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Studies of Internal Magnetic Fluctuation by Runaway Diffusivity in the HL-1M

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Abstract

The transport of runaway electrons in hot plasma can be comparatively easily measured by steady state or perturbation experiments, which provide runaway electron diffusivity D_r. The diffusivity can be interpreted in terms of a magnetic fluctuation level. The runway electron diffusion coefficient is determined by intrinsic magnetic fluctuations. The intrinsic magnetic fluctuations level ($\tilde{b}_r/B_T$) is estimated to be about (2–4) × 10^{-4} in the HL-1M plasma. The results presented here demonstrate the effectiveness of using runaway transport techniques for determining internal magnetic fluctuations. A profile of the magnetic fluctuation level can be estimated from D_r.

Keywords:

transport of runaway electron, diffusivity, intrinsic magnetic fluctuations, HXR, SXR, WUW

1. Introduction

The observed loss rate of both particles and energy from hot confined toroidal plasmas is much higher than the one predicted by neoclassical transport theory, which depends upon mean plasma parameters and Coulomb collisions. Many types of plasma turbulence have been proposed to explain anomalous plasma transport. The fluctuation of plasma parameters around their mean values can cause transport through electrostatic or magnetic fluctuations [1]. The fluctuation driven radial particle flux is given by $\Gamma = \langle\tilde{E}_0\tilde{n}\rangle / B_T + \langle\tilde{j}_\parallel\tilde{b}_r\rangle / eB_T$, where $\tilde{E}_\theta$ is the fluctuating poloidal electric field $\tilde{n}$ is the fluctuating electron density, $\tilde{b}_r$ is radial component of the fluctuating magnetic field $\tilde{j}_\parallel$ is the fluctuating current parallel to the magnetic field, and $\langle\cdots\rangle$ denotes a time average. The fluctuation driven energy flux is given by $Q = \frac{3}{2}K_b n\langle\tilde{E}_0\tilde{T}\rangle/B_T + \frac{3}{2}K_b T\langle\tilde{E}_0\tilde{n}\rangle/B_T$ where K_b is Boltzman's constant and $\tilde{T}$ is the fluctuating temperature.

The edge turbulence is well characterized; it can explain the fluctuation driven particle flux, but we are less well accounted for the energy fluxes. There still is insufficient experimental data available to assess the importance of magnetic fluctuation for internal transport. In ohmic heated low β plasmas the measured magnetic fluctuation is too small to contribute to the thermal losses, but can explain the runaway transport. The transport of runaway electrons in plasma can be comparatively easily measured using a steady state approach for values of the runaway confinement time τ_r deduced from hard X ray (HXR) bremsstrahlung spectra and using the perturbation techniques deduced from sawtooth oscillations of HXR flux, SXR intensity and λ = 3 cm microwave radiation intensity (WUW), recorded simultaneously, which provide local runaway electron diffusivity D_r. Assuming that magnetic turbulence is responsible for the runaway transport, the diffusivity can be interpreted in terms of a magnetic fluctuation level.

We find that the runway electron diffusion coefficient is determined by internal magnetic fluctuations rather than electrostatic fluctuations because

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of the high energy involved. Runaway electron behavior can be used as a probe for internal magnetic fluctuations. The results presented here demonstrate the effectiveness of using runaway transport techniques for determining intrinsic magnetic fluctuations. A profile of value of the magnetic fluctuation in HL-1M plasma can be estimated from D_r.

2. Experiments

The experiments reported in this paper have been carried out in the HL-1M, R = 1.02 m and a = 0.29 m. It was operated for this experiment with a plasma current of around 120–150 kA, a toroidal field B_T = 2 T and a line averaged electron density of 1.0–1.5 × 10^{19} m^{-3}. The device and diagnostics are described in more detail in ref. [2].

HXR flux was detected by 4 NaI (Ti) 3 in ×3 in scintillaters working in the current mode or in pulse height analysis mode to obtain the runaway electron energy and confinement time. The detectors housed in the tangential and perpendicular shields were used. An energy resolution of 10 keV/channel was obtained using a calibration with a ^{137}Cs source. Photons with energy lower than 50 keV were not detectable.

