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Abstract

We have developed and tested a compact collimated sixteen channel fiber optic array diagnostic for studying the light emission of railgun armature plasmas with ~mm spatial and sub-μs temporal resolution. The design and operational details of the diagnostic are described. Plasma velocities, oscillation, and dimension data from the diagnostic for the Livermore Fixed Hybrid Armature experiment are presented and compared with 1-D simulations. The techniques and principles discussed allow the extension of the diagnostic to other railgun and related dense plasma experiments.

I. Introduction

Plasma formation and behavior in ultra-high velocity (UHV) railguns [1-2] are of concern because they ultimately limit the obtainable velocity of the projectile. Traditional UHV railguns operate using 'Plasma armatures', because of the impracticality of plasma arc prevention at the high speeds involved (> 5 km/s) and the weight-minimization advantage that pure plasma armatures provide. Alternatively, 'Plasma brushes' may be used between a solid armature and the rail, forming a hybrid armature. In either case, the plasma can exhibit complex phenomena. Without confinement, the plasma may propagate behind the armature and become a conducting path for the rail current. This effectively redirects current away from the armature and stops or reduces the projectile acceleration. Plasma formation has also been observed in railguns in the high velocity (HV) regime (e.g., >1 km/s), and is essential to understanding the phenomena found in these guns known as 'transition'[3]. Hence, understanding plasma formation, behavior, and confinement is important for mitigating or utilizing plasmas in advanced railguns.

To study hybrid armatures and their plasma brushes with modern diagnostics, we reconstituted the Fixed Hybrid Armature (FHA) railgun experiment with static armature at LLNL [4] which allows for the creation and study of railgun plasmas in a controlled environment. The experiment is illustrated in Figure 1. In the FHA railgun, two thin aluminum foils are placed at X=0 in the gap between the solid armature and the copper rails. These foils are turned into a non-classical plasma when ~150-300 kA of current is created in the system by closing the switch in a high voltage capacitor bank. The aluminum plasma in the gap typically has densities on the order of ~10^{26}/m^3, Z~1, temperatures of ~eV, and pressures of 100's bars. Typically, depending on experimental parameters, the plasma spans X=0 to ~1-3 cm during the ~100 μs shot. The dynamics of interest are numerous, and include interactions between J × B and pressure forces, transient instabilities, and oscillations that can occur in the plasma. Ultimately, accurate simulation and understanding of these plasma dynamics are necessary for confining and utilizing plasma armatures in UHV railguns. Figure 2 provides sample simulation results based on MHD models of these railgun plasmas using ALE3D [5].

Accurate diagnostic information is very important in these static railgun experiments for benchmarking predictive simulations. In addition to an array of traditional diagnostics such as B-dots, current sensors and voltage probes, we have developed and tested a compact sixteen channel fiber-optic array (FOA) diagnostic with the goal of diagnosing the plasma via its ample UV-visible-IR emission. The FOA diagnostic differs from previous optical fiber based plasma armature diagnostics [6-7] by employing multiple tightly collimated and compact optical fiber channels to increase spatial resolution substantially. The FOA diagnostic, illustrated with the experiment in Figure 1, allows us to measure light emission from the plasma directly with sub-μs temporal and ~mm spatial resolution. The sightlines penetrate the plasma through a window in the copper rails (top view) or insulator (side view). The broadband signal from the FOA can be routed to fast Si diode detectors or spectrometers.

A large number of plasma parameters could be deduced from these light measurements. The raw light intensity can give the plasma extent or length as a function of time with potentially better spatial resolution than available via B-dots. These raw intensities, without requiring detailed diagnostic modeling, also allow important measurements such as plasma velocities and oscillation frequencies as a function of time. Further analysis of the broadband data using a synthetic diagnostic approach could permit estimates of the plasma density and temperature. Spectroscopic examination of the line emission from the plasma could provide more accurate estimates of key plasma parameters through for example Stark broadening and Doppler shifts, with additional information such as elemental composition.

