Report on BLP Spectroscopy Experiments Conducted on October 6, 2017: M. Nansteel

Summary

Several spectroscopic measurements were conducted on October 6, 2017 at BLP to characterize the radiant power of the plasma emission generated by the passage of a large ignition current pulse through a spheroidal silver shot containing H_2O that resulted in an explosive release of extreme ultraviolet radiation, a shock wave, and an electromagnetic pulse (EMP). The current pulse of about 12 ms duration typically peaking over 25 kA was supplied by a 75 kVA spot welder to the shot which was clamped between large copper electrodes inside an evacuated blast chamber. Due to the interference from the EMP, the voltage peaking at about 19 V during the blast was measured by measuring the current through a standardized shunt resistor in parallel with the shot current. The wavelength features and radiant power of the plasma emission was characterized in the wavelength interval from about 20 to 800 nm using three NIST-light-source absolutely calibrated spectroscopic systems, each of which was focused in a different part of this wavelength spectrum.

Measurements of plasma emission in the wavelength range 200-800 nm in nine separate tests indicated that emission typically began about nine milliseconds after initiation of the current pulse and was concentrated between 200 and 250 nm for this spectral range. The radiation typically reached peak intensity in less than about 100 μs and then gradually decayed. The total duration of this pulse of radiation was 800 to 960 μs and the mean duration of the radiation in the nine tests was about 860 μs. Peak radiant emission in the range 200-800 nm exceeded 3 MW in one of the tests and was only modestly lower in the other tests. Measurements of average plasma radiant power during the radiation pulse in the wavelength region from 200 to 800 nm ranged as high as 817 kW in the nine tests. In the particular test which yielded this power level the radiation persisted for 840 μs, hence in this test 686 J of energy was radiated from the plasma in the range 200-800 nm. In the other eight tests the plasma radiated similar but somewhat smaller amounts of energy in this wavelength range.

Probing the radiation at shorter wavelengths indicated that most of the energy is radiated from the plasma at wavelengths below 200 nm. By using the three spectroscopic systems, which were focused in different wavelength regions, the plasma spectral power was measured over the wavelength range from 22 to 644 nm. In this range the measured time-mean radiated plasma power was 2.77 MW. This power level, radiated for the nominal emission duration of 860 μs, corresponds to 2382 J of energy radiated from the plasma.

It was not possible to simultaneously measure the energy radiated from the plasma and the electrical energy input to the shot/plasma due to the EMP which results when ignition occurs in a high-vacuum capable chamber which also enables windowless EUV spectroscopic measurements. However, in a separate identical ignition experiment carried out on August 18,

2017, but conducted at atmospheric pressure without radiant energy measurements, the electrical energy input to the shot/plasma was only about 81 J.

This report documents the procedures used to obtain the spectral power measurements in the tests conducted on 100617 and details the calculation of electrical input energy in the test conducted on 081817.

Silver shot fabrication and blast tests

The silver shots were fabricated by melting approximately 80 mg wafers of 0.5 mm thickness silver foil using a 30 A current pulse from a TIG welder in the presence of deionized water. This resulted in the formation of 60-80 mg spheroidal pellets of silver with encapsulated H_2O measuring 2.5 to 3 mm in diameter. For each test an individual shot was clamped between copper electrodes inside a cylindrical stainless steel blast chamber measuring 14.6 cm in diameter and 28 cm long. The chamber was sealed and evacuated to 5 mTorr pressure before each test. Tests were initiated by applying a single cycle of quasi-sinusoidal current with approximately 12 ms duration to the shot from a Taylor-Winfield 75 kVA spot welder. According to measurements carried out on August 18, 2017, this procedure results in peak current flow in excess of 20 kA through the shot and a peak voltage across the shot determined using the current and standard resistance of the parallel shunt resistor circuit to be about 19 V.

Mightex UV-VIS spectrometer: 200-800 nm

The Mightex system featured 25 micron fixed slit width and a Mightex linescan CCD camera model TCE-1024-UF with 1024 pixels and 14 x 14 μm pixel size. Wavelength calibration of the Mightex spectrometer from 253 to 922 nm was carried out on 081817 using an Hg-Ar calibration source (Ocean Optics model HG-1). On the same date this spectrometer was calibrated for spectral irradiance using a NIST traceable D_2 lamp for wavelengths down to 200 nm and a NIST traceable quartz tungsten lamp for wavelengths as high as 800 nm. Ten calibration spectra were acquired and averaged from each source. The irradiance calibration setup using the tungsten lamp is shown schematically in Fig. 1. The primary spectral lines in the wavelength calibration and the spectrometer efficiency curve obtained are shown in Figs. 2 and 3.

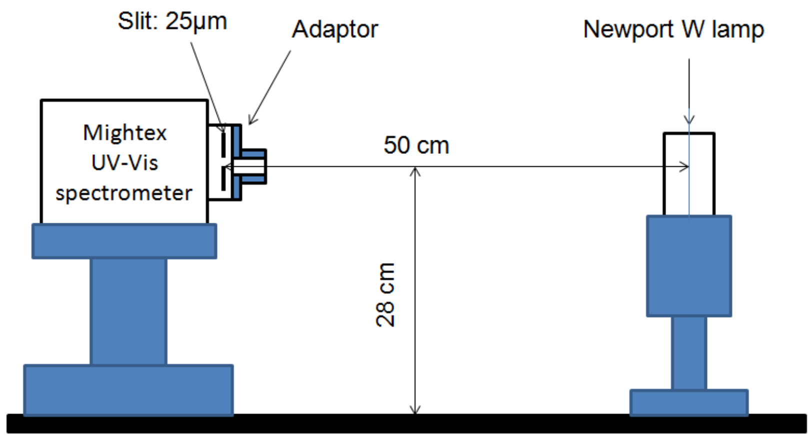

Figure 1. Mightex irradiance calibration setup with tungsten calibration lamp (BLP supplied graphic)

