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Research Plan for Studying Confinement in the LHD Plasma

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Abstract

The experimental plan for studying plasma confinement on the Large Helical Device (LHD) is presented in this paper. Current information about the main LHD device, heating devices, and diagnostics is summarized, and key physics issues are discussed. Based upon these considerations, a preliminary experimental plan is proposed.

Keywords:

Large Helical Device, experimental plan, plasma confinement, beta value, flexible magnetic configuration, confinement improvements

1. Introduction

The experimental plan for three of the main mission elements of the Large Helical Device (LHD) project is discussed in this paper. Elements of the mission include: (a) investigating plasma characteristics such as transport under reactor relevant plasma conditions, (b) demonstrating average beta values at a level of 5% in a helical system, and (c) understanding the general physics issues of toroidal plasmas.

First of all, the most recent information about the LHD device, heating devices, and diagnostics is summarized. The main machine parameters are presented in a separate paper [1]. Flexibility of the magnetic field configuration is one of the unique features of LHD. The details are described in the next section.

Plasma production and electron heating will be carried out by Electron Cyclotron Heating (ECH) up to 10 MW with gyrotrons of 168 GHz (second harmonic), and 84 GHz (fundamental). Neutral Beam Injection (NBI) at 180 keV and power levels up to 15–20 MW is planned. A good birth profile of the fast ions is expected under the various LHD experimental conditions calculated at $n_e(0)=1\times10^{20}$ m^{-3} and $\beta(0)=2\%$. More than 50% of the beam will be deposited inside the half radius ($r/a<1/2$) even when the low energy beam is injected into the plasma with a flat density profile. The power of Ion Cyclotron Range of Frequency (ICRF) heating in the frequency range of 25–100 MHz will be up to 3–12 MW.

Good diagnostics are inevitably necessary for the data base in order to carry out physics analysis. Large ports are prepared for good access. Conventional diagnostics with capability for spatial and temporal resolution such as 120 ch laser Thomson scattering with repetition of 50 Hz and 12 ch FIR interferometry, are planned. Several advanced diagnostics methods such as electric potential measurements with a 6 MeV heavy

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Table 1 Fueling methods

Gas Puff	H_2, He, Ar, D_2	100 Pa m^3/s 300 Pa m^3/s(planned)
Pellet	H_2, D_2	1.5, 2.0, 3.0, 3.8 mmϕ independent 10 barrells
		1.4×10^{20} - 3.5×10^{21} / pellet $\Delta n = 5\times10^{18}$ - 1.2×10^{20} m^{-3}
NBI	180 keV 15 MW H_2 $\Delta n = 1.8\times10^{18}$ m^{-3} / 0.1 sec	

ion beam probe are being developed. A data acquisition system also plays an important role in handling huge amounts of data (900 MB / shot) both due to the multi-channel feature of many diagnostics and due to long pulse operation. For this, a fully distributed acquisition system is being constructed.

2. Control Methods for Confinement Experiments

Control methods for plasma confinement experiments are very important to optimize the plasma confinement. Flexibility is essential for successful experiments. Various kinds of control methods are planned for LHD: (a) pumping, (b) wall conditioning, (c) fueling, (d) heating, and (e) flexible control of magnetic field configuration. Due to the steady-state magnetic field, a conventional DC glow discharge cleaning is not applicable, so ECR discharge cleaning will be the main cleaning method. Advanced wall conditioning methods such as real time boronization are being developed. Three kinds of fueling methods are listed in Table 1.

The operational flexibility of heating devices is summarized in Table 2. The focusing system of the ECH microwaves is carefully designed such that the beam waist becomes 15 mm in radial direction at the focal point. The injection angle of the beam can be changed within a span of 15 degrees in the radial direction. Thus, localized power deposition is expected, and also the power deposition location will be changed. In this way, the temperature profile can be varied, and heat transport will be studied. The power modulation of ECH and NBI is also planned. These will be useful for the study of transport and energetic particle behavior. Plasma production by ICRF is suited to changing the magnetic field, especially for high β experiments. Steady-state heating by ICRF is promising from the present technological developments.

