PSFC/JA-05-24

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OVERVIEW OF HIGH POWER CTS EXPERIMENTS IN MAGNETICALLY CONFINED PLASMAS

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A brief overview of collective Thomson scattering (CTS) diagnostics in magnetically confined plasmas is given from first discovery almost 50 years ago to present tokamak fusion energy experiments. CTS has evolved as an important diagnostic technique for ion temperature, plasma turbulence and waves, and fast ion distributions. Significant progress has been made in theoretical interpretation from electrostatic to electromagnetic theories, in technologies for implementing CTS diagnostics from lasers to gyrotrons, and in obtaining measurements in many plasma experiments from theta pinch plasmas to designs for the ITER tokamak.

1 Introduction

Collective Thomson scattering (CTS) refers to scattering of electromagnetic radiation by a plasma such that the scattered signal is dominated by collective electron fluctuations and not by random individual free electron motions. In a plasma, the minimum scale length at which the electron fluctuations are coupled corresponds to the Debye shielding length that defines an electrically neutral plasma and at longer scale lengths due to turbulence and plasma waves. Consequently, the CTS signal will provide information primarily about ion energy distributions and other plasma parameters that influence plasma fluctuations. CTS has been used for ion temperature, turbulence, plasma wave, and fast ion measurements and has great potential for providing a much needed diagnostic technology for fusion product alphas in ITER. The basic geometry of a CTS experiment and the definition of the wavevector and frequency components are shown in Figure 1, where $\mathbf{k}_i$, ω_i identify the incident beam, $\mathbf{k}_s$, ω_s identify the scattered beam and $\mathbf{k}$, ω are the plasma fluctuation values as determined by the incident and scattered beams and scattering angle, θ.

The main areas of CTS progress and applications are outlined in Figure 2. The discovery of CTS phenomena in plasmas is now almost 50 years old. Significant progress has been made in the theoretical understanding, the hardware technology, and in applying CTS to plasma experiments. This overview primarily deals with CTS for thermal fluctuation measurements requiring high power sources for ion energy distribution measurements. Low power CTS from non thermal plasma turbulence and waves is only briefly treated in the context of ion thermal CTS development. The organization of this review starts with a brief review of early work, followed by a summary of theoretical advances, technology developments, and an overview of CTS experiments that have been carried out and are currently in progress.

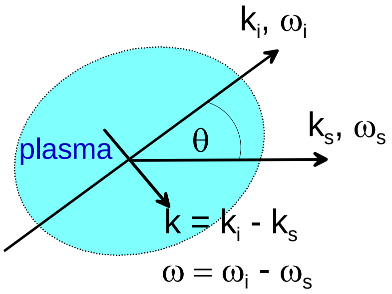

Figure 1. CTS scattering geometry

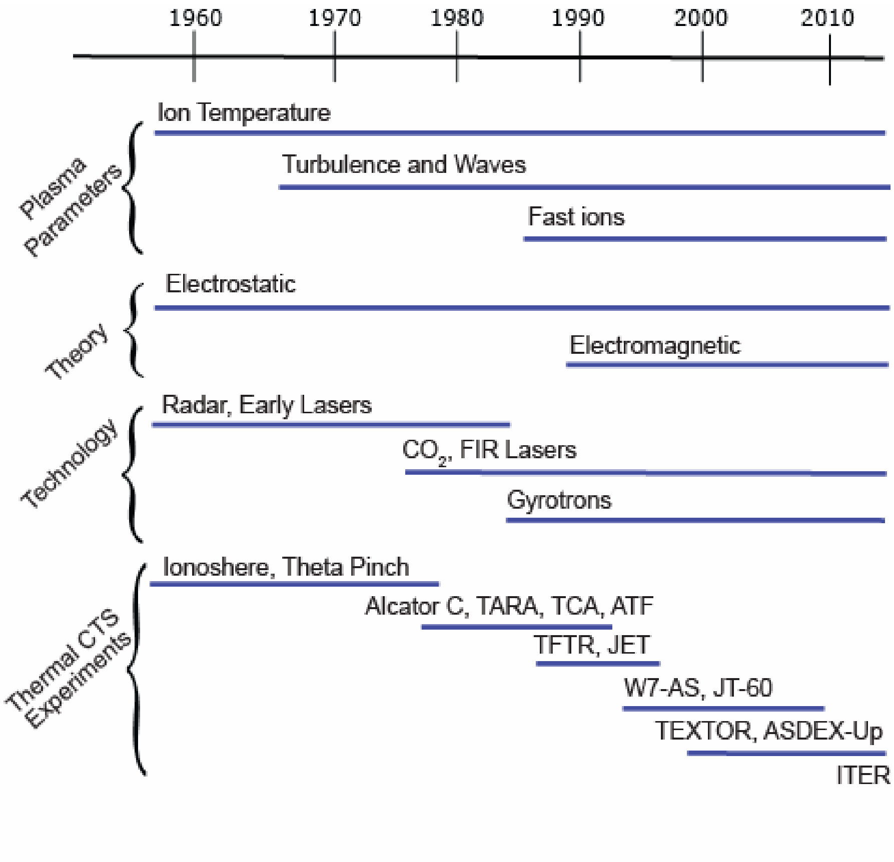

Figure 2. Outline of CTS progress.

