Near-field and Far-field beam control - ATIRCM

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ELDP 2008 Guided Demo and Homework Assignment

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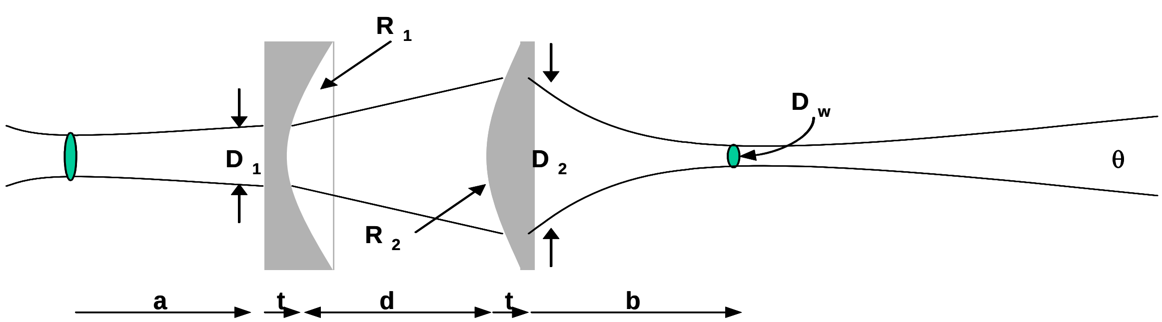
Given: laser beam at resonator - wavelength λ, $\mathbf{M^2}$, divergence θ_o , waist location **a**;
Required: produce a beam with divergence θ in the far-field, and waist at **b** in the near-field
Assume: plano-concave/convex lenses with thickness **t** and separation **d**.
Calculate: the radii of curvature of the lenses, and near-field waist diameter.



$\mathrm{mrad} := 10^{-3}\mathrm{rad}$

Input Parameters

Laser Wavelength	$\lambda := 4.6\mu m$
Beam Quality	$M_{sq} := 2.5$
Beam Divergence* out of the resonator	$\theta_o := 24\mathrm{mrad}$
Far-field Beam Divergence*	$\theta_{ff} := 2.26\mathrm{mrad}$
Distance from waist to F1	$a := 40\mathrm{mm}$
Telescope length	$d := 20\mathrm{mm}$
Near-field beam waist from F2	$b := 500\mathrm{mm}$

*Divergence = full angle at 1/e^2 points

Lens thickness	$t := 3\mathrm{mm}$
Index of refraction, ZnSe	$N := 2.43$

Input beam parameters (Do, θo, E, Zr)===

$E := \frac{4\lambda}{\pi} \cdot M_{sq}$ $\quad E = 14.642\ \mathrm{mm \cdot mrad}$

$\theta_o = 24.000\ \mathrm{mrad}$

$D_o := \frac{E}{\theta_o}$ $\quad D_o = 610.094\ \mu\mathrm{m}$

$zr := \frac{D_o}{\theta_o}$ $\quad zr = 25.421\ \mathrm{mm}$ $\quad q := \begin{pmatrix} \frac{i \cdot zr}{mm} \\ 1 \end{pmatrix}$

We can calculate some answers using equations, without knowing R1 and R2.

In far-field $\quad \theta_{ff} = 2.260\ \mathrm{mrad}$

New waist diameter $\quad D_{new} := \frac{E}{\theta_{ff}}$ $\quad D_{new} = 6.479\ \mathrm{mm}$

Beam diameter on lens 1 $\quad D_{lens\_1} := \sqrt{D_o^{\,2} + a^2 \cdot \theta_o^{\,2}}$ $\quad D_{lens\_1} = 1.137\ \mathrm{mm}$

We can use these values to check our calculation below.

