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Possible Applications of Powerful Pulsed CO_2-Lasers in Tokamak Reactors

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Applications of powerful pulsed CO_2-lasers for injection of fuel tablets or creation of a protective screen from the vapor of light elements to protect against the destruction of plasma-facing components are discussed, and the corresponding laser parameters are determened. The possibility of using CO_2-lasers in modelling the phenomena of powerful and energetic plasma fluxes interaction with a wall, as in the case of a plasma disruption, is considered.

1. INTRODUCTION

To build a commercial nuclear fusion reactor based on the tokamak (stellarators) concept requires the solution of several research and engineering problems [1-2]. First of all, it is necessary to find the optimum regimes with best plasma confinement in order to reduce the size of future reactors and, therefore, its cost. A notable success in this field has been recently achieved [3]. Then, it seems necessary to provide a contiinuous and reliable operation of the reactor, completely excluding occurence of the most hazardous hydrodynamical instabilities causing plasma disruptions. In the case of their inevitability measures for preventing any destructive consequences should be provided.

To solve the problems mentioned, together with traditional approaches [3], it is useful to consider new and promising technologies such as the use of powerful pulsed CO_2-lasers. The problems of plasma heating, non-inductive current drive, as well as physical principles of frozen hydrogen pellet injection based on CO_2-laser radiation have been discussed [4-7]. Applications of pulsed CO_2-lasers discussed below are aimed at solving such problems as monitoring the processes of stationary nuclear fusion burning including its quench and preventation of dangerous consequences of plasma instabilities.

Another engineering problem where laser systems can be successfully applied is modelling the effect of energetic plasma fluxes on first wall components [3]. The fact that the depth of plasma particle energy penetration, as well as that of the energy of laser radiation is substantially lower than the characteristic depth of heat wave penetration can be the basis for such modeling and simulation. As a result one can use the wide experience gained in laser experiments.

2. APPLICATIONS OF LASER PELLET INJECTION

To sustain a stationary burning regime in the reactor it is necessary to provide a continuous fuel feed. The most suitable solution of this problem is the well-known injection of frozen DT-pellets. In order to attain central and hottest plasma regions the fuel pellet must have a sufficiently high velocity [8]. A significant α-particles concentration is expected to be in the reactor plasma; e.g., in ITER according to estimates [1] it can reach about 0.1%. Because of such high α-particles concentration in the plasma these can cause a substantial contribution to pellet destruction. It is due to the large α-particles path in the hydrogen plasma that there is no significant screening effect [8] for the α-particles. The characteristic lifetime of the pellet in a condensed state depend on its demension. Similar considerations are also basically valid for pellets of reasonable sizes made of materials with the low atomic number (Be,B,C, etc).

2.1. Fuel pellet injection.

The pellet lifetime is the time required for heating the pellet up to the boiling temperature. The path of a 3.5 MeV α-particle in a frozen hydrogen is determined from the ionization losses; it is equal of ≈100 μm [9]. Thus the energy of α-particles ≈ 0.1 $n_\alpha \bullet J/cm^3$ is deposited at the surface of a pellet where n_α is the α - particle density. As a result, a dense nonideal plasma is formed. Assuming the transfer of the energy into pellet is achieved by diffusion of radiation, and applying the Kramers formula [10] for calculation of photon paths one can find

$$t_{cr} \approx 10^{-4}\, r^2,\ s \qquad (1)$$

where t_{cr} is the time for heating of a pellet with radius r, cm.

For conditions in the ITER-type reactor, in order for a pellet with r = 0.3 cm to penetrate into a 30-50 cm depth of hot plasma, its velocity must be not less than 30 km/s. With current methods of pellet injection one cannot provide accelerations up to similar velocities. Hower, when the laser reactive thrust is used pellet velocities could reach a value of the order of 100 km/s [4,5]. The conditions in the laser plasma corona (and those corresponding to CO_2-laser parameters) have been established where acceleration of the frozen DT-pellet occurs without any fault of its phase state [5]. Numerical calculations given in [5] comply with the case where the material for ablation is the frozen hydrogen itself. Together with this it is easy to show that for ablation one can use materials of $(C_2H_2)_n$ type. In addition to the economic advantages of the solid fuel, using plastics can substantially facilitate the technology of pellet manufacturing. In fact, the reactive traction is proportional to $M\sqrt{ZT_e/M}$ where M is ion mass and Z is its charge. In the case of coronal equilibrium total carbon ionization is reached at the electron temperature $T_e > 40$ eV. It is clear the thrust remains approximately the same as in the case of deuterium ablation. Linear and recombination radiation of carbon plasma can cause serious problems, however, at a sufficiently large thikness of the ablation part of the pellet (more than 1 mm) its effect on frozen hydrogen is trivial due to self absorption of the radiation [10].

In conclusion we present estimates for ITER-type reactor. The expected fuel feed rate of 0.1 g/s can be attained by means of injection of a DT-pellet of mass 0.01 g at a 10 Hz frequency. For accelerating the pellet up to v≈30 km/s a CO_2-laser is requitred with a pulsed energy of about 10-15 KJ. This is a well-developed area of laser parameters.