2 Early Work

Thermal collective Thomson scattering was first discovered in 1958 by Bowles [1] when 41 MHz radar backscattering from the ionosphere was observed to be much more narrowly broadened than expected for the electron energies. In 1960 Salpeter [2], and independently Dougherty and Farley [3] and Fejer [4], explained these observations as due to collective electron fluctuations shielding the ions. Salpeter introduced the now well known parameter α, the ratio of the plasma fluctuation wavelength to the Debye length, which defines the plasma and scattering parameters when collective scattering can be observed as:

$$\alpha = \frac{1}{k\lambda_D} = 1.07\times 10^{-4} \frac{\lambda_i}{\sin\left(\theta/2\right)} \sqrt{\frac{n}{T}} > 1 \qquad (1)$$

where k is the fluctuation wave number, λ_D is the electron Debye length, λ_i is the incident beam wavelength in cm, n is the electron density in cm^{-3}, T is the electron temperature in eV, and θ is the scattering angle. The fluctuation wave number and scattering angle are defined by the source wavelength and scattering geometry as given in Figure 1. The form of Equation 1 on the right is valid when $|\mathbf{k}| \ll |\mathbf{k}_i| \approx |\mathbf{k}_s|$.

This initial theoretical understanding and the invention of the ruby laser (λ = 693.6 nm) in 1960 motivated a number of CTS laboratory experiments in the 1960's. At this wavelength the condition for CTS, $\alpha > 1$, could be achieved in high density ($n \geq 10^{15}$ cm^{-3}), low temperature ($T \leq 5$ eV) plasmas where $\lambda_D < 1$ μm at scattering angles ($\theta > 1^o$) large enough to avoid the unscattered laser beam. A small sampling of these early experiments includes DeSliva et al [5] who published measurements taken in a hydrogen arc plasma, Evans et al. [6] who showed results for a thetatron, and many others such as Ramsden et al [7] and Röhr [8] with similar CTS measurements in theta pinch plasmas.

In the 1970's research on plasmas for fusion energy ($n < 10^{15}$ cm^{-3}, $T \geq 1$ keV, λ_D =50 - 200 μm) rapidly expanded with a growing demand for better plasma diagnostics. In particular, better diagnostics for localized tokamak ion temperature were needed. Simultaneously there were also rapid advances being made in the development of far infrared (FIR) lasers in the wavelength range of (λ = 0.1 – 1 mm) [9]. Jassby et al [10] recognized that CTS could be applied to tokamak plasma ion temperature measurements with a modest advancement in the then existing FIR laser technology. This realization motivated a number of efforts to develop CTS for tokamak ion temperature diagnostics.

3 Theoretical Progress

The first theoretical explanations of CTS depended on many simplifying assumptions. Foremost of these was that the scattering was off of only electron density fluctuations and that the longitudinal electrostatic approximation was valid for describing the plasma dielectric function. The initial theoretical treatments of Salpeter [2], Dougherty and Farley [3] and Fejer [4] also assumed unmagnetized, thermal equilibrium plasmas. These latter assumptions were relaxed in quickly following work by Hagfors [11] and others [12, 13] to include a magnetic field and by Rosenbluth and Rostoker [14] to allow departures from thermal equilibrium. The status of CTS theory remained this way into the late 1980's when the first modeling calculations were made for applying CTS to fast fusion product alpha particle diagnostics. Hutchinson et al [15], Vahalla et al [16, 17], and Hughes and Smith [18] carried out detailed calculations using the electrostatic approximation showing that CTS would be a viable diagnostic for fusion product alpha particles.

Shortly after these initial alpha particle CTS calculations it was realized that the electrostatic approximation was not valid for scattering geometries when the plasma fluctuation wavevector, $\mathbf{k}$, was oriented near perpendicular to the magnetic field where an interaction with the lower hybrid resonance occurs. In this case the scattered signal interacts with transverse electromagnetic fluctuations as well as with longitudinal electrostatic fluctuations requiring an electromagnetic treatment of the plasma dielectric function as shown by Chiu [19] and Aamodt and Russell [20]. Furthermore, the assumption of scattering only off of electron density fluctuations was found to be incorrect for scattering source frequencies in the vicinity of the electron plasma frequency and other nearby plasma resonances and cutoffs. Aamodt et al [20, 21] and Bindslev [22, 23] developed the full electromagnetic CTS theory that included scattering contributions from electric field, magnetic field, and current density fluctuations. It was shown that scattering from the field fluctuations could be more dominate than the electron density fluctuations under some millimeter-wave scattering conditions.

Another refinement in the CTS theory was the derivation of the dielectric coupling factor (geometrical form factor) between the incident and scattered beams in magnetized plasma. This was important because transparent, low noise accessibility to tokamak plasmas was limited to narrow millimeter-wave ranges in X-mode or O-mode propagation below or between the low ECE harmonics or above higher ECE harmonics depending on electron temperature. An early 6 Tesla ITER calculation shown in Figure 3 illustrates how the X-mode propagation frequency window is squeezed between the relativistic downshifted electron cyclotron emission (ECE) and lower X-mode cut off [24]. Bretz [25] derived the geometrical form factor for X-mode to X-mode scattering perpendicular to the magnetic field and showed it could significantly either decrease or increase the scattered signal level depending on the details of the plasma parameters and scattering geometry. Hughes and Smith [26] generalized Bretz's calculations to include X and O mode couplings and directions away from perpendicular to the magnetic field. Additional work by Bindslev [27] has modeled the effect of uncertainties in plasma parameters for determining fast ion energy distributions by CTS.

