Scope of the Lecture

1. Atomic gas lasers
2. Ion-gas lasers
3. Molecular lasers
4. Excimer lasers
5. Chemical lasers
6. Free electron lasers
7. How to choose a laser

Reading: Ch. 10

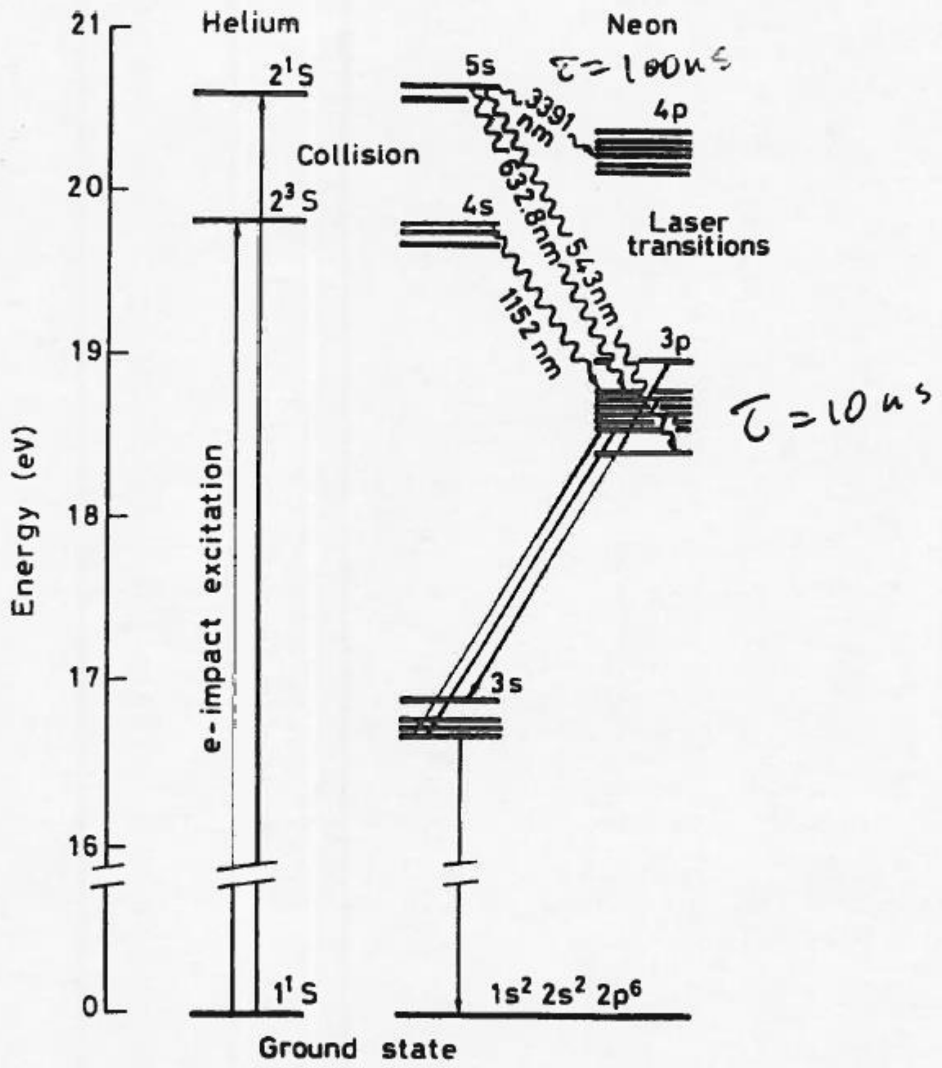


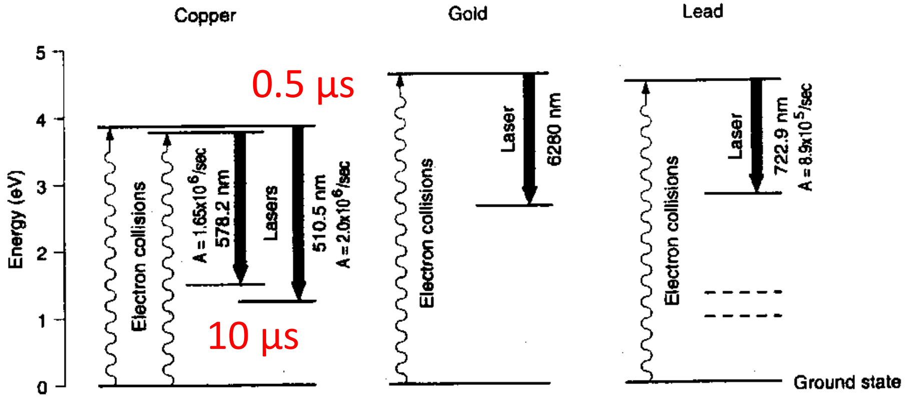
FIG. 10.1. Relevant energy levels of the He-Ne laser.

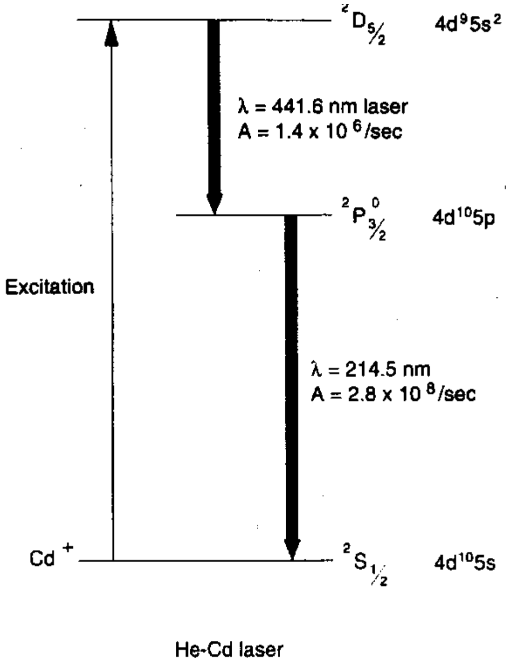
Gas lasers: Metal vapour

Cu: 510 nm, 578 nm
- Self-terminated 3-level system
- Applications: material processing, dye-amplifier pumping

He-Cd: 441, 353, 325
- Up to 200 mW CW
- Applications: lithography, , microscopy

Inefficient, bulky, limited lifetime





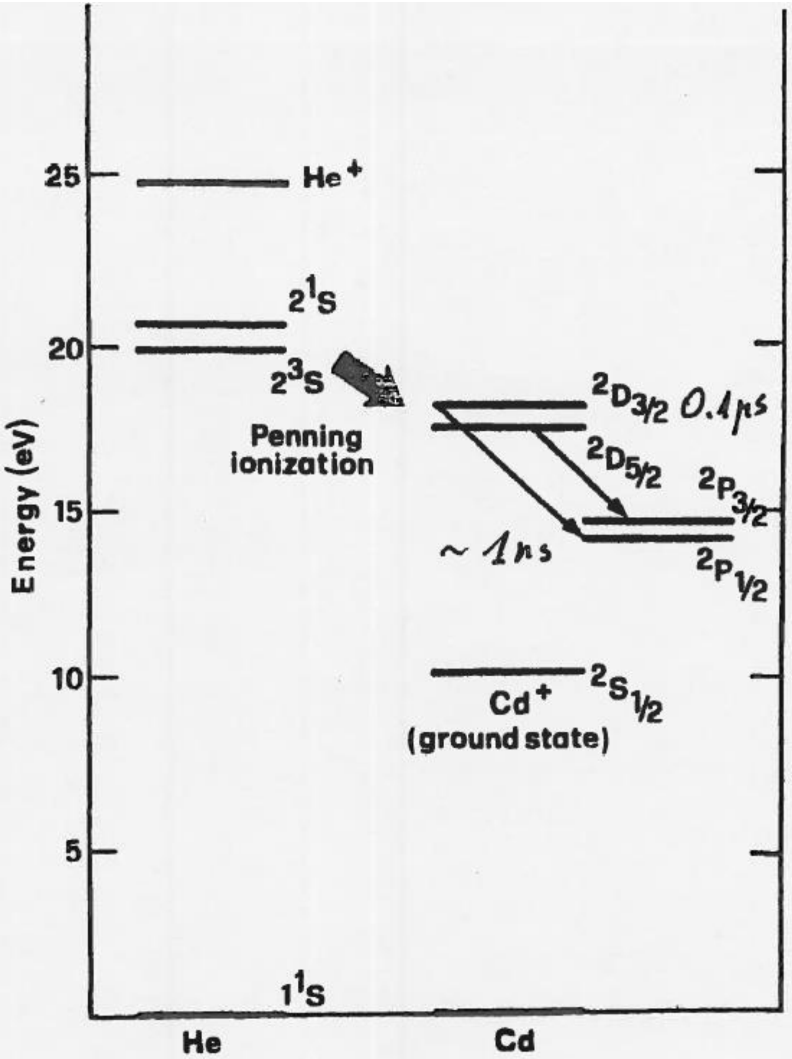
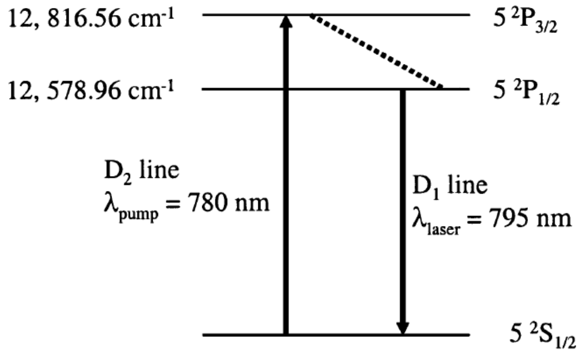


FIG. 10.8. Relevant energy levels in the He-Cd laser.

