Control of spoke movement in DCMS plasmas

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Abstract
Spokes appear as zones of increased ionisation in magnetron sputtering discharges. They rotate in front of a 2° target at a natural frequency between a few 10 kHz and several 100 kHz and move in $\vec{E} \times \vec{B}$ or anti $\vec{E} \times \vec{B}$ direction depending on plasma power. Spokes are known to cause strong gradients in plasma density and potential and can, thus, increase the ion transport from target to substrate. Here, we explore the possibility to control spokes by applying a given frequency $f$ to a set of control probes around the plasma to lock the spoke movement. The efficiency of this locking is analyzed by diagnostic probes and energy resolved mass spectrometry, which measure the integrated ion fluxes leaving the magnetic trap region. It was found that the spoke movement could be locked to the external control signal at frequency $f$ around the natural spoke frequencies $f_0$. The additional control signal affects the ion flux twofold: (i) a 15% increase in ion flux towards the substrate and a 15% reduction in radial direction irrespective of control frequency is observed, which is explained by a change in plasma confinement since electric fluctuations at the separatrix are induced; (ii) the locking at $f$ causes an increase in ion current in normal as well as in radial direction for $f < f_0$ and a reduction for $f > f_0$. This is explained by either longer or shorter residence times of ions in the electric fields caused by the spoke, or by an enhancement of these fields caused by the control. Using this spoke controlling technique an overall increase of ion flux towards the substrate of up to 30% was realized.

Keywords: control, spoke, magnetrons, plasmas

1. Introduction
Magnetron plasmas are an essential processing tool to convert a solid target into new materials. The magnetic confinement assures a high density plasma and an efficient sputtering of a target surface. Such plasmas can be operated in dc mode (dcMS) or in pulsed modes using very high powers during a pulse (HiPIMS—high power impulse magnetron sputtering). In the HiPIMS, the ionization degree of the sputtered material can be as high as 90% [1] and the very energetic growth fluxes yield materials with superior qualities [2–4]. In all these plasmas, localized ionization zones are formed that become visible in high speed images [5–7]. The number of these ionization zones along the plasma torus, their velocity, and their direction of movement were analyzed by many groups [8–10]. In short, such ionization zones may resemble drift waves that are driven by the strong gradients in these magnetized plasmas [11,12]. The velocity of these ionization zone is typically at 10 km s$^{-1}$ along the racetrack [13,14]. The electrons move much faster at typically 100 km s$^{-1}$, whereas the ions move only at 1 km s$^{-1}$ [15,16]. This shows that spokes are an excitation zone. The rotation occurs either in $\vec{E} \times \vec{B}$ or anti $\vec{E} \times \vec{B}$ direction depending on plasma power [11, 13, 17].

Spokes were analyzed by many groups by measuring the emitted species fluxes or using activate and passive spectroscopy to understand plasma excitation [18–20]. In general,
the existence of spokes is beneficial to the material transport since the local plasma density and the shielding of the electric field reduces the efficiency of the return effect in magnetron plasmas, where the sputtered species return to the target instead of traveling to the substrate after ionization [7, 20–24]. This led to the research question, whether an intentional control and taming of the spoke movement could be exploited to improve the magnetron processes in general.

For such a control of plasma waves, a synchronized controlling by electrical probes is a well established methodology in plasma physics studying various wave phenomena. An example is drift wave control in magnetized plasmas, where the periodic excitation of a probe array at the circumference of a linear plasma column [25–27] or a magnetron [28–30] can lock the frequency of these drift waves. This locking causes usually an enhancement of the wave amplitude, because the energy of the different modes is transferred to the locked mode at the control frequency. This interplay between the external control and the resonance frequencies in the system can be very well described by the model of a classical forced oscillator [27]. In this paper, we follow this concept of synchronizing the spokes in a Direct Current Magnetron Sputtering (DCMS) plasma to an external control signal and investigate, whether the transport can be enhanced by this method.

