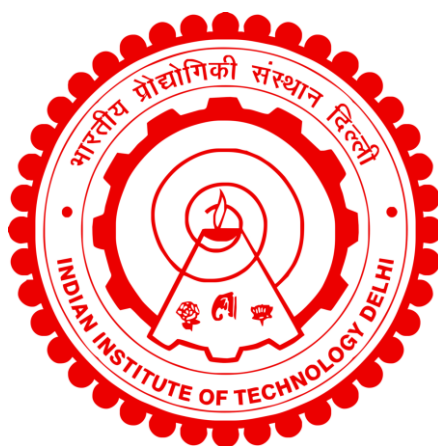


INVESTIGATION OF ECR-PRODUCED HYDROGEN PLASMAS SUITABLE FOR LARGE- AREA APPLICATIONS

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Investigation of ECR-produced Hydrogen Plasmas suitable for large-area applications

by

Shweta Sharma

Department of Energy Science and Engineering

submitted

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

to the



Indian Institute of Technology Delhi

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Dedicated to.....

*My Parents &
In-Laws*

UNDERTAKING

I hereby declare that the work presented here in the thesis has been carried out by me towards the partial fulfillment of the requirements for the award of the **Degree of Philosophy** at the Indian Institute of Technology Delhi. The content of this report, in full or in parts, has not been submitted to any other institute or university for the award of any degree.

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CERTIFICATE

This is to certify that the thesis entitled, “**Investigation of ECR produced Hydrogen Plasmas suitable for large-area Applications,**” submitted by **Ms. Shweta Sharma** 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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Shweta Sharma

Abstract

The current thesis focuses on the detailed characterization of Hydrogen plasmas in a large-volume chamber aiming toward the production of highly dense and uniform plasma over a large area. Hydrogen plasmas contain multi-variant species, e.g., H, H^+ , H_2^+ , H^- etc., and hence are well suited for diverse applications ranging from plasma-based material processing to the production of ion beams (both positive and negative), which are further applied for proton radiotherapy and high energy neutral beam production for heating of fusion plasma. The prerequisites of many of these applications are the generation of uniform dense ($10^{11} - 10^{12} \text{ cm}^{-3}$) plasma over a large cross-section ($\sim 1 \text{ m} \times 1 \text{ m}$) along with low temperatures ($T_e \sim 1 \text{ eV}$). It is also desirable for the source to be energy-efficient and maintenance-free under the operating conditions. Accordingly, in this work, a large volume cylindrical (dia and height $\sim 1 \text{ m}$) plasma system was configured vertically and optimized, using plasma source(s) mounted onto the top dome of the chamber to generate uniform, high-density, low-temperature downstream plasma, over a large cross-section. The Electron Cyclotron Resonance (ECR) mechanism was utilized to produce the plasma inside a small plasma source, viz. the Compact ECR Plasma Source (CEPS), which could be attached in single or multiple units (up to seven) on the top dome of the large chamber. Six of the sources are placed in a circular pattern (radius $r_{\text{pcd}} \approx 0.59 \text{ m}$) on the top dome, and one source is placed at the center of the dome. Axially poled permanent ring magnets provide the magnetic field for each CEPS, and the total field in the chamber is the combined field of all mounted CEPSs. Separate experiments were conducted with three different source configurations, viz.: (i) **Configuration A:** Six CEPS with opposite polarity on adjacent magnets are mounted circularly (radius $r_{\text{pcd}} \approx 0.59 \text{ m}$) on the top dome. A cusp field is formed between adjacent sources. The plasma in this configuration follows

