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On Runaway Transport under Magnetic Turbulence in Tokamaks.

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INTRODUCTION

It has been observed that some experimental HXR intensity spectra present anomalous features: the logarithm of intensity plotted versus photon energy shows two different slopes at different energy regions, joint by a flat area. This spectra are produced by Bremstrahlung emission of runaway electrons diffused onto the device wall. An appropriate treatment of the evolution of runaway distribution function can explain the experimental results, taking into account that runaway electron transport is mainly governed by magnetic topology. Therefore magnetic turbulence can be fundamental to explain the experimental results.

Electra, a 3D code to calculate the evolution of the electron distribution function in momentum (2D) and real (1D) space, has been developed. Evolution of the distribution function is obtained from Langevin equations and a diffusive behaviour is assumed in real space. A local confinement time that give us the probability that a runaway skips from a given magnetic surface to the neighbour one is introduced. The diffusion coefficient includes a factor $\Upsilon(\Delta)$[1] that takes account for runaway orbit averaging of the turbulence: when typical runaway drifts are larger than the radial correlation length of the turbulence, the effect of this one is weaker and the confinement is improved.

As key results we obtain the influence of magnetic turbulence on the evolution of runaway distribution function. The subsequent HXR emission spectra can be compared with experimental results of TJ-I tokamak.

THE MODEL

For the parameters considered here, two time scales appear in the model: The shortest one associated to the evolution in the momentum space and the other associated to the diffusion in real space. This fact allows the detachment of evolution of distribution function in both spaces.

The evolution of the distribution function in momentum space is calculated from 2D Langevin equations. Particle evolution under electric field, Coulomb collisions[2] and synchrotron radiation losses[3] are considered. The equation system is:

$$\frac{dp_{II}}{dt} = -eE_{II} - \nu_{II}\, p_{II} - F_S\, p_{II}$$

$$\frac{dp_{\perp}}{dt} = -\nu_{\perp}\, p_{\perp} - F_S\, p_{\perp}$$

$$\text{with:}\quad \nu_{II} = \frac{n_e e^4 \ln\Lambda}{4\pi\varepsilon_0^2}\gamma\left(Z_{eff} + 1 + \gamma\right)\frac{1}{m_e^2 c^3 p^3};\ \nu_{\perp} = \frac{(\nu p^2 - \nu_{II} p_{II}^2)}{p_{\perp}^2};\ \nu = \frac{n_e e^4 \ln\Lambda}{4\pi\varepsilon_0^2}\frac{\gamma^2}{m_e^2 c^3 p^3}$$

$$\text{and}\quad F_S = \frac{e^2}{6\pi\varepsilon_0 m_e c}\gamma\, p^2\left(\frac{1}{R_0^2} + \frac{e^2B^2}{m_e^2c^2}\frac{p_{\perp}^2}{p^4}\right)$$

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[1] J.R. Myra and P.J. Catto. Phys. of Fluids B 4 (1992) 176

[2] L. Rodríguez-Rodrigo, R.L. Vázquez and P. Navarro. Proc. 16th EPS Conference on Controll. Fusion and Plasma Physics. Venice, 1989. Vol. I, p. 311.

[3] J.R. Martín-Solís, J.D. Alvarez, R. Sanchez and B. Esposito Phys. of Plasmas Vol. 5, 6, 2370 (1998)

where $p=p/m_e c$, p_{II} is the component of electron momentum parallel to the magnetic field, $p_\perp$ is the perpendicular one, γ is the relativistic factor, $\ln\Lambda$ is the Coulomb logarithm, R_0 is the tokamak major radius, B and E_{II} are the toroidal magnetic and electric fields.

Since the model is only valid for high speed particles, it only allows to estimate the evolution of the part of the distribution function corresponding to runaway electrons. The non runaway part of the distribution function is supposed to keep Maxwellian. First of all, the critical curve that separates the runaway and non-runaway part in 2D momentum space is calculated by the code. Then runaway distribution function is allowed to evolve following Langevin equations. A Maxwellian distribution function is chosen as initial condition and the evolution in a single time step is given by:

$$f_t^L(p_{II}, p_\perp, r) = f_{t-1}(p_{II}(t-1), p_\perp(t-1), r)$$

The new distribution function then suffers a diffusion process in real space. This diffusion is simulated assigning a local confinement time to each radial position:

$$\tau_r(\vec{v}, r_i) = \frac{(\Delta r)^2}{D(\vec{v}, r_i)}$$

The diffusion coefficient, D(v,r), is given by:

$$D(\vec{v}, r) = D_M(r_i)\, |v_{II}|\, Y(\Delta)$$

I. e. , it is proportional to the magnetic line diffusion coefficient, D_M, to the absolute value of parallel speed and takes into account the runaway orbit averaging of the turbulence through the factor $Y(\Delta)$[4]. This factor depends on:

$$\Delta = d_r(v,r)\, k_r(r) = k_r c q \frac{\gamma}{\omega_c}(1-\gamma^2)^{1/2}$$

with d_r being the typical runaway drift and k_r^{-1} the radial correlation length of the turbulence.

