PLASMA FILAMENTATION IN TEXTOR-94

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Often plasmas in nature (e.g., solar flares, lightning) form thin threads: filaments. In fusion research plasma filamentation has long been ignored, until it was first demonstrated in 1994 in the Rijnhuizen Tokamak Project.[1] In RTP the phenomenon was extensively explored: physical conditions that are required, life time and size of plasma filaments and impact on macroscopic plasma behaviour.[2] In TEXT-U, filaments were observed with an ECE-Imaging system.[3] Recently, filamentation has also been reported in the TJ-II stellarator plasma.[4,5] An outstanding question regarding plasma filamentation is, whether it is a general feature of a magnetised plasma, or a peculiarity of small plasmas (RTP and TJ-II) with a very high power density of Electron Cyclotron Resonance Heating (ECRH). This, of course, called for a study of plasma filamentation in a large device, employing also different heating scenarios.

In the course of 2000 the FOM-team has implemented a number of high-resolution plasma diagnostics onto TEXTOR-94, including double-pulse Thomson scattering.[6] This system is used to measure the electron temperature, density and pressure profiles at 120 positions along a 900 mm long vertical chord through the plasma, with a spatial resolution of 7.5 mm. The spectrum at each position is resolved into 70 wavelength channels. The statistical accuracy in T_e is mainly determined by photon statistics and is typically 5% at $n_e = 3.5 \times 10^{19}$ m^{-3}. That in n_e at the same density is typically 3%. The system can be operated in the double-pulse mode and the time interval between the two pulses can be varied from 50 to 500 μs.

With the Thomson scattering diagnostic, hot filaments with temperatures of typically 1-3 keV above that of the surrounding TEXTOR plasma are routinely observed (see Fig. 1). The filaments are not only present in locally heated ECRH plasmas but also in Neutral Beam (NBI) and ohmically heated plasmas. The total number of filaments does not depend on the heating method, but with central ECRH deposition often a few filaments can become very pronounced. A very surprising observation is that the amplitude of the filaments, quantified as the root-mean-square of the temperature fluctuations with respect to a smoothed temperature profile appears to depend only on the electron collision time (see Fig. 2), irrespective of which heating method is used. A similar scaling has been reported for the TJ-II data,[3,4] albeit that the dataset only contained ECRH plasmas. For RTP data a scaling with $n_e^{-1.5}$ has been reported,[2] but a re-analysis has shown that the data do also match with the above mentioned scaling with collision time. It should be noted that a strong colinearity exists between density, temperature and heating power, such that other scalings cannot be excluded.

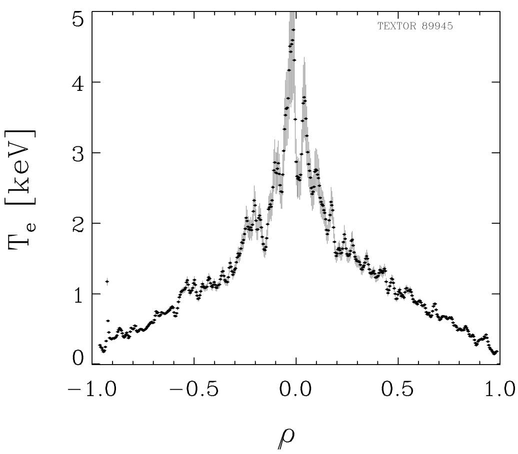

Fig. 1. Typical temperature profile for a ECRH discharge, obtained with multipoint Thomson scattering.

A part of the experimental programme at TEXTOR-94 has been devoted to study the response of plasma filaments to transient events like sawtooth crashes, ECRH and NBH switch on/off, etc. Although a clear indication was found that filaments are largely suppressed as a result of a sawtooth crash, it appeared that when corrected for the scaling with collision time the apparent suppression can be completely attributed to a change in temperature and/or density. In other words the scaled amplitude of the filaments is constant over the complete sawtooth period (see Fig.3). Similar conclusions could be made for the time behaviour of filaments after other types of transient events.

