XUV PREIONIZATION EFFECTS IN HIGH POWER MAGNETICALLY INSULATED DIODES*

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Abstract

Electrode surface desorption and photoionization by an intense XUV pulse has been shown to dramatically improve a vacuum diode impedance history. The 6-Terawatt Applied-B ion diode experiment on PBFA I is limited by a delay in both diode and ion current initiation. The insulation magnetic field impedes electron crossings which are believed to aid the ion source initiation. The diode is therefore initially a severe overmatch to the accelerator 40-nsec, 2.2-MV, 0.5-ohm pulse. The diode current increases during the pulse, leading to a rapidly falling impedance history. The application of an intense (30 to 50-kW/cm^2) XUV flux from an array of sixteen 60-kA spark sources is found to cause immediate diode current flow, resulting in both a greatly improved impedance history and the prompt initiation of an intense higher power ion beam.

Introduction

The Sandia National Laboratories Particle Beam Fusion Accelerator PBFA I has been used for the past several years to study the phenomena of high intensity focused light ion beams.[1] The accelerator is a 36-coupled-module device providing a 2.2 MV, 4.5 MA, 40-nsec pulse through 7 meter long self-magnetically-insulated vacuum transmission lines to a central vacuum diode load.[2-3] This paper discusses the recent improvements made in coupling the electromagnetic pulse energy from the accelerator into a magnetically insulated focusing ion diode (called the Applied-B). The techniques employed utilize surface discharge flashboards emitting hard ultraviolet photons from 10 to 70 eV, discussed by Woodworth et al. in these proceedings. An array of these sources bathe the vacuum diode surfaces with 30 to 50 kW/cm^2 of XUV before the accelerator pulse is applied, inducing photon stimulated desorption and photo-ionization in the high electric field regions. The electron flow between electrodes is immediate, enhancing the power flow into the diode region and accelerating the anode plasma formation. The process results in greatly increased power and energy coupling both from PBFA I to the diode and from the diode into the ion beam.

Apparatus

A magnetically insulated vacuum ion diode is the merging of space charge limited electron and ion flow accelerating across a high voltage pulsed vacuum gap with magnetic inhibition of the electron current. The Applied-B ion diode used in these experiments was developed by Johnson and tested on the Proto-I and -II accelerators.[4] It is shown schematically in Figs. 1 and 2. The 36 PBFA-I transmission lines couple to a common central disk forming two radial power feeds into the diode region. The anode is a 15 cm radius aluminum cylinder with a pattern of fine (0.5 mm wide) grooves cut into the inner surface and filled with a dielectric. The insulating magnetic field is generated by a matched pair of electromagnets buried behind the stainless steel cathodes and forms a vertical 15 kG flux structure in the 6.6 mm anode-to-cathode vacuum gaps. The electromagnet current pulse is adjusted so the magnetic field diffuses through the cathodes but is excluded from the higher conductivity anode. The 2.2 MV accelerator potential field emits electrons from the cathode tips and draws them toward the anode. The magnetic field impedes their crossing, deflecting the orbits into the azimuthal plane. This conserved drift direction leads to long electron residence times in the vacuum, and hence to high ion beam generation efficiencies.[5] The small electron fraction lost to the anode are used to initiate a surface flashover of the dielectric filled grooves, forming the anode plasma from which the ion beam is extracted. With the evolution of the ion beam space charge, the electrons are drawn vertically to form an equipotential cylinder between the two cathodes, forming a "virtual cathode": a ground electrode suitable for aiming the ions radially toward the axis without the dE/dx energy loss of passing through a material cathode.

A typical set of diode voltage and current waveshapes are shown in Fig. 3. This particular shot was performed with a 5 mTorr Argon glow discharge in the diode to study ion species control,[6] which was found to not affect the coupling waveshapes shown. The accelerator voltage pulse (see Fig. 3) rises in 5 to 10 nsec to peak then falls more slowly. The magnetic insulation field strength must be sufficient to stop the peak kinetic energy electrons and is over-insulating to the critical early time leakage electron flow. As seen in the figure the diode current lags the voltage, and the ion current is further delayed. The diode impedance is therefore initially large, then falls rapidly as the anode plasma initiates and expands toward the cathode. This is a poor match to a typically 0.5 ohm accelerator driver, and the experiment reported here is directed toward reducing the initial high impedance phase of the magnetically insulated ion diode while maintaining the high efficiency ion beam. The turn-on delay reduction is synergistic. That is: the vacuum power feeds act as diffuse loads in parallel with the diode diverting the accelerator pulse while the diode impedance is high. The loss in the feeds is reduced only by magnetic insulation, i.e. by current coupled through them into the diode. Thus even with a falling impedance history an earlier diode current turn-on results in more of the accelerator pulse available to the ion beam.

