AIP | Review of Scientific Instruments

Simulation of H− ion source extraction systems for the Spallation Neutron Source with Ion Beam Simulator

T. Kalvas, R. F. Welton, O. Tarvainen, B. X. Han, and M. P. Stockli

Citation: Rev. Sci. Instrum. **83**, 02A705 (2012); doi: 10.1063/1.3663244
View online: http://dx.doi.org/10.1063/1.3663244
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i2
Published by the American Institute of Physics.

REVIEW OF SCIENTIFIC INSTRUMENTS **83**, 02A705 (2012)

Simulation of H^- ion source extraction systems for the Spallation Neutron Source with Ion Beam Simulator[a)]

T. Kalvas,[1,b)] R. F. Welton,[2] O. Tarvainen,[1] B. X. Han,[2] and M. P. Stockli[2]
[1]*Department of Physics, University of Jyväskylä, Jyväskylä, Finland*
[2]*Spallation Neutron Source, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831, USA*

(Presented 14 September 2011; received 9 September 2011; accepted 7 October 2011; published online 7 February 2012)

A three-dimensional ion optical code IBSimu, which is being developed at the University of Jyväskylä, features positive and negative ion plasma extraction models and self-consistent space charge calculation. The code has been utilized for modeling the existing extraction system of the H^- ion source of the Spallation Neutron Source. Simulation results are in good agreement with experimental data. A high-current extraction system with downstream electron dumping at intermediate energy has been designed. According to the simulations it provides lower emittance compared to the baseline system at H^- currents exceeding 40 mA. A magnetic low energy beam transport section consisting of two solenoids has been designed to transport the beam from the alternative electrostatic extraction systems to the radio frequency quadrupole. © *2012 American Institute of Physics*. [doi:10.1063/1.3663244]

I. INTRODUCTION

Ion Beam Simulator, IBSIMU, is a freely available 3D ion optical code being developed at the University of Jyväskylä.[1,2] The code has a lot of capabilities, including multispecies particle tracking in electric and magnetic fields, self-consistent beam space charge effects, negative[3] and positive ion plasma extraction, and versatile diagnostics tools. IBSimu has been applied to designing of several positive and negative ion source extraction systems with good results.

The US Spallation Neutron Source (SNS) uses a RF-driven, multi-cusp, H^- source which now routinely delivers ~1 ms long pulses at 60 Hz to the SNS linac with peak beam currents of 35–40 mA. The source and the RFQ are currently coupled by an electrostatic, six-electrode, extraction and low energy beam transport (LEBT) system that forms, accelerates, focuses, steers, and chops the 65 keV beam while dumping the co-extracted electron beam using a strong transverse magnetic field near the outlet aperture of the source. Future SNS power upgrade plans will require linac peak beam currents of ~60 mA with about the same duty factor. To support this goal while maintaining high reliability, the existing system and a proposed high-current extraction system have been studied using IBSimu.

II. BASELINE EXTRACTION SYSTEM

In this simulation study, we have chosen a set of plasma parameters, which are believed to be correct and give a good match between simulations and experiments. The most important parameters affecting the beam are the transverse temperature of ions and electrons $T_t = 2.0$ eV, electron to ion beam ratio $I_{e^-}/I_{H^-} = 10$, plasma potential $U_P = 15$ V, and the initial energy of particles $E_0 = 2.0$ eV. These parameters have been kept constant in all the simulations shown in this paper.

The SNS ion source has an adjustable angle and offset with respect to the axis of the LEBT to compensate for the ion beam deflection caused by the permanent magnet electron dump. A set of simulations was done to study the effect of these parameters. It was noticed that the emittance and Twiss parameters of the beam at the RFQ entrance are quite insensitive to the ion source angle and offset as long as the beam does not intercept the electrodes. On the other hand the beam angle and offset are more sensitive. An optimization was done to find the case, which transports the H^- beam to the RFQ entrance centered and at 0° angle. The optimum was found at 1.4° source tilt angle and 0.8 mm offset (see Fig. 1). Although, these parameters have not been used for source operation at SNS, they were used in the simulations shown in this paper as a reference point. The sensitivity of the system can be seen by studying a deviation from the reference point: The beam at the RFQ entrance changes by 9.0 mrad and 0.1 mm if the source angle changes by 3.5 mrad (0.2°). If the source offset is changed by 0.2 mm, the beam at the RFQ entrance changes by 6.2 mrad and 0.2 mm. The effects of the angle and offset are discussed in further detail in a separate paper in these proceedings.[4]

The extraction system was simulated with the ion source producing H^- beam currents of 10–60 mA. The transverse emittance at the RFQ reference plane was recorded in the direction of the source tilt (x,x') and in the perpendicular direction (y,y'). The data is shown in Fig. 2 together with experimental (y,y') data from Ref. 5. It can be seen that the trend is well reproduced. There exists an optimum current at roughly 20–30 mA. Lower and higher beam currents lead to increasing emittance values. The reason for the increase at high currents is the low E-field at the first gap leading to highly convex plasma meniscus and beam blow-up at higher currents. Rest of the LEBT contributes to the emittance only slightly.

