Development of the ion cyclotron emission diagnostic on the HL-2A tokamak

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Abstract: An ion cyclotron emission (ICE) diagnostic, which is based on a B-dot probe, has been recently designed and installed on HL-2A tokamak. The diagnostic is used to study various high-frequency magnetic field fluctuations which can be excited by energetic ions and runaway electrons in the plasma. The ICE diagnostic on HL-2A includes a high-frequency B-dot probe, direct current (DC) block, radio frequency splitters, filter bank and power detectors. The filter bank is composed of 16 channels filters, with the center frequency covering from 10 to 160 MHz, 10 MHz step length and 8 MHz bandwidth. The log detectors with a large dynamic range (from $-80$ dBm to $-20$ dBm) are used to detect the bandpass power. Test results of the B-dot probe, filters and power detectors are shown. The signals can also be sampled with a fast analog-to-digital converter with a 14-bit depth, 100 MHz bandwidth and 250 MSample/s sampling rate.

Keywords: Nuclear instruments and methods for hot plasma diagnostics; Plasma generation (laser-produced, RF, x ray-produced)
1 Introduction

Emission from magnetically confined plasmas in the ion cyclotron frequency range (typical at cyclotron harmonics $n$ up to $n = 10$) is generally categorized as ion cyclotron emission (ICE) [1]. The ion cyclotron resonance heating (ICRH) antennas and magnetic B-dot probes are commonly used as ICE probes. They are typically used for studying the high-frequency plasma instabilities, which are mainly driven by energetic particles (EPs) [2–5]. Although the ICE is typically observed from electromagnetic emission, an electrostatic mechanism was proposed in theory [6, 7].

In a magnetic fusion device, the energetic particle can be generated by a variety of sources, e.g. fast ions from neutral beam injection (NBI), fusion reactions, acceleration by ICRH waves or during edge localized modes (ELMs) crash, and runaway electrons (REs) during low density discharge and major disruption. The instabilities driven by these energetic particles have been widely studied with ICE diagnostic in many devices including JET [8], TFTR [9, 10], DIII-D [3, 5, 11–13], ASDEX Upgrade [14, 15], KSTAR [16–18] and EAST [4] tokamaks, NSTX-U [19] spherical tokamak and LHD [20] stellarator.

The common type of ICE is excited by energetic ions at the plasma edge. However, it is found that ICE instabilities can also be excited by energetic ions, most of them are driven by neutral beam ions, in the plasma core on ASDEX Upgrade [2, 14], DIII-D [3] and EAST [4] recently. Whistler waves with $f \gg f_{ci}$ have also been observed by this diagnostic on DIII-D for the first time [21], where $f_{ci}$ is the ion cyclotron frequency. Furthermore, the ICE diagnostic is also shown to be sensitive to fusion products, it is found that the ICE intensity scaled linearly with the deuterium-deuterium (D-D) fusion reaction rate over six orders of magnitude on JET [8]. And the scaling is reproduced by fully nonlinear self-consistent kinetic simulations [22]. This kind of diagnostic is also compatible with the high radiation environment of deuterium-tritium (D-T) plasmas, and could thus provide a valuable additional route to the experimental study of energetic particles in ITER and future fusion devices. However, ICE on TFTR [10] exhibits a more complex behavior in contrast to that on JET, which indicates the excitation mechanisms may be different. Further experimental and theoretical studies are still needed if ICE is to be used as a fusion product diagnostic.
In this paper, the new ICE diagnostic developed on HL-2A is reported, it aims to study the high-frequency magnetic instabilities driven by fast ions and REs. The ICE diagnostic setup and test results are described in sections 2 and 3. A summary is presented in section 4.

2 ICE diagnostic setup

HL-2A is a medium-sized conventional tokamak (major radius $R_0 = 1.65$ m and minor radius $a = 0.40$ m), which performs with plasma current $I_p \sim 100–450$ kA, centre line-average electron density $n_e \sim (0.2–5.5) \times 10^{19}$ m$^{-3}$ and toroidal magnetic field $B_t \sim 1.0–2.7$ T. The electron and ion temperatures are up to $T_e = 5$ keV and $T_i = 3.5$ keV, respectively.

