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"An Overview of Copper Laser Development for Isotope Separation"

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An Overview of Copper-Laser Development for Isotope Separation*

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The copper laser has undergone 20 years of development since first demonstrated in 1966 by Walter et al.[1] The Lawrence Livermore National Laboratory, funded by the Department of Energy, has participated in copper-laser development since 1974 for application in atomic vapor laser isotope separation (AVLIS).

Separation of isotopes from a uranium vapor stream using lasers requires several unique properties from the laser system. We have chosen copper-laser-pumped dye lasers as our baseline technology for this process. We discuss the operating characteristics of the copper laser with emphasis on suitability for AVLIS. These characteristics include: average power, pulse-repetition rate, optical pulse length, and electrical to optical efficiency.

In the past 3 years, we have designed, built, and are at present running the Laser Demonstration Facility continuously. This facility has over 40 copper lasers. We discuss the copper-laser system as an extension of the operating characteristics of a single copper laser. Copper-laser oscillator amplifier chains, beam quality, and refurbishment cycles are discussed.

The overview is divided into five sections: an introduction to AVLIS, laser requirements for AVLIS, copper-laser chains, system maintenance and refurbishment, and conclusions.

Introduction to Atomic Vapor Laser Isotope Separation (AVLIS)

The AVLIS process uses lasers to selectively photoionize uranium 235 atoms within a vapor stream of uranium. The lasers interact only with the isotope of interest and not with the bulk stream of uranium. This allows highly selective use of the light and contributes to an efficient separation process. Once photoionized, the U-235 is collected by electrostatic plates. This is shown schematically in Fig. 1.

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AVLIS Laser Requirements

There are five basic requirements of the AVLIS laser system:

1. The laser system must produce narrow-band, precisely tuned light.
2. For a three-step photoionization scheme, the light must be in the orange-red part of the spectrum.
3. The laser system must be capable of producing light at high pulse-repetition rates.
4. The light pulse lengths should be short.
5. The laser system must be capable of producing high average powers at high efficiency.

In this section, we will discuss each of these requirements as they apply to our laser system.

Isotope shifts in uranium are typically 0.001 nm. This implies that the laser system must produce light that is precisely tuned to access the U-235 absorption spectra without overlap of the U-238 spectra. This selectivity and band width is easily achieved by dye lasers. For a three-step photoionization scheme, the process wavelengths are in the orange-red part of the spectrum. There are several dyes in the orange-red that are efficiently pumped by green or yellow light. A copper-laser-pumped dye-laser system satisfies these process requirements.

Generation of high average power laser light is expensive. For a cost-effective AVLIS process, the light must be used efficiently. High efficiency drives the laser system to a high pulse-repetition rate. The uranium vapor must be illuminated in the ion-extraction region. Since the uranium is flowing, the lasers are turned on to fill the extraction zone with light and then turned off while the ions are being collected and fresh uranium vapor flows into the extraction region. When one calculates the appropriate cycle time for this process, the repetition rate is in the several kilohertz range. The copper-laser-pumped dye-laser system is well suited for this approach since it can operate at nominally 5 kHz.

Short pulse lengths of light are also desirable. Relaxation times for uranium atoms in excited states are typically several hundred nanoseconds. It is preferable to photoionize the atom before significant relaxation occurs. This places a requirement of short pulse lengths, less than about 200 ns, on the laser system. Dye-laser pulse lengths are nominally the same as the pulse length of the pump laser. Copper lasers have pulse lengths from 10 ns up to 100 ns, producing dye-laser pulse lengths that are short enough to avoid spontaneous relaxation of the uranium levels during photoionization.

The last requirement of the laser system for AVLIS is particularly challenging. The separation of uranium for power plants is a big industry. The laser system must be capable of separating large amounts of material and therefore must be capable of producing high average optical powers. One can estimate the minimum required dye laser light by taking the ionization potential of uranium (6 eV), times the desired product rate (1000 metric tons per year, for example), times the number of enriched atoms in 1 g of product ($\sim 6 \times 10^{19}$ at./g). This results in a minimum of 2 kW average power. This minimum estimate does not include inefficiencies in the extraction process or loss of dye light that results from propagation losses. To get an estimate of the amount of copper-laser light, one must fold in a dye-conversion efficiency and a copper-transport efficiency. As a rough estimate, one can assume a collective system efficiency, including separator efficiency, of 1%. Multiplying our minimum dye power by 100 results in an estimate of 200 kW of average power for the copper-laser system. This system is only feasible because copper lasers are scalable into the hundreds of watts range and exhibit electrical-to-optical efficiencies of about 1%.

The following section will describe our approach for assembling a system that can meet these requirements.

Copper-Laser Chains

The architectural design of our copper-laser system is dependent on an important property of the copper-laser medium. The medium has very high small-signal gain (>0.1 cm^{-1}) and low saturation fluence (<100 $\mu J/cm^2$). In other words, the copper laser works very well as an amplifier. This allows us to use multiple amplification stages to increase the single-aperture power of a copper-laser beam. We call an oscillator, followed by multiple amplifiers, a copper-laser chain. The copper-laser chain is the building block for the copper-laser system. The output beams from a large number of chains are multiplexed together to reach the final required output power for the system.

