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EFFICIENCY OF CONVERSION OF HEAT FLUX INTO HARD X-RAY RADIATION

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The efficiency of the conversion of the heat flux into hard X-ray (HXR) radiation is analyzed, via time-dependent two-temperature one-dimensional non-LTE-radiation-hydrodynamic numerical modelling, for a heat-to-radiation flux converter linked to the edge of low atomic number hot Z-pinch. The domain of parameters in this scheme is found where about the same HXR yield can be achieved at those values of input energy which are lower, by the order of magnitude, than that in the conventional scheme of a radially imploding plasma.

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Formulation of the problem. The Pulsed Power Generator-based Z-pinch plasmas proved to be an effective and prolific sourse of soft X-rays (SXR) [1]. Here, multiwire array approach to creation of a high-Z plasma provides high efficiency of the magnetic energy conversion into SXR black body radiation. Alternatively, the magnetic pressure driven acceleration of a hollow heavy-atom plasma cylinder (the liner) and transformation of the kinetic energy into Z-pinch plasma thermal energy and radiation yield in spectral region of the L-shell and K-shell transitions in heavy atoms (Ar, Kr, Xe) is under investigation now [2]. These energy conversion schemes have limited control of redistributing the radiation flux over the spectrum (specifically, toward the hard X-rays (HXR)). The latter takes place because of rather slow energy transfer from hot ions to cold electrons that results in the long lifetime of ionization states where multiple transitions in L-shell and higher-lying atomic shells dominate. The necessity to make the emitted X-ray spectrum harder, as requested by a number of scientific and technological applications which are currently being actively discussed, makes it worth to seek for (i) speeding up the ionization process in the HXR radiator and (ii) having a freedom in increasing the electron density (and HXR intensity, respectively) in the HXR radiator. Pursuing these goals suggests the following two-step progression of energy, namely:

1) producing and heating the electron plasma in the conventional Z-pinch with *minimal* radiation losses, and

2) fast "transfer" of resulting high electron temperature to a converter taken in the form of the conventional target which is linked to the edge of the above Z-pinch plasma (i.e. the target is situated at the point where the edge of the cylindrical Z-pinch stops at its stagnation stage, cf. Fig. 1).

The time ordering of the above two processes is possible because of strong temperature dependence of thermal flux ($\propto T_e^{7/2}$) caused by electron thermocon-

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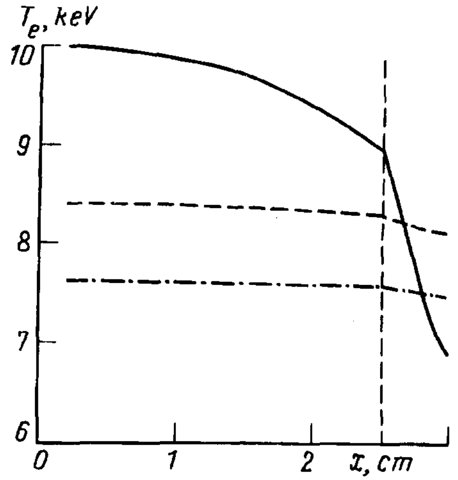

Fig.1. Evolution of electron temperature profile in the Z-pinch (on the left from vertical dashed line; Z-pinch axis would be a horizontal line) and the converter (on the right) $W^{(0)}_{pinch} = 1.25$ MJ, $M_{rad} = 0.8$ mg, $l = 0.5$ cm, $M_{pinch} = 1$ mg, $L = 2.5$ cm, $S = 1$ cm^2, $T^{(0)}_{pinch} = 15$ keV. Solid curve, 1 ns; dashed curve, 4 ns; dash-dotted curve, 10 ns .

duction. This scheme appears advantageous in the following aspects of energy progression. First, the energy cost of atom ionization E_{min}, i.e. a sum of the ionization energies and the ion and electron thermal energies required to reach the He-like stage of the relevant element of atomic number Z, appears, for rather large Z of radiating plasma, to be smaller, due to smaller losses on excitation (and subsequent radiation emission) during ionization. And, second, the profit in decreasing the E_{min} value is closely related to the faster reaching of the relevant ionization degree (i.e. lower "time cost" of a He-like ion) due to higher electron temperatures at initial stage of producing the radiating plasma (cf. thoroughful investigation of time-dependent kinetics effects in [2]).

In this scheme the "load function" is separated from conversion of thermal energy into radiation flux. Such a separation broadens the possibilities for the "generator-load" matching. Indeed, the use of a light-atom gas liner instead of heavy-atom gas liner (typically, krypton) allows (i) to form more thick liner and thus achieve more stable regime of compression, and (ii) to "match" the generator and load system with more freedom because of weaker constraints imposed over imploding velocity. This freedom makes it possible to optimize radiation yield via varying the density of the radiating plasma.

The present approach called the "Liner-Converter" scheme has been originally proposed in the Kurchatov Institute [3] for conversion of heat flux into SXR radiation. However it appears that this scheme is most valuable and efficient just for the case of heat conversion into the HXR radiation.

