激光加热等离子体中的电子分布函数

Electron distribution function in laser heated plasmas

E. Fourkal, V. Yu. Bychenkov, W. Rozmus et al.

摘要

A new electron distribution function has been found in laser heated homogeneous plasmas by an analytical solution to the kinetic equation and by particle simulations. The basic kinetic model describes inverse bremsstrahlung absorption and electron-electron collisions. The non-Maxwellian distribution function is comprised of a super-Gaussian bulk of slow electrons and a Maxwellian tail of energetic particles. The tails are heated due to electron-electron collisions and energy redistribution between superthermal particles and light absorbing slow electrons from the bulk of the distribution function. A practical fit is proposed to the new electron distribution function. Changes to the linear Landau damping of electron plasma waves are discussed. The first evidence for the existence of non-Maxwellian distribution functions has been found in the interpretation, which includes the new distribution function, of the Thomson scattering spectra in gold plasmas [Glenzer et al., Phys. Rev. Lett. 82, 97 (1999)]. (C) 2001 American Institute of Physics.

通过动力学方程的解析解和粒子模拟，我们在激光加热的均质等离子体中发现了一种新的电子分布函数。基本动力学模型描述了反轫致辐射吸收和电子-电子碰撞。非麦克斯韦分布函数由慢速电子的超高斯大体和高能粒子的麦克斯韦尾部组成。由于电子-电子碰撞以及超热粒子和分布函数主体中的光吸收慢电子之间的能量再分配，尾部被加热。对新的电子分布函数提出了实用的拟合方法。讨论了电子等离子体波的线性朗道阻尼的变化。在对金等离子体的汤姆逊散射光谱的解释中，发现了非麦克斯韦分布函数存在的第一个证据，其中包括新的分布函数 *[Glenzer 等人，Phys.(C) 2001* 美国物理学会。

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1 导言

INTRODUCTION

There has been an ongoing interest in the description of an electron distribution function (EDF) in collisionally heated laser plasmas. [1−5] Since the work by Langdon [1] it has been known that inverse bremsstrahlung (IB) absorption of powerful lasers in high Z plasmas can result in a nonMaxwellian EDF. These EDFs belong to a family of superGaussian distributions $\approx \exp(-v^{\mu})$ (Ref. 4) which can continuously vary from Maxwellian ($\mu = 2$), for $\alpha = Zv_E^2/v_{Te}^2 < 1$, to a super-Gaussian form with $\mu = 5$ for $\alpha \gg 1$ (v_E is the electron quiver velocity in a laser field, v_{Te} is the electron thermal velocity). Such nonequilibrium states can exist in a plasma for $\alpha > 1$ because the IB heating rate is sufficiently fast for slow particles so that electron-electron $(e-e)$ collisions cannot restore a Maxwellian EDF.

人们对描述碰撞加热激光等离子体中的电子分布函数（EDF）一直很感兴趣。[1−5] 自 Langdon [1] 的研究以来，人们已经知道高 Z 等离子体中强力激光的反轫致辐射（IB）吸收会导致非麦克斯韦 EDF。这些 EDF 属于超高斯分布 $\approx \exp(-v^{\mu})$ 系列（参考文献 4），可以从 $(\mu = 2)$ 的麦克斯韦分布（$\alpha = Zv_E^2/v_{Te}^2$ 为 < 1）持续变化到 $\mu = 5$ 的超高斯分布（$\alpha \gg 1$ 为 v_E 激光场中的电子震颤速度，v_{Te} 为电子热速度）。在 $\alpha > 1$ 时，等离子体中可能存在这种非平衡态，因为对于慢粒子来说，IB 加热速率足够快，因此电子-电子 $(e-e)$ 碰撞无法恢复麦克斯韦 EDF。

We have noticed that these results have been obtained from the approximate kinetic models (cf. Refs. 1 and 4) which include an $e-e$ collision operator acting only on the isotropic part of the distribution function and neglect $e-e$ collision terms involving the anisotropic part of the electron distribution function. [1,4] The omitted terms have a small effect on slow electrons ($v < v_{Te}$) which are heated by the laser. However, they cannot be neglected in the description of a high energy part of the EDF, particularly in the transition region between Maxwellian tails of fast electrons and

我们注意到，这些结果是通过近似动力学模型（参见参考文献 1 和 4）得到的，其中包括一个仅作用于分布函数各向同性部分的 $e-e$ 碰撞算子，而忽略了涉及电子分布函数各向异性部分的 $e-e$ 碰撞项。然而，在描述电子分布函数的高能量部分时，尤其是在快速电子和慢速电子的麦克斯韦尾之间的过渡区域，这些项是不可忽略的。

a) On leave from the P. N. Lebedev Physics Institute, Russian Academy of Science, Moscow 117924, Russia. the super-Gaussian bulk of the EDF. The EDF combining the super-Gaussian form at low electron energies and Maxwellian tails for $v \gg v_{Te}$ constitutes the main new result of this paper. This is a solution to the full kinetic equation, which includes the complete description of $e-e$ collisions in addition to the IB heating term. The EDF is characterized by a time varying scaling velocity in the entire range of particle velocities. The tail electrons increase their average energy due to $e-e$ collisions with slow particles. These results have been confirmed by particle simulations, which have also validated a useful analytical fit to the non-Maxwellian EDF.

a) 俄罗斯科学院列别杰夫物理研究所（P. N. Lebedev Physics Institute, Russian Academy of Science, Moscow 117924, Russia）休假。低电子能量时的超高斯形式与 $v \gg v_{Te}$ 时的麦克斯韦尾部相结合的 EDF 是本文的主要新成果。这是对完整动力学方程的求解，除了 IB 加热项之外，还包括对 $e-e$ 碰撞的完整描述。EDF 的特点是在整个粒子速度范围内的缩放速度随时间变化。由于与慢速粒子的 $e-e$ 碰撞，尾部电子增加了其平均能量。粒子模拟证实了这些结果，同时也验证了对非麦克斯韦 EDF 的有用分析拟合。

The existence of Maxwellian tails for energetic electrons in laser heated EDFs is particularly important for the description of Langmuir waves. Fast electrons determine the damping of Langmuir waves and therefore can play an important role in the evolution of parametric instabilities. The spectra of high frequency electrostatic fluctuations are measurable in Thomson scattering experiments [6] and are sensitive to the particular form of the EDF. We find that the experimental spectra compare well with theoretical predictions based on the new EDF in a gold plasma. Finally, the transition between the super-Gaussian part of the EDF and the Maxwellian tail can occur at velocities as low as $(2-3)v_{Te}$. These are velocities characterizing heat carrying electrons and therefore the new EDF can also alter thermal transport processes. [7]

在激光加热的 EDF 中，高能电子存在 Maxwellian 尾部，这对于描述朗缪尔波尤为重要。快速电子决定了朗缪尔波的阻尼，因此在参数不稳定性的演化过程中扮演着重要角色。高频静电波动的频谱可在汤姆逊散射实验中测量 [6]，并且对 EDF 的特定形式非常敏感。我们发现，实验频谱与基于金等离子体中的新 EDF 的理论预测结果比较吻合。最后，EDF 的超高斯部分与麦克斯韦尾部之间的过渡可能发生在低至 $(2-3)v_{Te}$ 的速度下。这些速度是携带热量的电子的速度特征，因此新的 EDF 也能改变热传输过程。

It is well known that a super-Gaussian EDF can lead to a reduced IB heating rate as compared to the Maxwellian distribution. This EDF contains a smaller number of slow elec- trons due to rapid heating of low energy particles by the IB process. At the same time the super-Gaussian EDF reduces plasma wave damping because of the absence of high energy tails. These tails are depleted because the kinetic model studied before in Refs. 1 and 4 does not include $e-e$ collisional terms involving an anisotropic part of the EDF. Deviations from the super-Gaussian distribution functions have been also examined by Chichkov et al. [5] Using perturbation theory, the authors found large differences as compared to super-Gaussian solutions at high velocities, which led to the breakup of the perturbative expansion and clearly demonstrated the existence of high energy particles. They noticed that because the laser energy absorbed by the fast electrons is much smaller than energy absorbed by the slow electrons, the EDF at high velocities should remain close to Maxwellian due to the $e-e$ collisions between fast and slow particles. However, the approach of Ref. 5 could not provide the electron distribution at high velocities.

