#### Collective Effects and Intense Beam-Plasma Interactions in Ion-Beam-Driven High Energy Density Matter and Inertial Fusion Energy

Igor D. Kaganovich (ikaganov@pppl.gov), Edward A. Startsev, Hong Qin, Erik Gilson

Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton NJ 08543

Thomas Schenkel, Jean-Luc Vay, Ed P. Lee William Waldron, Roger Bangerter, Arun Persaud, Peter Seidl, and Qing Ji

Accelerator Technology and Applied Physics Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720

Alex Friedman, Dave P. Grote, John Barnard,

Lawrence Livermore National Laboratory, P.O. Box 808, Livermore CA 94550

#### **Executive summary**

For the successful generation of ion-beam-driven high energy density matter and heavy ion fusion energy, intense ion beams must be transported and focused onto a target with small spot size. One of the successful approaches to achieve this goal is to accelerate and transport intense ion charge bunches in an accelerator and then focus the charge bunches ballistically in a section of the accelerator that contains a neutralizing background plasma. This requires the ability to control space-charge effects during un-neutralized (non-neutral) beam transport in the accelerator and transport sections, and the ability to effectively neutralize the space charge and current by propagating the beam through background plasma. As the beam intensity and energy are increased in future heavy ion fusion (HIF) drivers and Fast Ignition (FI) approaches, it is expected that nonlinear processes and collective effects will become much more pronounced than in previous experiments. Making use of 3D electromagnetic particle-in-cell simulation (PIC) codes (BEST, WARP-X, and LTP-PIC, etc.), the theory and modelling studies will be validated by comparing with experimental data on the 100kV Princeton Advanced Test Stand, and future experiments at the FAIR facility. The theoretical predictions that are developed will be scaled to the beam and plasma parameters relevant to heavy ion fusion drivers and Fast Ignition scenarios. Therefore, the theoretical results will also contribute significantly toward the long-term goal of fusion energy production by ion-beam-driven inertial confinement fusion. The proposed research places special emphasis on addressing critical scientific issues in the following areas:

- Theoretically study collective beam-plasma interactions during longitudinal and transverse compression of the beam pulse for the HIF driver; and identify and mitigate the effects of collective beam-plasma interactions during compression of the beam pulse;
- Identify existing available ion beam facilities where modeling results can be validated;
- Develop, test and apply advanced plasma sources that produce sufficiently dense plasma for intense ion beam neutralization that are compatible with accelerator vacuum requirements;
- Experimentally validate the feasibility of heavy ion beams based on negative ions; develop reliable theoretical models describing the effects of ion-atom collisions on the lifetime of negative ions in the accelerator; and study the fundamental properties of ion-ion plasmas produced on the Princeton Advanced Test Stand (PATS) facility;
- Develop models describing the nonlinear dynamics of intense non-neutral ion beams with the goal of minimizing deleterious collective effects and instabilities and optimizing ion beam transport and focusing in the non-neutral section of the accelerator system;

• Develop and test innovative beam delivery and instability control techniques to maximize the focused beam intensity on target, including the use of oscillating wobbler fields in the final focus system for beam smoothing and facilitate uniform deposition on the target on FAIR facility, and scaling the concept to heavy ion fusion driver systems.

### **Background and Motivation**

Charged particle beams produced in accelerators have a number of attractive features as potential drivers for IFE, and as a component in FI approaches [1,2]. To summarize the Refs. [1,2] HIF drivers can deliver high energy pulses more directly to a fusion target; they have high efficiency (>20% wall plug to beam); favorable final optic protection in a future reactor chamber; demonstrated long life of accelerator components; relatively high repetition rates (>10 Hz), etc. However, for HIF drivers the power requirements far exceed levels achieved in modern accelerators. White paper [2] is addressing ability to scale the accelerators to the HIF driver power levels.

A principal aim of the proposed research effort is to address the following compelling scientific questions as they pertain to ion-beam-driven High Energy Density Physics (HEDP) and HIF:

- How can heavy ion beams be compressed to the high intensities required to create high energy density matter and fusion conditions?
- How are intense charged-particle beams transported and focused?

An important long-term objective of the proposed U.S. HIF program is to provide a comprehensive scientific knowledge base and the enabling technologies required for IFE driven by high-brightness heavy ion beams, while the major near-term objective is to explore the limits of compressing ion charge bunches to very short pulses for purposes of investigating ion-driven HEDP and Warm Dense Matter (WDM) physics. A fundamental understanding of nonlinear space-charge effects on the propagation, acceleration and compression of high-brightness (high-current and low-emittance) heavy ion beams is essential to the identification of optimal operating regimes in which emittance growth and beam losses are minimized in periodic focusing accelerators and transport systems for applications of intense heavy ion beams to HEDP and IFE.

