Multi-machine experimental investigation of ion cyclotron emission

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Abstract.

Ion Cyclotron Emission (ICE) is an instability triggered by the resonant interaction between a population of fast ions and waves supported by the background plasma [1]. The analysis of the signal passively measured with Radio-Frequency probes in time and frequency domains can provide information on the characteristics of the barely trapped and lost fusion alpha-particles in a machine such as ITER. ICE can exhibit very different features in time (steady state, transient, cyclic) and in frequency (presence of doublets or triplets at low frequency, continuum at high frequency, chirping, complicated mode structure) depending on the operational parameters, which makes it difficult to investigate entirely on a single machine. A Joint Experiment was set up by the ITPA Energetic Particle Physics Topical Group to combine the experimental efforts of several machines (JET, DIII-D, ASDEX Upgrade, KSTAR, LHD and MAST) which have installed or upgraded ICE diagnostics.

The qualification of ICE as a diagnostic requires several steps which involve experimentation. The first step is to characterize the nature (mode numbers, effect of background plasma composition, comparison between conventional and spherical tokamaks) and evolution of the excited waves (in the linear, quasi-linear, fully non-linear and decay phases). Second, the method to reconstruct the properties of the exciting ions from the emission spectrogram has to be tested for different heating scenarios (using different geometries and power profiles of neutral beam injectors and/or Ion Cyclotron Resonant Frequency Heating) and benchmarked against other methods to characterize fast ion populations (^{4}He, protons, beam ions), such as fast ion deuterium-alpha (FIDA) spectroscopy, fast ion loss detectors (FILDs) or collective Thomson scattering (CTS), and then has to be applied to scenarios where instabilities such as ELMs (Edge Localized Modes) or TAEs (Toroidal Alfvén Eigenmodes) are present and analyzed with methods like Electron Cyclotron Emission imaging to check that ICE can indeed provide insights into the mechanism leading to fast ion losses. Finally, different diagnostic designs have to be tested to find the most flexible and least intrusive way of measuring the emission, especially to determine the quality of signal that is attainable by using an RF probe (voltage probe or power coupler) in the ICRF transmission line, away from the harsh environment inside the vacuum vessel.

1. Introduction

Ion Cyclotron Emission (ICE) is a plasma instability resulting from the resonant interaction between the gyromotion of fast ions and the circularly polarized electromagnetic field of waves supported by the plasma. It thus occurs in the range of frequency of the ion cyclotron frequency, i.e. in the MHz domain for the species and magnetic conditions typical of present fusion machines. The existence of this instability was predicted in the 1970s [1] but the first observations of ICE were carried out in the 1980s [2], followed by theoretical work aimed at explaining the details of the observed features (see e.g. [3]). A detailed review can be found in [4] but it is useful to summarize here the main findings and limitations of early work, which was mainly based on data from JET and TFTR.

ICE signals produced by three types of fast ion population were identified. First, fusion product (FP) ICE originated from the interaction between centrally-born charged fusion products with large excursion orbits and magnetosonic waves at the plasma edge. Secondly, minority ICE (mICE) was due to minority species (such as hydrogen) accelerated by Ion Cyclotron Resonance Heating (ICRH) which mimic the behaviour of fusion products (in the MeV range of energy) [5]. The third type of ICE involved particles from Neutral Beam Injection (NBI) ionized at the plasma edge with enough energy to support and excite radio frequency waves [6]. Different theories were constructed to explain the observed spectra, considering only the linear stage of wave growth and using various models of the fast ion population and plasma waves. These theories could explain the rough shape of the spectrum and the role of fusion products in the emission was demonstrated experimentally. However some experimental features could not be easily explained by linear theory, such as the excitation of odd harmonics of the deuterium cyclotron frequency by fusion protons (only even harmonics were expected to be excited). Moreover there were many unknowns, including the nature of the waves excited by the fast ions (free or contained modes, values of the wave vector, polarization, spatial structure), which part of the distribution function was in resonance (barely trapped, barely passing), and the exact relation between the emission intensity, spectrum shape and fast ion population characteristics. The main difficulty was the lack of experimental data accurate enough in the time domain to investigate these issues.

