Reproducibility of a Titanium Plasma Vacuum Spark Discharge

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The results of an extensive operation of a Vacuum Spark plasma using Titanium electrodes in a 120 ns 150 kA discharge are presented. The hot spots are found to form with a regular spacing in a zipping Z-pinch plasma, which forms close to the cathode and extends to approximately two thirds of the anode separation over a period of a few ns. The axis of the discharge is well defined by an initial plasma from a Nd:YAG laser focussed onto the cathode electrode surface. The statistics of the formation of the hot spots are given for the life of one anode electrode. Between one and three hotspots form and the favored positions are at 1.5 and 3.0 mm from the cathode and the strongest emission, as observed in a filtered X-ray pinhole camera, comes from the hot spot closest to the cathode. The emission spectra resolved between 50 and 350 Å shows a wide range of Ti ionization which allows the temperatures of the anode blow off plasma, the Z-pinch and the hot spot plasma to be distinguished. These results are compared with filtered PIN diode signals and filtered pinhole images.

Keywords: Vacuum Spark, X-ray emission, Titanium Plasma

I. INTRODUCTION

The Vacuum Spark [1] has long attracted interest as a rich source of plasma physics phenomena which have been thoroughly reviewed [2,3]. The most researched are the hot spots, often at extreme conditions of density and temperature. While the Vacuum Spark has provided much spectral information of highly charged metallic ions, its development as a reliable source for advanced technological applications has been less successful. Vacuum Spark discharges have been realized with various electrode shapes as well as with slow low voltage capacitor banks and medium power pulsed power coaxial line generators. Various trigger schemes have been tried to obtain better and more consistent operation of the discharge. A trigger spark behind the cathode has been generated electrically or by a focussed laser, a laser has been focussed onto the front surface of the anode and cathode. The hot spots have been observed in the anode blow-off plasma and as necking instabilities in the Z-pinch plasma which forms between the cathode and anode, beyond the blow-off plasma. Particular interest in the hotspots arises from the fact that, due to the high Z of the ions charge state, they exhibit the typical characteristics of radiative collapse a the Z-pinch plasma.

The present work form part of a series of results [4] in which a Vacuum Spark configuration using a small pulsed power generator firsts presented by Zakharov et al. [5] has been developed. The salient features of this configuration are that a relatively low energy laser pulse is focussed onto the front cathode surface though a perforated conical anode, which has a flat surface, rather than the rounded or pointed extreme commonly used. The electrical driver is a pulsed power 2 Ohm coaxial line. However, an important difference from previous work is that the hybrid mode [4] of operation has been found to be preferred to the normal switched line operation. In the hybrid mode the line gap is shorted so that the line charging ramp voltage is also applied to the Vacuum Spark. The Vacuum Spark itself switches the line. This results in a slightly longer applied current pulse with a lower maximum rate of current rise of 1.5 · 10^{12} A/s. Close to maximum current a Z-pinch is found to zipper upwards from cathode towards the anode, giving rise to the formation of a string from one to three hot-spots. This work presents some statistical observations of the frequency and the position the hotspots formed during the useful life of one anode cone electrode. The spectrum of a source for lithographic applications is of essential importance and we present a soft X-ray spectrum obtained with Ti electrodes. The relative timing between the X-Ray emission from the anode plasma and the Z-pinch column is also presented.

II. EXPERIMENTAL CONSIDERATIONS

The principal details of the operation of the Vacuum Spark have been described elsewhere [4]. The observations of the hot spot positions in the Z-pinch were taken with an electrode separation of 7.75 mm. The generator was operated in the hybrid mode. The laser pre-ionizing pulse was focussed at 0.3 J onto the cathode surface approximately 700 ns before the application of the generator. The hot spots were observed in a time integrated quadruple pinhole camera using four filters [6]. The images were recorded on Kodak DEF film and the spatial resolution was 200 μm for the pair of pinholes with softer
filters, and 400 µm for the pair with harder filtering. The softest of the four filters was 1.5 µm Al + 0.4 µm Zn and the hardest was 50 µm Be, whose transmission window may be taken as cutting off (<1% transmission) in this experiment at 13 Å. The Zn was added to the Al in order to eliminate the long wavelength window of Al from about 170 to 350 Å, while still preserving a short wavelength pass band to 25 Å. The soft X-ray spectra were taken with a compact grazing incidence Rowland circle spectrometer with a 600 lpi grating and a useful spectral window of from 50 to 350 Å. The image was recorded on film using a multi-channel plate intensifier, with a 3 ns gating time.

