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Detailergebnisse / Details

Plasma Diagnostics

Edge Diagnostics

Traditionally many of the diagnostics for the investigation of the plasma boundary and surface interaction region in TEXTOR are based on optical techniques. Existing methods in astronomy, low temperature plasma discharges and surface analysis have been tested in laboratory experiments and then adapted to TEXTOR. Moreover, TEXTOR also allows the use of active techniques, where either atoms or laser light is introduced into the region to be diagnosed.

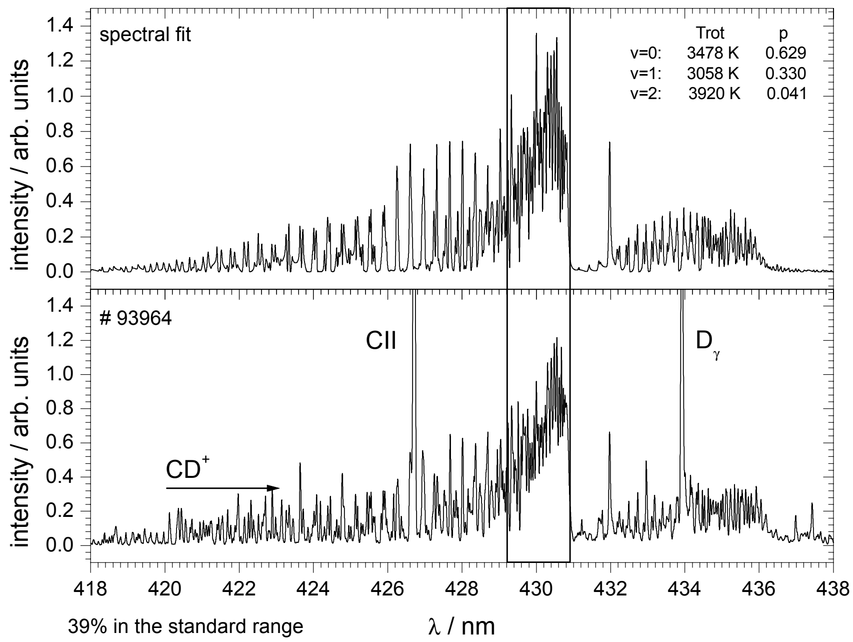

***Fig. 1**: High resolution measurement and modelling of a CD_4 gas puff through a nozzle into a TEXTOR boundary plasma.*

The *passive spectroscopy* of molecules and line profile measurements has been considerably improved by the use of an Echelle spectrometer, which allows the simultaneous recording of a wavelength range between 375 nm and 700 nm with a high resolution of $\lambda/\Delta\lambda = 20000$. Fig. 1 gives an example concerning measurements of molecular emission during a discharge on TEXTOR, which demonstrates the possibilities of the instrument. The accuracy allows for a reliable modelling of the spectrum.

The visible spectroscopy was considerably upgraded by the installation of several small "rack" spectrometers, which allow the simultaneous observation of a number of volumes near the limiters and close to the inner bumper in wavelength regions ranging from the air UV (λ = 200 nm) up to the near IR (λ = 1000 nm).

The very flexible test limiter spectroscopy equipment can now also be used for the observation of the spatial impurity distribution during the operation of the Dynamic Ergodic Divertor (DED, see fig. 2)

