Current fast ion collective Thomson scattering diagnostics at TEXTOR and ASDEX Upgrade, and ITER plans (invited)

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Fast ion physics will play an important role on ITER where confined alpha particles will affect plasma dynamics and overall confinement. Fast ion collective Thomson scattering (CTS) using gyrotrons has the potential to meet the need for measuring the spatially localized velocity distributions of confined fast ions in ITER. Currently, CTS experiments are performed at TEXTOR using a 150 kW, 0.2 s, 110 GHz gyrotron and a receiver upgraded at the Risø National Laboratory. The gyrotron and receiver optics have also been upgraded for rapid scanning during a plasma shot. The receiver consists of a nine-mirror quasioptical transmission line including a universal polarizer and a 42-channel data acquisition system, which allows complete coverage of the double sideband scattered spectrum for localized (~10 cm) time resolved (4 ms) measurements of the ion velocity distribution. At ASDEX Upgrade (AUG) a similar 50-channel CTS receiver has been installed. This CTS system will use the 105 GHz frequency of a dual frequency gyrotron. The gyrotron is presently being commissioned. CTS campaigns are scheduled for the summer of 2006 with a probe power of up to 1 MW for 10 s. This report presents the alignment of the quasioptical transmission line, calibration, and gyrotron tuning of the TEXTOR and AUG CTS systems. We will also review the progress on the design of the proposed fast ion CTS diagnostic for ITER. It is envisaged that scattered radiation from two 60 GHz probe beams launched from the low field side midplane port will be received by two arrays of receivers located on the low and high field sides of the plasma. This geometry will allow the ion velocity distribution near perpendicular and near parallel to the magnetic field to be measured in ten or more spatial locations covering the full plasma cross section. The temporal resolution can be significantly better than the required 100 ms. © *2006 American Institute of Physics.* [DOI: 10.1063/1.2217921]

MOTIVATION

Diagnosing and understanding the dynamics of confined fast ions is a very important challenge for a burning plasma experiment, such as ITER, where the physics and dynamics of fusion born alpha particles will be a key research topic. Unfortunately, only few diagnostics are available for these measurements. However, the fast ion collective Thomson scattering (CTS) diagnostic is proving to be a strong candidate, as the CTS technology is maturing in the CTS experiments at TEXTOR in Forschungszentrum Jülich and at ASDEX Upgrade in IPP Garching, both in Germany.

This article will be introduced by a brief description of the basics of CTS, followed by a section on the two CTS diagnostics at TEXTOR and ASDEX Upgrade. Next, the topics of alignment of the quasioptical transmission line, calibration of the CTS receivers, and tuning of gyrotrons to be

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used for CTS will be covered in detail. Finally, an update of the ITER CTS diagnostic design is presented.

CTS BASICS

Fundamentally, in CTS an incident probing beam (e.g., a millimeter wave gyrotron beam) scatters off ion driven collective fluctuations in a plasma. The scattered radiation is observed by a receiving antenna. In the scattering volume, defined by the intersection between the probing and the receiving beams, the fluctuations with wave vector $\mathbf{k}^{\delta}=\mathbf{k}^{\mathbf{s}}-\mathbf{k}^{\mathbf{i}}$ are resolved. $\mathbf{k}^{\mathbf{s}}$ and $\mathbf{k}^{\mathbf{i}}$ are the wave vectors of the received scattered radiation and the incident probing beam, respectively. From this information the one-dimensional ion velocity distribution along $\mathbf{k}^{\delta}$ can be inferred.

The dynamics being resolved depends on the scattering geometry due to the following: an ion reradiates (scatters) much less than an electron in the interaction with the incoming beam due to a much larger mass to charge ratio. Essentially, only the electrons scatter radiation. However, when an ion moves through the plasma it draws a wake, perturbing the electron distribution. A wake is also drawn by a moving electron. But at scale lengths larger than the Debye length λ_D, the electron wake is essentially like an electron hole covering the electron. This leads to destructive interference of the scattering from the electron and its wake. Therefore, for scales larger than the Debye length the dominant scattering comes from the coherent fluctuations in the plasma caused by the collective response of the electrons to the dynamics of the ions. The criterion for collective scattering is expressed using the Salpeter parameter: $\alpha=(\lambda_D k^{\delta})^{-1}>1$. The Salpeter criterion set limits to the scattering geometry as a function of the probe frequency. By using gyrotrons as the source,[1] the choice of geometries is virtually unrestricted. For more details on the theory of CTS please refer to Refs. 2 and 3.