The RTP data suggested that filaments only occur in areas with a low magnetic shear. For RTP these were either the regions within the q=1 surface or in the vicinity of q_{min} in reversed magnetic shear discharges with off-axis ECRH. In TJ-II, with relatively low shear the filaments occur at all radii: k-spectra (treating the filaments as broadband turbulence) determined in the core and at the edge of the plasma are basically similar in shape and magnitude (after scaling with the collision time).[4] In TEXTOR structures in the temperature profile are also seen all the way to the edge, albeit that they gradually become smaller there (see Fig. 4). To judge whether the structures at the edge are of the same nature as those in the center, an arbitrary profile was fitted to the bottom envelope of the experimental data. From the value of the filament amplitude in the center, the local electron collision time and the bottom envelope (the blue curve in Fig. 4), the red curve was obtained which matches the upper limit of the experimental data rather well over the entire profile. The same analysis was also done for a shot featuring a strong internal transport barrier, with essentially the same conclusion. Hence, also in TEXTOR the filaments occur at all radii; their local amplitude only depends on the local collision time. Re-analysis of RTP data shows the same. In other words: low shear is not a necessary condition. This was only suggested because in standard tokamak discharges the lowest shear is also where the collision time is longest: in the very center.

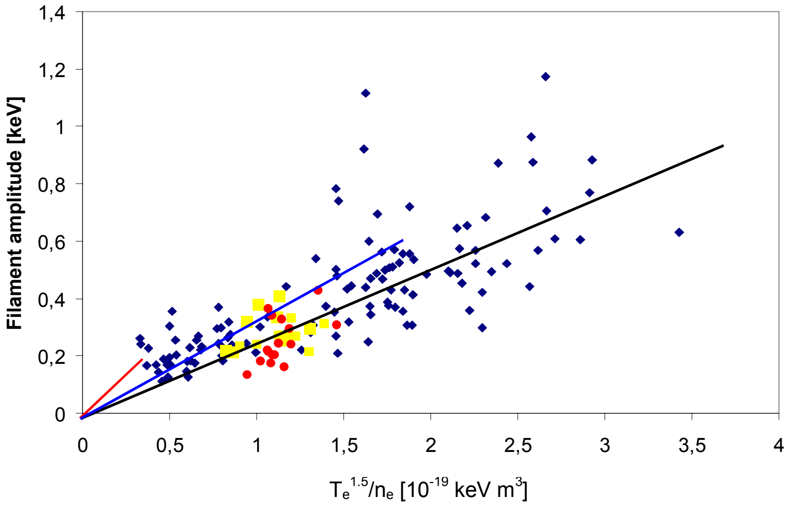

Fig. 2. Filament amplitudes in TEXTOR-94 plotted as a function of $T_e^{1.5}/n_e$. The dataset includes ECRH (blue), NBI (yellow) and ohmic (red) discharges. The scalings of RTP (blue line) and TJ-II (red line) are also indicated in the figure.

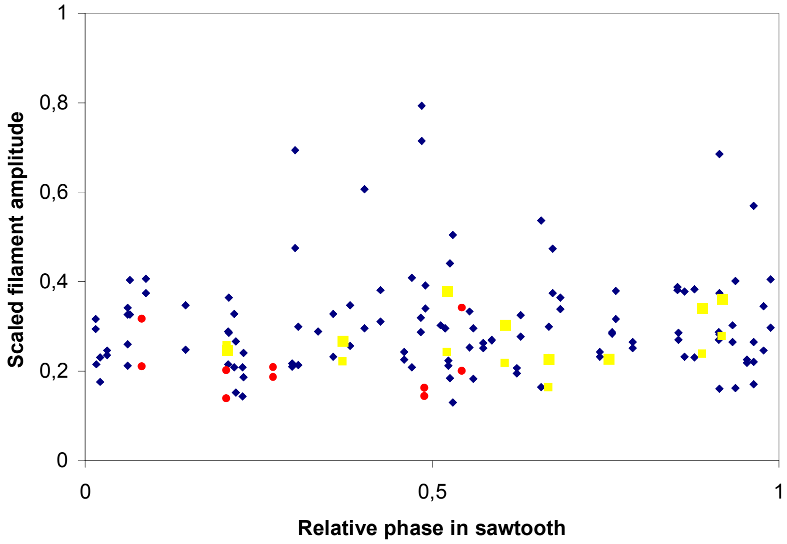

Fig. 3. Filament amplitude scaled for the collision time as a function of the relative phase in the sawtooth period (normalised to 1). No dependence is seen. The dataset includes ECRH (blue), NBH (yellow) and ohmic (red) discharges.

