New diagnostics for physics studies on TEXTOR-94 (invited)

A. J. H. Donné, R. Jaspers, C. J. Barth, H. Bindslev, B. S. Q. Elzendoorn, J. C. van Gorkom, H. J. van der Meiden, T. Oyevaar, M. J. van de Pol, V. S. Udintsev, and H. L. M. Widdershoven
FOM-Instituut voor Plasmafysica Rijnhuizen, Associatie EURATOM-FOM, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands[a)]

W. Biel, K. H. Finken, A. Krämer-Flecken, A. Kreter, H. Oosterbeek, B. Schweer, and B. Unterberg
Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, D-52425 Jülich, Germany[a)]

B. H. Deng, C. W. Domier, and N. C. Luhmann, Jr.
University of California at Davis, 228 Walker Hall, Davis, California 95616

E. Mazzucato, T. Munsat, and H. Park
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543

L. Porte and P. Woskov
Plasma Science and Fusion Center, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

L. Shmaenok
Phystex, Dukatenburg 30b, 3437 AC Nieuwegein, The Netherlands

(Presented on 21 June 2000)

Recently the Dutch, Belgian, and North-Rhine Westphalian Fusion Institutes have consolidated their fusion research on the medium-sized tokamak TEXTOR-94 in the so-called Trilateral Euregio Cluster. To aid the new physics program of TEC, a large number of advanced core diagnostics has recently been implemented. In this article we will discuss the reasoning that has led to the choices of the various diagnostics. Furthermore, we will briefly describe the new diagnostics systems.
 [DOI: 10.1063/1.1321740]

I. INTRODUCTION

In 1996 the three fusion research centers in The Netherlands, Belgium, and the German land North-Rhine Westphalia decided to combine their fusion research in the so-called Trilateral Euregio Cluster (TEC) and to concentrate the experimental work on the tokamak TEXTOR-94 (Toroidal Experiment for Technology Oriented Research).

The central research theme for the joint scientific program of TEC was chosen to be the development of a coherent concept for energy- and particle transport and exhaust and their control in fusion reactors. The basic idea behind the program is that plasma confinement cannot be understood unless the plasma is considered as a whole, including boundaries. In other words: the control of a burning reactor plasma necessarily encompasses active and interlinked control of the different plasma zones (core, edge, and wall).

The key elements of the TEC research program are:

(1) To clarify the physics mechanisms determining the fluxes in the various confinement zones, with emphasis on the effect of turbulence and self-organized small scale structures;
(2) to unravel the interdependencies between the various zones;
(3) to develop adequate diagnostics and tools to control the fluxes in every zone; and
(4) to develop appropriate theoretical models for this coherent approach.

This article will especially focus on the plasma core diagnostics that have been recently (or will be soon) installed on TEXTOR-94. In Sec. II a brief description is given of the TEXTOR-94 tokamak along with a concise overview of the main experimental research themes. In Secs. III–VI the new diagnostics are discussed, and illustrated with a limited number of first results. Because many of the new diagnostics are also described elsewhere in these Proceedings we have deliberately chosen to not describe the systems in too much detail, but more to concentrate on how the various diagnostics will contribute to the TEC research program.

II. TEXTOR-94

TEXTOR-94 is a medium-sized limiter tokamak ($R/a = 1.75/0.46$ m, $B_T < 2.9$ T, $I_p < 800$ kA) with circular plasma shape.[1] The machine is equipped with two Neutral Beam Injectors (co- and counterinjection, 2 MW each) as well as with two antennas (of 2.2 MW each) for ion cyclotron resonance heating (ICRH). Recently, a 400 kW, 200 ms, 110 GHz gyrotron has been installed for electron cyclotron resonance heating (ECRH) and current drive (ECCD). A second 800 kW, 3 s, 140 GHz gyrotron will follow in the course of 2001. From March 2001 onwards, TEXTOR-94 will be shutdown for about a year to install the so-called dynamic ergodic divertor (DED).[2] The DED consists of a set of coils wound around the inner part of the vacuum vessel and can be used to induce rotating ergodic magnetic field structures at

[a)]Partners in the Trilateral Euregio Cluster.

the edge of the plasma, as an additional tool to control particle and energy exhaust in the outer plasma layers.

Until the start of the TEC collaboration, the main emphasis of the TEXTOR-94 experimental program was heavily biased towards plasma wall interaction and plasma edge physics. For this purpose TEXTOR-94 is equipped with a very comprehensive set of plasma edge diagnostics. Only a small part of the original TEXTOR-94 work was devoted to study transport processes in the plasma core. For this reason the number of core diagnostics was limited, and many of them had a modest spatial and temporal resolution.

To aid the recently established TEC research program, it is necessary to implement a number of new core diagnostics featuring good spatial and temporal resolution. To be able to make an assessment of which diagnostics are needed for the future research program, it is good to first emphasize which are the most important research directions:

An important program on TEXTOR-94 is the so-called radiative improved (RI) mode.[3] In this operational mode, plasmas with a very high confinement ($f_{\mathrm{H93}} \approx 1$), high beta ($\beta_n \approx 2, \beta_p \approx 1.5$), and with densities close to or slightly above the Greenwald density are sustained for a long time (up to 160 energy confinement times). Because of the high densities, the standard method of diagnosing electron temperature, ECE at the second harmonic, does not work anymore because the emission is in cutoff. Also the interferometer that is used to measure the density has some problems with refraction and also during strong density transients with fringe jumps. Although third harmonic ECE and polarimetry can be used to measure the temperature and density indirectly, it is clear that a diagnostic like Thomson scattering which does not suffer from these problems is required. The neutral particle analyzer (NPA) used at TEXTOR cannot yield a detailed ion temperature profile, apart from the fact that the analysis of the spectra is tedious. Active charge exchange recombination spectroscopy (CXRS) using the neutral heating beam has a coarse spatial resolution, and can only be applied during neutral beam injection (NBI). Therefore, a new CXRS system, featuring a diagnostic neutral beam has recently been implemented.