[a)] Contributed paper, published as part of the Proceedings of the 14th International Conference on Ion Sources, Giardini Naxos, Italy, September 2011.

[b)] Author to whom correspondence should be addressed. Electronic mail: taneli.kalvas@jyu.fi.

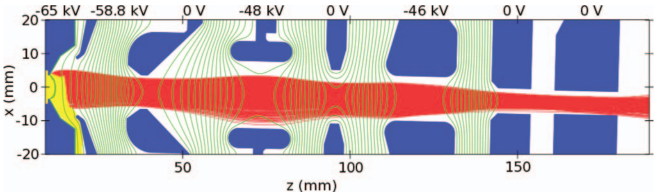

FIG. 1. (Color online) The baseline extraction system operating at optimal angle of 1.4° and offset of 0.8 mm with 60 mA H^- beam.

III. PROPOSED HIGH-CURRENT EXTRACTION

The increasing emittance at higher currents, possible extraction inefficiencies, alignment issues, and high voltage problems with the baseline extraction give justification for the development of a new high-current extraction system.[6] The new plasma and puller electrode geometry has been designed to get a high electric field in front of the plasma meniscus with 65 kV gap voltage and 100 mA H^- beam to get minimum emittance growth of the beam. The electric field maximum is 2100 V/mm, while the baseline extraction has 900 V/mm field strength. The electron dumping is done at a lower voltage at a later stage (see Fig. 3). The puller electrode voltage can be adjusted between 25 kV and 0 kV for optimal plasma meniscus shape and minimal beam emittance at beam currents ranging from 40 mA to 100 mA, respectively.

The Einzel lens following the puller electrode is at −55 kV. The electrode has an integrated SmCo dipole-antidipole magnet configuration with on-axis peak fields of 21.5 mT for deflecting the co-extracted electrons to a water cooled electron dump. The antidipole field corrects the H^- deflection and helps to spread the electron beam in the dump, which is capable of handling the expected 1 A, 10 keV electron beam at 6% duty cycle. The surface power density of the dump is shown in Fig. 4. The peak power density value during the pulse is below the critical value of 1 kW/mm^2 deduced from thermal simulations.

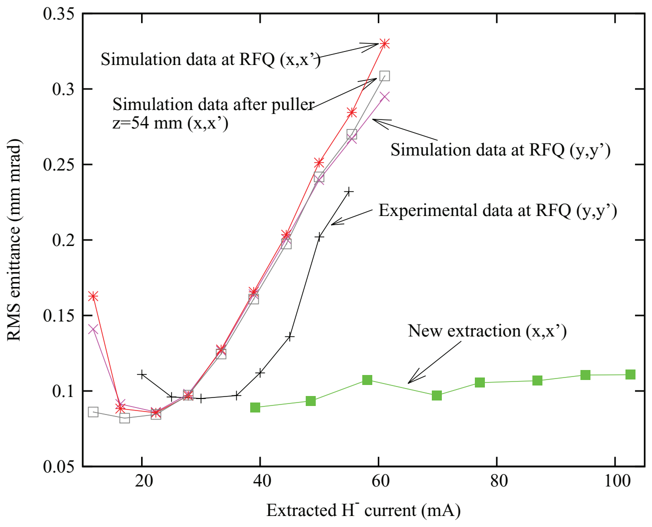

FIG. 2. (Color online) Emittance of H^- beam as a function of beam intensity. New extraction emittance values are from simulations with optimal puller electrode voltage.