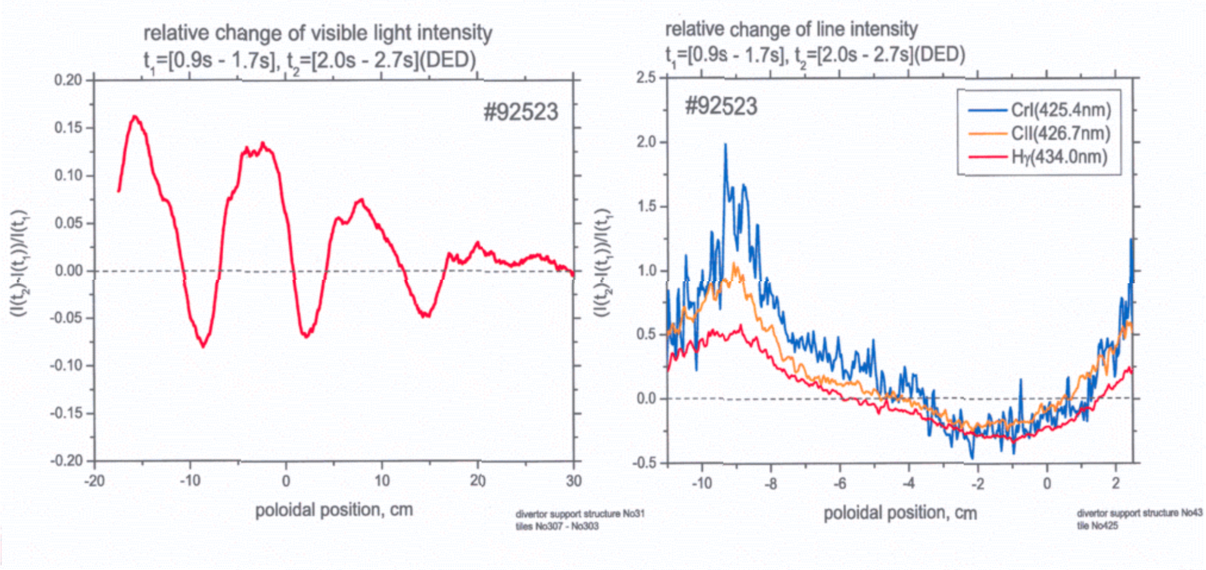

Fig. 2: *Relative changes of particle emission intensities on the DED via imaging spectroscopy.*

A *supersonic helium beam diagnostic* was developed for fluctuation measurements of the electron temperature and density. The beam injection system that provides a collimated beam with a pulse length of 0.1 s and 2 Hz repetition rate is attached on top of the TEXTOR vessel. The radial profiles of three emission lines are observed by two complementary detector units with a temporal resolution of 10 ms and 10 µs, respectively. The radial observation range of the "slow" unit covers about ±50 mm around the last closed flux surface (LCFS) at 460 mm. The emission profiles are used for normalisation of the fluctuation signals obtained with the "fast" unit which passed the final tests in the laboratory. First electron temperature and density profiles were measured with the "slow" detection systems.

Charge exchange recombination spectroscopy (CXRS) applied on a high energetic (50 keV) neutral H diagnostic beam is used for the measurement of radial profiles of ion temperature, impurities and poloidal velocities. The full radial range from centre to 500 mm at the low field side is observed by two spectrometers. The light of the central channels is conducted via fibres onto an entrance slit of a spectrometer. With optical lenses the edge region from 350 mm to 500 mm is imaged onto the slit of the second spectrometer. Additionally, the red and blue Doppler shifted CXR line intensities from top and bottom of the vessel are measured simultaneously by a high resolution spectrometer with 20 spatial channels distributed over the last close flux surface (LCFS). An in-situ measurement of the species distribution has been developed and applied at the hydrogen beam line allowing the determination of the beam density distribution inside the plasma.

DED diagnostics

The R&D work in 2003 mainly concentrated on the implementation and the commissioning of new diagnostics relevant for the DED operation.

A set of 18 Langmuir probes were implemented into the divertor target plates of TEXTOR (see Fig. 3). They measure the particle flux and the electron temperature in front of the plates. Thermocouples with high time resolution were implemented into the divertor tiles to measure the heat fluxes. A set of five Hall probes has been mounted on a slow probe drive at the low field side and first measurements were performed. These probes measure the modification of the magnetic field at the plasma edge induced by the DED. A fast IR camera observing the divertor target region was taken into operation. It measures the heat deposition pattern imposed by the DED. The camera has a time resolution of about 75 µs and is therefore suited for higher frequency operation of the DED.

