Spatial and time-resolved characterization of HiPIMS spokes

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INTRODUCTION

The magnetron sputtering process utilizes the kinetic bombardment of ions on a negatively biased target to eject the material and redeposit it on a substrate as a thin film [1]. A magnetic field is configured to be parallel to the target surface to trap electrons and enhance ionization. Electrons in the magnetic field perform an closed $\boldsymbol{E}\times\boldsymbol{B}$ drift above the target surface, this is represented graphically for a circular magnetron in figure 1 [1].

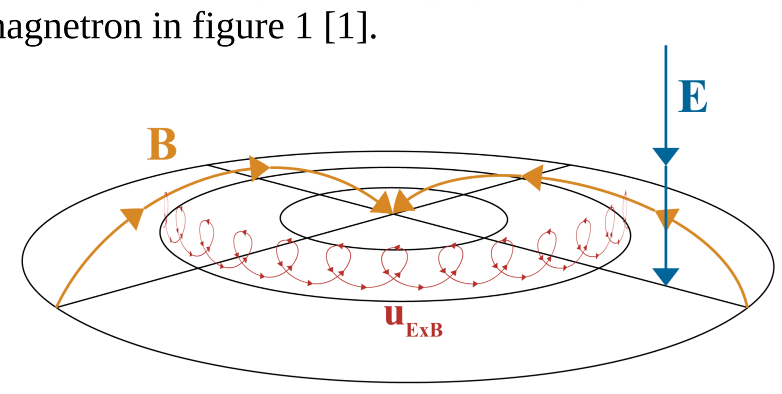

Figure 1: $\boldsymbol{E}\times\boldsymbol{B}$ drift.

The closed drift of the electrons gives rise to spoke instabilities in the plasma, named after a similar phenomenon observed in Hall thrusters [2]. Spokes are localized ionization zones that rotate azimuthally above the surface of the magnetron target. Spokes have been shown to be a mechanism for anomalous cross-field transport, contributing to a diffusion rate 5 times more than Bohm diffusion for high-power impulse magnetron sputtering (HiPIMS) systems [3]. Properties of spokes such as size, mode number, diffuseness, shape and speed are highly sensitive to discharge conditions; various studies have reported contradicting observations [4].

In this project a high-speed camera was used to collect images of the spokes over many discharges. A custom MATLAB script was implemented to automate the image processing, and identify areas of interest. This allows us to build a statistical picture of the spoke evolution in the microsecond timescale. We also used three floating probes to detect the oscillations in plasma potential caused by the rotating spokes.

EXPERIMENT

The experiment was performed using a custom magnetron machined by the University of Saskatchewan Physics Machine Shop. The magnetron was mounted in an inductively coupled plasma (ICP) ion implantation chamber, the ICP was used to assist the main magnetron discharge. Images were collected using a Chronos 1.4 camera, triggered by a custom circuit, signal delayed with respect to the start of the magnetron pulse. This allows us to capture multiple images from different pulses at the same time relative to the beginning of the pulse. A block diagram of the setup is shown below.

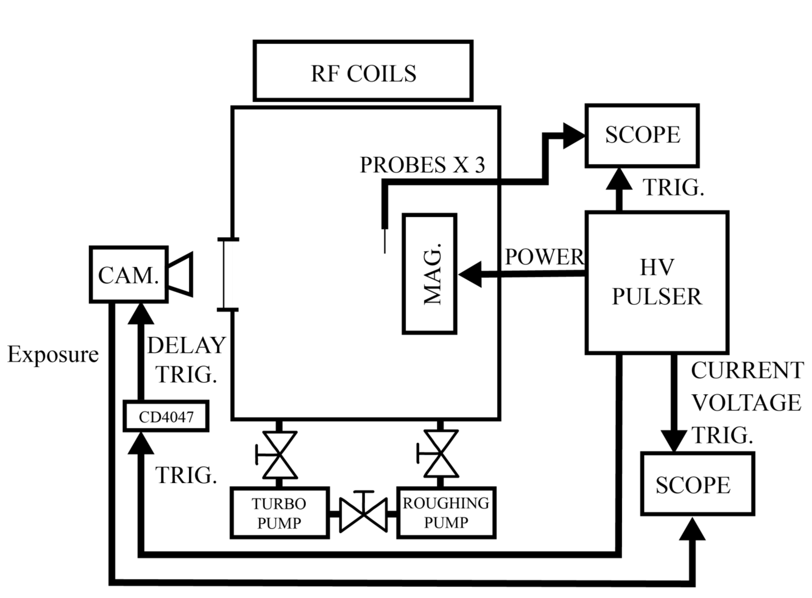

Figure 2: Experimental setup diagram.

