Using an Envelope and Matrix Code
PBO Lab TRACE 3-D Example Set 2

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Outline- Part II - Example Set 2

⇒ **Will use PBO Lab TRACE 3-D Module to work through some examples**

1. Set Up Global Parameters & Initial Beam Description for the Injector

2. Drift Beam to Estimate 1st Focusing Element Location, Check Space Charge

3. Use an Einzel Lens near Estimated Location of 1st Focusing Element

Injector Globals & Initial Beam

1a. Setup a "template" for the following beam using the PBO Lab Globals:

Particle Charge:	**+1**
Particle Mass:	**1500 amu**
Beam Energy:	**30 keV**
Particle Current:	**0 mAmp (will explore later)**
Frequency:	**0 MHz (for DC Beam) ?**
Maximum Step Size:	**1 cm (will explore later)**

No need to set anything on Tracing/Tracking or Floor Coordinates tab panels. Why?

⇒ No • to right of parameters ⇒ Not used by TRACE 3-D

Injector Globals & Initial Beam

1b. Add a "Beam" to the Model Space.

Open the "Beam" and set the Beam Parameters switch to the setting "Courant-Synder (Twiss) - Beam 2"

What to Use for "Emittance (x-x')" ?

To Begin, We Can Use the *Acceptance* of the First Einzel Lens

Emittance (x-x'): **120 π-mm-mrad, bnd**

⇒ ***Acceptance*** **Usually Implies a Boundary (bnd) Type Value**
Actual Beam *Emittance* Will Be Smaller (or Scraping Occurs)

Alpha Horizontal: **0 (phase ellipse upright)**

Beta Horizontal: **0.075 mm/mrad (will explore later)**

Why? What Size Beam Does This Correspond to?

⇒ ***Use*** $x_m = [\beta_x \varepsilon_x]^{1/2} = [120 \times 0.075]^{1/2} = [9]^{1/2} = 3$ mm

Injector Globals & Initial Beam

For a Beam with Circular Symmetry, the Vertical & Horizontal Phase Planes are the Same

⇒ **Use Same Parameters for Vertical as Used for Horizontal**

Emittance (y-y'): **120 π-mm-mrad, bnd**
Alpha Vertical: **0 (phase ellipse upright)**
Beta Vertical: **0.075 mm/mrad**

What to Use for "Longitudinal (z)" Parameters?
Temporarily Leave These as Their Default Values, *Except*
Alpha Longitudinal: **0 (phase ellipse upright)**
⇒ **We Will Set These Using the Semi-Axes Representation**

Before Changing to the Semi-Axes Representation Use the "AutoScale Plots" Button to See the Transverse Phase-Space

Label the Beam Piece (Comments) with Some Useful Info, Something Like "1500 amu with 120 pi-mm-mrad ACCEPTANCE"
⇒ **Save this model as "Source_1" (File: Source_1.pbol)**

Injector Globals & Initial Beam

1c. Change the Beam Parameters Switch to the Setting: "Semi-Axes - Beam 1"

Open the "Beam" and set the Beam Parameters switch to the setting "Courant-Synder (Twiss) - Beam 2"

Use the "Comp from Twiss" to Convert from the Twiss (Beam 1)

⇒ **Transverse Looks OK (May Need to Update Displays)**

Look at the "Longitudinal (z)" Parameters

⇒ **The "INF" (infinity or undefined) is One Problem With Using:**

Frequency: 0 MHz

What We Want to Use is a Frequency Whose Wavelength is:

Long Compared to the Length of the Beamline

Typically Choose a Frequency for Wavelength of ~100 meters

⇒ **Return to PBO Lab Globals and *Change Frequency***

Injector Globals & Initial Beam

Again Use the "Comp from Twiss" Button

⇒ **Transverse Unchanged**

Look at the "Longitudinal (z)" Parameters

⇒ **The "INF" Are Replaced by Finite Numbers**

Now We Will Modify the "Longitudinal (z)" Parameters

- **For the Beam "Bunch Length" We Will Use the Formula:**

$$(4/3)(r_z/\beta\lambda) = 1$$

Giving: $r_z = (3/4)\,\beta\lambda = (0.75)(0.000207)(100\text{ m}) = 15.525\text{ mm}$

⇒ **Even Easier: Use PBO Lab "β-Lambda" Smart Units!**

- **For the Beam "Energy Spread" Use the Ion Source Value:**

I Estimate: $\Delta E/E \approx 10^{-04}$ **(3 eV energy spread)**

Half Beam Extent (z): 15.525 mm
Half Momentum Spread (z'): 0.003 deltaE(keV)

Injector Globals & Initial Beam

Note that the Longitudinal Beam Parameters are Connected to Global Parameters: Particle Mass, Beam Energy, Frequency

For TRACE 3-D This Connection Needs to be Kept in Mind

Let us Update the Model for Consistency - to make the data stored in Beam 1 equivalent to the data stored as Beam 2.

- **Change the Beam Parameters switch to "Courant-Synder (Twiss) - Beam 2"**
- **Use the "Comp From Axes" Button to Update Twiss Params**
  ⇒ Only the Longitudinal Parameters Should Change

Beam 1 and Beam 2 Now Have Consistent Data - Use Either One

Suggest Adding to Beam Piece Comments Something Like "1500 amu with 120 pi-mm-mrad ACCEPTANCE & 100 m Wavelength"

⇒ Save this model (same name "Source_1")

Estimate Location of 1st Focusing Element, Check Space Charge

It is Often Worth Taking a Look at How a Given Beam *Drifts*

- **Can Tell How Quickly Beam Will Expand, and Consequently How Close to the Source the 1st Focusing Element is Needed**
- **Can Use the Global "Beam Current" to See at What Current Space Charge May Become Important**

