FLUID MODELING AND SIMULATIONS OF A FINITE SIZE UNMAGNETIZED PLASMA AND A FLOWING MAGNETIZED PLASMA

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Fluid Modeling and Simulations of a Finite Size Unmagnetized Plasma and a Flowing Magnetized Plasma

by

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in fulfillment of the requirements of the degree of Doctor of Philosophy

to the

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Dedicated to my parents

Certificate

This is to certify that the thesis titled **"Fluid Modeling and Simulations of a Finite Size Unmagnetized Plasma and a Flowing Magnetized Plasma"**, being submitted by **Subhasish Bag** to the Indian Institute of Technology Delhi, for the award of the degree of **Doctor of Philosophy** in Physics, is a record of the original, bona fide research work carried out by him under my supervision and guidance. He has fulfilled the requirements for the submission of the thesis, which to the best of my knowledge has reached the required standard. The results contained in this thesis have not been submitted in part or in full to any other University or Institute for the award of any degree or diploma.

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Subhasish Bag

Abstract

This thesis examines, using fluid modeling, two distinct regimes of plasma dynamics, evolution of a finite size unmagnetized plasma and a flowing magnetized plasma. The former case, discussed in the first half of the thesis, is relevant when a plasma with finite extent and inhomogeneous density profiles is formed as a result of laser irradiation of a thin foil. Detailed investigations, based on one-dimensional fluid simulations, of the fundamental modes and dynamics of a finite size plasma reveal the onset of phase-mixing induced wave breaking process featuring sharp structures formation in the plasma density profile along with the generation of higher harmonics. It is also highlighted that the addition of diffusion suppresses the sharp structures, while an external forcing leads to local resonances in the finite-size plasma under consideration. It is also reported that wave breaking via phase mixing happens faster for the plasma with a sharper density gradient because of the generation of a strong field at the plasma edge. The case of flowing magnetized plasma, which has been investigated in the second half of the thesis, directly relates to the experiments pertaining to plasma-based electric propulsion as well as plasma processing. Considering an inhomogeneous magnetic field configuration, directly taken from an experiment, as an input for our modeling, a magnetic field based coordinate system has been developed. The steady-state fluid equations are then transformed into this new magnetic coordinate system and are simplified by using appropriate ordering. These simplified equations are integrated to obtain the profiles of flow variables in the magnetic coordinate system and are then transformed into the cylindrical coordinate system before comparing them against the experimental data. It is found that while all the flow profiles are in agreement with the experimental observations, the radial density profile does not show significant variation, unlike what was observed in the experiments. It can be reasoned that this difference in the radial variation of the ion density appears due to the absence of warm electrons in our model. The inclusion of warm electrons in the current model, however, needs further investigations and will be considered in the near future. Apart from that limitation the model presented is generic and can be adapted to any given cylindrically symmetric magnetic field configuration for exploring magnetized plasma dynamics.

सार

यह शोध प्रबंध, तरल मॉडलिंग का उपयोग करते हुए, प्लाज्मा गतिकी की दो अलग-अलग व्यवस्थाओं, एक परिमित आकार के अचुंबकीय प्लाज्मा और एक प्रवाहित चुंबकीय प्लाज्मा के विकास की जाँच करता है। प्रथम भाग में चर्चा की गई पूर्व स्थिति, तब प्रासंगिक होती है जब एक पतली पन्नी के लेजर विकिरण के परिणामस्वरूप परिमित विस्तार और विषम घनत्व प्रोफाइल वाला प्लाज्मा बनता है। एक-आयामी तरल सिमुलेशन पर आधारित, परिमित आकार के प्लाज्मा के मूलभूत मोड और गतिकी के विस्तृत अध्ययन से, प्रावस्था मिश्रण प्रेरित तरंग विखंडन प्रक्रिया की शुरुआत का पता चलता है, जिसमें प्लाज्मा घनत्व प्रोफाइल में तीक्ष्ण संरचनाओं का निर्माण और उच्च हार्मोनिक्स का निर्माण शामिल है। यह भी रेखांकित किया गया है कि विसरण के योग से तीक्ष्ण संरचनाएं दब जाती हैं, जबकि एक बाहरी बल विचाराधीन परिमित आकार के प्लाज्मा में स्थानीय अनुनादों को जन्म देता है। यह भी बताया गया है कि प्रावस्था मिश्रण के माध्यम से तरंग विखंडन, प्लाज्मा के किनारे पर एक प्रबल क्षेत्र के निर्माण के कारण, अधिक घनत्व प्रवणता वाले प्लाज्मा के लिए तेज़ी से होता है। प्रवाहित चुंबकीय प्लाज्मा का मामला, जिसकी शोध प्रबंध के दूसरे भाग में जाँच की गई है, सीधे प्लाज्मा-आधारित विद्युत प्रणोदन और प्लाज्मा प्रसंस्करण से संबंधित प्रयोगों से संबंधित है। एक प्रयोग से सीधे लिए गए एक विषम चुंबकीय क्षेत्र विन्यास को हमारे मॉडलिंग के लिए एक इनपुट के रूप में मानते हुए, एक चुंबकीय क्षेत्र आधारित निर्देशांक प्रणाली विकसित की गई है। स्थिर-अवस्था तरल समीकरणों को फिर इस नई चुंबकीय निर्देशांक प्रणाली में रूपांतरित किया जाता है और उपयुक्त क्रम का उपयोग करके सरलीकृत किया जाता है। इन सरलीकृत समीकरणों को चुंबकीय निर्देशांक प्रणाली में प्रवाह चरों की रूपरेखा प्राप्त करने के लिए एकीकृत किया जाता है और फिर प्रयोगात्मक आँकड़ों से तुलना करने से पहले बेलनाकार निर्देशांक प्रणाली में रूपांतरित किया जाता है। यह पाया गया है कि यद्यपि सभी प्रवाह रूपरेखाएँ प्रयोगात्मक प्रेक्षणों के अनुरूप हैं, रेडियल घनत्व रूपरेखा में प्रयोगों में देखी गई भिन्नता के विपरीत कोई महत्वपूर्ण परिवर्तन नहीं दिखाई देता है। यह तर्क दिया जा सकता है कि आयन घनत्व की रेडियल भिन्नता में यह अंतर हमारे मॉडल में गर्म इलेक्ट्रॉनों की अनुपस्थिति के कारण दिखाई देता है। हालाँकि, वर्तमान मॉडल में गर्म इलेक्ट्रॉनों को शामिल करने के लिए और अधिक जाँच की आवश्यकता है और निकट भविष्य में इस पर विचार किया जाएगा। उस सीमा के अलावा, प्रस्तुत मॉडल सामान्य है और इसे चुंबकीय प्लाज्मा गतिकी की खोज के लिए किसी भी बेलनाकार सममित चुंबकीय क्षेत्र विन्यास में अनुकूलित किया जा सकता है।

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