Three tungsten tipped floating probes were placed radially around the magnetron to record the floating potential. The trigger time of the camera was recorded by the oscilloscope in order to synchronize the images to the floating probe readings. Signals from the three probes were processed using complete ensemble empirical mode decomposition (CEEMD) as described in [5] by Torres. This is to isolate oscillations caused by the spokes from the waveform of the discharge and other noise. Empirical mode decomposition is a data driven, algorithmic method of decomposing time varying signals into a series of intrinsic mode functions. The sum of the intrinsic mode functions returns the original signal with no loss of information.

RESULTS

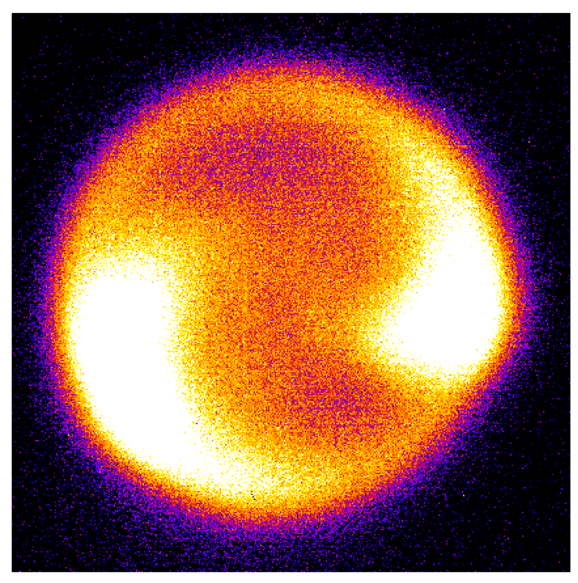

Figure 3.a: Image of spokes in discharge.

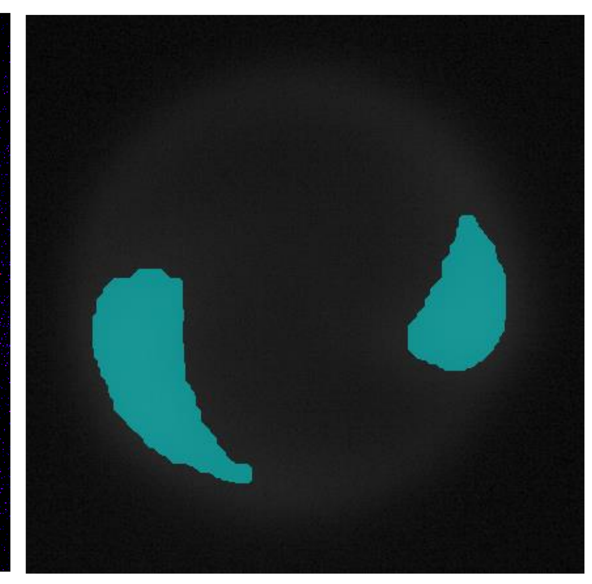

Figure 3.b: Identified spokes.

Figure 3.a shows the image captured by the camera, brightness boosted and in false colour. Figure 3.b shows the spokes from the same image as identified by our MATLAB script, overlaid on the original image. The image is an example of a mode two spoke since there are two distinct spoke structures. The size distributions for mode one and two spokes are shown below in figures 4 and 5, respectively.

