Excimer Lasers

- Currently best UV laser sources
- Consist two atom types which repel each other
- eg nobel gas and halide or oxide which normally do not bond
- But when excited/ionized these atoms attract
- Bound together separated by short distance
- Call this Excited state Dimer: Excimer
- Argon, Xenon, Krypton in excited states
- Oxygen or halids (Fluorine or Chlorine)
- ArF, XeF, KrF, XeCl, KrCl
- Deep UV operation: 195 - 350 nm
- Oxide excimers at 558 nm yellow green oxygen glow

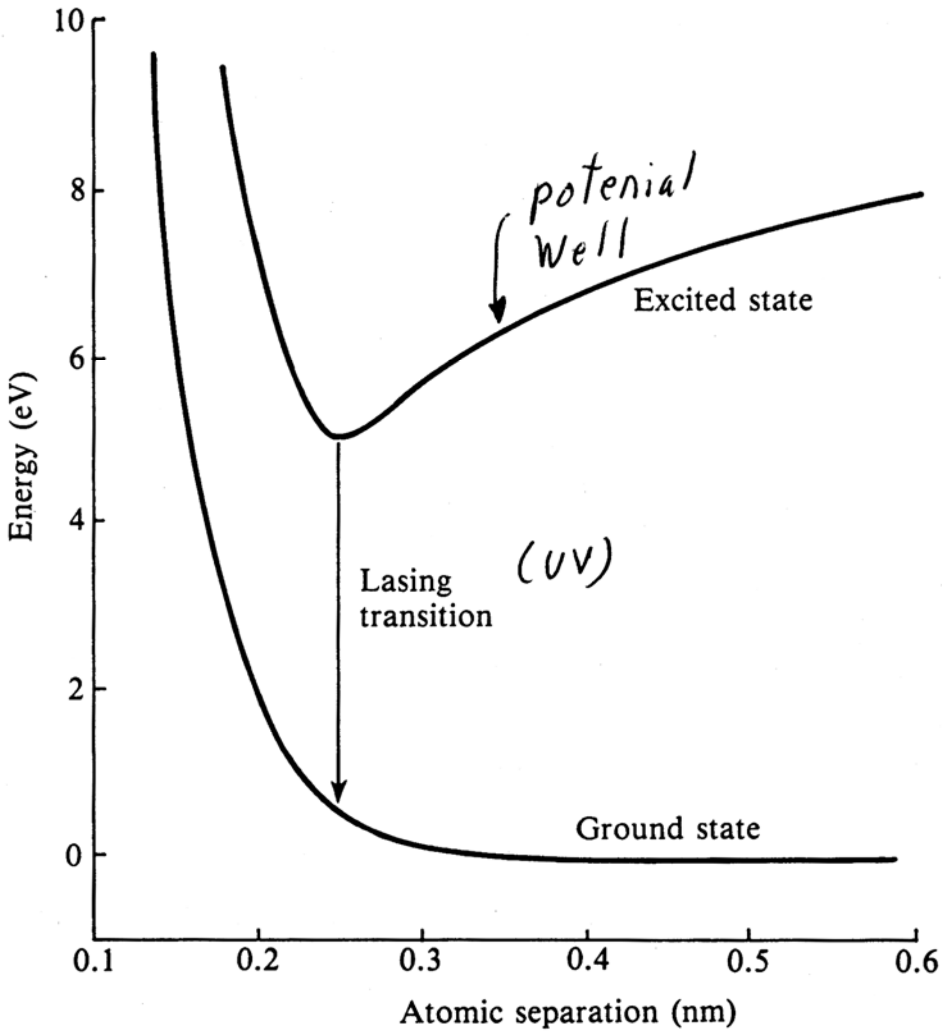


Fig. 2.34 Potential-energy curves for the KrF excimer laser.

Excimer Lasers

- Mixture of gases below 5 atm
- 90% - 99% buffer gas (He, Ne) for energy transfer
- 1% - 9% dimer, 0.1-0.2% halide
- Super-radiant lasers; 4% output mirror, reflective back
- Quartz optics for XeCl
- Fluorine would etch Quartz
- Hence F lasers use magnesium fluoride or calcium fluoride
- Cavity's under 1 m
- To stabilize beam use injection locking with a
  Master Oscillator Power Amplifier (MOPA)

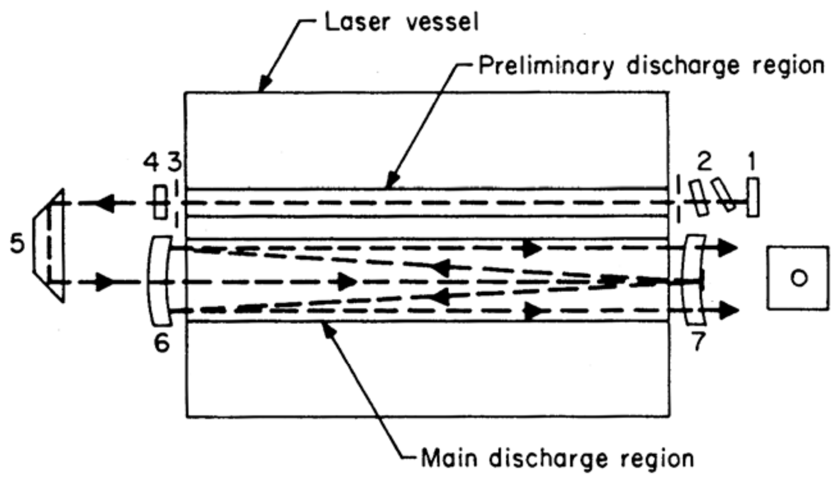
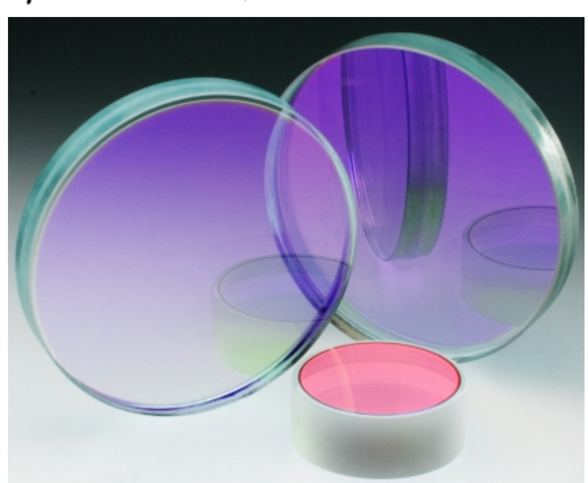


Figure 13.2 Narrow-line output of a master oscillator (top) is amplified in an unstable-resonator amplifier (bottom), extracting energy from most of the unstable-resonator cavity. Components are (1) master oscillator rear reflector, (2) etalons, (3) apertures, (4) master oscillator output coupler, (5) prism, (6) rear unstable-resonator optic, (7) front unstable-resonator optic. (*Courtesy of Lumonics Inc.*)



Excimer dielectric mirrors

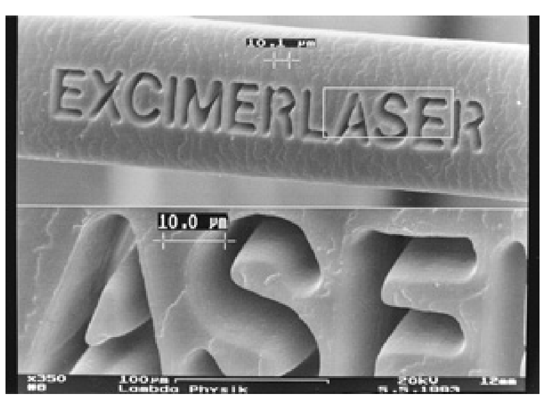
Excimer Lasers

- Excimer state short lived: pulses about 10 nsec
- Repetition rate 100 - 300 Hz
- Efficiency about 2% for KrF
- Pulses highly unstable
- 0.3 nm spectral width
- Highly unstable modes: 2500 measured
- Used for photoablation: wavelength so short destroys organics
- Micromachining and Lasik eye surgery
- KrF & ArF Main source for microelectronics exposure systems
- Wavelength 249, 195 nm Vacuum UV: air absorbs

Table 7.5 Rare gas–halogen lasing wavelengths, calculated lifetimes and stimulated emission cross-sections

	λ(nm)	τ(ns)	$\sigma_{SE}(10^{-16}\ cm^2)$
XeBr	282	12	2.2
XeCl	308	11	4.5
XeF	351	12–19	5.0
XeF (C → A)	490	~100	0.05
KrCl	222	–	–
KrF	249	6.5–9	2.5
ArCl	175	–	–
ArF	193	4.2	2.9

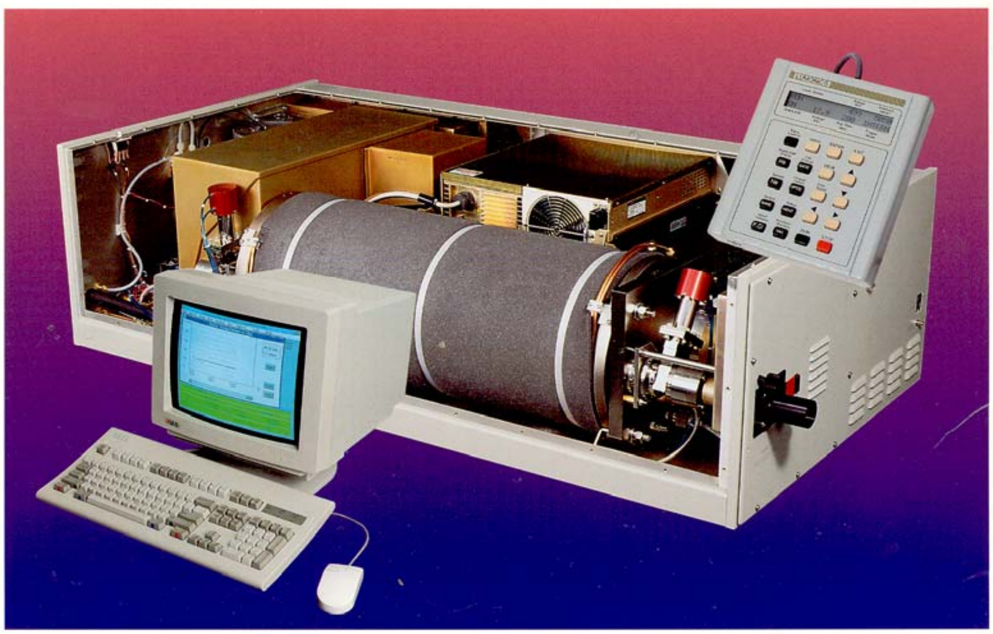
All transitions are $B \rightarrow X$ except for XeF, which also lases on the $C \rightarrow A$ transition.