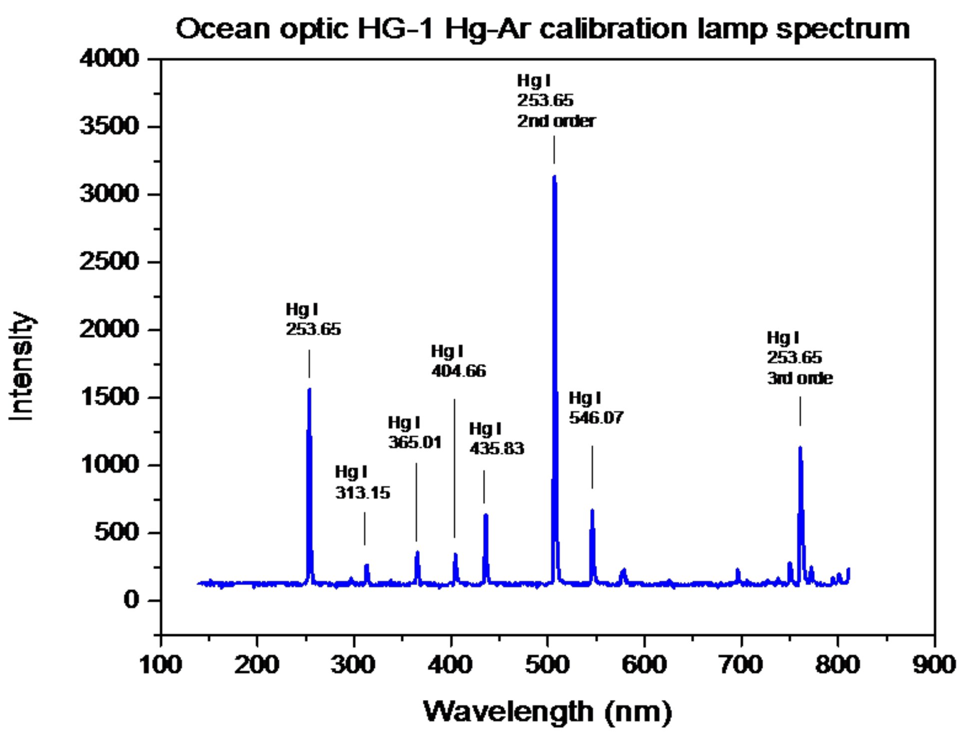

Figure 2. Spectral lines for wavelength calibration with Hg/Ar source (BLP supplied graphic)

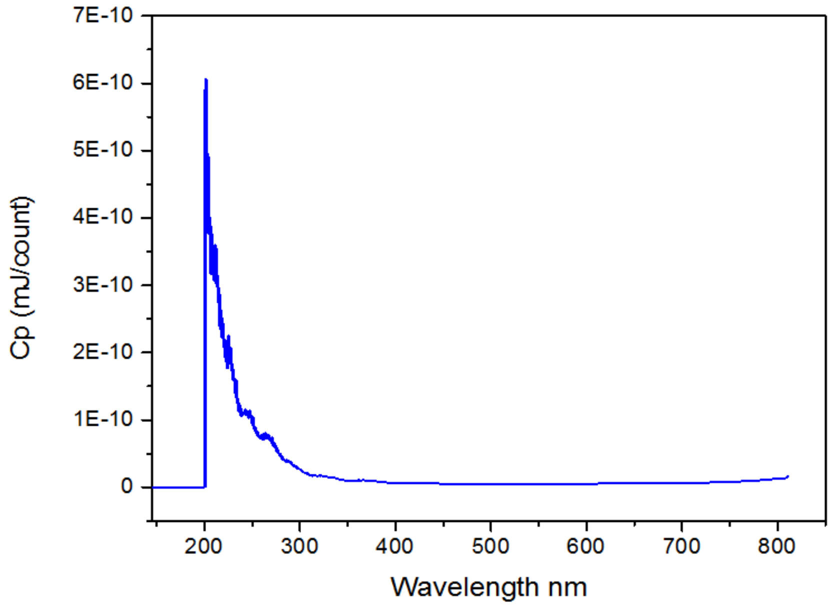

Figure 3. Mightex UV-VIS spectrometer efficiency curve (BLP supplied graphic)

Spectra in the shot blast tests were acquired through a 3.5 cm ID vacuum tube which connected the blast chamber to the spectrometer system. The radiation passed through a 7 mm diameter and 2 mm thick MgF_2 window a few centimeters upstream of the spectrometer. The distance between the shot/plasma and the window was 2.12 m and the distance from the window to the Mightex entrance slits was 8 cm. The blast chamber and the space connecting the blast chamber to the Mightex was evacuated to 5 mTorr prior to plasma initiation. The test setup is shown schematically in Fig. 4.

