Study of the ICRF minority heating performance by neutron signal on EAST

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Ion cyclotron range of frequencies (ICRF) heating has been considered as an effective means for upraise ion temperature in magnetic confinement fusion plasma. We were employment the time resolved neutron fluence and energy spectrum diagnostics to study the ICRF heating on EAST tokamak. The phenomenon of neutron yield rapid rise has been observed during the power of wave effect launch into deuterium plasma. However, that obvious increase was difficult occur in Lower Hybrid Wave (LHW) heating alone. The ICRF dominant heat minority hydrogen ions were supported by below 5% of n_H/n_D and depression high-energy tail in neutron spectrum that measurement by liquid scintillator. In this case, adopt neutron fluence and plasma density signals to inverse calculation the central ion temperature by classical fusion equation. Calculation results indicate that central ion temperature growth approximate 30% in L-mode plasma, and excess 50% in H-mode plasma during ICRF heating. Compare with other diagnostics, such as x-ray crystal spectrometer (XCS), those results were accordant. Furthermore, the relationship of neutron yield associate with plasma current and ICRF inject power has been statistic in this article.

Keywords: Neutron diagnostic, ICRF heating, Fusion

Introduction

Campaign of 2012 year, the plasma auxiliary heating experiment of EAST depends on LHW and ICRF; theirs source power were 2MW and 6MW respectively. The LHW of 2.45 GHz frequency drive high temperature deuterium plasma with quasi-steady-state operation excess four hundreds successfully and the central electron temperature nearly 2 keV. However, it toward the efficiency of fuel ion temperature promoting was weakly [1]. The ions heating mostly rely with high power ICRF. On EAST tokamak, four sets of 1.5MW transmitter were operated in this campaign that the ICRF total source power up to 6.0MW and the frequency can be changed from 25MHz to 70MHz. Unfortunately, mismatch plasma shape, antenna design and the gap between antenna and plasma that could induce wave coupling become badly and reflect worse. Generally, half of source power could be launch to plasma at the present of ICRF heating experiment. The transmissible fast wave interaction with deuterium plasma has a complex process, thus some shots of ICRF heating effect was indistinct. The DD yield provide a most intuitionistic way to estimation the ion heating effect by ICRF, case of the DD reaction rate with ion temperature in relationship of $<\sigma v> \approx \kappa T_i^{\gamma}$, Ti near 1keV then $\gamma \approx 5$ [2].

Furthermore, other electron and ion temperature measurement diagnostics can be provide lots of effective heating evidence such as poloidal XCS. That could be combination with neutron diagnostics result to research ICRF heating.

Diagnostic setup

The neutron diagnostic arrangement on EAST tokamak comprised time resolved emission monitor and DD neutron spectrometer. Neutron emission monitor systems have five channels of independent measurement that basis on four ^{3}He counters and one ^{235}U fission chamber. Those include two kinds of ^{3}He proportion counters which sensitivity were 133 cps/nv and 15 cps/nv respectively [3]. High sensitivity counters suitable for lower neutron produce plasma experiment of Ohmic and LHW. The fission chamber was coated with 1.4 gram uranium-235 which efficiency of thermal neutron reached 1.16 cps/nv. All neutron flux monitor counters were operated on counts mode. Besides these counters, liquid scintillator has been used to measurement neutron spectrum and profile emission rate. There is employment 2 inch diameter and thickness scintillator manufacture by Saint-Gobain which type is BC-501A [4]. One scintillator implemented to DD neutron spectrum measurement and another six were disposed in a superior radiation shield assembly with fan array collimation for neutron rate profile monitor. These detect system were used pulse shape discrimination technology to distinguish neutron and gamma signals that basis on traditional electronic circuit. The profile emission rate monitor system was first engineering test in the campaign of 2012 year. In addition, a BGO detector has been position with BC-501A sintillator in the same shield to monitor γ-ray strength and energy that signals will be used to judgment n/γ discrimination reliability in neutron spectrometer. Arrangement of neutron diagnostics around on EAST tokamak is shown in figure 1, which sub graph display the neutron counter configuration.

