First results and analysis of collective Thomson scattering (CTS) fast ion distribution measurements on ASDEX Upgrade

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Abstract. Experimental knowledge of the fast ion physics in magnetically confined plasmas is essential. The collective Thomson scattering (CTS) diagnostic is capable of measuring localized 1D ion velocity distributions and anisotropies dependent on the angle to the magnetic field. The CTS installed at ASDEX-Upgrade (AUG) uses mm-waves generated by the 1 MW dual frequency gyrotron. The successful commissioning the CTS at AUG enabled first scattering experiments and the consequent milestone of first fast ion distribution measurements on AUG presented in this paper. The first fast ion distribution results have already uncovered some physics of confined fast ions at the plasma centre with off-axis neutral beam heating. However, CTS experiments on AUG H-mode plasmas have also uncovered some unexpected signals not related to scattering that required additional analysis and treatment of the data. These secondary emission signals are generated from the plasma-gyrotron interaction therefore contain additional physics. Despite their existence that complicate the fast ion analysis, they do not prevent the diagnostic’s capability to infer the fast ion distribution function on AUG.

1. Introduction
Collective Thompson scattering (CTS) offers the capability to measure the fast ion distribution in magnetically confined plasmas which play an important role in magnetic fusion research. A CTS diagnostic detects plasma fluctuations along a wave vector \( \mathbf{k}^\delta = \mathbf{k}' - \mathbf{k} \) where \( \mathbf{k}' \) and \( \mathbf{k} \) are the wave vectors of the received scattered radiation and the incident probing beam, respectively. The extraction of the component of the ion fluctuations along \( \mathbf{k}^\delta \) from the scattered radiation \( (\omega^\delta \approx \Omega_{\text{ion}} \cdot \mathbf{k}^\delta) \) requires that the radiation is scattered dominantly off fluctuations larger than the Debye length \([1]\) \( ((\lambda_D \cdot \mathbf{k}^\delta)^{-1} > 1) \) which is well satisfied for millimetre-wave probes in tokamaks. The microwave based backscattering CTS system on ASDEX Upgrade (AUG) [2] uses a high power gyrotron as the probe at 105 GHz and is capable of measuring localized 1D ion velocity distributions and anisotropies dependent on the angle of \( \mathbf{k}^\delta \) to the magnetic field \( (\angle(\mathbf{k}^\delta, \mathbf{B})) \). The schematic in Figure 1 shows an example of a scattering geometry that resolves the fast ion component along \( \mathbf{k}^\delta \) for \( \angle(\mathbf{k}^\delta, \mathbf{B}) \approx 120^\circ \) where the...
Plasma current ($I_p$) is anti-parallel to the magnetic field. It is important to note that CTS-AUG operates with the electron cyclotron resonance layers ($\Omega_e$ and $2\Omega_e$) positioned outside the plasma to avoid gyrotron radiation absorption and minimize the ECE background. The weak scattered signal i.e. the spectral power density (SPD) of ~ 1–30 eV is extracted from the ECE background of typically 10–300 eV, with the aid of modulating the gyrotron with typically 2 ms on-times. A sensitive 50 channel CTS heterodyne receiver system is used, centred near 105 GHz with 10 GHz bandwidth and high frequency resolution of about ~100 MHz for each channel (except for the outermost channels). More details on the hardware and the CTS-AUG capabilities can be found in [2]. CTS experiments on AUG have been carried out successfully whereby fast ion distribution results have been attained and presented in section 2. The experiments however, have also uncovered challenges that required additional analysis and treatment of the data. Section 3 gives a brief overview of secondary emissions (SE) observed in the measured radiation (raw data) which, to a degree, complicate the analysis, but do not prevent the diagnostic from attaining the fast ion distribution. Section 4 which will describe the principles behind the analysis involved in extracting the spectra from the data which include secondary emission removal from the raw data and the principles involved in the ECE background removal in an H-mode plasma.

2. Results of the confined fast ion distribution for an NBI heated plasma on AUG

Figure 2(a) and (b) show results of the spectral power density and confined fast ion distribution function respectively for an NBI heated H-mode plasma on AUG. The graphs compare two NBI heating configurations using on-axis and off-axis ion beam sources ($P_{\text{source}} = 2.4$ MW). The error-bars shown in Figure 2(a) are one standard deviation of a number of spectral power densities during each heating phase. In this scattering geometry, the $k_\delta$ is oriented in the same toroidal direction as the plasma current ($I_p$) and Figure 2(a) show the frequency up-shift due to the fast ion flow direction as expected from $\omega_\delta \approx v_{ion} \cdot k_\delta$. To attain the fast ion distribution function in Figure 2(b), the measured CTS spectra in Figure 2(a) are fitted using a least squares fitting which takes prior information about parameters, including those from other diagnostics, and implements a Bayesian method of inference using a forward model. More details of the procedure can be found in [3] with its application to AUG in [4].