Paraxial Beam Functions ===

Used in this calculation

$\boxed{Zo(q) := \mathrm{Re}\left[q_0\,mm \cdot (q_1)^{-1}\right]}$ Distance from the RP to the waist in this region

$Zr(q) := \mathrm{Im}\left[q_0\,mm \cdot (q_1)^{-1}\right]$ Rayleigh range in this region

$\boxed{\theta(q) := \sqrt{E \cdot Zr(q)^{-1}}}$ Beam Divergence at far-field in this region

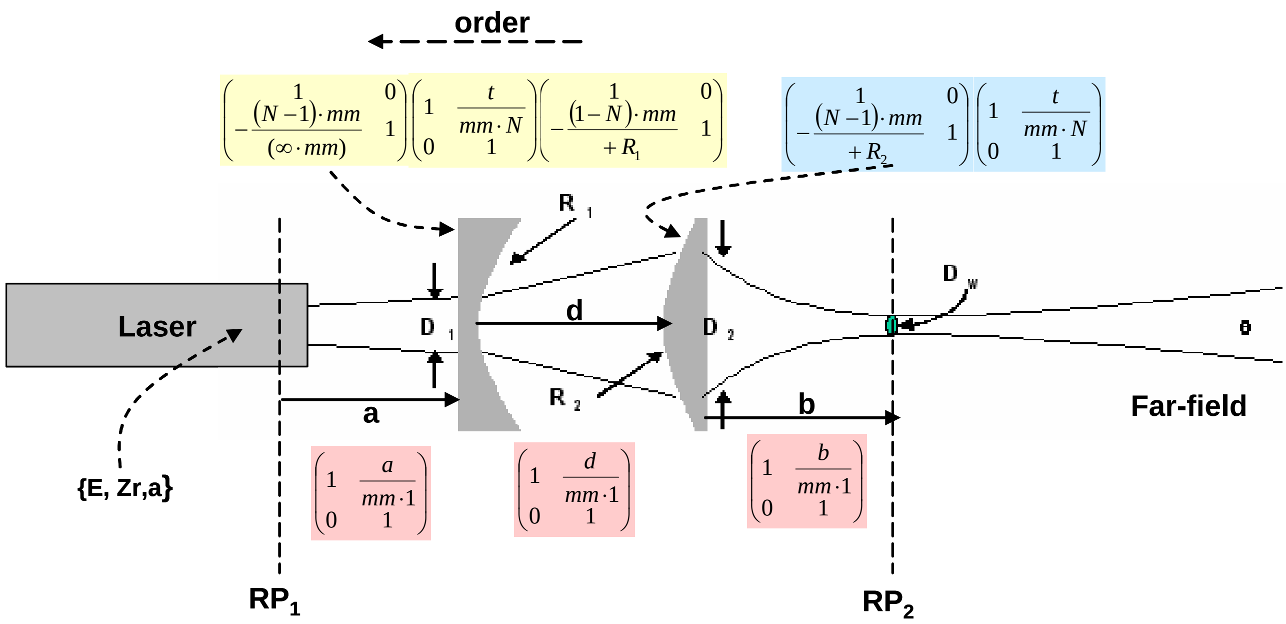
$\boxed{D_{waist}(q) := \sqrt{E \cdot Zr(q)}}$ Beam diameter **at waist** in this region (not at the RP)

$\boxed{D_{RP}(q) := \sqrt{-E \cdot \mathrm{Im}\left[\left[q_0\,mm \cdot (q_1)^{-1}\right]^{-1}\right]^{-1}}}$ Beam diameter **at the RP** (not at the waist)

$R(q) := \mathrm{Re}\left[\left[q_0\,mm \cdot (q_1)^{-1}\right]^{-1}\right]^{-1}$ Radius of curvature of beam at the RP.

What is the difference between the two diameters?
When are they equal? (The answer is not profound!)