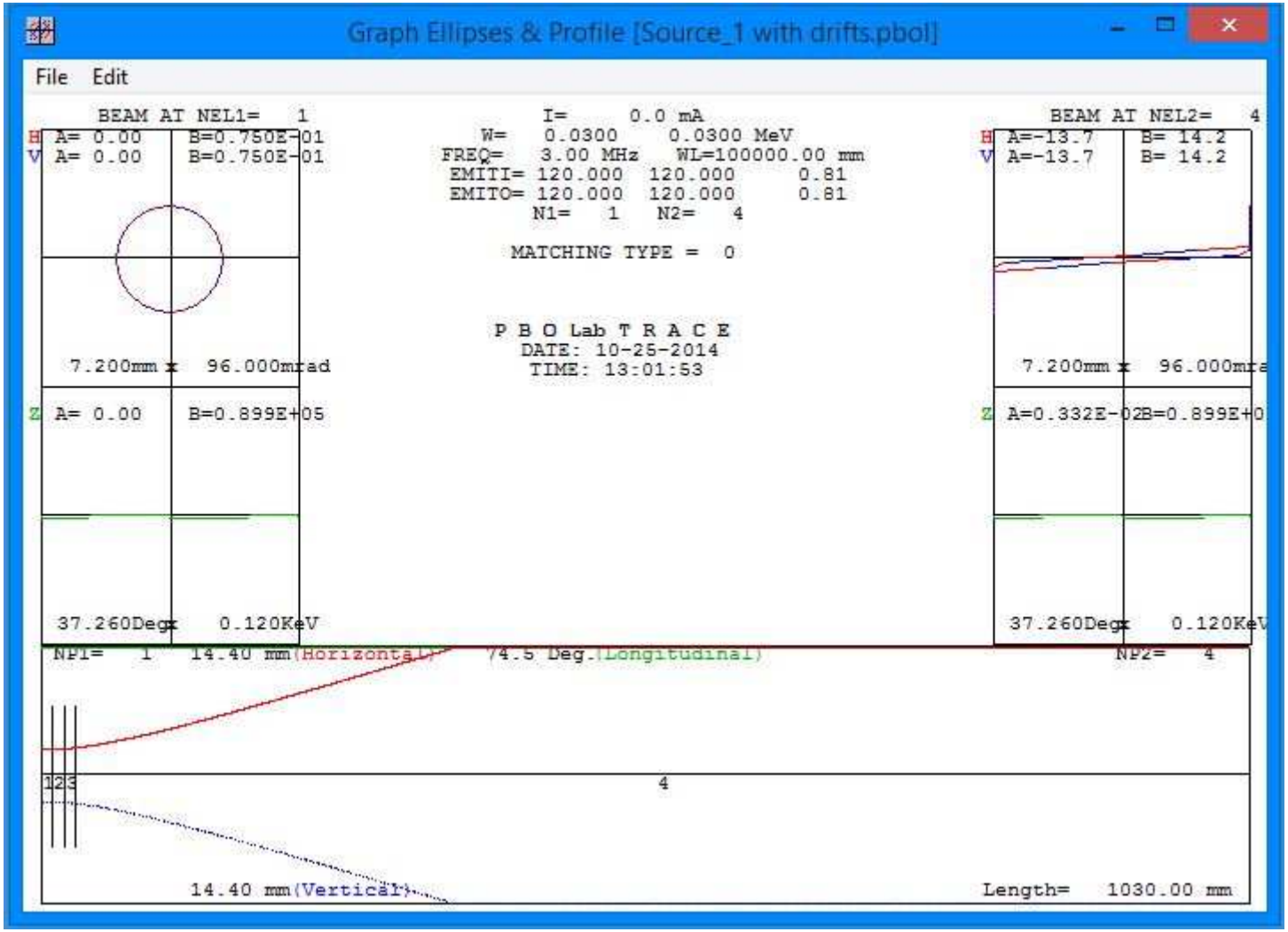
2a Add 3 Drifts to the Model "Source_1" & Graph Beam Line [Commands -> TRACE 3-D -> Graph Beam Line]

The Result Does Not Show Much - So Fix Up the Calculation:

- **Change Maximum Step Size: 0.1 mm**
- **Select TRACE 3-D Option Use Automatic Graph Scales**
- **Add Another (4th) Drift But Set the Length to 1 m**

Execute Graph Beam Line - Should Display Similar to Next Page

Estimate Location of 1st Focusing Element, Check Space Charge



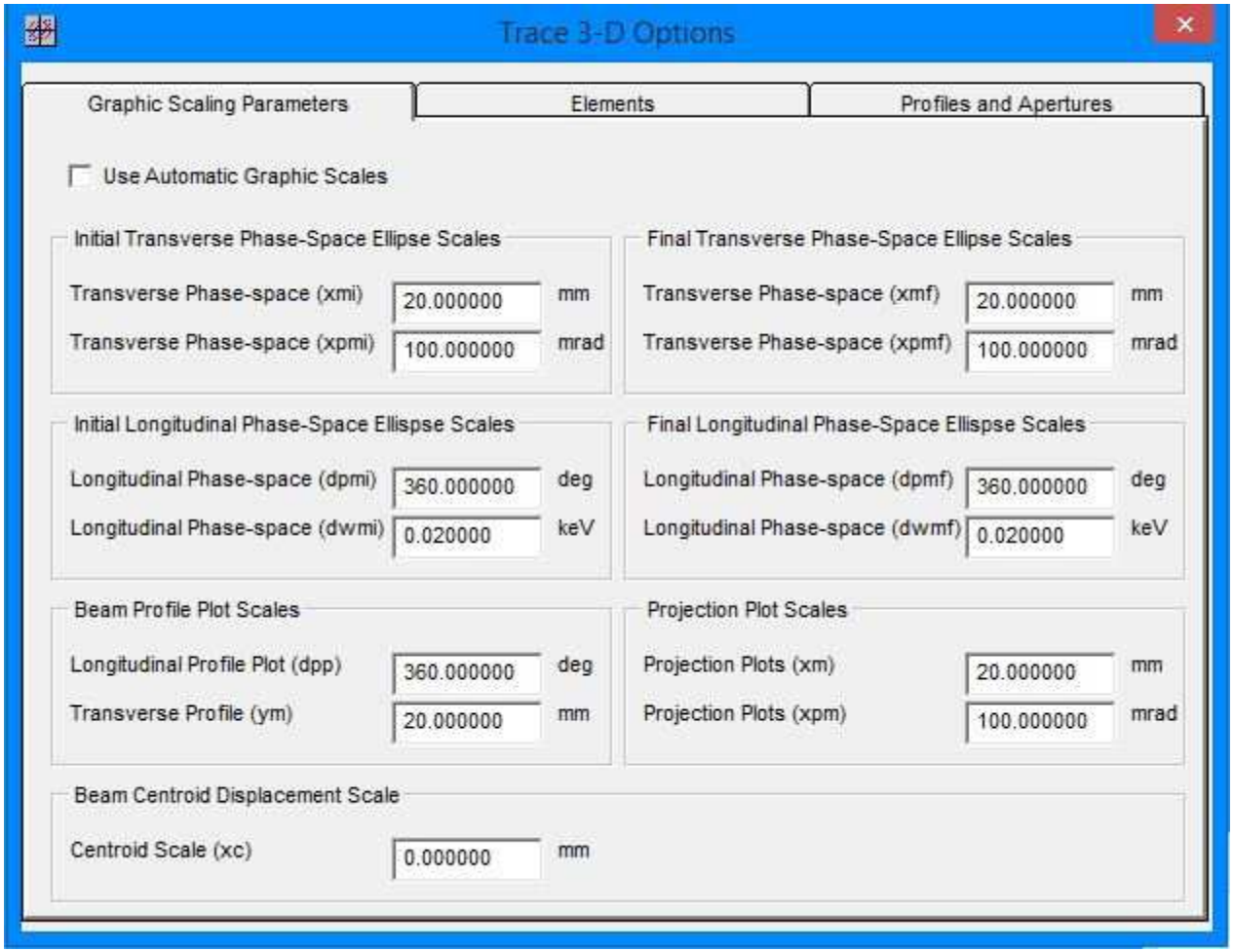
⇒ **1st Focusing Element Needs to be at 20 to 40 cm**

