Numerical Study for a Protection of Laser Beam Port by Magnetic Fields in the Laser Fusion Reactor KOYO-F

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A possible method for protecting beam ports from alpha particles which are produced by a nuclear fusion in the Fast Ignition Laser Fusion Power Plant (KOTO-Fast) is proposed. A simple dipole magnetic field generated by a coil equipped with the front of the beam port is used for protecting the beam port. And a new coil configuration which is virtually one ring coil formed by eight small rectangle coils is proposed and these coils can make a flexible magnetic field to protect the alpha particles coming into the inside of the beam port. To calculate the behavior of alpha particles in the magnetic field with different configurations, we use a 3D hybrid numerical simulation code. As a result, the intensity of 0.9 [T] of magnetic field is large enough for achieving the 10 % reduction of the collision energy of the alpha particles to the surface of the beam port compared with the case without protection. Furthermore, a new coil configuration can protect the alpha particles coming into the inside of the beam port perfectly.

Keywords: nuclear fusion, KOYO-F, laser beam port, numerical simulation, hybrid code

1. Introduction

The laser fusion power plant (KOYO-F) driven with cooled-Yb:YAG ceramic lasers was conceptually designed by Norimatsu et al.[1] The design of this reactor is based on the Fast-Ignition scheme. The KOYO-F is a more realistic power generation plant with smaller power output than the previous plant KOYO [2].

One of important design issues is a design of chamber. A damage of first wall by irradiation of low velocity alpha-particles is the most serious problem [2]. As a protection of first wall, LiPb liquid wall chamber has been proposed. On the other hand, naked laser beam ports are not protected. For protecting the beam ports from alpha-particles, one idea has been proposed such that covering the front of the beam port with the porous metal. The liquid metal oozes out from the inside and the beam ports are protected from the thermal load by keeping the surface colder to enhance condensation of LiPb vapour in every shot. But, under the condition that the wall temperature of beam port becomes around 873 [K], the adsorption rate on the liquid metal does not so change even if the surface temperature keeps low temperature by the cooling. So, it has been considered that this idea is not so reliable about the protection of beam ports.

In our past research [3], we proposed a method of protection from fusion-produced alpha particles by using an artificial magnetic field generated by the simple circular coil. We conducted a numerical simulation for evaluating the reduction of alpha particles by changing intensity and configuration of the magnetic field. The targeted reduction level of alpha particles is less than 10 % of the load without protection by the magnetic field. As a result, the intensity of 0.9 [T] of magnetic field at the center of beam port is large enough for achieving the 10 % reduction. On the other hand, there were some alpha particles coming into the beam port directly, and the simple dipole magnetic field generated by a simple circular coil could not protect these alpha particles.

In this paper, a new coil configuration which is virtually one ring coil formed by eight small rectangle coils is proposed in order to protect the inside of the beam port. These coils can make a flexible magnetic field by controlling the current in each small rectangle coil.

The amount of alpha particles produced by the nuclear fusion near the beam port is calculated based on the fusion energy of 200 [MJ/shot] in KOYO-F. The simulation is conducted under the assumption that alpha particles are emitted in all directions isotropically, although the alpha particle distribution depends on the irradiation

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direction of ignition beam to the fusion target or existence of guide cone with target fuel.

2. Simulation Code and Model

To calculate the behavior of alpha particles in the magnetic field, we use a 3D hybrid numerical simulation code which treated ions as individual particles and electrons as a fluid. This code is based on the model given by Horowitz [4]. A schematic calculation model is shown in Fig. 1.The simulation region is indicated as a dotted square in this figure. A predicted amount of alpha particles from fusion plasma is 7.1×10^{19} [particles/shot]. The calculated flux of alpha particles near a nozzle of beam port is 6.3×10^{17} [particles/m^2]. So the alpha particles produced by the fusion are emitted with the velocity of 1.4×10^6 [m/s], density of 3.5×10^{18} [/m^3] and thickness of 0.25 [m] as shown in Fig. 1. The size of beam port is also shown in the right side of figure 1. For reducing the calculation cost, it assumes that the alpha particles flow with the constant velocity from the fusion point to the region whose distance is 2.7 [m]. The coil configuration of each case is shown in Figure 2. Circular case is used where the simple circular coil is located at the top of the beam port. The current of this coil is I_A = 170 [kA・turn] and its frequency is 4 [Hz]. Rectangle-case1 is used where the one ring coil is formed by eight small rectangle coils. The current of each rectangle coil is I_u = 390 [kA・turn]. "Rectangle-case2" is used where the same coils as case1 is adopted and the current of upper four rectangle coils located above the dotted line in Fig. 2 is I_u = 390 [kA・turn], the current of lower four rectangle coils being half of the current of upper rectangle coil. "Rectangle-case3" used the same coils as in case1 and the current of upper rectangle coil is 390 [kA・turn], the current of lower rectangle coil being zero. The initial calculation parameters are listed in Table 1. The plasma beta which is the ratio of plasma kinetic energy to the energy of the magnetic field is less than one in every case, so the magnetic field in every case can reflect back the alpha particles generated by the fusion in the reactor. The Larmor radius (calculated from the intensity of magnetic field at the center of coil) of alpha particle in each case is comparable or grater than the size of radius of inner beam port r = 0.075 [m], so the ion kinetic effect should be considered. The calculation step size is equal to 0.001 of

