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Single Pass Amplifier for a Proof-of-Principle Optical Stochastic Cooling Experiment at IOTA

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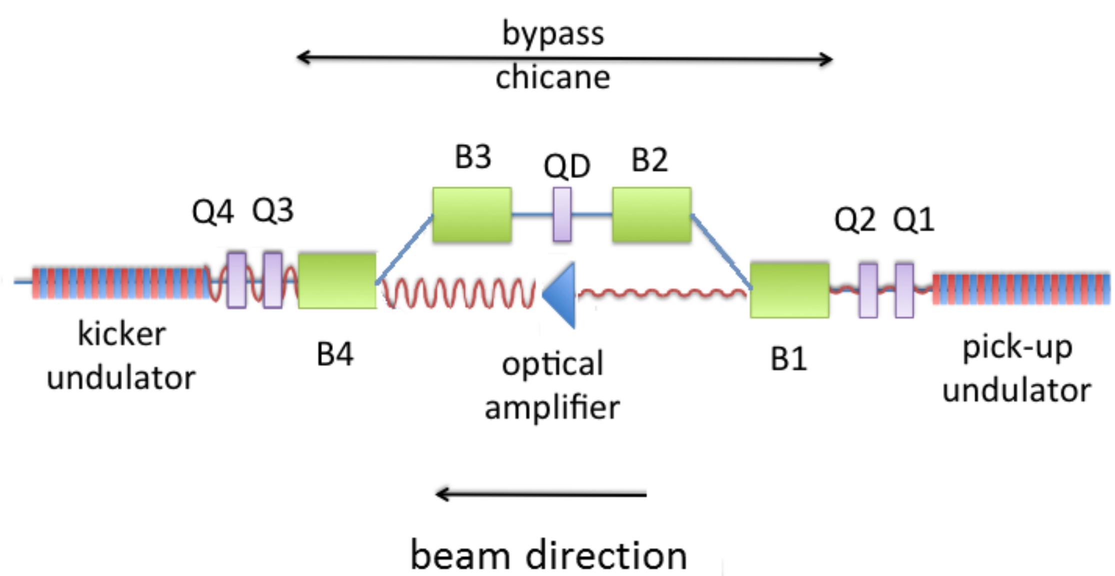
OSC BASICS

Particles made to interact coherently with their parent radiation. Same principle as stochastic cooling. Larger bandwidth available for faster cooling.

Relatively simple amplifier.
1) A gain medium.
2) A pump laser.
3) focusing optics.



Wavelength Selection

Cooling range for the case of equal damping rates in horizontal and longitudinal planes is

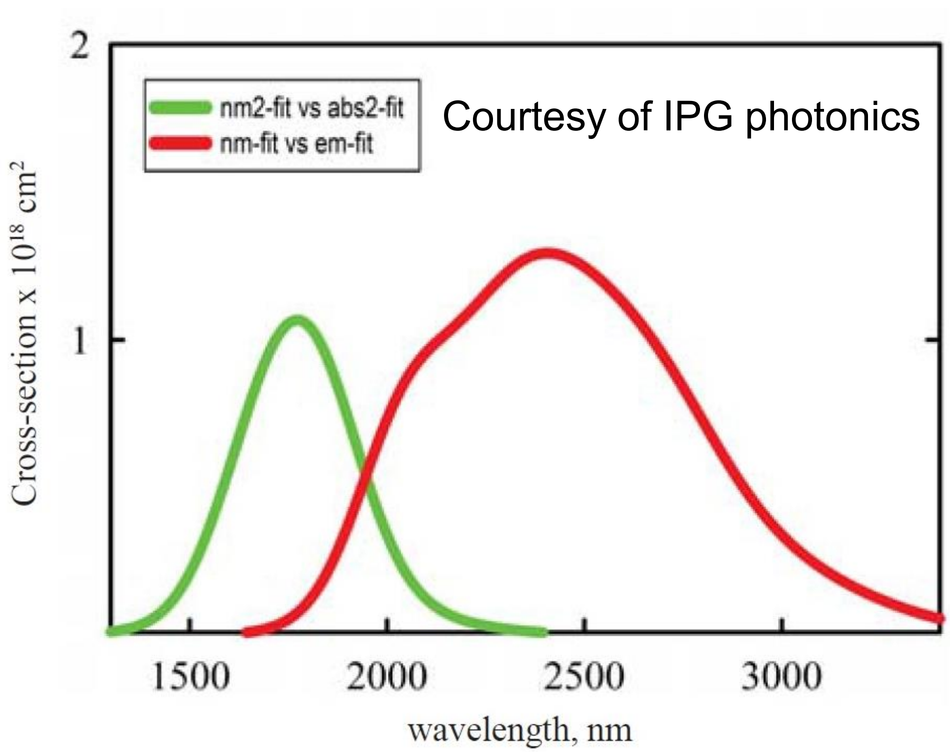
$$n_s \approx \frac{\mu_{01}}{\sigma_P k \Delta S} \qquad n_x \approx \frac{\mu_{01}}{2k\Delta S}\sqrt{\frac{D^{*2}}{\epsilon \beta^*}}$$

Here $k=2\pi/\lambda$ radiation wavevector, and ΔS is delay in the chicane.

$\mu_{01} \approx 2.405$, D^*, β^* are dispersion and beta function at chicane center. ϵ is horizontal emittance. σ_p is rms momentum.

