

**EXPERIMENTAL AND THEORETICAL STUDY
ON COMPACT ECR PLASMA SOURCE FOR
THRUSTER APPLICATION**

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**EXPERIMENTAL AND THEORETICAL STUDY ON
COMPACT ECR PLASMA SOURCE FOR THRUSTER
APPLICATION**

by

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Submitted

in fulfilment of the requirements for the degree of Doctor of Philosophy



to the

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Dedicated

to

my family

CERTIFICATE

This is to certify that the thesis titled **Experimental and Theoretical Study on Compact ECR Plasma Source for Thruster Application**, submitted by **Anshu Verma**, 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 her 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.

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Abstract

Electric thrusters are used for altitude control and station keeping of small satellites in low earth orbits, orbit raising of medium and large platforms to geostationary earth orbits or deep space exploration missions. However, the use of high voltage ion acceleration grids and beam neutralizers limits the life of an electric thruster since they are prone to erosion. Electrodeless thrusters have distinct advantage over the conventional ones that avoids erosion problem thereby enhancing their active life. Accordingly, a novel plasma thruster using Compact ECR Plasma Source (CEPS) is proposed as a competitive candidate, satisfying the electrodeless condition since microwave power is coupled to the plasma through a dielectric window as opposed to via an immersed electrode. Quasineutral plasma containing energetic ions is expelled outwards to impart momentum to the vehicle omitting the requirement of neutralizers.

The CEPS is a novel ECR plasma source (patented by IIT Delhi) employing a unique magnetic field configuration created by a set of NdFeB ring magnets. This design promotes not only high density plasma production but offers very efficient electron heating leading to the development of plasma potential drop near CEPS exit which leads to ion acceleration suitable for thrusters. In order to determine the propulsive performance of CEPS, it was attached to a large expansion chamber. A series of experiments and theoretical modelling were performed at different operational parameters. Specially designed and in-house fabricated Langmuir probe and ion energy analyzer were used to specify evolution of plasma parameters and assess the thrust attainable from CEPS.

LP measurements reveal high-density argon plasma ($\approx 10^{12} \text{ cm}^{-3}$), with high bulk electron temperatures ($\approx 20 \text{ eV}$) and plasma potentials ($\approx 100 \text{ V}$) at very modest microwave power ($\approx 600 \text{ W}$) over a wide range of pressures (0.3 to 1 mTorr). A potential step forms within CEPS near the

exit and provides advantage as a means to accelerate the escaping ions. Energy analyzer reported the ion energies as high as 87 eV in-front of CEPS at 0.5 mTorr.

In order to effectively describe the plasma behaviour in expanding geometry, we developed a zero dimensional, 2-zone global model of the plasma flow, where zone-1 and zone-2 represent the CEPS and expansion chamber respectively. The model considers the balance of particle density, momentum and energy in the two zones and predicts the thrust attainable from the CEPS. The computed thrust under actual space-like conditions for xenon and argon are ≈ 80 mN and ≈ 45 mN respectively at 600 W of microwave power. It is shown that CEPS has the potential to be developed into a novel thruster technology.

संक्षेप

विद्युत थ्रस्टर्स का उपयोग ऊंचाई नियंत्रण और छोटे उपग्रहों को पृथ्वी की निचली कक्षाओं में रखने, मध्यम और बड़े प्लेटफार्मों की कक्षा को पृथ्वी की भूस्थिर कक्षाओं या गहरे अंतरिक्ष अन्वेषण मिशनों के लिए उपयोग किया जाता है। हालांकि, उच्च वोल्टेज आयन त्वरण ग्रिड और बीम न्यूट्रलाइज़र का उपयोग इलेक्ट्रिक थ्रस्टर के जीवन को सीमित करता है क्योंकि वे क्षरण के लिए प्रवण होते हैं। इलेक्ट्रोड रहित थ्रस्टर्स का पारंपरिक थ्रस्टर्स पर विशिष्ट लाभ होता है जो क्षरण की समस्या से बचाते हैं जिससे उनके सक्रिय जीवन में वृद्धि होती है। तदनुसार, कॉम्पैक्ट ईसीआर प्लाज्मा स्रोत (सीईपीएस) का उपयोग करते हुए एक नवीन प्लाज्मा थ्रस्टर को एक प्रतिस्पर्धी उम्मीदवार के रूप में प्रस्तावित किया जाता है, जो इलेक्ट्रोड रहित स्थिति को संतुष्ट करता है क्योंकि एक डूबे हुए इलेक्ट्रोड के विपरीत एक असंवाहक खिड़की के माध्यम से प्लाज्मा में माइक्रोवेव पावर को जोड़ा जाता है। न्यूट्रलाइज़र की आवश्यकता को छोड़ कर वाहन को गति प्रदान करने के लिए ऊर्जावान आयनों वाले क्लासीन्यूट्रल प्लाज्मा को बाहर की ओर निष्कासित कर दिया जाता है।