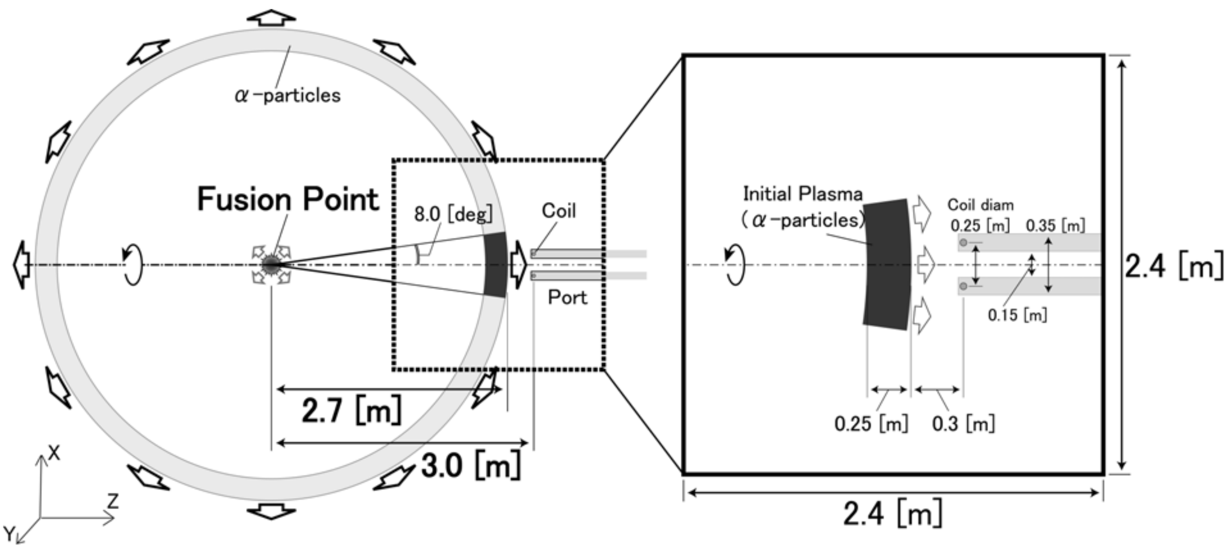

Fig.1 Schematic calculation model.

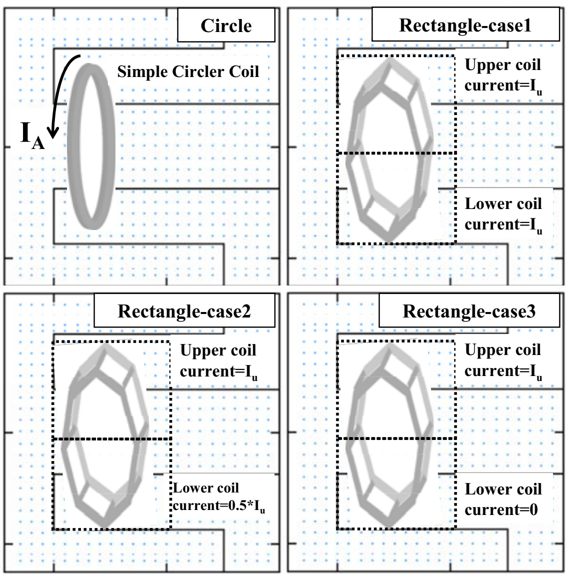

Fig.2 Coil Configuration of each case.

Table 1. Simulation parameters in each case.

