AN ACTIVE CHARGE –EXCHANGE q MEASUREMENTS IN ITER BASED UPON THE DIAGNOSTIC HYDROGEN BEAM

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The active charge exchange technique based upon Secondary Charge Exchange effect (SCX) is proposed for safety factor measurements in ITER. The performed numerical modeling shows that measurements of the magnetic pitch angle are possible up to the plasma center with radial resolution of 5 cm and integration time of about 10 ms. A systematic inaccuracy amounts several milliradians. An important advantage of SCX technique is the possibility of direct pitch angle measurements.

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1. INTRODUCTION

Development of a technique for safety factor (q) measurements is one of the most important and complicated problems to be solved by the ITER diagnostic community. There are a number of serious technical problems limiting use of existed techniques at the reactor relevant conditions. It compels to develop new approaches. The techniques considered in this paper can be treated as one of them.

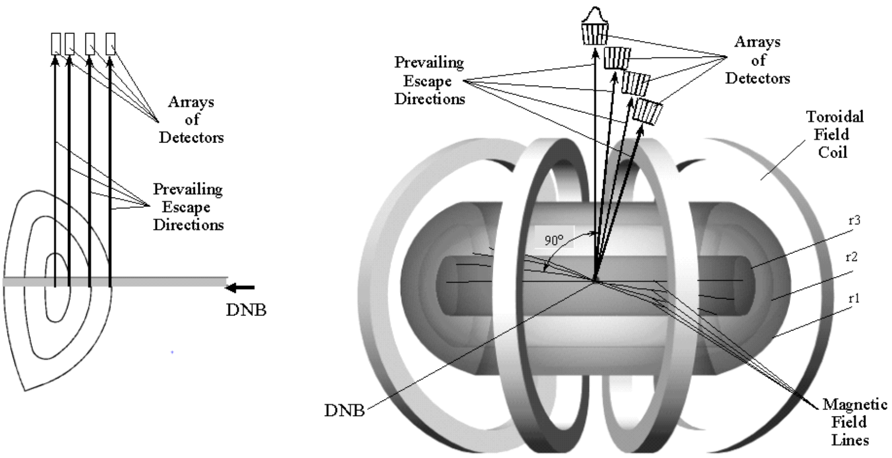

Fig.1. Experimental Geometry.
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The secondary charge exchange (SCX) atoms were originally revealed during experiments on T-10[1]. At the same time it was proposed to use the phenomenon for q measurements in a tokamak. Later an unfortunate attempt of SCX atoms detection was made on TEXT[2]. Authors know nothing about SCX experiments on present tokamaks. In 1999-2002 renewed experiments on T-10 proved that the technique is perspective for q measurements in magnetic confinement plasmas[3].

There are papers devoted to a similar active charge exchange diagnostic for the plasma magnetic structure investigation[4,5,6]. The approach mentioned in these papers substantially differs from SCX, as it is based on detection of E/2 atoms that originate at the dissociation of beam molecules. The SCX flux are treated in the papers[5,6] only as a background embarrassed measurements. It should be noted, that use of the molecular dissociation for measurements in the reactor is hopeless due to strong attenuation of the molecular fraction in large dense plasmas. Besides, the diagnostic injector of ITER supposed to be built on the basis of negative ion source; hence the molecular fraction of the beam is negligible.

2. PHYSICAL BASIS OF THE TECHNIQUE

The experimental geometry is exhibited in Fig.1. The hydrogen beam (DNB) is injected along the major radius of the machine. At this geometry the axis of the beam is directed normally to all the flux surfaces. At interactions (ionization and charge exchange) beam atoms with plasma particles ions having energy equal to that of the beam atoms are borne. If an ion has no longitudinal (in relation to the magnetic field direction) velocity, the particle gyrates along the Larmour circle. Since at least a part of the ion's trajectory is in the beam volume, the ion can be charge exchanged with a beam atom. The originated fast atom will escape plasma along straight trajectory directed normally to the magnetic field line. In such a manner, measuring the prevailing direction of SCX atoms' escape, one can get information about magnetic pitch angle that is immediately connected with the safety factor (q).

