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K.N. Sato, S. Murakami, N. Nakajima, K. Itoh

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Possibility of Simulation Experiments for Fast Particle Physics in Large Helical Device (LHD)

K. N. Sato, S. Murakami, N. Nakajima, K. Itoh
National Institute for Fusion Science

Abstract

The confinement of fusion-produced or high energy particles is one of the most important issues to be studied in the helical confinement system. A preliminary study has been carried out about the possibility of techniques for simulation experiments for the study of high energy particle physics in the Large Helical Device (LHD) project.

Candidates of the methods have been considered as follows: (a) a high energy (~3.5 MeV) He^0 beam injection method, (b) a medium energy (~200 keV) H^0 beam injection method, (c) a method of high energy tail production by ICRF wave and/or a method of reaction rate enhancement by ICRF wave, (d) a method of the combination of neutral beam injection and ICRF wave, and so forth.

Features of each method have been considered. Although the high energy He^0 beam injection method has a couple of advantages, the technique of production of this beam is extremely difficult because of the difficulties of both the production of negative helium and ground-state neutral-helium production by neutralization. It is pointed out on the other hand that wide range of simulation experiments for fast particle physics may be carried out even by the medium energy beam method, because the typical orbit deviation (e.g., equivalent super-banana size in a classical sense) can be largely controlled by controlling the magnetic field configuration in the case of helical system, for example by shifting the magnetic axis. This is one of the unique features of helical system in contrast to the axisymmetric system.

Key Words: Simulation experiment, Fast particle confinement, Alpha-particle physics, NBI, LHD (Large Helical Device)

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[1] Introduction

Helical confinement systems have several advantages such as the possibility of steady-state operation, less possibility of major disruptions, and so on, as a future fusion reactor. However, various physics and technical issues are remained to be studied and solved in order for them to be realized. Among those will be the behavior and confinement of high energy particles in the system.

The Large Helical Device (LHD)[1] is being constructed at NIFS-Nagoya (National Institute for Fusion Science, Nagoya). The main objectives of the LHD project are to achieve good confinement, high temperature and high beta plasmas in the LHD system, to demonstrate steady-state operation with divertor action, to perform complementary studies with tokamak researches, and so forth. The LHD has the major radius of 3.9 m and the magnetic field strength of 3-4 T (3T at the experimental phase-I and 4T at the phase-II) by using superconducting magnets. The main machine and plasma parameters are listed in Table I. The first plasma is expected to be held in the spring of 1998.

As to the study of fusion-produced or high energy particle physics in the system, however, there is no plan to have a DT plasma in the LHD project because of the limitation of circumstances of the site. Since the confinement of fusion-produced or high energy particles is the issue of great importance, we have started consideration on the possibility of simulation experiments related to the behavior and confinement of high energy particles[2]. The preliminary study about the possibility of simulation experiments is presented in this paper.

[2] Candidates of Simulation Experiment for Fast Particle Physics in LHD

One of the most important issues to be studied on the helical system is the behavior and confinement of high energy particles in the system. A simulation experiment may be one approach for the study on the confinement of fusion-produced or high energy particles before going into the burning plasma experiment.

From this viewpoint, several approaches of simulation experiments have been considered as candidates of the methods. Generally speaking, there seems to exist two approaches, the neutral beam injection method and the RF assisted method.

The first candidate will be the most direct and simple one; that is, a method of high energy helium beam injection in the energy range of about 3.5 MeV, when we consider the experiment as an alpha-particle simulation of DT plasmas. This method will have a couple of advantages and unique features. By this method we may carry out simulation experiments mainly concerning to the single particle behavior of fusion-produced or high energy particles; that is, the study on the slowing down process by the investigation of high energy particle loss at the wall. Here, the study on lost particles will be much more easy than that in the real DT-plasma because of the circumstances with less neutrons. However, the technique of production of a high energy helium beam is extremely difficult, because we have to start the ion source from a negative one, which seems to be extremely difficult to produce. In addition to this, we have to prepare the accelerated neutral beam with large fraction of ground state neutrals in order to perform the precise simulation experiment, because the neutrals with excited states are very easy to ionize and details of those relaxation times are not known, and thus the ambiguity of the initial condition of the experiment will become large. The other disadvantage of this method will be that we may not be able to carry out the simulation experiment concerning to collective behavior of high energy particles, like the production and effect of radial electric field, those of "TAE mode[3)] (Toroidal Alfven Eigenmodes)", those of "Fishbone", and so forth.

A method of hydrogen beam injection with medium energy, for example in the range of about 200 keV, has been considered as the second candidate. It should be pointed out that in a typical tokamak configuration the injection of such medium energy beam may not be an attractive simulation experiment because of the smallness of a typical banana size, however, it is entirely different in the case of helical confinement system. The typical orbit deviation of high energy particles in a helical system, which is mainly determined by the orbits of trapped particles, can be largely controlled and varied by the control of magnetic configuration, for example, by the shift of magnetic axis. Examples of the computer simulation on the orbit deviation will be explained later.