2. Experimental setup

2.1. DCMS setup and discharge parameters

Figure 1 shows a sketch of the experimental setup. The experiments were conducted in a vacuum chamber with a base pressure of $10^{-4}$ Pa. Argon was used as the working gas at a pressure of 0.4 Pa at 10 sccm of gas flow rate. Power to the target was delivered by a Melec SPIK 1000A power supply. The power supply was operated in d.c. mode, with a constant voltage of $-256$ V resulting in a discharge current of 25 mA and a power of 6.4 W. Under these conditions, strong and highly regular spokes were observed, redfacilitating a more reliable control. A single spoke was observed, moving in the retrograde $\vec{E} \times \vec{B}$ direction, as is typical under these conditions [11, 13, 22]. A planar magnetron assembly was used to create the discharge (Thin Film Consulting IX2U). Figure 1(b) shows the magnetic field configuration of the magnetron assembly. The employed magnetron assembly was equipped with an aluminium target of 3 mm thickness with a diameter of 50 mm.

2.2. Control scheme

Four control probes and a diagnostic probe were mounted around the target, parallel to the target surface and at a distance 20 mm from the center of the magnetron. The probe position is shown in figure 1. The tip of these probes was far away from the core of the plasma, just crossing the last closed magnetic field line (separatrix), to minimize the disturbance of the discharge. The distance of all probes to the target surface was 4 mm, unless otherwise mentioned, and could be enlarged by an additional distance up to 5 mm. Two of the control probes were at 12 and 1 o’clock position and the other two were at 6 and 7 o’clock. Each set of two adjacent control probes was connected to the same power amplifier and thus both were at the same voltage. The control signal was generated by a Tektronix function generator (AFG 3251) and amplified by two fast voltage amplifiers (Hubert A 1110-05-A). The control signal was applied in short burst pulses with a repetition frequency of 60 Hz. A typical pulse can be seen in figure 2. It consists of an off time of 2 ms, where the voltage on the probes was $-52$ V. During this time, only a small amount of ion saturation current is drawn from the plasma, causing only minimal disturbance. This voltage was adjusted to be slightly below the floating potential of typically $-48$ V at this location to ensure that the probes are only drawing ion saturation current. A difference of about 4 V between the floating potential and control probe voltage was kept intentionally to account for any minute drifts in the floating potential during an hour-long measurement. The floating potential at this location was estimated by first detaching the control probes from the amplifier and measuring the voltage across the control probes between the plasma and the ground with a 1 MΩ resistor in series. The off time was followed by 3 ms on time in which a rectangular signal with a
duty cycle of 50% was applied. The high voltage of the signal was 21 V and the low voltage was again −52 V. The high voltage was chosen to be above the maximum plasma potential when a spoke passes by the probes to assure optimal locking. The frequency of the signal during the on time was swept from 0.1 kHz to 46 kHz.

The biasing of the control probes may also alter the plasma properties by changing the discharge voltage and discharge current, thus causing changes in the observed ion flux as a consequence of a different absorbed power. To exclude this, we carefully monitored the discharge current and observed only a 10% change. This is not enough to strongly affect the changes in measured ion fluxes, observed here. These variations in discharge current could be avoided by operating the plasma in the current regulation mode, but the employed power supply did not allow this for such low powers.

The trigger output of the function generator was used to trigger an oscilloscope and the measurement of a mass spectrometer. All currents and voltages were measured by a Teledyne Lecroy HDO8058A oscilloscope. A time window of 5 ms was acquired for each control pulse and the data was written to the hard drive with a frequency on the order of 10 Hz. Thus, only a subset of all control pulses were recorded since the control signal pulsing frequency was 60 Hz.

