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Towards pump–probe experiments of defect dynamics with short ion beam pulses

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ABSTRACT

A novel, induction type linear accelerator, the Neutralized Drift Compression eXperiment (NDCX-II), is currently being commissioned at Berkeley Lab. This accelerator is designed to deliver intense (up to 3×10^{11} ions/pulse), 0.6 to ~600 ns duration pulses of 0.05–1.2 MeV lithium ions at a rate of about 2 pulses per minute onto 1–10 mm scale target areas. When focused to mm-diameter spots, the beam is predicted to volumetrically heat micrometer thick foils to temperatures of ~30,000 °K. At lower beam power densities, the short excitation pulse with tunable intensity and time profile enables pump–probe type studies of defect dynamics in a broad range of materials. We briefly describe the accelerator concept and design, present results from beam pulse shaping experiments and discuss examples of pump–probe type studies of defect dynamics following irradiation of materials with intense, short ion beam pulses from NDCX-II.

1. Introduction

Intense, short pulses of energetic ions are highly desirable for studies of warm dense matter, high energy density physics experiments with volumetrically heated targets, and for studies of defect dynamics in solids [1,2]. Irradiation with short ion beam pulses generates defects in a narrow time window and their diffusion and recombination dynamics can then be studied in time resolved "pump–probe" type experiments. Here, the short ion beam pulse acts as the "pump" which can be followed by a suitable "probe" beam, such as an X-ray pulse, which can track a selected defect signature. Combining a short pulse ion beam capability with pulsed probe beams from an X-ray free electron laser (FEL) was recently proposed for the study of radiation effects in nuclear materials by Froideval et al. [1]. Suitable driver beams can be formed through longitudinal compression of space-charge dominated ion beams where short pulses have been achieved by imposing head-to-tail velocity tilts to drifting ion beams [2–4]. High drift compression factors are reached when ion beams travel through a neutralizing plasma column during drift compression. Earlier, a 25 mA, 300 keV K^+ beam was compressed 50 to 150-fold, yielding an intense ~3 ns long pulse with a beam spot size of ~1 mm^2 [4]. In order to achieve uniform heating of micrometer thick foil targets to temperatures of 2–3 eV, we are currently implementing this beam compression concept with increased ion beam energy (up to 1.2 MeV) for lithium ions [3,5]. The induction linac based accelerator affords a high degree of flexibility in ion beam pulse shaping. In an intensity regime well below the onset of intense target heating and hydrodynamic motion, this flexibility enables the study of defect dynamics in solids and other materials (including soft matter and liquids). Here, targets can be exposed to short ion beam pulses and resulting defect structures can be probed with time-resolved *in situ* or with *ex situ* methods. This article is structured as follows: We first present results from ion beam pulse control experiments at NDCX-II in Section 2. We then outline concepts for pump–probe experiments for defect dynamics studies and present results from short pulse implantation of lithium ions into silicon (Section 3), followed by an outlook and conclusions.

2. Ion beam pulse shaping experiments

The NDCX-II accelerator is assembled from a modular cell structure, where pulsed induction cells are iterated with diagnostic cells and drift cells, all embedded with pulsed solenoid magnets [2–5]. The NDCX-II induction linac structure has a length of 12 m (Fig. 1). Each active induction cell presents either a purely accelerating voltage or a time-varying, ramped voltage to the

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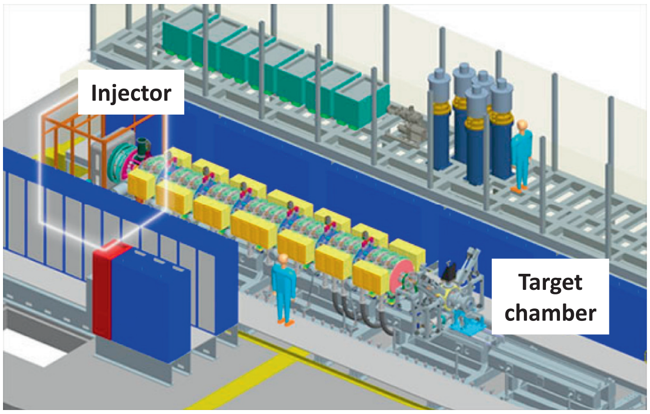

Fig. 1. Schematic of the NDCX-II accelerator. The total length from injector (left) to target chamber (right) is 12 m (color online).

