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

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1. Introduction

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]. There still is insufficient experimental data available to assess the importance of magnetic fluctuation for internal transport. The difficulties of extending magnetic probe measurements into hot plasma have not allowed a study of the magnetic fluctuation levels in the plasma interior. In this study, we demonstrate the use of steady state approach and perturbation techniques to measure the diffusion of runaway electrons as a probe of internal magnetic fluctuation in hot plasma. The transport of runaway electrons in plasma can be comparatively easily measured using a steady state approach and using the perturbation techniques. Assuming that magnetic turbulence is responsible for the runaway transport, the diffusivity can be interpreted in terms of a magnetic fluctuation level. 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 internal magnetic fluctuations.

2 Experiments

The experiments reported in this paper have been carried out in the HL-1M, R=1.02 m and a=0.29m. It was operated for this experiment with I_p=.120-150kA, B_T=2T and n_e=1.0-1.5 x $10^{19}m^{-3}$ [2]. HXR flux was detected by 4 NaI (Ti) 3 in ×3 in scintillates working in the current mode or in pulse height analysis mode to obtain the runaway electron energy and confinement time used. An energy resolution of 10 *keV*/channel was obtained using a calibration with a ^{137}Cs source.

2.1 Runaway diffusion coefficient deduced from hard x-ray bremsstrholung spectra

A one-dimensional numerical model [3] including generation and loss effects for runaway electrons is used to deduce the runaway energy ε_r dependence on the runaway confinement time. The simulation results are presented in the form of a scaling law for ε_r on plasma parameters. By using more than 80 different simulations the results can be approximated by the following expression: $\varepsilon_r = \left(\bar{n}_e^{0.2} T_e^{-0.1} Z_{eff}^{-0.05}\right)\left(V_p \tau_r^{1.1}\right)$ (1).

The scaling of ε_r and therefore the runaway confinement time τ_r, has been studied in

HL-1M tokamak, by measuring hard x-ray spectra under different experimental conditions. That has been described in Ref. [3]

Firstly we measure the bremsstrahlung radiation spectra by PHA. Using the expression (1), we can experimentally deduce 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. To relate runaway confinement time τ_r and diffusion coefficient D_r, we consider a stationary runaway electron density and the runaway electron flux $\Gamma_r(r)$. The D_r can be approximated by $\tau_r = a^2\left(1-(r_{SR}/a)^2\right)/\left(4D_r\right)$ [4] where r_{SR} is the radius for the runaway electrons maximum rate production profile s_r.

2.2 Runaway diffusion coefficient deduced from magnetic perturbation techniques

2.2.1 Runaway diffusion coefficient deduced from sawtooth perturbation

If we consider that runaway electrons diffuse racially 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 $\Delta t_r = a^2/P\,D_r$ ..... (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 $P = 4$. Fig.1 shows the signals from a central chord SXR detector and from HXR detector during the onset of sawteeth. In this case, considering the modifications by Y. Zheng [6], P depends on the inversion radius position of the initial bipolar pulse. For the HL-1M tokamak value of inversion radius r_s seen from SXR, it is about 5-6cm for B_t =2T. 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 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 0.1ms to 0.3ms in the range of B_T from 1.4 to 2.5T. It must be noted that in the same plasma conditions, both τ_r and Δt_r have the same increasing tendencies. D_r is the average effect of electronic locus along run away. If supposing runaway electronic density pulse from q=1 surface on radial quickly propagate with even speed to the limiter, we can approximate definition runaway diffusion coefficient is (2-5) m^2/s^{-1} at $r = (a+r_s)/2$.

2.2.2 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 (λ =3cm) intensity sawtoothing signals and sawtooth oscillation of the hard X-ray signals recorded simultaneously (see Fig.1). The simplest mode that we can assume is similar to diffusion model described during the Chapter 2.2.1. 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 $\Delta t_r = (\triangle X)^2/C\,D_r$ ·····(3).

The plasma density n_w, which stops propagation of this microwave frequency, is called

the cut-off density. For the microwave radiation (λ=3cm) cut-off density $n_w \approx 1.2\times10^{18}m^{-3}$ take place in radius r_w of density profile. We can estimate the runway diffusion coefficient D_r from the experimental values of time to peak.

If $\triangle X=a-r_w$, than $D_r = (\triangle X)^2 / C\Delta t_r$ ····· (4).