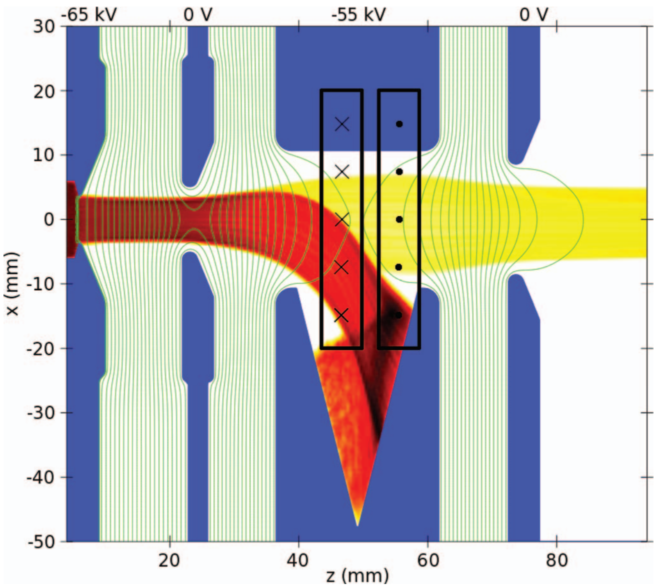

FIG. 3. (Color online) The proposed new extraction system with 100 mA of H^- extracted and 1 A of electrons dumped in the Einzel lens at 10 keV.

The H^- beam will exit the extraction with a slight angle, which depends on the voltage of the puller electrode. Therefore, the extraction must be followed by a pair of electrostatic deflector plates to return the beam back to axis. The deflectors also allow slight adjustments to be made to the beam location and angle making the design more robust to alignment issues. The corrections can also be made using magnetic elements if the electrostatic deflectors disturb the formation of the space charge compensation in the following magnetic LEBT. This will have to be studied further. The simulations of the proposed extraction show a roughly constant beam emittance between 40 and 100 mA as shown in Fig. 2. The emittance at 60 mA is 0.11 mm mrad, while for the baseline extraction, at the same beam current, the emittance value is 0.31 mm mrad after the puller electrode. This high difference in emittance is a strong reason to prefer the proposed extraction and dumping method with magnetic LEBT if handling the high power dumping can be experimentally proven.

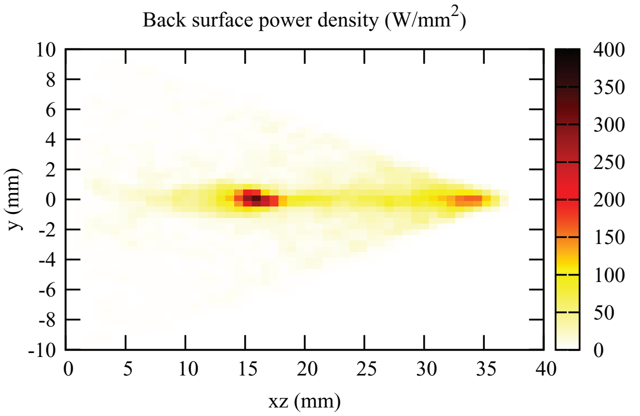

FIG. 4. (Color online) The power density on the electron dump during the beam pulse. The peak power density is below 400 W/mm^2.

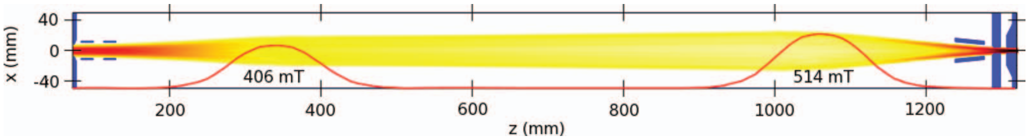

FIG. 5. (Color online) The 2-solenoid magnetic LEBT transporting 60 mA H$^-$ beam from the proposed extraction to the RFQ with 90% compensation assumed. The B$_z$ magnetic field profile is shown with red curve and peak field values are shown for achieving required Twiss parameters at RFQ entrance.

IV. TWO-SOLENOID MAGNETIC LEBT

The 2-solenoid magnetic LEBT, which is under development for the SNS front-end consists of the plasma electrode, electron dump, and puller electrode of the baseline system.[7] The same concept would also be a logical continuation to the proposed electrostatic extraction system. The magnetic LEBT has room for diagnostics between the solenoids and for deflector plates before the RFQ for high speed chopping of the beam. The upgrade from the baseline system to the magnetic LEBT would allow better control of the beam with independent solenoid focusing and electrostatic steering elements for correcting the alignment errors.

