Overview of Particle Beam Optics Utilized in the Matrix, Envelope, and Tracking Codes: TRANSPORT, TRACE 3-D, and TURTLE

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Presentation Outline - Part I

Overview of Particle Beam Optics Utilized in the Matrix, Envelope, and Tracking Codes: TRANSPORT, TRACE 3-D, and TURTLE

1. **Basic Matrix Premise, Coordinates, Linear / Nonlinear Particle Optics, …**
2. **Describing a Beam - Phase Space, Semi-Axes & Twiss Representations**

   ⇒ **Break**

3. **Equations of Motion: Drifts, Quads, Bends - Individual Particle Motion**

   ⇒ **Break**

4. **Introduction to the Beam Optics of TRANSPORT**
5. **Introduction to the Beam Optics of TRACE 3-D**
6. **Introduction to the Beam Optics of TURTLE**
7. **Summary**

Part II ⇒ **Will use the PBO Lab software in the class to illustrate concepts**

Presentation Outline - Part II

Overview of the PBO Lab Software with Examples and Sample Problems using TRANSPORT, TRACE 3-D, and TURTLE

8. Overview of the Particle Beam Optics Laboratory (PBO Lab)

Graphical Beamline Construction Kit
Interactive Tutorials
Built In First-Order Tools (Focusing & Bending)

9. Application Modules: TRACE 3-D, TRANSPORT & TURTLE

10. Using TRACE 3-D, TRANSPORT & TURTLE to Solve Some Problems

⇒ **You will use PBO Lab software in the class**

4. Introduction to TRANSPORT

TRANSPORT Overview

- **TRANSPORT**
  - **A First-, Second-, and (partial) Third-Order Code (FNAL, PBO-Lab)**
  - **Long History of Evolution - probably the oldest code still in use**
  - **Originally in "BALGOL" (~1960) - rewritten in FORTRAN (~1972)**
  - **Historically only included magnetic components (quads, bends, …)**
  - **Numerous versions around in varied states of maintenance (errors)**
- **Applies R-, T-, and U-Matrices to Advance Beam Through Each Element**
  - **Beam Described by 1st & 2nd Moments of the Particle Distribution**
  - **Matrix Model of Optical Components**
  - **Include Models for Higher-Order Effects of Magnets**
  - **Vary Parameters (up to 20) with Many Options for Fit Constraints**
  - **Parameters Can Be Described / Defined by Formulas**
  - **Extensive Options for Output (text, plot files) Available**
- **Principal Use is for Transfer Line Design**
  - **Limited application to linacs, synchrotrons, storage rings, …**
  - **No space charge modeling (except some early spin-off versions - 2D)**

4. Introduction to TRANSPORT (continued)

- **Several Magnetic Optical Elements Built into Standard Version**
  - **Drift Including All 2nd Order (but not 3rd order) Effects**
  - **Non-Bend Magnetic Elements (most through 3rd order):**
    Quadrupole (3rd), Solenoid (2nd), Sextupole (3rd), Octupole (3rd)
  - **Three Representations of Bending Magnet Elements (3rd order):**
    Bend with Edges (pole face rotations, pole face curvature, …)
    Sector Bend, or S-Bend, which has edge effects built-in
    Rectangular Bend, or R-Bend, which has edge effects built-in
  - **Bending Magnets Can Include Multipoles (combined function bends)**
  - **Geometry Type Elements:**
    Centroid Displacement / Reference Trajectory Shift
    Axial Rotation (Roll) about Beamline - PBO Lab Rotate Piece
    Increase in RMS Beam Properties

- **Several Other Optical Elements (kicker, septum, plasma lens, …)**

- **One Radiofrequency (RF) Built-in Optical Element in Standard Version**
  - **Traveling Wave Accelerator Model (1st order) for Electrons**

- **Can Use a Matrix (through 3rd order) Directly as an Element**

4. Introduction to TRANSPORT (continued)

- **Capable of Utilizing 2 Different Types of Input Files**
  - **Old Style "Positional" Notation - input file is "entirely" numbers**
  - **MAD (Methodical Accelerator Description) with Keywords - PBO Lab**
- **Can Accept Various Descriptions of Several Elements (MAD)**
  - **PBO Lab supports this ("Green Dots")**
- **PBO Lab TRANSPORT Has Additional Optical Elements Available**
  - **RF Gap*, Thin Lens*, Quad Doublet*, QuadTriplet***
    - ***TRACE 3-D Elements (see Section 5.)**
  - **Alias - Takes on the Identity of a Specified Element**
- **PBO Lab TRANSPORT Will Automatically Display Requested Plots**
- **PBO Lab Can Create a Beam & Matrix Pieces using TRANSPORT Results**
  - **Can Import TRACE 3-D Input Files from other TRACE 3-D versions***
  - **Can Write TRACE 3-D Input Files for other TRACE 3-D versions***
    - ***Assuming versions have some degree of compatibility!**
- **Task 2 Utilized PBO Lab Version of TRANSPORT to:**
  - **Add ElectroStatic Quad (through 3rd order)**
  - **Add Magnetic and ElectroStatic Quad 3rd order Fringe Field Integrals**

4. Introduction to TRANSPORT (continued)

- **Input Beam Usually in Semi-Axes Representation (with Correlations)**
- **TRANSPORT Can Accept as Input a Twiss Representation of Beam**
  - Only Transverse (x-, y-) Phase Plane Twiss Parameters & Emittances
  - Longitudinal Beam Uses $< l^2 >^{1/2}$ and $< \delta^2 >^{1/2}$ (i.e. no correlation)
- **But TRANSPORT Will "Complain" If You Use the Twiss Parameters with certain elements that mix phase planes (solenoid, …)**

To Complete This Introduction to TRANSPORT Let's Look At a Few of the Other Outputs that You Can Ask For