众所周知，与麦克斯韦分布（Maxwellian distribution）相比，超高斯分布（super-Gaussian EDF）会导致 IB 加热率降低。由于 IB 过程对低能量粒子的快速加热，这种 EDF 包含较少的慢速电子粒子。同时，由于没有高能量尾部，超高斯 EDF 减少了等离子体波的阻尼。由于参考文献 1 和 4 以前研究的动力学模型不包括涉及 EDF 各向异性部分的 $e-e$ 碰撞项，因此这些尾迹会被耗尽。Chichkov 等人也对超高斯分布函数的偏差进行了研究。[5] 作者利用扰动理论发现，在高速度下，超高斯分布函数与超高斯分布函数的差异很大，这导致了扰动膨胀的破裂，并清楚地证明了高能粒子的存在。他们注意到，由于快速电子吸收的激光能量远小于慢速电子吸收的能量，因此由于快速粒子和慢速粒子之间的 $e-e$ 次碰撞，高速下的 EDF 应保持接近于麦克斯韦式。然而，参考文献 5 的方法无法提供高速时的电子分布。

In the present paper we investigate the time evolution of an electron distribution function using an analytical solution to the Fokker-Planck kinetic equation and particle simulations. We accurately account for the $e-e$ collisional contribution in the equation for the symmetrical part of the electron distribution function which is different from the model used in Refs. 1 and 4. We confirm that the bulk electron distribution function can be well approximated by the superGaussian distribution [4] depending on the value of the parameter α. It is shown that indeed the tail of the distribution function approaches a Maxwellian form due to the $e-e$ collisions. The bulk remains in super-Gaussian form and there is a transition region in velocity space where the distribution function is neither super-Gaussian nor Maxwellian. The particle simulations confirm such a form of the distribution function for arbitrary values of the parameter α and allow finding a fit for the entire range of electron energies.

在本文中，我们利用福克-普朗克动力学方程的解析解和粒子模拟研究了电子分布函数的时间演化。我们在电子分布函数对称部分的方程中精确地考虑了 $e-e$ 碰撞贡献，这与参考文献 1 和 4 中使用的模型不同。我们证实，根据参数 α 的值，体电子分布函数可以很好地近似为超高斯分布 [4]。结果表明，由于 $e-e$ 碰撞，分布函数的尾部确实接近于麦克斯韦形式。大体保持超高斯形式，在速度空间存在一个过渡区域，在该区域分布函数既不是超高斯形式，也不是麦克斯韦形式。粒子模拟证实了在参数 α 的任意值下分布函数的这种形式，并且可以找到整个电子能量范围的拟合。

The paper is organized as follows. Section II presents a derivation of the equation for the symmetrical part of the electron distribution function in a homogeneous plasma heated by a dipole electromagnetic field with $e-e$ collisions taken into account. A self-similar solution to the EDF is discussed in Sec. III. Section IV describes particle simulations and gives a fit for EDF in the entire range of electron energies. Section V deals with the damping of electron plasma waves and electron plasma wave fluctuation spectra which compares well with observations from Thomson scattering. [6] We conclude with a discussion and summary in Sec. VI.

本文的结构如下。第二节介绍了在偶极电磁场加热的均质等离子体中电子分布函数对称部分方程的推导，并考虑了 $e-e$ 碰撞。第三节讨论了电子分布函数的自相似解。第四节介绍粒子模拟，并给出了整个电子能量范围内的 EDF 拟合。第 V 节讨论了电子等离子体波的阻尼和电子等离子体波的波动谱，这与汤姆逊散射的观测结果比较吻合。

2 电子分布函数对称部分的动力学方程

KINETIC EQUATION FOR A SYMMETRIC PART OF THE ELECTRON DISTRIBUTION FUNCTION

We start from the Fokker-Planck kinetic equation for the electron distribution function f in a homogeneous high- Z plasma in a presence of a high frequency electric field $\mathbf{E}=\mathbf{E}_0\cos\omega_0 t$,

我们从存在高频电场 $\mathbf{E}=\mathbf{E}_0\cos\omega_0 t$ 的均匀高 Z 等离子体中电子分布函数 f 的福克-普朗克动力学方程出发、

$$\frac{\partial f}{\partial t}+\frac{e\mathbf{E}}{m}\cdot\frac{\partial f}{\partial \mathbf{v}}=C_{ie}(f)+C_{ee}(f,f), \tag{1}$$

where $C_{ie}(f)$ and $C_{ee}(f,f)$ are the electron-ion and electron-electron collision integrals. For a moderate field intensity, $v_E/v_{Te}<1$, the anisotropic part of an electron distribution function $f_1=f-f_0$ is small as compared to the symmetrical part f_0 and therefore can be determined from Eq. (1) by using a perturbative approach

其中 $C_{ie}(f)$ 和 $C_{ee}(f,f)$ 分别为电子-离子碰撞积分和电子-电子碰撞积分。对于中等场强 $v_E/v_{Te}<1$，电子分布函数 $f_1=f-f_0$ 的各向异性部分与对称部分 f_0 相比很小，因此可以通过微扰方法从式（1）中确定

$$\begin{aligned}f_1=&-\frac{\mathbf{v_E}\cdot\mathbf{v}}{v}\frac{\partial f_0}{\partial v}\sin\omega_0 t+\frac{\cos\omega_0 t}{\omega_0}\left[\nu_{ei}\frac{\mathbf{v_E}\cdot\mathbf{v}}{v}\frac{\partial f_0}{\partial v}\right.\\&\left.-C_{ee}\left(f_0,\frac{\mathbf{v_E}\cdot\mathbf{v}}{v}\frac{\partial f_0}{\partial v}\right)-C_{ee}\left(\frac{\mathbf{v_E}\cdot\mathbf{v}}{v}\frac{\partial f_0}{\partial v},f_0\right)\right].\end{aligned} \tag{2}$$

Here $\nu_{ei}(v)=4\pi Zn_e e^4\Lambda/m_e^2v^3$ is the usual velocitydependent $e-i$ collision frequency, Λ is the Coulomb logarithm, and e, m_e, and n_e are the electron charge, mass, and density, respectively.

