The statistics of spoke configurations in HiPIMS discharges

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Abstract. Ionisation zones, or spokes to which the discharge self-organises during the HiPIMS pulse is a recently investigated phenomenon, however adequately describing or representing these highly dynamical features is a challenge. As the spokes rotate above the target their properties can change over time, with splitting or merging frequently occurring. Here we investigate the evolution of quasi-stable spoke configurations (modes) during the HiPIMS pulse by simultaneously employing six flush mounted strip probes evenly distributed over the target and through observation by a fast camera. This arrangement was used to track the changes in the spoke configuration. The effect of the discharge current at two different pressures on the spoke configuration was statistically examined. A large amount of data was evaluated to claim that at the pressure of 0.2 Pa, there exists an equal probability for spokes to merge and to split. In contrast, spoke configuration at pressure 4 Pa exhibited a strong driving force towards the higher spoke mode number, which was reflected by the significantly higher occurrence of spoke splitting over the spoke merging. A simple phenomenological model describing spoke merging and splitting is presented.

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1. Introduction

A few years ago, it was observed that the plasma is not always homogeneously distributed over the racetrack area of the target in high power impulse magnetron sputtering (HiPIMS) discharges [1, 2, 3], but under certain conditions it is self-organized into ionisation zones called spokes [2, 4]. Several non-perturbing diagnostic techniques have been used to investigate spokes these include photo-multiplier tube (PMT) [3, 5, 6, 7, 8], high-speed 2D imaging of the broadband emission [1, 2, 3, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18], spectrally filtered high-speed 2D imaging [19, 20, 20, 21], streak camera [21, 22, 23, 24], laser induced fluorescence (LIF) [20] and embedded probes [13, 25, 26]. Furthermore, more perturbing methods such as a Langmuir probe (single as well as multi-probe) [3, 5, 6, 7, 8], emissive probe [2], magnetic sensor probe [27] or triple probe [28] were employed for spoke investigation. The spoke phenomenon was also reported in direct current magnetron sputtering (dcMS) [29, 30], Hall thrusters [31, 32] and homopolar devices [33], all characterised by the $\mathbf{E}\times\mathbf{B}$ drifts.

In HiPIMS, spokes have been reported to rotate, depending on experimental conditions, in the $\mathbf{E}\times\mathbf{B}$ direction [1, 2, 3], as well as in the opposite direction to the $\mathbf{E}\times\mathbf{B}$ drift [8, 34]. The presence of spokes is restricted to a certain range of experimental conditions depending on the target material [9]. For the low currents, only non-recognizable or stochastic spokes are detected [5, 16]. The stable configuration of rotating diffusive, triangular or round spokes is observed when the current is further increased, typically at discharge current density of around $1\,\mathrm{A.cm^{-2}}$ [6, 16]. Using Cr, Cu, Mo or Ta targets, the spoke-dominated regime can shift to the homogeneous regime as a discharge current threshold is exceeded [9, 10, 12, 11]. The spoke mode number, i.e. the number of spokes was studied for various target materials by different groups [5, 7, 9, 10, 14]. It was found that in different experimental configurations contradicting results may be obtained. For example, using a titanium target and increasing the discharge current, different researchers observed that either an increase [1, 14] or decrease in spoke mode number [5, 7]. Recently, it was showed that by varying the pressure and the magnetic field it is possible to observe both an increase and decrease in the spoke mode number with increasing the discharge current within one apparatus [16]. Experimental conditions also strongly affect the spoke rotation velocity which is typically several km/s [16, 23].

Recently, phenomena of spoke merging [7] and splitting [13] were observed in HiPIMS plasma using both non-perturbing and perturbing diagnostic tools. In our previous work, observations of spoke merging and splitting were made using simultaneous measurements from embedded probes and high-speed camera imaging [13]. Based on these results a simple phenomenological model was developed relating the spoke mode number to the spoke dimensions, spoke velocity and gas atom velocity. Previously only three strip probes were utilised, embedded into the circular target, with a 25° gap in between them. Such a configuration provided information only from a small 15% portion of the target. The aim of this paper is to enrich the spoke study presented in the previous paper [13] by the employment of six strip probes evenly distributed around the whole target. Such an arrangement monitors the spoke configuration around the entire racetrack at any moment in time which enables us to study the stability of the spoke configuration under varying operating conditions.

2. Experimental set-up and procedure

Experiments were carried out using an Alcatel SCM 650 magnetron sputtering system equipped with a circular magnetron (Kurt J. Lesker) fitted with brand new 75 mm in diameter niobium target of 99.95% purity. The chamber was evacuated to the base pressure below $1 \text{x} 10^{-4}$ Pa by a roots and a turbo-molecular pump. The pressure in the chamber was controlled by adjusting the steady flow of argon gas with 99.999% purity. The discharge was driven by a Melec SIPP 2000 HiPIMS generator, supplying power in 150 μs pulses with a repetition rate of only 5 Hz in order to minimise film build-up on protective glass sheath and thus maximise the experimental runtime. For initiation of the discharge at low pressures, a Dressler Cesar 500 radio frequency (RF) generator pre-ionised plasma with a power of 20 W and frequency of 13.56 MHz was employed. More detailed information of the sputtering system and generators can be found elsewhere [13, 14, 16].