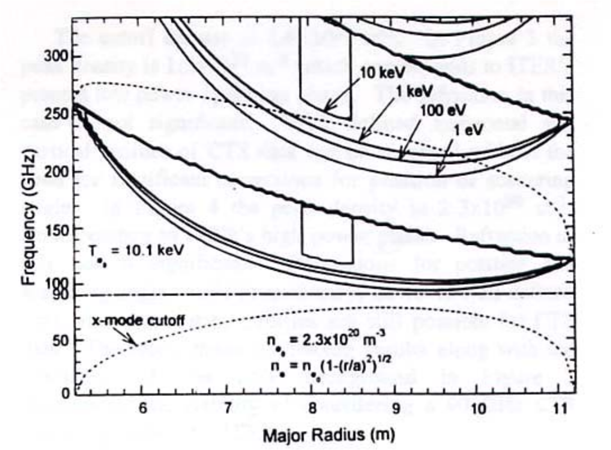

Figure 3. Contour plots of ECE and cutoffs for X-mode propagation in ITER 1993 design. CTS is possible between 70 and 90 GHz

4 Technology Progress

4.1 FIR Lasers

By the mid 1970's the need for better ion temperature diagnostics in fusion plasma tokamak experiments launched many efforts to develop the necessary improvements in FIR laser technology for CTS. For ion temperature measurements both high power pulsed and low power CW lasers were needed for the incident source and receiver local oscillator, respectively. The pulsed FIR laser requirements were estimated as: a power output of about 1 MW, in 1 μs, with a linewidth less than 100 MHz. The first efforts were based on the CO_2 laser pumped 496 μm CH_3F laser, discovered by Chang and Bridges [28]. High power 496 μm CH_3F laser experiments were carried out at by Temkin, Drozodwicz et al at MIT [29, 30], Semet and Luhmann at UCLA [31], and Evans et al at Culham [32]. Subsequently the development efforts evolved to shorter wavelengths at 385, 114 and 66 μm using D_2O [9, 33, 34] and 281, 252, and 152 μm using NH_3 [9, 35, 36] as higher plasma temperatures and magnetic fields mandated source frequencies further away from harmonic electron cyclotron background emission. Other laboratories also joined the effort and included Hutchinson et al, at ORNL [37], Siegrist's group in Lausanne [38, 39], and in Japan, Muraoka [40, 41], Yamanaka [42], and Hirose [43, 44] all experimented with and developed FIR lasers for CTS.

Controlling the linewidth as output power level was increased was a major challenge because these lasers had very high gain and would operate by spontaneous amplified emission over bandwidths 100's of MHz wide. Many schemes were tested to achieve narrow linewidth operation. These included building a small oscillator carefully designed for single mode operation followed by an amplifier [30, 31, 45] or to injection lock a high-power oscillator [46], unstable resonators to prevent oscillation on higher order modes [47], a high-power oscillator with an internal Fox-Smith mode selector [48] as shown in Figure 4, and a traveling wave ring resonator to eliminate standing wave feedback contributions to emission broadening [49, 50]. However, the greatest progress on narrow linewidth goals was made when it was recognized that these lasers operated by two-photon simulated Raman emission [51] and that a single-mode, narrow linewidth pump laser was critical to achieving narrow linewidth.

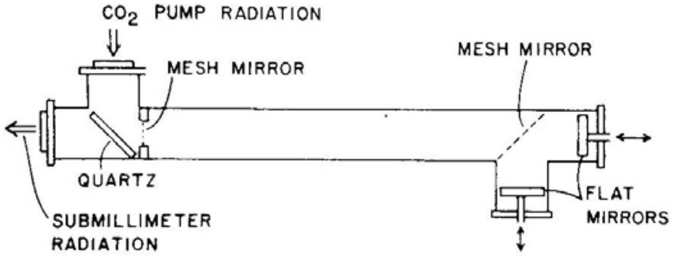

Figure 4. FIR laser oscillator with a Fox-Smith mode selector on right [50].

FIR lasers suitable for the first ion thermal CTS experiments with linewidths of less than 20 MHz FWHM were finally developed with the 385 μm D_2O transition by Woskoboinikow et al [52] using an etalon tuned single mode CO_2 pump laser oscillator-amplifier combination [53] and by Behn et al [54] using a CO_2 pump laser with a low pressure section to achieve single mode operation. Eventually at Princeton Plasma Physics Laboratory, Semet et al [55] set the record for high power from a 385 μm D_2O laser of about 2 MW with 5 J energy per pulse using an unstable resonator cavity design pumped by a single mode CO_2 laser ring amplifier driven by a low pressure CW CO_2 oscillator. The single mode CO_2 lasers developed for pumping the FIR lasers were also useful in there own right for small angle CTS experiments in tokamaks.

4.2 Gyrotrons

In the mid 1980’s it was proposed that millimeter-wave gyrotrons would be an attractive source technology for CTS diagnostics [56, 57]. Gyrotrons could produce much longer pulse lengths or could be pulsed much more rapidly than high power FIR lasers, making possible higher CTS signal to noise ratios through longer signal integration times. Also, the CTS condition $\alpha > 1$ could be met at larger scattering angles with millimeter-wavelengths for better spatial resolution. Gyrotrons at this time were being used for electron cyclotron resonance heating (ECRH) in magnetic confinement plasma experiments at power levels up to about 200 kW and frequencies up to about 60 GHz [58]. Significant development activity was focused on increasing the power and frequency for future plasma heating experiments. At MIT gyrotrons with frequencies over 100 GHz and power levels over 100 kW were being aggressively developed by Temkin et al [59, 60]. An experimental study by Kreischer et al [61] of the frequency properties of a 140 GHz gyrotron with a low Q (~400) resonator designed for ECRH found a linewidth of < 3 MHz in 1 μs pulses, narrower than pulsed FIR lasers, thus establishing the suitability of gyrotrons for CTS diagnostics. Consequently a 1 kW, high Q (~6000) gyrotron at 137 GHz was built for plasma wave CTS diagnostics at MIT as described by Saito et al [62] which was measured to have an upper limit linewidth of about 1 kHz [57]. This gyrotron is illustrated in Figure 5 and used internal and external modes converters to convert the TE_{03} resonator mode into a Gaussian beam [63].