Input energy threshold for producing a radiating plasma in the converter ("rough" optimization of the converter). A rough estimate of the energy required for producing a radiating plasma in the converter can be made, assuming approximate equalizing of temperatures in the Z-pinch and converter ("pinch-converter thermalization") after a short stage of the target ionization and heating (this approximation is suggested by numerical simulation results, see Fig. 1 and next Section). Neglecting the radiation losses during thermalization stage, we arrive at a simple relationship between the following parameters: namely, $W^{(0)}_{pinch}$, initial thermal energy of Z-pinch plasma (in MJ); M_{rad}, total mass of the gas in the converter (in mg); A, atomic mass; $T^{(0)}_{pinch}$, initial electron temperature in the Z-pinch; $T^{(0)}_{rad}$, initial electron temperature in the converter at the HXR emission stage (or, equivalently, final temperature in the Z-pinch and converter at thermalization stage) (in 10 keV units); $Z^{(0)}_{rad}$, initial average charge of converter plasma at the HXR emission stage; $E_{ion} \simeq 0.045[(Z-2)/10]^3$, the minimal energy (in 100 keV units) required for producing a He-like ion for the atom of atomic number Z (i.e. the sum of respective ionization potentials):

$$W^{(0)}_{pinch}(1 - T^{(0)}_{rad}/T^{(0)}_{pinch}) \sim 9.6(M_{rad}/A)[1.5(Z^{(0)}_{rad}/10)T^{(0)}_{rad} + E_{ion}], \qquad (1)$$

where we omitted losses on atomic/ionic excitation during ionization because of their relative smallness as mentioned above.

The optimal value of $Z^{(0)}_{rad}$ for HXR radiating converter (in K_α lines) should be close to atomic number Z (specifically, $Z^{(0)}_{rad} \approx Z-2$). The value of optimal Z can be evaluated from the fact that the relatively slow evolution of temperatures and ionization balance at the HXR emission stage makes the values of $Z^{(0)}_{rad}$ and $T^{(0)}_{rad}$ related to each other in the way which scales rather close to coronal equilibrium average charge $< Z >$ at a temperature T (cf. [4]).

Using Eq. (1), one may evaluate optimal mass M_{rad} of the converter gas for given values of optimal temperature and atomic number Z. The latter values are determined, in turn, by the requested spectral range of radiation. Thus, for $\hbar\omega > 10$ keV (and correspondingly, $Z > 30$) the krypton slab seems to be an optimal converter. Here, one has $T^{(0)}_{rad} \approx 1$, and Eq. (1) gives $M_{rad} \sim W^{(0)}_{pinch}$.

Numerical simulations. For evaluating the efficiency of Liner-Converter scheme and comparing it with that of conventional Z-pinch scheme, numerical simulations are carried out for both these schemes, for various values of input energy Q (or, equivalently, $W^{(0)}_{pinch}$), with the help of numerical code SS-9 [5] which treats self-consistently level population kinetics, radiative transfer and gasodynamics (see also [6]).

The HXR yield is calculated in a certain spectral region, integrated over certain time interval Δt_{rad}. The radiation kinetics allows for the ionization states from Ne-like to H-like ions. For H-, He- and Li-like ions the excited atomic levels, up to $n = 5$ level, are taken into account, with allowing for the fine structure of the 2P levels in Li-like ions. Each line is covered by at least 15 points spectral grid. We present here the results of calculations which do not allow for gasdynamics. The simulation are carried out for the following conditions:

a) conventional Z-pinch scheme: plasma column (cylinder, length L, square S) of a heavy-atom gas (krypton, total mass M_{rad});

b) Liner-Converter scheme: plasma slab (thickness l) of a heavy-atom gas (krypton, total mass M_{rad}) linked to plasma slab of a light-atom gas (nytrogen, total mass M_{pinch}, initial electron and ion temperature $T^{(0)}_{pinch}$). Slab geometry of the Z-pinch plasma is chosen for simplifying the simulations though final results for the radiation yield are presented for an equivalent cylindrical geometry with the same cross-section S of the Z-pinch.

The results are presented in terms of (i) spectral distribution of radiation flux (for the Line-Converter scheme at specific time, $t = 6$ ns, shown in Fig. 2), (ii) time integrated (from zero to a current time t) and frequency integrated (from zero to a current value ω) radiation flux, $Q_{rad}(t, \omega)$, (for the Liner-Converter and

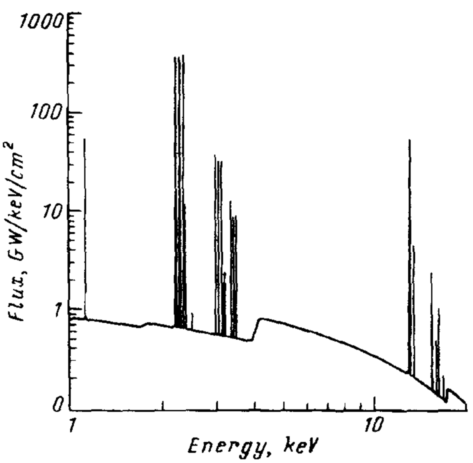

Fig.2. Spectral distribution of radiation flux from free surface of Kr converter at $t = 6$ ns (in double logarithmic scale) for $l = 0.2$ cm and all other parameters from Fig.1