Describe the optical configuration===



$$ABCD(R_1,R_2) := \begin{pmatrix} 1 & \frac{b}{mm} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -mm \cdot \frac{N-1}{R_1} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{d}{mm} \\ 1 & 1 \end{pmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{(1-N) \cdot mm}{R_2} & 1 \end{bmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{a}{mm} \\ 0 & 1 \end{pmatrix}$$

Is the order correct? NO ***Typo error***

$$ABCD(R_1,R_2) := \begin{pmatrix} 1 & \frac{b}{mm} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -mm \cdot \frac{N-1}{R_2} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{d}{mm} \\ 1 & 1 \end{pmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{(1-N) \cdot mm}{R_1} & 1 \end{bmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{a}{mm} \\ 0 & 1 \end{pmatrix}$$

Are the matrix elements correct? NO ***Which element is wrong?***

$R_1 := 100mm$ $\quad$ $R_2 := 100mm$ $\quad$ $|ABCD(R_1,R_2)| = -19.000$

Corrected

$$\boxed{ABCD(R_1,R_2) := \begin{pmatrix} 1 & \frac{b}{mm} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 \\ -mm \cdot \frac{N-1}{R_2} & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{d}{mm} \\ 0 & 1 \end{pmatrix} \cdot \begin{bmatrix} 1 & 0 \\ -\frac{(1-N) \cdot mm}{R_1} & 1 \end{bmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm \cdot N} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{a}{mm} \\ 0 & 1 \end{pmatrix}}$$

$$ABCD(R_1,R_2) = \begin{pmatrix} -0.764 & 346.380 \\ -4.090 \times 10^{-3} & 0.545 \end{pmatrix} \qquad |ABCD(R_1,R_2)| = 1.000$$

Calculate the radii of curvature which satisfy the requirements ======================================

Two degrees of freedom ====> Two restraints
(R1, R2) =====> (1) waist at the correct location, and(2) creates the correct divergence.

Beam in $q := \begin{pmatrix} \frac{i \cdot zr}{mm} \\ 1 \end{pmatrix}$ $q = \begin{pmatrix} 25.421i \\ 1.000 \end{pmatrix}$

$Q(R_1, R_2) := ABCD(R_1, R_2) \cdot q$

$R_1 := 100mm$ $R_2 := 100mm$

Given

(1) $Zo(Q(R_1, R_2)) = 0mm$

(2) $\theta(Q(R_1, R_2)) = 2.26mrad$

Go Mathcad! $\begin{pmatrix} R_1 \\ R_2 \end{pmatrix} := Find(R_1, R_2)$ $\begin{pmatrix} R_1 \\ R_2 \end{pmatrix} = \begin{pmatrix} 6.64838379 \\ 34.68542644 \end{pmatrix} mm$ Unique solution

Check answer $R_1 = 6.648\ mm$ $R_2 = 34.685\ mm$

$\theta(Q(R_1, R_2)) = 2.259999970\ mrad$ $\theta_{ff} = 2.26\ mrad$

$Zo(Q(R_1, R_2)) = -7.922 \times 10^{-5}\ mm$ convergence tolerance QED

Analyze the result ==

Beam diameter at lens#1

$Q_1 := \begin{pmatrix} 1 & \frac{a}{mm} \\ 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} \frac{i \cdot zr}{mm} \\ 1 \end{pmatrix}$ $D_{RP}(Q_1) = 1.137\ mm$

from above $D_{lens\_1} = 1.137\ mm$ QED

New waist diameter $D_{waist}(Q(R_1, R_2)) = 6.479\ mm$

from above $D_{new} = 6.479\ mm$ make lens#1 diameter > 3 x 1.137mm

Beam diameter at lens #2

$$D_{RP}\left[\begin{pmatrix} 1 & \frac{-500mm}{mm} \\ 0 & 1 \end{pmatrix} \cdot Q(R_1, R_2)\right] = 6.577\ mm$$

Make lens #2 at least 3 x larger

Beam diameter at 500mm from lens #2
Why should you have expected this answer?

$$D_{RP}\left[\begin{pmatrix} 1 & \frac{-500mm}{mm} + \frac{500mm}{mm} \\ 0 & 1 \end{pmatrix} \cdot Q(R_1, R_2)\right] = 6.479\ mm$$

What is beam at 1000 mm from lens #2?
Why should you have expected this answer?

