FAST CORRECTION OPTICS TO REDUCE CHROMATIC ABERRATIONS IN LONGITUDINALLY COMPRESSED ION BEAMS*

S.M. Lidia[1], E.P. Lee, D. Ogata, P.A. Seidl, W.L. Waldron, Lawrence Berkeley National Laboratory

S.M. Lund, Lawrence Livermore National Laboratory

Abstract

Longitudinally compressed ion beam pulses are currently employed in ion-beam based warm dense matter studies [1]. Compression arises from an imposed time-dependent longitudinal velocity ramp followed by drift in a neutralized channel. Chromatic aberrations in the final focusing system arising from this chirp increase the attainable beam spot and reduce the effective fluence on target. We report recent work on fast correction optics that remove the time-dependent beam envelope divergence and minimizes the beam spot on target. We present models of the optical element design and predicted ion beam fluence.

INTRODUCTION

The recently updated Neutralized Drift Compression Experiment (NDCX-1) at Berkeley National Laboratory includes an upgraded Induction Bunching Module (IBM) with approximately twice the available volt-seconds as its predecessor, as well as a longer neutralized drift section whose plasma is generated by a FerroElectric Plasma Source (FEPS). A pulsed, 8-Tesla (maximum) Final Focus Solenoid (FFS) compresses the beam onto the target plane. A set of Filtered Cathodic Arc Plasma Sources (FCAPS) provides higher-density neutralizing plasma in the Target Chamber. A schematic of the NDCX-1 beamline is shown in Figure 1.

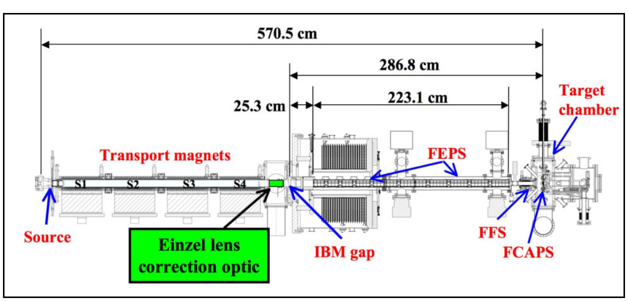

Figure 1. NDCX-1 beamline.

The IBM is designed to generate a bipolar waveform across a 3cm gap that induces a longitudinal velocity chirp over a 400-600ns section of the ~3-10μsec singly-charged, ~300keV potassium ion beam. The affected portion of the beam then ballistically compresses longitudinally between the IBM gap and the target plane, increasing the peak current from ~30mA up to several Amperes over a few nsec. The ideal and experimentally realized IBM gap voltages are shown in Figure 2.

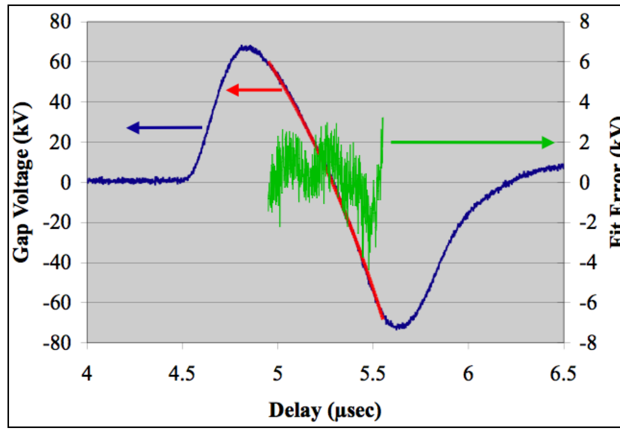

Figure 2. Ideal (red), actual (blue) IBM voltage waveforms. The difference is shown in green. The polarity has been reversed for convenience.

The time dependent change in the radial velocity of the beam ions as traverse the IBM gap is given by [3]

$$\Delta v_r \approx -\frac{qr}{2mv_{zo}^2}\frac{dV(t)}{dt}. \qquad (1)$$

For a gap length of L_g ~3cm, and an initial ion beam velocity v_{z0} ~ 1.2m/μsec, the beam will have a finite residence time within the gap of L_g/v_{z0} ~ 25nsec. This finite sampling time is sufficient to induce radial defocusing in all beam ions – including those that remain, on average, at the initial energy. The correlation of these radial defocusing offsets with the beam energy is a source of chromatic aberration. The fact that it is correlated with time suggests a method for removing the aberration, or compensating it before the beam reaches the target plane.

MODELING OF THE BEAM DYNAMICS

A numerical slice envelope equation solver was implemented in MatLab [4] to calculate the radial and temporal evolution individual slices carrying varying charge and energy. The slice tracking begins at the entrance to the IBM and follows the slices to the target plane. The IBM gap is assumed to be well modeled as a thin lens, while the FFS fringe fields are included. Except for a ~25cm length following the IBM gap, the rest of the ~287cm drift length is assumed to filled with a completely charge-neutralizing plasma.

