PSFC/JA-04-7

CONCEPTION OF THERMAL FAR-INFRARED COLLECTIVE THOMSON SCATTERING AND ITS EVOLUTION TO GYROTRON SCATTERING ON JET/TEXTOR/ASDEX UPGRADE

P. P. Woskov

March 2004

Plasma Science and Fusion Center
Massachusetts Institute of Technology
Cambridge, MA 02139

CONCEPTION OF THERMAL FAR-INFRARED COLLECTIVE THOMSON SCATTERING AND ITS EVOLUTION TO GYROTRON SCATTERING ON JET/TEXTOR/ASDEX UPGRADE

PAUL WOSKOV

Plasma Science and Fusion Center
Massachusetts Institute of Technology
NW16-110, Cambridge, MA 02139, USA

The author's involvement in the development of thermal collective Thomson scattering for ion energy distribution measurements in plasmas is reviewed from early work with far infrared lasers and experiments on Alcator C to gyrotrons and JET, TEXTOR, and ASDEX Upgrade experiments.

1   Introduction

Collective Thomson scattering (CTS) is defined as the scattering of electromagnetic radiation by free electrons that are coupled at some distance. In a plasma, the electron motions are coupled at a minimum distance corresponding to the Debye shielding length that defines an electrically neutral plasma. Consequently, the CTS signal will provide information about the ion temperatures and energy distributions. This review will be limited to thermal CTS caused by the ion thermal fluctuations in a plasma requiring a high power source for scattering observations. Plasma turbulence and plasma waves also couple electron motions at longer distances. However, non-thermal CTS due to turbulence and waves not requiring high power sources has not been the main motivation of the author's work reviewed here.

Thermal collective Thomson scattering was first discovered in 1958 by Bowles [1] when he aimed his radar up at the ionosphere and received a backscattered signal that was not broadened as expected for the electron energies. In 1960 Salpeter [2] explained these observations as due to the electrons shielding the ions and introduced the now well known parameter α that defines the plasma and scattering parameters when collective scattering can be observed as $\alpha > 1$.

$$\alpha = \frac{1}{k\lambda_d} = 1.35 \times 10^{-3} \frac{\lambda_o}{\sin\left(\frac{\theta}{2}\right)} \sqrt{\frac{n}{T}} \qquad (1)$$

where k is the fluctuation wave number, λ_d is the electron Debye length, λ_o is the scattering source 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 illustrated in Figure 1. The fluctuation frequency is also defined as the difference between the incident and scattered frequencies.

This 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
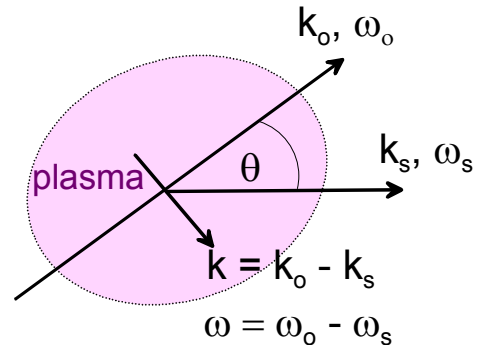

Figure 1. CTS scattering geometry

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 at scattering angles ($\theta > 1^\circ$) large enough to avoid the unscattered laser beam. A small sampling of these early experiments includes DeSliva et al [3] who published measurements taken in a hydrogen arc plasma, Evans et al. [4] who showed results for a thetatron, and many others such as Ramsden et al [5] and Röhr [6] 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) rapidly expanded with a growing demand for better plasma diagnostics. In particular, a diagnostic for localized tokamak ion temperature was desired. Simultaneously there were also rapid advances being made in the development of far infrared (FIR) lasers in the wavelength range of ($\lambda = 0.1 - 1$ mm) [7]. Jassby et al [8] recognized that CTS could be applied to tokamak plasma ion temperature measurements with a modest advancement in the then existing FIR laser technology. It was the consequences of this realization that launched the present author's professional career.

2   FIR Lasers and Receivers

2.1   FIR Lasers

After doing graduate research with electric discharge FIR lasers [9, 10], the author was hired in 1976 by the Francis Bitter National Magnet Laboratory at MIT to pursue the development of high power optically pumped FIR lasers for tokamak CTS diagnostics of ion temperature. FIR laser requirements for ion temperature CTS were estimated as: a power output of about 1 MW, in 1 μs, with a linewidth less than 100 MHz. Initial development efforts at MIT [11] and other laboratories [12, 13] were focused on the CO_2-laser pumped 496 μm methyl fluoride laser using a low power oscillator to achieve narrow linewidth followed by an amplifier section. Soon it became apparent that a shorter wavelength was needed to increase the CTS frequency away from background plasma electron cyclotron emission (ECE). The author and co-workers carried out initial experiments on the 385 μm D_2O laser using a very short oscillator and long amplifier as shown in Figure 2 producing up to 195 kW peak power [14].

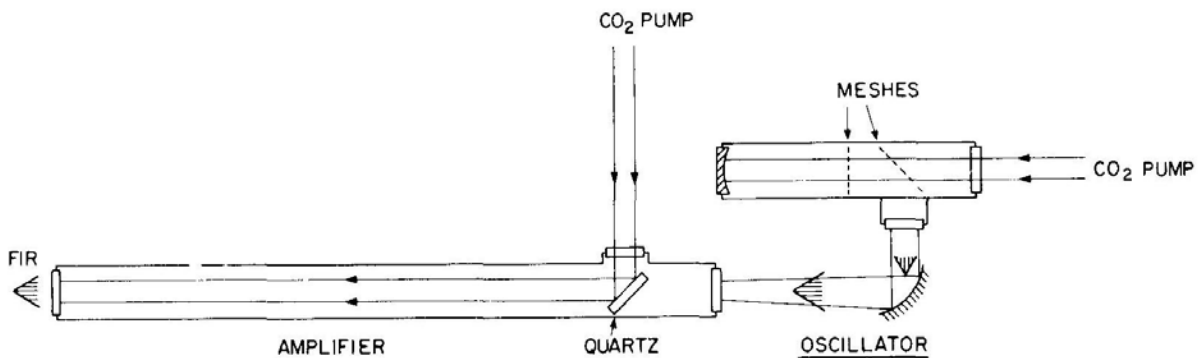Controlling the linewidth as output power level was increased was a major challenge because

Figure 2. 385-μm D_2O laser oscillator-amplifier system

these lasers have very high gain and can operate superradiantly. An oscillator with a Fox-Smith mode selector was tested in 1977 [15] to help control the laser linewidth as shown in Figure 3. Further development focused on the CO_2 pump laser when it was discover that these high-power pulsed FIR laser emissions were due simulated Raman emission and therefore limited by the linewidth of the pump laser.