The ion current history shown is measured with a B-dot array located behind the emitting cathode tips (see Fig. 2). The measurement is representative of the net (ion minus electron) current crossing this radius, and is therefore used to identify ion beam initiation time rather than precise beam generation efficiencies. The total ion currents are measured with nuclear activation and temporally resolved scattering diagnostics described elsewhere.[6]

The techniques employed to reduce the diode equilibrium evolution time were the result of the dramatic improvement in XUV power output from surface sparks reported by Woodworth.[7] The basic circuit (shown in Fig. 4) is a 23-kV 1.8-μF capacitor bank discharged through a 130-nH stripline to a series pair of sparks consisting of copper electrodes spaced 3-mm on a glass-fiber/polyimide substrate (Fig. 5). The substrate flashes around 15 kV, conducting about 60 kA with a ring period of 3 μsec. The spark source

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14. ABSTRACT

Electrode surface desorption and photoionization by an intense XUV pulse has been shown to dramatically Improve a vacuum diode impedance history. The 6- Terawatt Applied-B ion diode experiment on PBFA I is limited by a delay in both diode and ion current initiation. The insulation magnetic field impedes electron crossings which are believed to aid the ion source initiation. The diode is therefore initially a severe overmatch to the accelerator 40-nsec, 2.2-MV, 0.5-ohm pulse. The diode current increases during the pulse, leading to a rapidly falling impedance history. 2 The application of an intense (30 to 50-kW/cm) XUV flux from an array of sixteen 60-kA spark sources is found to cause immediate diode current flow, resulting in both a greatly improved impedance history and the prompt initiation of an intense higher power ion beam.

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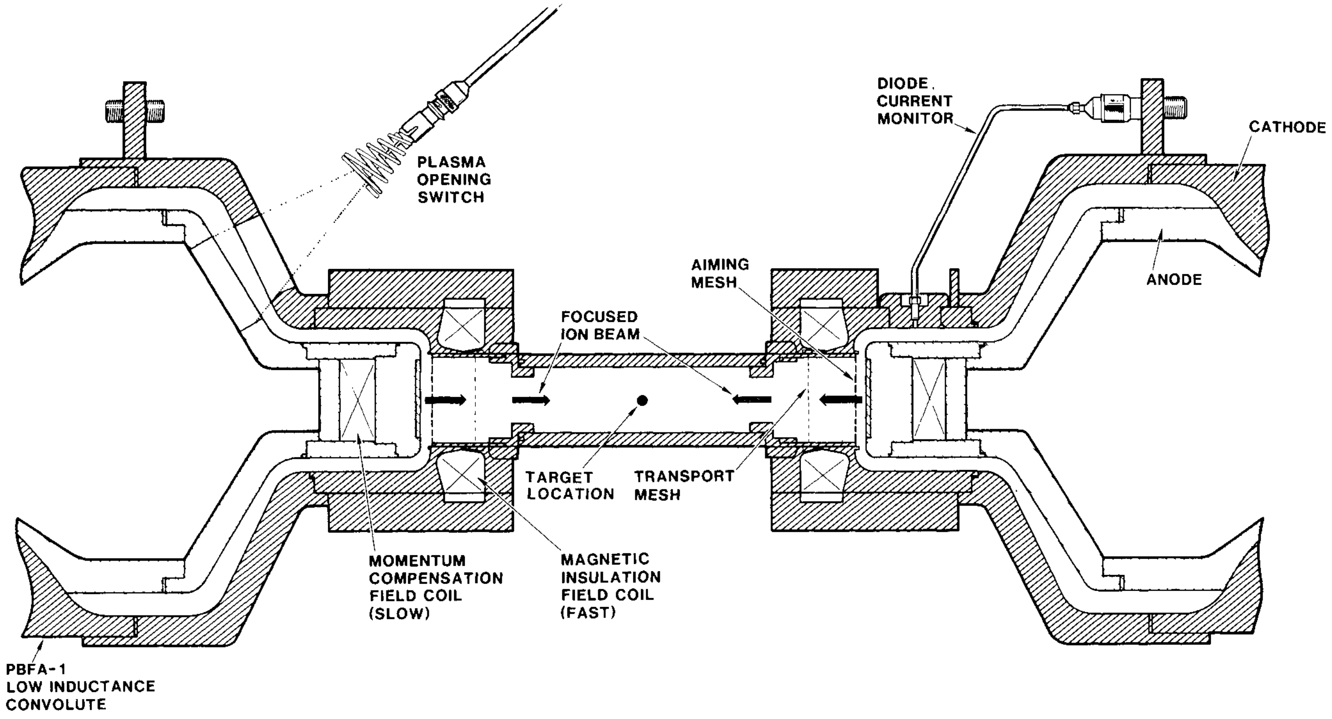

Figure 1. The PBFA-I Applied-B ion diode assembly.