$mil := 0.001in$

Alignment Tolerances===

Longitudinal displacement	$\delta z := 1mil$	$\delta z = 25.400\ \mu m$
Decenter, lateral displacement	$\delta x := 1mil$	$\delta x = 25.400\ \mu m$
Tilt	$\delta a := 1deg$	$\delta a = 17.453\ mrad$

Alignment Sensitivities===

Show that if $\delta z \cdot \delta a = 0$ then the displace+decenter+tilt can be combined

$$\begin{pmatrix} 1 & -\delta z & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & -\delta x \\ 0 & 1 & -\delta a \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} A & B & 0 \\ C & D & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & \delta x \\ 0 & 1 & \delta a \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \delta z & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 1 & -\delta z & -\delta x \\ 0 & 1 & -\delta a \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} A & B & 0 \\ C & D & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \delta z & \delta x \\ 0 & 1 & \delta a \\ 0 & 0 & 1 \end{pmatrix}$$

Alignment Sensitivity of lenses ==

$$\mathrm{Lens1}(\delta x, \delta a, \delta z) := \begin{pmatrix} 1 & \frac{-\delta z}{mm} & \frac{-\delta x}{mm} \\ 0 & 1 & -\delta a \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 \\ -\frac{(1-N)\cdot mm}{R_1} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm\cdot N} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{\delta z}{mm} & \frac{\delta x}{mm} \\ 0 & 1 & \delta a \\ 0 & 0 & 1 \end{pmatrix}$$

$$\mathrm{Lens2}(\delta x, \delta a, \delta z) := \begin{pmatrix} 1 & \frac{-\delta z}{mm} & \frac{-\delta x}{mm} \\ 0 & 1 & -\delta a \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{t}{mm\cdot N} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ -mm\cdot\frac{N-1}{R_2} & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & \frac{\delta z}{mm} & \frac{\delta x}{mm} \\ 0 & 1 & \delta a \\ 0 & 0 & 1 \end{pmatrix}$$

$$\boxed{\mathrm{ABCD}_1(\delta x, \delta a, \delta z) := \begin{pmatrix} 1 & \frac{b}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathrm{Lens2}(0,0,0) \cdot \begin{pmatrix} 1 & \frac{d}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathrm{Lens1}(\delta x, \delta a, \delta z) \cdot \begin{pmatrix} 1 & \frac{a}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

$$\boxed{\mathrm{ABCD}_2(\delta x, \delta a, \delta z) := \begin{pmatrix} 1 & \frac{b}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathrm{Lens2}(\delta x, \delta a, \delta z) \cdot \begin{pmatrix} 1 & \frac{d}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \mathrm{Lens1}(0,0,0) \cdot \begin{pmatrix} 1 & \frac{a}{mm} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}}$$

Divergence sensitivity and error===

$$q := \begin{pmatrix} \frac{i \cdot zr}{mm} \\ 1 \\ 1 \end{pmatrix} \qquad \mu rad := 10^{-6} rad \qquad \theta\left(ABCD_1(0,0,0)\cdot q\right) = 2.260\ mrad$$ no error

$$\Delta\theta_1(\delta x, \delta a, \delta z) := \theta\left(ABCD_1(\delta x, \delta a, \delta z)\cdot q\right) - 2.26mrad \qquad \Delta\theta_2(\delta x, \delta a, \delta z) := \theta\left(ABCD_2(\delta x, \delta a, \delta z)\cdot q\right) - 2.26mrad$$

$$\Delta\theta_1(\delta x, 0, 0) = 1.629\ \mu rad \qquad \Delta\theta_2(\delta x, 0, 0) = -2.005\ \mu rad$$

