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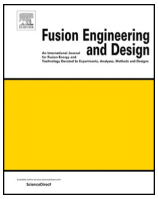

# Influence of low energy radiations on the fusion chamber dynamics and first wall response in a Z-Pinch driven fusion-fission hybrid reactor (Z-FFR)

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## ABSTRACT

In a Z-Pinch driven fusion-fission hybrid reactor (Z-FFR), a substantial thin spherical Cu shell and rare Ar buffer gas are introduced to mitigate the transient X-ray bursts to prevent the first wall from fatal damages. Preliminary simulations indicated that the peak ion and radiation (blackbody) temperatures of the Cu shell and Ar gas are on the order of $10^5$ and $10^4$ K respectively, which means low energy radiations might play important roles in the radiation transport processes in the fusion chamber. Therefore multigroup transports were adopted in simulations of the chamber dynamics, and influence of low energy radiations on the chamber dynamics and resulting first wall response were investigated. The results indicated that low energy radiations have significant influence on the chamber dynamics such as distributions and evolutions of the temperatures and heat fluxes in the Ar gas. And much intenser thermal heat fluxes would be loaded on the first wall, resulting in higher temperature rises and intenser thermal stresses. In addition, practical treatments of the multigroup radiative opacities of Cu and Ar by multiplying a series of artificial factors, varying from 0.1 to 5, were adopted to evaluate the safety of the chamber. It was shown that the opacity uncertainties of Cu have much important influence on the chamber dynamics than those of Ar. The thermomechanical response in the first wall such as maximum temperature rises and stresses, as well as the corresponding lifetimes, were not able to fulfill the safety requirements while the Cu opacities were reduced by two more times. Additional schemes might be required to effectively handle the problems to finally sustain current Z-FFR designs.

## 1. Introduction

The Z-Pinch driven fusion-fission hybrid reactor (Z-FFR) concept utilizes energetic neutrons produced by D-T fusion to drive a sub-critical fission blanket for energy production [1]. Almost 20% of the fusion energy yield, approximately 300 MJ, is released in forms of intense pulsed X-rays [2]. The pulsed X-rays will yield an energy fluence of approximately 50 J/cm$^2$ on a 7 m radius first wall, within a time scale of several tens of nanoseconds. As a primary candidate, a thin spherical Cu shell and rare Ar buffer gas were employed to absorb the transient energy bursts of X-rays and charged particles. And then the energy was released in a gentler way over a much longer time scale of several milliseconds, to finally reduce the peak wall temperatures and stresses [3].

Earlier investigations on radiation hydrodynamics in the Z-FFR fusion chamber were performed by using the MULTI code [4,5], in which single-group radiation transports coupled with hydrodynamic motions were adopted. The results indicated that the peak ion temperatures in the fusion target, metal shell, and Ar gas are on the order of $10^8$, $10^5$, and $10^4$ K, respectively. And the corresponding radiation (blackbody) temperatures are on the order of $10^7$, $10^5$, and $10^4$ K, respectively [3]. Hence low energy radiations with energies less than $10^2$ eV, including the soft X-rays, EUVs, visible and infrared radiations, might play important roles in the radiation transport processes in the fusion chamber. These are quite different from those in a typical laser inertial fusion energy (IFE) or magnetic fusion energy (MFE) plant, in which spectra of the X-rays are quite hard with energies of up to $10^6$ eV [6–9]. Since low energy radiations have significant variations in mean free paths (or radiative opacities) in materials employed in the chamber, single-group radiation transports utilized in earlier simulations seem to be insufficient to investigate the chamber dynamics. Therefore multigroup transports were adopted in current simulations of the chamber dynamics, and influence of low energy radiations on the chamber dynamics and first wall response were studied. In the simulations, multigroup radiative opacity data of Cu and Ar were derived from two sources: calculations based on the average atom (AA) models [10,11]

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and the SNOP code [12]. The average atom (AA) models are quite simple and common radiation opacity models used in fast and real-time calculations. And the SNOP code is commonly used to produce the required radiation opacity data from its own database.