A larger wavelength permits more delay for fixed cooling range. A larger delay allows for a longer crystal. A longer crystal yields higher gain. Hence Ti:Sapphire (800nm) was abandoned for Cr:ZnSe (2490nm).

Cr:ZnSe: Characteristics for gain

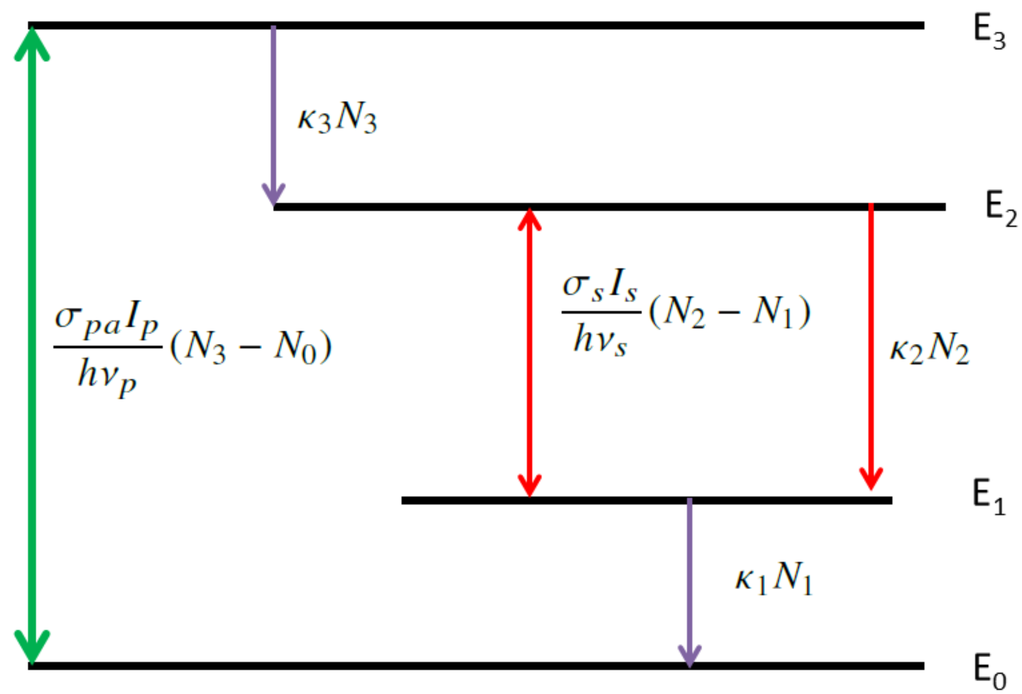


Property	Significance
σ_{pa}	Related to ability to absorb pump laser
σ_s	Related to probability for stimulated emission of signal
τ_2	Ability to hold a population inversion
Δf	Large bandwidth reduces cooling time

Other important parameters are index of refraction, thermal conductivity, expansion coefficient.
The large absorption spectrum prompted us to study in detail how pumping frequency and intensity determine gain.

Population Dynamics

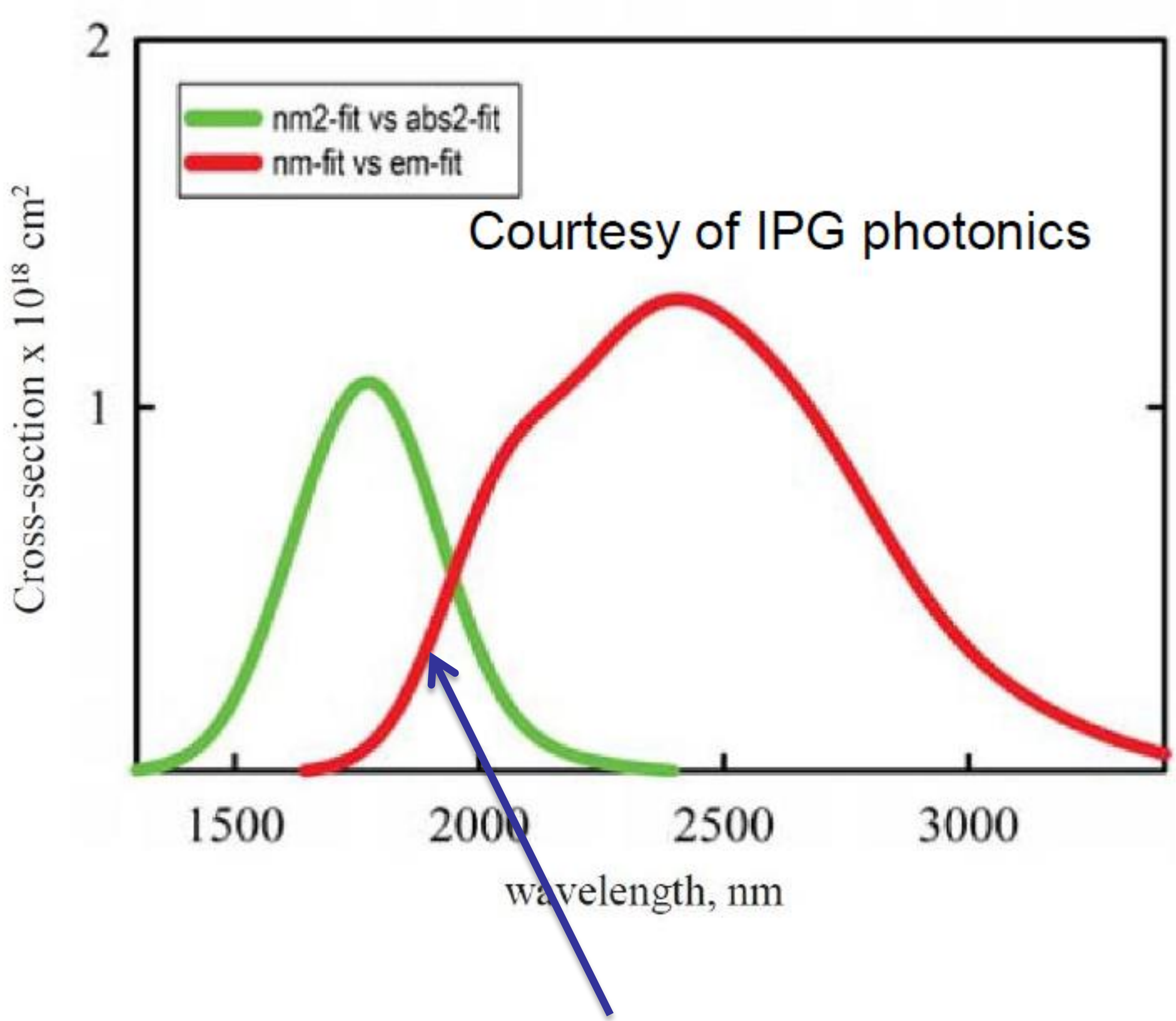
Cr:ZnSe is a 4 level system.
κ_1 and κ_3 are fast so that
$N_0 >> N_3$ and $N_2 >> N_1$
And so $N_t \approx N_2 + N_0$, N_t is total doping concentration of crystal.