这里 $\nu_{ei}(v)=4\pi Zn_e e^4\Lambda/m_e^2v^3$ 是通常的速度依赖型 $e-i$ 碰撞频率，Λ 是库仑对数，e, m_e 和 n_e 分别是电子电荷、质量和密度。

Expression (2) represents the fast varying anisotropic part of the electron distribution function. Substituting (2) into the kinetic equation (1) and averaging over the electric field oscillation period, $1/\omega_0$, we obtain the following equation for the slowly varying symmetrical distribution function:

表达式 (2) 表示电子分布函数中快速变化的各向异性部分。将（2）式代入动力学方程（1），并对电场振荡周期 $1/\omega_0$ 取平均值，就得到了下式，即缓慢变化的对称分布函数：

$$
\begin{aligned}
\frac{\partial f_0}{\partial t} = & \frac{v_E^2}{6v^2}\frac{\partial}{\partial v}\left(v^2\nu_{ei}\frac{\partial f_0}{\partial v}\right)+C_{ee}\left(f_0,f_0\right) \\
& -\frac{v_E^2}{6v^2}\frac{\partial}{\partial v}v^2\left[C_{ee}\left(f_0,\frac{\partial f_0}{\partial v}\right)+C_{ee}\left(\frac{\partial f_0}{\partial v},f_0\right)\right] \\
& -\frac{v_E^2}{2}C_{ee}\left(\frac{\partial f_0}{\partial v},\frac{\partial f_0}{\partial v}\right).
\end{aligned} \tag{3}
$$

Electron-electron collisional operators on the right-hand side of Eq. (3) can be written in the explicit form in accordance with Ref. 8:

公式 (3) 右侧的电子-电子碰撞算子可以根据参考文献 8 以显式形式写出：

$$
\begin{aligned}
& C_{ee}\left(f_0,f_0\right)=\frac{Y}{v^2}\frac{\partial}{\partial v}\left[f_0I_0^0+\frac{v}{3}\left(I_2^0+J_{-1}^0\right)\frac{\partial f_0}{\partial v}\right], \\
& C_{ee}\left(\frac{\partial f_0}{\partial v},\frac{\partial f_0}{\partial v}\right)=\frac{Y}{3v^2}\frac{\partial}{\partial v}\left[-\frac{\partial^2 f_0}{\partial v^2}I_2^0+\frac{\partial f_0}{\partial v}\right. \\
& \left.\times\left(4\pi v^2 f_0+\frac{1}{v}\left(I_2^0-3I_0^0\right)\right)\right] \\
& C_{ee}\left(f_0,\frac{\partial f_0}{\partial v}\right)+C_{ee}\left(\frac{\partial f_0}{\partial v},f_0\right) \\
& =\frac{Y}{3v}\frac{\partial^3 f_0}{\partial v^3}\left(I_2^0+J_{-1}^0\right) \\
& +\frac{Y}{3v^2}\frac{\partial^2 f_0}{\partial v^2}\left(3I_0^0-4I_2^0+2J_{-1}^0\right)+\frac{Y}{3v^3}\frac{\partial f_0}{\partial v} \\
& \times\left(-6I_0^0+4I_2^0-2J_{-1}^0\right)+8\pi Y\frac{\partial f_0}{\partial v}f_0,
\end{aligned} \tag{4}
$$

where $Y=4\pi n_e e^4\Lambda/m_e^2, \Lambda$ is the Coulomb logarithm and

其中 $Y=4\pi n_e e^4\Lambda/m_e^2, \Lambda$ 是库仑对数，而

$$
I_j^i=\frac{4\pi}{v^j}\int_0^v f_i v^{2+j}dv, \quad J_j^i=\frac{4\pi}{v^j}\int_v^\infty f_i v^{2+j}dv.
$$

By neglecting in Eq. (3) terms proportional to $v_E^2 C_{ee}$, which originate from $e-e$ collisions involving the anisotropic part of the EDF, we can reduce (3) to the model equation analyzed in Refs. 1 and 4. However, all of the $e-e$ collision terms in Eq. (3) are important for the correct description of the electron distribution function at large velocities ($v>v_{Te}$). Note also that Eq. (2.3) of Ref. 9, which is the kinetic equation for the symmetric part of the distribution function, is missing terms $\propto v_E^2\left[C_{ee}\left(f_0,\partial f_0/\partial v\right)\right.$ $\left.+C_{ee}\left(\partial f_0/\partial v,f_0\right)\right]$.

通过忽略式（3）中与 $v_E^2 C_{ee}$ 成正比的项，我们可以将式（3）简化为参考文献 1 和 4 中分析的模型方程。然而，式（3）中的所有 $e-e$ 碰撞项对于正确描述大速度下的电子分布函数（$v>v_{Te}$ ）都非常重要。还要注意的是，参考文献 9 中的式 (2.3)，即分布函数对称部分的动力学方程，缺少了 $\propto v_E^2\left[C_{ee}\left(f_0,\partial f_0/\partial v\right)\right.$ $\left.+C_{ee}\left(\partial f_0/\partial v,f_0\right)\right]$ 项。

3 电子分布函数

ELECTRON DISTRIBUTION FUNCTION

We use the standard definition for the electron density, n_e, thermal velocity, v_{Te}, and electron temperature, T_e :

我们使用标准定义来定义电子密度 n_e、热速度 v_{Te} 和电子温度 T_e：

$$n_e = 4\pi \int v^2 f_0 dv, \quad v_{Te}^2 = \frac{4\pi}{3n_e} \int v^4 f_0 dv \equiv \frac{T_e}{m_e}. \tag{5}$$

Multiplying Eq. (1) by v^2 and integrating over the entire velocity range one obtains an equation for the time evolution of the electron temperature

将公式（1）乘以 v^2 并对整个速度范围进行积分，就可以得到电子温度的时间演化方程

$$\frac{\partial T_e}{\partial t} = \frac{4\pi ZY}{9n_e m_e} v_E^2 f_0(0,t), \tag{6}$$

which demonstrates that the heating rate is entirely defined by very slow electrons $[f_0(0,t) \equiv f_0(v=0,t)]$. For times much longer than the $e-e$ collision time we look for a solution to the electron distribution function in the following form:

这表明加热速率完全由非常慢的电子 $[f_0(0,t) \equiv f_0(v=0,t)]$ 决定。对于比 $e-e$ 碰撞时间更长的时间，我们可以寻找以下形式的电子分布函数解：

$$f_0 = \frac{n}{(2\pi)^{3/2} v_{Te}(t)^3} \phi\left(\frac{v}{v_{Te}(t)}, t\right), \tag{7}$$

where $v_{Te}(t)$ grows in time according to Eq. (6). By introducing a dimensionless velocity $x = v/v_{Te}(t)$, the equation for $\phi(x)$ can be written in the following form:

