Peripheral Elements and Technology Associated with Pulsed Power Inertial Fusion[1]

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Abstract

From the various peripheral elements and technology associated with pulsed power inertial fusion, we selected two kinds of subjects to discuss our future direction of the IFE reactor design in this paper. The first is reactor wall ablations with the implosion X-ray, and the second is a probable way to adopt medium-mass ion sources as the future candidate energy driver for the IFE reactor design. After the recent results concerning these topics are shown, the future plans are described briefly to promote the advanced studies in these fields.

1. Significance of Overall Problem and Long-range Objectives

The fast pinch discharge can now transform the stored electrical energy into X-ray with very high efficiency as Sandia National Laboratories show. The pulsed ion beam with medium-weight is also interesting from the point of view of a candidate energy driver for IFE and the industrial application. These belong to the group of pulsed power inertial fusion. If the problem of the rep-rate operation of the pinch source will be solved, and if the tight focus of the medium-mass beam will be obtained, the power plant designs with both energy drivers will become more realistic in the near future. So that, we will try to investigate the peripheral elements and technology associated with these drivers.

2. Recent Results of Wall Material Ablation Induced by X-ray Associated with Target Implosion: Numerical Calculation

The first subject in this paper is our numerical estimation of the wall ablation with the target implosion X-ray. Recently we started the preliminary calculation of the thickness of the wall-material which is ablated with the implosion. At first we gathered the necessary data for X-ray absorption as a function of radiation wavelength. Taking into account of the spectral distribution of the implosion X- ray and the absorption data, we then obtained the absorbed X-ray energy to estimate the evaporated wall thickness, for example.

2.1. Example of X-ray Produced by Laser-Target Implosion

One example of laser target calculations is shown in reference [1]. When the laser energy of 3MJ hits a target with the energy gain of 148, we get nuclear fusion energy of 445MJ, X-ray energy of 4MJ, neutron energy of 303MJ and charged particle energy of 138MJ. The time history and the spectrum of the X-ray are shown in *FIG. 1(a) and (b)*. The inner radius of the solid reactor wall is assumed to be 4m. Although the energy of X-ray is lower than the other ones, it hits the reactor wall at first and the peak power is highest among others. As this kind of X-ray may degrade the first wall of the inertial confinement fusion reactor, we estimated the ablated thickness of the solid wall.

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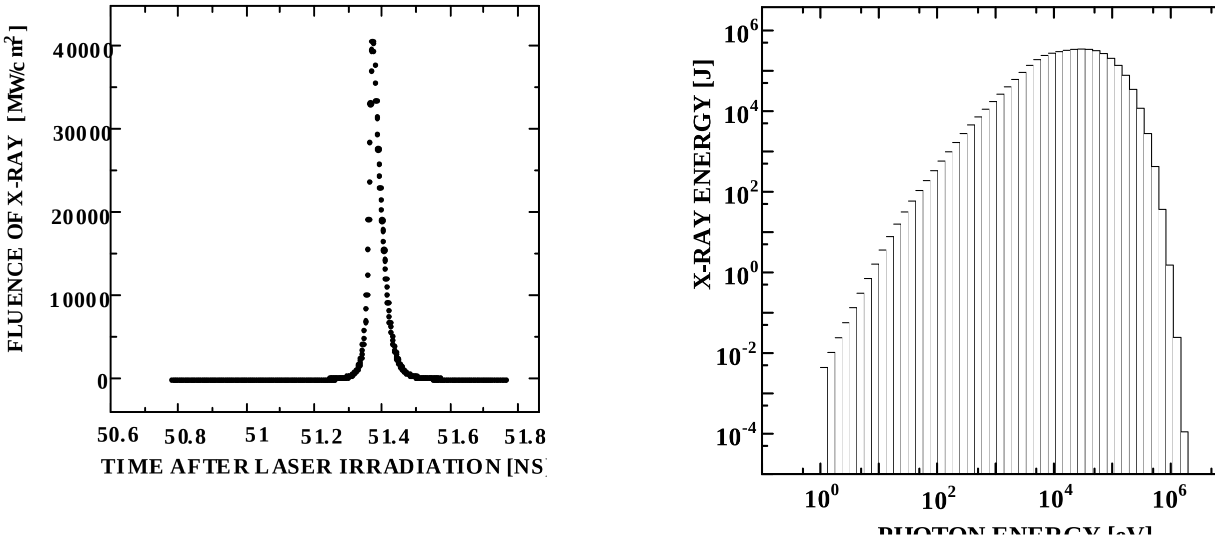