2.3. Plasma diagnostics

2.3.1 Diagnostic probe. The response of the spokes was measured by another probe, placed at the 9 o’clock position. The probe was placed 6 mm away from the racetrack in radial direction and was biased to a constant voltage of −37 V to measure ion saturation current. Each spoke passing by this probe caused an increase in the measured ion saturation current, as was already described elsewhere [20]. In dcMS mode, this current corresponds predominantly to the argon ion current. Thus, a change in spoke frequency or amplitude caused by the signal at the control probe could be observed by this diagnostic probe.

2.3.2 Mass spectrometer. A mass spectrometer was used to analyze the ions leaving the discharge in axial direction. The device was a Hiden EQP300 HE system, pointing onto the racetrack of the target, at a distance of 150 mm. Singly charged aluminium ions were measured with energies ranging from −1 eV to 4 eV. The manufacturer states a resolution of 0.75 eV for the energy analyzer. The mass was set to 27.4 amu in order to reduce the intensity of the signal and prevent detector saturation. It was checked that this change did not influence the measured Ion Energy Distribution Function (IEDFs).

Time resolved mass spectrometer measurements were realised with a multi channel analyzer, as previously described in greater detail [31]. This gave a temporal resolution of 500 ns and the data was averaged later on to distinguish the on and the off times of the control probe signals. For each applied control frequency, a full IEDF was measured and analyzed.

3. Results and discussion

3.1 Control of the spoke movement

During the off time of the control signal, the control probes are biased at a constant −52 V and a natural spoke frequency \( f_0 \) of 31 kHz was observed. At first we regard the impact of the control probe signal on the spoke movement, when a frequency \( f = 28 \) kHz is applied. The response of the system is followed with the signal at the diagnostic probe. Figure 3(a) shows a typical time trace for the diagnostic signal (red curve) that has been averaged over 570 cycles. During the off time of the control signal \( t < 2 \) ms, the signal peaks caused by the spokes are mostly averaged out since their frequency and phase is not stable. At \( t = 2 \) ms the control signal (blue curve) is switched on, and a regular oscillation of the diagnostic signal builds up, because the spoke movement is now locking to the control signal at \( f \). Both signals are normalised from 0 to 1 to be displayed in one graph.

The control signal at \( f \) affects the diagnostic probe signal twofold, namely a locking to the frequency \( f \) and an overall decrease of the signal. The locking alone is made visible by de-trending the signals as shown in figure 3(b). The graph was obtained by using a Savitzky–Golay filter on the diagnostic signal and subtracting the result from the original signal. Here the trends of the diagnostic signals are better seen: the amplitudes increases over time. After three oscillations (100 \( \mu s \)) a steady state in the diagnostic probe signal is reached. We attribute this increase to an increasingly stable phase and frequency of the spokes, thus causing less attenuation by the averaging. Figure 3 shows that the overall decrease of the diagnostic signal occurs on a different time scale. This indicates that several different mechanisms might affect the spoke movement control.

Frequency locking. As demonstrated by figure 3(b), the frequency locking does not occur instantly, but needs to build up over a specific time of about 100 \( \mu s \). Apparently, the applied control signal affects the spoke movement over time by either
accelerating or slowing down the spokes until they lock to the external control probe signal. Locking is defined as a very regular movement of the spoke in sync with the periodically applied control probe signal. Such a locking process could, for example, be caused by the interplay of the positive control signal and plasma density modulation leading to a positive plasma potential at the location of the spoke. If the positive part of the control signal coincides with density minimum, then the current drawn by the control probe is small and the spoke movement is not affected. If instead the positive part of the control signal coincides with a density maximum, a large electron current is drawn from the plasma and the spoke is suppressed until the control probe signal and spoke movement is in phase. Such a frequency locking apparently requires a specific time span of 100 μs to establish. Unfortunately, this time constant is in the same range as typical HiPIMS pulse lengths. Thus, any control of spokes during short HiPIMS pulses should be expected to be much more challenging than the present work on spokes in DCMS.