Other laboratories also recognized the potential of gyrotrons for plasma diagnostics. In Australia, low power (10 W) CW gyrotrons, step tunable at over 60 frequencies in the 96 – 325 GHz range were built by Brand et al [64, 65] for application to plasma wave CTS in tokamaks. In Japan, Idehara et al, [66, 67] developed second and third harmonic gyrotrons at frequencies up to 383 GHz and in Russia, Pankratova and Nusinovich [68] developed a 100 W second harmonic CW gyrotron at 250 GHz for plasma diagnostics. These high frequency gyrotron developments were not sufficiently powerful for ion thermal CTS but helped establish the gyrotron as a viable source for plasma diagnostic measurements where a high power source is not needed such a non thermal CTS.

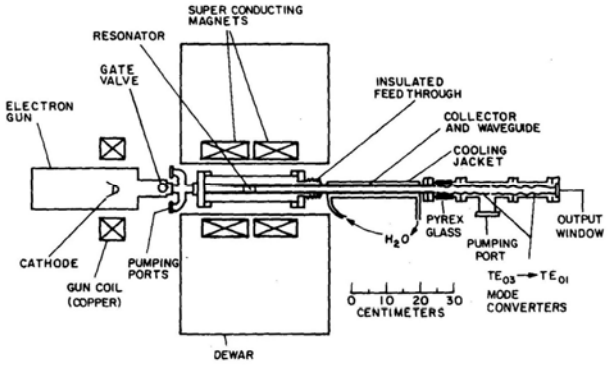

Figure 5. 137 GHz gyrotron for plasma diagnostics.

More recently megawatt scale gyrotrons have been implemented and are planned on many fusion plasma experiments for ECRH and current drive [69]. Power output levels of 1.5 MW from a single tube are being developed [70] and stepped frequency tuning capability is also being developed at the megawatt power level [71, 72]. The availability of these gyrotron sources is making possible the implementation of ion thermal CTS on a number of plasma experiments as described below where the plasma can be made transparent to the gyrotron beam by varying the magnetic field or step tuning the gyrotron frequency. Future prospects are also good for implementing a fast ion diagnostic on ITER by the availability of this technology.

4.3 Receivers and Other Components

Sensitive receivers to detect scattered signals with bandwidths of up to 2 GHz for ion temperature and 10 GHz for fast ions is another key requirement for CTS plasma diagnostics. In the late 1970's Feterman et al [73] at MIT Lincoln Laboratory developed quasi-optical GaAs Schottky diode mixers that achieved a system noise temperature 9700 K double sideband (DBS) at 670 GHz in a heterodyne receiver with a CW FIR laser as the local oscillator (LO). Various receiver quasi-optical diplexer designs to optimally couple the signal and LO to the mixer were also developed [74, 75]. Subsequently this receiver technology made possible the first FIR laser CTS experiments on tokamaks. It is still the best approach for wideband, sensitive receivers at frequencies up to about 2.5 THz [76] though the noise temperature increases by more than an order of magnitude over this frequency range. More recently, hot electron bolometer (HEB) mixers have been shown to have lower noise temperatures at frequencies above 1 THz in astronomy applications [77], but their low tolerance for large levels of background light may make them impractical for use in fusion plasma tokamak environments. For millimeter-wave gyrotron CTS receivers, low noise Schottky diode mixers are commercially available in efficient waveguide packaging. For small angle CO_2 laser CTS, receiver bandwidth has been a limiting factor. CO_2 laser receiver mixer technology has evolved from cryogenically cooled 0.24 GHz bandwidth Ge:Hg photoconductors as used by Kasparek and Holzhauer [78], to ~1 GHz bandwidth HgCdTe photodetectors as used by Richards et al [79], to most recently 8 GHz wide quantum-well infrared photodetetors (QWIP) as used by Kondoh [80].

Other components that are important for successful ion thermal CTS diagnostics are notch filters for stray light rejection, beam and viewing dumps, and for millimeter-wave scattering, universal polarizers. In the FIR and CO_2 laser wavelength ranges low pressure molecular gas cells were developed as notch filters. A 7 m long, -70 dB N_2O notch filter with an 8.4 MHz/torr pressure controllable linewidth for the 385 μm D_2O laser was demonstrated [81]. CO_2 gas hot cells were used to filter stray light in CO_2 laser CTS systems [79, 80]. For millimeter-wave CTS, fundamental mode waveguide resonator structures have been used as notch filters at frequencies up to 140 GHz with up to -140 dB peak rejection in bandwidths less than 300 MHz [82]. The commercial availability of deep millimeter-wave notch filters is an import advantage for gyrotron CTS systems.

Beam and viewing dumps have been an important part of most thermal CTS systems and are an absolute necessity if notch filters are not sufficiently deep or the high power source linewidth is not narrow over many orders of magnitude. Compact, high vacuum graphite tiles with submillimeter-wave radiation trapping structures were developed for the first CTS measurements on Alcator C at 385 μm as shown in Figure 6 [83]. On TFTR the use of silicon carbide pyramidal tiles was attempted at 60 GHz [84], but most current gyrotron systems do not use beam or viewing dumps because of the difficulty of implementation and the availability of deep notch filters. However, millimeter-wave CTS systems with spatial scanning capability do require a universal polarizer in each of the source and receiver signal beam lines to match the polarization of the beams to the characteristic propagating mode in a magnetized plasma [85, 86].