Six 2 mm wide flush-mounted rectangular niobium strips (same purity as the target) were isolated and evenly incorporated into the slotted target, see figure 1(a)-(c). They were used as strip probes [13, 25, 28]. The home-made anode able to be utilised with the strip probes was elevated 5 mm above the target surface. For better clarity, each strip probe was denoted in a clock-wise direction with the ascending number and the colour in respective order: red, blue, green, purple, orange and olive. Strip probes shared the same potential as the target and the current flowing through each of the strip probes was measured separately by a set of six Pearson current probes (Model 2877 with 1 V/A) whose signals were captured by a LeCroy WaveRunner 6100A and a Keysight Infiniium DSO-S 204A oscilloscopes working in the single shot mode, see figure 1(d). To suppress the rapid changes swinging in the signal during the HiPIMS pulse, a 2.4 Ω resistor was connected to the power supply circuit in series, between the measuring box and slotted target equipped with the strip probes, see figure 1(d). The added resistor worked as a negative feedback limiting the growth of the discharge current.

The optical system used for 2-D imaging of the spokes is shown in figure 1(c). The system consisted of a protective glass sheet situated on the substrate holder 51 mm above the magnetron head, a quartz vacuum window, an external convex lens with the focal length of 50 mm, a 45° mirror and an intensified charge coupled device (ICCD) camera. The ICCD camera PI-MAX 3 (Princeton Instruments) was equipped with Nikkor MF 80 − 200 f/4.5 camera lens. The ICCD camera possesses a dual image feature (DIF), which allows capturing two consecutive images with only a 3 μs delay between them. The exposure time was set to be 80 ns, and the start of the exposure was synchronized with respect to the beginning of the pulse. Grey-scale images with 1024×1024 pixels resolution captured by the camera were converted to the (false) colour using MATLAB Jet(72) colour scheme.

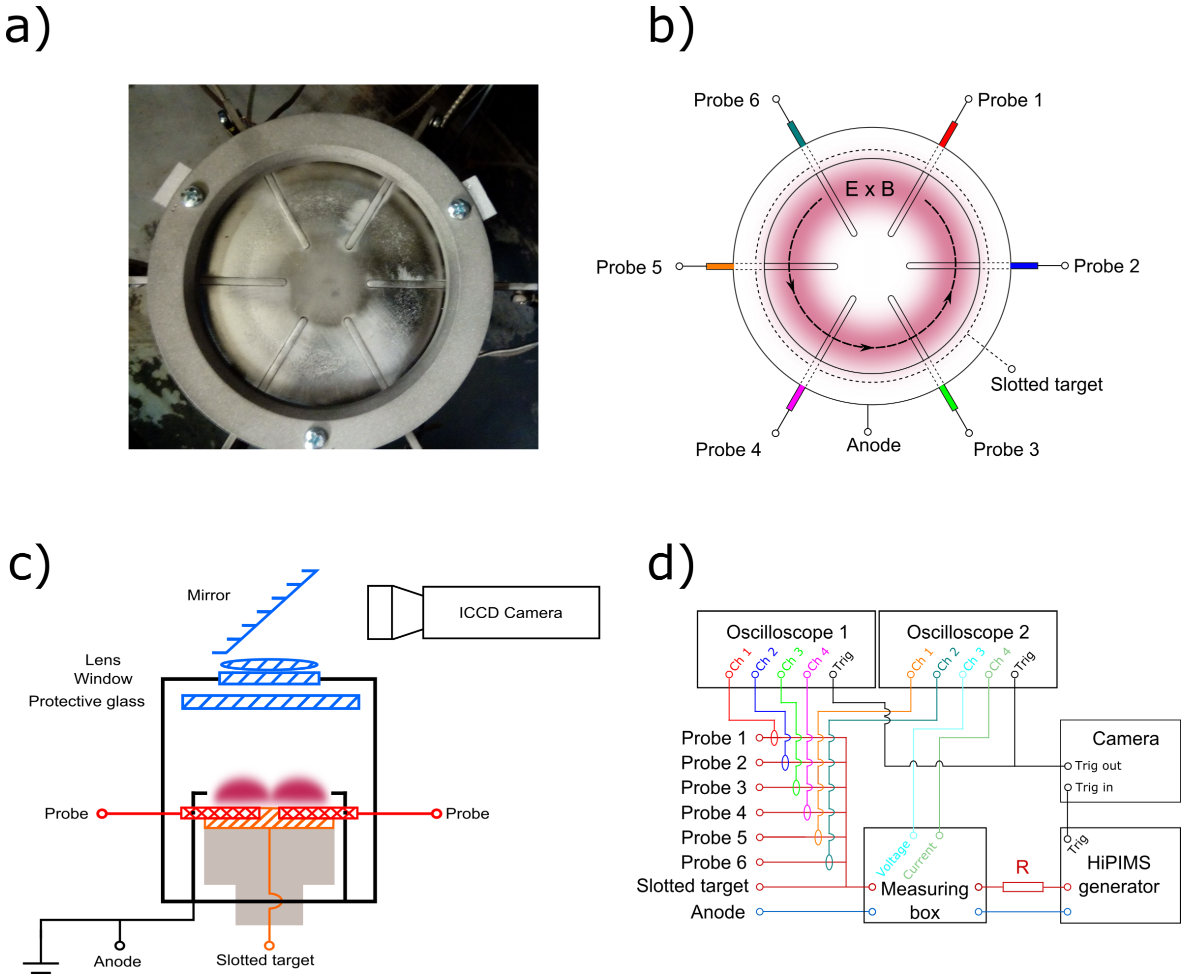

Figure 1. Experimental arrangement from a top view on the slotted target outfitted with six strip probes depicted as (a) photo and (b) schematics. (c) side view schematics of the experimental configuration with (d) measuring equipment.

