BULETINUL Universităţii Petrol – Gaze din Ploieşti	Vol. LIX No. 2/2007	67 - 72	Seria Matematică - Informatică - Fizică

Plasma Diagnostics Using Laser Radiations

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Abstract

This paper aims at studying different methods of plasmas diagnostic using laser radiation. Using laser radiation it is represent some advantages against other plasma diagnostic techniques like: weak perturbation of plasma by laser radiation, precise determination of electron concentration (using the interferometry with coupled cavities method for example), control on obtained data etc. For the laser radiation diffusion on plasmas particle method, interferometric diagnostics methods, Faraday rotation and holographic interferometries method we describe theoretical aspects and point out the advantages and disadvantages.

Key words: *laser, plasma diagnostics, interferometry, refraction index*

Introduction

The diagnostic methods with lasers permit to obtain quantitative dates about fundamental parameters of plasmas, about fluctuations in plasma, about the kinetic behavior plasmas, length Debye etc. Many forms of diagnostic methods are classic methods in different areas of Physics but they can't have a high sensibility because of plasma's low luminosity. Counting laser radiations properties (high intensity, chromaticity, coherence, directionality), the auto-luminosity of plasmas don't constitute an impediment for increasing the sensibility of optic methods.

Used-up methods for plasma diagnostics by means of laser radiations can be classified as follows: laser radiation diffusion on plasmas particle method, interferometric diagnostics methods, diagnostic methods in approximation of geometric optics, holographic interferometries method etc.

Diagnostic Methods with Laser Radiations

Laser Radiation Diffusion on Plasma Particle Method

The laser light scattering on plasmas particle take the information about non-equilibrium situations from plasma that represent an important element in kinetic theory of the interactions between charged particles. Although problems referring to multiple reflections on walls still, induced emission on plasmas and the Raman and Rayleigh diffusions remain unsolved, the diagnose techniques of the plasmas using the diffused radiation knew a great development since the discovery of high intensity lasers.

In principle, if the shapes of radiations pulse incident on plasma are given, from the angular distribution of the scattered light we can obtain information about spatial distribution of electron density contained in the studied medium and the wavelength displacement for incident radiations can characterize the electrons velocity distribution.

The diffused radiation spectrum $S\left(\vec{K},\omega\right)$ without the presence of external magnetic field can be written in the formal form:

$$S\left(\vec{K},\omega\right)=S_e\left(\vec{K},\omega\right)+S_i\left(\vec{K},\omega\right), \tag{1}$$

where $S_e\left(\vec{K},\omega\right)$ corresponds to the electronic component and $S_i\left(\vec{K},\omega\right)$ to the ionic component, $\vec{K}$ is the wave vector.

This spectrum depends on many parameters among these the most important is α :

$$S\left(\vec{K},\omega\right)=S\left[\frac{\omega}{\sqrt{2K^2kT_em^{-1}}},\alpha\left(K,n_e,T_e\right)\right]+S_i\left[\frac{\omega}{\sqrt{2K^2kT_im^{-1}}},Z,\frac{T_e}{T_i},\alpha\left(K,n_e,T_e\right)\right], \tag{2}$$

where

$$\alpha=\frac{1}{K\lambda_D}\cong\frac{\lambda_0}{4\pi\lambda_D\sin\frac{\theta}{2}}=\frac{\lambda_0}{4\pi\sin\dfrac{\theta}{2}}\sqrt{\frac{n_ee^2}{4\pi kT_e}} \tag{3}$$

and λ_D is the Debye length, T_e, T_i are the temperatures of electrons respective ions, n_e is the electrons density, Z is the ions charge, m electron mass, k is the Boltzmann constant, θ is the diffusion angle.

If integrating it along the frequency domain we obtain:

$$\begin{aligned} S\left(\vec{K}\right)&=S_e\left(\vec{K}\right)+S_i\left(\vec{K}\right)\\ S_e\left(\vec{K}\right)&=\frac{1}{1+\alpha^2}\\ S_i\left(\vec{K}\right)&=\frac{Ze^4}{\left(1+\alpha^2\right)\left\{1+\alpha^2+Z\left(\dfrac{T_e}{T_i}\right)\alpha^2\right\}} \end{aligned}\ . \tag{4}$$

We observe that the electronic component depends just on the parameter α and it has a frequencies domain determined only by the electrons temperature and the ionic component additional depends on the ratio between the electrons temperature, the ions temperature and the ions charge. The frequency domain for the ionic component is determined by the ions temperature.