⇒ **Save this model as "Source_1 with drifts"**

Estimate Location of 1st Focusing Element, Check Space Charge

Go to TRACE 3-D Options

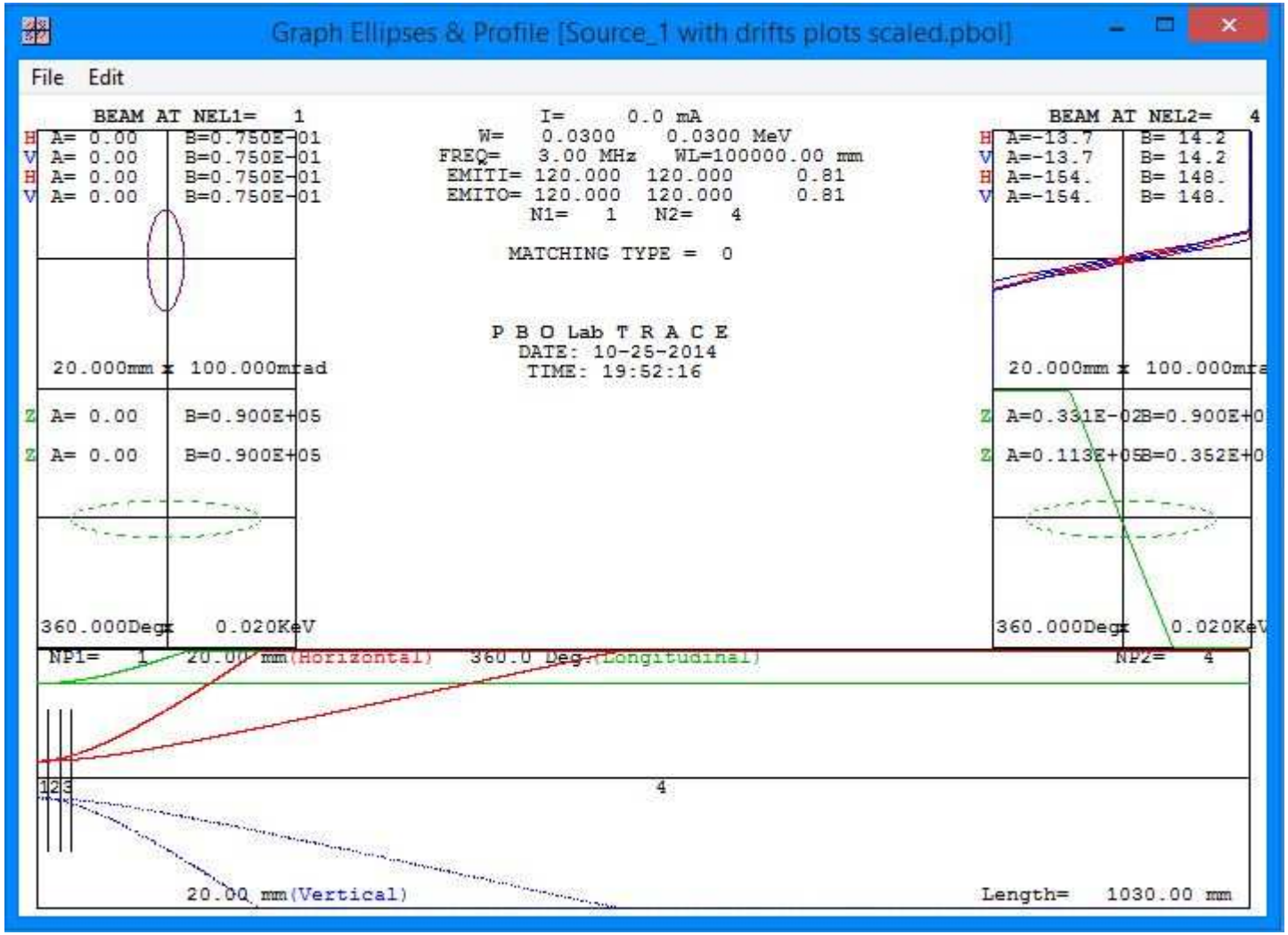
- **Uncheck the Box for Use Automatic Graph Scales**
- **Enter a More Suitable Set of Scales - Similar as These**



Estimate Location of 1st Focusing Element, Check Space Charge

Execute Graph Beam Line - The Gives Display for 0 mA

2b. Change Beam Current to 1 mA & Trace on Background:



⇒ **Save this model (same name "Source_1 with drifts")**

Einzel Lens as 1st Focusing Element

3a. Set a Tentative Location for the 1st Focusing Element

- Move ("Shift-Click") the 1 meter Drift to Work Space
- Delete 2 of the remaining 3 Drifts -
- For the one remaining Drift Piece:
  - Assign a label "D1" to the Comment Field
  - Effective Drift Length: 30 cm

Set the Beam Current to 0 mA and execute Graph Beam Line

⇒ **Graph Should Be Similar, but Shorter, to Prior Run: Beam Expands to About 12 mm at the End of D1**

- Drag the 1 meter Drift (on Work Space) to after D1

⇒ **Save this model as "Source_1 with D1"**

(The Desired Beam Focus is Assumed to be at 1300 mm, Adjust the "meter" Drift as Necessary for a Different Location.)