根据公式（6），$v_{Te}(t)$ 随时间增长。通过引入无量纲速度 $x = v/v_{Te}(t)$，$\phi(x)$ 的方程可以写成下面的形式：

$$\begin{aligned} &\phi I_0^0 + \frac{x}{3}\frac{\partial \phi}{\partial x}\left(I_2^0 + J_{-1}^0\right) + \frac{\alpha}{6x}\left[\frac{\partial \phi}{\partial x} + \sqrt{\frac{2}{\pi}}\frac{x^4}{3}\phi\phi(0)\right] \\ &\quad - \frac{\alpha}{6Z}\left[\frac{x}{3}\frac{\partial^3 \phi}{\partial x^3}\left(I_2^0 + J_{-1}^0\right) + \frac{\partial^2 \phi}{\partial x^2}\left(I_0^0 - \frac{7}{3}I_2^0 + \frac{2}{3}J_{-1}^0\right)\right. \\ &\quad \left. + \frac{1}{x}\frac{\partial \phi}{\partial x}\left(-5I_0^0 + \frac{7}{3}I_2^0 - \frac{2}{3}J_{-1}^0\right) + 3\sqrt{\frac{8}{\pi}x^2}\frac{\partial \phi}{\partial x}\phi\right] = 0, \end{aligned} \tag{8}$$

where $I_0^0 = \sqrt{2/\pi}\int_0^x \phi x^2 dx$, $I_2^0 = \sqrt{2/\pi}x^{-2}\int_0^x \phi x^4 dx$, and $J_{-1}^0 = \sqrt{2/\pi}x\int_x^\infty \phi x dx$. We have neglected the terms proportional to $\partial\phi/\partial t$ in deriving Eq. (8). We assume that these terms are small after the initial time corresponding to few $e-e$ collision times. In Eq. (8) the term proportional to α/x describes IB heating while all the others (with and without the factor α) are due to $e-e$ collisions. The interplay between IB heating and $e-e$ collisional relaxation determines the electron distribution function in the entire range of electron velocities. The function $\phi(x)$ in Eq. (8) satisfies two integral relations,

其中 $I_0^0 = \sqrt{2/\pi}\int_0^x \phi x^2 dx$, $I_2^0 = \sqrt{2/\pi}x^{-2}\int_0^x \phi x^4 dx$ 和 $J_{-1}^0 = \sqrt{2/\pi}x\int_x^\infty \phi x dx$. 在推导公式 (8) 时，我们忽略了与 $\partial\phi/\partial t$ 成比例的项。我们假定这些项在初始时间之后很小，对应于很少的 $e-e$ 碰撞时间。在式 (8) 中，与 α/x 成比例的项描述了 IB 加热，而所有其他项（包括和不包括因子 α）都是由 $e-e$ 碰撞引起的。IB 加热和 $e-e$ 碰撞弛豫之间的相互作用决定了整个电子速度范围内的电子分布函数。式（8）中的函数 $\phi(x)$ 满足两个积分关系、

$$\int_0^\infty x^2 \phi dx = \sqrt{\pi/2}, \quad \int_0^\infty x^4 \phi dx = 3\sqrt{\pi/2}, \tag{9}$$

which originate from definitions of the electron density and thermal energy (5).

源于电子密度和热能的定义 (5)。

The term proportional to Z^{-1} in Eq. (8) which originated from the anisotropic part of the $e-e$ collision operator can be neglected for electrons from a bulk of the distribution function ($x \leqq 1$). For such a case the equation for ϕ (8) and integral relations defining I_0^0, I_2^0, and J_{-1}^0 can be rewritten as a system of four first-order ordinary nonlinear differential equations:

式（8）中与 Z^{-1} 成比例的项来自 $e-e$ 碰撞算子的各向异性部分，对于来自分布函数 ($x \leqq 1$) 体的电子，该项可以忽略。在这种情况下，ϕ (8) 的方程以及定义 I_0^0, I_2^0 和 J_{-1}^0 的积分关系可以改写为四个一阶普通非线性微分方程系统：

$$\begin{aligned} &\frac{\alpha}{6}\frac{d\phi}{dx} + \sqrt{\frac{2}{\pi}}\frac{\alpha}{18}x^4\phi(0)\phi + xI_0^0\phi + \left(\frac{1}{3}x^2 I_2^0(x) + \frac{x^2}{3}J_{-1}^0\right)\frac{d\phi}{dx} \\ &= 0, \\ &\frac{dI_0^0}{dx} = \sqrt{\frac{2}{\pi}}x^2\phi, \quad \frac{d\left(x^2 I_2^0\right)}{dx} = \sqrt[5]{\frac{2}{\pi}}x^4\phi, \quad \frac{d\left(J_{-1}^0/x\right)}{dx} = -\sqrt{\frac{2}{\pi}}x\phi \end{aligned} \tag{10}$$

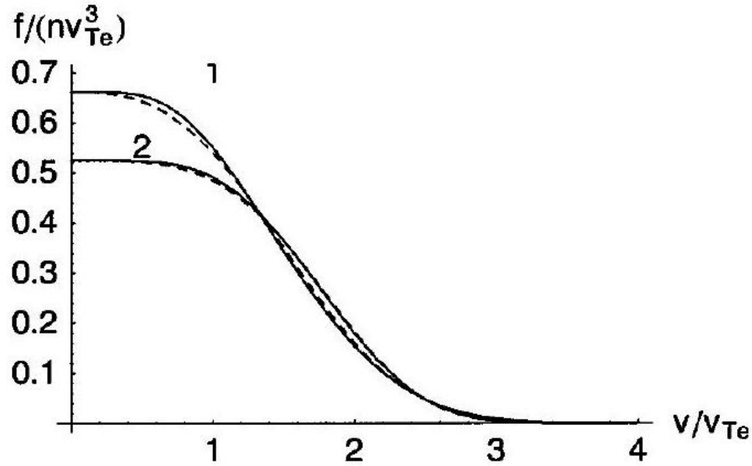

图 1: Solutions to the kinetic equation (10) for $\alpha = 0.5$ (1), and $\alpha = 3$ (2), represented by solid lines as compared to the super-Gaussian fit (11).
$\alpha = 0.5$ (1) 和 $\alpha = 3$ (2) 动力方程 (10) 的解，实线表示与超高斯拟合 (11) 的比较。

The system of equations given by (10) has been solved numerically using the MATHEMATICA program, [10] giving results that are similar to distribution functions obtained by numerical simulations in Ref. 11. We have found solutions for different values of the parameter α. Figure 1 shows electron distribution functions for $\alpha = 0.5$ and 3 in comparison with the super-Gaussian fit which has been obtained from the numerical solution to the Fokker-Planck kinetic equation, [4]

我们使用 MATHEMATICA 程序对 (10) 所给出的方程组进行了数值求解，[10] 得出的结果与参考文献 11 中通过数值模拟得到的分布函数相似。我们找到了不同参数 α 值的解。图 1显示了 $\alpha = 0.5$ 和 3 的电子分布函数与福克-普朗克动力学方程数值解得到的超高斯拟合结果的对比，[4]

$$\phi(x) = \phi_0 e^{-(x/x_0)^m} = 3\sqrt{\frac{\pi}{2}}\frac{m\Gamma(5/m)^{3/2}}{(3\Gamma(3/m))^{5/2}} \times \exp\left[-\left(\frac{x}{x_0}\right)^m\right], \tag{11}$$

where

其中

$$x_0 = \left(\frac{3\Gamma(3/m)}{\Gamma(5/m)}\right)^{1/2}, \quad m = 2 + \frac{3}{1 + 1.66/\alpha^{0.724}}.$$

As one can see the super-Gaussian fit (11) gives a good approximation for the bulk electrons of the laser heated distribution function. Note that the different fit has also been proposed to the solution of Eq. (10) in Ref. 12. It has a different functional form but similar accuracy to the results of Matte et al. [4]

可以看出，超高斯拟合 (11) 对激光加热分布函数的电子体给出了一个很好的近似值。请注意，在参考文献 12 中也对式 (10) 的解提出了不同的拟合。它的函数形式不同，但精度与 Matte 等人的结果相似。

However, in order to describe the evolution of an electron distribution in the entire region of particle velocities one has to include proper electron-electron collisional terms and solve the kinetic equation (8). We find the validity condition for the approximation leading to Eq. (8) by comparing $e - e$ collision terms omitted in (10) with the IB heating term. This gives

