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

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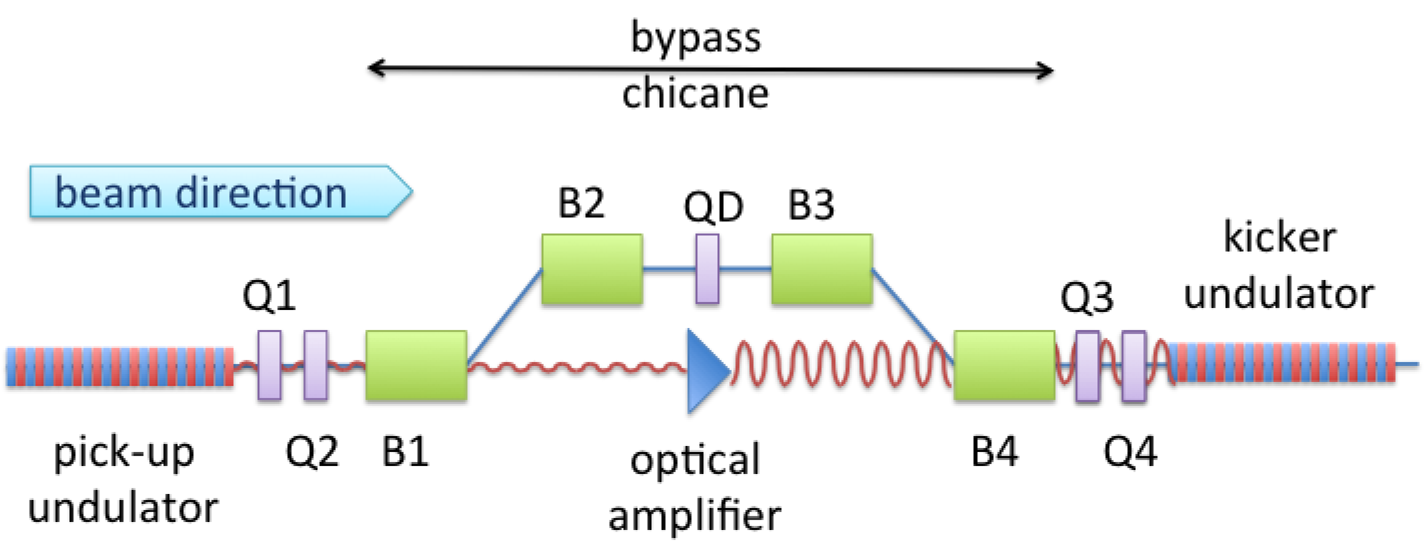
OSC BASICS

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=2π/λ radiation wavevector, and Δs is delay in the chicane.

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

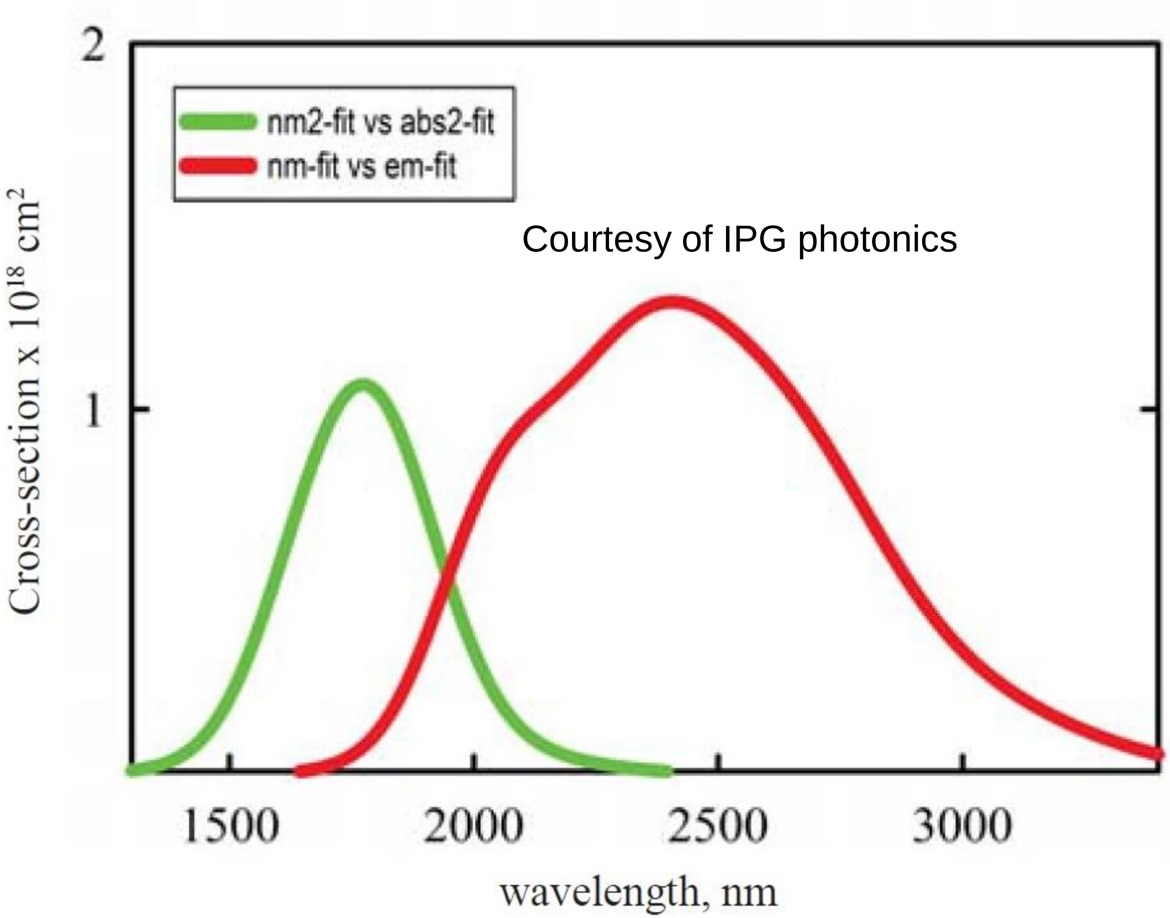
Cr:ZnSe: Characteristics for gain

Property	Value	Significance
σ_{pa}	$1.05*10^{-18}$ cm^2 *	Related to ability to absorb pump laser
σ_s	$1.2*10^{-18}$ cm^2 *	Related to probability for stimulated emission of signal
τ_2	5 µs	Ability to hold a population inversion
Δ f	~50 THz	Large bandwidth reduces cooling time