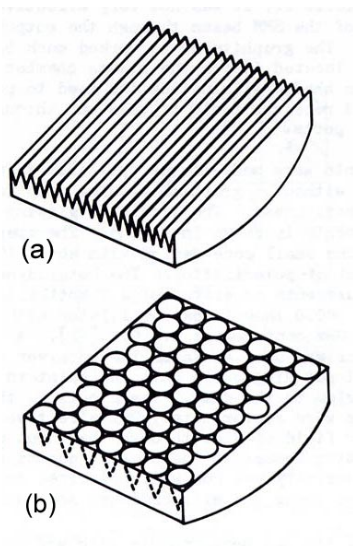

Figure 6. Graphite submillimeter-wave beam dump tiles (a) V-grooves for polarized beams, (b) conical holes for unpolarized beams

5 First Tokamak Experiments with FIR Lasers

In the early 1980's the first tokamak ion thermal CTS diagnostic system was implemented on Alcator C at MIT by Woskoboinikow et al. [87]. This system used a 200 kW, 1μs pulsed, 385 μm D_2O laser at a scattering angle of 20° through vertical ports on top and bottom of the tokamak. The heterodyne receiver had a noise temperature of 20,000 K DBS and used the 381 μm DCOOD LO for an intermediate frequency (IF) centered at 9.4 GHz with 32, 80 MHz wide channels. This receiver was previously used on Alactor A to map out the high harmonic ECE background emission using various LO formic acid (HCOOH) laser lines in the 400 – 800 GHz range. These measurements showed, for the first time, that at least for electron temperatures in the 1- 2 keV, the background above the 3rd ECE harmonic was low enough for detecting CTS signals [88-90].

Stray light from the D_2O laser was the main limitation for the CTS measurements on Alcator C due to the restricted access through long narrow diagnostic ports. Another limitation was that only one laser pulse could be fired per plasma shot. The CTS measurements required averaging many plasma shots (up to ten) to build up signal statistics. Nevertheless, the first CTS spectra of ion thermal fluctuations in a tokamak were obtained as shown in Figures 7 and 8 [87] in 8 Tesla plasmas with line averaged electron densities of 3.6 and 2.5 x 10^{14} cm^{-3}, in hydrogen and deuterium plasmas, respectively. Measurements in the central part of the spectrum are missing because of the notch filter. The signals in the remaining channels are consistent with the tokamak ion temperature and show a narrowing when the plasma gas is changed from hydrogen to deuterium, as expected.

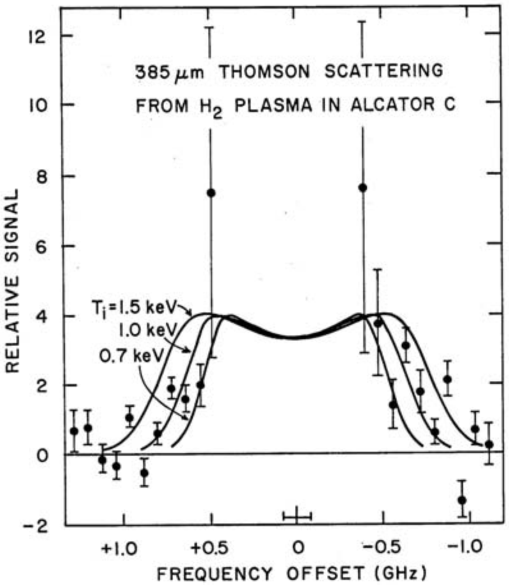

Figure 7. D_2O laser CTS spectrum form Alcator C hydrogen plasma

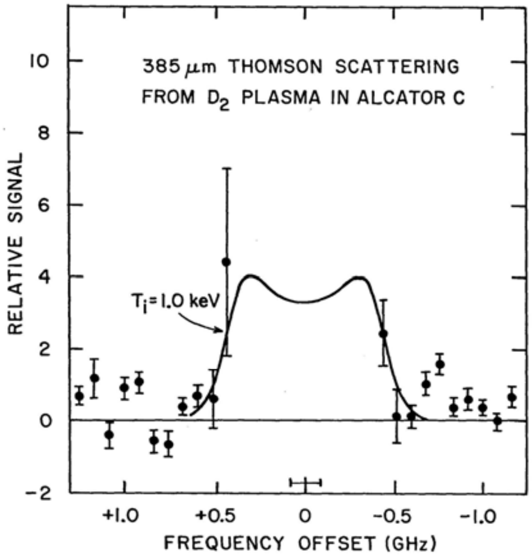

Figure 8. D_2O laser spectrum from Alcator C deuterium plasma

Improved CTS results for ion thermal fluctuation measurements in a tokamak were obtained a few years later by Behn et al [91, 92] on the TCA tokamak in Lausanne. They also used a 385 μm D_2O laser, but more powerful (0.5 J, 1.4 μs) than the MIT laser. The receiver had a noise temperature of 8000 K DSB using a 383 μm CD_3Cl laser LO with an IF centered at 3.6 GHz having 12, 80 MHz wide channels. With a scattering angle of 90° and good access to an external Pyrex cone beam-dump and an internal Macor ceramic viewing dump stray light was also lower. Several CTS spectra were obtained for ion temperatures in the range of 200 – 400 eV and for several plasma gases (H, D, He). An experimental uncertainty in the ion temperature measurement of 20 to 25 % was achieved. A similar result for ion temperature measurement accuracy was achieved on the UNITOR tokamak by Born et al. [93] also using 385 μm D_2O and 383 μm CD_3Cl lasers in a 90° scattering angle and 60 MHz wide receiver channels.

The signal to noise ratio (S/D) of these first tokamak ion thermal CTS measurements was limited not only by background noise but also more fundamentally by the short laser pulse lengths of about 1μs. Thermal fluctuation measurements at wavelengths in the infrared to millimeter-wave range are limited to a maximum S/N that is determined by the square root of the receiver channel bandwidth and integration time product ($\sqrt{\Delta f \cdot t}$) [56]. In these early ion thermal CTS experiments this corresponded to a maximum theoretical S/N of about 10, which in practice was much lower. Longer pulse or more rapidity pulsed sources (higher average power) to increase signal integration time would be need to make significant improvements in S/N for ion temperature CTS [56].