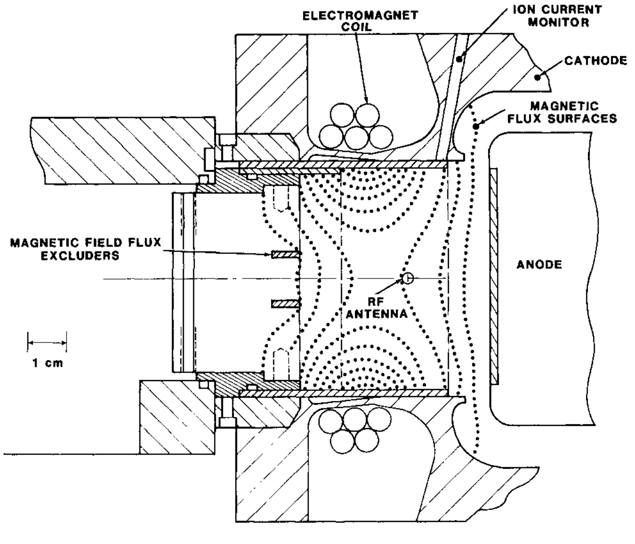

Figure 2. A detail of the ion diode region.

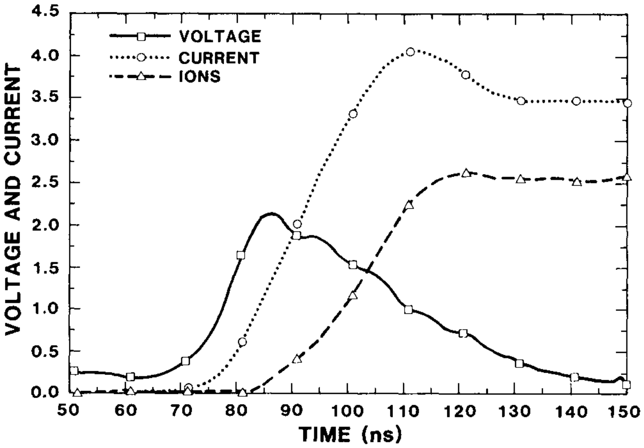

Figure 3. Voltage and current histories for the Applied-B ion diode in a standard configuration.

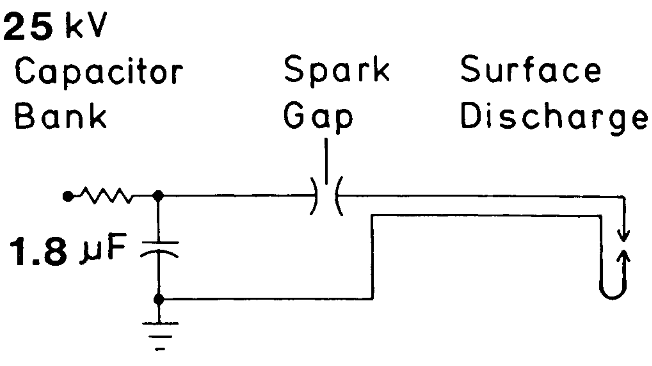

Figure 4. Schematic of the driving circuit for the PBFA-I XUV illumination discharge system.

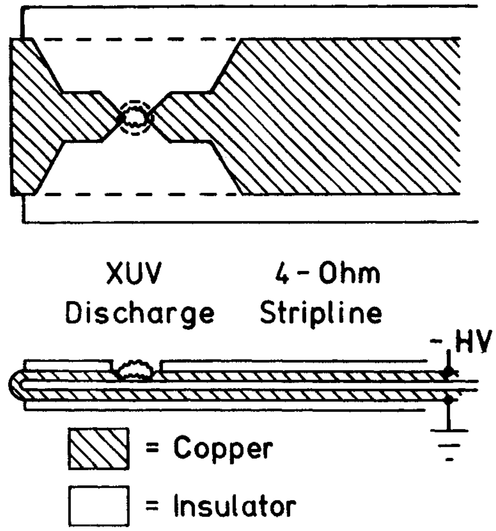

Figure 5. Schematic of the XUV spark source.

produces about 30 MW of XUV photons with a typical spectral history shown in Fig. 6: The spectrum is radiating principally in the lines and is cooling with time. The plasma generated from the spark is JxB accelerated from the sparks toward the diode, limiting the time of interest in these experiments to 350 nsec after the breakdown. At this time the spectrum is principally divided between the 10-20 eV and 20-70 eV channels.