These are the properties immediately related to gain. Other important parameters are index of refraction, thermal conductivity, expansion coefficient.

* Frequency dependent, peak values given.

Cr:ZnSe Characteristics for gain



Cr:ZnSe also has a broad absorption spectrum meaning many types of pump lasers available.
To choose the best one we need to better understand how to find the gain.

Rate Equations

$$\frac{dN_3}{dt} = -k_3 N_3 - \frac{\sigma_{pa} I_p}{h\nu_p}(N_3 - N_0)$$

$$\frac{dN_2}{dt} = k_3 N_3 - k_2 N_2 - \frac{\sigma_s I_s}{h\nu_s}(N_2 - N_1)$$

$$\frac{dN_1}{dt} = k_2 N_2 - k_1 N_1 + \frac{\sigma_s I_s}{h\nu_s}(N_2 - N_1)$$

$$\frac{dN_0}{dt} = k_1 N_1 + \frac{\sigma_{pa} I_p}{h\nu_p}(N_3 - N_0) \cdot$$

We are going to solve these equations for steady state

N_i i=1,2,3,4 is the ith population density.

I_P is the pump intensity, v_p is the pump frequency.

I_s is the pump intensity v_s is the signal frequency. h is Planck's constant.

κ_i are the spontaneous rate coefficients.

Rate Equations

$$0 = -k_3 N_3 - \frac{\sigma_{pa} I_p}{h\nu_p}(N_3 - N_0)$$

$$0 = k_3 N_3 - k_2 N_2 - \frac{\sigma_s I_s}{h\nu_s}(N_2 - N_1)$$

$$0 = k_2 N_2 - k_1 N_1 + \frac{\sigma_s I_s}{h\nu_s}(N_2 - N_1)$$

$$0 = k_1 N_1 + \frac{\sigma_{pa} I_p}{h\nu_p}(N_3 - N_0) \cdot$$

We can simplify by noting that $N_0 >> N_3$

So…..

$$N_3 = \frac{I_p \sigma_{pa} N_0}{h\nu_p k_3}$$

We use this to eliminate N_3 from all equations

also $N_2 >> N_1$

Rate Equations

$$N_3 = \frac{I_p \sigma_{pa} N_0}{h\nu_p k_3}$$

$$0 = \frac{\sigma_{pa} I_p}{h\nu_p} N_0 - k_2 N_2 - \frac{\sigma_s I_s}{h\nu_s} N_2$$

$$0 = k_2 N_2 - k_1 N_1 + \frac{\sigma_s I_s}{h\nu_s} N_2$$

$$0 = k_1 N_1 - \frac{\sigma_{pa} I_p}{h\nu_p} N_0$$

How can we have a steady state solution for a time dependent signal?

Because I_s ~10 W/cm^2

I_p ~10^5 W/cm^2

κ_2 ~10^5 s^{-1}

$\frac{\sigma_s}{h\nu_s}$ ~10 cm^2/J

$\frac{\sigma_{pa}}{h\nu_p}$ ~10 cm^2/J

Rate Equations

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Things are simplifying nicely but….

How can we have a steady state solution for a time dependent signal?