Case name	Intensity of the magnetic field at the center of coil [T]	Current of each coil [kA・turn]	Plasma β	Larmor Radius [m]
Circler coil	0.9	170	0.007	0.033
Rectangle-case1	0.15	390	0.27	0.2
Rectangle-case2	0.46	390	0.027	0.063
Rectangle-case3	0.9	390	0.007	0.033

the ion cyclotron frequency. The total calculation time is 0.7[μs] which corresponds to around $34\omega_{ci}^{-1}$. The grid size is 0.02 [m] which corresponds to 0.16 c/ω_{pi} in all cases and total number of simulation particles is 2.0×10^5, which corresponds to put 15 particles in each cell of the initial plasma region.

3. Simulation Results

Figure 3 shows the cross section of vector plot of the initial magnetic field generated by the coil in each case. This cross section is indicated at the center of the beam port (Y=0, XZ plane). The vector plot of the magnetic field in Circular case shows the dipole magnetic field and the only z-component of the magnetic field can be seen at the center of coil. This causes the behavior of alpha particles coming into the beam port. The same configuration of magnetic field can be seen in the Rectangle-case1. In Rectangle-case2 and Rectangle-case3, the currents of upper coil and lower coil are different. As shown in Fig. 3, this non uniform coil current in each rectangle coil can generate the strong x-component of magnetic field and it is expected that alpha particles can not come into the inner beam port because of the existence of this x-component of magnetic field.

Figure 4 shows the alpha particles distribution at t = 0.45 [μs] and vector plot of the magnetic field in the same plane as shown in Fig. 3. The magnetic field acts like a spring to push back the fusion plasma. This effect can be seen in all cases. They show that the alpha particles are collected in the range from y = −0.075 [m] to y = 0.075[m] whose distance is equal to the inner radius of the beam port. In the Circular case and Rectangle-case1, the surface of the beam port can be protected from alpha

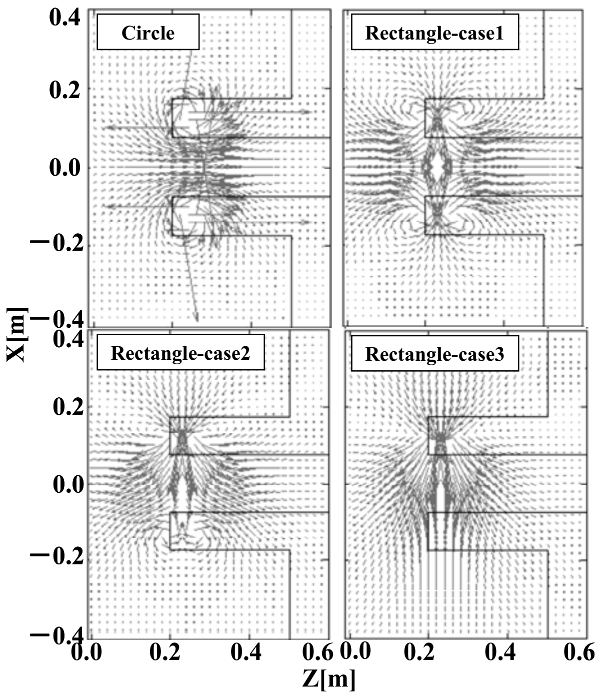

Fig.3 Cross section of the vector plot of initial magnetic field at the center of beam port in each case.

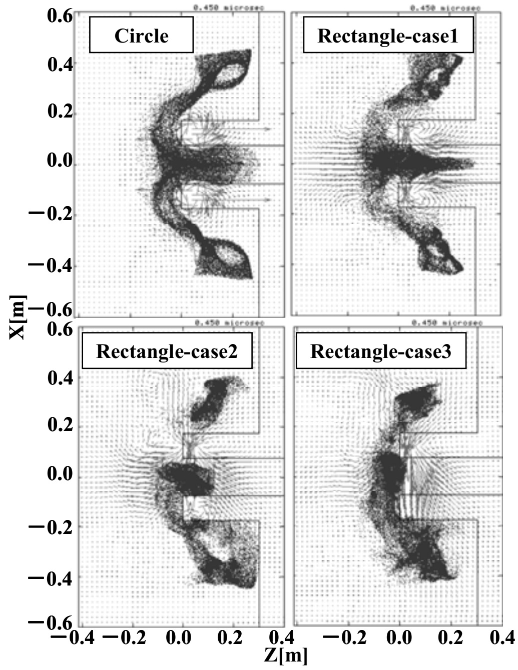

Fig.4 The vector plot of magnetic field and alpha particle distribution projected onto the XZ plane at 0.45 [μs]

