## High Power Pulsed Laser

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# Optical Power Enhancement of High Repetition Rate Copper Vapor Laser MOPA Chains

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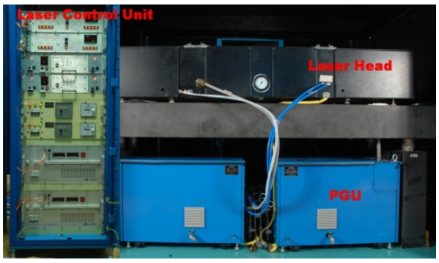

*Typical Copper Vapor Laser with High voltage pulse power supply*

ABSTRACT

Copper Vapor Laser (CVL) is a high power pulsed laser system with high repletion rate. The laser source is in the visible spectrum (510 & 578 nm) of electromagnetic radiation. One of the important application is laser based Fortification of stable isotopes for generation of radionuclide to be used in Medical Applications (Lu, Yb, Sm) for cancer therapy. CVL acts as a pump source for precisely tunable narrow band dye lasers. This paper describes methodology to increase the optical power of the individual CVL, thereby increasing the power output from the CVLs configured in Master Oscillator Power Amplifier (MOPA) configuration. The power enhancement is attained by increasing the energy storage capacitance in the DC resonant charging circuit at the primary of the pulse transformer. This paper depicts the optical power enhancement of individual system as well as output from CVL MOPA chain and its long duration optical power stability. The effect of this modifications on the charging time, charge transfer time, propagation delay and voltage amplification at the secondary of the pulse transformer is aptly described in this paper.

KEYWORDS: *Copper Vapor Laser, Storage capacitor, Pulse Transformer, MOPA, Magnetic Pulse Compression*

## Introduction

There has been ever increasing demand for radiopharmaceuticals like Lu-177 and Sm-153 for cancer therapy, bone pain palliation and synovectomy. Selective ionization of the desired isotope using laser beams of narrow linewidth, high repetition rate, and high intensity followed by collection of photo ions of desired isotopes using electro-magnetic fields is used for this process. Dye lasers are most apt selection for purification process as they meet the requirements of wavelength tunability, high average power (few tens of Watt)and high repetition rates (few tens of kHz). The tunable dye lasers are optically pumped by the fixed wavelength laser systems such as CVL and diode pumped solid state lasers (DPSSL). The CVL MOPA chains with high average power are used as the pumping source for the generation of the tunable dye lasers. The high average power pump source is necessary for generating high average power dye lasers. This high average power is generated by the CVL MOPA chain. Hence, dye laser energy per pulse increases with increase in the energy per pulse of the CVL pump source.

The CVL is pumped by the pulsed electric discharge of suitable rise time [1]. The electrical excitation of the CVL takes place at pulsed voltage of 10–15kV at 9 kHz pulse repetition frequency [2,3]. This pulsed laser source provides laser wavelengths at 510 nm (green) and 578 nm (yellow) in the visible region of the electromagnetic spectrum. Scalability of optical power is one of the important features of CVLs; which can be achieved by synchronized optical temporal pulses and spatially overlapped laser beam in each amplifier module. In MOPA configuration, the oscillator provides a good quality seed laser pulse which is further amplified using five consecutive CVL amplifier modules to extract maximum optical output power. The oscillator and the amplifiers are operated in 9 kHz pulse repetition frequency [4,5]. In order to further enhance the MOPA power efficiently, the power of the individual CVLs can be increased which is being described in this article.

## System Description

The electrical excitation system of the CVL consists of a variable DC Switched Mode Power Supply (SMPS), and Pulse Generator Unit (PGU). The PGU consists of pulse forming network, pulse transformer and three MPC stage for generation high voltage pulse with fast rise time. The PGU provides 10–15kV of peak pulsed voltage of 70–90ns rise time [6,7]. The high voltage ensures breakdown in between the high voltage electrodes of the laser head. The laser head with water cooled electrodes placed at the end of cylindrical alumina tube of inner diameter 38mm and the length 1800 mm, which is encapsulated with alumina wool to provide thermal insulation so that the operating temperature inside alumina tube is maintained at ~1500$^{o}$C. High purity neon gas is used as a buffer gas which provides electrical discharge and results in the collision between the electrons and the neon atoms to raises the temperature of the alumina tube. The solid copper pallets are evenly distributed along the length inside the alumina tube start and copper vapors are generated. The atomic transitions of copper provide the gain to fulfill lasing action under unstable resonator cavity configuration in the oscillator. The sharp rise time in the range of 70–90ns of the high voltage pulse ensures sufficient population inversion which is essential requirement for lasing action in the CVL [4,5]. The photograph of typical CVL system is shown in Fig.1.