The time to peak Δt_r is in the propagation of a pulse from r_w through $(a-r_w)$ to the limiter. 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 29. Assuming a peaked profile for the runway density and the same inversion radius for runway electrons and HXR sawtooth, we can estimate the runway diffusion D_r from the experimental values of time to peak. If supposing runaway electronic wave pulse from q = 1 surface on radial quickly propagate with even speed to the limiter, we can approximate definition runaway diffusion coefficient is (4-6)m^2/s^{-1} at $r=(a+r_w)/2$. To take over at the same time the microwave radiation of wavelength λ=1cm, λ=2cm can get radial other different location runaway diffusion coefficient.

2.2.3 Plasma shift experiment

An increase in the current in the vertical field coils causes an inward shift of the plasma position [7] 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 *k*eV can easily free fall accelerated from bulk electrons depending on the induced electric field. By letting the runaway flux to the detector reach a near steady state condition before shifting the plasma and examining its transient response, the time evolution of the original radial profile of the runaways need not be known. The plasma displacement, hard X-ray signal and the best fit to diffusion equation model are shown figure.2. We are concerned only with the short time scales of the transient signal of the hard X-ray, The following simple diffusion equation: $\frac{\partial n}{\partial t} = \frac{\partial}{\partial x}(D_r \frac{\partial n}{\partial x})$ ····· (5) can describe the behavior of runaway [7], 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 [7] to the hard X-ray flux during the shift measurements indicates that the diffusion coefficient of runaway electrons is $9m^2/s^-$. 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 20mm.

Now, we can not still measure runaway diffusion coefficient in core D_{ro}, but can calculate probably core diffusion coefficient$\sim 0.2m^2/s$, using the definitely linear diffusion equation model made by Myra[8]. The difference of the value of diffusion coefficient ΔD_r between D_r obtained using Hard X-ray (HXR) bremsstrahlung spectra and D_r obtained from experiment in the crash of sawtooth of SXR and HXR is$\sim 0.5m^2/s$. The experimental level is in good agreement with simulation calculated result.

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 [8] as

$$D_M=\pi qR(<(\tilde{b}_r/B_T)^2>, \quad \text{than } D_r=D_m\nu_{ll}\gamma \quad =qR(\tilde{b}_r/B_T)^2\nu_{ll}\gamma \qquad (6).$$

Using an example where u= c, q=3.5, D_r=1 m^2/s and R =1.02m, we observe< $(\tilde{b}_r/B_T)^2$> more than 3×10^{-8}. Fig.3 shows the magnetic fluctuation as a function for the HL-1M tokamak.

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 (0.5-10) m^2s^{-1} with a decreasing dependence on toroidal magnetic field as $B_T^{-1.5}$. Comparing this scaling with relation (6), 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 $(1\text{-}3)\times10^{-4}$,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 Fig. 3.

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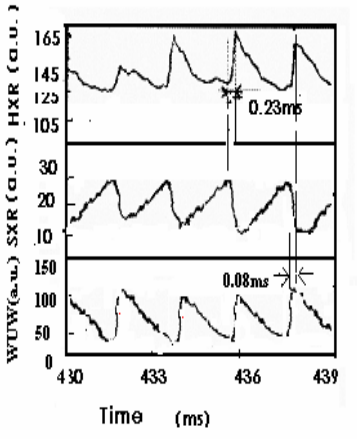

Fig.1 Signals from a central chord SXR detector and from HXR during the onset of sawteeth corresponding to the maximum current zone and microwave radiation (=3cm) intensity sawtoothing signals

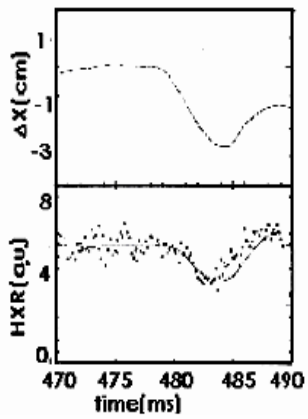

Fig.2 Plasma position and Hard x-ray signal during shift and best fit to diffusion equation model of hard x-ray signal.

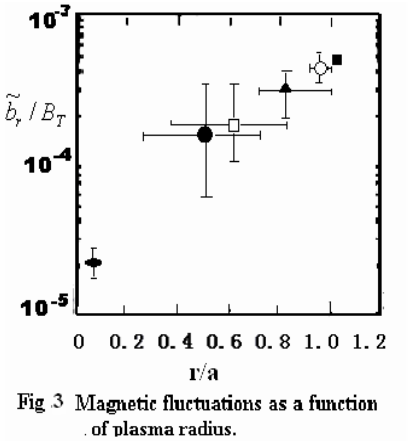

Fig 3 Magnetic fluctuations as a function of plasma radius.
■ magnetic prob at edge ○ shutt experiment
▲ Microwave Radiation □ from crash of sawtooth oscillations ● from Hard X-ray bremsstrahlung Spectra ◆ diffusion equation model