REVIEW OF SCIENTIFIC INSTRUMENTS **77**, 03B904 (2006)

Fast slit-beam extraction and chopping for neutron generator

T. Kalvas, S. K. Hahto, F. Gicquel, M. King, J. H. Vainionpää,
J. Reijonen, and K. N. Leung
Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, California 94720

T. G. Miller
Tensor Technology Inc., 254 Brentwood Lane, Madison, Alabama 35758

(Presented on 12 September 2005; published online 9 March 2006)

High-intensity fast white neutron pulses are needed for pulsed fast neutron transmission spectroscopy (PFNTS). A compact tritium–tritium fusion reaction neutron generator with an integrated ion beam chopping system has been designed, simulated, and tested for PFNTS. The design consists of a toroidal plasma chamber with 20 extraction slits, concentric cylindrical electrodes, chopper plates, and a central titanium-coated beam target. The total ion beam current is 1 A. The beam chopping is done at 30 keV energy with a parallel-plate deflector integrated with an Einzel lens. Beam pulses with 5 ns width can be achieved with a 15 ns rise/fall time ±1500 V sweep on the chopper plates. The neutrons are produced at 120 keV energy. A three-dimensional simulation code based on Vlasov iteration was developed for simulating the ion optics of this system. The results with this code were found to be consistent with other simulation codes. So far we have measured 50 ns ion beam pulses from the system. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2163271]

I. INTRODUCTION

A variety of neutron-based methods are being considered to be used in luggage and airline cargo screening applications in addition to the present x-ray screening.[1] These methods make it possible to determine the H, C, N, O, and possibly other elemental composition of materials. One of the neutron-based methods known to be able to discriminate the elemental composition of material is known as pulsed fast neutron transmission spectroscopy (PFNTS). This method is based on measuring the neutron transmission in the object as a function of neutron energy. This is done by using fast pulses of the white energy spectrum of neutrons and time-of-flight techniques.[2]

The PFNTS method has been further developed recently by Miller *et al.* at Tensor Technology Inc. (TTI) to be used in the detection of explosives and other illicit materials in airline luggage and cargo.[3] Neutron attenuation signatures of a number of substances, including typical suitcase items, drugs, and explosives, have been extensively studied at TTI. A neutron detector array is being used at TTI to screen the cargo in two dimensions. The data from the system is analyzed using a neural network.

Previously, neutrons for PFNTS have been made with large accelerator-based systems by colliding high-energy D^+ to beryllium or lithium targets. Now a compact, tritium-tritium fusion reaction, white neutron generator with slit-beam extraction, and fast integrated ion beam chopping system have been designed for the PFNTS application at Lawrence Berkeley National Laboratory (LBNL).

II. DESIGN

The design of the neutron generator described in this paper is based on the experience from our previous pulsing system.[4] In our previous tests we pulsed an axial 20 keV, 1 mA H^+ ion beam by sweeping it with a 110 ns rise/fall time of ±400 V voltage on the deflector plates. In that configuration 15 ns full width at half-maximum (FWHM) H^+ pulses were achieved.

The design consists of a toroidal plasma chamber with 20 extraction slits, four concentric cylindrical electrodes, chopper plates, and a central titanium-coated beam target (see Fig. 1). The extraction has been designed to give a total ion current of 1 A from 20 $3\times 33\ \text{mm}^2$ slits with $50\ \text{mA/cm}^2$ current density. After the extraction electrode, puller electrode, and a decelerating Einzel lens, the beam is swept with electrostatic deflector plates operated with a 625 kHz square wave voltage. These plates also function as the last electrode of the Einzel lens. The pulsing system generates 1.25 million, 5 ns beam pulses per second. After the collimator, the pulses are accelerated to 120 kV to form a neutron flux of 10^{12} n/s at a full 1 A beam.

III. SIMULATION CODE

A three-dimensional (3D) ion transport code was developed for simulating the beam extraction, focusing, and sweeping. The code is based on solving the Poisson equation $\nabla\cdot E=\rho/\epsilon_0$ in a rectangular mesh using the Vlasov iteration. The mesh can be defined in two areas with different resolution. A finer mesh can be used near the critical areas of the geometry, such as at the extraction slit, to increase the precision of the calculation, while the other areas have a coarse mesh to speed up the calculation.

