Amplifier design

Spatial dependence of gain

Frantz-Nodvick equation for saturated pulse amplification

Modeling spatial gain dependence

Multipass amplifier design

Transverse diode pumping

ASE

Spatial dependence

- Gain follows distribution of pump intensity
- Spatial variation of gain affects beam profile
- Examples:
  - longitudinal pumping with Gaussian beam leads to gain narrowing of spatial profile. More gain in center, less at edges
  - Saturated absorption by a Gaussian beam: saturation in center suppresses intensity there. Leads to widening of output beam.

Pulse amplification: saturated gain algorithm

Frantz-Nodvick Equation:

$$G = \frac{\Gamma_{sat}}{\Gamma_{seed}} \ln[1 + (e^{\Gamma_{seed}/\Gamma_{sat}} - 1)e^{\Gamma_{Pump}/\Gamma_{Sat}}]$$

No Spatial Dependence:

$$F_{Pump} = \frac{E_{Abs}}{\pi w_P^{\,2}}$$

$$F_{Seed} = \frac{E_{Seed}}{\pi w_S^{\,2}}$$

→ **Frantz-Nodvick** → Gain

Assumptions:

- Thermal Equilibrium within Stark Manifolds
- Square Temporal Profile of Seed

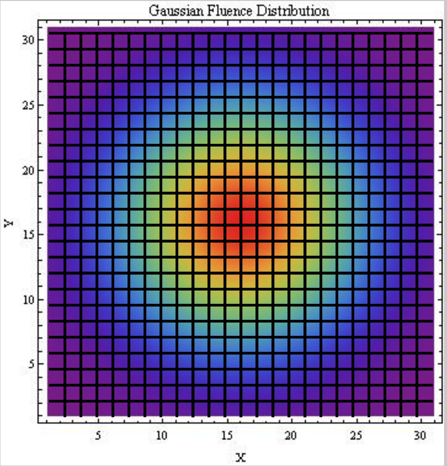
Transverse dependence: super-Gaussian

$$\Gamma(x,y) = \Gamma_0 e^{\frac{-[(\frac{x}{w_x})^{nx} + (\frac{y}{w_y})^{ny}]}{2}}$$

where:- ***nx,ny*** = 2 (Gaussian),
Even > 2 (Super-Gaussian)

-F$_0$ is defined via the Total Energy and integration of the distribution

$\xrightarrow{(\Delta x,\ \Delta y)}$


Gaussian Fluence Distribution

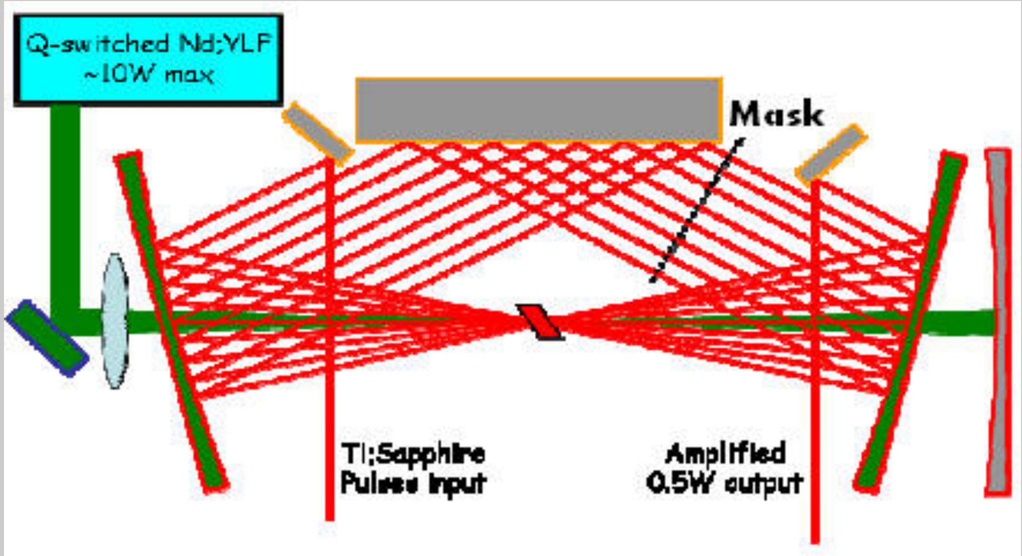
Define Spatial Arrays → **Define Gain Array** *(Frantz-Nodvick for each element in spatial array)* $\xrightarrow{F'_{Seed} = G \bullet F_{Seed}}$ **Compute Post-Gain Seed Energy** (Integrate Spatial Array) →