An issue that is related to the RI mode is to understand the detailed transport behavior of impurities puffed into the plasma. The standard method of diagnosing the impurities is via spectroscopy. At TEXTOR many spectrometers are in use and although many give important and interesting information, it is difficult to make a quantitative assessment of how the impurities are transported into the plasma. For this reason a five-camera, 500-channel ultrasoft x-ray diagnostic featuring multilayer mirrors is being designed and tested. Furthermore, a two-channel survey poor resolution extended domain (SPRED) spectrometer has recently come into operation.

Another theme that is related to the RI mode, is the magneto-hydrodynamic (MHD) research looking into classical and neoclassical tearing modes (NTMs). Although the electron temperature perturbations due to MHD and NTMs can be measured with a number of ECE spectrometers featuring high temporal and spatial resolution, the spectrometers only cover limited parts of the plasma (around the rational q surfaces for standard field settings). To have a better coverage, the number of ECE diagnostics is being extended by a 16-channel tunable frequency radiometer as well as with an ECE-imaging system. To visualize the density perturbations due to MHD and NTMs a ten-channel pulsed radar system is being employed.

Transport physics will gain in importance in TEXTOR because the team from FOM (FOM is the Dutch acronym for Foundation for Fundamental Research on Matter) will bring its specific expertise in the field of perturbative transport studies,[4] transport barriers,[5] and plasma filamentation.[6] To support this program ultrahigh resolution diagnostics like Thomson scattering and ECE imaging are needed. Furthermore, there is a need to diagnose the plasma turbulence in the core. This supports the implementation of correlation ECE and reflectometry. Important for the transport physics program is to have good knowledge of the safety factor profile with a spatial resolution that is better than that of the nine-channel polarimeter which is now routinely used to measure the q profile. For this reason a prototype motional Stark effect (MSE) system with four channels is being extended to a total of 30 measuring chords.

One of the newly installed diagnostics is fast ion collective Thomson scattering. The aim of this diagnostic is to study the population of fast ions, generated by means of ion cyclotron resonance heating and serve as a prototype test for future alpha-particle diagnostics on burning plasmas.

In the following sections the recently implemented diagnostics as well as the measuring equipment that will soon be installed on TEXTOR will be described. The various diagnostics are grouped according to their technique: laser diagnostics, microwave diagnostics, particle diagnostics, and spectroscopy. For those diagnostics that are described elsewhere in these Proceedings (basically all except for CXRS and the SPRED), we will only give a single reference to the corresponding contributions rather than giving an exhaustive list of references. For the same reason we have deliberately chosen to only show figures that are not presented elsewhere in these Proceedings.

III. LASER DIAGNOSTICS

The high-resolution multipoint Thomson scattering was first on the ''shopping list'' of the TEC team, since it is basic to most of the physics programs, as was indicated in Sec. II.

For this reason, a double-pulse multipoint Thomson scattering system has been installed to measure the electron temperature and density profile along a full vertical chord through the plasma.[7] A 25 J ruby laser is used as the source. Under most circumstances the laser is operated in the double-pulse mode. The time separation between the two 10–12 J laser pulses can be varied from 0 to 500 μs, albeit that the detection system cannot distinguish pulses that are separated by less than about 50 μs. The laser beam enters and exits the plasma through about 3 m long vacuum tubes, with baffles to reduce stray light from the windows. The laser chord is located 90 mm toward the low-field side (LFS)

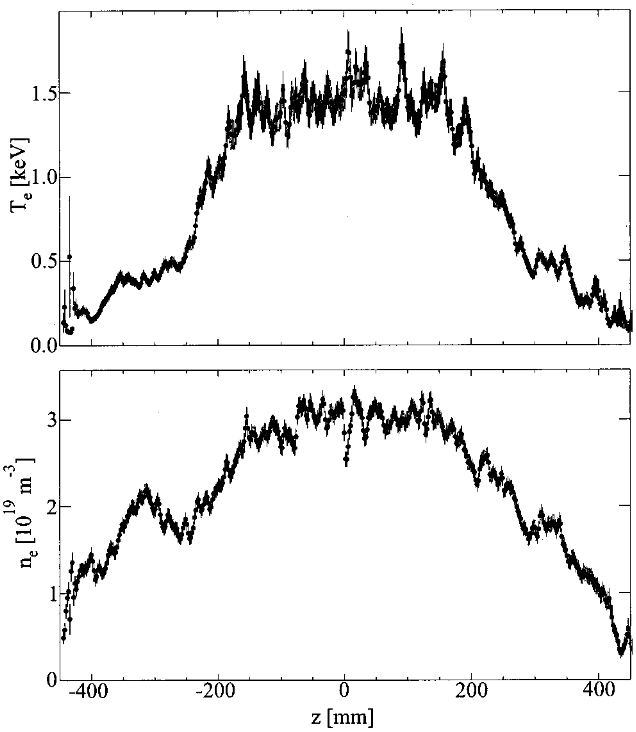

FIG. 1. Electron temperature and density profiles measured by Thomson scattering in a discharge exhibiting $m=2$ islands. Note the pronounced density peaking inside the island.