Most of the research on ICE ended at the beginning of the 2000s. However a decade or so later, the work restarted due to progress in several areas: 1) The relatively low magnetic fields in spherical tokamaksmade it possible to study the excitation of compressional Alfven eigenmodes (CAEs) in the sub-cyclotron range of frequencies, where the mode structure and its time evolution (splitting, chirping) is easier to observe and a better theory of these modes, which are suspected to be involved in ICE, was developed. 2) Technological progress in digitizers and computer memory made it possible to acquire ICE signals at higher resolution and sampling rate, for longer durations, and for a reduced price. 3) The use of Radio-Frequency (RF) filters and amplifiers enabled the acquisition of ICE signals from within the ICRF system outside the vacuum vessel, simplifying the deployment of the diagnostics. 4) Numerical codes reached a level of maturity which provided access to the nonlinear stage of the emission and insights into some previously unexplained features (for example the excitation of lower harmonics despite high damping rates). A new phase of ICE studies took place on ASDEX Upgrade, DIII-D, KSTAR, JET and JT-60U. The performance of the diagnostics used on these machines was convincing enough to provide hope that the previously-mentioned issues could be addressed, and that it would possible to reconstruct from the ICE measurements some characteristics of the exciting fast ions (concentration, maybe some constant of motions), especially those of barely-trapped fusion products, which are of special interest since they can channel a part of the energy from the centre to the edge of the plasma. The passive nature of the measurement, the possibility of positioning it outside the vacuum vessel and its relatively low cost makes it a possible candidate for a fast ion diagnostic on ITER. For this reason a Joint EXperiment (JEX) was set up in the framework of the ITPA Energetic Particle Topical Group to coordinate the activity of different fusion devices with the long-term objective of preparing this ITER diagnostic. The JEX is presently composed of four tokamaks (ASDEX Upgrade, DIII-D, JET and KSTAR) which are together able to cover a large range of plasma scenarios, one spherical tokamak (MAST), which provides a large database of CAEs measurements, and a stellarator (LHD), which can be used to observe ICE in a non-tokamak magnetic configuration and thus will help us to identify the effects of the plasma configuration on the emission (toroidicity, geometry of the eigenmodes,…). The JEX started at the beginning of 2016 and is open to further members.

2. JEX Methodology

To reach the goal of exploiting ICE as an effective fast ion diagnostic on ITER, three interrelated steps are necessary. The first step is to validate and improve the existing ICE theories and unify them in a single framework. A multi-machine database is being assembled to provide spectrograms for a wide range of plasma configurations and conditions so that, first, we can separate the effect of the local cyclotron resonance from the configuration-dependent parameters (fast ion orbits, wave eigenmode structure) and, second, we can explore this dependence on plasma scenarios. Therefore, the measurements should provide ICE spectra for different driving parameters (density profiles, fast ions type and concentration). The mode numbers (and if possible the spatial structure) should also be evaluated (with probe arrays) to determine the nature of the excited waves. The observation of the signal time evolution on short (microsecond) and long (milliseconds and seconds) timescales will provide data that will make it possible to analyse the strength of the instability and its transition from a linear to a nonlinear or quasilinear stage. These data should provide us with operational conditions for the existence of the instability and its scaling with machine parameters. This will enable us to relate the emission indirectly to the fast ion population. Other fast ion diagnostics (FILD, FIDA, Collective Thomson scattering) will be used to benchmark the results.

