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Possibilities of Laser Application for the Control of Periphery Currents

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Abstract

It is known that in helical devices, where the rotational transform is created by means of external magnetic field, a bootstrap current can appear in a finite-pressure plasma. This current can strongly affect the magnetic configuration and, consequently, plasma confinement [1]. The influence of bootstrap current on the magnetic configuration can be reduced by generating an additional oppositely directed current. The bootstrap current can vary essentially in the periphery region, and the standard methods of current drive (neutral beams, lower hybrid waves, etc) may be ineffective for compensating the bootstrap current. The proposed laser method of current drive allows the local control of the current density [2]. At the same time, at the periphery the electron temperature is lower than in the center. Therefore, at the periphery the mechanism of laser current drive will be different from that described in Ref. [2]: it should be similar to the mechanism typical for neutral beam injection. The difference is that the ion beams would appear because of the laser ablation of the solid pellet.

Parameters of CO_2-laser which could be used for the bootstrap current control in LHD are given.

Keywords:

peripheral layer, bootstrap current, additional current, laser methods

1. Introduction

In recent years a substantial improvement in magnetic confinement (see, *e.g.* [3]) and stabilization of some dangerous instabilities [4] has been achieved on large tokamaks as result of using control methods for plasma parameters and current profiles. In these experiments, neutral beam injection and low hybrid waves [3] as well as electron cyclotron current drive [4] were used for the control. An improved confinement was observed in the mode of "inverse magnetic shear" when the safety factor has its minimum near the center of the plasma column minor radius.

Of specific interest is the possibility to control the peripheral plasma as there occurs excitation of dangerous instabilities resulting in an amplified particle and heat transfer. In stellarator-type devices, undesirable bootstrap currents can appear in the peripheral plasma. The effect of bootstrap currents can be neutralized by generation of counter-currents in the plasma. The problem is that the bootstrap current density, which is proportional to the plasma pressure gradient in the peripheral plasma area, can substantially vary. So conventional methods of control such as neutral injection can be of no effect.

However, a local control of plasma parameters and peripheral currents could be done by high-power pulsed lasers [2,5-6]. With this aim [2] frozen-hydrogen pellets

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should be injected into a specified plasma volume and irradiated with a powerful laser pulse. As a result an expanding laser plasma would fill a certain volume close to a given magnetic surface. In such a plasma the ions can have a high directed velocity with an energy of the order of 30~100 keV at a quite usual laser power. These ions can maintain the current (and plasma rotation) for a fairly long time. The given current could be maintained with the help of a laser (or several lasers) with a given pulse repetition rate.

2. Ion Acceleration and Non-inductive Current Drive

Application of lasers for profiling plasma pressure and current density has been discussed in Ref. [5-8]. However the problem of maintenance of necessary profiles in the peripheral area has its own peculiarities which are considered below.

2.1. Ion acceleration

The laser application is based on unique features of a laser plasma expanding in a strong magnetic field [2]. In Ref. [2] rather moderate laser radiation intensities have been considered when electron distribution in the laser plasma is kept close to Maxwell's with temperature T_e. From analytical expression obtained in Ref. [2,5] it follows that in the one-dimensional case and at a sufficiently deep plasma expansion the ion velocity can reach

$$V_i \approx 10\, S\,, \tag{1}$$

where S is the ion sound velocity. According to Eq. (1) the ion energy at $T_e \sim 1$ keV can attain $E_i \sim 30\text{~}50$ keV. Now and further we present the estimations for a CO_2 -laser with a 10.6 μm wave length.

At a laser flux density w larger than 1 TW/cm^2 the collective mechanisms of laser irradiation absorption dominate and generation of fast ("superheat") electrons starts in the laser plasma corona. At a further increase of the laser flux density, as it has been experimentally established, the energy of superheat electrons can attain 90% or more of the total electron population energy.

In the process of laser plasma expansion fast electrons run forward generating an electric field of polarization which is balanced by the pressure gradient. The corresponding ion velocity can be found by taking into account the value of pressure produced by fast electrons in the expression for the velocity [2]. It means, roughly speaking, that the electron temperature T_e should be substituted by some mean value of kinetic energy of fast electrons. The estimations show that at high w the ion energy can exceed 1 MeV. An advantage of such ion source, for example, compared with neutral injection is that using the source one can locally affect plasma parameters.

2.2. Current sustaining in the peripheral layer

As mentioned earlier, at the expansion of the laser plasma corona along the magnetic surface the plasma fluxes arise with a sufficiently high energy of directed ion motion. In the regime of the plasma corona overheating when the pellet is being irradiated with an intense laser pulse and the absorbed radiation energy transfers into that of fast (super thermal) electrons, the ion energy can reach about 1 MeV at the expansion of this corona.

After $\tau_R \sim 2\pi R/V$, i.e. after the laser plasma flux becomes closed, the directed movement of "laser" plasma electrons begins braking at Coulomb collisions with ions of the background plasma. At the same time there appears an electric current and an electric field E is simultaneously induced which captures also the background plasma electrons. These electrons acquire a directed velocity at collisions with fast ions. The resulting velocity is determined by equation

$$m\mathrm{d}V_e/\mathrm{d}t = -eE - m\nu_D\,(V_e - V_D) - m\nu_e V_e\,, \tag{2}$$

where m is the electron mass, V_e is the electron directed velocity and ν_D and ν_e are the collision frequencies of electrons with fast ions and with ions of the background plasma.