2.1 Runaway Diffusion Coefficient Deduced from Perturbation Techniques

2.1.1 Plasma Shift Experiment

A change of the current in the vertical field coils moves the plasma inward, at constant plasma current, leaving a distance for the runaways to diffuse. Cosine coils measure the position of the plasma. It is necessary to move the plasma inward fast enough to see a drop in the hard X-ray signals, but sufficiently slowly that no instabilities develop in the plasma.

An increase in the current in the vertical field coils causes an inward shift of the plasma position [3] and runaway orbits, at constant plasma current, but with a change in induced electric field. This induced electric field accelerates not only the runaway electrons, but also bulk electrons. This acceleration can be a source term in the runaway diffusion equation. Electros with the energy of the order of 60 keV can easily free fall accelerated from bulk electrons depending on the induced electric field. In the short time scales the effect of induction, collisions, and drifts can be ignored even though these effect can be important in longer time scales. The shift of the plasma position leaves a longer distance for the runaway electrons to diffuse before reaching the limiter at the outer radius of the plasma. Since the runaway orbits are shifted outwards with respect to flux surfaces, due to the induced electric field the runaway electrons should not intercept the limiter on the inner side of the plasma. The plasma displacement, hard X-ray signal and the best fit to a diffusion equation model are shown in Fig. 1.

The temporal behavior of the flux measured by the hard X-ray detector in response to an inward shift can be understood from a simple model. Because only the short time scales of the transient signal (≦10 ms) are of interest, collisions, drifts, and induced electric field effects may be neglected and the initial radial runaway profile need not be known even though all these effects play an important role on the longer time scale necessary to obtain a quasi-steady-state hard X-ray signal. Therefore, the short time behavior of the runaway density N may be described [3] by a simple diffusion equation

$$\frac{\partial N}{\partial t} = \frac{\partial}{\partial x}\left(D_r \frac{\partial N}{\partial x}\right) \tag{1}$$

where a slab model in x is used since the changes in minor radius are small compared to the initial minor radius. D_r is assumed to be constant in both time and space. A numerical fit [4] to the hard X-ray flux during the shift measurements indicates that the diffusion coef-

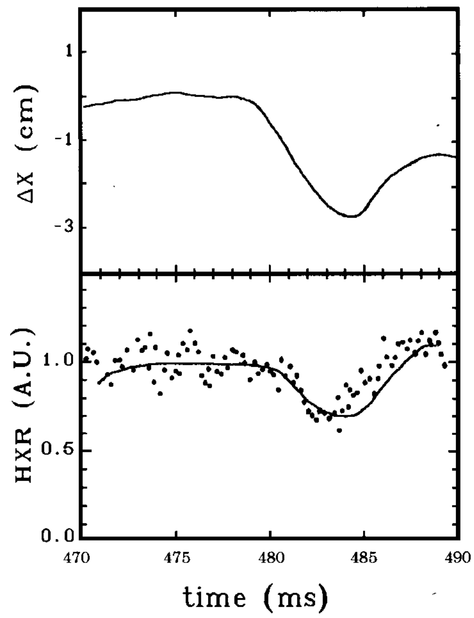

Fig. 1 Upper Figure: Plasma position
Lower Figure: Hard X-ray signal during Plasma shift experiment. The solid line is diffusion equation model of the hard X-ray signal.

ficient of runaway electrons is of the order 1 m^2/sec. The results are illustrated in Fig. 1. Unfortunately the diffusion coefficient D_r is unlikely to be a constant across the minor radius as the analytic models assume. Measurement of the background electron thermal conductivity χ_e in HL-1M find it to be much larger at edge than the center. If the actual runaway D_r has a similar radial dependence, the plasma shift experiments provide a measure of D_r near the edge rather than in the core since the short time evolution of a plasma slightly increased in size would be expected to be dominated by the local value of D_r. According to the distance of the plasma shift measured, this D_r measurement should be characteristic of the plasma conditions at the edge for a distance of the order 20 mm.

