Effect of Plasma Boundary and Electrode Asymmetry in Planar DC Discharges

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by

Prashant Kumar Barnwal

to the

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Dedicated to ....

... My Loving Family...

CERTIFICATE

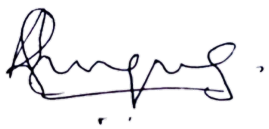
This is to certify that the thesis entitled, "**Effect of Plasma Boundary and Electrode Asymmetry in Planar DC Discharges**", submitted by **Mr. Prashant Kumar Barnwal**, to the Indian Institute of Technology, Delhi for the award of the degree of **Doctor of Philosophy**, is a bonafide record of the research work done by him under our supervision. The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

Prof. R. Narayanan

Dept. Energy Science and Engineering

IIT Delhi, New Delhi – 110016

India



Prof. A. Ganguli

Dept. Energy Science and Engineering

IIT Delhi, New Delhi – 110016

India

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enhanced my intelligence even at the moments of despair, inspired me to move forward, opened before me unexpected avenues, and enlightened my thoughts with His wisdom.

Prashant Kumar Barnwal

ABSTRACT

The work presented in this thesis focuses on the characterization of parallel plate DC discharges with various plasma confining boundaries. In DC discharges, it is standard practice to use a conducting vacuum vessel that is electrically grounded. Since the cathode is also grounded, the conducting chamber works as an extension of the cathode, providing an unlimited auxiliary cathode area relative to the anode. Such a system with a conducting chamber is labelled the Conducting Boundary or CB configuration in this work. To provide alternate boundary conditions to such a scenario, two more boundaries were considered. In one of these, the entire chamber wall along with other conducting surfaces were insulated with mica/glass tubes, *etc.* except the plasma-facing surfaces of electrodes. Such a system was termed the Large Volume Insulating Boundary (LVIB) configuration. One sees immediately that the latter configuration limits the cathode area severely. In effect, plasma in the entire chamber is driven by the planar anode and cathode only. To provide an alternative to the LVIB system in terms of volume, another insulated boundary system, the Small Volume Insulating Boundary (SVIB) system was configured, in which the electrodes are enclosed in a glass tube with mica sheets used for blocking from the top and bottom. It was observed that the discharge shows completely distinct behaviour with these two different boundaries (conducting and insulating). A relatively much higher discharge voltage is required to maintain the discharge in LVIB/SVIB than CB configuration. In addition to these, a leaky boundary was also created by introducing an annular gap in SVIB, which provides a new configuration termed the Leaky Boundary (LB) system in this work. LB discharges have exhibited several interesting nonlinear properties like Negative Differential Resistance (NDR), and hysteresis in their $V - I$ characteristics, anode glows that exhibit features like splitting into multiple blobs, spontaneous rotation of blobs, etc. Physically

and electrically, LB discharges are found either to operate in the SVIB mode or the CB mode, depending on the ratio of the Debye length (at the gap) to the gap width. If this ratio is greater than unity, the plasma produced in the glass tube is unable to escape into the outer conducting chamber and the LB discharge behaves predominantly as an SVIB discharge with almost matching $V - I$ characteristics. On the other hand, as the plasma density rises with increasing discharge current, a point is reached when the ratio of the Debye length to the gap width falls below unity and the plasma escapes into the outer conducting chamber. In the latter case, the $V - I$ characteristics of the LB discharge mimics that of the CB discharge. It is during the switch from the SVIB to CB regime of operation that the NDR mentioned above is observed.