3. Results and discussion

The paper studies the temporal behaviour of spokes using simultaneous plasma emission screening with ICCD camera and monitoring the current flow through the six strip probes. In the experiments 2.4 Ω resistor is connected in between the target and the generator to obtain sufficient stability of the discharge current. Typical cathode voltage and discharge current waveforms where the spokes are present during the pulse for the pressure of 0.2 and 4 Pa are depicted in figure 2(a)-(b). In both pressures the regime with the highest stability starts after 50 μs, where for the pressure 0.2 Pa a slow gradual rise of the discharge current up to the saturation and for the pressure of 4 Pa a plateau on discharge current up until the end of the pulse are observed. Due to its stability the period starting from 50 μs up to the very end of the pulse is chosen for the investigation of the spoke configuration.

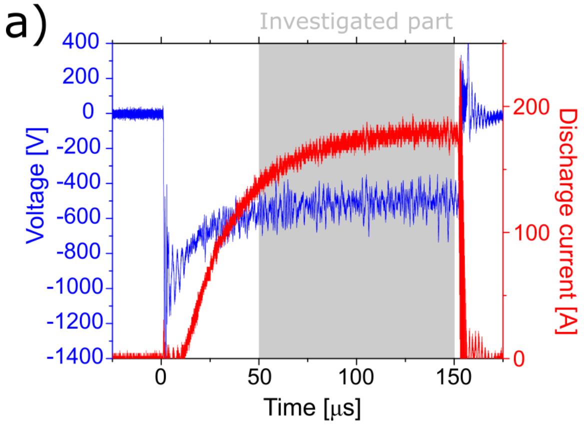

Figure 2. Typical cathode voltage and discharge current evolution in the experimental conditions where the spokes are investigated. Pressure is (a) 0.2 Pa and (b) 4 Pa, pulse length is 150 μs and repetition rate is 5 Hz.

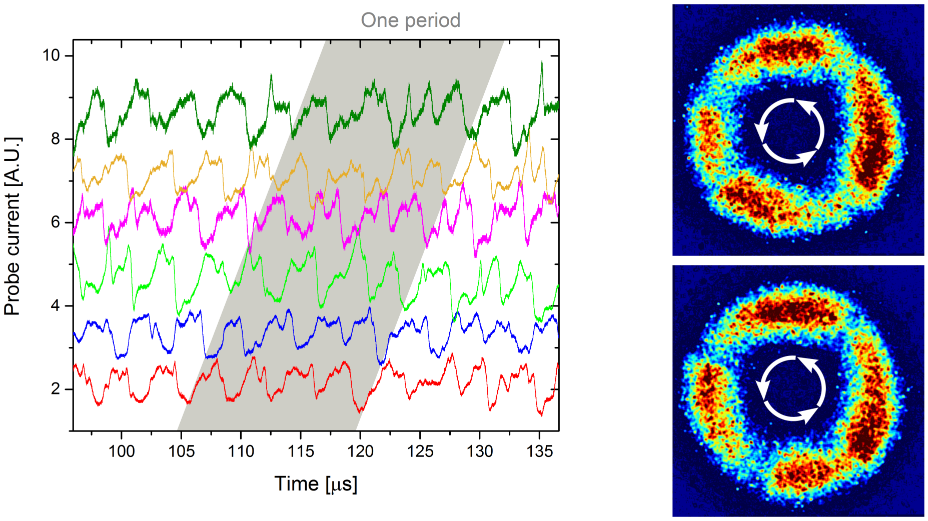

Figure 3. Typical strip probe current signal waveforms with respective plasma optical emission images at 0.2 Pa.

Strip probe signals together with dual images were captured and investigated in the stable region of the pulse. The typical strip probe signals obtained from all 6 strip probes together with dual images at 0.2 Pa are shown in figure 3. From the strip probe signals, it is possible to determine the shape, rotational velocity as well as the spoke mode number. The exact procedure for the determination of spoke properties is described in more detail in the previous paper [13]. In the depicted case, 4 diffusive spokes rotate at the $\mathbf{E}\times\mathbf{B}$ direction with a velocity of 15 km.s^{-1}. In our interpretation spoke begins at the end of the forgoing spoke, this can be backed also by the measurements of strip probes depicted in figure 3, where there is no plateau suggesting “empty area” before gradual rise of the probe current in the spoke. Therefore in this definition the change of the spoke mode number can be achieved only by spoke merging or splitting.

To recreate the spoke configuration in any point of time during the HiPIMS pulse, all six strip probe current signals were processed. The processing script utilises a least squares method to determine the rotational velocity of the spoke configuration at any time during the pulse. Afterwards, the temporal evolution of the rotation velocity obtained from the fit was used to transform the data to a frame rotating with the spokes. This gives a better visualisation, and missing data points between the probes were found from interpolation. This simple method allowed us to describe the spoke configuration at any moment in time. Contour maps were created to visualise the spoke configuration in the stable HiPIMS pulse conditions. Typical images are shown in figure 4 with colorscale from blue to red adjusted for the current minima and maxima, respectively. The data were interpolated with maximal temporal uncertainty of $2\,\mu$s at 0.2 Pa and $4\,\mu$s at 4 Pa. Each reconstructed configuration is depicted with 2D images of the spokes taken at 145 and $148\,\mu$s within one HiPIMS pulse.

The first reconstructed configuration depicted in figure 4(a) shows a case where at 0.2 Pa a constant number of four spokes was detected over the whole studied part of the HiPIMS pulse. Although no merging or splitting occurred as the spokes rotated in $\mathbf{E}\times\mathbf{B}$ direction, their characteristics were observed to slightly change over time. In a perfectly stable regime, one would expect the four spoke traces to retain their size, intensity and their mutual distance. This is however not the case, as their respective rotation velocities were seen to change by small fractions, seemingly independent of each other, which is represented by slight tilting of the spoke traces from the plane on the reconstructed picture. Additionally, spokes increased their size and intensity, which is represented by the broader and more intensive traces. The increase in the intensity is seemingly due to a slight increase in the discharge current over a studied duration of the pulse at a pressure of 0.2 Pa.