Various explanations for the occurrence of filaments have been brought forward. Following Mirnov[7] one could think of 'positive' islands, i.e. closed flux tubes with enhanced current den-

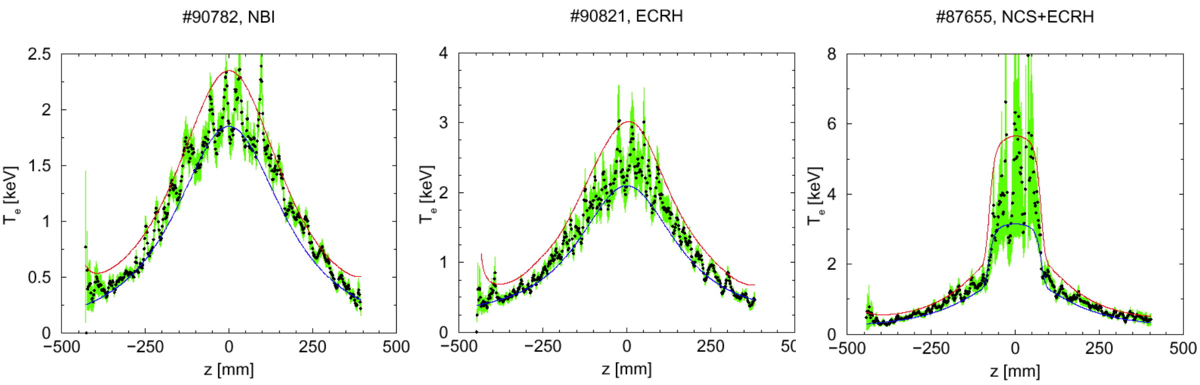

Fig. 4. Temperature profiles for three different discharge scenarios: NBI (left), central ECRH (middle) and a negative central shear discharge established by ECRH in the current ramp up phase (right). Filaments occur at all plasma radii. The blue line is an arbitrary profile fitted to the lower envelope of the experimental data (green). The red curve is calculated from the blue one (see text).

sity enabled by low shear. The fact that it now appears that low shear is not required makes this explanation doubtful. In another model it is suggested that the islands are caused by very localized ECRH of an m=1 sawtooth precursor.[8] This can lead to localized peaks in the temperature profile, but the model cannot explain the multitude of peaks at all plasma radii in TEXTOR and in TJ-II. Moreover, the model is falsified by the fact that filaments are also observed with more global heating methods as NBI and ohmic heating.

In their recent paper, the TJ-II team indicated that the k-spectrum of the filaments is very similar to that measured by Langmuir probes at the edge.[4] Moreover, it shows more or less the same features as in the k-spectrum of density fluctuations measured with a number of different techniques in other machines. As a logical consequence of this, the TJ-II team has put forward the working hypothesis that the filaments are snapshots of broadband turbulence. For RTP, k-spectra of the filaments have been published,[2] that are reminiscent to the ones of TJ-II. The k-spectra of filaments in TEXTOR have also roughly the same shape suggesting that the filaments in all three devices have a similar physical origin. The k-spectra from the three experiments suggest that $\langle k \rangle \propto a^{-1}$.

Before one might become tempted to assume that the underlying mechanism of the filaments is broadband turbulence, it is important to emphasize that the filaments in the Thomson profiles of TEXTOR-94 map back onto themselves in case the time difference between the two pulses is matched to an integer times the toroidal rotation period of the plasma. In TEXTOR-94 it has been observed that the filaments map back onto themselves after 300 μs, giving a minimum measure for the coherence time of a single filament (see Fig. 5). Furthermore, these findings indicate that the filaments rotate with the plasma fluid. Similar observations have been reported for RTP, but for a time of 80 μs between the two laser pulses.[2] This mapping of the filaments onto themselves is difficult to understand when one seeks their explanation in broadband turbulence. Instead it hints more to local structures in the magnetic topology. In case one assumes that the filament corresponds to a toroidally closed magnetic flux tube, one can calculate the value of the electron heat diffusivity χ_{fil} inside the filament. Both for RTP and TEXTOR it has been calculated that $\chi_{fil} \cong 0.05\ m^2s^{-1}$, which corresponds to 2-3 times the neo-classical value. The corresponding confinement time of the filament would then correspond to about 900 μs for TEXTOR and 100 μs for RTP.

