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THE ROLE OF ANODE AND CATHODE PLASMAS IN HIGH POWER ION DIODE PERFORMANCE

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ABSTRACT

We describe measurements, modeling, and mitigation experiments on the effects of anode and cathode plasmas in applied-B ion diodes. We have performed experiments with electrode conditioning and cleaning techniques including RF discharges, anode heating, cryogenic cathode cooling and anode surface coatings that have been successful in mitigating some of the effects of electrode contamination on ion diode performance on both the SABRE and PBFA accelerators. We are developing sophisticated spectroscopic diagnostic techniques that allow us to measure the electric and magnetic fields in the A-K gap, we compare these measured fields with those predicted by our 3-D particle-in-cell (PIC) simulations of ion diodes, and we measure anode and cathode plasma densities and expansion velocities. We are continuing to develop E-M simulation codes with fluid-PIC hybrid models for dense plasmas, in order to understand the role of electrode plasmas in ion diode performance. Our strategy for improving high power ion diode performance is to employ and expand our capabilities in measuring and modeling A-K gap plasmas and leverage our increased knowledge into an increase in total ion beam brightness to High Yield Facility (HYF) levels.

1. INTRODUCTION

The goal of US National Inertial Confinement Fusion (ICF) Program is to achieve a fusion yield in the range of 200 - 1000 MJ from a radiation-driven fusion capsule. The addition of a repetitive driver capability at this yield level would enable the development of a fusion power plant. Our present understanding suggests that in order to deposit the ~ 1 MJ of energy in the fusion capsule to achieve these yields it will require about 10 MJ of driver energy. Intense ion beams appear to offer the best combination of efficiency, cost effectiveness and potential for repetitive operation for use as a driver for high yield ICF and eventually a fusion power plant. At Sandia National Laboratories we are investigating the feasibility of using intense beams of light ions (Z~3) generated using a pulsed power accelerator driving an applied-magnetic field ion diode as a high-yield facility (HYF) driver [1]. The key issue is whether an ion diode can be developed that meets the power, energy, impedance and emittance requirements of an HYF driver.

Table 1 shows the HYF parameters for our present baseline ion diode design and the range of present day diode parameters achieved on the SABRE and PBFA accelerators. The voltage is set by the range of a lithium ion at 30 MeV in the ICF target deposition region. The current is chosen to give a power of about 25 TW/diode in order to satisfy the total beam power requirements. The ion beam divergence of 6-12 mrad is set by the target diameter (~1 cm), the standoff distance from the final focusing element to the target (1-4 meters) and whether a solenoidal magnetic lens or a self-pinch transport mode is used. A pulse length of 40 ns is chosen so that a rising diode voltage leads to a time-of-flight TOF bunching that shortens the pulse on target to 20 ns and increases the power to 50 TW/beam. The total ion current, the practical size of the diode, the need to keep the current density enhancement with respect to Child-Langmuir low, and the physics of ion sources sets the ion current density at the anode in the vicinity of 1-2 kA/cm^2. Increasing the ion beam current and current density, and decreasing the ion beam divergence are our key activities. Better impedance control will also be required in order to achieve the factor of two power multiplication by TOF bunching required by our HYF design. We believe that significant progress towards these parameters can be achieved

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through mitigation of the effects of anode and cathode plasmas and the development of active ion sources.

Table 1: HFY diode parameters compared to present SABRE and PBFA conditions

	PBFA	SABRE	HYF Parameters
Voltage	14-10 MV	5 MV	30 MV
Current	0.4 MA	0.04 MA	1 MA
Divergence	22 mR	20-40 mR	6-12 mR
Pulse length	15-25 ns	15 ns	40 ns
Current density	~0.6 kA/cm^2	0.4 kA/cm^2	1-2 kA/cm^2

2. "IDEAL" ION DIODE PHYSICS

Pulsed power machines first compress electrical energy in space and time and then accelerate ions as a final stage of power concentration. An ion diode converts electromagnetic power into an intense ion beam [2]. This section discusses "ideal" ion diode physics, neglecting the presence and effect of anode and cathode plasmas.