Figure 1: X-ray emission from the whole discharge operated in the hybrid mode, a) and b), and from half of the discharge closest to the cathode, c) to e). The current and voltage on the line transfer section are the two lower traces. Filters are: a) Al 3 µm, b) Ag 3 µm, c) Mylar 5 µm + Al 0.28 µm, d) Ti 1.2 µm and e) Be 34 µm.

In figure 1 the time resolved X-ray emission is shown from the whole volume of the discharge and from the 5 mm closest to the cathode, where the Z-pinch column is observed to form. The discharge holds the full line charging voltage for approximately 150 ns before the current exceeds a few kA. The 3 µm Ag filter shows the early beam target emission from the anode, as the current builds rather slowly to a few kA. Slightly later the 3 µm Al filter registers emission from the plasma forming from the ablated material of the anode. The 3 µm Ag filter also records the hotter plasma from appreciable beam target emission from the anode and the anode plasma as well as from the hotspots of the Z-pinch. In a very crude approximation it may be said that in this quite hard filter the emitted energies are approximately equal. The plasma emission from the hot spots occurs at an inflection of the peak current of approximately 150 kA. The inflection is an artefact of the generator. The softest of the three filter signals that observe only the Z-pinch, 1.2 µm Ti, shows the 15 ns period in which the Z-pinch channel is formed. The hot spot signal occurs in the halfway through this filter signal, as is seen from the other two filters. The hardest filter, 34 µm Be, has the shortest signal and records principally Ti XIX and higher ionization stages associated with the hotspot formation. It is worth stressing that a multi keV component of emission has never been observed in this configuration of vacuum spark if hot spots are formed with the characteristic energy signature of this figure.

Figure 2: Histograms of the axial position measured from the cathode of the hot spots of 59 shots, when one hot spot is observed, upper graph, when two hot spots are present, middle graph and for three hot spots, lower graph.

The statistical properties of the hot spots are recorded for a sample of 59 shots taken on one pair of electrodes. The useful life of the electrodes is approximately 150 shots. Of these 59 shots, 18 had one hotspot, 26 had two and 15 had three. It should be noted that all shots produce hotspots. The only requirement for consistent operation over a substantial number of shots is that the laser focus must not be too tight in order to avoid pitting.
in the cathode. By defocussing the laser to a focal spot of 300 µm diameter in excess of 100 shots can be obtained before realignment is required. The distribution of the axial position measured from the cathode for these hot spots is shown in a series of three histograms in figures 2a, 2b and 2c, for one two and three hotspots respectively. The spacing of the electrodes was 7.7 mm, which was found to be the optimum spacing for the production of hot spots. The most favored position for a hot spot is between 2.6 and 3.2 mm with a total of 29 hot spots. The next most favored position is between 0.6 and 1.2 mm from the cathode, with a total of 27 hot spots. The frequency of hot spots per unit axial length rapidly diminishes from 4 mm; as between 4 to 4.6 mm only 9 are observed. The position of the hottest and also the most intense spot is plotted in figure 3. The hotspot is nearly always the only one visible in the 50 µm Be filtered pinhole image. This histogram corresponds to the 31 shots where two or more hot spots were observed. On comparing figures 3 and 4, it may be easily seen that there is a correlation between the position of greatest frequency of occurrence and the most intense hotspot.