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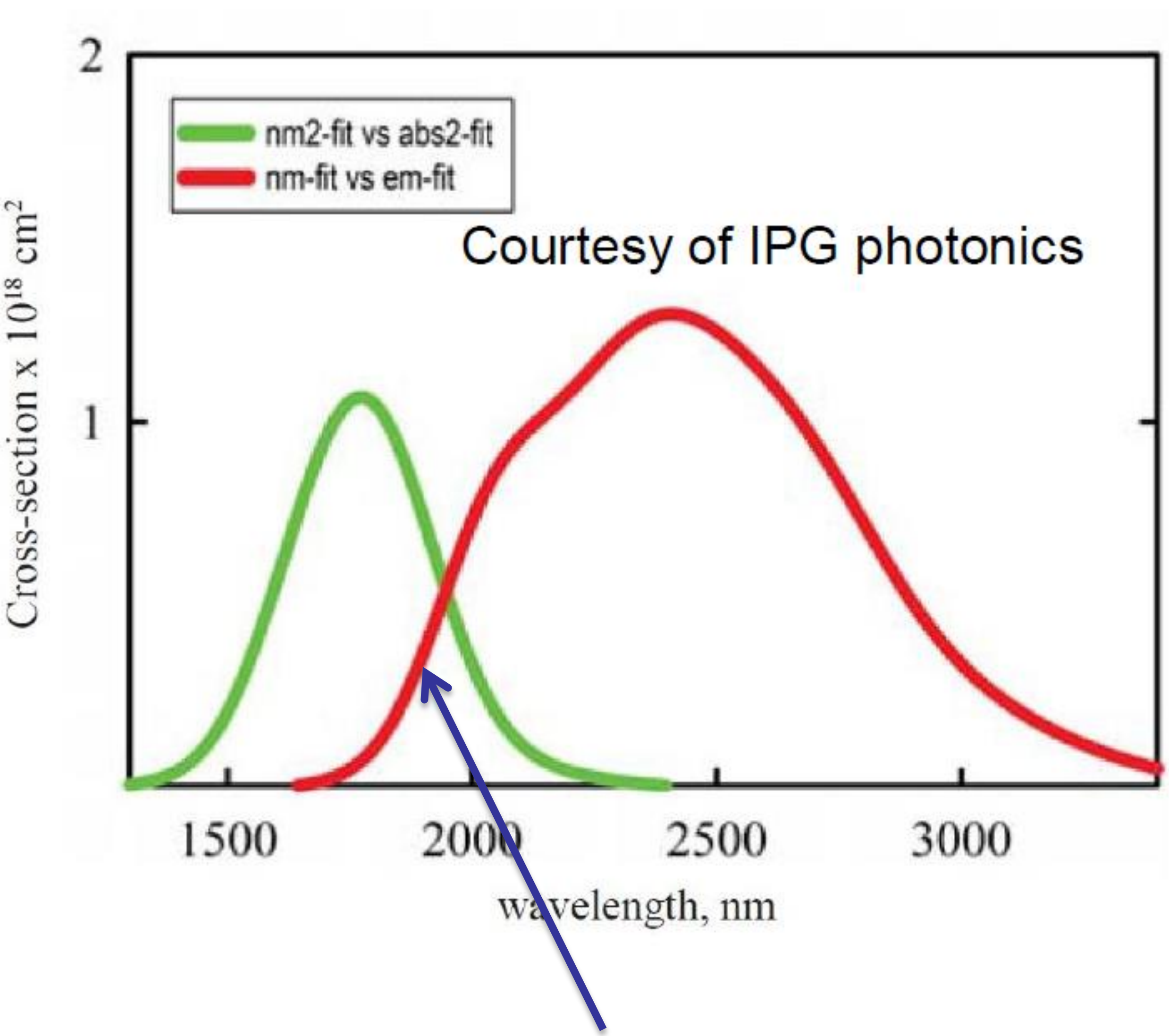
κ_2 ~10^5 s^{-1}

$\frac{\sigma_s}{h\nu_s}$ ~10 cm^2/J

$\frac{\sigma_{pa}}{h\nu_p}$ ~10 cm^2/J

Stimulated emission from undulator intensity is negligible

Rate Equations



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!

The rate equations need to be modified accordingly.

Rate Equations

$$N_3 = \frac{I_p \sigma_{pa} N_0}{h\nu_p k_3}$$

$$0 = \frac{\sigma_{pa} I_p}{h\nu_p} N_0 - k_2 N_2 \quad - \frac{\sigma_{pe} I_s}{h\nu_p}(N_2 - N_0)$$

$$0 = k_2 N_2 - k_1 N_1$$

$$0 = k_1 N_1 - \frac{\sigma_{pa} I_p}{h\nu_p} N_0 + \frac{\sigma_{pe} I_s}{h\nu_p}(N_2 - N_0)$$

Finally we say that the total doping $N_T \approx N_2 + N_0$

So that we can solve for the ground state

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

With

$$A = \frac{\tau_2}{h\nu_p}$$

Growth/Decay Equations

The pump decays as it propagates through the medium:

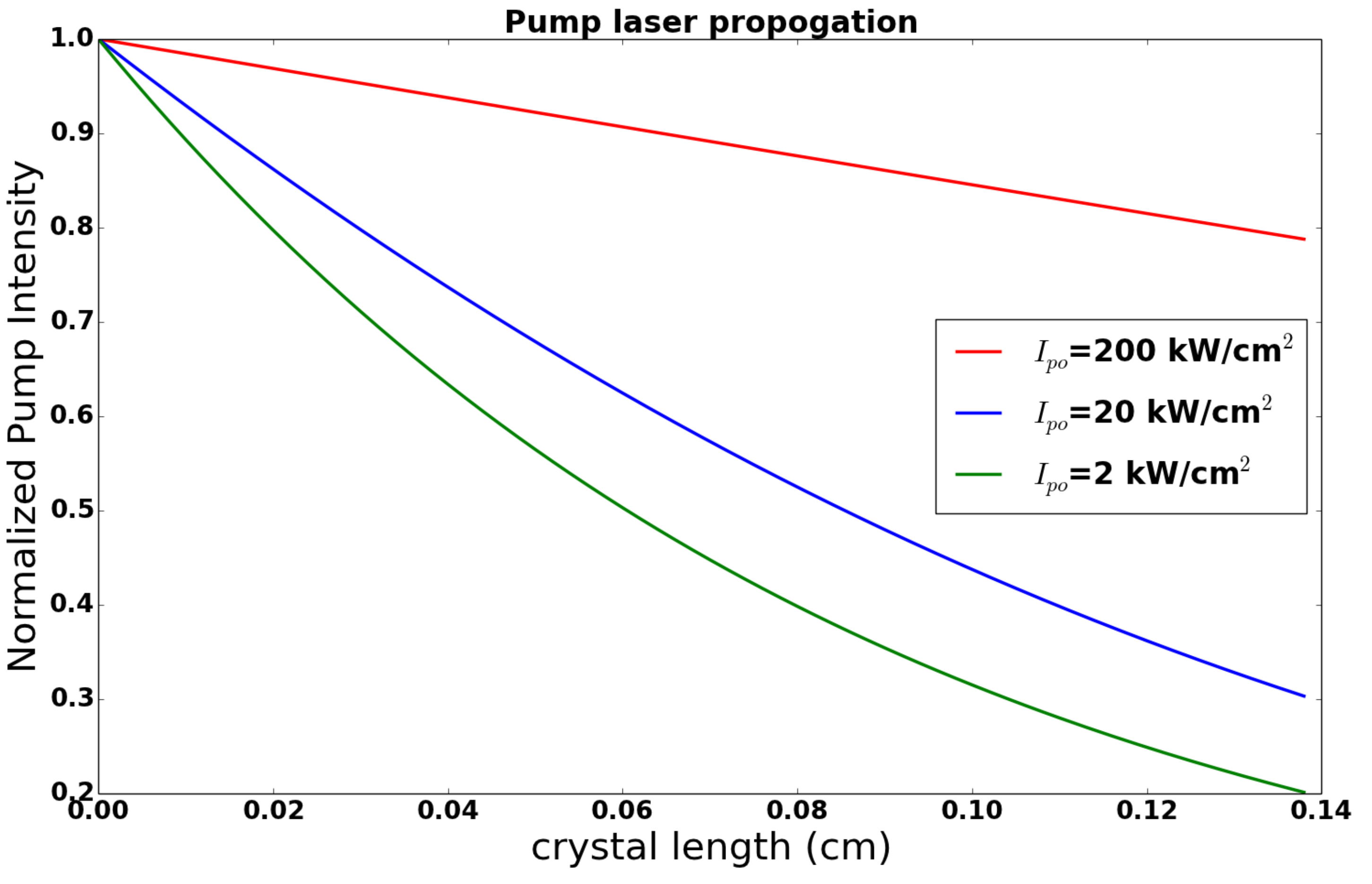
$$\frac{dI_p}{dz} = -I_p(\sigma_{pa}(N_0 - N_3) + \sigma_{pe}(N_0 - N_2))$$