This method will have various advantages from a practical viewpoint as follows: We can utilize the standard NBI technique with negative ion source, and thus, if we inject enough amount of beam, we may be able to simulate phenomena not only of the single particle behavior but also of the collective behavior of fast particles, such as the radial electric field and "TAE mode", and might be able to simulate the situation of inverted velocity distribution of high energy particles. Of course, we have to be careful on the shine-through problem, the anisotropy of initial condition as a simulation experiment, and so on. However, this method will be much more advantageous compared to the one by high energy ($\sim$3.5 MeV) helium beam injection.

The other possibility will be the utilization of RF heating of high energy tail and its combination with fast particle injection.

We may produce a high energy tail by a simple ICRF heating, or may create fusion products of fast alpha particles and protons by applying ICRF wave in DHe^3 plasma, or may enhance the DHe^3 reaction rate by both He^3 beam injection and ICRF heating. Each method will have a possibility as a simulation experiment on the single particle behavior and, even in some cases, each might become a simulation for the collective behavior of high energy particles. However, it is considered that large amounts of requirements will exist for these to become a reasonable simulation experiment. Also, it seems very difficult for us to have an inversion profile in the velocity distribution of high energy particles by these methods. Details of those are going to be discussed in a separate paper.

The control of the velocity distribution of energetic particles has been examined in the CHS device. By choosing the injection angle of NBI such that considerable amount of hot particles is near the trapped-transit boundary, the direct loss can be increased. In such a condition, the velocity distribution of fast particles are found to satisfy the condition $\partial f(E)/\partial E > 0$ [4], and the positive slope could be high. This positive slope can enhance the free energy source of the instability which is driven by energetic particles [5]. This experiment gives a basis for the possible simulation experiment on the LHD, in which much larger amount of hot ions could be confined.

Candidates of the methods are summarized in Table II.

[3] Monte-Carlo Calculation of Particle Orbits in an LHD Plasma

Because of the breaking of axisymmetry the particle orbit in a helical system is complex depending on the magnetic field configuration. Additionally the Shafranov shift in finite beta changes the magnetic configuration significantly. Therefore we must carefully introduce the magnetic configuration of the LHD plasma for calculating the particle orbit. A Monte Carlo simulation code has been developed[6,7,8] for studying the NBI and ICRF heating in the helical system including the complicated motion of particles, the configuration change in the finite beta, and Coulomb collisions with background plasma. The three dimensional finite beta MHD equilibrium is first solved using the VMEC code and the Boozer coordinates[9] are introduced based on the obtained MHD equilibrium. Then we follow the particle orbit in the Boozer coordinates.

Several examples of the orbit calculations are shown as follows. Figure 1 shows orbits of gyration centers of passing particles in the case of "co-injection" as a function of beam energy (E_B) and/or of magnetic field strength (B_0), where two cases with the central beta value (β_0) of 0.0 % and 6.0 % are shown. Since the guiding center drift equation is simply given[9,10] by

$$\vec{v} = \frac{1}{D_j} \cdot \frac{e\rho_\parallel}{m} \left[\vec{B} + \nabla \times (\rho \vec{B}) \right]$$

Where $D_j = 1 + \rho_{||}(\vec{B} \cdot \vec{j} / B^2)$ and $\rho_{||}(E, \mu, \vec{x}) = mv_{||} / eB$, one finds that particles with same $\rho_{||}$ draw the same orbit. Therefore the particles of H^0(125 keV) in B_0=1.0 T, H^0(200 keV) in B_0=1.3T, and He^0(3.5 MeV) in B_0= 5.3 T with the same other initial conditions show the same orbit.

A comparison of "co-" and "counter-injection" cases with the 125 keV hydrogen beam at B_0=0.5 T is shown in Fig.2. Also, orbits of passing particles in the case of "counter-injection" are shown in Fig.3. In addition, the distribution of lost positions of high energy particles in the cases of "co-" and "counter-injection" are shown in Figs.4 and 5, respectively. Here, Figs.4(a) and 5(a) indicate the lost particle distributions in whole toroidal and poloidal position with the initial condition of particles to be at one toroidal position. On the other hand, Figs.4(b) and 5(b) represent the distributions in one helical pitch, which means equivalent to the cases where the initial positions of particles are uniformly distributed toroidally.