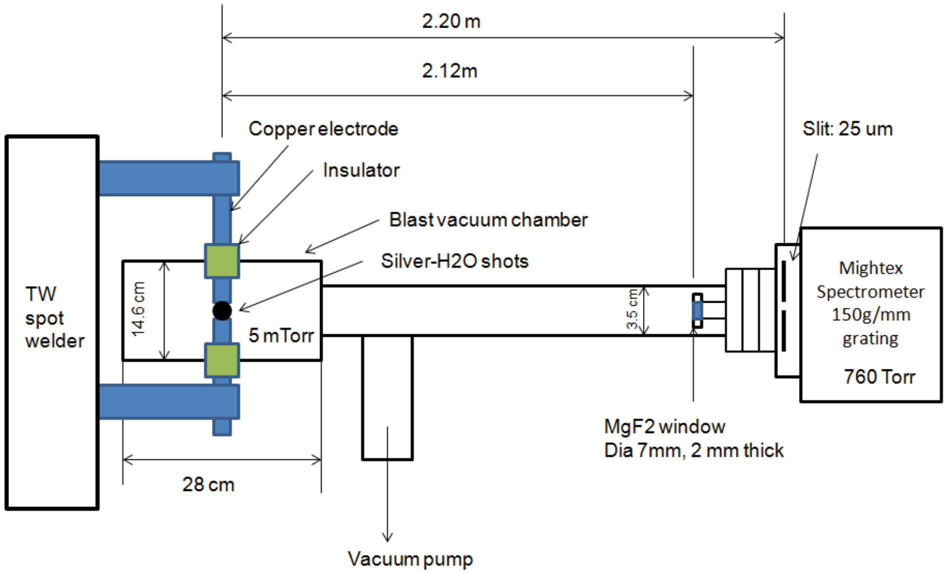

Figure 4. Setup for measuring UV-VIS spectrum with Mightex (BLP supplied graphic)

In each test the current pulse was initiated by manually activating the spot welder. Upon receiving a trigger signal from the spot welder the spectrometer acquired 2000 consecutive spectral frames, each spanning the wavelength range from 200 to 800 nm with $\Delta t = 40\ \mu s$ time duration for a total acquisition time of 80 ms. Note that the Mightex spectrometer views the plasma radiation through the MgF_2 window which has known spectral transmissivity τ_λ. Therefore, the apparent plasma spectral power, uncorrected for attenuation by the window, is

$$s'_\lambda\,[\mathrm{W/nm}] = \frac{Cp(S-D)4\pi R^2}{A\Delta t d\lambda},\ \text{Uncorrected}$$

where Cp is the Mightex efficiency, S and D are the measured intensities for the plasma spectrum and dark spectrum (counts), R is the distance from the silver shot to the spectrometer entrance slits [m], Δt is the acquisition time for each frame [s], A is the slit area [m^2] and $d\lambda$ is the wavelength interval between pixels [nm]. This uncorrected spectral power is equal to the product of the true or corrected spectral power and the window transmissivity. Therefore the spectral power, corrected for the window absorption, is

$$s_\lambda[\mathrm{W/nm}] = \frac{s'_\lambda[\mathrm{W/nm}]}{\tau_\lambda},\ \text{Corrected}$$

Figure 5 shows spectral data from Test 3 which featured the strongest plasma radiation. In this test emission began in frame 215 at 8.6 ms after the system was triggered by the spot welder and continued through frame 235 corresponding to 9.4 ms after the trigger. Hence plasma emission occurred for 21 frames or 840 μs in this test. The peak emission occurred in frame 217 or at about 8.7 ms. Both the uncorrected and corrected spectral power for this frame are plotted in Fig. 5. Note that emission is particularly strong between 200 and 250 nm for this spectral range. The peak corrected spectral intensity occurs near 225 nm and is in excess of 50,000 W/nm. The total plasma irradiance for frame 217 is the spectral power integrated over wavelength:

$$\text{Peak power, frame 217}\begin{cases} s'_{tot} = \displaystyle\int_{200\,\text{nm}}^{800\,\text{nm}} s'_\lambda d\lambda = 2.88\ \text{MW}, & \text{Uncorrected} \\ s_{tot} = \displaystyle\int_{200\,\text{nm}}^{800\,\text{nm}} s_\lambda d\lambda = 3.13\ \text{MW}, & \text{Corrected} \end{cases}$$

Therefore, the peak emission in Test 3 between 200 and 800 nm exceeded 3 MW. The time average of the spectral power over the 840 μs duration of the event is also plotted in Fig. 5. This is the power at each wavelength, averaged over the 21 spectral frames. Like the peak spectral power, the average spectral power is greatest near 225 nm with peak (corrected) magnitude of about 16,000 W/nm. The time average total irradiance is

$$\text{Average power}\begin{cases} s'_{tot} = \displaystyle\int_{200\,\text{nm}}^{800\,\text{nm}} s'_\lambda d\lambda = 752\ \text{kW}, & \text{Uncorrected} \\ s_{tot} = \displaystyle\int_{200\,\text{nm}}^{800\,\text{nm}} s_\lambda d\lambda = 817\ \text{kW}, & \text{Corrected} \end{cases}$$

The corrected average power of 817 kW, radiated for a period of 840 μs, corresponds to 686 J of radiated energy.