$$\approx -I_p(\sigma_{pa} N_0 + \sigma_{pe}(2N_0 - N_t))$$

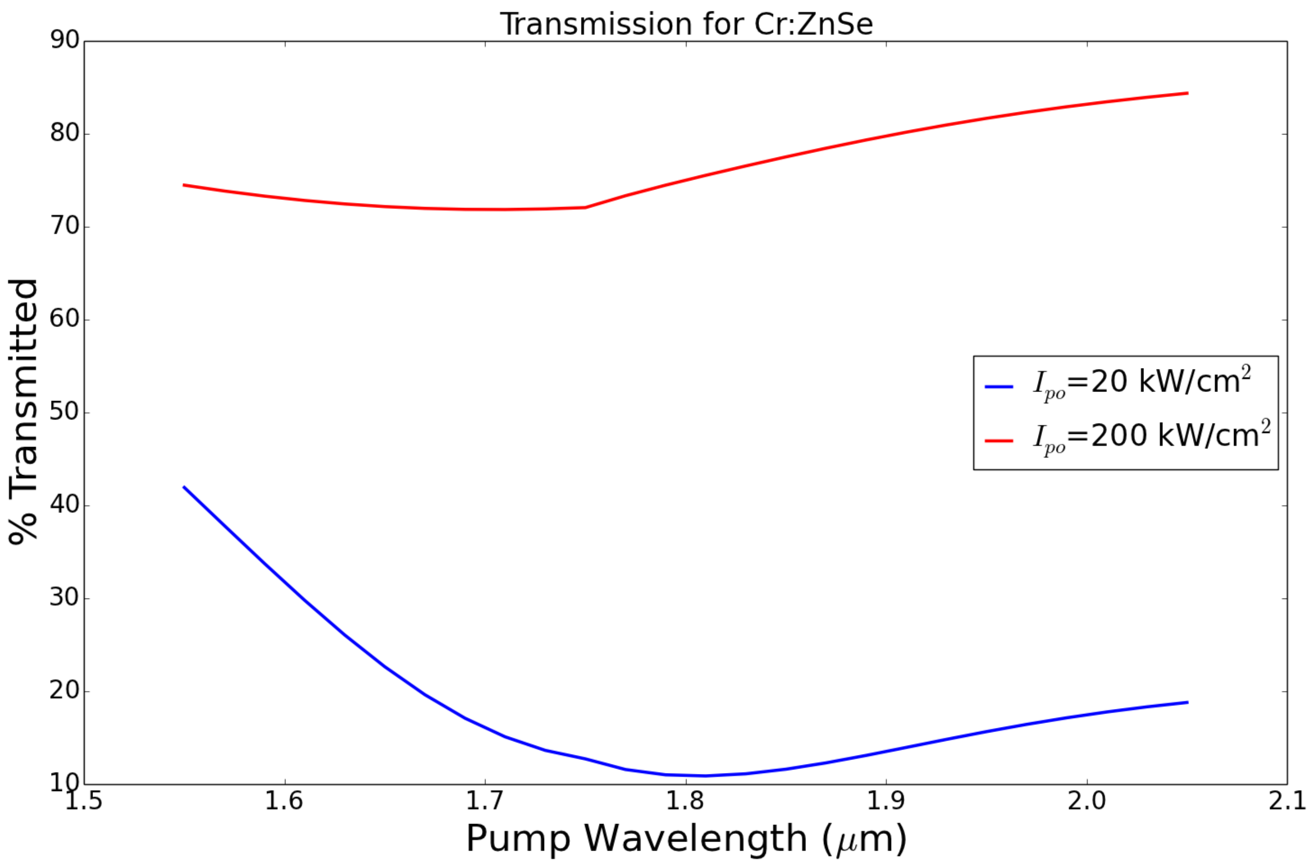
$$= -I_p N_t \left(\frac{(1 + I_p \sigma_{pe} A)(\sigma_{pa} + 2\sigma_{pe})}{I_p A(\sigma_{pa} + 2\sigma_{pe}) + 1} - \sigma_{pe} \right)$$

For wavelengths where σ_{pe}=0 analytic solution exist in terms of Lambert W function

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



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



Depletion of the ground state causes intensity dependent transmission. Here we see the dependence on intensity and wavelength.

