OVERVIEW OF TEXTOR-94 RESULTS WITH ECRH AND HIGH RESOLUTION DIAGNOSTICS

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After the closure of RTP at the end of 1998 the experimental research in tokamak physics of the FOM Institute was relocated at TEXTOR-94 in the framework of the TEC agreement. Since spring 2000 the FOM-equipment started to yield results of which this presentation will give a summary. Details will be found in contributions to this conference.

New equipment at TEXTOR-94:

ECRH/ECCD systems:

Here we report on the results with a preliminary system: 300 kW, 200 ms, 110 GHz for 2X-mode heating and current drive with variable toroidal and poloidal launching angles and focal distance. This system acted also as a source for Collective Scattering to study (with MIT) fast ion dynamics to be presented on this conference [1].

Diagnostic systems relevant for this paper:

A Thomson scattering system with a spatial resolution of 0.8 % of the full plasma diameter has been installed which system is similar to the ones used in RTP and TJ-II. This instrument is a powerful tool for the study of electron dynamics on meso-scale length in particular together with the ECE-I(maging) system (with UCDavis). This observes the central part (± 10 cm with respect to the equatorial plane) of a vertical chord of plasma at the same toroidal position as Thomson scattering. By tuning the local oscillator frequency of the heterodyne detection circuit, it is possible to overlap the vertical viewing chord with that of Thomson scattering for calibration. The spatial resolution of ECE-I is about 1.2 cm in all three directions with a time resolution of 2.5 μs.

A multi-channel Pulse Radar Reflectometer gave important information on density fluctuations by the variations in the time-of-flight of the 300 ps microwave packets.

Results on Electron transport:

The findings with ECRH in RTP raised the suspicion that magnetic turbulence is a neglected aspect of tokamak transport, which should be integrated with the current view that driftwave turbulence is the prime reason for poor confinement. Low frequency temperature and thereby resistivity fluctuations with modest wavelength as predicted by driftwave theory will lead to current-density fluctuations which will destroy the idealized magnetic topology of neatly nested flux surfaces. The topology will be broken up (KAM-theorem) by magnetic islands and filaments stretched along magnetic field lines that close on themselves. These structures will be embedded in areas with stochastic field lines bounded by unbroken flux-surfaces (KAM-tori) acting probably as electron transport barriers (e-ITB's). Electrons are much more sensitive to the magnetic topology than ions and are therefore investigated in TEXTOR-94. As an example: 30 MeV runaway electrons were created at various plasma current levels in low density Ohmic discharges followed by NBI at various power levels and diagnosed with synchrotron radiation measurements [2]. The birth rate of high-energy runaways increases with an increasing population of medium energy runaways of which the loss-rate is not sensitive to electrostatic fluctuations but exclusively to magnetic field line stochasticity. The measured loss-rate increases with NBI power and decreases with plasma current just as L-mode scaling predicts. This gives evidence for the importance of magnetic turbulence.

Self-organized magnetic structures in tokamak turbulence as filaments, islands and e-ITB's as observed in TEXTOR-94 will be discussed below.

Filaments:

The observation of high electron temperature filaments in RTP has been reported extensively [3,4]. Also TEXT observed them [5]. Recently they were found in the stellarator TJ-II [6,7] and in TEXTOR-94 [8]. All these experiments have in common that the electrons were mainly heated by ECRH. This caused suspicion that filamentation was a special feature of ECRH. In [8] it will be shown that they exist for all types of heating. The ω- and k-spectra are very close to results found by collective scattering on density-fluctuations. Filaments appear to rotate with the local toroidal plasma rotation. The small dimensions and the fast rotation speed could explain why they have escaped observation in many tokamaks. With standard ECE at limited spatial and temporal resolution filaments can be averaged out of observation, as the resulting amplitude will be reduced by at least an order of magnitude. The TJ-II team [7] has shown that measured ECE-fluctuations, albeit at reduced amplitude, do follow the Thomson scattering scaling results: the filament amplitude appears to be proportional to the local electron collision time. This scaling has been confirmed at TEXTOR-94 for all types of plasmas at any radius with TS and with ECE-I. The latter rules out low-shear as a necessary condition. Re-analysis of RTP-results confirmed the same scaling. The proportionality factor between amplitude and collision time appears to decrease with plasma size. Caveat: a strong co-linearity exists between n, T and heating power-density.

