Experimental Program for the Princeton Ion Source Test Facility*

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Abstract

A 100 kV ion source test stand formerly operated at Lawrence Livermore National Laboratory (LLNL) has been relocated to Princeton Plasma Physics Laboratory (PPPL), where it is being installed and prepared for operation. A variety of topics relevant to ion-beam-driven high energy density physics and heavy ion fusion will be explored on this facility. The practicality of magnetic insulation to improve the performance of electrostatic accelerators will be investigated by determining whether a pair of parallel plates forming a high-voltage gap can sustain higher electric field gradients when an electric current is passed through the electrode at the cathode potential so as to produce a magnetic field which is everywhere parallel to the surface. The facility will also be used to develop and characterize improved plasma sources for space charge neutralization of intense ion beam systems such as the Neutralized Drift Compression Experiment-II (NDCX-II) facility. The negative halogen ion beam and ion–ion plasma studies previously initiated when this test facility was located at LLNL will be resumed, and other experimental topics are also under consideration.

Keywords: ion – ion plasmas, negative ion beams, magnetic insulation, space-charge neutralization

1. Introduction

The 100 kV test is designed with clearances to stand off voltages of up to 100 kV. The main chamber is a box approximately six feet long with approximately a 2.5′ x 2.5′ square cross-sectional area. There is excellent access for diagnostics and pumping: three 13.25″ diameter ports and numerous 4.5″ and 2.75″ ports. The complete system rests on a custom-built stand and includes: an RF plasma source, a pulser oil tank, an oil transfer tank, an two slit emittance scanner, and a Faraday cup. Assorted other components include: pressure gauges, needle valves, delay generators, bias power supplies, and the LabView software for controlling the diagnostics. The plasma source that will be used for ion-ion plasma experiments is a multi-cusp RF source that employs a compact oscillator that operates at 13.56 MHz and can provide pulses of 18 kW for durations of 500 μs. This source is floated up to 100 kV. The primary pumping for the initial configuration of the test stand will be a 1500 l/sec turbopump.

The remainder of this paper describes some of the topics which are expected to form the experimental program for this facility over the next several years.

2. Magnetic Insulation

Electrostatic accelerators in general, and more especially, the multibeamlet accelerators used to accelerate beams for heating and current drive in magnetic confinement fusion, and planned as the injectors for heavy ion fusion driver beams, all suffer from high voltage breakdowns mediated by electrons flowing between either their high voltage grids or the support structures for these grids. These electrons arise through two primary processes: spontaneous emission from electric field concentration at surface imperfections, and secondary emission due to ion bombardment of the electrodes. In many cases, some electrons are likely released due to the photoelectric effect induced by ultraviolet light and by X-rays arising from electrons hitting the grids.

The facility will be used to test whether it might be feasible to use magnetic insulation to suppress some or all of these mechanisms by enveloping the accelerator grids and their electrically connected support structures in enveloping magnetic fields. This idea was proposed in a recent publication by one of us. (Grisham, 2009a) A very simple configuration will be used, consisting of two polished rectangular copper electrodes within the facility, with a high voltage applied across a vacuum gap between them. A high current will be run through one of the electrodes to produce an enveloping field conforming to the electrode surfaces. The amount of voltage that can be held across the gap as a function of the magnetic field and field-generating current will then be measured. The power supply producing the magnetic insulation current can be at ground potential if the configuration is set up such that the power supply ground is the negative side; this will circumvent the need to float the high-current supply at the potential of the electrode. The high-current supply, which should be capable of at least several hundred amperes, does not need to have much voltage capability, as the test electrode will have negligible resistance. It is difficult to estimate how high a magnetic field would be needed for a given electric field strength, but the strength of the electric field can be adjusted to find a region where the available magnetic field has an effect.