The second case depicted in figure 4(b) shows the spoke configuration within another pulse at the same pressure of 0.2 Pa. In the region denoted as I. one of the spokes firstly splits at $75\,\mu$s and then two newly formed spokes merge shortly after at $105\,\mu$s. This configuration remains stable until the end of the pulse. Similar to the previous case, both 2D optical images and reconstructed spoke current traces show changes in the spoke size and mutual spacing. The most prominent change is observed on the spoke traces belonging to the spokes neighbouring region I. It seems that both neighbouring spokes reacted to the spoke splitting by varying their velocities seemingly to keep their mutual distance constant. During the merging process, the spoke forgoing the region I. increased, while the trailing spoke decreased their respective rotational velocities. As the spokes in the region I. merged the situation reverses, the forgoing spoke decreased and trailing spoke increased their respective rotation velocities. The reaction of the neighbouring spokes to the events of spoke merging and splitting was instantaneous. This suggests that some fast process is responsible for the changes in a spoke reconfiguration. One of such processes is an interaction of spokes with the electric field. It was suggested that each spoke can be interpreted as a double layer [23]. During the spoke splitting a new double layer is formed, consequently a perturbation in the electric field is created well beyond the effects of Debye shielding. Another possible explanation of this fast reaction of spokes is an influence of the electrons drifting in the $\mathbf{E}\times\mathbf{B}$ direction, which may transport the information of the change towards the neighbouring spokes with velocities an order of magnitude higher than the spoke rotation velocity [2, 4, 35, 36].

A third representative case of spoke behaviour at 0.2 Pa is shown in figure 4(c). At the beginning of the studied region, a configuration of 5 spokes is observed. In region II., at 70 μs, two spokes are seen to merge. Similar to the previous case, the neighbouring spokes reacted to the merging with the adjustment of their respective sizes and velocities. The newly created configuration remained unchanged until the spoke that had been formed by the merging, subsequently split at 95 μs in the region denoted as III. One of the newly formed spokes merged shortly after at 110 μs. On this occasion it did not merge with its sibling counterpart as it was described before, rather it merged with its trailing neighbour. One should note, the reaction of the neighbouring spokes to these events is less noticeable than as described before. One of the reasons may be that the spoke created by the splitting had a smaller size and lower intensity, thus their effect on the neighbours was much less pronounced, to the point that the trailing spoke merged with it.

The last case from figure 4(d) tracks the spokes at the pressure of 4 Pa. Compared to the previous cases discussed for a pressure of 0.2 Pa, the initial configuration consisted of a higher number of spokes, similar to observations reported earlier [16] and their rotation velocity was 8 km.s^{-1}. At first, the configuration consisted of eight evenly distributed spokes, two of which merged at 65 μs in the region denoted as IV. Here the results suggest that merging of the spokes does not occur in the same way as the previously mentioned cases. The two spoke intensity maxima did not merge, but the less intensive spoke gradually diminished itself and preceding neighbour took its place. The process is still treated as the spoke merging, as the spoke mode number changed and preceding spoke occupied the position left after merging. Consequently, there was a clear shift of spokes preceding the merged one, which indicates a decrease of rotational velocity, while the following spoke retained its velocity. The situation denoted as V. in figure 4(d) suggests a simultaneous merging on one part of the target together with splitting in close vicinity. As the temporal uncertainty in figure 4(d) is up to 4 μs it is hard to draw final conclusions, but it is clear that the number of spokes did not change. Also, the effect on the closest neighbours is not significant, only the forgoing spoke is effected and it slows down at the beginning of the event and then progressively returns to its former position.

Events reconstructed throughout the images in the figure 4 show several possible scenarios of spoke behaviour during the HiPIMS pulse. Even though the most stable scenario was achieved, spoke merging and splitting events were still observed. The merging and splitting events occurred in different combinations either in the succession or seemingly simultaneously on the different parts of the target. It was found that the merging and splitting of the spokes affect the neighbouring spokes. The spokes have a tendency to keep a constant gap between them, therefore during the spoke merging, the neighbouring spokes are attracted towards the newly created space and during the spoke splitting they are repelled. Additionally, the reaction of the neighbouring spokes to the merging and splitting events was very fast, much faster than the spoke rotation velocity and it could be captured by a multiple strip probes at once. Based on this, two possible causes are considered to be responsible; the electric field associated with the double layer of the newly created spoke, or fast electrons rotating in the $\mathbf{E}\times\mathbf{B}$ direction transferring the changing plasma density. The underlying physical processes that allow spokes to be effectively linked cannot be determined as they occur on much faster time scales than the temporal resolution of our diagnostic methods.

The spoke configurations depicted in figure 4 were investigated further by determining the overall charge supplied by the whole spoke configuration to any particular strip probe during a single rotation. It was found that regardless the change in spoke mode number, the overall charge collected by the strip probe was constant. Contributions from both the spokes and the background discharge were conserved. This is in agreement with previous results in which only a single spoke was evaluated [13].

