SIMULATING AN ACCELERATION SCHEDULE FOR NDCX-II*

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Abstract

The Virtual National Laboratory for Heavy-Ion Fusion Science is developing a physics design for NDCX-II, an experiment to study warm dense matter heated by ions. Present plans call for using 34 induction cells to accelerate 45 nC of Li$^+$ ions to more than 3 MeV, followed by neutralized drift-compression. To heat targets to the desired temperatures, the beam must be compressed to a millimeter-scale radius and a duration of about 1 ns. A novel NDCX-II acceleration schedule has been developed using an interactive one-dimensional particle-in-cell simulation ASP to model the longitudinal physics and axisymmetric WARP simulations to validate the 1-D model and add transverse focusing. Three-dimensional Warp runs have been used recently to study the sensitivity to misalignments in the focusing solenoids.

INTRODUCTION

NDCX-II [1,2] is an accelerator now being designed by the Virtual National Laboratory for Heavy-Ion Fusion Science to study warm dense matter (WDM) heated by ions. This mission requires a beam of at least 100 mJ compressed to a sub-millimeter radius and a duration of about 1 ns. To minimize the cost of NDCX-II, induction cells and other hardware from the decommissioned Advanced Test Accelerator (ATA) at Lawrence Livermore National Laboratory will be reconditioned and reused. Use of ATA parts fixes important lattice parameters, specifically a 28-cm period, a 0.014 V-s flux limit of the ferrite cores, a 200-kV breakdown voltage, and a 70-ns maximum pulse length of the Blumleins. Custom pulse lines can be fabricated for longer pulses, but cost considerations limit these to a maximum voltage of 100 kV and motivate use of a minimum number. The 6.7-cm ATA beam-pipe radius is found to produce fringe fields across the 2.8-cm gaps that fill nearly an entire period, giving excessive gap-transit times for Li$^+$ ions. Consequently, the design here uses a 4-cm beam-pipe radius. The present design uses 34 ATA cells to accelerate 45 nC of 160-keV Li$^+$ ions to an energy in excess of 4 MeV, followed by neutralized drift-compression.

This paper presents a novel acceleration schedule worked out using the interactive 1-D particle code ASP and then reviews axisymmetric source-to-target simulations using the particle-in-cell code WARP [3] to verify this schedule with full transverse dynamics. We discuss the design of the solenoids used for transverse confinement, and we briefly discuss recent 3-D simulations that investigate sensitivity of beam transport to misalignments of the focusing solenoids.

1-D SIMULATIONS

A 1-D particle-in-cell code ASP (for Acceleration Schedule Program) [1 2] has been developed to explore NDCX-II lattice layouts and acceleration scenarios. The code, which is written in Python and Fortran 95, uses a leapfrog advance and includes a simple 1-D electrostatic field solver [4] that gives a close approximation to the longitudinal component of the space-charge field of a beam with uniform radius and charge density. Waveforms at induction gaps can be chosen from a library of simple analytic waveforms, read from tables, or calculated from circuit models, and we model the gap fringe fields using a 1-D analytic model by E. P. Lee [5]. An important aspect of the code is that it automatically adjusts each waveform to match the transit time of the beam as it enters the gap and to respect user-specified limits on the induction-module voltage and volt-seconds. After the acceleration lattice, the effect of a neutralizing plasma is modeled by reducing the space-charge field smoothly to zero over a user-specified distance, providing estimates of the longitudinal focal length and the minimum beam duration.

