEP242, p. 1936 (2012).
[2] B. X. Han and M. P. Stockli, "The new LEBT for the Spallation Neutron Source Power upgrade Project", Proceedign of PAC'07, Albuquerque, New, Mexico, USA, p. 1823 (2007).
[3] A. Friedman, D. P. Grote, and I. Haber, "Three-dimensional particle simulation of heavy-ion fusion beams," *Phys. Fluids B* **4**, 2203 (1992).
[4] D. P. Grote, A. Friedman, I. Haber, "Methods used in WARP3d, a Three-Dimensional PIC/Accelerator Code", Proc. of the 1996 Comp. Accel. Physics Conf., *AIP Conference Proceedings* **391**, p. 51 (1996).
[5] J.-L. Vay, P. Colella, P. McCorquodale, B. Van Straalen, A. Friedman, D.P. Grote, "Mesh Refinement for Particle-In-Cell Plasmas Simulation: application - and benefits for - Heavy Ion Fusion", *Laser and Particle Beams* **20**, p. 569 (2002).
[6] T. Kuo et al, "On the development of a 15mA direct current H^- multicusp source", Rev. Sci. Instrum. 67, p.1314(1996).
[7] Q. Ji et al, "Research and development of H- ion source and low energy transport for a kaon-neutrino factory", Rev. Sci. Instru., 83, p. 02A718 (2012).
[8] M. Stockli et al, "Ramping up the SNS beam current with the LBNL baseline H- source", Proceeding LINAC08, Victoria, BC, Canada. TUP119, p. 682 (2008).
[9] R. Baartman and D. Yuan, "Space charge neutralization studies of an H- beam", EPAC'88, Italy, p. 949 (1988).
[10] D. T. Abell et al, "Simulation of H- Beam Chopping in a solenoid-based low-energy beam transport (LEBT)", PAC'2011, New York, WEP254, p. 1957(2011).
[11] A.V. Phelps, J. Phys. Chem. Ref. Data, 19, 653(1990).
[12] http://www.txcorp.com/products/TxPhysics/index.php
[13] F. Barnett et al, ORNL-6086 V1, ORNL (1990).

ISBN 978-3-95450-118-2