Fast-Ion-Diagnostics for CHS Experiment

Mitsutaka ISOBE, Shoichi OKAMURA, Kenichi NAGAOKA, Masaki OSAKABE, Kazuo TOI, Yasuo YOSHIMURA, Keisuke MATSUOKA, Mamiko SASAO[1)] and Douglass. S. DARROW[2)]

National Institute for Fusion Science, Toki 509-5292, Japan
[1)]*Department of Quantum Science and Energy Engineering, Tohoku University, Sendai 980-8579, Japan*
[2)]*Princeton Plasma Physics Laboratory, Princeton, NJ 08543 USA*

(Received 4 December 2006 / Accepted 20 February 2007)

Fast-ion-diagnostics have played an important role in investigating issues related to fast ion orbits and fast-ion-driven MHD instabilities in CHS experiments. The fast-ion diagnostics employed in CHS are reviewed and experimentally obtained knowledge is summarized.

Keywords: CHS, NBI, fast ion, scintillator, loss cone, MHD instability, TAE, EPM

DOI: 10.1585/pfr.2.S1076

1. Introduction

The Compact Helical System (CHS) project [1] since June 1988 came to a close at the end of August 2006. The CHS was a medium-sized helical device having a major radius R of 1 m and averaged plasma minor radius a_p of ~0.2 m and was characterized by its low aspect ratio. The toroidal magnetic field strength B_t can be increased up to 2 T. This project has primarily aimed at clarifying confinement properties of a low-aspect-ratio helical plasma. Study of fast ion confinement has been one of key physics targets because of the symmetry breaking of the system and enhanced toroidicity. For this reason, various fast ion diagnostics have been developed and applied to the CHS device to investigate fast ion behaviors. In the early days' experiment of CHS which was in operation at the Higashiyama site of Nagoya University (June 1988-March 1999), our interest was mainly focused on issues related to fast-ion-orbit and/or loss cone structure. In the latter half of CHS project at the Toki site (October 2000-August 2006), we stressed on the studies on fast-ion-driven magnetohydrodynamic (MHD) instabilities and their effects on fast ion transport although the studies had already been started in the initial half of CHS project. In this article, fast-ion-diagnostics for CHS experiment are reviewed. Also, experimentally obtained knowledge on the issues related to fast ions in CHS is described.

2. On Fast Ions in CHS

Neutral-beam (NB) injection heating has been a primary heating method over a whole period of the project. The CHS was equipped with two NB injectors. One (NB#1) can provide the port-through power P_{nb} of 800 kW with injection energy E_b of 40 keV. The NB#1 was capable of varying the injection angle from tangential to perpendicular direction in order to explore efficient heating condition. The other (NB#2) provides P_{nb}/E_b of 800 kW/32 keV. In the Higashiyama site, two NBs were injected in the balanced manner to study confinement property of low-aspect-ratio helical plasma in the net-current-free condition. When CHS was moved to the Toki-site, NB injectors were rearranged so as to inject beams in the same direction. NBs have been typically co-injected to obtain efficient plasma heating. Beam ions also have played an important role for the studies of fast-ion-driven MHD instabilities such as toroidicity-induced Aflvén eigenmodes (TAE) [2] and energetic particle modes (EPM) [3] since they can be free energy source to destabilize those instabilities.

In order to clarify characteristics of beam ion orbits, typical collisionless guiding center orbits of co- and counter-going transit beam ions (H^+) are shown in Fig. 1 in the configuration having magnetic axis position R_{ax} of 0.962 m and the volume-averaged magnetic field strength of 0.94 T. The energy and initial pitch angle $v_{//}/v$ are 38 keV and 0.8, respectively. In this calculation, beam ions are launched at the several radial positions on the outboard side of the torus ($R > R_{ax}$) because beam ions are primarily born in the domain of $R > R_{ax}$ due to the tangential injection of NBs from the outboard side. As can be seen, trajectories of passing beam ions substantially deviate from the magnetic flux surfaces in the low field (< 1 T) operation of CHS because of fairly high energy of beam ions and enhanced toroidicity. First orbits of co-going transit beam ions born in the domain of $R > R_{ax}$ can stay in, resulting in not only effective heating but also efficient destabilization of fast-ion-driven MHD modes.