2.1 The ideal A-K gap environment

An applied-magnetic field ion diode uses a transverse magnetic field in the acceleration gap to minimize the electron loss current. The high diode voltages lead to high electric fields on the cathode, field emission of electrons and the formation of an electron sheath or virtual cathode. For example, the PBFA-X ion diode generates voltages up to 15 MV across an A-K gap of ~2 cm yielding initial electric fields of up to 7.5 MV/cm with an initial transverse insulating magnetic field of ~3 T. The electron sheath, or virtual cathode, rotates in the azimuthal symmetry direction due to ExB drift. This represents a diamagnetic current that compresses the magnetic field against the conducting anode resulting in unique voltage-current characteristics for applied-B diodes [2]. The electric field also increases as the effective gap between anode and virtual cathode narrows. Electric fields ≥10 MV/cm and magnetic fields approaching 10 T exist in this dynamic acceleration gap.

The resulting electron sheath in this cross-field (ExB) device is unstable. The diocotron mode is a high frequency electron instability that adds little ion beam divergence. The ion mode is a lower frequency mode that is driven by the interaction of the ion beam with the electron sheath and leads to large ion beam divergence. Our 3-D E-M PIC simulations of ion diodes suggest that the ion mode can be controlled by controlling the electron sheath through high magnetic fields or by physical limiters that keep electrons away from the anode [3]. Electron control is also important because cross field diffusion allows electrons to reach the anode which reduces power efficiency. Finally, two-stage acceleration [4] is desired because acceleration at roughly constant emittance in the second stage decreases the total divergence, helps increase the total efficiency of the diode-to-beam power coupling and allows impedance control in the second stage [5]. However, this decrease in divergence and increased ion power coupling efficiency can only be achieved if the first stage achieves sufficient control of divergence, current and impedance.

2.2 Diagnosing the A-K gap using spectroscopy

Spectroscopy is an important tool for diagnosing the extreme environment of the A-K gap in a high-power ion diode. The electric field is determined by measuring the Stark shift of LiI *2s-2p* emission. Electric fields up to 10 MV/cm have been measured via the Stark shift of the 6708 Å line in neutral lithium [6]. Spectra from eleven spatial locations are measured in a single experiment to measure the temporally- and spatially-resolved electric field on 1 ns and 2 mm time and spatial scales. The lines of sight can be arranged in many different ways, depending on the desired field measurement. For example, they can be arranged sequentially across the gap to measure the acceleration E-field or azimuthally to measure electric field symmetry. Cross-gap measurements at various azimuthal locations around the diode have shown the presence of stationary, persistent nonuniformities of the electric field profile. Measurements have also indicated that the azimuthal electric field has a finite value and since it is transverse to the direction of acceleration, it can contribute to the ion beam divergence.

We have also studied ion source physics using spectroscopy. Measurements at the anode surface have revealed 8 MV/cm electric fields that indicate the LiF thin-film source is a field threshold emitter [7]. Since the LiF ion source is not a space-charge-limited (SCL) emitter it is susceptible to parasitic anode plasmas that are capable of shielding electric fields and providing SCL-level currents. The ion beam source divergence is measured via the Doppler broadening of the spectral lines viewed near the anode. For LiF, roughly half of the total beam divergence, ~17 mrad, is caused by the ion source with ion mode instabilities adding the majority of the remainder. The inability of the passive LiF thin-film source to supply SCL lithium currents, its susceptibility to parasitic plasmas, and its high source divergence make it imperative to develop a better lithium ion source.

2.3 QUICKSILVER simulations of A-K gap physics

QUICKSILVER is an electromagnetic particle-in-cell (PIC) code that performs a fully dynamic solution to Maxwell's equations in three spatial dimensions and applies relativistic three-dimensional particle kinematics with the full Lorentz force. This code is used for self-consistent simulation of time-dependent high-current particle flows in complex geometries without anode and cathode plasmas. QUICKSILVER has been used extensively to simulate the electron sheath dynamics and instabilities that occur in ion diodes.