If this initial test, which seeks to inhibit only the spontaneously emitted electrons, shows promise, then an ultraviolet light source can be added to check the utility of the magnetic insulation effect upon photoelectric electrons. If these tests prove promising, then the efficacy of magnetic insulation in suppressing secondary electrons can be tested by either hitting the high voltage gap with a beam from the test stand ion source, or, perhaps, by adapting the ion source accelerator of the test stand for magnetic insulation. As discussed in (Grisham, 2009a) it is likely that higher magnetic fields will be required to suppress breakdowns due to photoelectric effects and secondary emission, since the birth energy of these electrons can be considerably higher than that of electrons arising from spontaneous field emission.

If magnetic insulation should prove practical, it may have wide applicability in heavy ion fusion, magnetic fusion, and many other fields. It should have relatively little steering effect upon the ion beams in an accelerator, since the directions of the magnetic field are opposite on each side of an electrode. In multi-stage accelerators, the currents could flow in different directions in successive electrodes to further reduce any net steering.

3. Halogen Ion Beams and Ion – Ion Plasmas

More than a decade ago (Grisham, 2009b) it was suggested that halogens, with their very large electron affinities, might allow the production of beams of high enough current density to make negative ions feasible as a driver for heavy ion fusion. Negative ions would have the advantage that, unlike positive ions, they would not accumulate electrons that might cause emittance growth, and they presented the appealing option of being suitable for energy-efficient photodetachment (Grisham, 2003) to neutrals, which would result in a lower average beam self-perveance during propagation across a fusion target chamber, even with subsequent reionization by target-emitted x-rays and collisions with flibe vapor. These advantages, however, would only be merit pursuit if negative heavy ion beams of comparable quality to corresponding positive ion beams could be easily produced.

Experiments subsequently carried out at Lawrence Berkeley Laboratory and LLNL (Grisham and Kwan, 2009) demonstrated that under similar discharge conditions in tandem filter cusp-confined ion sources similar in principal to those used for negative hydrogen beam production in magnetic fusion energy applications, the current density of Cl^- which could be successfully extracted from the source and through the gas flowing from the source through the accelerator was similar to the positive ion current density ($Cl^+$and Cl_2^+) which could be extracted if the extraction polarity was reversed, and that both were quite close to the current density of Ar^+ which could be extracted with the same electrode system from an argon discharge with similar RF drive and pressure. Argon, which has no electron affinity and forms no stable negative ions, was chosen for comparison because it has approximately the same mass as chlorine, and thus should have about the same optimum perveance in an electrostatic accelerator as does chlorine.

Argon plasmas are ordinary electron – ion plasmas, whereas the chlorine beam experiments produced several independent lines of evidence supporting the conclusion that, at least in the region from which the beam was extracted, an ion – ion plasma with very few free electrons existed.

Since all of the stable halogens have similar electron affinities (3.06 eV to 3.62 eV) and they all form diatomic molecules in the vapor phase that are amenable to the formation of negative ions through dissociative attachment of low energy electrons, the implication of these experiments was that any of the stable halogens should be a suitable choice for negative ions of current densities and optical qualities similar to what could be obtained with a positive ion beam of similar mass. Moreover, as discussed in (Grisham et al., 2007), the fact that little more Cl^- than Cl^+ was lost in traversing the gas in the source extractor, where the neutral gas density was much higher than would be the case in a heavy ion fusion accelerator, and where the destruction cross section was much higher at the low extraction energies than would be the case at heavy ion fusion accelerator energies, showed that the survival rate of negative halogens should be acceptable for fusion applications.