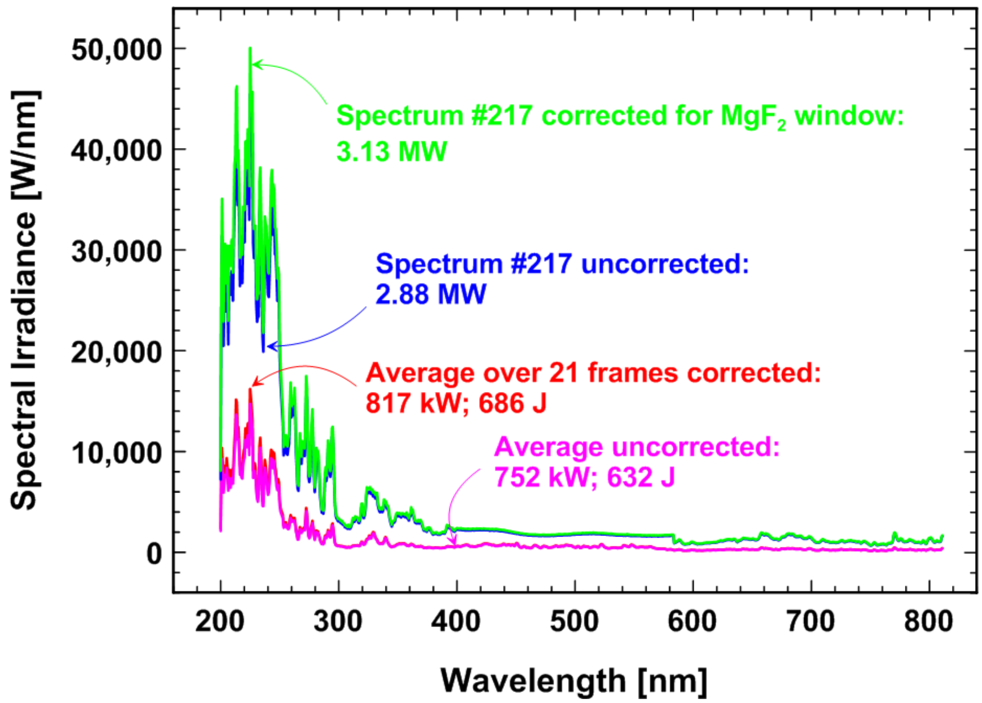

Figure 5. Measured spectral irradiance in Test 3: Peak and time-averaged spectra

Similar data to Fig. 5 for the average spectral power is shown in Fig. 6 corresponding to Test 6. In this test the plasma emission persisted for 23 frames or 920 µs. The spectral intensity was again greatest at around 225 nm with a corrected magnitude of about 14,500 W/nm. The corrected average power integrated over wavelength is 713 kW corresponding to 656 J of radiated energy during the 920 µs event. The uncorrected peak power, average power and total radiated energy for all nine tests with the Mightex spectrometer are summarized in Table 1.

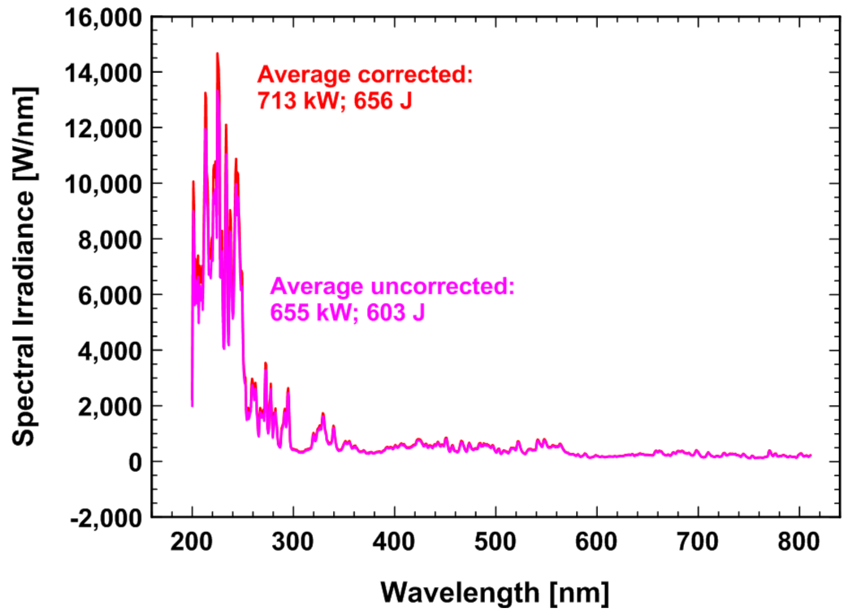

Figure 6. Measured spectral irradiance in Test 6: Time-averaged spectra

Table 1. Mightex radiant power and energy data (uncorrected): 200-800 nm

		Power		
Blast	Duration [ms]	Peak [MW]	Average[kW]	Total Energy [J]
1	0.80	2.3	696	557
2	0.96	2.2	562	539
3	0.84	2.88	752	632
4	0.84	2.67	608	510
5	0.88	1.88	535	470
6	0.92	2.9	655	603
7	0.80	2.55	675	540
8	0.84	2.84	670	562
9	0.88	1.72	467	411

Normal incidence (NIM: 40-700 nm) and grazing incidence (GIM: 1-65 nm) monochrometers

The NIM and GIM spectrometers were set up similarly to the Mightex except for slightly different separation distances between the plasma and the spectrometer entrance slits. The system arrangement is shown for each in Figs. 7 and 8.