The NDCX-II layout presented here has 34 induction gaps, grouped in six blocks of six, with two unused cells in the first block. Except for two induction cells used to control the longitudinal space charge, referred to as "ear" cells, all the waveforms are simple and can be generated using elementary pulse-forming circuits. The unconventional acceleration strategy developed using ASP makes effective use of ATA hardware. The first two cell blocks impose a 30% head-to-tail velocity variation or "tilt", and drift sections between blocks allow the initially 500-ns ion beam to compress longitudinally until it is short enough to traverse the gap field, including fringes, is less than 70 ns, allowing the use of the 200-kV ATA Blumleins for the final 24 induction cells. The compressed beam is shorter than the longitudinal extent of the fringe fields, so precision control of beam-end expansion is not possible. Instead, in the next three cell blocks, we allow the compressed beam to expand, relying on acceleration to keep the transit time below the 70-ns limit. In this acceleration section, which uses flat-topped or trapezoidal waveforms, the beam length nearly triples while the duration, shown in Fig. 1, remains nearly constant. The velocity tilt needed for the final longitudinal compression is applied mainly by triangular pulses in the final block of six cells. As the beam exits the last gap, it has an average energy of 4.3 MeV and an 8% head-to-tail velocity tilt, allowing it, after neutralization, to compress to a 1-ns duration over a 3.4-m focal length. These results

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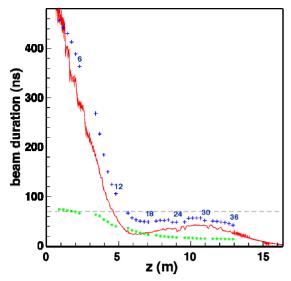
D05 - Code Developments and Simulation Techniques

Figure 1: ASP plot of the NDCX-II beam duration. Just enough voltage variation is applied in blocks three through five to keep the beam duration below the 70-ns limit of the Blumleins, shown as a dashed horizontal line. Blue crosses note the transit time of the full beam through each gap, and the green stars indicate the single-particle transit time at the average beam energy. The red shows the beam duration as a continuous function of the longitudinal co-ordinate z.

are not highly sensitive to details of lattice and waveforms in the acceleration section.

Initialization of ASP requires some care. For an accel-decel injector of the sort that we plan to use for NDCX-II [6], WARP simulations show that the beam reaching the first acceleration gap has an energy that is about 20% above the nominal energy at the head and drops off about 50% near the tail. A similar variation in energy and charge density must be imposed on the ASP beam in order to model the blow-off of the ends correctly and to calculate appropriate ear fields in the first cell blocks. If uncorrected, the initial energy variation will introduce phase-space distortions that hamper the initial compression, so it is also important to remove this variation in the first gap to the extent possible. The energy variations at the beam ends occur over about 50 ns, while the time it takes a 160-keV Li ion to traverse the full gap field is nearly 100 ns, preventing accurate correction. Instead, we average the deviation of the energy of particles in the gap, suitably weighted by the spatial envelope of the gap field, and construct an approximate correction field from this average. The correction replaces the rise and fall with energy undulations of about ±7% at the ends.

R-Z SIMULATIONS

For source-to-target *r-z* WARP simulations using this ASP acceleration schedule, we need to add a transverse focusing lattice. Regularly spaced solenoids are used for focusing NDCX-II because they are relatively simple to
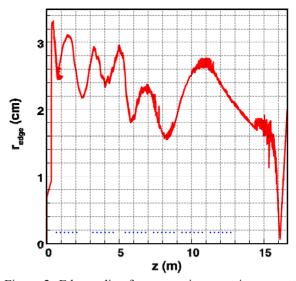

Figure 2: Edge radius from an axisymmetric source-to-target WARP simulation of a 45-nC L^+ beam. The acceleration waveforms were obtained from a 1-D simulation of the same beam and lattice. The small blue "x"s mark the axial centers of the thirty induction gaps in this simulation.

design and fabricate, and because they are more effective than magnetic quadrupoles for this energy range. We first choose a pair of solenoids to catch the beam from the injector and match it into the main focusing lattice by iteratively running an envelope model to give the desired final radius and divergence. The remaining solenoids are specified by solving an axisymmetric envelope equation, using the beam length found by ASP at the center of each solenoid and the nominal 2.5-cm radius used in the 1-D space charge model. The resulting lattice requires solenoids of 2 T or less throughout the acceleration lattice. The procedure is found to match the beam imperfectly, as Fig. 2 illustrates, and it overestimates solenoid strengths over the final 5-m of the lattice. Nonetheless, the calculated solenoids keep the beam edge well away from the 4-cm beam-pipe wall and leads to acceptable results.