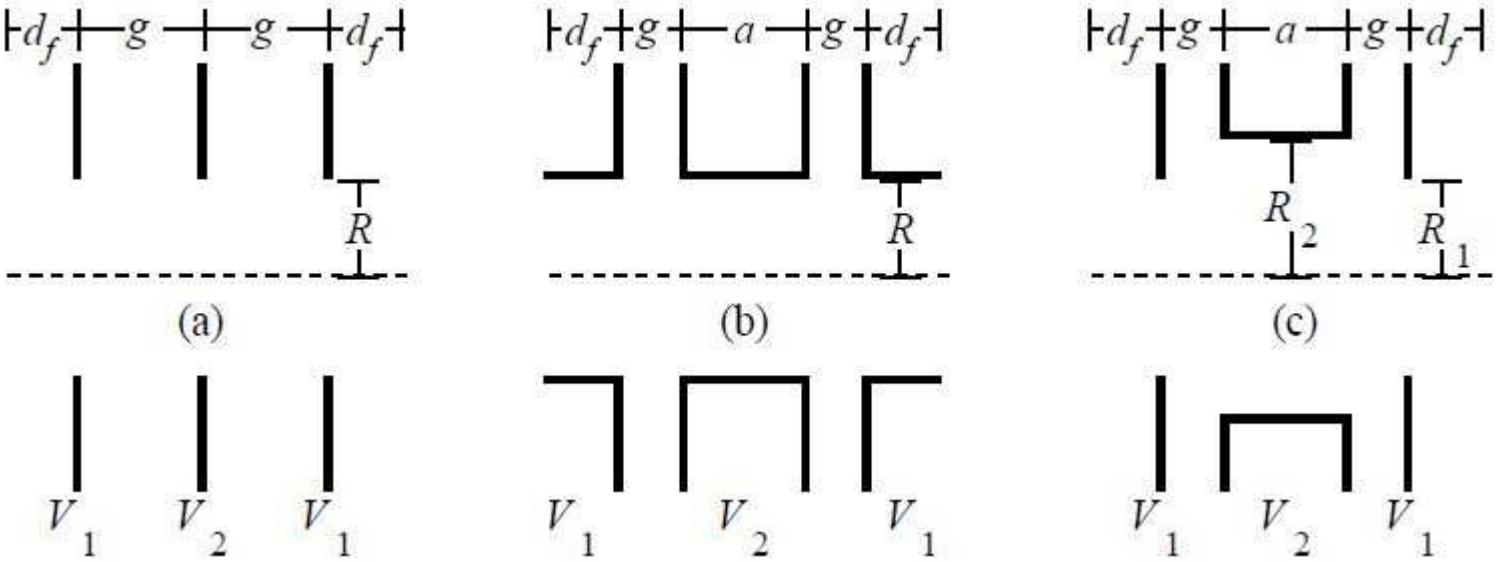
Einzel Lens as 1st Focusing Element

3b. Adding an Einzel Lens as 1st Focusing Element

PBO Lab has several options for setting up an einzel lens

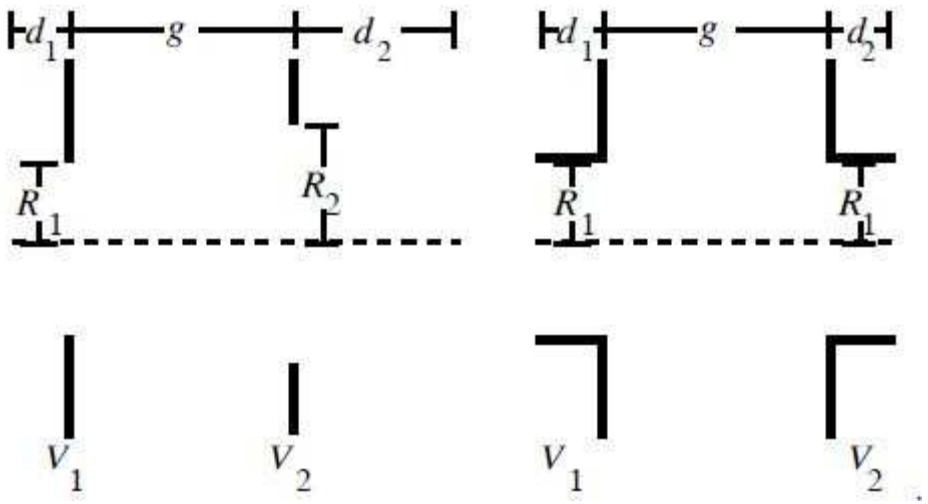
- **•1 Three (3) Types of Einzel Lens "Basic" Geometries**
- **•2 Use Accel/Decel Combinations of (2) Types of Columns**
- **•3 Combinations with Some "0 Potential Difference" Pieces**

•1 Three (3) Types of Einzel Lens "Basic" Geometries:



Einzel Lens as 1st Focusing Element

•2 Use Accel/Decel Combinations of (2) Types of Columns:



•3 Combinations with Some "0 Potential Difference" Pieces:

This Capability is a "Beta" Version ⇒ Use with Caution

Fringe Fields Distances for •1 and •2 are d_f , d_1 , or d_2

⇒ **Depend on Apertures and "Fringe Field Extension Factor"**

Fringe Fields Distances for •3 in "0 Potential Difference" Pieces

⇒ **User Defined (with/without "Fringe Field Extension Factor")**

Einzel Lens as 1st Focusing Element

Which Approach to Use: •1, •2, or •3?

Start with the Simplest Approach

⇒ Select geometry choice from •1 that is Closest to Design

Later, use approaches •2 and •3 to develop alternate models

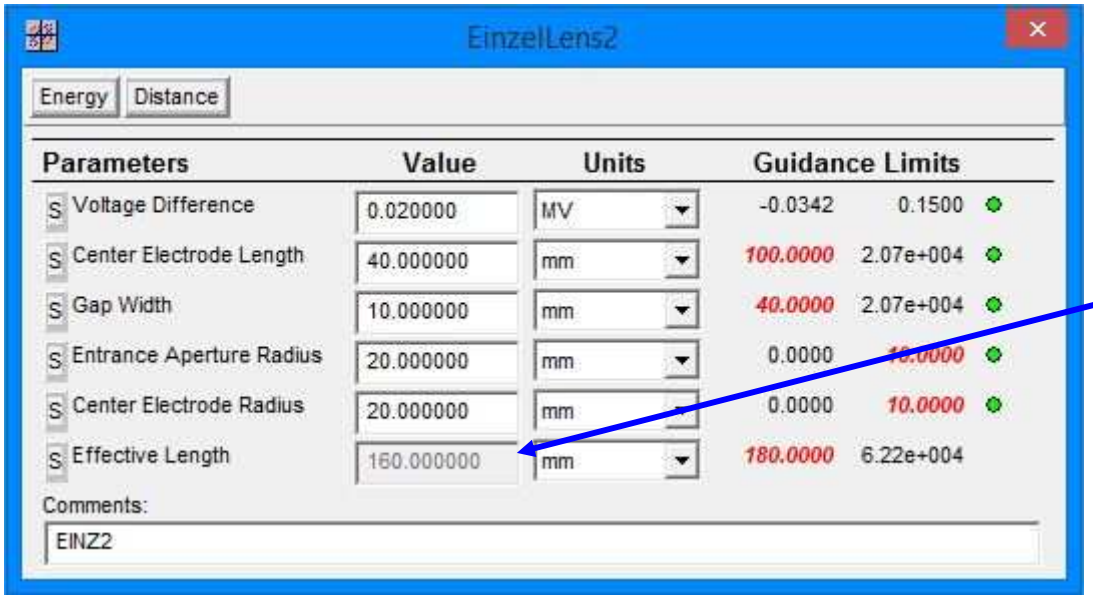
Compare results from models to see if differences important

Einzel Lens as 1st Focusing Element

3b. Select geometry choice from •1

- Einzel type (c) "Aperture-Tube-Aperture" seems good
- The "Aperture Tub Aperture " geometry is in Einzel2
- Add an Einzel2 Piece at the end of the D1 Drift Piece

Open the Einzel2 Piece and set parameter values:

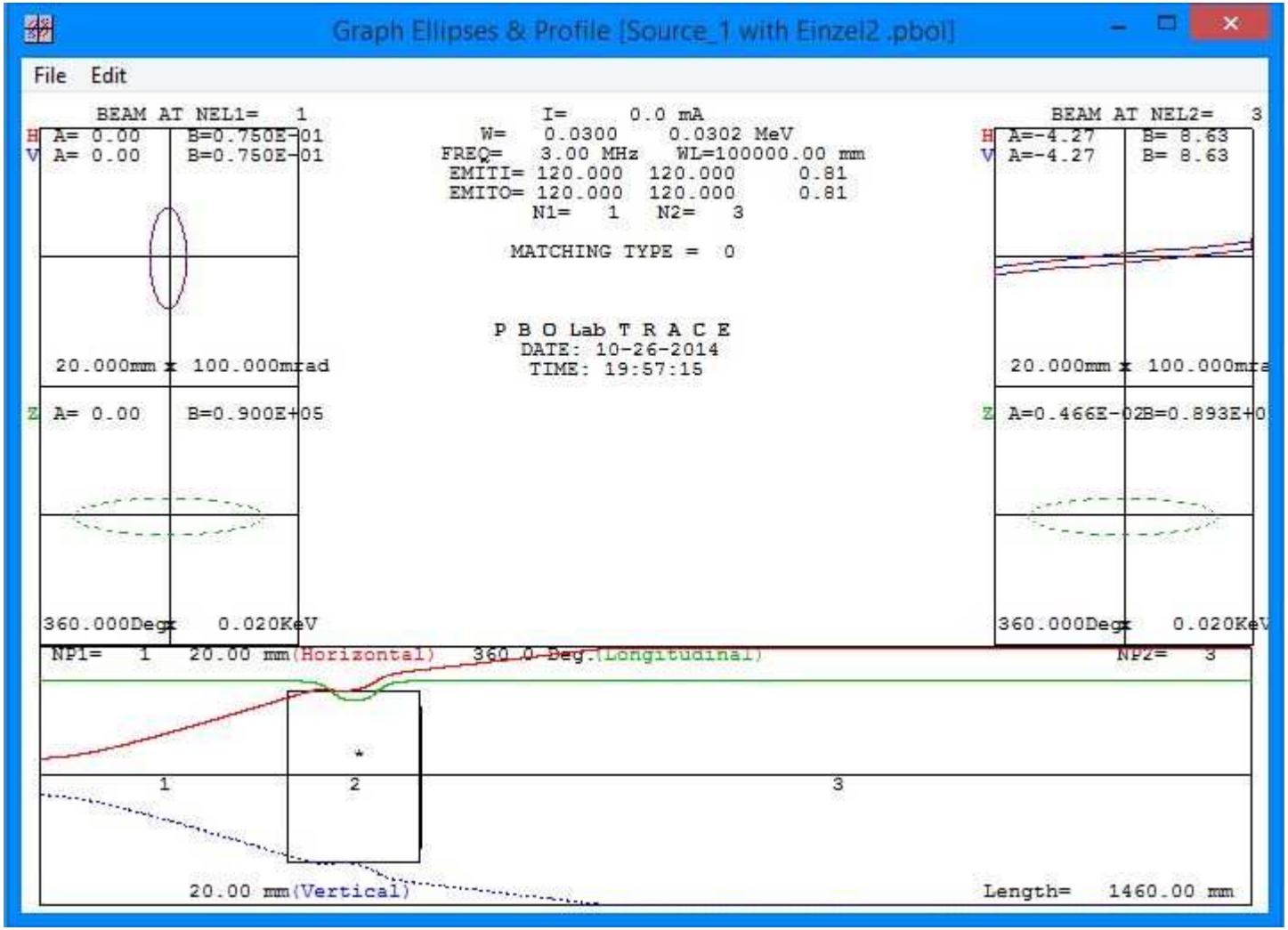


Note that "physical" length is 40+10+10 = 60 cm, but the "Effective Length" = 160 cm, which two 50 cm fringe field distances before and after.

⇒ Save this model as "Source_1 with Einzel2"

Einzel Lens as 1st Focusing Element

Execute Graph Beam Line - Display Should Be Similar to Below

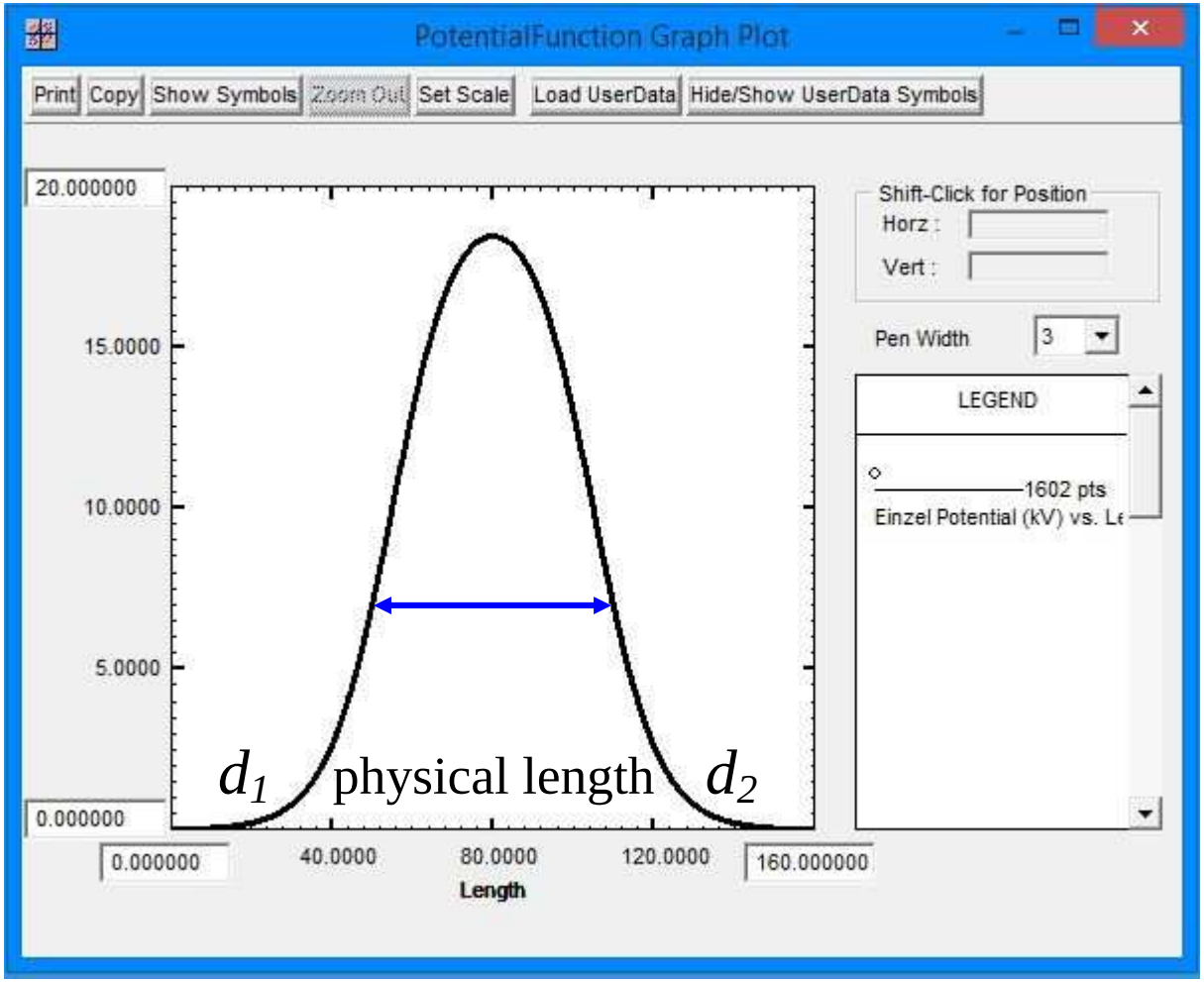


⇒ **Need to Adjust Drifts to Accommodate Fringe Distances**

Einzel Lens as 1st Focusing Element

3c. Adjust Drift Pieces

First Look At On-Axis Potential Function for the Einzel Lens



⇒ May be Able to Remove Some Fringe Distances

Einzel Lens as 1st Focusing Element

How Much Fringe Field Can Be Removed?

- **First Look at the R_{21} Matrix Element for Current Model**

⇒ **Commands -> TRACE 3-D -> Show R-Matrix:**

```
R-MATRIX (mm, mrad):
 -7.29789234e-001  8.02765872e-001  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000
 -1.60118604e+000  3.91040992e-001  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000 -7.29789234e-001  8.02765872e-001  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000 -1.60118604e+000  3.91040992e-001  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  1.00000000e+000  1.44764879e+000
  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  1.00000000e+000
```

$R_{21} = -1.60118604$

- **To Remove 10 mm of Fringe Field Before & After Einzel**

$d_1 = d_2 = \text{FFEF} \times R$ where R = Aperture Radius

since $R = 20$ mm, need to reduce FFEF by 0.5

- **Use Commands -> TRACE 3-D -> Option to Open Options**

⇒ **Select the "Elements" Tab Panel**

⇒ **Change the "Fringe Field Extension Factor"**

From 2.5 **To** 2.0 **(**0.5 **smaller)**

- **Execute: Commands -> Compute All AutoCalcs**

Einzel Lens as 1st Focusing Element

How Much Fringe Field Can Be Removed? (continued)

- **Look at the R_{21} Matrix Element for the FFEF=2.0 Model**
  Execute Commands -> TRACE 3-D -> Graph Beam Line
  Followed by Commands -> TRACE 3-D -> Show R-Matrix:

```
R-MATRIX (mm, mrad):
 -5.75221228e-001  8.57196825e-001  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000
 -1.47207648e+000  4.55232311e-001  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000 -5.75221228e-001  8.57196825e-001  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000 -1.47207648e+000  4.55232311e-001  0.00000000e+000  0.00000000e+000
  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  1.00000000e+000  1.42791459e+000
  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  0.00000000e+000  1.00000000e+000
```

