CHARACTERIZING THE PHOTON SPECTRUM IN THE DARHT AXIS-I DIODE

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Abstract

An array of photon diagnostics have been deployed on a high power relativistic electron beam diode. Surface flashover of a carbon fiber velvet cathode generates a discharge from which electrons are accelerated through a 17.8 cm diode. This discharge is assumed to be a hydrocarbon mixture. A small portion of the off energy electrons (1-3 MeV) accelerated during the rise and fall of the 80 ns FWHM pulse impact the beam pipe and generate a Bremsstrahlung spectrum of 0.1-3 MeV photons. The principal objective of these experiments is to quantify the dynamics of the hard X-ray and γ-ray flux generated in the diode region, in addition to quantifying dynamics of the visible photons generated, and the ion species of the surface discharge on the velvet cathode. A qualitative comparison of different diagnostic results are presented, which include time resolved measurements with X-ray PIN diodes, a PMT, and CCD images. In addition initial visible spectroscopy measurements will also be presented.

I. INTRODUCTION

There are a vast number of electron beam and Bremsstrahlung sources in the scientific community. Some of these facilities are dedicated to studying cathode materials and the relevant physics associated, while others focus on improving the radiographic quality of their facility. Each of these facilities produces a different X-ray spectrum and axial and transverse distributions [1-8]. The spectrum and distributions are characteristic of the achievable electron beam or X-ray spot size on target and the energy distribution. Many of these facilities generate a rich spectrum of photons ranging from visible light (λ < 700 nm) to high energy γ-rays (E < 6 GeV).

Bremsstrahlung γ-rays are measured through photon tagging techniques in the High Energy Physics community, where γ-rays up to 6 GeV have been measured on the JLab CEBAF Hall B experiment [3]. Other hard X-ray and γ-ray measurements have been made in the accelerator community through several methods, indirectly with Compton spectrometers capable of measuring γ-rays from 1-20 MeV [9]. The gas Cherenkov detector measures 16.7 MeV γ-rays from fusion reactions [10], however this diagnostic limited to E > 4.5 MeV. Pulsed power diode machines and the Z-machine at SNL have measured Hard X-rays and γ-rays directly with CaF₂ TLDs, X-ray PIN diodes, and X-ray pinhole cameras [11,12]. Finally a transmission crystal spectrometer has been used to measure hard X-rays in laser plasmas with energies up to 80 keV [13,14].

Cathode imaging has been performed to characterize the cathode physics on a number of diodes that can be separated into two categories: the first being diodes with γ < 1.6 and β < 0.78 and A-K gaps ranging from 0.8-5 cm [15-19] and the second are relativistic diodes with γ > 4.9 and β > 0.98 with A-K gaps > 8 cm [20,21]. Refs. [15-19] characterize the emission properties, uniformity and outgassing of cathodes in short A-K gaps where the electrons are terminated into a solid anode and an anode plasma is present. The relativistic diodes are used to produce intense electron beams that are accelerated through a hollow anode and transported into a linear induction accelerator.

In addition to cathode imaging, visible spectroscopy measurements have been made with several different cathode materials and diode geometries with γ < 1.6 and β < 0.78 and A-K gaps ranging from 1.3-5 cm [17,22,23]. Refs. [6,24] performed spectral survey measurements on RITS-6 which indicate a rich spectrum of Aluminum and Carbon lines, although recent results, further away from the cathode surface, indicate distinguishable spectral lines. Refs. [17,22,23] have each performed temporally and spatially resolved spectral measurements of Hₙ, H₀, and CII lines to resolve Tₚ, Tₑ, and nₑ for ferroelectric, velvet, and carbon-epoxy cathodes. CsI doped carbon velvet has also been examined at low resolution indicating 3 x 10⁴ pulses were required to measure Hₖ [16].

The first axis of the Dual-Axis Radiography for Hydrodynamic Testing (DARHT) facility [25,26] is characterizing the photon spectrum generated in the diode in motivation to gain a better understanding of the electron beam generation through the use of a cold cathode, including the beam and plasma dynamics, and beam emittance. In addition there is a motivation to use of this cathode technology for longer (~µs) pulsed and multi-pulsed operations and continue to develop improved high brightness (B = J/µ) cold cathodes. As indicated by

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refs. [17,22,23], line intensities from the visible photon spectrum can be used for both ion Doppler broadening measurements (measure $T_i$) and gas impurity line measurements (infer $T_e$) [27]. Each of these measurements will provide further clarification of the gas desorption, ionization process, and gap closure velocity of the plasma generated on the surface of the cathode. In addition, the electron temperature of the plasma can be used to calculate the emittance of the extracted electron beam. The hard X-ray and $\gamma$-ray measurements on DARHT Axis-I are different than in pulsed power diodes [1,6,7] because they are not generated from electron impact on a single target surface. They are generated over a large surface area by the scraping of lower energy electrons during the rise and fall of the extraction pulse. The spatial distribution of the X-rays confirms the electron beam transport through the diode and downstream. In addition, the symmetry of the spatial X-ray distribution indicates the alignment quality of the beam as it is injected downstream.