Gas lasers: Alkali matel vapour (Rb, K, Cs)

First laser diode-pumped gas laser: Rb (2003)

- 3-level system
- Low quantum defect (2%): large efficiency (98%)
- Dipole-allowed transitions: careful design required
- Operation temperature 120 C
- Designs for MW-class CW lasers investigated
- Applications: material processing, power beaming



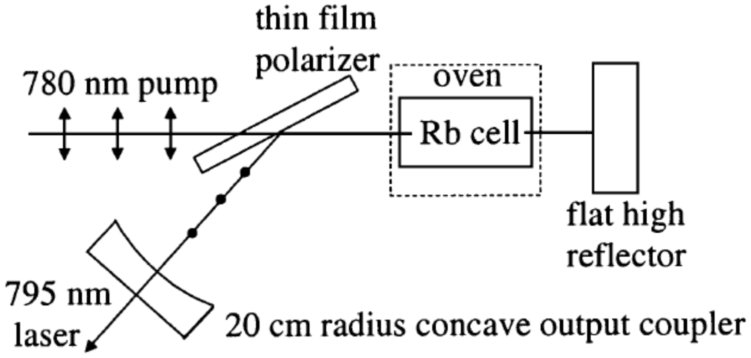


Table 1. Atomic Rb Vapor Laser Parameters

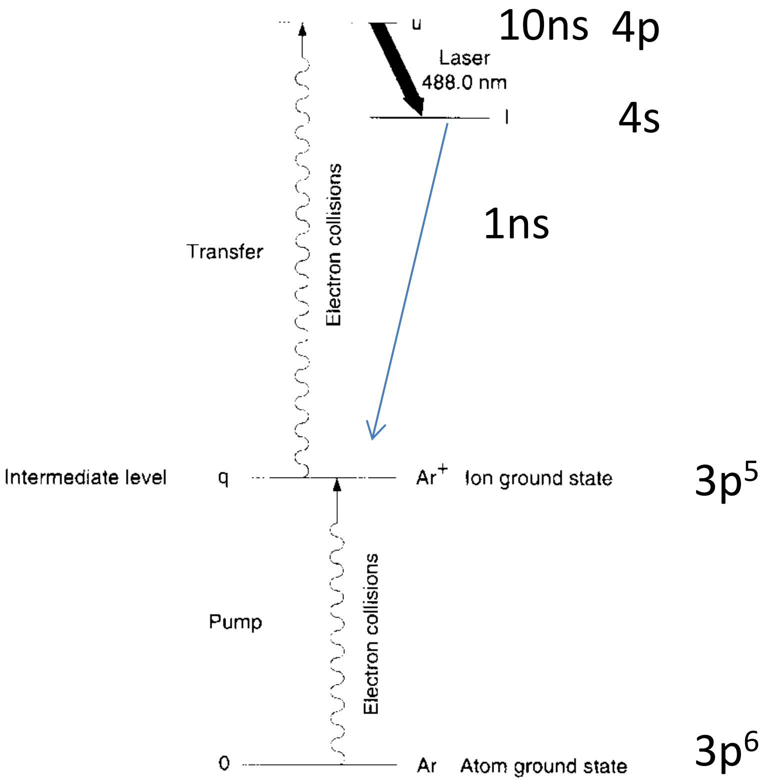
He buffer gas	525 Torr at room temperature
Ethane buffer gas	75 Torr at room temperature
Ti:sapphire laser pump source	780 nm with 0.1 nm FWHM
D_2 transition line	780 nm with 0.024 nm FWHM
Peak absorption cross section (D_2)	4.6×10^{-13} cm^2
Rb number density	$1.7 \times 10^{13}/\text{cm}^3$
Laser transition cross section (D_1)	2.65×10^{-13} cm^2
Excited-state radiative lifetime	28 ns
Effective pump saturation intensity (D_2)	243 W/cm^2
Laser saturation intensity (D_1)	33 W/cm^2

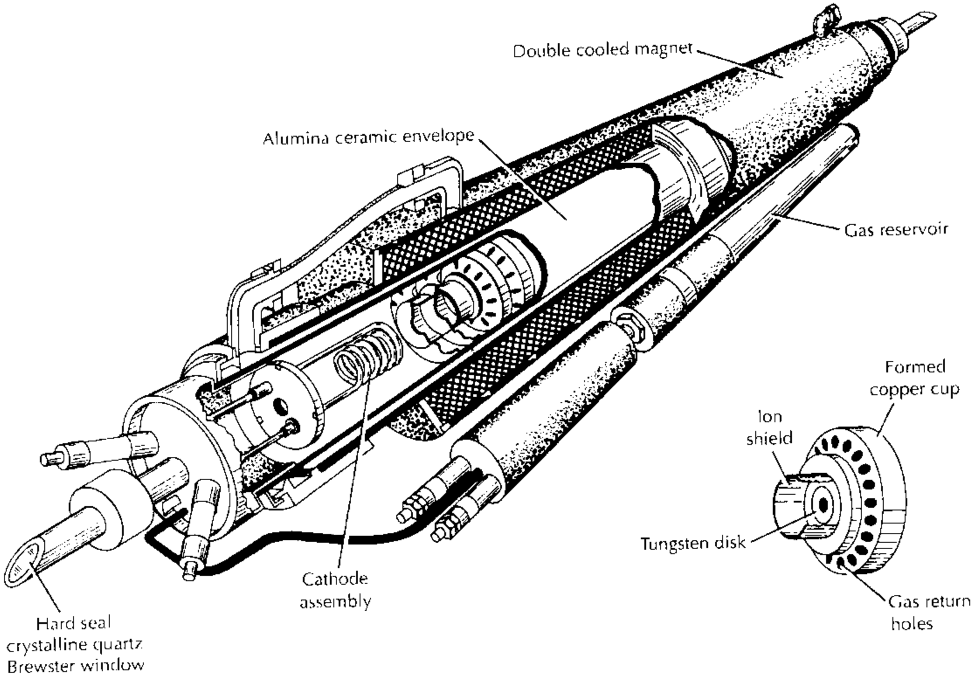
Gas lasers: Noble gas lasers Ar^+, Kr^+

- CW, or mode-locked
- Visible lines:

Ar: 488 nm, 514 nm, 244 nm
Kr: 530 nm, 568 nm, 647 nm, 676 nm

- Up to 20W
- Applications: holography, microscopy
- Inefficient, bulky, limited lifetime





