EXTRACTION COMPRESSION AND ACCELERATION OF HIGH LINE CHARGE DENSITY ION BEAMS*

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Abstract

High Energy Density Physics (HEDP) applications require high line charge density ion beams. An efficient method to obtain this type of beams is to extract a long pulse, high current beam from a gun at high energy, and let the beam pass through a decelerating field to compress it. The low energy beam-bunch is loaded into a solenoid and matched to a Brillouin flow. The Brillouin equilibrium is independent of the energy if the relationship between the beam size *(a)*, solenoid magnetic field strength *(B)* and line charge density is such that *(Ba)^2* is proportional to the line charge density. Thus it is possible to accelerate a matched beam at constant line charge density. An experiment, NDCX-1c is being designed to test the feasibility of this type of injectors, where we will extract a 1 microsecond, 100 mA, potassium beam at 160 keV, decelerate it to 55 keV (density ~0.2 μC/m), and load it into a 2.5 T solenoid where it will be accelerated to 100–150 keV (head to tail) at constant line charge density. The head-to-tail velocity tilt can be used to increase bunch compression and to control longitudinal beam expansion. We will present the physics design and numerical simulations of the proposed experiment.

INTRODUCTION

The Neutralized Drift Compression Experiment (NDCX) is being constructed at the Lawrence Berkeley National Laboratory. NDCX will help develop novel, still unexplored beam manipulation techniques in order to establish the physics limits on compression of heavy ion beams for creating high energy density matter and fusion ignition conditions [1]. A critical early component being developed in this series of experiments is the Accel-Decel Injector which will enable a dramatic increase in ion beam line charge density after extraction from the ion source.

The second critical component of the NDCX series of experiments is the accelerating scheme for the high-current, short-bunch ion beams that are of interest for HEDP applications. The Pulse Line Ion Accelerator (PLIA) uses a slow-wave structure based on a helical winding, on which a voltage pulse is launched and propagated to generate the accelerating fields [2]. In one scenario, likely to be used as a first stage, a pulse moves through the beam, accelerating the tail of the bunch first and acting as a "snowplow" (with "snow" ultimately passing over the top of the "blade" and falling behind). This method has the advantage that the acceleration can be varied in the experiment and can provide significant bunch compression. In later stages, the pulse would move with approximately the beam speed, so that the beam "surfs" on the pulse, continually accelerating as it moves through the structure. An issue which will be examined is control of the space-charge expansion of the bunch.

In the next sections we will describe a proposed experiment (NDCX1c) which will test the Accel-Decel Injector as well as the slow wave structure to accelerate the beam.

THE NDCX-1c EXPERIMENT

The NDCX1c experiment (Figures 1 and 2) consists of an Accel-Decel Injector, a matching section, and the slow wave structure (Helix) surrounded by high field transport solenoids to contain the beam.

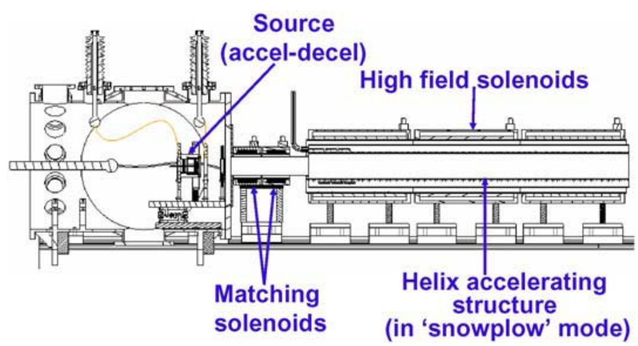

Figure 1: NDCX1c Experiment.

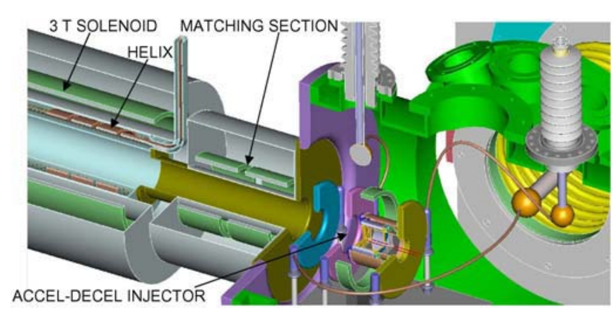

Figure 2: NDCX1c Experiment (cut-away view).