In reality, the fast ions, originated at the beam – plasma interaction, may have some longitudinal velocity due to the beam divergence and the transfer of the momentum at the ionization. Hence, the ions will move along spiral trajectories. The lifetime of an ion inside the beam volume depends on drift velocity and width of the beam and is, in the considered condition, significant, that leads to ‘accumulation’ of the fast ions. Their density is well over than that of the beam atoms. The more the longitudinal velocity of an ion the less it’s lifetime inside the beam target, and, consequently, less the probability to be charge exchanged. That is why, the effective width of SCX atoms’ angle distribution, is significantly less than that of the initial fast ions. The narrow angle distribution enables to get low systematical error of the measured pitch angle value. The trajectories of the SCX atoms, which were borne at the same point, are practically in one plane. That is why, the specific flux of the particles is detectable in spite of its strong attenuation in plasma.

3. RESULTS OF SIMULATIONS

At numerical simulation we modeled generation and movement of the fast ions, charge exchange of the fast ions with the beam atoms, attenuation of the SCX atoms’ outflux. Besides, values of the background signals due to charge exchange of the thermalized plasma ions both with residual neutrals and with beam atoms were calculated. We used the plasma parameters for one of the main scenarios of ITER performance: $T_e(0)=T_i(0)=15$ keV; $n_e=10^{14}$ cm^{-3}; $B_t=5$ T; partial content of the hydrogen in plasma 5%. The used parameters of the hydrogen beam are the following: energy of atoms 100 keV; equivalent current 20 A; dimensions – 30×30 cm; effective divergence 7 mrad. It was supposed that dimensions of the observation are (toroidal×radial) 10×5 cm, and detectors are arranged at 10 m from the first wall.

The attenuation of the beam was calculated using an effective beam-stopping cross-section that takes into account ionization at electron impact and interactions (ionization and charge exchange) at the collisions with hydrogen and main impurities (He, C) ions[7]. The density of the residual hydrogen atoms was computed by means of a 1D penetration code.

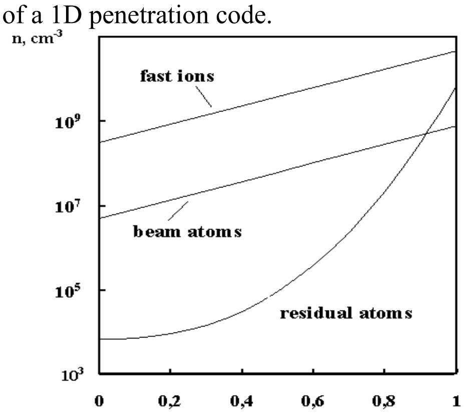

Fig.2. Profiles of densities of atoms and fast ions

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For the fast ions’ density calculations one has to know the shape of their initial distribution on angle between velocity vector and magnetic field direction. This width of the distribution, besides, strongly influences the systematical error of the measurements. Three main processes that determine the angle distribution are the following: the divergence of the diagnostic beam, the momentum transfer at the ionization, and scattering at the plasma charged particles. The performed analysis showed, that the main factor is the divergence of the beam. In Fig.2 the densities of the beam and residual atoms, as well as the concentration of the fast ions, are shown.

Fig.3 shows the specific densities of the SCX and background fluxes as function of the radial position (r_{obs}) of the observed area for the beam energy 100 keV.

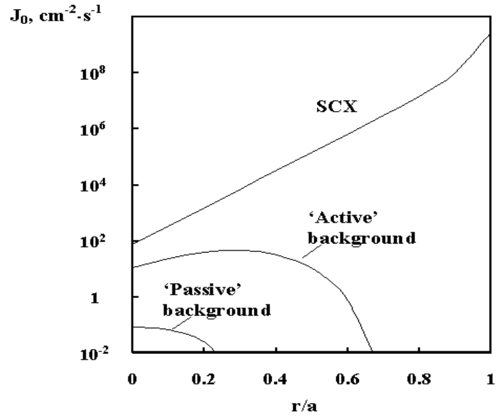

Fig.3. Dependencies of SCX and background signals on radial position of the observation region. E_b=100 keV.

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We supposed that the background fluxes of atoms having this energy originated from the charge exchange of the thermalized plasma ions both with residual neutrals (‘passive’ background) and with beam atoms (‘active’ background). It is seen, that as the value of the ‘passive’ signal is negligible, and the ‘active’ one becomes considerable for the plasma core. However, since signal-to-noise ratio is nearly proportional to exp $(-T_i/E_b)$, here E_b – is the energy of the beam, T_i – ion temperature, this ratio can be drastically improved by increasing of the beam energy (Fig.4). The picture shows that growing of the beam energy from 100 to 200 keV leads both to improvement of signal-to-noise ratio and to gain of the SCX signal. The further increase of E_b is inexpedient due to fast drop of the charge exchange cross-section that leads to decrease of the SCX flux.