- **Any Matrix Can Be Printed at End (Exit) of Each Element**
  - Beam Matrix in the Reduced Form
  - R_{ij} Elements as a 6 x 6 Matrix, T_{ijk} as a Lower Half Matrix for Each i
  - U_{ijlk} as a Lower Half Matrix for Each i
- **Twiss Parameters (Beam in "Accelerator Notation") at Element Exits**
  - Includes Phase Advances & Emittances for Transverse Phase Planes
- **And Quite a Few Others $\Rightarrow$ Data Can Also Be Output to a Plot File**
- **Essentially Anything that You Can Ask for as Output Can Also Be Used for Fitting Constraints $\Rightarrow$ Extensive Fitting Capabilities**

4. Introduction to TRANSPORT (continued)

Some Useful R-Matrix Fitting Constraints

- **Trace of** R-Matrix **for stability in a periodic system:** $(1/2)\ |\mathrm{Tr}[R]| \leq 1$
- **For point-to-point optics in the horizontal (**x**) direction:** $R_{12} = 0$
- **For parallel-to-parallel optics in the horizontal (**x**) direction:** $R_{21} = 0$
- **For parallel-to-point optics in the horizontal (**x**) direction:** $R_{11} = 0$
- **For point-to-parallel optics in the horizontal (**x**) direction:** $R_{22} = 0$
- **Similar conditions for the vertical (**y**) direction involving** R_{yy} **submatrix**
- **For achromatic optics in the horizontal (**x**) direction:** $R_{16} = R_{26} = 0$

Useful Beam (σ) Matrix Constraints

- **For a beam waist in the horizontal (**x**) direction:** $\alpha_x = 0$ **or** $r_{12} = 0$
- **For beam size in the horizontal (**x**) direction:** $[\sigma_{11}]^{1/2} = X_{size}$

⇒ **TRANSPORT Documentation (pages 262-7) has more examples**

4. Introduction to TRANSPORT (continued)

- **In 1st Order Calculation, TRANSPORT Advances $[q_i]_c$ and $[\sigma_{ij}]$ by**

$$[q_{i\,b}]_c = R[q_{i\,a}]_c \quad \text{and} \quad [\sigma_{ij\,b}] = R[\sigma_{ij\,a}]R^T$$

Note the "c" for Centoid

- **Computes $[q_i]_c$ and $[\sigma_{ij}]$ at the End (Exit) of Each Optical Element**

⇒ **To Get $[q_i]_c$ and $[\sigma_{ij}]$ Inside an Optical Element Must Split the Element**

- **In 2nd and 3rd Order TRANSPORT Also Advances $[q_i]_c$ and $[\sigma_{ij}]$, but the Formulas are More Complicated (involve T and U matrices)**

⇒ **Higher Order Effects on $[q_i]_c$ and $[\sigma_{ij}]$ are Essentially RMS Treatments**

- **Other "Ray Tracing" or "Tracking" Codes Advance each Particle's $[q_i]$**

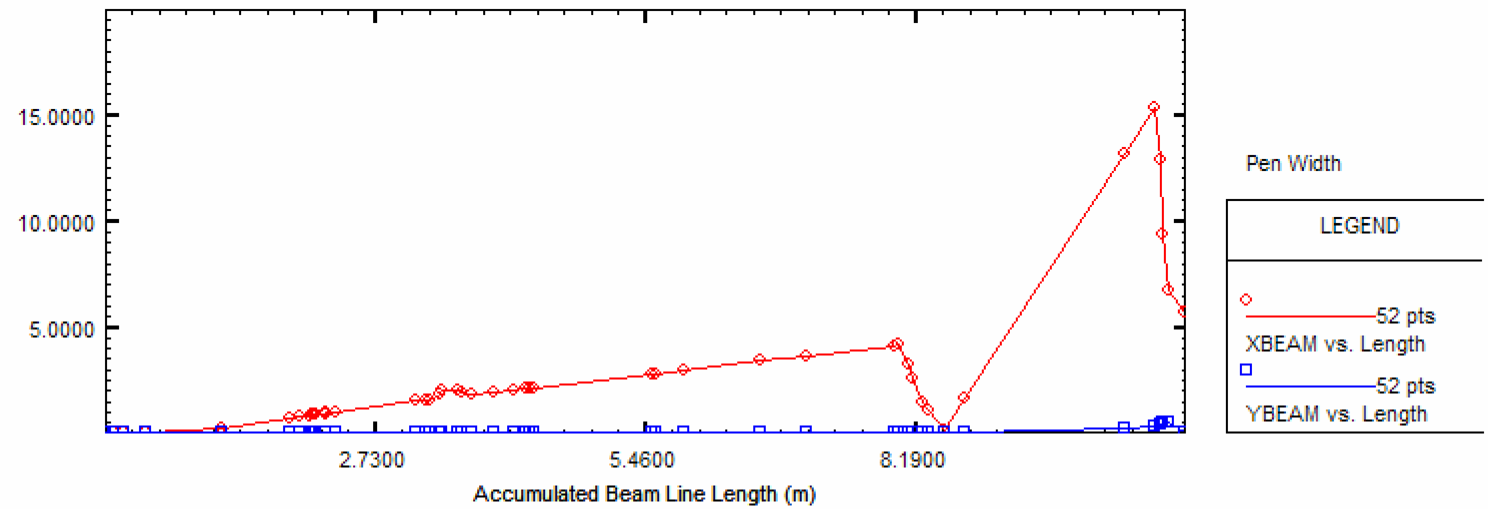
⇒ **Ray Tracing Program TURTLE Tracks Individual Particle's $[q_i]$**

- **TRANSPORT is Useful for Eliminating/Reducting Higher Order Effects (e.g. higher-order fitting during the design process for a transfer line)**

