Design and Optimization of Herriot Cells for Non-Linear Optics

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LCLS II Upgrade

Background

In September of 2023, LCLS II, the long awaited upgrade to LCLS, produced its first x-rays. This upgrade, among other feats, increased the x-ray pulse repetition rate by orders of magnitude. Pump-probe experiments require a matching upgrade in optical and infrared laser systems. Consequently, there is now a pressing need to increase pulsed laser systems average power output and frequency conversion efficiency at LCLS.

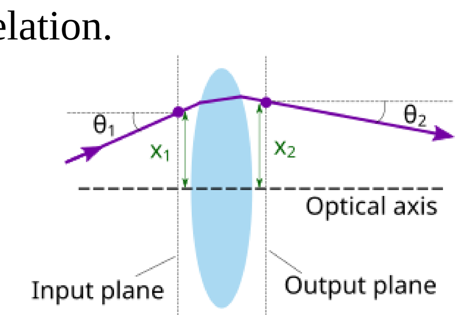
Objective

We suggest a multi-pass cell for both self-phase modulation and increased efficiency in parametric down conversion, which has seen great promise in recent years. To engineer a multi-pass cell, we require simulations to understand beam propagation and non-linear interactions within the cell.

Gaussian Beam Propagation

Ray Transfer Matrix

In geometric optics, an ABCD matrix is used to determine the trajectory of a beam with the following relation.



$$\begin{pmatrix} x_2 \\ \theta_2 \end{pmatrix} = \begin{pmatrix} A & B \\ C & D \end{pmatrix} \begin{pmatrix} x_1 \\ \theta_1 \end{pmatrix}$$

For our system, we can treat a spherical mirror as a thin lens and so our ABCD matrix for an N pass cell becomes

$$M^N = \left\{ \begin{pmatrix} 1 & d/2 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 \\ -1/f & 1 \end{pmatrix} \begin{pmatrix} 1 & d/2 \\ 0 & 1 \end{pmatrix} \right\}^N$$

Gaussian Beams

The fundamental transverse mode of a laser resonator (TEM 00) is a solution to the Helmholtz Equation constrained to having spherical wavefronts.

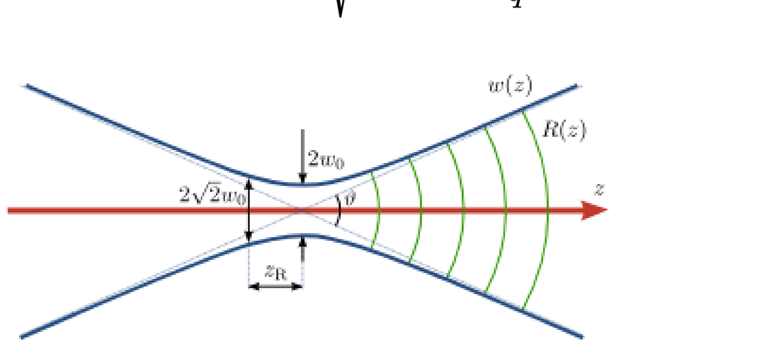
$$U(r,z) = \frac{w_0}{w(z)} \exp\{-i(kz-\phi) - r^2(\frac{1}{w(z)^2} + \frac{ik}{2R(z)})\}$$

The complex beam parameter $q(z)$ describes the transverse evolution of the beam given the following relation.

$$\frac{1}{q(z)} = \frac{1}{R(z)} + \frac{i\lambda}{\pi w(z)^2}$$

In tandem with the ABCD matrix, we can solve for the beam waist $w(z)$ and the wavefront's radius of curvature $R(z)$ inside our cell computationally, using

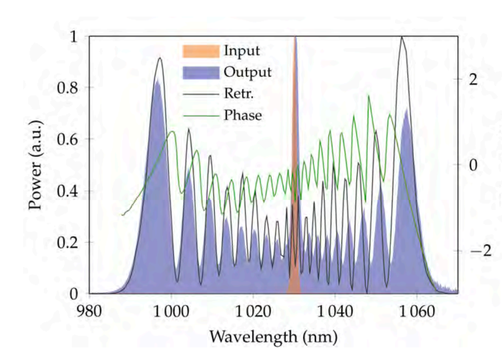
$$BD + q^2AC = 0 \qquad w_1 = \sqrt{w_0^2(A^2 + \frac{B^2}{q^2})/(AD-BC)}$$



Non-Linear Interactions

Self-Phase Modulation

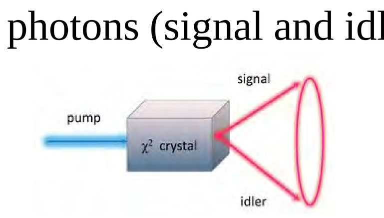
For pulse compression, the beam will propagate through a gaseous medium which will induce a varying refractive index. The resulting phase shift will broaden the beam's spectrum allowing for shorter pulses in time.