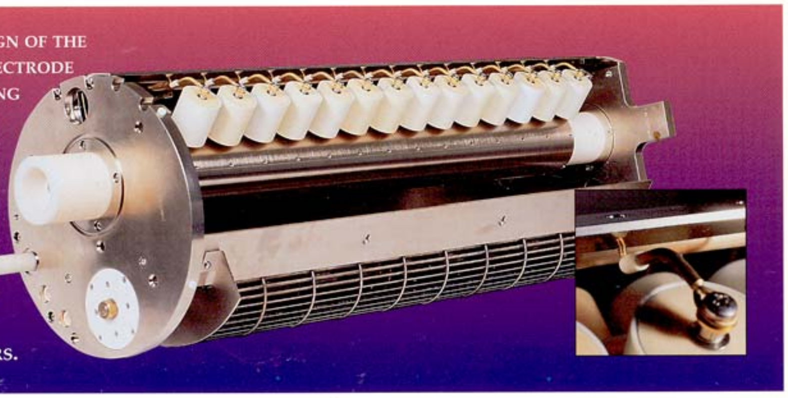


Excimer Lasers

- Excimer Lasers expensive to set up
- Beam quality very poor
- Emission area very large (eg 12x30 mm) -bearly a laser
- Need considerable support devices
- Laser is heavy ~ 200-400 kg
- Must have gas bottle cabinets (eg Xe & Cl) & ventilation system
- Gas cabinets needed to catch leaks – deadly
- Need a beam shaper to get good quality beam
  shapes wavefront so it can be focused ~ 10x
- Costs high – laser $100K, but optics, gas cabinets another $100K

INTERNAL VIEW OF PULSEMASTER PM-800 LASER, SHOWING THE SIMPLE MODULAR DESIGN, HAND-HELD REMOTE CONTROL UNIT AND OPTIONAL PERSONAL COMPUTER CONTROL SOFTWARE.





THE UNIQUE DESIGN OF THE PULSEMASTER ELECTRODE ASSEMBLY, SHOWING THE SINGLE CERAMIC FEEDTHROUGH, THE CERAMIC-ENCAPSULATED PEAKING CAPACITORS AND (INSET) THE SOFT PRE-ION CERAMIC TRACKERS.

Typical Excimer Lasers

Typical Eximer Lasers

TABLE 13.1 Pulse Energy, Average Power, and Repetition Rate for Representative Commercial Excimer Lasers*

Laser and gas	F2	ArF	KrCl	KrF	XeCl	XeF
Wavelength, nm	157	193	222	249	308	350
Lambda Physik LPX105						
Pulse energy, mJ	—	125	—	225	150	75
Average power, W	—	4	—	10	6	3
Repetition rate, Hz	—	50	—	50	50	50
Lambda Physik LPF205 (Vacuum Ultraviolet Optics Only)						
Pulse energy, mJ	60	100	—	—	—	—
Average power, W	3	5	—	—	—	—
Repetition rate, Hz	50	50	—	—	—	—
Lambda Physik LPX315i						
Pulse energy, mJ	—	500	—	800	600	400
Average power, W	—	45	—	100	75	45
Repetition rate, Hz	—	150	—	150	150	150
Lumonics Inc. Index-210 (Industrial)						
Pulse energy, mJ	—	100	—	250	150	—
Average power, W	—	30	—	75	45	—
Repetition rate, Hz	—	300	—	300	300	—
Lumonics Inc. Excimer-600						
Pulse energy, mJ	—	225	—	400	300	250
Average power, W	—	55	—	100	70	60
Repetition rate, Hz	—	350	—	500	600	600
Questek Inc. 2580vβ						
Pulse energy, mJ	—	300	—	500	400	300
Average power, W	—	40	—	100	60	50
Repetition rate, Hz	—	500	—	500	500	500
Questek Inc. 2920						
Pulse energy, mJ	—	700	—	900	500	400
Average power, W	—	5.6	—	7.2	4	3.2
Repetition rate, Hz	—	10	—	10	10	10
Siemens 2020						
Pulse energy, mJ	—	—	—	2000	—	—
Average power, W	—	—	—	40	—	—
Repetition rate, Hz	—	—	—	40	—	—

*All figures are maximums stated by manufacturers on data sheets or in industry directories. It may not be possible to realize all three at once. The lasers listed are representative of those available in 1990; each company offer other lasers, and other companies also produce excimer lasers.

Chemical Laser

- Chemical reaction to create laser action
- Proposed by J.C. Polanyi (USSR) 1960
- First shown by Kasper & Pimentel 1965
- Gases mixed in a reaction chamber with laser cavity
- Chemical have good energy storage
  Most other lasers need electrical power supply
- Problem is the gas dynamics of the mixing is complex
- How to get reactants in, react them, and get waste products out
- Two main type: reactants are the source wavelength
- Transfer: chemical reaction creates exited molecule
- Excited state transferred to another materials that does the lasing
- Almost all current applications are military
- Hence main type used for aircraft carried lasers
  Store the energy in large fuel tanks

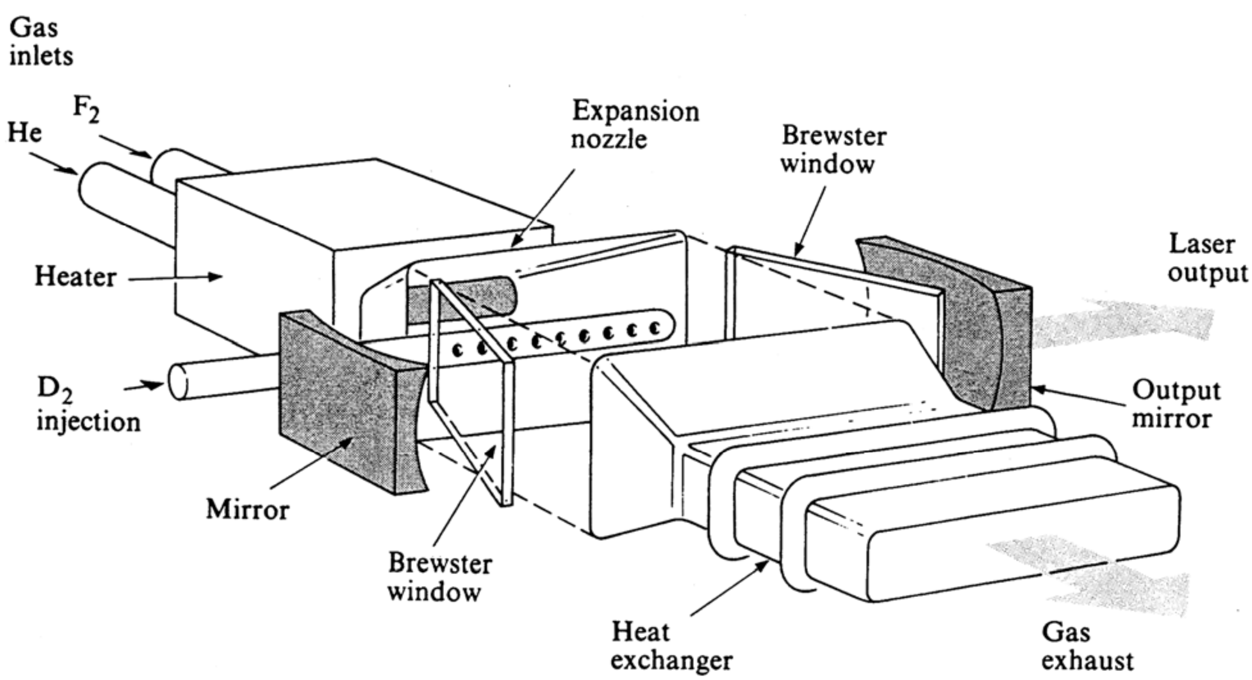


Fig. 6.11 Schematic of a chemical laser. One of the chemical reactants (in this case, F_2) is heated with a carrier gas (He) and allowed to expand just before mixing with the second reactant (D_2). The reaction takes place in the region between the two Brewster windows. (The enclosure around this area has been omitted for the sake of clarity.) The output beam is in a direction transverse to the gas flow, as in the gas dynamic laser.