An artist's rendition of our Laser Demonstration Facility is depicted in Fig. 2. In this figure, the copper-laser system, on the right of the figure, has six copper chains in each corridor, with five corridors on each of two floors. In the past 3 years, we have built and activated one corridor of this system and are currently running it continuously. The figure also shows the dye laser-chain configuration, which is pumped by the output from the copper system. The facilities in the upper right of the figure are copper-laser workstations where maintenance and repair are done. This will be described in more detail in a later section. The amplifiers are interchangeable to any position in the chain and to any chain in the system. In the following discussion, we will describe the design and performance of the oscillator and amplifier packages.

The copper-laser oscillator package produces the initial light that propagates and increases in power as it travels down the chain. The light from the oscillator package must have sufficient beam quality and power to efficiently extract light from the successive amplifiers in the chain. With this requirement in mind, we designed an oscillator package with two laser heads, one to injection-lock the other. The nominal design and performance parameters are as follows:

Tube diameter	4 cm
Gain length	90 cm
Input electrical power	5 kW (each head)
Repetition rate	4.3 kHz
Output power	25 W
Beam quality	<15 X diff. limit
Pulse length	40 ns FWHM, 55 ns at 10%

A drawing of the oscillator package is displayed in Fig. 3. There are seven key components: the laser heads, the pulsed-power electronics tank, the switching power supplies, the low-level electronics for thyratron control, the on-board computer, the gas-handling chassis, and the enclosure structure itself. All of these components are designed in modular form, so they are interchangeable from package to package. The oscillator enclosure is precisely aligned on kinematic mounts on the walls in the copper-laser corridors.

The injection-locking optics are mounted inside the oscillator enclosure. Figure 4 shows the optical configuration. The output from the master oscillator (MO) is telescoped down to a 2.5-mm beam and injected into the injection-locked oscillator (ILO) through an injection-reflector button. This optic serves as the reflector in the ILO resonator and the mode-matching optic for the injected beam. The output from the ILO exits from a scraper mirror and is directed out the end of the enclosure with a turning mirror. We found injection-locking a prerequisite to obtain high-quality beams from the copper oscillators. The fraction of the pulse that will propagate through a lens and pinhole, which corresponds to 15 X (2.44λ/D), improves from 25% to 100% with the ILO locked. Similarly, the optical pulse length of the beam through the pinhole increases from 15 ns to the full 40 ns FWHM.

The 4-cm diam output from the oscillator package is beam expanded to 8 cm to fill the entrance aperture of the first amplifier in the chain. The amplifiers boost the power from the oscillator by hundreds of watts while maintaining the high beam quality. Their nominal design and performance parameters are summarized:

Gain volume	9 liters
Input electrical power	30 kW
Repetition rate	4.3 kHz
Extractable power	300 W
Pulse length	80 ns at 10%
Color split	66% 510 nm
	33% 578 nm

The amplifiers add a radial time dependence to the optical pulse. Large-diameter copper lasers exhibit a plasma skin effect, which delays the penetration of an applied electric field.[2] This effect introduces 30 to 40 ns of delay time between the onset of gain at the outer diameter and at the beam centerline. The amplifier enclosure is shown in Fig. 5. It has the same seven key components as the oscillator, but only one laser head. To supply the 30 kW of electrical input power for the pulse modulator, there are three 15-kW switching power supplies that convert 480-V ac to 10-kV dc. Both the oscillator and the amplifier packages are self-contained, requiring only conventional utilities: cooling water, neon buffer gas, 480-V ac electrical power, timing signal, and a low-flow vacuum line.

Measurements of individual amplifiers indicate an extractable power of 300 W with saturation fluence less than 100 $\mu J/cm^2$. Extraction of high power from a chain of amplifiers is also dependent on optical alignment, optical losses in optics, performance repeatability, and timing. In the past year and a half that we have been bringing the LDF on line, our performance has improved. We are currently achieving several hundred watts per amplifier. In the process of running LDF, we have accumulated over 60,000 total hours of copper-laser amplifier run time and are now increasing that number by 2000 hours a week. It is through the continuous operation of this laser system that we can build a database of component reliability and increase both the lifetime and performance of the copper-laser system.

Laser Maintenance and Refurbishment

As discussed above, all the amplifiers are identical in design and can be interchanged in the copper-laser corridor. This minimizes the system downtime when a problem in an amplifier occurs, because it can be replaced by a spare. In the event of a laser failure, the chain is temporarily shuttered, the amplifier is lifted out of its position with a forklift, and another is placed in its spot and warmed up. Shortly after the new amplifier is in place, the chain can be reactivated to deliver light to the system. The failed amplifier is transported to the copper-laser workstations (see Fig. 2). The workstations are equipped with diagnostics and personnel to troubleshoot the laser problem. Once the failed component is discovered, it is removed and replaced by a spare. The laser is now ready for burn-in to guarantee its performance. Once verified, it is available for placement in the copper-laser corridor.