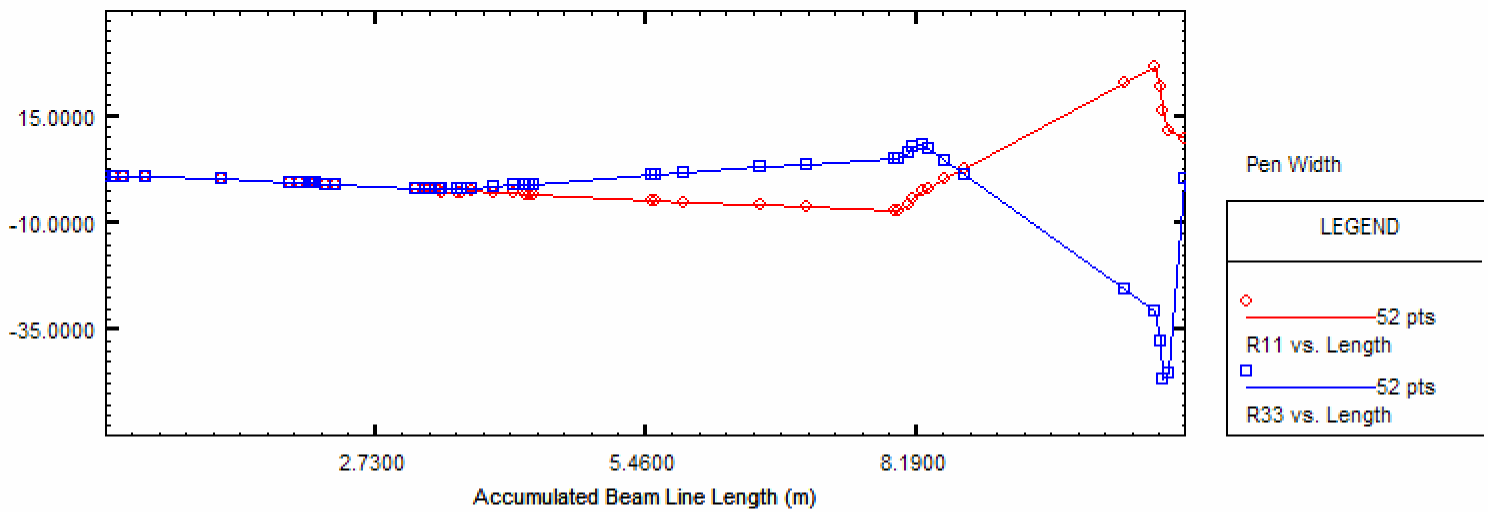
- **Has Extensive Data Output for Plotting - PBO Lab provides the plots**

4. Introduction to TRANSPORT (continued)

Beam Properties



Machine Properties



5. Introduction to TRACE 3-D

- **TRACE 3-D**
  - **Primarily a First-Order Code with a Space Charge Model**
  - **Evolved from an Earlier Two-Dimensional Code (TRACE)**
  - **Similar to an Early (LBNL) TRANSPORT Spin-Off**
  - **Includes several radiofrequency (RF) components**
- **Solves (Numerically "Integrates") the Envelope Equations**
  - **Beam is an Ellipsoid in Three Dimensions - "Bunched"**
  - **Differential Matrix Model of Optical Components**
  - **Beam Envelopes Advanced in Steps, Using R-Matrices for Elements of Short Length, Δs**
  - **Space Charge Impulse Applied at Each Step**
  - **Can Include Models for Fringe Fields, Higher-Orders, Non-Linearities - But Only Computes Their Effect on the Second Moments of the Beam Distribution (σ Matrix)**
- **Principle Uses Are for Ion and (Low-Energy) Electron Beams**
  - **Especially for Radiofrequency Acceleration, Space Charge**
- **PBO-Lab Version Can Also Model ElectroStatic (ES) Elements**
  - **Einzel Lenses, ES Quadrupoles, ES Columns, ES Deflectors**

5. Introduction to TRACE 3-D (continued)

- **Initial Beam Usually Specified with 3-D Twiss (CS) Parameters**
  - **May Also Specify the Initial σ Matrix Directly**

- **6 $\times$ 6 σ Matrix Advanced, from Location j to $j+1$, through an Increment, $\Delta s = s_{j+1} - s_j$, Along the Central Trajectory:**

$$\sigma(j+1) = R(\Delta s)\, \sigma(j)\, R(\Delta s)^T$$

- $R(\Delta s)$ **is the First-Order Transfer Matrix for Optical Element of Length Δs**

- **At Each Increment, a Space Charge Impulse is Applied Using a Thin Lens R Matrix Based Upon 3-D Ellipsoid**

- **Since $R(\Delta s)$ is Computed At Each Increment j, Non-Linear & Non-Constant Fields Can be Modeled by Using $R(j, \Delta s)$**

5. Introduction to TRACE 3-D (continued)

- **Sixteen Built-in Optical Elements in Standard Version**
  - **Six are Same as TRANSPORT Elements:**
    Drift, Quad, Solenoid, Bend, Edge, Rotate
  - **Three are "Compound" Magnet Elements:**
    Symmetric Doublet*, Triplet*, PMQ with Fringe Fields
  - **Four are Radiofrequency Elements:**
    RF Gap*, RFQ Cell, RF Cavity, Coupled Cavity Tank
  - **Thin Lens***
  - **Alias (Identical) - Takes on the Identity of a Specified Element**
  - **Special = Free Electron Laser (FEL) Wiggler**

- **PBO Lab TRACE 3-D Has Additional Optical Elements Available**
  - **2 Traveling Wave RF Accelerator Elements for Electron Linacs**
  - **Electrostatic (ES) Elements - These Are on Simulation Lab Computers**
    3 Einzel Lenses, 3 Prisms (Deflectors), 2 DC Columns, 2 ES Quads
  - **TRANSPORT / MAD S-Bend and R-Bend Supported**

- ***PBO Lab TRANSPORT Supports Doublet, Triplet, RF Gap, Thin Lens**

5. Introduction to TRACE 3-D (continued)

Space Charge Model in TRACE 3-D

- **The Charge Density of a Uniformly Filled 3-D Ellipsoid is**

$$\rho(x,y,z) = \rho_o \Theta\left[1 - (x/x_m)^2 - (y/y_m)^2 - (z/z_m)^2\right]$$

Where Θ is the Heaviside Step Function and

$$\rho_o = \frac{3Q}{4\pi\, x_m y_m z_m}$$

With Q Equal to the Total Charge in the Ellipsoid

- **The Three Semi-Axes of the Ellipsoid Are Computed from**

$$x_m = (\sigma_{11})^{1/2} \qquad y_m = (\sigma_{33})^{1/2} \qquad z_m = (\sigma_{55})^{1/2}$$

$\Rightarrow$ **Important to get σ_{55} correct, even for pure magnetic systems**