The pellet injection system was installed and taken into operation in the laboratory. In collaboration with CEA-Grenoble/France three of the nine barrels were replaced in order to produce pellets of larger size (2.5 mm instead of 1.5 mm). Preparations have been done for the new pellet guiding system, which will be installed in 2004 in collaboration with the Technical University of Applied Physics at St. Petersburg/Russia.

A fast valve which was developed in recent years was implemented at TEXTOR. The valve opens within less than a millisecond and releases some hundred millibar-liter of gas into the discharge chamber. First experiments to mitigate disruptions by massive helium puffs were performed successfully.

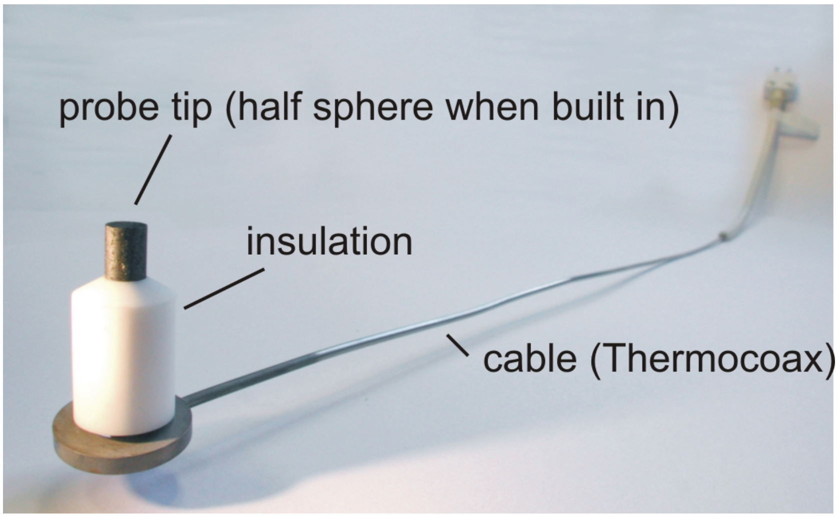

Fig. 3: *Langmuir probe for the DED tiles.*

Core Diagnostics

A variety of diagnostics is operated at TEXTOR in order to determine the properties of the hot plasma, especially now under the conditions imposed by the Dynamic Ergodic Divertor (DED). These include magnetic diagnostics to measure and control the position of the plasma, the plasma current and the internal structure of the magnetic fields, as well as measurements of the plasma radiation – ranging from the microwaves up to the x-rays. In addition, active diagnostics in the microwave and far infrared spectral range are applied in order to determine the plasma density by interferometry and to derive the density profile by reflection of microwaves at the cut-off density.

The radiation is measured integrally over the appropriate spectral range in order to determine the total emitted power by bolometry. Furthermore, it is recorded in broad bands in the x-ray region with energies above approximately 1 keV to determine the structure of the hot plasma in the core, and in narrower bands using instruments such as the SPRED VUV spectrometers and solid state detectors in order to measure the impurity content of the plasma. The plasma radiation is also studied by means of high resolution x-ray spectroscopy to determine the plasma parameters in the plasma core. Experience gained with these instruments at TEXTOR has been applied to the design and construction of diagnostics for the next generation of magnetic fusion machines, such as W7-X and ITER.

Many of the diagnostics dedicated to the plasma core are used not only for the characterisation of the plasma, but they are also incorporated into the online control system of TEXTOR. The most important ones are the magnetic and interferometric real time control systems for the vertical and horizontal plasma position as well as for the plasma density. Due to the installation of the DED, many of the diagnostics had to be modified and recommissioned in order to ensure a proper operation of TEXTOR.

The **magnetic systems** for the plasma position depend on the measurements of the magnetic fields outside the plasma column. The magnetic fields are determined from long-term integrated signals of magnetic loops. Due to the DED, both the positions of the magnetic pick-up coils, as well as the feedthroughs had to be changed. In addition, the level of electromagnetic interference significantly increases during operation of the DED, as its frequency range directly coincides with the frequencies of the signals to be recorded. The online control systems have been hardened to withstand this new quality of interference and they have been recalibrated. It has been demonstrated that reliable real time positioning of the plasma is obtained even under high electromagnetic interference levels.