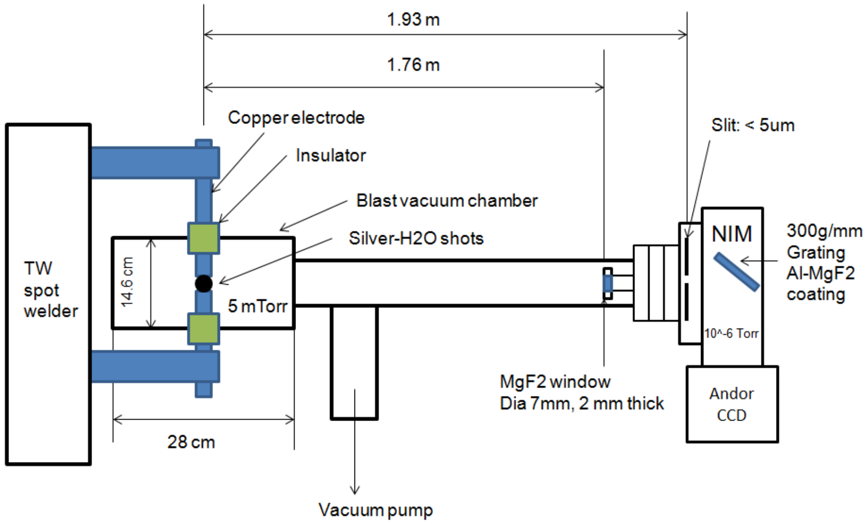

Figure 7. NIM measurement setup (BLP supplied graphic)

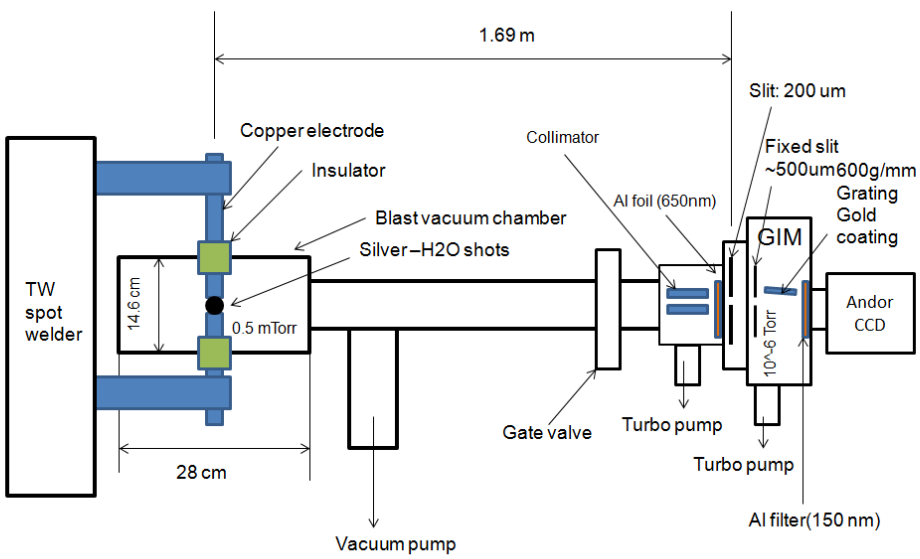

Figure 8. GIM measurement setup (BLP supplied graphic)

For both devices spectral data were collected for a period of 10 seconds after receiving the trigger signal from the spot welder. For the NIM, four spectra were acquired in separate shot blast tests, each with a different CCD center wavelength: 300 nm, 400 nm, 500 nm and 200 nm windowless. These four spectra are shown in Figs. 9 and 10. Each of the four NIM spectra has greatest efficiency at the center wavelength so these spectra are joined together to yield a comprehensive measurement of plasma spectral intensity extending from less than 50 nm to 650 nm, as shown in Fig. 11. One spectrum was acquired with the GIM using a 55 nm CCD center.

This corrected data is shown in Fig. 12 extending from about 22 to 68 nm. The GIM spectral data is joined with the NIM data as shown in Fig. 13, covering wavelengths from about 25 to 650 nm. This joined spectrum was corrected for CCD quantum efficiency and then scaled to match the intensity of the absolutely calibrated Mightex spectrum from 200 to 644 nm. The result of this procedure is the plasma spectral power from 22 to 644 nm shown in Fig. 14.

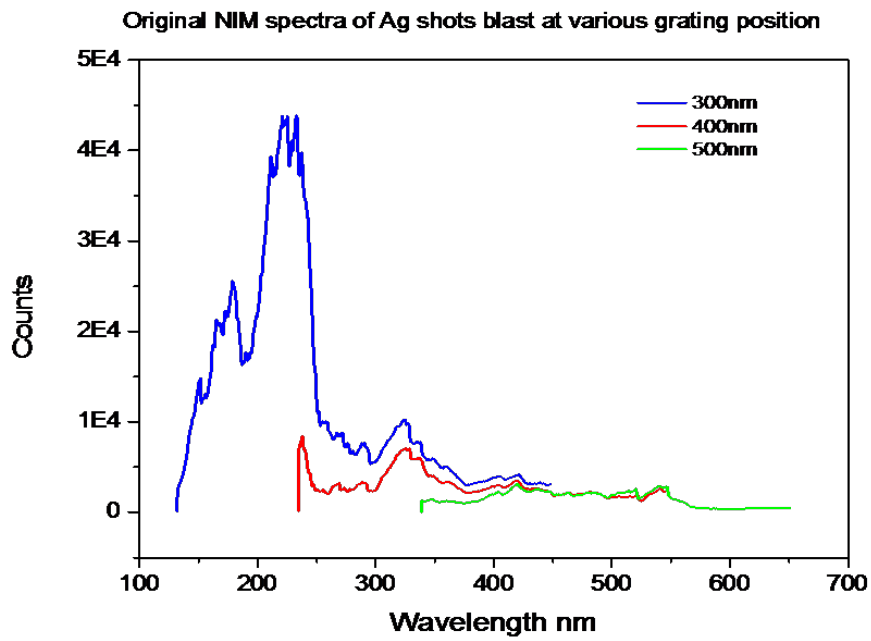

Figure 9. Raw plasma spectral intensity data for NIM (300-500 nm) [BLP supplied graphic]