On the other hand, orbits of trapped particles in a helical confinement system have unique features, especially in contrast to those in a tokamak system. A typical orbit deviation, which is so-called a "super-banana"[11] in a classical sense, will determine the main part of the fast particle confinement in a helical system. The important point is that the orbit of a "super-banana" is characterized by the orbit of banana center and this orbit is mostly determined by the structure of B_{min} along the magnetic field line. That means the orbit deviation of a "super-banana" particle depends only on the topology of the magnetic field and is independent of $\rho_{||}$, i.e. independent of the fast particle energy and of the magnetic field strength. For the trapped particle the value of $\rho_{||}$ determines the banana width. In Fig.6, two cases are shown with two different magnetic field configuration. Figure 6(a) represents the case of the "standard configuration" of LHD, where the magnetic axis is chosen to be at -15 cm. A fairly large orbit deviation is seen in this case. On the other hand, if we shift the magnetic axis to -30 cm (more 15 cm inward from the "standard configuration"), the orbit deviation is extremely suppressed to an extent of negligible small compared to the plasma minor radius, as shown in Fig.6(b). Usually the shift of magnetic axis can be easily made by the vertical-field control. This typical example clearly shows that, generally speaking, the orbit deviation can be largely controlled by controlling the magnetic field configuration, such as by the control of vertical field.

Thus, we may say that one can test the effect of orbit deviation on plasma performance by changing the magnetic field configuration in the case of helical confinement system. This is the main reason that we will be able to perform the effective simulation experiment even by the medium energy ($\sim$200 keV) beam injection approach.

[4] Summary

The confinement of fusion-produced or high energy particles is one of the most important issues to be studied especially in the helical confinement scheme.

Several candidates of simulation experiments have been considered for the study of fast particle physics in the LHD plasma or in the helical confinement system.

Orbits of high energy particles in an LHD plasma have been calculated by using Monte-Carlo Simulation codes. The calculations have been carried out as to the characteristics of the passing particle and trapped particle orbits.

The results on the trapped particles show that the trapped particle orbits in a helical confinement system have unique features, especially in contrast to those in a tokamak system. The orbit deviation, which is so-called a "super-banana" in a classical sense, is determined only by the magnetic field configuration and the pitch angle of the particle, not by the energy of fast particle nor by the magnetic field strength. Since the main part of the fast particle confinement in a helical system is determined by the behavior of trapped particles, it can be said that the confinement will be largely controlled by controlling the magnetic field configuration, such as, by the shift of magnetic axis, and consequently by the control of the vertical field.

In this sense, it may be concluded that even a medium energy beam injection (e. g. $\sim$200 keV injection) will become a useful approach for the simulation experiment in a helical confinement scheme. Also it is suggested that simulation experiments in a helical system even by the existing technology level, for example by 200 keV NBI, might offer useful informations on alpha-particle physics in a reactor-relevant device of axisymmetric system through understanding basic physics process, such as the mutual interaction between the orbit deviation, electric field and confinement[12)].

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Table and Figure Captions

Table I Major machine and plasma parameters of LHD

Table II Candidates of the methods of simulation experiments

Fig.1 Typical results of particle-orbit calculations by the Monte-Carlo simulation in the case of co-injection of passing particles.
(a) and (b) : the injection of 125 keV hydrogen (H^0) into toroidal field (B_0) of 4.0 T, or of 200 keV H^0 into B_0= 5.0 T.
(c) and (d) : of 125 keV H^0 into B_0= 1.0 T, or of 200 keV H^0 into B_0= 1.3 T, or of 400 keV D^0 into B_0= 2.5 T, or of 3.5 MeV He^0 into B_0= 5.3 T. (a) and (c) are the cases with central beta value (β_0) of 0.0 %, and (b) and (d) are with β_0= 6.0 %.

Fig.2 Comparison of orbits of passing particles between co- and counter-injection. (a) Counter-injection, and (b) co-injection. Here, the case of 125 keV H^0 into B_0= 0.5 T, or of 200 keV H^0 into B_0= 0.6 T, or of 400 keV D^0 into B_0= 1.3 T, or of 3.5 MeV He^0 into B_0= 2.6 T is shown.

Fig.3 Effect of central beta value on passing particle orbits in the case of counter-injection. (a) : β_0= 0.0 %, and (b) : β_0= 6.0 %.
The injection condition is the same as in Figs.1(c) and 1(d).

Fig.4 Typical results of lost positions of passing particles in the case of co-injection. The injection is of 125 keV H^0 into B_0= 0.5 T, or of 200 keV H^0 into B_0= 0.6 T, or of 400 keV D^0 into B_0= 1.3 T, or of 3.5 MeV He^0 into B_0= 2.6 T. (a) : the lost distribution in whole toroidal and poloidal position with the initial condition of particles at one toroidal position, and (b) : the distribution in one helical pitch, which means equivalent to the case where the initial positions of particles are uniformly distributed toroidally.

Fig.5 The same as in Fig.4 in the case of counter-injection.

Fig.6 Typical results of particle-orbit calculations by the Monte-Carlo simulation in the case of trapped particles. (a) : the case of the standard configuration of LHD, where the magnetic axis is -15 cm . (b) : more inward shifted case, where the magnetic axis is -30 cm. The important thing is that the orbit deviation is determined only by the magnetic field configuration and the pitch angle of the particle, not by the energy of fast particle nor by the magnetic field strength. Thus, it is clearly seen that the orbit deviation can be largely controlled by controlling the magnetic field configuration, such as by the control of vertical field.

