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Spectroscopic analysis of sodium-bearing Z-pinch plasmas for their x-ray-laser pumping efficiency

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Using axially resolved spectra, we have derived temperature and density profiles of sodium-bearing Z-pinch plasmas produced on the Naval Research Laboratory's Gamble-II generator. The variations in the output power of the Na X $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ line which can be used to pump a Ne IX x-ray laser, are analyzed as functions of mass loading, temperature, and density. The fractional conversion of plasma energy to lasing lines is projected as 10^{-3} if an optimum neon lasant plasma can be prepared and pumped to saturation. This would require an increase in load current of less than or equal to 50% from the present 1.2 MA.

Resonant photopumping has long been considered an attractive technique for achieving soft-x-ray lasing in plasmas.[1–7] However, the shortest wavelength at which gain has thus far been achieved by using this method is 2163 Å.[8] One of the most promising schemes for achieving photopumped lasing at much shorter wavelengths involves the use of heliumlike Na X whose $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ line lies at 11.0027 Å. A sodium plasma would pump a cooler more tenuous neon plasma whose heliumlike Ne IX $1s^2\,{}^1S_0$–$1s4p\,{}^1P_1$ line lies at a wavelength of 11.0003 Å. This excellent wavelength match would, under proper conditions, result in inversions in the 4-3, 4-2, and 3-2 singlet lines of Ne IX, leading to gain at wavelengths of approximately 230, 60, and 82 Å, respectively.

Recently, a significant step in this direction has taken place in the realization of a technique which has produced dense high-temperature plasmas from NaF-loaded capillaries[9] on the Naval Research Laboratory's Gamble-II generator. In this Rapid Communication axially resolved spectroscopic measurements of sodium-fluorine plasmas are presented, the temperatures and densities are inferred from them, and the gain, fluorescence, and lasing efficiency these discharges could deliver when pumping a properly prepared neon plasma are calculated.

In these experiments, a peak current of 1.2 MA was delivered to the NaF Z-pinch load with a rise time of 70 ns. The sodium K-shell x rays were emitted in a 14–20-ns full width at half maximum pulse approximately 100 ns after initiation of the driving current. The total electrical energy coupled to the plasma is typically ~10 kJ. The experimental diagnostics deployed as well as the capillary-discharge technology are discussed elsewhere.[9–12] The measurements of relevance here are time-integrated Al-filtered pinhole images of the sodium K-shell emission, and sodium K-shell spectra obtained with a mica crystal spectrograph. The narrow slit utilized with this spectrograph provides spatial resolution of each spectral line along the axis of the discharge. K-shell line yields are obtained from the spectrograph calibration according to a procedure described elsewhere,[12] as well as from Al- and Ge-filtered x-ray diodes.[11] Also, the total K-shell radiation time history is recorded by an Al-filtered x-ray diode. These two different methods have given consistent results for the line energy output.

We have analyzed in detail the spectra from three different shots, labeled A, B, and C in Table I. For each shot, line intensities were measured at three different spatial positions, each 0.15-cm long, distinguished in Table I by their distance Z from the plasma nozzle. The intensities were converted to peak power per cm length of plasma by dividing the time-integrated energy output by the full width at half maximum of the radiation pulse as determined by the x-ray diode. Finally, for each location the diameter of the K shell emitting region was obtained from the pinhole image intensity profile (full width at half maximum) after proper reduction of the film density. The plasma diameters and radiated powers in the α transitions are listed in Table I.

Given the pinch diameter and the local line power in GW/cm, we have used a collisional-radiative equilibrium (CRE) atomic model of K-shell sodium ions to determine approximate densities and temperatures at each axial point. This model is analogous to the one for neon previously described[13] and includes self-consistent determination of the ionic stage and level populations, as well as solution of the radiative transfer equation for the optically thick lines. The procedure followed was to adjust the theoretical plasma density and temperature (assumed radially constant) such that the predicted Na X $1s^2\,{}^1S_0$–$1s2p\,{}^1P_1$ and Na XI $1s$-$2p$ line powers agreed with those measured within a few percent for both lines. These inferred temperatures and densities are presented in Table I along with the line powers, emitting diameters, and axially integrated line yields. Axially averaged linear mass loadings obtained from these derived plasma parameters are 33, 17, and 14 μg/cm for shots A, B, and C, respectively. These values are consistent with the observed time to implosion relative to the driving current pulse, and with previously observed[12] and computed[14] mass loadings of neon gas puff implosions. The temperatures vary by less than 15% in the axial direction for a given shot, but can vary a factor of 2 from shot to shot. The best yield for the principal heliumlike pumping line was obtained in shot A, with the lowest temperature (~240 eV), and highest

TABLE I. Properties of the three sodium fluoride capillary discharge plasma implosions. The left four columns are experimentally measured quantities; the remaining two columns are quantities inferred by matching model predictions to the spectrum. The emitted line peak powers (P) are given in GW per cm length of pinch plasma.