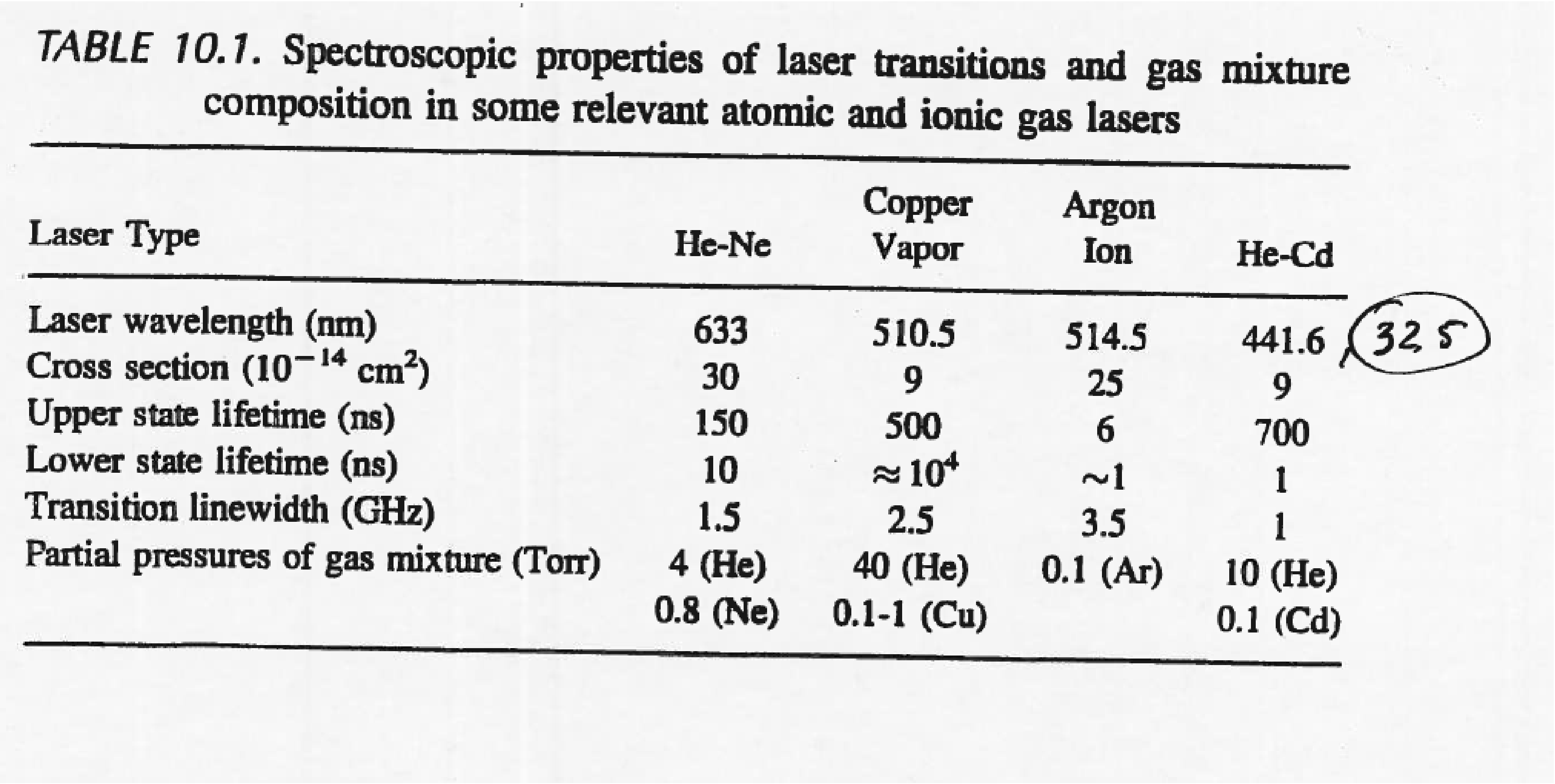


TABLE 10.1. **Spectroscopic properties of laser transitions and gas mixture composition in some relevant atomic and ionic gas lasers**

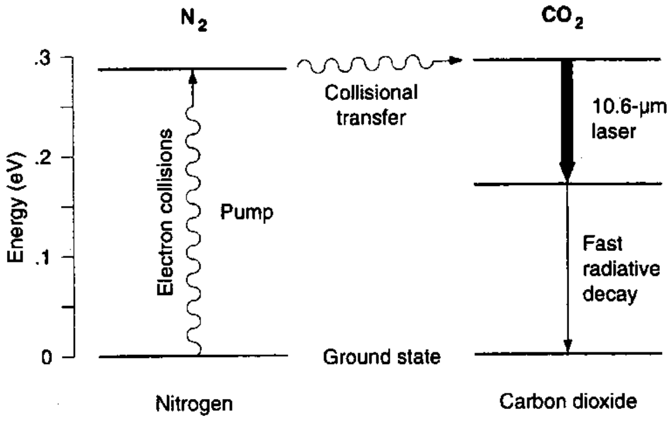
Laser Type	He-Ne	Copper Vapor	Argon Ion	He-Cd
Laser wavelength (nm)	633	510.5	514.5	441.6 325
Cross section (10^{-14} cm^2)	30	9	25	9
Upper state lifetime (ns)	150	500	6	700
Lower state lifetime (ns)	10	$\approx 10^4$	~ 1	1
Transition linewidth (GHz)	1.5	2.5	3.5	1
Partial pressures of gas mixture (Torr)	4 (He) 0.8 (Ne)	40 (He) 0.1-1 (Cu)	0.1 (Ar)	10 (He) 0.1 (Cd)

Gas lasers: Molecular lasers

CO_2: ro-vibrational transitions at 9µm -10 µm
CO: ro-vibrational transitions at 4µm – 5 µm

High-pressure (1atm) operation possible

- CO_2 CW powers in 100 kW class
- CW, Q-switched, mode-locked
- Applications: material processing, welding, cutting, etc.



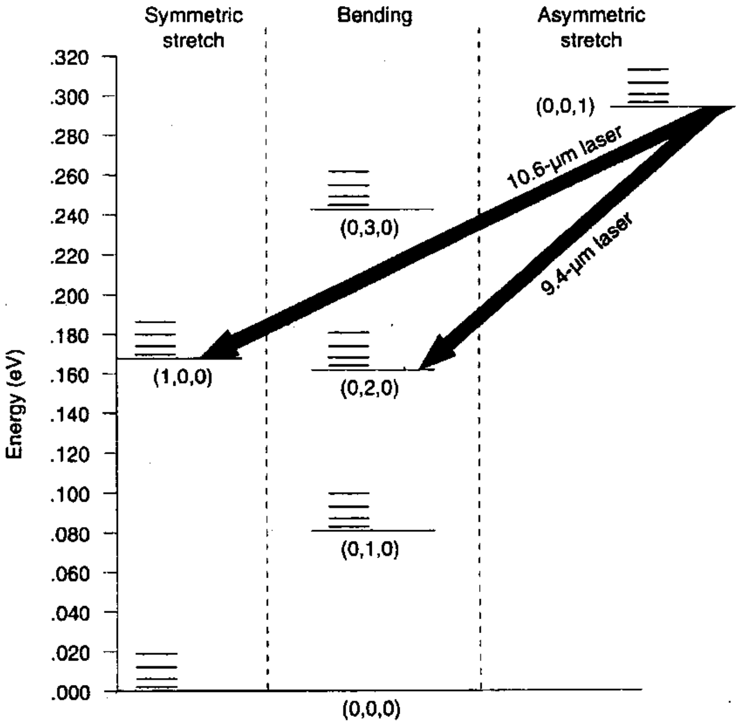


Figure 5-6(b) Laser transitions between vibrational levels of the CO_2 molecule

Laser employing electronic transitions in molecules

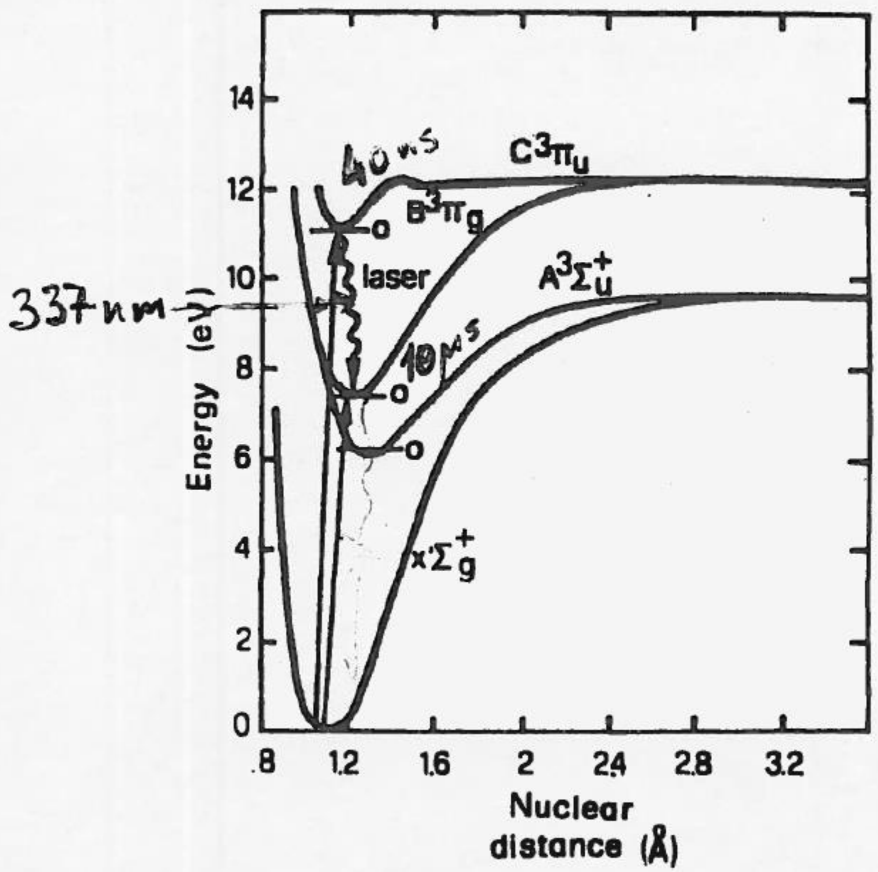


FIG. 10.19. Energy states of the N_2 molecule. For simplicity, only the lowest vibrational level ($v = 0$) is shown for each electronic state.