Especially challenging was the reinstallation of the '**compensated magnetic loop**' to measure the plasma energy. In this device, the diamagnetism of the plasma is determined by comparing the magnetic flux in a loop enclosing the plasma with the flux in a loop outside the plasma. Due to the installation of the Dynamic Ergodic Divertor, the geometry of the compensated loop had to be modified and thus, its properties have changed considerably. Taking into account all the unavoidable effects such as misalignments and bendings of the loops due to temperature changes in TEXTOR, the signal can be corrected using data of the other magnetic field measurements. Now, the signal delivering the total plasma energy is available again.

A new set of **fast Mirnov-coils** has been designed and installed on TEXTOR. The coils are made of molybdenum wire and the windings are isolated by a high temperature spray ceramics. These pick-up coils are arranged as close to the plasma as possible. Two different kinds of coils have been mounted in TEXTOR: One stack of coils consists of two coils, one measuring the radial magnetic field component and the other one measures the poloidal field component.

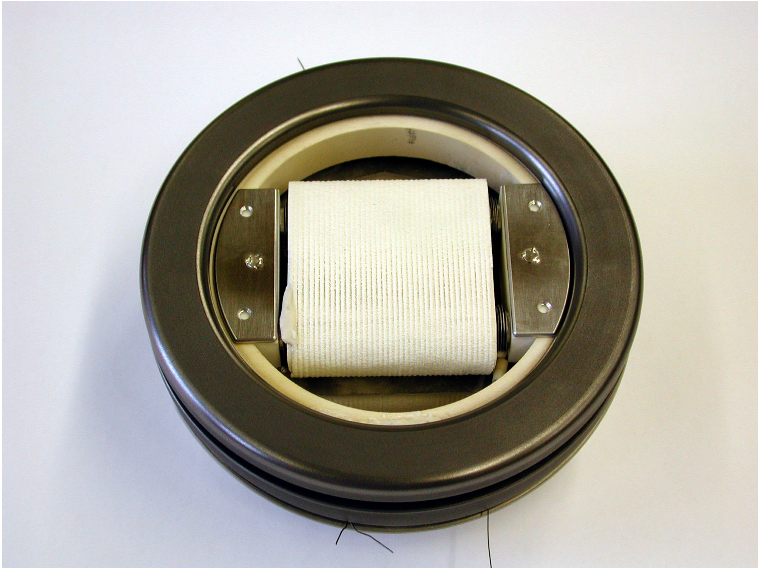

Fig. 4: *Pick up coil with a graphite limiter ring.*

One coil stack is located in front of the liner – close to the plasma – and another one is placed behind the liner. An array of eight poloidal coils is fixed at the top of the torus, serving for the toroidal mode number determination, while another array of coils is located in a poloidal cross-section in order to analyse the m-number of MHD instabilities. The coils facing to the plasma are shielded by a small carbon limiter. The highest sampling frequency at the moment is limited to 100 kHz and will be increased next year. Most coils have been sampled at a frequency of 25 kHz.

Fig. 5 shows the effect of different heating methods on the behaviour of the MHD-instabilities. In this figure, the influence of low-power NBI co-injection on the frequency of the 2/1 mode can be seen. The slowing down is in good agreement with a reversal of plasma rotation with co-injection, as has been analysed in the past. The spectrogram shows a broad-band turbulent feature during the phase with ECRH heating.

