Magnetic turbulence probed using 30 MeV electrons

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1 Introduction

Particle and heat transport in tokamaks is anomalously high, thereby reducing the efficiency of a future power plant. One of the possible causes is turbulence in the confining magnetic field. Significant effects on transport may already arise with magnetic field fluctuations of $\tilde{B}/B = 10^{-5}$, where B is the magnetic field. There have been several clues to support this. For instance, on RTP and TEXTOR-94 small scale structures, filaments, have been observed with a scale size of in the order of 0.5 to a few cm[1][2]. Also, steps have been observed on the electron temperature profile[3], which have been contributed to electron internal transport barriers close to rational values of the safety factor. On Tore Supra[4], measurements indicated a magnetic fluctuation level in the order of 10^{-4}, which is sufficiently large to contribute to the energy transport. Measurements on TEXTOR-94 of the synchrotron radiation emitted by 30 MeV runaway electrons have shown an increasing level of magnetic turbulence with increasing additional heating power[5]. This conclusion is obtained by relating the delay between application of NBI and decay of the radiation signal to a radial correlation length of the turbulence. In this paper this work is refined by performing scans of different plasma parameters, and study the influence of these parameters on the synchrotron radiation signal. The analysis is assisted by a computer code which simulates the radiation time trace as function of plasma parameters and deduce from that a typical correlation length of magnetic turbulence.

2 Set-up

On TEXTOR-94 the synchrotron radiation stemming predominantly from 30 MeV runaway electrons is measured using a 2D thermographic camera operating at 50 Hz[6]. This setup records radiation in the wavelength range $3-8\ \mu$m. The tangential view, together with the small opening angle of the radiation of 30 MeV electrons causes the captured images to be close to a poloidal cross-section of the runaway radiation. Since the synchrotron radiation is strongly weighted with the runaway energy the signal is dominated by the highest energetic electrons. Moreover, after the maximum energy of about 30 MeV has been reached, where the power gain from the electric field equals the power loss, this signal is approximately proportional to this runaway density.

3 Experimental results

A model has been designed to assist analysis of the observed synchrotron radiation traces. This model takes into account primary (i.e. according to Dreicer theory) and secondary (close collisions between existing runaway and thermal electrons) generation, acceleration due to the loop voltage, friction and small angle pitch angle scattering due to electron-electron and electron-ion collisions (the drag force) and an energy dependent runaway confinement time.

Since runaway transport is governed only by magnetic turbulence the energy dependence of the confinement time is determined by the sensitivity of the runaways to magnetic turbulence. Therefore the confinement time is parametrized using a scale size of the magnetic turbulence, δ. When the drift orbit shift of the runaway electrons is significantly larger than δ the turbulence is strongly reduced [7][5]. In the following Ohmic discharges will be addressed first to check the essential ingredients of this model. Thereafter, heated discharged are analyzed to quantify the contribution of magnetic turbulence in the enhanced transport regime.

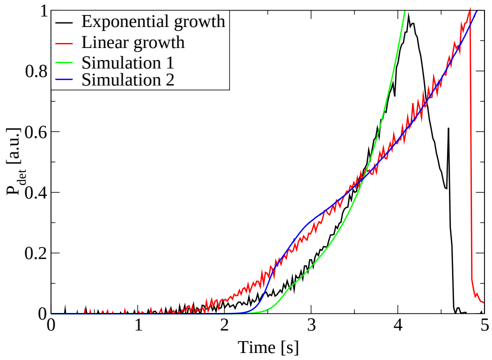

Figure 1: *Synchrotron radiation signal in two Ohmic discharges and the simulated signals. The difference between the two simulations is the scale size of the magnetic turbulence, which parameterizes the runaway confinement time.*

Ohmic discharges

The synchrotron radiation signal in the Ohmic phase of the discharge can behave in two different ways. First, an exponential growth for the duration of the discharge may be observed. Second, a predominantly linear growth of the synchrotron radiation signal may be observed. In Figure 1 an example of these two cases is shown.