2.1.2 Sawtooth Perturbation

If we consider that runaway electrons diffuse radially after each internal crash into the limiter, the simplest model that we can assume is similar to the heat pulse diffusion model described by Soler and Callen [5], where we should consider the runway electron density instead of the temperature. The time to peak Δt_r in the propagation of a pulse through a medium of size 'a' with a diffusion coefficient D_r can be written from dimensional arguments as

$$\Delta t_r = a^2 / P\, D_r \qquad (2)$$

where P is a constant that takes into account the geometry and pulse characteristics of the problem. For a single pulse in cylindrical co-ordinates it is easy to show that $P = 4$. For sawtooth pulses, if the pulse is created by the flattening of a peaked profile inside the $q = 1$ surface, the perturbation has a negative component in the axis zone and a positive one in the zone close to $q = 1$. Figure 2 shows the signals from a central chord SXR detector and from HX1 during the onset of sawteeth. Therefore, the pulse has a bipolar character. In this case, considering the modifications by Zheng Y. [6], P depends on the inversion radius position of the initial bipolar pulse. For the HL-1M tokamak value of inversion radius seen from SXR, it is about 5–6 cm for $B_t = 2$ T. P has an approximate value of 14. Assuming a peaked profile for the runway density and the same inversion radius for runway electrons and SXR, we can estimate the runway diffusion coefficient D_r from the experimental values of time to peak as $D_r = a^2/\,(14\,\Delta t_r)$.

Experimental results for Δt_r exhibit a clear increase from 0.1 ms to 0.3 ms in the range of B_T from 1.4 to 2.5 T. It must be noted that in the same plasma conditions, both runaway electron confinement time τ_r and Δt_r have the same increasing tendencies. Experimentally, τ_r is greater than Δt_r by a factor of 3 to 5, as can also be deduced from the expressions (2).

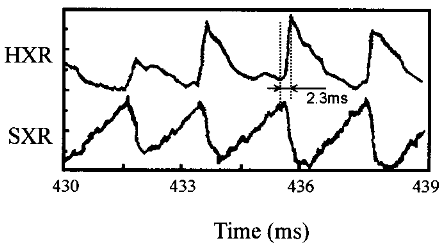

Fig. 2 Signals from a central chord SXR detector and from HXR during the onset of sawteeth corresponding to the maximum current zone.

2.1.3 Runaway Diffusion Coefficient Deduced from Microwave Radiation

If we consider that runaway electrons diffuse radially after each internal crash into the limiter, induced the additional runway electron wave diffuse in plasma; the microwave radiation ($\lambda = 3$ cm) intensity sawtooth signals and sawtooth oscillation of the hard X-ray signals recorded simultaneously (see Fig. 3). The simplest mode that we can assume is similar to diffusion

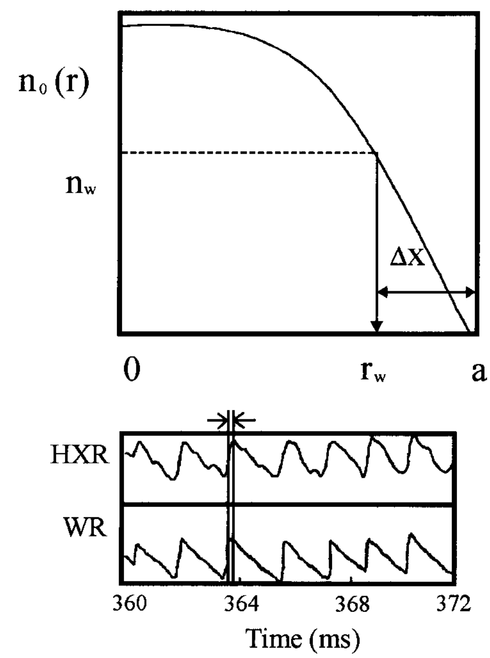

Fig. 3 Upper Figure: Density function of plasma radius. Lower Figure: Sawtooth oscillations of Hard X-ray and Microwave radiation.

model described during the Chapter **2.1.2**. The time to peak Δt_r in the propagation of a pulse with a diffusion coefficient D_r can be written from dimensional arguments as

$$\Delta t_r = (\Delta X)^2 / P\, D_r \,. \tag{3}$$

The plasma density n_w, which stop propagation of this microwave frequency, is called the cut-off density. For the microwave radiation ($\lambda = 3$ cm) cut-off density $n_w \approx 1.2 \times 10^{18}\ m^{-3}$ take place in radius r_w of density profile, as shown in Fig. 3. We can estimate the runway diffusion coefficient D_r from the experimental values of time to peak. If $\Delta X = a - r_w$, then

$$D_r = (\Delta X)^2 / C\Delta t_r. \tag{4}$$

The time to peak Δt_r is in the propagation of a pulse from r_w through $(a-r_w)$ to the limiter. The pulse has a bipolar character. Considering the modifications by Zheng Y. [6], C depends on the inversion radius position of the initial bipolar pulse and the microwave frequency. For the HL-1M tokamak C has an approximate value of 3 and the distance r_w = 160 mm. Assuming a peaked profile for the runway density and the same inversion radius for runway electrons and HXR, we can estimate the runway diffusion D_r from the experimental values of time to peak.

