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Research Plan for Long-Pulse/Steady-State Experiments in LHD

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Abstract

When a long-pulse operation once obtained with a power level of more than several hundreds kW, physical and technological experimental programs will be possible with this long-pulse condition. Parametric survey on bootstrap current and energy transport can be performed within one shot by real time swing of the magnetic configuration. A long-pulse/steady-state operation is essential for a net erosion study of plasma facing surfaces and demonstration of electric power generation. Particle control is necessary for the steady state operation, and a study on gaseous impurities and hydrogen recycling is important with the active pumping condition. A start-up scenario of the long-pulse operation is proposed.

Keywords:

steady state operation, real time swing of magnetic field, bootstrap current, net erosion of divertor plates, redeposition, heat and particle control

1. Introduction

Long-pulse/steady-state operation is one of the major issues in the LHD project[1-3]. A set of helical and poloidal coils is designed and constructed as a superconducting system, which gives a confinement magnetic configuration in a steady-state. Heating devices are also designed for long-pulse operation. An ECH (Electron Cycrotron resonance Heating) system consists of two gyrotrons of 84 GHz, which provides continuous power of 1 MW[3]. An ICRF (Ion Cyclotron Range of Frequency) system gives 3 MW heating power for more than 1 hour[4]. An NBI (Neutral Beam Injection heating) system is designed to be operated with 1 MW for half an hour[5]. The plasma vacuum vessel and the divertor plates are actively cooled by water. These arrangements enables a long-pulse/steady-state experiments in LHD.

The goal of the steady-state operation in the early stage of the project is to realize a 3 MW, one hour discharge. In order to reach this goal, a lot of technological problems have to be solved[6]. It is a challenging program itself to approach this goal. On the way to this goal, if a long-pulse operation once obtained with a power level of more than several hundreds kW, physical and technological experimental programs will be

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possible with this long-pulse condition. The experimental plan is now under discussion and some examples are presented. A start-up scenario of the long-pulse operation is another problem and a proposal is given in this paper.

2. Real-time Swing of Magnetic Configuration: Boot-Strap Current and Transport

It is possible to study plasma transport properties in detail in long time discharge experiments.

By varying a plasma parameter of interest independently of other parameters in a time scale much longer than transport time scales, we can measure the parameter dependence of several transport fluxes in a single discharge without uncertainty caused by problems of reproducibility. The continuous change in the magnetic configuration could give us a chance to notice a possible fine structure in plasma behavior depending on a particular parameter.

2.1 Experimental verification of theoretically predicted bootstrap current

A bootstrap current results from particles trapped in magnetic ripples and is driven by a radial pressure gradient. In helical systems like LHD which have a variety of magnetic field components, the transport coefficients for the bootstrap current strongly depend on the magnetic configuration through G_b called as geometrical factor. In LHD, the geometry factor G_b can be controlled in a wide range. By varying G_b slowly in a single discharge, the variation of the current magnitude is expected to be observed. Thus, we can verify the validity of the neoclassical theory on the bootstrap current.

There are two ways to change the geometrical factor in LHD. One is by controlling poloidal coil currents to change dipole and quadruple components of the magnetic field. It is predicted that the bootstrap current and the Shafranov shift increase (or decrease) with increasing (or decreasing) the quadruple component[7]. Another way is to change the ratio of currents in two helical coils. This affects the bootstrap current more effectively than the former one. Recent numerical calculations show that the total bootstrap current changes its direction when the ratio becomes larger than 2.5 in the $1/\nu$ regime in LHD[8].

In ATF experiments[9], they observed a bootstrap current in good agreement with theoretical predictions[10]. It is still important to investigate the bootstrap current in LHD since it affects MHD equilibrium and stability.

2.2 Nondimensional transport scaling study

An energy confinement time τ_E is written in terms of the gyrofrequency Ω, the normalized gyroradius $\rho_* = \rho/a$, the normalized collision frequency $\nu_* = a\nu/v_T$, the plasma beta β, and other nondimensional parameters as

$$\tau_E \Omega = \rho_*^{\alpha\rho} \nu_*^{\alpha\nu} \beta^{\alpha\beta} F(R_0/a, \iota, \ldots).$$

Here, the Bohm and gyro-Bohm scaling correspond to $\alpha_\rho = -2$ and $\alpha_\rho = -3$, respectively, and the LHD scaling is close to the gyro-Bohm scaling.