The solenoid field was calculated with Finite Element Method Magnetics (Ref. 8) and the magnetic field data was imported to IBSimu. The magnetic LEBT was simulated starting with the particle data from the high-current extraction system simulations. The solenoid currents were tuned to find a solution, which transports the H$^-$ beam into the RFQ with roughly the required Twiss parameters $\alpha = 1.7$ and $\beta = 0.06$ m/rad.[7] Exact matching is impossible because of deviations from xy-symmetry. A high level of space charge compensation between z = 250 mm and z = 1200 mm was used, which is expected in such a system.[9] According to the simulations, the 2-solenoid LEBT is capable of transporting beams up to 80 mA within the RFQ acceptance of 0.35 mm mrad at compensation levels of >90% and up to 100 mA at compensation levels of >99% by adjusting the solenoid currents. At the 60 mA beam intensity, the rms emittance achieved at the RFQ was 0.27 mm mrad in (x,x′) plane and 0.35 mm mrad in (y,y′) plane assuming 90% compensation (see Fig. 5). The magnetic LEBT was also simulated using 60 mA particle data from an extraction consisting only of the plasma electrode, electron dump, and puller electrode of the baseline system. A decent solution was also found for transporting this particle distribution by adjusting the solenoid field strengths. The rms emittance achieved at the RFQ was 0.37 mm mrad in (x,x′) plane and 0.65 mm mrad in (y,y′) plane. See Fig. 6 for phase space distributions at the RFQ entrance. Comparisons of the emittance values should be done with caution because the beams are asymmetric and contain aberrations due to the electron dumping. There are parts in the phase space which carry low amount of current but have a significant impact to the Twiss parameters and emittance values. Therefore, the complete ion optical system including the RFQ should be optimized by also simulating the beam propagation all the way through the RFQ to achieve a total transmission for the system.

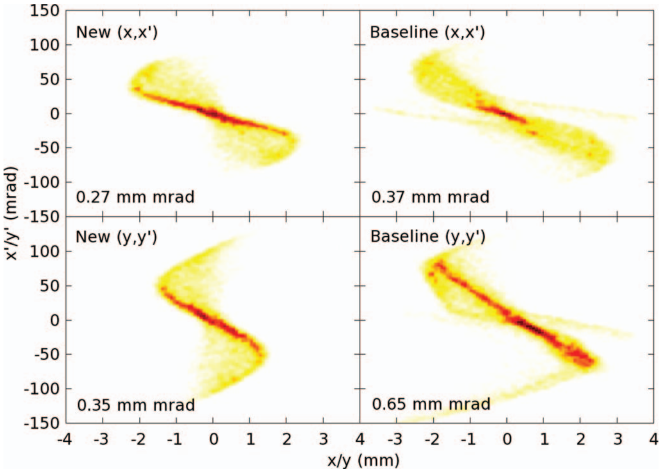

FIG. 6. (Color online) Phase space distributions at the end of the magnetic LEBT with calculated rms emittances for both extraction systems.

ACKNOWLEDGMENTS

M. Kronberger is acknowledged for providing an assessment of the electron dump heat tolerance.

[1] T. Kalvas, O. Tarvainen, T. Ropponen, O. Steczkiewicz, J. Ärje, and H. Clark, Rev. Sci. Instrum. **81**, 02B703 (2010).
[2] T. Kalvas, Ion Beam Simulator website, see http://ibsimu.sourceforge.net/.
[3] T. Kalvas, O. Tarvainen, H. Clark, J. Brinkley, and J. Ärje, AIP Conf. Proc. **1390**, 439 (2010).
[4] B. X. Han, T. Kalvas, O. Tarvainen, R. F. Welton, S. N. Murray, T. R. Pennisi, M. Santana, and M. P. Stockli, "Low energy beam transport studies supporting the Spallation Neutron Source 1-MW beam operation," Rev. Sci. Instrum. (these proceedings).
[5] B. X. Han, M. P. Stockli, R. F. Welton, T. R. Pennisi, S. N. Murray, M. Santana, and C. D. Long, Rev. Sci. Instrum. **81**, 02B721 (2010).
[6] R. F. Welton, N. J. Desai, B. X. Han, E. A. Kenik, S. N. Murray, T. R. Pennisi, K. G. Potter, B. R. Lang, M. Santana, and M. P. Stockli, AIP Conf. Proc. **1390**, 226 (2010).
[7] B. X. Han, D. J. Newland, W. T. Hunter, and M. P. Stockli, in *Proc. of 2011 Particle Accelerator Conf.*, New York, USA, p. 1564 (2011).
[8] D. C. Meeker, Finite Element Method Magnetics, version 4.0.1, 03 December 2006 Build, see http://www.femm.info/.
[9] J. Sherman, E. Pitcher, R. Stevens, and P. Allison, in *Production and neutralization of negative ions and beams: Sixth international symposium*, Upton, New York, USA, p. 686 (1992).