A powerful, single mode ~100 MW CO_2 laser oscillator-amplifier system with an etalon tuned oscillator was developed. This pump laser used an innovative combination of SF_6 as a 10-μm absorber and formic acid as a 9-μm saturable absorber in the amplifier chain to suppress self-oscillation [16]. With this pump laser 800 kW at 385 μm was achieved in a linewidth suitable for CTS [17]. It was also shown that the optimum pump frequency for high

Figure 3. FIR laser oscillator with Fox-Smith mode selector.

power operation was obtained by using the etalon to tune the CO_2 laser frequency away from the line center absorption of the D_2O laser, as expected for a stimulated Raman laser. Single pulse linewidth measurements using a SAW depressive delay line confirmed the narrow linewidth and tunablity of the FIR frequency with the pump frequency tuning [18]. The SAW device was considered a great innovation at the time because we didn't have digital oscilloscopes and instantaneous FFT processing capability back then.
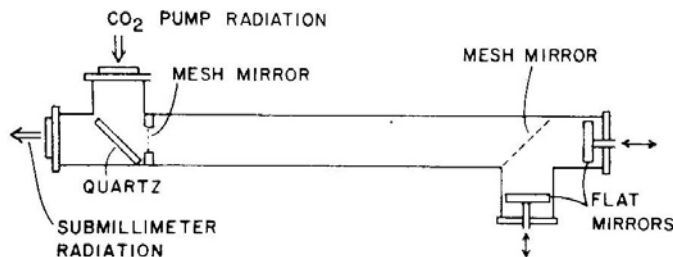
2.2 Other Groups

To be fair, it is necessary to recognize that many other groups besides the author's group at MIT were developing FIR lasers for CTS diagnostics at this time. In the United States there were parallel efforts at MIT, UCLA, and ORNL. Luhmann's group at UCLA was researching many laser configurations [12] including a pulsed CO_2 laser pumped FIR ring laser to achieve narrow linewidth and high power [19, 20]. At Oak Ridge, Hutchinson's group was developing an injection locked CO_2 pump laser to achieve narrow linewidth operation [21]. Eventually at Princeton Plasma Physics Laboratory, Semet et al [22] set the record for high power from a 385 μm D_2O laser of about 2 MW with 5 J energy per pulse.

There were other international efforts as well. In Japan, Muraoka's group built and experimented with a D_2O laser system [23, 24]. Also in Japan, Yamanaka built a D_2O laser system for CTS [25]. In another effort in Japan, Hirose experimented with intracavity pumped FIR lasers [26, 27]. In Europe, besides Evans's group already mentioned [13], Siegrist's group in Lausanne, Switzerland did significant research on the D_2O laser for CTS diagnostics [28, 29].

2.3 Receivers and Other Components

A CTS diagnostic system for ion thermal fluctuation measurements on a tokamak requires more than a high power FIR laser. A very sensitive, wide bandwidth (> 2 GHz) receiver is also needed to

detect the weak scattered signals. At MIT quasi-optical Schottky diode mixers were developed at Lincoln Laboratory for FIR heterodyne receivers using cw FIR lasers as the local oscillator (LO) [30]. A Schottky diode heterodyne receiver operating in the frequency range of 400 – 800 GHz using various formic acid laser lines for the LO was implemented on the Alcator A tokamak in 1980. With this receiver the first plasma background emission measurements were made for plasma conditions that would later be used for FIR CTS ion thermal measurements. These first measurements showed that, at least for electron temperatures in the 1- 2 keV, range ECE background emission would not be a problem [31-33].

Other components that are important for a successful CTS system for thermal ion diagnostics are the beam and viewing dumps and a notch filter for stray radiation. The beam dumps need to be compatible with the high vacuum and compact in size to fit inside the tokamak. Graphite tiles with submillimeter-wave radiation trapping structures were developed for the first CTS measurements on Alcator C as shown in Figure 4 [34]. The other component, a narrow frequency notch filter for the 385 μm D_2O laser was developed by using a low pressure N_2O gas cell. Using this notch filter and the Shottky diode heterodyne receiver the author made the first measurements of the D_2O laser linewidth over a 60 dB dynamic range [35].
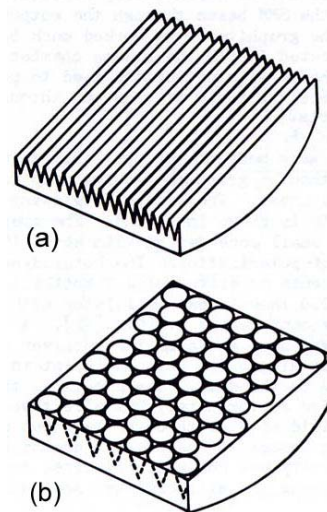
Figure 4. Graphite beam dump tiles (a) V-grooves for polarized beams, (b) conical holes for unpolarized beams

3   First Tokamak Experiments

In 1983, seven years after the author began working on FIR CTS, a complete D_2O laser CTS diagnostic system was ready for ion thermal fluctuation measurements on Alcator C, a few weeks before Alcator C would be permanently shut down. The scattering angle was 20° through vertical ports on top and bottom of the tokamak. The author remembers that working on Alcator C on a run day could be a challenging experience because Alcator C was cooled by a large liquid nitrogen dewar that totally enclosed the entire tokamak. One day while adjusting the FIR optics below Alcator he felt the sensation of liquid nitrogen dripping down his back from a leak in the dewar above him around his port. He learned to be quick with his adjustments on run days.