Pick-up undulator radiation is on the order of mW/cm^2 which is neglible in the rate equations.

This fact along with CW pumping allows us to look for steady state solutions to the rate equations.

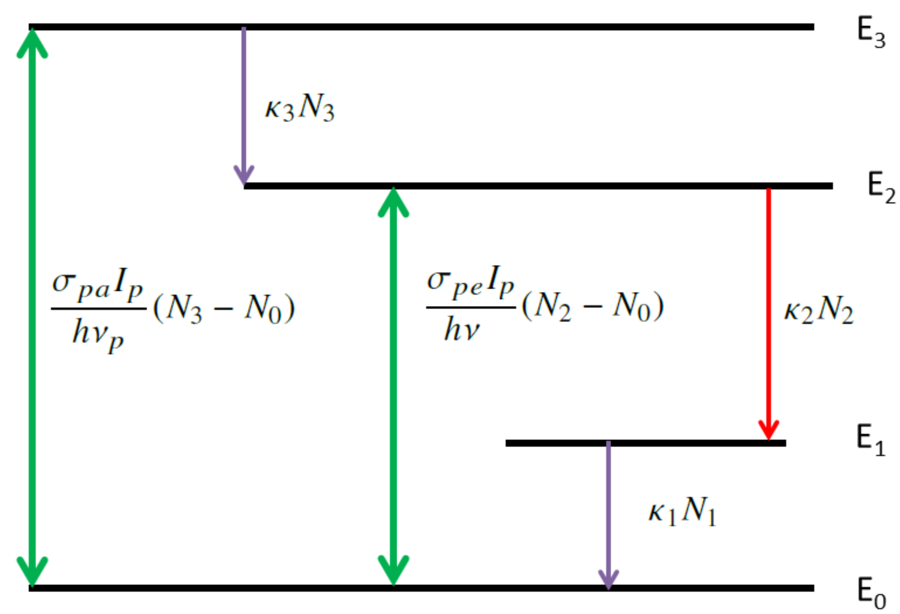
Population Dynamics



There is an overlap with the emission and absorption cross sections.

This means not only does the signal cause spontaneous emission…..so can the pump!

Population Dynamics



We can solve for the ground state population density:

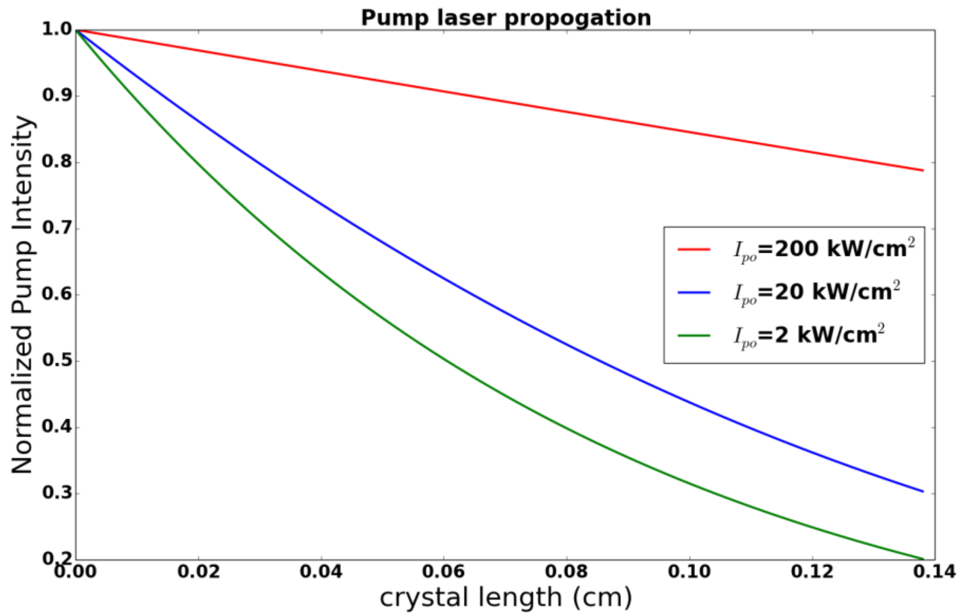
$$N_0 = \frac{N_t(1 + I_p \sigma_{pe} A)}{I_p A(\sigma_{pa} + 2\sigma_{pe}) + 1}$$