Chemical Laser

- Aggressively developed by military
- 3 main types
- Hydrogen Fluoride: HF
- 2.6 - 3.3 μm: in atmosphere absorption band
- Substitute Deuterium for H to shift wavelength
- DF laser: 3.5 - 4.2 μm: not absorbed by atmosphere

USAF has a 747 anti missile laser plane: DF laser

100 T chemicals gives you 10 shots: and waste is HF acid!

- Iodine emits at 1.3 μm

  pumped in I Oxygen reaction – energy transferred to Iodine
- Called a COIL (Chemical Oxygen Iodine Laser)

TABLE 11.1 Major Chemical Lasers

Laser	Typical reactions	Wavelength, μm
I	$O_2^* + I \rightarrow O_2 + I^*$ (transfer)	1.3
HF overtone	Same as HF	1.3–1.4
HF	$F + H_2 \rightarrow HF^* + H$	2.6–3.5
	$H + F_2 \rightarrow HF^* + F$	
HCl	$H + Cl_2 \rightarrow HCl^* + Cl$	3.5–4.1
DF	$F + D_2 \rightarrow DF^* + D$	3.5–4.1
	$D + F_2 \rightarrow DF^* + D$	
HBr	$H + Br_2 \rightarrow HBr^* + Br$	4.0–4.7
CO	$CS + O \rightarrow CO^* + S$	4.9–5.8
CO_2	$DF^* + CO_2 \rightarrow CO_2^* + DF$ (transfer)	10–11

USAF 747 DF Laser: 100 T gives 10 laser shots

HF laser

- Output from HF/DF vibrational bands
- Tune laser to get wavelength
- Possible to get 1.3 μm if suppress others
- Commercial CW 1 - 500 W
- Pulsed 1J at 50 - 400 nsec, 0.5 - 5 Hz
- Military much higher

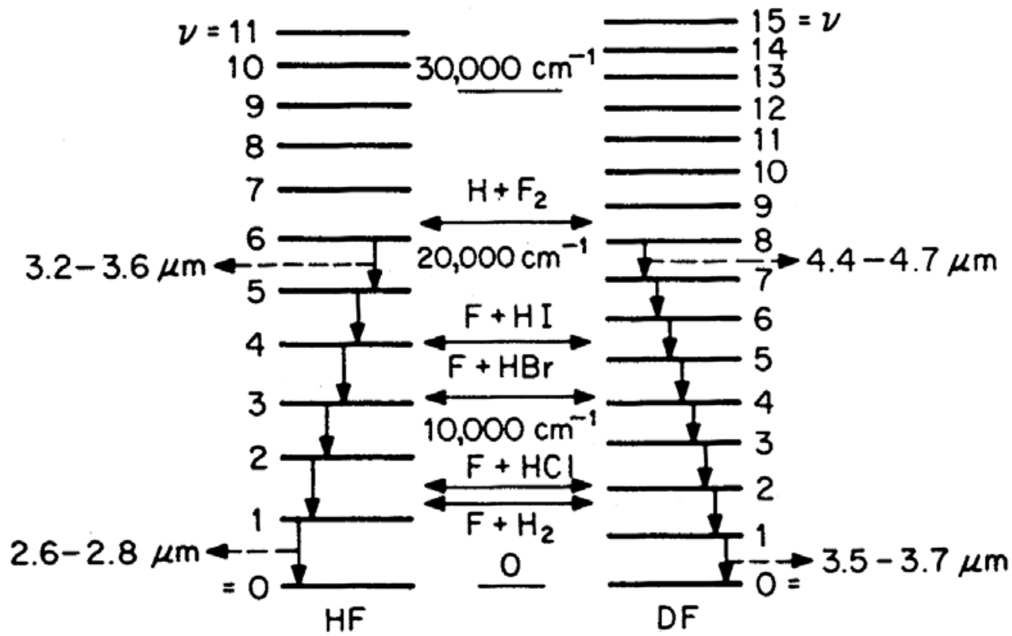
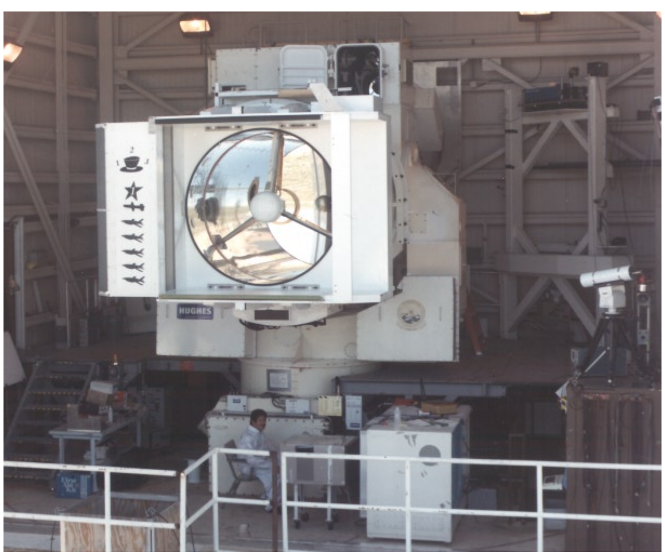
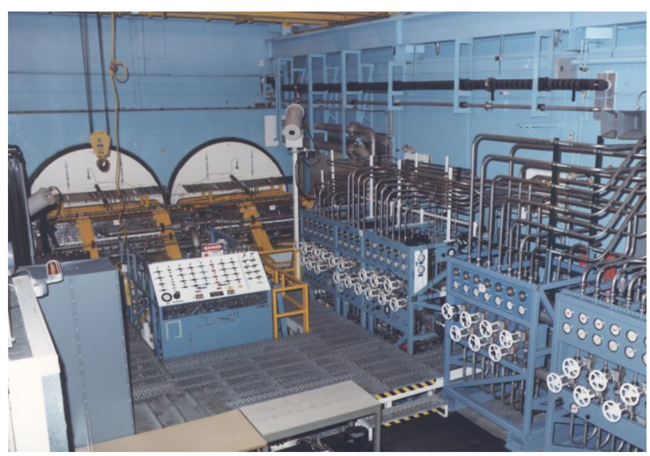


Figure 11.2 Vibrational energy levels of HF and DF, shown with energies of certain reactions which produce HF and DF. Only fundamental-band transitions are shown; rotational sublevels are not shown, but account for the ranges in wavelength. (*From Chester, 1976.*)





Anti Ballistic Missile HF laser

⇐Targeting mirror:laser weapon

Chemical Laser

- Commercial CW Chemical HF laser
- Uses electrical discharge to break down SF_6
- Oxygen removes sulfur
- Mixed with H in chamber

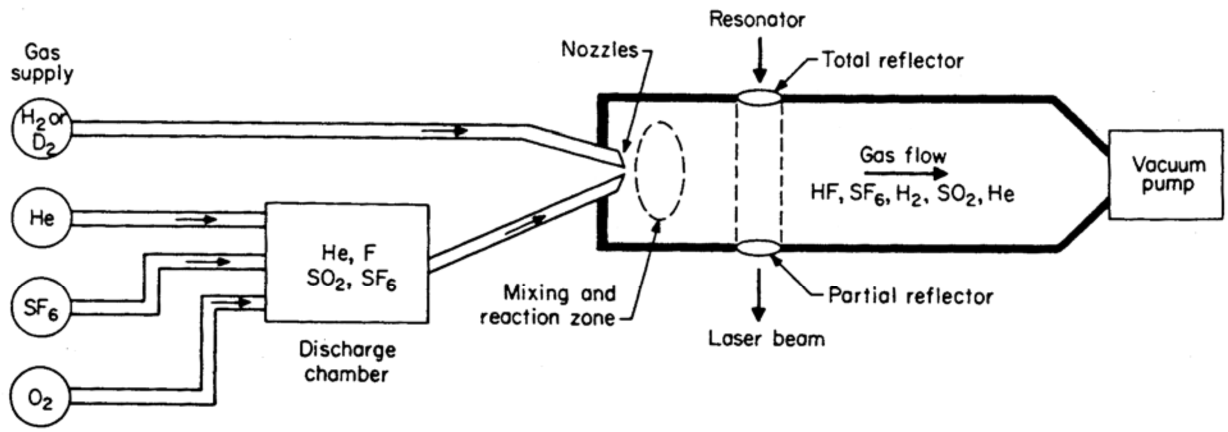
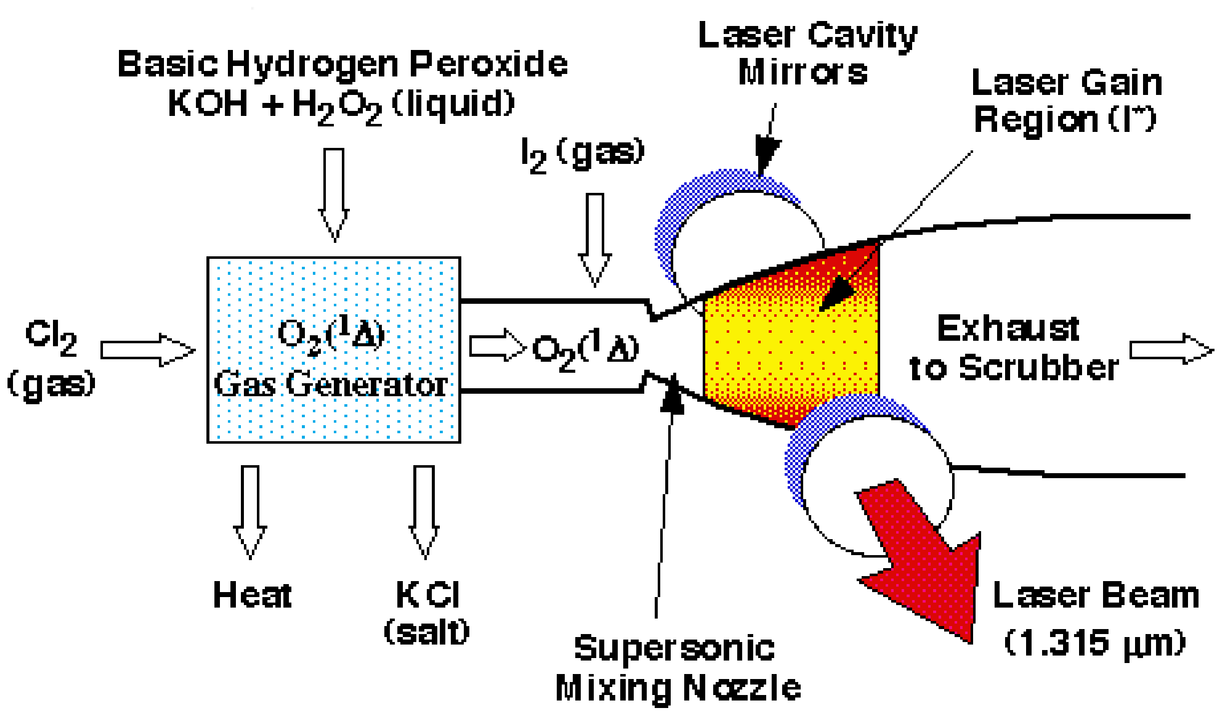


Figure 11.1 Basic elements of a commercial continuous-wave chemical laser include a gas supply, a discharge chamber that produces free fluorine, nozzles which mix the reactants, a mixing region, a laser resonator, and a vacuum pump to collect spent laser gas. Gas flow is from left to right; the laser beam is perpendicular to the gas flow.



