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Research Article

Optimizing beam transport in rapidly compressing beams on the neutralized drift compression experiment − II

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Abstract

The Neutralized Drift Compression Experiment-II (NDCX-II) is an induction linac that generates intense pulses of 1.2 MeV helium ions for heating matter to extreme conditions. Here, we present recent results on optimizing beam transport. The NDCX-II beamline includes a 1-m-long drift section downstream of the last transport solenoid, which is filled with charge-neutralizing plasma that enables rapid longitudinal compression of an intense ion beam against space-charge forces. The transport section on NDCX-II consists of 28 solenoids. Finding optimal field settings for a group of solenoids requires knowledge of the envelope parameters of the beam. Imaging the beam on the scintillator gives the radius of the beam, but the envelope angle is not measured directly. We demonstrate how the parameters of the beam envelope (radius, envelop angle, and emittance) can be reconstructed from a series of images taken by varying the *B*-field strengths of a solenoid upstream of the scintillator. We use this technique to evaluate emittance at several points in the NDCX-II beamline and for optimizing the trajectory of the beam at the entry of the plasma-filled drift section.

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1. Introduction

NDCX-II is a 10-m-long pulsed induction ion accelerator which produces short (2−30 ns FWHM) intense pulses of 1.2 MeV helium ions. Presently, the device is capable of delivering a fluence of 0.7 J/cm^2 and studying the radiation damage in materials [1]. In parallel, an effort to tune the accelerator to increase fluence on target is underway.

The NDCX-II beamline is illustrated in Fig. 1. The helium beam is extracted from a multicusp filament-driven plasma ion source [2] at an initial energy of 135 keV. As the ion bunch travels through the beamline, it passes through 12 induction cells that accelerate the beam to a final energy of 1.2 MeV. Besides accelerating the beam, the induction cells are designed to apply a head-to-tail velocity tilt to the ion bunch, i.e., the head of the bunch is decelerated and the tail is accelerated. This results in longitudinal compression of the bunch and a corresponding increase in beam current and line charge density.

The 12 accelerating induction cells are embedded in a 28-solenoid transport lattice. After the transport lattice, the beam

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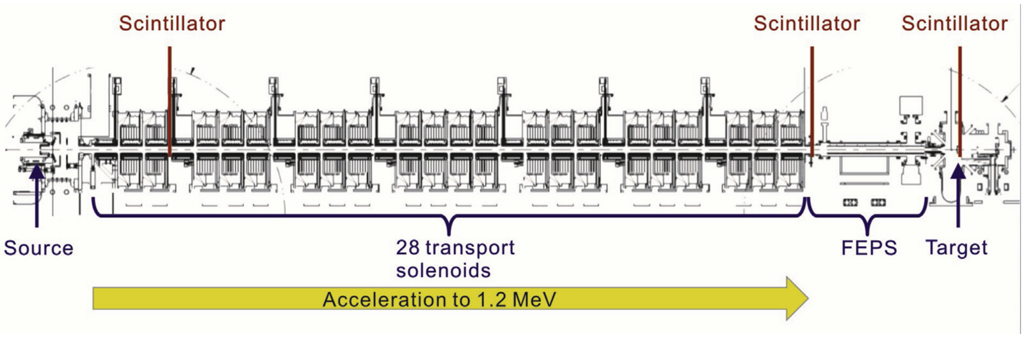

Fig. 1. NDCX-II beamline. The accelerator is 10-m-long from source to target. The He^+ ion beam is extracted from a multicusp plasma ion source and transported through a 28-solenoid lattice towards the Ferroelectric Plasma Source (FEPS). Inside the FEPS, a volume plasma is generated that neutralizes the space-charge of the beam and enables longitudinal and transverse compression of the ion pulse. The locations where the scintillator measurements of the beam spot size were taken are indicated in this Figure.

passes through a 1-m-long plasma-filled drift column where it undergoes the final longitudinal compression stage before the target. The plasma is generated by a Ferroelectric Plasma Source (FEPS) [3]. The plasma neutralizes the space charge of the beam [4], which enables a high degree (~×10) of the longitudinal compression. Immediately downstream of the FEPS, the beam enters an 8-T 10-cm-long final focus solenoid (FFS), which focuses the beam onto the target. The bore radius of the final focus solenoid is small ($R = 2$ cm) compared to the radius of the beam pipe in the accelerator (4 cm). Passing the beam through the small bore of the FFS with minimal scraping losses is a significant challenge, as we will describe later.