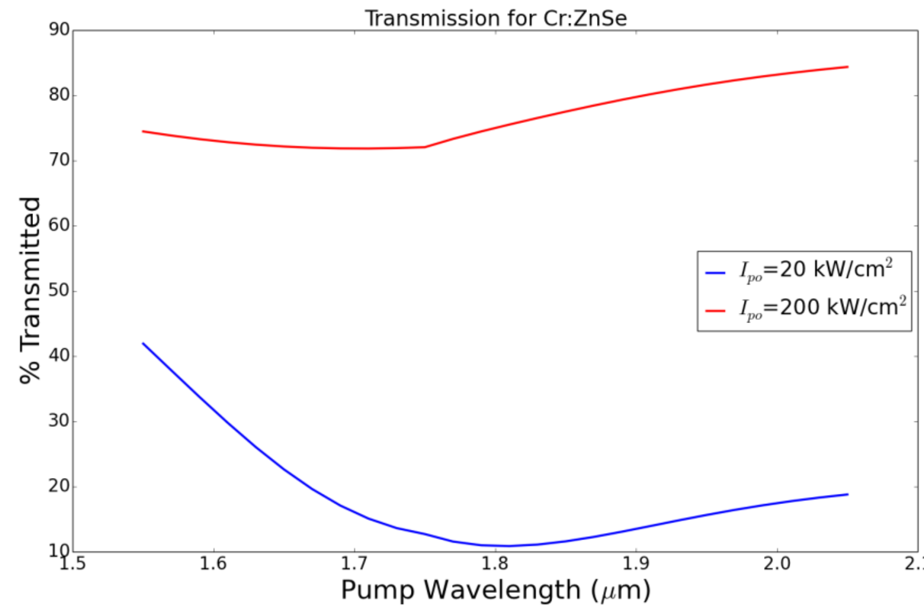
And relate this to the attenuation of the pump as it propagates through crystal:

$$\frac{dI_p}{dz} = -I_p N_t \left(\frac{(1 + I_p \sigma_{pe} A)(\sigma_{pa} + 2\sigma_{pe})}{I_p A(\sigma_{pa} + 2\sigma_{pe}) + 1} - \sigma_{pe} \right) \qquad A \equiv \frac{\tau_2}{h\nu_p}$$

When σ_{pe} =0 can solve with Lambert *W* function $z = W(z)\exp[W(z)]$.

$$I_p = I_{sat} W\left(\frac{I_{po}}{I_{sat}} e^{-\alpha T + \frac{I_{po}}{I_{sat}}} \right) \qquad \alpha \equiv N_t \sigma_{pa} \qquad I_{sat} \equiv \frac{h\nu_p}{\sigma_{pa}\tau_2}$$





High intensities cause depletion of the ground state. Lower intensities approach exponential decay.

Amplification

The undulator intensity grows as it propagates

$$\frac{dI_s}{dz} = I_s \sigma_s (N_2 - N_1)$$

$$\frac{dI_s}{dz} = -\sigma_s A \frac{dI_p}{dz} \longrightarrow \boxed{G = e^{\sigma_s A (I_{po} - I_p)}}$$

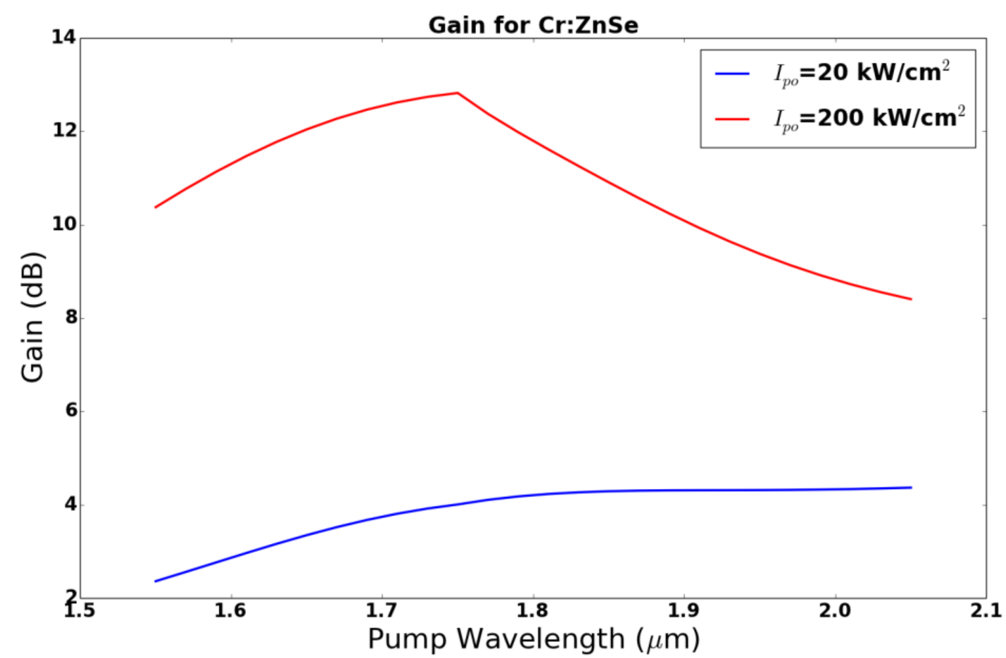
growth of signal can be related to loss of the pump as:

$$G = I_s / I_{so}$$

$\nu_s = 2.49\ \mu m$

L=1.4 mm (2mm optical delay)

$N_t = 2.0 \times 10^{19}$ ion/cm^3



Thermal Lensing

Primary contribution to thermal lensing comes from temperature dependence of index of refraction:

$$f = \frac{\kappa A}{P_h}\left(\frac{1}{2}\frac{dn}{dt}\right)^{-1} = \frac{\kappa}{I_h}\left(\frac{1}{2}\frac{dn}{dt}\right)^{-1}$$

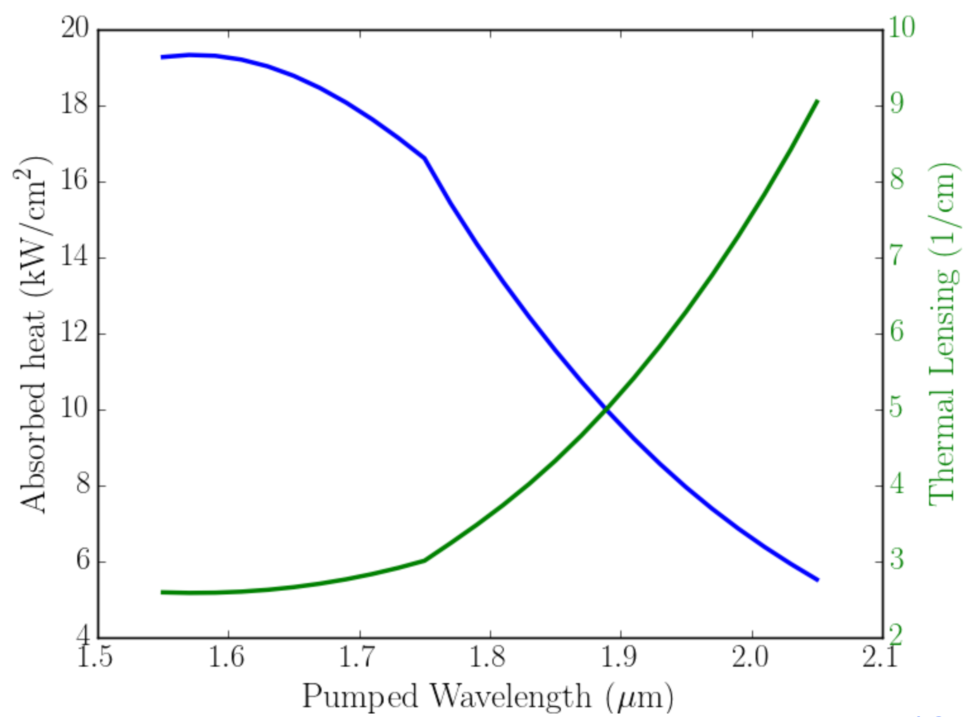
$\frac{dn}{dt}$ =7*10^{-5} K

$\kappa = 1$ W/m*K

I_h is the fraction of absorbed intensity that goes into heat

$$I_h = \Delta I_p\left(1 - \frac{\lambda_p}{\lambda_s}\right)$$

Decrease in absorbed heat for higher wavelengths from explicit dependence but also from cross sections.