$$Gain = \frac{E'_{Seed}}{E_{Seed}}$$

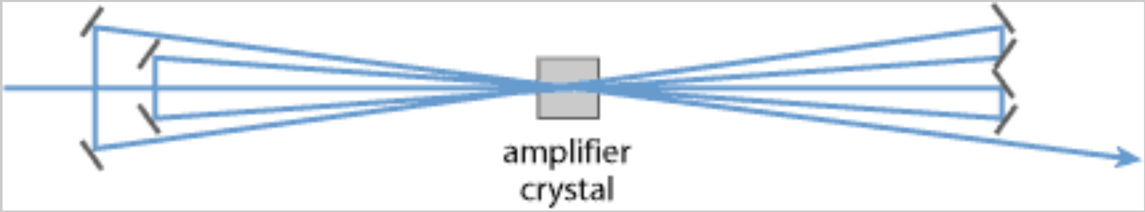
Example: Ti:sapphire multipass amp

- Seed pulse from pulsed laser oscillator: 1nJ (800nm)
- Amplify to 1mJ, use 7mJ of pump energy (532nm)
- Multipass designs: spatially separate beams

Three-mirror ring preamp:
- Up to 12 passes
- Focused beam in crystal
- 2 mirror alignment



Bowtie power amp:
- Collimated beam
- 8 mirrors



Multipass design

- Assume uniform pumping with round beams
- Calculate stored fluence and small signal gain
- Use saturated gain expression to calculate new energy after 1st pass
- Subtract extracted energy from stored energy (over seed spot area)
- Repeat for N passes

Conditions: 1nJ seed, 7mJ pump energy, 95% absorption, 10% loss/pass

Stored energy:

$$E_{stor} = E_{pump}\eta_{abs}\frac{h\nu_{seed}}{h\nu_{pump}} = 4.4mJ$$

Small signal gain estimate:

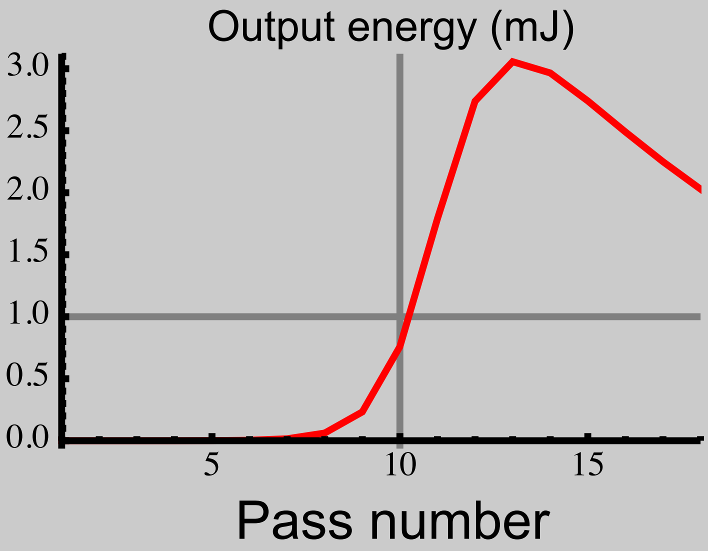
$$G_0 = \left(\frac{E_{\text{target}}}{E_{\text{seed}}}\right)^{1/N}\frac{1}{1-L} = 4.42$$

Estimated spot size:

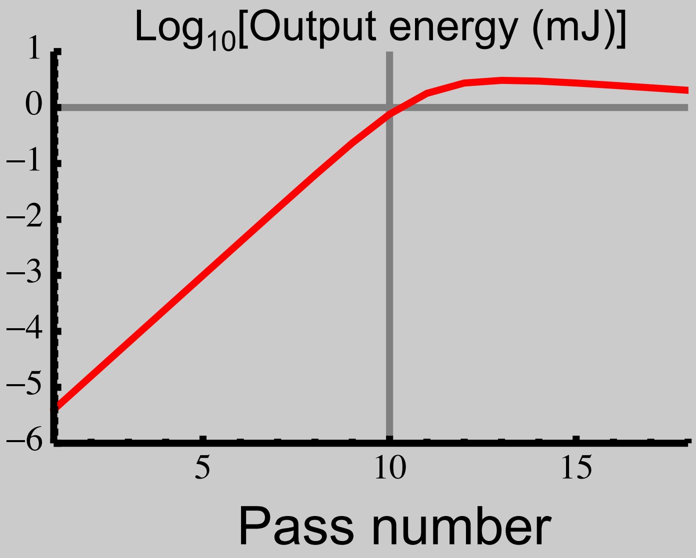
$$A_{pump} = \frac{E_{stor}}{\Gamma_{sat}\ln\left[G_0\right]}, \quad w_p = 300\mu m$$

Multipass: Simple calculated results

- Small signal gain estimate works as long as stored energy is not depleted



Output energy (mJ)

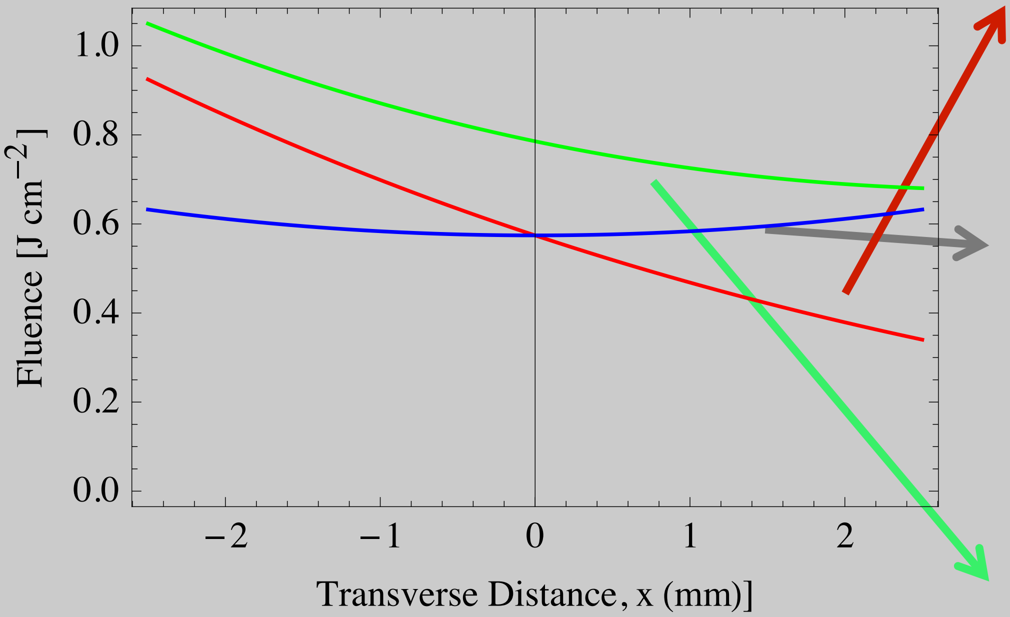


Log_{10}[Output energy (mJ)]

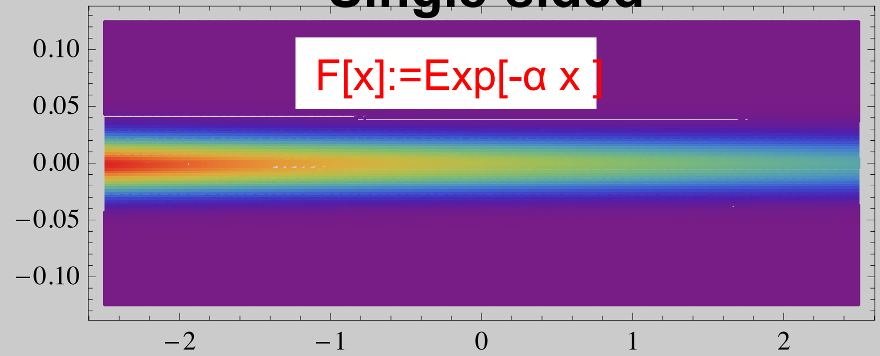
  - Smaller seed size to ensure full overlap with pump
  - Avoid damage thresholds for pump and seed
  - Saturate at desired energy to reduce noise
  - Account for size change in Brewster cut crystal