*This work was supported by the Director, Office of Science, Office of Fusion Energy Sciences, of the U.S. Department of Energy under Contract No. DE-AC02-05CH11231.
[1]SMLidia@lbl.gov

The uncorrected envelopes for the range of slice energies are shown in Figure 3. This ensemble represents a magnetic lattice tune that optimizes the beam fluence at the target plane, but does not yet correct for chromatic aberrations.

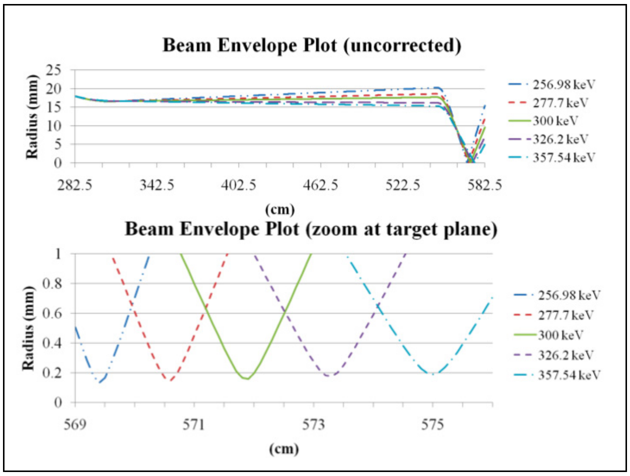

Figure 3. Slice envelopes (uncorrected) for different energies between the IBM exit and the target plane (top). Slice envelopes near the target plane (bottom).

The beamline coordinates and initial beam envelope conditions are given in Tables 1 and 2.

Table 1. Initial Beam Conditions

Center Energy	300 keV
Initial Current	27 mA
Initial Pulse Duration	400 ns
Longitudinal temperature	1 eV
Norm. transverse emittance	0.06π mm-mrad
Target Plane	570.5 cm
FFS Peak Field	7.4 Tesla
Beam pipe aperture radius	20 mm

Table 2. Initial Envelope Parameters.

Plane	z (cm)	a (mm)	a' (mrad)
'Box 1'	262.5	21.4	-13.5
IBM Entrance	282.5	18	-13.5
IBM Exit	282.5	18	-10.5

Correlated Slice Envelope Correction

From Figure 3 it is readily seen that there is a considerable spread in focal planes for slices of varying energies. Hence a target placed at any one location will intercept a narrow range of energies at the slice waists, but that off-energy slices will have much larger radii. The beam fluence suffers accordingly.

A prescriptive, correlated correction to the envelope convergence angle as it exits the IBM has been empirically found to improve the beam fluence at the target plane. The correction is shown in Figure 4. An iterative search procedure re-optimizes the initial envelope parameters so that an additional correlated correction to the envelope angle places the slice envelope waists nearer to the target plane.

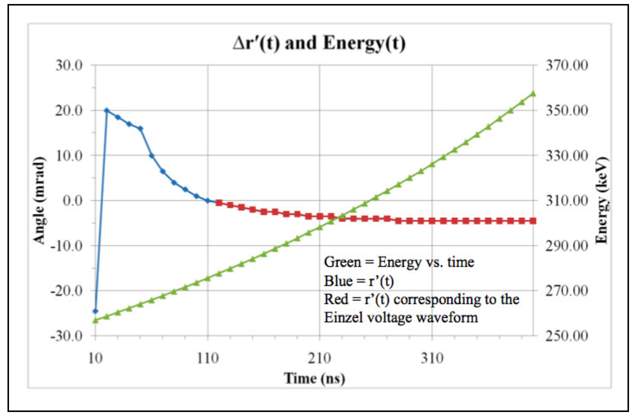

Figure 4. Correlated envelope angle correction and IBM voltage.

The corrected envelopes are shown in Figure 5. The lowest energy slice (~257keV) is shown to scrape and is presumed lost. The beam aperture (20mm radius) just upstream from the target chamber effectively filters transmission of the beam spectrum to energies greater than ~270keV.

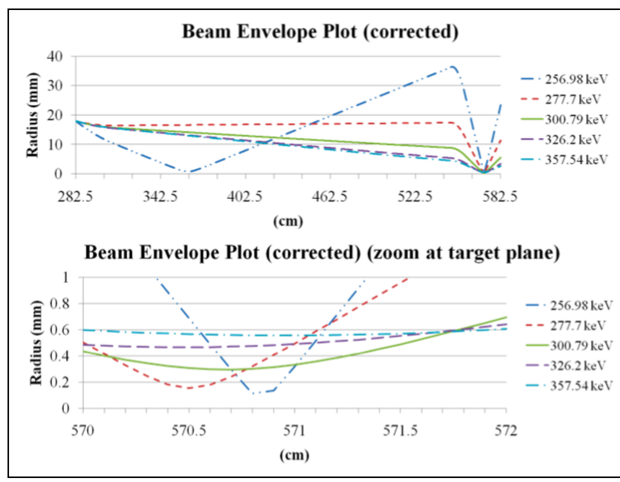

Figure 5. Corrected slice envelopes over the drift length (top) and nea the target plane (bottom).