The electron distribution function after each diffusion step is obtained as the difference between the electrons that come from the inner radius and the electrons that diffuse to outer radius.

If τ_r is the local runaway confinement time, the probability that a runaway is in a magnetic surface after a time Δt is given by $P_{in} = \exp(-\Delta t / \tau_r(\vec{v}, r_i))$ and the probability that a runaway skips from a given magnetic surface r_i to the next outer one r_{i+1} is $P_{out} = 1 - P_{in}$. With this probabilities, the runaway distribution function after the diffusion time step is:

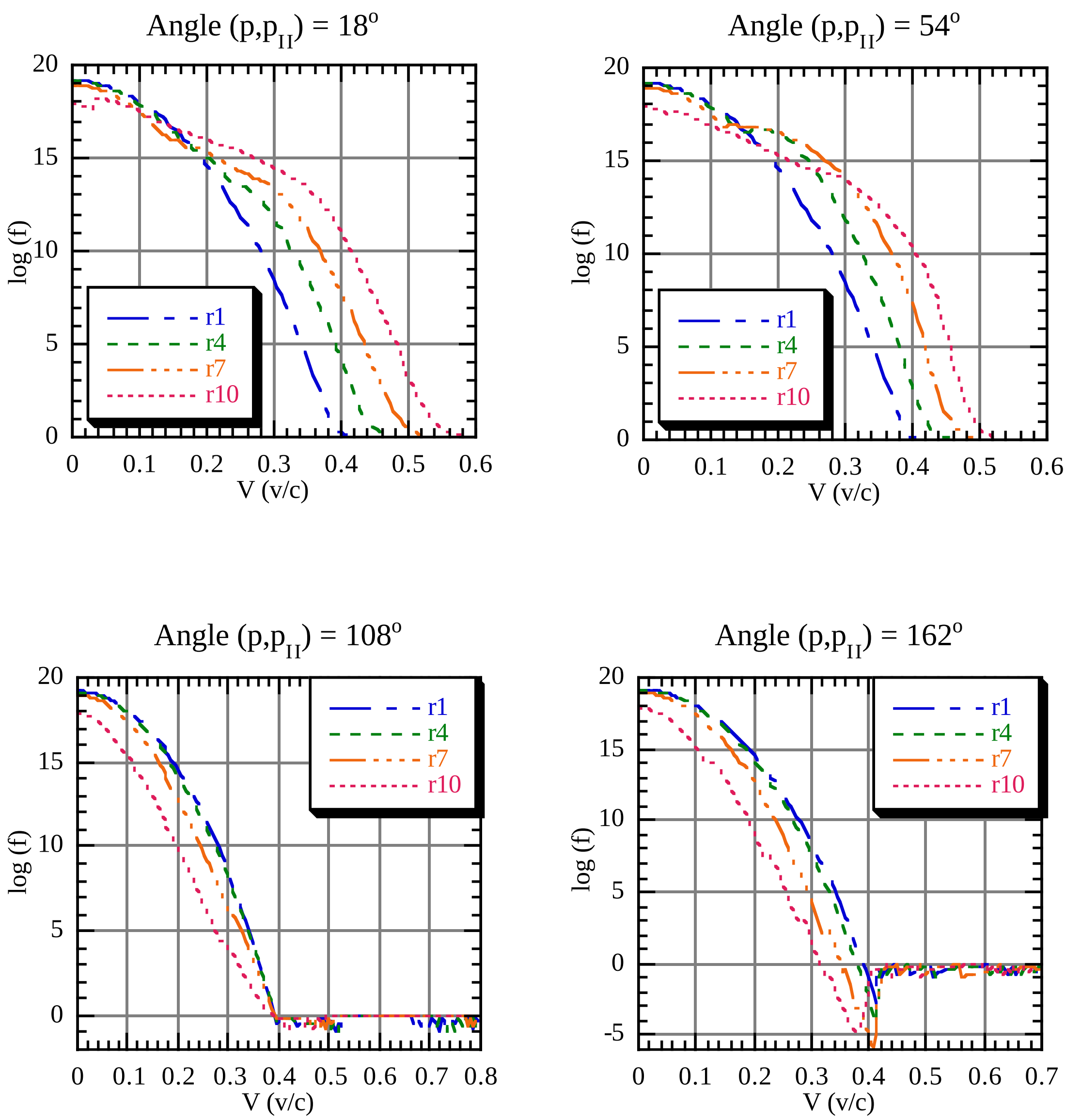
$$f_t(p_{II}, p_\perp, r_i) = f_t^L(p_{II}, p_\perp, r_i)\ \exp\left(-\frac{\Delta t}{\tau_r(\vec{v}, r_i)}\right) + f_t(p_{II}, p_\perp, r_{i-1})\left[1 - \exp\left(-\frac{\Delta t}{\tau_r(\vec{v}, r_{i-1})}\right)\right]$$

The code Electra assumes that the runaway distribution function is over the Maxwellian value everywhere, since the collisions should prevent that its value falls down under the thermal values.