Amplification

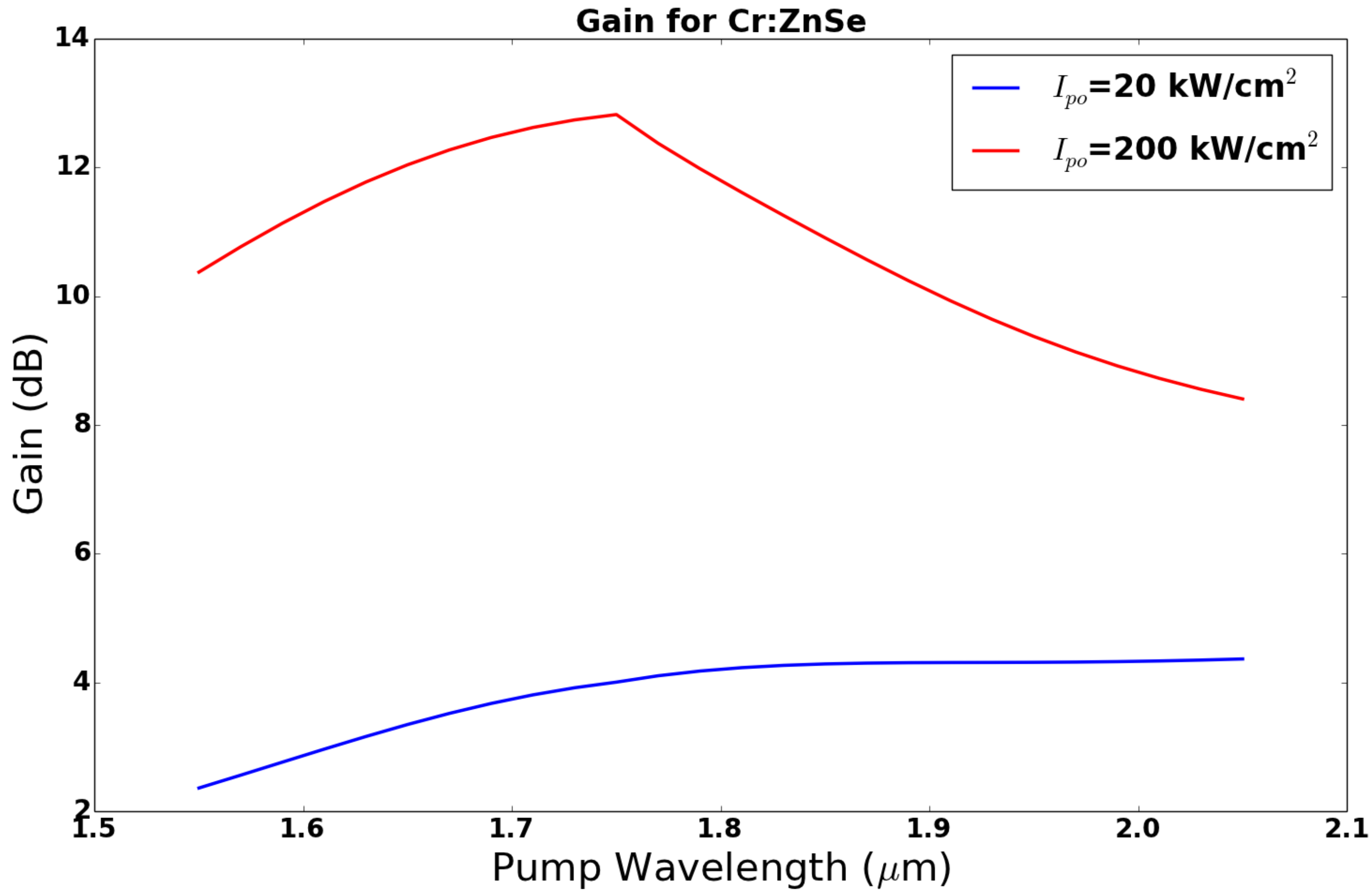
The undulator intensity grows as it propagates through the crystal:

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

Using the rate equation for N_2 growth of signal can be related to loss of the pump as:

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

Gain can be calculated for Cr:ZnSe as a function of doping concentration crystal length, pump laser wavelength and intensity.