2.2 Hard X-ray Bremsstrahlung Spectra

2.2.1 Scaling Law for Runaway Electron from 1-D Model

The runaway confinement time τ_r has been deduced using a simple one-dimensional model for generation, acceleration and losses. Calculating the bremsstrahlung radiation, which caused by runaway collisions with the background plasma and the limiter, has simulated HXR spectra. For this purpose, electron distribution functions are obtained numerically by a simple scheme of deformation of a Maxwellian distribution function. We are obtained a slide-away distribution function. The kinetic model that is applied to obtain the runaway energy has been described in ref. [5], and considers electron acceleration in a parallel electric field E and drag forces due to ion-electron and electron collision as well as impurities. The model input parameters are n_e, T_e, Z_{eff} and E for the source and τ_r for the losses. The output value is the inverse slope of the simulated HXR spectra, which we have called the "runaway average energy" ε_r. By using more than 80 different simulations results can be approximated by the following expression:

$$\varepsilon_r = (\bar{n}_e^{0.15}\, T_e^{-0.06}\, Z_e^{-0.03})(V_P^{1.02}\, \tau_r^{1.1}). \tag{5}$$

Mentioned above the expression (5) has called scaling law for ε_r on plasma parameters and the runaway confinement time τ_r, where ε_r and T_e are in keV, n_e is in cm^{-3}, V_p is in volts and τ_r is in ms. The variation range of n_e (0.4–$1.5 \times 10^{19}\ m^{-3}$), Z_{eff} (1–6), T_e (0.4–1 keV) and V_p (0.4–0.5 V) used for these simulations.

By fitting the experimental and modeled HXR spectra, τ_r can be inferred from the runaway energy ε_r, i.e. from the inverse of the slope of the HXR spectrum. Using the expression (5), we can deduce experimentally the value of τ_r, as a global measurement, assuming that the inverses slope of the HXR spectrum is the mean energy of runaway electrons in the plasma. The range variation of the results for ε_r that gives variation in the confinement time from 2 ms to 16ms is 60 keV to 1.2 MeV.

2.2.2 Determining Diffusion Coefficient D_r from the Hard X-ray Spectra

To relate runaway confinement time τ_r and diffusion coefficient D_r, we consider a stationary runaway electron density from $\partial n_r/\partial t = \nabla(D_r \cdot n_r') + s_r$ where s_r is the production rate for runaway electrons and n_r is the density gradient, we obtain the runaway electron flux $-\ D_r n_r' = \frac{1}{r}\int_0^r S_r s ds = \Gamma_r(r)$, Therefore, the runaway density can be inferred, $n_r = a\int_r^a \frac{\Gamma_r(r)}{D_r} dr$ the following expression yields: $\tau_r = \frac{\int n_r dV}{\Gamma_r(a)\, A} = \frac{\int_0^a n_r dr}{\Gamma_r(a)\, a}$,

where A is the area of flux impact on the limiter.

FoHL-1M, if D_r is constant and also considering S_r calculated from the work by Connor and Hastie [4], τ_r can be approximated by

$$\tau_r = a^2 (1 - (r_{SR} / a)^2) / (4D_r) \tag{6}$$

where r_{SR} is the radius for the maximum rate production profile s_r for runaway electrons. Using $B_T = 1.9$ T, $V_L = 2V$, and experimental profiles of electron density and temperature, as wall as the safety factor q and Z_{eff}, obtained from ECE and HCN data. s_r exhibits maximum value around a/2. Nevertheless, for these conditions the calculated runaway density profiles is peaked in the plasma center.