4 F. Castejón and L. Rodríguez-Rodrigo. Proc. 6th European Fusion Theory Conf. Utrecht, 1995.

RESULTS

Electra allows to obtain runaway distribution function in the momentum space for different radial positions at any time. Here we show the results for diverse cross section TJ-I tokamak typical parameters: B=1 T, E_{II}=-1 V/m, $n_e=1.5\cdot10^{19}$ m^{-3}, T_e=1 keV, R=0.3 m, a=0.1 m, $D_m=6\cdot10^{-8}$, $k_r=100$ m^{-1}, Z_{eff}=2. and q=1-4. Distribution function in velocity spaces is shown for four pitch angles and four radial positions in TJ-I:results of the model and previous experimental data obtained in the small TJ-I tokamak.



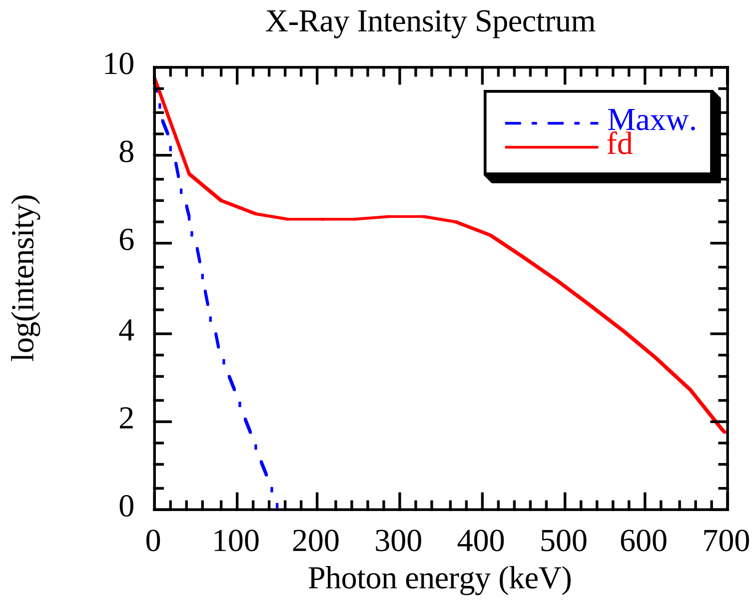
Once the distribution function is calculated by the code, HXR emission can be estimated using a relativistic cross section that includes Elwert factor[5] . The emission calculated in this way show the same behaviour that the experimental results. We obtain two different slopes and

[5]F.Castejón, C.Alejaldre, J.C.Girado, V.Krivenski and V. Tribaldos. Proc. 16th EPS Conference on Controll. Fusion and Plasma Physics. Venice, 1989. Vol. IV p.1389

a flat zone between them The second slope starts at an energy value that coincides approximately whit the critical value, ε_k[6], for which the typical runaway drifts d_r are larger than the radial correlation length of the turbulence k_r^{-1}

$$\varepsilon_k = \frac{m_e \omega_{ce} c}{q} \frac{1}{k_r} = 300\text{keV}$$

for the parameters q=4 (plasma edge), B=1T and k_r= 250 m^{-1}.



CONCLUSIONS

Electra is a code that has been developed to study runaway diffusive transport under the effect of magnetic turbulence. The model that has been introduced in the code allows us to reproduce the experimental Hard X Ray intensity spectra with two different slopes at different energy regions. The energy of this two different regions is related to the ability of high energy runaway electrons to average the effect of the turbulence. This fact causes an improvement of their confinement when their typical drifts (d_r) are larger than the radial correlation length of the turbulence (k_r^{-1}). This characteristic is included in the model through the orbit averaging factor, Y(Δ), in the runaway diffusion coefficient.

Even it has not been considered here, the model allows to include the radial as well as the temporal dependence of the relevant magnitudes that cause runaway transport, namely parallel electric field and magnetic turbulence.

The HXR spectra is evaluated using a relativistic cross section that takes into account Coulomb screening through Elwert’s factor. A remarkable agreement is obtained between the results of the model and previous experimental data obtained in the small TJ-I tokamak.

[6]L. Rodriguez Rodrigo and F. Castejón. Phys. Rev. Lett. 74, 1995 (3987)