Stray light was a major 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. Figures 5 and 6 show these historic results [36]. Measurements in the central part of the spectrum are missing because of the filtering used to minimize the stray light. 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. Though these particular measurements were marginal for ion temperature diagnostics, they did show that with improvement in the signal to noise ratio CTS measurements of ion thermal fluctuations in a tokamak were possible.
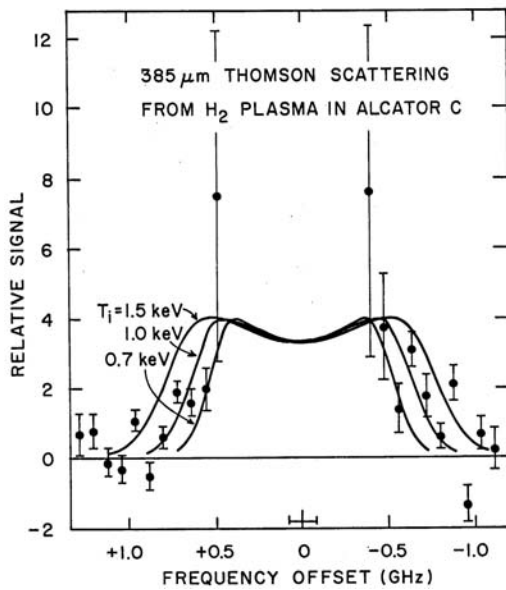
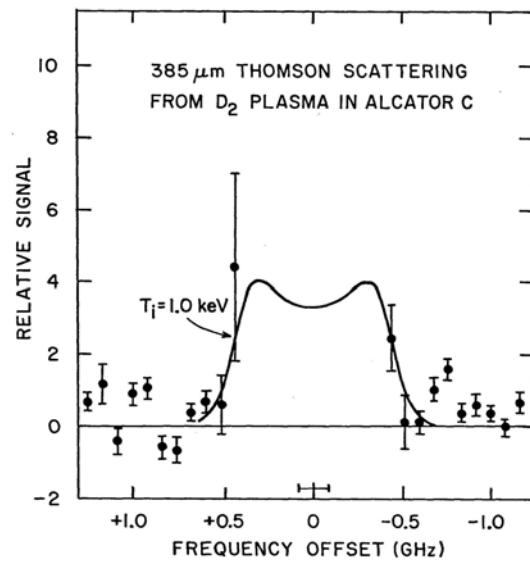Figure 5. D$_2$O laser CTS spectrum form Alcator C hydrogen plasma

Figure 6. D$_2$O 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 [37] on the TCA tokamak in Lausanne. They also used a 385 μm D$_2$O laser, but slightly more powerful (0.5 J, 1.4 μs) than the MIT laser. With a scattering angle of 90° 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).

4   Gyrotrons and Alpha Particles

By the time the first tokamak laser CTS measurements of ion thermal fluctuations were being carried out there were two developments that changed the course of the research. First, it was recognized that higher average power than available by the FIR lasers developed for those first tests would be needed to achieve higher signal to noise ratios. This would necessitate longer pulses or rapidly pulsed sources. The author and his colleagues proposed in 1983 [38] that the rapidly advancing capabilities of gyrotrons might be attractive for thermal CTS. The second development was that there was no longer a need for a thermal CTS diagnostic for localized ion temperature because of advances in x-ray Doppler broadened spectroscopy of impurity radiation [39, 40]. However, a new need for thermal CTS was recognized and that was to provide a diagnostic for fast fusion product alpha particles [41, 42].

4.1   Gyrotrons

In the early 1980's gyrotron research at MIT was being actively advanced by Temkin et al [43-45]. The author became involved in a number experiments to study the frequency properties of gyrotrons to advance the understanding of gyrotrons and to determine their suitability for plasma diagnostics.

5

Using the SAW filter instrumentation first used for D_2O laser frequency measurements, the frequency pulling and bandwidth of a 140 GHz gyrotron were studied [46]. The measured gyrotron linewidth (< 3 MHz) in 1 μs pulses, with a low Q resonator (~ 400) designed for electron cyclotron heating, was found to be less than that for an FIR laser, thus establishing the suitability of gyrotrons for diagnostics. In another experiment, high power second harmonic emission at 241 GHz was demonstrated [47] showing the feasibility of scaling up the frequency of gyrotrons for diagnostics. Research was also carried out on gyrotrons with high Q resonators specifically designed for plasma diagnostics [48] and novel methods for cold testing the resonator Q [49]. There were similar efforts elsewhere. Most notably in Australia, Brand et al [50] and in Japan, Idehara et al [51] were developing high frequency gyrotrons for plasma diagnostics. There was also similar work in Russia [52].

4.2   First Gyrotron Plasma Experiments

A 137 GHz, 1 kW, long pulse (~ 0.1 s) gyrotron was designed and implemented by the author and his colleagues on the TARA tandem mirror experiment in 1985 for CTS measurements of plasma instabilities driven from thermal levels [53, 54]. The main features of this gyrotron, probably the first purposely designed for plasma diagnostics, are illustrated in Figure 7. The gyrotron used a high-Q (~ 6000) resonator to optimize frequency stability and minimize linewidth. The measured linewidth with a frequency tracking heterodyne receiver was approximately 1 kHz, the instrumental limit of the receiver. In homodyne mode, where the gyrotron beam is mixed with itself, the linewidth was the Fourier transform limit of the pulse length or about 100 Hz for 10 ms pulses. Internal waveguide mode converters were used to convert the resonator mode from the circular TE_{03} to the TE_{01} [55] for transmission 12 m to the TARA diagnostic port in 12.7 mm diameter waveguide, where additional TE_{01} to HE_{11} mode converters produced a Gaussian beam. The CTS diagnostic geometry on the TARA axicell midplane is shown in Figure 8. Three homodyne receivers were used at different scattering angles. Ion Bernstein harmonics were observed during ICRH that could be modeled with thermal CTS calculations [56].
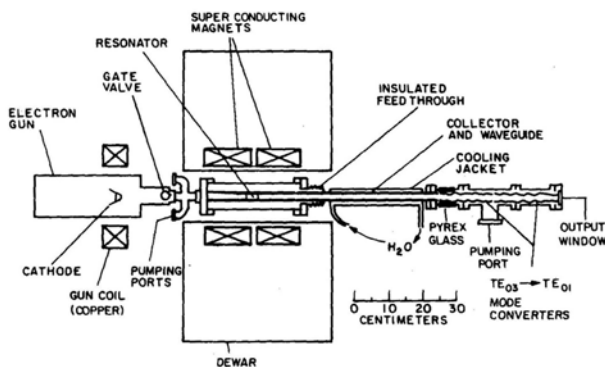

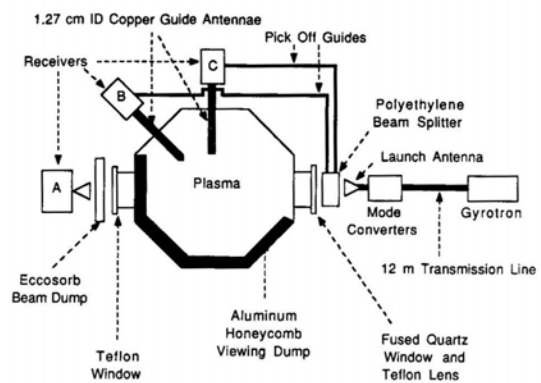Figure 7. 137 GHz gyrotron for plasma diagnostics.