It was not initially obvious that the lattice layout and acceleration voltages developed with the 1-D ASP model would give comparable results in an axisymmetric WARP simulation. When gap voltages vary with time, particles traversing a cell at different radii get different longitudinal kicks and receive a non-zero net transverse impulse. These small mismatches contribute to the longitudinal and transverse emittance and might degrade the final focus. In addition, any fluctuations in the beam radius introduce errors in the 1-D space charge model. These effects, however, prove to be small, and results from the two codes show remarkable agreement for identical layouts and acceleration schedules. While the Warp beam is systematically longer than the ASP beam, due in part to the radius in Warp being smaller than assumed in ASP, we find that the energy distributions agree remarkably well, and the differences in current are easily accounted
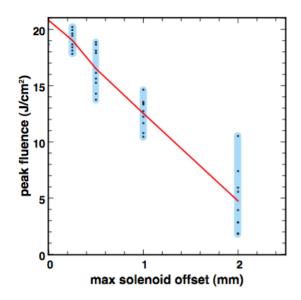
Figure 3: 3-D results from Warp showing the sensitivity of peak fluence when both ends of the focusing solenoids are given a transverse displacement with a magnitude up to a preset maximum offset. The dots mark the results of eight trials with different random numbers made for values of maximum offset, and the range of results for each value is indicated by a blue bar.

for by the different lengths and the greater smoothing expected in Warp runs. The length difference also leads to a 5% particle loss at the beam ends for Warp, compared with about 2.5% for ASP. An important finding of this WARP simulation is that the transverse emittance shows little secular growth during acceleration and compression, despite the severe changes in the longitudinal phase space. The normalized r-r' emittance, which removes the contribution of beam rotation, varies in the range 1-2 mm-mrad, a sufficiently small value that the final focal spot is dominated by chromatic aberration rather than emittance.

When the beam has entered the neutralization region, ballistic trajectories are used in calculating the plane of best longitudinal focus, defined as the z position with the highest average current in any 1-ns window. We place the final-focus solenoid to give a coincident radial and longitudinal focus. For the case discussed here, we find a current at focus of nearly 50 A and a minimum rms radius of about 0.5 mm. About 85% of the beam current falls within a 1-mm radius of the axis, and the on-axis energy fluence is 32 J/cm^2.

3-D SIMULATIONS

Recently, a series of 3-D WARP simulations has been run to test the sensitivity of the beam to misalignments of the focusing solenoids. We use the same ASP-derived schedule but introduce random transverse displacements of the solenoid ends, with a prescribed maximum offset magnitude L_{off} in both transverse directions and a flat distribution of errors within this range. Such an error specification produces random transverse offsets up to

$2^{1/2} L_{off}$ and tilts with an angle up to $\sin^{-1}(L_{sol}/L_{off})$, where $L_{sol} = 28.0$ cm is the solenoid length. Four values of L_{off} up to 2 mm have been run to date, with eight sets of random displacements for each. The maximum fluence averaged over the eight error sets, shown in Fig. 3, decreases almost linearly with L_{off}, and the scatter of the values shows a more irregular increase. The focal spot wanders in the transverse plane as errors increase, but it spreads out by a much smaller amount. Even with 2-mm maximum displacements, the beam reaches the target with negligible particle loss to the walls. We note that the fluence for zero maximum offset is lower than that quoted in the previous section because the final-focus solenoid for these runs had not yet been placed at the optimum position.

SUMMARY

The NDCX-II simulations presented here provide a firm basis for developing a complete NDCX-II physics design that meets all cost and operational requirements. The good longitudinal and transverse compression achieved in these runs suggests that the strategy of rapid compression followed by acceleration may be highly effective. Transverse emittance shows insignificant growth during acceleration despite aggressive initial beam compression, so that the beam can be focused by an 8-T solenoid to a spot radius of less than 1 mm. We find that solenoids with strengths of 2 T or less are adequate for transverse focusing, and the good agreement between the 1-D and 2-D simulations verifies that transverse dynamics is largely decoupled from the longitudinal dynamics, greatly simplifying the design of the accelerator.

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