the cusped field lines, penetrating adjacent sources, thereby generating severe crosstalk and feedback between adjacent sources and causing strong instabilities and fluctuations in microwave power and plasma. (ii) **Configuration B:** Seven CEPS (six placed on a circle with $r_{pcd} \approx 0.59$ m and one at the center) are mounted on the top dome with identical polarity on all magnets. Field lines from the adjacent peripheral sources bunch into curved, discrete columns that repel each other and bend sharply to penetrate the chamber wall (close to its mid-plane). In contrast, the field from the central source forms a separate column and remains bunched close to the axis all the way to the chamber bottom. In this configuration, plasma from each of the six peripheral sources flows out along the curved field lines to form discrete columns of plasma that terminate on the vessel wall. In contrast, plasma from the centrally placed source follows the central field column, with very little fanning out all the way downstream. (iii) **Configuration C:** Only a single CEPS is placed at the dome center. For this configuration, one obtains a uniform diverging magnetic field from the central dome region, moving into the downstream region of the system. Using an axially and radially rotatable single Langmuir probe, one obtains uniform plasma over ~ 35 cm radius ($n_e \sim 4 \times 10^{16} \text{ m}^{-3}$, $T_e \sim 1\text{--}2$ eV) about ~ 60 cm downstream of the source mouth with only 400W power at $\sim 1\text{--}3$ mTorr pressure. An additional warm population ($n_w \sim 4 \times 10^{14} \text{ m}^{-3}$, $T_w \sim 40\text{--}60$ eV) was also found to co-exist. While configurations A and B were discarded as being unsuitable for the plasma requirements for this work, the results from configuration C were identified as ideal for volume mode H^- production over a large area since volume H^- production involves the dissociative attachment of excited hydrogen molecules, the warm electrons aiding the excitation of the hydrogen molecules with the colder electrons responsible for the dissociative attachment process. Hence, among the configurations considered, the single CEPS configuration was found to be the most efficacious for large-area H^- generation. These results provide one with the motivation to

examine the axial and radial profiles of the plasma parameters (steady state) at other r - z planes and along the axis for configuration C.

In the present work, one could detect ions with energy $\sim 40 - 45$ eV using Retarding Field Energy Analyzer (RFEA) about ~ 10 cm in front of the source mouth. It is anticipated that the ion energies are higher closer to the source mouth (~ 100 eV or greater); but due to repeated damage to the RFEA, measurements could not be undertaken closer to the source. To determine how ions acquire these high energies, plasma parameters were measured from the source mouth into the chamber. Measurements at low pressures ($\sim 1 - 2$ mTorr) revealed plasma with moderately high density ($n_e \approx 2 \times 10^{17} \text{ m}^{-3}$), high electron temperature ($T_e \approx 50$ eV), and high plasma potential ($V_p \sim 230$ V) close to the source mouth ($z \approx 0$). At $z \approx 5$ cm, *outside* the plasma source in the expansion chamber, the plasma jumps into a state with two distinct electron populations: (i) a high-density, low-temperature bulk electron population ($n_e \sim 2 - 6 \times 10^{17} \text{ m}^{-3}$, $T_e \sim 4 - 6$ eV) and (ii) a low density, high-temperature warm electron population ($n_w \sim 4 \times 10^{14} \text{ m}^{-3}$, $T_w \sim 40 - 60$ eV); concomitant with this transition, the plasma potential is also seen to drop drastically ($V_p \sim 20$ V). The large drop in plasma potential as the plasma passes from a single electron to a two-electron population provides the energy boost to the ions. Although the plasma in front of the ECR zone is a high T_e (≈ 50 eV), high V_p (≈ 250 V) plasma, it is difficult to observe this in experiments since, in most cases, the plasma makes a transition to the two-electron population within the source region where the harsh plasma precludes measurements. This observation has been found in this work for low pressures.

In front of the source, the axial magnetic field is high enough ($\sim 300 - 400$ G) to provide good radial confinement. The magnetic field diverges and weakens downstream from the source region, which could be instrumental for the noticeable improvement in radial uniformity observed as one moves from the upstream region, i.e., near the CEPS source, to downstream regions, albeit at the

expense of a fall in plasma density. Power scaling studies in the range of 400 – 800 W show a slight increase in plasma density as power increases, with no noticeable variation in T_e observed.

The indication of optimal conditions for large-area H^- production prevailing in the downstream region of the chamber motivated the construction of a theoretical model for the estimation of H^- ions in this region. The two-step volumetric dissociative attachment (DA) process was considered. Accordingly, the experimental system was virtually divided into two zones: one near the CEPS source (Top - zone 1) with high T_e , a preferable condition to produce vibrationally excited H_2 molecules- a precursor to the H^- ions, and another one at far downstream (Bottom - zone 2, 35 cm away from zone 1) with low T_e suitable for H^- production. H^- density of the order of 10^{15} m^{-3} was found in zone 2 with an input power of 400 W and 2 mTorr of pressure, assuming the precursor species directly transported from zone 1 to zone 2 without any loss.