Currently, the FOA diagnostic is in operation. Here, we review the design, construction, and operational details of the diagnostic, examine bulk plasma velocities and oscillation data taken with the instrument, and discuss initial benchmarking comparisons with ALE3D simulations.

II. Diagnostic design and considerations

The FOA diagnostic design is based on estimates of the plasma signal using typical plasma parameters coupled with a free-free bremsstrahlung emission model [8]:

$$j(\nu) = 5.03\times10^{-54} n_i n_e Z^2 \left(\frac{T}{eV}\right)^{-0.5} e^{-\frac{h\nu}{T}} g_{ff} \frac{W}{m^3 srHz} \quad (1)$$

where n_i and n_e is the plasma density in $1/m^3$, Z the effective ion charge state, T the plasma temperature in eV, h planck's constant, ν the photon frequency, and g_{ff} the Gaunt factor. The Gaunt factor is typically ~1 for the emission of concern here [8].

The signal voltage from a diode detector system operating in current mode observing optically thin plasma through the fiber optics is:

$$D(V) = \int\int j(v)R(v)L(v)GA\Omega ds dv \qquad (2)$$

Where $A\Omega$ is the étendue of the detector, s is the path length or the sightline, R is the responsivity of the detector in A/W, G the electronic gain in V/A, and L encompasses any signal attenuation in the system such as due to fiber characteristics.

The signal is expected to be higher than the estimate from Equation 2 since line radiation should increase the total output, however, without a detailed atomic model of the plasma species, this is difficult to account for. Also, the diagnostic response to sightlines in the Y direction is more complicated because the plasma is not optically thin for sightlines that span more than a few mm across the plasma. Nevertheless, Equations 1 and 2 proved to be adequate for design estimates and were used to determine the fiber, collimator, and detector parameters for achieving a diagnostic that provides sub-microsecond temporal and ~millimeter spatial resolution with detector voltages at the ~volt level.

The current FOA diagnostic design is schematically shown in detail in Figure 3, and consists primarily of 16 channels made up of Edmund Optics 100 μm NA=0.12 NFT-59 series UV-VIS-IR sensitive fibers individually aligned with collimator holes 0.020" in diameter and 0.4" long. The fibers were first laid into the black, matt, glass-filled polycarbonate body or plug shown in Figure 3 and potted with optical fiber epoxy to secure them in place. The ends of the fibers were then polished and optically examined for smoothness. The collimator structure was made in two pieces to facilitate drilling of the small diameter 0.4" deep holes. It should be noted that the characteristic numerical aperture of a fiber does not collimate a fiber completely and that these collimators are required. The collimators are mated via epoxy. The fibers of the plug break-out to standard ST connectors. During the experiment, the diagnostic is anchored and placed flush against a 3 mm thick polycarbonate window sealed with vacuum grease to prevent gas and plasma flow into the diagnostic. The 16 ST connectors are currently connected to standard low-cost ~100 ft long multi-mode telecomm fibers which are then routed to the detectors in a screen room. For detailed spectroscopic analysis, these links can be replaced with more of the Edmund Optics fiber with characterized transmission properties. The telecomm fibers are connected to Thorlabs PDA36A Si detectors typically operated at 20-30 dB gains with better than μs resolution. The detectors are connected to standard oscilloscopes and terminated into 50 Ω. The FOA diagnostic is designed so that the FHA plasma could be observed from either the top or side of the plasma, with resolutions of ~1 and ~2 mm respectively.

III. First Operational Results and Discussion

Presently, the FOA diagnostic has been operated with FHA shots using only the side view (i.e. sightlines parallel to the Y axis in Figure 1). Before each experiment, the device is calibrated using a broadband tungsten lamp in order to deduce the relative calibration factor for each channel. The diagnostic is also calibrated and examined post-shot in order to determine loss of transmission efficiency due to any coating or damage of the fibers.