The multi-group opacity describes the capability of plasmas of given temperature and density to absorb the X-rays within specific energy range. Up to now, the radiative opacity data are obtained mainly from theoretical models and calculations [13–15]. The existed experimental data are quite rare, and limited in specific X-ray energy ranges and finite plasma temperatures and densities of specific elements. The lack of experimental data is mainly attributed to the difficulties of creating 'steady-state' plasmas with given temperatures and densities, and obtaining precise measurements of the plasma parameters as well as the absorption spectra [16,17]. It is believed that the theoretical and experimental radiative opacities of low Z elements have relative errors of approximately 20–50%, while the relative errors of the mid-Z and high Z elements are generally 50–100% (or even larger) [18–21]. An uncertainty of 100% means the given opacity data might be one time lower or higher than the real value. Thereby, it is necessary to investigate the influence of the opacity uncertainties on the chamber dynamics and first wall response to evaluate the safety of the chamber. A simple and practical method is to adjust the multigroup radiative opacity data of Cu and Ar by multiplying a series of artificial factors (varying from 0.1 to 5). A factor larger than 1.0 means that the opacity data is overestimated with increased absorption of plasmas to the X-rays, while a factor of less than 1.0 means that the opacity data is underestimated with decreased absorption of plasmas to the X-rays. Thermal heats and mechanical overpressure loads on the chamber wall, as well as the resulting thermomechanical response, were obtained. The viability of the fusion chamber as a long-lived component was evaluated, and the Z-FFR chamber design was also optimized.

## 2. Fusion chamber dynamics and first wall response with multigroup radiation transports

### 2.1. Fusion chamber dynamics with multigroup radiation transports

In current Z-FFR designs, a thin spherical Cu shell with a radius of 40–60 cm and a thickness of 0.2-0.3 mm, and Ar buffer gas with a modest pressure on the order of several hundreds Pascals (at room temperature), were employed to mitigate the intense pulsed X-rays and charged particles on the chamber wall. The chamber dynamics were studied by radiation hydrodynamic simulations. The chamber model is mainly consisted of the fusion target, W wire/strip array, RTL (Cu), Cu shell, Ar gas, and the first wall (see Fig. 1). The simulations started at the time when fusion target igniting ($t = 0$, or $t_0$), and lasted to $t = 9$ ms. The radiative opacity data of both Cu and Ar were employed in the simulations including the single-group opacities (marked as 'SG'), as well as multigroup opacities based on AA models (marked as 'AA-MG') and the SNOP code (marked as 'SNOP-MG').