Gas lasers: Excimer lasers

Noble gas+halogen+He: XeF 353 nm, XeCl 308 nm, KrF 248 nm, ArF 193nm.

1 atm operation

- Pulsed ~10 ns, J class
- Applications: lithography, material processing, dye-amplifier pumping
- Corrosive gasses, limited lifetime, safety issues, poor beam quality.

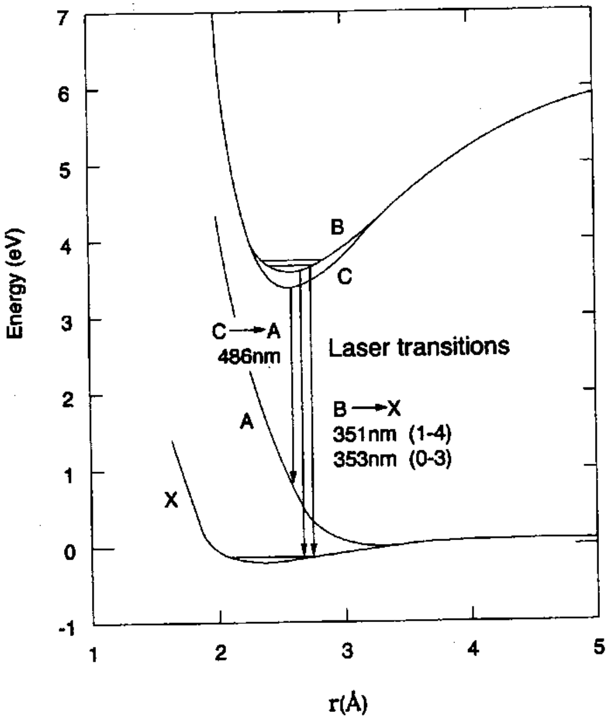
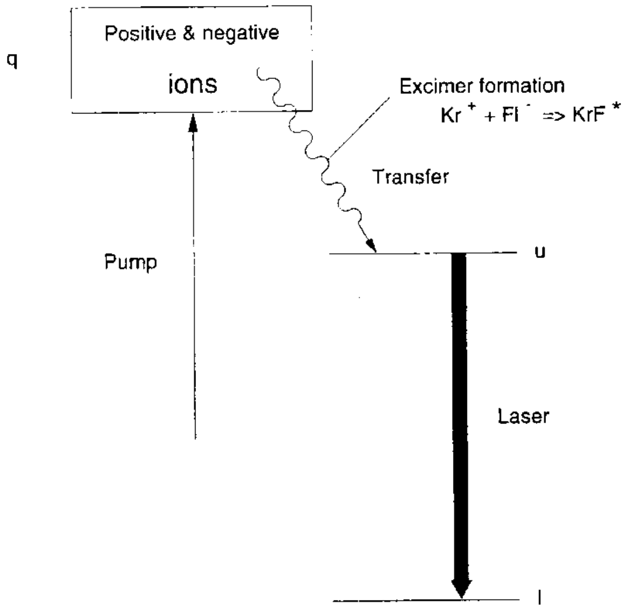


Figure 5-9 Molecular energy levels involved in a xenon–fluoride excimer laser



Chemical Lasers (ro-vibrational transitions)

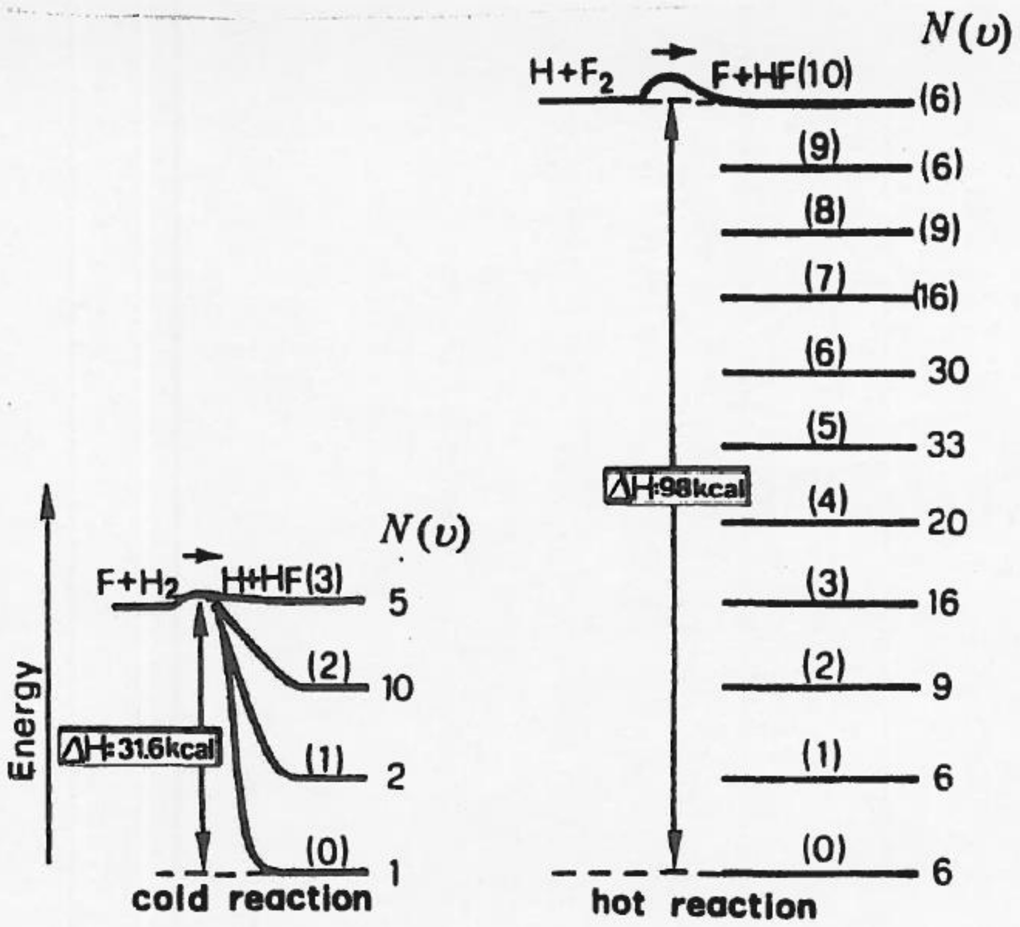


FIG. 10.22. Pumping vibrational levels of the HF molecule by the two reactions (a) $F + H_2 \rightarrow HF^* + H$ and (b) $H + F_2 \rightarrow HF^* + F$. The relative populations $N(v)$ of each vibrational state of quantum number v are also indicated in the two figures.

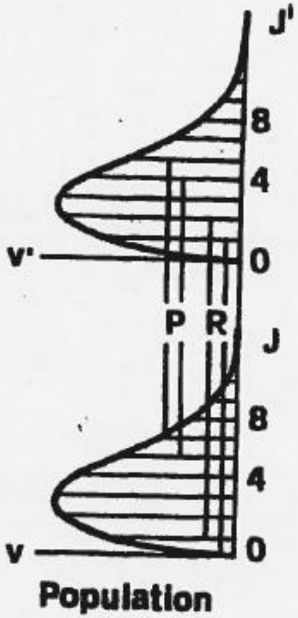
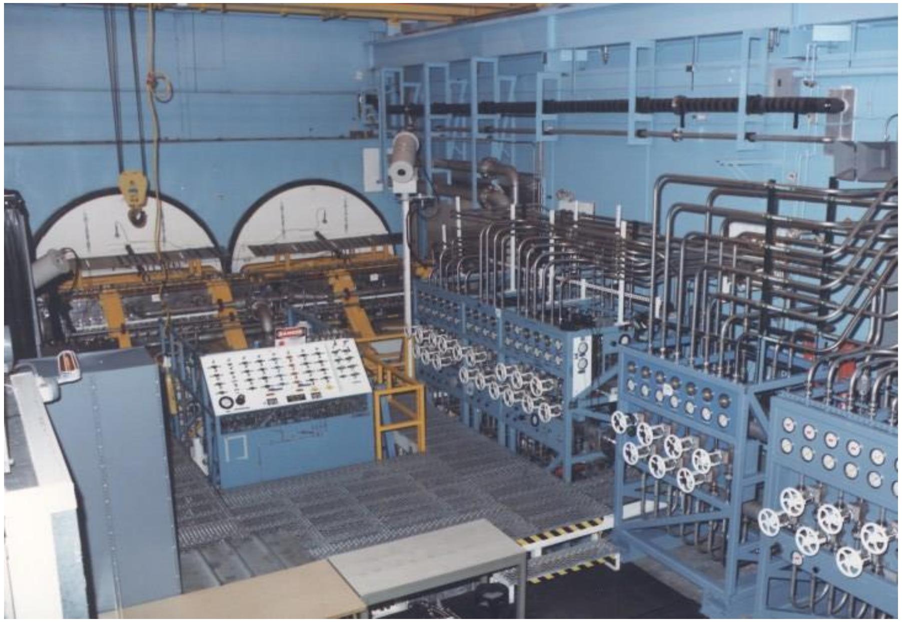


FIG. 10.18. Partial inversion between two vibrational transitions (v and v') with the same total population.