A diagnostic neutral beam (DNB) injector (E_b < 40 keV, P_{nb}~50 kW) was convenient for the detailed study of loss cone structure [4]. The DNB as a test particle source is characterized by the narrower beam and much lower injection power than NBs for heating. Because the DNB

author's e-mail: isobe@nifs.ac.jp

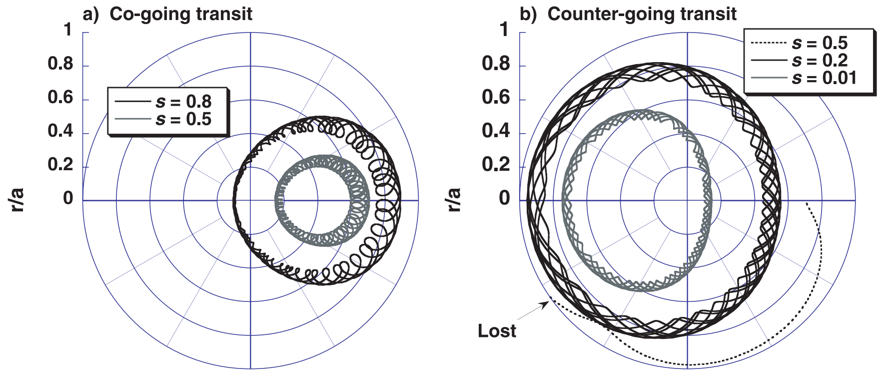

Fig. 1 Collisionless guiding center orbits of passing beam protons in the vacuum configuration having R_{ax} of 0.962 m and volume-averaged field strength of 0.94 T on the Boozer coordinates. The energy and initial pitch angle $v_{//}/v$ are 38 keV and 0.8, respectively. a) Orbits of co-going transit beam ions launched at $s = 0.5$ and 0.8 at the poloidal angle $\theta = 0$ on the outboard side. b) Orbits of counter-going transit beam ions launched at $s = 0.01$, 0.2 and 0.5. Here, s stands for the normalized toroidal flux, approximately corresponding to $(r/a)^2$.

does not influence parameters of background plasmas, it was useful to investigate experimentally behaviors of single particles under the fixed slowing down and deflection times [5].

3. Fast-Ion-Diagnostics

3.1 Neutral particle analyzers

The NPA has been one of popular fast particle diagnostics in fusion experiments, providing time-resolved energy distribution of confined fast ions. The NPA system employed in CHS was a relatively conventional and consisted of a gas-filled stripping cell and an energy analyzer having electrostatic parallel deflection plates, detecting neutral particles of energy from 0.1 keV to 50 keV, according to a voltage applied to the deflection plate. It was fabricated by Toshiba Co. in 1989. After entering charge-exchanged neutral-particles are re-ionized to ions in the stripping cell, they are discriminated in energy and are counted by aligned 16 microchannel plates (MCP). Output pulses from each MCP are counted in a CAMAC latching scaler with the sampling frequency of 5 kHz. The maximum counting rate of the system is about 3×10^5 cps. Energy resolution ΔE/E of the system was examined by use of a test proton beam source of which energy is up to 10 keV, depending on each MCP. The energy resolution was fairly good, namely ΔE/E at the lowest energy channel was evaluated to be ~3.7 % whereas ΔE/E at the highest energy channel was ~1.3 %. The NPA was installed at an equatorial plane of CHS and was capable of changing its viewing angle from tangential to perpendicular as shown in Fig. 2. This function allowed us to study confinement of fast ions over a wide range in their pitch angles [4–6]. Further detailed description of NPA system is available in Ref. 5.

Also, a compact NPA based on electrically cooled silicon-diode detector was developed and tested in CHS

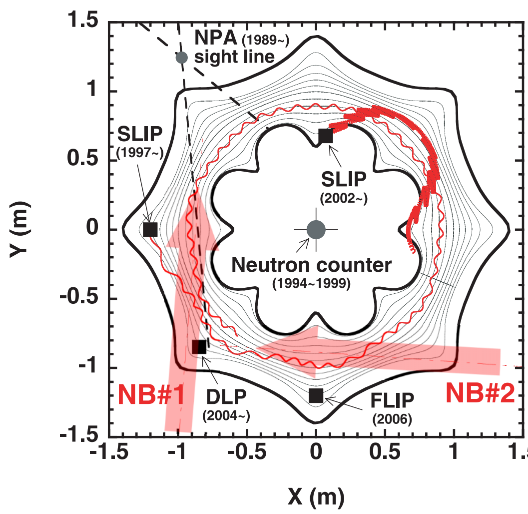

Fig. 2 Arrangement of neutral beam injectors and fast-ion diagnostics in CHS. The magnetic flux surfaces are of R_{ax} = 0.974 m. Computed lost-fast-ion orbits, i.e. barely co-going transit beam ion (38 keV) and helically trapped ions (17 keV) reaching probes are given in the figure.

to verify whether it can work as NPA during 1999 CHS operation [7]. The principle was successfully verified and a similar type of NPA is currently operated in LHD [8]. It should be noted that this type of NPA is applicable only to fast-particle-diagnostic because of the energy loss of incident particles in the electrode existing at the semiconductor surface.