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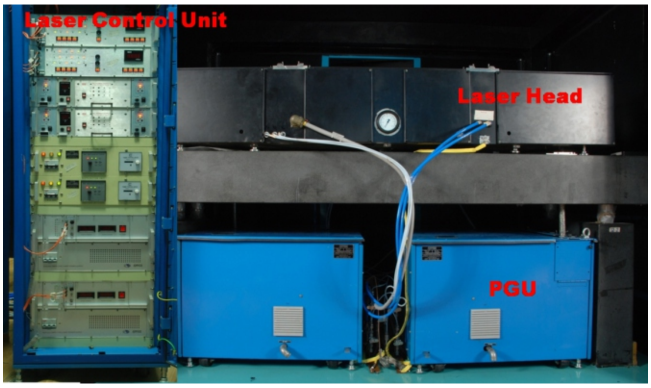


*Fig.1: Typical Copper Vapor Laser with High voltage pulse power supply.*

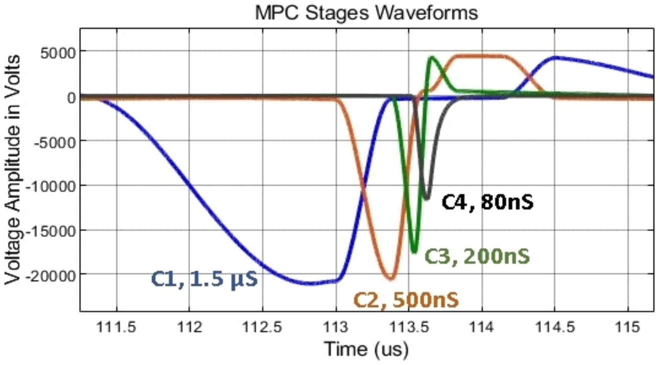


*Fig.3: The Typical high voltage waveforms across the capacitors inside the PGU.*

The PGU schematic is shown in Fig.2. The pulsed power source consists of High voltage SMPS (450 V and 25 A) is used to store the energy in the storage capacitor (Cs). The main energy storage capacitor Cs is charged approximately to double the SMPS voltage using resonant charging circuit. The resonant charging circuit includes the inductor of 150 μH and the main energy storage capacitor (Cs) of 1.98 μF. The IGBT switch SW-1 initiates the charging of the capacitor. Once the capacitor is completely charged in 54 μs (charging time = $\Pi\sqrt{LC}$), the main discharge IGBT switch SW-2 closes thereby transferring the energy to the secondary side of 1:32 pulse transformer [8,9].

The rise time of the high voltage pulse appearing at the secondary of the pulse transformer is given by $\pi\sqrt{LC}$, where L=leakage inductance of the pulse transformer (0.22 μH) and C is the series combination of the primary storage capacitor (1.98 μF) and secondary capacitor C-1 referred to the primary (2 nF x $32^2$ = 2.048 μF). Hence the rise time of the secondary voltage pulse is 1.48 μs. This high voltage pulse traverses through the three stage Magnetic Pulse compression (MPC) circuit. The high voltage pulse is compressed to 500 ns, 200 ns and 80 ns at the end of first, second and third stage respectively [6,7]. Thus the compression ratio is designed approximately to be to be in the range of 3, 2.5, 2.5. hence the rise time of the pulse is compressed to approximately 18.75 times the value at the secondary of pulse transformer. The typical waveforms obtained at different capacitors in the PGU are shown in Fig.3.

The voltage pulse of 10–15 kV and rise time around 80 ns is applied to the laser head. The IGBT switch SW-3 is used for dissipating the residual energy on the storage capacitor before the arrival of next pulse. This command charging circuit helps in reducing jitter. The timing sequence of the command charging IGBTs i.e. SW-1 and SW-3 and main discharge IGBT SW-2 is generated by the IGBT gate driver circuit which includes the timer card, IGBT Driver and Booster cards.

*Average current in the primary circuit:* The Impedance of the resonant charging circuit comprising of the Inductor (L=150 μH) and Capacitor (C =1.98μF) is given by,

$Z_{pri} = \sqrt{(L/C)} = 8.7\ \Omega$

The peak primary current ($I_m$) is given by,

$I_m = V_0 / Z_{pri} = 44.82$ A,

where $V_0$ is the operating SMPS Voltage viz. 390 V

The average primary current is given by,

$I_{avg} = 2x\,(I_m/\Pi) \times$ Duty cycle = 13.9 A,

Where duty cycle is the ratio of the time required by the capacitor to fully charge to the total time period between the consecutive pulses.