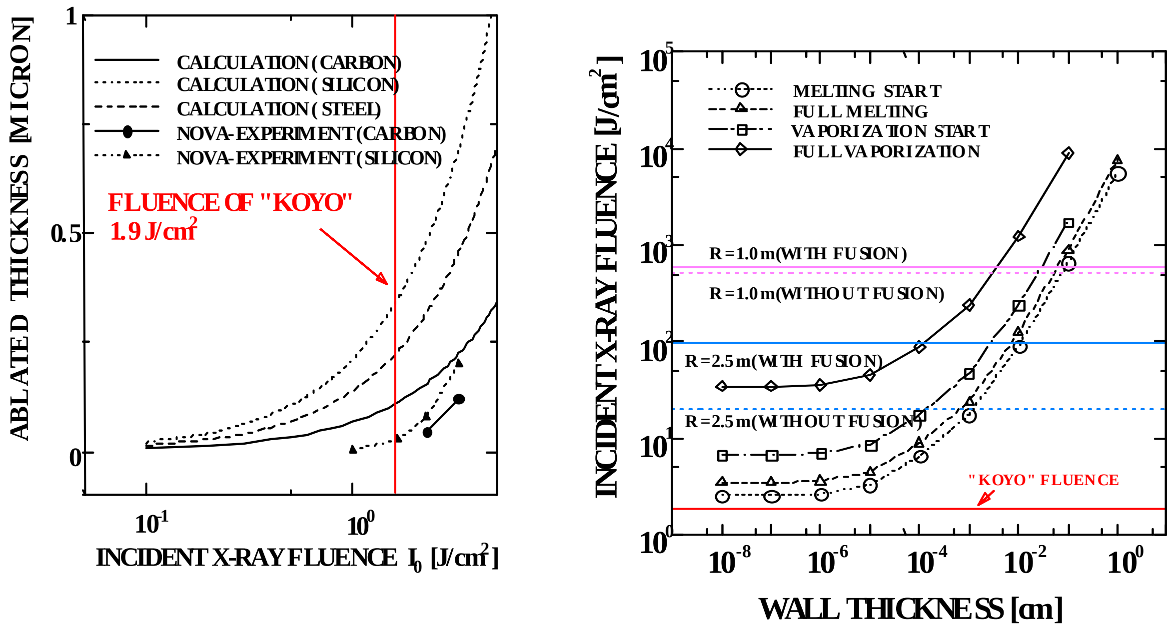
(a) Time history (b) Energy spectrum

FIG. 1. Typical Characteristics of X-tray Associated with Target Implosion in Laser Fusion.

2.2. Ablated Wall Thickness in Various Cases

Three kinds of species (carbon, silicon and steel) were considered as the wall material for the case of laser target implosion X-ray. The classical absorption coefficients as a function of X-ray energy were gathered. Then, we calculated the ablated thickness as a function of X-ray fluence, which result is shown in *FIG. 2(a)*. The NOVA experimental results for carbon and silicon [2] and the fluence of "KOYO" reactor design of ILE-Osaka University are also shown in the same figure.

The same calculations were performed for the case of Z-pinch implosion X-ray. Some people of Sandia National Laboratories and their collaborators in other places are estimating how strong the X-ray is if a steel first wall is placed in the neighborhood of a wire-arrayed high



(a) Ablation by Laser Implosion X-ray *(b) Ablation by Z-pinch Implosion X-ray*

FIG. 2. Comparison of Solid Wall Thickness Ablated by Two kinds of Target Implosion X-rays.

speed pinch implosion to protect the reactor [3]. The X-ray fluences are shown with horizontal lines in *FIG. 2(b)*, for the cases of steel wall radii of 1.0 and 2.5m and with and without the nuclear fusion reaction. The "KOYO" X-ray fluence is also shown in the same figure. Four kinds of curves correspond to the necessary fluences (1) to start the melting, (2) to complete the melting, (3) to start the vaporization and (4) to complete the vaporization of the relative amount of ablated thickness.