These data will be used in a second step, the purpose of which is to develop methods for reconstructing fast ion characteristics from ICE measurements. Which characteristics can be evaluated will depend on both the accuracy of the measurements and also on the capabilities of the theoretical tools. It is very probable that we can evaluate the fast ion concentration from the integrated intensity of the signal, provided that we know which model to apply: JET data showed a linear dependence of ICE intensity on neutron rate over six orders of magnitude [6]. A similar dependence has not been observed in TFTR or ASDEX Upgrade, possibly because the fast ion populations in these devices had insufficient density to reach the same regime. More ambitious is the deconvolution of ICE spectra to infer the constants of motion (COMs) of the exciting fast ion population. A proof-of-concept was proposed using the linear growth rate: The spectrum is a sum of integrals of the COMs [7].The linear growth rate is not sufficient to determine uniquely the fast ion parameters, but improved models could help to remove such ambiguities.

The third step combines the knowledge acquired using the diagnostics of the different machines with the reconstruction methods to determine the specifications and the design of an ICE measurement system suited to the needs of ITER.

The work of 2016 has mainly focused on the first and third steps with the main aim to understand the experimental configuration of each machine and to compare the first results to establish a preliminary database. The experiments made it possible to sketch the first requirements for ITER.

3. Experimental results

3.1. **Configuration**

The diagnostics of the different machines are summarised in Table 1.

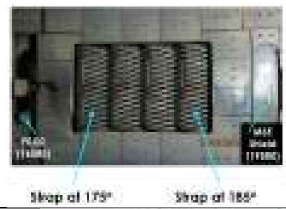
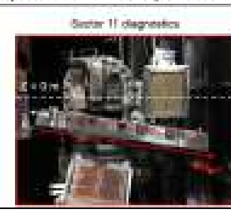
Machine	Diagnostic configuration
DIII-D	180 degree Fast Wave Antenna straps separated toroidally by $\Delta\phi$=13.3deg 4 channels - 200MS/s [8] 
JET	Sub-harmonic arc detection (SHAD) system installed in JET ICRF A2 antenna transmission lines with fast oscilloscope 
AUG	B-dot probes in array on low field side next to ICRF antenna. Linear detector linked to 200kS/s digitizer.
MAST	Outboard Mirnov Array for High-Frequency Acquisition (OMAHA): Set of 9 probes each containing three concentric orthogonal coils designed for measuring fluctuations up to 7 MHz. [9]
KSTAR	Fast radio-frequency spectrometer: bow-tie antenna (bandwidth: 100MHz-2GHz) connected to amplifier bandpass filter and in parallel to 20GS/s ADC or 8 channels filter banks (40 -800MHz) + 1MS/s ADC [10]
LHD	Spare ICRF heating antennas [11] and Dipole antenna at the outboard equatorial port. Two pairs of high-frequency magnetic probes with one-turn loop were installed in upper ports. 

Table1. Comparison of the diagnostics used for the JEX

Most machines are equipped with array probes which means that mode number measurements (in the toroidal direction) will be possible, which should help to validate the CAE nature of the excited waves and validate the CAE codes.

All have or will have fast digitizer to capture the evolution of the emission on long time scale.

3.2. Results

We have structured the presentation of the data in four parts: 1) the spectrum structure which shows which frequencies are present and their corresponding amplitude; 2) the time evolution of the signal; 3) the conditions for the existence of the signal and the scaling with main plasma parameters when statistical sampling is possible; 4) the correlation of the emission with other plasma phenomena, in particular toroidal Alfvén eigenmodes (TAEs) and edge localised modes (ELMs). The presentation of the data is accompanied by a preliminary analysis which puts in perspective the results from the JEX with past data and existing theories. The main purpose is to see where new knowledge can be gained and where difficulties in reconstructing the fast ion population can be expected.