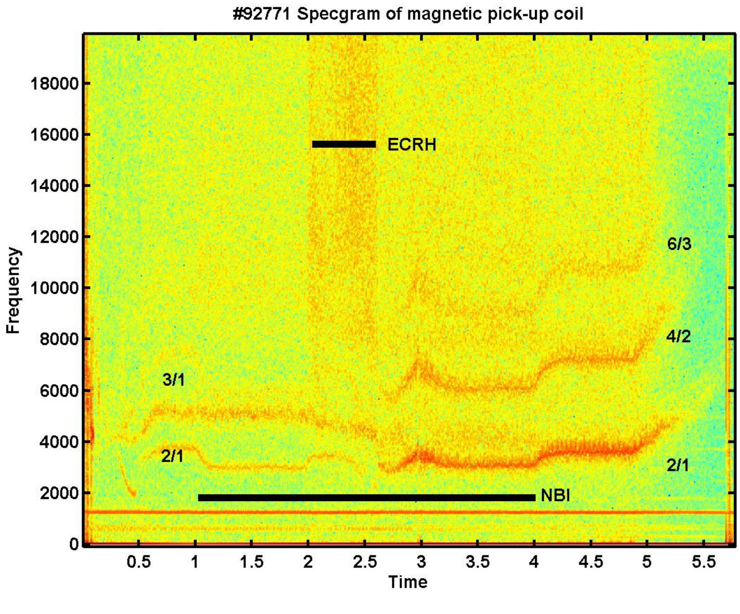

Fig. 5: *Spectrogram of a pick-up coil during a TEXTOR shot with NBI and ECRH heating.*

The new Mirnov coils complement the ability of the core diagnostics like ECE, interferometry, and SXR cameras to measure instabilities like sawteeth, sawtooth precursor and postcursor modes, and tearing modes.

The aim of the ongoing research is the analysis of the influence of external error fields induced by the DED on the MHD characteristics of the plasma, as well as detailed studies of the penetration and amplification of error fields.

For the **bolometer system** to determine the total radiated power from the plasma, a fully digital coupling between the analog amplifiers and the digital data acquisition system has been introduced. The noise level has been reduced, enabling measurements under the harsh conditions of the DED. The software codes to analyse the data have been rewritten for the new computer systems at TEXTOR. An example for the local emission of radiation is shown in Fig. 6. The image has been obtained from Radon transformed bolometer signals during a discharge with DED operation, showing a highly radiating spot in front of the DED.

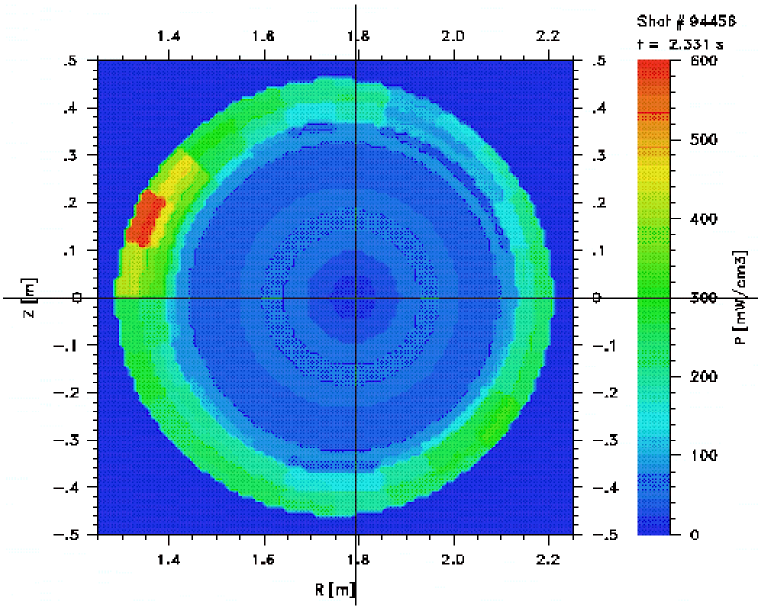

Fig. 6*: Radiation pattern of a TEXTOR discharge with DED operation. The DED coils are located on the left-hand side, where a highly radiating spot is formed.*

The joint experiment '**tangential x-ray camera',** which was planned and built in close cooperation with our Japanese collaborators from the **N**ational **I**nstitute of **F**usion **S**ciences (NIFS) and the **P**rinceton **P**lasma **P**hysics **L**aboratory (PPPL) in USA, has been reinstalled at TEXTOR. The major components such as the light guide with a large diameter of 100 mm, the image converter tube to compress the image to the size of the CCD detector and the fast camera system have been supplied by NIFS. Using a newly developed CCD camera, the framing rate could be increased up to about 10,000 frames per second. Impressive pictures of the modes within the plasma, especially the mode with number m=2/n=1 have been obtained and locking to the externally applied frequency of the DED has been detected. The analysis of the data is still going on. In the meantime, the system has been sent back to NIFS and has been reinstalled to the Large Helical Device (LHD) experiment.