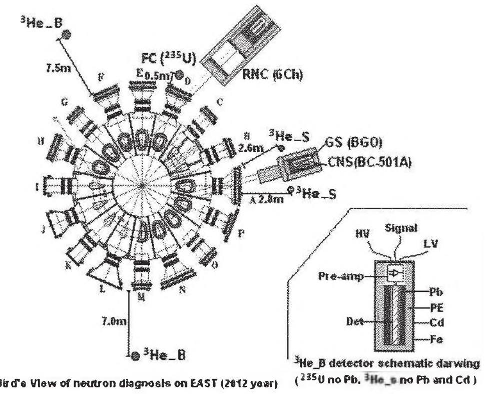

Figure 1. Diagram of the neutron diagnostics arranged on EAST tokamak (2012 year). ^{3}He_B, ^{3}He_S and FC denote high, lower sensitive ^{3}He counter and ^{235}U fission chamber respectively. CNS and GS express BC-501A neutron and BGO gamma spectrometer. RNC was 6 channel of neutron profile monitor array testing on this campaign.

A part of detectors has been calibration with neutron source that was generated by ion accelerator in the Nuclear Physics and Technology lab of Peking University. The detection efficiency of two sensitive ^{3}He and ^{235}U was absolute calibration by 2.5MeV neutrons that results were 7%, 6.9% and 0.14% respectively. Liquid sintillator for spectrum measurement has been make six points monoenergetic neutron calibration at the accelerator, and done three points gamma energy calibration by isotopic radioactive source at ours lab. The energy of neutron calibration is 1.61MeV, 2.02MeV, 2.45MeV, 3.00MeV, 3.60MeV and 4.27MeV, and the gamma calibration adopt ^{22}Na and ^{137}Cs source which energy are 0.511MeV, 1.275MeV and 0.661MeV respectively [5]. Presently tokamak device transport coefficient with DD neutron has not obtained by ^{252}Cf source in situ calibration. Thus we were adopted a three dimension model, construct by 1/8 of EAST device, to do simulation with Monte Carlo code (MCNP) [6]. The coefficient computing results indicate in figure 2. Consider the factors of detector efficiency, distance, capture area and time resolution for ^{235}U fission chamber signal, the absolute conversion coefficient is $4.1\times10^{9}ns^{-1}$/count.

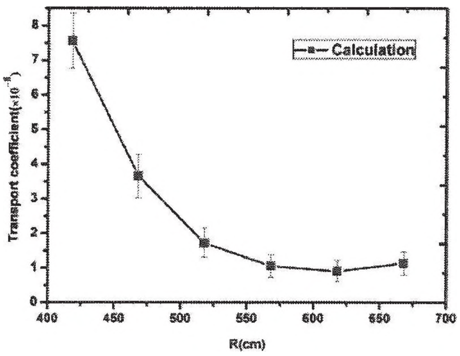

Figure 2. Neutron transport coefficient of EAST tokamak simulation by monte carlo method.