Figure 8. TARA gyrotron CTS scattering geometry

Other groups were also applying gyrotrons to plasma diagnostics at this time, though for non-thermal CTS. The earliest report in 1984 was by Terumichi et al [57] of a 70 GHz gyrotron used for density fluctuation measurements in the WT-2 tokamak in Japan. Also, Bowden et al [58] reported in 1988 using a step-tunable gyrotron in the frequency range of 75-330 GHz for scattering measurements on the TORTUS tokamak in Australia. Most notable, however, in 1995 were the gyrotron thermal CTS measurements by Suvorov et al [59, 60] in the W7-AS stellarator. Using a 140 GHz, 0.45 MW gyrotron and a backward scattering geometry, they were able to measure ion temperature and beam-driven waves with better signal to noise ratio than the first FIR laser experiments on tokamaks [36, 37].

4.3   The Prospect for CTS Alpha Particle Diagnostics

By the early 1980's the physics of fusion product alpha-particles became a leading topic of plasma fusion theoretical research [61, 62]. It was also recognized that diagnostics would be needed for fast confined alpha-particles in the then planned D-T experiments in TFTR and JET tokamaks if the experimental understanding of alpha-particles was to be advanced. In 1985 CTS was recognized as a leading candidate for providing the need measurement capability by Hutchinson et al [41] and Vahala et al [42] using small angle CO_2 laser scattering. In 1986 the author pointed out that large angle gyrotron CTS would have advantages for alpha-particle diagnostics over using CO_2 lasers and that there would be X-mode transparent windows in millimeter-wave frequency space in tokamaks [63]. Subsequent calculations of CTS alpha-particle spectra by Hughes et al [64] and Vahala et al [65] using the electrostatic plasma model for CTS originally derived by Salpeter [2] verified that CTS with gyrotrons could succeed in making the desired fast ion measurements. Also about this time Bretz [66] derived the corrected geometrical form factor for millimeter-wave X-mode CTS in a tokamak.

Significant theoretical and experimental developments of CTS for fast ion measurements followed. Theoretical advancements by Aamodt [67] and Bindslev [68, 69] generalized the CTS theory to include all the electromagnetic field fluctuations. The corrections would be important for CTS in the millimeter-wave range near plasma resonances and cutoffs. On the experimental front activities were started to implement gyrotron CTS diagnostics on both TFTR at Princeton in the U. S. and JET at Abington in the U. K. The author was involved in both of these activities as described below. Also the author was involved in initial design calculations in the early 1990's of gyrotron CTS for the then ITER fusion burning tokamak design [70, 71]. Figure 9 shows the calculated X-mode millimeter-wave frequency space in the 6 Tesla ITER design with the relativistically downshifted ECE resonances. A window for CTS between the X-mode cutoff and the downshifted ECE fundamental resonance would exist between 75 and 90 GHz. This X-mode window for CTS continues to be the primary choice for alpha-particle diagnostics in the most current ITER design at the time of this writing.
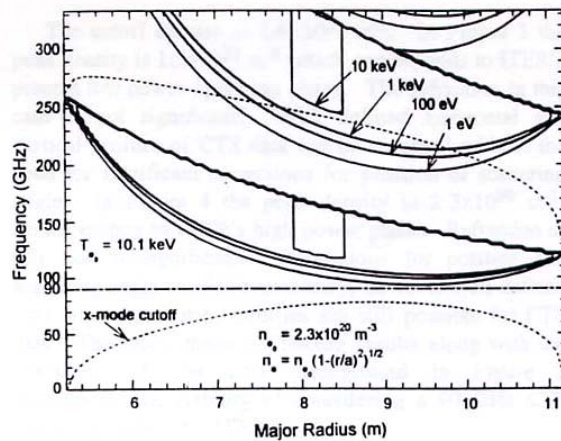

Figure 9. Contour plots of ECE and cutoffs for X-mode propagation in ITER 1993 design.

5   JET and TFTR

5.1   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 [72,73]. Progress was made in implementation [74, 75], but unfortunately costs inflated significantly as problems were encountered with getting 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 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 TARA diagnostics gyrotron built by the author 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 [76].   Though the old CTS
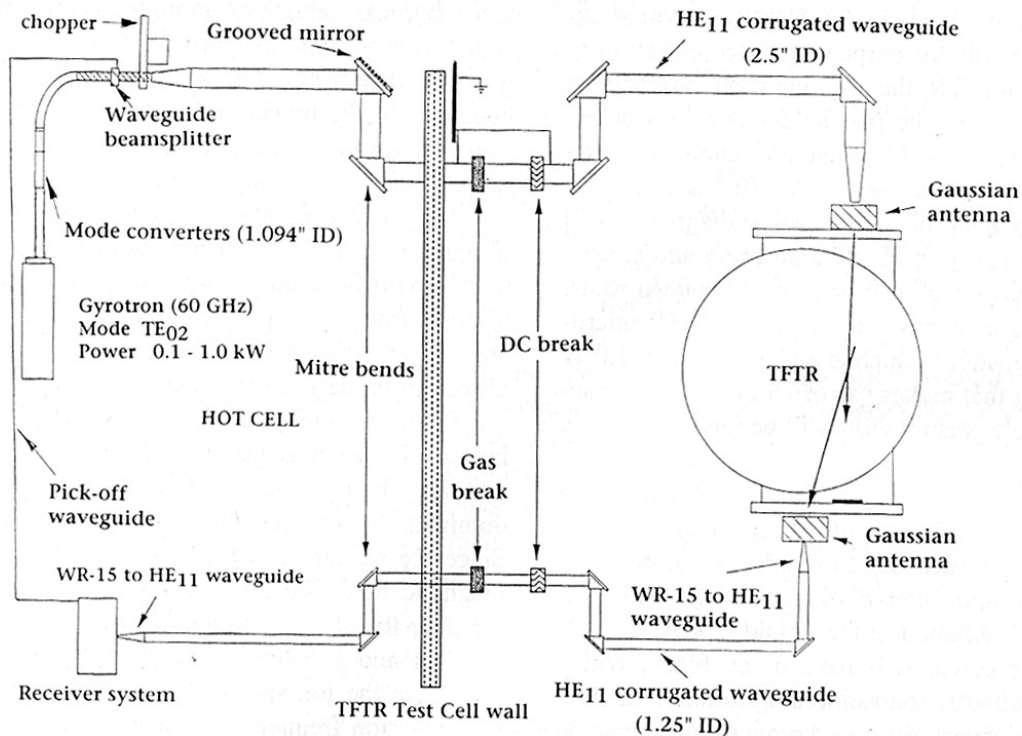