THE CTS SYSTEMS AT TEXTOR AND ASDEX UPGRADE

The design of the CTS diagnostics at TEXTOR and ASDEX Upgrade was described in Ref. 4. Since then the TEXTOR CTS diagnostic has been installed (August 2004), and during the winter 2004/05 the system was commissioned and is now routinely producing fast ion CTS data. See the installed in-vessel mirrors of the TEXTOR CTS system in Fig. 1. During the TEXTOR summer opening of 2005, a set of two motors was installed 2.5 m from the tokamak. These are connected to the linear drives of the mechanical arms manipulating the front in-vessel mirror via shafts and belt transmission (see Fig. 2).

The installed motors for the antenna enable remote controlled movements of the front-end mirror during a plasma shot. This facilitates search for an overlap between the probe and the receiving beam. Such a search is typically performed over a period of 2 s by sweeping the receiving beam across the probe beam, which is injected in a fixed direction. Since the maximum pulse length of the gyrotron is 200 ms, the duty cycle is kept low by, e.g., 2 ms on and 20–40 ms off. To ensure an optimum overlap we generally perform an overlap search for new scattering geometries. The data obtained during the scan clearly identify the viewing angle where maximum overlap occurs. This angle position is then used for successive discharges to study fast ion dynamics.

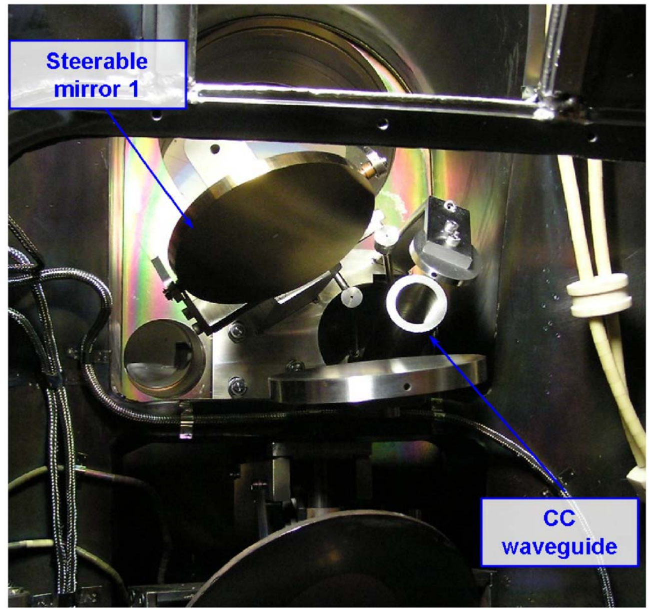

FIG. 1. (Color online) The in-vessel mirrors of the TEXTOR CTS antenna.

As described in Ref. 4 the ASDEX CTS receiver was installed in late 2003. It awaits the final commissioning stage of the two frequency ASDEX Upgrade ECRH gyrotron. Current planning aims at having the first CTS campaigns at ASDEX Upgrade take place during the summer of 2006.

QUASIOPTICAL TRANSMISSION LINES AND ALIGNMENT PLUS MAPPING

Alignment of the quasioptical transmission lines for the TEXTOR and ASDEX CTS receivers is a crucial and laborious task. The methods and equipment that facilitate this task are described here.

The first step of the alignment is achieved using a diode laser. During the machining process of the quasioptical mirrors, small holes are drilled through at the position where the microwave beam center is incident. Small metallic pins (alu-

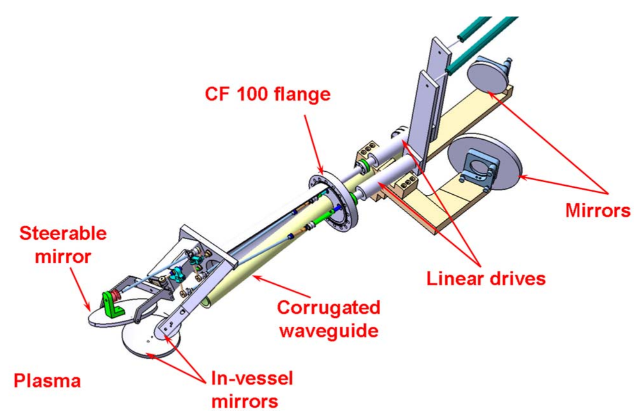

FIG. 2. (Color online) The in-vessel part of the quasioptical transmission line for the CTS antenna at TEXTOR. The connections to the motors are not shown in this CATIA (Ref. 5) drawing.

