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Striation enhanced non-local collisional heating in capacitive radio-frequency CF4 plasmas

关键词

非局域碰撞加热；电容性射频等离子体；CF4 放电；电子动力学；条纹模式

Keywords

Non-local collisional heating; Capacitive radio-frequency plasmas; CF4 discharge; Electron kinetics; Striation mode

摘要

本工作研究了以条纹模式运行的低温射频（RF）容性耦合 CF4 等离子体中电子非局部碰撞加热的增强。在射频电压幅值 V0 = 300 V、CF4 气体压力 p= 60 Pa、间隙 d = 2 cm、驱动频率 f 在 6.78 MHz 到 27.12 MHz 之间的条件下，进行了质点网格法/蒙特卡洛碰撞模拟，呈现了放电模式从条纹模式（striation mode）到漂移-双极（DA mode）模式的过渡。我们发现，在条纹模式下，电子平均能量 εe 的空间分布在主等离子体中呈现出具有高能量峰值的条纹轮廓。对电子加热功率密度时空分布的比较分析表明，在条纹模式中，非局域碰撞加热在这些峰值处占主导地位，而在 DA 模式放电中，与欧姆加热相比，非局域碰撞加热在主等离子体的贡献可以忽略不计。利用无碰撞测试粒子轨迹分析进行的进一步研究表明，低能电子可以在条纹模式放电的主等离子体区中被束缚，并在条纹之间进行多次反弹。高能电子虽然不会被束缚，但会在条纹电场之间输运的过程中经历周期性的加速和减速，并沿轨迹形成条纹状的动能空间分布。这些发现证明了条纹模式下 CF4 电容耦合射频放电中主等离子体区的条纹状电场在增强非局域碰撞加热中的关键作用。

Abstract

We investigate the mechanism of the enhanced electron non-local collisional heating process in radiofrequency (RF) CF4 capacitively coupled plasmas (CCPs) operating in the striation mode. Particle-in-cell/Monte Carlo collision (PIC/MCC) simulations are conducted under an RF voltage amplitude V0 of 300 V, a CF4 gas pressure p of 60 Pa, a gap d of 2 cm and driving frequencies f within the interval of 6.78 MHz to 27.12 MHz, presenting a discharge mode transition from the striation mode to the drift-ambipolar (DA) mode. We show that in the striation mode, the mean electron energy εe within the bulk plasma exhibits a striated profile with high-energy peaks. A comparative electron heating analysis reveals that non-local collisional heating dominates the formation of these high-energy peaks in the striation mode, whereas its contribution to the bulk plasma produced by the DA-mode discharges is negligible relative to that of Ohmic heating. A further investigation conducted using a collisionless test particle analysis demonstrates that low-energy electrons can be trapped in the bulk plasma of striation-mode CF4 CCPs, triggering multiple rebounds among the striations. High-energy electrons are not trapped but rather undergo periodic acceleration and deceleration during transport through the bulk region in the striation discharge mode. These findings support the critical role of striations in enhancing the non-local collisional heating process in CF4 capacitive RF discharges operated in the striation mode.

Author: ZHOU, Zhenhua (Department of Engineering Physics, Tsinghua University)

Co-authors: Ms WANG, Xiaokun (Chair of Applied Electrodynamics and Plasma Technology, Faculty of Electrical Engineering and Information Sciences, Ruhr University Bochum, 44801 Bochum, Germany); Mr YANG, Dong (Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China); Ms LI, Hanyang (Department

of Electrical Engineering, Tsinghua University, Beijing, 100084, China); Mr DONKÓ, Zoltán (Institute for Solid State Physics and Optics, Wigner Research Centre for Physics, 1121 Budapest, Hungary); Mr SCHULZE, Julian (Chair of Applied Electrodynamics and Plasma Technology, Faculty of Electrical Engineering and Information Sciences, Ruhr University Bochum, 44801 Bochum, Germany); Mr LIU, Yongxin (Key Laboratory of Materials Modification by Laser, Ion, and Electron Beams (Ministry of Education), School of Physics, Dalian University of Technology, 116024 Dalian, People's Republic of China); Mr FU, Yangyang (Department of Electrical Engineering, Tsinghua University, Beijing, 100084, China & State Key Laboratory of Power System Operation and Control, Department of Electrical Engineering, Tsinghua University, Beijing 100084, China & Sichuan Energy Internet Research Institute, Tsinghua University, Sichuan 610213, China)

Presenter: ZHOU, Zhenhua (Department of Engineering Physics, Tsinghua University)

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