1) Spectrum structure

The spectra from the different machines show that we get a signal at the harmonics of the cyclotron frequencies of the background ions at the edge when NBI beams are injected (cf. Fig.1 for DIII-D as an example) or during ICRF heating (on JET, cf. Figure 2 or ASDEX Upgrade [12]). Only a limited number of harmonics were probed and no continuum at high frequency could thus for the moment be detected. One limitation is that tritium was not used in any of the machines, so that the fusion reaction rates and concentrations of fusion products were low: FP-ICE was detectable, but typically had an intensity comparable to or below that of beam-driven ICE. The strength of beam-driven ICE is illustrated by a strong correlation between the ICE signal and the position of the neutral beam in LHD, and the fact that only one beam is sufficient to trigger ICE inn DIII-D: the signal observed is probably beam-driven ICE.

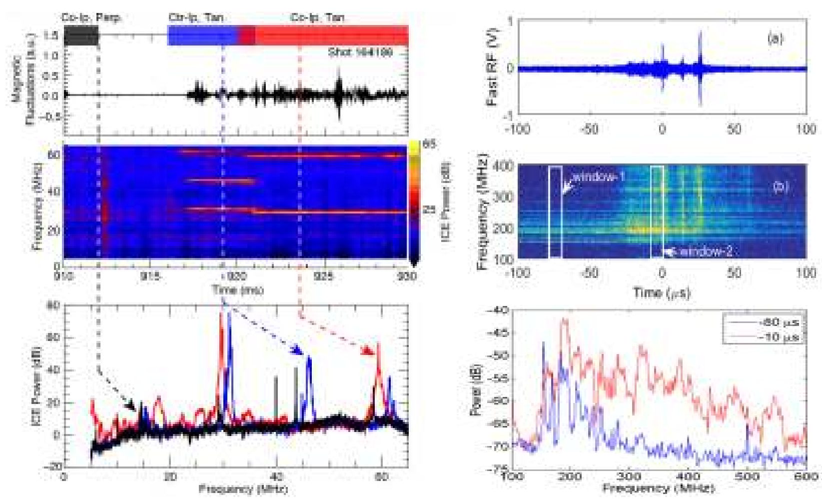


Figure 1. Examples of ICE measurement; this includes the raw data of magnetic fluctuations (top), spectrogram of the fluctuations (middle), and line-cuts showing differences in the auto-power a) a) in DIII-D [8] for different neutral beams with indicators of the geometry of the injecting neutral beam (top), . b) in KSTAR [10] before (window 1) and during (window 2) an ELM crash.

This raises an important issue for future measurements: how to distinguish beam-driven ICE from FP-ICE? Tritium campaigns on JET will probably be helpful since the FP-ICE signal will have a higher intensity. But the determination of the wave nature will be possible only with measurement of the wave numbers with the probe arrays and the comparison with CAE codes.

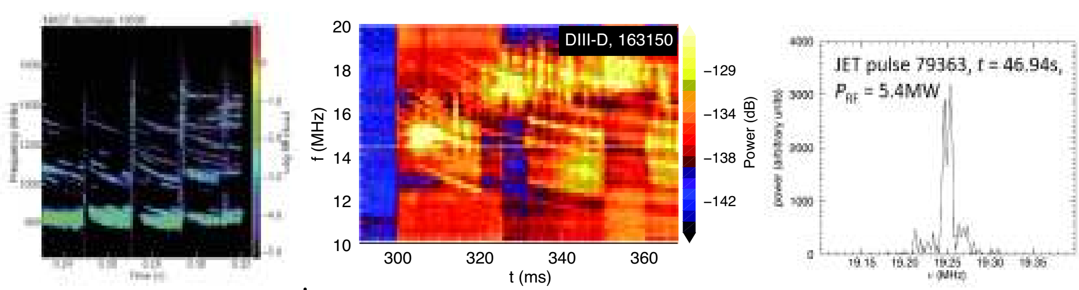


Figure 2. Observations of ICE mode structure on a. MAST b. DIII-D and c. JET

Another important observation common to several machines is the spectral fine structure in the neighbourhood of cyclotron harmonics, as seen in Fig. 2. This strongly suggests that CAEs are being excited. The presence of these modes has been clearly demonstrated on MAST using polarisation measurements [9]; those detected in DIII-D, JET and AUG have yet to be confirmed as CAEs.

