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Particle-in-cell simulation of non-collective Thomson scattering as a diagnostic method in relativistic conditions of ITER

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Abstract

The non-collective Thomson scattering (TS) in the relativistic condition from the edge plasma of ITER as a diagnostic system is simulated through the particle-in-cell (PIC) method via XOOPIC code. Different temperatures of the edge plasma of ITER measured by the edge Thomson scattering (ETS) system are selected to study the effect of the relativistic conditions on the scattering. The wavelength, intensity, and FWHM of the laser applied in the ETS system of ITER are $\lambda_{i,0} = 1.064 \times 10^{-4}$ cm, $I_i = 2.24 \times 10^{17}$ erg/s $\cdot$ cm^2 and 12.00 ns respectively. The obtained results indicate the ability and validity of collective PIC method to study the non- collective phenomena even in relativistic conditions.

Keywords: Non- collective Thomson scattering, relativistic conditions, Plasma Diagnostics, ITER, particle in cell method, plasma parameters.

Introduction

Thomson scattering as a diagnostic method to determine the plasma parameters is the only method through which provide the plasma parameters like density and temperature simultaneously and can be applied in the non- relativistic, relativistic, collisional, magnetized, non-thermal and impure plasmas as well as in equilibrium or non-equilibrium, medium or high pressure and fusion plasmas [1]. This method is divided into two classes, the collective or non-collective TS that is determined by the parameter α which is related to the scattering angle, the Debye length and the incident wave vector. In the present fusion experiments where the electron temperature can be increased to several keV they should be considered relativistic experiments. The scattered radiation polarizes in a plane different from the plane of polarization of the incident wave in the relativistic condition [2]. The propose of this paper is to simulate the relativistic effects on TS from the edge plasma of ITER using Particle In Cell (PIC) method as a collective statistical method via XOOPIC code. To do it some different temperatures in the range of the edge plasma of ITER is chosen and the non-collective relativistic TS from is simulated. The results show the reliability of TS in the whole temperature range as a diagnostic tool to measure the density and temperature measured by ITER Edge Thomson Scattering system (ETS).

Methods

Beside many other diagnostics, ETS is planned to study the edge plasma. The estimated electron temperature and density of this area are $0.05\ \text{KeV} < T_e < 10\ \text{KeV}$ and $5.00 \times 10^{12}\ \text{cm}^{-3} < n_e < 3.00 \times 10^{14}\ \text{cm}^{-3}$ respectively. To occur TS phenomenon in this situation a z-polarized laser with a wave length, energy, repetition rate and pulse duration of $\lambda_{i0} = 1064$ nm, 7.66 J, 100 Hz and 30 ns propagates through the plasma with intensity, FWHM, frequency and waste size of $I_i = 2.24 \times 10^{17}$ erg/s $\cdot$ cm^2, 12.00 ns, $\omega_{i0} = 1.77 \times 10^{15}$ rad/s and $W_{i0} = 7.7 \times 10^{-2}$ cm. The central toroidal magnetic field of ITER is $B_{z0} = 5.30 \times 10^4$ G at $R_0 = 620.00$ cm which reduces to $B_{z,\text{edge}} = 4.08 \times 10^4$ G at $R_{\text{edge}} = 805.00$ cm in the measurement area at the edge and leads to electron cyclotron frequency of $\omega_{ce,\text{edge}} = 7.18 \times 10^{11}$ rad/s shows that the toroidal magnetic field is ignorable ($\omega_{ce,\text{edge}} \ll \omega_{i0}$).Based on the edge plasma parameters assessed by the ETS, some arbitrary temperature values of are chosen to study the effects of high temperatures on the accuracy of ETS. For scattering in the relativistic condition the power tends to scatter into the direction of v to retain the symmetry in the electron frame of reference. For a plane incident wave, $\mathbf{E}_i(\mathbf{r}, t) = \mathbf{E}_{i0} \cos(\mathbf{k}_{i0} \cdot \mathbf{r} - \omega_{i0} t)$, which passes through a plasma with a toroidal magnetic field of B_0 the electric field of the scattered wave from each electron with the cyclotron radius of ρ_e in the relativistic limit at a very long distance R from electrons is expressed as [3]:

$$\mathbf{E}_s(\mathbf{R}, t) = \frac{q^2}{m_e c^2 R} \frac{(1-\beta^2)^{1/2}}{(1-\hat{\mathbf{s}} \cdot \boldsymbol{\beta})^3} \{\hat{\mathbf{s}} \times [(\hat{\mathbf{s}} - \boldsymbol{\beta})(\mathbf{E}_{i0} + \boldsymbol{\beta} \times \{\boldsymbol{n}(\hat{\mathbf{i}} \times \mathbf{E}_{i0})\} - \boldsymbol{\beta}(\boldsymbol{\beta} \cdot \mathbf{E}_{i0}))]\} \times \cos[k_i \cdot r(t') - \omega_i t']$$