with respect to the geometric machine axis. This has been done to ensure that the laser beam hits the plasma center, which experiences a Shafranov shift of 50–120 mm, depending on the plasma parameters. The laser chord is imaged by means of a triplet lens onto a fiber-optic dissector. Fibers guide the scattered light to a Littrow spectrometer, which is equipped with two separate CCD cameras to record the two laser pulses. The full vertical chord of 900 mm length is resolved into 115 spatial positions of 8 mm each. The spectrum at each position is resolved into 50 wavelength channels. The statistical accuracy in T_e is typically 3% at $n_e = 3.5\times 10^{19}\,\mathrm{m}^{-3}$; the accuracy in n_e at the same density is typically 2%.

During its few months of operation, the Thomson scattering diagnostic has already given a wealth of new physics information.[7] Electron temperature and density profiles have been measured in a large range of different experiments. High-density RI-mode profiles turned out to be relatively broad and smooth. In low-density ECRH discharges, a strong filamentation of the plasma core has been observed, with profiles very reminiscent to the ones observed before on the RTP tokamak.[5] At somewhat higher densities, very clear MHD islands have been seen with a density peaking inside the islands (see Fig. 1). This confirms earlier work with a prototype four-channel pulsed radar reflectometer, which indicated a similar density peaking.[8]

IV. MICROWAVE DIAGNOSTICS

A. Electron cyclotron emission diagnostics

TEXTOR is already equipped with a large range of ECE diagnostics. First, there is an 11-channel heterodyne ECE radiometer,[9] observing the second harmonic *X*-mode radiation in the frequency range 105–145 GHz, with a modest time resolution of 50 μs. This system is calibrated absolutely by means of a hot/cold source in the vacuum vessel approximately once a year. All other systems are cross calibrated to the 11-channel system. Second, for the purpose of MHD studies, TEXTOR is equipped with three six-channel ECE spectrometers.[10] These spectrometers have a high spatial resolution (~10 mm), but cover only limited regions inside the plasma. For standard plasma conditions these regions are located around the rational q surfaces. The temporal resolution of the channels is up to 2 MHz. Finally, TEXTOR has a four-channel third harmonic ECE system to give a very rough temperature profile during RI mode discharges.[11]

The set of ECE diagnostics at TEXTOR has recently been extended by three additional systems for reasons that will be explained below. The total number of ECE channels has been increased from 33 to 69.

1. 16-channel tunable frequency ECE radiometry

Although not of immediate value for the high-performance RI-mode plasmas in TEXTOR, an extension of the ECE diagnostics was needed for the MHD research and the transport physics research, that is usually done at lower densities. One drawback of the present ECE system is that the profile system is rather slow, whereas the faster system of ECE spectrometers only covers relatively small parts of the plasma. For nonstandard plasma conditions it is possible that the observation regions are not at the optimum position.

For this reason a 16-channel tunable frequency ECE radiometer has been recently installed.[12] The radiometer is of the double heterodyne type, with four front ends that convert the radiation to an IF bandwidth of 6–18 GHz. The local oscillators of the second downconversion step are frequency tunable, and are shared by the different front ends. In other words, the frequencies of channels 1, 5, 9, and 13 are coupled, as are 2, 6, 10, and 14, etc. The 16-channel tunable frequency radiometer has been recently installed at exactly the same toroidal cross section as the three ECE spectrometers so basically this implies that at a single toroidal location we now have an ECE system with 3×6 fixed frequency channels and 4×4 tunable frequency channels. This opens many different possibilities. First, the tunable channels can be set for an optimum coverage of the full plasma (98–146 GHz), such that electron temperature profiles can be measured with a good spatial resolution and coverage. Second, for research programs in which the interesting phenomena are expected to occur in certain regions of the plasma (e.g., MHD islands, transport barriers, etc.) the channels can be tuned to have a high density of channels exactly in those regions. Third, because the distance between the various ECE channels can be changed it is possible to measure electron temperature fluctuations and correlation lengths by means of correlation ECE.

The 16-channel system was installed very shortly before the HTPD 2000 meeting in Tucson, and at the time of writing this article, results were not yet available.

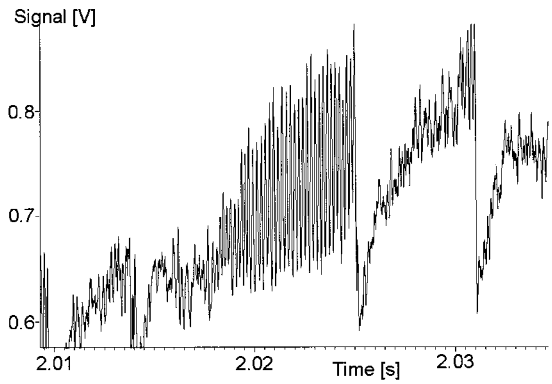

FIG. 2. Time trace of a sawtooth precursor measured with the central channel of the ECE imaging system in a low density ECR heated discharge. During the strong precursor activity, the temperature profile measured with Thomson scattering shows a pronounced filamentation. A closer look to the precursors seems to indicate that it is made up of multiple structures that are rotating in the central part of the plasma with slightly different velocities. Analysis is underway.