6 First Experiments with Gyrotrons

The earliest reported application of a gyrotron to plasma diagnostics was made in 1984 by Terumichi et al [94] in Japan. A 70 GHz gyrotron was used for drift wave turbulence measurements in the WT-2 tokamak. At about the same time the first gyrotron designed for CTS plasma diagnostics, a 137 GHz, 1 kW, ~ 0.1 s pulsed gyrotron described above [62], was implemented on the TARA tandem mirror experiment at MIT for CTS measurements of plasma instabilities driven from thermal levels [95, 96]. The CTS diagnostic geometry on the TARA axicell midplane is shown in Figure 9. Three homodyne receivers were used at different scattering angles to look at a range of fluctuation k values between 4 and 42 cm^{-2}. Evidence of the axial loss cone instability was seen and ion Bernstein harmonics were observed during ICRH that could be modeled with thermal CTS calculations perpendicular to the magnetic field [97]. In another early CTS gyrotron application Bowden et al [98] reported using a step-tunable gyrotron in the frequency range of 75-330 GHz for scattering measurements on the TORTUS tokamak in Australia. These first gyrotron applications did not target thermal ion CTS measurements but did establish that gyrotrons could be useful sources for plasma diagnostics.

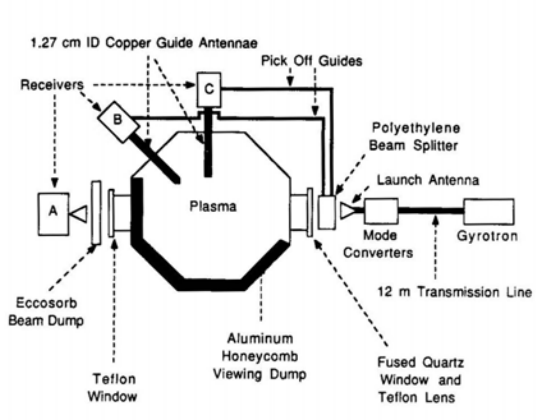

Figure 9. TARA gyrotron CTS scattering geometry

7 Other Experiments

7.1 TFTR

Efforts to implement gyrotron CTS diagnostics for alpha-particles on JET and TFTR were both started at about the same time in the late 1980’s. At TFTR the effort did not go to completion as originally planned. The TFTR plan was to exploit the X-mode window below the electron cyclotron resonance as described above using an existing ~200 kW, 56 or 60 GHz gyrotron from another project in the U. S. Design calculations showed that alpha-particle energy distributions could be resolved [99-101]. Progress was made in implementation [102, 103], but unfortunately costs inflated significantly as problems were encountered with obtaining a healthy gyrotron tube and with installation of the beam dumps. At one point the TFTR vacuum vessel was severely contaminated for one month when after installation about 200 silicon carbide beam dump tiles (5 x 5 cm^2) out gassed a detergent used in their machining. However, the main problems for the project were the costs and lack of a high power working gyrotron tube. Eventually the diagnostics gyrotron used on the TARA tandem mirror at MIT was modified with a 60 GHz resonator and installed on TFTR. The completed TFTR system is shown in Figure 10. The gyrotron power output was only 1 kW, changing the goals of the experiment to look for resonance enhancements of the CTS spectra for fluctuation vector (**k**) orientations perpendicular to the magnetic field [104]. Though the old CTS electrostatic theory predicted that with 1 kW the lower hybrid resonance could be observed, the new generalized electromagnetic theory predicted that scattering from the field fluctuations would cancel out the electron density term. The results supported the new theory [20-23]. This experiment and that of Bertz et al [105] also demonstrated for the first time the suitability of the millimeter-wave X-mode window for CTS in tokamaks.

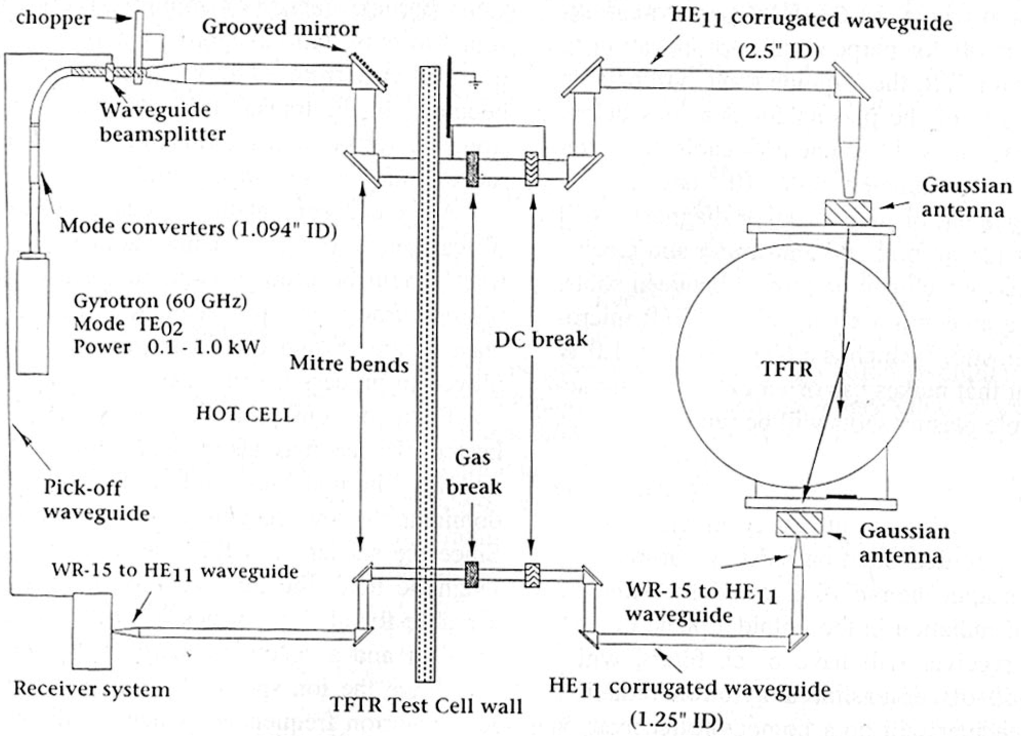

Figure 10. Schematic layout of the TFTR gyrotron CTS system.