सार

वर्तमान थीसिस एक बड़े क्षेत्र में अत्यधिक घने और समान प्लाज्मा के उत्पादन की ओर लक्षित एक बड़ी मात्रा में चैंबर में हाइड्रोजन प्लाज्मा के विस्तृत लक्षण वर्णन पर ध्यान केंद्रित करता है। हाइड्रोजन प्लाज्मा में बहु-विचित्र प्रजातियां, जैसे, एच, एच⁺, एच²⁺, एच⁻ आदि होते हैं, और इसलिए प्लाज्मा-आधारित सामग्री प्रसंस्करण से लेकर आयन बीम (दोनों सकारात्मक और नकारात्मक) के उत्पादन तक विभिन्न अनुप्रयोगों के लिए अच्छी तरह से अनुकूल हैं, जो कि सकारात्मक और नकारात्मक दोनों हैं, जो फ्यूजन प्लाज्मा के ताप के लिए प्रोटॉन रेडियोथेरेपी और उच्च ऊर्जा तटस्थ बीम उत्पादन के लिए आगे लागू किया जाता है। इनमें से कई अनुप्रयोगों की पूर्वापेक्षाएँ एक बड़े क्रॉस-सेक्शन ($\sim 1 \text{ मी} \times 1 \text{ मी}$) के साथ-साथ कम तापमान ($T_e \sim 1 \text{ ईवी}$) के साथ एक समान घने (10^{11} - $10^{12} \text{ सेमी}^{-3}$) प्लाज्मा की पीढ़ी हैं। ऑपरेटिंग परिस्थितियों में ऊर्जा-कुशल और रखरखाव-मुक्त होने के लिए स्रोत के लिए यह भी वांछनीय है। तदनुसार, इस काम में, एक बड़ी मात्रा में बेलनाकार (डीआईए और ऊंचाई $\sim 1 \text{ मीटर}$) प्लाज्मा सिस्टम को लंबवत और अनुकूलित किया गया था, जो कि प्लाज्मा स्रोत (एस) का उपयोग करके चैम्बर के शीर्ष गुंबद पर रखा गया था, जो कि समान, उच्च-घनत्व, निम्न-कम- कम- घनत्व, कम- कम- घनत्व, निम्न- तापमान डाउनस्ट्रीम प्लाज्मा, एक बड़े क्रॉस-सेक्शन पर। इलेक्ट्रॉन साइक्लोट्रॉन रेजोनेंस (ईसीआर) तंत्र का उपयोग एक छोटे से प्लाज्मा स्रोत के अंदर प्लाज्मा का उत्पादन करने के लिए किया गया था, अर्थात् कॉम्पैक्ट ईसीआर प्लाज्मा स्रोत (सीईपीएस), जो कि शीर्ष डोम पर एकल या कई इकाइयों (सात तक) में संलग्न किया जा सकता है। बड़े कक्ष। स्रोतों में से छह को शीर्ष गुंबद पर एक गोलाकार पैटर्न (त्रिज्या R_{PCD}) 0.59 मीटर) में रखा जाता है, और एक स्रोत को गुंबद के केंद्र में रखा जाता है। अक्षीय रूप से पोल्ड स्थायी रिंग मैग्नेट प्रत्येक सीईपी के लिए चुंबकीय क्षेत्र प्रदान करते हैं और कक्ष में कुल क्षेत्र सभी घुड़सवार सीईपीएस का संयुक्त क्षेत्र है। तीन अलग-अलग स्रोत