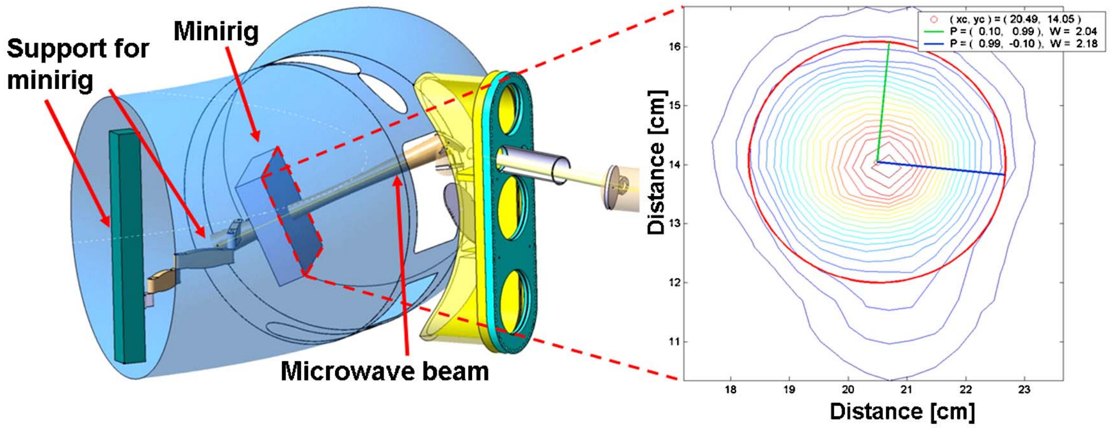

FIG. 3. (Color online) Overview of the setup for the beam pattern measurement by the minirig (left). Measured microwave beam pattern (contour plot) and its Gaussian fit (red ellipse) inside the machine (right).

minum outside the vessel and stainless steel inside)—polished to optical quality—are inserted in the holes. These are used as reflection points in the first order adjustment throughout the transmission line. The second step is alignment using microwaves. A 110 GHz Gunn oscillator, installed in the receiver box, radiates through the receiver horn into the transmission line towards the tokamak. In order to measure the beam pattern within the transmission line, a compact measuring rig has been constructed with outer dimensions of $43 \times 61 \times 6$ cm^3 and a scanning area of 30×42 cm^2. This so called minirig was converted from an old Roland plotter and modified to carry a 110 GHz detector diode. We use the existing motors of the plotter and the control language of the plotter to read and control the position of the diode by a generic interface written in LABVIEW.[6] This valuable tool to measure the microwave beam pattern in the transmission line enables us to improve the alignment and verify the beam quality. A more compact version of the minirig is currently under construction at Risø.

ASDEX Upgrade

As mentioned in Ref. 4, the CTS system at ASDEX Upgrade uses an ECRH launcher and transmission line for the receiver. An intercepting mirror between the second phase correcting mirror and the polarizer couples radiation to the CTS transmission line. Prior to October 2005, the measured transmission line throughput was about 70%–75% from the torus hall to the CTS receiver. In addition, the beam pattern was not known. Using a specially designed two-way laser as a reference, the alignment of each quasioptical component was done by changing the mirror angles to match the beam pattern maximum to the laser reference. The mobile receiver minirig was used to measure the beam pattern at each beam segment. The most sensitive part of the transmission line is the receiver horn position and the mirror closest to the long transmission line waveguide. The beam pattern was finally measured at the end of the transmission line in the torus hall, where the beam shape was good. The minirig was used in combination with the 110 GHz Gunn diode, as described in the previous subsection. However, although 105 GHz is the central frequency of the ASDEX CTS receiver, the 110 GHz is still within the bandwidth of the receiving system. Calculations on the quasioptics have shown very little difference between 105 and 110 GHz. With corrected alignment throughput was improved to about 85%–90%, which is close to the expected theoretical limit, taking into account the losses in the miter bends, etc. in the 70 m transmission line.

TEXTOR

As mentioned above, a set of motors for the movement of the in-vessel plasma facing mirror were installed in August 2005. Furthermore, some mechanical modifications were made to optimize the alignment of the three in-vessel mirrors. Therefore, the last part of the transmission line (five mirrors and a corrugated waveguide) required realignment to match the rest of the transmission line towards the receiver. As described above, the laser alignment was first done, followed by measuring the microwave beam pattern inside the TEXTOR vacuum vessel using the minirig. The main challenge was to adjust the quasioptical mirrors outside the vessel to properly couple the beam to the corrugated waveguide, i.e., at the right angle and as a Gaussian beam. Any misalignment was clearly seen in the form of sidelobes on the two-dimensional (2D) beam pattern. In Fig. 3, the setup is presented and a typical beam pattern measured inside the vessel after alignment is shown. One can see that the shape of the beam transmitted through the CTS antenna and measured inside the machine is very close to a Gaussian.