Negligable

$$\Delta\theta_1(0, \delta a, 0) = -0.603\ \mu rad \qquad \Delta\theta_2(0, \delta a, 0) = -0.085\ \mu rad$$

$$\Delta\theta_1(0, 0, \delta z) = -29.831\ \mu rad \qquad \Delta\theta_2(0, 0, \delta z) = 63.438\ \mu rad$$

$$\frac{\Delta\theta}{\mu rad} = \left(1.629\cdot\frac{\delta x_1}{mil}\right) + \left(-0.603\cdot\frac{\delta a_1}{deg}\right) + \left(-29.831\cdot\frac{\delta z_1}{mil}\right) + \left(-2.005\cdot\frac{\delta x_1}{mil}\right) + \left(-0.085\cdot\frac{da_2}{deg}\right) + \left(63.438\cdot\frac{\delta z_2}{mil}\right)$$

If all errors are uncorrected, the RSS the components.

$$\Delta\theta_{RMS} := \mu rad\sqrt{\left(1.629\cdot\frac{\delta x}{mil}\right)^2 + \left(-0.603\cdot\frac{\delta a}{deg}\right)^2 + \left(29.831\cdot\frac{\delta z}{mil}\right)^2 + \left(-2.005\cdot\frac{\delta x}{mil}\right)^2 + \left(-0.085\cdot\frac{\delta a}{deg}\right)^2 + \left(63.438\cdot\frac{\delta z}{mil}\right)^2}$$

$$\Delta\theta_{RMS} = 70.152\ \mu rad \qquad \frac{\Delta\theta_{RMS}}{2.26mrad} = 3.104\ \%$$

The requirement is less than 5%.

What tolerances dominate?

$$\Delta\theta_{RMS} := \mu rad\sqrt{\left(29.831\cdot\frac{\delta z}{mil}\right)^2 + \left(63.438\cdot\frac{\delta z}{mil}\right)^2}$$

$$\Delta\theta_{RMS} := \mu rad\cdot\left(70.102\cdot\frac{\delta z}{mil}\right) \qquad \Delta\theta_{RMS} = 70.102\ \mu rad$$

Decenter sensitivity and error===

$$\Delta x_1(\delta x, \delta a, \delta z) := ABCD_1(\delta x, \delta a, \delta z)_{0,2}\cdot mm \qquad \Delta x_2(\delta x, \delta a, \delta z) := ABCD_2(\delta x, \delta a, \delta z)_{0,2}\cdot mm$$

$$\Delta x_1(\delta x, 0, 0) = 0.590\ mm \qquad \Delta x_2(\delta x, 0, 0) = -0.525\ mm$$

$\Delta x_1(0, \delta a, 0) = 0.077\ \text{mm}$ $\Delta x_2(0, \delta a, 0) = 0.022\ \text{mm}$

$\Delta x_1(0, 0, \delta z) = 0.000\ \text{mm}$ $\Delta x_2(0, 0, \delta z) = 0.000\ \text{mm}$

$$\frac{\Delta x}{\text{mm}} = \left(0.590 \cdot \frac{dx_1}{\text{mil}}\right) + \left(0.077 \cdot \frac{\delta a_1}{\text{deg}}\right) + \left(-0.525 \cdot \frac{dx_2}{\text{mil}}\right) + \left(0.022 \cdot \frac{\delta a_2}{\text{deg}}\right)$$

If all errors are uncorrected, the RSS the components.

$$\Delta x := \text{mm} \cdot \sqrt{\left(0.590 \cdot \frac{\delta x}{\text{mil}}\right)^2 + \left(0.077 \cdot \frac{\delta a}{\text{deg}}\right)^2 + \left(-0.525 \cdot \frac{\delta x}{\text{mil}}\right)^2 + \left(0.022 \cdot \frac{\delta a}{\text{deg}}\right)^2} \qquad \Delta x = 0.794\ \text{mm}$$

Which tolerances are important?