Table I Major machine and plasma parameters of LHD

	Phase - I	Phase - II
Machine Configuration		
ℓ	2	
m	10	
γ (pitch parameter)	1.25	
α (modulation parameter)	0.1	
major radius	3.9 m	
magnetic field strength	3.0 T	4.0 T
stored magnetic energy	0.9 GJ	1.6 GJ
Plasma Configuration		
plasma major radius	3.75 m	
plasma minor radius	0.6 m	
plasma volume	30 m^3	
$\iota(0)/\iota(a)$	0.4 / 1.3	
Heating System		
ECH Power	10 MW	10 MW
NBI Power	15 MW	20 MW
ICRF Power	3 MW	9 MW

Table II Candidates of the methods of simulation experiments

Method	Condition	Phenomena to be Simulated	Features	Problems/Issues to be Solved	Orbit Deviation Helical Δ_{OD}/a	Orbit Deviation Tok. Δ_B/a	Com't*
[1] High Energy (~3.5MeV) He^0 Beam Injection	$B_T = 3$ - 4 T $I_B \sim \mu A$ H-plasma (preferably)	Single Particle Behavior * Slowing down * High energy particle loss (esp. for helical system)	NBI with accelerator (Negative ion source) Rather easy for lost-particle study (i.e. neutron free circumstances)	Development of He^- source Neutralization of He^- (esp. to ground state) Anisotropy of initial condition (depend on analysis)	~1	~0.5	D
[2] Medium Energy (~200keV) H^0 Beam Injection	$B_T \sim 1$ - 4 T $I_B \sim 10A$ D-plasma	Single Particle Behavior * Slowing down * High energy particle loss (esp. for helical system) Collective Behavior * Radial electric field * TAE mode, Fishbone * Thermonuclear insta.	Standard NBI (Negative ion source) Clear initial conditions and can be varied Possibility of inverted profile of f(v) [by ⊥-inj.]	Shine through Anisotropy of initial condition (depend on analysis)	0.1 - 0.5	< 0.1 (0.3)	A
[3] ICRF Heating							
(a) High E. Tail by ICRF	$\omega = (1\sim3)\Omega(^3He)$ $\varepsilon(^3He) \sim 10\%$ $P_{RF} \sim 1$ - 2 MW/m^3	Single Particle Behavior * Slowing down * High energy particle loss (esp. for helical system)	No inversion profile of f(v)	Large requirements for plasma Anisotropy of initial condition Should clarify initial condition	0.1 - 0.5	~0.3	B
(b) Reaction Rate Enhancement by ICRF		Might exist a possibility to simulate Coll. Behavior	Isotropy of initial condition	Large requirements for plasma Should clarify initial condition	~ 1	~ 0.5	C
[4] NBI + ICRF Heating ($He^3 \rightarrow$ D-plasma)	NBI = 100-200keV $\omega = (1\sim3)\Omega(^3He/D)$ $P_{RF} \sim 1\ MW/m^3$ $P_{NBI} \sim 1\ MW/m^3$	Single Particle Behavior Might exist a possibility to simulate Coll. Behavior	No inversion profile of f(v)	Anisotropy of initial condition Should clarify initial condition	~ 1	~ 0.5	C

* A: Possible, B: Probably possible, but need careful study on initial condition, C: Probably possible, but need detailed study, D: Extremely difficult.