Transverse diode bar pumping

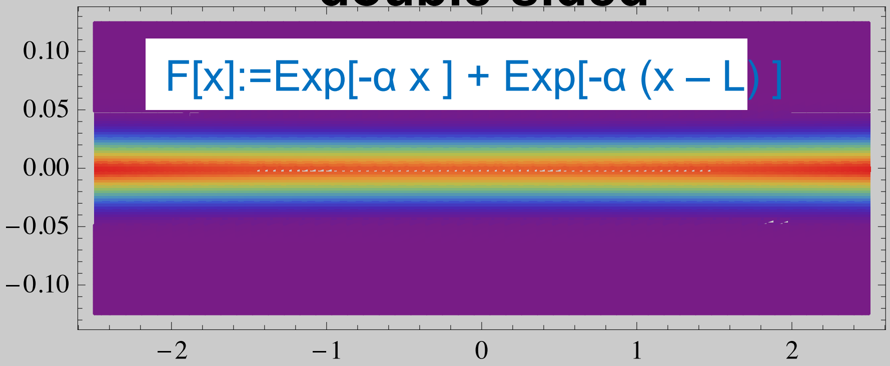
For good absorption, pump must have sufficient path length


Central Fluence Distribution Across Crystal

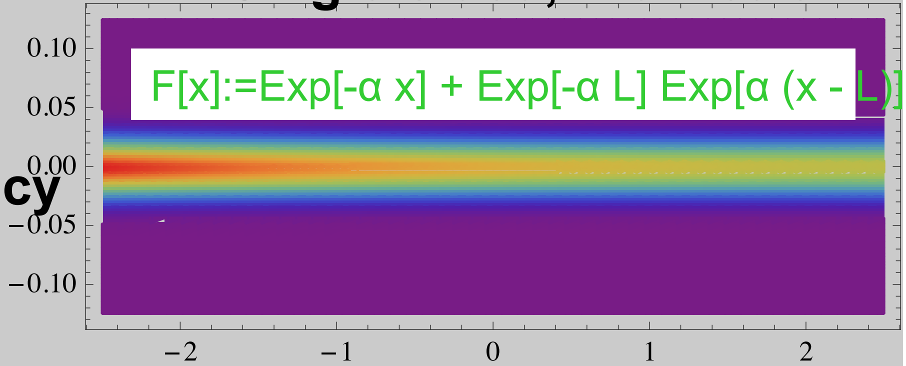
Single-sided


F[x]:=Exp[-α x]

double-sided


F[x]:=Exp[-α x] + Exp[-α (x – L)]

Single-sided, with retro

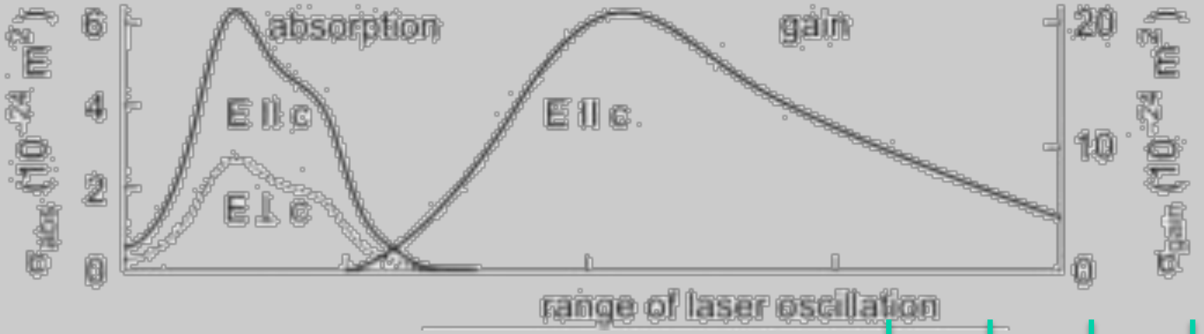

F[x]:=Exp[-α x] + Exp[-α L] Exp[α (x - L)]

