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MASTER

STUDY OF ATOMIC PHYSICS AND POPULATION INVERSIONS WITH PLASMA FOCUS*

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ABSTRACT

The plasma focus can be used to generate high temperature and high density plasmas. Neon-like plasmas have previously been studied in Z-pinches and laser produced plasmas as sources for XUV and X-ray lasers.

The plasma focus provides a simple and inexpensive source for studying atomic physics of highly ionized atoms. A detailed understanding of atomic physics at high temperatures, densities, and megagauss magnetic fields is necessary for possible X-ray laser designs. Methods that are generally used for obtaining population inversions include collisional ionization of the inner shells of multi-electron atoms and ions, photoexcitation, and electron collisional excitation of ions, collisional combination of ions, and atom-ion resonant charge exchange.

We will discuss some possible experiments to help understand the atomic physics under the above condition. Some ideas and calculations will be given to show the feasibility of doing atomic physics relating to X-ray lasers with a plasma focus.

Plasma focus experiments have been used to create high density and temperature (1 to 3-Kev) plasma pinches. Observation of the pinch shows a significant number of neutrons and an intense fluence of UV and x-ray radiation. We propose to use this device to study the atomic physics of highly ionized atoms which is necessary for the development and understanding of x-ray laser designs. Other laboratories (Sandia, Livermore, PI, and others)[1,2,3,4] have used gas puff z-pinches and high power lasers for the same purpose. The plasma focus machine is presently working at Los Alamos and due to its simplicity and versatility could serve as a convenient tool for these studies. The machine parameters (density and temperature) compare favorably with the other systems but does not have the complexity and maintenance requirements of them. Therefore, a multitude of shots (~20) can be done per day, which makes it appealing for parametric studies.

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The Plasma Focus Machine at Los Alamos uses a 72-K joule capacitor bank and has produced temperatures as high as 6 Kev and densities of several 10^{20} per cm^3 with dimensions of the pinched plasma column of roughly 1 mm by 1 cm. The time period of the pinch is less than a nanosecond. Calculations by Hagelstein[5] and others[6,7,8] have shown that lasing could occur in neon-like krypton with T_e of about 1 kev and density of about 2-3 $\times 10^{20}$ cm^3. Our aim is not to develop a laser but to do a parametric atomic physics study that can help devise x-ray laser schemes that can later be driven by flux compression generators.

There are several methods for producing population inversions for XUV and x-ray lasers these include collisional ionization and excitation of high-z atoms and ions by electrons; photo ionization and excitation; and charge exchange in atom-ion collisions.

Many x-ray laser studies have concentrated on the neon-like recombination laser schemes. Whether the excitation is done by electron collisions or photon excitation, the decay schemes are similar. In both cases we start with the ground state of $2s^2 2p^6$, and the population inversion is due to the difference in radiative decay rates of the $(1s)^2(2s)^2(2p)^5(3s)$ and $(1s)^2(2s)^2(2p)^5(3p)$. In the case of krypton, the spontaneous decay rate for the $3p$ to $3s$ is about 3.5×10^{10} per second and for the $3s$ to the ground state of $2p^6$ it is about 5.1×10^{12} per second. Figure 1 shows some of the decay scheme generally used for photon pumped and electron pumped neon-like recombination lasers. This figure only shows the general features and does not include the details of the transitions. In the electron pumped systems several channels of pumping can occur. As shown in Fig. 1a an electron from the ground state can collisionally be excited to the $3p$ level and since this transition to the ground state is dipole forbidden it decays to the $3s$ state which is the lasing transition. One can collisionally excite to the $3d$ (Fig. 1b) level and have two separate lasing transitions. The system can decay via cascades to give the $3p - 3s$ laser, or it can decay to the $3p$ state which quickly decays to the ground state and leaves a population inversion between the $3d$ and $3p$ levels. In the photon pumped systems (Fig. 1c) the aim is to photoionize from the ground state to $1s2s^2 2p^6$ and then this cascades down to the $3p - 3s$ laser as shown in the figure. Numerous lasing schemes can be devised not only in neon-like systems but in many multiply ionized atomic systems.