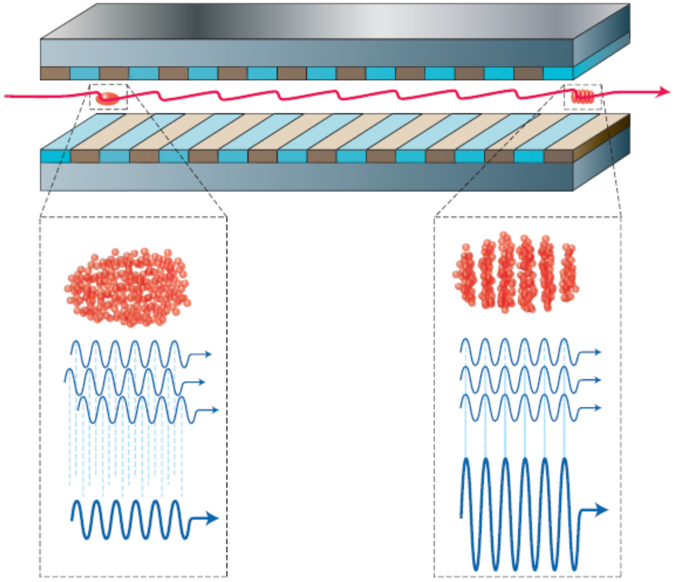
Chemical lasers



CW MW-class DF laser 3.6 µm – 4.2 µm

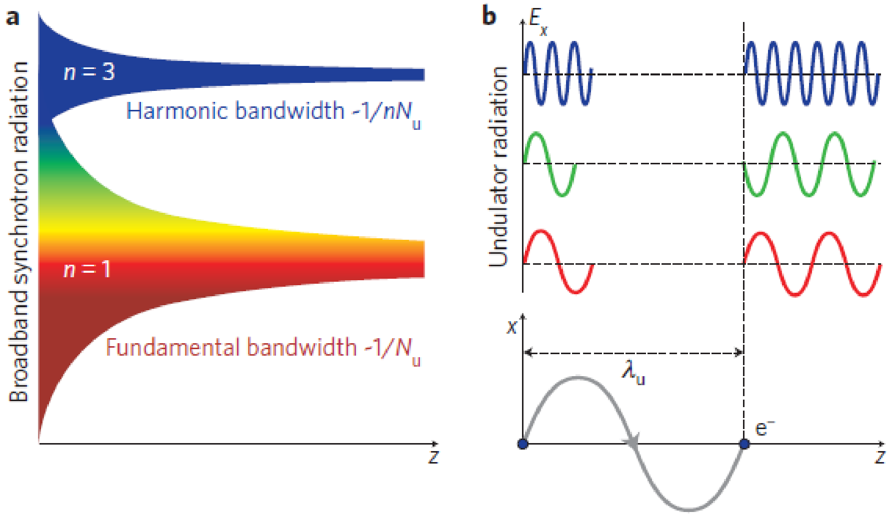
MIRACL DF laser:
High Energy Laser Systems Test Facility
White Sands Missile Range, New Mexico
Cost: 800 M$

FELs



Incoherent emission: electrons randomly phased

Coherent emission: electrons bunched at radiation wavelength



$$\lambda_n = \frac{\lambda_u}{n}\left(\frac{1-\bar{v}_z/c}{\bar{v}_z/c}\right);$$

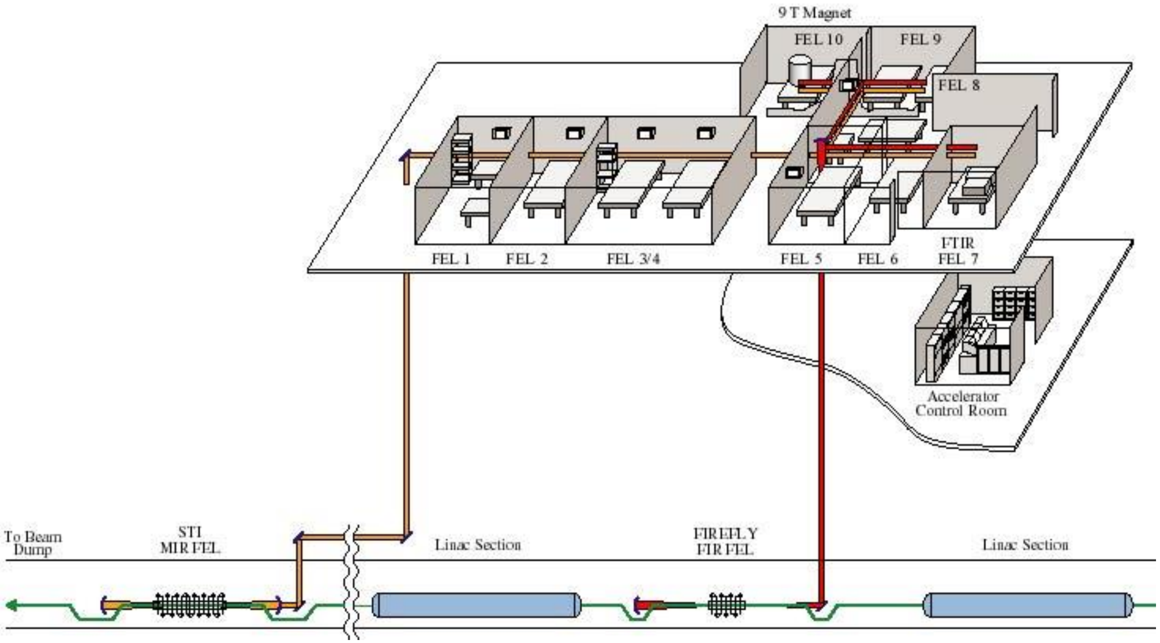
TABLE 14-11

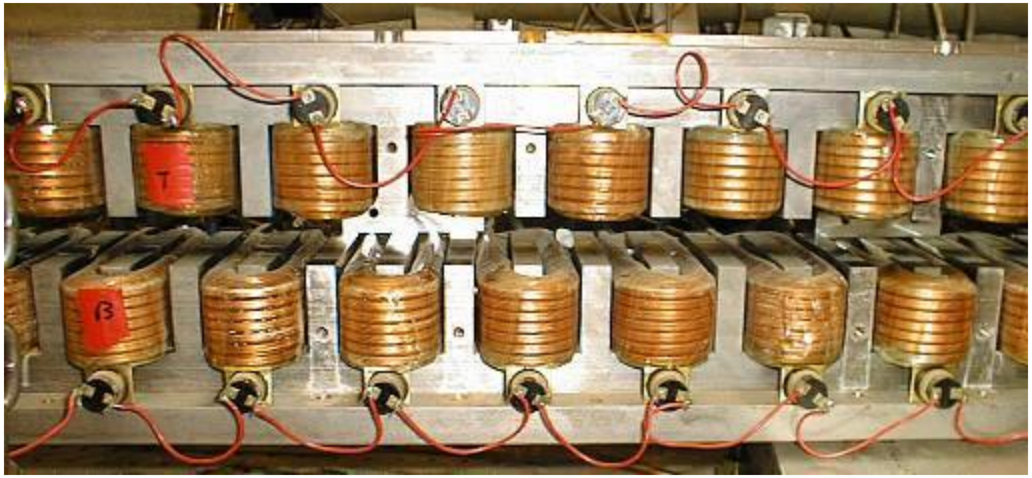
Typical Free-Electron Laser Parameters

Laser wavelengths (λ_{ul})	2.48 nm to 8 mm
Fractional laser bandwidth	10^{-3} to 10^{-7}
Gain per pass	1–300%
Laser gain-medium length (L)	1–25 m
Pumping method	high-energy electron beam
Electron beam peak current	0.1–800 A
Electron beam energy	200 kV to 1 GeV
Electron beam pulse length	2 ps to cw
Undulator magnet period	5 mm to 0.2 m
Magnetic field strength	0.02–1.0 T
Output power	up to 1 GW (pulsed), up to 10 W (cw)
Mode	TEM_{00}

- W class CW or ultrashort pulse
- Applications: research
- Major facility, large running costs