A spectrum from the whole plasma taken with the grazing incidence spectrometer is shown in figure 4. Within the time resolution of the micro-channel gating, the recorded spectrum corresponds to the time of hot spot formation. As the spectrum covers a wide range, it is shown in two halves to appreciate the smaller scale details. A wide range of ionization stages is found indicating a plasma with regions of widely differing temperature. The ionization stages cover Ti V to Ti XX, in three or four groups which may be associated with different plasmas as will be discussed as follows. The second order transitions are indicated with a down-pointing arrow. The four Ti XX lines are second order transitions, the corresponding first order lines are seen, but are close to the lower useful limit of the grating and are not indicated in the figure. The presence of this ionization stage is to be expected from the presence of an image on the 50 µm Be filter and corresponds to the hotspot plasma previously estimated from filtered PIN diode and filtered pinhole images at about 700 eV [6]. The following group of ionization stages that may be identified is from Ti XVI to Ti XVIII. For this group there are a large number of lines that may be identified. Their intensities are in accordance with available transition probabilities in the NIST database [7]. The lines indicated are those whose transition probability value $A_{ki}$ is greater than approximately $4 \times 10^9$ s$^{-1}$, when the value is available, or the brightest observed lines in the notation of Kelly database [8]. Ti XV is found to be all but absent, the only unambiguously observed is at 147.4 Å, while the equally probable transition at 115.0 Å is not unambiguously identifiable. On the other hand Ti XIII and Ti XIV are well represented. Ti XII is most strongly represented by two of the stage’s transitions at 116.5 and 140.3 Å, while others with a high transition probability at 90.5, 108.1 and 109.1 Å are weak. In comparison it would appear that Ti XIII and Ti XIV are more abundant. Evidence of lower temperature plasma is found from the ionization stages from the representative lines identified from Ti VI to Ti XI.

An anomaly is presented in the form of two lines, one of them very prominent at 106.5 Å, indicated by an upwards pointing arrow. While there are Ti XV, XVI and XVII lines tabulated within the resolution of the spectrograph at 106.5 Å, their transition probabilities are an order of magnitude below the criteria of the other lines identified of these ionization stages. Lines from possible contaminants, such as Cu, Zn, C, Si and F may all be discounted. There are many extremely fast dynamic processes associated with the formation and dissipation of a hot spot, including plasma jets and charged particle beams, which might affect the transition probabilities giving rise to energy level shifts or polarization enhancements [9]. A more detailed analysis of this unidentified emission lines is beyond the present investigation.

### III. DISCUSSION

In common with other fast vacuum discharge work referred to above, the hot spots are seen to form a Z-pinch which "zippers" up within a few ns starting from the position defined by the incident laser on the cathode. This formation was seen first in interferograms [4], then in visible streak photography [6] and later in soft X-ray frames [10]. In soft filtered pinhole images of the Z-pinch column [6], a plasma volume which extends two thirds of the distance to the anode is seen to be nearly continuous, with slight bulges where the hot spots are observed. In the
Figure 4: Soft X-ray spectrum for one representative shot from 50 to 350 Å. The single spectrum is divided in two sections for clarity. The most probable transitions for the Ti ionization stages that coincide with observed lines are shown. The downwards directed arrows denote second order lines and the upwards directed lines are anomalies in the Ti spectra. The vertical intensity scale is in arbitrary units and is not linear.

hardest filter, which is transparent to emission from Li-like and higher ionization stages, a much more compact and irregular axially elongated plasma volume is seen. In the optical interferometric images the anode plasma is seen to “boil” off the anode with too many shift fringes or even optically dense for any estimate of the electron density. However soft X-ray emission from the plasma is barely seen in micro-channel plate frames even in 3 µm filtered images. The anode itself is usually quite a bright emitter, although an order of magnitude less than the Z-pinch, except in the case where the plasma density is too low in the pinch region and very intense e-beams arise. On relating these observations to the spectrum presented, it is reasonable to infer that the ionization stages from Ti V to XII are associated with the plasma boiling off from the anode. These ionization stages do not have any lines that would appear in images filtered with 1.5 or 3.0 µm of Al. The plasma temperature may be obtained from the collisional radiation code, FLY [11]. The stages from Ti XIX to Ti XX are associated with the hottest plasmas of the hotspots. Li-like Ti has many lines in the pass-band of the Be filter. Some of the lower energy transitions are seen in the spectrum. The most intense lines of the wavelength range of spectrum are those corresponding to the Ti XIII to Ti XVIII species. Such a wide range of stages is not expected from a single temperature plasma but rather the species are consistent with a range of temperatures from 200 to 500 eV. All of these stages have lines that may be seen in the softer filters used in the pinhole image camera. For these pinholes and especially the case of the 2.0 µm Ti filter, with its L-shell pass band between 28 and 35 Å, the 1 mm diameter Z-pinch column is the principal feature. Hence it may be inferred that this plasma occupies this range of ionization stages. A wide variety of ionization stages has been found in earlier work [2], where Fe XVIII to XXVI were recorded in the same discharge.