Dye lasers

- Solid state lasers have fixed materials
  Also can be damaged by beam
- Gas lasers are low density of materials
- Thus liquid can mix at high density
- Chemical dyes fluoresces:
  Wide absorption at short wavelength, emit at longer λ
- Separation of peaks is called Stoke's Shift
- Laser operation 1965 by Sorokin & Schafer at IBM
- Emission dependent on dye composition
- Generally pumped by other lasers

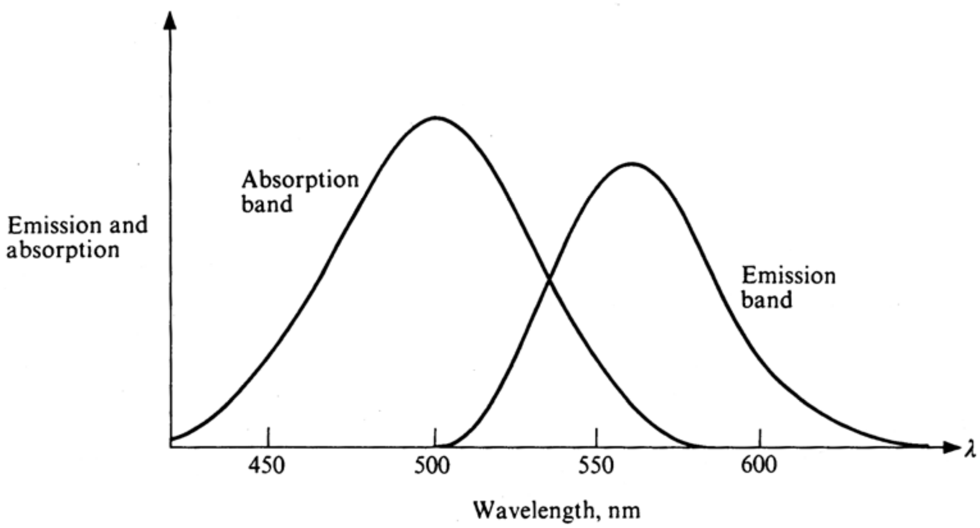
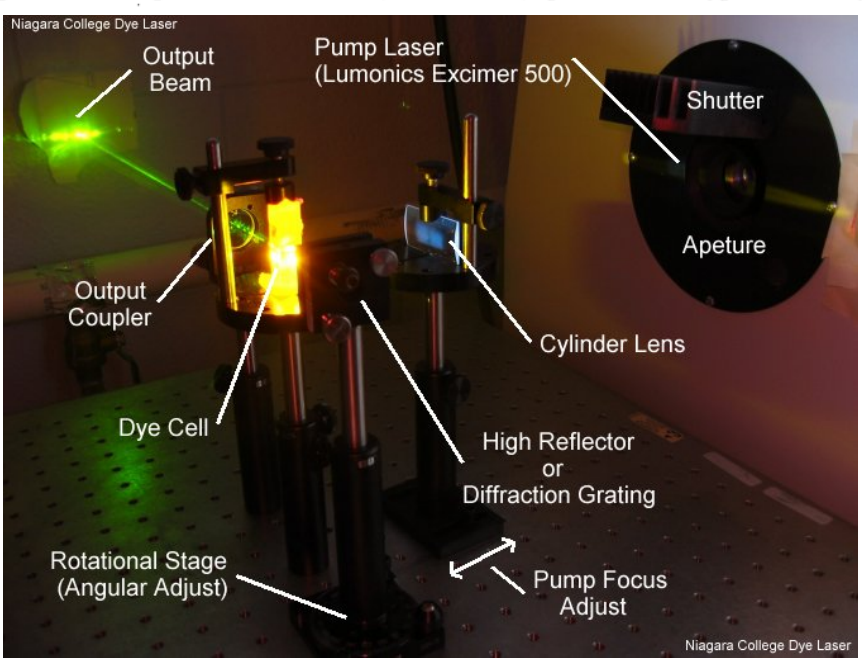


Fig. 6.27 Absorption and emission (fluorescence) spectrum of a typical laser dye.



Dye lasers

- Dye molecules have two states: Singlet & Triplet
  connected to the quantum spin numbers
- Singlet (S) total spin = 0: highly absorbing
  even number of electrons with spin ±½
- Triplet (T) state spin = 1
  electron spins are aligned
- S-S and T-T transitions most likely
  combination less likely
- Pump S_0 to S_1
- T-T transitions can cause absorption if S-T transition

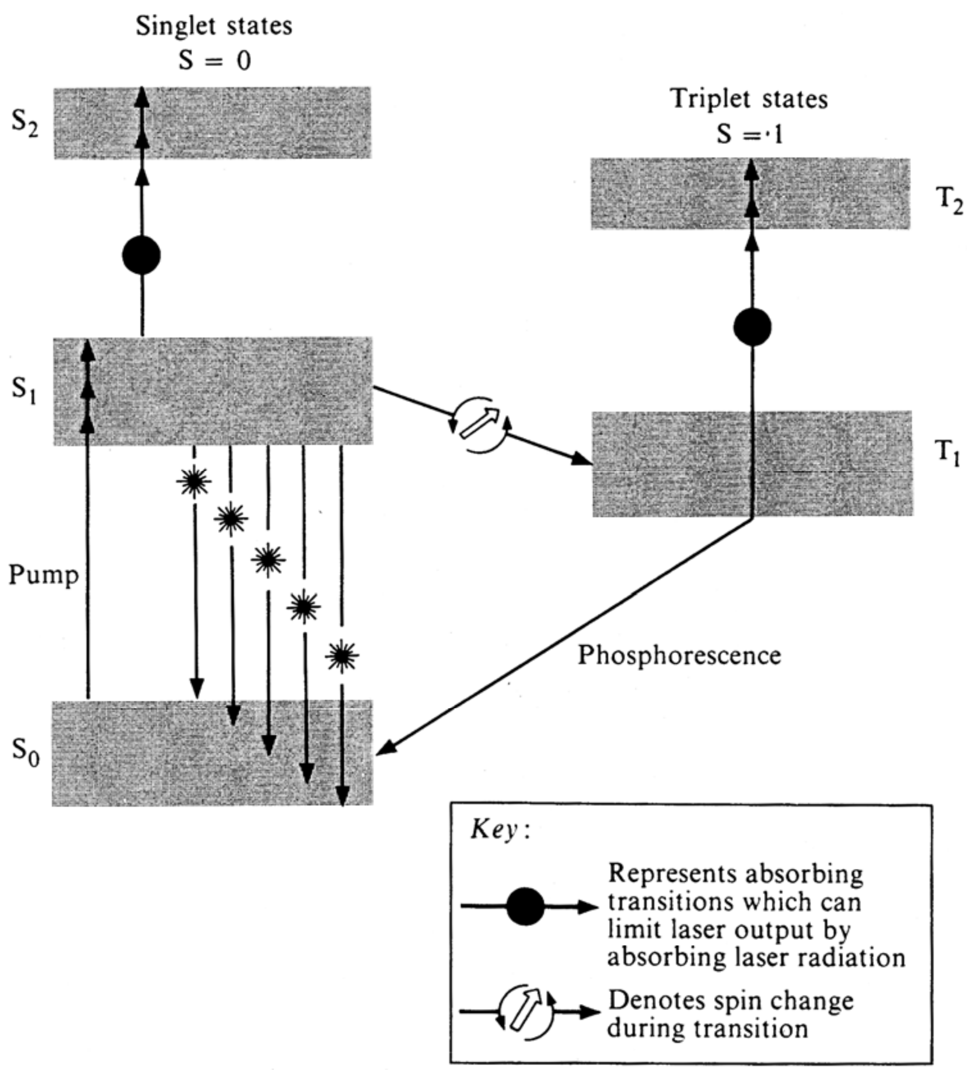


Fig. 6.28 Energy-level scheme for a dye laser. Singlet-triplet ($S_1 \rightarrow T_1$) transitions lead to strong absorptions ($T_1 \rightarrow T_2$) at the laser transition wavelengths, quenching laser action.