.

3.2 Lost-fast-ion diagnostics

Two lost-fast-ion probes (LIP) based on the scintillator called SLIP [9–14] have been used to detect escaping fast ions directly near the last closed magnetic flux surface (LCFS). This project was initiated in 1997. One is placed on the outboard side to measure escaping barely

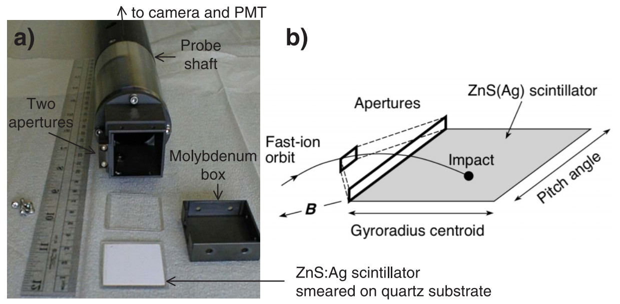

Fig. 3 Scintillator-based lost fast ion probe. a) Section of probe tip. b) Function of lost fast ion probe. The ZnS:Ag scintillator has a size of 32 mm × 32 mm and is mounted in the molybdenum box.

co-circulating beam ions and the other is installed on the inboard side to detect pitch-angle scattered, partially thermalized helically trapped fast ions [15]. These probes can be classified into a sort of magnetic spectrometer. The function of SLIP is schematically illustrated in Fig. 3. The detector end is essentially a molybdenum steel box with an inorganic scintillator ZnS:Ag on the bottom of the box. Two apertures, one behind the other, are on one side, and restrict the orbits of fast ions that can enter the probe. Fast ions with lager gyro-radii strike the scintillator surface farther from the apertures than those with smaller gyro-radii and their impact points are dispersed across the line passing through the center of two apertures according to the pitch angle. In our system, the scintillation light was divided into two by use of the beam splitter and each light was measured with an image-intensified camera and a set of photomultipliers (PMT). In order to follow fast events associated with fast-ion-driven MHD instabilities, the performance of measurement section of SLIP on the outboard side are enhanced [16]. This SLIP was equipped with a fast C-MOS camera with a maximum frame rate capability of 2 kHz and a set of photomultipliers of which frequency response up to 200 kHz. Based on our experiences in CHS, similar type of probe was fabricated and is currently operated in LHD [17]. In addition to the SLIP, Faraday cup type lost-fast-ion probes (FLIP) were also developed to measure the current of escaping fast ions reaching the probe [18,19]. In NB-heated discharges, both SLIP and FLIP installed at the same position in the poloidal cross section but the different toroidal angle show similar time evolution of flux of escaping fast ions. These probes have been primarily used to study fast ion losses caused by fast-ion-driven MHD instabilities [16, 20–25]

In addition to probes mentioned above, we have demonstrated that the directional Langmuir probe (DLP) can work as a fast-ion probe [26]. In this probe, metal probe tips mounted on a probe shaft are oriented toward both co-going and counter-going ions. By subtracting the electric current of couner-going ions from that of co-going ions, the current originated from co-going beam ions can be evaluated. The DLP was designed to be tough for heat load so as to insert into an NB-heated plasma and to provide local information of fast ion behavior inside a plasma. MHD-induced fast ion transport in an interior region of CHS plasmas has been successfully measured with the DLP [25, 27].

3.3 Neutron measurements

Neutron measurement provides information of global confinement of NB-injected fast ions. In our experiments, D-D neutrons were generated by injecting 1 % deuterium-doped hydrogen NB of which pulse duration was less than 5 ms into deuterium ECRH plasmas at the Higashiyama site. Neutron diagnostic system consisting of $^{10}BF_3$ and ^3He proportional counters [28] and a fast plastic scintillator [29] was employed to study confinement property of NB-injected fast ions in CHS [30–32]. When the deuterium (D^0) beam is injected into the deuterium plasma, the total neutron emission rate S_n is dominated by neutrons generated from beam-target reactions and can be scaled as $S_n \propto n_d \cdot n_{fd} \cdot \langle\sigma v\rangle_{D\text{-}D}$. Here, n_d and n_{fd} represent deuteron (D^+) density in the target plasma and fast D^+ beam density, respectively. $\langle\sigma v\rangle_{D\text{-}D}$ is the fusion reaction rate producing D-D neutrons. Confinement of beam ions can be experimentally investigated if we measure S_n in the condition mentioned above. The experimental decay time of S_n after NB turn-off was compared with the decay time predicted by classical slowing down model [33] to check whether losses of beam ions exist or not. It is noted that this experiment was performed only in the Higashiyama site.