$R_{21} = -1.47207648$

- **Reducing the Fringe Field Before & After Einzel by 10 mm:**

R_{21} magnitude decreased from -1.601 to -1.472, or about 8.06%

- **A Change of this Size May, or May Not, Be OK**

$\Rightarrow$ **Could Depend Upon Einzel Tuning (Power Supply) Range If Becomes Necessary to Compensate for Underestimate**

- **Since this May Not Be Acceptable, Return FFEF to** 2.5

Einzel Lens as 1st Focusing Element

3c. Adjust Drift Pieces (continued)

- **Generally Want to Reduce Drifts on Each Side of Einzel**

$\Rightarrow$ **To Compensate for the "drifts" Produced by** $\mathrm{FFEF} \times R$

- **Since** $\mathrm{FFEF} \times R = 50\ \mathrm{mm}$ **Want to Reduce Drifts by 5 cm**

$\Rightarrow$ **Change D1 to 25 cm, Change "meter" Drift to 95 cm**

- **Also Want to Reduce "meter" Drift by "physical" Length**

$\Rightarrow$ **Further Reduce "meter" Drift Down to 89 cm**

$\Rightarrow$ **Save this model (same name "Source_1 with Einzel2")**

- **Can Compare This Model Directly to "Source_1 with D1"**

$\Rightarrow$ **Models Have Same Overall Length: 1300 mm (Focus Pt.)**

Einzel Lens as 1st Focusing Element

3d. Find Einzel Center Electrode Potential to Focus at 1300 mm

- **Will Use a Point-to-Point Fitting Constraint**

⇒ **Constraint ("Match Specification") To Use is $R_{12} = 0$**

- **Do We Also Need a Similar "y" Constraint $R_{34} = 0$?**

⇒ **No. Why Not?**

- **TRACE 3-D Match Specification Sets Constraint $R_{12} = 0$**

⇒ **Use Commands -> TRACE 3-D -> Match Specification to Open the Match Specification Window**

- **Select**

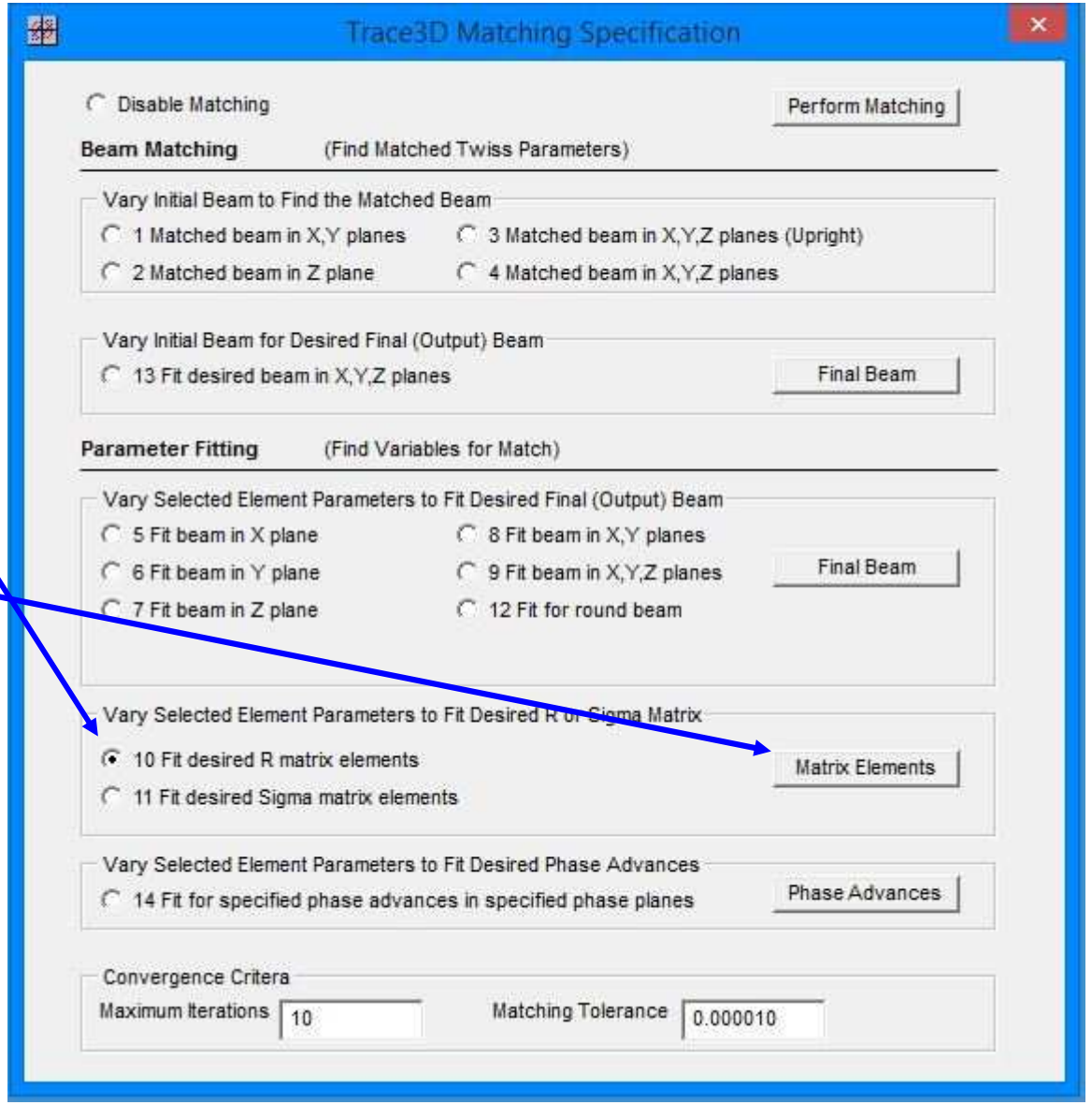
⇒ **Use Commands -> TRACE 3-D -> Match Specification to Open the Match Specification Window (on Next Page)**

Einzel Lens as 1st Focusing Element

(1) Select the Match Specification: "10 Fit desired R matrix elements"

(2) Use Button: "Matrix Elements"

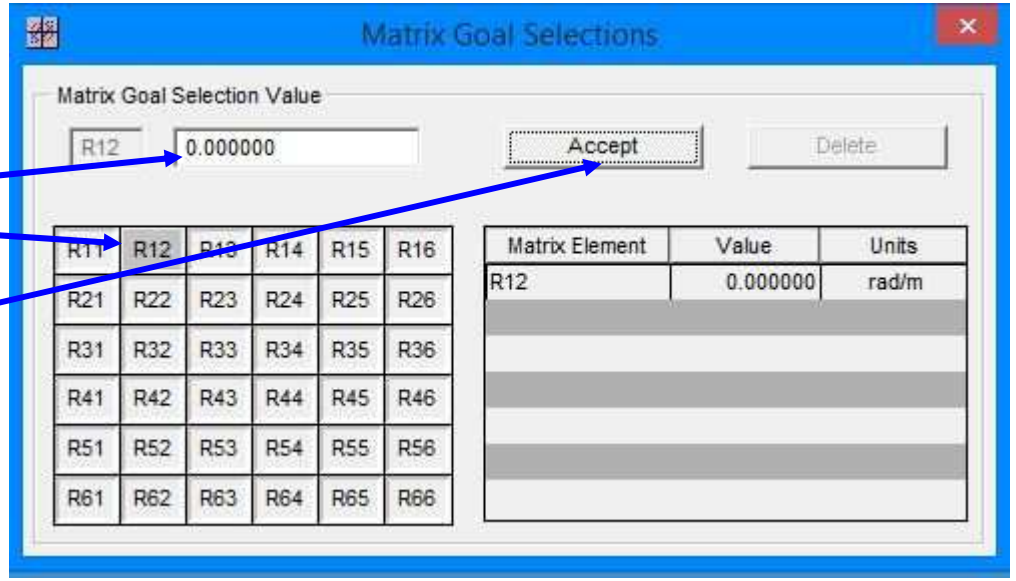
⇒ This Will Open Matrix Goal Selection Window (Next Page)