The **poloidal x-ray camera system** has been used for a long time to determine the mode structure and the islands at magnetic surfaces with rational q in the plasma. It has been upgraded to higher time resolution in order to detect islands caused by the DED with a sufficiently high sampling frequency. The positions and the widths of the modes could be detected, both for the operation of the

DED with DC and AC current. It is now being equipped with new front end amplifiers to reduce noise and pickup of electromagnetic interference. A new data acquisition system – based on PXI modules – is currently being installed to provide a sampling rate of up to 200 kHz over the full discharge.

A prototype of the CO_2 **dispersion interferometer** for TEXTOR has been built at the Budker institute in Novosibirsk and has been tested at the gas dynamic trap (GDT). On TEXTOR, a further developed instrument will be installed in the second half of 2004.

Diagnostics FOM-Instituut voor Plasmafysica

In this field projects have been concluded that received preferential support by EURATOM under the special rules for equipment of smaller associations applied on preferentially supported larger devices of another association. Three systems were accepted in 1998 by EURATOM:

1. A double-pulse high-resolution Thomson scattering diagnostic;
2. An upgraded version of the ECE imaging diagnostics tried out at RTP;
3. A wavelength-selective ultra soft x-ray tomography (USXT) diagnostic.

The Thomson scattering system was already operational in 2000 and contributed significantly to the scientific output of the FOM-group at TEXTOR. The success was so convincing that a completely new project has been started in 2002 together with the German colleagues of IPP and Russian colleagues from the Ioffe Institute, St. Petersburg. The aim of the project is the development of a 10 kHz burst-mode operated Thomson scattering system. A new laser system has been developed that is able to generate three bursts of 50-75 pulses per plasma discharge. The repetition rate of the pulses within a burst is up to 10 kHz and the energy for each individual pulse is 10–15 J. The spectrometer has been equipped with fast CMOS cameras that can cope with the high repetition rate. The whole system has been set up in such a way that 120 points along the laser chord are sampled with a spatial resolution of 7.5 mm. The laser system has been installed at TEXTOR and successfully tested for one burst of pulses. First Thomson scattered light from TEXTOR has been observed with the new system in December 2003.

The ECE imaging system in its originally planned form has been successfully concluded and gave a lot of input to a PhD thesis that was defended in November 2003. The original ECE-I system monitored an array of 16 sample volumes that are aligned along a vertical chord. In 2003 the system was upgraded to a system featuring a two-dimensional coverage of the plasma. It is now possible to monitor the electron temperature profile and its fluctuations in a two-dimensional matrix of sample volumes (8 radial x 16 vertical). The spatial resolution of the system is approximately 1 cm in the poloidal plane and the time resolution is up to 1 MHz. The ECE-I system is fully integrated with a Microwave Imaging Reflectometer that monitors the density fluctuations at 16 positions along the cut-off surface. Both systems were installed and tested at the end of 2003. A short movie has been produced about the evolution of the electron temperature profile during a sawtooth in TEXTOR. The work in the field of microwave imaging is done in tight collaboration with physicists from UC Davis and Princeton, USA.

In 2003 the ultra soft x-ray tomography (USXT) system was almost completed. The system that has been procured by a consortium of the Dutch consultancy firm Phystex, the Ioffe Institute (St. Petersburg) and the Institute for Applied Physics (Nizhny Novgorod) and by the end of the year it was almost ready for installation onto TEXTOR. The system will deliver the 2-D emission distributions of several spectral impurity lines at the same time. The spectral window can be varied to detect lines in the wavelength range from 0.3 to 12.5 nm. The system will be used for the study of the penetration of impurities into the plasma in space and time.