Experiment and result

Generally the ICRF heating experiment do not expect the background parameter of plasma too lower, because of lower current, density and temperature are disadvantage for RF wave energy absorbed. Therefore, during ICRF experiment on EAST, plasma current (I_p) exceed 400kA and the central electron density (n_e) high than $1.5\times10^{19}m^{-3}$ ordinarily. Beside this there is often cooperation heating with LHCD in order to increase background temperature. A typical shot (#40441) of ICRF heating deuterium plasma experiment data waveforms are shown in Figure 3. In this shot, the phase of plasma current plateau, I_p was constant with 500kA and n_e raise from $2.1\times10^{19}m^{-3}$ to $2.5\times10^{19}m^{-3}$ during ICRF launch. Premeditation injecting power of LHCD was 1.5MW and their reflect rate less than 10% in plateau. The 30MHz frequency of ICRF feed in to plasma through four antennas that total power was 1.4MW. Unfortunately, one set of transmitter reflecting protection lead to injected power lost about 30% after 5.5 second. The plasma store energy was calculated by diamagnetic signals, central electron and ion temperature were calculated by soft X-ray energy spectrum and X-ray Crystal Spectrometer (XCS) that measure Ar atom excitation spectra. The neutron yields deriver from the product of ^{235}U fission chamber pulse counts and DD neutron transport coefficient. In addition, the time resolved of core ion temperature was estimated by neutron yield display on last row with XCS calculation result in this figure. As for inverse calculation ion temperature by neutron signal will detail in follow text. The preferable ion heating performance was appeared on ICRF inject that bring the neutron yield sharp increase five times and the central ion and electron temperature upraise more than 0.3keV. Besides, the plasma store energy gains 35kJ and energy confinement time $\tau_e \approx 54$ms. In this shot, high field side at 1.358m and the removable limiter of low field side at 2.335m on toroidal major radius, the antenna position of LHCD and ICRF were 2.345m and 2.335m respectively. So the ICRF antenna positing closely plasma edge was an important factor for valid heating than conjecture support by next experiment practical.

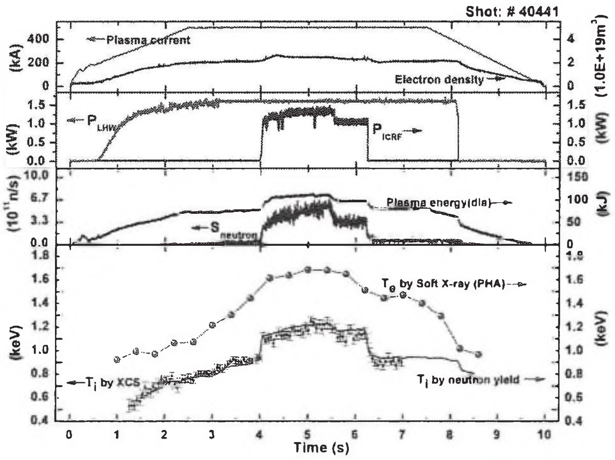

Figure 3. EAST experiment data waveform of ICRF coupled heating on L-mode plasma (#40441). Te and Ti indicate the central temperature of electron ant ion respectively.

The spectrums of recoil proton measurement by BC-501A scintillator are shown in figure 4. Another shot (#40349) of result adopt to compare with the coupling heating (#40441), that have similarly plasma current and density except without ICRF injection. The compare result indicated that high energy tail of recoil protons are nothing serious during ICRF heating, in despite of there is high event counts of relatively. Furthermore, than reflect the contribution of second harmonic ICRF heating was weakly on this type of experiment condition [7][8]. Impurity spectrum of hydrogen give a judgment of n_H/n_D was lower than 5% in #40441 shot, and synthetically analysis with the resonance layer position of hydrogen that minority heating was occupied domination. So the injection RF energy mostly absorbed by hydrogen ions which through kinetics collision to transport energy heating bulk plasma. There are plentiful event counts in low energy region of the recoil proton spectrums that due to heaviest scattered neutrons. We had attempt two methods to unfold the recoil proton spectrum with the detector response function [9]. Unfold obtain the DD fusion neutron spectra is show on figure 5. The 2.45MeV fusion neutron peak demonstrates a similar Maxwell distribution that the full width at half maximum (FWHM) is approximately 90keV. Estimate the average temperature of central deuterium ion about 1keV by formula of $\mathrm{FWHM(keV)}=82.6(\mathrm{Ti})^{1/2}$, that result agrees with XCS despite recently it none time resolution and lower precision. In order to obtain better time resolve temperature information by neutron signals, there could be inverse calculation with DD neutron yield [10]. However this method was always adopting in Ohmic plasma. During ICRF minority heating process in EAST recently experiment, the neutron yield measured by ^{235}U detector is generally unnecessary to consider the contribution of photo reaction and fast ion that improved by DD neutron spectra. So, we were attempt calculation central ion temperature T_i (0) with neutron yield that results compare with SXC are show on figure 6. There are fifteen shots of ICRF minority heating employment and each shot take two or three points. Classical neutron yield formulas basis on the thermal reactive given by Bosch and Hale were express with computer code to inverse calculation T_i (0) [11]. The temperature and density distribution on plasma were adopted a invariable type of value for EAST. Central deuterium ion density had been take HCN laser interferometer measurement the central electron density multiplies 0.8 to substitute. There inverse calculation results agree with SCX in despite input many parameters with assuming that because of DD neutron yield strong correlation with fuel ion temperature.