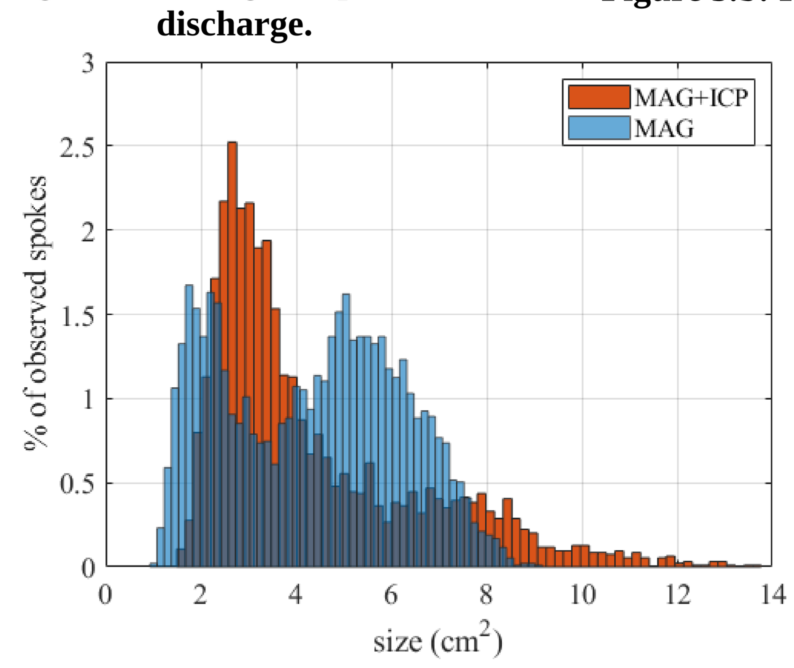

Figure 4: Mode 1 spoke size distribution.

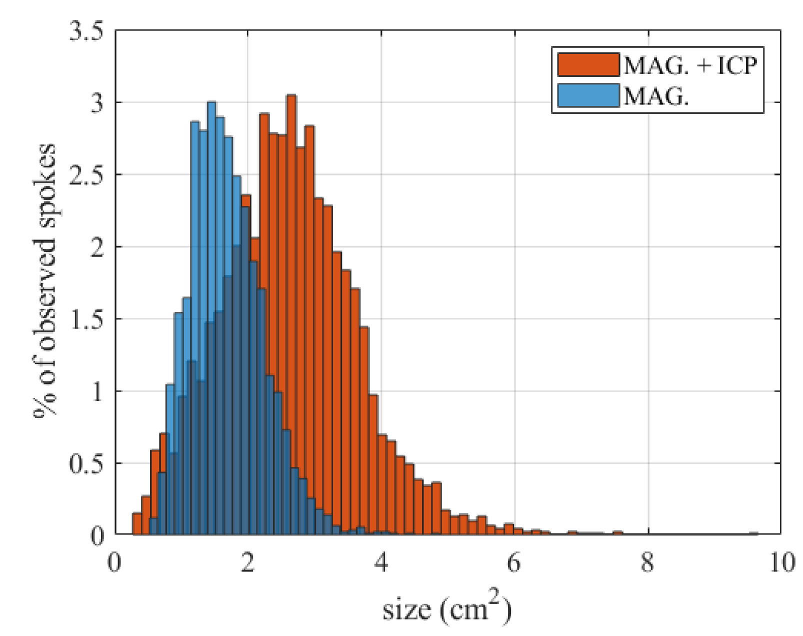

Figure 5: Mode 2 spoke size distribution.

The addition of a secondary ICP discharge changes the size distribution for both mode numbers, we postulate this is due to increased gas rarefication. For the mode one spokes, the magnetron only discharge is at a lower power, therefore experiences less gas rarefaction. The excess background gas allows for larger, more diffuse spokes to form. In the case of the combined discharge, the higher power leads to more sputtering, causing gas rarefaction thus reducing the sizes of the observed spokes. It was discussed by Hecimovic in [6] when there are two spokes, they compete with each other for argon gas. As one grows, it causes more gas rarefaction which causes the other spoke to decrease in size. This would produce the smaller spokes we see in the combined discharge size distribution for mode two. For the lower power, magnetron only discharge, the excess argon gas is able to feed both spokes and maintain their sizes, thus the distribution is closer to the peak.