Dye lasers

- Many dye's possible
- Tonic water emits white glow
- Tonic wafer + ethanol: creates drinkable laser
- Most common dye Rhodamine 6G: 20% efficient

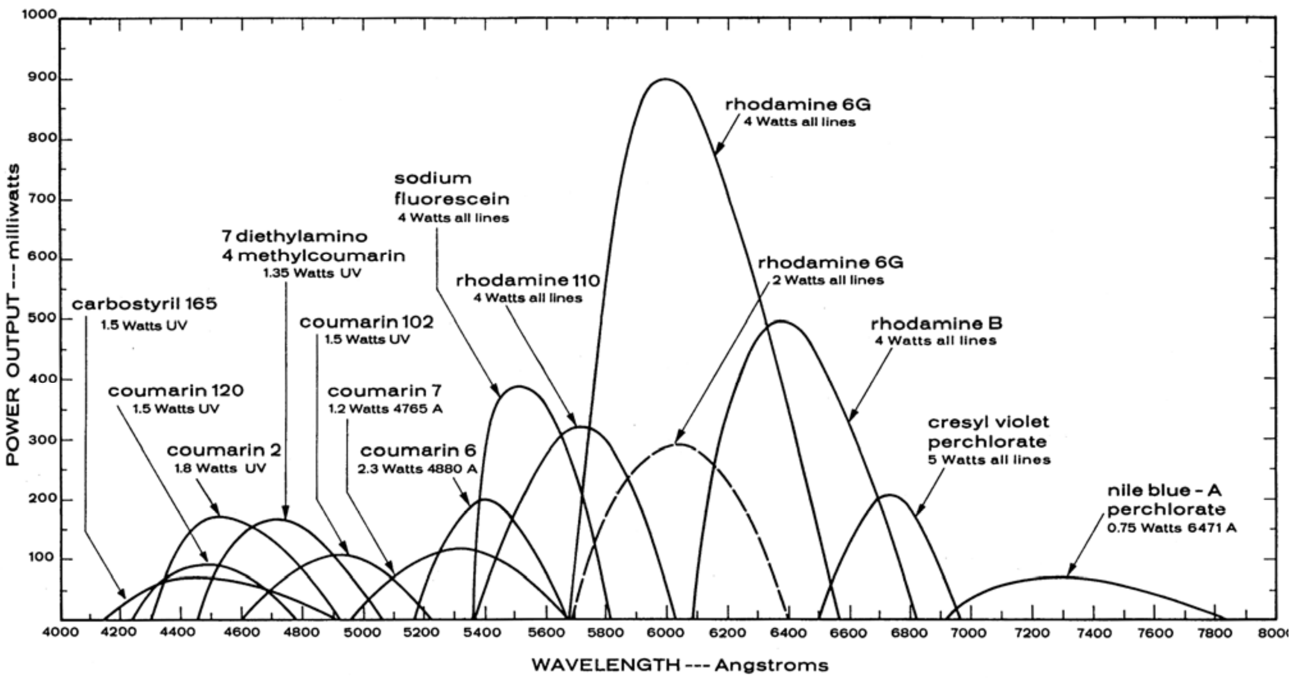
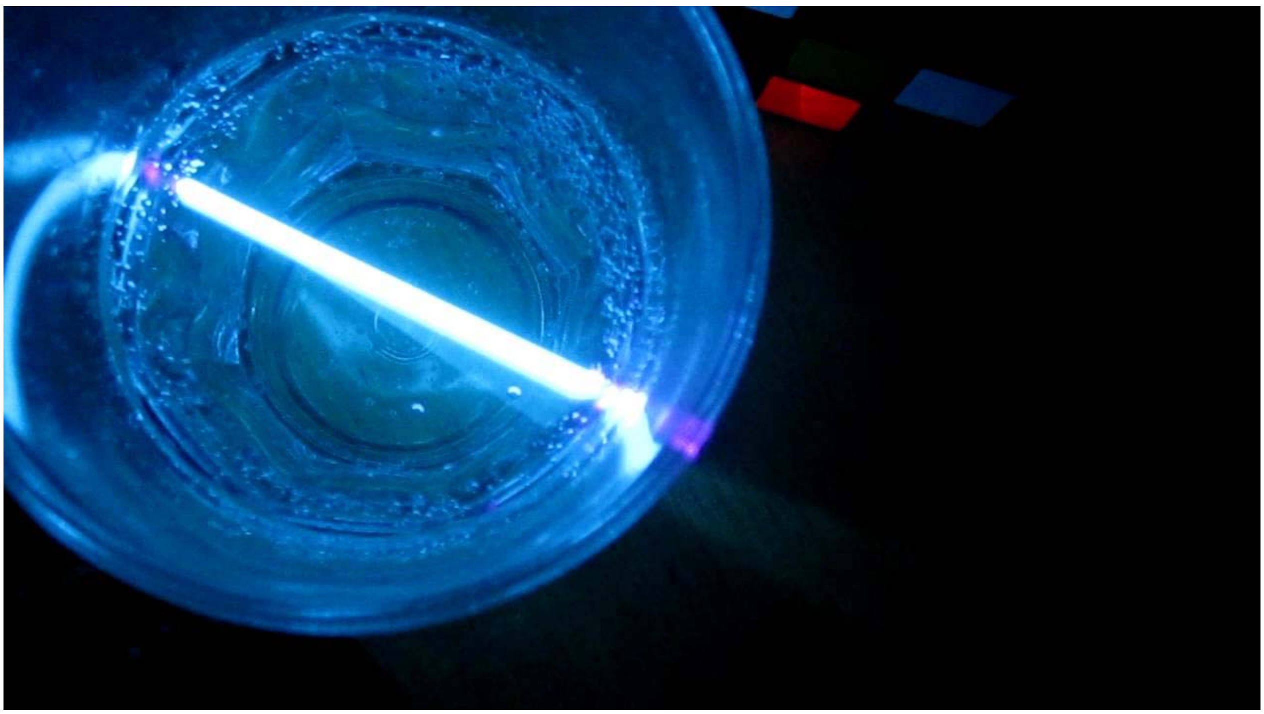


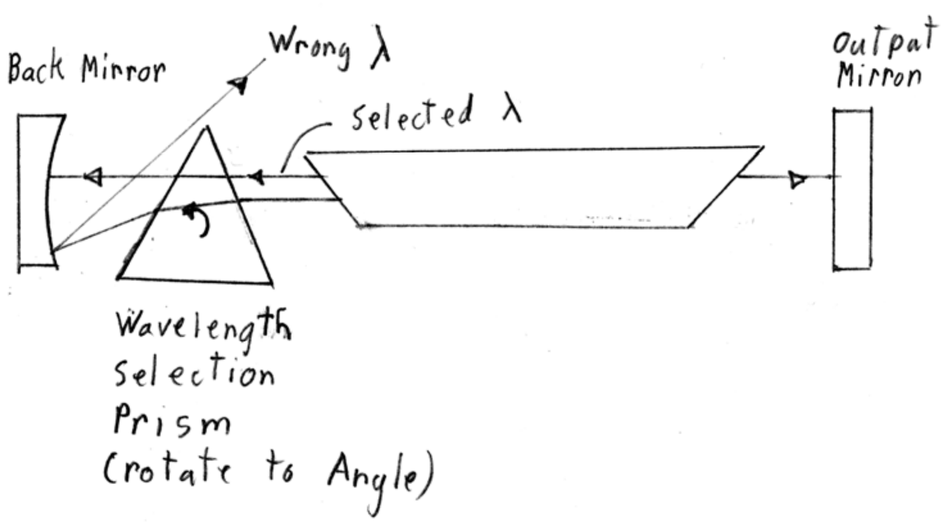
Fig. 6.29 Dye laser output curves of some common laser dyes. Figures below the dye indicate the typical pump power from an argon ion laser required to achieve the tuning curves shown. (Courtesy of Coherent Radiation, Inc.)



Tonic Water pumped by eximer

Dyes for Lasers

- Changing dye composition changes wavelength range
- Range ~310 - 1200 nm
- Basic dye cell allows you to change composition
  Thus can tune wavelength range
- Use prism/diffraction grating in cavity to select wavelength
- Typically dye in a solvent (eg methanol)
- Used to select specific wavelengths for detection of materials
- Also to optically stimulate specific chemical reactions
- Dyes can be infused into plastics to create rods



Flash Pumped Dye lasers

- Dye placed in Dye cell (Cuvette)
- Cell usually has Brewster windows at ends
- Or parallel path at Brewster angle
- Typical Dye optically pumped
- Normally laser but can use flash tube pumping
- Range from CW to ultrashort pulsed (few psec)
- Short pulses if sealed Dye cell