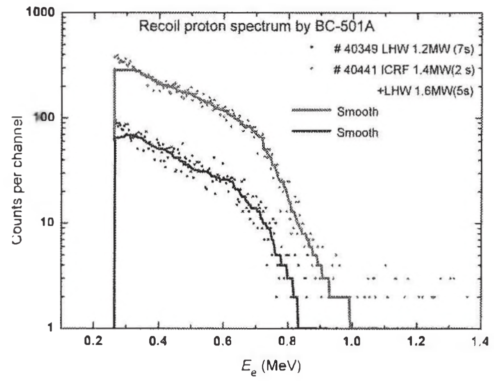

Figure 4. Liquid scintillator measured the DD neutron recoil proton spectrum in RF heating plasma.

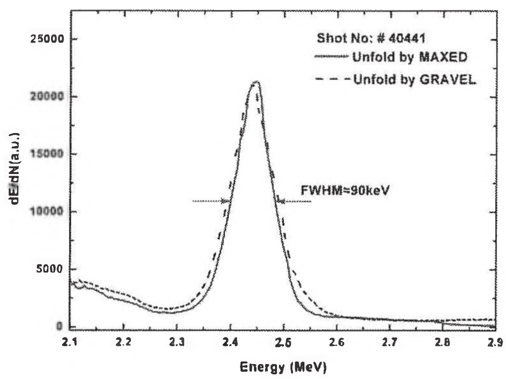

Figure 5. BC-501A scintillator obtain the DD neutron energy spectrum unfold by two method.

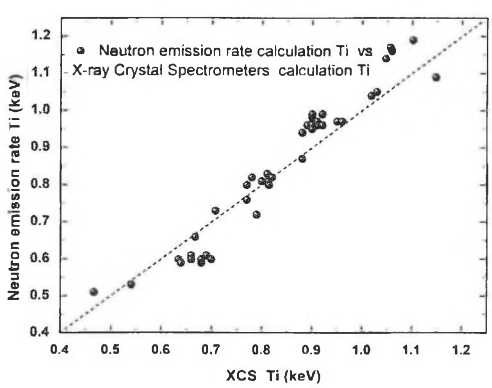

Figure 6. Neutron yield calculate the central ion temperature compare with XCS diagnostic results on ICRF minority heating status.

At present experiment of EAST, there was high confinement of H-mode plasma regular obtainment on the condition of total heating power excess a threshold. LHW and ICRF were achieved H-mode plasma respectively, but this always to thought decrease plasma parameter and power threshold. Thus the RF coupled heating were easily access H-mode on ordinary discharge status [12]. Figure 7 displays a shot of ELMs H-mode plasma on coupled heating. The injection power of LHW has maintained on 1.5MW except small reflecting fluctuate. However, the ICRF injected power was slow raise from 1.0MW to 1.4MW. When total power excess threshold, there was access H-mode status that could be indicate by Dα and MHD signals. The neutron yield, plasma story energy and central ion temperature have twice obvious upraise at the time of ICRF launch and H-mode transform. In the phase of ICRF injected, ion temperature increase from 0.7keV to 1.15keV (up 64%) that heating effect had a decided advantage over the L-mode operation. The electron temperature fall in the H-mode transition that cause was plasma density and electron collision rate raise along with particle confinement improve.