The main plasma parameters electron density (n_e), plasma current (I_p), magnetic field (B_T), electron temperature (T_e) and the loop voltage (V_{Loop}) do not differ remarkably between the discharges. As can be seen in Figure 1 the first radiation becomes visible at around $t = 1.5$ s. This is the time necessary for thermal electrons to become accelerated into the visible regime $\geq$ 20 MeV. This is followed by an exponential-like increase of the signal for about $0.5 - 1$ s. In that time the runaways are accelerated to 30 MeV, where they reach the radiation limit. After this time, the signal is dominated by radiation from 30 MeV electrons, and the behavior of the signal is proportional to the population of 30 MeV runaways. This shows an exponential growth in one example, and a more linear growth in the other. The exponential growth is predominantly the effect of the secondary runaway generation process. This leads to an avalanche of the runaway population. Simulations of these discharges are also shown in this figure.

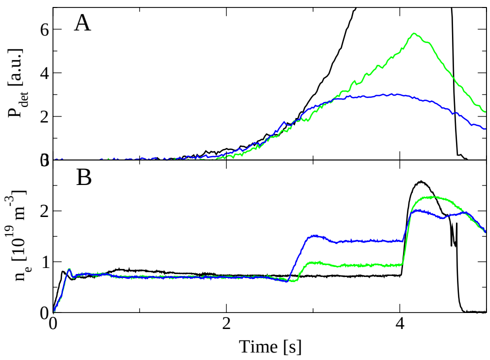

Figure 2: *Synchrotron radiation signals from a gas puff scan.*

Both cases could be satisfactorily modeled by only varying the scale size of the turbulence. This has been taken 1.3 mm in the exponential case, and 1.6 mm in the linear case, showing a strong sensitivity to δ. These values are in agreement with the typical Ohmic scale size found in [5] (less than 5 mm). The reason why δ differs might be found in the fact that the exponential signal was found in a discharge which was preceded by a disruption.

Another experiment which has been performed in Ohmically heated discharges is a gas-puff experiment. In this experiment a runaway distribution is created in the standard low density phase ($t \leq 2.75$ s). Then, a gas puff is applied of 30% or 100% of the previous density. This experiment is important to verify the modeling tool, as well as important for the analysis of NBI heated discharges, in which the density is slightly increased due to the application of the beam.

In Figure 2a the synchrotron radiation signals corresponding to this experiment are presented. A reference signal (Exponential growth from Figure 1 is included. The line averaged density signals are shown in Figure 2b. It is seen that with increasing density, the growth rate of the signal decreases. The decrease observed is significantly less than modeling shows. Simulation of the discharge with a density increase 30% and equal δshows a decaying signal, in contrast to measurements. This indicates that an increase of density results in increased confinement of runaway electrons, otherwise the signal would also decay. The experimental results thus suggest an increased confinement of runaways with density, in agreement with Neo-alcator scaling.

Neutral Beam heated discharges

Two sets of NBI experiments have been carried out. The first is a power scan of long (1.5 s) NBI pulses, and is essentially a repeat of the experiments already presented in [5]. In these experiments it was seen that there is a delay between application of NBI and a decay of the synchrotron emission. The delay is shorter for higher power, and the decrease is found to go more rapidly with higher power. This reduced confinement with higher power is also found in the L-mode scaling law. The delay could only be explained assuming an energy dependent runaway confinement mechanism. By interpreting the delay as the time needed for affected runaway electrons to be accelerated into the observed energy range, and deducing the energy of these runaway electrons at that time, the maximum loss energy is found. The drift orbit shift of runaway electrons with that energy can then be interpreted as being close to δ.

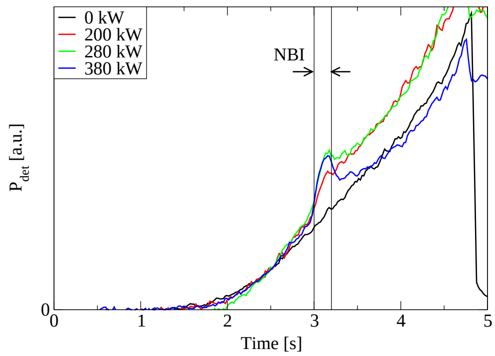

Figure 3: *Neutral Beam power scan. All neutral beam pulses are from $t = 3$ to $t = 3.2$ s.*

The second experiment is a power scan with short (0.2 s) NBI pulses. This power scan is shown in Figure 3. This scan is interesting for several reasons.