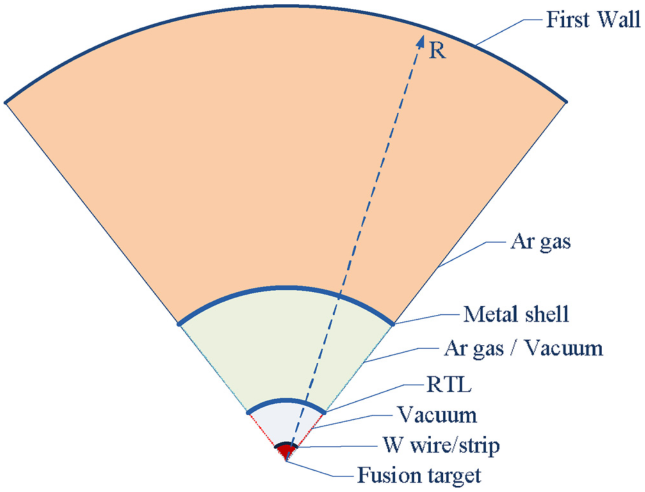

**Fig. 1.** Radiation hydrodynamic model of the Z-FFR fusion chamber [1].

The radiation hydrodynamic behaviors of main components in the fusion chamber from $t = 0$ to 9 ms by simulations with 'SG' and 'AA-MG' opacities of Ar, are shown in Fig. 2. A Cu shell with a radius of 40 cm and a thickness of 0.2 mm absorbed nearly all of the X-rays and charged particles, which were generated from extremely hot materials in the central region of the chamber. And a prompt temperature rise from 500 K to 50,000 K (averaged in the shell) was produced. The shell subsequently expanded, and a series of shock waves were yielded in the Ar gas (with a density of $7 \times 10^{-6}$ g/cm$^3$) which finally impinged on the first wall. Evolutions of the hydrodynamic fields were derived from simulations with 'SG' and 'AA-MG' opacities of Ar, and both of them behaved similarly in the first 4 ms. It must be noticed that the impinging and rebounding of the shock waves after $t = 3$ ms are just artificial phenomena inherent to 1-D simulations, and should not appear in multi-dimensional simulations because of inevitable non-uniformities [9]. However, distributions and evolutions of temperature and heat flux in the Ar gas, exhibited quite different behaviors between the results with single-group and multigroup opacities of Ar.

Ion temperature and heat flux evolutions in the fusion chamber derived from simulations with 'SG', 'AA-MG', and 'SNOP-MG' opacities of Ar, are shown in Figs. 3 and 4 respectively. The middle layer of the Cu shell had a prompt temperature rise of approximately 50,000 K immediately after $t = 0$. And radiations in the energy range from 10° to $10^2$ eV were subsequently re-emitted. Radiations with energies of a few eV (mostly the visible and infrared radiations) have quite long mean free paths in the Ar buffer gas, and could penetrate the Ar gas with almost no absorptions. However, radiations with energies of several tens of eV (mostly the soft X-ray and EUVs) have extremely short mean free paths, and would be strongly absorbed by the Ar gas. In single-group radiation transports, single-group opacity data were employed and averaged in the whole energy range. Thus the Ar gas was able to absorb all the low energy radiations emitted from the Cu shell, and subsequently re-emitted the radiations with lower energies. As a result, there were large gradients in spatial distributions of the temperatures and heat fluxes in the chamber. And peak of the thermal heats loaded on the first wall was 1200 W/cm$^2$, which appeared at $t = 0.9$ ms when the shock waves impinged on the wall. When employing multigroup radiation transports with multigroup opacity data of Ar, the soft X-rays and EUVs were completely absorbed by the Ar gas near the Cu shell with radius of less than 1–2 m. Thereby higher temperatures than those in the single-group case were produced. The visible and infrared radiations, emitted from the Cu shell, could penetrate the Ar gas and finally reach the wall surface. An instantaneous heat flux peak of more than $10^5$ W/cm$^2$ immediately after $t = 0$, and a hydrodynamic heat flux peak of $2 \times 10^4$ W/cm$^2$ at $t = 0.9$ ms when the shock waves impinging on the first wall, were yielded. The results indicate that low energy radiations have significant influence on the energy transport processes in the Ar gas, such as distributions and evolutions of the temperatures and heat fluxes, which show little differences in cases with 'AA-MG' and 'SNOP-MG' opacities of Ar.

Ion temperature and heat flux evolutions in the fusion chamber in cases with 'AA-MG' and 'SNOP-MG' opacities of both Cu and Ar, are shown in Figs. 5 and 6 respectively, in which geometric parameters in the simulations were unchanged. There were little differences in temperature evolutions when employing the multigroup and single-group opacities of Cu, but some changes in the heat flux evolutions. That is, the heat flux gradually decreased from $t = 0$ to $t = 0.7$ ms when the Cu shell and Ar gas moving toward the first wall, and then rapidly increased to a hydrodynamic peak at $t = 1$ ms when the shock waves impinging on the wall. While in cases with single-group opacities of Cu, the heat flux rapidly dropped to a very low level from $t = 0$ to $t = 1$ μs,