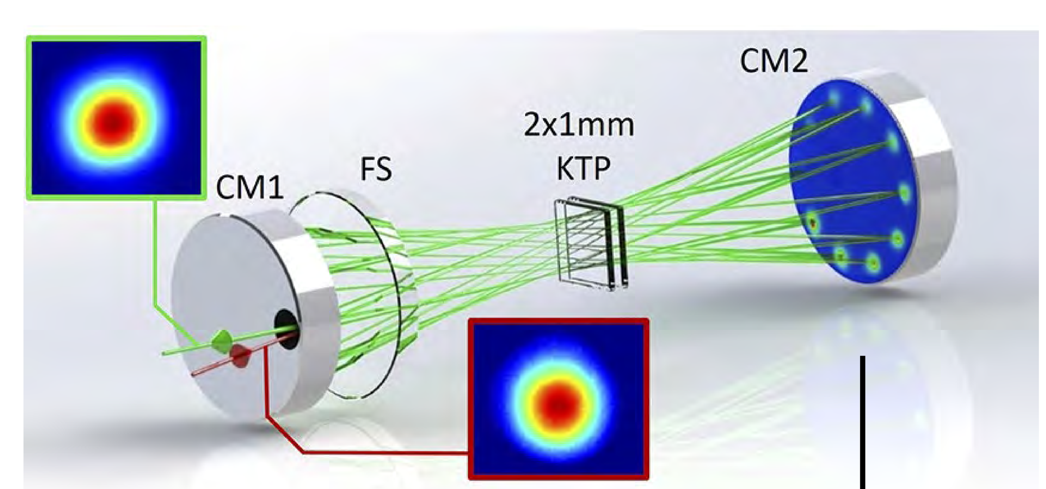
$$\mathbf{P}(t) = \varepsilon_0 \left(\chi^{(1)}\mathbf{E}(t) + \chi^{(2)}\mathbf{E}^2(t) + \chi^{(3)}\mathbf{E}^3(t) + \ldots \right),$$

Parametric Down Conversion

A higher frequency pump beam will pass through the cell interacting with a crystal that converts higher energy photons into a pair of lower energy photons (signal and idler).



Stable Mode Simulations



Cell Geometry

With two spherical mirrors the beams propagation forms an ellipse governed by cell and input beam parameters.

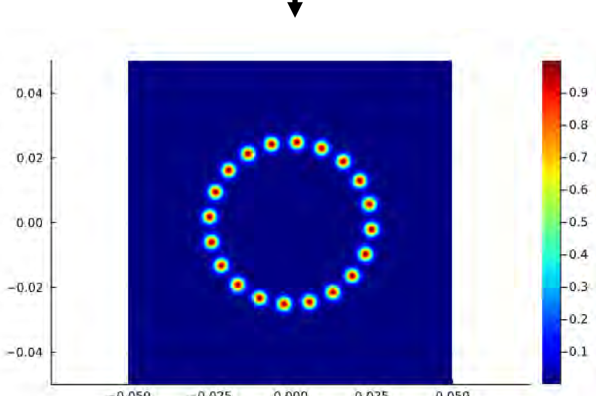
$$x_n = x_0 \cos n\theta + \sqrt{\frac{d}{4f-d}}(x_0 + 2fx_0')\sin n\theta$$