Figure 10. Schematic layout of the TFTR gyrotron CTS system.

electrostatic theory predicted that with 1 kW the lower hybrid resonance could be observed, the new generalized electromagnetic theory predicted that it could not be observed. The results supported the new theory [77]. This experiment and that of Bertz et al [78] also demonstrated for the first time the suitability of the millimeter-wave X-mode window for CTS in tokamaks.

5.2   JET

Detailed design studies for implementing gyrotron CTS on JET settled on using a frequency of 140 GHz between the fundamental and second harmonics of the ECE in O-mode [79, 80]. 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. A schematic of the JET CTS system is shown in Figure 11. The gyrotron beam and the receiver field-of-view accessed the plasma through top and bottom ports, respectively. 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. We 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, MIT did not miss this power supply and a better one with a higher average power rating was obtained from Lawrence Livermore Laboratory. The engineering of the
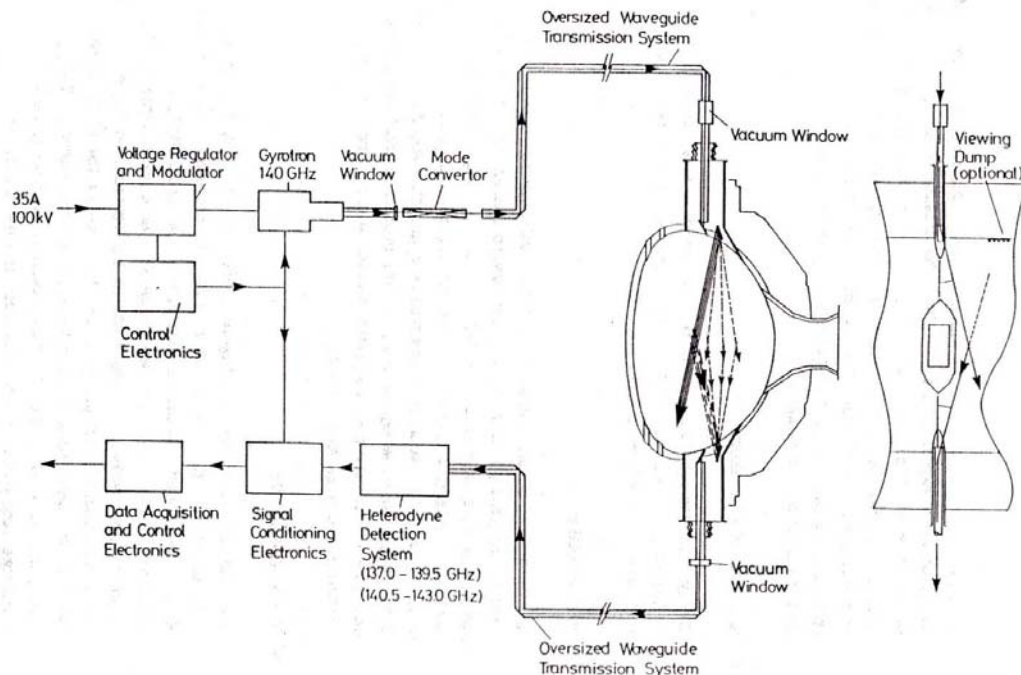

Figure 11. Schematic layout of the JET gyrotron CTS system.

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 gradually 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 [81]. In 1997 the full CTS system with the gyrotron finally became 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 obtained 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, which would have been ok at 10 keV temperatures. The first CTS results of fast ions were obtained with ICRH heated energetic ions after the D-T campaign ended [82, 83]. Post run calibration activity and gyrotron linewidth measurements helped in analyzing the data [84, 85]. The JET data did demonstrate that CTS diagnostics could observe fast ions in tokamak, but with difficulty and at great cost on JET. Continued CTS research at JET was terminated. The author and some of his colleagues from the JET experience looked elsewhere to continue the CTS development effort.

6   TEXTOR and ASDEX Upgrade

6.1   Initial TEXTOR 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 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 ECE. TEXTOR also had ICRH and neutral beam injection systems to generate fast ions. The author had available the CTS receiver system previously used on TARA and the filter bank from the Alactor C experiments, which could be 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 on TEXTOR [86-88]. This experience was a refreshing change, and in sharp contrast, to the long and difficult times the author spent on Alcator C and JET getting CTS diagnostic systems implemented.

The TEXTOR CTS scattering geometry as originally planned is shown in Figure 12. Only the first receiver was implemented. The second receiver displaced toroidaly is still in the plans for future deployment. The gyrotron and receiver beams 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. A CTS spectra was obtained for each cycle. More ion thermal CTS spectra were obtained in one plasma shot on TEXTOR than the sum all pervious efforts in which the author was involved. For the first time CTS was showing the evolution of the localized
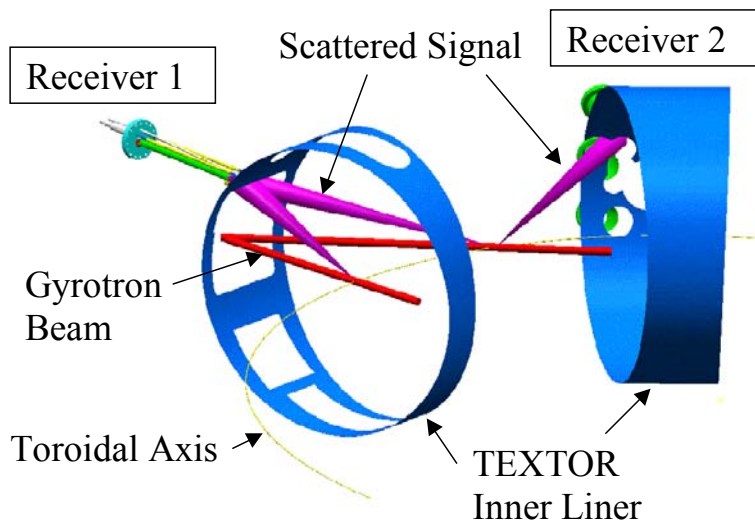
Figure 12. CTS scattering geometry on TEXTOR.

energetic ion energy distributions as auxiliary heating was turned on and off and variations in energy distributions for different orientations to the magnetic field. The initial TEXTOR measurements were highly successful [89].