We can make use of a long time discharge to determine the values of the exponents α_ρ, α_ν, α_β and a better scaling law. The collisionality and the plasma beta are independently varied by modulating the input power and the density with the ratio of their modulation amplitudes adjusted appropriately. By measuring a resultant variation of the energy confinement time, the exponents α_ν and α_β are obtained.

In ATF[11], they determined the collisionality and beta dependencies in this way and obtained the scaling $\tau_E \propto \tau_{gB} \nu_*^{-0.18} \beta^{0.3}$. In order to derive an accurate transport scaling and compare it to transport theories, it is significantly important to determine dependencies on these nondimensional parameters as well as on other parameters related to the magnetic configuration in LHD.

3. Net Erosion Study of the Plasma Facing Walls

Erosion lifetime of LHD divertor plates was estimated by a numerical calculation code TEDY (Temperature and Erosion Dynamic calculation) developed for this purpose[12]. Since graphite materials are considered for divertor plates, its erosion rate due to physical and chemical sputtering and radiation enhanced sublimation is a function of surface temperature, which repeatedly goes up and down under intermittent high-heat loading in a series of plasma operations. Furthermore, in a long life of divertor plates, the maximum surface temperature in a discharge may gradually change depending on the plate thickness which also changes due to net erosion. In this TEDY code, therefore, all of surface temperature, erosion rate and plate thickness are functions of time and they are simply linked to another. The main calculation of heat diffusion is done by a finite element method for intermittent plasma loading on an one-dimensional multilayered plate cooled passively or actively by water with heat transfer coefficients given by the Dittus and Boelter's formula[13].

Figure 1 shows that the isotropic graphite plate 20 mm thick cooled by water is eroded to about a half in thickness under various operating conditions. Two of them correspond to pulsed operations of 5 $MW/m^2 \times$ 10 s and 10 $MW/m^2 \times$ 5 s. One case corresponds to steady state operation with 0.8 MW/m^2. Shot numbers are assumed as shown in the figure. Thickness of graphite is assumed to be 20 mm. This result means the erosion lifetime to be less than one year under the condition mixed with each operation mode. Under real discharges, however, the erosion lifetime is expected to be much longer than this estimation, because there may be a large amount of compensation due to redeposition of once eroded materials[14].

It is one of top issues to control redeposition process on high-heat flux components for fusion devices from view points of erosion lifetime and tritium inventory. The steady state operation mode in LHD must be quite powerful to study redeposition process. Figure 2 shows erosion depth as a function of shot number in CHS (top) and of operation time with steady state experiment in LHD (bottom). Heat load at the target is assumed as shown in the figure. A typical pulse length is 100 ms in CHS, and the target is not directly cooled by water. The results in this figure clearly show that, in order to make erosion depth deeper than 10 μm for instance, it takes a few 100 shots, namely a few days, in a CHS like device with good reproducibility of each discharge, but it takes only a half hour, namely one shot, in LHD.

Another interest is a behavior of a thin coated layer on the wall surface such as a boron films. Boronization works well in pulsed operations in present experimental devices. A combination of the boronization with high Z, erosion-resistant divertor plates is proposed for future machines[15]. If the thin low Z film could be maintained in a long term operation, it would work as a protecting layer from impact of energetic particles[16]. But question is whether the thin boron film can be maintained for long time or not. A long life time of the thin boron film could be possible because boron hydride is fragile, easily broken by plasma impact, redeposited inside the torus, and hardly reach pumping ducts. This means that the thin films is maintained for a long time if a gross-immigration of boron atoms is not significant. A systematic study on the long time behavior of the boron films is one of the programs in the steady-state experiment.

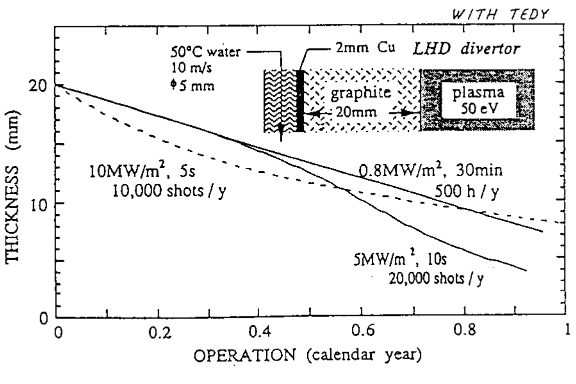

Fig. 1 Operation time dependence of divertor tile thickness under various operation mode in LHD.