$\nu_s = 2.49\ \mu m$ L=1.38 mm, N_T =2.0*10^{19} ion/cm^3

Thermal Lensing

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

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

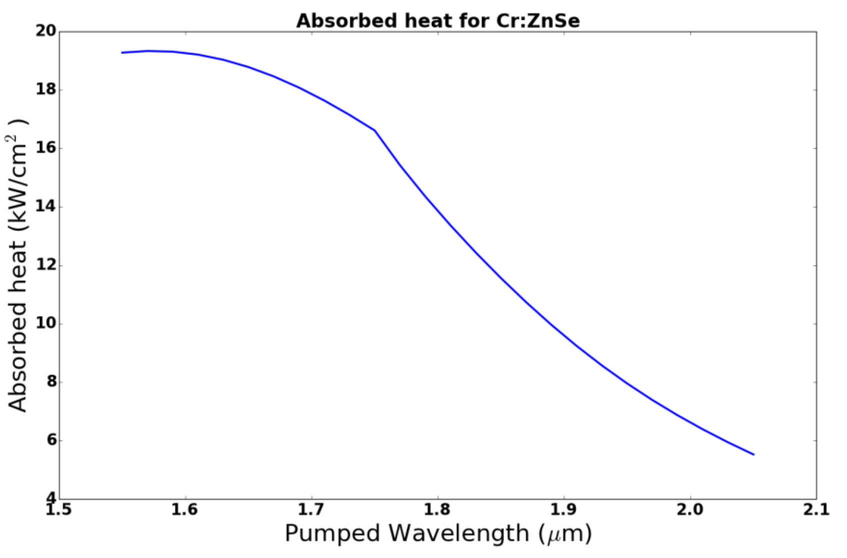
$\frac{dn}{dt}$ =7*10^{-5} K

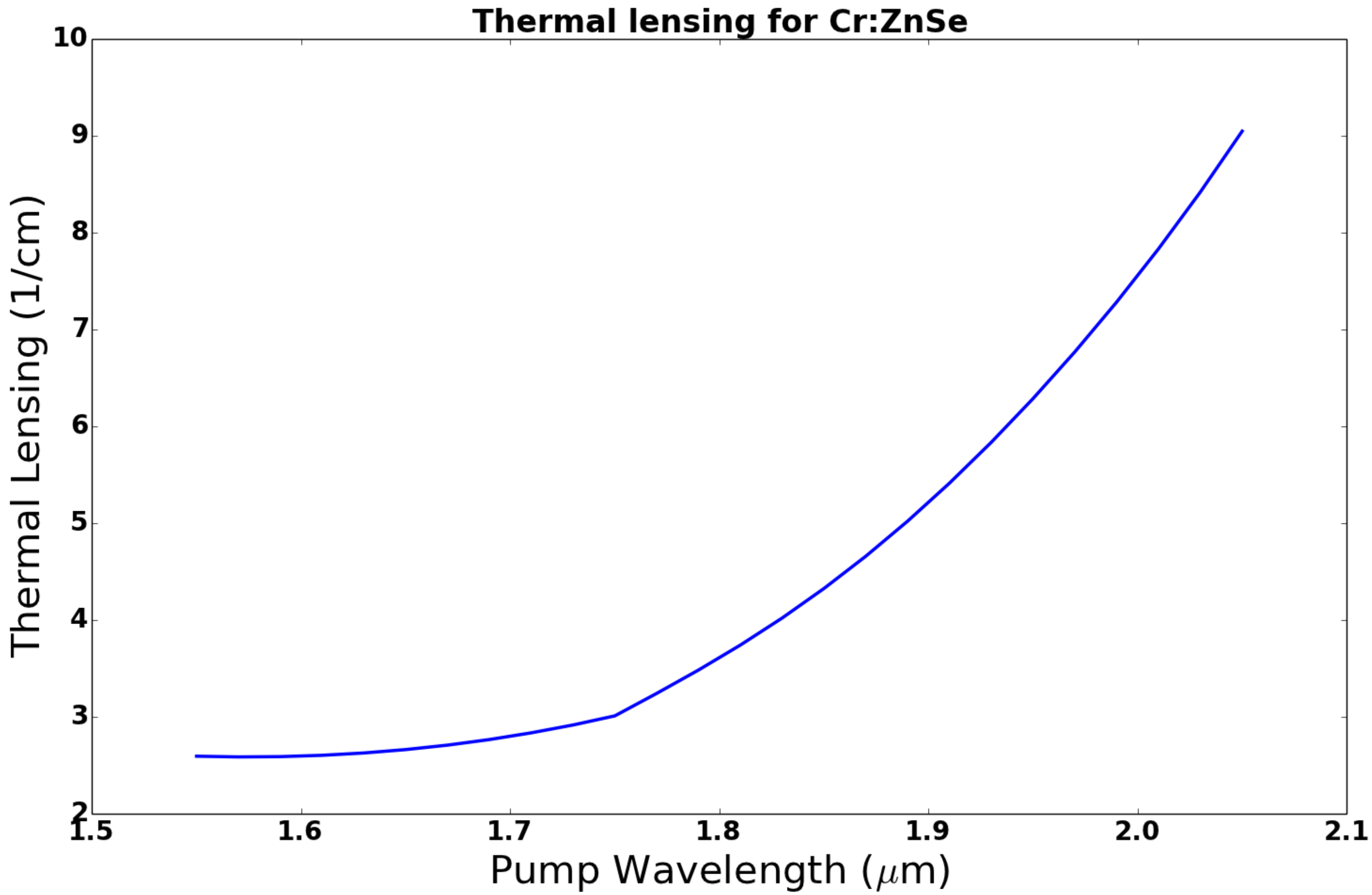
$\kappa = 1$ W/m*K

I_h is the fraction of absorbed intensity that goes into heat

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

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





I_{po}=200 kW/cm^2 . Same crystal parameters as before

Thermal Lensing

Another contribution to thermal lensing comes from bulging of the ends

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

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