Consequently, results for D_r obtained from three perturbation techniques and bremsstrhlung radiation point to the fact that those values come from a resulting

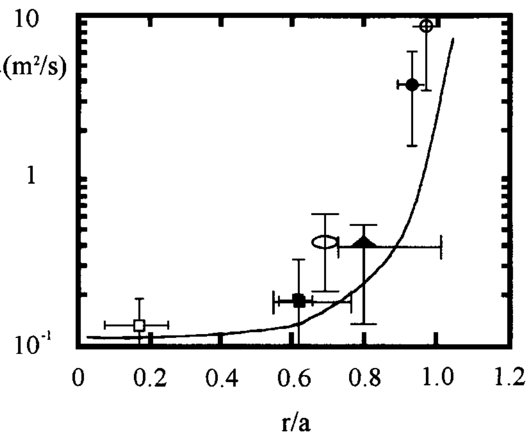

Fig. 4 Local runway diffusivity D_r as a function of radius ○ magnetic probe at edge, ● shift experiment, ▲ from microwave radiation, ⬭ sawtooth perturbation, ■ HXR bremsstrahlung spectra, □ from diffusion

local effect along runaway electron trajectories. The typical results for local runway electron diffusivity D_r in the HL-1M tokamak show as Fig. 4.

3. Magnetic Turbulence

Assuming that internal stochastic magnetic field results in the runaway diffusion, we can bind the runaway diffusion coefficient by $D_r < uD_M$, where u is the runaway velocity and D_M is the magnetic diffusion coefficient. We can further compute D_M [10] as

$$D_M = \pi q R < (\tilde{b}_r / B_T)^2>. \tag{7}$$

Using an example where u = c, q = 3.5, D_r = 1 m^2/sec and R = 1.02 m, we observe $<(\tilde{b}_r / B_T)^2>$ more than 3 × 10^{-8}. Under the similar to experimental conditioned as this experiment, $(\tilde{b}_r / B_T)$ is found to be around 4 × 10^{-8} using magnetic probes behind the limiter in the HL-1M. Such agreement between magnetic probe measurements and the runaway perturbation technique at the edge validates the runaway perturbation technique for measuring magnetic fluctuation; it also indicates that the runaway diffusion is due to internal magnetic field fluctuations. The magnetic fluctuation as a function for the HL-1M tokamak show as Fig. 5. We can confirm that magnetic fluctuation increase from the edge to the inner minor radius, as was observed in the HL-1M tokamak.

The scale length of the random step of runaway electrons due to the magnetic fluctuation is so large that the process cannot be diffusive but “non-local”.

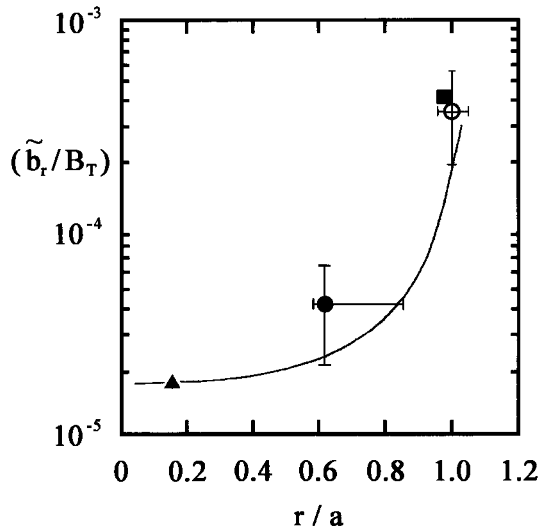

Fig. 5 Magnetic fluctuations as a function of radius for HL-1M plasma.
○ magnetic probe at edge, ■ shift experiment, ▲ from sawtooth perturbation and HXR Bremsstrahlung spectra from diffusion equation model.

4. Conclusions

The runaway diffusion coefficient has been obtained using two methods: a stationary one that uses a confinement time deduced from HXR bremsstrahlung radiation, and the magnetic perturbation experiments. Both methods give local values for D_r in the range of (0.4–10) m^2s^{-1} with a decreasing dependence on toroidal magnetic field as $B_T^{-1.5}$. Comparing this scaling with relation (7), we can say that changes in B_T can affect the structure of the magnetic turbulence since the averaging drift effect is not important in this type of discharge.

The deduced magnetic fluctuations level are about (2–5) × 10^{-4}, corresponding to averaged values of magnetic fluctuation levels measured inside and at the plasma edge using other diagnostics in the HL-1M tokamak. The $\tilde{b}_r$ / B_T values have a decreasing dependence on toroidal magnetic field. We can confirm that magnetic fluctuations values increase from the edge to the inner minor radius, as was observed in the HL-1M tokamak.

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