2.3. Surface Ablation of Optical Elements for Laser IFE Reactors

The absolute value of the ablated wall thickness was not so large so far in the above results. The severity is anticipated if the optical machine parts of the laser fusion must be used in such IFE reactors. Then, we considered the ablation of the corresponding dielectric mirror surfaces. The results are shown in *FIG. 3* for the various species of surface coating materials (Al_2O_3, NaF, MgF_2, SiO_2, TiO_2, ZrO_2 and PbF_2). The X-ray fluence of "KOYO" reactor design is 1.9J/cm^2 at the reactor wall radius of 4m. This value is reduced with the increase of distance from the chamber center as is shown with the horizontal lines in *FIG. 3* (15, 25, 35 and 45m). Many curves in the same figure correspond to the X-ray fluences at the radius of 4m, which are necessary to start the melting of the various coating materials. The curves can be divided into three groups. The strongest one is Al_2O_3, the weakest one is PbF_2 and the others in a same group which come between the first two ones.

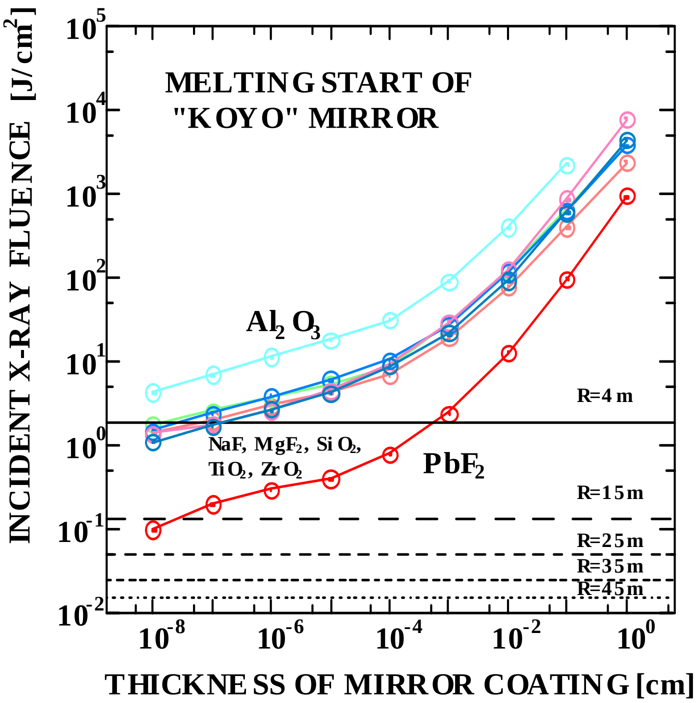


FIG. 3. Ablation of Mirror Coating Materials by Laser Implosion X-ray

3. Recent Assessment of Medium-weight Pulsed Ion Beam as a Future Candidate for Fusion Energy Driver

Although almost all programs concerning light ion beams for IFE or ICF are stopped or sleeping for the moment, we still continue the operation of our pulsed power machines which were manufactured for the former light ion beam research works more than twenty years ago. Although we use the same machines in our recent experiments, our research subjects shift a little bit to different directions, some of which are described in this paper. As the recent budget to support our experiments is not high enough for us to build new machines and to use new spaces, we must consider what we can do only with a small amount of money.

The subject in this section is our basic experiment for the development of future ion beam driver. After we developed a cryogenic diode to produce very pure proton beam from hydrogen ice, one of the guiding principles to continue our experiments has been the finding a new research field under the combination of the pulsed power technology and the cryogenic engineering. Although we could produce the high efficiency proton beam, the beam brightness has not been enough high (in the world- wide experiments which followed) for the future application to the target implosion. This was because the ratio (of the ion mass over the number of ion charge) is lowest in the case of proton beam, and the micro-divergence angle at the ion source was large. On the other hand, the ratio was enough high to get the enough small micro-divergence angle in the case of heavy ion beam. So that, the recent development of particle beams in the world seems to be concentrated on the heavy ion beams. Never the less, the order of ion current of the most recent heavy ion beams is too low to make implosion-oriented experiments. This is because the cost for the heavy ion beams is very high, compared with the one for the light ion beams. This kind of consideration about the situations in the particle beam development induced us to adopt the medium-mass ion beams as a probable approach. This may enable us to develop a compromised ion beam driver with a medium-mass ion from the point of view of the micro-divergence angle and the cost.