The failed component is returned to a local shop that specializes in repair of that piece of equipment. We have shops for the pulsed-power modulator, the switching power supplies, the laser heads, and the low-level electronics. As the reliability of the copper-laser components increases, the shops are able to keep up with a larger total number of operating units, allowing expansion of the copper-laser system without increasing the facility size or staff.

Conclusion and Acknowledgments

We have developed a copper-laser pumped dye-laser system that addresses all of the requirements for atomic vapor laser isotope separation. The requirement for high average power for the laser system has led to the development of copper-laser chains with injection-locked oscillators and multihundred-watt amplifiers. By continuously operating the Laser Demonstration Facility, we gain valuable data for further upgrade and optimization.

This overview reports on the work of hundreds of dedicated members of the Laser Isotope Separation Program at LLNL. The copper-laser development has progressed with invaluable contributions from E. I. Moses and the Laser Program Management; R. G. Finucane, E. R. Ault, T. W. Alger, P. D. Weber, B. T. Merritt, and the rest of the staff of the Copper Laser Section; and A. R. Clobes, V. G. Draggoo, and the LDF Operations Staff.

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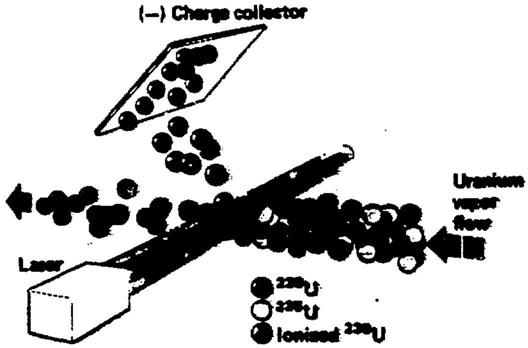

Fig. 1. Schematic drawing of the Atomic Vapor Laser Isotope Separation process

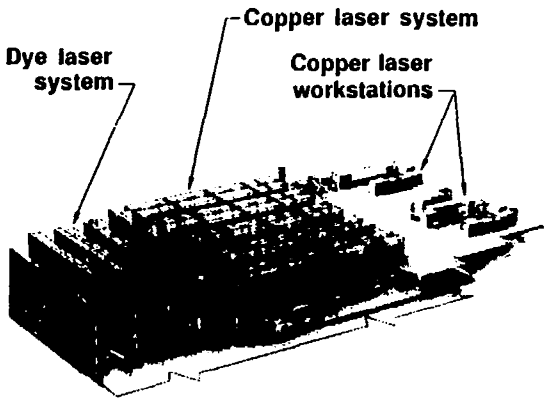

Fig. 2. Artist rendition of a fully deployed laser demonstration facility

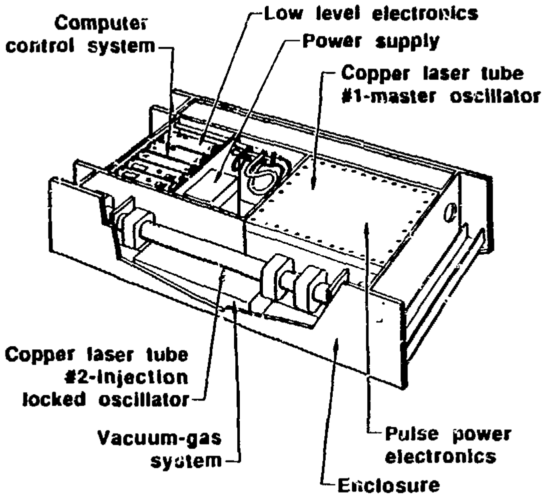

Fig. 3. Cut-a-way drawing of the copper-laser oscillator package showing the seven major components

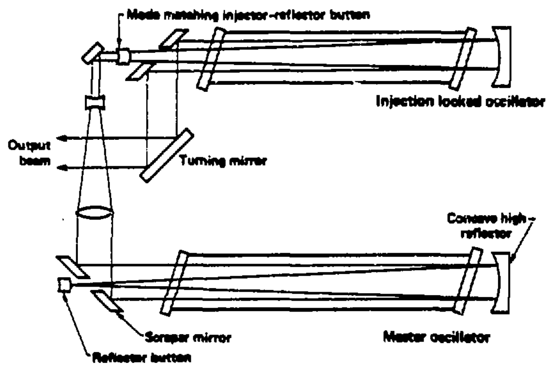

Fig. 4. Optical layout of the injection-locking system used in the copper-laser oscillator package

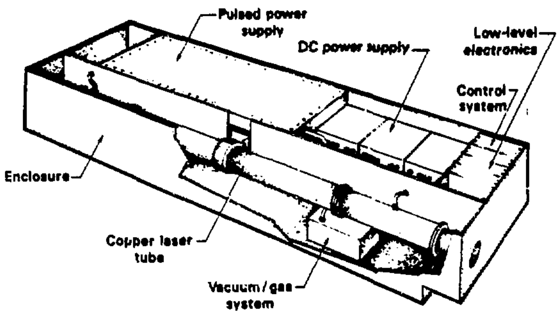

Fig. 5. Cut-a-way drawing of the copper-laser amplifier package