6.2   TEXTOR and ASDEX Upgrade

Shortly after the initial CTS success, TEXTOR started a long shut down to install an ergodic limiter. The CTS diagnostic equipment was removed and activities to make improvements were started for its eventual return to TEXTOR. The CTS receiver was sent to Risø National Laboratory in Denmark to add a dedicated data acquisition system and additional channels. A new receiver beam line was also designed and fabricated at Risø. At the time of this writing these components are being reinstalled. More studies of fast ions by CTS on TEXTOR are anticipated in the near future.

Another development was the start of an association with the ASDEX Upgrade tokamak experiment to install a gyrotron CTS diagnostic at that site. Like TEXTOR, ASDEX Upgrade has 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 status of both the TEXTOR and ASDEX-Upgrade CTS diagnostic implementations were recently presented [90]. 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.

References

[1] K. L. Bowles, Phys. Rev. Let. **1**, 454 (1958).

[2] E. E. Salpeter, Phys. Rev. **120**, 1528 (1960)

[3] A. W. DeSilva, D. E. Evans, and M. J. Forrest, Nature **203**, 1321 (1964)

[4] D. E. Evans, M. J. Forrest, and J. Katzenstien, Nature **212**, 21 (1966)

[5] S. A. Ramsden and W. E. R. Davies, Phys. Rev. Let. **16**, 303 (1966)

[6] H. Röhr, Phys. Let. **25A**, 167 (1967)

[7] T. K. Plant, L. A. Newman, E. J. Danielewicz, T. A. Detemple, and P. D. Coleman, IEEE Trans. on Microwave Theory and Techniques, **MTT-22**, 988 (1974)

[8] D. L. Jassby, D. R. Cohn, B. Lax, W. Halverson, Nucl. Fusion **14**, 745 (1974)

[9] P. Woskoboinikow and W. C. Jennings, Appl. Phys. Lett., **27**, 658 (1975)

[10] P. Woskoboinikow and W. C. Jennings, IEEE J. Quantum Electronics, **QE-12**, 613 (1976)

[11] R. J. Temkin, D. R. Cohn, Z. Drozdowicz, Optics Communications, **14**, 314 (1975)

[12] A. Semet and N. C. Luhmann, Jr., Appl. Phys. Let., **28**, 659 (1976)

[13] D. E. Evans, L.E. Sharp, W. A. Peebles, and Gary Taylor, IEEE J. Quantum Electronics, **QE-13**, 54 (1977)

[14] P. Woskobonikow, Z. Drozdowicz, K. Isobe, D. R. Cohn, and R. J. Temkin, Phys. Let., **59A**, 264 (1976)

[15] Z. Drozdowicz, P. Woskoboinikow, K. Isobe, D. R. Cohn, R. J. Temkin, K. J. Button, and J. Waldman, IEEE J. Quantum Electronics, **QE-13**, 413 (1977)

[16] P. Woskoboinikow, H. C. Praddaude, and W. J. Mulligan, Optics Letters, **4**, 210 (1979)

[17] P. Woskoboinikow, H. C. Praddaude, W. J. Mulligan, D. R. Cohn, and B. Lax, J. Appl. Phys., **50**, 1124 (1979)

[18] H. R. Fetterman, P. E. Tannenwald, C. D. Parker, J. Melngailis, R. C. Williamson, P. Woskoboinikow, H. C. Praddaude, and W. J. Mulligan, Appl. Phys. Lett., **34**, 123 (1979)

[19] D. Umstadter, W. A. Peebles, N. C. Luhmann, Jr., 6th International Conf. on IR and MM Waves, M3-3/1-2 (1981)

[20] W. A. Peebles, D. Umstadter, D. L. Brower, N. C. Luhmann, Jr., Appl. Phys. Lett., **38**, 851 (1981)

[21] D. P. Hutchinson and K. L. Vander Sluis, Appl. Optics, **16**, 293 (1977)

[22] A. Semet, L. C. Johnson, and D. K. Mansfield, Int. J. Infrared and Millimeter Waves, **4**, 231 (1983)

[23] T. Okada, R. Noudomi, F. Nishimura, K. Muraoka, M. Akazaki, Japanese J. of Appl. Phys., **22**, 1344 (1983)

[24] T. Okada, F. Nishimura, S. Inoue, K. Muraoka, M. Akazaki, 8th International Conf. on IR and MM Waves, W5.3 (1984)

[25] M. Yamanaka and Y. Tsunawaki, Proc. Kyushu Intern. Symp. On Laser-Aided Plasma Diagnostics, 103 (1983)

[26] H. Hirose, S. Kon, Japanese J. of Appl. Phys., **19**, 1131 (1980)

[27] H. Hirose, H. Matusada, S. Kon, Optics Comm., **46**, 217 (1983)

[28] M. R. Siegrist, M. R. Green, P. D. Morgan, I. Kjelberg, and R. L. Watterson, J. Appl. Phys., **51**, 3531 (1980)

[29] R. Behn, I. Kjelberg, P. D. Morgan, T. Okada, M. R. Siegrist, J. Appl. Phys., **54**, 2995 (1983)

[30] H. R. Fetterman, P. E. Tannenwald, B. J. Clifton, C. D. Parker, and W. D. Fitzgerald, Appl. Phys. Lett., **33**, 151 (1978)

[31] P. Woskoboinikow, H. C. Praddaude, I. S. Falconer, and W. J. Mulligan, Nuclear Fusion, **21**, 1028 (1981)

[32] P. Woskoboinikow, H. C. Praddaude, I. S. Falconer, and W. J. Mulligan, Appl. Phys. Lett., 34, 548 (1981)