Upon completing the alignment procedure, a comparison of the alignment laser spot and the microwave beam center (measured by the minirig) for a few different viewing directions inside the vacuum vessel was performed. For extreme angles the difference was on the order of 2 cm which is close to the measuring uncertainty in the comparison. For the typical orientations of the front-end mirror the difference was less than 1 cm.

After noting the good correspondence between the laser and microwave orientations, the laser was used to make a mapping of the motor position and the corresponding mirror orientation. Naturally, such a mapping exists from the design drawings (see Fig. 4), but TEXTOR is not fully documented in CATIA;[5] hence some deviance to the experimentally ob-

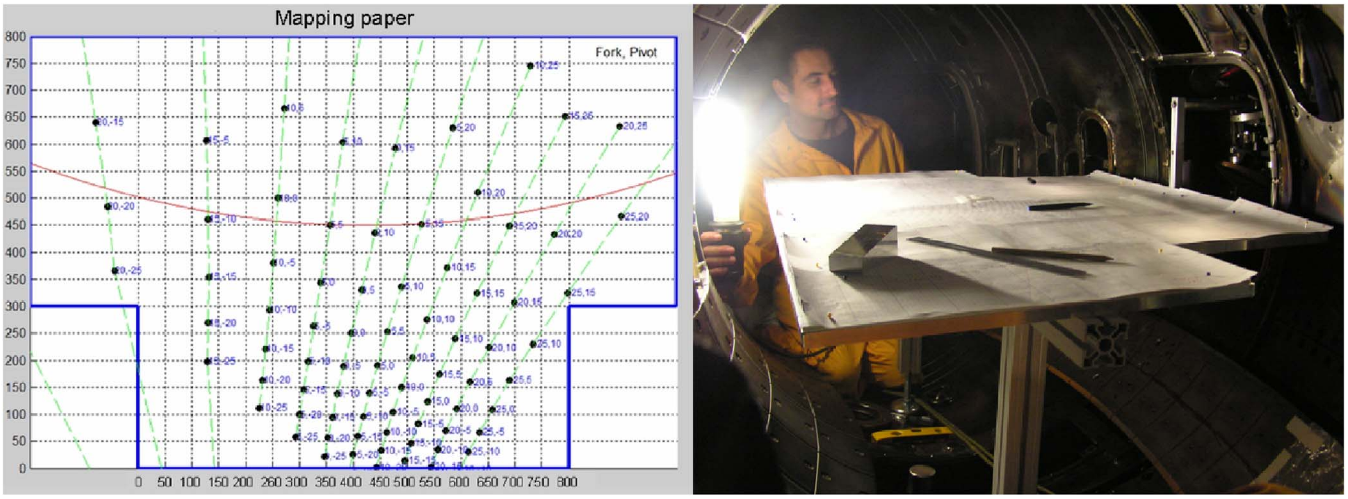

FIG. 4. (Color online) The mapping paper used inside TEXTOR (left). Some reference points from CATIA (Ref. 5) are plotted with the corresponding motor settings. The red line represents the magnetic axis. The mapping setup inside TEXTOR (right).

tained values should be expected. For most angles the agreement was near to perfect, and in extreme angles the difference could be up to 4–5 cm. In total more than 300 points were mapped and imported into the code controlling the viewing direction of the moveable first mirror.

CALIBRATION

The calibration of the CTS receivers is a two step process. The principle and actual method are the same for the receivers at ASDEX and TEXTOR. In the first step the absolute calibration of the receiver channels is obtained by measuring—in turn—blackbody radiation at room temperature and at liquid nitrogen (LN2) temperature, using a chopping mirror in front of the horn of the receiver, directing the beam towards a LN2 container lined with eccosorb. This measurement also gives the noise temperature of the receiver. Generally, the noise temperature of the channels in both receivers is in the order of 10–20 000 K. This calibrates the receiver and is done routinely. To measure the losses in the transmission line, calibration is also done with a LN2 source at other locations in the transmission line. For example, for the system at ASDEX Upgrade, calibration is also done with the liquid N2 source located at the end of the transmission line in the torus hall (after the last miter bend) just outside the vacuum vessel. This of course does not include the components inside the vessel and the antenna. Liquid nitrogen inside the tokamak is usually not permitted for safety reasons. Therefore, to correct any frequency dependent transmission profiles caused, for example, by the diamond window, a relative calibration is needed as the second step of the calibration process. This is done by measuring the electron cyclotron emission (ECE) radiation from the plasma when the magnetic field is tuned for a resonance in the plasma matching the central frequency of the CTS receiver. The known temperature profile shape from other diagnostics such as the ECE radiometer and Thomson scattering is used to correct for frequency dependent structures in the transmission.