A detailed study of highly-ionized systems are therefore necessary. There is a need to know some of the basic parameters that include the transition rates, ionization balance and a general overview of the spectrum. The electron and ion temperatures and density play a crucial role in the gain of the laser and we need to study these at different implosion conditions. For example if the electron density is too low, excitation from the ground state to the upper states will be low and if it is too high collisional depopulation of the upper states will take place and will destroy the population inversion. Trapping of the $3s - 3p$ resonance transition that depopulates the lower lasing state posses additional constraints on the possible highest density for the system. Optimal performance is also determined by physical properties and the design needs to consider excitation uniformity and simultaneity. The Livermore designs use a high power laser beam to produce a line focus on a target that produces the pump electrons. In this fashion a high degree of uniformity can be maintained. The Sandia design uses a gas puff z-pinch to stagnate onto a target that generates photons that will in turn photoexcite the lasing material. Both techniques work well in producing uniform and simultaneous excitation of the lasant.

Plasma focus has been generally overlooked for doing these types of parametric studies. However due to its rather simple design it lends itself well to modifications and therefore to a variety of plasma physics experiments that can be done on the same system. Whether we want to observe the effects with collisional excitation, photoionization or studies with ion beams, the necessary modifications are minor. The experimental plan will be to study the x-ray spectrum as a function of electron and ion density and temperature. Figure 2 shows a schematic of the plasma focus and it shows the evolution of the plasma to the pinch region. The plasma is initiated at the left hand side of the figure and due to the $J \times B$ forces it moves to the right and finally pinches at the end of the electrode. At the focus or pinch area, which is labeled by five, it is possible to place a variety of targets. The targets may consist of cylindrical shells designed such that when the pinch stagnates on the cylinder, photons are generated that in turn photoionize and excite the lasing material in the interior of a target. Or, the implosion (pinch) can be of the plasma of the fill gas and in this case high density and temperature plasma is produced at the focus as shown in Fig. 2. We have control of the parameters in the pinch area by changing the fill gas, voltage on the capacitor bank or modifying the geometry of the cylindrical target. The initial experiments will concentrate on a study of atomic parameters with krypton but other model gases will also be used. X-ray spectroscopic observations will be made radially and along the axis pinch of the pinch. Some experiments[10] have been done by others that indicate that ion beams are produced along the axis of the plasma focus. These beams can be used for generating population inversion via atom-ion collisions or charge exchange due to the promotion of electrons along molecular orbitals during a collision. The ion beams, if they are essentially monoenergetic, can also be used to determine transition probabilities as done with beam-foil techniques.[11,12,13]

Numerous state-of-the-art diagnostic methods are available to us. These include spectrometers and pinhole cameras that use microchannel plate intensified and gated detectors. The x-ray spectrometers are designed to either look at several regions of the spectra or can be used to look at the same region of spectra at different time intervals. The spectrometers are either grazing incidence or crystal type and typically have resolutions of the order of a fraction of a volt. High speed (5-ns) optical multichannel analyzers will also be available and measurements of electric and magnetic fields in the plasma region and the fields will be determined by spectral line splittings.

In conclusion, the aim is to develop techniques on plasma focus for atomic physics studies. We will observe effects of density and temperature and other parameters aimed at later development of soft x-ray lasers. We believe plasma focus can be a versatile tool and that it can provide insight to the problems associated with x-ray laser design.

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FIGURE CAPTIONS

Fig. 1. Possible transitions of electron collisional pumping are shown in a) and b). Lasing transitions are noted. Photon-excited transitions are shown in c). The atom delays via cascades to the lasing transitions. Note: this is only a partial delay scheme, many transitions are left out.

Fig. 2. Evolution of the plasma focus sheath. The plasma is initiated at the insulator and the $J \times B$ forces move it to the end of the barrel. The numbers indicate stages of the sheath motion. The number (5) indicates he implosion of where focus occurs.