2) Time evolution

The analysis of the signal time evolution can provide information on the dynamics of the fast ions. On LHD, it was shown (Fig. 3) that when the NBI source was turned off, the decay time of ICE was corresponding to the confinement time of the barely trapped fast ions as calculated by transport codes. This means that the ionized beams neutrals are responsible for the emission and that, conversely, it is possible to measure this confinement time from the time evolution of ICE.

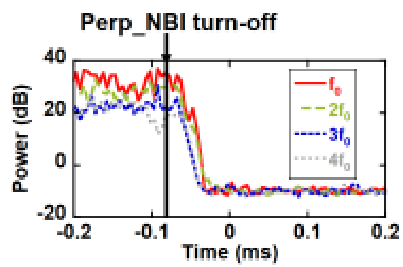


Figure 3. Decay of ICE signal in LHD at various cyclotron harmonics when NBI is turned off [LHD-2]

3) Sensitivity to plasma parameters

On AUG and DIII-D a statistical analysis has been started of ICE intensity as a function of plasma parameters that could be drivers of the instability. The results are presented on Figure 4.There is no obvious correlation between the ICE level and the injected power on either machine; yet the concentration of resonating fast ions is expected to be roughly proportional to the injected power, both in the FP-ICE and beam-driven ICE cases.

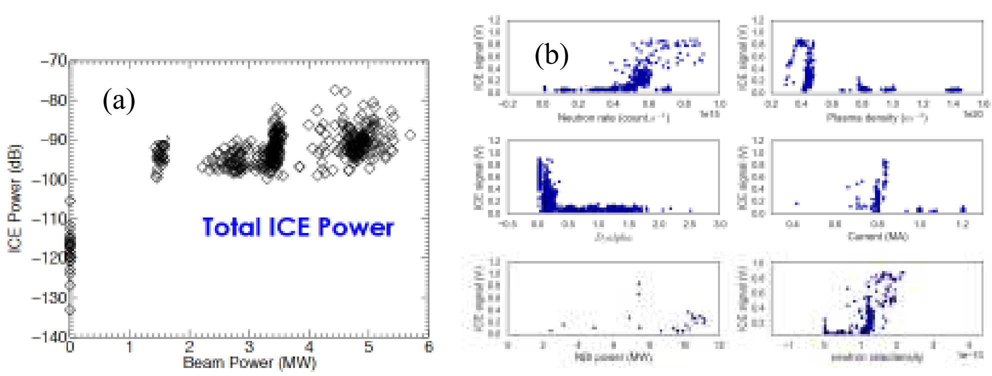


Figure 4. Sensitivity of ICE intensity versus operational parameters for a) DIII-D. b) AUG

On ASDEX-Upgrade the neutron rate was used as a marker of the fusion product concentration. The intensity is proportional to the neutron rate at low values of the latter but above 6×10^{14} neutrons/s, it seems to reach a plateau and saturate. This could be the indication of a change of regime. The integrated intensity has been used for the statistics; a more refined analysis based on the intensity of each frequency is required in the future to confirm this trend.

4) Correlation with other plasma phenomena

The evolution of the ICE signal was correlated on LHD and AUG with other instabilities, in particular TAEs (on LHD) and ELMs (on AUG but also on JET in past experiments [13]). Different types of correlation are observed in the case of ELMs, with the ICE signal being either in phase or out-of-phase with the ELM crashes. It is not clear what determines this phase relationship..

