the joining of dissimilar metals and metals and ceramics in a way that ensures excellent heat conductivity and vacuum integrity. The actual design of the bore shape has to take plasma and discharge uniformity and stability into account carefully to enable optimum performance and maximum plasma tube lifetime.

An ion laser plasma tube also requires a cathode and an anode to sustain the arc discharge. The cathode must be capable of supplying electrons to the discharge at currents of up to 65 A. This can only be accomplished practically by tungsten dispenser cathodes of the type commonly used in satellite radio transmitter tubes. These cathodes rely upon the fact that barium metal substantially lowers the work function of tungsten. This enables the efficient emission of electrons from the cathode surface at the required plasma currents of up to 65 A. Barium is formed through a chemical reaction from barium-calcium-aluminate, which is impregnated into the tungsten cathode structure. This process requires the cathode to be constantly heated to about 1,100°C, which is commonly accomplished by resistive heating. The anode is constructed from oxygen-free, high-conductivity copper.

Besides being able to sustain a low pressure noble gas arc discharge with high heat generation, an ion laser plasma tube also needs to provide an optical path along its axis, through the discharge region. This is necessary since the lasing process requires feedback from an optical resonator for self-sustained oscillation. The plasma tube thus also becomes an optical element inside the optical resonator. The optical resonator of an ion laser typically involves a curved and a flat mirror in Fabry–Pérot configuration. To allow for light passing through the discharge, while maintaining the vacuum integrity of the plasma tube, the tube is typically sealed off at its ends by Brewster windows or by resonator mirrors directly. Brewster windows are windows mounted under Brewster's angle. Under this angle the window will have 100 percent transmission for linearly polarized light, which is polarized parallel to the Brewster plane.

The main challenge from a laser optical perspective is to minimize any optical losses in this complicated laser resonator to achieve the maximum lasing performance and optical efficiency. Laser mirrors contribute losses in the form of absorption and scatter in the reflective dielectric thin film. High-quality laser mirrors today need to have total losses of less than 100 ppm (0.0001%). The plasma tube will contribute optical losses in a variety of ways. As transmissive optical elements, Brewster windows can contribute scatter losses due to surface conditions; absorption losses due to impurities in the bulk window material; and residual reflection due to the deviation from the exact Brewster angle. The straightness of the tube is also important. The design and manufacture of laser bores that remain straight under vastly different thermal conditions is a very challenging task. The gas discharge itself can become absorptive to the laser light because of plasma turbulences and impurities in the gas. The impurities can originate from the fill gas itself or from hydrocarbon residues left on the components used in the tube construction. This can only be avoided by employing ultraclean manufacturing techniques and careful selection of materials. Sophisticated spectroscopic techniques such as Fourier transform infrared spectroscopy and time-of-flight secondary mass spectroscopy become invaluable as production control and as problem-solving tools. Plasma tube assembly under class-100 clean room conditions is paramount.

In summary, an ion laser plasma tube could be described as a high-power heating element constructed from an ultraclean, ultrahigh-vacuum vessel, which also constitutes a very low loss optical element that allows powerful lasing inside an optical resonator by means of an argon or krypton arc discharge.

See also: BREWSTER'S LAW; FOURIER SERIES AND FOURIER TRANSFORM; LASER; LASER, DISCOVERY OF; OSCILLATION; PLASMA

Bibliography

HITZ, C. B. *Understanding Laser Technology: An Intuitive Introduction to Basic and Advanced Laser Concepts,* 2nd ed. (PennWell, Tulsa, OK, 1991).

SIEGMAN, A. E. *Lasers* (University Science Books, Mill Valley, CA, 1986).

WEBER, M. J. *Handbook of Laser Science and Technology,* Vol. 2: *Gas Lasers* (CRC Press Inc., Boca Raton, FL, 1982).

ALFRED FEITISCH

LASER COOLING

Laser cooling is the process of slowing, and thus cooling, atoms using laser light. The technique was first applied to ions (electrically charged atoms) held in electromagnetic traps and was later used on electrically neutral atoms. Remarkably low temperatures have been achieved using laser cooling; atoms have been cooled from room temperature to less than one millionth of a degree above absolute zero. Current research using laser-cooled atoms and ions includes the development of high-precision atomic clocks and fundamental studies of atomic properties. Also, interesting collective behavior has been produced, such as the crystallization of cold ions, and Bose–Einstein condensation of a vapor of ultracold neutral atoms. This condensation is a new form of matter where nearly all the atoms are in a single quantum mechanical state.