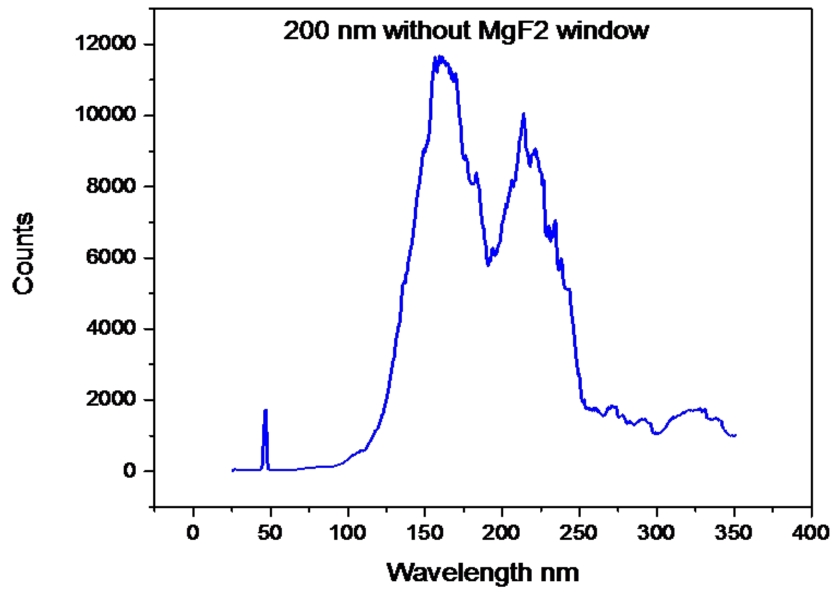

Figure 10. Raw plasma spectral intensity data for NIM at 200 nm without MgF_2 window (BLP supplied graphic)

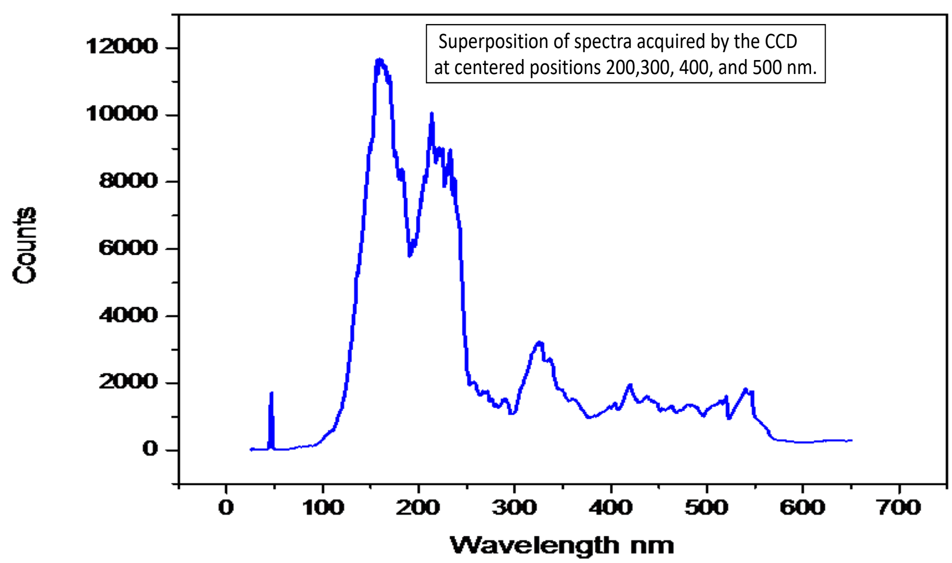

Figure 11. Superposition of spectra acquired by the CCD at centered positions 200,300, 400, and 500 nm (BLP supplied graphic)

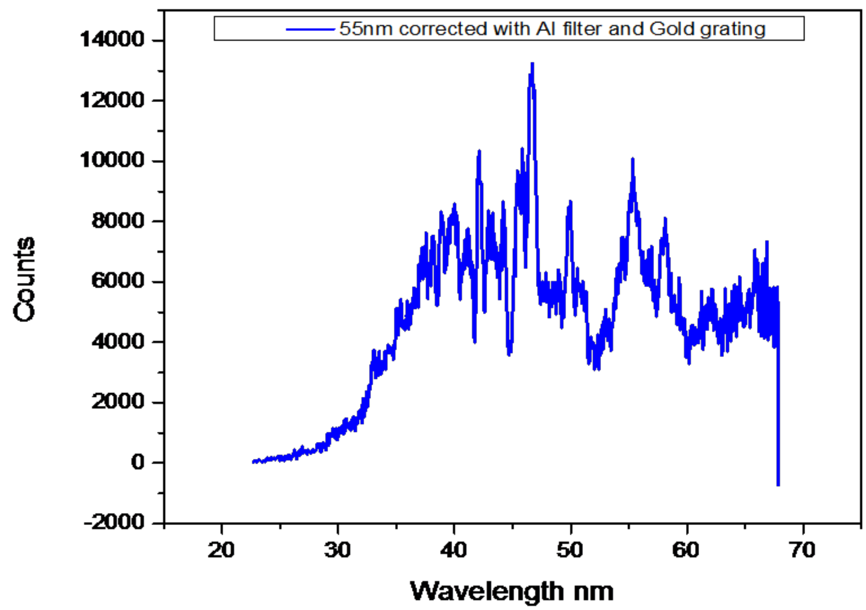

Figure 12. Corrected GIM spectrum (BLP supplied graphic)