In the previous paper [13] it was suggested that the overall amount and stability of the spoke configuration is bound to the actual experimental conditions. Here for both studied pressures (0.2 and 4 Pa) the applied voltage was changed, which consequently changed the discharge current. In each experimental condition, the evolution of spoke mode number during the stable part of the pulse was investigated. Multiple pulses at the same experimental conditions were evaluated to obtain sufficient statistical data. The results are shown as a probability distribution of the spoke mode number for several discharge currents at pressures of 0.2 Pa and 4 Pa in figure 5(a)-(b), respectively. For a pressure 0.2 Pa for all discharge currents the most dominant configuration has 4 spokes, with a probability ranging from 58% to 73%. Configurations with the larger amount (5 spokes) and the smaller amount (3 spokes) are present for all studied discharge currents and if the system is in one of these configurations it has a tendency to shift into the most probable 4 spoke configuration. The highest probability of 5 spokes detected at the pressure 0.2 Pa was achieved for the discharge current of 140 A. Any alteration of the discharge current decreases the average spoke mode number. The similar observation was then made concerning the effect of pressure [16], where the spoke mode number firstly increased with increasing pressure and afterwards decreased. The probability distribution of the spoke mode number for the 4 Pa case depicted in figure 5(b) was more straightforward. Generally, the increase in the discharge current also increased the probability of detecting higher spoke mode numbers. For a discharge currents up to 140 A, the most probable configuration was with the 6 spokes; for the discharge current of 150 A the most probable configuration was with the 8 spokes. At this current, no 6 spoke configurations were observed. The overall increase in spoke mode number with

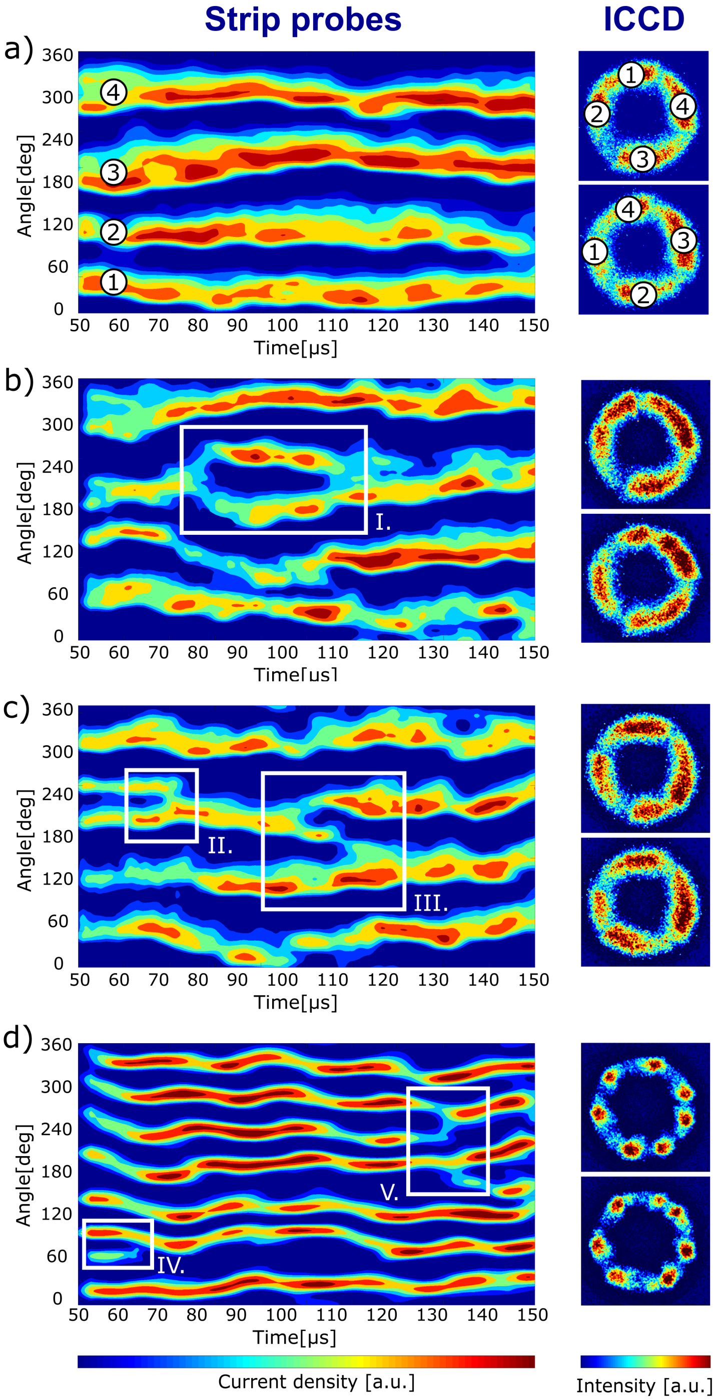

Figure 4. A typical reconstruction of the spoke configuration during the pulse from 50 to 150 μs for pressure (a)-(c) 0.2 Pa and (d) 4 Pa including the reference plasma emission images taken at 145 and 148 μs. The spokes in part a) are numbered in ascending order for better tracking. The sections of interest are marked by the Roman numerals I.-V.

the discharge current and pressure is in agreement with the results reported in [14].

All the data used for figure 5 were evaluated with the aim to characterize simple events the spoke configuration may undergo during the studied part of the pulse. Five

