FAST PULSING NEUTRON GENERATORS FOR SECURITY APPLICATION*

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Abstract

Active neutron interrogation has been demonstrated to be an effective method of detecting shielded fissile material. A fast fall-time/fast pulsing neutron generator is needed primarily for differential die-away technique (DDA) interrogation systems. A compact neutron generator, currently being developed in Lawrence Berkeley National Laboratory, employs an array of 0.6-mm-dia apertures (instead of one 6-mm-dia aperture) such that gating the beamlets can be done with low voltage and a small gap to achieve sub-microsecond ion beam fall time and low background neutrons. Arrays of 16 apertures (4×4) and 100 apertures (10×10) have been designed and fabricated for a beam extraction experiment. The preliminary results showed that, using a gating voltage of 1200 V and a gap distance of 1 mm, the fall time of extracted ion beam pulses is approximately 0.15 μs at beam energies of 1000 eV.

INTRODUCTION

Active neutron interrogation has been demonstrated to be an effective method of detecting shielded fissile material. The penetrating ability of neutrons allows them to "see" through material that may be surrounding the fissile material. When the neutrons interact with fissile material they induce fission resulting in the emission of neutrons and gammas that may then be detected. A fast fall-time/fast pulsing axial neutron generator is needed primarily for differential die-away technique (DDA) interrogation systems. The DDA has been used for some time to measure the fissile content of nuclear waste containers, and is a sensitive technique for detecting the presence of fissile materials such as ^{235}U and ^{239}Pu. In DDA analysis, a neutron generator produces repetitive pulses of neutrons that are directed into a cargo container that is under inspection. As each pulse passes through the cargo, the neutrons are thermalized and absorbed. The thermalization process is very rapid and the epithermal neutrons decays within microseconds. The thermal neutrons, however, decay much slower, which is on the order of hundreds of microseconds. If Special Nuclear Material (SNM) is present, the thermalized neutrons from the source will cause fissions that produce a new source of neutrons. These fast fission neutrons decay with a time very similar to that of the thermal neutron die-away of the surrounding cargo. A fast fall-off of the neutron pulse and low neutron background will improve the DDA signal and SNM detection [1,2].

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The basic principle of neutron generator is to bombard an ion beam of either deuterium or tritium onto a target. Neutrons are produced via the D+D, D+T, or T+T reactions if the target surface is loaded with the D or T molecules. By switching on and off the deuterium or tritium ion beams reaching the target, one can obtain a pulsed neutron source. A compact neutron generator, with enhanced features such as sub-microsecond ion beam fall time and low background neutrons, is being developed in Lawrence Berkeley National Laboratory. The goal is to achieve (1) pulse width of tens of μs; (2) pulse fall time of less than 1 μs; (3) repetition rate of 10 kHz; and (4) peak neutron yield $>10^9$ n/s. Different methods of beam switching have been evaluated, in terms of fall-off time, reliability, system complexity, and neutron background level. Gating multiple small ion beamlets at low energy offers the best approach for a compact neutron generator to obtain less than 1 μs pulse fall time, compared with other schemes such as switching on and off the plasma, pulsing the acceleration high voltage while keeping the plasma running continuously, or sweeping a beam across an aperture or a knife-edge [3]. The total beam current requirement can be met by using multiple beamlets. Experimental setup to obtain fall-time less than 1 μs with both 4×4 and 10×10 array of small apertures is described and results are discussed in this article.

EXPERIMENTAL SETUP

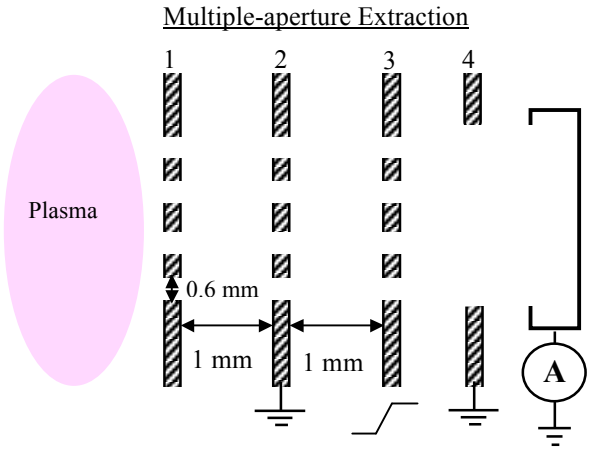
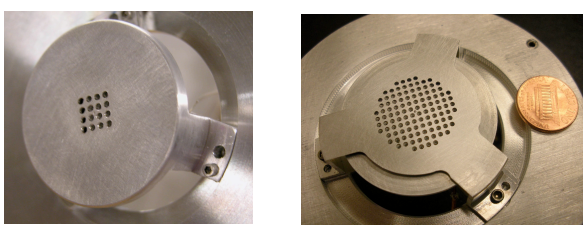


Figure 1: Schematic drawing of beam pulsing by gating the ions in the second gap (not to scale).