![Figure 2](image_url)

**Figure 2.** The CTS results: the red (blue) data points on both graphs represents NBI heating configuration with two (one) ion sources. (a) Spectral power density and (b) fast ion distribution function, for a low triangularity standard H-mode plasma with $n_e(0) = 6 \times 10^{19}$ m$^{-3}$, $B_t = 2.6$ T. The abscissa in (a) is the frequency and in (b) is the velocity component which is along $k_\delta$. The $g(u)$ in Figure 2(b) is the projection of the velocity distribution function $f(v||, v_\perp)$ along the direction of $k_\delta$. More details are described in Reference [4]. The scattering volume is located at the centre of the plasma with $\angle(k_\delta, B) = 120^\circ$ where $I_p$ and $B$ are anti-parallel. The dashed lines are the bulk ion distribution.

The error bars in Figure 2(b) represent the uncertainty of one standard deviation and includes the uncertainties of parameters from diagnostics other than CTS such as electron/ion...
temperature, and electron density. Additionally, the uncertainty is such that it could be represented by a scaling factor in the velocity distribution [4]. It can be seen in Figure 2(b) the effect an off-axis beam has on the co-Ip fast ion distribution at the centre of the plasma on AUG.

3. Secondary emissions in the raw data

This section describes the secondary emissions observed in the measured radiation (raw data) during AUG H-mode plasmas that required additional analysis and treatment of the data in order to attain the fast ion distribution function. Reference [2] reported the existence of secondary emissions from the gyrotron itself under certain operating regimes. Notwithstanding operating the gyrotron under the required parameters for a clean spectrum, secondary emissions of a different type appear in the raw data that originate from the antenna front-end and are correlated to the plasma. These signals exist regardless of the antennae orientation or whether the overlap between the probe and receiver is present or not. The intensity values can reach levels of above 3-5 keV (receiver saturation). Nonetheless, the CTS-AUG receiver is sufficiently robust against gain compression and there exists enough isolation between channels in the presence of these secondary emissions. Three types of secondary emissions have been identified each appearing under different experimental conditions and hence believed to be created by different physical mechanisms. Due to limited space, the section will only briefly summarize the characteristics of each and hypothesize on the physics mechanism involved in their creation.

3.1. Secondary emissions from ELMs (SE-ELM)

The most prevalent secondary emission in CTS experiments in AUG H-mode discharges is correlated to ELMs. Shown in Figure 3, the SE signals appear as spikes during the gyro-on periods (in red) and show a clear correlation with the rise of the bolometer signal (shown in black) during an ELM event. These SE-ELM mainly affect the central channels (3 - 5 channels ± 500 MHz on either side of the gyrotron line). The occurrence and intensity of SE-ELM decrease for channels further away from the gyrotron line and can be asymmetric in frequency. One hypothesis is local heating of ELM filament structures that pass through the 2Ω_e layer in front of the ECRH antenna as they propagate outward. The ELM filaments can carry a significant portion of the pedestal density [3] and can absorb a portion of the gyrotron power when crossing the resonance layer. The high energy electrons created re-emit radiation detected by the neighbouring receiver antenna at μs time scales due to the low confinement time because of the high parallel conductivity. Regardless of the physics mechanism behind their creation, SE-ELM signals can be avoided in principle by triggering the gyrotron shortly after an ELM is detected by the diode bolometer camera located in the same sector as the ECRH antennae.

3.2. Secondary emissions from NBI ion sources near perpendicular to the magnetic field (SE-NBI⊥)

Figure 4(a) shows two types of secondary emissions generated by a different type of mechanism. The SE-ELM signal, described in the previous section, appears only during the onset of an ELM event as can be seen during the first, fourth, and second-to-last gyro-pulse in Figure 4(a). However, the figure also shows secondary emissions at distinct channels (22-23 & 35-36) on either side of the gyrotron
These signals (SE-NBI⊥) are independent of any ELM event and appear only when the two most perpendicular NBI ion sources (ion sources #1 and #4 in the AUG nomenclature) are on. The spectral power density plotted in Figure 4(b) clearly shows the two peaks at ≈ 670 MHz from either side of the gyrotron line. The two signals are strongly correlated to each other and weakly correlated to the SE-ELM signals present in the more central channels.