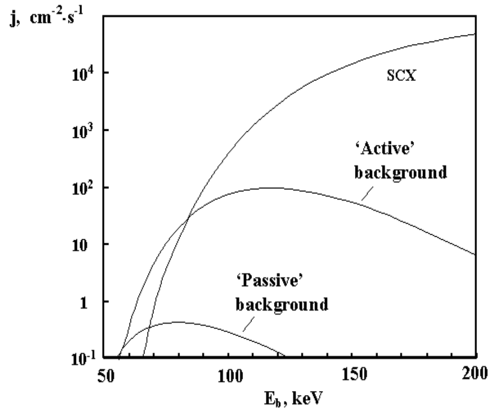

Fig.4. SCX and background signals versus the beam energy. r_{obs}=0.

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The systematical error of the pitch angle measurements is determined by the width of the SCX atom's angle distribution. The effective width of the distribution practically does not depend on that of the fast ions and does not exceed $5\cdot10^{-3}$ rad (Fig.5).

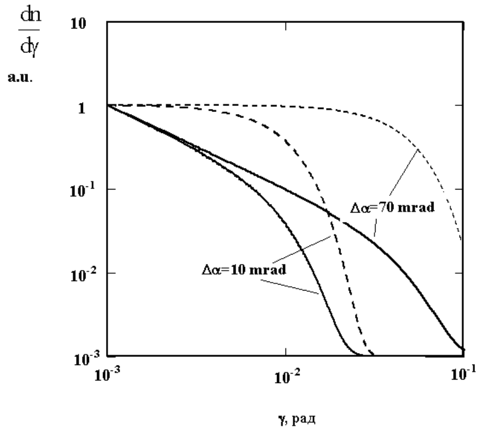

Fig.5. The fast ions' and SCX atoms densities versus the angle between observation line and plane normal to magnetic field direction. Dashed curves refers to ions, solid ones to SCX atoms

It is due to reduce of the fast ions' lifetime inside the beam target at the increase of the longitudinal velocity component. It means that if the pitch angle is about 0.2 rad, we can get relative error less than few per cent. But, it should be noted, that at large angle dispersion of fast ions (e.g. due to inaccurate beam alignment) the friendly signal drops, and, consequently, the statistical error of the measurements rises.

4. CONCLUSION

A novel active charge exchange technique for q measurements in ITER is proposed. A preliminary feasibility study allows one to make the following conclusions:

- The technique enables to carry out *direct* measurements of the magnetic pitch angle. No sophisticated data processing and calibration procedures are needed.
- For a typical discharge scenario signal value is enough for measurements down to ρ=0; signal to background ratio in the plasma core is acceptable at the beam energy of 100 keV and exceeds 10^4 at the optimum E_b (200…250 keV).
- Lowest systematical error, can be achieved not exceed 0.005 rad.
- At the optimum E_b the temporal resolution of 10 ms and the radial resolution of 5 cm seem to be achievable for measurements in the plasma core.

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АКТИВНЫЕ КОРПУСКУЛЯРНЫЕ ИЗМЕРЕНИЯ q В ITER НА БАЗЕ ДИАГНОСТИЧЕСКОГО ВОДОРОДНОГО ПУЧКА

А.А. Медведев, В.С. Стрелков

Активная корпускулярная методика, основанная на эффекте вторичной перезарядки (SCX), предлагается для измерения коэффициента запаса устойчивости в ITER. Проведенное численное моделирование показывает, что измерения магнитного питч-угла возможны вплоть до центра плазмы с радиальным разрешением 5 см и временем накопления информации около 10 мс. Систематическая ошибка составляет несколько миллирадиан. Важным достоинством методики является возможность проведения прямых измерений питч-угла.

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Активна корпускулярна методика, заснована на ефекті вторинного перезарядження (SCX), пропонується для виміру коефіцієнта запасу стійкості в ITER. Проведене чисельне моделювання показує, що виміри магнітного пітч-кута можливі аж до центра плазми з радіальним розділом 5 см і часом накопичування інформації близько 10 мс. Систематична помилка становить кілька міліралдіан. Важливим достоїнством методики є можливість проведення прямих вимірів пітч-кута.