non-relativistic ion beam. Additional inactive (i.e. unpowered) induction cells as well as diagnostic cells are necessary to allow the velocity-modulated ion beam to complete its initial compression phase. Here, we report results from beam compression experiments with a 27-cell configuration that utilizes seven active induction cells, six diagnostics cells and 14 inactive ("drift") cells. Lithium ions are extracted in ~600 ns long pulses from a large area (10.9 cm diameter), lithium doped, thermionic alumino-silicate emitter with an emitted current density of ~1 mA/cm^2. The ion source operates at a surface temperature of ~1200 °C and is radiatively heated by a filament with power consumption of ~4 kW. Ions are extracted, accelerated and focused within the injector by a triode structure [6]. Emitted ion beam currents are ~50 mA. The same source type has also been used to form intense pulses of other alkali ions, e.g. K$^+$ [4]. Lithium ions are generated and then injected into the first acceleration cell with an initial kinetic energy of up to 140 keV. In the first cell, we apply a voltage that accelerates the beam by another 20 keV. Using several more ramped-voltage induction cells, we have achieved compression of lithium ion pulses from ~600 to 20 ns (FWHM) with this 27-cell beamline configuration (Fig. 2). Radial beam focusing is enabled by pulsed solenoid magnets within each cell with magnetic fields ranging from ~0.8 to 2.5 T. In the example in Fig. 2, the peak intensity is 918 mA with about 13 nC of charge in the 20 ns pulse (FWHM), corresponding to 8×10^{10} ions/pulse. Here, the un-neutralized beam pulses are not yet strongly focused laterally and beam spots have diameters of about 10 mm. Adaptation of a plasma chamber for space charge neutralization and an 8 T pulsed solenoid magnet will focus the beam to a spot with a diameter of ~1 mm [3–5], as well as continue longitudinal compression of the beam pulse to its ultimate pulse duration of ~0.6 ns. However, for studies of defect dynamics, it is desirable to avoid intense sample heating and the energy fluence can be controlled by varying the beam spot size or the number of ions present in a beam pulse. In Fig. 3 we show an image of the beam induced intensity distribution of light emission from a 0.1 mm thick aluminum oxide scintillator. Ionoluminescence from the aluminum oxide target is imaged in transmission with a fast (~30 ns), gated CCD camera. In the example shown in Fig. 3, the beam energy was 160 keV, the total charge per pulse was 28 nC and the beam spot had a diameter of 12 mm (FWHM). The resulting peak energy fluence was 1.8 mJ/cm^2. We summarize the beam parameters of NDCX-II in Table 1, comparing the current status to the design goals. The design goals of NDCX-II will enable volumetric heating of thin foils to a few eV temperatures. For studies of defect dynamics, the tuning flexibility of the modular induction linac will allow us to vary dose rates and pulse lengths over a large parameter range (e.g. with pulse lengths of sub-ns to hundreds of ns and dose rates of a few mA/cm^2 to >1 A/cm^2).

Thermionic alumino-silicate emitters are known to generate very pure, high brightness, single charge state alkali ion beams [6]. In the present study, we did not measure the elemental composition of the ion beam pulses. Pulses from the injector show indications of impurities present (predominantly K$^+$), mostly during early stages of ion source activation and at lower operating surface temperatures. The accelerator configuration with alternating pulsed voltage gaps and solenoids is very restrictive to the ion mass and charge state and quickly filters out any impurities through time of flight and magnetic solenoid transport optics.

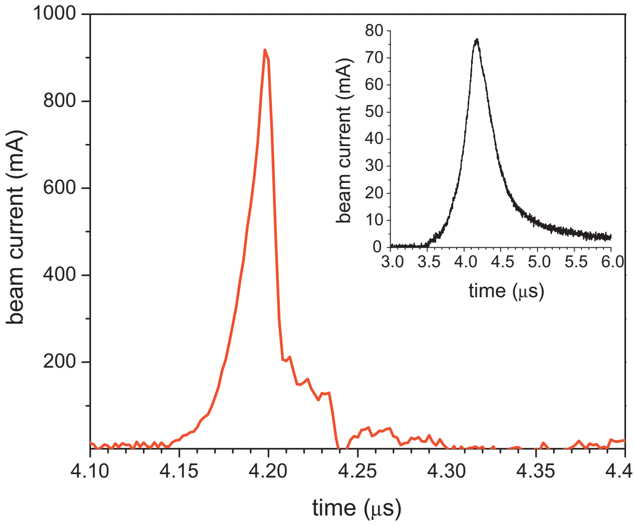

Fig. 2. Lithium ion beam current traces for a single, compressed pulse. The pulse width is 20 ns (FWHM) with 13 nC (8×10^{10} ions), E_{kin} = 320 keV. The insert shows a 430 ns long pulse (FWHM) with 25 nC (1.5×10^{11} ions), E_{kin} = 135 keV, from the injector with no active induction cells.

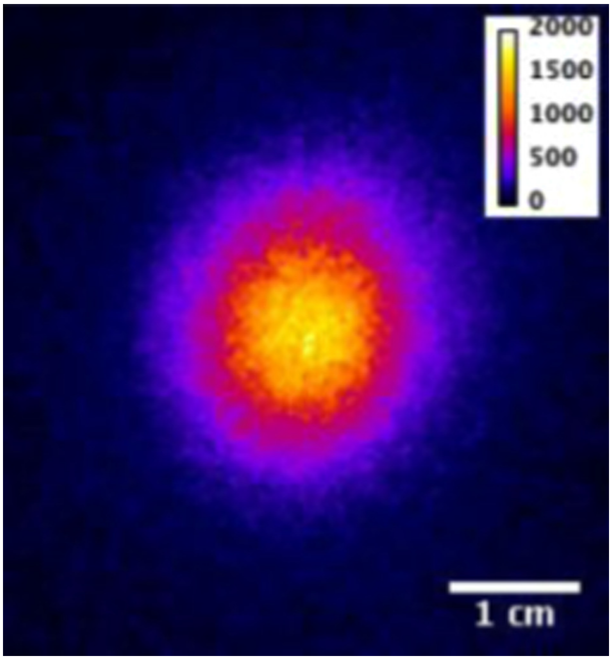

Fig. 3. Gated CCD-camera image of ion beam induced luminescence from a single, compressed pulse impinging on a thin alumina scintillator with a beam diameter of 12 mm (FWHM) (color online).