As with all secondary emissions described in section 2, they are present regardless of the antennae position and overlap. The strong correlation between the two peaks and the symmetry in frequency suggests a wave mixing process between the gyrotron radiation and a wave (or waves) in the plasma with a narrow frequency bandwidth of 600-700 MHz created by a resonant process which occurs when perpendicular NBI ion sources are on. A similar observation was made by a microwave based CTS system on W7-AS where the signal was explained by lower hybrid (LH) instability driven turbulence created by perpendicular fast ions [6] [7]. This well known coupling between LH waves and the perpendicular component of the ions is stochastic in nature and can occur when the wave amplitude is large and when the perpendicular phase velocity (ω/k⊥) approaches the ion perpendicular thermal velocity [8]. This energy coupling from LH to ions has been measured with charge exchange spectroscopy [9][10].

### 3.3. Secondary emissions from ion cyclotron resonance heating (SE-ICRH)

CTS experiments on AUG discharges with ICRH hydrogen minority heating at fICRH = 36.5 MHz have revealed a third type of secondary emission shown in Figure 5(a), present only with ICRH heating. Independent from the ELM signal (bolometry), SE-ICRH signals are present at every gyro-pulse and are concentrated in the frequency range close to the centre channels i.e. ±300 MHz corresponding to three channels on either side of the gyro-line. The contour in Figure 5(a) clearly shows the presence of only SE-ELM when the ICRH is switched off (seen at T=4.215 sec). The amplitude of the SE-ICRH in general is much higher than the SE-ELM signal. Experiments were carried out where a portion of the heterodyned IF signal (via a 3dB coupler) was fed to a Tektronix Digital Phosphor Oscilloscope (model DPO 7104) with a fast 120 Mbyte memory frame grabbing capability and 1 GHz bandwidth. Figure 5(b) shows the spectrogram of one gyro-pulse during an ICRH heated plasma discharge. The figure shows the first 500 μs being attenuated by the Voltage Controlled Variable Attenuator (VCVA) and the frequency chirping of the gyrotron. The spectrogram clearly shows harmonic structures that follow the gyrotron frequency chirp and the drift due to thermal expansion of the gyrotron cavity. The frequency between each harmonic is about 36.5 ± 0.5 MHz which is equal to the ICRH generator frequency. In addition, bursts at ≈ 300 μs intervals shown Figure 5(b) are also observed by the CTS.
receiver. These harmonic signals around the gyrotron separated by $f_{\text{ICRH}}$ were also observed on the CTS at TEXTOR [11]. This suggests a non-linear wave mixing between the gyrotron and the ICRH waves. This interaction is likely to be located in the edge region where parasitic absorption of ICRH waves exists thus creating rectified sheaths on opened field lines [12]. It is not clear yet if the amplitude of SE-ICRH is dependent on the ICRH coupling or other plasma parameters. The nonlinear wave mixing between two very different frequencies is believed to be very weak. However, it is important to note that the CTS detector measures powers that are $\sim 10^{10}$ to $10^{12}$ times weaker than the power of the gyrotron radiation.

![Graph showing harmonic signals and gyrotron line](image)

**Figure 5.** (a) Contour of raw CTS data for H-mode AUG discharge. The ICRH minority hydrogen heated discharge ($f_{\text{ICRH}} = 36.5 \text{ MHz}$) ends at $T=4.195$ sec. The ordinate is channel number and abscissa the time. The red rectangles at the top indicate the gyro-on time periods. The green time trace superimposed onto the contour is the bolometer signal. (b) spectrogram of one gyrotron pulse in same discharge during ICRH heating. The spectrogram intensity has not been calibrated using the system’s instrument function. The braces on the right axis represent the corresponding channel of the CTS receiver.

### 4. Signal analysis

#### 4.1. Secondary emission rejection

Each of the SE signals described in section 2 are well constrained in a narrow frequency range, hence it is possible to process the data to attain the fast ion distribution function. The first two types of secondary emissions in section 2 usually affect only a part of a gyro pulse. Hence several methods have been used to remove portions of gyro-pulses that contain secondary emissions. In the most successful method, each gyrotron pulse is divided into smaller parts where the normalized signal fluctuation level, defined as the standard deviation of the signal normalized by the mean for the pulse part, is used to identify and reject those pulse parts which cause outliers in the upper tail of the distribution of normalized fluctuation levels. Evidently tolerances on identifying outliers are not generic and require manual testing and verification. Improvements include using the ECE background of neighbouring data during the gyrotron off period as a normalizing factor. A wavelet approach is being considered.