In Tore Supra it has been measured that the relative level of magnetic fluctuations in the plasma core is in the order of 10^{-4}. Even though being very small, the level is sufficiently high to break up the normally assumed nested perfect flux surfaces. The resulting magnetic topol-

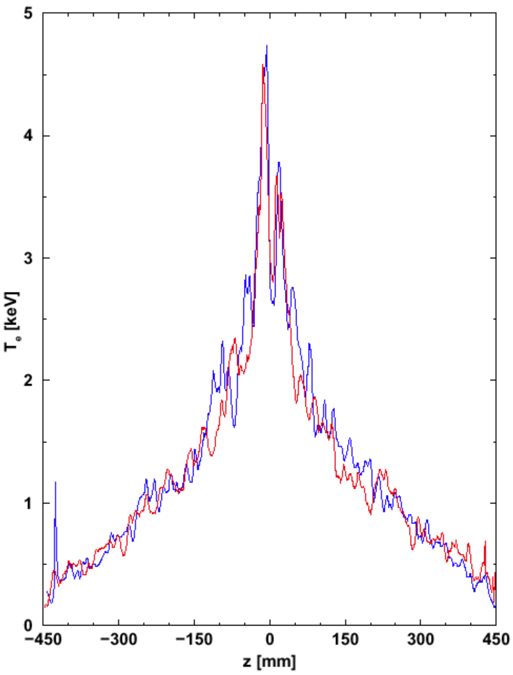

Fig. 5. Two temperature profiles measured at a time separation of 300 μs, corresponding to exactly 3.5 toroidal rotations of the plasma column, showing that the coherence time of filaments is at least 300 μs. The blue profile has been horizontally flipped.

ogy is not incompatible with small-diameter flux tubes which are toroidally closed into themselves embedded in regions in which the magnetic field lines are chaotic. Layers of unperturbed magnetic flux surfaces and, hence, good confinement, separate alternate chaotic regions. The layered structure of the plasma has been very clearly demonstrated in RTP. A supporting argument from TEXTOR-94 is that recent measurements of synchrotron emission from runaway electrons could be explained by magnetic fluctuations with radial correlation lengths in the range of 1-5 cm. The correlation length might be interpreted as the width of a single chaotic region (i.e. the region between two barriers). The hypothesis of broadband magnetic turbulence is not inconsistent with long-lived local structures in the magnetic topology. It is clear that this hypothesis needs to be verified/falsified in the future research programmes of the various devices.

An important question is what would be the amplitude of filaments in a large device like JET. In case one only looks at the scaling with collision time, one would conclude that the filaments in these devices would be of giant proportions. However, although the filaments in a single device scale linear with the collision time, the scaling factor is different for TJ-II, RTP and TEXTOR-94, being the steepest for TJ-II and the least steep for TEXTOR (see Fig. 2). The origin of this difference in scaling is not yet clear it suggests that the proportionality factor decreases with plasma size.

A possible mechanism that could perturb the ideal magnetic topology is the presence of beams of supra-thermal electrons. In the T-10 tokamak is was recently observed by a tangential x-ray imaging system that mildly energetic supra-thermal electrons are generated in magnetic reconnection processes.[9] The amplitude of the current driven by the supra-thermal electrons in T-10 is estimated to be about 20 kA, which is high enough a value to perturb the magnetic topology over a large part of the plasma column. If one wants to adopt this explanation, however, one should come up with an explanation how bursts of mildly energetic electrons that are generated approximately every 10 ms can keep the magnetic topology perturbed continuously. Furthermore, it maybe clear that this specific mechanism cannot explain the TJ-II results.

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