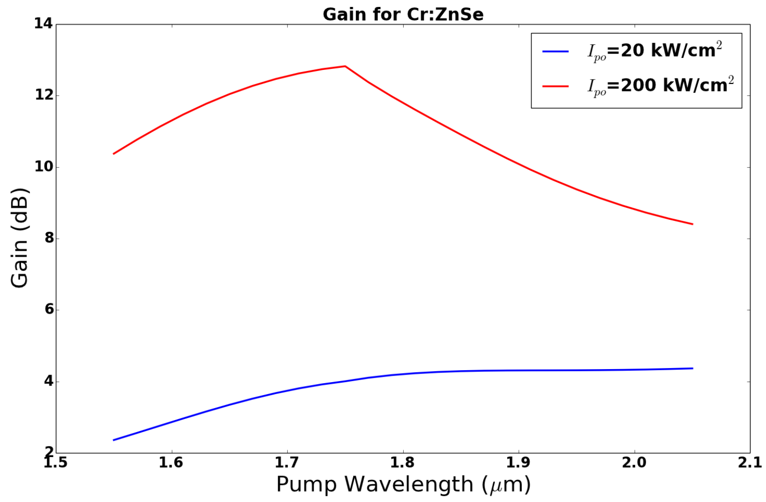
L=1.38mm

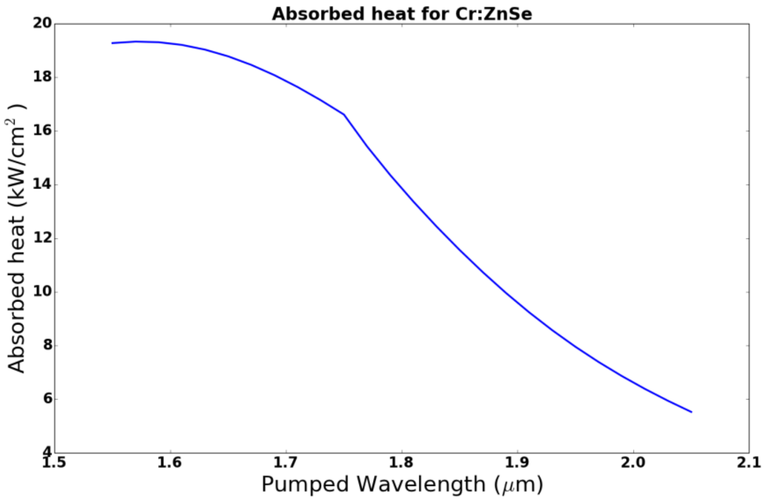
This contribution is much smaller. For a laser with a spot size of 70 µM at an intensity of 200 KW/cm^2 f_b ~250 cm.

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

Pump Selection

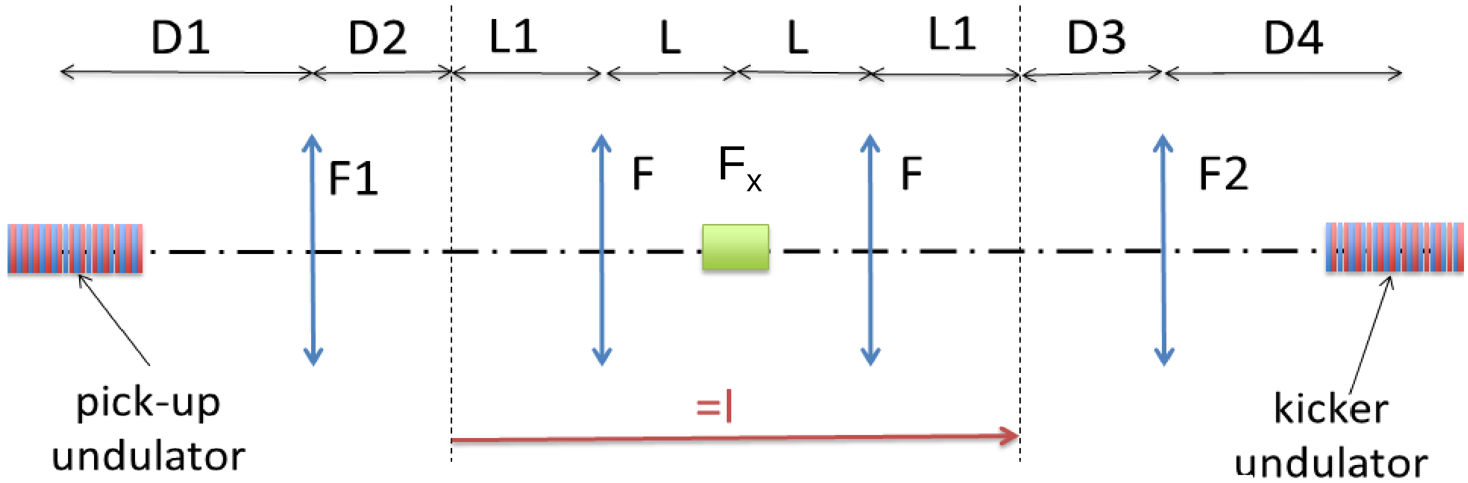
Two candidate pumps. Erbium fiber laser at 1550 nm or a Thulium fiber laser at 1930 nm. Assume both have 50 W.





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



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

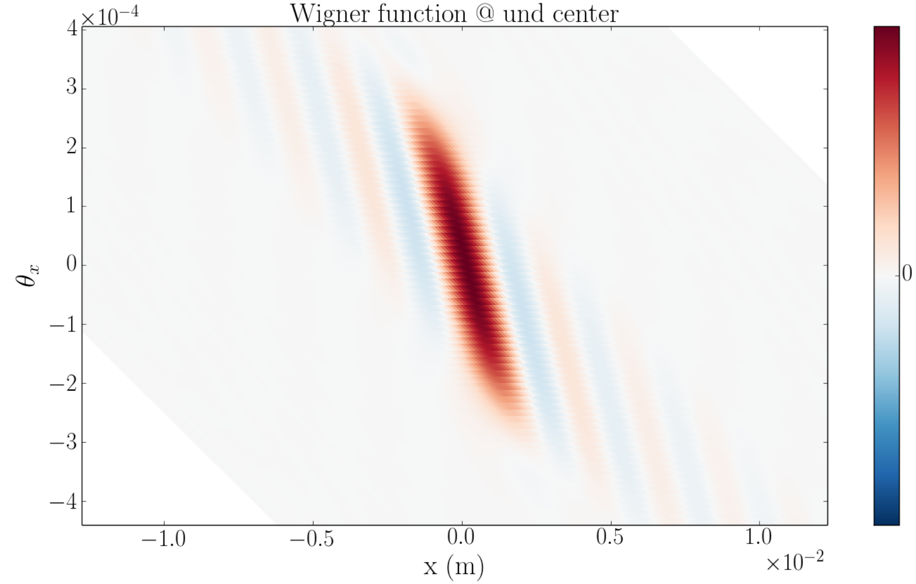
To eliminate depth of field effects transfer matrix should be ‘I’ the identity matrix since D(-L)ID(+L)=I