2. Electron cyclotron emission imaging

The argument for the ECE imaging system is in gross lines similar to that of the 16-channel tunable frequency system. However, in the work on RTP, where an ECE imaging system was used next to a 20-channel double heterodyne system, it was demonstrated that the ECE imaging has a number of additional benefits. The most important one is the fact that the default position of the vertical chord which is viewed by ECE imaging is directly on top of that of Thomson scattering. Since this is also the case in TEXTOR-94, this implies that one has a direct cross calibration to the absolutely calibrated Thomson profile for every discharge. The provisional ECE imaging system that has recently been installed at TEXTOR-94, in collaboration with UC Davis, features 16 measuring channels.[13] The vertical spacing between the channels is about 1.3 cm, and part of the plasma that is covered by the diagnostic is a vertical chord ranging from -90 to $+90$ mm with respect to the equatorial plane. Thanks to large-sized focusing lenses the spatial resolution is (in all directions) typically 1.3 cm. In other words, the spatial resolution is almost as good as that of Thomson scattering (at least in the vertical direction). The combination Thomson scattering/ECE imaging is especially powerful for the observation of the dynamics of small-scaled structures in the plasma (e.g., filaments). Thomson scattering can make one or two snapshots of these features in a discharge, whereas ECE imaging can follow their evolution with high time resolution. Recently, good observations have been made of filaments with Thomson scattering and ECE imaging (Fig. 2). The filaments seem to show up in ECE imaging as very large precursors to sawteeth. However, in case one looks at the detailed time behavior of the precursors, it becomes clear that they often do not have a nice harmonic behavior (not clearly visible in Fig. 2). Indications are that they seem to be caused by a number of distinct spatial structures moving through the plasma with different frequencies. The comparison between the Thomson scattering results and ECE imaging will give important information to verify/falsify present filamentation models.[6,14]

Apart from the direct comparison with Thomson scattering, ECE imaging has the additional feature that the vertical observation chord can be scanned radially through the plasma. The scanning range of the provisional system is 114–120 GHz (corresponding to a 10 cm wide region inside the plasma; the position of which depends on the value of B_T). The future ECE imaging system, to be installed after the DED shutdown, should be able to scan over the full plasma radius (105–145 GHz). ECE imaging can also be used to measure electron temperature fluctuations and correlation lengths as was evidenced by the work on TEXT-U and RTP.[13]

Finally, by having three major ECE systems at almost 120 degrees toroidally from each other (the 11-channel system, the 3×6 channel spectrometer plus 16-channel frequency tunable radiometer, and the ECE imaging system) it is possible to deduce toroidal mode numbers and also to study locked modes.[15]

3. Four channel second/third harmonic frequency ECE radiometry

Recently, the level of magnetic turbulence in TEXTOR was estimated from detailed observations of the synchrotron emission of runaway electrons with typical energies of 20–30 MeV.[16,17] The runaway electrons are collisionless and are therefore ideal tools to study phenomena like collisionless diffusion. One aspect that is lacking in the study of runaway electrons is the dynamic behavior of low-energy suprathermal populations. For this purpose the third harmonic ECE system at TEXTOR has been extended with four second harmonic channels that view through the same antenna but at a frequency of exactly 2/3 that of the third harmonic channels.[12] In most cases the plasma is optically thick for the second harmonic X mode. This measurement therefore reveals the electron temperature, to be corrected for possible downshifted third harmonic emission. The optically thin third harmonic measurement depends on the electron temperature (measured at the same location by the second harmonic), the electron density (estimated from a fit to the profile measured by a nine channel interferometer), the spectrally dependent reflection coefficient of the wall at the high-field side (HFS), and the presence of suprathermal electrons giving downshifted ECE emission. The combined second/third harmonic system offers the unique possibility to measure the reflection coefficient in medium- to high-density ohmic plasmas that have no suprathermal electrons (which can be verified by measuring at ECE frequencies that correspond to locations outside the plasma). First observations of nonthermal electrons have been made in the mean time and correspond well with simulations done with the so-called NOTEC code.[12]

B. Reflectometry

1. Ten channel pulsed radar reflectometry

The electron density profile in TEXTOR is measured by a nine-channel FIR interferometer.[18] Because of the line-integrated nature of the measurements, the interferometer is not well suited for measuring local perturbations in the plasma core. At the plasma edge other diagnostics can be employed, like a thermal He beam, probes, etc. To make it possible to study perturbations to the density profile which are due to neoclassical tearing modes (NTMs) and MHD, an already available prototype four-channel pulsed radar reflectometer has been extended.

The pulsed radar reflectometer is used to monitor the electron density profile evolution as well as coherent and broadband density fluctuations. The system is based on a direct measurement of the flight time of short ($\sim$1 ns) microwave pulses which are reflected off the plasma, and which contain information on the position of the reflecting density layer.[19] Because of the very short (less than 10 ns) time the pulse travels through the plasma, fluctuations can be regarded as frozen. The technique also allows for a high pulse repetition rate, and thus a high time resolution to study fast fluctuations. This is one of the reasons for using the pulsed radar technique on TEXTOR, together with the possibility of combining profile and fluctuation measurements in a single diagnostic.