3.1. Experimental Apparatuses

In our recent experiments, we produced nitrogen ion beams (including a small amount of oxygen ions), and measured the micro-divergence angle on the anode surface of the ion diode [4]. The schematic diagram of the experimental setup including the ion diode (on the left) and the arrayed pinhole camera for five images on CR-39 (on the right) is shown in *FIG. 4*.

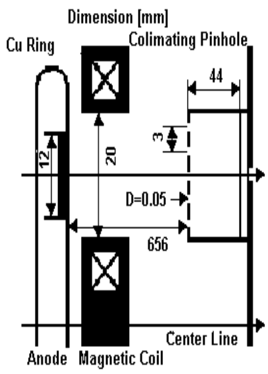


FIG. 4. Experimental Setup Including Ion Diode and Arrayed Pinhole Camera.

3.2. Experimental Results

We measured the divergence angle along the anode surface, which result is shown in *FIG. 5*. The measured value was 5-6mrad for the above mixture beam with 300-400keV energy, 300A peak current and 50ns duration. This value is enough small and tolerable in the future development of the energy driver for the target implosion, if the absolute value does not become larger under the (voltage and current) scale-up of our machine.

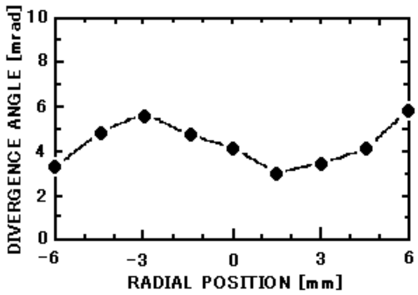


FIG. 5. Micro-Divergence Angle of Nitrogen Beam vs. Anode Radial Position.

3.3. Comparison with Light Ion Beam Case

The corresponding value for the proton beam with higher peak current was 20-30mrad, which was too large for our future purpose. So that, the scale-up experiment with the above kind of medium-mass ion beam driver must be done urgently to clarify the beam characteristics in more details.

4. Temporary Discussion and Summary of the Above Results in Section 2 and 3

It is still necessary to consider deeply the effects, which are brought with the surface ablation of the solid wall materials in the future. For the moment, we cannot say clearly if the above amount of ablated thickness is small or large enough to keep the surface conditions of the wall materials to continue the successful rep-rate operation of the inertial fusion reactors or not.

For HIF, the current mainline target requires a particle current of about 5kA per beam, and each beam must hit a spot on the target that is elliptical with a minor axis of 0.18cm. Typically, the beam radius at the final focus magnet is less than 10cm, and the beam is ballistically focused over a distance of 5m or more to the target. To hit a 2mm radius spot at 5m requires a beam divergence at final focus of 0.4mrad (or considerably less if the ion beam is not adequately charge-neutralized). The present paper reports about a cryogenic ion source coupled with a high voltage diode. For a diode voltage of 400kV, an ion current of 240A is reported with a divergence of about 6mrad. If the ions are all nitrogen ions with charge state q=1, then the beta=0.008; and if these ions could be post accelerated with no emittance growth to the beta > 0.1, then the divergence would be reduced to < 0.6mrad. In HIF accelerators, allowance for an emittance growth in the accelerator of a factor of 100 or more is typically included, so the typical HIF ion source should have an emittance of a factor of about 100 better than the emittance at the final focus. While the present paper has interesting results, it does not appear to be an adequate ion source for a HIF linear induction accelerator. If post acceleration with no emittance growth can be achieved, then the ion source of this paper may be of interest for a medium-mass ion IFE driver.

The ablated wall thickness by the implosion X-ray under laser-target and Z-pinch-target interaction showed us the different response of various materials including carbon, silicon, steel and a variety of coating materials for the optical components for the laser and Z-pinch facilities. The recent results of our preliminary experiments and calculations concerning beam divergence diagnostics and wall surface ablation calculations were shown briefly. We obtained a rather small beam micro-divergence angle for the nitrogen beam (medium-mass ion beam), compared with the result for hydrogen beam (light ion beam). It is expected for us to extend our experiments to the higher power region in the near future to demonstrate the potentiality of such beams so as to show that the medium-mass ion beam is one of the future candidates of energy drivers for the inertial fusion.