# Short Overview of the Current Status

For the successful generation of ion-beam-driven high energy density matter and heavy ion fusion energy, intense ion beams must be transported and focused onto a target with small spot size. One of the successful approaches to achieve this goal is to accelerate and transport intense ion charge bunches in an accelerator and then focus the charge bunches ballistically in a section of the accelerator that contains neutralizing background plasma. This requires the ability to control space-charge effects during un-neutralized (non-neutral) beam transport in the accelerator and transport sections, and the ability to effectively neutralize the space charge and current by propagating the ion beam pulse through background plasma.

The High Current Experiment (HCX) was a very successful proof-of-principle experiment that demonstrated that intense ion beams with large space charge of up to several kV can be routinely transported and focused as un-neutralized beams to a spot size of a few mm diameter [3]. Another important series of experiments in HCX showed that electron clouds produced by

background gas or surface ionization can be cleared from the ion beam pulse by making use of clearing electrodes or quadrupole magnetic fields, even for high-current ion beams [4].

The Neutralized Drift Compression Experiments -I and II (NDCX) were also a very successful proof-of-principle experiment that demonstrated the ability to longitudinally compress the beam current by a factor of up to 100, and transversely focus the neutralized ion beam from a 3 cm radius down to a few mm spot size [5]. By producing a background plasma with density large compared to the beam density, it was shown experimentally, theoretically, and in numerical simulations that the beam space charge and current can be neutralized to a sufficiently high degree to provide a very high degree of ballistic focusing [6].

The background plasma was created by ferroelectric plasma sources developed at PPPL which produced high density plasma (up to 10<sup>15</sup> cm<sup>-3</sup>) near the walls of the plasma source, and then filled the neutralized transport section of the NDCX-I device with plasma with density up to 10<sup>11</sup> cm<sup>-3</sup> [7]. The plasma density in the central region was adequate for neutralized beam transport in the neutralized drift section of NDCX. There were four additional plasma sources based on vacuum cathodic arc technology that were employed near the target to increase the plasma density in the focal plane of the compressing beam pulse for better neutralization in this region. It was shown experimentally that individual plasma jets streaming from the periphery region of the strong solenoidal magnetic field near the focal plane can fill the center of the transport region with plasma and neutralize the ion beam pulse [8]. The mechanisms for plasma penetration across the magnetic field are still not fully understood. One possible mechanism is the time-dependent nature of the external solenoidal magnetic field, which is affected by eddy currents in the nearby metal walls. Another possible mechanism may be plasma instabilities that provide anomalous transport of the plasma across the magnetic field [9].

Theoretical analyses and PIC modeling have been performed to describe (i) beam transport in the unneutralized (nonneutral) section of the accelerator [10], and (ii) quasi-steady-state propagation of the neutralized beam pulse in a background plasma [11]. Possible collective instabilities associated with the large beam space charge in both the neutralized and unneutralized sections have been surveyed, and the linear growth of several collective instabilities have been calculated. For the most robust instabilities, the nonlinear stage of instability has been simulated using both particle-in-cell and nonlinear delta-f codes [12]. Examples include: the two-stream instability between the beam ions and the background plasma electrons in the neutralized drift section of the accelerator; and the Harris and Weibel instabilities can lead to longitudinal emittance growth due to a coupling through a collective 3D mode between the longitudinal and transverse degrees of freedom of particle motion. For the neutralized drift transport section, two-stream electrostatic and electromagnetic instabilities have also been analyzed [12]. For parameters in the NDCX and HCX experiments, it was shown that the growth rates (exponentiation lengths) were sufficiently slow (long) that these instabilities were not of concern in these experiments [13].

Experiments at PATS showed that very high degree of neutralization can be achieved due to accumulation of cold electrons in the beam path [14] and further confirmed by recent experiments [15].

Important details on limitation of neutralization of an ion beam pulse by emission by filaments was investigated recently making use of 2D [16] and 3D PIC [17]. It was found that solitary and surface waves are excited in the process of neutralization and can affect the remaining space

charge. Another important finding was that 3D simulations can be needed to adequately describe the process [17]. It is timely that there has been robust development of high-performance PIC codes (Chaos [17], Warp-X [18], LTP-PIC [19]) that can be used effectively to simulate these complex phenomena. The white paper [20] describes planned modeling efforts using Warp-X code.