The Basics of Laser Cooling

A beam of laser light is made up of discrete particles or quanta called photons. The primary force used in laser cooling is the momentum transferred to an atom when photons scatter from it. This scattering is the process of an atom absorbing a photon, going up to an excited state, and then re-emitting a photon in a random direction; an atom absorbs a photon when the photon's energy is nearly the same as the energy difference between two atomic energy levels. The scattering force is similar to the force applied to a bowling ball when it is bombarded by a stream of ping pong balls. The momentum kick that the atom receives from each scattered photon is small; a typical velocity change is about 1 cm/s (room temperature gas atoms have typical velocities of several hundred meters per second). However, if the laser frequency is adjusted to match a strong atomic transition, it is possible to scatter more than ten million photons per second and produce accelerations of approximately 10,000 × g, where g is the acceleration due to gravity.

To cool a sample of atoms, their velocities must be reduced. The photon-scattering force can *push* atoms in a particular direction; however, by itself, this force will not *slow* a collection of atoms. Laser cooling is achieved by using the Doppler effect to make the photon-scattering force depend on the velocity of the atom. Just as the light emitted from a receding star is redshifted toward lower frequencies (longer, and thus redder wavelengths), an atom moving in a laser beam will see the frequency of the laser light shifted due to the atom's velocity in, or opposite to, the direction of the laser beam. The basic principle is illustrated in Fig. 1. If an atom is moving in a laser beam, it will see the laser frequency ν_{laser} shifted by $(V/c) \times \nu_{\text{laser}}$, where V is the component of the atom's velocity that is opposite to the direction of the laser beam, c is the speed of light, and ν_{laser} is equal to the speed of light divided

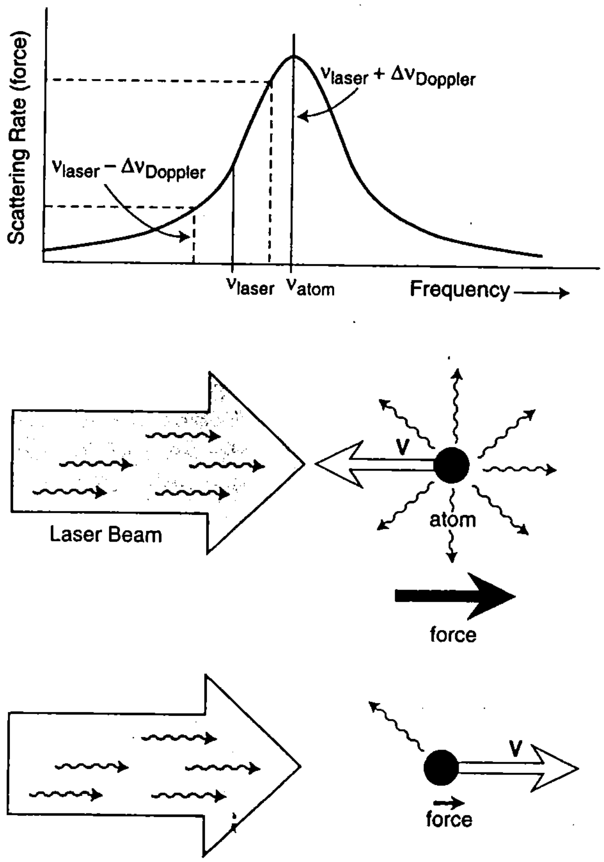

Figure 1 Velocity-dependent photon scattering force. The upper diagram shows the frequency dependence of the atomic excitation (scattering) rate, which is maximum at the frequency ν_{atom}. The laser frequency ν_{laser} is tuned to the low-frequency side of the atomic resonance. When an atom is moving in the direction opposite to the laser beam (middle of figure), it sees the laser frequency Doppler-shifted to higher frequency by the amount $\Delta\nu_{\text{Doppler}} = (V/c) \times \nu_{\text{laser}}$ and scatters many photons. When an atom is moving in the same direction as the laser beam (bottom), however, it sees the laser frequency Doppler-shifted to lower frequency and scatters very few photons. Thus the laser photons exert a much larger force if the atom is moving opposite to the laser beam.