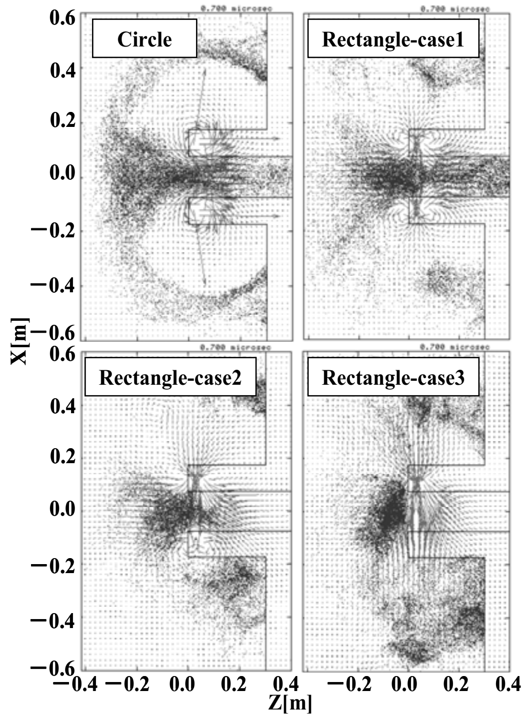

Fig.5 The vector plot of magnetic field and alpha particle distribution projected onto the XZ plane at 0.7 [μs]

particles by the magnetic field. On the other hand, in Rectangle-case2 and Rectangle-case3, a lot of alpha particles collide to the surface of the beam port compared with the results of the previous two cases.

Figure 5 shows the alpha particles distribution at t = 0.7 [μs] and vector plot of magnetic field in the same plane as shown in Fig. 3. In the Circular case and Rectangle-case1, a part of the alpha particles moved in the +Z direction across the center of the structured ring coil. This is because the magnetic field generated by each coil is canceled at the center of the structured ring coil. In Circular case, almost all alpha particles coming into the beam port impinge to the inside surface of the beam port since the vector of magnetic field in the beam port is the direction to the wall of beam port. On the other hand, in Rectangle-case1, almost all alpha particles coming into the beam port do not impinge to the inside surface of the beam port and flow toward the laser device since the intensity of the magnetic field directed to the wall of beam port is weaker than that of Circular case. In Rectangle-case2 and Rectangle-case3, no alpha particles come into the beam port since the strong x-component of magnetic field is generated by non uniform coil current in each rectangle coil. The strength of the magnetic field in −X region (lower region) is weaker than that in + X region (upper region), so the alpha particles tend to push the weak magnetic field generated by the coils in the lower region, but the alpha particles are finally reflected and some of the alpha particles move along the strong magnetic field line generated by the upper coils. The total amount of this reflected plasma depends on the current intensity of coils in lower region.

Figure 6 shows the percentage of the energy of alpha particles in each region normalized by the each energy in the case without magnetic field. The definition of the places (Surface, Inner port, Region A) is shown in Fig. 7. The line "Surface" indicates the ratio between the amounts of alpha particles colliding to the surface of the beam port with and without magnetic field. The 100 % of this value is the case without magnetic field. The targeted reduction level of energy of alpha particles is less than 10 % of the load without protection by the magnetic field. The intensity of the magnetic field of 0.9 [T] at the center of coil which corresponds to the coil current of 170 [kA・turn] is enough for achieving the 10 % reduction of the alpha particles. In Rectangle-case1, this reduction level is almost satisfied. In Rectangle-case2 and Rectangle-case3, a lot of alpha particles collide to the surface of the beam port, so the 40-50% energy of alpha particles in the case without magnetic field is given to the surface of the beam port.

The line "Inner port" indicates the ratio between the total amount of alpha particles coming into the inside of the beam port with and without magnetic field, while the line "Region A" indicates the ratio between the amount of the alpha particles reaching the "Region A" as shown in Fig. 7 with and without magnetic field. In Circular case, it is found that the amount of alpha particles coming into the inside of the beam port is 80% of the energy in the case without magnetic field. On the other hand, in Rectangle-case3, no alpha particle comes into the beam port, so the value of "Inner port" and "Region A" are zero. So, it is not necessary for protecting such particles to equip with the mechanical shutter at the entrance of the beam port or to use the additional coil. But in Rectangle-case2 and Rectangle-case3, it will be required to improve the protection of the surface of the beam port by LiPb liquid wall more effectively.