# **Research Objectives**

As the beam intensity and energy in the HIF driver are increased compared to the previous NDCX experiments, it is expected that nonlinear processes and collective effects will become much more pronounced, therefore critical scientific issues needs to be addressed:

*High-brightness heavy ion beam transport in accelerator:* Develop a basic understanding of the limits on beam space charge imposed by gas and electron cloud effects, together with beam matching and magnet nonlinearities, and determine the effects of collective interactions on beam quality and transport.

Longitudinal and transverse compression of intense ion beams: Develop a basic understanding of the limits on longitudinal compression within neutralizing background plasma, and the effects of beam-plasma instabilities over distances required for focusing in the chamber. Develop a basic understanding of the limits on transverse compression and focal spot size set by chromatic aberrations due to uncompensated velocity spreads from upstream longitudinal compression, and the beam emittance growth from imperfect charge neutralization and beam-plasma interactions.

The theory and modeling studies need to be validated making use of experimental data on the 100kV Princeton Advanced Test Stand (PATS), past data available from the NDCX facility, and new experimental data to be obtained from experiments on the FAIR facility or others [1]. The theoretical predictions that are developed will be scaled to the beam and plasma parameters relevant to heavy ion fusion drivers. Therefore, the theoretical results will also contribute significantly toward the long-term goal of fusion energy production by ion-beam-driven ICF.

#### **Research Thrusts**

Emphasis is placed on the following Research Thrusts relevant to ion-beam-driven HEDP and HIF:

**Thrust Area #1** – Develop effective neutralization and focusing schemes for neutralized beam transport in HIF drivers

The key research objectives in this area are to design and test advanced plasma sources for robust neutralization of intense ion charge bunches and to perform a feasibility study of practical implementation of novel plasma sources for neutralized drift sections in current and future heavy ion accelerator systems with a long lifetime and low cost. Specific research tasks include: Demonstrate that the beam charge and current can be controlled or neutralized during neutralized drift compression by judicious choice of background plasma parameters; Demonstrate that collective instabilities can be controlled or mitigated during neutralized drift compression by profiling the plasma density or magnetic field; and Study the neutralization process and effects of transients on beam emittance during beam entry into the plasma.

A further research objective in this thrust area is to design and test advanced collective focusing schemes [21] in the PATS and other available high energy density laboratory physics facilities,

which effectively utilize the large self-electric fields of the beam pulse and do not require large focusing magnets.

**Thrust Area #2** – Develop innovative beam driver concepts for energy delivery in heavy ion fusion systems using *negative ion beams* extracted from ion -- ion plasmas

In order to avoid possible electron cloud effects and charge exchange effects many linear accelerators use negative ions instead of positive ions. Consequently, the research objective in this thrust area is to develop a comprehensive justification for the use of negative ion beams for heavy ion fusion drivers and propose experimental tests of the concept based on halogen negative ions on the Princeton Advanced Test Stand [22].

**Thrust Area #3** – Minimize deleterious collective effects and optimize ion beam transport and focusing in nonneutral section of accelerator system

The research objective in this thrust area is to demonstrate that the large space charge in the ion charge bunch can be transported quiescently through the non-neutral section of the accelerator system for driver-scale parameters. The specific research tasks include: Investigate transverse emittance growth due to coupling of collective modes with focusing element misalignments and beam mismatch; Study longitudinal emittance growth due in finite-length charge bunches due to collective effects and instabilities such as the Harris instability [23]; Design achromatic focusing system for simultaneous transverse and longitudinal compression on future heavy-ion-driver scale facility [24].

**Thrust Area #4** – Develop innovative beam delivery and instability control techniques to optimize target performance

The research objective in this thrust area is to investigate the use of oscillating electric fields in wobbler system and innovative beam delivery methods for beam smoothing technique to mitigate instabilities and facilitate uniform deposition on the target. Specific research tasks include develop wobbler design concepts for beam smoothing and the Rayleigh-Taylor instability control in driver-scale systems [25].

# Conclusion

Heavy-ion-beam drivers offer number of advantages as potential drivers for IFE. Initial experimental study successfully addressed critical issues of controlling instabilities and large space charge of the driver beam in past HCX and NDCX experiments. Further progress can be achieved by combined experimental, modeling and theoretical research efforts. Princeton Test Stand is available at PPPL and can be used to test innovative concepts such us collective focusing, negative ion beams, neutralization by filaments and undersense plasma [26], and for development innovative plasma sources for neutralization [27].

Future experiments on focusing of intense ion beams at FAIR [1], DARHT [28] and other facilities will provide sufficient data to validate well established theories of space charge and current neutralization by plasma and in combination with the use of high-performance PIC simulations [18, 19] will enable well-grounded designs of Heavy Ion Fusion Driver [2].

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