Q-switching:

1) pump, hold off lasing.
2) open cavity
   - fast compared to build-up time
   - or slow.
3) pulse builds up
4) energy extracted, depletes, terminates pulse.

Analysis - fast switching.

1) pump phase

pump pulse: $\tau_{pump} < \tau_{fl}$

$$E_p = \int P_p(t)\,dt$$ count only absorbed power

$$N_i = \frac{E_p}{V_a h\nu}$$ N_i = initial inversion

let $x = \frac{N_i}{N_{th}} = \frac{E_p}{E_{cr}}$ where $N_{th} = \frac{\gamma}{\sigma l}$

γ = loss w/ switch open

for fast switching, start with

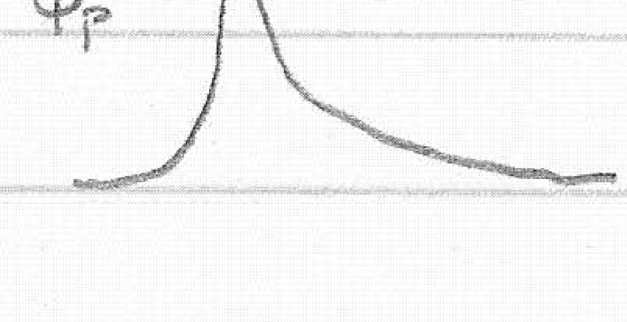
$N(0) = N_i$ $\quad \phi(0) = 1$

build up + output is typically fast $\ll \tau$, R_p

$\therefore$

$$\frac{dN}{dt} = -B\phi N$$

$$\frac{d\phi}{dt} = \left[V_a B N - \frac{1}{\tau_c}\right]\phi$$

$\phi(t) \rightarrow$ 

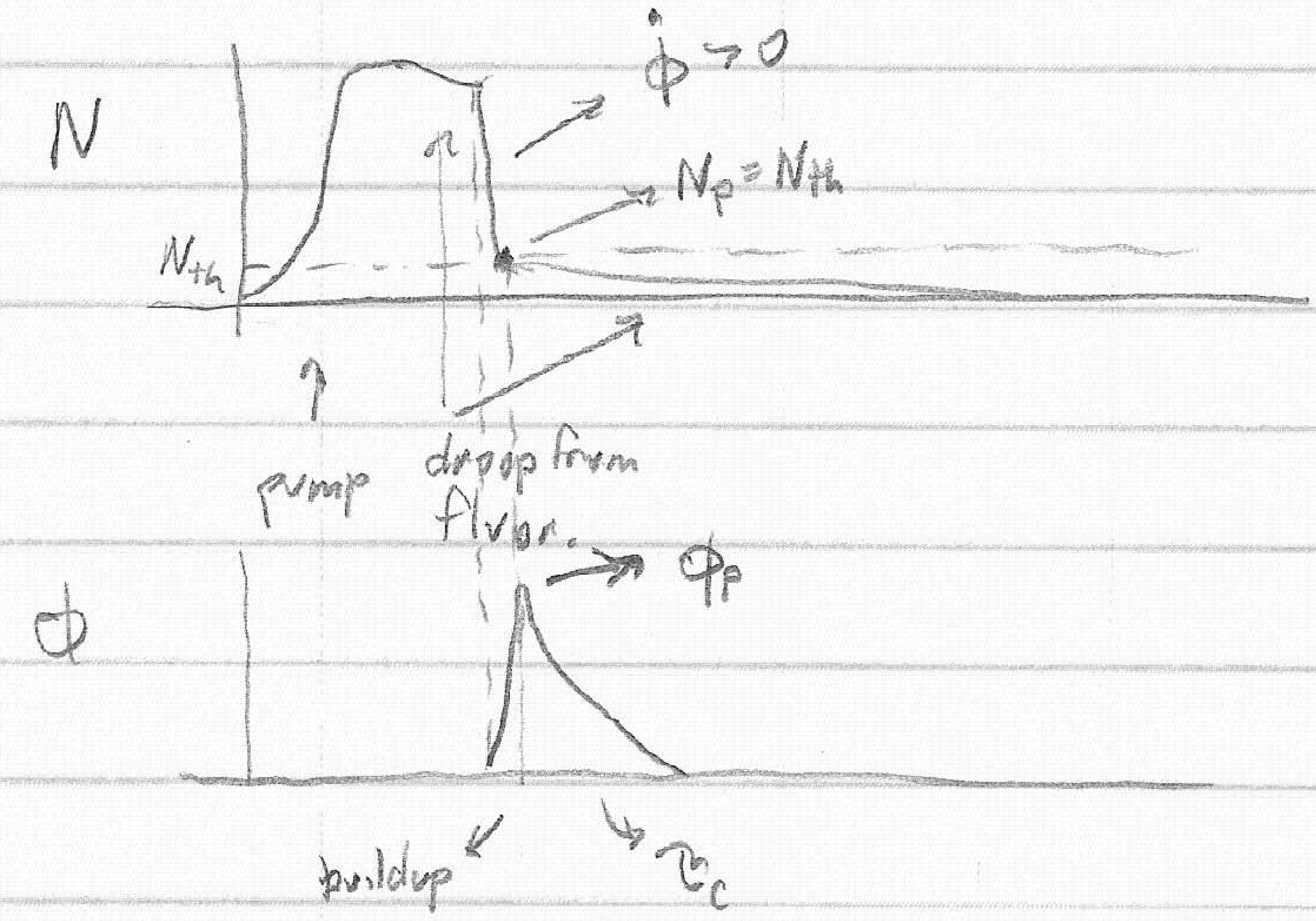
At peak, ϕ_p $\quad \dot{\phi} = 0$ and $\left[V_a B N_p - \frac{1}{\tau_c}\right] = 0$