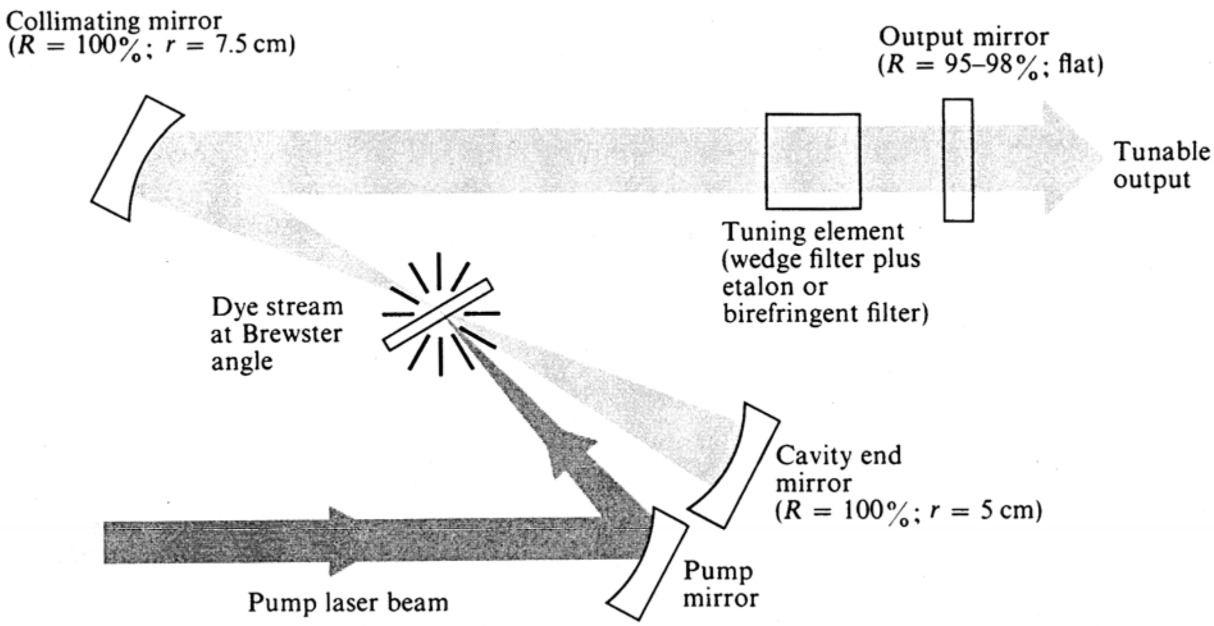
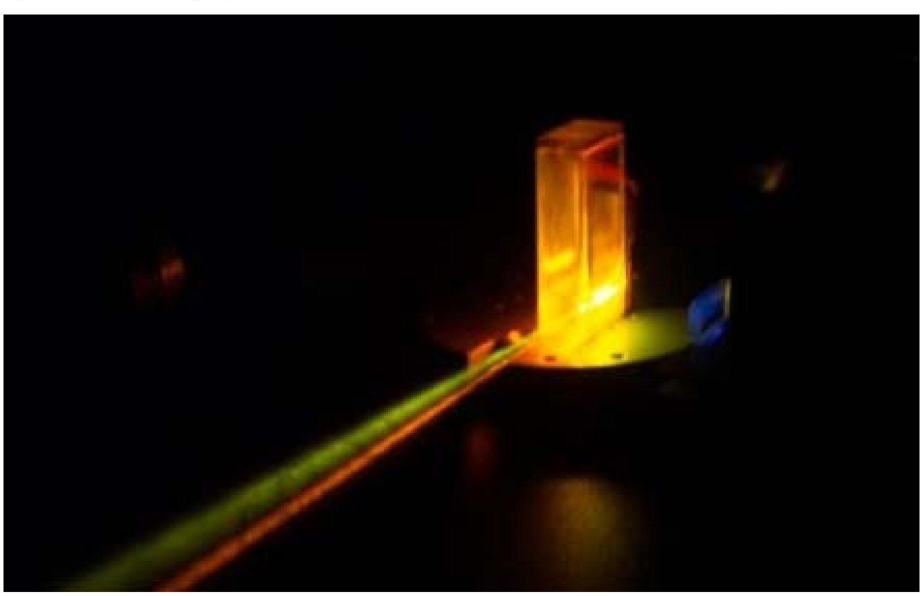


Fig. 6.31 Schematic diagram of a laminar-flow dye laser. The dye-laser cavity is formed by the reflector (radius 5 cm) and the output coupler. The other reflector (radius 7.5 cm) serves to fold the cavity so that the dye-laser output is parallel to the input pump beam. Dye stream flow is perpendicular to page.



Lamer Flow Dye Lasers

- To get CW flow dye through cavity
- Otherwise dye saturates – gives very short pulse
- Need fresh dye unless it returns to base state

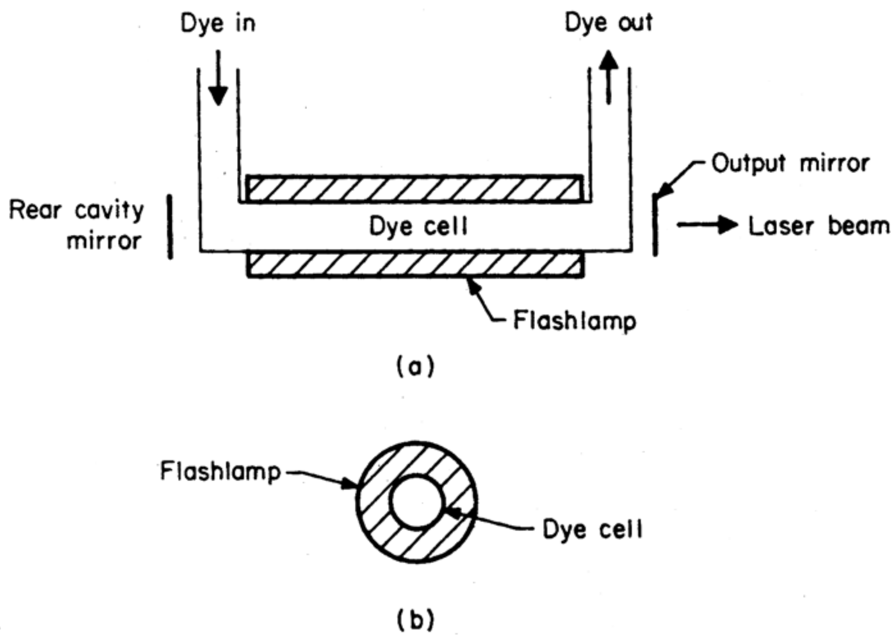
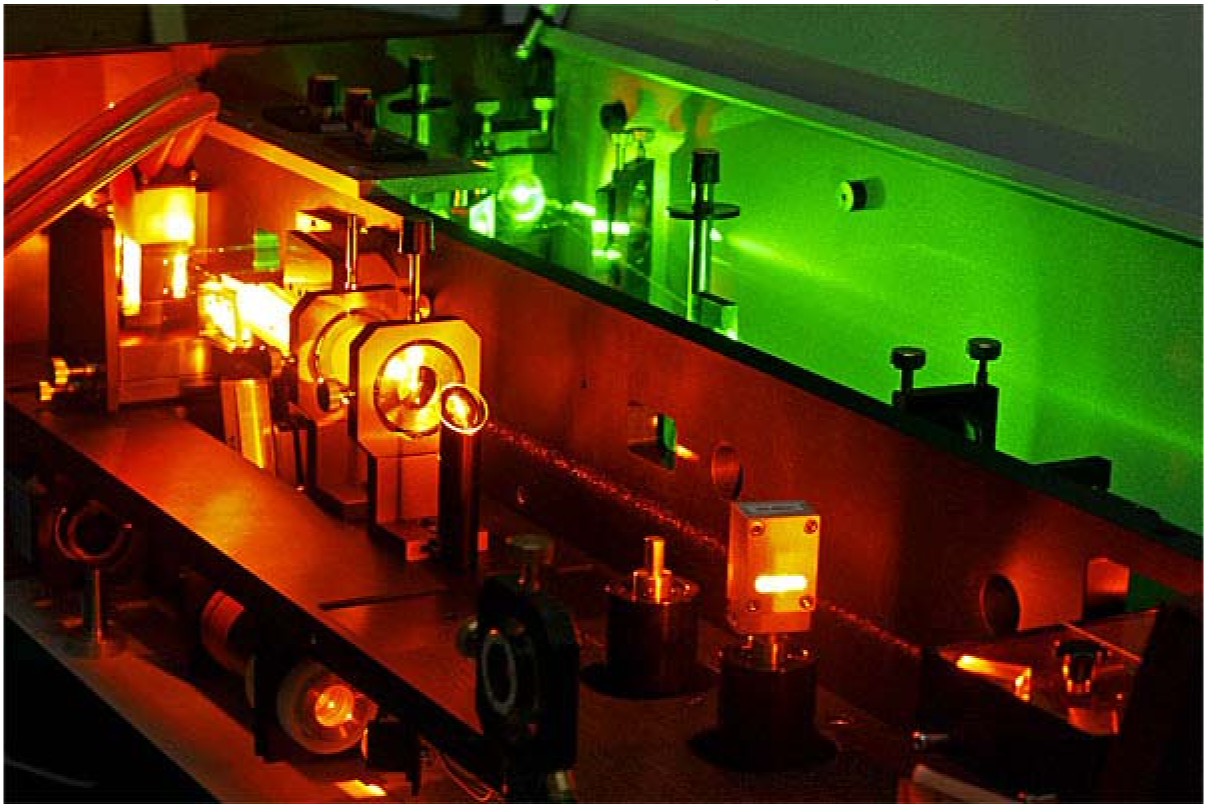


Figure 17.4 Design of a coaxial flashlamp dye laser. (*a*) Side view; (*b*) cross section.



Metal Vapour Lasers

- Use vapourized metal as a gain medium
- Developed by W. Silfvast (1966)
- Put metal in a cavity with a heater
- Vapourize metal, then pump metal vapour with current
- Walter at TRG (1966) then developed neutral metal vapour lasers
- Two types of metal vapour lasers:
  Ionized Metal vapour (He-Cd)
  Neutral Metal vapour (Cu)
- All operate by vaporizing metal in container

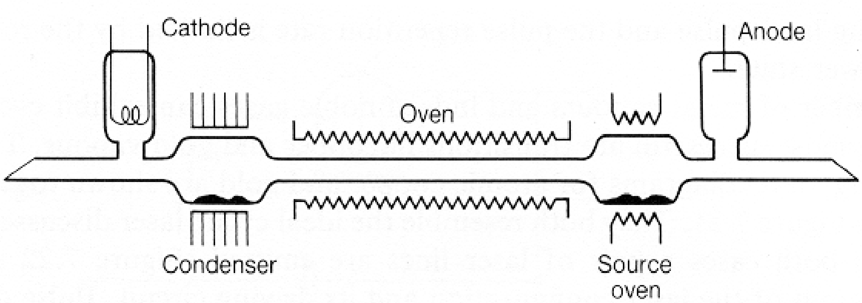


Figure 7.19 Design for discharge tube configuration used in catephoric flow He–Cd^+ laser.