5. Future Plans to Solve our Research Subjects

5.1. Work Plan for the Coming Years

The ablation of various materials with intense X-ray must be calculated in more details. We consider the X-ray which is produced under different model-target implosions with the fast pinch in this case. The object materials are the kinds which are used as a candidate IFE reactor wall and the necessary viewing port. If possible, preliminary experiments to measure the ablated thickness of the materials with intense X-ray are tried, and the value is compared with the calculated thickness.

The production of medium-weight pulsed intense ion beam is revisited, and the beam micro-divergence angle at the anode surface is measured under different conditions. If the value is enough small, we extend the experiment to higher voltage and current region. If possible, we proceed to a design of a power plant with such a medium-weight ion.

The ablation processes of various materials with high fluence pulsed laser and ion beams are investigated to enrich the database for the ablation of various materials under the IFE implosion with the pulsed power energy drivers. Solid and liquid state materials are used in these experiments.

5.2. Brief Description of Facilities Available

We have a few pulsed power machines to produce pulsed ion beams. Conventional room temperature diodes and original cryogenic diodes can be used to produce necessary ion beams. These are used for the production and the measurement of the medium-weight ion beam, and also for the ablation of various materials.

A schematic diagram (or a cross sectional view) of an ion diode is shown in *FIG. 6*. Various parts are denoted with the characters from A to I. A pulsed power apparatus with a PFL and a TL supplies the high voltage to the diode from the left side in the same figure. A magnetically insulated diode was used to produce ion beams. The inner and outer diameters of the ring-shaped anode ion source were 122 and 98mm. Nitrogen is one of the probable medium-mass ion specie. If the anode must be cooled as in the case of nitrogen beam production in the following sub-section, we circulated He-gas through a cold cooler-head and the anode. The thermal shroud cooled by liquid nitrogen was also used to suppress the heat income to the anode.

To make the ablation experiments with ion beams, it is necessary to focus the ion beams on the target plates. A schematic diagram of a diode for the beam focus is shown in *FIG. 7*, where a magnetically insulated ion diode and a temperature controlled target must be used. The typical size of the diode is same with the one shown in the former figure.

There are two kinds of excimer lasers in our laboratory, the one is a type of rather single shot operation [5] and the other is a type of rather high rep-rate operation [6]. The more details about the laser apparatuses and the schematic diagrams are shown in these references. These lasers can be used for the ablation of various materials.

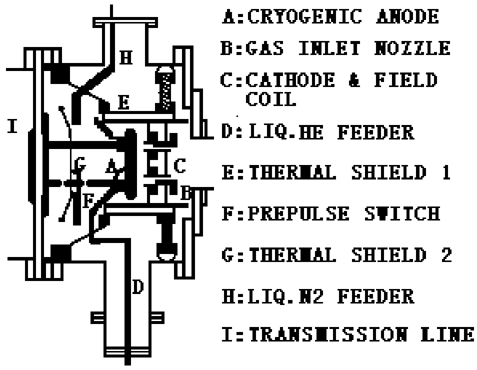


FIG.6. Cryogenic Diode for Medium-mass Pulsed Ion Beam

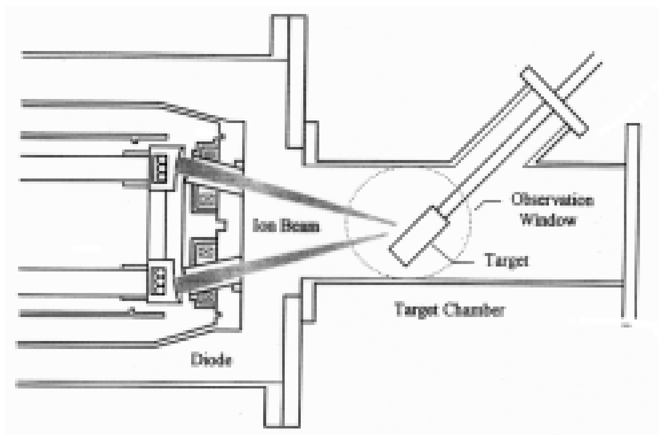


FIG. 7 Irradiation of Target with Focused Ion Beam.