[33] P. Woskoboinikow, H. C. Praddaude, I. S. Falconer, and W. J. Mulligan, J. Appl. Phys., **52**, 7099 (1981)

[34] P. Woskoboinikow, R. Erickson, and W. J. Mulligan, Int. J. Infrared and Millimeter Waves, **4**, 1045 (1983)

[35] P. Woskoboinikow, W. J. Mulligan, and R. Erickson, IEEE J. Quantum Electronics, **QE-19**, 4 (1983)

[36] P. Woskoboinikow, W. J. Mulligan, J. Machuzak, D. R. Cohn, R. J. Temkin, T. C. L. G. Sollner, and B. Lax, Europhysics Conference Abstracts, 11th European Conference on Controlled Fusion and Plasma Physics, Aachen, **7D**, Part II, 81 (1983)

[37] R. Behn, D. Dicken, J. Hackmann, S. A. Salito, M. R. Siegrist, P. A. Krug, I. Kjelberg, B. Duval, B. Joye, and A. Pochelon, Phys. Rev. Lett., **62**, 2833 (1989)

[38] P. Woskoboinikow, D. R. Cohn, and R. J. Temkin, Int. J. Infrared and Millimeter Waves, **4**, 205 (1983)

[39] F. J. Kuehne, J. Erickson, R. Heuer, Proc. 10th Sym. of Fusion Engineering, IEEE, **1**, 279 (1983)

[40] A. J. Liebar, S. S. Wojtowicz, K. H. Burrell, Nuclear Instruments and Methods, **A235**, 565 (1985)

[41] D. P. Hutchinson, K. L. Vander Sluis, J. Shefield, D. J. Sigmar, Rev. Sci. Instrum., **56**, 1075 (1985)

[42] L. Vahala, G. Vahala, D. J. Sigamr, Nuclear Fusion, **26**, 51 (1986)

[43] R. J. Temkin, K. E. Kreisher, W. J. Mulligan, S. MacCabe, and H. R. Fetterman, Int. J. Infrared and Millimeter Waves, **3**, 427 (1982)

[44] K. E. Kreischer, R. J. Temkin, Int. J. Infrared and Millimeter Waves, **2**, 195 (1980)

[45] R. J. Temkin, D. R. Cohn, B. G. Danly, K. E. Kreischer, and P. Woskoboinikow, Proc. Soc. Photo Optical Instr. Eng. (S.P.I.E.), **544**, 31 (1985)

[46] K. E. Kreischer, B. G. Danly, P. Woskoboinikow, W. J. Mulligan, and R. J. Temkin, Int. J. Electronics, **57**, 851 (1984)

[47] J. L. Byerly, B. G. Danly, K. E. Kreischer, R. J. Temkin, W. J. Mulligan, and P. Woskoboinikow, Int. J. Electronics, **57**, 1033 (1984)

[48] H. Saito, B. G. Danly, W. J. Mulligan, R. J. Temkin, and P. Woskoboinikow, IEEE Trans. on Plasma Science, **PS-13**, 393 (1985)

[49] P. Woskoboinikow and W. J. Mulligan, IEEE Trans. on Microwave Theory and Techniques, **MTT-35**, 96 (1987)

[50] G. F. Brand, Z. Chen, N. G. Douglas, M. Gross, J. Y. L. Ma, L. C. Robinson, Australian Institute of Nuclear Science and Engineering 15th Plasma Physics Conf., 19 (1985)

[51] T. Idehara, T. Tatsukawa, S. Matsumoto, K. Kunieda, K. Hemmi, K. Kanemaki, Physics Letters A, **132**, 344 (1988)

[52] T. B. Pankratova, G. S. Nusinovich, Zhurnal Tekhnicheskoi Fiziki, **59**, 110 (1989)

[53] P. Woskoboinikow, D. R. Cohn, M. Gerver, W. J. Mulligan, R. S. Post, and R. J. Temkin, Rev. Sci. Instrum. **56**, 914 (1985)

[54] J. S. Machuzak, P. Woskoboinikow, D. R. Cohn, M. Gerver, W. Guss, M. Mauel, W. J. Mulligan, R. S. Post, and R. J. Temkin, Rev. Sci. Instrum., **57**, 1983 (1986)

[55] J. Trulsen, P. Woskoboinikow, and R. J. Temkin, *MIT Plasma Fusion Center Report*, PFC/RR-86-2, (1986)

[56] J. S. Machuzak, P. P. Woskov, R. C. Myer, W. J. Mulligan, D. R. Cohn, M. Gerver, S. N. Golovato, S. Horne, S. Kubota, R. S. Post, D. Rhee, J. Sullivan, and R. J. Temkin, Rev. Sci. Instrum., **59**, 1562 (1988)

[57] Y. Termumichi, S. Kubo, A. Ando, Y. Yanagimoto, K. Ogura, H. Tanaka, J. Takahashi, I. Tonai, M. Nakamura, T. Maekawa, S. Tanaka, I. Idehara, Conf. Digest 9th Int. Conf. on Infrared and Millimeter Waves, Takarazuka, 411 (1984)

[58] M. D. Bowden, P. W. Fekete, M. J. Ballico, G. F. Brand, I. S. Falconer, B. W. James, K. J. Moore, T. Idehara, Proc. of the SPIE-The Int. Soc. For Otical Engineering, **1039**, (1988)

[59] E. V. Suvorov, V. Erckmann, E. Holzhauer, W. Kasparek, Y. A. Dryagin, S. E. Fil'chenkov, A. A. Faiman, T. Geist, M. Kick, L. M. Kukin, A. V. Kostrov, L. V. Lubyako, A. M. Shtanyuk, N. K. Skalyga, O. B. Smolyakova, W VII-AS Team, NBI Team, Plasma Phys. Control. Fusion, **37**, 1207 (1995)

[60] E. V. Suvorov, E. Holzhauer, W. Kasparek, L. V. Lubyako, A. B. Burov, Y. A. Dryagin, S. E. Fil'chenkov, A. A. Faiman, L. M. Kukin, A. V. Kostrov, D. A. Ryndykt, A. M. Shtanyuk, N. K. Skalyga, O. B. Smolyakova, V. Erckmann, T. Geist, M. Kick, H. Laqua, M. Rust, Plasma Phys. Control. Fusion, **39**, B337 (1997)