The Vlasov iteration used by the code is a standard way to solve problems where the beam is affecting the electrostatic field of the electrode geometry. First, the solids (the electrodes) are defined with assigned potentials with primitive objects or with a set of functions. The potential distribu-

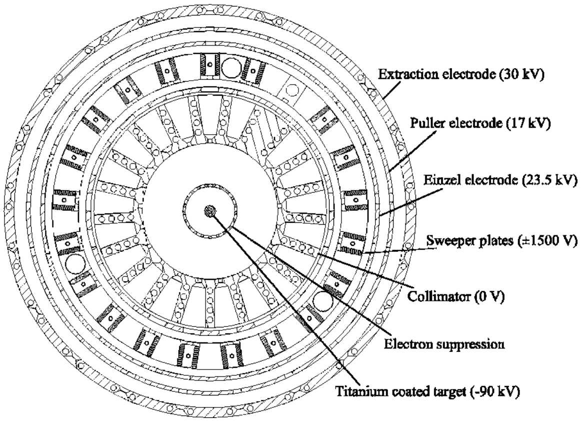

FIG. 1. Schematic of the extraction and chopping geometry.

tion of free space is then solved with the Poisson equation ($\rho=0$). Then the ion beam is injected into the geometry and the particle trajectories are calculated. Space-charge distribution is then calculated from the trajectories and the Poisson equation is solved with the resulting space-charge distribution. Recalculating the trajectories and the potentials is then continued until the solution converges.

The ion beams are simulated using macroparticles that propagate in the electric and magnetic fields as if they were single ions, according to the Lorentz force law. The numerical calculation of the trajectories is done with the fourth-order Runge-Kutta integration. Each of the macroparticles in the ion beam is assigned a part of the total ion beam current, and this current is used to calculate the space-charge density along the trajectory. The code also features the possibility for manually setting a space-charge compensation function in 3D space. In addition to calculating electric fields, the code also has a possibility for importing magnetic fields with three or less dimensions to the simulations.

Currently the code does not feature plasma calculation. The ions are started from a virtual plasma emitter with an arbitrary shape. So far we have used plasma emitter shapes extrapolated from other two-dimensional (2D) simulations.

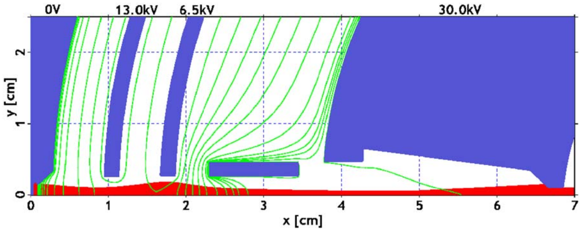

FIG. 2. (Color online) The design of the extraction was made with the 2-D simulation code PBGUNS. The ion optics was designed for 50 mA/cm^2 T$^+$ beam, but the same geometry can be used with D$^+$ or H$^+$ ion beams with minor changes in the voltages of the first two electrodes.

An analysis of the simulation can be done using plotting tools of the simulation code. Currently the code can plot 2D slices of the geometry with solids, equipotential lines, and trajectories shown. Also, beam profiles, emittances, electrostatic, magnetic, and space-charge fields, and beam energy distributions can be plotted.

IV. SIMULATIONS

The ion optics and the geometry of the 50 mA/cm^2 T$^+$ extraction were optimized with the 2D simulation code PBGUNS.[5] The extraction was designed to give a well-focused 2 mm beam width at the collimator of the chopper system from the slit beam extracted from a 3 mm wide extraction slit. At the same time the distance between the parallel plates was minimized and the distance from the plates to the collimator was maximized to lower the needed voltage for ion beam sweeping. The design of the 30 keV T$^+$ beam chopper is presented in Fig. 2.