Comparing the two optimized tunes (Figure 3 and Figure 5), the correction works by increasing the waist size and the Rayleigh range of the slices over the specified energy range. The overlap of the slice envelopes at the target plane is dramatically increased.

The beam fluence near the nominal target plane have been calculated for the optimized (uncorrected) and optimized (corrected) tunes. These are shown in Figure 6. Allowing for every slice to contribute, the corrected fluence shows a 4X increase. Removing those slices that impinge on the beam pipe aperture reduces this factor to a 1X increase.

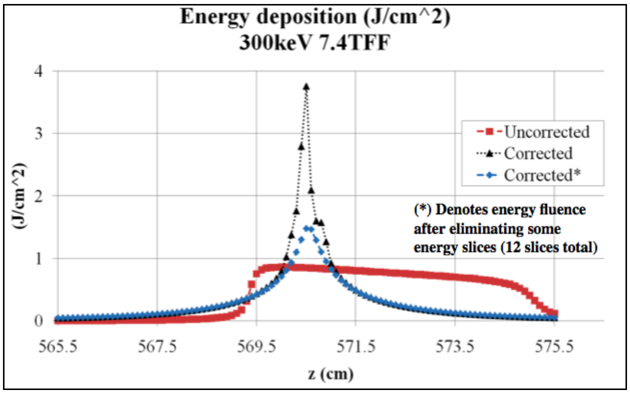

Figure 6. Target plane fluence for the uncorrected and corrected tunes.

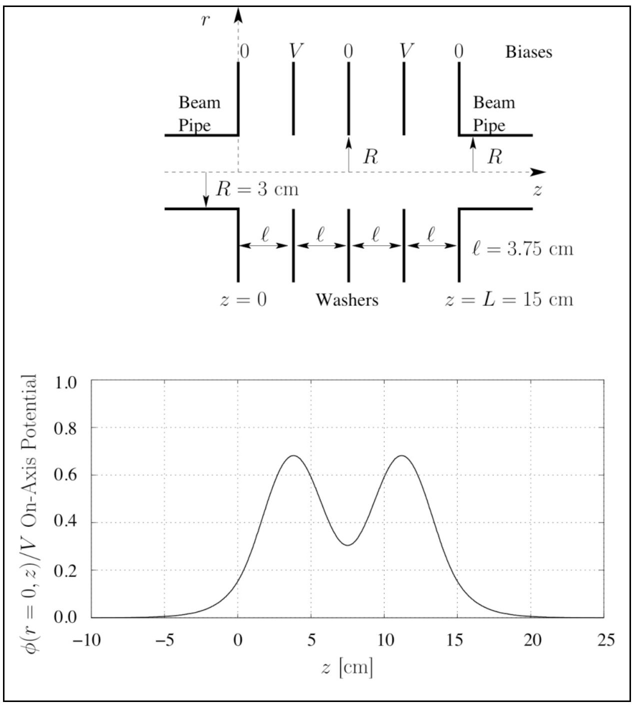

Figure 7. Schematic cross-section of the Einzel lens (top) and on-axis electrostatic potential distribution (bottom).

EINZEL LENS CORRECTION OPTIC

An electrostatic, Einzel lens [5] has been studied to implement the time-dependent focusing correction over the beam pulse. This 15cm long element will be inserted into the beamline upstream of the IBM (see Figure 1) and used in a predictor-corrector strategy. The cross-section of the proposed Einzel lens is shown in Figure 7. A unipolar biasing scheme has been developed for the electrodes in the lens. A grounded electrode at the midplane enforces symmetry and periodicity. The on-axis electrostatic potential distribution is also shown in Figure 7.

A driving waveform (Figure 8) has been synthesized to drive the voltage on the lens electrodes to match the required focusing correction schedule (Figure 4). This waveform can be easily generated from a simple RC circuit discharge.

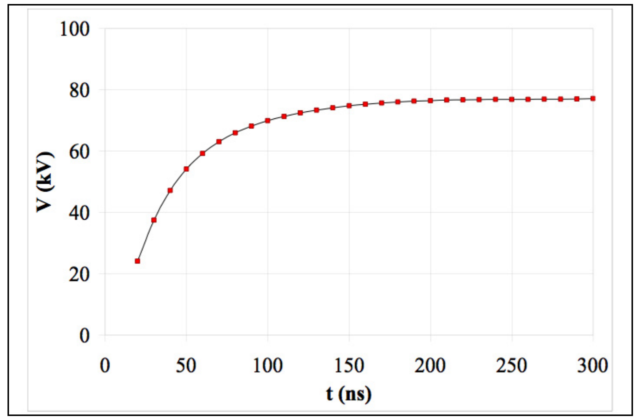

Figure 8. Required drive voltage waveform for the Einzel lens.

CONCLUSIONS

Chromatic aberrations limiting the ion beam fluence in the NDCX-1 beamline have been analyzed and corrected with a time-dependent electrostatic focusing element. Predicted beam fluences have doubled.

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[4] *MATLAB®* is a product of The Mathworks, Inc.
[5] See, for example, M. Reiser, *Theory and Design of Charged Particle Beams*, Wiley, New York, 1994.