Orbits of Beam Particles

Passing Particles : Co-Injection

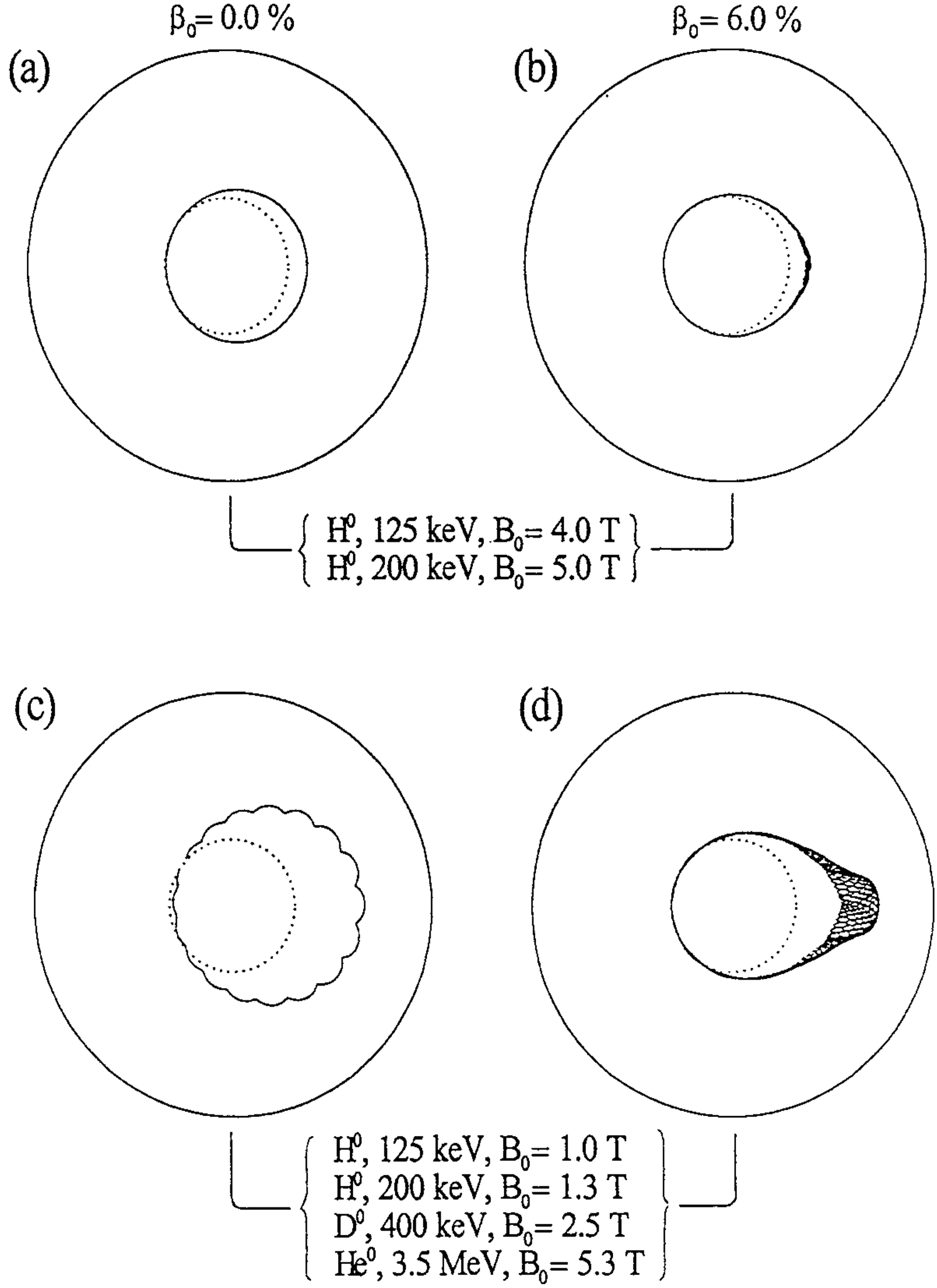


Fig.1

Passing Particles : Co- & Counter-Injection $\beta_0 = 0.0$ %

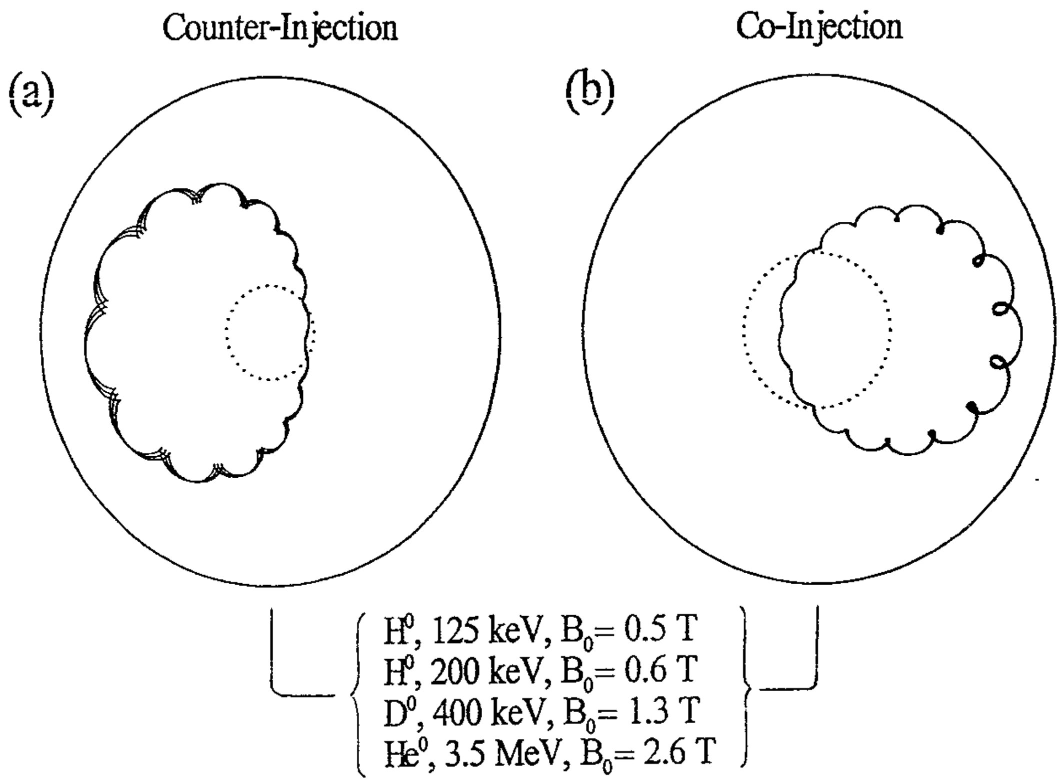


Fig.2

Passing Particles : Counter-Injection

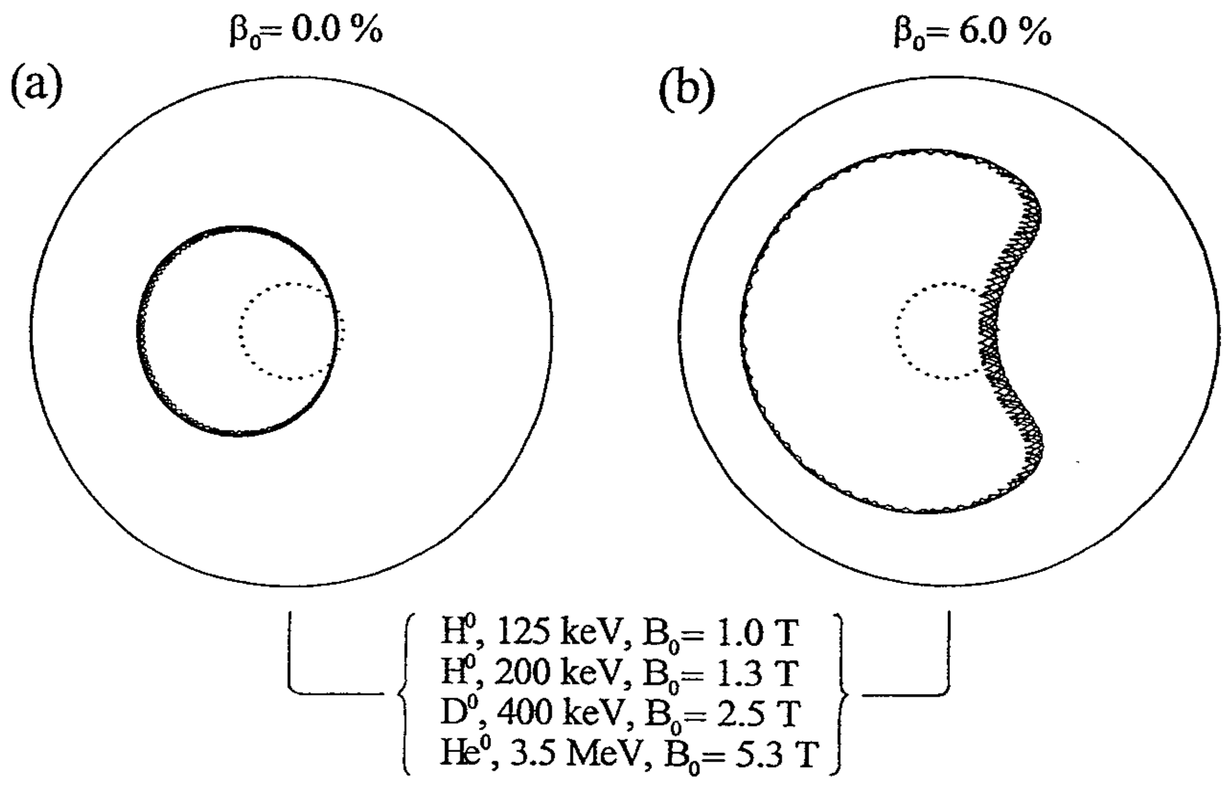