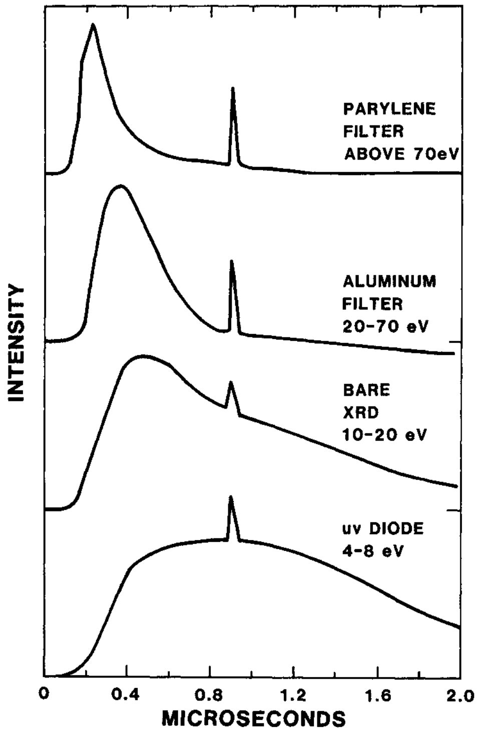

Figure 6. XUV spark source spectral history. A fiducial timing mark has been added to each trace.

The experimental configuration is shown in Fig. 7. An array of 16 equispaced sparks were assembled at an 11 cm radius aiming at the anode midplane from above and below. Each pair of sparks were driven by separate capacitor banks timed together, resulting in 500 kA of total spark current in the assembly. The angular distribution of the XUV output is nearly isotropic, resulting in a uniform illumination of the anode cylinder estimated at 30 to 50 kW/cm^2. Since the physical details of the interaction between this extreme ultraviolet illumination and the anode surface are not known, the experiment was designed using rough estimates of the photo stimulated desorption and photo-ionization cross sections. The results presented therefore are empirical, with our best understanding of the dominant mechanisms offered.

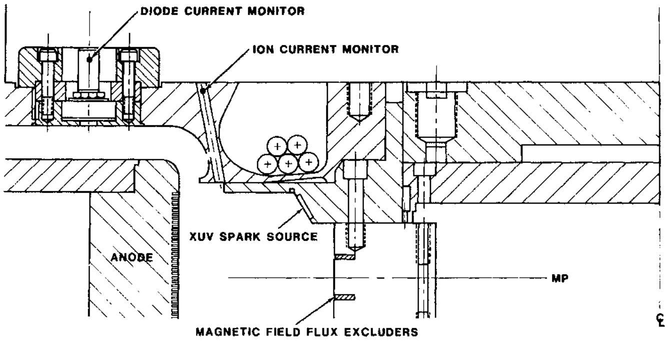

Figure 7. Schematic of the XUV illumination assembly in PBFA I (top half only is shown).

Experimental Results

Figure 8 shows a voltage and current history of the Applied-B diode with the XUV illumination. The delay in diode current initiation is dramatically reduced from normal (compare with Fig. 3), rising promptly with the voltage pulse. The diode acts as a nominal 1 ohm load through the time of peak power, serving to magnetically insulate the vacuum feeds and actually increase the voltage coupled to the diode. Figure 9 compares the power and impedance histories of the two experimental configurations shown. Although the initial impedance of the diode is reduced (yielding improved energy coupling), the impedance collapse is not significantly changed: the XUV seems to only affect the initiation of the diode and not its evolution. The ion current delay is similarly reduced, showing again a high conversion efficiency from electromagnetic energy into a focusing ion beam.

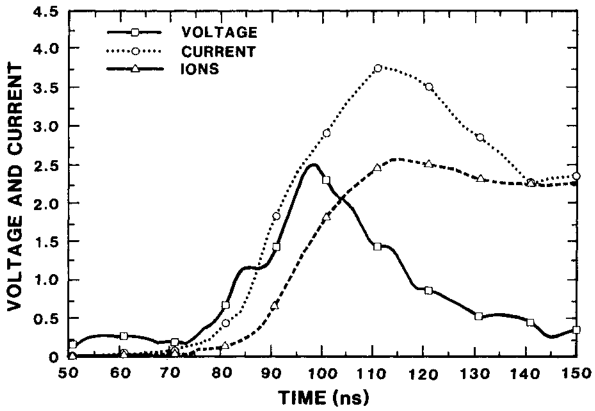

Figure 8. Voltage and current histories for the Applied-B ion diode with XUV illumination.