The simulation results of the code described in this paper were compared with KOBRA3-INP[6] and PBGUNS codes. In both 3D simulations it was noted that more beam is lost at the collimator because of edge effects at the ends of the slit. Otherwise, the results were similar with all three codes. In

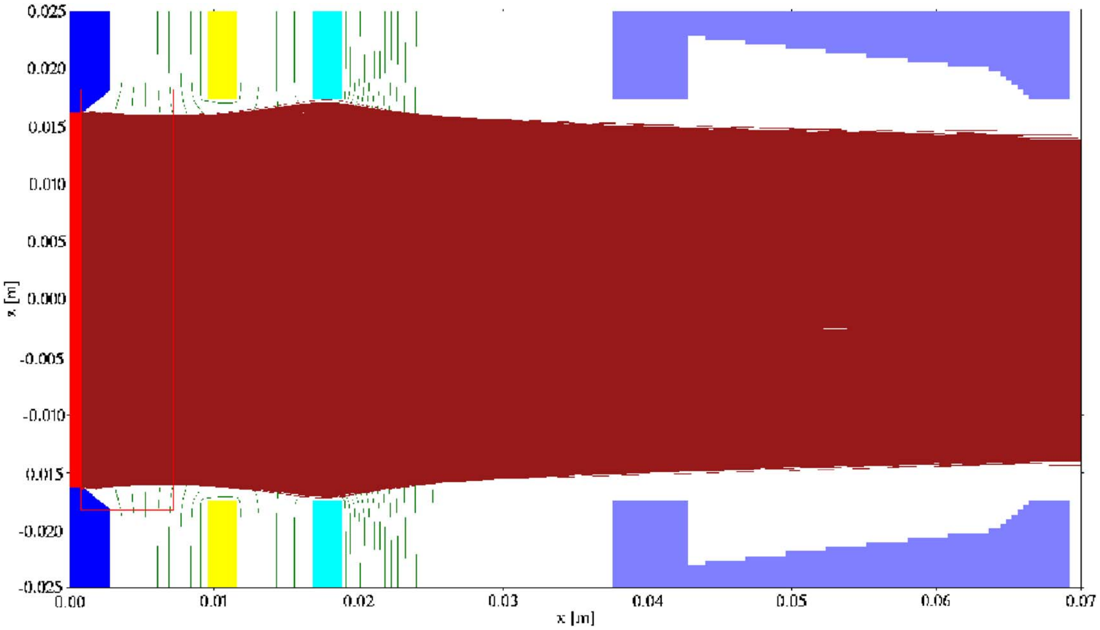

FIG. 3. (Color online) It was noted that the ion beam stays in focus in the y and z directions.

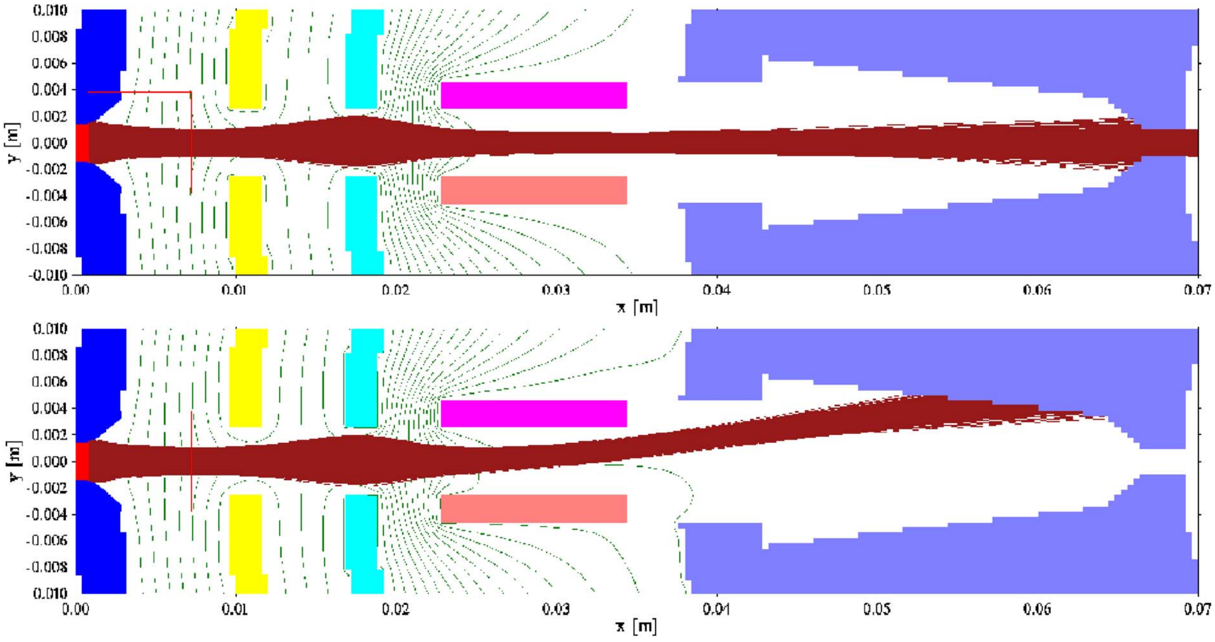

FIG. 4. (Color online) The ion beam sweeping is done with ±1500 V voltage on the deflector plates.