Pointing angle error due to alignment tolerances ==

$\Delta a_1(\delta x, \delta a, \delta z) := \text{ABCD}_1(\delta x, \delta a, \delta z)_{1,2}$ $\Delta a_2(\delta x, \delta a, \delta z) := \text{ABCD}_2(\delta x, \delta a, \delta z)_{1,2}$

$\Delta a_1(\delta x, 0, 0) = 958.512\ \mu\text{rad}$ $\Delta a_2(\delta x, 0, 0) = -1.047 \times 10^3\ \mu\text{rad}$

$\Delta a_1(0, \delta a, 0) = -75.221\ \mu\text{rad}$ $\Delta a_2(0, \delta a, 0) = 0.000\ \mu\text{rad}$

$\Delta a_1(0, 0, \delta z) = 0.000\ \mu\text{rad}$ $\Delta a_2(0, 0, \delta z) = 0.000\ \mu\text{rad}$

$$\frac{\Delta a}{\mu\text{rad}} = \left(958.512 \cdot \frac{\delta x_1}{\text{mil}}\right) + \left(-75.221 \cdot \frac{\delta a_1}{\text{deg}}\right) + \left(-1047 \cdot \frac{\delta x_2}{\text{mil}}\right)$$

If all errors are uncorrected, the RSS the components. δa1 is negligible.

$$\Delta a := \mu\text{rad} \cdot \sqrt{958.512^2 + (-1047)^2} \cdot \frac{\delta x}{\text{mil}} \qquad \Delta a := \mu\text{rad} \cdot \sqrt{958.512^2 + (-1047)^2} \cdot \frac{\delta x}{\text{mil}} \qquad \Delta a = 1.419\ \text{mrad}$$

$\theta_{ff} = 2.260\ \text{mrad}$ The requirement is $\Delta a < 10\%\ \theta ff = 0.226$ mrad.

What must the decenter tolerance be to meet the pointing requirement?

$$\delta x_{req} := 1 \cdot \text{mil} \cdot \frac{0.226\text{mrad}}{1.419\text{mrad}} \qquad \delta x_{req} = 0.159\ \text{mil}$$

6300 threads/inch! not reasonable.

If too large, the adjust δx_1 to compensate for the other errors. Must be able to see when it is aligned.

$$0 = 958.512 \cdot \frac{\delta X_1}{\text{mil}} + \sqrt{\left(-75.221 \cdot \frac{\delta a}{\text{deg}}\right)^2 + \left(-1047 \cdot \frac{\delta x}{\text{mil}}\right)^2}$$

$$\delta X_1 := -\frac{\text{mil}}{958.512} \cdot \sqrt{\left(-75.221 \cdot \frac{\delta a}{\text{deg}}\right)^2 + \left(-1047 \cdot \frac{\delta x}{\text{mil}}\right)^2}$$

$\delta X_1 = -1.095\ \text{mil}$ fine adjustment!

Comments ==

These results are nicely summarized in alignment sensitivity table.

	Lens Alignment Tolerances					
	Transverse				Longitudinal	
Beam Errors	Displacement (mil)		Tilt (deg)		Displacement (mil)	
	δx_1	δx_2	δa_1	δa_2	δz_1	δz_2
ΔX / mm	+0.590	-0.525				
ΔA / μrad	+959	-1047				
$\Delta\theta$ / μrad					-29.83	+63.44

Question: What happens when $\delta x_1 = \delta x_2$? Modular alignment. or single lens.

Problem Set, 2008

Introductory comments:

1) The goal is to enable you to apply the ABCD method to an important BAE optical problem - with real conditions, issues, designs, and performance requirements. However, understanding the theory, applying it to a practical problem, and knowing how to use Mathcad to get solve it, is too much for 4 hours of lecture.

2) The "Guided Demonstration" is intended to be a "short cut" through the Mathcad, and freeing you to understand the theory, seeing how is applied to arrive at the answers to the salient questions.

3) You are to applied the Guided Demo" to the homework problem along. You are free to ask each other about the course material and the guided demo, but not about the problem set. It is important that you reproduce the equations and generate the results yourself, in order to see how the theory is applied, and to familiarize yourselves with Mathcad. You might start by reproducing the demo analysis, them modify it to the homework problem.