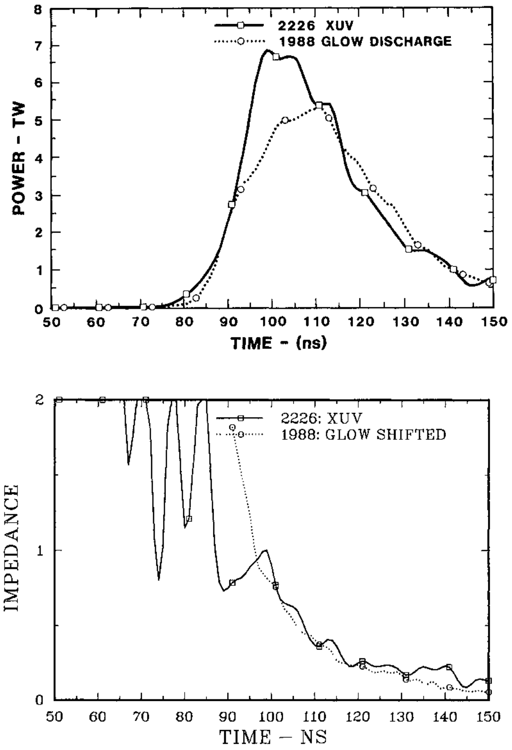

Figure 9. Comparison of diode power and impedance for the PBFA-I Applied-B ion diode with and without XUV illumination.

These voltages and powers are the largest recorded for the Applied-B diode on PBFA I, and represent a substantial improvement in energy coupling from the accelerator (170 kJ above 1 MV out of 225 kJ total as compared to 140 out of 180 kJ normally). More recent XUV experiments have coupled record energies (215 kJ at voltages above 1 MV) at peak powers over 8.5 TW.

We speculate that the improved diode performance is due to several related XUV induced phenomena. The photon fluence will (marginally) desorb, melt, and photoionize the anode dielectric material creating a globally uniform neutral gas and plasma layer. The uniformity is an important factor needed to produce a highly focusable ion beam. This initial anode plasma should be capable of emitting a low current ion beam immediately as the power pulse is applied, which is confirmed by Thomson parabola measurements of peak voltage ions. The space charge from such a beam should reduce the virtual cathode formation time, allowing for an improved beam extraction from the diode toward the axial focus as well. There are insufficient XUV photons to account for the entire ion beam charge however, so a secondary mechanism must exist.

The XUV fluence will also produce a similar surface condition where the radial power feeds bend into the diode region. Shot data where the latter illumination is removed do not show the prompt diode current initiation or the rapid ion beam development. We believe therefore that the disk illumination allows low voltage (early time) electrons to accelerate along the axial magnetic insulation field lines (see Fig. 2) to collide with and further ionize the anode surface layer. This conjecture explains both the prompt diode current (as composed of electron flow from the disks which will continue until either the source plasma is exhausted or the flow is magnetically insulated by the ion beam's self magnetic field), and the prompt ion current (when the XUV fluence is insufficient to account for the ion beam charge).

Another XUV shot configuration was tested to verify the calculations of in situ light intensities and corroborate our estimates of the photoionization effects in the Applied-B diode. For this shot the diode was filled with an 5-mTorr Argon/Oxygen gas differentially pumped through the double disks. In the absence of the XUV, this gas had minimal affect on the diode performance and was the configuration used on the shot shown in Fig. 3. The XUV illumination preionized the gas sufficiently to short out the accelerator pulse (0.5 MV and 8 MA), drawing current either from the disk or across the applied 14 kG magnetic fields before the voltage had risen to field emission levels. This is consistent with calculations of photoionization for the light intensities measured in a test cell, and suggests that the XUV intensity and surface modification abilities are as we believe.

Summary

We have improved the electrical coupling from the high power PBFA-I accelerator to a magnetically insulated ion diode by preionizing the diode area with an intense (30 – 50 kW/cm^2) XUV illumination system. Pre-forming both the anode and vacuum feed surface plasmas appears necessary to substantially affect the electrical parameters of the diode. The XUV improvements reduce the early time impedance but do not degrade the impedance later in the 40 nsec pulse, allowing record levels of power and energy to be coupled. The ion beam generated is prompt, moving the ion power pulse forward in time and accessing the higher diode potentials needed to achieve a high intensity focused ion beam on target. We are presently redesigning the XUV spark apparatus to allow operation on PBFA I on a routine basis for further ion beam development research.

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