For $\alpha<<1$ we have negligible correlations case between electrons that is electron plasmas are independent diffusers. In this case the intensity of diffused radiation have only electronic component. This is the case of normal Thomson diffusion and the spectrum of frequency for diffused light under different angles just depends on the electrons thermal agitation. If the electrons are characterized by the maxwellian distribution of velocity for a temperature T_e, therefore the spectrum of diffused radiations $S_e\left(\vec{K},\omega\right)$ is:

$$S_e\left(\vec{K},\omega\right)=n_e\sqrt{\frac{m}{2\pi K^2 kT_e}}e^{-\frac{m\omega^2}{2K^2kT_e}}. \tag{5}$$

The total diffused intensity in direction characterized by θ is

$$I=I_0\frac{n_e\sigma}{r^2}, \tag{6}$$

where I_0 is the intensity of incident waves, σ is the efficacious differential section of diffusion on electrons, r is distance between plasma and observer.

The total half-width is:

$$\Delta\omega_{\frac{1}{2}}=4\omega_0\sin\frac{\theta}{2}\sqrt{\frac{2kT_e}{mc^2}\ln 2}. \tag{7}$$

From one noticed above, can be observed that through the measured intensity and spectrum width of the diffused light we can determine n_e and T_e.

If $\alpha>>1$ the spectrum diffused light is modified due to collective effects of electrons - ions interaction, appear lateral components against the incident frequency. This in case the diffused spectrum has a central component given by the ionic component, $S_i\left(\vec{K},\omega\right)$ and two symmetrical components against central which component which represents the electronic component for the electrons density fluctuations.

Half-width for ionic components determined by the thermal velocity of ions (Doppler width) is:

$$\Delta\omega\cong 2K_0\sin\frac{\theta}{2}\sqrt{\frac{2KT_i}{m_i}}. \tag{8}$$

The electronic components, ω, are displaced against central line, ω_0, by this amount:

$$\left(\omega-\omega_0\right)^2=\omega_p^2+\frac{3KT_e}{m}\alpha^2, \tag{9}$$

where ω_p is the plasmas oscillation proper frequency.

Transition between this two type of spectra is produced for $\alpha\cong 1$.

Interferometric Plasmas Diagnosis Methods

There is three interferometric method of plasmas diagnosis the using laser radiation: usual interferometry, interferometry with coupled cavities and the interferometry through heterodyne.

In the case of usual interferometry the interference phenomenon of two coherent monochromatic light fascicles is utilized; one fascicle is referential and the second is driven through the studied plasma. The observation of interference fringes is done initially without plasmas and after that with the studied plasma. The supplementary optic road introduced by plasma attracts the displacement of interference fringes with the amount:

$$\Delta=\frac{\left(n_r-1\right)l}{\lambda}, \tag{10}$$

where l is the length of radiation road through plasma and n_r is the plasma optical refraction index.

If is taking into consideration only the contribution of free electrons to the plasma optical refraction index, therefore for this we obtain:

$$n_r - 1 \cong -\frac{\omega_p^2}{2\omega^2} = -\frac{1}{\omega^2}\frac{\mu n_e e^2 c^2}{2m_e} \tag{11}$$

and for the fringes displacement we obtain:

$$\Delta = -\frac{\upsilon_p^2}{c^2}\lambda l = -4{,}46\cdot 10^{-14} n_e \lambda l\,. \tag{12}$$

We can observe as through the measuring the fringes displacement n_e can be calculated.

If allowing for the contribution of ions and atoms to the fringes displacement we obtain:

$$\Delta = \frac{\left(n_r - 1\right)_{at} l - \dfrac{\mu e^2 n_e c^2}{m_e \omega^2} l}{\lambda}\,. \tag{13 }$$

The most used interferometer for plasmas diagnostics using this method is the Mach-Zehnder interferometer.