II. EXPERIMENTAL SETUP

The experimental configuration used to characterize the photon spectrum is the DARHT Axis-I diode shown in Fig. 1. A graded transmission line (or Blumlein) provides the nominal 3.8-4 MV, 80 ns (FWHM) pulse to drive a 5 cm black velvet cathode. The voltage in the 17.8 cm diode is monitored by a flush mounted coaxial E-dot aligned axially with the edge of the cathode shroud. The current is monitored with beam position monitors described in Ref. [25,26].

An array of optical diagnostics was used to characterize the photon spectrum generated in the diode. These consisted of an image intensified fast gated charge-coupled device (CCD), a photomultiplier tube (PMT), an array of PIN diodes, and a visible spectrometer. Upon deployment of the CCD camera additional photon speckle was picked up consistently at specific times during the extraction pulse. So, a PMT was used to characterize the time dependence of the photon spectrum on a shot-to-shot basis. In addition an array of PIN diodes were also deployed to characterize the X-rays and $\gamma$-rays. Finally, once it was determined there was enough light emitted by the flashover on the cathode surface a visible spectrometer was setup to characterize the plasma ion species. Each of these diagnostics is described in detail below.

Figure 1. View of the DARHT Axis-I diode with photon diagnostics used to diagnose the cathode plasma and X-rays generated in the diode region. The imaging station for the cathode face is shaded in red and the imaging station for the A-K gap is shaded in orange. The PIN diode arrangement is shown in green and the PMT replaces the cathode face imaging camera in red. The spectrometer is shown in purple.
III. CATHODE IMAGING

We have fielded optical diagnostics for imaging the light on the cathode surface and across the A-K gap as stated above in Section II. and shown in Fig. 1.

A. Cathode Face

Fig. 2 below shows two images of the cathode face, recall that these are images reflected off a mirror with the camera axis at a 30° angle relative to the beam propagation axis, explaining the elliptical profile on the CCD. This is done to help minimize any direct X-ray flux onto the micro-channel plate and CCD, additional high-Z shielding material can be used, but it is often difficult to shield all of the background X-rays. Instead we have chosen to characterize the additional photons. The image on the left (Fig. 2(a)) is a 500 μs open shutter of the 5-cm cathode face and surrounding anodized aluminum shroud; this was taken without pulsing the diode. The image on the right (Fig. 2(b)) is a 10 ns gate of the emission on the cathode face in the middle of the extraction pulse (t = 225 ns).

Figure 2. (a) Open shutter calibration image of a 5-cm diameter cathode installed in the Axis-I diode; and (b) 10 ns gate of the surface flashover on the cathode face in the middle of the extraction pulse (t = 225 ns) (false color). Note the scale in the images applies to the horizontal axis which is half the vertical scale due to the 30° elliptical image.

A montage of multiple gated images through the rise and fall of the diode extraction pulse is shown in Fig. 3. The third image at 205 ns indicates the X-ray speckle evident on the CCD due to the off energy (E < 3 MV) electrons scraping the beam pipe as will be shown with PIN and PMT data in the sections below. The triggering of the camera gate is synchronized with the onset of the diode voltage and is monitored in parallel with the E-dot and BPM diagnostics to verify the gate time is accurate.

The light we see during the main extraction pulse is fairly uniform across the center surface of the cathode with random intense spots; however there is a 4-10x increase in intensity on the edge. This light is most likely excitation of the desorbed and ionized monolayers of gas on the surface of the cathode. In Section V. below we will confirm there is a hydrogen plasma present.