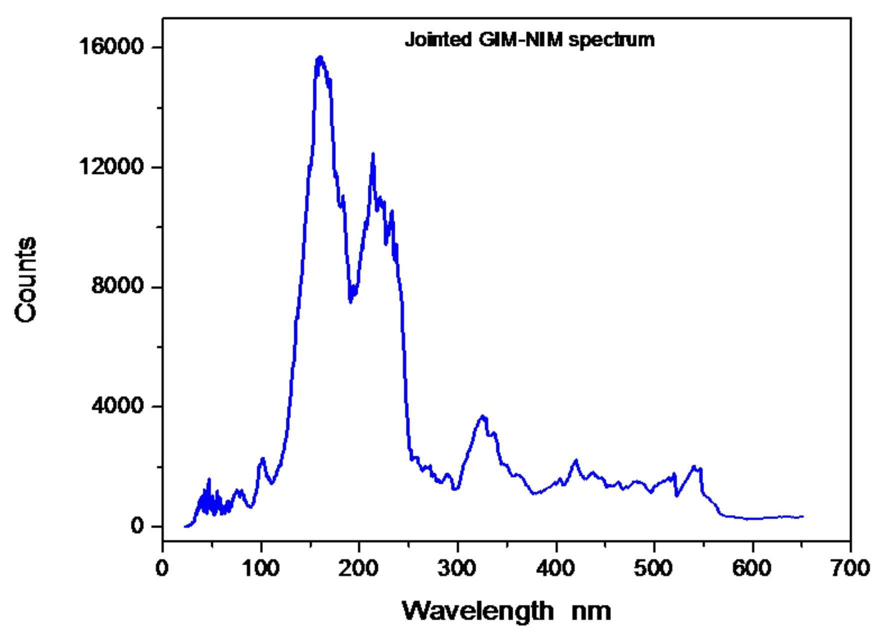

Figure 13. Joined NIM and GIM spectrum (BLP supplied graphic)

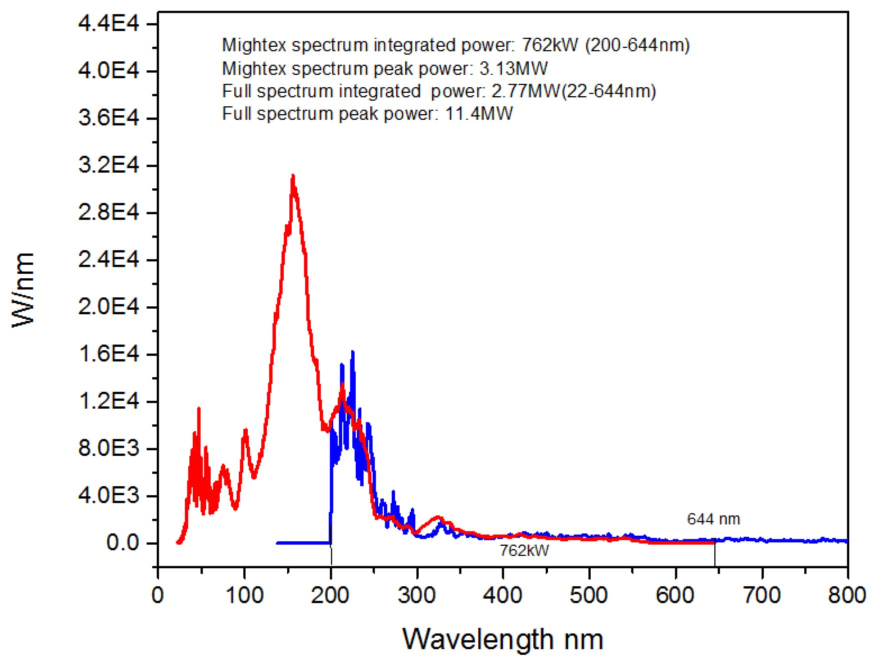

Figure 14. Plasma spectral power from 22 to 644 nm (BLP supplied graphic)

<u>Estimate of full spectrum plasma radiant power and energy</u>

The plasma time-average radiant power and energy from 200 to 800 nm were measured using the Mightex spectrometer. In Test 3 the corrected average power in this range of wavelengths was 817 kW during the 840 μs event corresponding to 686 J of radiated energy. However, Fig. 14 showing the plasma emission over the full spectrum indicates that most of the energy is radiated at shorter wavelengths, below 200 nm. The major emission wavelength was concentrated at about 160 nm for the full spectral range, 20-800 nm. The full spectrum integrated power from 22 to 644 nm (which excludes the small energy radiated in the range 644-800 nm) in Fig. 14 is 2.77 MW. In the nine tests conducted with the Mightex spectrometer the mean duration of the radiation, from the data tabulated in Table 1, is 860 μs. Assuming the full spectrum power, 2.77 MW, to be sustained over 860 μs results in 2382 J of plasma energy radiated between 22 and 644 nm.

<u>Electrical input power</u>

Electrical power and energy deposition in the shot/plasma was not measured during the tests in which spectral data was collected. This is because a shunt circuit is required in parallel with the shot in order to accurately measure voltage across the shot during plasma formation. A schematic diagram of the required shunt circuit is shown in Fig. 15. Furthermore, this circuit cannot be placed inside the blast chamber without causing strong distortion in the shunt current measurement due to EMP effects. Therefore, a test was conducted with the shunt connected to but outside the chamber on August 18, 2017. No spectral data was acquired during this test because the chamber was open to the atmosphere. Rather, the purpose of this test (Test 5 on 081817) was to determine the electrical power input to the shot during a typical blast test. In this test the currents I_{shunt} and I_{tot}, cf. Fig. 15, were measured with Rogowski coils (PEM, LFR 15/150/700) and the voltage V_{tot} was measured with a 25 MHz 70V 10:1 differential voltage probe. All electrical data were acquired by a 60 MHz digital oscilloscope (Picotech Picoscope 5442B) at the acquisition rate of one sample every 56 ns or 17.86 kS/ms.