Another exiting diagnostic that was installed in 2003 with normal EURATOM support is a 20 channel Motional Stark Effect (MSE) system to measure the evolution of the q-profile as a function of time. The system has been developed in close collaboration with Phystex and has come into operation by the end of the year. The first data that have been taken are quite promising and we are confident the system will play an important role in the transport physics programme of the FOM team at TEXTOR.

Diagnostics LPP – ERM / KMS

The diagnostic for the determination of Zeff from bremsstrahlung in the visible range has been upgraded. The detection system was changed from a tilting mirror with a photomultiplier (repetition time 150 ms) to a CCD camera with 21 viewing chords. In contrast to the previous system, the simultaneity of the detection of bremsstrahlung along all the 21 chords now allows Zeff to be determined also for transient phases. A few channels have been left available for future use with photomultipliers – in order to allow for a data acquisition with a higher time resolution than being possible with cameras.

From the line-integrated signal of a central chord a line-averaged Zeff is computed, presently every 100 ms (this can be reduced by a factor of two), using also density and temperature profiles from the HCN-interferometry and ECE diagnostics. The line-averaged Zeff is available online. The system also allows the Zeff profile to be derived, and work is being done to improve the accuracy of the profiles via statistical signal processing techniques.

A new diagnostic for the detection of C III and C V spectral lines has been installed. The system is now operational at TEXTOR. The brilliance of the two spectral lines is detected simultaneously along nine lines of sight, being located on the high field side of the tokamak. The repetition time for the 18 signals (9 for C III and 9 for C V) at present is 100 ms, but work is being done to increase the time resolution to about 1 ms. This diagnostic has been especially designed to evaluate the influence of the Dynamic Ergodic Divertor on the radiation and transport properties of the intrinsic carbon.

The electrical probe system has been upgraded to measure potential and density fluctuations with a bandwidth of 1 MHz. The system is built in such a way that various schemes are available to concomitantly measure fluctuations of the density, temperature and the plasma potential. In a first application long space correlation and zonal flows were measured using the existing rake probe. Furthermore, a new probe head to measure Reynolds stress has been designed and is presently under construction. Together with the new electronic set-up, questions on sources and sinks of rotation can now be tackled.

The detection of both slowing down and escaping alpha particles remains one of the crucial and most delicate issue in reactor grade plasmas. The lack of established techniques to measure these particles has been recognized as one of the diagnostic weaknesses of the tokamak community, requiring further R&D in the ITER perspective. At the moment no diagnostic is available to measure the alpha particle losses. We have continued our developments in this field. Our approach is mainly based on the activation technique. To obtain some preliminary confirmation of the technique's capability, we did test experiments on the JET tokamak during the C9 campaign. Here, the particle drift was opposite to the normal direction, and thus the particle fluxes collected should be particularly high.

To this end, the reciprocating probe shield cap has been suitably prepared and exposed to D-D plasmas using the vertical manipulator on top of the machine. The shield cap material is made of boron which is a suitable material for the subsequent activation reaction $^{10}B(p,\alpha)^{7}Be$. Protons escaping from the plasma with energies above about 1.5 MeV produce the element ^{7}Be, which is a radioisotope with a half-life of 53.3 days. Preliminary results from the JET C9 campaign are very promising. Gamma spectra taken after exposure during the whole campaign clearly show a line at 477 keV which is associated with the radioactive ^{7}Be decay. The preliminary signal analysis reveals that the ^{7}Be line intensity is found to be equal to the calculated intensity expected from classical losses of 3.024 MeV fusion protons within a factor of two.

For the development of position sensitive detectors for TEXTOR new measurements with nuclear track detectors have been performed in a collaboration with the Soltan Institute at Warsaw, Poland. Clear distinction is made between impact of protons and Tritium. The analysis of position dependence is in progress.