The value of the electric field, in its turn, can be found from Maxwell's equation

$$\mathrm{d}^2E/\mathrm{d}x^2 = 4\pi/c\ \mathrm{d}J/\mathrm{d}t \tag{3}$$

where $J = e\,(n_D V_D - n_e V_e)$ is the total density of the electric current and x is the coordinate in the direction transverse to the peripheral layer considered.

An approximate solution of Eqs. (2) and (3) can be found using the fact that Eq. (2) contains the terms varying in time slowly (a characteristic frequency is $\nu_D \sim n_D$) and fast (a frequency $\nu_e \sim n_e >> n_D$), for instance, $E = E_s + E_f$.

As a result of integration (2), we find

$$V_e = -eE_s/m\nu_{ef} + \nu_D/\nu_{ef}\,V_D - E_{f0}\,t_t/m\,\exp\,(-\nu_{ef}\,t)\,, \tag{4}$$

where $\nu_{ef} = \nu_e + \nu_D$ and E_{f0} is the amplitude of the fast varying field, $E_f = E_{f0} \exp(-\nu_{ef} t)$.

At $\nu_{ef}\, t >> 1$ we have for the current density (regarding $n_D << n_i$, where n_i is the ion density of the background plasma with an effective charge Z)

$$J = n_D V_D (1 - Z^{-1})\,. \tag{5}$$

In the case of a quasi-stationary regime of current sustaining, electric field E_s in Eq. (4) can be neglected.

The current density initially concentrates only in a narrow region close to a certain magnetic surface which includes the point where the pellet had been irradiated. Due to diffusion of fast ions the current region will expand and simultaneously the current density will decrease and an electric field will be induced in accordance with Eq. (3). In this equation the current density consists of two parts: the density of the current carried by fast ions (5) and the density of the conduction current

$$J = \sigma E\,. \tag{6}$$

The space-time dependence of changes in the fast ion density and correspondingly current density (5) in the case of a single laser pulse is described by a fundamental solution of the diffusion equation

$$n_D = N_D / \sqrt{2(\pi D t)}\, \exp(-x^2/4Dt)\,, \tag{7}$$

where D is the diffusion coefficient of fast ions and N_D is the initial number of fast ions per 1 cm^2 of magnetic surface. Using Eqs. (5)-(7) one can find solution of Eq. (3). The induced magnetic field tends to keep the current density constant.

We restrict ourselves to the case of a quasi-stationary regime when the required profile of current density is sustained by an uninterrupted injection of pellets with subsequent irradiation of them with laser pulses.

The density distribution of fast ions is determined from diffusion equation

$$\mathrm{d}/\mathrm{d}x\,(\mathrm{D}\,\mathrm{d}n_D/\mathrm{d}x) = s(x) \tag{8}$$

with a source $s(x)$. The laser pulse repetition rate is selected such as the profiles of density $n_D = n_D(x)$ and corresponding current density be close to stationary ones. If the slow down time of fast ions in plasma is fairly large then the current density will be proportional to that of the fast ions. Since in real conditions it could be desirable to suppress current density at a certain distance from the place of fast ions birth, the laser flux density must be selected accordingly.

If the current profile to be sustained is known then the required source $s(x)$ is found from Eq. (8). In such a way one can control the current distribution in the peripheral plasma area. As was indicated above the necessity can arise if we need to avoid some dangerous hydrodynamic instabilities in tokamaks or bootstrap current in stellarators.

3. Required Laser Parameters

Laser system parameters required for conducting the experiment substantially depend upon the particular task and upon the size of the experimental installation. Besides, an optimal energy of fast ions depends on the thickness of the peripheral layer. In fact, if an additional current is undesirable beyond the layer then it is natural to demand that the ions during their diffusion transverse to peripheral layer lose their directed velocity at collisions with other plasma particles. In the general case the task is solved by numerical methods with due regard to experimental values of coefficient D and real profiles of plasma parameters in the peripheral layer. However, we restrict ourselves to some estimates which can demonstrate orders of magnitudes. As an example we consider a device with a major radius $R \sim 3$ m and a thickness of the peripheral layer $\Delta \sim 0.2$ m, and actually achieved laser parameters. It is known, that the experimentally observed values of D for fast ions are somewhat lower than for ions of background plasma. Assuming $D \sim 0.1$ m^2/s, for the diffusion time of fast ions transverse to the peripheral layer we obtain $\tau \sim 0.5$ s, i.e. an optimal ion energy is $E_i \sim 10$ keV at a plasma density $\sim 10^{13}$ cm^{-3}. To obtain accelerated ions with similar energy, it is sufficient to have ~ 10 GW/cm^2 density of radiation power on the pellet surface. At a $\sim$ 10 kJ pulse laser energy one can have $\sim 10^{19}$ fast ions of ~ 10 keV energy. At $R \sim 3$ m the linear density of fast ions will be $\sim 5 \times 10^{15}$ cm^{-1} and the related current $J \sim$ 50 kA at Z $\sim$ 2. With $\tau \sim 0.5$ s obtained above the desirable pulse repetition rate of the laser must be not less than 10 Hz in order to maintain a quasi stationary current density. Accordingly, the total current will rise (compared to a single pulse) $\sim$ 10 times and attain $\sim$ 500 kA. Additional currents of similar magnitude are sufficient for efficient control of peripheral currents in any large tokamak or suppress undesirable bootstrap current in large stellarators of LHD type.

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