A rich experimental study on EPs physics and EP induced instabilities has been carried out on HL-2A tokamak with the help of a powerful auxiliary heating system [23–28]. The neutral beam injection (NBI) system consists of two independent beamlines, both beamlines are co-injected into the HL-2A tokamak tangentially with an injection angle of 58.1°. The maximum port-through power of the two beamlines is about 1.2 MW and 1.0 MW, respectively [29]. The energy of the beam ions (deuterium) can be accelerated up to about 50 keV. The low-hybrid wave/current drive (LHW/LHCD) system is composed of four 3.7 GHz/500 kW klystrons and the passive active multi-junction (PAM) antenna, the total power can reach up to 2.0 MW [30]. There are 6 sets of electron cyclotron resonance heating and current drive (ECRH/ECCD) systems with 68 GHz/0.5 MW/1 s and 2 sets with 140 (105) GHz/1 MW/3 s. The maximum power of the 68 GHz ECRH is about 3 MW.

The ICE B-dot probe is mounted on the low field side (LFS) of the HL-2A NO port (at $\phi \approx 45^\circ$ near NBI 1#), shown in figure 1(a). The probe is a single-turn loop made of copper with the Teflon insulating sleeve. The probe is aligned parallel and perpendicular to the toroidal $B$-field direction, which aims to be sensitive to the fast and the slow ICRF wave respectively, which is shown in figures 1(b) and (c). The probe has a loop area of $\sim 40$ cm$^2$. A stainless steel (316L) frame is designed to hold and protect the probe. The radio frequency (RF) signal detected by the probe is transmitted to the atmosphere side via a high temperature, high vacuum tolerance coaxial transmission line and coaxial vacuum feedthrough.

Figure 2(a) shows the $R$ dependence of cyclotron frequencies for H ion and D ion at $B_0 = 1.3$ T on HL-2A. Based on the calculation, the ICE diagnostic is designed to measure the core D ICE harmonics up to nearly $n = 10$. A block diagram of the ICE diagnostic is shown in figure 2(b). When high-frequency magnetic field fluctuations are present in the plasma, an opposing current will be induced in the loop. The resulting voltage fluctuation signals will firstly travel through a $\sim 1$ m coaxial vacuum cable (26 AWG, 50 Ohm Coaxial Cable from Accu-Glass Products, Inc.), which can tolerate a max bake temperature up to 250 °C. Then it will travel through a cable coaxial feedthrough (KT19218, SMA 50 Ohm, from Solid Sealing Technology), and transmit to the airside. The direct current (DC) break is used to block the DC part of the signal to protect other components of the diagnostic system works, which works in the frequency range of 5 MHz–18 GHz and an operating voltage of 3000 V. The power divider separates the high-frequency signal into two ways, one for the high-speed digitizer and the other one goes to a set of filters and power detectors. The fast analog-to-digital converter (ADC) digitizer (NI PXIe-5172) works with 14-bit depth, 100 MHz bandwidth and 250 MSample/s sampling rate. It works with 250 MSample/s for
one channel or 125 MSample/s for multi-channels. The lower sampling rate for multi-channels is mainly limited by the read/write speed of the hard disk, which will be solved in near future. The digitizer records data in the form of time series voltage fluctuations with maximum amplitudes of \( \pm 5 \text{ V} \) at 50 Ohm input impedance. And 1 GB of data will be recorded per shot for the typical discharge length of 2 s in HL-2A. The 16 bandpass filters are used to allow signals in the range of the frequencies of interest to pass through. The log power detectors are applied to detect the bandpass integrated power, and the 16 integrated powers are recorded with a 20 kHz acquisition system. The 16 integrated powers with low acquisition rate benefits from less data, which can be used to fast analyze the time interval and the frequency range of the ICE instability. For a detailed analysis, the window fast Fourier transform analysis will be carried out with the fast ADC data.