At high velocities most of the power scatters in the direction of $\mathbf{v}$ to satisfy the symmetry in the electron frame of reference. The power spectral density $P_s(\mathbf{R}, \omega_s)$ scattered into the solid angle element $d\Omega$ in the relativistic non-collective condition ($\alpha \ll 1$) is expressed as:

$$P_s(\mathbf{R},\omega_s)\mathrm{d}\Omega\mathrm{d}\omega_s = \frac{0.53\times10^{15}P_i r_0^2 n_e L_s}{c^2(v_{th})^2\pi^{1/2}}\exp\left\{-\left(\frac{\omega}{v_{th}k}\right)^2\right\}\frac{\omega}{k^3}$$
$$\times\left[1-1.22\left(\frac{v_{th}}{c}\right)^2+\frac{3.5}{c}\frac{\omega}{k}+\frac{7.25}{c^2}\frac{\omega^2}{k^2}-\frac{3}{4}\left(\frac{1}{v_{th}c}\right)^2\frac{\omega^4}{k^4}\right]\mathrm{d}\Omega\mathrm{d}\omega_s$$

where P_i, and n_e are the incident power, and the electron density. $\omega=\omega_s-\omega_{i0}$ is the difference between the incident and scattered waves frequencies, $r_0 = 2.82\times10^{-13}$ cm is the classical electron radius, L_s is the scattering length.

Results and discussion

The simulated region is so that the incident laser can launch from the left boundary of a slab with L_x and L_y dimensions composed of N_x and N_y grids in x and y directions to the right in the x direction while $\lambda_{i0}=16\,dx$ and $dy=\varepsilon dx$ where ε is the aspect ratio of the grids determined based on the desired value of L_y The right boundary type is determined as the incident wave exits upon its contact. Simulation is run on a slab with a homogenous electron density of $n_e = 3.00\times10^{13}\ \mathrm{cm}^{-3}$ while $n_D = n_T = n_e/2.0$ (50-50 DT plasma), where n_D and n_T are the deuterium and tritium densities. Based on the size of the grids, $d=(dx^{-2}+dy^{-2})^{-1/2}$ the time step is chosen as $dt = 0.99d/c$. Based on these computational parameters, the calculation time for each run is about 13 hours. At first we simulate the pure incident wave by setting $L_x = 32\lambda_{i0}$, $L_y \approx 20W_{i0}$, $N_x = 512$ and $N_y = 384$, the incident z-polarized Gaussian wave, propagated in the x-direction at time $t\approx 1988\,T_{i0}$. The time evolution of the z-component of the electric field for the incident wave is obtained by measuring it on a line at the center of the port along the propagation direction, $y=0$ from $t=0$ to $t\approx1988\,T_{i0}$. By taking a 2D fast Fourier transform on the (x,t)profile of the incident electric field the spectra in ($k_{x,i}$, ω_i)space is obtained. By using the correlation between the power and the electric field the power spectral density of the incident wave is yield. The frequency spectrum of the incident wave at $k_{x,i}=k_{i0}$ point is shown in Fig. 2.

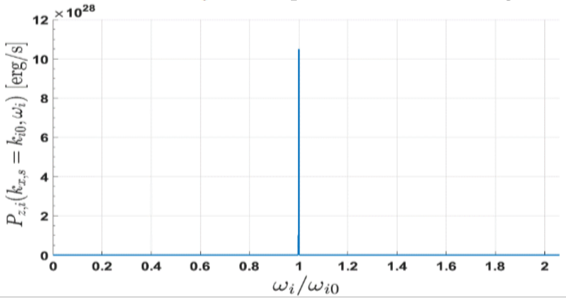

Figure 2: The frequency spectrum of the incident wave at $k_{x,i}=k_{i0}$.

To study the scattered power due to relativistic non-collective TS the simulation is run exactly in the same way while super particles are loaded in simulation volume. In this way the peak is observed around $\omega_s=\omega_{i0}$ for a given temperature as shown in Fig. 2.

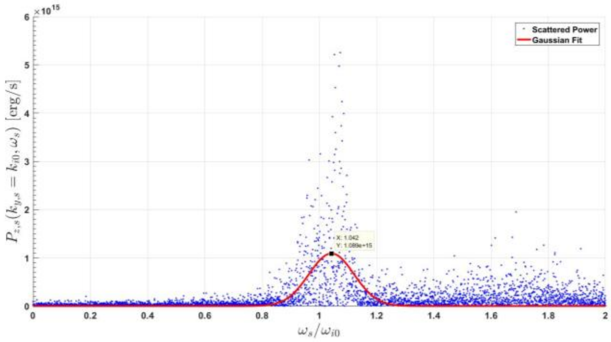

Figure 2: The frequency spectrum of the scattered wave at $k_{y,s}=k_{i0}$.

Plasma parameters can be found by comparing the equation governing these curves with the non- collective and relativistic Thomson scattering theory. The obtained resulte are in a very good agreement with input values of plasma.

Conclusions

The ability and validity of the PIC method to assess the non-collective regimes are verified and shows this method specially XOOPIC code is reliable in simulating the non-collective phenomena like the non-collective TS even in relativistic conditions by removing the ambiguities rising from the contradiction between the PIC statistical collective mechanism due to the super-particle concept and the non-collective nature of TS. The accuracy of the ETS system is reconfirmed as a diagnostic tool in measuring the plasma parameters even in relativistc conditions of ITER.

References

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