We have compared the electric spatially-resolved electric field across the A-K gap as measured by spectroscopy with the results from QUICKSILVER simulations and find good agreement up to 46 ns, which is a very long time compared to any characteristic electron timescale [6]. By the time of peak ion beam power (approximately 54 ns), however, the agreement is no longer good and grows progressively worse. Simultaneous with this loss of fidelity of simulation and experiment is the onset of impedance collapse, the appearance of the parasitic load (non-lithium beam ions) and a sharp increase in ion beam divergence. It is obvious that there are physical processes that become important at this time that are not contained in the present QUICKSILVER modeling capability.

QUICKSILVER does not have the ability to simulate ionization and breakdown or include neutral particle physics. Idealized ion emission and electron emission algorithms simply inject charge into the gap without the formation and expansion of any electrode plasmas. Particles that strike boundaries are simply removed from the simulation without interaction. Traditional EM PIC simulation codes can not handle high density plasmas, such as may form on electrodes, due to constraints on practical grid sizes and on related grid heating issues. The azimuthal asymmetries in the electric field that were discussed in the previous section may also have their advent in nonuniform plasmas. Since these nonuniformities persist and remain stationary for several electron ExB drift periods around the diode it seems likely that the inertia of material from electrode plasmas is involved.

3. ELECTRODE PLASMAS IN “NON-IDEAL” ION DIODES

The “non-ideal” presence of electrode plasmas can cause impedance collapse, ion divergence (through nonuniformities), parasitic ion currents, and etc. Both cathode and anode plasmas can have an important effect on ion diode operation. Electrode plasmas are formed in the extreme electric and magnetic field conditions found in an applied-B ion diode. Measurements, mitigation and modeling of these plasmas are discussed below.

3.1 The non-ideal A-K gap environment

At the high electric fields described in the previous section, electron emission probably occurs through the explosive electron emission (EEE) process described by Mesyats [8] and the resulting expanding cathode plasma contributes to gap closure, impedance collapse, and electron loss. The cross-field transport of electrons to the anode limits the electrical efficiency of the ion diode and also heats the anode leading to thermal and stimulated desorption of surface contaminants that become ionized and generate a source of parasitic ion current [9,10]. The expanding anode plasma can lead to reduction of magnetic insulation and impedance collapse. Diffusion of the diamagnetically compressed magnetic field into a resistive anode plasma has the same impedance collapse effect as anode plasma expansion, but can occur much more rapidly. Nonuniform anode plasmas can result in increases in ion beam divergence. Electrons that strike the anode can also be scattered back into the gap as well as generate secondary electrons [11]. Initial calculations indicate that the reflected/secondary electrons may not directly change the diode operating point, but their cascade and buildup at low energy may significantly enhance neutral contaminant desorption and ionization. Ions striking the cathode can similarly heat, desorb, and ionize neutrals. The interaction of particles with electrode surfaces, the formation of anode and cathode plasmas, and the expansion and interaction of those plasmas with the diode particles and fields are important to high power ion diode performance.

3.2 Diagnosing the electrode plasmas using spectroscopy

Contaminant ions (e.g. hydrogen, carbon and oxygen) has been observed with emission and absorption visible spectroscopy as a function of time. In addition, continuum emission is observed that is indicative of the formation of dense, optically thick plasmas ($\sim 10^{18}$ cm^{-3}). We observe that these dense plasmas form first on the cathode, then on the anode, and expand into the A-K gap. Effective expansion velocities of the dense electrode plasma front of several cm/microsecond have been observed. The observation of continuum emission is our most direct evidence for the presence of anode and cathode plasmas in ion diodes. Although less dense plasma regions are expected further into the A-K gap we have not been able to directly observe them. Plasma densities of only 10^{13} cm^{-3} can modify the applied fields in the diode and are thus important to measure. From some PBFA experiments we also have spectroscopic data that simultaneously shows Stark-shifted 6708 Å Li emission and unshifted 6104 Å light on the same line of sight near the anode surface. This indicates that a finite electric field is present along some portions of the anode and that plasmas are screening the field from others; i.e. "spotty" plasmas appear to form on the anode. Thus, the anode plasmas that form and expand into the gap may not be uniform.