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

Optics

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

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



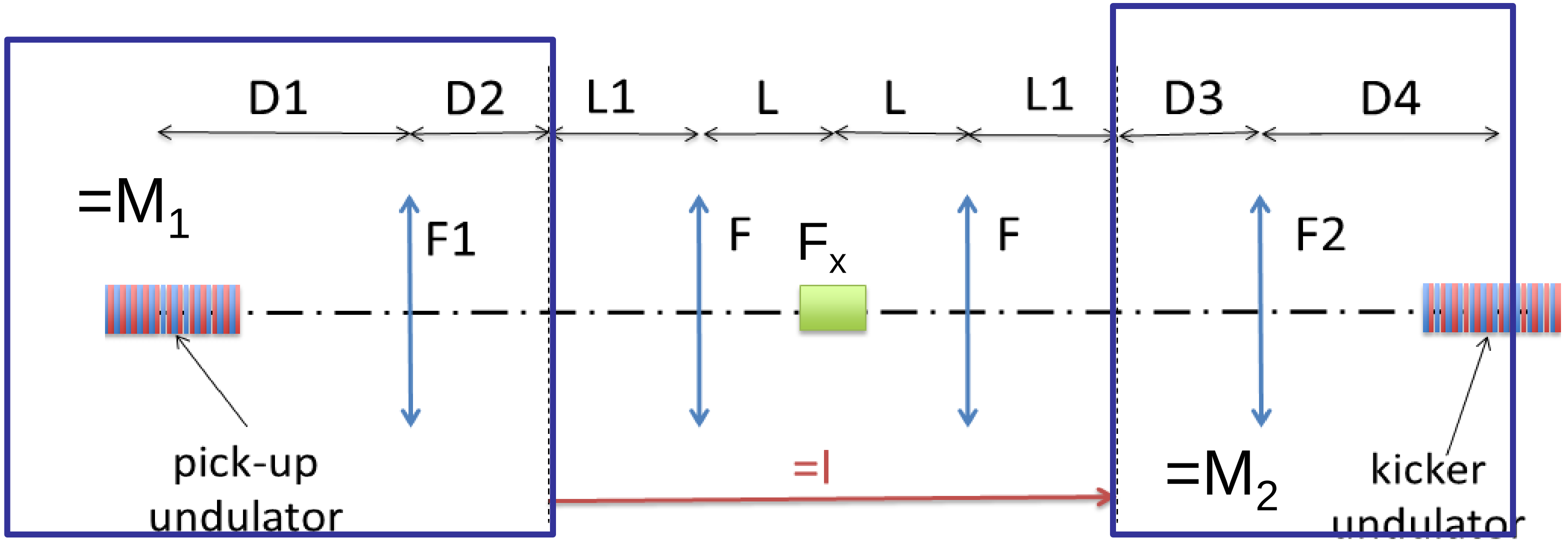
Can then calculate Courant-Snyder parameters for photon beam.

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

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



Requirement for inside system to be identity

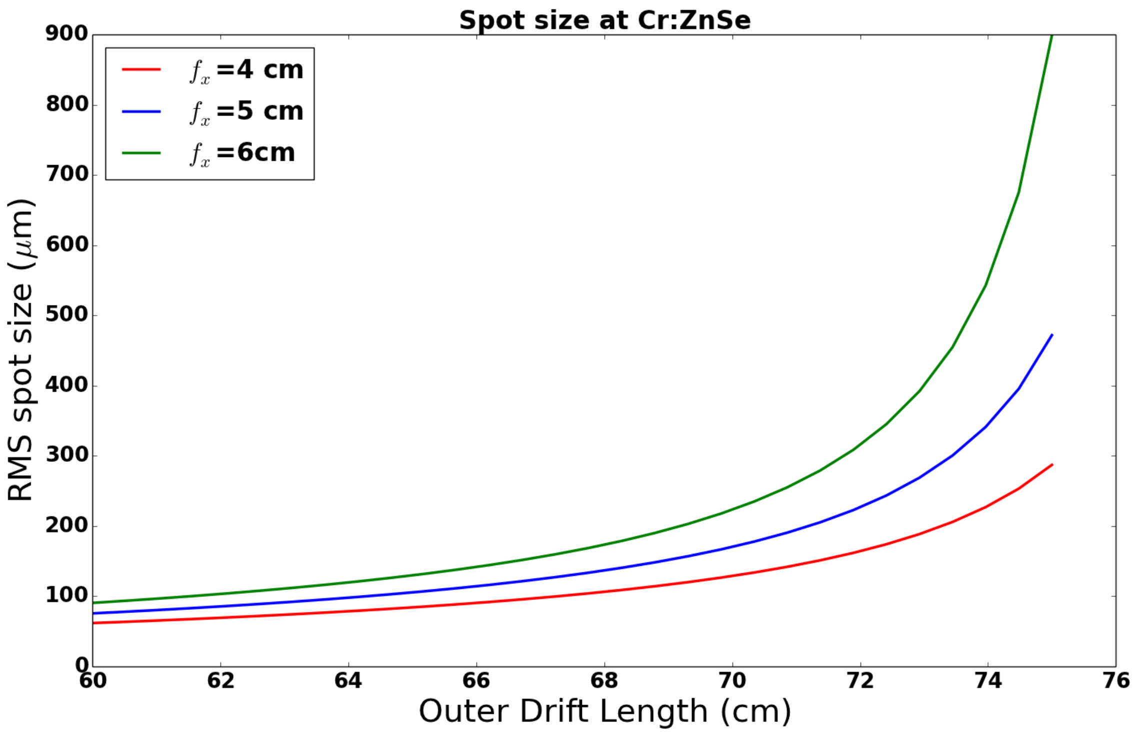
$F = LL_1/(L+L_1)$ $F_x = L_1^2 / 2(L+L_1)$

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 $F_1 = F_2$. Lens placement constrained by beam optics. For further analysis we set $D_1 = D_4$

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.