Reduction of the signal. Figure 3(a) shows, that not only the modulation of the signal is influenced during the on time of the control probe signal but also its average. A reduction of the average diagnostic probe signal can be seen when the control signal is switched on. It takes around 1 ms for the signal to reach steady state. Thus, this change occurs on a much longer time scale compared to the frequency locking, indicating a different physical process, as will be discussed below.

3.2. FFT of the diagnostic probe signal

The nature of the frequency locking is analyzed by calculating the Fast Fourier Transform (FFT) of the diagnostic probe signal under different conditions. For each acquisition, the signal is separated into the on and off time of the control signal, and for each part, the FFT is calculated. This is performed for each of the 45 acquisitions and the results are averaged, as shown in figure 4. The FFT of the diagnostic probe signal when no control signal is being applied (blue line) shows a single peak at around $f_0 = 31 \text{kHz}$, which is the natural frequency to which the spokes adjust at a discharge power of 6.4 W without external influence. The FFT of the diagnostic probe signal when a control signal of 20 kHz is being applied (red line in figure 4) shows a slight shift of the natural spoke frequency towards a higher frequency of around 32 kHz. This might be caused by a slight overall reduction of the electron density inside the plasma, as we now draw a bit of current during the positive part of the control signal. The peak at the control frequency of 20 kHz also shows up in the FFT, as expected. This peak is caused by some of the spokes locking onto the control signal. This peak is very narrow, indicating a rather precise locking. However, the peak is also much smaller than the peak around the natural spoke frequency of 31 kHz. This is because the locking is imperfect: only few spokes adjust to the control frequency while others are still rotating at the natural frequency.

The analysis described above was performed for a range of control probe frequencies, varied in steps of 0.2 kHz. Figure 5 shows a map of the FFTs obtained during the on time of the control probe signals.
At low and high frequencies, the figure shows the natural spoke frequency $f_0$ as a broad band around 32 kHz. The applied frequency $f$ is visible as a diagonal on that map over a large range of frequencies, indicating that at least some locking occurs even if the control frequency is very different from the natural frequency. When this diagonal line approaches the natural spoke frequency, the band around the natural spoke frequency of 32 kHz begins to reduce in intensity. This indicates that most spokes begin to adjust to the control frequency instead of following the natural frequency $f_0$, thus lowering the intensity of the broad band around $f_0$ and increasing the sharp peak at $f$. The spoke locking is strongest around control frequencies from 28 kHz to 36 kHz and, accordingly, the broad frequency band around $f_0$ mostly disappears.

In addition, FFT peaks for higher harmonics can also be seen on the map. The second harmonic becomes visible when locking of the spokes is the strongest around $f \approx f_0 = 32$ kHz. The third harmonic only becomes visible at around 10 kHz control frequency since it overlaps with the natural spoke frequency around 32 kHz.

3.3. Impact of the control probe signal on ion fluxes

So far, we demonstrated that the spoke movement can be locked to an external frequency showing a particular strong effect for control frequencies close to the natural frequency. In the following, we analyze how this spoke movement control affects the ion fluxes leaving the discharge in radial and axial direction. For this, mass spectrometer and diagnostic probe measurements were performed during the time spans when the control was off and are compared to time spans when the control was on. For this, we quantify the impact of the control probe signal by averaging the ion saturation current at the diagnostic probe and the ion flux onto the mass spectrometer for the time span when the control is on $\langle I_{on} \rangle$ with respect to the time averaged signal when the control is off $\langle I_{off} \rangle$. For example, such an averaging yields a reduction of the average signal for the data shown in figure 3(a) of 20%. We will first discuss the energies of ions arriving at the mass spectrometer above the target.

3.3.1. Ion energies. $\text{Al}^+$ ion fluxes are measured with the mass spectrometer while varying the control probe frequency $f$. As an example, figure 6 shows the IEDFs for a control frequency of 28 kHz, where we would expect strong locking. One can see that the energy distributions exhibits a peak at around 2.6 eV for the uncontrolled case. The position of this peak is a function of the velocity distribution function of the sputtered and then ionized species, the electric fields they experience since ionization and the local plasma potential in front of the grounded mass spectrometer. In the controlled case, the maximum of the energy distribution is shifted by 0.25 eV to higher energies and the maximum ion current also increases by 30%. Apparently, both the flux as well as the energy of ions increases, when the spokes are locking to the frequency $f = 28$ kHz.