Z (cm)	Diameter (cm)	P (GW/cm) $1s^2$–$1s2p\,{}^1P_1$	P (GW/cm) $1s$-$2p$	N_e (cm^{-3})	T (eV)
		Shot A ($1s^2$–$1s2p\,{}^1P_1$ yield 610 J)			
0.5	0.10	5.7	6.3	5.8×10^{20}	260
2.5	0.32	12.4	6.4	1.8×10^{20}	240
3.0	0.23	10.3	5.1	3.2×10^{20}	220
		Shot B ($1s^2$–$1s2p\,{}^1P_1$ yield 380 J)			
0.5	0.18	5.5	11.3	1.2×10^{20}	520
1.5	0.31	9.5	15.3	7.8×10^{19}	490
2.5	0.35	7.0	7.2	4.9×10^{19}	460
		Shot C ($1s^2$–$1s2p\,{}^1P_1$ yield 350 J)			
0.5	0.19	5.3	8.2	1.0×10^{20}	460
1.5	0.29	9.1	12.6	8.0×10^{19}	460
2.5	0.47	3.3	2.3	2.1×10^{19}	480

mass load and density of the shots. This yield of 610 J for shot A represents 6% of the 10 kJ energy coupled into the plasma by the generator. Shots B and C produced much higher temperatures, but lower densities and lower pumping line yields of 380 and 350 J, respectively.

The physical factors governing the line power output have been simulated through use of a time-dependent pinch model[15] self-consistently coupled to a collisional-radiative equilibrium ionization and radiation transport model. The model assumes a one-cell plasma of spatially constant temperature and density. Even though inhomogeneities obviously cannot be interpreted with such a model, the basic factors affecting the yield are the imploded mass and the resultant plasma temperature and density. Figure 1 presents the model-predicted pumping line peak power versus mass load for a NaF load using the current profile employed in the present experiments. The experimental points from the three shots are included. These experimental points represent spatially averaged peak power in GW/cm for each shot, determined within an estimated experimental uncertainty of 15%. The diameter of the plasma is also subject to experimental uncertainty of about 15%. Calculations show that the inferred density typically decreases by 15–20% if the diameter is assumed to be 15% larger. The resulting uncertainty in mass load (proportional to d^2N) is therefore also about 15%. This uncertainty must be convolved with that arising from the inferred density uncertainty of 10% which is due solely to the 15% uncertainty for the line power measurements. The overall uncertainty in mass load determination is thus estimated to be 20%. Clearly, when a very large mass is imploded, the kinetic energy per particle is too modest to permit stripping to the heliumlike stage and efficient excitation of the pump line. Conversely, a low mass results in high temperature, overstripping, and fewer radiating heliumlike ions. Thus in shot A the sodium ions were about equally divided between hydrogenlike and heliumlike, whereas in the hotter, low-mass shots B and C the ratio of hydrogenlike to heliumlike sodium was of the order of 2.

The phenomenon of a decrease in K-shell yield, with a corresponding decrease in density and increase in temperature as the mass load decreases, has also been previously observed in aluminum imploding wire plasmas.[16] At present, the capillary discharge technique permits only crude control over the injected NaF mass load. As this

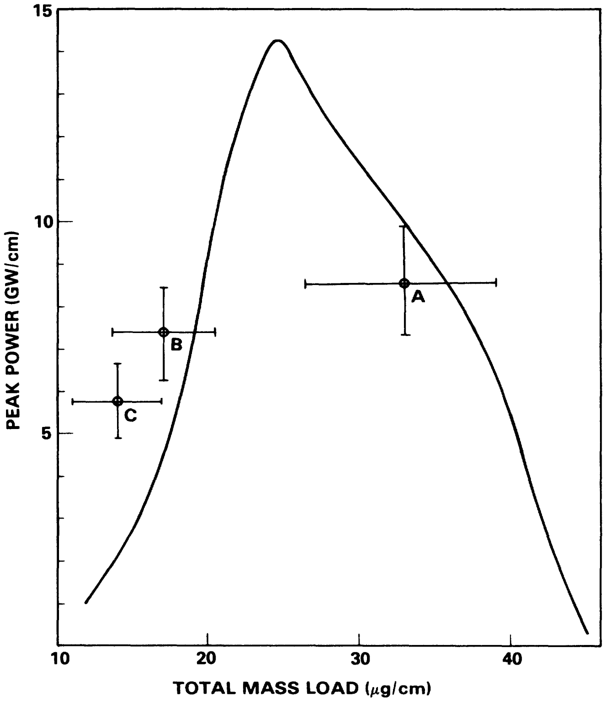

FIG. 1. Peak power radiated in the heliumlike sodium principal resonance line at 11 Å as a function of Z-pinch mass load for a Gamble-II peak load current of 1.2 MA. Calculations are described by the solid curve; the points A, B, and C are the experimental results for the shots of the same designation discussed in the text.

improves, we expect to be able to obtain higher power and yield by consistently optimizing the mass loading (Fig. 1).

