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THE DYNAMIC PINCH AS A HIGH-INTENSITY LIGHT SOURCE
FOR OPTICAL MASER PUMPING

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THE DYNAMIC PINCH AS A HIGH-INTENSITY LIGHT SOURCE
FOR OPTICAL MASER PUMPING^{*}

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March 31, 1961

ABSTRACT

The optical radiation that occurs in a dynamic plasma pinch experiment depends in part on the amount and type of impurity atoms present in the system. By proper choice of these impurities, it should be possible to tailor the optical radiation from the pinch in intensity, spectrum, and duration such that the kinetic energy of motion (100 to 1000 joules) appears as radiation energy in less than 10^{-6} sec. This should provide a good method of optical pumping for pulse optical maser operation. This paper discusses the optical radiation from the dynamic pinch and describes an experiment that is being set up to use this radiation as the pump source for an optical maser.

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I. INTRODUCTION

One of the important experimental problems in the field of plasma physics is that of diagnostics, i. e., the measurement of the density and temperature as a function of position throughout the plasma. The present popular method of measuring the phase shift and attenuation of microwave signals propagating through the plasma falls somewhat short of this goal in that it usually gives information about the average temperature and density, and does not give a detailed picture of the spatial variation of these quantities.

To obtain somewhat more detailed information concerning the density and temperature variations in a plasma, one might consider an optical diagnostics scheme. Such a scheme would involve passing a beam of light obtained from an atomic transition source through the plasma and then examining the intensity and line width of the scattered light. The former is related to density and the latter, as a result of Doppler broadening, is related to temperature. The spatial resolution of this scheme depends on the intensity and line width of the light source and the optical system employed to detect the scattered light. Unfortunately, the ordinary atomic transition light sources presently available make such a scheme of optical diagnostics unfeasible.

However, the advent of the optical maser has revived interest in the possibility of optical methods of plasma diagnostics, particularly in the realm

of high temperature plasmas such as encountered in the fusion research effort of Project Sherwood. This revived interest stems from the fact that if a monochromatic, coherent, high-intensity light source such as those that have been recently reported in the literature were available, then optical diagnostics methods should be feasible.

To carry out a program of evaluation of optical maser¹ sources for optical plasma diagnostics, it is of course necessary to have such sources available. The first obvious requirement is a high-intensity light source for the purpose of pumping.

Since intense optical radiation is known to emanate from high temperature plasmas as a result of the presence of various impurities in the neutral gas background, it was decided to investigate one of the well-known plasma experiments, the dynamic pinch,² to see if it would be feasible as a pump.

Figure 1 is a schematic drawing of the experimental scheme whereby optical impurity radiation from a dynamic pinch is being tested as the pumping source for an optical maser.

A few-thousand-joule charged capacitor bank is connected between the conducting end plates of the deuterium-filled (3×10^{16} particles/cm³) pinch tube, and simultaneously the ring of pinch triggers are fired. This causes a tube-shaped axial current to flow in the plasma between the two end plates. The current causes a circumferential magnetic field outside the plasma. The magnetic field inside the discharge is zero and consequently there is a net inward pressure force on the plasma. This inward pressure causes the plasma column to collapse toward the axis, driving a shock wave ahead of it. If the pinched discharge column can be kept in its contracted state long enough for randomization to take place, the inward-directed kinetic energy of motion, gained from the capacitor bank, will be converted into random thermal

energy. In addition to the bremsstrahlung radiation from this plasma, there will be the line radiation from impurities.

It is the purpose of this paper to describe some of the essential features of this impurity radiation, with the particular aim of showing how it might be useful as a high-intensity light source for optical maser pumping.

II. DISCUSSION

Figure 1 is a schematic drawing of the experimental apparatus that will be used to create a dynamic or shock pinch. The pinch tube is 10 cm in diameter and 10 cm long. Not shown in this diagram is the capacitor bank that has 2400 joules stored energy at 20 kv. This bank is connected, with a switch, across the two end plates of the pinch tube. To initiate the discharge, a ring of pinch triggers in one end plate are given a pulse. An initial density of gas (deuterium) of about 3×10^{16} particles/cm³ is provided by a "puff" valve, together with about 1% concentration of some impurity of higher atomic number.