然而，为了描述整个粒子速度区域内电子分布的演变，我们必须加入适当的电子-电子碰撞项，并求解动力学方程 (8)。通过比较 (10) 中省略的 $e - e$ 碰撞项和 IB 加热项，我们可以找到导致公式 (8) 的近似值的有效性条件。由此得出

$$v/v_{Te} < x^* \equiv Z^{1/2(m-1)}\left[\frac{3\Gamma(3/m)}{\Gamma(5/m)}\right]^{m/4(m-1)}, \quad \alpha \gtrsim 1, \tag{12}$$

which defines energies of particles described by the superGaussian distribution function (11). For example, if $m = 5,$[1] condition (12) reads $v < (2-2.5)v_{Te}$ for $Z = 10-40$. For velocities larger than $v_{Te}X^*$ (12), the $e-e$ collision operators will dominate the heating term thus redistributing electron tails toward the Maxwellian. The laser energy absorbed directly by fast electrons is much smaller than the energy absorbed by the bulk electrons and their distribution is close to Maxwellian. However, the characteristic temperature of the tail is increasing simultaneously with the slow electron energy due to $e-e$ collisions between fast and slow particles.

定义了超高斯分布函数 (11) 所描述的粒子能量。例如，如果 $m = 5,$[1] 的条件 (12) 为 $v < (2-2.5)v_{Te}$，$Z = 10-40$ 的条件 (12) 为 $v < (2-2.5)v_{Te}$。当速度大于 $v_{Te}X^*$ (12) 时，$e-e$ 碰撞算子将主导加热项，从而使电子尾部向麦克斯韦方向重新分布。快速电子直接吸收的激光能量远小于电子体吸收的能量，因此它们的分布接近于麦克斯韦分布。然而，由于快速粒子和慢速粒子之间的 $e-e$ 碰撞，电子尾部的特征温度与慢速电子能量同时增加。

4 粒子模拟

PARTICLE SIMULATIONS

Kinetic simulations of the laser heated EDF in homogeneous plasmas have been performed using a particle code. Collisions between electrons and ions, and electrons and electrons have been introduced using the binary collision model by a Monte Carlo method, [13,14] which conserves particle number, energy, and momentum. No self-consistent fields are included into the numerical model, which provides an efficient alternative to the usual Fokker-Planck simulations. By using a two temperature relaxation problem as a test we have found very good agreement between the results from the Fokker-Planck code with exact nonlinear $e-e$ collisional term [15] and our particle code.

使用粒子代码对均质等离子体中激光加热的 EDF 进行了动力学模拟。电子与离子以及电子与电子之间的碰撞是通过蒙特卡洛法引入二元碰撞模型的。数值模型中不包含自洽场，这为通常的福克-普朗克模拟提供了一种高效的替代方法。通过使用两个温度弛豫问题作为测试，我们发现带有精确非线性 $e-e$ 碰撞项 [15] 的福克-普朗克代码与我们的粒子代码的结果非常一致。

The particle velocity and position are changed during each time step due to both the electric dipole pump field and scattering on other particles. Simulations start from a given initial electron distribution function, which is often taken to be a nonequilibrium EDF. We illustrate our findings by discussing results of the particular example where the laser frequency ω_0 is chosen to be equal to $6\omega_{pe}$. In order to decrease the computation time, we have used relatively high thermal $e-i$ collision frequency, $\nu_{ei}(v_{Te})/\omega_{pe} = 0.05$, and the ratio between the initial quiver and electron thermal velocities at $t = 0$ has been chosen $1/4 < v_E^2/v_{Te}^2 < 1/2$. The total number of particles, electrons, and ions is 256000 , so that the electron distribution function can be resolved in the velocity range $0 < v/v_{Te}(t) < 6$.

由于电偶极泵场和其他粒子的散射作用，粒子的速度和位置在每个时间步长内都会发生变化。模拟从给定的初始电子分布函数开始，该函数通常被认为是非平衡 EDF。我们通过讨论激光频率 ω_0 与 $6\omega_{pe}$ 相等的特定示例结果来说明我们的发现。为了减少计算时间，我们使用了相对较高的热 $e-i$ 碰撞频率 $\nu_{ei}(v_{Te})/\omega_{pe} = 0.05$，并选择了 $t = 0$ 处的初始震颤速度与电子热速度之比 $1/4 < v_E^2/v_{Te}^2 < 1/2$。粒子、电子和离子的总数为 256000，因此可以在 $0 < v/v_{Te}(t) < 6$ 速度范围内解析电子分布函数。

First, we have calculated an electron heating rate. Figure 2 shows an electron temperature normalized to its initial value versus time. The plot demonstrates that the heating rate changes with time. This is understandable since the heating rate depends on the form of the EDF, which changes in time as well. The initial heating rate is the largest. As the distribution function evolves toward the superGaussian and the depletion of the number of slow electrons occurs, the plasma heating rate decreases. We have also plotted in Fig. 2 the heating rate which is predicted by Eq. (6) with f_0 given by the solution to Eq. (10). There is a good agreement between particle simulations and the theory.

首先，我们计算了电子加热率。图 2 显示了电子温度归一化后的初始值与时间的关系。从图中可以看出，加热率随时间而变化。这是可以理解的，因为加热率取决于 EDF 的形式，而 EDF 的形式也会随时间发生变化。初始加热速率最大。随着当等离子体的等离子函数向超高斯演化，慢速电子的数量减少时，等离子体的加热速率就会降低。我们还在图 2 中绘制了由式 (6) 预测的加热率，以及由式 (10) 的解给出的 f_0。粒子模拟结果与理论结果非常吻合。

$$
\begin{aligned}
&\phi(x) = \phi_0 e^{-(x/x_0(x))^{m(x)}}, \\
&m(x) = 2 + \frac{m-2}{1+(x/x^*)^9}, \quad x_0(x) = x_0(m(x))
\end{aligned} \tag{13}
$$

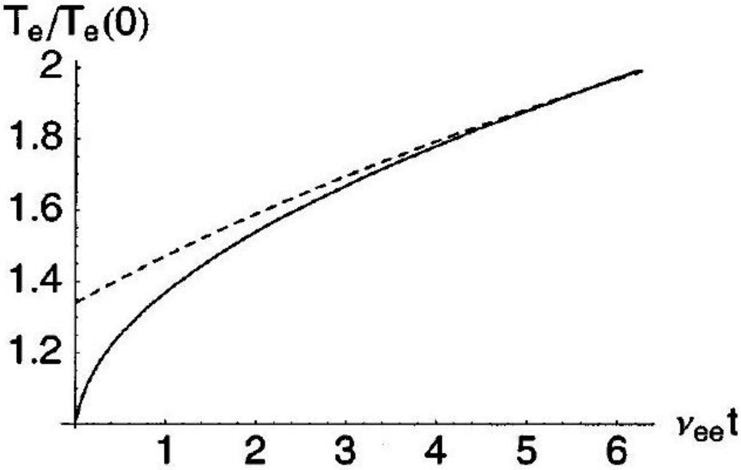

图 2: The electron temperature (solid line) from particle simulation in comparison with a theoretical result for the heating rate given by Eq. (11) (dashed line) in a plasma with $Z = 40$ and $\alpha(0) = 4.8$.
在 $Z = 40$ 和 $\alpha(0) = 4.8$ 等离子体中，粒子模拟的电子温度（实线）与公式（11）给出的加热率理论结果（虚线）的对比。