The system consists of ten fixed-frequency microwave oscillators launching from the LFS midplane in the O-mode polarization in the frequency range 18–57 GHz [corresponding to $n_e = (0.4-4) \times 10^{19}\,\mathrm{m}^{-3}$], which makes it possible to measure ten points over the LFS density profile. In order to attain the required 1 ns pulse width, each of the sources is equipped with a fast varactor diode switch. The time of flight of the pulses can only be measured with sufficient accuracy at the desired high pulse repetition rate by a fast digital counter system. This custom-built system clocks the time delays with an accuracy of 74 ps into a 64-Mb-memory bank, allowing a 3-s-time window at the maximum time resolution, or up to 12 s at lower time resolution. The total pulse repetition rate of 20 MHz can be divided over the channels in different ways, e.g., into a ten-channel profile measurement at 2 MHz, a two-channel fluctuation measurement at 10 MHz, etc.

The accuracy of 74 ps in time-of-flight corresponds to 11 mm radial accuracy when reflecting in vacuum (in plasmas, due to the lower group velocity of the pulse, the accuracy will typically be higher). The accuracy can be further improved by averaging subsequent pulses: the average over four pulses gives an accuracy of 5 mm in vacuum. Note that four subsequent profile measurements are obtained within 2 μs, which is still faster than most fluctuations.

The diagnostic has already been demonstrated to be well suited for detailed studies of local macroscopic perturbations of the density profile. It has provided direct evidence of density peaking inside magnetic islands.[19] Future studies of broadband density fluctuations in different tokamak regimes will be aided much by the planned addition of two tunable sources for measuring radial correlation lengths of the fluctuations.

2. Microwave imaging reflectometry

Very important for obtaining a better understanding of anomalous transport in tokamak plasma is to have good measurements of the microscopic fluctuations in the various plasma parameters. A widely used diagnostic for measuring density fluctuations in magnetically confined plasma is microwave reflectometry. Although reflectometry has certainly enhanced our qualitative understanding of density fluctuations, it is impossible with the present systems to make a quantitative analysis of the measured data. The basic difficulty stems from the fact that present reflectometric diagnostics are all set up as 1D instruments, whereas the plasma fluctuation spectrum is intrinsically 3D.[20] When the plasma permittivity fluctuates perpendicularly to the propagation direction of the probing wave, the spectral components of the backward field will propagate along different directions, resulting in a very complicated interference pattern on the detector plane. From this it is very difficult to extract quantitative information on the density fluctuations.

An important step forward is the microwave imaging reflectometer (MIR). A prototype of this instrument, being developed in collaboration with Princeton and UC Davis, will be tested in the summer of 2000. In this system, waves reflected from a large portion of the plasma cutoff layer (in the poloidal direction) are collected by a wide aperture antenna and imaged onto a detector array, in a way that is reminiscent to ECE imaging. To be able to study a large portion of the plasma cutoff layer the probing wave should also have a large physical size. At TEXTOR-94, a system of two large-sized polyethylene lenses is used to ensure that the rays impinge perpendicularly onto the cutoff surface. The reflected waves are separated from the incoming beam by a beam splitter and imaged onto a detector array of a similar type as that used for ECE imaging. The prototype instrument at TEXTOR will operate at 85 GHz X mode and will be made by using as much as possible, available components from the ECE imaging system. After successful demonstration of the MIR this summer, the next step will be a combined ECE-I/MIR system that can simultaneously measure the electron temperature and density fluctuations in a poloidal plasma cross section. The design goal is to have first operation of this instrument by the end of 2001.

C. Fast ion collective Thomson scattering

The diagnostics that have been discussed are aimed at studying the detailed evolution of the electron temperature and density profile. However, to obtain a coherent image of the plasma confinement it is necessary to also diagnose the parameters of the various ion populations. One particular group of ions that is very difficult to diagnose with a good spatial and temporal resolution, is the population of fast ions. In future burning reactors these ions are basically the products of the fusion reaction. For this reason it is very important to develop adequate diagnostic tools to observe these ions on present confinement devices. In medium-sized tokamaks, like TEXTOR, the fast ions can be generated by auxiliary heating, in particular by ICRH.

Apart from the general interest in the development of fast ion diagnostics for the future generation of fusion devices, it is also important to have a better understanding of the fast ion dynamics, to verify/falsify our theoretical models on fast ion diffusion, to see whether fast ions are expelled from the plasma core by sawtooth instabilities, etc. Also specific issues of ICRH physics need observations to test the existing models.

To diagnose the confined fast ions in TEXTOR a fast ion collective Thomson scattering (CTS) system has been recently installed, in collaboration with MIT, and is presently in the commissioning phase.[21] The system is based on measuring the scattering of radiation from a 110 GHz, 400 kW, 200 ms gyrotron.

Currently the diagnostic is set up to measure the 1D distribution of ion velocity components perpendicular to the magnetic field. With a planned upgrade this capability will be extended to two simultaneous measurements of 1D distributions along different directions given by the wave vectors of resolved fluctuations associated with the two separate receivers. These directions are variable, permitting for instance, simultaneous measurements of the parallel and perpendicular velocity distributions.

The location of the scattering volume can be changed between plasma shots and placed almost everywhere poloidally. Currently the resolution in major radius is approximately 10 cm. This will improve to 5 cm with the upgrade.