- **A Particle Will See an Electric Field Due to This Charge Density**
  - **Inside the Ellipsoid, the Field is Linear in x, y, z**
  - **The Coefficients of the Linear Field Depend Upon x_m, y_m, z_m**
  - **TRACE 3-D Model Has No "Particles" Outside the Ellipsoid**

5. Introduction to TRACE 3-D (continued)

Space Charge Model in TRACE 3-D (con't)

- **Particles Experience an Electric Field Due to** $\rho(x,y,z)$
  Inside the Ellipsoid, this Field in the Beam Frame is Given by:

$$E_x = \frac{\rho_o}{\varepsilon_o} \left[\frac{(y_m)}{(x_m + y_m)} \right] (1 - f)\, x$$

$$E_y = \frac{\rho_o}{\varepsilon_o} \left[\frac{(x_m)}{(x_m + y_m)} \right] (1 - f)\, y$$

$$E_z = \frac{\rho_o}{\varepsilon_o} f\, z$$

- $f = f(p)$ **is the Ellipsoidal *Form Factor* Which Depends Upon the Semi-Axes of the Ellipsoid (**x_m, y_m, z_m**) Through the Ratio** p**:**

$$p = \left[z_m / (x_m y_m)^{1/2} \right]$$

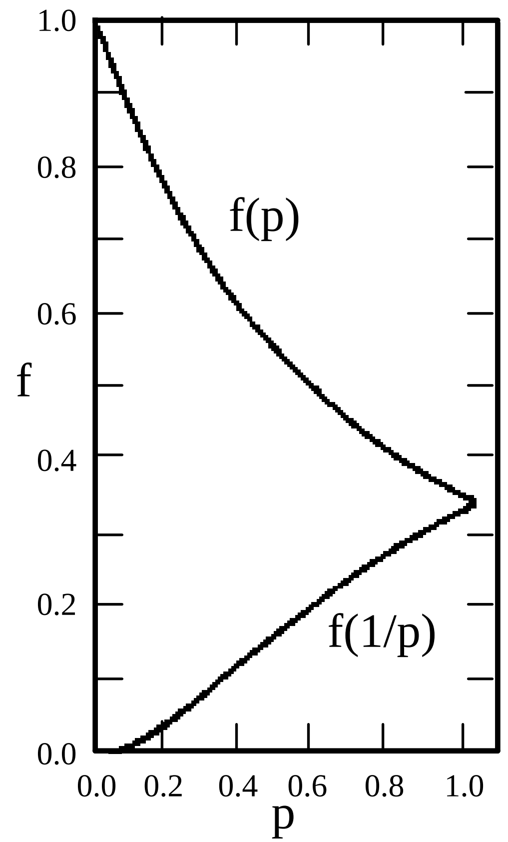
5. Introduction to TRACE 3-D (continued)

Space Charge Model in TRACE 3-D (con't) Ellipsoidal Form Factor

- **For** $0 \le p \le \infty$**, the Ellipsoidal Form Factor is** $0 \le f(p) \le 1$
- **When** $p \cong 1$ **(near spherical bunch) then** $f(p) \cong 1/(3p)$

$$f(p) = \begin{cases} \dfrac{1}{1-p^2} - \dfrac{p}{(1-p^2)^{3/2}} \cos^{-1}(p) , & \text{for } p < 1 ; \\ \dfrac{p \ln \cdot \left[p + \sqrt{p^2 - 1}\right]}{(p^2-1)^{3/2}} - \dfrac{1}{p^2 - 1} , & \text{for } p > 1 . \end{cases}$$

$$f(1) = \frac{1}{3}$$



5. Introduction to TRACE 3-D (continued)

Space Charge Model in TRACE 3-D (con't)

- **For One Beam Bunch Passing a Point in the Beamline Every RF Cycle, the Total Charge is Related to the Beam Current** I**:**

$$Q = I/f = (\lambda/c)I$$

- **For Relativistic Beams with Kinectic Energy** $W = (\gamma-1)mc^2$**:**

$$(E_{x,y})_{\text{lab frame}} = (E_{x,y})_{\text{beam frame}} / \gamma$$
$$(z_m)_{\text{lab frame}} = (z_m)_{\text{beam frame}} / \gamma$$

- **Effective** R **Matrix is Equivalent to a 3-D Diverging Thin Lens**

$$R_{21} = -1/f_x = qe\,(\partial E_x/\partial x)\,\Delta s\,/\,(\gamma\,\beta^2\,mc^2)$$

$$R_{43} = -1/f_y = qe\,(\partial E_y/\partial y)\,\Delta s\,/\,(\gamma\,\beta^2\,mc^2)$$

$$R_{65} = -1/f_z = qe\,(\partial E_z/\partial z)\,\Delta s\,/\,(\gamma\,\beta^2\,mc^2)$$

- **A Few Computational Details (Automated in TRACE 3-D)**
  - **Ellipsoid May Be Tilted** ⇒ **Must Transform Coordinates**
  - **Calculation Accuracy** ⇒ **Elements at** $\Delta s/2$**, Some Adjust** Δs

5. Introduction to TRACE 3-D (continued)

TRACE 3-D Matching Capabilities

- **"Matching" is TRACE 3-D Equivalent to TRANSPORT "Fitting"**

- **Fourteen (14) Matching Options in TRACE 3-D**
  - **Four (4) Find Twiss (C-S) Parameters for Matched Beams**
  - **One Varies Initial Beam Parameters to Produce Specified Twiss Parameters at the Output**
  - **Six (6) Vary (Match) Beamline Parameters to Produce Specified Twiss Parameters at the Output**
  - **Three (3) Vary Beamline Parameters to Produce**
    Specified R Matrix Elements (for Overall Beamline)
    Specified σ Matrix (Modified) Elements (at Output)
    Specified Phase Advances μ_x, μ_y, μ_z (at Output)