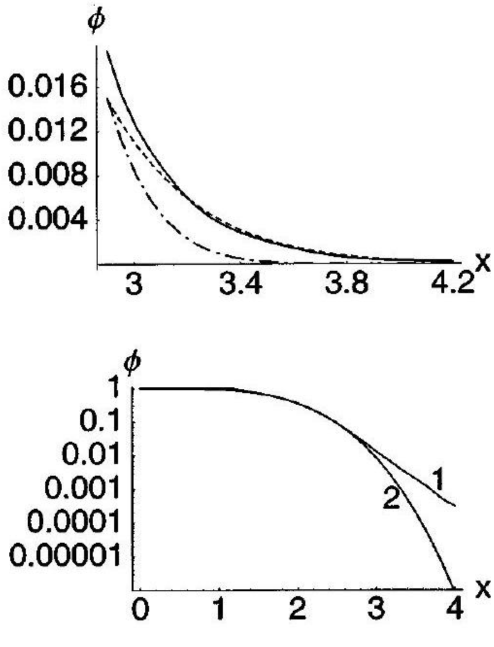

图 3: The time averaged electron distribution function from the particle simulation (the solid line in the top panel and line 1 in the bottom panel) vs velocity ($\alpha = 3.1$) when the EDF is already in a self-similar form (Z =30). The dashed line in the top panel represents the Maxwellian distribution and the super-Gaussian distribution (13) is shown as a dot-dashed curve in the top panel and curve 2 in the bottom panel.
粒子模拟的时间平均电子分布函数（上图中的实线和下图中的线 1）与速度（$\alpha = 3.1$）的关系，此时 EDF 已处于自相似形式（Z =30）。上图中的虚线表示麦克斯韦分布，超高斯分布（13）在上图中以点虚线表示，在下图中以曲线 2 表示。

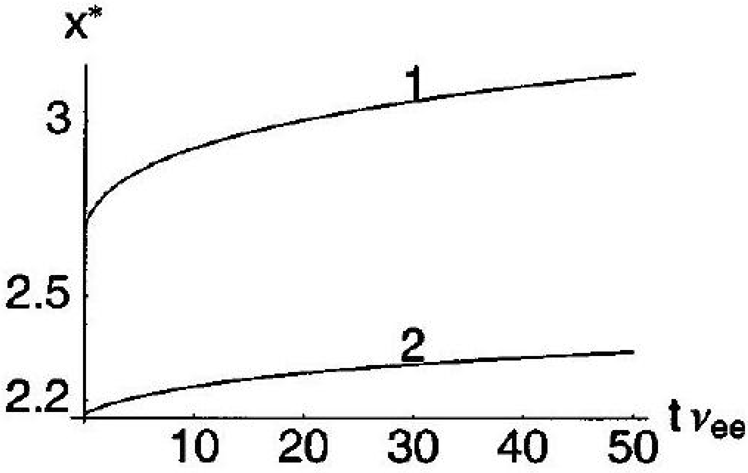

图 4: Evolution of x^* [Eq. (12)] for $\alpha(0) = 4.8$ and $Z = 40$ (1) and $\alpha(0) = 0.6$ and $Z = 5(2)$.
$\alpha(0) = 4.8$ 和 $Z = 40$ (1) 以及 $\alpha(0) = 0.6$ 和 $Z = 5(2)$ 的 x^* [公式 (12)] 的演变。

such that at $x \ll x^*, m(x) = m$ and $x_0(x) = x_0$. Expressions (11), (6) with a new definition of m (13) give the superGaussian distribution at thermal velocities and describe well the transition to the Maxwellian tail at high velocities. We have found very good agreement between (13) and the simulation results. The evolution of x^* is shown in Fig. 4 . In the dimensional form, $v_{Te}X^*$ increases in time a little faster than thermal velocity (cf. Fig. 4).

这样，在 $x \ll x^*, m(x) = m$ 和 $x_0(x) = x_0$. 表达式（11）、（6）和 m 的新定义（13）给出了热速度下的超高斯分布，并很好地描述了高速下向麦克斯韦尾部的过渡。我们发现（13）与模拟结果非常吻合。x^* 的演变如图 4 所示。在维数形式下，$v_{Te}X^*$ 的时间增长速度略快于热速度（参见图 4）。

5 电子等离子体波阻尼和波动谱

ELECTRON PLASMA WAVE DAMPING AND FLUCTUATION SPECTRUM

Non-Maxwellian EDFs affect many processes in laserproduced plasmas. In particular, they can reduce the rate of laser light absorption, modify thermal transport, or reduce damping on Langmuir waves and therefore change the evolution of parametric instabilities involving electron plasma waves. The new solutions discussed in this paper are varying in time and therefore can be applied to the descriptions of processes which are faster than the IB heating rate.

非麦克斯韦 EDF 会影响激光产生的等离子体中的许多过程。特别是，它们会降低激光光吸收率、改变热传输或减少朗穆尔波的阻尼，从而改变涉及电子等离子体波的参数不稳定性的演变。本文所讨论的新解决方案是随时间变化的，因此可用于描述比 IB 加热速率更快的过程。

In order to fully understand the impact of non-Maxwellian EDFs on the long time scale, when transport processes may be as equally important as the IB heating, one needs to examine the effect of plasma inhomogeneity. Such simulations [4] have shown that the EDF reaches quasistationary state without changing its functional form, which is well approximated by a fit quoted in Eq. (11). However, the kinetic model in Ref. 4 omits $e-e$ collision terms which are important for the formation of energetic electron tails. Thus, it is likely that a more complete theory of inhomogeneous plasmas will produce quasistationary EDF with tails of fast electrons, particularly in view of the strong experimental evidence from Thomson scattering spectra as described in the following. For similar reasons more recent Fokker-Planck simulations in the geometry relevant to random phase plate laser beams are likely underestimating the importance of tails and overestimating the reduction of Langmuir wave damping. [16] In fact the tails in the non-Maxwellian EDF have

为了充分理解非麦克斯韦 EDF 对长时间尺度的影响，即传输过程可能与 IB 加热同等重要，我们需要研究等离子体不均匀性的影响。这种模拟 [4] 表明，EDF 在达到准稳态时不会改变其函数形式，这可以很好地近似为式（11）中引用的拟合。然而，参考文献 4 中的动力学模型省略了 $e-e$ 碰撞项，而这些碰撞项对于高能电子尾巴的形成非常重要。因此，更完整的非均质等离子体理论很可能会产生具有快速电子尾巴的类稳态 EDF，特别是考虑到下文所述的汤姆逊散射光谱的有力实验证据。[16] 事实上，在只有电子-离子碰撞的非均质低密度等离子体的模型计算中，已经从理论上预测了非麦克斯韦 EDF 的尾部。

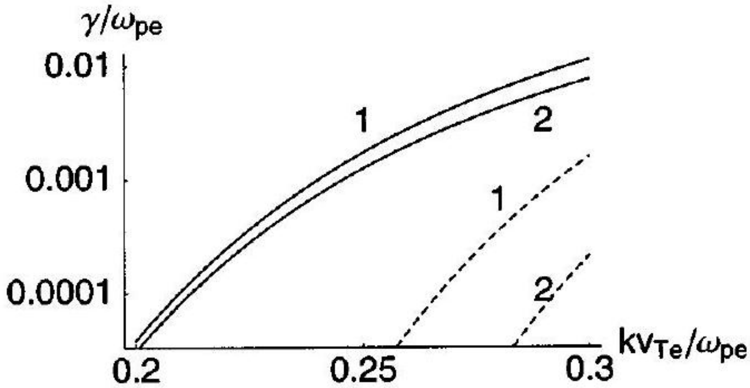

图 5: The collisionless electron plasma wave damping vs wave number for $\alpha = 1$ and $Z = 10$ (1) and $\alpha = 4$ and $Z = 40$ (2) in collisionless plasma. Dashed lines correspond to the super-Gaussian distribution function.
在无碰撞等离子体中，$\alpha = 1$ 和 $Z = 10$ (1) 以及 $\alpha = 4$ 和 $Z = 40$ (2) 的无碰撞电子等离子体波阻尼与波数的关系。虚线对应超高斯分布函数。

been theoretically predicted in the model calculations relevant to inhomogeneous underdense plasmas in the presence of only electron-ion collisions. [17] These tails display powerlike dependence on electron velocity.