three dimensions it was noted that the geometry provides ion beam focusing in both *y* and *z* directions (see Fig. 3). The geometry allows us to use ±1500 V sweeping voltage (the maximum voltage difference between the plates being 3000 V) on the deflector plates (see Fig. 4). To achieve 5 ns ion beam pulses, a 15 ns rise/fall time high-voltage switch is necessary. There are commercial high-voltage switches available that can drive the 65 pF capacitance between the plates at this speed.

V. MEASUREMENTS

So far we have tested the designed extraction and chopping system with a full-size prototype device that has only one slit beam extraction hole and a 50 Ω impedance matched Faraday cup after the collimator for measuring the pulses. The plasma in the prototype source was formed in the toroidal plasma chamber with one 5 cm diam internal 1.5 loop water-cooled quartz antenna near the extraction slit, operated with 13.56 MHz rf frequency. In our preliminary tests we have extracted hydrogen current densities around 7 $\mathrm{mA/cm^2}$ with 2 kW rf power at a 15 mTorr source pressure. The electrode voltages were adjusted to get maximum focusing at the collimator. In our measurements the source was biased at 4.6 kV, Einzel at 3 kV, and the collimator, puller, and the Faraday cup at ground potential. The ion beam was swept with a ±800 V pulse generator, providing 100 ns rise and fall times. The pulse generator was connected to one deflector plate while the other plate was connected to the ground.

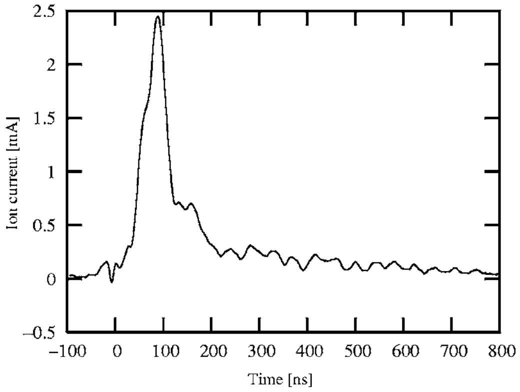

FIG. 5. Hydrogen pulse measured with ±800 V, 100 ns rise/fall time sweeping on one deflector plate. The system cannot separate H^+, H_2^+, and H_3^+ peaks.

A hydrogen pulse measured with this configuration can be seen in Fig. 5. The flight times of H^+, H_2^+, and H_3^+ are 66, 94, and 115 ns, respectively, and the widths of these pulses are about 50 ns, so the pulses cannot be separated. This pulse width corresponds to a beam spot of 5 mm at the collimator. In order to meet the system specifications, we will increase the plasma density to get higher extracted current and higher voltages at the extraction for better focusing at the collimator. This can be done by improving the rf antenna geometry and by increasing the rf power. We are also planning to use faster and higher voltage pulse generators for the tests in the near future.

ACKNOWLEDGMENTS

This work is funded by Tensor Technology Inc. under contract No. Z2ISTE and by Department of Energy under Contract No. DE-AC02-05CH11231. Principal author (T. Kalvas) would like to acknowledge financial support from the Finnish Academy of Science and Letters (Vilho, Yrjö ja Kalle Väisälän Rahasto).

[1] A. Buffler, Radiat. Phys. Chem. **71**, 853 (2004).
[2] J. C. Overley, Int. J. Appl. Radiat. Isot. **36**, 185 (1985).
[3] T. G. Miller and R. A. Krauss, Proc. SPIE **2511**, 14 (1995).
[4] S. K. Hahto, S. T. Hahto, K. N. Leung, and J. Reijonen, Rev. Sci. Instrum. **76**, 023304 (2005).
[5] J. E. Boers, Proc. IEEE Particle Accelerator Conference (American Physical Society, New York, 1995), p. 2312.
[6] P. Spädtke, KOBRA3-INP, INP, Junkernstr. 99, 65205 Wiesbaden, Germany, 2004.