कॉन्फिगरेशन के साथ अलग-अलग प्रयोग किए गए, अर्थात: (i) कॉन्फिगरेशन A: आसन्न मैग्नेट पर विपरीत ध्रुवीयता के साथ छह CEPS को शीर्ष गुंबद पर परिपत्र (त्रिज्या R_{PCD}) 0.59 मीटर) माउंट किया जाता है। आसन्न स्रोतों के बीच एक पुच्छ क्षेत्र बनता है। इस कॉन्फिगरेशन में प्लाज्मा कस्प फ़ील्ड लाइनों का अनुसरण करता है, आसन्न स्रोतों में प्रवेश करता है, जिससे आसन्न स्रोतों के बीच गंभीर क्रॉसस्टॉक और प्रतिक्रिया उत्पन्न होती है और माइक्रोवेव पावर और प्लाज्मा दोनों में मजबूत अस्थिरता और उतार-चढ़ाव होता है। (ii) कॉन्फिगरेशन बी: सात सीईपी (छह एक सर्कल पर रखे गए। 60 सेमी और एक केंद्र में एक) को शीर्ष गुंबद पर सभी मैग्नेट पर समान ध्रुवीयता के साथ रखा गया है। आसन्न परिधीय स्रोतों से फ़ील्ड लाइनें घुमावदार, असतत स्तंभों में गुच्छा होती हैं, जो एक दूसरे को पीछे हटाते हैं और चैम्बर की दीवार (इसके मध्य-प्लेन के करीब) में प्रवेश करने के लिए तेजी से झुकते हैं, जबकि केंद्रीय स्रोत से क्षेत्र एक अलग कॉलम बनाता है और करीब रहता है। चैम्बर के नीचे सभी तरह से धुरी। इस कॉन्फिगरेशन में, छह परिधीय स्रोतों में से प्रत्येक से प्लाज्मा प्लाज्मा के असतत कॉलम बनाने के लिए घुमावदार क्षेत्र लाइनों के साथ बहता है जो पोत की दीवार पर समाप्त हो जाता है, जबकि सेंट्रल रूप से रखे गए स्रोत से प्लाज्मा केंद्रीय क्षेत्र के स्तंभ का अनुसरण करता है, बहुत कम प्रशंसक के साथ बाहर निकलता है। सभी तरह से नीचे की ओर। (iii) कॉन्फिगरेशन C: केवल एक सीईपी को गुंबद केंद्र में रखा गया है। इस कॉन्फिगरेशन के लिए एक केंद्रीय गुंबद क्षेत्र से सिस्टम के डाउनस्ट्रीम क्षेत्र में एक समान विचलन चुंबकीय क्षेत्र प्राप्त करता है। एक अक्षीय और रेडियल रोटेटेबल सिंगल लैंगमुइर जांच का उपयोग करते हुए, एक ~ 35 सेमी त्रिज्या ($n_e \sim 4 \times 10^{16} \text{ मी}^{-3}$, $T_e \sim 1-2$ ईवी) से अधिक समान प्लाज्मा प्राप्त करता है। $\sim 1-3$ mtorr दबाव। एक अतिरिक्त गर्म आबादी ($n_w \sim 4 \times 10^{14} \text{ मी}^{-3}$, $T_w \sim 40-60$ ईवी) भी सह-अस्तित्व में पाया गया। जबकि कॉन्फिगरेशन ए और बी को इस काम के लिए प्लाज्मा आवश्यकताओं के लिए अनुपयुक्त होने के रूप में छोड़ दिया गया था, कॉन्फिगरेशन सी के परिणामों को एक बड़े क्षेत्र पर वॉल्यूम मोड एच-उत्पादन के लिए आदर्श के रूप में पहचाना गया था, क्योंकि वॉल्यूम

एच-उत्पादन में उत्साहित हाइड्रोजन का विघटनकारी अनुलग्नक शामिल है। अणु, गर्म इलेक्ट्रॉनों को हाइड्रोजन अणुओं के उत्तेजना का समर्थन करने वाले ठंडे इलेक्ट्रॉनों के साथ विघटनकारी लगाव प्रक्रिया के लिए जिम्मेदार। इसलिए, सिंगल सीईपीएस कॉन्फ़िगरेशन माना जाने वाले कॉन्फ़िगरेशन के बीच बड़े क्षेत्र के एच-पीढ़ी के लिए सबसे प्रभावशाली पाया गया। ये परिणाम अन्य आर-जेड विमानों में और कॉन्फ़िगरेशन सी के लिए अक्ष के साथ प्लाज्मा मापदंडों (स्थिर स्थिति) के अक्षीय और रेडियल प्रोफाइल की जांच करने के लिए एक प्रेरणा प्रदान करते हैं।