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THE ACCEL-DECEL INJECTOR

The Accel-Decel Injector (Figure 3) delivers a high line-charge density beam by extracting a long pulse, high current beam from a gun at high energy, and letting the beam pass through a decelerating field to compress it. Figure 3 shows the components of the Accel-Decel Injector. The emitter is a 6 cm diameter aluminosilicate potassium source surrounded by a Pierce electrode. A time-dependent voltage pulse is applied to the emitter and Pierce .electrode, going from ground potential to +60 kV and back again to ground. The rise and fall times are 300 ns, and the flat top is 1 μs. This source delivers 100 mA of K^+ for a total charge of 0.1 μC. After the beam is extracted at 160 keV, it is decelerated to 55 keV to be injected into the matching section. The final beam energy from the injector is 5 keV less than the potential difference on the electrodes due to the energy depression from space charge.

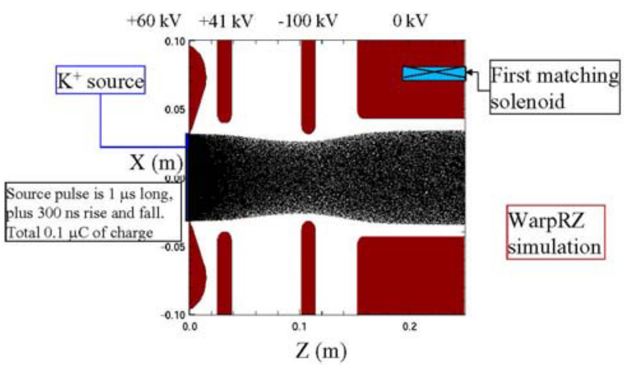

Figure 3: The Accel-Decel Injector.

MATCHING AND TRANSPORT SOLENOIDS

The low energy beam-bunch is loaded into a matching section that consists of two short (10cm long) and small bore (9 cm diameter) solenoids located immediately after the source ground plate. This matching section is required in order to match the beam to a Brillouin flow inside the solenoids located downstream; the field strength required is between 3 and 4 Teslas.

The acceleration helix is housed within the transport solenoids and the helix feed assembly enters radially between the matching and the transport solenoids. This arrangement is shown in figure 2. Three transport solenoids each 50 cm long and 20 cm diameter bore are required to contain the beam; the field strength required is also between 3 and 4 Teslas.

The baseline design for the matching and transport solenoids was to use three conventional pulsed solenoids very similar to the solenoids built and incorporated into the NDCX-1b experiment [3]. These could be designed and built relatively quickly and would provide a friendly way of reconfiguring the magnet system for future experiments. The down side was the large cost required to procure and build the pulsers.

A superconducting magnet design option was pursued in parallel to the conventional approach. It consists of two small matching coils and a single 1.5-meter long transport coil housed within a single cross-bore cryostat in order to meet the stringent coil spacing requirements. Each winding would have its own controlled power supply. A difficult requirement was to keep the cryostat ends as short as possible. A maximum space of 10 cm was allowed between the matching and transport coil windings in order to contain the rapidly expanding beam. Additionally, this space is the area that the acceleration helix feed assembly must egress. Figure 2 shows the arrangement of the solenoids and the helix feed area.

THE PULSE LINE ION ACCELERATOR

The accelerating scheme (PLIA) chosen to accelerate the high-current, short-bunch ion beam delivered from the Accel-Decel Injector uses a slow-wave structure based on a helical winding, on which a voltage pulse is launched and propagated to generate the accelerating fields.

The acceleration helix design is for an epoxy encapsulated, 1.5 m helix coil. A 8 mm pitch helix is wound onto an epoxy layer cast onto a 15 cm diameter Pyrex glass tube (Figure 4). A 3-turn primary (shown in Figure 2) is placed over the feed end of the helix and both coils are epoxy encapsulated. The requirement to make the finished helix assembly compact in radial buildup and in the area of the feed creates high electric field levels within the encapsulated volume. The encapsulation technique involves procedures to avoid formation of voids in the high field areas. Additionally, exothermic and shrinkage issues associated with the large (40 liter) epoxy volume required careful technique, choice, and testing of the epoxy formulation. The feed area of the helix required careful 3D modeling to insure electric fields did not exceed 100 kV/cm.

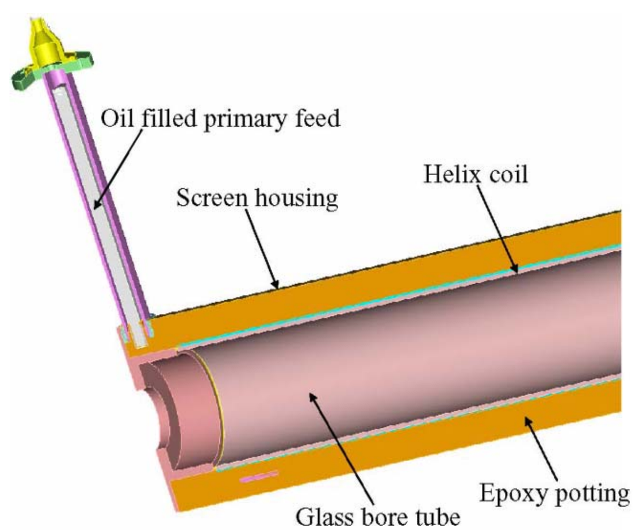

Figure 4: The PLIA assembly concept.