The interferometry with coupled cavities methods are based on the fact that if a part of a laser radiation power is redirecting to the laser cavity by an external mirror, the lasers is modulated. If the plasma with length l is introduced in external cavities the optic road is modified with a number of fringes given by following expression:

$$N = \frac{2l\left(n_r - 1\right)}{\lambda}\,. \tag{14}$$

Considering only the electrons contribution to plasmas refractivity we can obtain:

$$N = \left(\frac{\omega_p}{\omega}\right)^2 \frac{l}{\lambda} = 8{,}98\cdot 10^{-12} n_e \lambda l\,. \tag{15}$$

From expression (15) the concentration of electrons n_e can be determined.

In the case interferometry through heterodyne is obtain the eldest sensibility in the determination electrons concentration. In this case, as opposed to coupled cavities method, the studied plasma is placed in the interior of laser cavity. Initially, without plasma, lasers generates the radiation with same wavelength. At appearance of plasmas in one laser cavity, the resonator optic length is changed and the frequency modification is:

$$\Delta\upsilon = -\frac{\upsilon}{\lambda}\Delta\lambda = \frac{1}{4\pi}\frac{\omega_p^2}{\omega}\frac{l}{L} = \frac{n_e e^2 \lambda l}{2\pi m_e c L}\,. \tag{16}$$

Faraday Rotation

It is known that in nature exist certain optic active substances that have the property to rotate the plan of polarization of an electromagnetic wave propagating through the substance. The substances that don't present this natural property, to rotate the plan of polarization, can get this property under the influence of external magnetic field. If a polarized wave is propagated parallel to the magnetic induction vector $\vec{B}$ founded in the plasma then the wave is decomposed in two circular polarized components, right and left. If they have different component velocity in plasma then after travel a distance l in plasma the wave leaves the plasma with the plan of polarization rotated with the angle φ given by expression:

$$\varphi = \left(n_L - n_R\right)\frac{\pi l}{\lambda_0}, \tag{17}$$

where λ_0 is the wavelength in vacuum and n_L, n_R are the components refraction indexes

The phenomenon is known as the Faraday rotation. For small ratios ω_P/ω and ω_e/ω, relation (17) becomes:

$$\varphi = \frac{1}{2}\left(\frac{\omega_P}{\omega}\right)^2\frac{\omega_e}{c} = \frac{1}{2\pi}\frac{e^3}{m_e^2 c^4}\lambda^2 n_e B l = 2{,}63\cdot 10^{21}\lambda^2 n_e B l[\text{rad}]. \tag{18}$$

The Faraday rotation is dependent on the product $n_e B$, therefore if we known the other one we can determine one of two quantities.

Holographic Interferometry Method

Holography is a method of registration and subsequent reestablishment of the electromagnetic wave fronts. In the case plasmas the role of the object is taken by plasma.

The plasmas refraction index in the domains situated away from the atomic lines of absorption is given by the formula:

$$n - 1 = \left(A + \frac{B}{\lambda^2}\right)n_a - 4{,}5\cdot 10^{-14}\lambda^2 n_e, \tag{19}$$

where n_a, n_e are the atoms and electrons concentrations.

One of the method advantages consist in absence of sensibility against the plasmas self-radiation. This radiation does not contribute to the formation of holograms because it isn't coherent and it influences very little the holograms' quality.

Conclusions

To determine some physical proprieties of plasma we can choose from a large range of plasma diagnostic methods. In each case we must oriented to that method which is appropriate to proposed goal. The main physical proprieties that ca be determined by diagnostic methods with lasers are: n_e - electrons concentrations, n_a - electrons concentrations, T_e - electrons temperature, T_e - ions temperature, $\vec{B}$ - magnetic induction vector.

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Diagnosticarea Plasmelor cu Ajutorul Radiației Laser

Rezumat

În această lucrare sunt studiate diferite metode de diagnosticare a plasmei cu radiație laser. Utilizarea radiației laser prezintă câteva avantaje față de alte metode de diagnosticare cum ar fi: perturbarea slabă a plasmei de către fasciculul laser, determinarea precisă a concentrației electronilor (folosind metoda interferometrică cu incinte cuplate), controlul asupra datelor obținute etc. Pentru metoda difuziei radiației laser pe particulele plasmei, pentru metode interferometrice de diagnosticare, rotația Faraday şi metoda interferometriei holografice sunt descrise aspectele teoretice şi apoi enumerate avantajele, respectiv dezavantajele acestora.