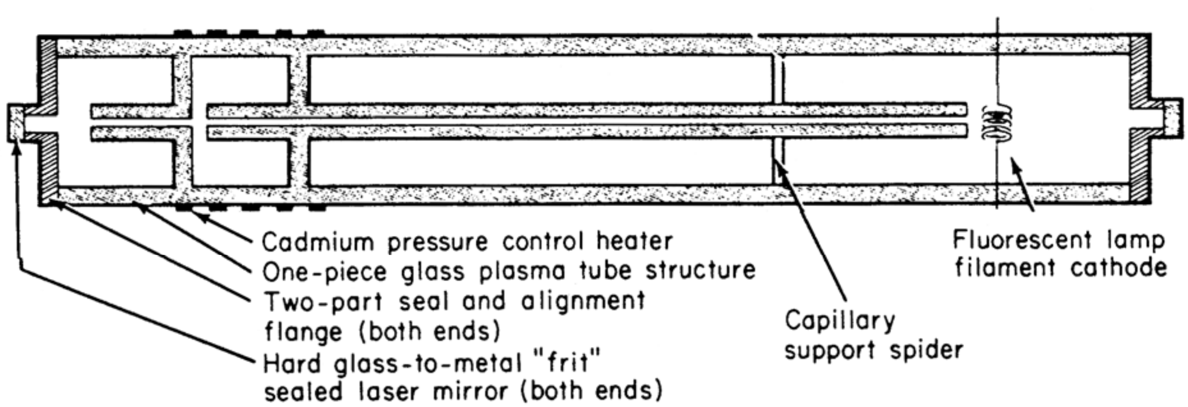


Figure 9.3 Coaxial tube design, with the bore suspended in the center of a cylindrical tube; optics are bonded directly to the tube. Helium and cadmium reservoirs are within the outer cylinder. (*Courtesy of Omnichrome.*)

Helium Cadmium Lasers

- Cadmium is heated to 250°C to vaporize
- He at 3-7 torr in container
- Electrical arc eg. 1500 V, 4 A through the chamber
- Cadmium reservoir contain 1 gm Cd/1000 Hrs operation
- Must compensate for Cd ions migrating to negative electrode
- Have both side tube and coaxial designs

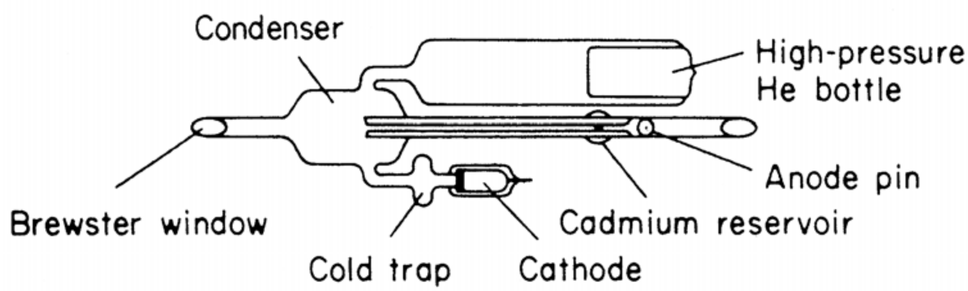


Figure 9.2 Simplified diagram of a He–Cd tube with high-pressure helium bottle to the side and a condenser and cold trap to catch cadmium metal. This tube has Brewster angle windows, but integral mirrors also can be attached. (*Courtesy of Liconix.*)

Large Omnichrome Helium-Cadmium Laser Tube

Helium Cadmium Lasers

- 3 excitement modes
- Penning ionization: He ion collides & ionizes Cd

$$He^{+} + Cd \rightarrow He + Cd^{+} + e^{-}$$

- He transfers energy to 2D Cd^{+} levels: lifetime 100 nsec
- Charge Transfer (dominant in neutral metal vapour)

$$He^{+} + Cd \rightarrow He + \left(Cd^{+}\right)^{*}$$

- Electron excitation

$$e^{-} + Cd \rightarrow Cd^{+} + 2e^{-}$$

$$e^{-} + Cd \rightarrow \left(Cd^{+}\right)^{*} + e^{-}$$

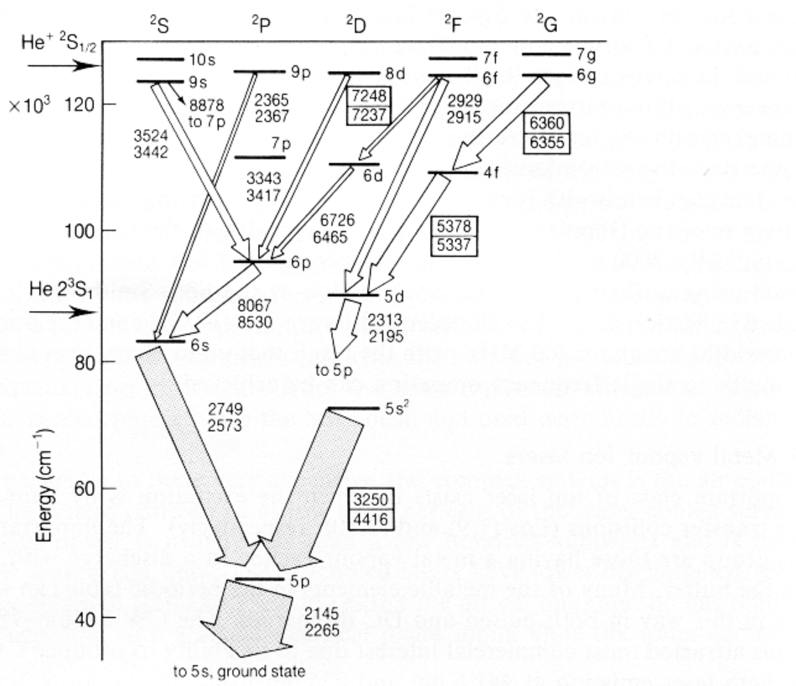


Figure 7.18 Energy diagram of the Cd^{+} ion showing the excitation routes for some laser transitions. (Data taken from Ref. 10.)

Helium Cadmium Lasers

- >12 lines available: selected by optics
  442 nm blue and 325 nm UV most important
- Can emit 636 nm red and 533.7 nm green lines also
- Used as source for Fluorescence of currency dies by US Treasury
- Slow to start due to warm up
- Generate 50 mW in TEM_{00} 150 mW in multimode, 2% efficient
- White light He-Cd mix red, green and blue to near white

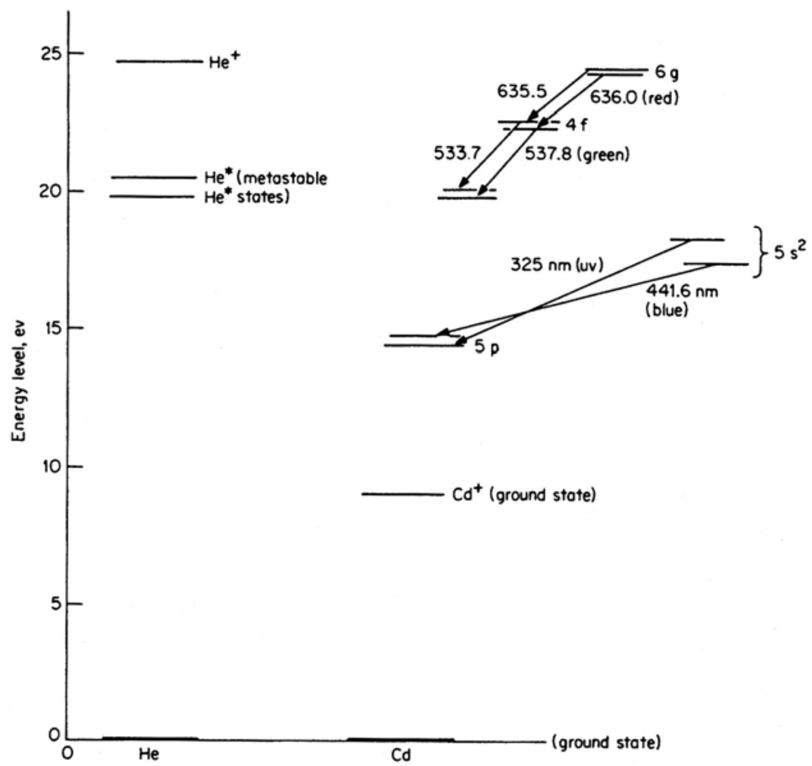


Figure 9.1 Energy levels in helium and cadmium, showing the laser transitions in the ultraviolet, blue, green, and red (wavelengths are in nanometers). The blue and ultraviolet lines are largely excited by energy transfer from the metastable helium excited states near 20 eV above ground level. Higher energy is needed to excite the red and green lines, which are emitted in a cascade process.

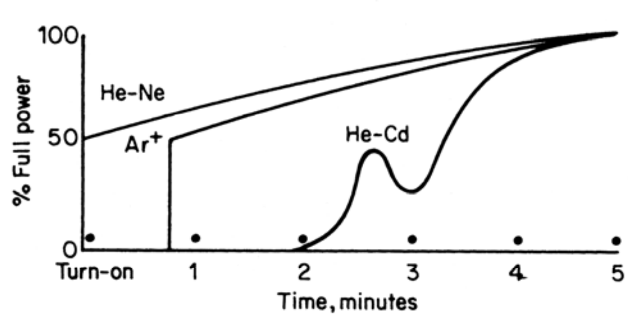


Figure 9.4 Types of power variations seen in He–Cd lasers during initial warm-up, as compared to those of He–Ne and argon ion lasers. (*Courtesy of Omnichrome.*)

Neutral Metal Vapour (Copper)

- First developed by Walter at TRW 1966
- Require vaporized metal: 1500 - 1800 ^{o}C
- creates 0.1 torr of metal gas pressure
- Copper and Gold most common types

TABLE 12.1 Wavelengths of Major Neutral Metal Vapor Laser Lines, with Relative Powers That Might Be Expected from Devices of Comparable Scale*

Element	Wavelength, nm	Relative power	Remarks
Copper	511, 578	1	
Gold	628	0.1–0.3	
	312	Low	Secondary line
Barium	1130	Low	Ba liquid a problem
	1500	0.3–0.5	Ba liquid a problem
Lead	722.9	0.2–0.3	1000–1100°C temperature
Manganese	534	0.2–0.3	Mn vapor a problem
	1290		Mn vapor a problem
Calcium	852.4	—	
	866.2	—	

*For copper vapor and the 628-nm gold line, values are for commercial devices; other results are from laboratory experiments. Laser action has been demonstrated experimentally on many other lines.