A considerable portion of the investigations in this work pertains to anode glows. It is well known that the glow arises on account of electrons present in the anode sheath exciting the gas atoms as they are accelerated towards the anode. Now, the standard anode sheath is an electron-ion (e-i) sheath comprised of an ion layer (at the sheath edge) followed by a layer of electrons adjacent to the anode. (The presence of the ion layer depresses the potential within the sheath that helps push excess electrons back into the plasma.) However, in the present work, it was found the standard e-i sheath may be replaced by a pure ion sheath. Such types of sheaths are found in SVIB discharges, where electrons arriving at the anode in large numbers need to be heavily restricted (to match the discharge current). It turns out that it is possible to reverse this situation by *reducing the size of the anode drastically in comparison to that of the cathode* (labelled highly asymmetric case), so that *electron collection by the anode becomes highly inefficient* and the anode sheath has to revert back to the standard e-i sheath where anode glows are possible. It is possible to operate highly asymmetric LB discharges over a large range of discharge currents so that anode sheath is an e-i sheath that supports anode glows that exhibit various interesting features like splitting into twin or multiple blobs, fluctuations in their size, and intensities, rotations, *etc*. It is possible that the splitting into multiple anode blobs is

indicative of the existence of constricted current channels while the periodic rotation of the blobs within a specific current regime could be associated with a current-driven instability.

To summarize, the work undertaken in this thesis provides a systematic study of all the different discharge configurations (CB, LVIB, SVIB, and the LB) to determine their characteristic features and identify the various discharge regimes of operation that help the build-up to further interesting studies on anode sheaths / glows, mode switches, *etc*. Some of these features have been investigated in considerable detail.

शोध सार

इस थीसिस में प्रस्तुत कार्य विभिन्न प्लाज्मा सीमित सीमाओं के साथ समानांतर प्लेट डीसी डिस्चार्ज के लक्षण वर्णन पर केंद्रित है। डीसी डिस्चार्ज में, विद्युत रूप से ग्राउंडेड एक कंडक्टिंग वैक्यूम पोत का उपयोग करना मानक अभ्यास है। चूंकि कैथोड भी ग्राउंडेड है, इसलिए कंडक्टिंग चैंबर कैथोड के विस्तार के रूप में काम करता है, जो एनोड के सापेक्ष असीमित सहायक कैथोड क्षेत्र प्रदान करता है। एक संवाहक कक्ष के साथ इस तरह की प्रणाली को इस काम में कंडक्टिंग बाउंड्री या सीबी कॉन्फ़िगरेशन के रूप में लेबल किया जाता है। ऐसे परिदृश्य में वैकल्पिक सीमा की स्थिति प्रदान करने के लिए, दो और सीमाओं पर विचार किया गया। इनमें से एक में, इलेक्ट्रोड की प्लाज्मा-फेसिंग सतहों को छोड़कर, अन्य संवाहक सतहों के साथ पूरे कक्ष की दीवार को अभ्रक/ग्लास ट्यूबों आदि से अछूता किया गया था। ऐसी प्रणाली को लार्ज वॉल्यूम इंसुलेटिंग बाउंड्री (एलवीआईबी) कॉन्फ़िगरेशन कहा जाता है। एक तुरंत देखता है कि बाद वाला विन्यास कैथोड क्षेत्र को गंभीर रूप से सीमित करता है। वास्तव में, पूरे कक्ष में प्लाज्मा केवल प्लेनर एनोड और कैथोड द्वारा संचालित होता है। आयतन के संदर्भ में एलवीआईबी प्रणाली का विकल्प प्रदान करने के लिए, एक अन्य अछूता सीमा प्रणाली, स्मॉल वॉल्यूम इंसुलेटिंग बाउंड्री (एसवीआईबी) प्रणाली को कॉन्फ़िगर किया गया था, जिसमें इलेक्ट्रोड एक ग्लास ट्यूब में संलग्न होते हैं जिसमें ऊपर और नीचे से अवरुद्ध करने के लिए उपयोग की जाने वाली अभ्रक शीट होती है। यह देखा गया कि डिस्चार्ज इन दो अलग-अलग सीमाओं (संचालन और इन्सुलेट) के साथ पूरी तरह से अलग व्यवहार दिखाता है। सीबी कॉन्फ़िगरेशन की तुलना में एलवीआईबी / एसवीआईबी में डिस्चार्ज को बनाए रखने के लिए अपेक्षाकृत बहुत अधिक डिस्चार्ज वोल्टेज की आवश्यकता होती है। इनके अलावा, एसवीआईबी में एक कुंडलाकार अंतराल को शुरू करके एक लीकी सीमा भी बनाई गई थी, जो इस