$$\cos\theta = 1 - (d/2f)$$

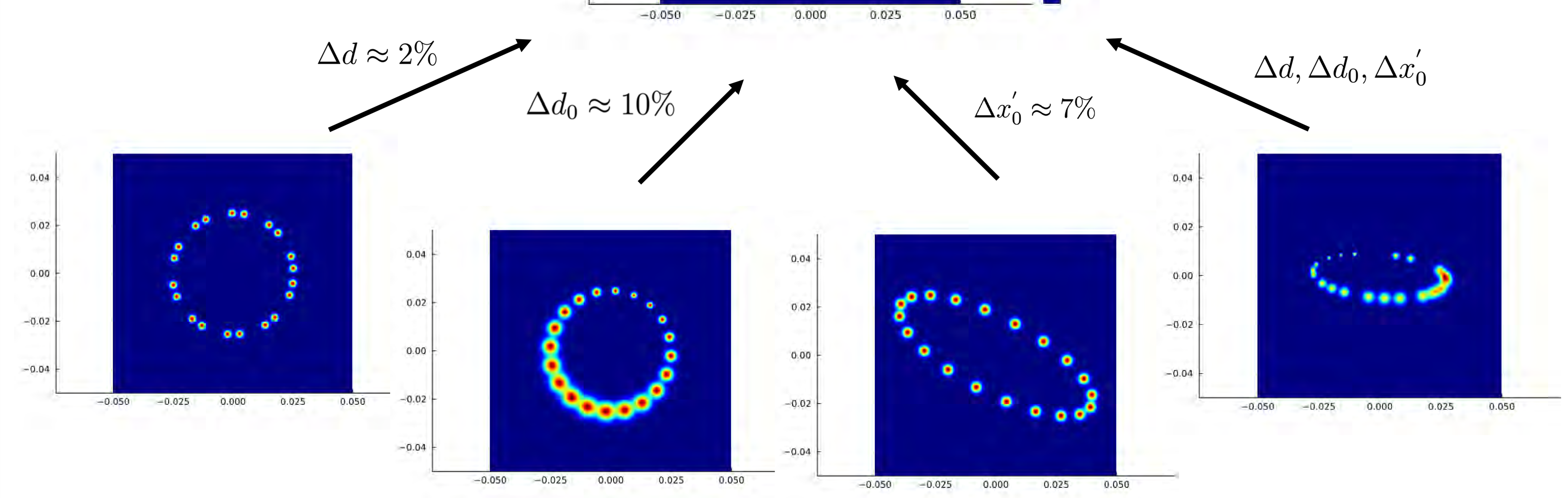
Stable Mode Conditions

To maintain a stable circular pattern on the mirror, the parameters must meet these conditions.

$$d = 2f(1+\cos(\frac{\pi}{N})) \qquad x_0' = -\frac{2x_0}{d}$$

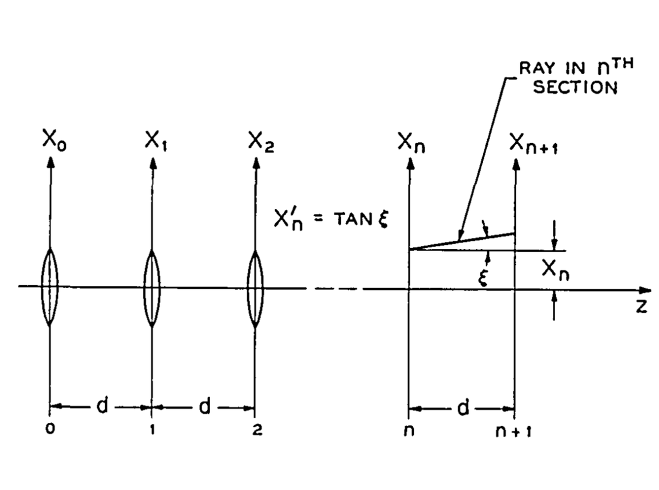


f - focal length of spherical mirrors
d - distance between the mirrors
d_0 - distance between input beam waist and mirror
n - pass number
(x_0, y_0) - position of input beam
(x_0', y_0') - gradient of input beam



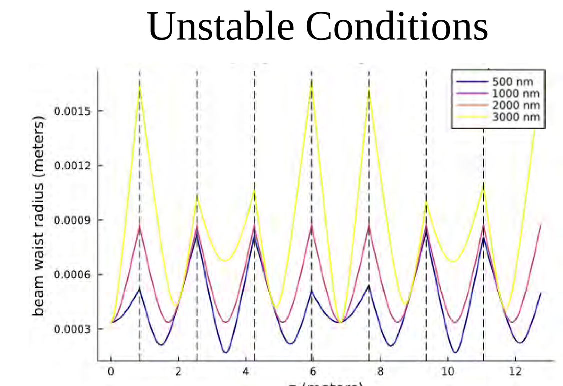
Eigenmodes For Periodic Lenses

There exist modes where the complex beam factor q is periodic inside a system of equidistant lenses for given in coupling beam parameters. Because spherical mirrors have the same effect on gaussian beams as a thin lens, we can use these results for our multi-pass cell.