It is straightforward to show that the new EDF based on expressions (11) and (13) increases Langmuir wave damping as compared to a simple super-Gaussian fit (11). The changes due to the non-Maxwellian distribution function occur mostly in an imaginary part of the electron susceptibility $\chi_e(\omega, k)$, which can be approximated by the following formula: [18]

很容易看出，与简单的超高斯拟合（11）相比，基于表达式（11）和（13）的新 EDF 增加了朗缪尔波阻尼。非麦克斯韦分布函数引起的变化主要发生在电子感性 $\chi_e(\omega, k)$ 的虚部，可用下式近似：[18]

$$\begin{aligned} \operatorname{Im}\chi_e(\omega, k) = {} & \frac{2\pi^2}{n_e}\frac{\omega_{pe}^2}{k^3}\omega f_0\bigg|_{v=|\omega/k|} \\ & + \frac{(2\pi)^{3/2}}{n_e}\frac{\omega_{pe}^2}{\omega^3}v_{Te}^3\nu_{ei}f_0\bigg|_{v=0}, \end{aligned} \tag{14}$$

where ν_{ei}^T is the standard transport electron-ion collision frequency, $\nu_{ei}^T = 4\sqrt{2\pi}Ze^4 n_e\Lambda/(3m_e v_{Te}^3)$. In Fig. 5 the resonant wave damping, which corresponds to the first term in Eq. (14) $\gamma_p = \omega_{pe}\operatorname{Im}\chi_e(\omega_p, k)/2$, where $\omega_p^2 = \omega_{pe}^2 + 3k^2 v_{Te}^2$, is plotted versus wave number.

其中 ν_{ei}^T 是标准传输电子-离子碰撞频率 $\nu_{ei}^T = 4\sqrt{2\pi}Ze^4 n_e\Lambda/(3m_e v_{Te}^3)$。图 5 是共振波阻尼与波数的关系图，共振波阻尼与公式（14）中的第一项 $\gamma_p = \omega_{pe}\operatorname{Im}\chi_e(\omega_p, k)/2$（其中 $\omega_p^2 = \omega_{pe}^2 + 3k^2 v_{Te}^2$）相对应。

In view of the important role played by the non-Maxwellian EDF for different laser-plasma coupling processes, an experimental verification of the particular form of these nonequilibrium states is of fundamental importance. Unfortunately there has been no direct evidence supporting the existence of these EDFs in laser-produced plasmas. The strongest confirmation so far is from the microwave experiment [19] where the Langmuir probe measurements in cold weakly ionized plasma indicated that the isotropic component of the EDF is non-Maxwellian.

鉴于非麦克斯韦 EDF 在不同的激光-等离子体耦合过程中发挥的重要作用，对这些非平衡态的特殊形式进行实验验证具有根本性的重要意义。遗憾的是，目前还没有直接证据支持激光产生的等离子体中存在这些 EDF。迄今为止最有力的证实来自微波实验 [19]，其中在冷弱电离等离子体中进行的朗缪尔探针测量表明，EDF 的各向同性分量是非麦克斯韦态的。

The favorable conditions for the existence of non-Maxwellian EDF have been recently achieved in gold disk plasmas [6] created by powerful Nova laser beams. The experiment involved simultaneous measurements of ion-acoustic and Langmuir fluctuation spectra by Thomson scattering of a 2ω beam, which led to the ac-

最近，在由强大的新星激光束产生的金盘等离子体 [6] 中实现了非麦克斯韦 EDF 存在的有利条件。该实验通过汤姆逊散射 2ω 光束同时测量了离子声学和朗缪尔波动光谱，从

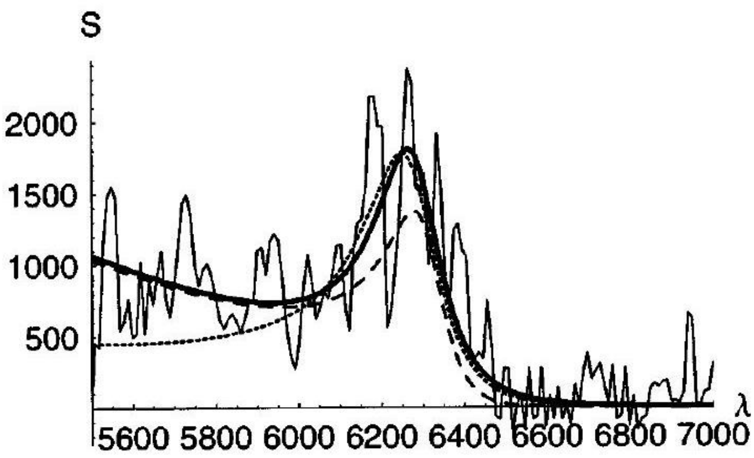

图 6: The electron plasma wave fluctuation spectra (in arbitrary units) as a function of the scattered light wavelength in . Experimental data (noisy solid line) is taken from Ref. 6 and corresponds to the measurement at $t = 2.25$ ns. A Maxwellian fit $\left(T_e = 750\text{eV}, n_e = 5.5 \times 10^{19}\ \text{cm}^{-3}\right)$ is given by a dotted line. The dashed line shows a fit with the super-Gaussian EDF (11) and the solid line corresponds to the spectrum calculated with a new nonMaxwellian EDF (13) for the following plasma parameters $m = 4, n_e = 4.5\ \times 10^{19}\ \text{cm}^{-3}, T_e = 950\text{eV}, Z = 26$.
电子等离子体波波动光谱（任意单位）与 散射光波长的函数关系。实验数据（嘈杂的实线）来自参考文献 6，对应于 $t = 2.25$ ns 时的测量值。虚线表示 Maxwellian 拟合 $\left(T_e = 750\text{eV}, n_e = 5.5 \times 10^{19}\ \text{cm}^{-3}\right)$。虚线表示用超高斯 EDF (11) 拟合的结果，实线则对应于用新的非麦克斯韦 EDF (13) 计算出的下列等离子体参数 $m = 4, n_e = 4.5\ \times 10^{19}\ \text{cm}^{-3}, T_e = 950\text{eV}, Z = 26$ 的光谱。

curate prediction of the ionic charge Z and T_e. Langmuir fluctuations have been measured at relatively large values of k/k_{D} making the spectra very sensitive to the form of the EDF (here k is the probed wave vector defined by the geometry of the scattering and k_{D} is the Debye wave number). In addition, the Thomson probe has reached high intensity values up to 10^{15} W/cm^2 giving values for the parameter α up to four, particularly at the late time when the background plasma temperature is low.