GYROTRON PROPERTIES FOR CTS

There are two essential properties that need to be studied when using gyrotrons for CTS experiments. The first is the frequency dynamical behavior at different operating scenarios and the second is the mode purity.

To block out the gyrotron main line, each CTS system is equipped with two notch filters, each with about 60 dB attenuation and 200 MHz bandwidth. Hence it is important that the frequency is known to within 0.01 GHz. In addition, it is important to study the temporal behavior of the frequency for different operating conditions. The main concern is that the total frequency sweep, mainly due to thermal effects in the gyrotron tube cavity, should be smaller than the notch width. In addition, a large frequency drift during the measurements will make the CTS analysis more difficult. Experiments to measure frequency on both gyrotrons were done from a pickoff horn/waveguide installed in the vicinity of the main central high power loads. Two methods of frequency measurements were done simultaneously, either offering long measurement times or high temporal resolution; the first used a spectrum analyzer, and the second method heterodyned down the signal using a harmonic mixer/oscilloscope setup. More information on the techniques of this experiment can be found in Ref. 7. The results from that article show the frequency evolution of the ASDEX Upgrade gyrotron as a function of powers ranging from 100–500 kW in cw operation. The total frequency drift from a cold start was reported to be about 100 MHz for the highest power, hence within the notch filter bandwidth. The data also show that after about 0.1 s (at 500 kW), the quasithermal equilibrium of the gyrotron tube where the frequency drift is acceptable for CTS is attained. Studies have also been done during modulation with 20 ms at 50% duty cycle. Results show a rapid thermal recovery (larger frequency drift), suggesting a large cooling efficiency of the tube.[7] Further studies need to be done for larger modulation frequencies to study the frequency recovery which can be an issue. The frequency dynamics of the TEXTOR 110 GHz gyrotron was also mea-