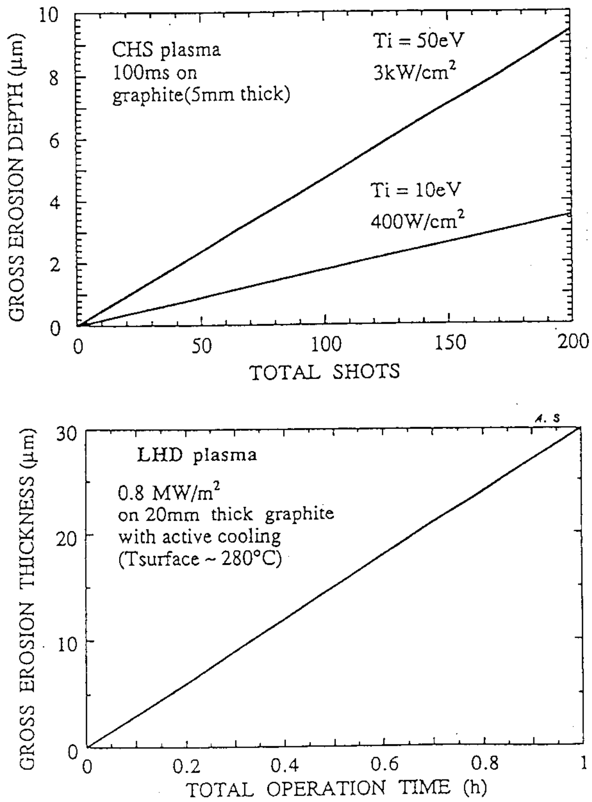

Fig. 2 Operation time dependence of gross erosion thickness expected on graphite plates in LHD and CHS.

In order to investigate the net erosion and redeposition, a surface station is under fabrication with a collaboration between NIFS and RIAM in Kyushu University[17]. A test sample of 30 mm × 30 mm can be inserted to the plasma edge region with a transport mechanism. Its stroke is 2000 mm and movable during a discharge. Temperature of the test pieces can be controlled by water cooling. The station will be applied first to TRIAM-1M tokamak in Kyushu University, and moved to the LHD site afterward.

4. Particle Control by Divertor Pumping

In a long pulse operation, active pumping is more or less needed to achieve a steady state because a saturated wall surfaces does not play a role of pumping any more, whereas it does effectively in short pulse discharge of present devices. A realistic way in the first stage is to use a local island divertor (LID) for the active pumping[18], in which particle recycling is localized to a small region around the divertor head. Gaseous impurity reduction and hydrogen recycling control will be studied with a combination of LID and core fueling with NBI and multi-pellet injectors[19].

Oxygen is one of dominant impurities in present devices. In short pulse operations, it is mainly controlled by pre-conditioning the plasma facing surfaces by a low power hydrogen discharge or by film deposition of a gettering material[20]. Equilibrium of the oxygen level with the pumping is expected lower than that without pumping because oxygen recycles from the wall mainly as a form of gaseous compound. Quantitative study on the oxygen equilibrium is one of the issue to be investigated in the steady state discharge with the active pumping.

Hydrogen recycling with active pumping is a new issue, which is pointed out and discussed in Ref. [21]. Transient behavior of hydrogen emission after a change in heat load to a wall surface is another interest[22]. It could be investigated only in a long-pulse operation due to its time constant as long as hundreds of seconds.

5. Demonstration of Electric Power Generation

Demonstration of power generation is proposed by utilizing heat load from a steady-state plasma[23]. Electron emission from a high temperature, plasma-facing surface can be converted to the electric power and utilized for the surface cooling simultaneously. This experiment is possible only in a long-pulse operation mode.

6. Start-up Scenario of the Long-Pulse Operation

It is very important to start a preliminary experiment on steady-state operation in the early experimental stage and to obtain a database useful for the development of high power handling method. In the initial stage of the experiment, the divertor plates and the first wall panels will not be optimized. However, as the plasma chamber has a very big heat capacity, there is a possibility of a long pulse operation with an average heating power of 200 ~ 300 kW, depending on the build-up of the ECH system for plasma production and heating. The available heating power of ECH depends on the degree of aging of the gyrotrons. The conditioning is performed by switching the gyrotron on and off with a duty cycle of several tens % (intermittent operation). This operation mode may be available for sustaining the ECH plasma for long time. Although this is not quite a steady state, it gives us a chance to pile up experiences and data base for real steady state operation. Thus the intermittent operation is proposed as an approach to the steady state discharge.

