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INTENSE ION PULSES FOR RADIATION EFFECTS RESEARCH

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Abstract

A new facility for providing intense, short ion pulses has become available at the Lawrence Berkeley National Laboratory. The novel induction accelerator can deliver a few nanosecond long pulses of 1.2 MeV light ions such as helium, deuterium and protons. For helium ion beams focused into a ~2 mm FWHM diameter spot, a charge per pulse of 20 nC corresponds to an ion fluence per pulse of ~$3 \cdot 10^{12}$ ions/cm^2 and a dose per pulse to the target on the order of 1 MGy(Si). The short pulse length and the very high ion fluence could provide new opportunities such as the observation of the time-resolved multi-scale dynamics of radiation-induced effects. High 1 MeV neutron energy equivalent damage to silicon rates corresponding to ~10^{15} neutrons/cm^2/ns may enable the characterization of transient radiation effects and nuclear survivability testing of electronics components.

Introduction

A unique, new capability has become available at the Lawrence Berkeley National Laboratory (LBNL) to produce intense, short pulses of ion beams that could be used to study radiation defect dynamics. Beams of protons and helium and possibly other ions impart a dose of up to 1 MGy per pulse on a target or test device.

Correlation between damage produced by various types of radiation has been extensively studied in the past. Device degradation and damage equivalency between ions and fast neutrons has been established based on the concept of Nonionizing Energy Loss (NIEL) [1]. Bielejec *et al.*, for example, studied the displacement damage correlation between neutrons and light ions in bipolar junction transistors [2], [3]. The novel ion beam facility at LBNL, the Neutralized Drift Compression Experiment (NDCX-II), could provide neutron equivalent damage rates and fluences that may significantly benefit the characterization of transient radiation effects on electronics and nuclear survivability testing when fast burst reactors (FBRs) are no longer available. The short pulse length on the order of a few ns to 20 ns combined with the very high ion fluence per pulse are unique capabilities of the NDCX-II facility and provide new opportunities such as the observation of time-resolved multi-scale dynamics of radiation-induced effects. This is complementary to capabilities of more conventional ion beam facilities that typically operate with orders of magnitude lower fluxes (but higher average currents). Intense ion beams from NDCX-II are also characterized by a relatively low energy spread compared to ultra-short MeV-range ion pulses from laser-plasma acceleration [4] and allow experiments in a lower radiation environment without the electron and x-ray radiation accompanying laser acceleration [4].

The NDCX-II Ion Beam Facility

This novel ion beam facility, the Neutralized Drift Compression Experiment (NDCX-II) at Berkeley Lab, is a pulsed induction linear accelerator that has been developed to deliver intense, up to 50 nC/pulse/mm^2, sub-ns pulses of light ions with kinetic energy up to 1.2 MeV for high-energy density experiments in the warm dense matter

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regime [5]-[7]. The ~12 m long NDCX-II accelerator, shown in Fig. 1, is comprised of an ion source, a pulsed injector, and an induction LINAC that is capable of accelerating and rapidly compressing beam pulses (schematically indicated in Fig. 2) by adjusting the slope and amplitude of the voltage waveforms in each acceleration gap. This is accomplished with 12 compression and acceleration waveforms driven with peak voltages ranging from 15 kV to 200 kV and durations of 0.07–1 µs.

The first seven acceleration cells are driven by custom spark-gap circuits and compress the ion bunch to <70 ns so that it can be further accelerated and compressed by the Blumlein pulsers that drive the last five acceleration cells. Each lattice cell has a pulsed solenoid to provide focusing fields for balancing the space charge forces and maintaining an approximately constant beam radius through the accelerator. The five Blumlein driven cells increase the beam energy from approximately 0.3 MeV to 1.2 MeV in a few meters. At the exit of the final acceleration gap the bunch duration is 30–40 ns. In the final drift section, the bunch has a head-to-tail velocity ramp that further compresses the beam by an order of magnitude. Here, an externally generated plasma is needed to reduce the beam's space-charge forces and to enable focusing and bunching of the beam to the millimeter and nanosecond range.