There is the possibility of appearance of Rayleigh-Taylor instability for plasma expanding to the magnetic field. But in all cases, this instability was not found since the beta value is lower than one near the front of the beam port. So, it does not affect the protection of the beam port. Regarding the future works, we will investigate the possibility of protection of surface of beam port by using this Rectangle coil. It will be expected that the strong

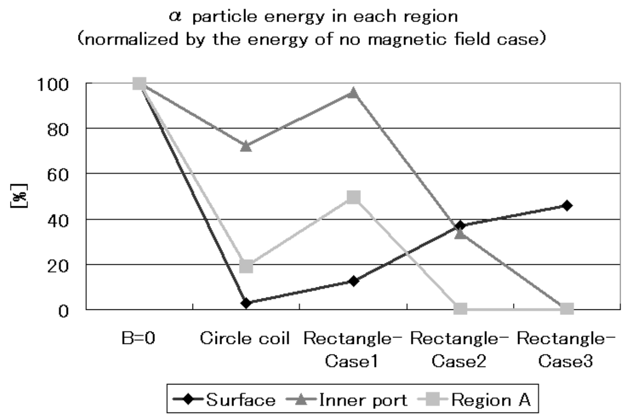

Fig.6 The percentage of the energy of alpha particles in each region normalized by the each energy in the case without magnetic field.

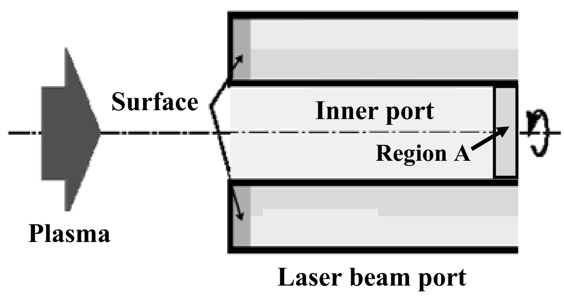

Fig.7 The definition of the places

magnetic field can protect the surface of the beam port by using the Rectangle coil, but the current of coil should be grater than I_u = 390 [kA・turn]. We have to take care of the detachment of the LiPb liquid on the surface of laser beam port by the Lorenz force between the current in LiPb and strong magnetic field. It is necessary for improvement of the protection of the beam port to clarify whether such a large electric current can be sent to the Rectangle coils and the cooling of these coils can be realized effectively.

4. Summary

To evaluate the amount of alpha particles colliding to the surface of the beam port and coming into the inside of the beam port, the numerical simulation by using a 3D hybrid code was conducted. As a result, the coil current of 170 [kA・turn] is enough for achieving the 10 % reduction of the alpha particle colliding to the surface of the beam port in Circular case. On the other hand, the amount of alpha particles coming into the beam port would increase in Circular case, so new configuration of magnetic field generated by the eight rectangle coils is proposed. By controlling the each current of eight coils, the strong x-component of magnetic field can be generated and can perfectly prevent all alpha particles from coming into the inner beam port in Rectangle-case2 and case3. On the other hand, the amount of energy colliding to the surface of beam port increases in this new configuration of magnetic field. In the present results, the amount of the alpha particle energy colliding to the surface of beam port and the amount of energy coming into the beam port have a trade-off relationship between Rectangle-case1 and Rectangle-case3. So, we should consider the use of combination of additional coils and another method for protecting the inside of beam port such as the mechanical shutter.

Acknowledgements

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[1] T. Norimatsu, J. Kawanaka, M. Miyanaga, H. Azechi, K. Mima, H. Furukawa, Y. Kozaki, K. Tomabechi, "Conceptual Design of Fast Ignition Power Plant KOYO-F Driven by Cooled YB:YAG Ceramic Laser." ,Fusion Science and Technology, **52**, 4, pp 893-900, (2007).

[2] Y. Kozaki, et,al. "Basic Concepts and a Total Design of Fast Ignition Laser Fusion Reactor", J. Plasma Fusion Res. **82**, 12, 819-822, (2006).

[3] Y. Kajimura, R. Kawabuchi, K Hayashida and H. Nakashima, "Numerical study for beam port protection by magnetic fields in the Laser Fusion Reactor KOYO-F." Proc. of the IAEA technical meeting on Physics and Technology of IFE targets and chambers (IAEA-TM in IFSA2007), (2007).

[4] E. J. Horowitz, et al.: QN3D: A Three-Dimensional Quasi-neutral Hybrid Particle-in-Cell Code with Applications to the Tilt Mode Instability in Field Reserved Configurations, J. Comp. Phys., **84**, 279-310, (1989).