#### 4.2. Updated ECE background subtraction procedure

In order to remove the ECE background for extraction of the scattered radiation, the ECE background measured during the passive ECE-only periods (gyro-off) is used to predict and remove the background during the gyro periods (gyro-on). The background of a CTS channel is well correlated with the outermost channels of the CTS receiver ($\Delta \nu \approx \pm 5 \text{ GHz}$) where no scattered signal is measured nor expected. The procedure involved estimating the background of the gyro-on pulse for each channel, by the use of the adjacent gyro-off pulse(s) of the same channel and the use of the signal in the outermost channels during the gyro-on periods. However, the ECE background emanating from an H-mode AUG plasma has a high variability in time due to ELMs and other MHD events making this
procedure problematic on AUG - contrary to the relatively quiescent TEXTOR plasma where this approach was very robust [13]. A new approach on AUG was adopted where for each channel, correlation coefficients are created from a variety of data sets during the gyro-off periods and used to predict the channel background during the gyro-on periods. The data used in the correlation coefficients are the outmost channels of the CTS and from other diagnostics such as plasma position, D\textalpha\textsubscript{r} radiation, and plasma density in the pedestal and scrape-off layer. This method was tested on a time window of the CTS receiver that passively viewed the plasma (with no gyrotron pulses), hence only ECE radiation. By assigning chosen time intervals considered as pseudo-gyro-on periods, the background of the pseudo-gyro-off periods are reconstructed and compared to the actual ECE data. Such tests have shown that the standard deviation of the difference between the two is less than 1 eV and is lower than the standard deviation of a series of spectral power densities from actual data measured during a steady state plasma phase.

5. Conclusion

Fast ion distribution results have been attained using the CTS-AUG. Challenges inherent to the CTS-AUG such as secondary emissions in the raw data necessitated additional study and analysis in order to attain the fast ion information. This was possible due to the non-random nature of the SE signals in frequency (unlike the secondary emissions from the gyrotron itself [2]). In some instances, the exclusion of entire channels was required in the inference procedure. Preliminary studies have shown that the exclusion of certain channels do not significantly affect the determination of the fast ion distribution function. There is a possibility that a microwave based fast ion CTS diagnostic on ITER [15][16][17] may encounter new SE signals from alpha driven instabilities, but many of the possibilities such as Alfvén eigenmodes would be too low in frequency to effect the fast ion CTS spectra. In the event that new high frequency SE is found, it is likely as shown in Figure 5 that measurements with a high frequency resolution (in conjunction with the CTS receiver) can identify the SE and thus facilitate removal from the SPD data. The CTS diagnostic on AUG will become a valuable experimental tool in understanding fast ion physics in confined plasmas. Knowledge gained in achieving the physics and technical objectives of such a system is an important step toward a fast ion CTS diagnostic on ITER.

References

[1] Salpeter E E, 1960 Phys. Rev. 1528, 120
[2] Meo F et al 2008 Rev. Sci. Instrum. 79, 10E501
[3] Bindslev H 1999 Rev. Sci. Instrum. 70 1093–1099
[4] Salewski M et al, 2010 Nucl. Fusion 50 035012
[5] Herrmann A, Schmid A, Müller H W, Maraschek M, Neuhauser J and the ASDEX Upgrade Team, 2008 Proceedings of the 22nd IAEA Fusion Energy Conference, Geneva, Switzerland
[6] Suvorov E V et al, 1998 Nuclear Fusion, 38, No. 5 661-671
[7] Shalashov A G, Suvorov E V, Lubyako L V, Maassberg H and the W7-AS team, 2003 Plasma Phys. Control. Fusion 45 395–412
[8] Karney C F F, September 1978 Phys. Fluids 21 (9)
[9] Ryter F et al, 1986 Proceedings of the 15th European Conference on Controlled Fusion and Plasma Heating, Schliersee edited by G. Briffod and M. Kaufman (European Physical Society, Petit-Lancy, 10c, Pt. I, p. 101
[10] Nemoto M et al, 1991 Phys Rev Lett, 67, 70
[11] Woskov P P et al 2006 Rev. Sci. Instrum. 77 10E524
[12] Brambilla M at IPP Garching, private communication
[13] Bindslev H et al, 2006 Phys Rev Lett 97, 205005
[14] Nielsen S K et al 2008 Physical Review E 77 016407
[15] Meo F et al Rev. 2004 Sci. Instrum. 75 3585–3588
[16] Leipold F et al, 2009 Rev. Sci. Instrum. 80, 093501
[17] Salewski M et al, 2009 Nucl. Fusion 49 025006