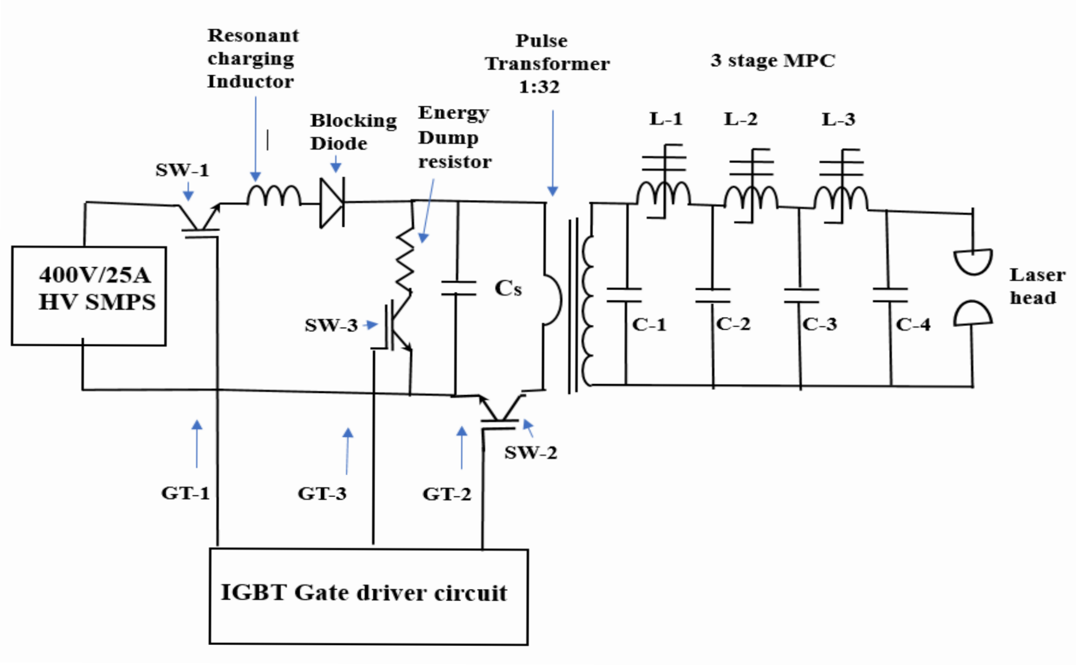


*Fig.2: Schematic of Pulse Generator Unit.*

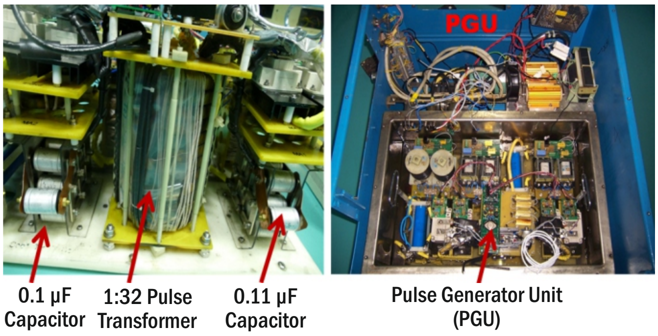


*Fig.4: Photograph of capacitor addition across the parallel capacitor banks and Pulse Generator Unit.*

### *Modification in the primary circuit*

The primary circuit consists of two parallel sections, each section being identical, in which the primary storage capacitor is split into these two circuits. Each section consists of 9 capacitors (0.11µF, 1500 VAC, KP-12, ELCIAR make) connected in parallel in the capacitor bank. Thus overall primary capacitance results in 1.98 µF. In order to increase the optical power output from the each CVL, the pump power delivered into the individual laser head needs to be increased. The CVLs are arranged in the Master Oscillator Power Amplifier (MOPA) configuration to boost the overall optical power which is being utilized for pumping tunable dye lasers [5]. The optical output power of the dye lasers is directly dependent on the energy per pulse of the CVL. Hence the energy delivered per pulse needs to be increased. This is achieved by adding additional capacitor of 0.11 µF the two primary capacitor banks. The resultant capacitance value of capacitor bank with additional capacitors of 0.11 µF is 2.2 µF. The value of $C_s$ in Fig.2 has been increased by 11.11%. The location of this modification carried out in the pulse generator units is shown in Fig.4.