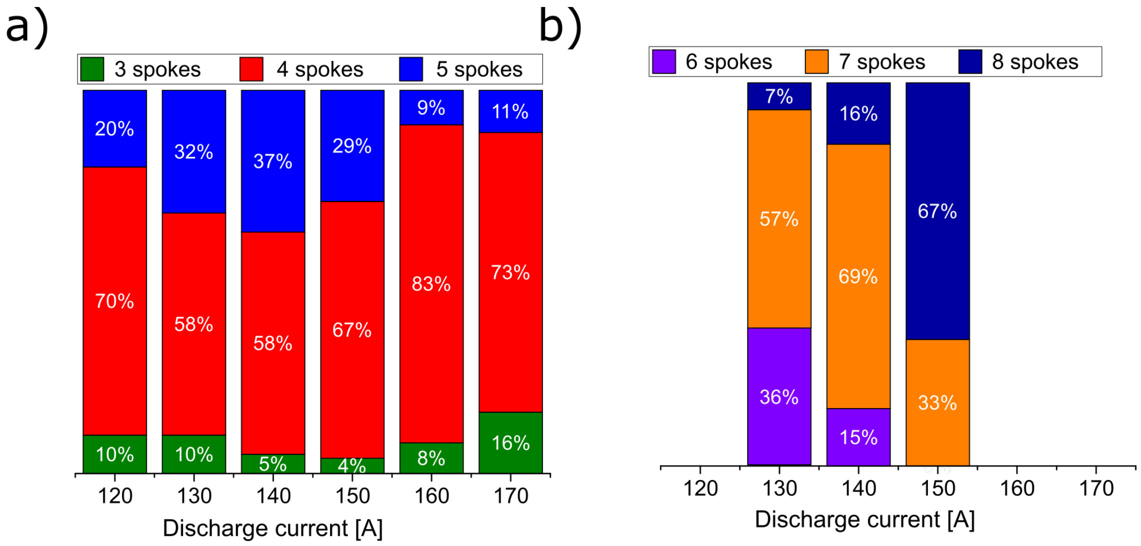

Figure 5. Probability distribution of the spoke mode number on discharge current for (a) 0.2 Pa and (b) 4 Pa.

simple events were distinguished, see figure 6(a). The first event denoted as I represents the situation where the spoke mode number is conserved over the whole studied part of the pulse. Note, this also includes the case where the spokes split on the one part of the target and merge at the same moment on the other part of the target. The second event denoted as II refers to the case where the overall spoke mode number decreases by 1 over the studied part of the pulse. This represents an overall merging process. A similar distinction is for overall spoke splitting marked as III, where the spoke mode number during the pulse increases by 1. During the pulse, however, some spoke merging might be followed by splitting, or vice versa. The last two groups are therefore a combination of merging followed by splitting (IV) and splitting followed by merging (V).

In the experiments here, there were also some occurrences of spoke mode number increasing, or decreasing by 2 from the initial value over the studied duration of the pulse, however, that happened only in less than 2% cases, therefore such behaviour was excluded from the general description of the spoke behaviour. Moreover, during the pulse the spoke configuration may change multiple times, these changes may be described as a sequence of simple events. This is illustratively depicted in figure 6(b), where during the pulse spoke configuration undergoes three simple events in succession; splitting and merging (IV), followed by merging and splitting (V) and finally a merging event occurs (II).

Using the events notation described in figure 6(a), the probability of occurrence during a pulse for the pressure 0.2 Pa and 4 Pa was created, see figure 6(c). For the pressure of 0.2 Pa the probabilities of simple merging (II) and splitting (III) processes during the pulse were practically the same, therefore the system was overall in a semi-stable state where the spoke mode number had no tendency to change. On the other hand, the combination of splitting and merging (V.) was more frequent than the opposite combination (IV), so the system preferred to increase the spoke mode number, but soon after it decreased to the former state. In contrast at 4 Pa the simple splitting (III) was strongly favoured over the simple merging (II) process, therefore the system had a strong tendency to increase the spoke mode number over the investigated duration of the pulse even in a seemingly stable configuration. At 4 Pa both combinations of merging and splitting were occurring nearly with the same probability slightly favouring event where spokes split and then merged (V) afterwards. The spoke configuration for the 4 Pa was less stable than that for 0.2 Pa, which can be also seen on the occasions where no variation of spoke mode numbed (I) was observed over the whole pulse. For pressure 4 Pa spoke configuration remained stable only for 15% of pulses, while for pressure 0.2 Pa it was 25%.

Even though the spoke configuration was investigated in the part of the pulse where cathode voltage and discharge current were stable, only in up to a quarter of occasions the spoke mode number was constant. For a pressure of 0.2Pa the spoke mode number in any observed experimental condition ranged from 3 to 5. Merging and splitting processes at this pressure had the same probabilities. The system was in a semi-stable state where the dominant configuration consisted of 4 spokes and any change in the spoke mode number had a tendency to return into the former state. For the 4 Pa the situation was different, spoke mode number ranged from 6 to 8 and the dominant spoke configuration changed with the discharge current. Increasing the discharge current the spoke mode number increased. Additionally spoke splitting was favoured over the merging, therefore during a pulse the spoke mode number had a tendency to rise even when the discharge current was kept constant. This suggests that on the background some inherent discharge parameters such as ionization fraction, secondary electron production, electron concentration or electron temperature progressively change, which consequently affects the spoke system to the degree that the spoke splitting is favoured. This is in strong contrast with the prediction in our previous work where only a small part of the target was monitored [13] and at the steady experimental conditions, only a stable spoke configuration was observed and all the merging or splitting processes occurred were soon after negated by the opposite processes.

