EP-9 Assessment of Ion Cyclotron Emission (ICE) for diagnosing lost and barely confined fast ions

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| **TG priority:** High | **Start date:** 2016 | **Status:**  New | **Personnel exchange:**  Yes |
| **IO priority:** | **End date:** 2018 | **Motivation:** Physics Basis | |

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| **Device / Association** | **Contact Person** | **2016 TG Request** | **Activity (from JEX/JA spreadsheet)** | | |
| **2016** | **2017** | **2018** |
| AUG | R. D’Inca | Essential |  |  |  |
| JET | K. McClements  P. Jacquet | Essential |  |  |  |
| DIII-D | D. Pace | Essential |  |  |  |
| ITER | P. Lamalle | Desirable |  |  |  |
| MAST | S. Sharapov | Data mining |  |  |  |
| EUROfusion | R. Dumont | Modelling |  |  |  |
| KSTAR | G. Yun | Essential |  |  |  |
| LHD | T. Takiyama | Desirable |  |  |  |

**Purpose**

The purpose of the Joint Experiment is to assess and optimize possible options for developing ion cyclotron emission (ICE) detection system in ITER, which can be used as a diagnostics of fast ions. The detection of ICE is possible using any technique for measuring magnetic, electric or density fluctuations in the ion cyclotron range. Dedicated radio frequency probes have been used at a wide range of poloidal locations, for example at the top of the vessel in TFTR [1] and the high field side in JET [2]. The design requirements of an ICE diagnostic system for ITER are thus flexible. Other detection possibilities include microwave reflectometry, which is planned for ITER [3] and has been used to measure the spatial structure of modes at frequencies up to the compressional Alfvén eigenmode (CAE) range in NSTX [4]; this is not a passive technique. For a dedicated diagnostic, the detector could be a modified plasma-facing component, as in DIII-D [5]. The detector should be capable of detecting frequencies ranging from below the alpha-particle/deuteron cyclotron frequency on the low field side edge of the ITER plasma (about 30 MHz) up to the tenth harmonic or so of the cyclotron frequency in the plasma core (~400 MHz). ICE measurements in JET and ASDEX Upgrade show that a dedicated ICE probe can operate well during ICRH [2,6]. Alternatively, or in addition to a dedicated diagnostic, a detection capability could be added to the ITER ICRH antenna system; for a technical description of this system, see [7]. ICE measurements could be carried out with the antenna in passive reception mode, as in the JET preliminary tritium experiment [8].

**Plans for 2016**

* AUG: the diagnostic is being upgraded for the 2015 campaign. It will now use a toroidal B-dot probe installed inside the vacuum vessel. First measurements show a good signal-to-noise ratio, even without pre-amplification. The system will also measure the signal from voltage probes inside the ICRF transmission lines. The acquisition system has been changed using 125MS/s 14bits ADC connected to a FPGA/CPU system: this gives real-time processing capabilities like filtering and frequency detection, and large acquisition times. The cost of an acquisition unit is of the order of 300 euros and the system fits on SD cards. If it works, it will be straightforward to standardize the ICE instrumentation and to use it on other tokamaks. The first objective is to measure the *k*II of the waves and their polarization. The second objective is to characterize the time evolution of the emission, alone or triggered by other instabilities (particularly ELMs).
* JET: Analysis of ICE data obtained in carbon wall plasmas using the ICRH sub-harmonic arc detection system (SHAD) will continue, supported by modelling of the CAE spectrum and of the underlying (magnetoacoustic cyclotron) instability. A new SHAD system (provided by CEA) will be installed on JET for the 2015 campaign and used to search for ICE excited by ICRF-accelerated fast ions and fusion products. It is intended that both of the ICRF antennas will be used, in order to determine the effect on the measured ICE signal of changing the configuration of the ICRF transmission lines.
* KSTAR and LHD: Correlations of ICE with other fast particle-driven modes (e.g. TAEs) and ELMs [both KSTAR and LHD]; NBI modulation experiments will be carried out to study the dependence of the ICE decay time on the beam injection geometry and plasma parameters [LHD]; correlations of ICE with thermal/turbulent fluctuations (measured in 2D poloidal cross section by ECE imaging) will be investigated [KSTAR]; interpretation of these measurements using hybrid code [KSTAR/LHD].
* DIII-D: Measurement of ICE with ICRF antennas and RF-probes mounted on their frames; more particularly, measurement of toroidal wave numbers.
* JT-60U: data-mining (this is the only device in which measurements of ICE *k*II have previously been reported).
* MAST/MAST-U: OMAHA, an array of Mirnov coils used on MAST with a maximum sampling rate of 10 MS/s (hence allowing ICE/CAE measurements up to 5 MHz) should be re-installed in MAST-U. In the first physics campaign in MAST-U in 2017, the toroidal field at *R* = 0.85m (roughly the magnetic axis location) will be 0.6 T, giving a deuterium cyclotron frequency at that point of 4.6 MHz, and perhaps as low as 3 MHz in the outer midplane edge. These figures will be slightly higher in subsequent campaigns, with *B* = 0.75 T at *R*= 0.85 m, but the experience of MAST suggests that fundamental ICE will be excited, and should be observable using the OMAHA array (cf. Fig. 4 in [11]). If necessary the toroidal magnetic field could be lowered, as in MAST pulses in which strong Mirnov coil signals in the ion cyclotron range were observed [9-11]. In core scope MAST-U will be equipped with deuterium beam injectors, providing a maximum total power of 5MW (2.5MW on-axis, 2.5MW off-axis). The flexibility provided by off-axis neutral beam injection will make it possible to study high frequency instabilities such as ICE/CAEs for a wider range of fast particle distributions than was possible in MAST. Additional beam power may become available in the future