7.2 JET

Detailed design studies for implementing gyrotron CTS on JET settled on using a frequency of 140 GHz between the fundamental and second harmonic of the ECE in O-mode [106, 107]. The X-mode below the fundamental ECE emission was not accessible in JET because the maximum magnetic field of JET (3.4 Tesla) was too low to raise the fundamental ECE emission above the X-mode cutoff. The gyrotron beam and the receiver field-of-view accessed the plasma through top and bottom ports, respectively, similar to the TFTR CTS geometry. Internal motor scanned mirrors were use to access a range of scattering angles, plasma positions, and orientations perpendicular and parallel to the magnetic field. Corrugated transmission lines with universal polarizers connected the gyrotron and receiver to the tokamak ports.

The period of installation and making operational the JET CTS system was a long and difficult one. There were many setbacks and challenges that had to be overcome. One problem was with the gyrotron tube. It was learned that high power gyrotrons were not as reliable as originally envisioned. They failed and needed to be replaced. Spares tubes were needed on site. The high voltage power supplies to operate the gyrotron required more work than planned. MIT loaned two power supplies to JET (from the terminated TARA mirror project) that could be used in parallel to marginally meet the long pulse power requirement for the CTS gyrotron. During refurbishment one of these oil filled power supplies caught fire and burned to total destruction. Luckily, a better one with a higher average power rating was obtained from Lawrence Livermore Laboratory. The engineering of the mechanically scanned mirrors inside the tokamak vacuum vessel also proved challenging. JET joined TFTR in having its vacuum vessel severely compromised by a CTS diagnostic when one mirror steered beyond its range and broke the vacuum seal. Despite these problems and others the CTS diagnostic on JET eventually became operational.

As usual with these diagnostic systems the receiver system became operational first. By 1992 the background ECE measurements were being made with the receiver [108]. In 1997 the full CTS system with the gyrotron was finally operational, but not in time for D-T plasmas and alpha-particles. The gyrotron vacuum widow on the tokamak was not fully tested and permission to fire the gyrotron during D-T operation could not be obtained. It is likely, in retrospect that alpha-particle data would not have been possible because the ECE background was too high in the 12 keV plasmas during the peak of the fusion burn. This is a shortcoming of using the O-mode widow between the ECE harmonics at high temperatures in a tokamak, because overlap between the harmonics increases exponentially with temperature and what was calculated to be ok at 10 keV becomes unacceptable at 12 keV. The first CTS results of fast ions were obtained with ICRH heated energetic ions after the D-T campaign ended and are shown in Figure 11 [109, 110]. Post run calibration activity and gyrotron linewidth measurements helped in analyzing the data [111, 112]. The JET data demonstrated for the first time that CTS diagnostics could observe fast ions in a tokamak.

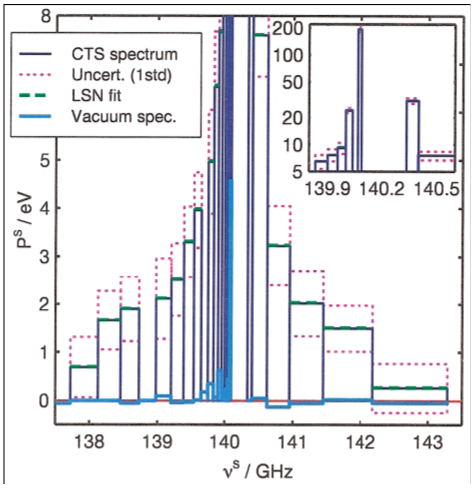

Figure 11. CTS fast ion spectrum in ICRH JET plasma (shot 44198) with 400 kW RF and a vacuum shot for comparison. The frequencies offset 2 GHz from gyrotron line center at 140 GHz correspond to about 50 keV proton energies (from Bindslev [110]).

7.3 W7-AS

In the mid 1990's, in parallel with the efforts on JET, gyrotron CTS measurements of the ion thermal feature were obtained by Suvorov et al [113, 114] in the W7-AS stellarator. Using a 140 GHz, 0.45 MW gyrotron and a 160° backward scattering angle, they were able to measure ion temperature in the T_i = 200 - 500 eV range with better signal to noise ratio than the first FIR laser experiments on tokamaks [87, 91]. The improved signal to noise ratio was a result of the low ECE backgrounds of 1 – 2 eV at the fourth harmonic in the 1.25 Tesla, T_e=500 eV plasmas and the long signal integration times made possible by gyrotron pulses of up to 30 ms. The scattering geometry was restricted to one plasma location to minimize stray light due to the lack of beam and viewing dumps, but nevertheless the superiority of long pulse gyrotrons over short pulse lasers for thermal CTS was demonstrated. They also observed beam driven plasma wave scattering at the lower hybrid frequency. This nonthermal lower hybrid wave scattering was only triggered by the transverse diagnostic neutral beam and not by the more powerful tangential heating beams. They concluded that this would not be an issue for alpha-particle diagnostics in burning plasmas. The study by CTS of this phenomenon in W7-AS is continuing [115].