- **Number of Beamline Element Match (Vary) Parameters Limited to Six (6)**

5. Introduction to TRACE 3-D (continued)

TRACE 3-D Matching Capabilities (con't) Mismatch Factor

- **Useful to Have One Number (Figure of Merit) to Compare Two Ellipses**

- **One Measure of Comparison is the Mismatch Factor (MMF)**
  - **Two Ellipses (a and b) with Different Twiss Parameters in x Plane**
  - **Mismatch Factor Between Ellipses a and b Defined as**

$$MMF_x = \left[(1/2)(R_x + [(R_x^2 - 4)]^{1/2})\right]^{1/2} - 1$$

where $R_x = \beta_a \gamma_b + \gamma_a \beta_b - 2\, \alpha_a \alpha_b$

  - **If Ellipses Are Identical (a=b):** $R_x = 2(\beta_a\gamma_a - \alpha_a^2) = 2$ & $MMF_x = 0$
  - **Different Ellipses** $MMF_x > 0$

- **Most TRACE 3-D Fitting Minimizes Mismatch Factors** MMF_x, MMF_y, MMF_z

- **Mismatch Factor defined by Twiss Parameters.**

5. Introduction to TRACE 3-D (continued)

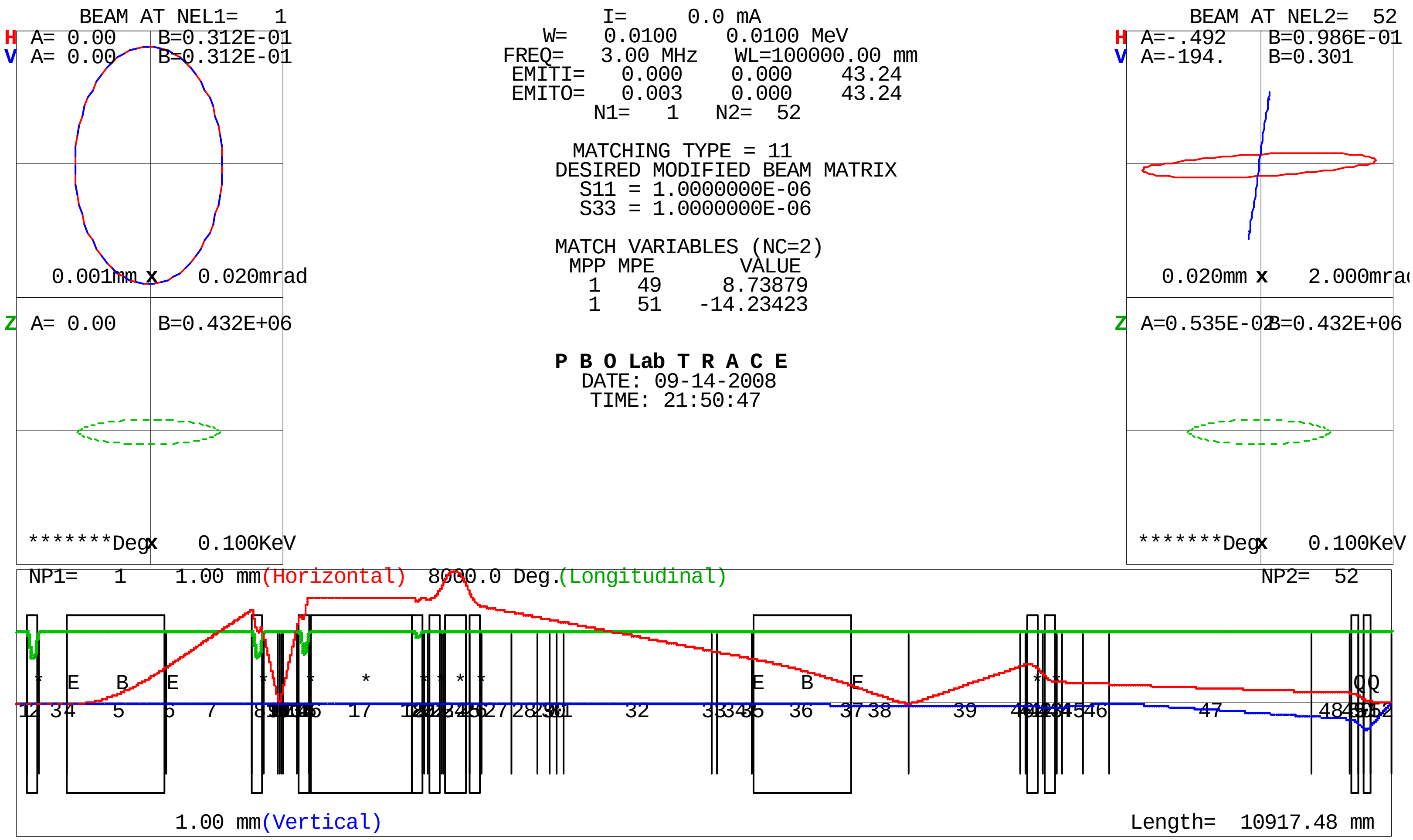
Some Other TRACE 3-D Features

- **TRACE 3-D Can Run Beam in Reverse (Backward) Direction**
  - **PBO-Lab Put "Initial" Beam at End of Beamline, "Final" Beam at Start**
- **Supports Misalignment of Elements (computes beam centroid)**
- **Can Couple Elements Parameters to Match Parameters**
  - **k=+1 Coupling: Couple Parameter = Match Parameter**
  - **k=-1 Coupling: Couple Parameter = - Match Parameter,**
    EXCEPT for Drift Lengths: Sum of 2 Drifts = Constant

- **PBO Lab version of TRACE 3-D**
  - **Electrostatic (ES) Elements that can be used by TRACE 3-D**
  - **Can Import TRACE 3-D Input Files from other TRACE 3-D versions***
  - **Can Write TRACE 3-D Input Files for other TRACE 3-D versions***
    ***Assuming versions have some degree of compatibility!**

- **Display Options Limited: Profiles and Phase Space Plots**
  - **Can Overlay ("Trace on Background") Profiles for Comparison**