4. Experimental Results

4.1 Issues on fast-ion-orbits and loss cone

Loss cone physics experiments were conducted by injecting NB#1 perpendicularly in the beginning of CHS project. The experiments revealed that perpendicularly injected NB could not increase plasmas stored energy in the standard configuration having R_{ax} of 0.921 m [6, 34], suggesting poor confinement of helically trapped beam ions. Although particle orbit is expected to be improved as the plasma column is shifted inward [35], NPA viewing perpendicularly showed significant depletion on the energy spectrum of beam ions even for R_{ax} of 0.878 m [6]. The result of "blip" injection experiment of perpendicular D^0-DNB was similar to that mentioned above as well [32]. This is because the ratio of gyro-radius of beam ions to a_p is large in the peripheral region of CHS, i.e. 0.1 ~ 0.2, depending on field strength, and trapped beam ions easily strike the vacuum chamber wall on the inboard side.

Confinement property of tangentially co-injected beam ions was also investigated by the method described in Sec. 3.3. The dependence on the field strength was clearly seen. In B_t of 0.88 T, beam ion losses were particularly significant in the long slowing down time regime whereas losses in B_t of 1.76 T were largely suppressed [31]. Losses of co-going transit beam ions were interpreted as the multiplier effects of strong deviation of orbits from the flux surfaces toward the outboard side as seen in Fig. 1 and resulting high probability of charge exchange (CX) loss in a peripheral region where neutral density is high.

Effect of radial electric field E_r on fast ion confinement was of great interest because theory predicts that positive E_r can improve trapped ion orbit in CHS-type helical plasma [36]. In the NB-heated plasma ($T_i(0) = 0.6$ keV), the dip was seen in the energy range from 1.5 keV to 3 keV on the energy spectrum measured with perpendicular NPA. When we superposed ECRH on the NB-heated plasma, the dip disappeared. The CX recombination spectroscopy indicates that the superposition of ECRH changes E_r from negative to positive. After the careful analysis by considering effects of change in plasma parameters on the neutral flux, we came to conclusion that the disappearance of depletion on the energy spectrum is due to change in loss cone domain due to positive E_r [37, 38]. It should be noted that effect of positive E_r on ions having higher energy was not seen.

4.2 Effect of fast-ion-driven-MHD modes on fast ion transport

Studies on this subject have been intensively carried out in CHS [20–25]. EPM and TAE are excited when NB is tangentially coinjected into relatively low density plasmas. Most of experiments were performed in the outward shifted configuration ($R_{ax} \geqq 0.949$ m) where $m/n = 3/2$ EPM and $n = 1$ TAE were alternatively destabilized in the same shot. EPM shows repetitive bursting nature accompanied with rapid frequency downshift from ~100 kHz to ~50 kHz having characteristic time less that 1 ms. It is noted that in R_{ax} of 0.921 m, $m/n = 2/1$ EPM of which frequency changed from ~50 kHz down to ~5 kHz was often excited. Correlated with EPM bursts, periodic pulsed increase of fast-neutral flux is observed with the NPA oriented to co-passing beam ions. This is caused by transport of fast ions to the peripheral region where neutrals are dense. Fast-neutral flux begins to increase right after magnetic fluctuations begin to glow [25], suggesting that fast ion transport begins right after EPM is excited. Also, both SLIP and FLIP located on the outboard side indicate significant increase of barely co-passing beam ions in the EPM phase. The experiments reveal that co-passing beam ions are transported toward the outboard side and are lost due to EPM. This observation is qualitatively supported by the orbit calculation by considering perturbed magnetic field modeled as $\delta\mathbf{B} = \nabla \times (\alpha\mathbf{B})$ where α is a general function of position. TAE induces anomalous transport and loss of fast ions as well. It was found that anomalously induced fast ion losses by EPM and TAE sensitively depend on the magnetic configuration and amplitude of magnetic fluctuation. Detailed analysis for the identification of TAE is available in Ref. 22. Effect of EPM and TAE on fast ion transport and/or loss is well described in Ref. 16.