Thermal Lensing

Another contribution to thermal lensing comes from bulging of the ends

$$f_b = \frac{\kappa}{I_h} \frac{\alpha r_o (n_o - 1)}{L}$$

$n_o = 2.44, \alpha = 7.3 \times 10^{-6}\ \mathrm{K}^{-1}$

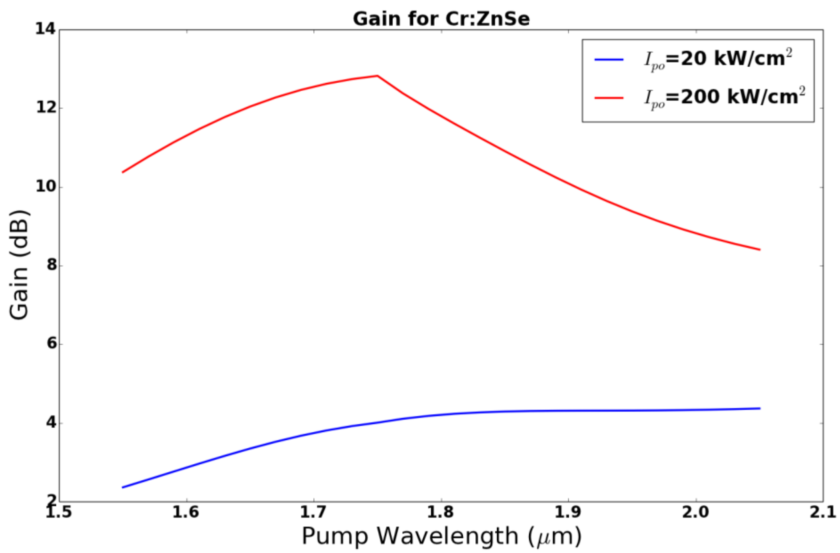
L=1.4mm

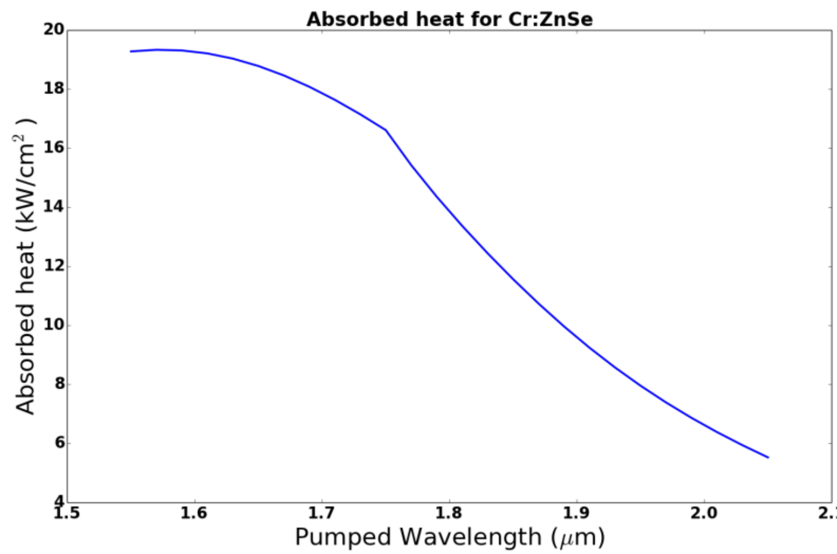
This contribution is much smaller. For a laser with a spot size of 100 μm at an intensity of 200 KW/cm^2 f_b ~160 cm.

Another contribution comes from heat induced strain but this is also expected to be small.

Pump Selection

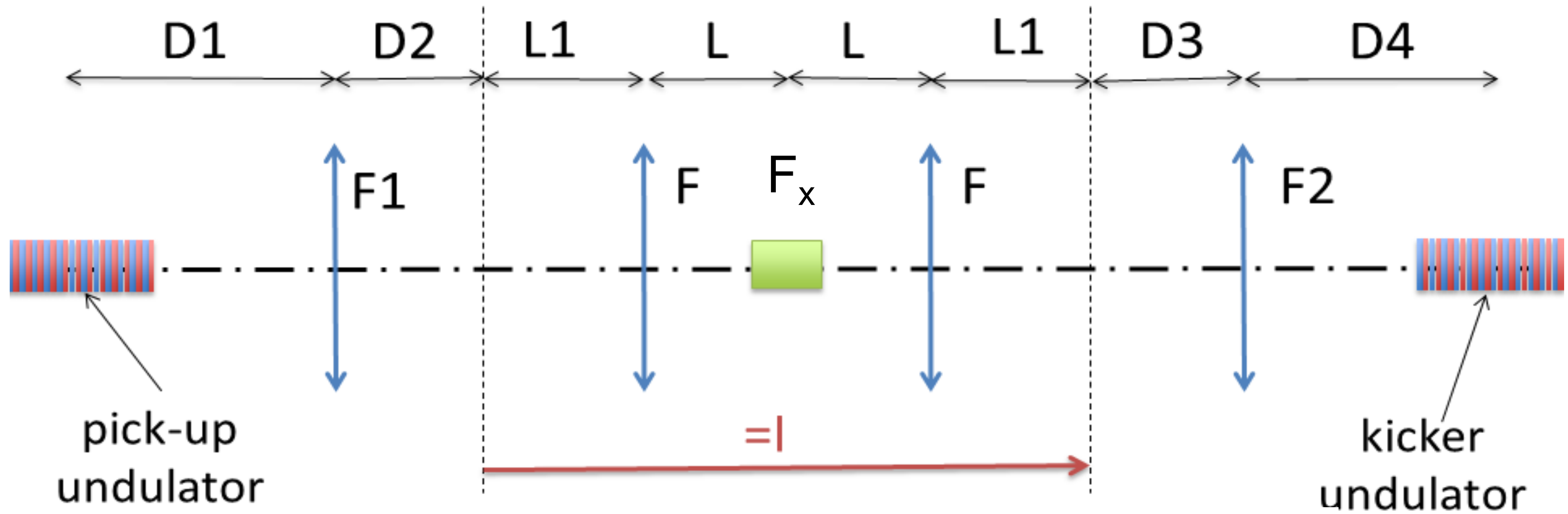
Two candidate pumps. Erbium fiber laser at 1550 nm or a Thulium fiber laser at 1930 nm. Assume both have 50 W.





Amplifier will be pushed close to damage threshold by pump. Higher wavelengths absorb less heat. So pumping can be done with a higher intensity with Thulium laser, and so performs better.