7.4 TEXTOR

After the JET experiments all the ingredients for continued fast ion CTS development and research were found to be available at the TEXTOR tokamak in Jülich, Germany. A 100 kW, 110 GHz gyrotron system was installed on TEXTOR and the tokamak magnetic field could be tuned to 2.6 Tesla so that gyrotron frequency was between the fundamental and second harmonic ECE for transmission through the plasma. This is the same O-mode window as used on JET, but with electron temperatures no more than 2 keV there would be no problems with background ECE. TEXTOR also had ICRH and neutral beam injection systems to generate fast ions. The CTS receiver system equipment that was previously used on TARA and TFTR was readily adapted for CTS in TEXTOR. The diagnostic system came together very quickly. About two years after initial discussions and planning a complete fast ion gyrotron CTS diagnostic system was operational [116-118]. This experience was a refreshing change, and in sharp contrast, to the long and difficult experience on JET getting the CTS diagnostic system implemented.

The scattering geometry was approximately a back scattering one (~160°) with gyrotron and receiver beams accessing the plasma through the same outboard horizontal port. They could be steered to look at different plasma locations and to change the orientation of the fluctuation wavevector relative to the magnetic field. After optimizing the gyrotron operating parameters to tune the frequency into the receiver notch filter and minimize spurious modes, the CTS plasma measurements were very successful. The gyrotron was modulated to be on for 2 ms and off for 2 ms typically for 90 cycles during one plasma shot. A CTS spectrum was obtained for each cycle. The set of CTS spectra obtained for TEXTOR shot 89509 through NBI turn off is shown in Figure 12. More ion thermal CTS spectra were obtained in one plasma shot on TEXTOR than the sum all pervious efforts in tokamaks. For the first time CTS was showing the evolution of the localized energetic ion energy distributions as auxiliary heating was turned on and off, during sawteeth, and variations in energy distributions for different orientations to the magnetic field. The initial TEXTOR measurements represent a significant advance in thermal CTS diagnostics [119]. After a long hiatus for installing an ergodic limiter on TEXTOR the fast ion CTS diagnostic is operational again in 2005 with improvements to further develop this diagnostic and obtain new fast ion data [120].

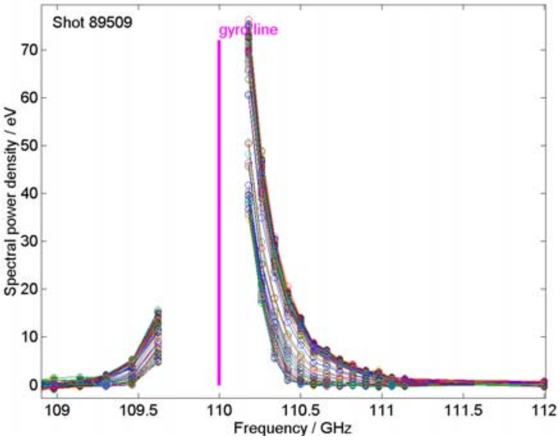

Figure 12. 90 CTS spectra obtained during a single TEXTOR shot showing a time evolution narrowing of the spectrum as the NBI was turned off and the ion energies relaxed (from Bindslev [120]).

7.5 JT-60

Small angle, 10 μm CO_2 laser CTS is a potential alternative approach to millimeter-wave gyrotrons for alpha-particle diagnostics. It main advantages being the well developed laser technology and a wavelength far from background plasma emission and refractive effects. This approach was initially proposed by Hutchinson et al [15] and a proof of principal result was obtained on the ATF stellarator [79]. At the turn of this millennium a major test of this approach was implemented on the JT-

60 tokamak [80]. To meet the condition for collective scattering (Eq. 1) a scattering angler of 0.5° was required. So far the results have been inconclusive due to electrical noise from the laser and large stray laser light levels and due to higher order laser modes outside the notch filter [121].

7.6 ASDEX Upgrade

A gyrotron fast ion CTS diagnostic is currently being implemented at ASDEX-Upgrade to study the role of fast ions ion in high performance plasmas with up to 20 MW NBI and 7 MW ICRCH auxiliary heating capability. Like TEXTOR, ASDEX-Upgrade has ECRH gyrotron facilities that will be available for CTS. New step tunable gyrotrons, tunable to one of two frequencies at 105 or 140 GHz, are being installed on ASDEX-Upgrade. Risø national Laboratory has built and installed a new receiver at 105 GHz with 50 channels for CTS measurements. This receiver with a movable mirror taps into an existing gyrotron beam line to provide access into the tokamak. The receiver and the first step tunable gyrotron are currently being commissioned [120]. CTS measurements will be possible at 2.5 Tesla magnetic fields where the 105 GHz frequency is between the fundamental and second harmonic of the ECE background. Though this window in ASDEX-U frequency space is hotter than TEXTOR it is expected have a background noise temperature less than 100 eV for CTS.

7.7 ITER

The promise of unprecedented capability for localized fast ion energy distribution measurements by CTS in plasmas is finally being realized, but the challenge for future fusion burning plasmas such as ITER remains. It does now appear that CTS will be capable of meeting the important alpha-particle diagnostic need for ITER. Recently Bindslev et al [122] have reviewed the options of fast ion CTS for ITER and have concluded that a gyrotron system at about 60 GHz in the X-mode window, similar to what was originally planned for TFTR, will be best able to provide the needed measurements. Edgel et al [123] have shown that the 1 MeV D_2 neutral heating beams will not be a significant impediment to alpha particle diagnostics on ITER. A conceptual design has shown that up to 20 fixed receiver views both from outside and inside the torus will be able to provide the spatial and anisotropic resolution to fully map out the alpha-particle energy distributions [124]. By using fixed views, moving parts are eliminated from the harsh ITER environment for increased reliability. It was also shown that a dedicated receiver to view the bulk ion thermal feature could provide a diagnostic of the D-T fuel ratio. Consequently CTS may provide ITER with important experimental measurement abilities where other approaches are not available.

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