In the inferred fast ion distribution there is naturally a tradeoff between confidence, velocity space resolution, and temporal resolution. Typically ten measurements can be acquired per discharge, with a temporal resolution of 20 ms.

The fast ion CTS is approaching the end of the commissioning phase. The various components (gyrotron, launcher, and receiver antennas as well as the receiver system) are all working well. Initially a high level of ECE background emission was observed, but this can be suppressed considerably by avoiding gas feeding during the CTS. Preliminary experiments suggest the presence of a fast ion scattering signal. Analysis of these experiments is presently underway.

V. PARTICLE DIAGNOSTICS

A. Charge exchange recombination spectroscopy using DNB

The CXRS system that is presently employed at TEXTOR-94, utilizes the neutral heating beams.[22] This system has two major drawbacks: first, the spatial resolution is rather coarse, and second, it can only be applied during neutral beam heated discharges. To circumvent these disadvantages a diagnostic hydrogen beam has recently been installed at the tokamak TEXTOR-94.[23] The Russian diagnostic injector (RUDI) is based on a rf-discharge ion source and provides an equivalent neutral current of 1 A with an extracting voltage of 20–50 kV. Together with a small angle divergence of $\pm 0.6°$ it leads, on the one hand, to a beam current density for sufficiently high charge-exchange signals; on the other hand, heating power and plasma dilution are negligible, so that measurements under all discharge conditions are possible. A RUDI pulse duration of currently up to 4 s enables measurements of ion temperature and impurity densities during almost the whole TEXTOR discharge. An overview on the beam parameters is given in Table I.

The observation system covers the whole beam path in the TEXTOR plasma. Three windows are available for the high field side, central, and edge plasma observation. The two latter ports currently used provide the observation from the edge to the center with a radial resolution from 15 mm at the edge to about 50 mm in the center limited by the beam width.

TABLE I. Characteristics of the diagnostic neutral beam injector RUDI.

Beam energy	50 keV
Ion/neutral beam current	1.7/1 A
Operated pulse length	4 s (modulated)
Modulation frequency	500 Hz
Max. pulse length	10 s
rf power to source plasma at 4.5 MHz	2.3 kW
Ion species mix (H^+:H_2^+:H_3^+)	50:20:30
1/*e* beam width at 2.2/4.1 m	40/80 mm
Neutral beam divergence	∀ 0.5°
Max. neutral beam current density at 2.2/4.1 m distance	50 (measured)/15 mA/cm^2 (calculated)
Gas flow rate into source	2 mbl/s

Ion temperature measurements are routinely done using CXRS at the carbon line CVI at 529.0 nm.[22] A typical ion temperature profile for an ohmic discharge is shown in Fig. 3. The ratio of active and passive components of CX signal can vary between 1:2 in case of ohmic discharges with moderated plasma density and 1:10 in high density discharges with additional heating. The beam modulation allows an easy separation of the active component from passive background. Because the beam is oriented perpendicular to the toroidal field, it cannot be used for measurements of the toroidal rotation. For this one still needs CXRS employing the neutral heating beams at low power (such that they do not influence the rotation). For the same reason the DNB is not of any use for the motional Stark effect diagnostic.

B. Motional Stark effect

The current density (or safety factor) profile in TEXTOR is measured with a nine-channel polarimeter.[18] Although the spatial coverage of this device is reasonably suited for MHD studies, it is desirable to have a much better spatial coverage of the measured current density profile if it comes to a quantitative analysis of transport barriers and plasma

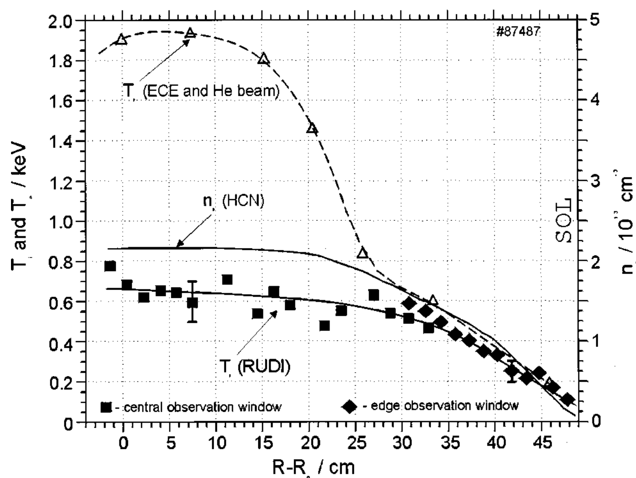

FIG. 3. Ion temperature profile measure by active CXRS for a 400 kA ohmic TEXTOR discharge. The electron temperature and density are shown for comparison.

filamentation. For this reason a prototype four-channel motional Stark effect (MSE) diagnostic is being drastically improved and extended to 30 measuring channels.[24] Most of the existing MSE setups use a narrow band interference filter to select one of the Stark lines and determine the polarization by using two crossed photoelastic modulators (PEMs), disregarding any spectral information. The new MSE system for TEXTOR, exploits both the spectral information, as well as the polarization.