[61] Ya. I. Kolesnichenko, Nuclear Fusion, **20**, 727 (1980)

[62] V. Ya. Goloborod'ko, Ya. I. Kolesnichenko, V. A. Yarvoskiij, Nuclear Fusion, **23**, 399 (1983)

[63] P. Woskoboinikow, Rev. Sci. Instrum., **57**, 2113 (1986)

[64] T. P. Hughes, S. R. P. Smith, Nuclear Fusion, **28**, 1451 (1988)

[65] L. Vahala, G. Vahala, D. J. Sigmar, Nuclear Fusion, **28**, 1595 (1988)

[66] N. Bretz, J. Plasma Physics, **38**, part 1, 79 (1987)

[67] R. E. Aamodt, D. A. Russell, Nuclear Fusion, **32**, 745 (1992)

[68] H. Bindslev, Plasma Phys. Control. Fusion, **35**, 1615 (1993)

[69] H. Bindslev, J. Atmos. Terr. Phys. **58**, 983 (1996)

[70] J. S. Machuzak, D. Y. Rhee, P. P. Woskov, and D. R. Cohn, Rev. Sci. Instrum. **71**, 3544 (1990)

[71] P. P. Woskov, D. R. Cohn, J. Gilmore, J. S. Machuzak, and D. Y. Rhee, 15th IEEE/NPSS Symposium on Fusion Engineering, **Vol. I**, 101 (1993)

[72] P. Woskov, J. S. Machuzak, R. C. Myer, D. R. Cohn, N. L. Bretz, P. C. Efthimion, and J. L. Doanne, Rev. Sci. Instrum., **59**, 1565 (1988)

[73] D. Y. Rhee, J. S. Machuzak, P. P. Woskov, and D. R. Cohn, Rev. Sci. Instrum., **61**, 3217 (1990)

[74] D. Y. Rhee, D. R. Cohn, J. S. Machuzak, P. Woskov, N. Bretz, R. Budny, P. C. Efthimion, H. K. Park, Rev. Sci. Instrum., **63**, 4644 (1992)

[75] H. K. Park, N. Bretz, R. Ellis, P. C. Efthimion, R. Marsala, M. McCarthy, G. Renda, K. M. Young, D. R. Cohn, J. S. Machuzak, D. Y. Rhee, P. Woskov, Rev. Sci. Instrum. **63**, 4647 (1992)

[76] J. S. Machuzak, P. P. Woskov, J. Gillmore, N. L. Bretz, H. K. Park, R. E. Aamodt, P. Y. Cheung, D. A. Russell, and H. Bindslev, Rev. Sci. Instrum., **66**, 484 (1995)

[77] J. S. Machuzak, P. P. Woskov, J. Gilmore, N. L. Bretz, H. K. Park, and H. Bindslev, Rev. Sci. Instrum., **68**, 458 (1997)

[78] K.L. Wong, N. Bretz, G. Y. Fu, J. Machuzak, J. R. Wilson, Z. Chang, L. Chen, D. K. Owens, G. Schilling, Phys. Lett. A, **224**, 99 (1996)

[79] A. E. Costley, J. A. Hoekzema, T. P. Hughes, P. E. Stott, M. L. Watkins, JET Joint Undertaking, Abingdon, UK, JET-R(88)08, 105 pp (1988)

[80] H. J. Barkley, W. Kasparek, G. A. Muller, L. Rebuffi, P. G. Schuller, M. Thumm, JET Joint Undertaking, Abingdon, UK, JET-R(88)14, 53 pp (1988)

[81] J.S.Machuzak, P.P.Woskov, H.Bindslev, M.Comiskey, J.Fessey, J.A. Hoekzema, and T.P.Hughes, Rev. Sci. Instrum., **63**, 4648 (1992)

[82] J. A. Hoekzema, H. Bindslev, J. Egedal, J. A. Fessey, C. P. Gatcombe, N. P. Hammond, T. P. Hughes, J. S. Machuzak, J. W. Oosterbeek, P. J. Roberts, A. L. Stevens, P. E. Stott, Rev. Scien. Instrum., **68**, 275 (1997)

[83] H. Bindslev, J. A. Hoekzema, J. Egedal, J. A. Fessey, T. P. Hughes, J. S. Machuzak, Phys. Rev. Lett., **83**, 3206 (1999)

[84] J. S. Machuzak, P. P. Woskov, J. A. Fessey, J. A. Hoekzema, J. Egedal, H. Bindslev, P. Roberts, A. Stevens, P. Davies, C. Gatcombe, and T. P. Hughes, Rev. Sci. Instrum., **70**, 1154 (1999)

[85] J. Egedal, J. S. Machuzak, J. A. Fessey, H. Bindslev, J. A. Hoekzema, T. P. Hughes, P. Davies, C. Gatcombe, and P. P. Woskov, Rev. Sci. Instrum., **70**, 1167 (1999)

[86] H. Bindslev, L. Porte, A. Hoekzema, J. Machuzak, P. Woskov, D. Van Eester, J. Egedal, J. Fessey, T. Hughes, Fusion Engineering and Design, **53**, 105 (2001)

[87] A. J. H. Donné, R. Jaspers, C. J. Barth, B. S. Q. Elaendoorn, J. C. van Gorkom, H. J. vander Meiden, T. Oyevaar, M. J. van de Pol, V. S. Udintsev, H.L. M. Widdershoven, W. Biel, K. H. Finken, A. Krämer-Flecken, A. Kreter, H. Oosterbeek, B. Schweer, B. Unterberg, B. H. Deng, C. W. Domier, and N. C. Luhmann, Jr., E. Muzzacato, T. Munsat, H. Park, L. Porte, P. Woskov, and L. Shmaenok, Rev. Sci. Instrum., **72**, 1046 (2001)

[88] L. Porte, H. Bindslev, F. Hoekzema, J. Machuzak, P. Woskov, D. Van Eester, Rev. Sci. Instrum., **72**, 1148 (2001)

[89] H. Bindslev, Bull. American Phys. Soc., **46**, 287 (2001)

[90] S. B. Korsholm, H. Bindslev, J. Edegal, J. A. Hoekzema, F. Leuterer, F. Meo, S. Michelsen, P. K. Michelsen, E. L. Tsakadze, P. Woskov, Bull. American Phys. Soc. **48**, 34 (2003)