[1] K. Nishimura *et al.*, Fusion Technol. **17**, 86 (1990).
[2] C.Z. Chen and M.S. Chance, Phys. Fluids **29**, 3695 (1986).
[3] L. Chen, Phys. Plasmas **1**, 1519 (1994).
[4] H. Matsushita *et al.*, Rev. Sci. Instrum. **75**, 3607 (2004).
[5] H. Matsushita, ph D thesis, The Graduate University for Advanced Studies 2006.
[6] S. Okamura *et al.*, Plasma Physics and Controlled Nuclear Fusion Research 1992 (Proc. 14th Int. Conf. Würzburg, 1992), IAEA, Vienna Vol.**2**, 597 (1993).
[7] T. Yamamoto *et al.*, Rev. Sci. Instrum. **72**, 615 (2001).
[8] M. Osakabe *et al.*, Rev. Sci. Instrum. **72**, 788 (2001).
[9] D.S. Darrow *et al.*, J. Plasma Fusion Res. SERIES **1**, 362 (1998).
[10] T. Kondo *et al.*, 1998 Int. Congress on Plasma Physics and 25th EPS Conf. on Contr. Fusion and Plasma Physics, Praha, June 29 - July 3, 1998 ECA Vol.**22C**, 1462 (1998).
[11] M. Isobe *et al.*, Rev. Sci. Instrum. **70**, 827 (1999).
[12] D.S. Darrow *et al.*, Rev. Sci. Instrum. **70**, 838 (1999).
[13] M. Isobe *et al.*, 26th EPS Conf. on Contr. Fusion and Plasma Physics, Maastricht, 14-18 June 1999 ECA Vol.**23J**, 21 (1999).
[14] M. Isobe *et al.*, Rev. Sci. Instrum. **74**, 1739 (2003).
[15] M. Isobe and K. Shinohara, J. Plasma Fusion Res. **80**, 1036 (2004). [in Japanese]
[16] M. Isobe *et al.*, Nucl. Fusion **46**, S918 (2006).
[17] M. Nishiura *et al.*, Rev. Sci. Instrum. **75**, 3646 (2004).
[18] M. Isobe *et al.*, Rev. Sci. Instrum. **77**, 10F508 (2006).
[19] S. Masuda *et al.*, Nucl. Fusion **37**, 53 (1997).
[20] K. Toi *et al.*, J. Plasma Fusion Res. SERIES **1**, 267 (1998).
[21] K. Toi *et al.*, Nucl. Fusion **39**, 1929 (1999).
[22] K. Toi *et al.*, Nucl. Fusion **40**, 1349 (2000).
[23] T. Kondo *et al.*, Nucl. Fusion **40**, 1575 (2000).
[24] K. Toi *et al.*, J. Plasma Fusion Res. SERIES **5**, 50 (2002).
[25] M. Isobe *et al.*, 21st IAEA fusion energy conference, Chengdu, 16-21 October 2006, EX/P6-8.
[26] K. Nagaoka *et al.*, Plasma and Fusion Res. **1**, 005-1 (2006).
[27] K. Nagaoka *et al.*, to be submitted.
[28] M. Isobe *et al.*, Rev. Sci. Instrum. **66**, 923 (1995).
[29] M. Isobe *et al.*, Annu. Rep. Natl Inst. Fusion Sci. (1998-1999) 240.
[30] M. Isobe *et al.*, Rev. Sci. Instrum. **68**, 532 (1997).
[31] M. Isobe *et al.*, J. Plasma Fusion Res. SERIES **1**, 366 (1998).
[32] M. Isobe *et al.*, Nucl. Fusion **41**, 1273 (2001).
[33] J. Strachan *et al.*, Nuclear Fusion **21**, 67 (1981).
[34] S. Okamura *et al.*, 20th EPS Conf. on Contr. Fusion and Plasma Physics, Lisboa, 26-30 July 1993, Vol.17C, Part I, I-385 (1993).
[35] S. Okamura *et al.*, Nuclear Fusion **39**, 1337 (1999).
[36] K. Hanatani and F.-P. Penningsfeld, Nuclear Fusion **32**, 1769 (1992).
[37] M. Osakabe *et al.*, Proc. of the 6th IAEA TCM on energetic particles in magnetic confinement systems, October 12-14, 1999, Naka, JAERI-Conf 2000-004, 85.
[38] K. Ida *et al.*, Nucl. Fusion **39**, 1649 (1999).