3 Test results

A laboratory test of the B-dot probe is performed before the installation. The purpose of the test experiments was to determine the attenuation coefficient of the probe and prove that the diagnostic system can acquire the spectrum of an RF wave. The simplified test experiment in the laboratory is shown in figure 3(a). The network analyzer is used to give an excitation to the 9-inch RF coaxial transmission line. And the B-dot probe is installed inside the transmission line. Another side of the coaxial transmission line is connected to a resistor of 50 \( \Omega \). Another test is using one probe as the source and the other one as the receiving, the distance between two probes is 20 mm. The waves with
Figure 2. (a) $R$ dependence of cyclotron frequencies for H ion and D ion at $B_{10} = 1.3$ T. Vertical dashed lines indicate $R$ positions of the plasma edge. (b) Block diagram of the ICE diagnostic on HL-2A.

different frequencies (20, 60, 100, 140, 180 MHz) and power amplitude of 0 dBm are transmitted, and the received powers are shown in figure 3(b). The power received is around −16 dBm for different frequencies. The test results demonstrate that the B-dot probe can work well in the frequency range of ICE.

Figure 3. (a) The network analyzer was used to get the attenuation coefficient. $S_{21}$ parameter is the value of the attenuation coefficient of the B-dot probe. A simplified test experiment in the laboratory is shown in the subfigure; (b) the results from the spectrum analyzer with different frequencies (20, 60, 100, 140, 180 MHz), using one probe as the source and the other one as the receiving as shown in the subfigure.

The filter bank is designed which employs a 16-way power divider or two 8-way power dividers and 16 separated bandpass filters to fulfill the power and frequency separation. Figure 4(a) shows the test response function of the 16 filters. The center frequencies of the filter channels are from
10 MHz to 160 MHz with a 10 MHz step length. Each channel of the filters has an 8 MHz bandwidth. The max power loss is less than 7 dB (160 MHz channel). The test results show that the filters have high consistency and excellent out-of-band rejection (>50 dB at 20 MHz offset).

Figure 4. (a) The response curves of the filters measured by a network analyzer. \( f \) means the operation frequency; \( S_{21} \) parameter means the attenuation coefficient. (b) The response of the log power detector with different frequencies (test results). Three typical frequencies (20, 100, 200 MHz) are shown.

The log detector is used in ICE diagnostic on HL-2A to test the wide range magnitude of ICE intensity detection technology. It is mainly based on AD8362, and several low and high pass filters, amplifiers and attenuators are used. The AD8362 is a true root mean square (RMS) responding power detector that has a 65 dB measurement range. It is intended for use in a variety of high-frequency communication systems and in instrumentation requiring an accurate response to signal power. It operates from arbitrarily low frequencies to over 3.8 GHz and accepts inputs from \(-52 \text{ dBm}\) to \(+8 \text{ dBm}\). Due to several low and high pass filters, amplifiers and attenuators being used in the power detectors, the actual working frequency is limited in the range of 10 MHz to 1.5 GHz. And the final power response of the log detector is adjusted to the range of \(-80 \text{ dBm}\) to \(-20 \text{ dBm}\). Figure 4(b) shows the power responses of the log power detector with different frequencies. The detector has very similar output voltage responses for the three different frequencies (for typical working frequency of ICE diagnostic).

4 Summary

For the study of high-frequency magnetic fluctuations driven by energetic particles. An ICE diagnostic is developed on HL-2A. It consists of a high-frequency B-dot probe, DC block, radio frequency splitters, filter bank and power detectors. The signal can be sampled with a fast analog-to-digital converter with 14-bit depth, 100 MHz bandwidth and 250 MSample/s sampling rate. Test results of the B-dot probe and filters show the ICE diagnostic can work in the range of
10 MHz to 200 MHz. The log power detector is applied in the ICE diagnostic for power detection. It has an advantage of a large power dynamic range (>60 dB from −80 dBm to −20 dBm), which would be useful for ICE measurement from many different possible sources in the future.

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