वर्तमान कार्य में, रिटार्डिंग फील्ड एनर्जी एनालाइजर (RFEA) का उपयोग करके स्रोत मुख के लगभग ~ 10 सेमी सामने $\sim 40 - 45$ ईवी ऊर्जा वाले आयनों का पता लगाया जा सकता है। यह अनुमान लगाया गया है कि आयन ऊर्जा स्रोत मुख के करीब अधिक होती है (~ 100 ईवी या अधिक); लेकिन RFEA को बार-बार नुकसान पहुंचने के कारण, स्रोत के करीब माप नहीं किए जा सके। यह निर्धारित करने के लिए कि आयन इन उच्च ऊर्जाओं को कैसे प्राप्त करते हैं, प्लाज्मा मापदंडों को स्रोत मुख से कक्ष में मापा गया। कम दबाव ($\sim 1 - 2$ mTorr) पर माप से मध्यम रूप से उच्च घनत्व ($n_e \approx 2 \times 10^{17} \text{ m}^{-3}$), उच्च इलेक्ट्रॉन तापमान ($T_e \approx 50$ ईवी), और स्रोत मुख ($z \approx 0$) के करीब उच्च प्लाज्मा क्षमता ($V_p \sim 230 \text{ V}$) का पता चला। $z \approx 5$ सेमी पर, विस्तार कक्ष में प्लाज्मा स्रोत के बाहर, प्लाज्मा दो अलग-अलग इलेक्ट्रॉन आबादी वाली अवस्था में पहुंच जाता है: (i) उच्च घनत्व, कम तापमान वाली बल्क इलेक्ट्रॉन आबादी ($n_e \sim 2 - 6 \times 10^{17} \text{ m}^{-3}$, $T_e \sim 4 - 6$ ईवी) और (ii) कम घनत्व, उच्च तापमान वाली गर्म इलेक्ट्रॉन आबादी ($n_w \sim 4 \times 10^{14} \text{ m}^{-3}$, $T_w \sim 40 - 60$ ईवी); इस संक्रमण के साथ-साथ, प्लाज्मा क्षमता में भी भारी गिरावट देखी जाती है ($V_p \sim 20 \text{ V}$)। प्लाज्मा के एक इलेक्ट्रॉन से दो-इलेक्ट्रॉन आबादी में जाने पर प्लाज्मा क्षमता में बड़ी गिरावट आयनों को ऊर्जा बढ़ावा प्रदान करती है। यद्यपि ईसीआर क्षेत्र के सामने का प्लाज्मा एक उच्च T_e (≈ 50 ईवी), उच्च V_p ($\approx 250 \text{ V}$) प्लाज्मा है, प्रयोगों में इसे देख पाना मुश्किल है क्योंकि, ज्यादातर मामलों में, प्लाज्मा स्रोत क्षेत्र के भीतर दो-

इलेक्ट्रॉन आबादी में संक्रमण करता है जहां कठोर प्लाज्मा माप को रोकता है। यह अवलोकन कम दबाव के लिए इस काम में पाया गया है। स्रोत के सामने, अक्षीय चुंबकीय क्षेत्र अच्छा रेडियल कारावास प्रदान करने के लिए पर्याप्त उच्च ($\sim 300 - 400$ G) है। चुंबकीय क्षेत्र स्रोत क्षेत्र से नीचे की ओर विचलित और कमजोर हो जाता है, जो रेडियल एकरूपता में उल्लेखनीय सुधार के लिए सहायक हो सकता है, जैसा कि कोई व्यक्ति अपस्ट्रीम क्षेत्र, यानी CEPS स्रोत के पास से, डाउनस्ट्रीम क्षेत्रों में जाता है, हालांकि प्लाज्मा घनत्व में गिरावट की कीमत पर। कक्ष के डाउनस्ट्रीम क्षेत्र में बड़े क्षेत्र में H^- उत्पादन के लिए अनुकूलतम स्थितियों के संकेत ने इस क्षेत्र में H^- आयनों के आकलन के लिए एक सैद्धांतिक मॉडल के निर्माण को प्रेरित किया। दो-चरण वाली वॉल्यूमेट्रिक डिसोसिएटिव अटैचमेंट (DA) प्रक्रिया पर विचार किया गया। तदनुसार, प्रायोगिक प्रणाली को वस्तुतः दो क्षेत्रों में विभाजित किया गया था: एक CEPS स्रोत के पास (शीर्ष - क्षेत्र 1) उच्च T_e के साथ, कंपन से उत्तेजित H_2 अणुओं के उत्पादन के लिए एक बेहतर स्थिति - H^- आयनों के लिए एक अग्रदूत, और दूसरा बहुत दूर डाउनस्ट्रीम पर (नीचे - क्षेत्र 2, क्षेत्र 1 से 35 सेमी दूर) H^- उत्पादन के लिए उपयुक्त कम T_e के साथ। 400 W की इनपुट शक्ति और 2 mTorr दबाव के साथ क्षेत्र 2 में 10^{15} m^{-3} के क्रम का H^- घनत्व पाया गया।

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