Similar analysis of the charging time of the capacitor, primary impedance, peak primary current, average primary current, energy transfer time from primary to secondary is done and the results have been tabulated for comparison between the system before and after the modification.

*Table 1: Comparison of system parameters before and after modifications.*

| Parameter | Before Modification | After Modification |
|---|---|---|
| Capacitor charging time ($\pi\sqrt{LC}$) | 54 µs | 57 µs |
| Primary Impedance ($\sqrt{L/C}$) | 8.7 Ω | 8.25 Ω |
| Average Current [ 2 x ($I_m/\pi$) x Duty cycle ] | 13.9 A | 15.4 A |
| Energy Transfer time from primary to secondary | 1.48 µs | 1.52 µs |
| Rise time of first stage MPC | 500 ns | 506 ns |
| Rise time of second stage MPC | 200 ns | 202 ns |
| Rise time of third stage MPC | 80 ns | 81 ns |

As seen in the table 1, the capacitor charging time has increased from 54 µs to 57 µs. This value is within the limit of charging IGBT (SW-1) ON time of 60 µs. This was incorporated while conceptualising the modification. The Average primary current increased by 10.8% from 13.9 Amp to 15.4 Amp. In order to test the improvement of the modified system, a single laser head was configured in plane-plane resonator configuration. For comparison purpose the CVL was operated firstly with the unmodified PGU in which the optical output power was measured to be 26 W using Ms Ophir make power meter. The capacitor bank of the same PGU was increased to 2.2 µF and used with the same CVL head. The optical power generated was around 35 W. Thus in plane-plane resonator configuration the optical power increased by ~ 34% from 26 W to 35 W. The value storage capacitances of all the PGUs in the two MOPA chains each consisting of one oscillator followed by five successive amplifiers were increased to 2.2 µF. The optical power additions at the end of the individual stages of both MOPAs have been summarised below in Table 2.

*Table 2: Comparison of optical power additions of two MOPAs before and after modifications.*

| laser | MOPA 1 Power (Watts) | | MOPA - 2 Power (Watts) | |
|---|---|---|---|---|
| | Before Modification | After modification | Before Modification | After modification |
| OSC | 12 – 13 | 15-16 | 7 – 8 | 10 – 12 |
| AMP-1 | 35 – 36 | 39 – 41 | 18 – 20 | 25 – 28 |
| AMP-2 | 50 – 52 | 58 – 60 | 38 – 42 | 48 – 52 |
| AMP-3 | 72 – 75 | 90 – 92 | 55 – 58 | 68 – 70 |
| AMP-4 | 86 – 88 | 108 – 110 | 72 – 74 | 92 – 95 |
| AMP-5 | **105 – 107** | **125 – 127** | **90 – 93** | **115 – 120** |

The above data mentioned in the table 2 has been generated keeping the SMPS Voltage of each laser system fixed at 390 V and partial pressure of the CVL systems around 40 mbar. As seen from the above table there is around 20–30% increase in the power addition of the CVL MOPA. The current drawn by the SMPS also increased by 1.3 A to 1.5 A in the MOPA systems. The average current drawn from the system earlier were in the range of 12.7 A to 13.6 A. These current in the modified PGU increased to 14.2 A to 15.2 A at SMPS voltage of 390 V. This ensures higher current drawn from the supply at the same SMPS voltage. The laser head voltage and current waveforms before and after modifications have been shown in figure 5 and 6 respectively. The laser head voltage was measured using 1000:1 high voltage probe while the current measurement was done using high frequency current monitor having sensitivity of 0.1 V/A. Since the current is measured across only one out of four of the return conductors, the voltage developed across current monitor is to be multiplied by 40 to get the peak value of current flowing through the laser head. There is an increase in the laser head voltage from 12.2 kV to 13.2 kV and laser head peak current from 420 A to 500 A as shown in figure 5 and 6.

The input electrical power drawn by power supply increased by around 11% while the electrical power coupled into the laser head as well as CVL MOPA optical output power increased by around 22–28%. The entire system is currently working with higher efficiency as compared to the system prior