Optics

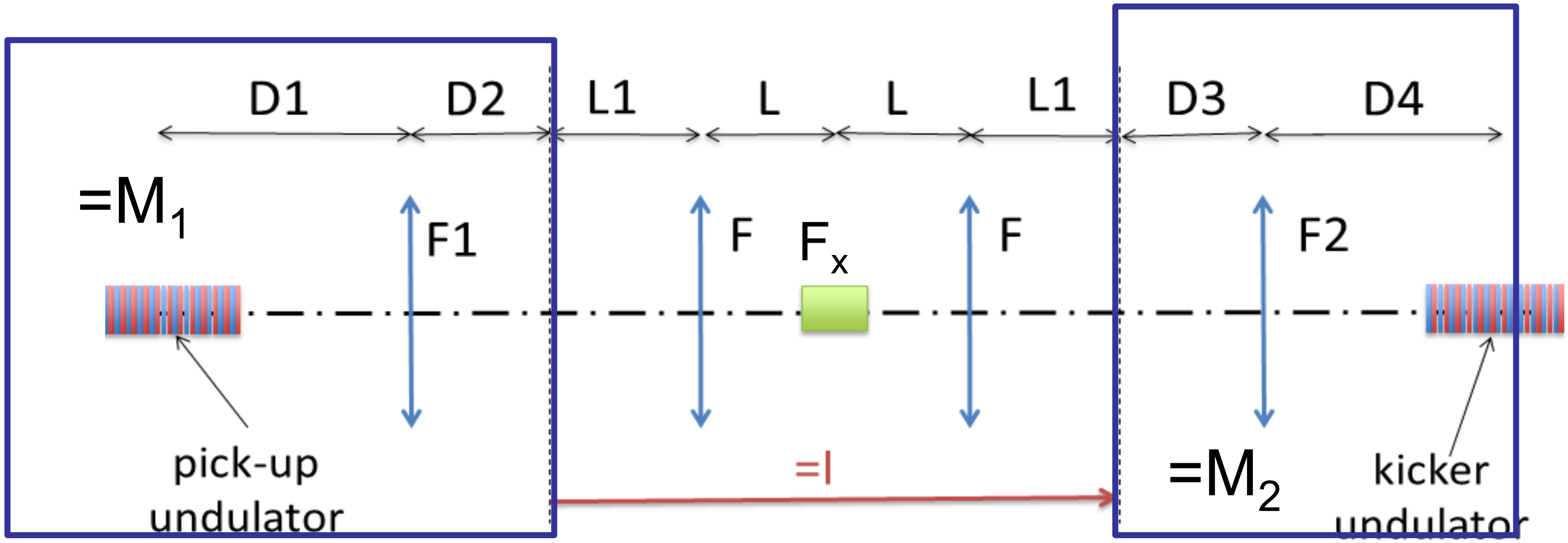


$$\begin{pmatrix} \langle x_f^2 \rangle \\ \langle -x_f x'_f \rangle \\ \langle x'_f \rangle \end{pmatrix} = \begin{pmatrix} C^2 & -2CS & S^2 \\ CC' & CS' + C'S & -SS' \\ C'^2 & -2C'S' & S^2 \end{pmatrix} \begin{pmatrix} \langle x_i^2 \rangle \\ \langle -x_i x'_i \rangle \\ \langle x'_i \rangle \end{pmatrix}$$

To eliminate depth of field effects transfer matrix should be ‘I’ the identity matrix since D(-L)ID(+L)=I

Additionally RMS spot size must be small at crystal to keep laser power reasonable.

Optics



Requirement for inside system to be identity

$$F=LL_1/(L+L_1) \qquad F_x=L_1^2/2(L+L_1)$$

Then choose M_1 M_2 to be inverses so. $M_1 I M_2= I$
This requires $D_1= D_3$, $D_2= D_4$ and $F_1= F_2 = (D_1+D_2)/2$.
Lens placement constrained by beam optics. For further analysis we set $D_1=D_4$

Optics

Synchrotron Radiation Workshop (SRW) is used to find Wigner function numerically.

$$\mathcal{W}_x(x,k_x) = \frac{1}{\lambda^2}\int_{-\infty}^{+\infty} E_x\left(x-\frac{x'}{2}\right)E_x\left(x+\frac{x'}{2}\right) \times e^{ik_x x'}\,dx'$$

Can then calculate Courant-Snyder parameters for photon beam.

$$\begin{pmatrix} \langle x_i^2\rangle \\ \langle -x_i x_i'\rangle \\ \langle x_i'\rangle \end{pmatrix}$$