Fig.3

Passing Particles : Co-Injection

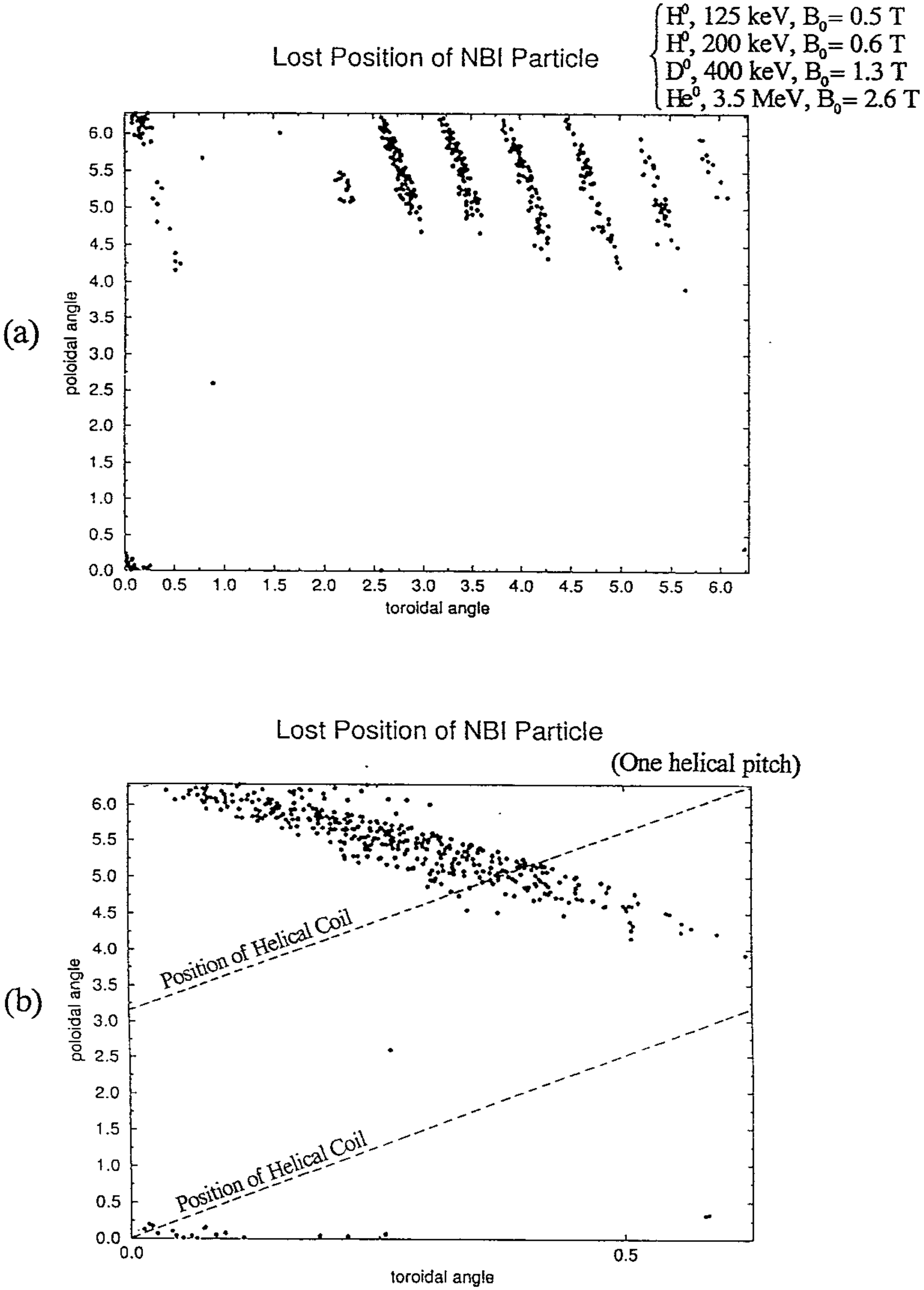
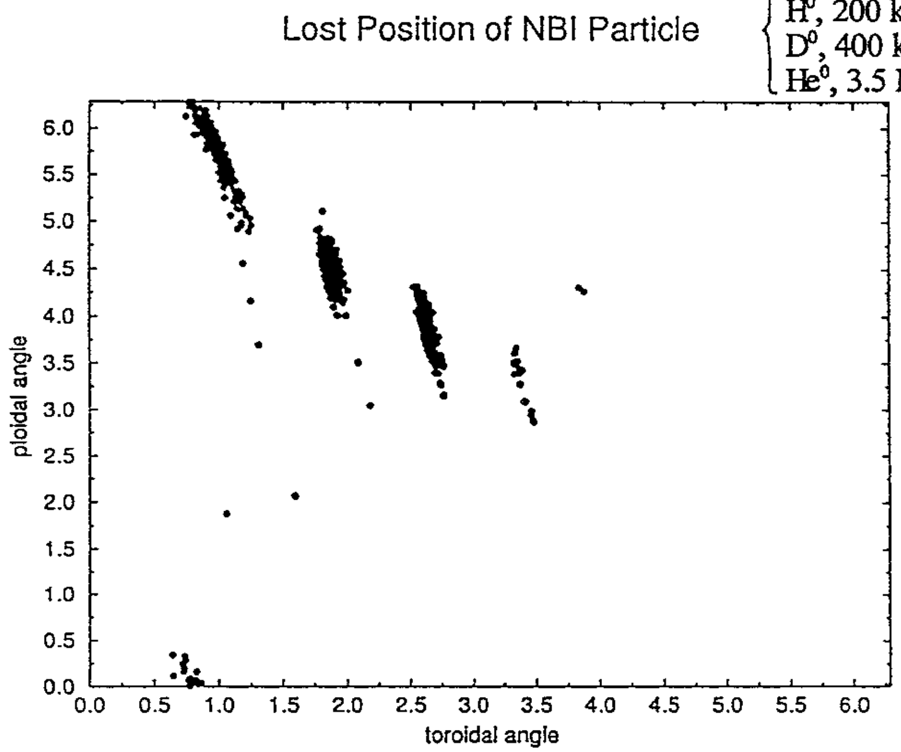