The above are installed in our laboratories at Yokohama, Japan. On the other hand, if the collaborators at Sandia National Laboratories and the University of Wisconsin agree, we can also use the fast pinch machine and an ion diode with higher repetition rate at Albuquerque, USA. The author is scheduled to stay at Sandia National Laboratories to work on these.

References

[1] Nakao, Y., Johzaki, T., et al., "Nuclear burning and reactor design for inertial confinement fusion", Report on Reactor Technology for Inertial Confinement Fusion, ILE-Osaka University, (1997) 83, and personal communication (2000) (in Japanese).

[2] Anderson, A., et al., "X-ray response of national ignition facility first surface materials", Fusion Technology, **26** (1994) 804.

[3] Peterson, R., Kulcinski, G., et al., "X-1 experiment chamber design and analysis: University of Wisconsin Contribution to X-1 CD1 Report", personal communication (2000).

[4] Kasuya, K., Kishi, Y., et al., "First measurement of small divergence angle accompanied with medium mass ion source", Proceedings of the 1st International Conference on Inertial Fusion Sciences and Applications, (2000) 752.

[5] Kasuya, K., et al., "Laser Assisted Works for Pulsed Ion Sources", Proceedings of the 11th International Workshop on Laser Interaction and Related Plasma Phenomena, AIP Conference Proceedings, **318** (1994) 566.
[6] Kasuya, K., Suzuki, T., et al., "Quality Measurements of KrF Laser Beams under High Repetition Rate Operation with Advanced High Speed Photography", Proceedings of the 10 International Symposium on Gas Flow and Chemical Lasers, **SPIE-2502**, (1995) 451.

Appendix

An example of X-ray absorption data in the case of carbon is shown in *FIG. 8*. The temperature increments of the three kinds of wall material candidates with the implosion X-ray are shown in *FIG. 9*.

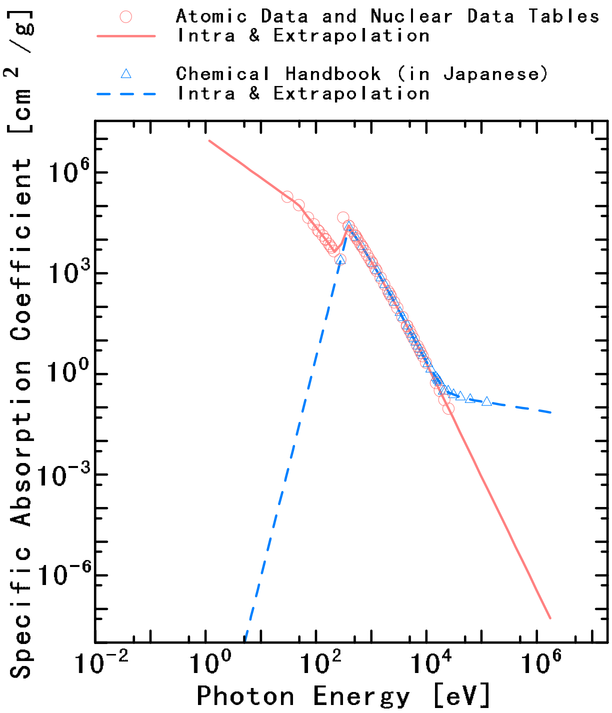


FIG. 8. Absorption Coefficient in the Case of Carbon

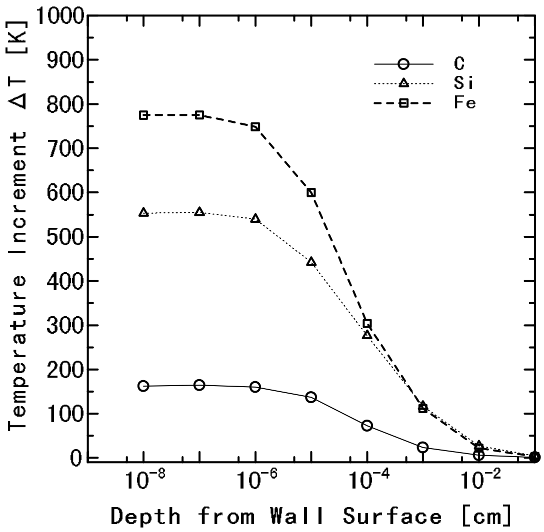


FIG. 9. Temperature Increase vs. Wall Depth