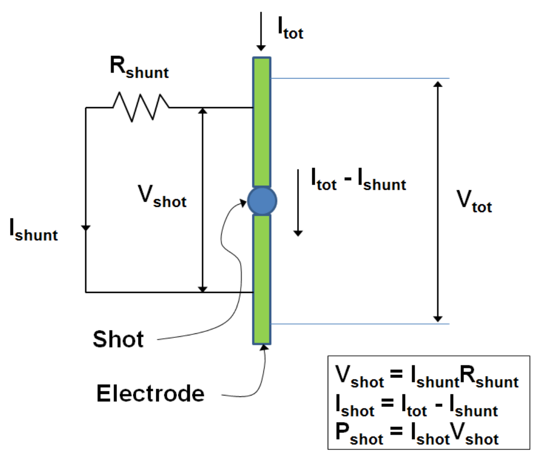

Figure 15. Shunt circuit used for measuring input power

Using the known shunt resistance R_{shunt} = 1.2 mΩ, calculations of the shot voltage, current and power are carried out according to Fig. 15. The cumulative energy supplied to the shot during the event is

$$E_{shot}(t) = \int_{\tau=0}^{\tau=t} P_{shot}(\tau)d\tau$$

and the power and energy for the shunt circuit are

$$P_{shunt} = I_{shunt}^2 R_{shunt}, \quad E_{shunt}(t) = \int_{\tau=0}^{\tau=t} P_{shunt}(\tau) d\tau$$

These data are plotted in Fig. 16 versus time during the single cycle current pulse which had approximately a 12 ms duration. Figure 16 indicates that peak shot current exceeded 22 kA and the peak voltage was about 19 V. Note that the shot current and voltage waveforms are typical for a load of constant impedance up until about 9 ms. At this time the power dissipation in the shot, P_{shot}, is about 40 kW, causing rapid heating, and the accumulated energy deposited in the shot is E_{shot} ~60 J. This is, roughly, sufficient energy to heat 80 mg of silver to the melting point (1235 K), melt it, heat the liquid silver to the normal boiling point (2435 K), and then vaporize less than about 5% of the silver mass. Shortly after 9 ms the shot current drops as most of the total current I_{tot} is diverted through the shunt. At the same time the shot voltage rises dramatically while the power dissipation in the shot increases rapidly to about 140 kW and then decays to zero in about a half millisecond. This event probably corresponds to plasma formation between the electrodes and is consistent with the timing of the radiant emission pulse observed during spectroscopic tests. Note that the power dissipation in the shunt circuit peaks near 300 kW. The total energy supplied to the shot during the 12 ms electrical current pulse is about 81.4 J while the energy dissipated in the shunt circuit is about 203 J.

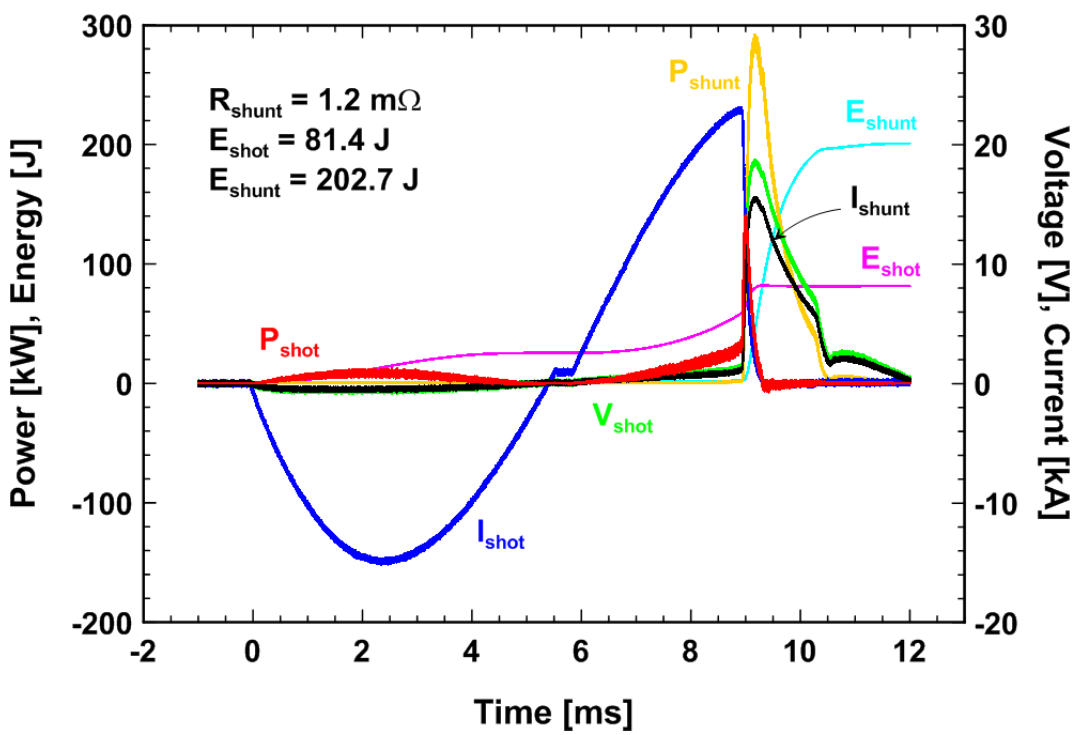

Figure 16. Electrical input power data for Test 5 conducted on 081817