Unfortunately, the STS-100 test stand at LLNL ceased operation before these experiments could be completed, leaving unanswered some questions of critical interest if halogen beams are used for heavy in fusion, warm dense matter generation, or other applications, and also of some fundamental plasma physics applications. These include whether ion beams extracted from ion – ion plasmas have lower effective ion temperatures than corresponding ion beams extracted from electron – ion plasmas and whether the magnetic filter is superfluous in halogen plasmas. Since the average charged particle mass is approximately a factor of two higher in an in ion – ion plasma than it is in an electron – ion plasma, the fluctuation levels in the ion – ion plasma might be expected to be lower than in an electron ion plasma of a similar mass feedstock by a factor of approximately the square root of 2, leading to a lower ion temperature within the ion – ion plasma for similar discharge drive power and pressures. If this lower temperature could be preserved through the extraction process, then it might allow production of lower temperature beams with reduced emittance, in which case ion – ion plasmas might be preferable to electron – ion plasmas whether one wanted positive or negative ion beams for applications such as heavy-ion-driven fusion, warm dense matter production, or ion lithography, all of which could benefit from lower emittance beams.

Emittance measurements of the beams in these earlier experiments (Grisham et al., 2007) showed an effective transverse beam temperature of 0.3 eV for the Cl-, the Cl+ + Cl2+, and the Ar+ beams. However, it was surmised that, since, for all three beams, the normalized emittance increased with beam perveance, the beam extraction optics was probably contributing to the apparent beam temperature. Thus, 0.3 eV was taken to be an upper limit on the ion temperature in the extraction plane of the source plasma, and it was not possible to determine which of the beams started out colder.

Among the experiments planned for the Princeton Ion Source Test Facility is a more accurate comparison of the emittance of the Cl- , Cl+, and Ar+ beams extracted from plasmas with similar discharge parameters. The measurements in the previous experiments measured the emittance of a single beamlet extracted from circular aperture optics. The measured emittance in these experiments increased with the beam perveance, which is usually a sign that the extraction optics is contributing to the emittance. Thus, the reason that all three beams were observed to have about the same emittance, and the same apparent temperature, 0.3 eV, was thought to be that the extraction optics were obscuring the underlying source ion temperature. Future experiments will use a slot extraction system to produce a slot beamlet, with one dimension (the parallel dimension) several times greater than the other dimension (the perpendicular dimension). In such optical systems, as long as there is no gradient in the plasma illuminating the slot in the plasma grid, then the emittance in the direction parallel to the slot depends only upon the beam ion temperature, except for end effects. In order to minimize the end effects, it is desirable to have the aspect ratio of the slot length to the slot width as large as possible. However, the need for there to be no significant plasma gradient along the slot means that, prior to designing the slot optics, it will be desirable to measure the beam uniformity by first extracting circular aperture beamlets, one at a time, from several positions forming a line running across the centerline of the extraction plane. This will be done by procuring a set of plates with a line of apertures, and masking all but one at a time on the plasma grid. The emittance will be measured with the double-slit Allison scanner accompanying the STS-100 facility components.

The earlier experiments conducted with chlorine beams found five independent lines of evidence (Grisham et al., 2007) supporting the inference that the extractor plasma in these two tandem ion sources was an ion – ion plasma consisting of positive ions, a nearly equal number of negative ions, and relatively few electrons. Comparisons of chlorine (electron affinity 3.61 eV) and oxygen (electron affinity 1.46 eV) discharges and the beams extracted from them also showed that the degree to which an ion – ion plasma could be formed depended very strongly upon the electron affinity of the feedstock gas.

Exploring the ion-ion plasma regime by analyzing the properties of the negative ions, positive ions, and electrons extracted form the plasma is, insofar as we are aware, unique to the approach described here. It is proposed to use the emittance scanner and the Faraday cup to measure the effective temperature and relative abundance of the positive and negative ions, and to determine the amount of accompanying electrons. We will also attempt to operate without a magnetic filter to determine whether it is unnecessary when using highly electronegative feedstocks. In addition to oxygen and chlorine, we may use other gases with intermediate electro-negativities to try to better understand the minimum electro-negativity required to achieve ion – ion plasma conditions in which the electron population is minimized. In addition, the positive-ion/negative-ion/electron three-species plasma and sheath will be studied by employing numerical simulations and analytic modeling to compliment and help understand the experimental data.