by the wavelength of the laser light. Suppose that the laser frequency is adjusted so that it is slightly below the resonant frequency of the atom's transition between energy levels. As a result of this Doppler shift, the atom will scatter photons at a higher rate if it is moving opposite to the direction of the laser beam (V positive) than if it is moving in the same direction (V negative). Thus, although the photon-scattering force is always in the direction of the laser beam, it is strongest when the atom is moving in the direction opposite to the laser beam, which is when scattering force is slowing the atom down. Six laser beams are needed to cool atoms in all three dimensions (three pairs of oppositely directed beams at right angles to each other, as shown in Fig. 2). The combination of the forces from these beams slows the atoms regardless of the direction of their motion and thereby cools the atomic vapor. This technique has been given the descriptive name "optical molasses."

At certain laser frequencies, researchers found they could achieve atomic temperatures lower than can be explained by the Doppler cooling just described. This accidental discovery is now understood to arise from some very fortuitous atomic physics. As atoms move through the hills and valleys of potential energy produced by the intersecting laser beams, the atoms tend to make transitions between states in such a way as to efficiently transfer their thermal energy to the scattered photons.

Neutral Atom Trapping

Although atoms can be cooled by optical molasses, they will still slowly wander out of the laser beams. Holding the atoms in a particular place (trapping) can be accomplished in several ways. Ions, since they are electrically charged, can be easily trapped using electric and magnetic fields. Neutral atoms, however, are a more difficult problem. The most popular trap for neutral atoms is the magneto-optical trap shown in Fig. 2. It uses a combination of the photon-scattering force and a nonuniform magnetic field. By shifting the energy levels of the atom, the magnetic field regulates the rate at which an atom at a particular position scatters photons from the different beams. With the right arrangement of magnetic field and polarization of the laser beams, atoms are pushed to the location where all six laser beams intersect and the magnetic field is zero. As well as holding the atoms, this trap greatly increases the atomic density, since many atoms are pushed to the same point. The dipole-force trap is another type of laser trap that is less widely used. In this trap the atoms are drawn into the high-intensity region of a focused laser beam.

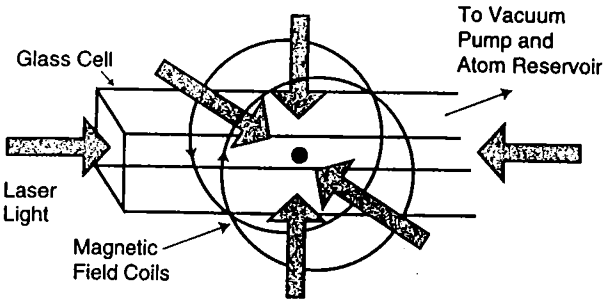

Figure 2 A magneto-optical trap in a glass cell. All of the laser beams are derived from the same laser. The nonuniform magnetic field is produced by running electrical current in the circular loops of wire shown.

While laser cooling and trapping research in the 1970s and 1980s demonstrated tantalizing benefits, the size, cost, and complexity of the apparatus limited the potential applications. Recent simplifications in the technology, particularly the use of low-cost diode lasers operating in the near infrared, have dramatically changed this situation; laser cooling and trapping experiments are now being conducted in many laboratories and are even being carried out by college students.

See also: DOPPLER EFFECT; LASER; PHOTON; SCATTERING

Bibliography

CHU, S. "Laser Trapping of Neutral Particles." *Sci. Am.* **266** (2), 70–76 (1992).

GILBERT, S. L., and WIEMAN, C. E. "Laser Cooling and Trapping for the Masses." *Optics and Photonics News* **4** (7), 8–14 (1993).

PHILLIPS, W. D.; GOULD, P. L.; and LETT, P. D. "Cooling, Stopping, and Trapping Atoms." *Science* **239**, 877–883 (1988).

WINELAND, D. J., and ITANO, W. M. "Laser Cooling." *Phys. Today* **40** (6), 34–40 (1987).

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