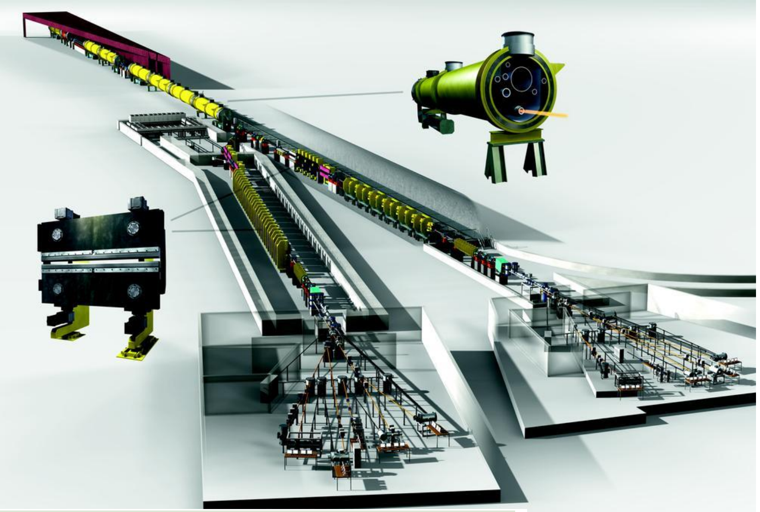
FEL Center Laboratory Layout





FEL: FLASH, European XFEL Hamburg

3.4 km long linear e –accelerator
Superconducting RF cavity acceleration
Electron E~17.5 GeV



τ<100 fs

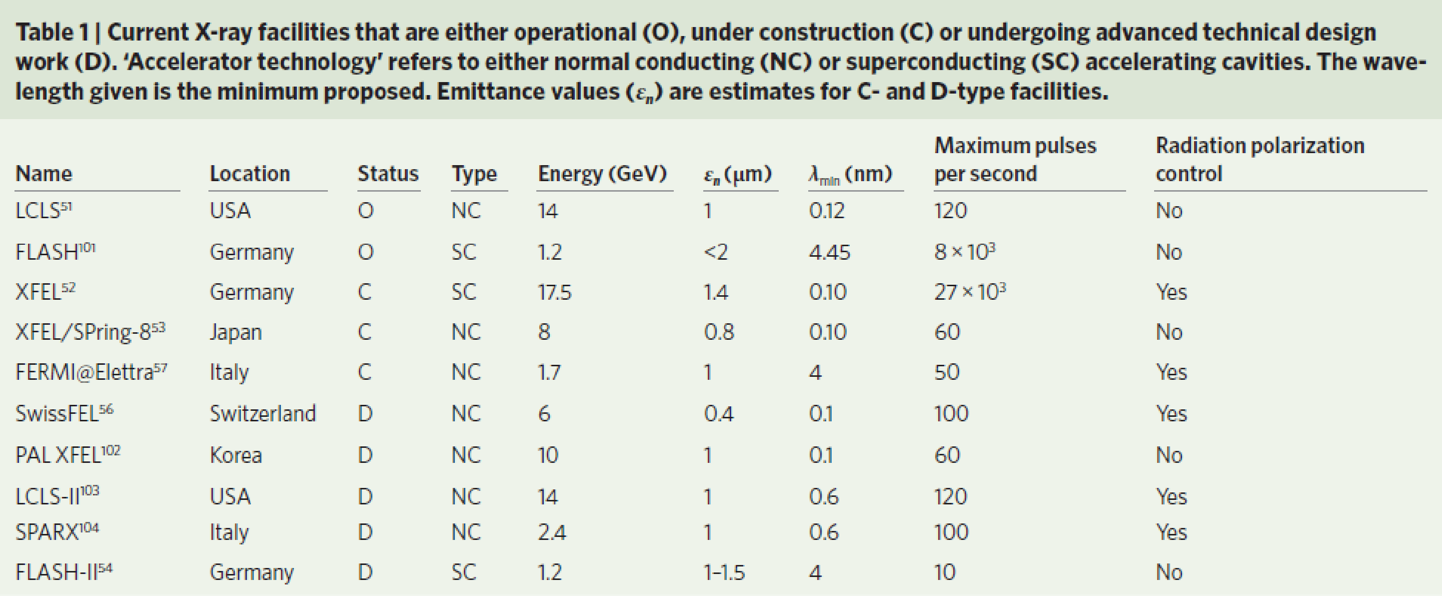


Table 1 | Current X-ray facilities that are either operational (O), under construction (C) or undergoing advanced technical design work (D). 'Accelerator technology' refers to either normal conducting (NC) or superconducting (SC) accelerating cavities. The wavelength given is the minimum proposed. Emittance values (ε_n) are estimates for C- and D-type facilities.

Name	Location	Status	Type	Energy (GeV)	ε_n (μm)	λ_{min} (nm)	Maximum pulses per second	Radiation polarization control
LCLS[51]	USA	O	NC	14	1	0.12	120	No
FLASH[101]	Germany	O	SC	1.2	<2	4.45	8×10^3	No
XFEL[52]	Germany	C	SC	17.5	1.4	0.10	27×10^3	Yes
XFEL/SPring-8[53]	Japan	C	NC	8	0.8	0.10	60	No
FERMI@Elettra[57]	Italy	C	NC	1.7	1	4	50	Yes
SwissFEL[56]	Switzerland	D	NC	6	0.4	0.1	100	Yes
PAL XFEL[102]	Korea	D	NC	10	1	0.1	60	No
LCLS-II[103]	USA	D	NC	14	1	0.6	120	Yes
SPARX[104]	Italy	D	NC	2.4	1	0.6	100	Yes
FLASH-II[54]	Germany	D	SC	1.2	1-1.5	4	10	No

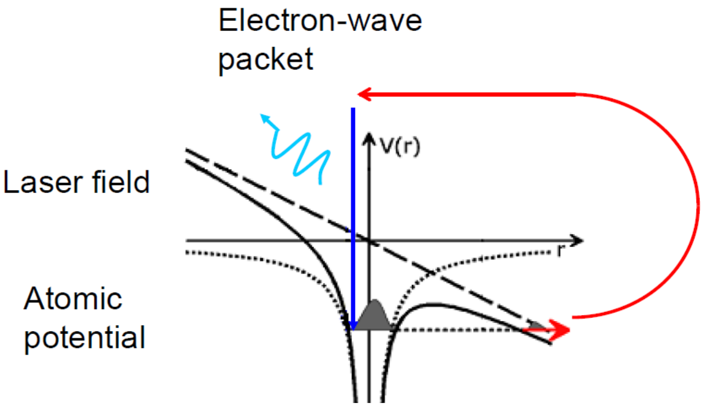
Comissioning costs 1.22 B€. Annual running costs: ~118 M€

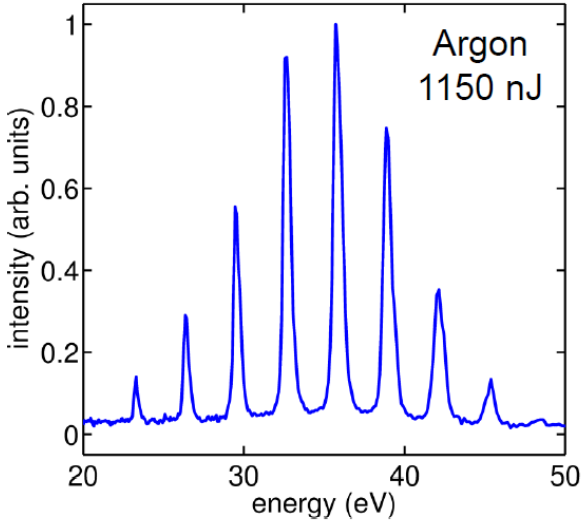
Coherent soft x-ray generation

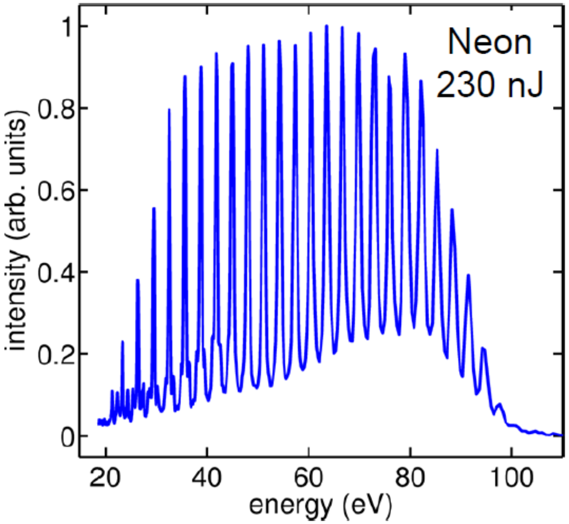
- Atom ionization by electric field of the optical pulse
- Three-step process: e- tunneling, e- acceleration, e-recombination
- High-harmonic generation
- Attosecond pulse train