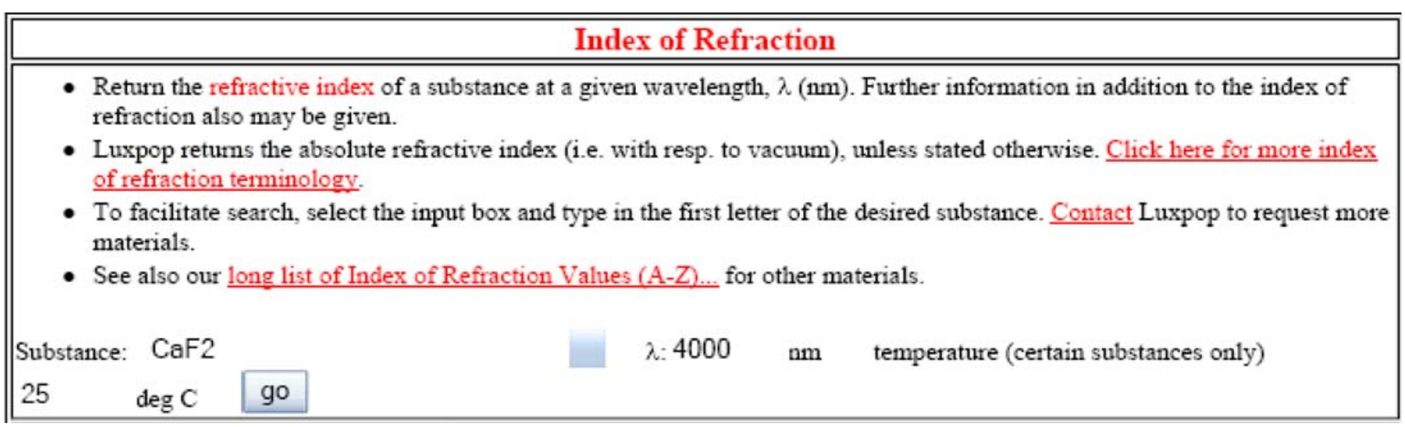
4) Write a Technical Brief. (I) Describe the design problem; identify the assumed parameters and performance requirements. (II) Present the Mathcad analysis, with comments for each step regarding what and how; then clearly summarize the results relative to the requirement. (III) Concluding remarks. What insights or useful knowledge/skills did you acquire.

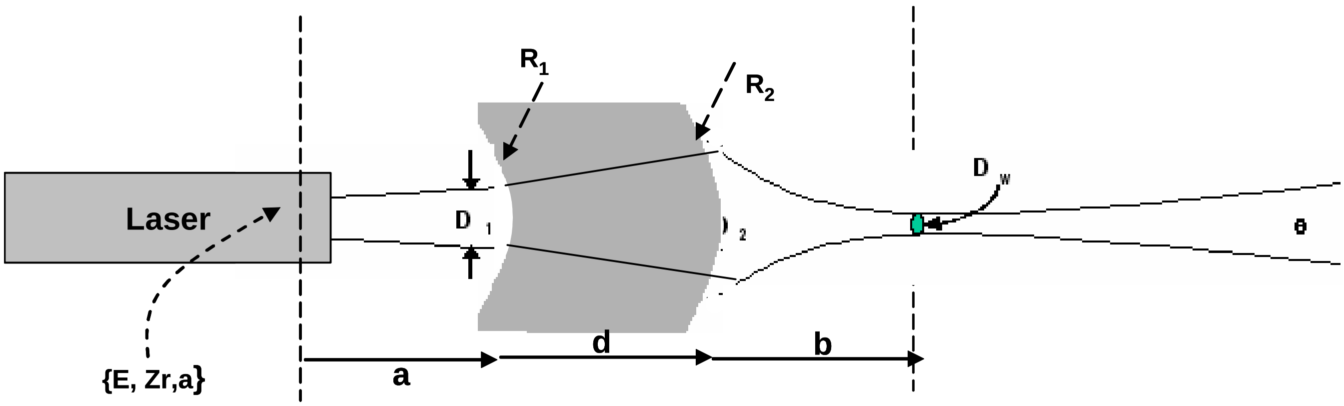
The ELDP single lens design ==

Assume $\lambda := 4.0\mu m$ $\quad M_{sq} := 2.9$ $\quad \theta_o := 22mrad$ $\quad \theta_{ff} := 2.1mrad$

