A Theta-Pinch Laser

C. J. B. Pagan, J. A. Pomílio, I. Doi, and G. N. Wakamatu
School of Electric and Computing Engineering
State University of Campinas - UNICAMP
Campinas 13081 970 Brazil

Recebido em 4 de maio 1998

A theta-pinch discharge was used to excite the active media of an argon laser. The capacitor bank can deliver 100 joule per pulse, but only a small fraction is transferred to the plasma that we calculated as around 10%. Ar II-IV spectra was observed at our experiment. The device produced a laser pulse oscillating at 476.5 nm, corresponding to Ar II blue laser emission.

1. Introduction

Theta-pinch was widely used in the 60's as a device for hydrogen fusion experiments. At that time many laboratories throughout the world started to use these devices to produce atomic spectral information, for studies from the visible to the vacuum ultraviolet region of spectra [1-5].

A special feature of theta-pinches is the fact that, for a given initial pressure and capacitor voltage, the radiation emitted corresponds to a well-defined range of ionized stages [6]. For example, for a given experimental setup, for 10 μbar and 10 kV a rich Ar II- III spectrum can be found, but no Ar I or Ar IV lines are present. On the other hand, for 14 kV and same pressure, no Ar I-II are present, but Ar III-IV are. Theta pinches are systems out of termal equilibrium [7,8]. This is a favorable condition, *a priori* 2.18, to observe population inversion.

In the present work we achieved a laser oscillation for an argon active media, excited by a theta-pinch discharge. We could found the best pressure and voltage parameters for our experiment, and measure the laser line time profile. Stability problems and transversal modes observed are discussed. For the best of our knowledge, no other citations of such kind of laser are present in the literature.

2. Experimental Setup

We built a small theta-pinch for our experiments. We used a 1.9 μF low inductance pulse capacitor (smaller than 20 nH), 30 kV maximum voltage. Total measured inductance is 112 nH. The power supply can deliver 30 mA continuous current at 12 kV, but a resonant power source able to charge the capacitor up to 50 times per second (5 kW/12 kV) was built specially for this end [9]. Figure 1 shows a schematic for the theta-pinch electrical parts.

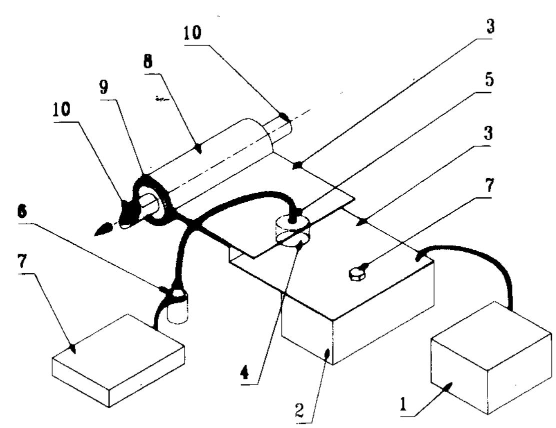

Figure 1. The Theta-Pinch Laser, electrical parts: (1) Power Supply, (2) Capacitor, (3) Transmission Line, (4) Spark-Gap switch, (5) Trigger, (6) Pulse Coil, (7) Pulse generator, (8) Plasma coil, (9) Insulation, (10) Brewster Windows.

The theta-pinch coil is 19-cm long, 5-cm diameter, made in aluminum, the same material of the transmission line. Discharge tube was made in quartz to improve the plasma purity. A set with a turbomolecular pump and a diaphragm mechanical pump (as the first pumping stage) was used to provide a good (less than 10^{-7}

mbar) vacuum in the discharge chamber. A 25 Watts radio frequency source provide electromagnetic field for plasma pre-ionization.

Electric current in the coil was recorded using a Rogowsky coil [10] connected to a HP-54501A/100 MHz oscilloscope through a low pass filter. Electric period of damped oscillation is 2.88 μs and the maximum current at 10 kV discharge voltage is around 41 kA. Optical spectroscopy in the 350-700 nm wavelength range was done using a SPEX (ISA) 50 cm focal length monochromator, f/4 aperture, with a Hamamatsu R955 photomultiplier tube (PMT). The signal from the PMT amplifier was recorded in the HP oscilloscope.

3. Energy Transfer

Initially, we considered the usual expression to the coil current in a second order circuit [11]:

$$i(t) = I_0 e^{-\alpha t} \mathrm{sen}(\omega t)$$

From our measurements we found the damping coefficient, α, as 0.1523 $\mu\mathrm{s}^{-1}$ for the system without plasma, and $\alpha = -0.1805$ $\mu\mathrm{s}^{-1}$ with plasma. This change in a is related to the energy transferred to the plasma, and we calculated it. In a more precise approach, we supposed the theta-pinch electrical equivalent circuit in the presence of plasma as a RLC circuit magnetically coupled to a plasma (RL) circuit. In that case the third order equivalent system circuit equations:

$$L\frac{d^2Q}{dt^2} + R\frac{dQ}{dt} + \frac{1}{C}Q - M\frac{di_p}{dt} = 0$$

$$L_p\frac{di_p}{dt} + R_p i_p - M\frac{d^2Q}{dt^2} = 0$$

where Q is the capacitor charge, R is the circuit resistance, L is the total circuit inductance, and i_p is the plasma current. This approach takes in to account that all circuit parameters are constant that is no long true. Plasma inductance (L_p), mutual inductance (M) and plasma resistance (R_p) varies as charge density varies. Our model is simple and similar to other published before, but good enough to rougly estimate the total plasma usefull energy. Solving for plasma current, and considering the total enery transferred to plasma as the integral of Ri_p^2, we obtained an approximated formula to the fraction of total energy transferred to the plasma, that is:

$$E_p = R_p M^2 I_0^2 \left[\frac{\alpha^2+\omega^2}{(\omega L_p)^2 + (\alpha L_p + R_p)^2}\frac{1}{4}\left[\frac{\mathrm{sen}(\phi_p)}{\sqrt{\alpha^2+\omega^2}} - \frac{1}{\alpha}\right]\right]$$

where

$I_0 = V(0)\sqrt{C/L}$ is the current amplitude

$V(0)$ is the capacitor initial voltage,

R_p is the plasma resistance,

L_p is the plasma inductance,

ω is the angular oscillation frequency, $\omega = 2.182$ $\mu\mathrm{s}^{-1}$,

For a capacitor initial tension $V(0) = 10$ kV, we have:

$R_p = 33.43$ mΩ

$L_p = 5.67$ nH

α = -0.1805 $\mu\mathrm{s}^{-1}$

$\phi_p = \mathrm{tg}^{-1}(\alpha/\omega) = 0.0825$ rad.,

that means $E_p = 9.46$ *Joule* or around 10% of total capacitor initial energy is transferred to the plasma.

4. Results and Analysis

Experiments were performed at 5, 7.5, and 10 kV, for pressures between 0.8 and 10 μbar. Figure 2 shows line time profile for Ar II, III and IV for 0.8, 1.6, 5.0, and 10.0 μbar at 10 kV. We could observe that in all experiments the same behavior, that is, the first line to appear and rising is Ar II, afterwards Ar III, and then Ar IV. No Ar I line could be observed at 10 kV at any experienced pressure.

Line intensities in the graphics are in arbitrary units. In order to compare different ionization degrees, one should multiply Ar II intensity by a factor of 15, Ar III by a factor of 7, and Ar IV by a factor of 2 to find relative line intensities. In order to obtain relative emitters densities, one should take in to account that densities N are proportional to line intensity I by the relationship:

$$I_{12} = \gamma A_{12} N_1 h\nu_{12}$$

where:

the subscripts means initial (1) and final (2) states,

A_{12}, the spontaneous transition Einstein coeficient,

$h\nu_{12}$ foton energy, and

γ is a optical system constant.

In our case, A_{12} is for Ar II, for Ar III, and for the selected Ar IV transition. Taking these values in to account, we can conclude that there are much more Ar^{+} in the plasma than Ar^{++} or Ar^{+++}, that means aroud 30 times more.

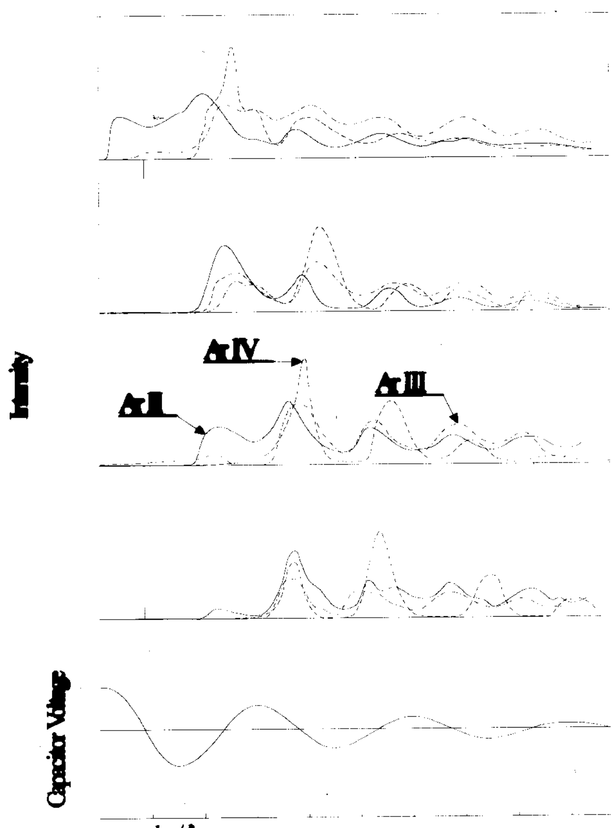

Figure 2. Spectral emission of the theta-pinch plasma for 1,6 μbar and 10 kV. The PMT signal for Ar II @ 476.5 nm, Ar III @ 379.5 nm, and Ar IV @ 292,6 nm is shown as a typical profile for our experiments.

The atomic Ar absence can be understood since electrical field is not efficient enough to carry this neutral atom to the hot region of the plasma. The presence of low ionized levels of argon at the beginning of the discharges works as a pre-ionization. Its efficiency improves the plasma ionization at later stages.