$$m\frac{d\vec{v}}{dt} = -e\vec{E}$$

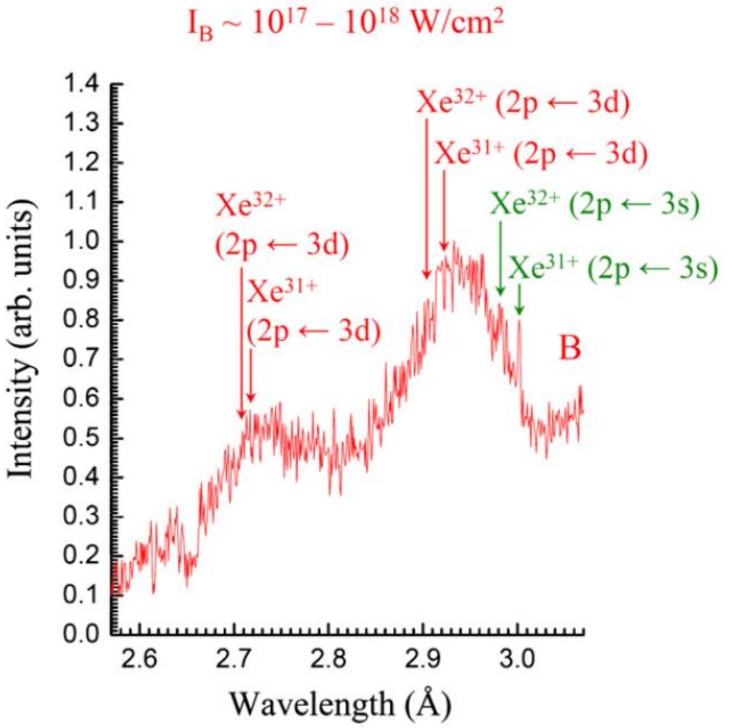
$$E_{ph} = \tfrac{1}{2}mv^2 + I_p$$

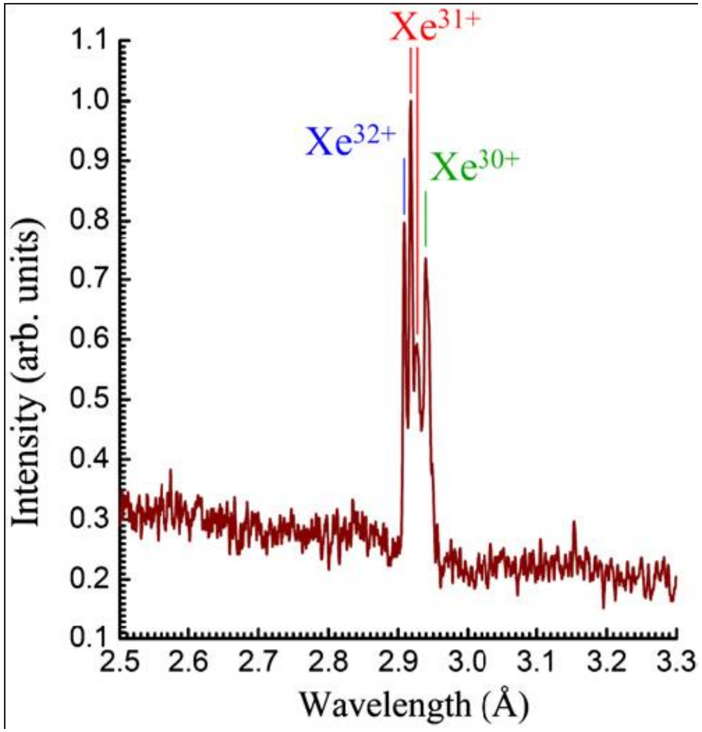


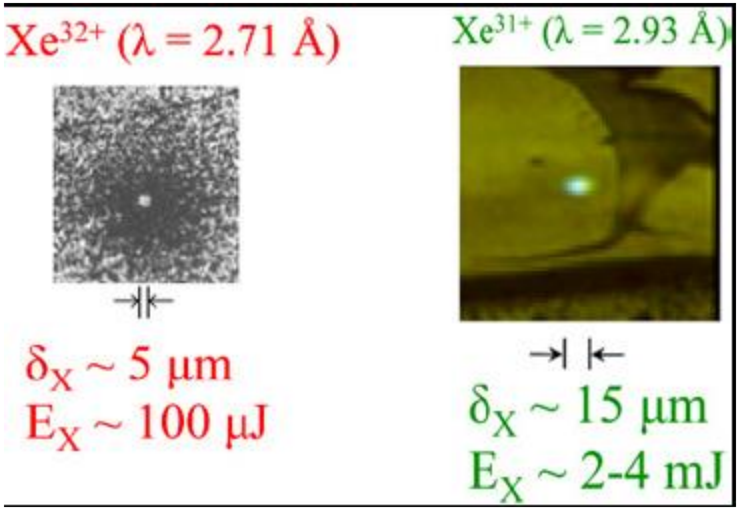




Coherent Hard X-ray generation



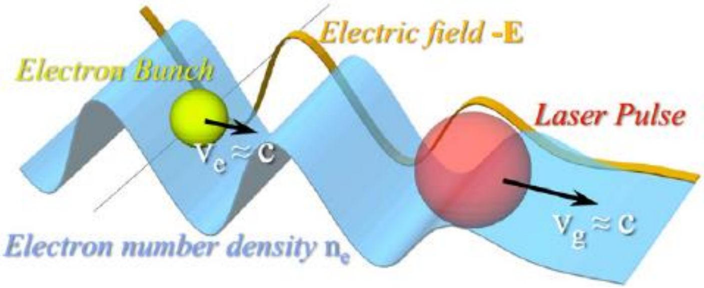




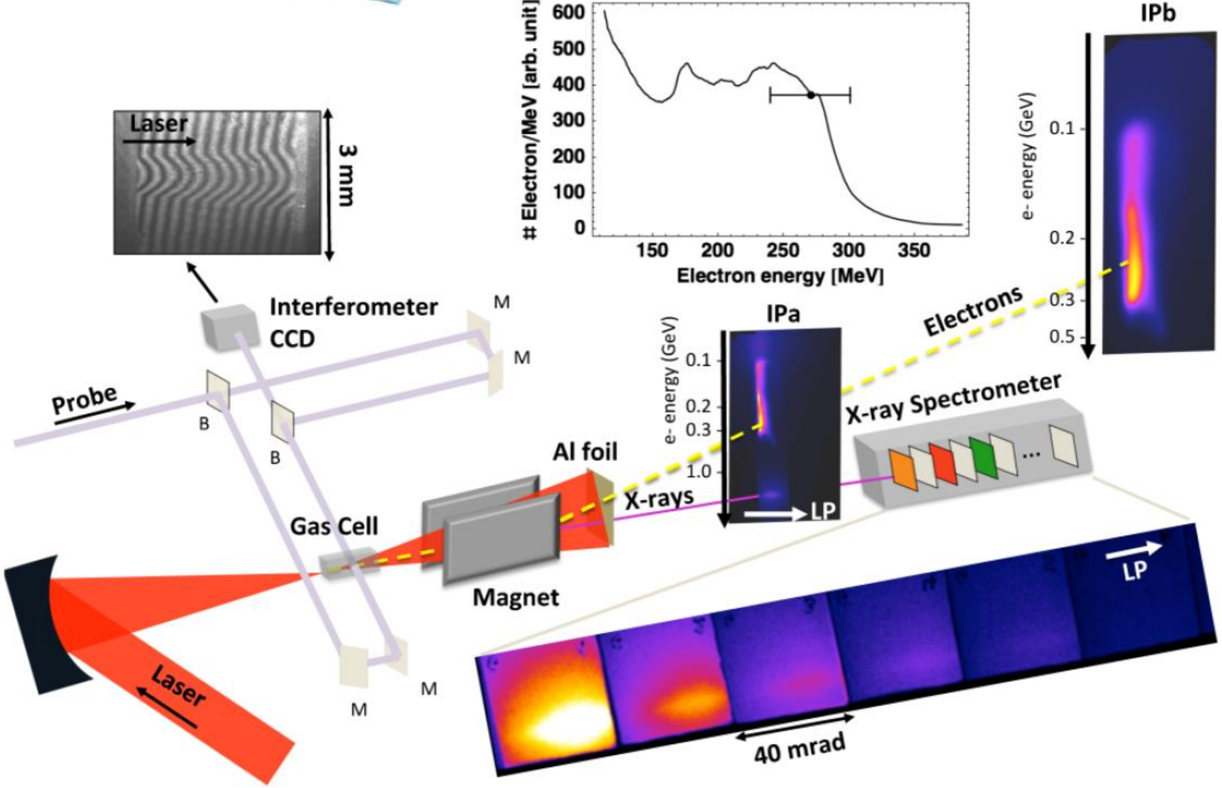
- Xe^{54}: (Kr)$4d^{10}5s^{2}5p^{6}$
- Xe(L shell), hollow-core multiphoton excitation
- Radiative lifetime ~50 fs (allowed x-ray range)
- Exitation @ 248 nm, τ<50fs, I>10^{16}W/cm²
- X-ray peak power can exceed PW (10^{15} W)
- Pulse length should be about 35 as (10^{-18} s)