The advantages of exploiting the full spectral information are obvious: (i) the system is insensitive to variations in beam velocity or magnetic field; (ii) the Doppler shift is measured as well, allowing to determine the observation volume directly from the spectrum; (iii) the polarization is measured at several lines simultaneously, increasing the accuracy of the deduced direction of the magnetic field; (iv) the Stark splitting is obtained allowing to compute the magnitude of the magnetic field and finally; (v) if in addition to motional Stark electric field a radial electric field is present in the plasma this can, albeit with limited accuracy, be determined as well by comparing the polarization direction of two different energy components of the neutral beam.

The new MSE setup is optimized for good spatial resolution. It consists of 30 radial channels (divided over five modules) covering the plasma from the center to the edge, with a radial variation of less than 5% over the full profile. This is accomplished by inserting all the optical components, including the polarization optics, inside the vessel looking towards the beam at different angles for different channels. Polarized light is transferred by means of fiber optics to a Littrow spectrometer outside the vacuum vessel. The 2D CCD camera in the Littrow spectrometer limits the time resolution to 50 ms. Therefore, a provision is also made to couple the optical fibers to a narrow band interference filter followed by a linear array. This increases the time resolution to less than 1 ms, at the cost of losing the spectral information.

VI. SPECTROSCOPIC DIAGNOSTICS

A. SPRED spectrometry

In the RI mode, impurities (usually Ne, Ar, Si) are deliberately injected into the tokamak to create a radiating mantle. Also in many of the plasma wall interaction studies impurities are introduced into the plasma edge by means of laser ablation, gas puffing, and micropellets. Although TEXTOR is equipped with a large range of spectrometers it was necessary to extend the diagnostics with a new VUV/XUV overview spectrometer of the double survey poor resolution extended domain[25] (SPRED) type. The system has been installed at a port near the horizontal midplane of TEXTOR-94 in order to study the relative concentrations and the transport behavior of low- and medium-Z plasma impurities from helium ($Z=2$) to copper ($Z=29$) in the plasma core. The spectrometer chamber contains two complete spectrometer branches. Each of them consists of an entrance slit, a toroidally shaped diffraction grating illuminated under about 20° in near grazing incidence geometry, and a plane open MCP detector (40 mm diameter) with a fast P46 phosphor screen

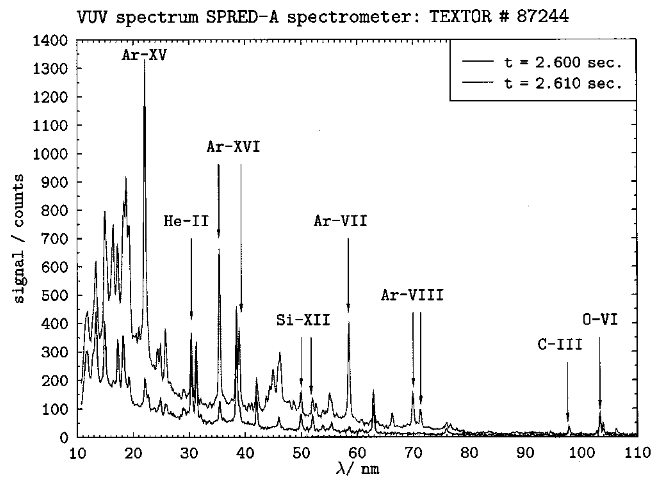

FIG. 4. VUV spectra (SPRED spectrometer channel A) of an argon puffing experiment in a TEXTOR L-mode discharge.

to convert the VUV photons to visible light. Spectrometer channel ''A'' uses a Pt coated diffraction grating with 450 grooves per mm, thus covering the entire wavelength range from 11 to 114 nm with a wavelength resolution of 0.3 nm full width at half maximum (FWHM), which is mainly determined by the detector. The second spectrometer channel ''B'' further expands the range 10–32 nm with 0.08 nm resolution, using an Au coated grating with a groove density of 2105/mm. In order to record the spectra with high frame rate (1000 full spectra per second), fast camera heads have been developed which are based on commercially available linear arrays (1024 pixels, each 2.5 mm high and 0.025 mm wide) and a fast switching integrator and amplifier circuit. The geometrical size of the spectra is adapted to the linear arrays by means of a coherent fiber taper (reducing the image from 40 mm down to 25 mm diameter), while the light intensity of the spectra is adapted to the full charge capacity of the arrays using an external plane light amplifier (''diode'' type, amplification factor 10–20). The data acquisition and data evaluation are based on a standard PC system with an analog–digital converter card, which picks up 1000 full spectra per second for each spectrometer channel during the whole TEXTOR discharge (up to 10 s). The total camera head and data acquisition system allows for measuring spectra with a 10 bit dynamical range at 1 ms integration time.

Two examples of VUV spectra (channel A) of a TEXTOR discharge are displayed in Fig. 4. The spectra show the time evolution of lines from several different ionization stages of argon after a short (2 ms) argon gas puff at $t=2.6$ s into a neutral beam heated (L mode) discharge. Argon lines from Mg-, Na-, Be-, and Li-like ions can be clearly identified, while some other spectral line groups around 15 and 45 nm are difficult to separate and to identify due to the limited resolution of the instrument. The SPRED-B spectrum (not shown here) contains among others the signals from ''intrinsic'' impurities, like the lines from Be-like ions of different stainless steel components as well as lines from low-Z materials like helium, carbon, and oxygen.