B. AK Gap

In addition to imaging the cathode face, we also performed measurements on the A-K gap to determine if there was any axial migration of the plasma off the surface of the cathode. Fig. 4(a) shows an open shutter image of the edge of the cathode shroud, cathode face, and A-K gap without running the diode. The cathode face seems enhanced due to the backlighting source reflecting off the velvet fibers. Fig. 4(b) shows a zoomed-in montage of 20 ns images where we resolve the 2.5 mm recessed cathode over a 6 x 1 cm rectangular portion of the CCD. 20 ns gates were used to step through the pulse because the light intensity was slightly lower than our cathode face images. These camera gates correspond to t = 180-320 ns with respect to Fig. 3. After imaging the A-K gap (Fig. 4(b)) it was apparent the bulk of the densely illuminated plasma was only on the surface of the cathode and inside the 2.5 mm recess.

Figure 4. (a) Open shutter calibration image of the A-K gap, anodized aluminum shroud and 5-cm cathode; (b) 20 ns time resolved images through the diode pulse of the flashover away from the surface of the velvet cathode. The camera gates correspond to t = 180-320 ns. Note scale differences.

IV. TIME RESOLVED PHOTON MEASUREMENTS

Time resolved photon measurements were made with a pair of diagnostics, a PMT and an array of PIN diodes. The PMT was used characterize the temporal profile of the visible photons generated on the surface of the cathode and the hard X-rays and γ-rays in the diode vicinity. The PIN diodes, which were shielded from
visible light, were used to characterize the temporal and spatial profile of the hard X-rays and γ-rays generated due to beam scraping.

A. PMT Measurements
The PMT has an MCP, which are known for their sensitivity to X-rays [28-30]. So, the PMT was capable of providing a measurement of the hard X-rays and γ-rays generated in the diode, in addition to the visible photons on the cathode face. In order to discriminate between the two, gaffers tape was used on the aperture of the PMT to completely exclude the visible photons as shown below in Fig. 5(a). A 5 shot average of the raw PMT signal is shown in black in Fig. 5(a), which is a measure of all of the photons generated in the diode. After shielding the visible photons we measured the segregated hard X-rays and γ-rays in red. Note that there are two pulses of hard X-rays and γ-rays. Processing the difference between total photons in black and the high energy X-rays and γ-rays in red we can determine the temporal profile of the visible light generated by the cathode shown in blue in Fig. 5(a).

![Figure 5. Temporal profile of the (a) total photons (black) measured in the diode by the PMT, segregated hard X-rays and γ-rays (red), and the visible photons (blue) and (b) normalized hard X-ray and γ-ray profile (blue) overlaid with the diode extraction voltage (black) and diode current (red) for the 5 cm cathode.](image)

Fig. 5(b) indicates the synchronized generation of X-rays in the diode with the rise and fall of the diode extraction voltage. The electrons with E < 3 MV extracted though the diode have an envelope that is overfocused by the first transport magnet (anode magnet) and begin to scrape the beam pipe between z = 90-180 cm; generating Bremsstrahlung X-rays.

The time response of the PMT as function of diode voltage was also measured in Fig. 6. The bias voltage was held fixed on the photocathode. The X-ray intensity as a function of voltage at the head and tail of the pulse as well as the visible photons were examined. We measure ~10x increase in all three photon counts over the voltage range of interest.

B. PIN Diode Measurements
After determining there was a consistent flux of X-rays generated in the diode region from shot-to-shot with the PMT and CCD cameras it was of interest to gain a more quantitative understanding of the X-ray distribution as a function of energy and space. PIN diodes were deployed in 4 different axial locations horizontally parallel with the beam line, radially displaced from the beam axis by 1 m. After initial deployment of the PINs, the photon flux as a function of bias voltage was measured in Fig. 7. The location of this PIN was downstream of the cathode shroud by 22.9 cm (refer to Fig. 1 above). It is evident from the measurements in Fig. 7 that the X-ray signal increases linearly versus bias voltage. The PIN is supposed to be fully depleted at -100 V, however the data shown in Fig. 7 indicates that this is not the case. As shown above in Fig. 5(b) the hard X-rays and γ-rays are generated during the rise and the fall of the voltage pulse due to the “off-energy” (< 3 MeV) electrons scraping the beam pipe and generating Bremsstrahlung impact photons.

![Figure 7. (a) Temporal profile of the hard X-rays and γ-ray flux as a function of bias voltage and (b) the average peak X-ray signal in the tail vs. bias voltage.](image)

In order to maximize the intensity of the signal the highest bias voltage was maintained, which is limited to 200 V by the bias tee. Most of our measurements were conducted with the bias voltage held constant at -150 V. The response of the PIN as function of the electron beam diode voltage was also measured in Fig. 8 below. The bias voltage was held fixed on the PIN. The X-rays in the head and tail were examined and in each case, exponential growth of each signal is observed from a ~2x increase in voltage and >2x increase in the extracted current. This is in strong agreement with the increase of the X-ray intensity measured with the PMT in Fig. 6.