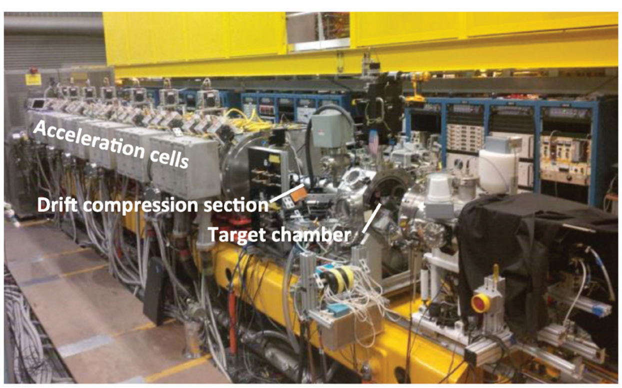

Figure 1. NDCX-II induction linear accelerator for intense ion beam pulses at Berkeley Lab.

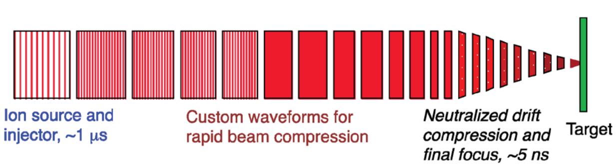

Figure 2. Beam compression in NDCX-II.

For the beam diagnostics, non-intercepting devices are used to monitor beam current, centroid, and particle loss. Capacitive-coupled beam position monitors, each segmented into four independent quadrants, detect the beam centroid at seven locations in the accelerator. Inductive current monitors at eight other lattice positions monitor the beam current. The target is housed in a dedicated diagnostic station; here, the time dependent beam current can be measured with a fast Faraday cup (<1 ns time resolution). The transverse distribution of the beam is imaged with a 30 mm diameter alumina (Al_2O_3) scintillator using a gated CCD camera with a pixel resolution on the object plane of 0.2 mm. Beam pulses can be delivered onto the targets at a rate of up to one shot every 40 seconds.

NDCX-II Beam Characteristics

NDCX-II operates with helium ions, which are injected from a multi-cusp plasma ion source [7]. Up to 1.3×10^{11} He^{+} ions or 20 nC per pulse are accelerated to 1.2 MeV and focused into a spot with a diameter of about 2 mm [8].

The helium ion current and the integrated charge versus time, measured with the fast Faraday cup at the target location, are shown in Fig. 3. With 50 nC of He^{+} ions in a 1 µs pulse injected from the source and drift compressed, a peak current of 0.8 A and a pulse width of about 10 ns have been reached. Beam losses in the acceleration

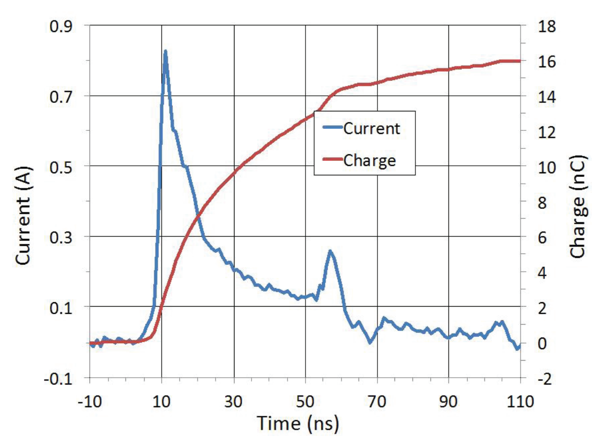

Figure 3. Helium current and integrated charge versus time at the target measured with the fast Faraday cup. The sharp peak in the current measurement shows the beam pulse compression from 1 µs to a few ns. The full temporal extension of the pulse is ~50 ns with a ~1 ns rise time. The second peak around 56 ns is formed by late arriving ions with slightly lower energies due to ringing in one of the acceleration voltage pulses.

section reduced the total charge in a pulse from the 50 nC at injection to the measured 16 nC on target. The transverse distribution of the beam (shown in Fig. 4) is controlled by the 0.2 m focal length final focusing solenoid. The beam can be focused down to a FWHM of the beam distribution of ~1 mm on the alumina scintillator. Efforts are under way to increase the charge/pulse on target from the 16 nC seen in Fig. 3 to 50 nC and to improve the temporal distribution of the beam pulse, i.e., to reduce the tail, by tuning the acceleration and compression waveforms.