5. Introduction to TRACE 3-D (continued)



5. Introduction to TRACE 3-D (continued)

Quick Comparison of Main Features

TRANSPORT	TRACE 3-D
1^{st}, 2^{nd}, 3^{rd} Order Optics	1^{st} Order Optics +
No Space Charge (low current)	Linear Space Charge (high current)
Outputs Data Files for Post Plotting	Graphic Display of Beamline
Up to 20 Vary Parameters	Up to 6 Match Parameters
Formula Coupling	$k = \pm 1$ Coupling
Numerous Fitting Conditions	14 Matching (Fitting) Conditions
Magnetic Elements, 1 RF	Magnetic & RF Elements
RMS Beam Properties	$(5)^{1/2}$ RMS Beam Properties
Transfer Lines a Main Application	RF Linacs a Main Application
40+ Years of Usage	30+ Years of Usage
Source Available from FNAL (other versions exist)	Executable Available from LANL (other versions exist)

PBO Lab Versions Have a Number of Additional Capabilities

6. Introduction to TURTLE

- **Acronym: "Trace Unlimited Rays Through Lumped Elements"**
- **Companion Code to TRANSPORT**
- **"Performance Code" Rather Than a "Design Code"**
  - **Calculates the 6-D coordinates of macroparticles through beamline**
  - **Same 6-D coordinates as TRANSPORT:** $(q_i)=(x,x',y,y',l,\delta)$
  - **Can routinely run 1,000 - 10,000+ particles on a PC**
  - **No parameter variation, fitting, matching, …**
- **Can examine effects not modeled in TRANSPORT**
  - **Three distributions in standard TURTLE:**
    Gaussian, Rectangular, Uniform
  - **Beam loss on apertures and slits**
  - **Non elliptical beams - either as input, or created in a beamline**
  - **Can add phase space "cuts" to distributions along beamline**
- **Output Used by Some Radiation Transport Codes - Shielding**

6. Introduction to TURTLE (continued)

- **TURTLE is complimentary program to TRANSPORT**
  - **Both use same description of beamline and elements**
  - **1st, 2nd, 3rd order calculated in both**
  - **Use the same 6-D phase space coordinates**

  $\Rightarrow$ **Use TRANSPORT to get a design; use TURTLE to evaluate it**

- **A special version, called DECAY-TURTLE, for radioactive beams**
  - **Tracks particles that have a finite lifetime**
  - **Primary particles (parents) decay randomly during beamline passage according to their lifetime**
  - **Tracks the decay product particles (daughters) thru beamline**
  - **User specifies parent lifetime, masses and charges of daughters**
  - **Transparency of apertures and slits can be particle dependent**

- **PBO-Lab provides TURTLE support for the same "non-TRANSPORT" optics elements that PBO-Lab makes available for TRANSPORT**
  - **TRACE 3-D Elements: Doublet, Triplet, RF Gap, Thin Lens**

- **Task 2 Utilized PBO Lab Version of TRANSPORT to:**
  - **Add ElectroStatic Quad (through 3rd order)**
  - **Add Magnetic and ElectroStatic Quad 3rd order Fringe Field Integrals**

6. Introduction to TURTLE (continued)

- **Generates Data for 2 Types of Plots**
  - **Scatter Plots of Phase Space Data (2-D Plot) e.g.** x' **versus** x
  - **Histograms of Data (1-D Plot) e.g. # particle is at bin location** x

- **Any of the 6-D Phase Space Variables Can be Used** x, x', y, y', l, δ
  - **36 Possible Scatter Plots**
  - **6 Possible Histograms**

- **Plots are Text Based - "Line Printer" (without a post processor)**

- **Multiple Locations in Beam Line - User Specified Plots at Each**

- **Apertures (on magnets, etc,) Can Be Ignored or Included (Particle Loss)**

- **DECAY-TURTLE Version Has Above Capabilities for Decay Particles**
  - **But DECAY-TURTLE does not fully support 3rd order**

6. Introduction to TURTLE (continued)

Typical Scatter Plot (TURTLE native output)

```
1HISTOGRAM NO  1
 HORIZONTAL AXIS    Y IN M        0.959 M    FROM THE START
 VERTICAL AXIS     Y' IN R        0.959 M    FROM THE START
                    -0.011    -0.007    -0.003     0.001     0.005     0.009
+                                                                               TOTALS
                     I**---**---**---**---**---**---**---**---**---**---**---I--------
   -0.014 TO  -0.013 I                                                       I      0
   -0.013 TO  -0.012 I                                                       I      0
   -0.012 TO  -0.011 I                                                       I      0
   -0.011 TO  -0.010 I                                                 12 1  I      8
   -0.010 TO  -0.009 I                                              2 231221 I     15
   -0.009 TO  -0.008 I                                          1 122253 1 3 I     22
   -0.008 TO  -0.007 I                                       111313234 31124 I     32
   -0.007 TO  -0.006 I                                    112262  6413135    I     37
   -0.006 TO  -0.005 I                                 1 1 54332362425221    I     46
   -0.005 TO  -0.004 I                                12341221676334532      I     55
   -0.004 TO  -0.003 I                            3 11434451242311243        I     48
   -0.003 TO  -0.002 I                         2134252435321444332           I     57
   -0.002 TO  -0.001 I                      22222236864561233412 1           I     67
   -0.001 TO   0.000 I                    1453124433284431711111             I     64
    0.000 TO   0.001 I                   434543544562 233 1                  I     58
    0.001 TO   0.002 I               31122447855358362111                    I     72
    0.002 TO   0.003 I             221525624428534222321                     I     67
    0.003 TO   0.004 I           123232432532246 2131                        I     51
    0.004 TO   0.005 I        2165 242473574211 1                            I     57
    0.005 TO   0.006 I     1 1116364337434233111                             I     58
    0.006 TO   0.007 I  1 1314253523323  3 1                                 I     42
    0.007 TO   0.008 I   2 12214332243   1                                   I     30
    0.008 TO   0.009 I 22235 53 2121 1                                       I     29
    0.009 TO   0.010 I 25354121 3 1                                          I     27
    0.010 TO   0.011 I 221221                                                I     10
    0.011 TO   0.012 I                                                       I      0
    0.012 TO   0.013 I 1                                                     I      1
    0.013 TO   0.014 I                                                       I      0
                     I**---**---**---**---**---**---**---**---**---**---**---I--------
                     I                                                       I
                     I                                                       I
                     I                                                       I
                     I  1 11 11121111121122232221222222221111222111211111    I
             TOTALS  I 70816540138578828674703588495722354948041747087250458 I    953
0          TOTAL NUMBER OF ENTRIES =      1000 INCLUDING UNDERFLOW AND OVERFLOW AS FOLLOWS
0                           LEFT                         RIGHT
           ABOVE               0              0              0
                              35            948             17
           BELOW               0              0              0

   SUM OF SQUARES =          3603.
           CENTER =     0.000   RMS HALF WIDTH =     0.006
           CENTER =     0.000   RMS HALF WIDTH =     0.005
           CORRELATION =   -0.9506
0NO   1 TWO DIMENSIONAL PLOT OF
 HORIZONTAL AXIS    Y IN M        0.959 M    FROM THE START
 VERTICAL AXIS     Y' IN R        0.959 M    FROM THE START
```