**Previous results**

ICE due to fusion products

The emission was first observed on TFR [9] where a signal corresponding to the deuterium cyclotron frequencies at the outer midplane edge of the plasma was recorded with a magnetic probe during neutral beam injection. The absence of the signal coming from the microwave scattering diagnostic probing the centre for density fluctuations confirmed the edge location of the signal. But the decisive experiments that shed light on the phenomenon were due to Cottrell’s team who analyzed the emission coming from JET [10,12]. The key points of these experiments can be summarized as follows:

* During Ohmic deuterium discharges, emission peaks were observed at the deuterium cyclotron frequency and its first few harmonics at the outboard plasma edge;
* With injection of hydrogen neutral beams, a similar spectrum was observed but the intensity of each peak increased;
* Discharges with deuterium or a mixture of deuterium and tritium again had a similar spectrum, with a higher intensities in the deuterium/tritium case;
* Odd harmonics in the spectrum were less intense than even harmonics, and the peaks were replaced by a continuum above the 7th harmonic. The discrete part of the spectrum represented 2% of the total signal;
* Fine structure could be observed within some peaks;
* The signal was proportional to the fusion reactivity measured with a neutron detector; it followed the time signal from neutron rate but with a delay comparable with fast ion slowing-down time;
* A temporal correlation was observed between the emission and MHD instabilities, including ELMs and sawteeth.

A useful comparison was carried out with plasmas in TFTR [1] characterised by highly peaked density profiles (those in JET were much flatter); this study revealed that the emission is very transient when fusion products are sub-Alfvénic at the plasma edge. When the density profile was changed, it was found that the emission could become steady and similar to JET when the density was high enough at the edge for the fast particles to be super-Alfvénic. In addition, it was shown that emission corresponding to the deuterium cyclotron frequency at a location even further outboard than that of the fusion product ICE was steadily present during beam injection.

A series of ICE measurements was also carried out on JT-60U [11]. The emission had similar features to that observed in TFTR, with transient fusion product-driven ICE and steady beam-driven ICE. In this case fusion product-driven was due helium-3, tritium and protons. Unlike other devices, in JT-60U it was possible to measure the toroidal wave number of the ICE, and it was found that whereas the fusion product-driven ICE had a finite toroidal wavenumber, the beam–driven ICE had no parallel propagation. For the helium-3 ICE, a doublet spectral peak was observed, with the two frequencies having opposite directions of propagation.

ASDEX-Upgrade detected the presence of ICE emission in the same regime as TFTR and JT-60U, with mainly millisecond bursts of ICE at the proton and helium-3 cyclotron frequencies during ELMs. The signal reveals fine frequency structure. There is no continuum observed above the fifth harmonic. The signal is found to be more intense during counter-current beam injection.

ICE due to minority species during ICRF heating

Another type of ICE emission was observed by Cottrell during minority ICRF heating of hydrogen in JET deuterium plasmas [2]. The ICE signal usually appeared with a delay of 0.4s after ICRF power was raised to its maximum value, with an excitation threshold in injected power and diamagnetic plasma energy. The fast ions producing the emission were protons accelerated at the ICRF resonance in the plasma core to MeV energies, and undergoing large orbits excursions to the plasma edge similar to those of fusion products producing ICE in JET.

In ASDEX-Upgrade, ICE emission during ICRF heating is visible at low densities (below 3×1019m-3) and high injected power, so that a tail of highly energetic hydrogen ions (1MeV) is created and can reach the edge. The emission can last several seconds as long as these conditions are maintained. The signal displays a mode structure similar to that of CAEs observed in spherical tokamaks, with three characteristic frequency spacings (around 800kHz, 100kHz and 5kHz). The modes evolve in time in correlation with the Alfvén velocity (due to changes in the plasma density).

ICE in the plasma centre

This is a less common type of ICE, which has been observed on only a few machines. The first observations date back to controlled experiments on JFT-2M in which a train of neutral beam pulses was injected into the plasma. Each pulse was accompanied by a short burst of emission with a frequency corresponding to the cyclotron frequency of the beam species in the centre of the plasma. When the beam ions slowed down, these bursts disappeared. More recently, central ICE was measured in high pressure deuterium plasmas in JT-60U at harmonics of the triton cyclotron frequency [13]. The signal showed some precursors before ELMs and peaked with them, but more commonly it appeared at the beginning of the NBI pulse. The signal was also observed on ASDEX-Upgrade during parallel NBI heating at frequencies corresponding to the proton cyclotron frequency. The signal changes in time, with stable phases, oscillations, period doubling and chaotic behaviour, which could be the sign of a weakly non-linear instability.

In addition to the results from tokamaks, ICE was observed also on spherical tokamaks and stellarators. We give hereafter the references to these results and explain why they should support the investigations of ICE on tokamaks.

Spherical tokamaks

CAEs have been detected in the large spherical tokamaks NSTX [14] and MAST [15-16] across a broad band of frequencies up to the ion cyclotron range. In the case of some MAST pulses, the emission intensity was observed to be strongly-peaked at the beam ion cyclotron frequency close to the magnetic axis [17]. Due to their relatively low magnetic field, beam ions in these devices are generally born at super-Alfvénic speeds, and can thus provide strong instability drive of a range of Alfvénic modes, including CAEs, and the low magnetic field makes it possible to study these modes in great detail using Mirnov coil data sampled at a relatively modest rate (10 MS/s in MAST).

Stellarators

ICE has been observed on W7-AS [18] and on LHD [19]. The specific magnetic configurations of these devices results in fast ion populations differing from those in tokamaks, and makes it possible to explore a wider range of distribution functions parameters than those otherwise accessible. It is anticipated that ICE will also be produced in the W7-X stellarator.

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