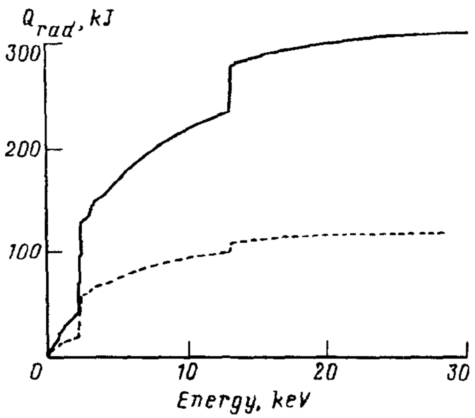

Fig.3. Spectral distribution of time- and frequency-integrated radiation flux Q_{rad} at $t = 10$ ns ($W^{(0)}_{pinch} = 1.25$ MJ) for the Liner-Converter scheme ($M_{rad} = 0.8$ mg, $l = 0.2$ cm, $M_{pinch} = 1$ mg, $S = 1$ cm^2, $L = 2.5$ cm, $T^{(0)}_{pinch} = 15$ keV) (solid curve) and the conventional Z-pinch scheme ($M_{rad} = 1.9$ mg, $L = 2.5$ cm, $S = 1$ cm^2) (dashed curve)

conventional Z-pinch schemes shown in Fig. 3), and (iii) time integrated HXR yield, $Q_{\rm HXR}$, which allows for the photon energies $\hbar\omega > 12.5$ keV (see numbers below).

The input and HXR output parameters in the case of 60 MA driver are as follows:

a) $W^{(0)}_{pinch} = 10$ MJ, $M_{rad} = 15$ mg, $L = 5$ cm, $\Delta t_{rad} = 10$ ns, $S = 1\,{\rm cm}^2$, $Q_{\rm HXR} = 890$ kJ; and $S = 4\,{\rm cm}^2$, $Q_{\rm HXR} = 84$ kJ;

b) $W^{(0)}_{pinch} = 10$ MJ, $M_{rad} = 4$ mg, $l = 0.4$ cm, $M_{pinch} = 4$ mg, $L = 5$ cm, $S = 1$ cm^2, $T^{(0)}_{pinch} = 30$ keV, $\Delta t_{rad} = 10$ ns, $Q_{\rm HXR} = 1.6$ MJ.

Under conditions of multi-megajoule driver both numerical simulations and semi-analytic estimates show that both the Liner-Converter scheme and the conventional Z-pinch scheme attain optimal regime of HXR emission within their own frames, though radiation yield in conventional scheme appears to be more sensitive to the degree of plasma compression. Thus, in conventional scheme the 70% population of He-like ions is achieved for $S = 1\,{\rm cm}^2$ and $S = 4\,{\rm cm}^2$ at 5th and 8th ns, respectively, whereas for Liner-Converter scheme this happens at 1 ns. With decreasing input energy the efficiency of emitting the energy $Q_{\rm HXR}$ during relevant time period (~ 10 ns) in the HXR spectral region ($\hbar\omega > 12.5$ keV) in the conventional Z-pinch scheme goes down faster (and scales approximately as Q^2) as compared with the Liner-Converter scheme (where it scales as Q). The following comparative example illustrates such a phenomenon. In this domain of lower input energies the Liner-Converter scheme attains its threshold for the optimal HXR radiator whereas the conventional Z-pinch scheme fails to do the same:

a) $W^{(0)}_{pinch} = 1.25$ MJ, $M_{rad} = 1.9$ mg, $L = 2.5$ cm, $\Delta t_{rad} = 10$ ns, $S = 1$ cm^2, $Q_{\mathrm{HXR}} = 21$ kJ; and $S = 2$ cm^2, $Q_{\mathrm{HXR}} = 5$ kJ;

b) $W^{(0)}_{pinch} = 1.25$ MJ, $M_{rad} = 0.8$ mg, $M_{pinch} = 1$ mg, $L = 2.5$ cm, $S = 1$ cm^2, $T^{(0)}_{pinch} = 15$ keV, $\Delta t_{rad} = 10$ ns, $l = 0.2$ cm, $Q_{\mathrm{HXR}} = 82$ kJ; and $l = 0.5$ cm, $Q_{\mathrm{HXR}} = 31$ kJ.

It should be noted that omitting the low-Z ionization states beyond Ne-like ions substantially overestimates radiation yield in conventional scheme (cf.[2]), whereas values of Q_{HXR} in the Liner-Converter scheme are much less sensitive to this approximation.

It follows that in Liner-Converter scheme about the same HXR yield can be achieved at those values of input energy which are lower, by the order of magnitude, than that in conventional scheme. This makes the Liner-Converter approach a sound canditate for designing a Pulsed Power Generator-based HXR source in the range of moderate input energies.

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