The intensity and duration of the optical radiation of this dynamic pinch can be determined approximately by the following considerations.

The thickness of the plasma shell when the shock reaches the axis will be about 1/6 the initial radius. For the pinch tube described here, the minimum radius will thus be about 1 cm and the resulting maximum particle density about 10^{18} /cm³.

During the time the pinch is at its minimum radius, the inward-directed velocity is converted to random motion in about the transit time of sound across the shock thickness ($v = 10^7$ cm/sec, $r = 1$ cm, τ conversion = 10^{-7} sec). The thermalization time is given by $(M/m)(1/n\sigma v)$, where n is the particle density, σ is the Coulomb cross section, and v is the particle

velocity. If about one-half bank energy were given to the random motion, the plasma would have a mean energy of about 100 ev. Computing the thermalization time for such a plasma gives about 0.6×10^{-7} sec.

If the plasma behaved as a blackbody at this temperature of 100 ev, it would radiate away its total energy content in about 10^{-12} sec. However, the dimensions of the plasma considered here are much less than a mean free path for an average photon of Planck radiation at 100 ev, so the plasma does not radiate its energy in a blackbody manner, but rather it gives up its energy by bremsstrahlung and by impurity radiation.

If there were no impurities in the plasma, then the time for radiation of the energy content of the plasma by bremsstrahlung would be of the order of a millisecond. This time is very much longer than the pinch process itself, and for the situation described here can be neglected as a loss mechanism.

The principal loss mechanism will be the excitation and reradiation of highly ionized impurity atoms present in the plasma.³ The most important impurity atom state for optical transitions is the lithiumlike or three-electron configuration. The radiation rate is given approximately by saying the plasma radiates like a blackbody over a frequency range equal to the line width of the atomic transitions in question. Using the Planck radiation law in the small $h\nu/kT$ limit and adding sufficient impurities to give 10% optical transmission, or a relative line width of $\Delta\nu/\nu = 0.1$, the radiation intensity is about 10^8 watts/cm². At this rate, the plasma will give up its total energy in a little less than a microsecond.

This latter radiation rate was calculated by assuming the plasma to be made up of 100-ev ions and electrons together with some small percent of impurity atoms that were stripped down to say a three-electron configuration.

Tacitly contained in this assumption is the requirement that the stripping time of these impurity atoms in the plasma be short compared with the impurity radiation time constant. The stripping time is approximated by computing the reaction rate ($n\sigma v$) for 3 KT Coulomb collisions; for the plasma considered here it will be less than 0.1 μ sec.

The discussion given here describes approximately the situation that occurs when the plasma in a dynamic pinch experiment is "seeded" with some high-Z impurity. During the time the plasma is collapsed, it converts its inward-directed energy to thermal motion, strips the impurity atoms to a three-electron "lithium" configuration, and loses its energy by excitation-reradiation of the stripped impurity atoms.

The radiation intensity given here can be compared with the xenon flash lamp by noting that the xenon lamp gives up 2000 joules in about a millisecond, while the dynamic pinch gives up its energy of 2000 joules in less than a microsecond. This represents about three orders of magnitude greater intensity for the dynamic pinch process.

III. CONCLUSIONS

The dynamic plasma pinch properly "seeded" with an impurity is proposed as a high-intensity light source for optical maser pumping. A semi-quantitative analysis predicts an improvement over commercially available xenon flash lamps of three orders of magnitude in intensity of light and a reduction of pulse duration of about three orders of magnitude.

An experimental and theoretical study of the dynamic pinch as an optical maser pumping source is being carried out. The first efforts will be to repeat the ruby optical maser experiments^{4,5} to provide some basis for determining the comparative effectiveness of the dynamic pinch and the xenon lamp.

Consideration is also being given to the possibility of optical maser operation using some of the highly ionized impurity atoms in the plasma. These stripped atoms may have a suitably located metastable state that would not be available in low temperature plasmas. The experiment to study these possible situations would be the same as Fig. 1 with the modification that the inner quartz tube would be removed and the end plates of the pinch would be mirrored.

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Fig. 1. Dynamic pinch for pumping an optical maser.