At present most effort in intense X-ray sources for lithography is centered on the wavelengths where multilayer mirrors are available, that is between 120 and 150 Å. In this range we observe a number of comparatively intense lines of Ti XIV and XVII. No absolute X-ray measurements of the soft X-ray emission is available in this work. Absolute measurements have been obtained using rather low efficiency multilayer mirrors at much shorter wavelengths, centered on 8 and 24 Å [12].

The reproducibility of hotspot formation has been studied in fast capacitor bank driven vacuum sparks. In an early work [13] a laser beam was focussed onto the anode electrode and the probability of observing the hotspot in the plasma formed from electrode ablation under different conditions of electrode separation was observed. The position of the hotspot was well defined but the probability of occurrence was never greater than 80%. This work is the first to present a statistical analysis over a large number of shots. More recent laser triggered work in the vacuum spark [14] has concentrated on hard X-ray emission. Other recent work [15] has studied various methods of electrical triggering of fast capacitor bank vacuum sparks, with characteristic X-ray energies of between 3 and 40 keV. Other work on reliable vacuum spark operation includes the generation of a sliding spark on a PTFE sleeve covering part of the cathode [16]. The system is called passive, as part of the applied generator voltage is resistively fed to a ring electrode on the PTFE
sleeve to initiate the sliding spark.

In this context, the present work may be the first to present statistical results of a fast pulsed power driven vacuum spark. Whereas there are a number of favoured axial positions, where, if for example a 0.5 mm axial bin length is considered, there is a 100% probability of finding a hotspot. This hot spot is, however, only an approximately 25% probability of finding the hottest hotspot even at the most favoured positions of 2 and 3 mm from the cathode. However modification of the experimental assembly is possible so that the X-ray energy is extracted through the hollow anode, in which case the entire integrated axial X-ray emission would be available. In this case the laser triggering onto the cathode surface would come in obliquely, at approximately 30° to the normal. As the Z-pinch column is well stabilized on its axis by the laser pre-ionizing spark and is observed to be well formed, with only \( m = 0 \) instabilities, end-on extraction of X-ray energy should present an order of magnitude improvement in brightness over any radial energy extraction.

Observations of the Si pin diode signals over many shots indicate a less than 35% shot to shot variation for the softest filter used, sensitive out to approximately 25°, whereas the variation of harder filters sensitive to Li-like and He-like transitions shows a 60% shot to shot variation. The temporal behaviour of the X-ray pulse and the voltage and current waveforms are very reproducible.

IV. CONCLUSIONS

The vacuum spark driven by a small pulsed power generator and triggered by a laser spark on the cathode compares very favourably with lower voltage fast capacitor bank drivers. In particular the hotspots are formed within a rather cooler and well formed Z pinch. The characteristic line emission from this pinch is from Ti XIII to XVIII ionization stages. A statistical analysis of the \( m = 0 \) hotspot special occurrence indicates favoured positions which also coincide with the brightest hotspot, which has very significant Li-like emission. The anode plasma is very dense and considerably cooler. No hotspots are ever formed in the ablated anode plasma. Whereas extraction of the soft X-ray energy in a radial direction is possible, considering a 0.5 mm axial segment, the experimental scheme is susceptible to important improvement using axial energy extraction.

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