Figure 4 shows some raw intensity data at X=2.5, 5.5, 8.5, and 9.5 mm versus time along with the measured rail voltage. For this shot, the capacitors were charged to 4.9 kV at an energy of 36 kJ and discharged a peak current of 330 kA. At t=8 μs, the foil bursts and the plasma is formed. The signal from the fiber array tracks the rail voltage. The flattops seen in the data for X=2.5 and 5.5 mm are artificial as the detectors can only output up to 5.5 V; the detector gain for those traces were too large. Examination of the leading edges of the emission data indicate a plasma front speed of ~1.8 to 2 km/s at t~10 μs, and oscillation of the plasma signal at 330-360 kHz after t~50 μs. These relatively small amplitude oscillations are not seen in the B-dot or voltage data. The emission data also indicates a plasma length of ~14.5 mm near the end of the shot. This is in agreement with brush lengths estimated from post-shot analysis of aluminum deposits on the copper rails shown in Figure 5. For comparison with modeling, 1-D ALE3D simulations of the same shot result in front velocities of ~5 km/s, while preliminary 2-D simulations gave lower velocities closer to the measured values. Concerning the oscillations at later times, 1-D simulations estimate frequencies on the order of ~100 kHz, which is lower than the measured values. We are working on fully utilizing the FOA diagnostic and its data for benchmarking purposes and to further our understanding of these plasmas. Detailed comparisons with 2-D simulations are to be documented in a later work.

Operationally, the intense environment during a FHA shot is a challenge for the diagnostic. Initial tests of the FOA diagnostic resulted in physical ejection of the plug due to escaping plasma, snapping of collimators, severe coating of the diagnostic window, and general damage to the plug. These issues were partially resolved by eventually using the large and thick 3 mm polycarbonate window sealed with vacuum grease. It was experimentally found that the polycarbonate window was notably less likely to be plasma coated than a quartz window, possibility due to vapor shielding as discussed in ref [6]; additionally, quartz windows were found to fracture easier. Related to this issue, the signal dips at later times in Figure 4, specifically Ch 1, could be due to coating of the polycarbonate window from the plasma and coating of the fibers themselves due to plasma leakage. Post-shot calibrations and examination confirm coating of the Ch 1 fiber which reduces its transmission notably. The post-shot polycarbonate window is shown in Figure 5, along with debris/coating found on a fiber inside its collimator. We found, as expected, that typically more damage or coating is seen with the channels nearest to the initial foil position.

From an analysis point of view, the coating or obstruction of the fibers during the shot can make it difficult to extract quantitative information that depends on the relative strength of the signals. This would suggest that if coating and debris continues to be a problem, spectroscopic analysis of the data should be pursued since analyses using lines to deduce density and electron temperature are less affected. Oscillation frequency and velocity data are somewhat immune to this issue, and can be extracted easily without much modeling as shown above. Work is ongoing to further ruggedize the diagnostic by incorporating high pressure seals which should alleviate this issue.

V. Conclusion

We have developed a compact collimated fiber array diagnostic for diagnosis of railgun armature plasmas and demonstrated its utility in providing first benchmarking plasma velocities, oscillation, and extent data from the LLNL FHA experiment. The diagnostic in principle can provide extensive plasma parameter information, such as density, temperature, and composition. The techniques and principles discussed allow the extension of such a diagnostic to other railgun and related dense plasma experiments.

Acknowledgment

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Captions

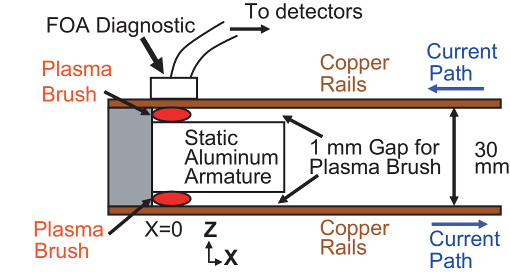
Figure 1: Rendering of the LLNL FHA experiment. The aluminum plasma brushes are created from thin foils and typically extend to ~1.5 cm during a shot. The width in the Y direction is 3 cm. The FOA diagnostic is shown mounted on top giving sightlines through the plasma in the Z direction; the diagnostic can also be mounted on the side to provide sightlines in the Y direction.