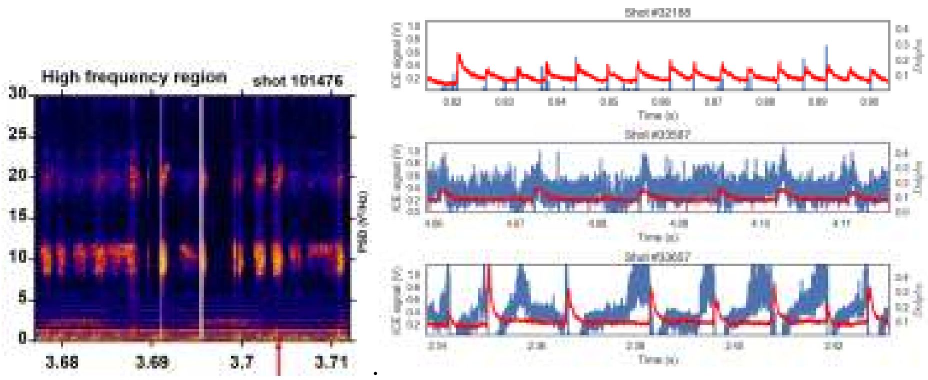


Figure 5. Correlation of ICE signal with a. sawteeth on LHD [LHD-1] b. ELMs on AUG

4. Preliminary diagnostic requirements.

The development and operation of ICE diagnostics on machines with various constraints have helped to elucidate the essential requirements of an operational ICE measurement system for ITER. A key point is that any such system must distinguish the ICE signal from background noise in the MHz range (for example due to electronics, arcs or ICRF waves).

The baseline solution is to use captors in the ICRF transmission line. These can be voltage probes or power couplers (in this case the reflected power coupler). The advantage is that it requires no additional installation except for splitters to direct a part of the signal to the ICE acquisition system. The drawback is that the signal is disturbed by several factors: the Faraday shield of the antenna, the matching system which will be tuned only to a narrow bandwidth of the spectrum, and the ICRF wave present in the transmission line. The study of the ICE single-to-noise ratio with ICRF probes is not yet exhaustive and it is difficult to predict the quality of the ICE signal that might be generated in ITER. However it is clear from existing experiments that the probe should be located as near as possible to the antenna: it is less affected by the tuning system since the wave there comes directly from the vessel.

The best solution would include a captor for each strap transmission line: in this case it is possible in principle to measure the wave numbers, both toroidally and poloidally. In this case, an accurate measurement of the electrical lengths is necessary to reconstruct the phase between the different probes.

Due to the different attenuations along the signal path, a low-noise pre-amplifier will be required. If we want to measure ICE during ICRF, a notch filter is also required to remove the ICRF frequency. The difficulty here is that it has to be tunable because the ICRF frequency can change with the operational parameters. The acquisition system will convert the analog signal into a digital one. There are three requirements for this system: it has to be fast (high sampling rate for the MHz frequency), it has to be accurate (high bit resolution), and it has to store only a limited amount of data, in view of the very long pulses expected in ITER. Several strategies are possible to meet the third requirement: 1/ trigger of acquisition only when there is a RF signal; 2/ filter only the interesting frequencies by using a tunable filter bank at the input of the digitizer or a field-programmable gate array (FPGA) to perform a real-time fast Fourier transform and select the interesting parts; 3/ record the whole signal and post-process the data to keep only the interesting parts. The effort is here more on the processing software than on the hardware. But it requires data analysis software that is capable of extracting only the most useful data.

The choice of sampling rate and the bit resolution of the digitizer will result from a trade-off between our needs (highest ICE frequency required and smallest ICE signal intensity) and the technological capabilities, which are evolving rapidly. Presently a resolution of 12bits and 125MS/s is easily affordable. But it may be possible to go as high as the GHz range, as in KSTAR [10], to resolve more harmonics and achieve higher time resolution

5. Conclusion

The ICE JEX has led to the first detailed comparison of data on multiple machines. Several diagnostics still have to be upgraded (on AUG and JET with the use of FPGAs for real-time data processing) but the database already contains promising data in terms of spectral structure and correlations of the signal with other plasma instabilities. The next experimental challenges will be the measurement of the wave mode numbers for the characterization of the wave nature and to find improved methods of distinguishing FP-ICE from beam-driven ICE.

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