4. Spoke model

As of today there is no single unified spoke model that would qualitatively describe all the spoke properties and spoke configurations, even though several were proposed [8, 13, 23, 37, 38, 39, 40, 41]. Here we would like to propose a model explaining experimentally observed spoke behaviour. The model itself is similarly to the model proposed by Anders *et al* [37], based on ionization of sputtered metal by the electrons rotating in **E**×**B** direction, subsequent back-attraction of these ions to the target and re-sputtering. The proposed model does not consider the effects of the argon, as it was shown that the spoke motion is driven by argon gas only in DCMS, where argon dynamic induces the counter **E**×**B** spoke rotation [21]. In HiPIMS the ionisation of the sputtered

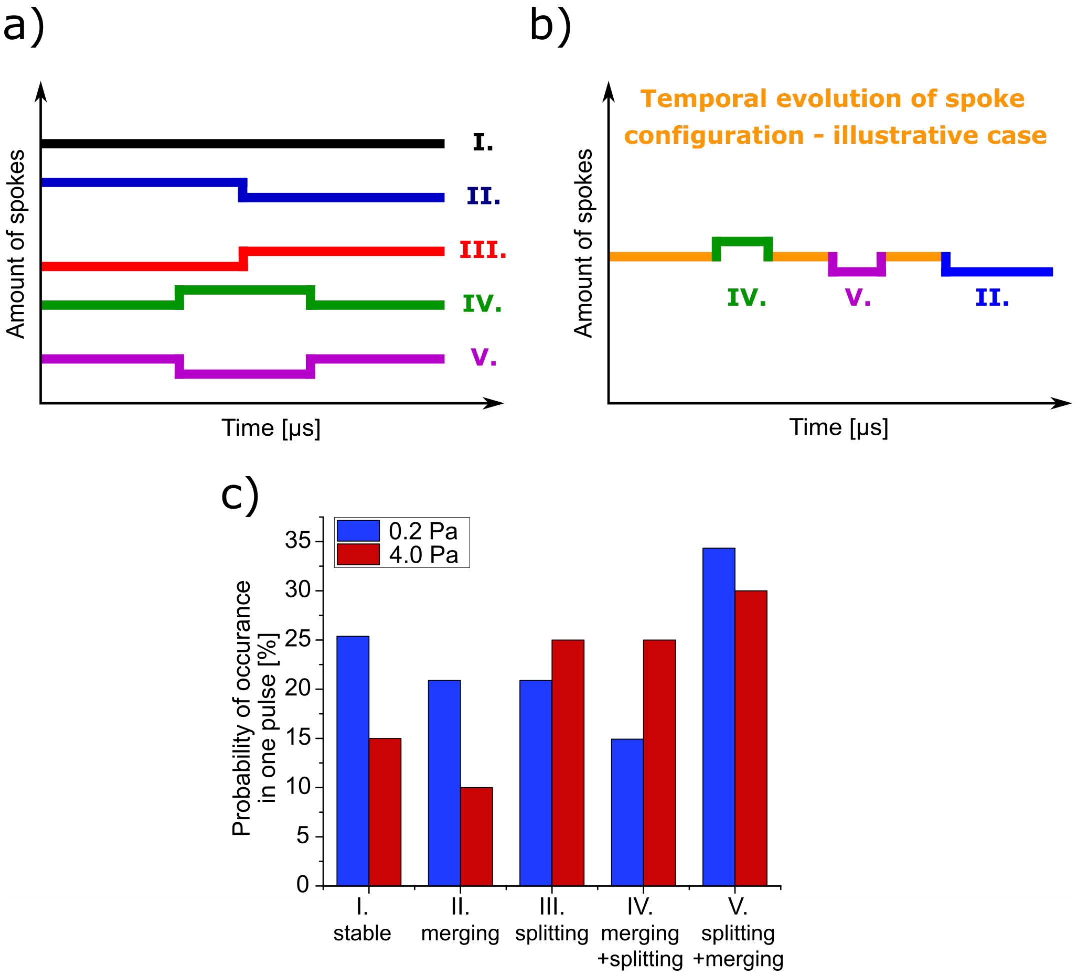

Figure 6. (a) schematic representation of elementary spoke behaviour (b) illustrative case with spoke configurations change in one pulse. (c) probability of these processes occurring during one pulse as 0.2 Pa and 4 Pa. I. spoke amount is conserved, II. spokes merges, III. spoke splits, IV. spoke merges and then splits, V. spoke splits then merges.

species as well as the gas rarefaction are both high, and according to the model proposed by Anders, the spoke motion is governed by the ionised sputtered species dynamic [21]. Consequently, the spoke characteristics in our model are described only in terms of the Ti atom and ion concentrations as well as the concentration of electrons. Although in the HiPIMS discharge the ionisation is very high (for titanium nearing 100% [42, 43]), the metal atom concentration could not be neglected as it is presumed that titanium atoms are sputtered from the target and only then they are ionised by the collisions within the discharge. For simplicity the effect of metal ions is reduced to singly ionised Ti, even though in similar experimental conditions to those described here (pressure of 0.5 Pa and cathode voltage of 800 V), the ion flux consisted from high concentration of multiply ionised metal ions [44] and even four times ionised metal species were detected [45].

For simplicity the model presumes one well developed spoke spread over the whole circumference of the racetrack as it is shown in figure 7(a). The concentration of the

Ti neutral is gradually increasing over the spoke until the trailing edge where it drops and the strong concentration of Ti ions is observed. These Ti ions are created through electron impact ionisation of the neutral metal atoms in the trailing edge of the spoke rotating in the $\mathbf{E}\times\mathbf{B}$ drift channel. Such spoke inner arrangement is in agreement with the spectroscopical measurements [19, 21]. Ti ions created at the trailing edge of the spoke are back-attracted to the target surface where they induce re-sputtering of the metal in a similar manner as was described earlier in the model by Anders [37]. Re-sputtered Ti atoms then serve as a "fuel" for following spoke and the process repeats itself similarly to the model described before [13]. The ions back-attracted to the target also induce local higher secondary electron production which is represented by the higher concentration of the electrons at the beginning of the spoke. If the total charge of the electrons and ions is considered the evolution reflects the asymmetric shape of potential hump described here [23].