At low power the long pulse experiments only begin to show a reduction of the synchrotron radiation growth for a delay time of up to 1 s, but still with activated beam. The short pulse experiment allows the separation of beam application and observation of the effects.

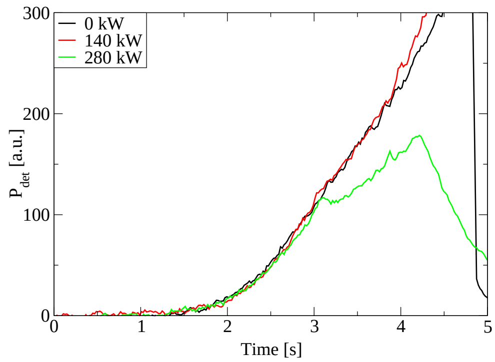

Figure 4: *ECRH scan. ECRH is from $t = 3$ to $t = 3.2$ s.*

A long beam pulse tends to empty the runaway electron distribution below the threshold energy altogether. A shorter pulse does not have this effect and permits the investigation of the rate of decrease of runaways in this region. From the fact that the signal still grows after application of NBI shows that the runaway distribution in the directly affected energy range has not been depleted completely as is the case with 1.5 s NBI pulses.

ECRH heated discharges

As an alternate source of additional heating electron cyclotron resonance (ECRH) heating was chosen. ECR heating does not increase the density, and exhibits excellent localization (FWHM approx 5 cm). It also decreases the electric field locally. The duration of ECRH is limited to 0.2 s, the maximum power is 280 kW. The power can be decreased by modulation.

In Figure 4 a power scan using ECRH is shown, with the power varying from 0 kW (Ohmic) to 280 kW well localized (compared to approx. 350 kW of total Ohmic power). It is seen that 140 kW ECRH hardly affects the signal, also not after the time thermal electrons need to be accelerated to 30 MeV. The runaway distribution is thus hardly affected. Higher ECRH powers show a decreased growth rate after application, indicating that the runaway losses have increased. These effects take place within a few 100 ms after the start of ECRH meaning that also highly energetic runaway electrons are affected.

Plasma Current Scan

L-mode scaling shows an increased bulk electron energy confinement with higher currents. In order to see whether this increased confinement also applies for runaway electrons measurements were made with a plasma current of 300 and 400 kA. The discharges have been heated with a long NBI pulse (duration 1.5 s) starting at 3.5 and 3 s respectively. The growth rate in the preceding Ohmic phase are practically identical, indicating that the plasma conditions do not vary significantly. It is seen that the delay between application of NBI and the decay in synchrotron radiation signal is longer for a higher current, indicating a better runaway confinement. For 300 and 400 kA, values of $\delta = 2.6$ and 2.0 cm are found, i.e. a linear scaling. This is similar to the global energy confinement scaling in L-mode.

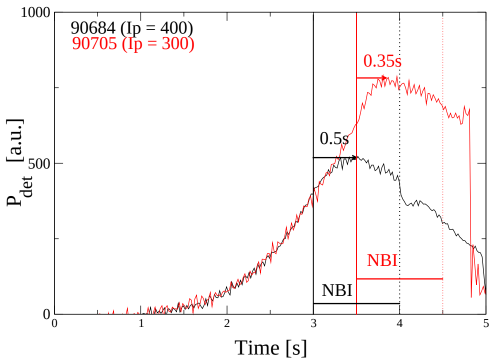

Figure 5: *Current scan with NBI heating*

4 Discussion and conclusions

The data presented in this paper represents a broad domain of plasma parameters in which runaway transport studies have been carried out. Ultimately, runaway transport theory must be able to describe all these cases accurately, and thus give a consistent view on effects of magnetic turbulence on runaway transport. The results shown in indicate that this is within reach.

The scaling of the runaway confinement with density, plasma current and additional heating power show a behavior comparable to bulk energy confinement. Since runaway electron transport is predominantly determined by the magnetic turbulence, this could indicate that global transport is significantly influenced by magnetic fluctuations in the L-mode as well.

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