Fig.4

Passing Particles : Counter-Injection

$\left\{\begin{array}{l} H^0\text{, 125 keV, } B_0\text{= 0.5 T} \\ H^0\text{, 200 keV, } B_0\text{= 0.6 T} \\ D^0\text{, 400 keV, } B_0\text{= 1.3 T} \\ He^0\text{, 3.5 MeV, } B_0\text{= 2.6 T} \end{array}\right.$

(a)



(b)

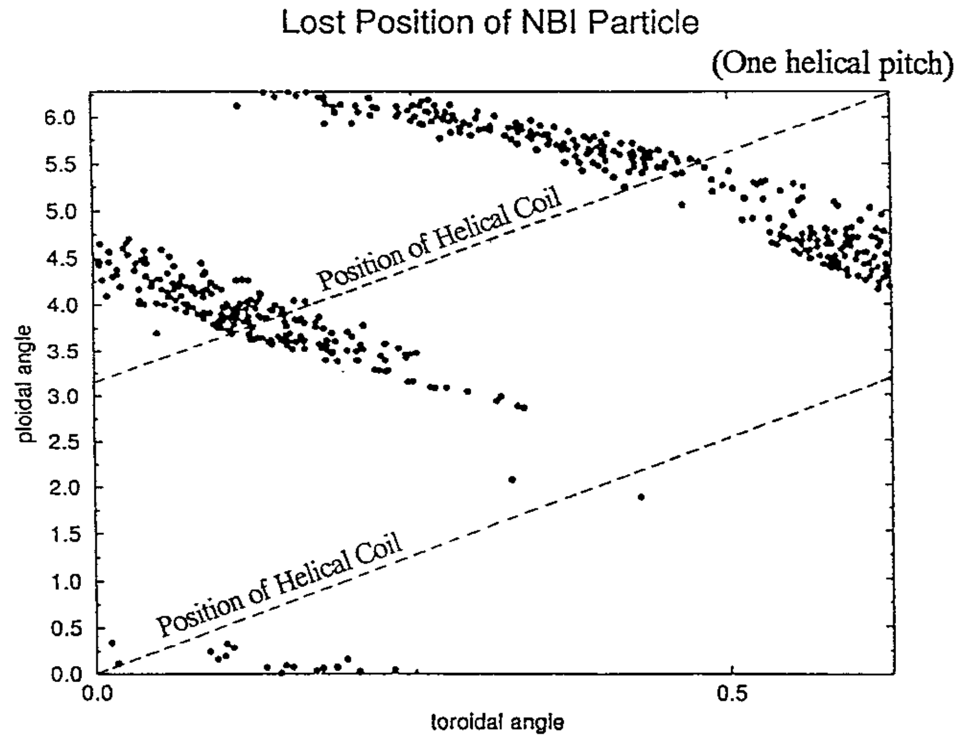
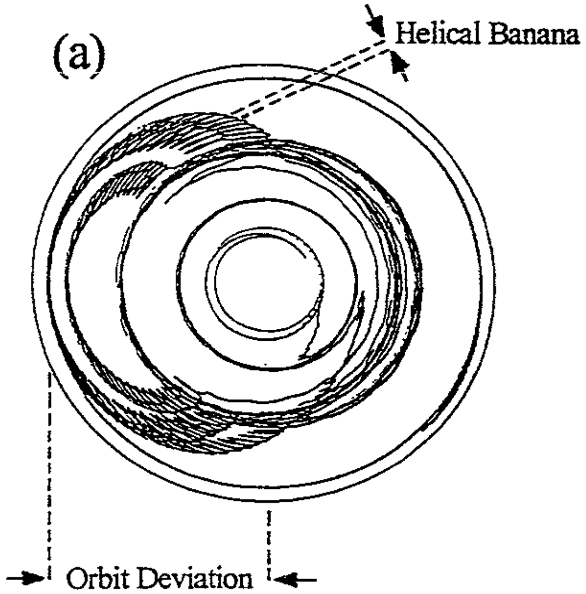


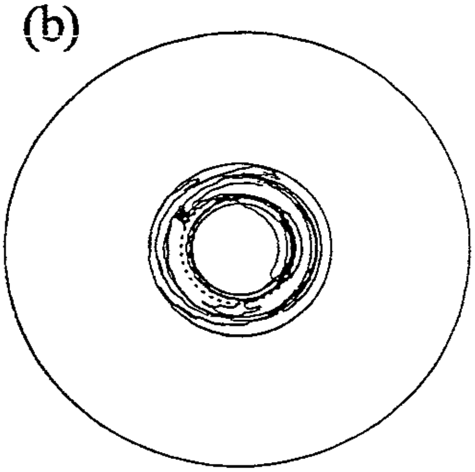
Fig.5

Trapped Particles :



Standard Configuration of LHD

(Mag. Axis = -15 cm)



Inward Shifted Configuration

(Mag. Axis = -30 cm)

Fig.6

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