$$\therefore N_p = \frac{1}{V_a B \tau_c} = \frac{\gamma}{\sigma l} \quad \text{same as CW!}$$

$$= N_{th}$$

Note that this time t_p where $\dot{\phi}(t_p) = 0$ is where the pulse starts to decrease in energy.

- most energy has been extracted from gain medium
- trailing edge is determined by τ_c



what is peak power?

$$P_{out} = \frac{\gamma_2 c}{2 L_{eff}} h\nu \, \phi_p$$

trick to get ϕ_p:

$$\frac{d\phi}{dN} = \frac{d\phi/dt}{dN/dt} = \frac{\left(V_a B N - \frac{1}{\tau_c}\right)\phi}{-BN\phi} = -V_a + \frac{1}{BN\tau_c}$$

but $N_p V_a = \frac{1}{B\tau_c}$

$$\rightarrow \frac{d\phi}{dN} = -V_a\left(1 - \frac{N_p}{N}\right) \quad \text{integrate} \rightarrow \phi = V_a\left[N_i - N - N_p \ln\left(\frac{N_i}{N}\right)\right] + \phi_0$$

$\phi_0 \rightarrow 0$

As N decreases, ϕ increases

get ϕ_p at $N \to N_p$

$$\phi_p = V_a \left[N_i - N_p - N_p \ln\left(\frac{N_i}{N_p}\right)\right]$$

$$= V_a N_p \left[\frac{N_i}{N_p} - 1 - \ln\left(\frac{N_i}{N_p}\right)\right]$$

Now we can use this for the peak output power: $P_{pk} = \frac{\gamma_2 c}{2L_{eff}} h\nu \cdot V_a N_p [\ ]$

Output energy: $E_{out} = \int_0^\infty P_{out}(t)\, dt$

$$= \frac{\gamma_2 c}{2L_{eff}} h\nu \int_0^\infty \phi(t)\, dt$$

From rate eqn: (note upper limit ∞ end of pulse)

$$\int_0^\infty \frac{d\phi}{dt} dt = \phi(\infty) - \phi(0) \approx 0 = V_a B \int_0^\infty N\phi\, dt - \frac{1}{\tau_c}\int_0^\infty \phi\, dt$$

$$\int_0^\infty \frac{dN}{dt} dt = N_f - N_i = -B \int_0^\infty N\phi\, dt$$

$$\Rightarrow \int \phi\, dt = V_a \tau_c (N_i - N_f)$$

$$\therefore E_{out} = \frac{\gamma_2 c}{2L_{eff}} h\nu \cdot V_a \tau_c \underbrace{(N_i - N_f)}_{\text{amt extracted}} \qquad \tau_c = \frac{L_{eff}}{c\gamma}$$

$$= \frac{\gamma_2}{2\gamma}(N_i - N_f) V_a h\nu$$

What is N_f = inv. density at end of pulse?

$$\phi(N_f) \approx 0 = V_a \left[N_i - N_f - N_p \ln\left(\frac{N_i}{N_f}\right)\right]$$