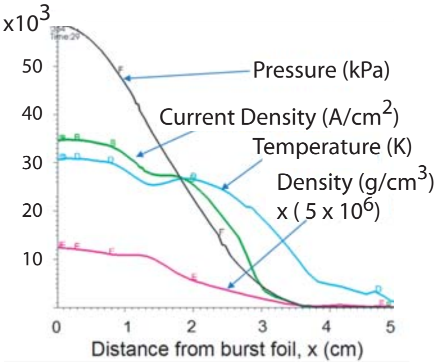
Figure 2: ALE3D simulation of 290 kA FHA experiment with 4.5 cm long static armature 18 µs after the foil burst.

Figure 3: The FOA diagnostic plug houses sixteen 100 µm diameter fibers with individual collimation. The front of the plug sits flush against a 3 mm thick window during the FHA experiments.

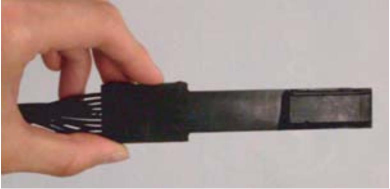
Figure 4: FOA diagnostic signals and brush voltages for a 330 kA FHA shot.

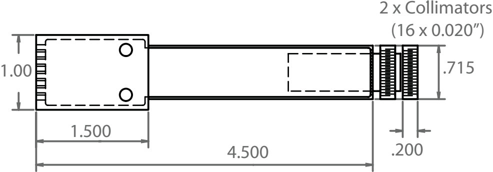
Figure 5: FHA bottom rail and side insulator post-shot. The bottom rail was moved a ~cm in the x-direction for the photograph. The FOA polycarbonate window was minimally coated and shown in the upper right insert. The bottom right insert shows one of the lighted fibers post-shot; the darkened spots are resultant from plasma coating.

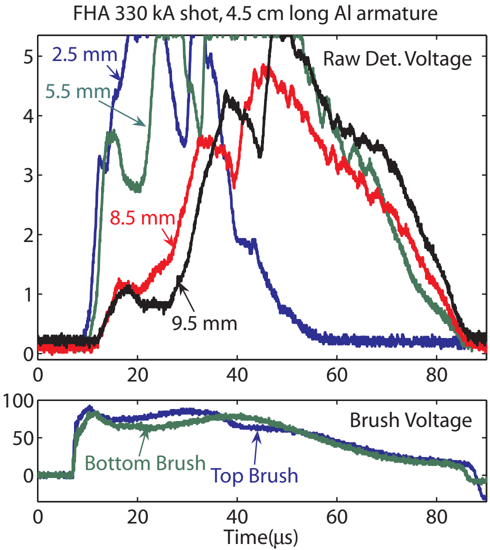

To detectors
FOA Diagnostic
Plasma
Brush
Copper
Rails
Current
Path
Static
Aluminum
Armature
1 mm Gap for
Plasma Brush
30
mm
Plasma
Brush
X=0
Z
X
Copper
Rails
Current
Path

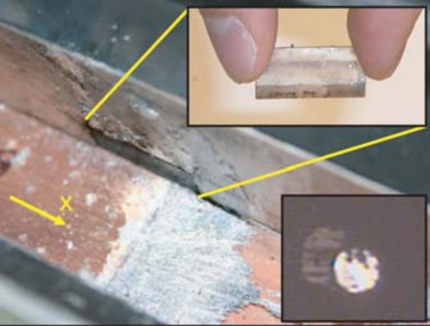


x10^3
50
40
30
20
10
0
1
2
3
4
5
Pressure (kPa)
Current Density (A/cm^2)
Temperature (K)
Density (g/cm^3)
x (5 x 10^6)
Distance from burst foil, x (cm)




2 x Collimators
(16 x 0.020")
1.00
.715
1.500
4.500
.200


FHA 330 kA shot, 4.5 cm long Al armature
Raw Det. Voltage
2.5 mm
5.5 mm
8.5 mm
9.5 mm
0
1
2
3
4
5
0
20
40
60
80
Brush Voltage
Bottom Brush
Top Brush
100
50
0
0
20
40
60
80
Time(μs)


X