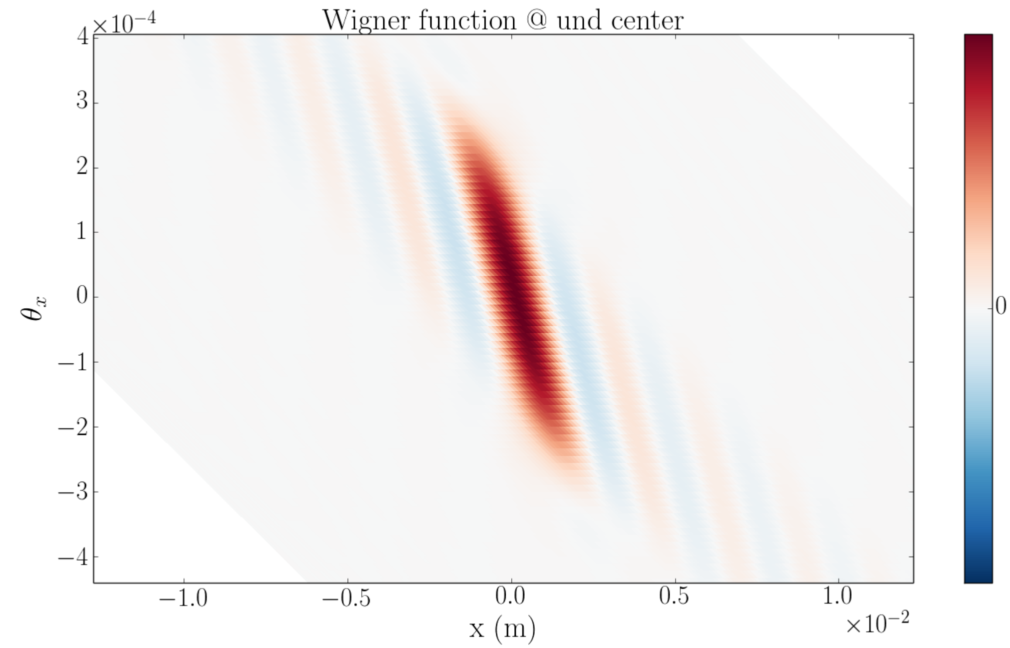
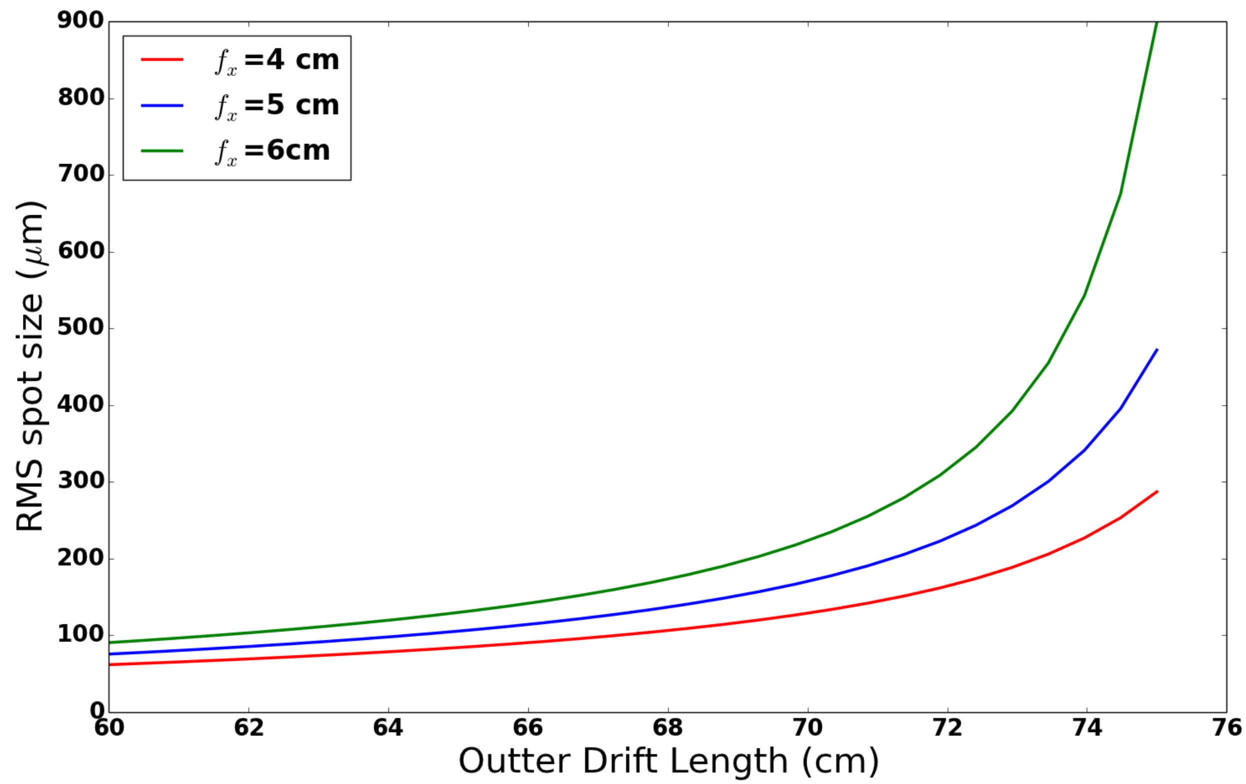


Table 1: Undulator Parameters

Beam Energy	100 MeV
Undulator Period	12.9 cm
Number of Periods	6
Peak Magnetic Field	664 G
Zero angle wavelength	2.2 μm

Optics

2 lens system results in a 600 µm spot size at the crystal. Would require 2300 W of laser power!



Additional lenses reduce size to 100 µm or 60 W.

Spot size can not be reduced further because of constraints brought on by beam optics.

Future work

Dispersion:

-Optics must be chosen to reduce dispersion.

-Fortunately Cr:ZnSe has an opposite dependence of most glasses that can be used for lenses (for example CaF_2)

Phase distortion:

-Amplification can cause phase distortion that can spoil cooling.

-Interferometry experiment will be done with an OPA as a stand in for broadband undulator radiation. Similar work is being done with Ti:Sapph.