काम में लीकी बाउंड्री (एलबी) सिस्टम नामक एक नया कॉन्फ़िगरेशन प्रदान करती है। एलबी डिस्चार्ज ने कई दिलचस्प नॉनलीनियर गुणों का प्रदर्शन किया है जैसे कि नेगेटिव डिफरेंशियल रेजिस्टेंस (एनडीआर), और उनके वी-आई विशेषताओं में हिस्टैरिसीस, एनोड ग्लो जो कई बूँदों में विभाजित होने, ब्लॉब्स के सहज रोटेशन आदि जैसी विशेषताओं को प्रदर्शित करता है। शारीरिक और विद्युत रूप से, एलबी डिस्चार्ज या तो एसवीआईबी मोड या सीबी मोड में संचालित होता है, जो डिबाई लंबाई (गैप पर) और गैप की चौड़ाई के अनुपात पर निर्भर करता है। यदि यह अनुपात एक से अधिक है, तो ग्लास ट्यूब में उत्पादित प्लाज्मा बाहरी संचालन कक्ष में बाहर निकलने में असमर्थ है और एलबी डिस्चार्ज मुख्य रूप से लगभग मिलान वी-आई विशेषताओं के साथ एसवीआईबी डिस्चार्ज के रूप में व्यवहार करता है। दूसरी ओर, जैसे-जैसे प्लाज़्मा घनत्व, बढ़ते डिस्चार्ज करंट के साथ बढ़ता है, एक बिंदु पर पहुँच जाता है जब डिबाई लंबाई और गैप की चौड़ाई का अनुपात एक से नीचे हो जाता है और प्लाज्मा बाहरी संवाहक कक्ष में निकल जाता है। बाद के मामले में, एलबी डिस्चार्ज की वी-आई विशेषताएँ सीबी डिस्चार्ज की नकल करती हैं। यह एसवीआईबी से सीबी के संचालन के शासन में स्विच के दौरान है कि ऊपर उल्लिखित एनडीआर देखा जाता है।

इस काम में जांच का एक बड़ा हिस्सा एनोड ग्लो से संबंधित है। यह सर्वविदित है कि एनोड शीथ में मौजूद इलेक्ट्रॉनों के कारण ग्लो उत्पन्न होती है क्योंकि वे गैस परमाणुओं को उत्तेजित करते हैं और एनोड की ओर त्वरित होते हैं। अब, मानक एनोड शीथ एक इलेक्ट्रॉन-आयन (ई-आई) शीथ है जिसमें आयन परत (शीथ किनारे पर) शामिल होता है, जिसके बाद एनोड से सटे इलेक्ट्रॉनों की एक परत होती है। (आयन परत की उपस्थिति शीथ के भीतर क्षमता को कम करती है जो अतिरिक्त इलेक्ट्रॉनों को प्लाज्मा में वापस धकेलने में मदद करती है।) हालांकि, वर्तमान कार्य में, यह पाया गया कि मानक ई-आई शीथ को शुद्ध आयन शीथ द्वारा प्रतिस्थापित किया जा सकता है। एसवीआईबी डिस्चार्ज में इस तरह के शीथ पाए जाते हैं, जहां बड़ी संख्या में एनोड पर पहुंचने वाले इलेक्ट्रॉनों को (डिस्चार्ज करंट से मेल खाने के लिए) भारी प्रतिबंधित करने की आवश्यकता होती है। यह पता चला है कि कैथोड (अत्यधिक