Figure 1 illustrates the approach to gate ion beams by a retarding potential. Forward bias in the second gap will allow the extracted ions to continue acceleration. Reverse bias will stop the ion flow. The fall time depends on the

ion energy and retarding field strength. A multiple-aperture extraction system has been used in the beam pulse characteristics measurement. A hydrogen plasma was generated using a 2.45 GHz microwave-driven ion source. The detailed description of the ion source was reported by J. Kwan *et al* in Ref. [4]. The plasma chamber is 9.2 cm in diameter and 12.7 cm long. Microwave power is transmitted via a rectangular waveguide through an aluminum nitride window into the plasma chamber. An axial magnetic field, that is required to set up the electron cyclotron resonant condition, is produced by passing approximately 109 A of dc current through the field coils. In the experiment, the microwave power was at 320 W and the gas flow was at 0.5 sccm. Hydrogen ions are extracted from an array of 4×4 apertures (Fig. 2a) with each aperture 0.6 mm in diameter. The center-to-center distance between adjacent apertures is 1.75 mm thus the grid transparency is around 13%. The extraction voltage V_1 was varied from 400 V to 1200V, and the peak voltage of gating power supply V_2 varied from 800V to 1600 V. The rise-time of gating pulse was approximately 500 ns, and the pulse width was 5 μs. The fourth electrode, at ground potential, was inserted to reduce the capacitive couple current in the Faraday cup induced by the gating voltage.



(b) (a)

Figure 2: Photographs of the multiple-aperture extracting system. (a) 4×4 array, (b) 10×10 array.

To achieve higher beam current, an array of 10×10 apertures (Fig. 2b) was also fabricated. The size of each aperture and their spacing stay the same as those of 4×4 array. Several modifications have been made in the 10×10 array column: the extraction gap was reduced from 1mm to approximately 0.5 mm; the distance between the gating electrode (#3) and Faraday cup was reduced from 19 cm to 12 cm. The ECR source chamber was also UHV cleaned to eliminate all the possible contaminants from prior operation, namely boron nitride coating on the source wall.

RESULTS AND DISCUSSIONS

Beam extracted from an array of 4×4 apertures:

Results of the hydrogen ion beam current extracted from the array of 4×4 apertures as a function of time are shown in Fig. 3, with extraction beam energy varying from 800 eV to 1200 eV. For each beam pulse, the current doesn't start to drop until a period of time (t_1) after the gate voltage is on. It then drops off to approximately 20% of the total amplitude within 0.5 μs, entering a "knee". The current level stays more or less the same for another period of time, and then starts to drop again after t_2. It is believed that t_1 and t_2 are the time of flight for hydrogen and impurity ions such as C^+ and N^+ that have already exited the gate electrode (#3) travelling through the gap and reaching the Faraday cup. Table 1 lists the time of flight for H^+, C^+, and N^+ at various energies. As the distance between the gate electrode and the Faraday cup is 19 cm in the experimental setup, the calculated time of flight for hydrogen ions with energies of 800 eV to 1200 eV are 0.475 μs and 0.387 μs, respectively. The calculated time of flight for C^+ and N^+ at energies of 800 eV, 1000 eV, and 1200 eV are 0.475 μs, 0.424 μs, and 0.388 μs, respectively. These match with the t_1 and t_2 shown in Fig. 3 quite well.

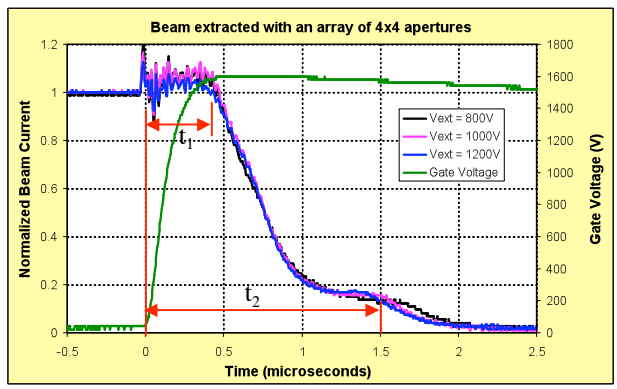


Figure 3: Measured pulse beam current extracted with an array of 4×4 apertures. The gate voltage was set at 1600 V. The extraction voltage varies from 800V to 1200V.

Table 1. Lists of corresponding time for different ions (H^+, C^+, and N^+) to travel from the gating electrode to Faraday cup.