Using retro: better absorption efficiency

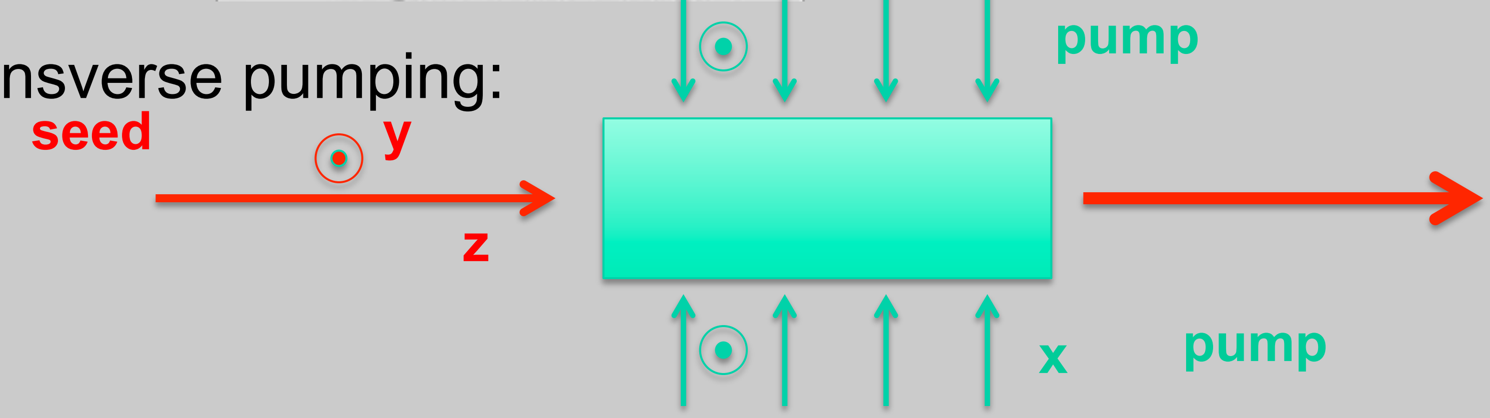
Double-sided: better uniformity

Polarization issues in pumping birefringent materials

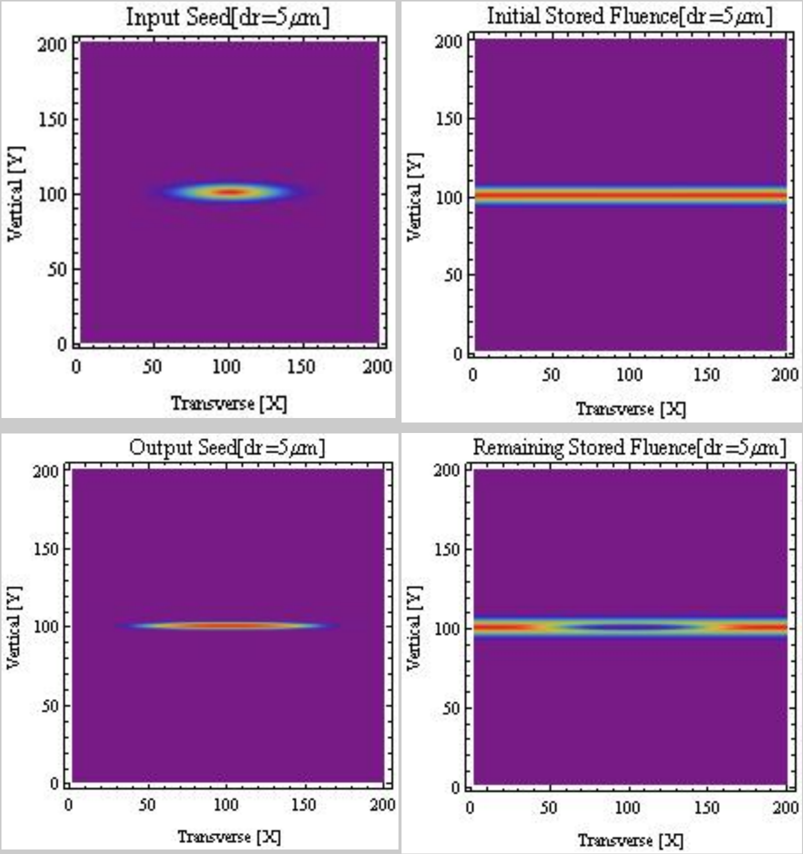
- For Ti:sapphire, both polarizations contribute to seed gain along c-axis
- Much higher pump absorption for E along c-axis
  - α across c-axis is about 40% lower than along c-axis