3.3.2. Ion fluxes. Figure 7 shows the ratio $\langle I_{on} \rangle / \langle I_{off} \rangle$ for the diagnostics probe signals as well as for the mass spectrometer ion fluxes, obtained by integration over the IEDF for each control frequency $f$. Below a frequency of 100 Hz, the control probe signal does no longer oscillate within the set time window for spoke control. This corresponds then to the influence of a constant positive (DC) signal on the spoke movement.

The first thing to note is that both ion saturation currents as well as MS measured ion fluxes show a moderate offset for any applied control signal: independent of the control signal frequency, the ion flux recorded by the mass spectrometer is always increased by around 15% compared to the off-time while the ion saturation current recorded by the diagnostic probe is always reduced by roughly the same amount. Apparently, any kind of applied frequency leads to additional transport of the plasma across the magnetic field lines, thus increasing the ion flux to the mass spectrometer while reducing slightly the plasma density left behind in the magnetic trap. A simple explanation for such an overall change in fluxes...
irrespective of the applied frequency might be the assumption that the electric signal by the control probe modifies the confinement directly at the separatrix of the confined plasma. The oscillating control signal periodically extracts electrons and ions from the plasma creating a perturbation in the ambipolar electric field around the control probe. These perturbations may enhance the cross B-field transport across the separatrix and enhance thereby the overall ion flux towards the substrate and reduce the radial fluxes onto the diagnostic probe.

This interpretation is supported by an experiment varying the height of the control probes and diagnostic probes above the magnetron target, as shown in figure 8. A close inspection of the position \( z \) of the control probe in relation to the magnetic field topology (see figure 1) reveals that the offset of \( \langle I_{on} \rangle / \langle I_{off} \rangle \) for the mass spectrometer data is the largest for positions of the control probe close to the separatrix of the magnetic confinement.

This height variation of the probe position also indicates a shift of the \( \langle I_{on} \rangle / \langle I_{off} \rangle \) signal to lower frequencies for \( z \) positions at 4 mm and 6 mm. Apparently at this location the spikes can be locked to an even lower frequency in comparison to the experiments with the control probe at 5 mm. One may argue that the control probe at the \( z = 5 \) mm position corresponds to a location at the maximum of the plasma density, whereas the \( z \) position at 4 mm and at 6 mm affect regions with a density gradient in the plasma towards the substrate and towards the target. Apparently, this slows down the spoke pattern and could be explained as follows: in the simplest picture, the spoke pattern corresponds to a gradient drift wave with a spoke velocity corresponding to the gradient in plasma density. If this gradient is lowered by the periodic control probe signal the spoke velocity would decrease as observed. However, this explanation is only a rough estimate and more detailed experiments are required to identify the exact mechanism.

On top of the frequency-independent signal offset, a moderate modulation of \( \langle I_{on} \rangle / \langle I_{off} \rangle \) with the applied control frequency is seen in figure 7. From 0 to about 28 kHz, \( \langle I_{on} \rangle / \langle I_{off} \rangle \) increases slowly with \( f \). After the peak at 28 kHz, both signals quickly drop into a distinct minimum around 38 kHz and then begin to increase again, seemingly moving back towards the respective baseline value. It should be noted, that figure 5 shows strong locking of the spikes up to at least 36 kHz, thus the minimum occurs while the spikes are still locked to the applied signal.

It is interesting to note that the ion flux measured by the diagnostic probe and the mass spectrometer exhibit opposing trends in their frequency independent signal offset (increasing for MS, decreasing for the probe) while their control frequency response is the same, with a maximum and a minimum around the natural spoke frequency. This leads to the hypothesis that while the frequency independent shift of the signals is caused by perturbations at the separatrix, the frequency dependent modulation of the signal needs to be explained by a different physical process. This will be discussed in the following.