Two other methods are available to further increase the 6% plasma-to-pump line conversion efficiency. First would be the implosion of a pure sodium plasma. This would eliminate the waste of energy in the stripping and excitation of fluorine ions which are equal in number density to those of sodium, and therefore probably increase the yield by nearly a factor of 2. Also, use of a plasma erosion opening switch[17] has already increased radiative yields in neon[18] by shortening the current rise time and improving pinch uniformity. Therefore, the 6% conversion efficiency is realistically subject to substantial improvement.

We now consider the overall efficiency of this version of the Na-Ne system as an x-ray laser. This efficiency is also dependent upon the characteristics of the pumped plasma, its gain, and the efficiency of transfer of pump radiation to the pumped neon plasma. The energy required to create the neon plasma is nearly negligible compared to that needed for the pumping sodium plasma, since the optimal neon plasma temperature[4] is only 50–60 eV. In estimating the fraction of the sodium pump line energy that can be coupled to pump the $1s4p\ ^1P_1$ Ne IX level, the major controlling factor is the differing widths of the pumping and pumped lines. The hotter, denser sodium plasma will emit a $1s^2$–$1s2p\ ^1P_1$ pump line whose width is determined principally by opacity broadening and motional and thermal Doppler broadening. We have measured this width as 3.5×10^{-2} Å. This measurement includes instrumental and source size broadening as well as the effects of time integration, and therefore represents an upper limit to the actual instantaneous linewidth. The width of the Ne IX line has not been measured experimentally under the proper conditions but is likely to be considerably narrower. The difference in Doppler broadening alone for the cooler neon plasma will result in an absorbing line about twice as narrow as the pump line. Many of the sodium photons will therefore be emitted on the transparent wings of the narrower neon line and not be absorbed. Furthermore, to achieve significant gain, the neon plasma cannot be highly opaque, effectively eliminating opacity as a broadening mechanism for the absorbing neon line. At most, opacity broadening is calculated to increase the ratio of sodium-to-neon linewidths by another factor of 5, resulting in an estimated pumping linewidth ten times greater than that of the pumped line. Therefore, about 10% of the pump energy can be coupled into an optimally prepared annular neon plasma which subtends an angle of 4π steradians relative to the pump radiation. If the pumped plasma subtends less than 4π, the efficiency estimates given below must be reduced proportionately.

If no gain is present in the pumped neon plasma, 5% of the coupled pump energy is calculated to appear as isotropically emitted fluorescence in the 4-3, 4-2, and 3-2 lines which would lase if gain were present. Under conditions of gain saturation, requiring about 20 gain lengths, every coupled pump photon would be converted to stimulated emission in these lines. This conversion fraction (quantum efficiency) would represent 20% of the coupled energy since the energy difference of the $n=4$ and $n=2$ levels is 20% of that between $n=4$ and the ground state. Most of the other 80% of the coupled energy would appear as spontaneous emission in the Ne IX $1s^2$–$1s2p\ ^1P_1$ principal resonance line. Therefore, a high-gain configuration would achieve an overall efficiency of conversion of plasma energy to lasing radiation of $0.06\times0.10\times0.20\approx10^{-3}$.

What is required in pump energy to achieve gain saturation? At a distance of 1 cm from the axis, we calculate a gain coefficient in the $4f\ ^1F$–$3d\ ^1D$ line of 0.5 cm^{-1} using the measured pump line power for shot *A*. This calculation assumes a 10% coupling factor, as estimated above, and a neon plasma of electron density $N_e=2.5\times10^{19}$ cm^{-3}, and temperature 50 eV. If the neon density is reduced by a factor of 3, the gain is reduced to 0.25 cm^{-1}. The gain is linearly proportional to the pump flux. For a 4-cm gain length, saturation therefore requires an order of magnitude more pump power, i.e., yields of $\geqq 6$ kJ. Use of a pure sodium plasma rather than NaF should provide nearly a factor of 2 of this required increase. Sharpening the driving current pulse rise time demonstrably increases[18] the yield at a given peak current by another factor of 2.5. Experimental data obtained from neon gas puff plasma also presented in Ref. 18 show that the yield is proportional to the fourth power of the peak driving current. An increase in peak current from 1.2 to 1.7 MA would therefore be expected to provide another factor of 4 in a pump line energy.

Thus, relatively straightforward, experimentally tested improvements in the present pump plasma and driver should produce pumping fluxes capable of generating gain saturation in an optimally prepared neon plasma. Under such conditions, an overall conversion efficiency of plasma energy to lasing radiation of 10^{-3} appears to be attainable if a neon lasant plasma of proper conditions can be created to surround the sodium pump plasma at a distance of ~1 cm.

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