असममित मामले के रूप में लेबल) की तुलना में एनोड के आकार को काफी कम करके इस स्थिति को उलटना संभव है, ताकि एनोड द्वारा इलेक्ट्रॉन संग्रह अत्यधिक अक्षम हो जाए और एनोड शीथ को वापस करना पड़े वापस मानक ई-आई शीथ पर जहां एनोड ग्लो संभव है। डिस्चार्ज धाराओं की एक बड़ी रेंज पर अत्यधिक असममित एलबी डिस्चार्ज को संचालित करना संभव है ताकि एनोड शीथ एक ई-आई शीथ है जो एनोड ग्लो का समर्थन करता है जो विभिन्न दिलचस्प विशेषताओं को प्रदर्शित करता है जैसे कि जुड़वां या कई बूँदों में विभाजित, उनके आकार में उतार-चढ़ाव, और तीव्रता, घुमाव, आदि। यह संभव है कि कई एनोड ब्लॉब्स में विभाजन संकुचित वर्तमान चैनलों के अस्तित्व का संकेत है, जबकि एक विशिष्ट वर्तमान शासन के भीतर ब्लॉब्स के आवधिक रोटेशन को वर्तमान-संचालित अस्थिरता से जोड़ा जा सकता है।

संक्षेप में, इस थीसिस में किए गए कार्य उनकी विशिष्ट विशेषताओं को निर्धारित करने के लिए सभी अलग-अलग डिस्चार्ज कॉन्फ़िगरेशन (सीबी, एलवीआईबी, एसवीआईबी, और एलबी) का एक व्यवस्थित अध्ययन प्रदान करते हैं और ऑपरेशन के विभिन्न डिस्चार्ज शासनों की पहचान करते हैं जो एनोड शीथ / ग्लो, मोड स्विच आदि पर और दिलचस्प अध्ययन के बिल्ड-अप में मदद करते हैं । इनमें से कुछ विशेषताओं की काफी विस्तार से जांच की गई है।

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cam) shown in figure 5.10. The LBDs were initiated at $p \approx$ 2000 mTorr and $I_d \approx$ 7 mA with remaining specifications same as in figure 5.7 (a).

Figure 5.10: Temporal variation of anode glow intensity (captured by Front cam) at $p \approx$ 2000 mTorr and $I_d \approx$ 7 mA. The sequence of images from 'a' to 'i' represents a half period of rotation. (a) t ≈ 0, (b) t ≈ 0.2 s, (c) t ≈ 0.4 s, (d) t ≈ 0.6 s, (e) t ≈ 0.8 s, (f) t ≈ 1.0 s, (g) t ≈ 1.2 s, (h) t ≈ 1.4 s, (i) t ≈ 1.6 s. The blobs have maximum separation at (a) t ≈ 0, after a quarter cycle rotation the blobs are seen to merge at (e) t ≈ 0.8 s, and after another quarter cycle rotation, the balls are separated again after "swapping" at (i) t ≈ 1.6 s. Remaining LB specifications are same as in figure 5.7 (a).

Figure 5.11: Variation of light intensity (arbitrary units) from the blobs (captured by the Front cam) derived from MatLab's Image Processing Toolbox. Each intensity peak corresponds to the center of a blob, and the spatial intensity variation about the peak gives the variation of light intensity within the blob. The horizontal axis gives radial distance (in pixels) from the anode center, with 100 pixels ≈ 8 mm. The blobs have maximum separation (≈ 14 mm) at t ≈ 0 and nearly zero separation at t ≈ 0.8 s. At t ≈ 1.6 s, the blobs are separated once again, with the blobs interchanged. The LB discharges were initiated at $p \approx$ 2000 mTorr and $I_d \approx$ 7 mA. Remaining LB specifications are same as in figure 5.7 (a).

Figure 5.12: Pixel calibration: The anode (dia ≈ 8 mm) is used to calibrate the pixels. It is found that 100 pixels ≈ 8 mm. At maximum separation, the two blobs have a separation of $d \approx$ 14 mm. The diameter of blob "1" ≈ 8.5 mm and that of blob "2" ≈ 7.4 mm. The LB discharges were initiated at $p \approx$ 2000 mTorr and $I_d \approx$ 7 mA. Remaining LBD specs are same as in figure 5.7 (a).

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