4. Short Pulse Beam Control of Ions from Aluminosilicate Sources

Aluminosilicate surface ionization sources are useful in producing beams with low ion temperatures for heavy ion fusion applications. However, these sources are traditionally heated by electric resistance heaters, usually behind or around the aluminosilicate, resulting in either continuous or very-long-pulse ionization and evaporation of the beam feedstock from the porous source. Ideally, as the input to a heavy ion fusion driver, one would like a short pulse length of order a microsecond with as rapid a rise time as possible. While it is probably not practical to achieve such a sharp pulse from an aluminosilicate, finding a way to produce reasonably short pulses that are much shorter than the present quasi-continuous operation could greatly improve the lifetime of aluminosilicate sources, allowing them to be used for several to many orders of magnitude more beam shots than is possible with quasi-continuous operation. It is proposed to attempt flash-heating an aluminosilicate source with a bright pulsed radiant heat source to explore whether this might produce sharp short ion pulses in a reproducible way suitable for a heavy ion fusion driver . (Kwan, 2009)

An aluminosilicate source on the test facility, equipped with an ion extraction system, and with the Faraday cup to measure the time dependence of the positive ion beam current extracted. While it would be possible to flash heat it with either a laser or a xenon flash lamp, a xenon flash lamp may be preferable so that one can easily control the intensity. The experimental plan is to vary the intensity, and perhaps also the width of the xenon flash, and the resistive preheating of the source, and measure the magnitude and shape of the extracted positive ion beam to see whether this appears promising as a feeder to a heavy ion fusion driver .

5. Plasma Sources for Space Charge Neutralization of Intense Ion Beams

Several methods of plasma production for ion beam space-charge neutralization are being considered as candidates for development and testing on the test facility.

Pulsed high-voltage discharges using ceramic or plastic materials will be tested to determine if materials and geometries that are different than the present ferroelectric plasma source can be used to generate high density plasmas (Dunaevsky et al., 2001al.; Dunaevsky et al. 2001b). Due to the small transverse size of the compressing ion beam near the target spot, plasma sources can be placed close to the beam axis near the target. Placing sources nearer to the beam axis should lead to higher plasma density because there is less opportunity for plasma expansion and the accompanying decrease in plasma density. Ferroelectric plasma sources with modified electrode structures and pulsers with sharp rise and fall times controlled with crowbars will be tested. In addition, a simple design using a commercial-grade circuit board as the dielectric and copper traces or surface pads as the electrodes will be tested.

Laser-ionized plasmas are an attractive alternative that could be used to generate high-density, localized plasmas because they do not require strong externally applied electric or magnetic fields to aid in plasma formation or to guide the plasma from the plasma source to the region near the target plane. A highly collimated gas jet or metal vapor jet can be directed across the beam path in front of the target and ionized by a brief, intense burst of laser radiation. For example, Lithium vapor can be made into a plasma by single photon ionization from a pulsed UV excimer laser (Dimaggio, et al, 1999). Plasma sources using gas jets or metal vapor jets will have to be designed to minimize the pressure rise in the NDCX-II vacuum chamber that would limit the repetition rate.

Laser ablation of solids can also produce high density plasmas (Oguri, Y.,et al., 2000). A piece of material, such as copper, can be placed immediately upstream of the target spot and ~1 cm away from the beam axis in order to not interfere with the ion beam propagation. The plasma generating material would be several centimeters long, corresponding to the length of the region where the high density plasma is needed. The laser radiation can be uniformly spread along the length of the plasma generating material by using line generator optics.

6. Conclusion

The test facility being reactivated at the Princeton Plasma Physics Laboratory will provide a venue to explore a wide range of topics of potential value to heavy-ion-driven inertial fusion, magnetically confined fusion, warm dense matter, and, if magnetic insulation proves tractable, to a broad range of electrostatic accelerator applications.

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