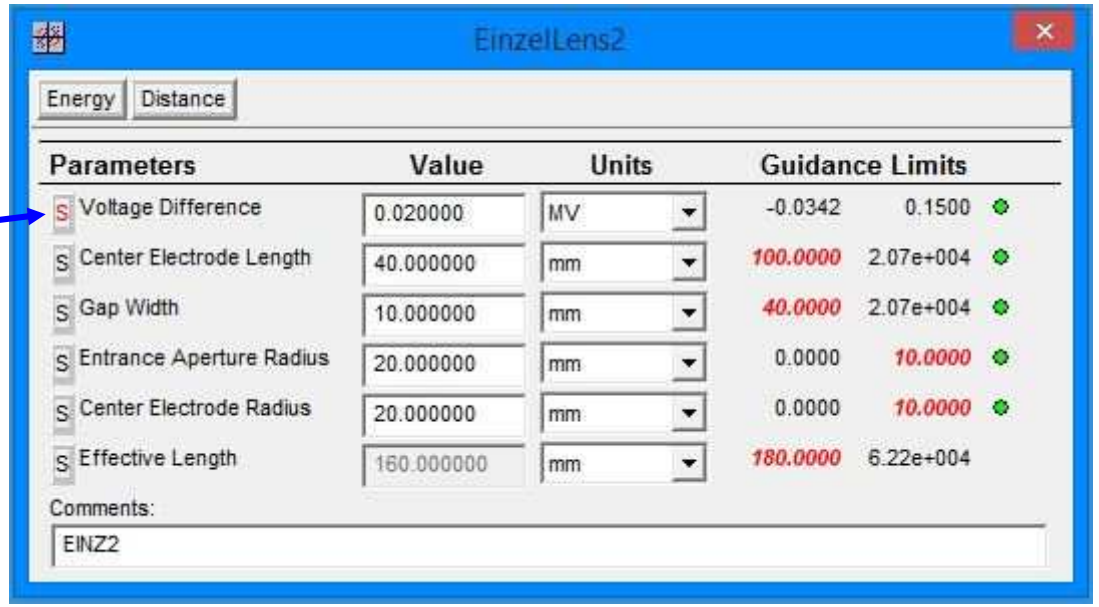
Einzel Lens as 1st Focusing Element

(3) Set Constraint:
" $R_{12} = 0.0$ "

(4) Use Button:
"Accept"



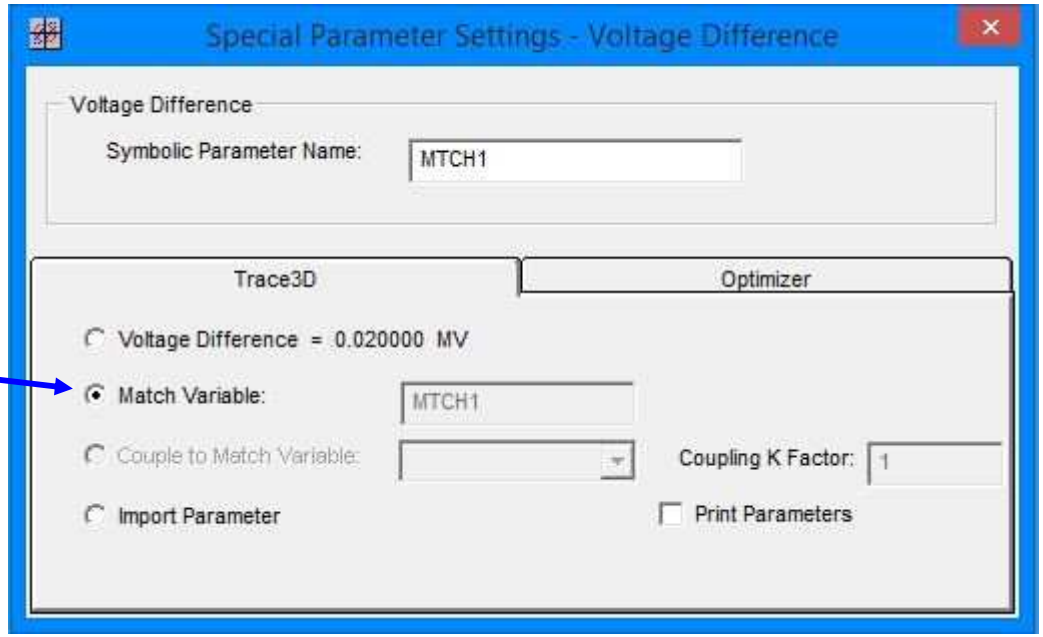
Open Einzel2 Piece Window to Select Vary ("Match") Parameter Using "S" Button ("S" Will Turn Red After Step on Next Page)



Einzel Lens as 1st Focusing Element

The Special Parameter Settings Window ("S" Window) is Used to Assign Selected Attributes to Piece Element Parameters

For the Einzel2 Piece "Voltage Difference" We Want to Assign the Attribute: "Match Variable" (This is the TRACE 3-D Terminology for a Parameter to be Varied)



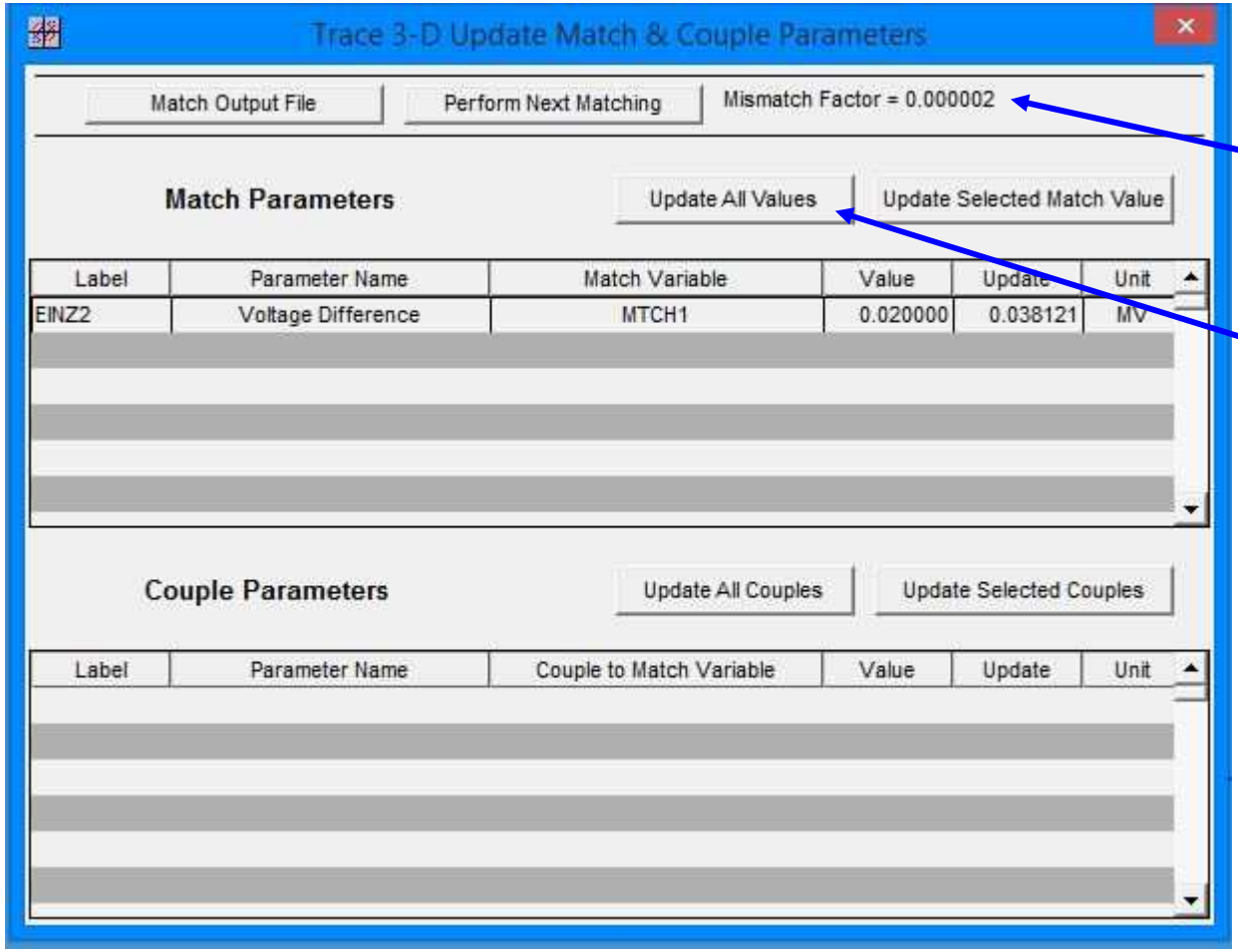
When an Attribute is Assigned in an "S" Window, a Symbolic Parameter Name May Automatically Generated by PBO Lab, Depending Upon the Attribute: MTCH1 in this Case