BEAM DYNAMICS

The WARP code has been used to carry out axisymmetric, self-consistent simulations of beam propagation in a helix. The field from the helix was applied to the beam as a time-dependent transverse Dirichlet boundary condition on the solution of Poisson's equation for the self fields. A time dependent potential is set on the wall at the start of the helix and is advected along the wall at the circuit speed. Also, at the beginning and end of the helix, a finite length region was included where the potential along the wall linearly rises from and falls to ground. This model (Figure 5) implicitly includes the short wavelength filtering of the longitudinal electric field as well as the associated radial electric field. The beam is injected at the source and propagated through the accel-decel section described above. This gives a realistic initial beam distribution, including the initial blow-off of the head due to space-charge.

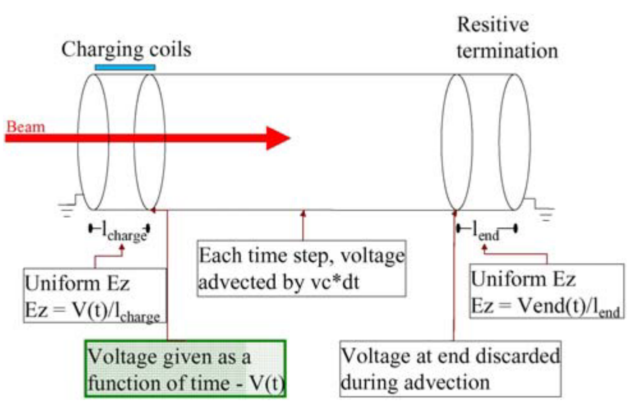

Figure 5: The Helix model.

For the helix running in the snowplow mode [2], the simulations show that while the helix acceleration works as designed, the beam is significantly perturbed by its longitudinal self fields. To maintain control of the beam pulse, pre- and post voltage pulses are included with the main snowplow ramp, and the shape of the ramp is modified. Before the head of the beam enters the helical coil, a pre-pulse is applied to create a decelerating field that is tailored to control the beam head as it enters, removing the initial space-charge blow-off. Then, as the rest of the beam enters, a small, increasing accelerating pulse is applied to give a small overall tilt to the beam. This provides an additional control on the bunch, giving overall compression against space-charge expansion. Before the beam leaves the helix, the pulse speed is adjusted so the head of the beam gets to the end of the helix before the tail of the pulse, so the head is not accelerated as much as the rest of the beam. The shape of the pulse is adjusted to provide fine control over this effect. Note that the shape of the pulse has no effect on the beam acceleration from the snowplow and little on the compression since the full pulse passes through each part of the beam (except for the head). Then finally, a post-pulse is applied which arrives at the end of the helix just and the beam tail does to give it an additional kick. This combination of methods provides a good degree of flexibility in dealing with the beam-space charge, allowing the beam to be held together at the low currents in NDCX1c. The "knobs" also afford a high degree in flexibility in the amount of compression. Snowplow waveforms have been developed to give longitudinal compressions in the range of 2 to 8. Higher compressions could be achieved as well, but at the expense of severe beam degradation and beam over-taking

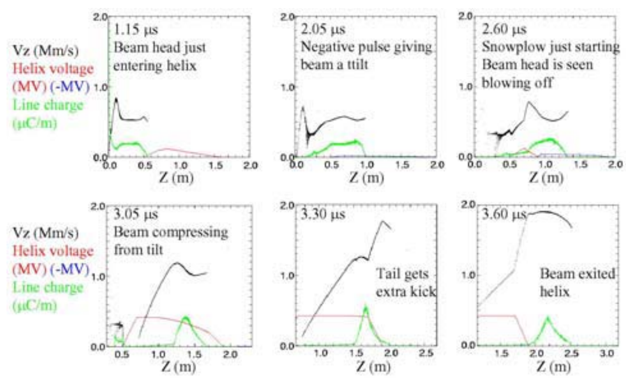

Figure 6: Snowplow mode with moderate compression.

An example run using a waveform producing moderate compression is presented in Figure 6; it shows the longitudinal phase space, helix voltage, and line-charge density at various times. The pre- and post-pulses can be seen along with their effect on the beam.

SUMMARY

The NDCX1c experiment will help to develop and test novel particle accelerator concepts like the Accel-Decel Injector and the Pulse Line Ion Accelerator. This system will accelerate high-current, short-bunch ion beams to establish the physics limits on compression of heavy ion beams for creating high energy density matter and fusion ignition conditions.

REFERENCES

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