B. Ultrasoft x-ray tomography

Although the measurements of the SPRED spectrometer are line integrated, it is possible to derive the localized impurity emission in the plasma core. This needs some modeling and proper knowledge of the electron temperature and density distributions in the plasmas. To make it possible to directly measure the 2D impurity emission in the plasma core, a five-camera ultrasoft x-ray tomography system has been designed and built by Phystex. The first three of the miniature pinhole cameras have been recently installed onto TEXTOR and the first data have already been collected.[26] Each camera features a total of five multilayer mirrors (MLM) on a rail. The MLMs have a graded coating to correct for the varying angle of incidence over the image. The MLMs create ultrasoft x-ray images of the plasma in selected spectral intervals (depending on which MLM is used) on a phosphor, which simultaneously acts as a vacuum break. Light from the phosphor is guided by fiber optics to electron bombarded CCD tubes. Each camera resolves a poloidal cross section of the plasma in at maximum 100 separate viewing chords of 10 mm width. The highest temporal resolution that can be achieved by this system is 1 ms in burst mode or 10 ms in continuous mode.

VII. CONCLUSION

A number of advanced core plasma diagnostics has been recently installed onto the TEXTOR tokamak. Many plasma parameters can now be measured with good spatial and temporal resolution as well as with high accuracy. It is expected that the diagnostics will deliver the input to many plasma physics publications. Although the installation of all systems is not yet complete and further upgrades, to be installed in the years 2000 and 2001 are foreseen, there are still a number of plasma parameters that are not yet well diagnosed. Magnetic fluctuations in the plasma core are not diagnosed yet, even though these might be important for the understanding of (electron) transport barriers and filaments. A diagnostic that is presently being considered is crossed-beam cross polarization scattering employing imaging techniques to be able to measure a large part of the k-spectrum simultaneously.[27] The radial electric field is not yet well diagnosed. Motional Stark effect can yield the electric field as a second order effect. The optimum would be a heavy ion beam probe from the physics point of view. However, due to manpower and budget restrictions the application of this diagnostic to TEXTOR does not seem likely.

ACKNOWLEDGMENTS

The work described in this article was performed as part of the Research Program of the Stichting voor Fundamental Onderzoek der Materie (FOM), with financial support from the Nederlandse Organisatie voor Wetenschappelijk Onderzoek (NWO) and EURATOM.

[1] H. Soltwisch *et al.*, Plasma Phys. Controlled Fusion **26**, 23 (1984).
[2] K. H. Finken and G. H. Wolf, Fusion Eng. Des. **37**, 337 (1997).
[3] J. Ongena *et al.*, Plasma Phys. Controlled Fusion **41**, A379 (1999).
[4] N. J. Lopes Cardozo, Plasma Phys. Controlled Fusion **37**, 799 (1995).
[5] N. J. Lopes Cardozo *et al.*, Plasma Phys. Controlled Fusion **39**, B303 (1997).
[6] N. J. Lopes Cardozo *et al.*, Phys. Rev. Lett. **73**, 256 (1994).
[7] C. J. Barth *et al.*, Rev. Sci. Instrum. (these proceedings).
[8] P. C. de Vries *et al.*, Nucl. Fusion **37**, 1641 (1997).
[9] G. Waidmann *et al.*, Rev. Sci. Instrum. **68**, 492 (1997).
[10] P. C. de Vries *et al.*, Plasma Phys. Controlled Fusion **39**, 439 (1997).
[11] A. Krämer-Flecken, G. Waidmann, and P. C. de Vries, *Proceedings of the Tenth Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Ameland, 1997*, edited by A. J. H. Donné and A. G. A. Verhoeven (World Scientific, Singapore, 1997), p. 209.
[12] V. S. Udintsev *et al.*, Rev. Sci. Instrum. (these proceedings).
[13] B. H. Deng *et al.*, Rev. Sci. Instrum. (these proceedings).
[14] F. Porcelli *et al.*, Phys. Rev. Lett. **82**, 1458 (1999).
[15] R. F. G. Meulenbroeks *et al.*, Phys. Plasmas **6**, 3898 (1999).
[16] I. Entrop *et al.*, Phys. Rev. Lett. **84**, 3606 (2000).
[17] R. Jaspers *et al.*, Rev. Sci. Instrum. (these proceedings).
[18] H. Soltwisch, Rev. Sci. Instrum. **59**, 1599 (1988).
[19] J. C. van Gorkom *et al.*, Rev. Sci. Instrum. (these proceedings).
[20] E. Mazzucato, Princeton Report PPPL-3408 (1999); Nucl. Fusion (submitted).
[21] L. Porte *et al.*, Rev. Sci. Instrum. (these proceedings).
[22] E. Busche *et al.*, Plasma Phys. Controlled Fusion **39**, 1327 (1997).
[23] A. Kreter *et al.*, Proceedings of the 27th EPS Conference on Contr. Fusion and Plasma Physics, Budapest 2000 (to be published).
[24] R. Jaspers *et al.*, Rev. Sci. Instrum. (these proceedings).
[25] R. Fonck, Appl. Opt. **21**, 2215 (1982).
[26] L. Shmaenok *et al.*, Rev. Sci. Instrum. (these proceedings).
[27] A. J. H. Donné and A. A. M. Oomens, *Proceedings of the Ninth Joint Workshop on Electron Cyclotron Emission and Electron Cyclotron Heating, Borrego Springs, 1995*, edited by J. Lohr (World Scientific, Singapore, 1995), p. 645.