而准确预测了离子电荷 Z 和 T_e。朗缪尔波动是在相对较大的 k/k_{D} 值下测量的，这使得光谱对 EDF 的形式非常敏感（这里 k 是由散射几何定义的探测波矢量，k_{D} 是 Debye 波数）。此外，汤姆逊探针的强度值高达 10^{15} W/cm^2，参数 α 的值高达 4，尤其是在背景等离子体温度较低的后期。

In Fig. 2 of Ref. 6 four Langmuir wave spectra have been shown. Three of them, at the later times $t > 1.5$ ns, have been measured after the heater beams are off and decreasing

参考文献 6 的图 2 显示了四个朗缪尔波谱。其中三幅是在加热器光束关闭后测量的，时间为 $t > 1.5$ ns 后。

background plasma temperature creates conditions of $\alpha > 1$. The theoretical interpretation of the Langmuir wave spectra has been based on the generalized expressions for the scattered power in inhomogeneous plasmas [6] and the standard model of the dynamical form factor $S(k, \omega)$, [20]

背景等离子体温度创造了 $\alpha > 1$ 的条件。朗缪尔波谱的理论解释基于不均匀等离子体中散射功率的广义表达式 [6] 和动力学形式因子的标准模型 $S(k, \omega)$, [20]。

$$S(k, \omega) = \frac{2\pi}{|\boldsymbol{\epsilon}(k, \omega)|^2} \int d^3v f_0(v) \delta(\omega - \mathbf{k} \cdot \mathbf{v}), \tag{15}$$

where ω is the frequency shift of the scattered from 5026 wavelength of the probe and $\epsilon(k, \omega)$ is a plasma dielectric function.

其中，ω 是来自 5026 探头波长的散射频移，$\epsilon(k, \omega)$ 是等离子体介电函数。

Figure 6 shows the experimental data at $t = 2.25$ ns (this is the latest time spectra from Fig. 2 of Ref. 6). All Langmuir wave spectra in Ref. 6 have been interpreted by using a local Maxwellian distribution function for $f_0(v)$ in (15) (the dotted line in Fig. 6). The difficulty of trying to reproduce experimental data with a super-Gaussian EDF (11), in spite of $\alpha > 1$, is illustrated in Fig. 6. A reduced

图 6 显示了 $t = 2.25$ ns 时的实验数据（这是参考文献 6 图 2 中最新的时间光谱）。参考文献 6 中的所有朗缪尔波谱都是通过使用 (15) 中 $f_0(v)$ 的局部麦克斯韦分布函数（图 6 中的虚线）来解释的。图 6 说明了尽管有 $\alpha > 1$，但试图用超高斯 EDF (11) 重现实验数据的困难。超热电子数量的减少

number of superthermal electrons cannot support the broad Langmuir wave resonance (the dashed line in Fig. 6). However, non-Maxwellian EDF can well reproduce the short wavelength part ($5500 < \lambda < 6500$) of the experimental spectrum (cf. Fig. 6) where the scattered power displays a local minimum (this feature of the experimental measurement is also apparent on two other plots, $t = 2$ and 1.75 ns, in Fig. 2 of Ref. 6). Theoretically, these local minima are only present for nonequilibrium distribution functions. The combined effect of the large fluctuation levels at the plasma wave resonance and the local minima at the shorter wavelength is well reproduced by our new distribution function as shown in Fig. 6 (solid line). This is the first, "almost", direct measurement showing signatures of the non-Maxwellian distribution functions in laser produced plasmas. In calculating the theoretical spectrum in Fig. 6 we assumed that the symmetric part of the EDF (13) is constant in time.

无法支持宽泛的朗缪尔波共振（图 6 中的虚线）。然而，非麦克斯韦 EDF 可以很好地再现实验光谱的短波长部分（5500 $< \lambda <$ 6500）（参见图 6），在这部分散射功率显示出局部最小值（实验测量的这一特征在参考文献 6 图 2 中的另外两幅图 $t = 2$ 和 1.75 ns 上也很明显）。从理论上讲，这些局部最小值只存在于非平衡分布函数中。如图 6（实线）所示，我们的新分布函数很好地再现了等离子体波共振处的大波动水平和较短波长处的局部极小值的综合效应。这是首次" 几乎" 直接测量激光产生的等离子体中的非麦克斯韦分布函数。在计算图 6 中的理论光谱时，我们假设 EDF (13) 的对称部分在时间上是恒定的。

6 结论与总结

CONCLUSIONS AND SUMMARY

In this paper, we have revisited the old problem of the temporal evolution of the EDF in laser heated plasmas for the case of moderate intensity laser fields ($v_E/v_{Te} < 1$ and $Zv_E^2/v_{Te}^2 > 1$). We have confirmed that the bulk of the electron distribution function is well approximated by the superGaussian form with the exponent m varying with laser intensity according to the well-known fit by Matte et al. [4] However the tail of the electron distribution is much more pronounced and approaches a Maxwellian distribution at velocities much larger than thermal velocity due to the $e - e$ collisions. In the transition region where velocities are slightly higher than the thermal velocity, the EDF is neither the usual super-Gaussian nor Maxwellian. The smaller the ion charge, the closer this transition region (12) is to the electron thermal velocity. This distribution function varies in time with increasing average kinetic energy of electrons due to IB heating. These analytical results have been confirmed using the particle simulation method. In the code the electrons evolve under the influence of a dipole laser field and collisions with like and unlike species. [14] Our simulations have allowed the description of a smooth transition between the super-Gaussian electron bulk and the Maxwellian tail. We believe that our fit for the electron distribution function (13) can be useful for many practical applications.

在本文中，我们重新审视了激光加热等离子体中电子分布函数的时间演化这一老生常谈的问题，即中等强度激光场 ($v_E/v_{Te} < 1$ 和 $Zv_E^2/v_{Te}^2 > 1$) 的情况。我们证实，电子分布函数的主体部分可以很好地近似为超高斯形式，其指数 m 随激光强度的变化而变化，这与著名的 Matte 等人的拟合结果是一致的。在速度略高于热速度的过渡区域，EDF 既不是通常的超高斯分布，也不是麦克斯韦分布。离子电荷越小，这个过渡区域（12）就越接近电子热速度。由于 IB 加热，该分布函数随电子平均动能的增加而变化。这些分析结果通过粒子模拟方法得到了证实。在代码中，电子在偶极激光场的影响下发生演变，并与同类和异类发生碰撞。[14] 我们的模拟描述了超高斯电子体和麦克斯韦尾部之间的平滑过渡。我们相信，我们对电子分布函数 (13) 的拟合可以在许多实际应用中发挥作用。

In particular, the new EDF shows an increase in the Landau damping for most of the Langmuir waves as compared to results obtained with the super-Gaussian fit. We have interpreted the experimental spectrum of electron plasma wave fluctuations from Thomson scattering measurements. [6] This provides the first evidence for the existence of non-Maxwellian distribution functions in laserproduced plasmas.

特别是，与超高斯拟合结果相比，新 EDF 显示大多数朗穆尔波的朗道阻尼增加了。我们从汤姆逊散射测量中解释了电子等离子体波波动的实验频谱。[6] 这为激光产生的等离子体中存在非麦克斯韦分布函数提供了第一个证据。

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