[MS Word font: Courier New 7 pt., normal spacing]

6. Introduction to TURTLE (continued)

Typical Histogram (TURTLE native output)

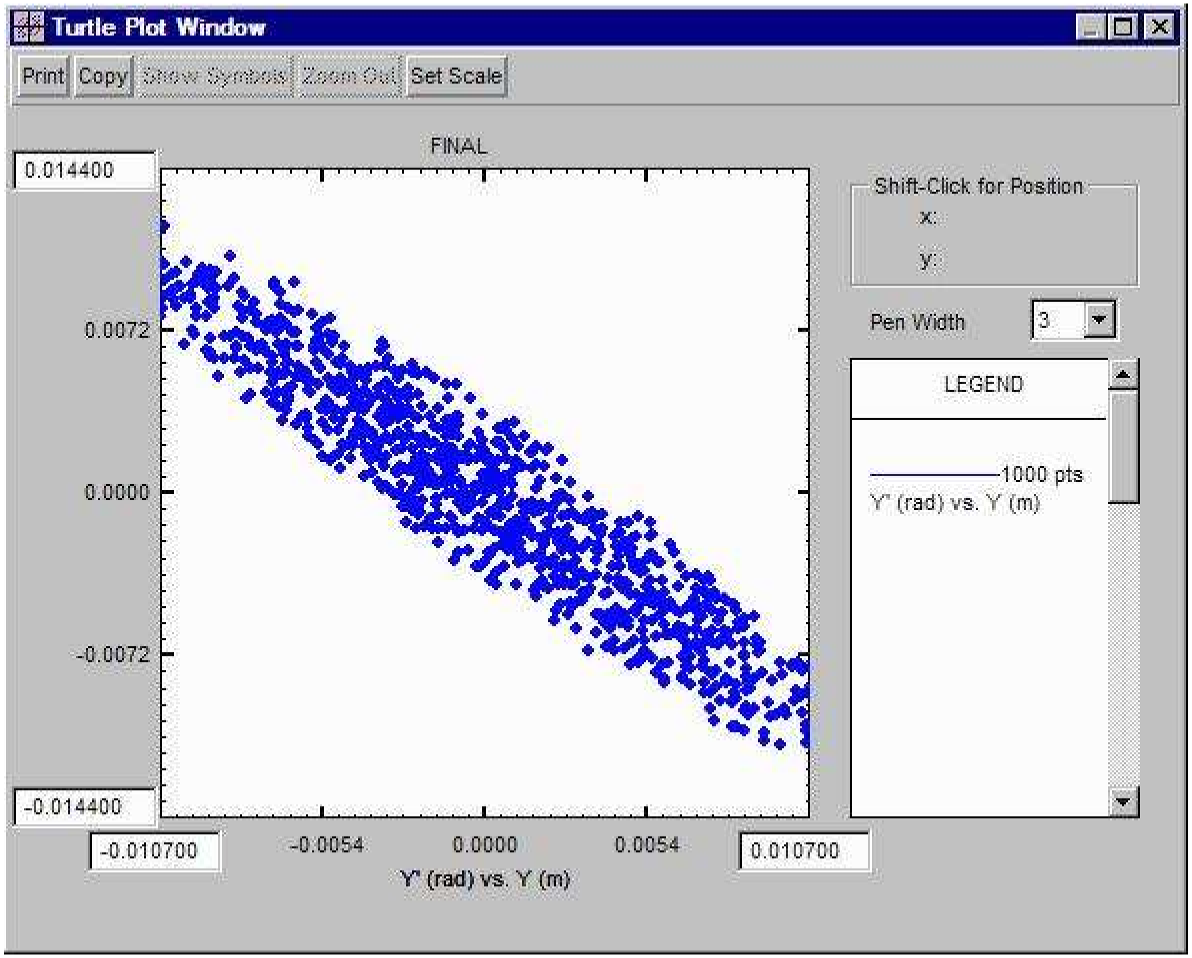
```
1HISTOGRAM NO  1
 DISTRIBUTION OF    Y IN M        0.959 M    FROM THE START
0
           INTERVAL                              SCALE FACTOR:  100 X'S EQUAL    33 RAYS
0LESS THAN     -0.011       33   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX

   -0.011 TO   -0.010        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.010 TO   -0.010        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.010 TO   -0.009       13   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.009 TO   -0.009       11   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.009 TO   -0.009        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.009 TO   -0.008       16   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.008 TO   -0.008       13   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.008 TO   -0.007       17   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.007 TO   -0.007       13   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.007 TO   -0.007        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.007 TO   -0.006       18   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.006 TO   -0.006       19   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.006 TO   -0.005       18   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.005 TO   -0.005       22   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.005 TO   -0.005       16   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.005 TO   -0.004       15   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.004 TO   -0.004       25   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.004 TO   -0.004       18   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.004 TO   -0.003       18   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.003 TO   -0.003       24   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.003 TO   -0.002       25   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.002 TO   -0.002       28   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.002 TO   -0.002       28   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.002 TO   -0.001       28   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.001 TO   -0.001       28   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
   -0.001 TO    0.000       24   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.000 TO    0.000       17   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.000 TO    0.000       30   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.000 TO    0.001       23   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.001 TO    0.001       27   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.001 TO    0.002       26   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.002 TO    0.002       23   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.002 TO    0.002       20   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.002 TO    0.003       22   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.003 TO    0.003       15   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.003 TO    0.004       20   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.004 TO    0.004       19   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.004 TO    0.004       24   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.004 TO    0.005       18   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.005 TO    0.005       20   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.005 TO    0.006       24   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.006 TO    0.006       19   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.006 TO    0.006        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.006 TO    0.007       17   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.007 TO    0.007       10   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.007 TO    0.008       13   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.008 TO    0.008       13   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.008 TO    0.008        7   XXXXXXXXXXXXXXXXXXXXX
    0.008 TO    0.009        9   XXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.009 TO    0.009       16   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.009 TO    0.010       14   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
    0.010 TO    0.010        5   XXXXXXXXXXXXXXX
    0.010 TO    0.010       10   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0GREATER THAN   0.010       24   XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
0          TOTAL NUMBER OF ENTRIES =      1000     INCLUDING UNDERFLOW AND OVERFLOW
0          CENTER =     0.000   RMS HALF WIDTH =     0.006
0
 DISTRIBUTION OF    Y IN M        0.959 M    FROM THE START
```