Accelerated ions and electrode plasmas may more appropriately be diagnosed in the VuV (500-1500 Å) and EuV (100-400 Å) portions of the spectrum since the more highly populated ground states are directly observed. Observations of anode plasmas in the VuV show high charge states of oxygen and carbon (contaminant ions) [10]. We have made preliminary measurements of the emission of excited lithium ions in the acceleration region and ground state neutrals in the gap using absorption in the VuV regime; more measurements need to be made and compared with models. We are investigating the advantages of observing electrode plasmas and the A-K gap in the EuV region.

3.3 Hybrid fluid-PIC simulation capability for electrode plasmas

As described in Section 2.3, traditional EM-PIC codes can not model the dense plasmas that are formed on the electrode surfaces of our ion diodes. In order to better understand the role of anode and cathode plasmas (including ion sources) in ion diodes we are developing a hybrid fluid-PIC simulation capability. We have added diagnostics to our PIC codes to tabulate the spatially- and temporally-resolved particle fluxes to the electrodes. Interestingly, we see a large increase in electron loss to the anode associated with the low frequency ion mode instability. Thus, the ion mode may have implications for contaminant plasma formation as well as ion beam divergence. The interaction of the electrons with the anode including electron scattering, secondary production, Bremsstrahlung production and energy deposition are modeled and tabulated as a function of energy and angle using the ITS [12] Monte-Carlo code. The tabulated electron losses, the energy deposition per electron, and the specific heat of the anode are combined to compute the time-dependent anode temperature. We are incorporating the parameterized electron interaction physics into QUICKSILVER to study the effect of scattered and secondary electrons on ion diode equilibria.

In the electromagnetic PIC code IVORY [13], neutrals are injected from the anode as fluid macroparticles with a Maxwellian velocity distribution according to a temperature-dependent desorption formalism. The neutrals are desorbed from the anode at a rate determined by the typical adsorbate binding energy. The model allows ions and neutrals to interact via elastic collisions, ionization and charge-exchange reactions. The neutral layer undergoes significant ionization when the layer thickness corresponds to about twice the secondary electron Larmor radius (which scales as E/B^2).The expansion of this layer is accelerated by charge-exchange reactions between the neutrals and the ions in the applied electric field. A shortened lithium ion current, the growth of contaminant ion current, and diode impedance collapse is seen in our IVORY simulations due to the production of parasitic plasmas and the expansion of the anode plasma on the timescale of our ion diode power pulse (tens of nanoseconds).

We need to continue to develop and refine our capability to simulate electrode plasmas and their interaction with the diode environment. Laser and ohmic heating of the anode surface needs to be included in our models so that we can simulate the production of active ion sources. We plan to develop better emission models for QUICKSILVER based on the parameterized results of our hybrid fluid-PIC modeling.

3.4 Control and mitigation of electrode plasmas

Our situation is similar to that found in traditional high voltage gap electrical breakdown in that we are attempting to support the highest possible electric fields, which are required to give the highest intensity ion beams, and we wish to do this without making a transition into a "breakdown regime" before the pulse is over [8]. Under typical ion diode vacuum conditions (10^{-5} to 10^{-6} torr), the diode electrode surfaces and bulk are contaminated by hundreds of monolayers (1 m.l. $\approx 10^{15}$ cm^{-2}) of primarily hydrocarbon neutral layers. Electron thermal and stimulated desorption of surface and bulk electrode contaminants with subsequent rapid ionization lead to turn-on of hydrocarbon anode and cathode plasmas. It appears that the contaminant binding energies which have the largest effect on diode performance are also those which prevent rapid pumpouts to low base pressures at room temperature ($\approx$ 0.7 - 2.2 eV).