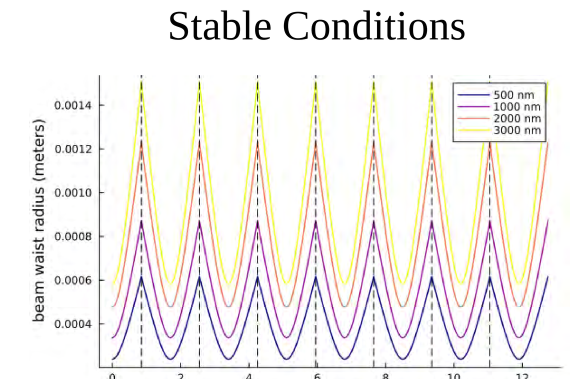


Multi-Color Beam Propagation

Unstable Conditions



Stable Conditions

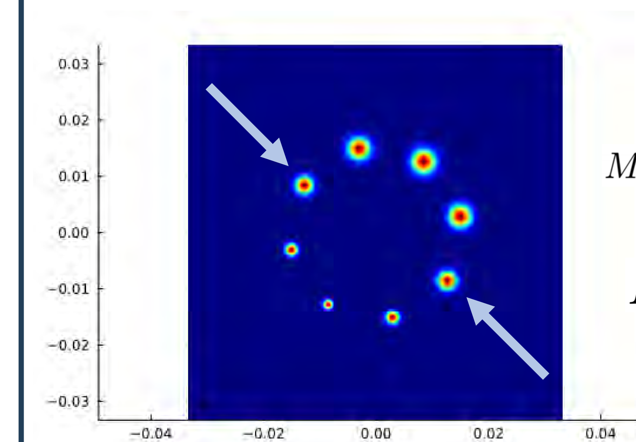


When coupling different wavelengths into the same cell, the input beam parameters for stable propagation differ. Therefore, if we want to have a multi-pass cell that can optimize non-linear processes we must be conscientious of how we couple in differing wavelengths. Alternatively, we can search for other periodic structures.

Imaging Conditions

Imaging Conditions

When B = 0 in the ABCD matrix, we reach an imaging condition. If stable mode conditions are met in the cell, we can image an identical beam at pass number N/2 and N.



$$M\lambda = \lambda\Lambda \qquad P = [\Lambda_1, \Lambda_2]$$

$$M^N = PD^NP^{-1}$$

This will give us another place to couple out a beam with the same size as the input. We can efficiently compute the conditions for imaging in Mathematica by diagonalizing the transfer matrix, M.

Self-Focusing Correction

Change to Complex Beam Factor

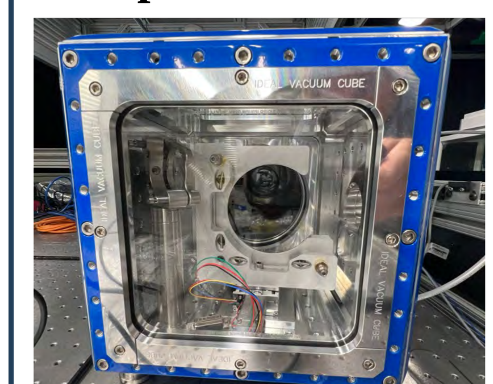
Self-focusing occurs when a non-uniform (gaussian) beam of light alters the intensity dependent index of refraction in a non-linear medium. It is suggested that for gaussian beams, the self focusing affects the complex beam factor as follows.

$$\frac{1}{q(z)} = \frac{1}{R(z)} + \frac{i\sigma\lambda}{\pi w(z)^2} \qquad \sigma = 1 - P/P_{crit}$$

This will alter our alignment procedure, as the focusing conditions for a high intensity beam will be different than for a low intensity alignment beam. In the future, we will do further simulations to better understand how to align a low intensity beam, so that the high intensity pulsed beam is focused properly.

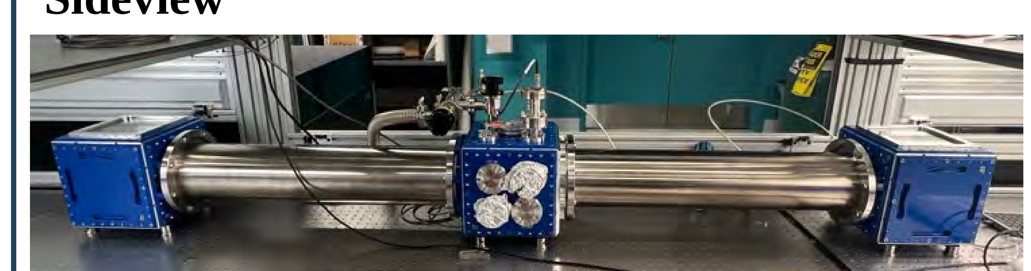
MPC Design for LCLS II

Viewport



- 2mJ, 300 fs, 1030nm input pulses
- Compression down to ~20 fs duration
- 20 passes (in half circle configuration)
- 0.5m focal length of the mirrors
- 2 m cell length
- ~0.9 bar of Ar as the nonlinear medium

Sideview



We can use the viewport to image beam propagation inside the cell.

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CITATIONS

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