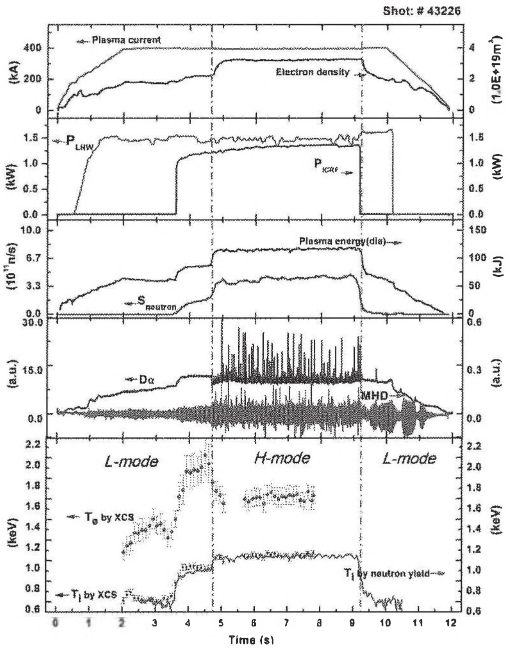

Figure 7. H-mode plasma operation on ICRF and LHW coupled heating condition.

Data statistics

The neutron yield direct relative with fuel ion temperature but plasma current and ICRF absorb power are important indirect influence factors. More than 80 shots statistic of neutron yield verses ICRF heating power in L-mode plasma are show on figure 8. They were having same toroidal field (Bt), RF frequency, antenna distance and single heating operation condition. The plasma density was little different in these shots but it influence neutron yield are not serious (less than 35%) for this verses. There are obvious trend on statistical result indications of the neutron yield increase with current and RF power raise. In order to get distinct scaling relation with current and RF power, we were fitting these experiment results and obtained a scale law of $Y(n)=5.3\times10^{11}\cdot P_{ICRF}^{1.59}\cdot I_P^{2.51}(s^{-1})$. This scale law calculated neutron yield compare with diagnostic measurement results are show in figure 9. That can be satisfaction the recently experiment status on EAST.

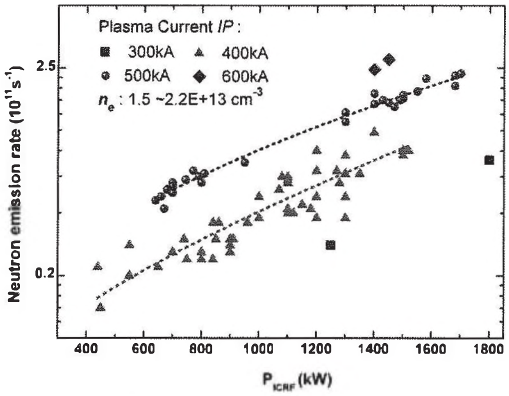

Figure 8. DD neutron yield verses inject ICRF power on different current plateau of L-mode plasma.

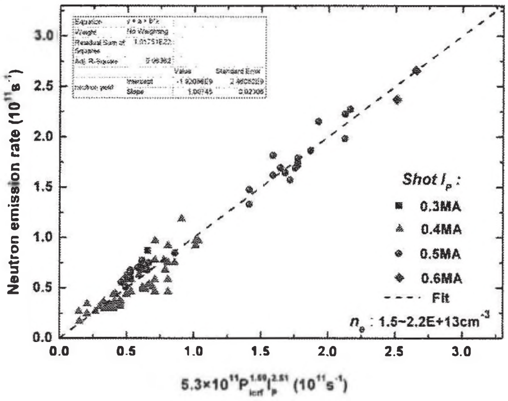

Figure 9. Statistic gets the DD neutron yield scale law with injection ICRF power and plasma current in thermal plasma.

Conclusion

The ICRF minority heating plasma effective was directly observation by neutron diagnostic, and achievement attempt calculation central ion temperature by DD neutron yield. Those results are agreed with other ion temperature diagnostic such as XCS. The H-mode plasma heating by ICRF has better effective than ordinary L-mode, and the ion temperature increase more than 50% by neutron yield calculation. Statistic 85 shots of ICRF heating, we are obtain a neutron yield scaling law with plasma current and RF injected power that suitable for recently experiment on EAST.

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