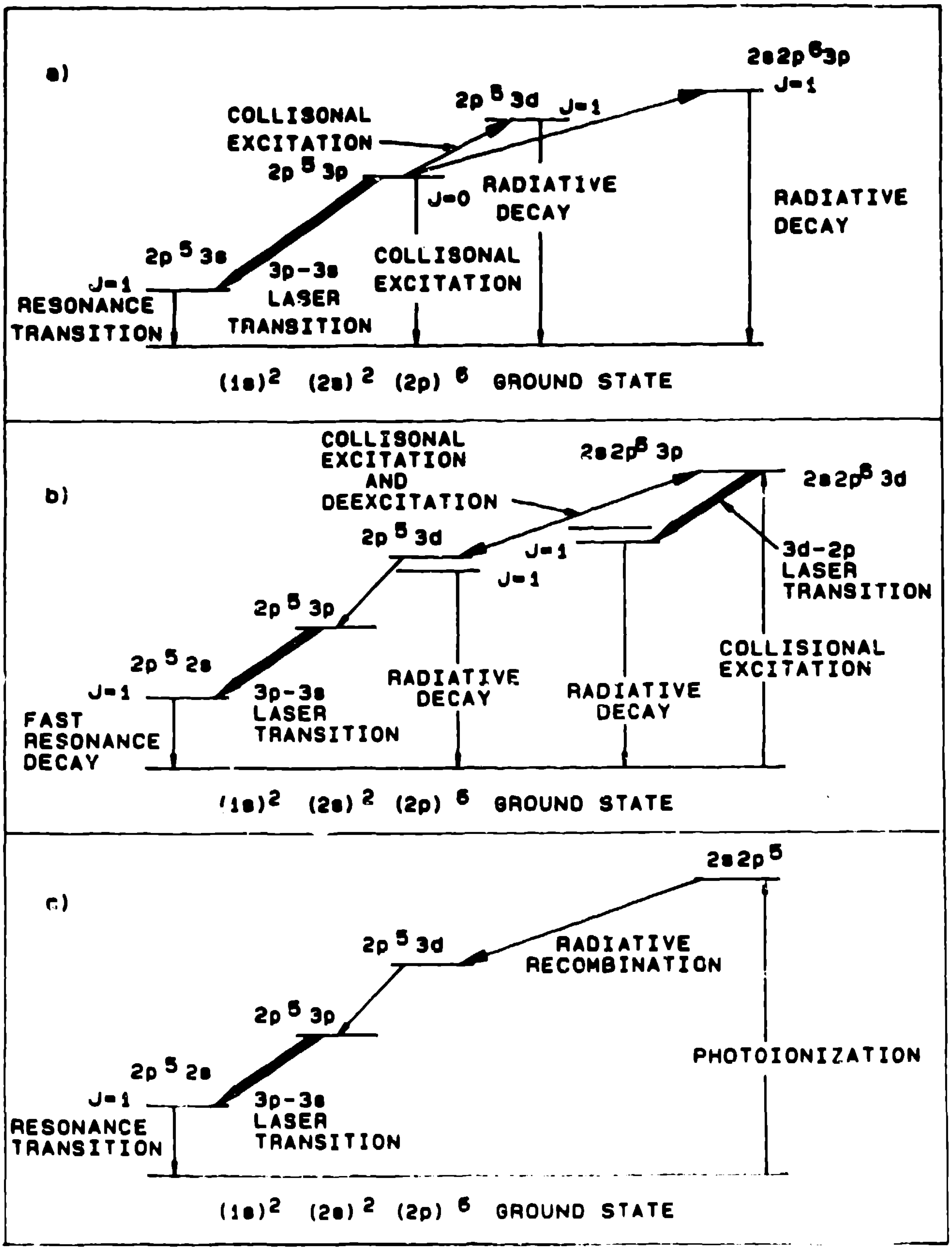
a)
2s2p^6 3p
J=1
2p^5 3d
J=1
COLLISONAL EXCITATION
2p^5 3p
J=0
RADIATIVE DECAY
RADIATIVE DECAY
2p^5 3s
J=1
3p-3s LASER TRANSITION
COLLISONAL EXCITATION
RESONANCE TRANSITION
(1s)^2 (2s)^2 (2p)^6 GROUND STATE
b)
COLLISONAL EXCITATION AND DEEXCITATION
2s2p^6 3p
2s2p^6 3d
2p^5 3d
J=1
J=1
3d-2p LASER TRANSITION
2p^5 3p
2p^5 2s
J=1
COLLISIONAL EXCITATION
RADIATIVE DECAY
RADIATIVE DECAY
3p-3s LASER TRANSITION
FAST RESONANCE DECAY
(1s)^2 (2s)^2 (2p)^6 GROUND STATE
c)
2s2p^5
2p^5 3d
RADIATIVE RECOMBINATION
2p^5 3p
PHOTOIONIZATION
2p^5 2s
J=1
3p-3s LASER TRANSITION
RESONANCE TRANSITION
(1s)^2 (2s)^2 (2p)^6 GROUND STATE

Figure 1.

