

Radiation attenuation, laser gain and cavity modes

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Radiation attenuation, laser gain and cavity modes

A photon beam has no definite range, yet a heavy charged particle does; shielding calculations fail if the two are swapped.

Prerequisites: 7, 17, 21.

- Distinguish charged-particle stopping and range from exponential photon attenuation
- Compute attenuated intensity and detected counts with stated coefficients
- Explain stimulated emission, population inversion and optical cavity resonance conditions

Choose the interaction model

Heavy charged particles lose energy continuously through many small collisions, so they have an approximate range: under a constant-loss model a particle with initial energy E_0 and loss rate dE/dx stops after $E_0/(dE/dx)$. Electrons straggle more and radiate. Photons instead interact in single events, so a narrow beam attenuates exponentially as $I=I_0 e^{(-\mu x)}$ with no definite maximum depth; the half-value layer is $\ln 2/\mu$.

Attenuate and count

Apply the exponential only to the stated narrow-beam geometry: $\mu=0.2$ /cm gives a half-value layer of 3.47 cm and $I/I_0=e^{(-2)}\approx 0.135$ after 10 cm. Multiply by detector efficiency for recorded counts: with $\mu x=\ln 4$ and $\varepsilon=0.25$ the recorded fraction is $0.25\times 1/4=1/16$. Build-up from scattered photons makes broad-beam shielding transmit more than the narrow-beam exponential; state the geometry.

Invert the population

Stimulated emission produces a photon matching the stimulating photon in frequency, direction and phase, giving coherent amplification. It competes with absorption; net gain needs population inversion $N_2/g_2>N_1/g_1$ ($N_2>N_1$ for equal degeneracies). Positive-temperature equilibrium has $N_2/g_2<N_1/g_1$ by the Boltzmann factor, so a two-level system in equilibrium cannot lase continuously; practical lasers pump a third level or a metastable state.

Resonate in the cavity

A linear cavity of length L supports standing modes with $L = m\lambda/2$, i.e. frequencies $\nu_m = mc/(2L)$ with spacing $c/(2L)$: for $L = 30$ cm the spacing is 500 MHz. Gain must exceed the round-trip losses for oscillation. Interferometers such as Michelson use the same coherence: fringe counts track optical path changes, as in the gas-cell measurement.

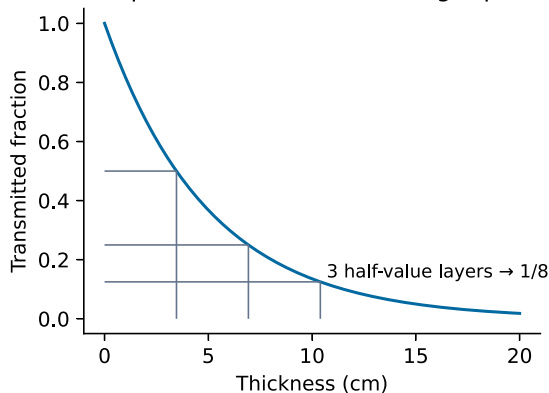
Worked method

A narrow beam has attenuation $I = I_0 e^{-\mu x}$ and half-value layer $x_{1/2} = \ln 2 / \mu$.

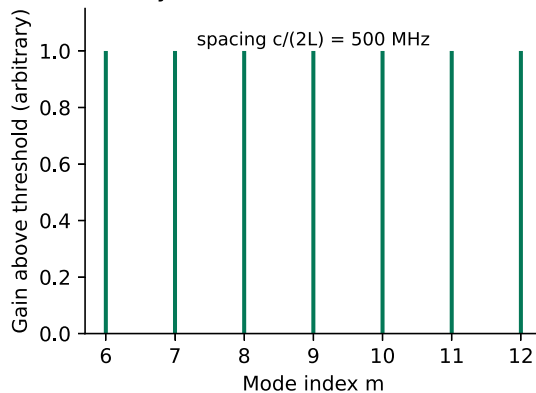
$$x_{1/2} = (\ln 2) / (0.20 \text{ cm}^{-1}) = 3.47 \text{ cm}.$$

Three half-value layers transmit $1/8$. This model excludes scattered build-up into the detector. For a linear vacuum laser cavity, adjacent longitudinal modes are separated by $c/(2L)$. Net stimulated gain requires $N_2/g_2 > N_1/g_1$; the simpler $N_2 > N_1$ assumes equal degeneracies.

Photons: exponential, no definite range ($\mu = 0.2$ /cm)



Cavity $L = 30$ cm: $\nu = m \times 500$ MHz



Radiation attenuation, laser gain and cavity modes: original GRE teaching diagram.

Check conditions and vocabulary

Assigning photons a definite range or charged particles a single exponential law, and forgetting that equilibrium two-level populations cannot invert. Check which interaction model the beam species requires.

half-value layer: The material thickness that halves an exponentially attenuated beam, equal to $\ln 2 / \mu$.

population inversion: A non-equilibrium state with more population in the upper laser level than the lower, enabling net stimulated emission.