The average mode number throughout a 100μs discharge is shown in figure 6, the corresponding discharge power waveforms are shown in figure 7 below. We observed a positive correlation between average mode number and discharge power up to a certain threshold, beyond which, the average mode number is stable around 1.5, the same relationship was also observed when using an aluminum target.

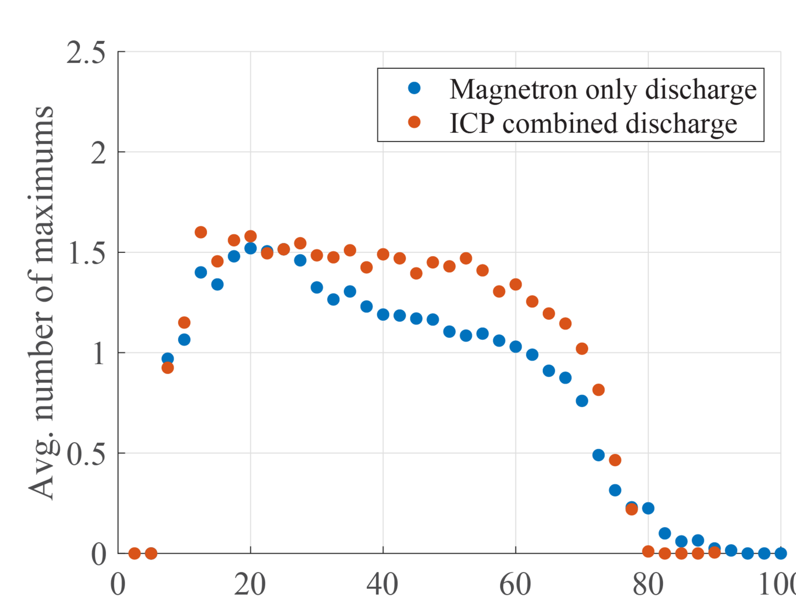

Figure 6: Average spoke number.

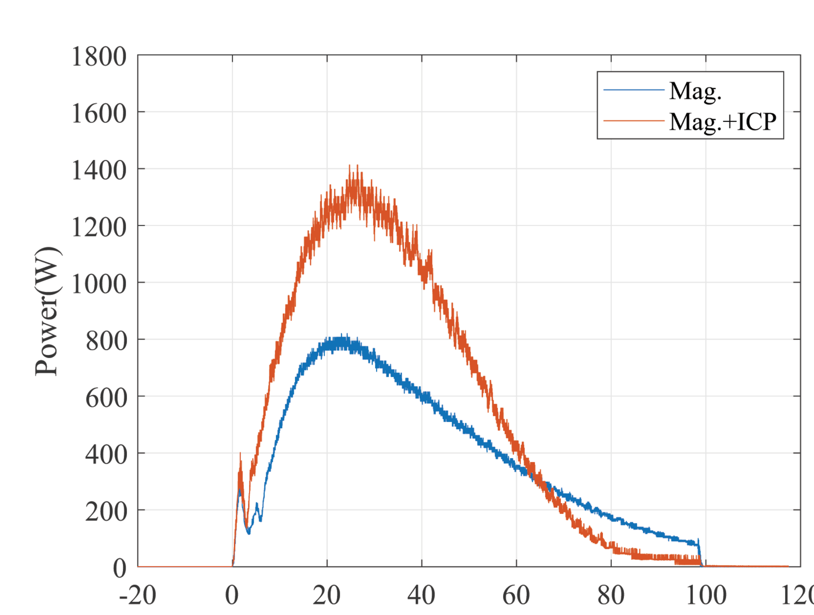

Figure 7: Discharge power.

The EMD processed floating probe signals are shown below in figure 8, the signals are offset vertically for readability. A clear oscillation can be observed in all three channels. Cross-correlating the signals we find a delay between the probes that corresponds to a clockwise rotation (in $\boldsymbol{E}\times\boldsymbol{B}$ direction) at ~13 km/s. The vertical lines indicate the time of the 1μs camera exposure shown in figure 9, the probes labeled in the image corresponds to the signals in figure 8. From the image, we can see that probes three and two are located near the front of the spoke and probe one is located on the tail end. The leading edge of the spoke is a source of electron flux from secondary electron generation [7]. This causes a drop in the plasma potential. Correspondingly, the signals from probes three and two show a lower potential at the time of the exposure, while probe one approaches a higher potential.