Table 2 Heating methods and operational schemes

ECH	Plasma Production	Initial Plasma Production	
		Study of Low Collisionality Regime	
		CW Operation	
	Localized Power Deposition	Beam Waist $\delta r = 15$ mm, $\delta R\phi = 50$ mm	Profile Control
		Beam Injection Angle $\delta\theta = 15$ deg, $\delta\phi = 5$ deg	Transport Study
	Pulse Modulation	Transport Study	
		Simulation of CW operation	
	Electric Field Control, Current Drive / Suppress		
NBI	Plasma Heating	High $n\tau T$ Plasma	
		High T_i Plasma	
	Pulse Modulation, Current Drive / Suppress, Long Pulse		
ICRF	Plasma Production	Variable B for High β Experiments	
	Fast Wave Heating	From Low and High Field Side	CW or Long Pulse Operation
	IBW Heating	Folded Wave Guide, Long Operation	

Magnetic axis shift by poloidal coils strongly affects the MHD stability of plasmas and the confinement of high energy particles. The favorable shift directions for these two criteria are opposite, therefore a certain compromise is necessary. The condition of such a compromise with full cancellation of the quadrupole field is called the "standard configuration," in which the major radius of the magnetic axis is shifted to 3.75 m from the major radius (3.9 m) of the helical coil. The shape of the plasma cross section can be controlled with a quadrupole field produced by poloidal coils, which affects the bootstrap current, and stability [2]. The helical coil consists of three separate blocks in which the current can be flown independently. The helical coil pitch parameter, γ_c, can be changed by changing the ratio of the currents in the three separate helical coil blocks, which results in substantial change of rotational transform, ι. The use of the outer block increases γ_c. The ι value at the edge can be changed from 1.7 to 0.7 as γ_c is changed from 1.120 to 1.377. The γ_c value has a large effect on the equilibrium β limit and also on the stability limit.

A helical magnetic axis can be realized by controlling the ratio of the currents in the pair of helical coils. This affects the intensity and direction of bootstrap current, and thus, the change of the rotational transform and well depth affects the MHD stability. It is shown that the stability is improved, for example, at the current ratio of 0.3 [3].

3. Key Physics Subjects

The following key physics subjects are reviewed: (1) equilibrium and stability, (2) electric field and transport, (3) high-energy particle confinement, (4) particle control, (5) confinement improvement. Significant themes on these subjects are summarized below.

(1) A high n ballooning mode is one of the possible candidates to limit the β value. The present

experimental data of high β experiments on CHS are marginal around 2% to determine whether this mode is significant. The effect of pressure profile has also been studied, and the peaked profile is found to be favorable for Mercier stability. A bootstrap current may flow at the level of 200 kA. This current can be much decreased by choosing a combination of moderate temperature and high density for high β experiments. An optimum magnetic field strength for high β experiments has been studied while taking fast ion loss into consideration. When it is combined with the LHD empirical scaling, the optimum field strength is about 0.5 T, and the average β value reaches a level of 5%.

(2) Positive potential is widely observed in low density plasmas heated by ECH. In the case of high power ECH with low density plasmas in CHS, a central electric potential of 400 V was observed with a heavy ion beam probe [4] and the shear of the electric field in the core region is estimated at the level of 0.1 MV/m^2. On the other hand, negative potential is observed in case of NBI and high density ECH plasmas. The role of electric field in transport will be studied intensively on LHD with a systematic electric potential measurement.

(3) Confinement of fast ions in the case of NBI and ICRF has been studied. Inward shift of the magnetic axis is favorable for confinement of high energy ions. Simulation shows that the heating efficiency of ICRF is substantially improved by shifting the magnetic axis by 15 cm inward from the standard configuration. Adequate electric field will improve the confinement of high energy particles, so this issue is linked with the confinement improvement of the bulk plasma with the electric field. A high energy proton and alpha particle simulation experiment is also planned.

(4) Plasma-wall interaction will be controlled with several methods such as carbon tiles, real time boronization, titanium gettering, and local island divertor. Available fueling methods are gas puffing, pellet, and NBI. A large amount of gas can be puffed, while the fine control of gas puffing is also possible with separate accurate piezo valves. The injection of 10 pellets by 10 independent barrels as shown in Table 1 is planned for fueling and particle deposition profile control.

(5) Confinement improvement is one of the central subjects of LHD experiments. The practical methods for obtaining a good plasma are: a) reduction of impurities, b) reduction of neutrals, c) finding the optimal magnetic configuration with magnetic axis shift, shaping of plasma cross section, changing helical coil pitch parameter γ_c, and introducing a helical axis, d) control of the density profile with gas puffing, pellet, and NBI, e) control of the temperature profile with a change of NBI acceleration voltage, ECH resonance location, and ICRF heating layer, f) control of the electric field and its gradient by controlling the ion pressure profile, the loss of fast electrons (ECH) and fast ions (NBI and ICRF).