The NDCX-II project pushes the capabilities of induction linac technology to develop a compact, low-cost approach to generating extremely high ion beam fluence with short (ns) pulse duration. The beam dynamics on NDCX-II is inherently complex for a number of reasons. The successive applications of the longitudinal velocity tilt result in growing complexity of the longitudinal phase-space of the beam. This velocity spread affects transverse dynamics because the focusing strength of the transport solenoids is a function of the particle velocity. The effect of space charge forces (generally nonlinear) is further complicated by the fact that both the bunch current and energy increase during the propagation, resulting in non-monotonic variation of the beam perveance $Q \propto I/V^{3/2}$. Lastly, some sections of the accelerator are filled with plasma to neutralize the space-charge of the beam, which rapidly reduces the self field of the beam and introduces further complexity.

As a result of these factors, source-to-target simulations can easily diverge from experimental reality. This especially concerns transverse beam parameters, such as the radius and angle of the beam envelope (r, dr/dz). Direct measurements of the transverse phase space distribution are difficult due to limited diagnostic access in a crowded lattice of a compact accelerator. However, reliable knowledge of the envelope parameters is often necessary for tuning the solenoid lattice. The previously-mentioned problem of optimizing the trajectory of the beam in the 1-m-long plasma-filled drift section is one example.

While tackling these issues on NDCX-II, scintillator imaging has emerged as a powerful and flexible diagnostic technique. Reliance on scintillators (instead of 2-slit emittance scanners, for instance) is largely the result of practical concerns. Scintillators can be inserted into the beam with minimal (few cm) longitudinal "real estate" requirements. A single intensified CCD camera positioned at the downstream end of the accelerator can image scintillators at several z-locations to measure the transverse current density $j(x,y)$ of the beam. Nonetheless, most of the beamline is inaccessible to direct measurements due to the limited number of diagnostic access ports. Furthermore, the envelope angle dr/dz cannot be measured directly without inserting additional hardware (such as a movable slit in front of the scintillator plane) into the beam.

The amount of useful information generated by the diagnostics can be increased by measuring the response of the system to its controls. For instance, the spot size of the beam can be measured as a function of the solenoid field strength. Then, an inverse problem can be formulated: given some measured dependence of beam radius on solenoid strength $R(B)$ at $z = L$, what are the parameters of the beam envelope (r, dr/dz) at $z = 0$? Solving this problem requires defining a model to calculate the experimentally-measurable quantities as a function of the unknown variables. Then, unknown model parameters can be found by numerical optimization methods.

In the present article, we describe the technique developed on NDCX-II for reconstructing beam parameters inaccessible to direct measurement. The reconstruction technique is based on measuring the spot size of the beam as a function of the solenoid strength. Extracting an effective beam radius from the data is accomplished by identifying and exploiting self-similarity in the scintillator images. An envelope model with 3 unknown parameters (beam radius, angle, and perveance) is matched to the data generated by a particle-swarm optimization algorithm. The validity of reconstructed parameters has been confirmed through agreement with other diagnostics. Our reconstruction technique is similar in spirit to the well-known "solenoid scan" approach to measuring emittance, where emittance is determined from the minimum beam radius downstream of a solenoid lens. However, in contrast with some of the previous work on this subject (e.g. Ref. [5]), the complete shape of the radius vs. B-field curve is taken into