- Ex: transverse pumping:



Transverse Pumping Gain Estimates



- Seed: 2nJ
  - Cavity Losses: ~1%
  - τ_{pass}: 1ns

- Pump (CW): 1kW (Total: 2X .5kW Bars)
  - η_{Abs}=63.2%
  - η_{QD}=55.6%
  - $\eta_{Pump}=\eta_{Abs}\ \eta_{QD}$=35.1%
  - Heat: ~560 W
  - Significant (Cylindrical) Thermal Lens Expected
  - w=30um

- Single Pass Gain (small signal)
  - Astigmatic Seed: g≈1.64
    - w_x=200um, w_y=30μm
  - Spatially Chirped Seed: g≈1.64
    - w_x=2mm, w_y=30μm

- Multi-Pass Extraction: 37 Passes
  - -Astigmatic Mode: ~136uJ (small extraction area)
  - -Spatially Chirped:~.53mJ (46% extraction)

Central dip in gain: spatial gain mode *expansion*.

This could be used to counter gain narrowing for spatially-chirped seed

Frequency dependence: account for lineshapes

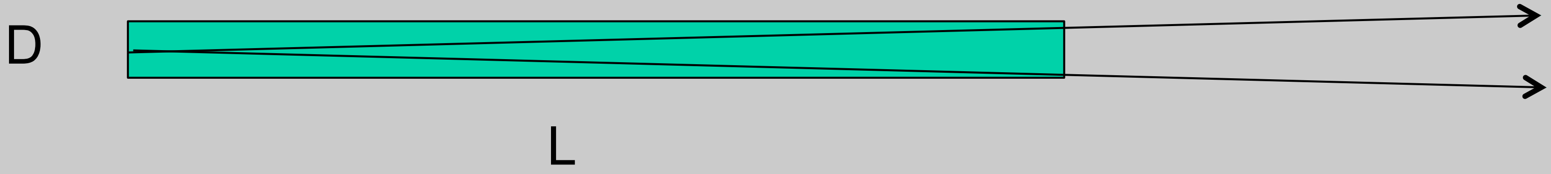
- Absorption and gain coefficients and saturation intensity both depends on frequency

$$\alpha(I,\nu)=\frac{\alpha_0(\nu-\nu_0)}{1+\frac{I(\nu)}{I_{sat}(\nu-\nu_0)}}$$

- For broadband input, saturation changes shape of transmitted spectrum
  - Absorption: power broadening
  - Gain: spectral gain narrowing

Amplified Spontaneous Emission (ASE)

- Spontaneous emission is emitted into 4π steradians, but is amplified on the way out if there is gain.



  - ASE can be considered to be a noise source
  - ASE is more directional than fluorescence, but not as directional as a coherent laser beam
  - Some high-gain lasers are essentially ASE sources (no mirrors)
- Implications for amplifier design
  - ASE can deplete stored energy before pulse extraction
  - Use timing and good seed energy to extract energy from medium before ASE
  - Ensure that transverse gain is smaller than longitudinal to avoid parasitic depletion.

Self-absorption and “optically-thick” media

- A related phenomenon for an absorbing medium is when radiation is *absorbed* along the way out.
- More absorption near the line center, so the transmitted light is broader in spectrum.
- For an extended luminous body (e.g. the Sun), the individual spectral lines get merged together to look like the blackbody.