extraction eff: $\eta_E = \frac{N_i - N_f}{N_i}$

$$\eta_E = \frac{N_p}{N_i} \ln\left(\frac{1}{\eta_E - 1}\right)$$

$\eta_E = 1 - x$

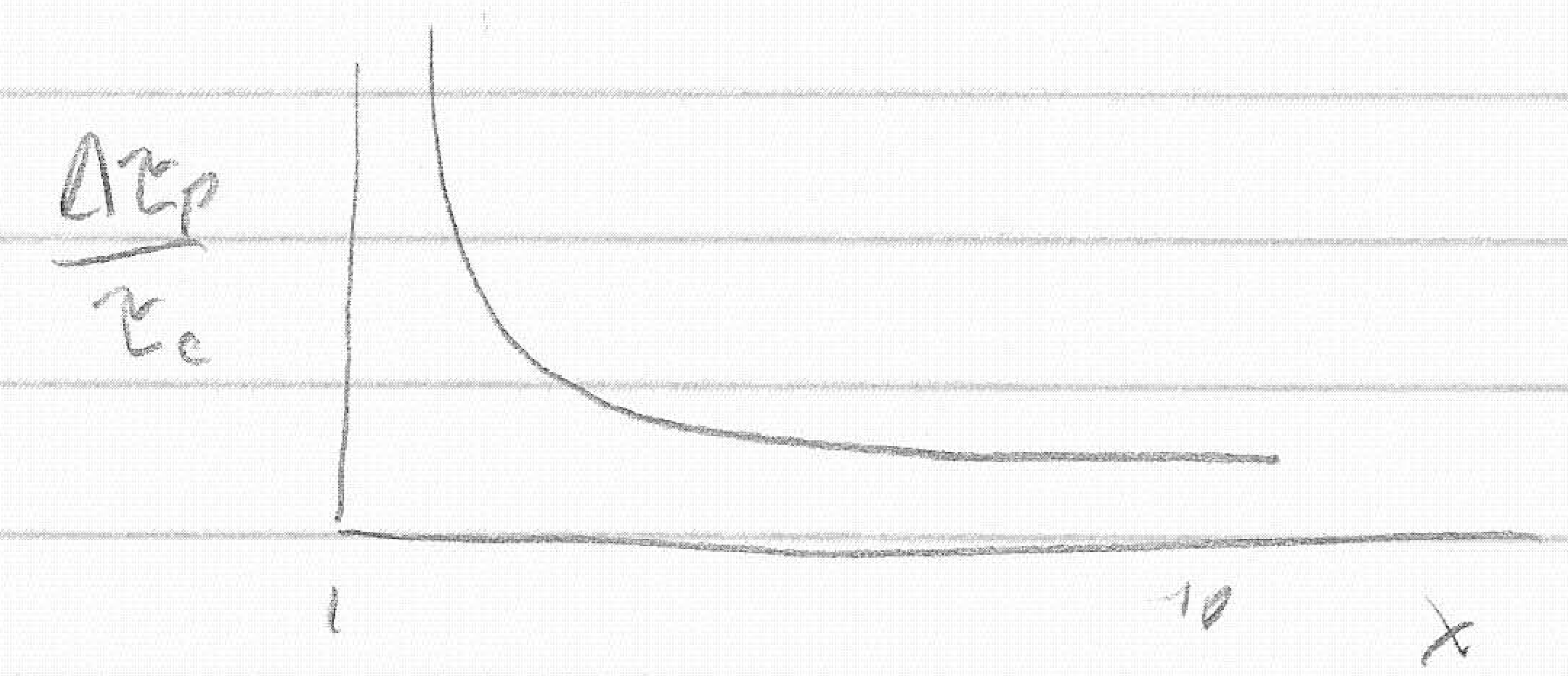
$\frac{1}{x} = \frac{1}{\eta_E - 1}$

or $$\eta_E\left(\frac{N_i}{N_p}\right) = -\ln\left(\eta_E - 1\right)$$

solving for η_E as $f\left(\frac{N_i}{N_p}\right)$ $\rightarrow$ ~ 95% for $\frac{N_i}{N_p} > 4$

Can now estimate pulse duration by $\frac{E_{out}}{P_{pk}}$

$$\Delta\tau_p = \tau_c \cdot f\left(N_i/N_p\right)$$



for $x > 5$

$\Delta\tau_p \sim 1.5\,\tau_c$

minimize $\tau_c = \frac{L_{eff}}{c\gamma}$ $\gamma_2 = \gamma_{oc}$ high

short cavity.

CW pumping:

pump phase: ϕ no

$$\frac{dN}{dt} = R_p - \frac{1}{\tau} N \rightarrow N_i = R_p \tau - (R_p \tau - N_f) e^{-\tau_p/\tau}$$

$\tau_p = 1/\text{reprate} = 1/f$

$N_{th} = R_{cp} \cdot \tau$ let $f^* = \tau/\tau_p$

if $x = \frac{R_p}{R_{cp}}$ $R_p \tau = x N_{th} = x N_p$

$$\rightarrow N_i = x N_p - (x N_p - N_f) e^{-1/f^*}$$

$$x \frac{N_p}{N_i} - 1 = \left(x \frac{N_p}{N_i} - \frac{N_f}{N_i} \right) e^{-1/f^*}$$

$$x \frac{N_p}{N_i} \left(1 - e^{-1/f^*} \right) = 1 - \frac{N_f}{N_i} e^{-1/f^*}$$

also have $\frac{N_i - N_f}{N_i} \equiv \eta_E = \frac{N_p}{N_i} \ln \left(\frac{N_i}{N_f} \right)$ → get $\frac{N_i}{N_p}$

can optimize CW pumped, Q switched lasers for max E_{out} or max avg power.

- longer τ → higher E_{out} Nd:YLF → max power @ 3 kHz. Nd:YAG 10 kHz.

note pulse duration scales w/ gain

∴ longer pulses CW pumped.