We have performed experiments with electrode conditioning or cleaning techniques including 13.56 MHz RF discharges, anode heating up to 450 °C, cryogenic cathode cooling (-195° C), and gold surface coatings that have been successful in mitigating some of the effects of electrode contamination on ion diode performance through the control of anode and cathode plasmas. Lithium beam intensities were increased by factors of 50 - 100%, with a large increase in diode impedance on the 1 TW SABRE accelerator [10]. Recently, we have seen significant improvement in diode operation with RF discharge cleaning of the LiF source on PBFA-X. The diode voltage was increased at fixed magnetic insulation strength with >2 hour of > 1:1 kW RF with Ar/10% O_2 discharge and Au substrate coatings. The FWHM of the voltage pulse increased to that of input accelerator pulse for a matched load (50 - 55 ns) from (20-30 ns). The diode impedance was increased a factor of 2 to 5 at peak ion power. The voltage at peak ion power was increased for one comparison from 7 to 12 MV. Other experiments showed that the parasitic load and impedance collapse scales inversely with anode area; that is smaller area anodes show faster impedance collapse, and more parasitic ion current, consistent with a model based on electron-driven thermal desorption.

4. ION SOURCE DEVELOPMENT - A BENIGN ANODE PLASMA

Controlling the ion mode instability to reduce ion beam divergence by increasing the magnetic field strength or by mechanical limiters can also reduce the electron flux to the anode which limits the anode temperature rise and minimizes the parasitic current problem. However, limiting the electron flux to the anode means that a passive ion source, such as the thin film LiF lithium ion source, can not be used. An active ion source, where an independent energy source is used to preform an anode plasma, is required to allow both control of the electron distribution and reduce the source divergence to an acceptable level; an active ion source is a benign anode plasma. Our HYF diode designs call for a SCL source of lithium ions that can supply 1-2 KA/cm^2. The ion source must be uniform to minimize divergence and allow maximum total current from a minimal anode area. Presently we are investigating the use of lasers or ohmic discharges to produce a lithium plasma. Since the energy input used to generate lithium plasmas is well above those required to desorb contaminants, it is essential that we remove and control surface and bulk contaminants. We will emphasize characterization of surfaces and surface and bulk contamination and the formation of anode plasmas in light lab experiments to facilitate the development of an active ion source. We will make extensive use of spectroscopic techniques and other advanced plasma diagnostics in diagnosing both light lab and accelerator ion source experiments.

5. CONCLUSIONS

Anode and cathode plasmas play a significant role in the performance of high power ion diodes. Anode-cathode (AK) gap closure resulting from expanding anode and cathode plasmas can lead to loss of magnetic insulation and a decrease in diode impedance. The formation of contaminant plasmas on anode surfaces is a parasitic ion source that competes with lithium ion beam production. We have performed experiments with electrode conditioning and cleaning techniques including RF discharges, anode heating, cryogenic cathode cooling and anode surface coatings that have been successful in mitigating some of the effects of electrode contamination on ion diode performance. We are developing sophisticated spectroscopic diagnostic techniques that allow us to measure the electric and magnetic fields in the A-K gap. We compare these measured fields with those predicted by our 3-D particle-in-cell (PIC) simulations of ion diodes. Spectroscopic diagnostics also monitor the formation of anode and cathode plasmas and their expansion velocities into the gap. We are developing E-M simulation codes with fluid-PIC hybrid models for dense plasmas in order to understand the role of these plasmas in ion diode performance. As we control the formation of parasitic anode plasmas via heating and cleaning techniques we will need to be able to produce a SCL ion source (a benign anode plasma).

6. ACKNOWLEDGEMENTS

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