With presented simple model it is even possible to describe spoke merging and splitting events. If the stable state described in the figure 7(a) is disturbed, i.e. the discharge current is increased, a surplus of sputtered titanium may occur, see figure 7(b). A small perturbation in sputtered particles can emerge, represented by a small bump at the beginning of the spoke depicted in figure 7(c), which due to availability of electrons may be self-amplified over a short period of time and the new smaller spoke forms, see figure 7(d)-(e). In the ideal case, the system reaches an equilibrium state where there are two essentially identical spokes evenly distributed over the whole racetrack circumference as it is shown in figure 7(f). In reality, this is not often the case, as most of the time the spoke sizes are different as well as their mutual spacing and the perturbations in form of bumps are created randomly. Our experimental observations revealed that even though these events are occurring randomly, usually the spoke number remains constant over the pulse and events such as splitting and merging are relatively rare. Here, the described model directly presents a view on the spoke splitting, but the same pattern can be used in reverse case for a description of spoke merging.

5. Conclusions

Using optical and electrical diagnostics the evolution of spokes during the active and stable phase of the HiPIMS pulse was studied. A range of operating conditions was chosen as follows; discharge current 120-170 A at 0.2 Pa and 130-150 A for 4 Pa. In all studied conditions the spoke configurations were prone to change via spoke merging and splitting events. For the lower pressure of 0.2 Pa the most probable configuration was with mode number 4 and the statistical analysis revealed that spoke merging and splitting are equally probable. However, at a pressure of 4 Pa higher mode numbers were observed with the most probable mode number increasing from 7 to 8 as the discharge current increased from 130 to 150 A. At this pressure and at 150 A there is approx. 70% chance of 8 spokes being established. For this pressure during any single pulse splitting events are more probable than merging. In addition, a simple

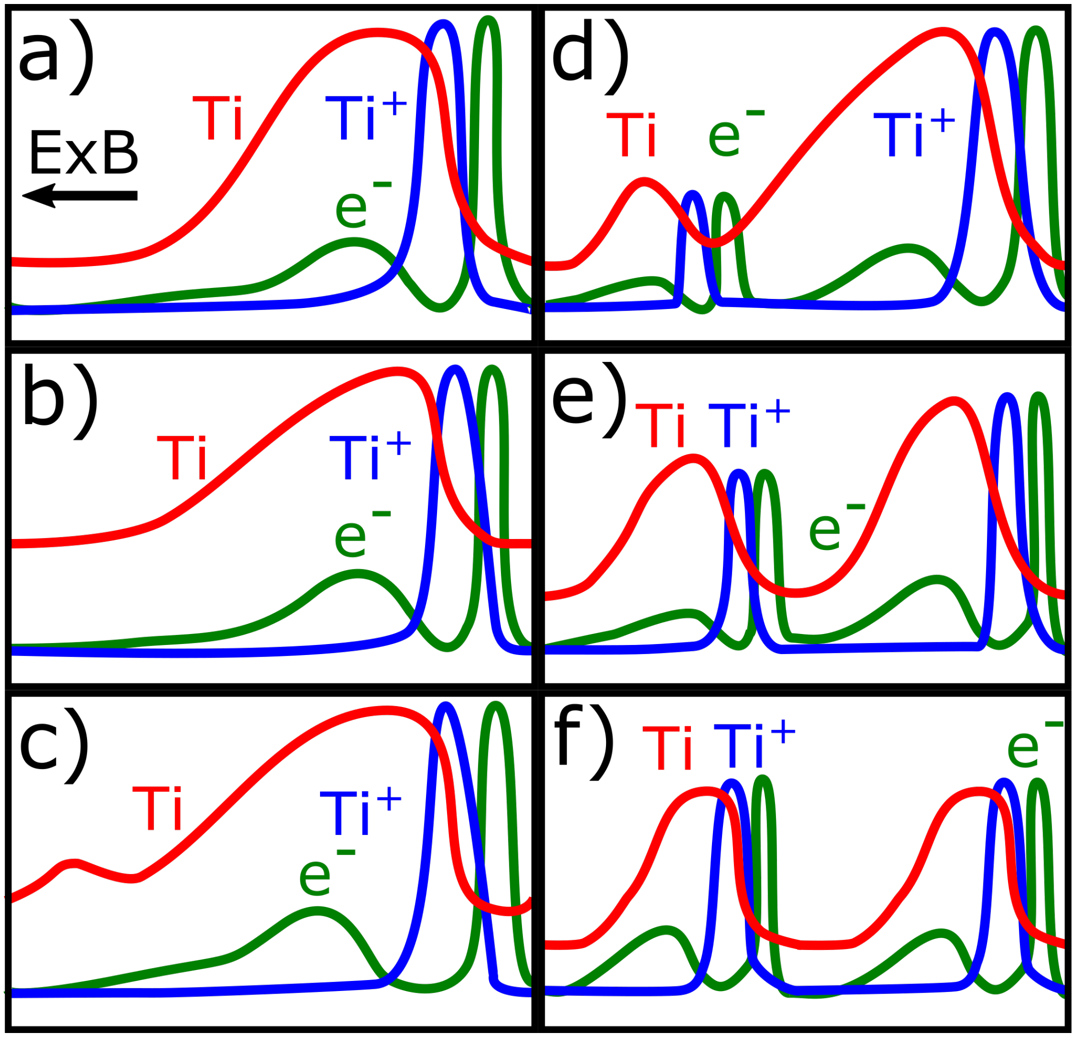

Figure 7. Schematic drawing of the spoke model concerning spatial evolution of electron, Ti atom and ion concentration. (a) Stable one spoke configuration gradually changes (b)-(f) towards the stable two spoke configuration (f).

phenomenological model of spoke behaviour is presented which allows us to interpret observed stable spoke configuration as well as merging and splitting events.

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