The data show that the modulation of \( \langle I_{on} \rangle / \langle I_{off} \rangle \) is centered at a frequency of 31 kHz, which is a bit lower than the natural frequency of the spikes at 32 kHz. Such a shift in frequency is expected for external controlling of a wave phenomenon: an oscillator with an eigenfrequency \( f_0 \) and a damping constant \( \gamma \) yields a resonance frequency of \( 2\pi f_1 = \sqrt{(2\pi f_0^2 - 2\gamma^2)} \). From the difference in frequency between \( f_0 \) and \( f_1 \) of typically 1 kHz, the full width at half maximum of the resonance peak can be extracted of \( \Delta_{1/2} f = 2\gamma \sqrt{2/(2\pi)} = 19 \) kHz. This is consistent with our data considering the frequency range over which the ratio \( \langle I_{on} \rangle / \langle I_{off} \rangle \) is modulated.

It is believed that the electric fields surrounding a spoke affect the cross B-field transport of electrons and thus also the transport of ions due to the build up of ambipolar fields [24, 32, 33]. This is illustrated in figure 9 showing the schematic side view of a spoke moving in \(-\vec{E} \times \vec{B}\) direction. Spokes are positively charged and thus an azimuthal electric field is created pointing away from the spoke along the racetrack. Electrons travel in the \( \vec{E} \times \vec{B} \) at a much higher velocity than the spoke movement and enter the spoke at the leading edge and move towards the target. Behind the spoke, they move

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**Figure 7.** Ratio of the averaged ion saturation currents \( \langle I_{on} \rangle / \langle I_{off} \rangle \) from the diagnostic probe at \( z = 0.8 \) mm (solid squares) and the ion flux from the MS (open squares).

**Figure 8.** Ratio \( \langle I_{on} \rangle / \langle I_{off} \rangle \) for the ion flux average from the MS for controlling the spokes at different positions \( z \) above the racetrack.
Figure 9. Sketch of the $E \times B$ transport in the ambipolar field $E$ and the azimuthal electric fields $E_{\phi}$.

away from the target. This additional electron transport causes also an additional ion transport across the field lines.

In the following, we discuss three different physical mechanisms of how the control signal might affect ion transport as observed in the modulation of $\langle I_{on}/I_{off} \rangle$ around $f_0$. Ion transport may be affected by (i) a change in the amplitude of the density modulation of a spoke, (ii) by the frequency of the spokes or more directly by (iii) an enhancement of the azimuthal electric fields at the trailing and leading edge of the spokes:

(i) Amplification of spokes. It was already reported that spokes cause strong plasma potential, electron density and electron temperature fluctuations [18, 22, 23]. Since these spoke induced plasma parameter fluctuations may lock to the varying control probe potential, it is quite possible that these fluctuations might be amplified. Since spokes are believed to cause additional ion transport against the strong electric field in the magnetic trap region, as described above, we expect that stronger spokes should cause stronger ion transport towards the mass spectrometer. However, such an amplification of spokes should cause an increase of $\langle I_{on}/I_{off} \rangle$ over the complete frequency range for which strong locking occurs. Instead, we observe a modulation of $\langle I_{on}/I_{off} \rangle$, with a distinct minimum for frequencies above $f_0$.

(ii) Change in spoke frequency. We have previously proposed that the ion transport should depend strongly on the absolute spoke frequency [14, 16]: if the spoke frequency is high, the inertia of ions is too large for them to follow the change in electric field. The ions will mostly move according to the average electric field strength, just as they would if no spokes existed in the plasma. In the other extreme, if the spokes are very slow the ions may cross the magnetic trap region while being inside a single spoke, where the axial electric field strength is strongly reduced [22].