Theory on filaments is starting up as two contributions to this conference will show [9,10].

Islandography:

Magnetic islands are a more familiar form of magnetic perturbation than filaments. A distinction between the two is that with positive shear islands have a lower current density than the immediate surrounding whilst filaments appears to have a higher one. Large m=2 islands show signs of improved confinement within their separatrix as can be seen from the pronounced density peaking [11] and a mild temperature enhancement [12] inside the island. Very interesting is the observation with pulse radar reflectometry that fluctuations in the time-of-flight of the reflected radar wave packages have a completely different frequency spectrum in O-point than in X-point. ECE-I [12] shows strong fluctuations at the X-point. Under some circumstances secondary islands with m=12-20 could be observed with pulse radar in the immediate surroundings of the large m=2 islands.

Transport barriers:

L-mode:

In RTP very sharp e-ITB's were observed close to (but not at) rational q-surfaces for plasmas with an ECRH-power exceeding Ohmic power with an order of magnitude and with only a weak electron-ion coupling [13]. An empirical electron transport model was set up [14] assuming a layered heat diffusivity alternating between very high and very low values at positions that were related to local q-values. This model could describe all RTP observations of e-ITB's. It was expected that this empirical description would break down for TEXTOR-94 discharges with an Ohmic power somewhat larger than the available ECRH-power and with moderate electron-ion coupling. With inclusion of the electron-ion energy sink in the electron energy balance the RTP layer model holds very well for TEXTOR-94 [15].

Current-rise Phase with NBCD and ECRH:

As current-drive capabilities in TEXTOR-94 were limited low- or inverted-shear plasmas could only be created during the current ramp-up phase assisted by a 20-40 kA NBCD in counter direction [16]. Without ECRH this counter drive prevented sawteeth to occur before the end of the NB-pulse. With central ECRH two strong e-ITB's show up simultaneously. With off-axis ECRH outside the inner most barrier at $\rho\approx0.13$ this barrier becomes invisible but the outer at $\rho\approx0.35$ is unaffected. When the ECRH deposition is placed outside $\rho\approx0.35$ also this 2nd barrier becomes invisible and the T_e-profile becomes nearly identical to the one without ECRH. Central deposition gives rise to extremely high electron temperatures (up to 6 keV) like has been seen in many tokamaks during ECRH heated ramp-up phases. The very low resistivity in the center attracts current notwithstanding the low field diffusion coefficient and against the counter current-drive. Therefore sawteeth occur much earlier with than without ECRH. Before sawteething other collapses indicate the passage of q_{min} through rational values. The experimental identification of the strong e-ITB's with q-values is hampered by the lack of reliable q(r)-measurements. However numerical simulation of the (neoclassical) current diffusion together with NBCD predicts rather well the moment of collapses like the q_{min}=3/2 passage and the appearance of sawteeth. The qprofile found by the simulations indicates q=3/2 and 2/1 near the positions of the two e-ITB's. However at other points of time the relation with rational q-values cannot be established whilst the redistribution of j(ρ) due to collapses cannot be numerical simulated anyhow. Next year MSE will help in verification of the eITB relation with q(ρ).

RI-mode with ECRH:

Application of ECRH on RI-mode plasmas is very effective. A 9% increase of total power due to ECRH leads to a 9% increase in energy content whilst the RI- and L-mode scaling found for NBI or ICRH heating predicts 3-4 %. This high efficiency is only found when the localized ECRH deposition is placed within an e-ITB related to q=1. Deposition outside this barrier gives only 3%. The T_e ramp-rate during sawteeth is 4 times larger with central ECRH than without. This indicates that only a tiny fraction of the NB+ICRH-power heats the central electrons and that even better confinement results might be obtained with RI-mode if one really heats the central electrons substantially. The influence of ECRH on sawteeth changes dramatically with increasing Neon-density from normal L-mode behavior to "hump-back' behavior at the highest RI-mode confinement [17]

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