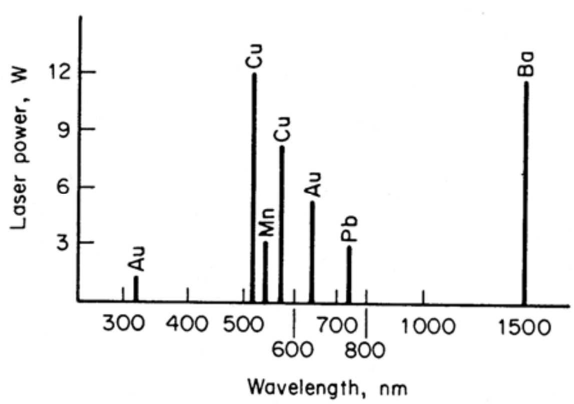
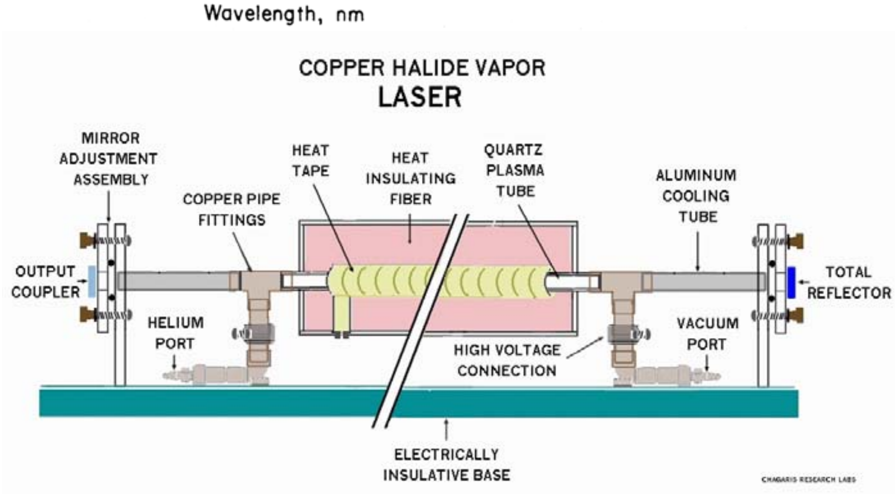


Figure 12.3 Wavelengths and relative intensities of some major neutral metal vapor laser lines. (*Courtesy of Quentron Optics Pty. Ltd.*)



Copper Vapour Lasers

- Use electrical arc to excite vapour
- Add Neon at 25 torr to improve discharge
- Electron or ion collision excite Cu
- Upper state 10 msec metastable lifetime
- Emit at 510.6 green and 578 nm yellow lines
- Pulsed: 100 nsec

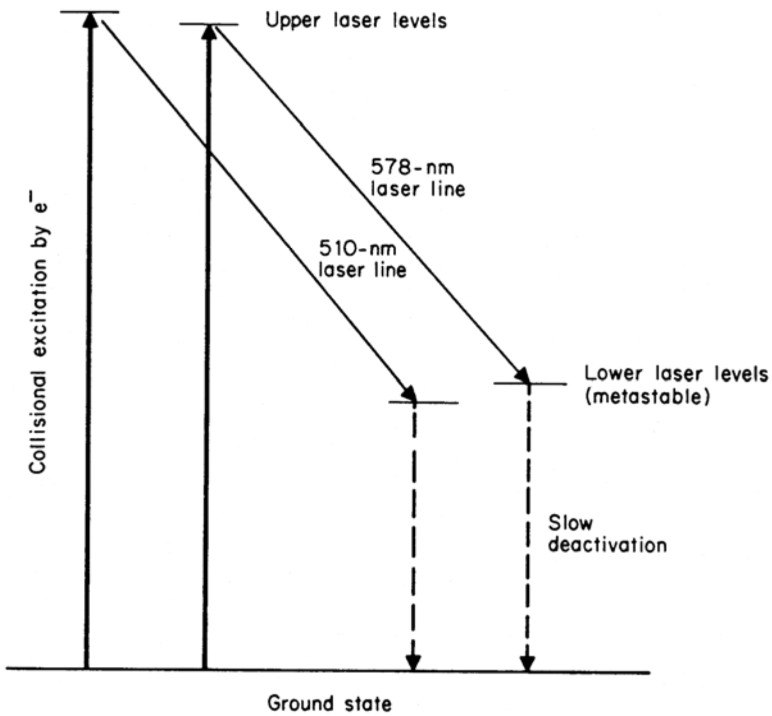
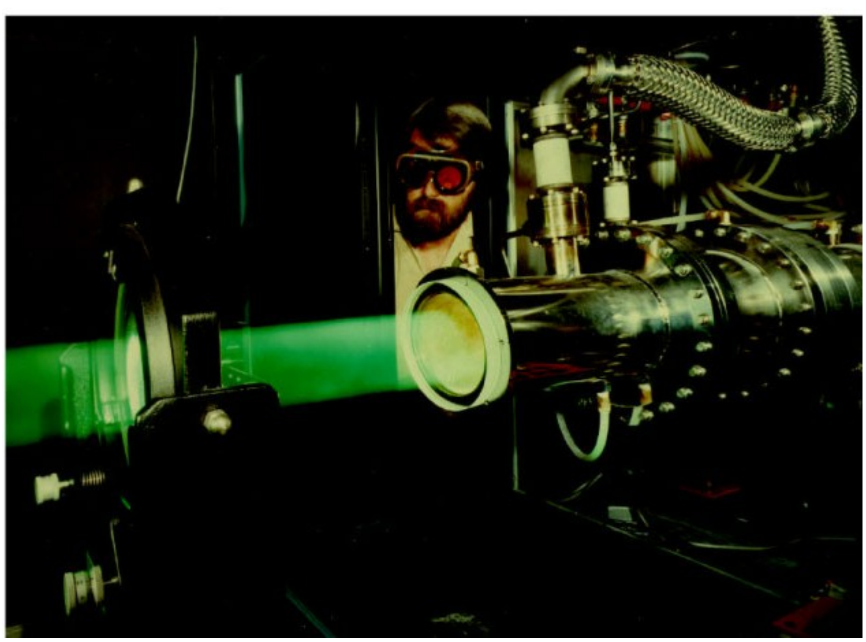


Figure 12.1 Energy levels and laser transitions in copper vapor.

COPPER VAPOR LASER



Copper Metal Vapour & Isotope Separation

- Ratio of lines in Cu laser depends on temperature
- Commercial application to pump dye lasers for photochemistry
- Major application: Atomic Vapor Laser Isotope Separation AVLIS
- Isotopes: same element, different number of neutrons in nucleus
- Thus different atomic weight but same atomic number
- Eg. Uranium: U^{238} does not fission but 99.3% of U in earth
- U^{235} which fissions for atomic bombs or reactors 0.71%
- Need to enrich amount of U^{235} for light water reactors (~1-4%)
- Atomic bombs need ~98% U^{235}
- Different isotopes have slightly different wavelengths
- Tune laser to line that ionize one isotope (U^{235}) but not U^{238}
- Then Electric field can separate ionized from unionized vapour
- Get several % enrichment per attachment
- Much greater than diffusion or centrifuge enrichment
- U^{235} and Pu^{239} separation
- Lawrence Livermore Labs major developer: cancelled 1999

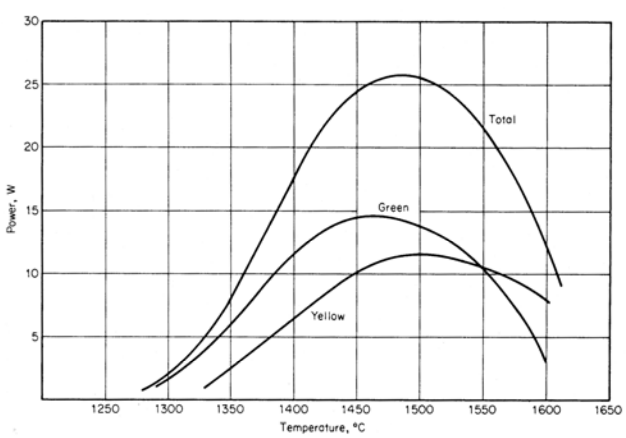
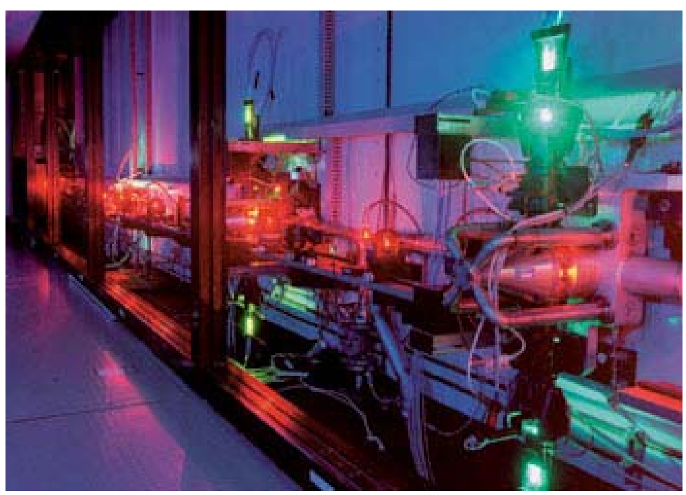


Figure 12.2 Relative strengths of copper vapor lines as a function of temperature. (*Courtesy of Oxford Lasers Ltd.*)



Silex: Newest Laser Uranium Enrichment

- Laser U enrichment advance is the Silex process
- Developed in Australia ~2000
- Uses modified CO_2 laser to pump parahydrogen
- Parahydrogen is H where the spins are aligned
- Creates 16 um long wavelength that is absorbed by $U^{235}F_6$
- Separates the isotopes