If we regard a spoke with a length of 30 mm moving at 2.45 km s$^{-1}$ (corresponding to the frequency $f_0$ on the 2 inch target), the time to pass a specific location is 12.2 $\mu$s. This has to be compared with the time needed for a sputtered and ionized particle to cross the magnetic trap region with a height of roughly 15 mm. If we assume a kinetic energy of 2 eV, corresponding to a typical maximum of the Thompson distribution for sputtered aluminium species, this time needed to pass the magnetic trap region is 4 $\mu$s. Thus, Al particles pass through the magnetic trap region while being located inside the spoke the entire time, where the strong electric field is shielded off. Slower particles might not be able to cross the magnetic trap region in time. However, any decrease in spoke frequency, and thus velocity, will again lower the ion velocity required to cross the magnetic trap region, thus, increasing the ion flux towards the substrate.

Thus, a varying spoke frequency might in fact cause a modulation of the ion transport towards the mass spectrometer and can also explain the trends observed in figure 7: at frequencies $f$ slightly below the natural spoke frequency $f_0$, we have strong locking and, thus, lower the frequencies and velocities of all spokes slightly, leading to a maximum in $\langle I_{on}/I_{off} \rangle$ towards the mass spectrometer. The reverse is true for frequencies $f$ above the natural spoke frequency $f_0$; here, we increase the frequency, thus reducing $\langle I_{on}/I_{off} \rangle$. For frequencies much higher or much lower than the natural frequency, the locking between spokes and the control signal becomes imperfect. Thus, we now only affect a smaller subset of spokes and $\langle I_{on}/I_{off} \rangle$ returns towards the baseline. Such a change in the ion transport dynamic is similar in normal and in radial direction. Therefore, we see an identical modulation of $\langle I_{on}/I_{off} \rangle$ in both the mass spectrometer as well the diagnostic probe measurements.

(iii) Affecting the azimuthal electric field. Finally, one may assume that the control probes directly affect the azimuthal electric fields ($E_{\phi}$ in figure 9). Any enhancement of the local azimuthal electric field may enhance transport as follows: (i) at $f < f_0$, the control frequency is lower than the natural frequency and the change in the control probe potential affects the trailing edge of the locked spoke more strongly. The control signal corresponds to a positive potential that draws electrons from the spoke and it is reasonable to assume that this causes an enhancement of $E_{\phi}$. As a consequence, an increase in ion flux in radial and normal direction occurs. (ii) For $f > f_0$ the control frequency is higher than the natural frequency and the change in the control probe potential affects more the leading edge of the locked spoke. The corresponding enhancement of the electric field at the leading edge, however, reduces the transport in normal and radial outward direction since the $E_{\phi} \times B$ direction of electrons is now directed towards the target. This explanation is consistent with our data.

Summarizing, both the change of spoke frequency alone, as well as the direct manipulation of the azimuthal electric fields by the control probe can explain the modulation of the ion flux when locking of the spoke frequency to a control signal occurs.

4. Conclusion

Spikes in dcMS can be controlled by applying rectangular signals with a frequency $f$ close to the natural spoke frequency $f_0$. It was found that the spoke frequency can be manipulated to closely follow the applied frequency, leading to a stable phase between spokes and applied control frequency. This locking of spikes to the control signal is stronger for control frequencies close to the natural spoke frequency.

Comparing the flux of Al$^+$ with and without applied control signal, we found a modulation of about 15% with varying control signal frequency. This effects was on top of a 15% change in ion flux due to perturbation of the plasma confinement at
the separatrix. In the optimum case, the ion fluxes towards the substrate could be enhanced by up to 30%, which is substantial and may compensate for a loss in growth rate due to the return effect. Any technological implementation of such a control scheme is not trivial and adds significantly to the complexity of operating a magnetron discharge. Nevertheless, a design route is presented, which may allow to construct more efficient deposition systems in the future.

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Data availability statement

The data generated and/or analyzed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

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