Reproducibility is important for beam target experiments. Repeated shots of the beam were measured to characterize the stability of the ion source, correction dipoles, and focusing solenoids. The centroid variation was independently measured to be $\sigma_{xy} < 0.1$ mm, consistent with the upstream measurements and within the pixel resolution of the CCD camera optics. The variation of the peak light emission amplitude was $\sigma_A/A < 7\%$. This level of stability makes it possible to tune the beam so that single shots can be accurately placed on the target samples.

Capabilities for Radiation Effects Experiments

NDCX-II can now deliver up to ~20 nC of 1.2 MeV He^+ ion pulses into a ~2 mm FWHM diameter spot. This corresponds to roughly 1.3×10^{11} ions/pulse, or an ion fluence per pulse of $3 \cdot 10^{12}$ ions/cm^2 and a peak flux of ~$3 \cdot 10^{20}$ ions/cm^2/s for a 10 ns long beam pulse. For such a beam the dose (to silicon) delivered per pulse is roughly 1 MGy(Si). Other light ion species than helium, including protons, could also be accelerated. Beam parameters such as number of ions per pulse, pulse length, and beam spot size on target can be varied according to experimental needs.

The ratios of the NIEL values of 1.2 MeV protons and He ions to those of 1 MeV neutrons are roughly 35 and 700, respectively. This suggests that damage rates equivalent to neutron fluences of 10^{14} to 10^{15} n/cm^2/pulse could be delivered to a device to be tested. Ranges of 20 µm and 4 µm in silicon for 1.2 MeV protons and He^+ ions in silicon, respectively, allow the study of radiation effects on transistors and other circuit elements. Beam energies could be decreased from the maximum value of 1.2 MeV to create neutron-equivalent damage at different depths in a vertical structure.

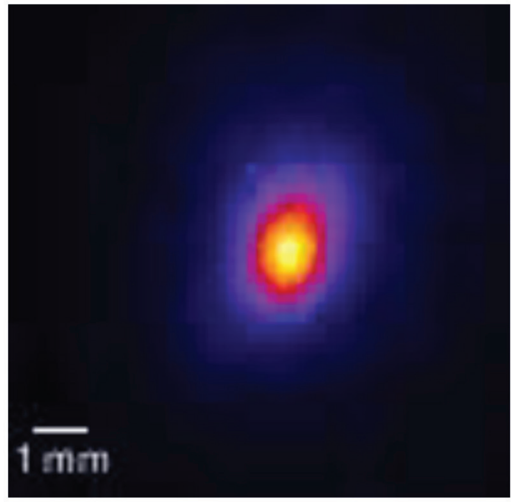

Figure 4. Transverse intensity distribution of He^+ beam measured with a scintillator and a CCD camera.

Laser-driven ion acceleration is currently under development [4] at several laboratories. With this method intense ion beam pulses can be generated that are even shorter than the NDCX-II pulses. However, laser accelerated ion beams exhibit broad energy and angular distributions and, in contrast to NDCX-II beams, may be accompanied by other types of radiation such as high-energy electrons and x rays, both factors complicating radiation effects studies. It should also be noted that short neutron pulses could be generated by accelerating deuterons into a deuterium target. Here, the neutron flux at the target from a 50 nC deuterium ion pulse would be about 10^6 neutrons/mm^2/ns, with a neutron energy of 2.45 MeV from DD fusion reactions.

Outlook

NDCX-II is a new accelerator that could quite readily be made available for a range of experimental uses, including for the characterization of transient displacement radiation effects on electronic components. Its unique beam properties, such as the high ion fluence per pulse and short pulse duration, could provide capabilities that complement those of existing ion beam facilities for applications such as radiation damage and survivability studies of semiconductor devices.

NDCX-II can deliver up to ~20 nC of 1.2 MeV of H^+ or He^+ ion pulses into a ~3 mm^2 spot, corresponding to an ion fluence of $3 \cdot 10^{12}$ ions/cm^2, per ~10 ns long beam pulse. Ongoing work is aimed at increasing the beam intensity to 50 nC/pulse and shortening the pulse length to ≤ 1 ns. Furthermore, the design of NDCX-II allows for the addition of more acceleration cells, which would increase the beam energy to 3 MeV or more.

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