सीईपीएस एक नवीन ईसीआर प्लाज्मा स्रोत (आईआईटी दिल्ली द्वारा पेटेंट) है जो एनडीएफईबी वृतीय चुंबक के एक सेट द्वारा बनाए गए एक अद्वितीय चुंबकीय क्षेत्र विन्यास को नियोजित करता है। यह डिजाइन न केवल उच्च घनत्व प्लाज्मा उत्पादन को बढ़ावा देता है बल्कि सीईपीएस निकास के निकट प्लाज्मा संभावित गिरावट के विकास के लिए बहुत ही कुशल इलेक्ट्रॉन ताप प्रदान करता है जिससे थ्रस्टर्स के लिए उपयुक्त आयन त्वरण उत्पन्न होता है। सीईपीएस के प्रणोदन प्रदर्शन को निर्धारित करने के लिए, इसे एक बड़े विस्तार कक्ष से जोड़ा गया था। विभिन्न परिचालन मापदंडों पर प्रयोगों और सैद्धांतिक मॉडलिंग की एक श्रृंखला का प्रदर्शन किया गया। प्लाज्मा मापदंडों के विकास को निर्दिष्ट करने और सीईपीएस से प्राप्य थ्रस्ट का आकलन करने के लिए विशेष रूप से डिजाइन और प्रयोगशाला में निर्मित लैंगमुइर यंत्र और आयन ऊर्जा विश्लेषक का उपयोग किया गया था।

एलपी माप उच्च घनत्व वाले ($\approx 10^{12}$ सेमी⁻³), उच्च तापमान (≈ 20 ईवी) बहुसंख्यक इलेक्ट्रॉन और प्लाज्मा क्षमता (≈ 100 वाल्ट) के साथ बहुत निम्न माइक्रोवेव पावर (≈ 600 वाट), दबाव की एक विस्तृत श्रृंखला पर (0.3 से 1 मिलिटोर) आर्गन प्लाज्मा को प्रकट करते हैं। निकास के निकट सीईपीएस के भीतर एक संभावित सीढी बनता है और बचने वाले आयनों को तेज करने के साधन के रूप में लाभ प्रदान करता है। ऊर्जा विश्लेषक ने 0.5 मिलिटोर पर सीईपीएस के सामने आयन ऊर्जा को 87 ईवी जितना ऊंचा बताया।

ज्यामिति के विस्तार में प्लाज्मा व्यवहार का प्रभावी ढंग से वर्णन करने के लिए, हमने प्लाज्मा प्रवाह का एक शून्य आयामी, दो-क्षेत्र वैश्विक मॉडल विकसित किया, जहाँ ज़ोन -1 और ज़ोन -2 क्रमशः सीईपीएस और विस्तार कक्ष का प्रतिनिधित्व करते हैं। मॉडल दो क्षेत्रों में कण घनत्व, गति और ऊर्जा के संतुलन पर विचार करता है और सीईपीएस से प्राप्त होने वाले थ्रस्ट का पूर्वानुमान करता है। ज़ेनॉन और आर्गन के लिए वास्तविक अंतरिक्ष जैसी स्थितियों के तहत गणना की गई थ्रस्ट क्रमशः ८० मिली न्यूटन और ४५ मिली न्यूटन है जो ६०० वाट माइक्रोवेव पावर पर है। यह दिखाया गया है कि सीईपीएस में एक नई थ्रस्टर तकनीक के रूप में विकसित होने की क्षमता है।

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