![Figure 6. Temporal profile of the PMT light intensity as a function of diode voltage.](image)
While operating the diode at full voltage we measured the X-ray flux along the beam axis in 4 locations, \(z = 22.9 - 71\) cm downstream of the diode. It is evident from Fig. 9, the X-ray flux increases axially which is explained by the expected source of the X-rays. The flux is \(77x\) greater when comparing the most upstream PIN signal (\(z = 22.9\) cm) to the downstream PIN location at \(z = 71\) cm (just slightly upstream of BPM02, Fig. 1). TRAK and LSP calculations indicate the 1 MeV electrons begin to scrape 90 cm downstream of the cathode face and electrons up to 2.8 MeV scrape as far downstream as 190 cm.

After performing the post-processing we are able to perform a Doppler fit on the distribution in Fig. 10(b). The resolution of the measured distribution is \(7 \times 10^{-2}\) Å and the calculated \(\sigma = 0.11\) nm (38 pixels), which correlates to a hydrogen ion temperature of 25.4 eV and velocity of \(4.95\) cm/\(\mu\)s as calculated with the two equations below:

\[
T_i = \left(\frac{\sigma}{\lambda_0}\right)^2 \frac{m_i c^2}{}, \tag{1}
\]

and

\[
v_i = \sqrt{\frac{T_i}{m_i c^2}}, \tag{2}
\]

where \(T_i\) is the ion temperature, \(\sigma\) is the width of a Gaussian distribution, \(\lambda_0\) is the center wavelength, \(m_i\) is the ion mass, \(c\) is the speed of light, and \(v_i\) is the ion velocity. Several improvements need to be made to these measurements. Currently it is believed the distribution is intrinsically broadened due to the large fiber size (1500 \(\mu\)m), slit width (500 \(\mu\)m), and long gate (1 \(\mu\)s).

VI. CONCLUSION

We confirmed there is a measurable light output during emission of our cathode. We developed a spatial and temporal profile of the light on the cathode surface, which agrees well for multiple diagnostics. We quantified the axial growth of the light emission across the A-K gap is negligible for this pulse length. Preliminary spectral measurements confirm there is a hydrogen plasma on the surface of the cathode. We plan to improve the quality of the visible spectral measurements through temporally resolved Doppler broadening of the \(\text{H}_\alpha\) line. With these ion temperature measurements we will infer the ion expansion velocity of the plasma. If \(\text{H}_\beta\) and carbon

![Figure 8](image1.png)

**Figure 8.** Temporal profile of the hard X-ray and \(\gamma\)-ray flux as a function of diode voltage looking just downstream of the anode shroud (\(z = 22.9\) cm).

![Figure 9](image2.png)

**Figure 9.** Temporal profile of the hard X-rays and \(\gamma\)-ray flux at four different axial diode locations.

![Figure 10](image3.png)

**Figure 10.** (a) CCD distribution of the \(\text{H}_\alpha\) line captured over a 1 \(\mu\)s gate with the 1800 G/mm grating and 500 \(\mu\)m slit width. (b) Integrated spectrum with Doppler broadened fit.

V. VISIBLE SPECTROSCOPY MEASUREMENTS

Preliminary visible spectroscopy measurements were made of the light generated on the surface of the cathode face with the configuration shown Fig. 1. We were able to resolve \(\text{H}_\alpha\) (656.279 nm) with both the 150 and 1800 G/mm gratings. The spectral distribution on the CCD measured with a 1 \(\mu\)s gate width and 1800 G/mm grating is shown in Fig. 10(a). Since we are gating through the rise and fall of the voltage pulse, the signal is clouded with X-ray speckle and the S/N < 2. However, the X-ray speckle is random from one row of pixels to the next and the height of the distribution on the CCD is 80 pixels high. So, we are able to average out the X-ray speckle and calculate the integrated spectra in Fig. 10(b).
emission lines are visible we will infer the electron temperature and possibly the density.

We have developed X-ray & γ-ray diagnostics which provide a spatial and temporal profile of the Bremsstrahlung spectrum that is generated in the diode. We have begun to understand the spatial and temporal dependence of the X-rays and γ-rays generated in the diode. Axial measurements and particle simulations indicate the X-rays are generated due to low energy (E < 3 MeV) electrons scraping the beam pipe. We also plan to improve the precision of our X-ray measurements with X-ray imaging that may yield more precise information about the Bremsstrahlung spectrum.

VII. REFERENCES