$a = 40.000\,mm$ $\quad d := 20mm$ $\quad b = 500.000\,mm$

Use CaF2 glass. Go to http://www.luxpop.com/ and find the index of refraction, n, at this wavelength at 25 deg C.





$$ABCD(R_1, R_2) := \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \cdot \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \cdot \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \cdot \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix} \cdot \begin{pmatrix} \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \\ \blacksquare & \blacksquare & \blacksquare \end{pmatrix}$$

1) Calculate the ABCD matrix for this new configuration. Check to see if the signs make sense.

2) Calculate R_1 and R_2 for which the two constraints are satisfied. (Be careful! R1 and R2 are negative or positive. Put them into the matrices as unsigned variables, and let Mathcad calculate their sign.) Verify these R's satisfy the two constraints.

3) Calculate the beam diameter at

- R1
- R2 surface (entrance of ATIRCM)
- 500 mm from the R2 surface (middle of ATIRCM
- 1000 mm from the R2 surface (exit of ATIRCM).
- Lens diameter must be greater than 2 R. **Why?** The lens diameter should be at least 3 beam diameters IF they are not to clip the beam. Can these two requirements be satisfied? A common size is 0.5 in diameter. Is that okay?

4) Calculate the alignment sensitivity matrix of this lens?

	Lens Alignment Errors	
	Transverse	Longitudinal
Beam Errors	δx (mils)	δz (mils)
ΔX / mm		
ΔA / μrad		
$\Delta\theta$ / μrad		

5) Are nominal tolerances adequate. Assume δz = 1 mil (0.001 in); δx = 1 mil; δa = 1 degree (be careful). Calculate the errors, and RSS them together, and the % error. Is the one-lens design less sensitive to alignment tolerances than the two lens design?

6) If the manufacturing tolerances for each of the radii of curvature is $\Delta R/R$ = 2%, calculate the RSS error of the beam diameter at 500 mm and of the beam divergence at the target, and the % change in each.

7) Assuming the same alignment tolerances as in the original design, is the ELDP design less sensitive to alignment tolerances in beam divergence, decenter, and angle (pointing error)?

8) How temperature dependent is the beam divergence angle?
The coefficient of thermal expansion CTE in ppm/ΔT(C) are

$$CTE_{Al} = 24\cdot\frac{10^{-6}}{\Delta T_C} \qquad \begin{pmatrix} a \\ b \end{pmatrix}_{at\_T} = \begin{pmatrix} a \\ b \end{pmatrix}_{at\_25C} \cdot\left[1 + CTE_{Al}\cdot(T - 25C)\right]$$

$$CTE_{CaF2} = 4.0\cdot\frac{10^{-6}}{\Delta T_C} \qquad \begin{pmatrix} R_1 \\ R_2 \\ d \end{pmatrix}_{at\_T} = \begin{pmatrix} R_1 \\ R_2 \\ d \end{pmatrix}_{at\_25C} \cdot\left[1 + CTE_{CaF2}\cdot(T - 25C)\right]$$

We neglect the slight temperature dependence of the index of refraction, and assume the system is aligned.

Calculate the beam divergence at T = -20C, +25C, and +40C .

9) In ATIRCM, the wavelength is not 4.0 μm, but rather a spectrum from 3 μm to 5 μm. The design for λ = 4 μm is intended to be a compromise. At 4 μm, the divergence is θ = 2.1 mrad.

Use LUXPOP to find the index of refraction at 3 μm and 5 μm, calculate the change in beam divergence. Does it meet the 5% requirement?

This beam forming optic has never been build. Maybe it is worth patenting?