The rather widely accepted scenario of confinement improvement by electric field is: the shear of the electric field can cause a shear flow which is considered to decorrelate the turbulence, thereby suppressing the growth of turbulence, and reducing the anomalous diffusion. The toroidal and poloidal viscosity of LHD is high, so it is rather difficult to produce enough electric

Table 3 Schedule of LHD experiments

FY 1997	FY 1998	FY 1999	FY 2000	FY 20001	FY 2002 .....
Construction and Planning	Ist Phase			2nd Phase	
LHD Device Completion	1.5T 3 T		4 T		
Pumping of Vessel					Target
Cooling of Coils	ECH 0.5-1MW	3-9 MW 10 s			10 MW 10 s
Activation of Coils	84GHz 168GHz	1 MW CW			3 MW CW
Meas. of Mag. Surface					
Plasma Production	NBI 5 MW 1 s 10MW	15 MW 10s			20 MW 10 s
	H Beam 180 keV		D Beam		3 MW CW
Heating Devices					
Diagnostics	ICRF 1 MW 10 s	3 -12 MW 10 s			12 MW 10 s
Study of Research Plan	500kW CW	1-3 MW CW			3 MW CW
	Heating & Transport			D Beam & D Plasma	
Plasma Production & Utility	High Te, High Ti, High nτT, Density Limit				
Confinement	Confinement of High Energy Particles & Simulation Experiment				
	High β Experiment				
Long Pulse Operation	LID Exp.	Local Divertor Exp.		Full Divertor Baffles	
Divertor	Long Pulse Operation		High Power Steady-state		

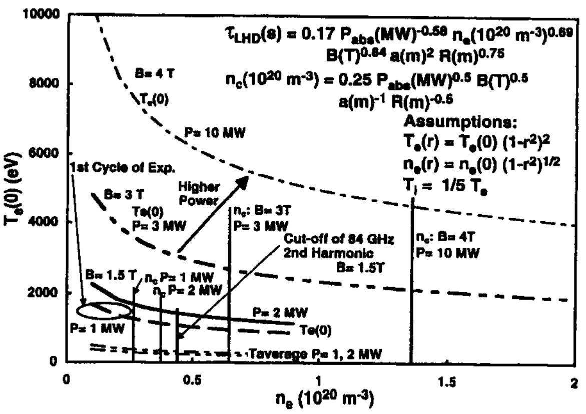

Fig. 1. Expected ne-Te(0) diagram for ECH plasmas based on LHD scaling. The assumptions given in the figure are made from the experimental experience from the experiments on the existing helical devices. The cut-off density of ECH and the empirical density limit are also shown.

field by rotation of the plasma. From the balance equation, ion pressure gradient also can induce the electric field. So, a possible method of introducing electric field on LHD is being considered where the formation of a peaked density profile may lead to a peaked ion pressure profile. The peaked density profile can be produced by an appropriate NBI and also by pellet injection. Such confinement improvement with pellet injection has been seen on Heliotron E [5].

4. Experimental Plan

Based upon the above considerations with the available hardware, the experimental schedule is preliminarily planned as in Table 3. Fundamental experiments with large flexibility will be carried out mainly at $B=3$ T for the first three years, and after that, high performance experiments are planned at $B=4$ T for several years. The discussion of deuterium beam injection into deuterium plasmas in the later phase has also started.

The n_e-$T_e(0)$ diagram for ECH plasmas estimated from the empirical scaling [6, 7] is shown in Fig. 1, where the parameters to be expected from the first cycle starting in the spring of 1998 up to the high power experiments at B=4 T are shown. In case of NBI, the central temperature can be estimated roughly to be 60 % of that for the same absorbed power given in Fig.1, because the empirical confinement time scaling is the same for ECH and NBI. Of course, these estimates are based on the basic considerations, and higher parameters will be sought with several measures described above. A wide range of collisionalities from the plateau to collisionless regimes (ratio of collision frequency versus banana frequency: ν^{**} of up to 0.01) are also expected.

5. Summary

The basic hardware such as heating devices, utilities, and diagnostics are well prepared in addition to nearing completion of LHD itself. The experiments in a wide range of plasma parameters for studying many aspects of plasma confinement are expected by means of a wide variety of control and diagnostic methods.

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