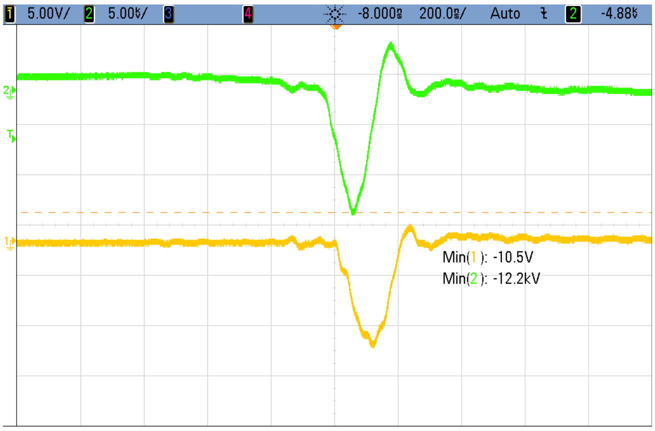
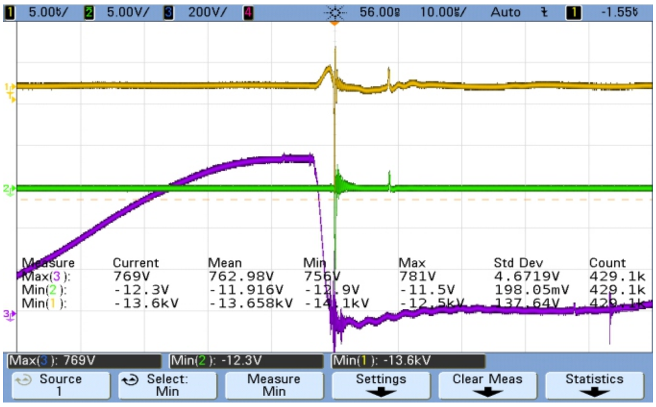


*Fig.5: Laser head voltage & current waveforms before modification.*



| Measure | Current | Mean | Min | Max | Std Dev | Count |
|---|---|---|---|---|---|---|
| Max(3): | 769V | 762.98V | 756V | 781V | 4.6719V | 429.1k |
| Min(2): | -12.3V | -11.916V | -12.9V | -11.5V | 198.05mV | 429.1k |
| Min(1): | -13.6kV | -13.658kV | -14.1kV | -12.5kV | 137.64V | 429.1k |

Max(3): 769V
Min(2): -12.3V
Min(1): -13.6kV

*Fig.6: Laser head voltage & current waveforms after modification.*

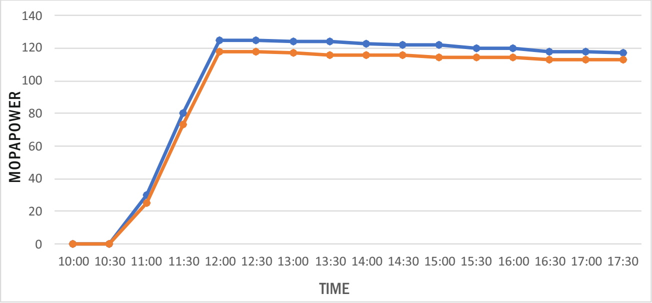


*Fig.7: MOPA-1 Power (Blue) & MOPA-2 Power (Orange) v/s Time.*

to the modifications in the PGU which is resulting in higher wall plug efficiency. In order to study the long term MOPA power stability, both MOPA–1 and MOPA–2 were operated and optical output power was monitored for five hours thirty minutes. The variation in the output power with time is plotted for each MOPA as depicted below in Fig.7.

As seen from Fig.7, The CVLs require around one hour forty-five minutes to two hours reaching the maximum optical power and this time in generally termed as warm up time for the CVLs. The optical powers remained almost constant within 5– 6 % range for the entire duration of operation.

## Conclusion

The optical power of the CVL MOPA chains has been enhanced by increasing the input energy storage capacitance value by 11.11%. Input electrical power drawn by the individual CVL increased around 11%. This resulted in the higher electrical energy coupled to discharge of the laser head. The single CVL operation in plane-plane resonator configuration resulted in the optical power enhancement of 34% while CVL MOPA optical power increased by around 22 - 28%. The primary reason behind this is the increase in the energy gained by the electron on account of increased voltage developed across the electrodes of the CVL. The excitation cross-section of the Cu atoms in vapor state also contributes to the increase in the optical power of the laser. The MOPA optical power remained stable for 330 minutes of continuous operation. This method of enhancement involves increasing energy per pulse of the CVL output which is essential one of the requirement of dye-laser pumping. This higher energy per pulse is advantageous in the laser based fortification process of stable isotopes to be used for generating radio isotopes.

## Acknowledgement

The authors would like to express their sincere gratitude to Dr. Archana Sharma, Group Director, BTDG and Dr. S. Kundu, Head ATLAD for their interest and encouragement in this work. They also wish to thank their colleagues in the Laser Development section of ATLAD for their collaboration, technical discussions and dedicated efforts.

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