V_{gate} (V)	t_1 (μs)	t_H (μs)	t_2 (μs)	t_N (μs)	t_C (μs)
800	0.472	0.475	1.676	1.777	1.645
1000	0.444	0.424	1.524	1.589	1.472
1200	0.396	0.388	1.392	1.451	1.343

Beam extracted from an array of 10×10 apertures:

Figure 4 compares the fall-off time between beams extracted from an array of 4×4 and 10×10 apertures. The extraction voltage and gate voltage were kept the same in both cases, which are 400V and 1200V, respectively. The beam fall-off time is around 0.5 μs for both cases, except that t_1 and t_2 (as defined in Fig. 3) have been significantly reduced when using the 10×10 array. This is caused by the fact mentioned in the "Expermental Setup" that the Faraday cup has been moved forward towards the column in the set up of 10×10 array. After the source being

cleaned, the level of impurities is reduced from 20% to around 12%.

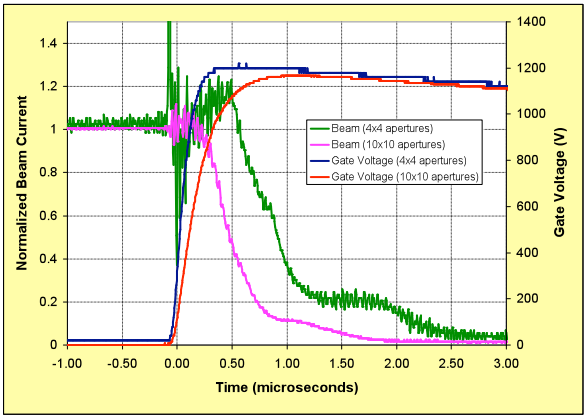


Figure 4: Comparison of pulsed beam current extracted with an array of 4×4 apertures and 10×10 apertures. In both cases, the extraction voltage was 400 V and the gate voltage was set at 1200 V.

As analysed in prior work, the fall time of the beam pulse Δt is proportional to the square root of V_{ext} and inversely proportional to the retarding field E [3]. Provided that the rise time of the gate pulser is negligible, the fall time of a beam extracted at 400eV and gated in an electric field of 10 kV/cm is predicted to be less than 20 ns. Nevertheless, these experimental results are significantly larger than the values calculated. So far, all the data of beam current shown above was measured through a 470 Ω sensing resistor. To further explore the actual limit of the pulse fall-off time, different sensing resistors have been used to determine the RC delay in the diagnostic circuitry. As shown in Fig. 5, with a sensing resistor of 50 Ω, the fall off time is significantly reduced from 0.6 μs to approximately 0.15 μs, for the same beam condition.

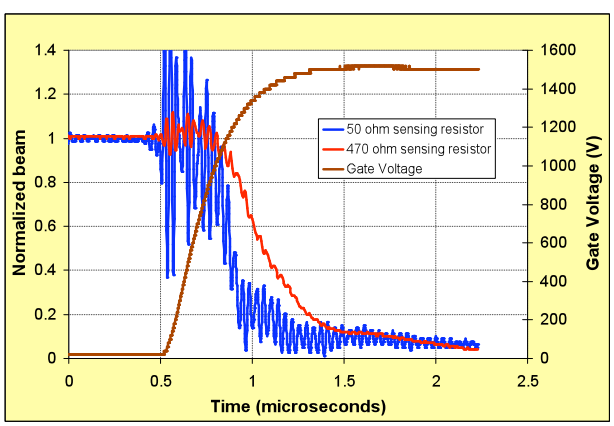


Figure 5: Comparison of pulsed beam current measured with different sensing resistors.

Higher "ON"-state beam level is expected in the column of 10×10 apertures. As shown in Fig. 6, the total ion beam in the 10×10 column is more than five times higher than that in the 4×4 column. When extracted at 1 kV, the "ON"-state beam level reaches as high as 3.3 mA.

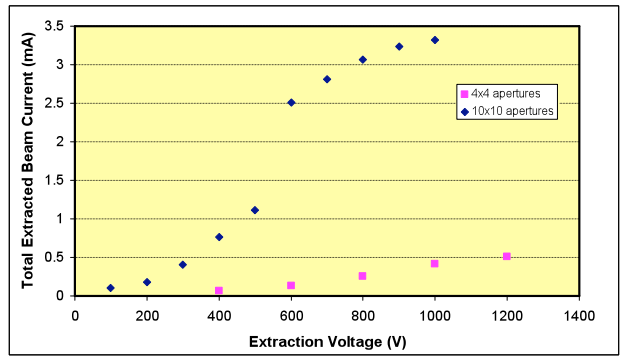


Figure 6: Comparison of the total extracted beam between the columns of 10×10 array and 4×4 array.

CONCLUSIONS

Beam fall time of approximately 0.15 μs has been achieved by gating multiple beamlets at low voltage and with a small gap. The scaling capability from an array of 4×4 to 10×10 beamlets has also been demonstrated. Using the 10×10 column, the "ON"-state beam level has reached 3.3 mA. The design of prototype fast fall-time pulsed neutron generator using an array of 10×10 beamlets is in progress. The detail design and fabrication and results of testing the prototype neutron generator will be reported in future publication.

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