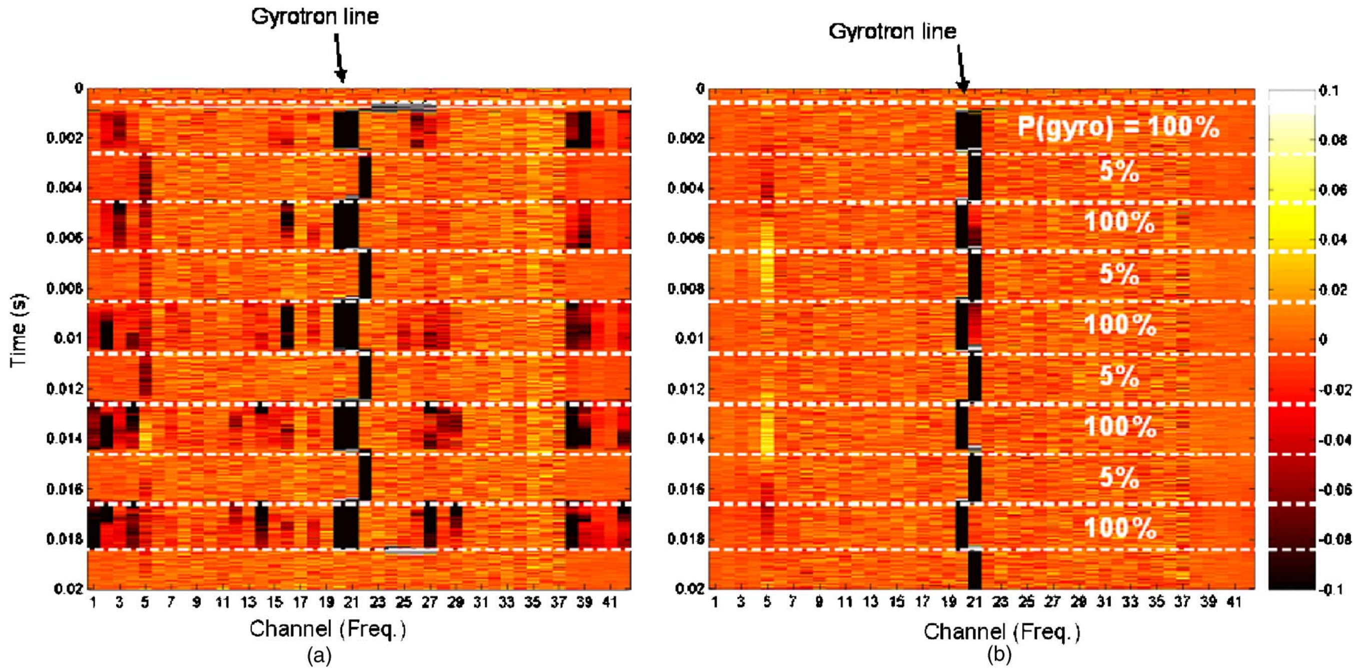

FIG. 5. (Color online) Two examples of impure (a) and pure spectra (b). The ordinate and abscissa axes represent the time and the frequency channels (106.625–113.375 GHz). The contour values are the voltage normalized to the initial background levels. Displayed between the dashed lines are the gyrotron power levels.

sured by the same techniques. The frequency drift of the gyrotron was at most 27 MHz depending on the modulation duty cycle.[7]

A gyrotron spectrum free of spurious modes is essential in the CTS experiments. Therefore any spurious modes that appear outside the notch, even at 100 dB down, will corrupt the CTS signal. Experiments have been carried out to measure stray radiation launched power into the TEXTOR vacuum vessel. Two examples of impure and pure spectra are shown in Figs. 5(a) and 5(b), respectively. The ordinate and abscissa axes represent the time and the frequency channels (106.625–113.375 GHz), respectively. The contour values are in volts normalized to the background level. The main gyrotron line can be seen in the center channels. Modulation during CTS experiments is done by gating the voltage; however, for technical reasons, the gyrotron tuning experiments were conducted with the so-called power modulation where the gyrotron power is varied between 100% and 5%. To tune the gyrotron there are four main control parameters, namely, the electron beam acceleration voltage, the cathode voltage, the magnet current, and the filament voltage. Hence, it is a formidable task exploring a multidimensional operation space to obtain a clean gyrotron spectrum at sufficient power. Figure 5(b) shows a clean spectrum after tuning and an output power of about 180 kW. One can notice a slightly different frequency for the "clean" gyrotron settings compared to the "impure" settings. Not shown are spurious-free measurements with the same clean gyrotron settings with gate modulation, which were done at a later date.

Similar experiments were also conducted on the two frequency ASDEX Upgrade gyrotron where power was launched into the main load. The panel separating the matching optics unit (MOU) boxes was removed to measure the stray radiation from MOU 1 where the gyrotron is located. Thus far for the largest power of 500 kW, the spectrum was clean. Studies are still preliminary.

ITER CTS

The present CTS experiments are a stepping stone to the design of a CTS system for ITER to diagnose confined fast ions including fusion born alpha particles. A comprehensive physics feasibility study summarized in Ref. 8 concludes that a CTS diagnostic with a probe frequency below the electron cyclotron emission spectrum is the only CTS option capable of meeting the ITER measurement requirements for the fusion alphas, with present or near term technology. The design of the 60 GHz based CTS system for ITER was published in Ref. 9. Technologically robust with no moveable components near the plasma, the design consists of two separate systems: one measuring the fast ion distribution perpendicular to and the other parallel to the magnetic field at different radial locations simultaneously. Each system has its own rf launcher and a separate set of detectors. The first system measures the perpendicular component of the fast ion velocity distribution. It consists of radially directed rf launcher and receivers, both located in an equatorial port on the low field side (LFS). This system will be referred to by the acronym LFS-BS system referring to the location on the low field side of the receiver and the fact that it measures backscattered radiation. The second part of the CTS diagnostic measures the parallel component of the fast ion distribution. It consists of a rf launcher located in the same equatorial port on the LFS and a receiver mounted on the inner vacuum vessel wall that views the plasma from between two blanket modules. This system will be referred to as HFS-FS referring