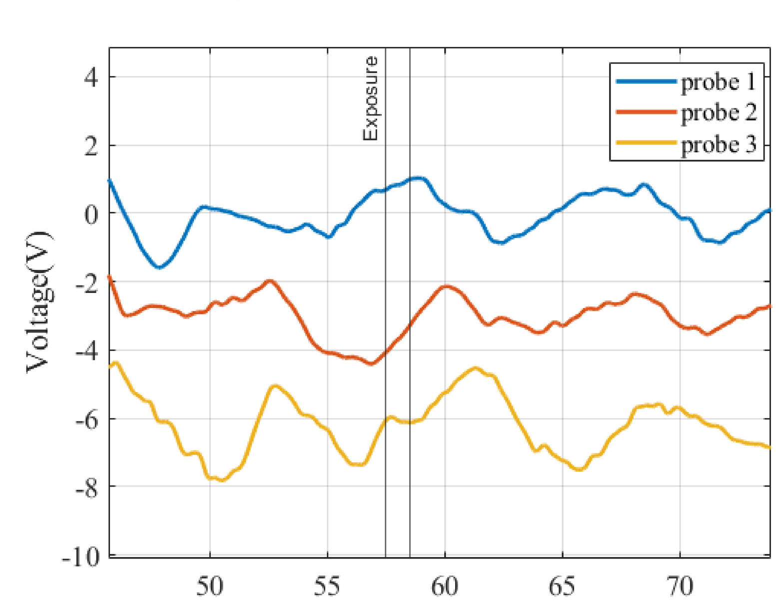

Figure 8: Processed floating probe signals

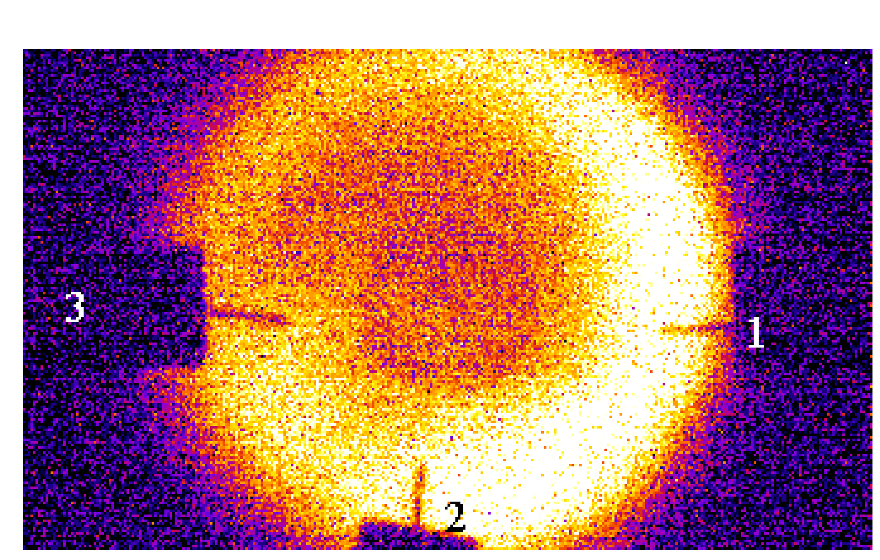

Figure 9: Image of discharge captured by camera

CONCLUSION

- Spoke instabilities in $\boldsymbol{E}\times\boldsymbol{B}$ devices are stochastic and happen on small time scales.
- We observed a rotation speed of ~13km/s using floating probes.
- A statistical picture of the spokes was constructed by combining images taken from different pulses.
- Less diffuse spokes were observed at higher power discharges due to gas rarefication.
- Gas rarefication causes more variation in the size distribution of mode two spokes.
- Our observations from the probes and camera showed decreasing plasma potential caused by increased secondary electron production at the leading edge of the spoke.
- Average spoke mode number follows the discharge power up to a certain threshold, past which it becomes stable around 1.5.

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ACKNOWLEDGEMENTS