In order to find the possibility of the intermittent operation, the operating regime of long-duration discharges is investigated by using a simple global power balance equation[24], which is obtained by integrating the equations for ions and electrons over the minor radius, using model profiles for density and temperature. In the experiment with a small input power, the main power losses are caused by the conduction and the line radiation. The thermal diffusivity in the conduction term is estimated by the global energy confinement time, which is calculated by the international stellarator scaling[25]. These losses increase with the plasma density and the line radiation loss increases with the impurity concentration. Moreover, the radiation for oxygen impurity, which is dominant in the initial experiment, increases strongly with decreasing the electron temperature. Therefore, in the regime of high density and high impurity level, radiation collapse occurs and we cannot find a power balance in steady state. On the other hand, this simple model indicates the possibility of power balance in the low density plasma ($n_e < 1.0 \times 10^{19}$ cm^{-3}) with small impurity content as shown in Fig. 3. In this figure, the time evolution of the plasma density and the impurity concentration are given in advance. The electron temperature and the radiation loss are calculated by the model equation. Therefore, if the impurity generation is suppressed and the concentration is controlled at the low level ($< 1.8\%$ for oxygen), we could find the operating regime that is able to sustain the ECH plasma for long time. In this way, we are planning to start the experiment on long-pulse operation by using the conditioning mode of the gyrotron and go to the experiment with steady-state high heating power.

7. Summary

Real-time swing of magnetic configuration enables us to investigate parametric dependence of bootstrap current within a single discharge without suffering from a problem of reproducibility of discharges. Similar

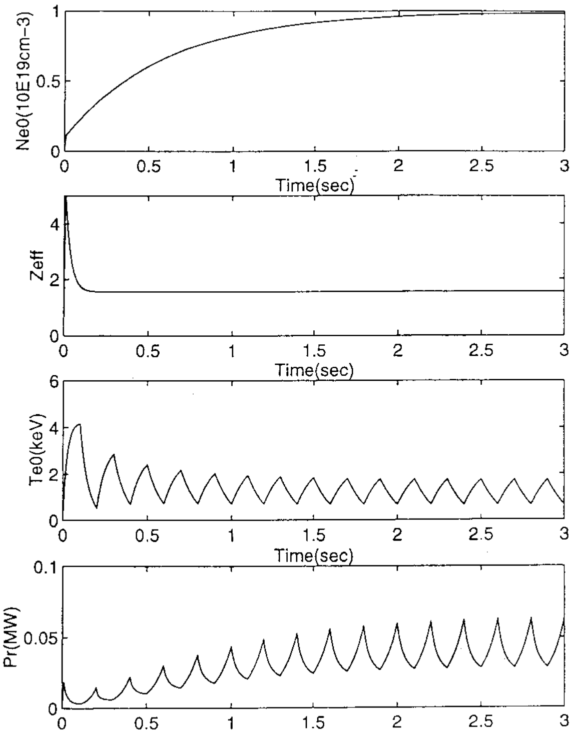

Fig. 3 Long-pulse operation with intermittent ECH power. BT = 1.5 T, PECH = 0.5 MW and the duty ratio is 50%.

experiments will be possible for a nondimensional transport scaling study.

Net erosion of divertor plates is one of the crucial issues in future reactor design. Maintainability of a thin boron film is another interest for future devices. A long-pulse/steady-state discharge is essential for these studies. In order to investigate the net erosion and re-deposition, a surface station is under fabrication with a collaboration between NIFS and Kyushu University.

In a long pulse operation, active pumping is more or less needed to achieve a steady state because a saturated wall surfaces does not play a role of pumping any more. A realistic way in the first stage is to use a local island divertor (LID) for the active pumping. A study on gaseous impurities and hydrogen recycling is important with the active pumping condition.

The steady-state operation is attractive for a demonstration of electric power generation.

It is important to start a preliminary experiment on steady-state operation in the early experimental stage and to obtain a database useful for the development of high power handling method. Utilization of an intermittent operation is proposed to approach real steady-state operation. Energy balance is discussed to realize this approach.

Analyses and discussion will be continued to obtain more quantitative view in these programs.

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