J. Phys. B: At. Mol. Opt. Phys. **40** (2007) F131–F143

X-rays in laser-driven plasma wakefield acceleration

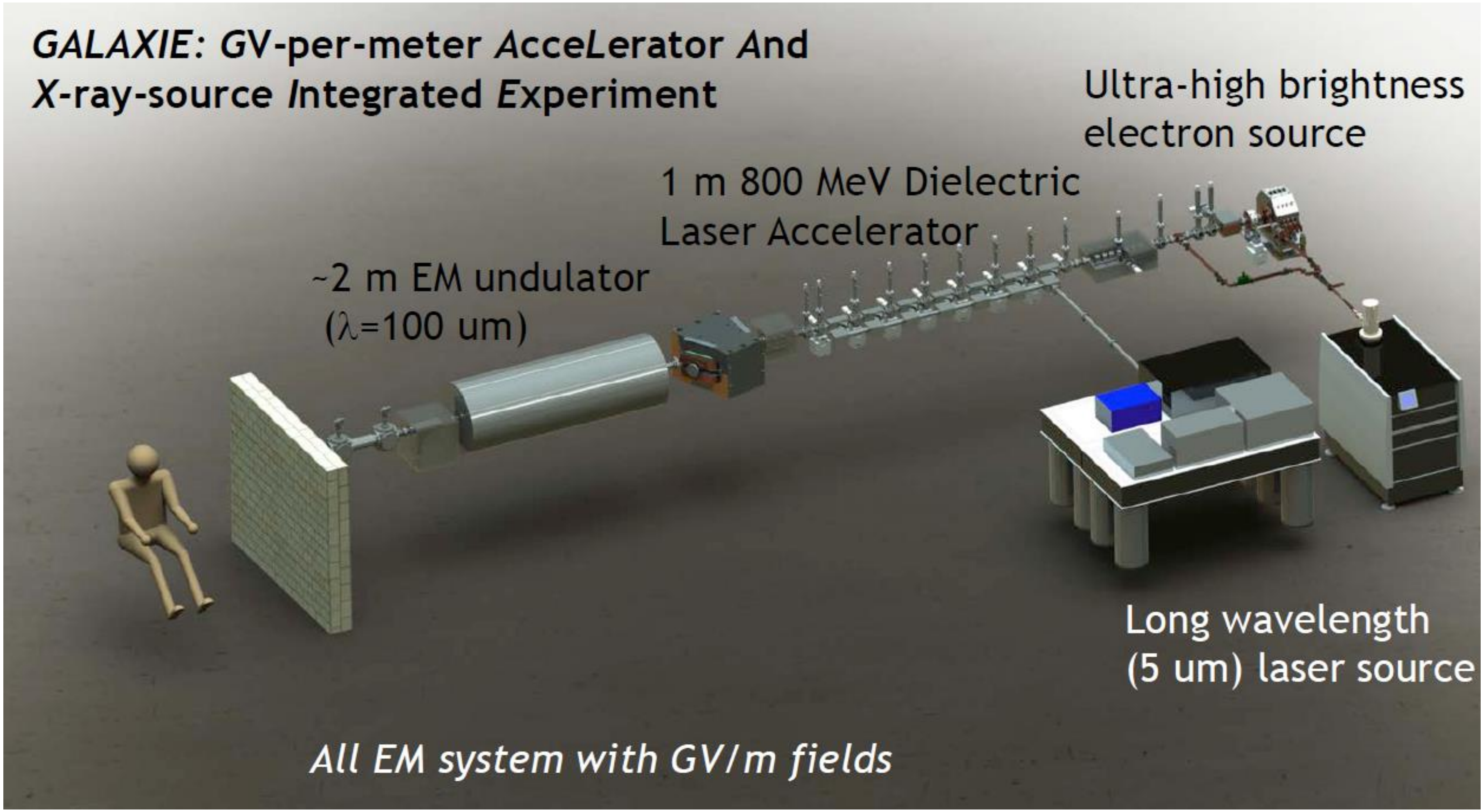


200 TW laser: 60fs, 12 J, 1 shot/30 min



F. Albert et al, Phys. Rev. Lett. 111, 235004 (2013)

Laser-driven accelerators
”table-top” X-ray FELs

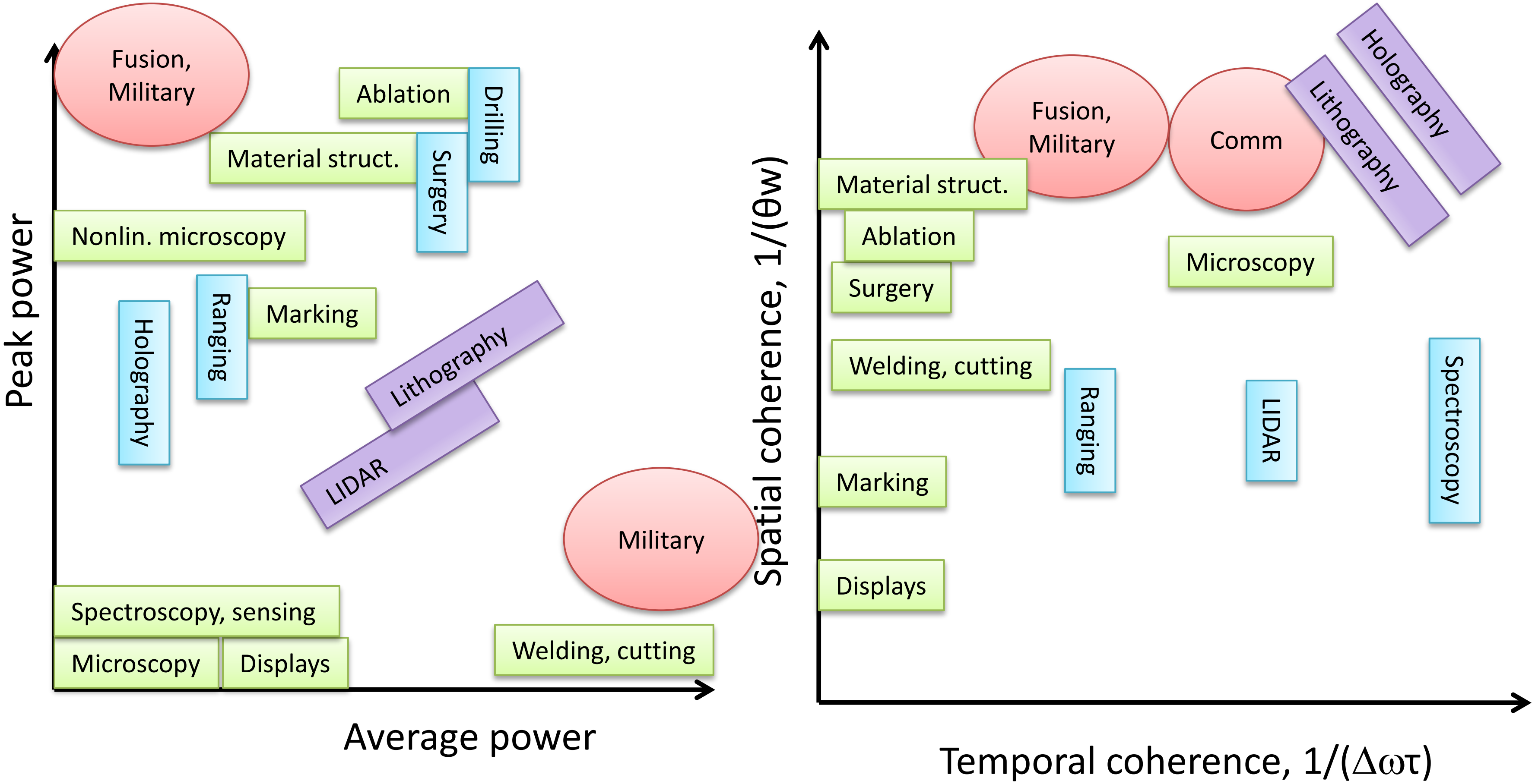


Courtesy J. B. Rosenzweig, UCLA

Critical parameters and laser choice

- **High peak intensity:** SSL, fiber, NLO
- **High CW power:** LD, SSL, fiber, chemical, CO_2
- **High energy:** SSL, chemical, NLO
- **Short pulses:** SSL, fiber, LD, NLO
- **Compact:** LD
- **Cheap:** LD
- **Extreme wavelengths:** FEL, Excimer, NLO, CO_2

Choosing laser



$$\text{Price}=(\alpha\times \text{PeakP}+\beta\times \text{AverageP})\times(\exp(1/\Delta\omega\tau)\times\exp(1/\theta w))\times(\lambda \text{specificity})\times(1/\text{customer knowledge})$$