Figure 3 shows the laser line at 476.5 nm. This is an Ar II line, corresponding to 4p 2P3/2 -4s 2P1/2 transition, known as a high gain line for pulsed laser emission [12]. Laser emission was observed as a 250 ns single pulse, 3.6 μs from the beginning of the discharge. When no resonant cavity is present both, line intensity is a factor of 20 less intense, and pulse profile increases up to around 400 ns. Laser emission occurs around 1-2 μbar argon pressure. Best results are at 10 kV and 1,6 μbar.

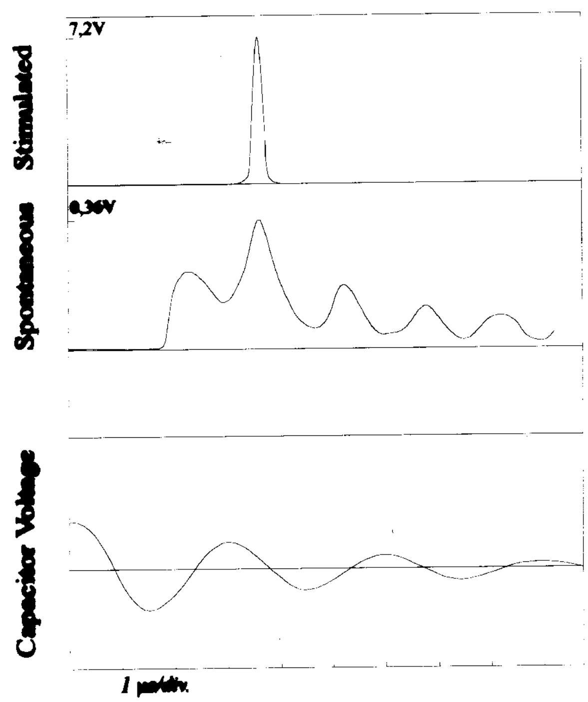

Figure 3. Spontaneous and stimulated (laser) emission. Laser occurs around 1-2μbar. The absence of resonant cavity decreases emission by a factor of 20. Voltages indicated are the maximum value of the Rogowsky coil signal for each experiment.

The laser emission oscillated in high transversal electromagnetic modes (TEM) in the cavity. We consider that the reason for this phenomenon is the dynamical nature of the theta-pinch discharge. The active media changes its place during the laser pulse, changing the retracing path where we have gain and producing high TEM spatial profiles as consequence.

5. Conclusion

We present preliminary results of the theta-pinch laser, built at our laboratory in the UNICAMP. This work will be continued until we can understand the laser dynamics and measure its gain.

We are now changing the tube design to improve the matching of the RF antenna with the plasma. Later results of other laser lines and gases will be analyzed.

Acknowledgements

This work has been financially supported by the "Programa de Apoio ao Desenvolvimento Científico e Tecnológico PADCT/Conselho Nacional de Desenvolvimento Científico e Tecnológico CNPq".

At present the device presents an unstable operation. Difficulties have been found to reproduce two consecutive experiments, and for this moment we do not know if it is possible at all.

References

1. A. S. Kaufman, T. P. Hughes, and R. V. Williams, Proc.Phys. Soc. London **76**, 17 (1960).
2. R. Hallin and T. P. Hughes, Proc.Phys. Soc. London **78**, 201 (1960).
3. K. Bockasten, R. Hallin and T. P. Hughes, Proc.Phys. Soc. London **81**, 522 (1963).
4. G. A. Sawyer, A. J. Bearden, I. Henins, F. C. Jahoda, and F. L. Ribe, Phys. Rev. **131**, 1891 (1963).
5. K. Bockasten, R. Hallin, Reinhold, and N. R. Nilsson, Ark. Fys. **32**, 437 (1966).
6. C. J. B. Pagan, "Estudo Espectroscópico de Gases Nobres Medianamente Ionizados", PHD Tesis, IFGW-UNICAMP (1991).
7. H. R. Griem, *Plasma Spectroscopy*, McGraw-Hill, NY (1964).
8. M. Niimura, *Experimental Plasma Diagnostic* in Física de Plasma, Universidade Federal Fluminense, RJ (1979).
9. J. A. Pomílio C. J. B. Pagan, Resonant High-Voltage Source Working at Resonance for Pulsed Laser, 27th Power Electronic Specialist Conference, Italy, june 24-27 (1996).
10. I.H. Hutchinson, *Lectures in Plasma Diagnostics*, IV Latin American Workshop on Plasma Physics - Courses -, 143-206, Buenos Aires, Ar. (1990).
11. Y. Burian Jr., *Circuitos Elétricos*, Y. Burian Jr. Ed., Campinas, Brazil (1991).
12. W. R. Bennett, Jr., J. W. Knutson, Jr., G. N. Mercer, and J. L. Detch, "Super-Radiance Excitation Mechanisms, and Quasi-CW Oscillation in the Visible Ar^+ Laser", Appl. Phys. Lett., **4**, 180 (1964).