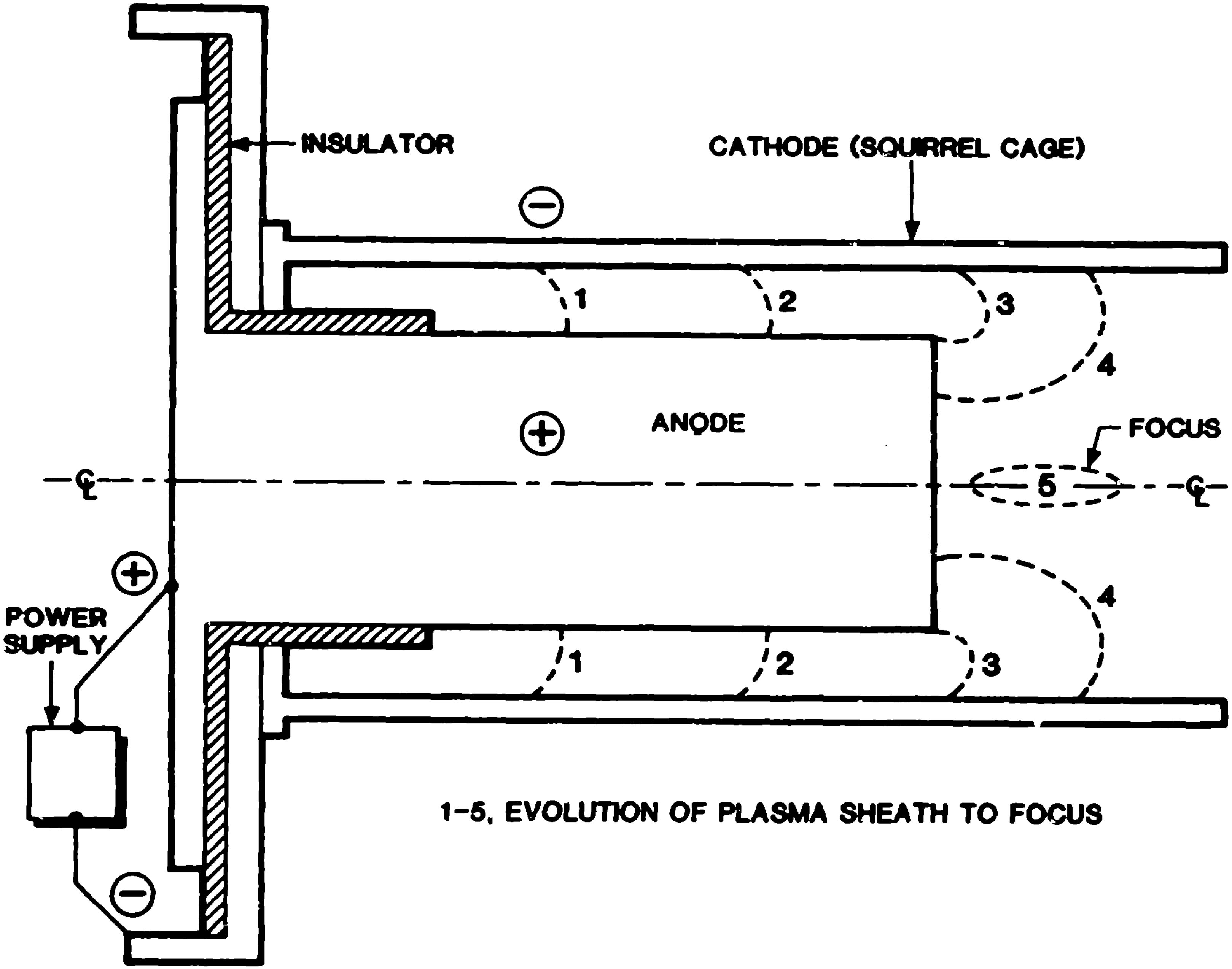
INSULATOR
CATHODE (SQUIRREL CAGE)
⊖
1
2
3
4
ANODE
⊕
FOCUS
℄
5
℄
⊕
POWER SUPPLY
4
1
2
3
⊖
1-5, EVOLUTION OF PLASMA SHEATH TO FOCUS

Figure 2.