2.2. Prevention of Plasma Disruption, its Consequences, and Burning Control

Up to now plasma regimes with perfect particle and heat confinement are not yet achievables and plasma disruption events will occur in tokamak reactors. So it is necessary to take preventive measures against dangerous consequences of disruption instabilities. A protective screen from the vapor of light elements (Be, B, C, etc) seems to be the most effective means to protect components of the first wall against a destructive effects of hot plasma. The shieding properties of these elements is roughly the same.

As the boiling temperature of the elements indicated is two orders of magnitude greater than the corresponding one for hydrogen requirements the velocity of dopant pellets are substantially lower. Hower such advantages of laser systems as their actual inertness and a possibility to "shoot" the pellet inside the chamber can be crucial. In fact, the protective curtain must be established in a time which is less than the characteristic time of disruption instability development (≈ 10 ms). So it seems desirable that pellets reach plasma region with a rather high concentration of α - particles which can promote the pellet destruction (in ITER the corresponding time is about 100-300 μs). Regarding a relatively low 3-5 km/s velocity expansion of the ionized vapor, it might be as well to bring about 10 pellets each of mass about 1 g to a 30 cm depth in plasma and to distribute them along minor and major perimeters of the plasma loop. In this case the vapor of the dopant elements in time $\Delta t \approx 1$ ms is able to create a practically uniform curtain around the plasma loop. The laser pulse energy required for pellet acceleration up to 3 km/s is about 10-15 kJ. After the discharge the quenched vapor of dopant elements is uniformly distributed on the first wall surface forming a coating of 10^{-6}cm in thickness.

When the reactor shut-down is in plan, discontinuation of the burning process can be executed as described above. A simpler method is the injection of a large single pellet of mass about 10 g accelerated up to about 3-5 km/s. However, in this case a pulsed laser energy in the order of several hundred kJ would be necessary. Besides, it seems expedient to also investigate possibile causing and prevention of dangerous hydrodynamic instabilities in addition to further applying this concept.

3. SIMULATION OF PLASMA - WALL INTERACTION

The plasma-facing components in the reactor experience permanent and strong damage due to energetic plasma particles which can result in their gradual erosion and degradation. The first wall and divertor plates undergoe severe thermal effects during plasma disruption. That is why great attention is payed to investigate these problems. Measures considered in the preceeding section were aimed at diminishing this effect. However, at the same time due to frequent disruptions substantial erosion of walll reactor materials is inevitable. It seems desirable to make estimations of possible damages beforehand in order to provide for the necessary measures. At present active theoretical and experimental investigations are being carried out including those where plasma injectors are used [11].

In laser experiments concerning interactions of laser beams with surfaces of condensed media, a broad experience has been obtained which can be used for estimations of possible damages. The characteristic time of the development of plasma disruption is likely to be not less than 1 ms. In this case penetration of the heat wave into metal significantly exceedes plasma particles range or radiation mean free path. It means that the phenomena of plasma-wall interaction will be similar to those which are usually observed at corresponding laser fluxes. On the base of this analogy one can estimate the critical density of the energy flux which initiates evaporation of material

$$w_{cr} = T_{cr} (C_p \lambda)^{1/2} / \sqrt{\tau}, \qquad (2)$$

where τ is the duration of the energetic interactin, T_{cr} is the critical temperature of evaporation, C_p and λ are the specific capacity and heat conductivity of the wall, respectively. For a number of metals studied in the laser experiments (Cu, Be,...) usually $w_{cr} \approx 5 \cdot 10^5$ W/cm^2 at $\tau \approx 10^{-3}$ s.
If the density of the energy flux surpasses w_{cr} then at $t < \tau$ the wall distruction occurs in a regime of evaporation wave and its front will go into the depth of the wall with a velocity

$$v = w / H \rho, \qquad (3)$$

where ρ is the mass density and H is the spesific heat of wall material evaporation. A heated-up layer δ with its depth decreasing with v , moves in front of the evaporation wave,

$$\delta \approx \lambda / v C_p \qquad (4)$$

Thus at w > > w_{cr} there appear regimes characterised by a high-rate material evaporation. Because of vapor condensation as well as of expansion and formation of droplets there also arise a screening effect which has been well studied. Nevertheless possible applicability of any analogy here requires further studies.

4. CONCLUSION

The considerations developed above show that powerful pulsed CO_2-lasers can have a wide application in tokamak reactors including the maintenance of a stationary nuclear fusion reaction by injecting high-velocity fuel pellets, creation of a protective shield from light elements with low Z to prevent the destructive influence of plasma disruption and reactor shut-down. The required laser parameters for the above mentioned applications are within the achievable current laser engineering.

Besides it is possible to use laser radiation to simulate the phenomena of intensive plasma energy fluxes interaction with reactor wall materials. The experience in the field of laser experiments shows that at a quite moderate power fluxes of order of $w \geq 0.5$ MW/cm^2, the destruction of a wall will occur in a regime of an evaporation wave.

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