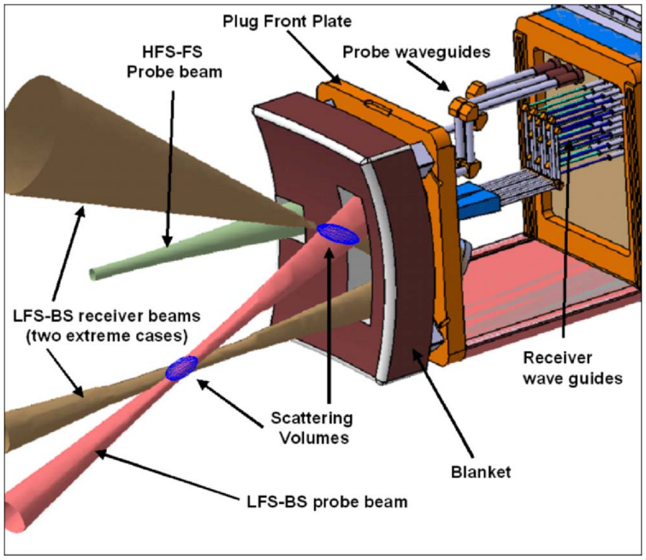

FIG. 6. (Color online) ITER port plug 12 showing the beams of the low field side CTS receiver antennae, the two probe beams (for each CTS system), apertures, and waveguides.

to the location on the high field side of the receivers and the fact that they measure forward scattered radiation. Significant progress has been made in the design and integration of the CTS diagnostic into ITER, whereby the measurement requirements are still satisfied with additional engineering constraints. The latest design of the components in the equatorial port 12 with the three-dimensional Gaussian beams is shown in Fig. 6. The two extreme LFS-BS receiver beams are in brown, the LFS-BS probe beam is shown in pink, and the HFS-FS probe beam is in light green. The blue ellipses are the scattering volumes for the two extreme angles.

The latest design of the HFS-FS receiver is shown in Fig. 7. For illustrative purposes, the upper blanket and the cooling manifold are not shown. The front end is a complete unit consisting of two mirrors and a series of ten horns encased beneath the second mirror. A two-mirror approach has

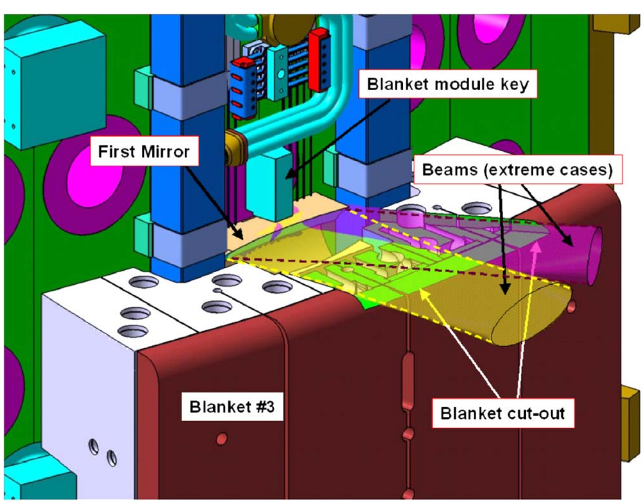

FIG. 7. (Color online) The CTS HFS-FS receiver viewed from the plasma. The upper blanket is not shown. The yellow and magenta semitransparent beams are the two extreme viewing directions (LFS and HFS radial positions, respectively).