[MS Word font: Courier New 5 pt., normal spacing]

6. Introduction to TURTLE (continued)

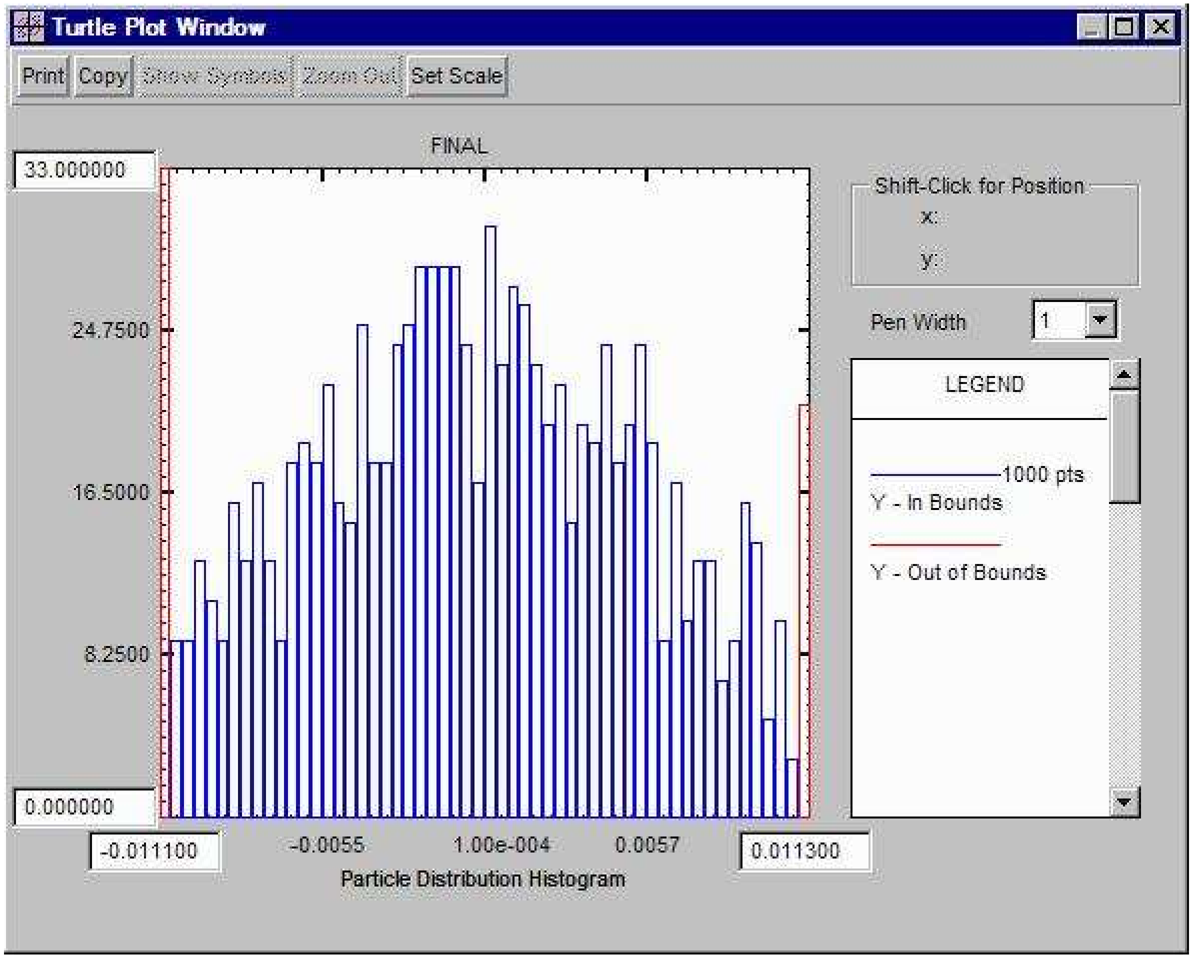
Typical Scatter Plot (PBO Lab postprocessor plot)



- **PBO-Lab uses same (default) color assignments for all codes**
- **Provide for "Auto-Scaling" of Plots - Useful for Initial Setup**
- **Can Adjust Scales <u>After</u> a Run- Unlimited "Zoom" Capability**

6. Introduction to TURTLE (continued)

Typical Histogram (PBO Lab postprocessor plot)



- **PBO-Lab plots provide data visualization & document preparation tools**
- **Print, Copy, scale adjustment, …**
- **Need to look at TURTLE (text) output for selected quantitative data**

7. Summary of Part I

- **Overview of Coordinate Systems and Basic Matrix Descriptions**
- **Relationship Between Semi-Axes and Twiss Beam Description**
- **Overview of Drift, Quad, and Bend Equations of Motion & Matrix Solutions**
- **Guide to Fitting Constraints (Point-to-Point, etc.)**
- **Summary of Primary TRANSPORT, TRACE 3-D & TURTLE Capabilities**

Part II $\Rightarrow$ **Will use the PBO Lab software in the class to illustrate concepts**
Complete some typical computations with the codes in the class