⇒ **Save this model as "Source_1 with Einzel2 for Fitting"**

Einzel Lens as 1st Focusing Element

Execute a Perform Matching Command

⇒ Use Commands -> TRACE 3-D -> Match Specification



Good Solution

MMF ≈ 0

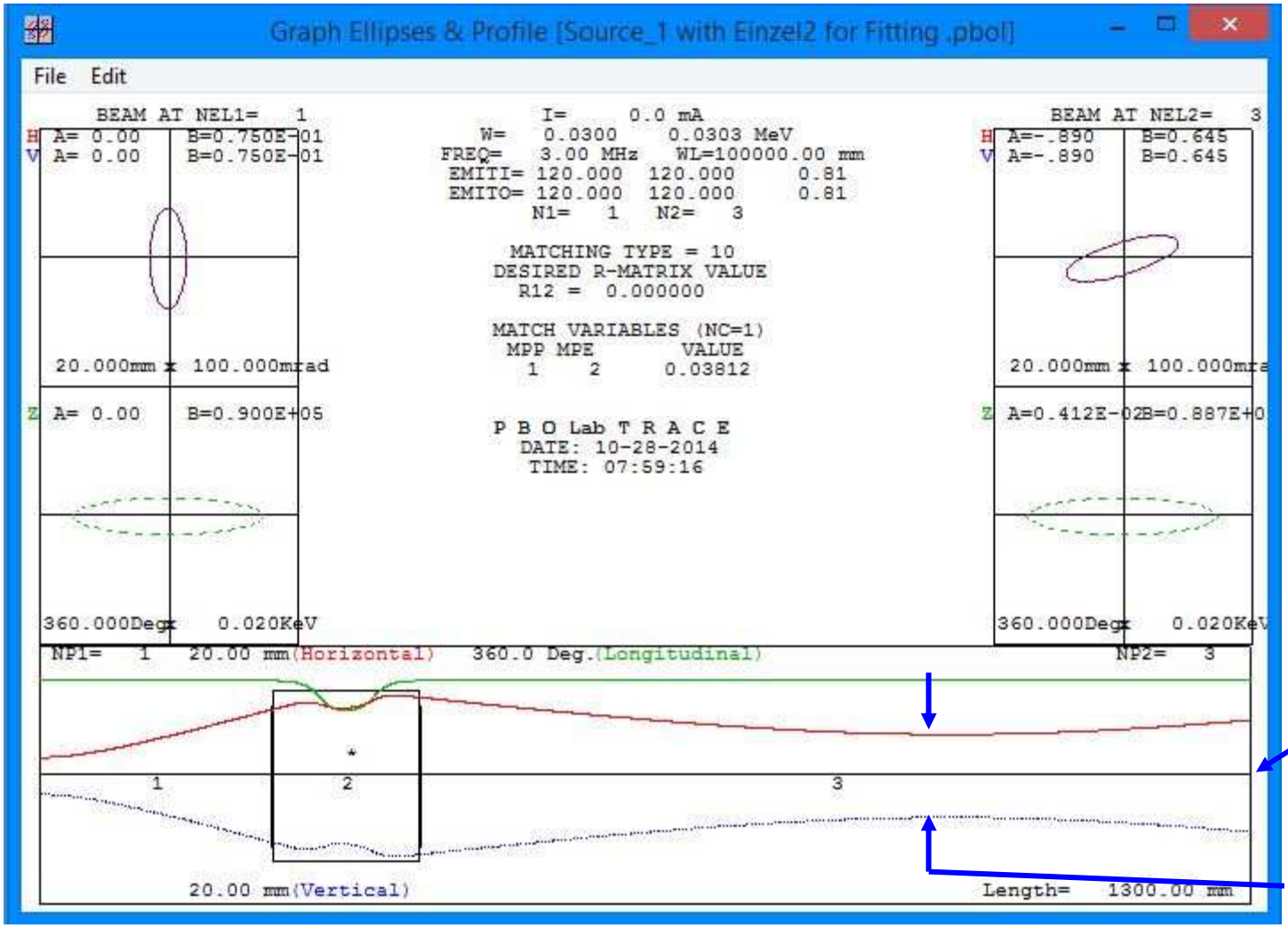
Update Values

⇒ Save this model as "Source_1 with Einzel2 after Fitting"

Einzel Lens as 1st Focusing Element

Execute a Graph Beam Line Command

⇒ Use Commands -> TRACE 3-D -> Graph Beam Line



Focus Point

Note "Waist"

Einzel Lens as 1st Focusing Element

- **A Point Focus Constraint, e.g. a Point-to-Point Focus such as $R_{12} = 0$, Gives the Smallest Spot at Focus Point**
- **The Spot Size is Determined by the Beam Emittance**
- **A Smaller Spot Size will be Upstream of the Focus Point The Smaller Spot Size will be at a Beam "Waist"**
- **It is Tempting to Think That by Fitting a Waist Condition ($r_{12} = 0$, $\sigma_{12} = 0$, or $\alpha_x = 0$) a Smaller Spot May be Achieve at the Focus Point - This is Not Correct**
- **As the Beam Waist is Moved Out to the Focus Point It Increases in Size Such that it Will Be Larger than (Smallest) Spot Size Obtained in the Point Focus**
- **This is Illustrated Explicitly on the Next Page Where a Waist Fit ($\alpha_x = 0$) is Compared to the Point Fit ($R_{12} = 0$) (Details Left as an Exercise to the Reader)**

Einzel Lens as 1st Focusing Element

Point Focus Constraint ($R_{12}=0$) Gives a Smaller Spot Size than Waist Fit Constraint ($\alpha_x=0$) for the Same Location in Beam Line