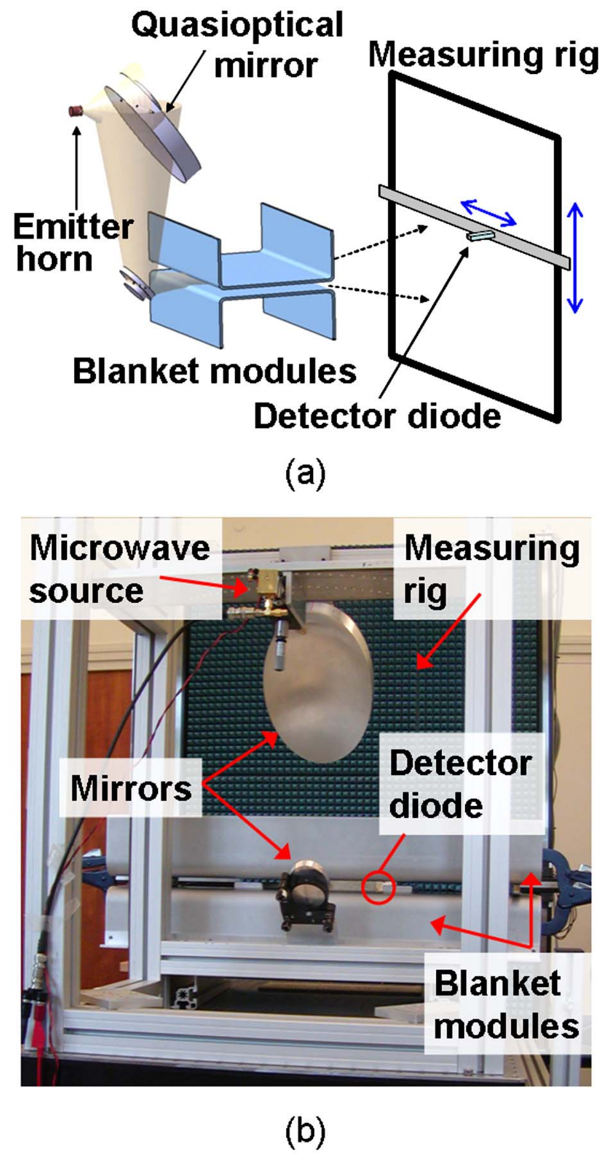

FIG. 8. (Color online) Schematic (a) and photo (b) of the experimental setup viewed from the emitter/horn.

been chosen due to the limited space available for ten horns. The horns are distributed toroidally, each representing a different toroidal angular view in the plasma. The unit is mounted on the vacuum vessel and is independent of the blanket modules. The unit is cooled by the vacuum vessel wall through conduction.

Figure 7 also shows the required cutout in the lower blanket which is essential to the diagnostic performance. The feasibility study[8,10] concluded that the minimum vertical gap between the blankets should be 30 mm in order to satisfy the ITER measurement requirements for the confined fast alphas. This conclusion was based on a 2D full wave modeling of the emission from a slot aperture antenna. In order to experimentally investigate the effect of the blanket gap on the microwave beam propagation, a simplified mock-up of the ITER blanket module and the CTS HFS-FS receiver system has been designed, constructed, and tested at Risø (shown in Fig. 8). The setup has been scaled to 6/11 of the actual size of the ITER components, since a microwave equipment of 110 GHz was used instead of 60 GHz.

A Gunn oscillator emits radiation through a circular corrugated horn coupled to the mirrors. The mirrors were designed to produce the required beam parameters to transmit radiation through the blanket gap. The beams in the proposed design are astigmatic. However, for these experiments, if the propagation axis is normal to the mirror, each dimension can be separated into two separate setups (different mirrors) to study the beam properties separately in the "horizontal" and "vertical" planes. In other words, the horizontal and vertical systems produce a symmetrical beam with the same beam properties as the horizontal and vertical dimensions of the astigmatic beam. The 2D beam pattern is measured by a moveable detector, as illustrated in Fig. 8. To represent the horizontal cutout, two bars with rounded edges are placed parallel to each other and perpendicular to the front of the blanket [Fig. 8(b)]. Different experiments have been conducted for different vertical and horizontal dimensions of the effective viewing slot.

As expected, the results from the experiments have concluded that the horizontal dimensions of the gap become important when it is comparable to the beam diameter (Gaussian radius $\times 3.2$) where the bars start acting like a waveguide. The more important goal of the experiment is to study the effect of the vertical gap dimension on the beam divergence angle which will have a direct impact on the CTS signal. Using two vertical gap distances, the beam patterns were measured at different distances from the blanket, hence calculating the divergence angle. The results show that at vertical distances of 30 and 20 mm, the divergence angles were measured to be $\alpha_\theta = 7.5°$ and $9.4°$, respectively. These are in good agreement to the full wave calculations from the feasibility report that calculate divergence angles of 7° and 10.5° for 30 and 20 mm vertical gap, respectively. Therefore, it confirms the conclusion that the vertical dimension should be no less than 30 mm in order to satisfy the ITER measurement requirements for the confined fusion alphas.

Future tasks include development of an improved mock-up experiment for testing front-end components. The mock-up will be equipped with noncircular horns and new shaped mirrors that will transmit astigmatic beams, a more realistic blanket model, a better alignment system including a mechanism for precise motion of mirrors, and a faster motion of the detector on the beam pattern rack. This will give the possibility to optimize the high field side antenna system by testing various mirrors and horn systems. An assessment of the importance of blanket edge shapes in the acceptable tolerances for positions of antenna system and blanket modules will also be studied. The mock-up experiment will also give valuable information for the assessment of alignment and assessment of acceptable tolerances for misalignment.

SUMMARY

The fast ion CTS diagnostic system installed at TEXTOR is routinely producing data, and the ASDEX Upgrade CTS system is expected to have first campaigns in the summer of 2006. In the present article the topics of alignment of a quasioptical transmission line, calibration, and preparation of gyrotrons for CTS operation have been described in some detail. Finally, the current status of the design of a fast ion CTS diagnostic for ITER was presented. More information on CTS may be obtained from the website www.risoe.dk/fusion/cts.

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