New Test and Analysis Approaches for SEE Characterization

GOMACTech-10

24 March 2010

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Outline

- Describe the Milli-Beam™ raster scanning technique
  - Most recent test advance by Micro-RDC
  - New technique to raster scan complex integrated circuits
  - Spatial resolutions easily varied between 10 µm and 500 µm
  - Automated calibration, scanning, and data acquisition
  - Provides surface plot of IC error cross section as function of position

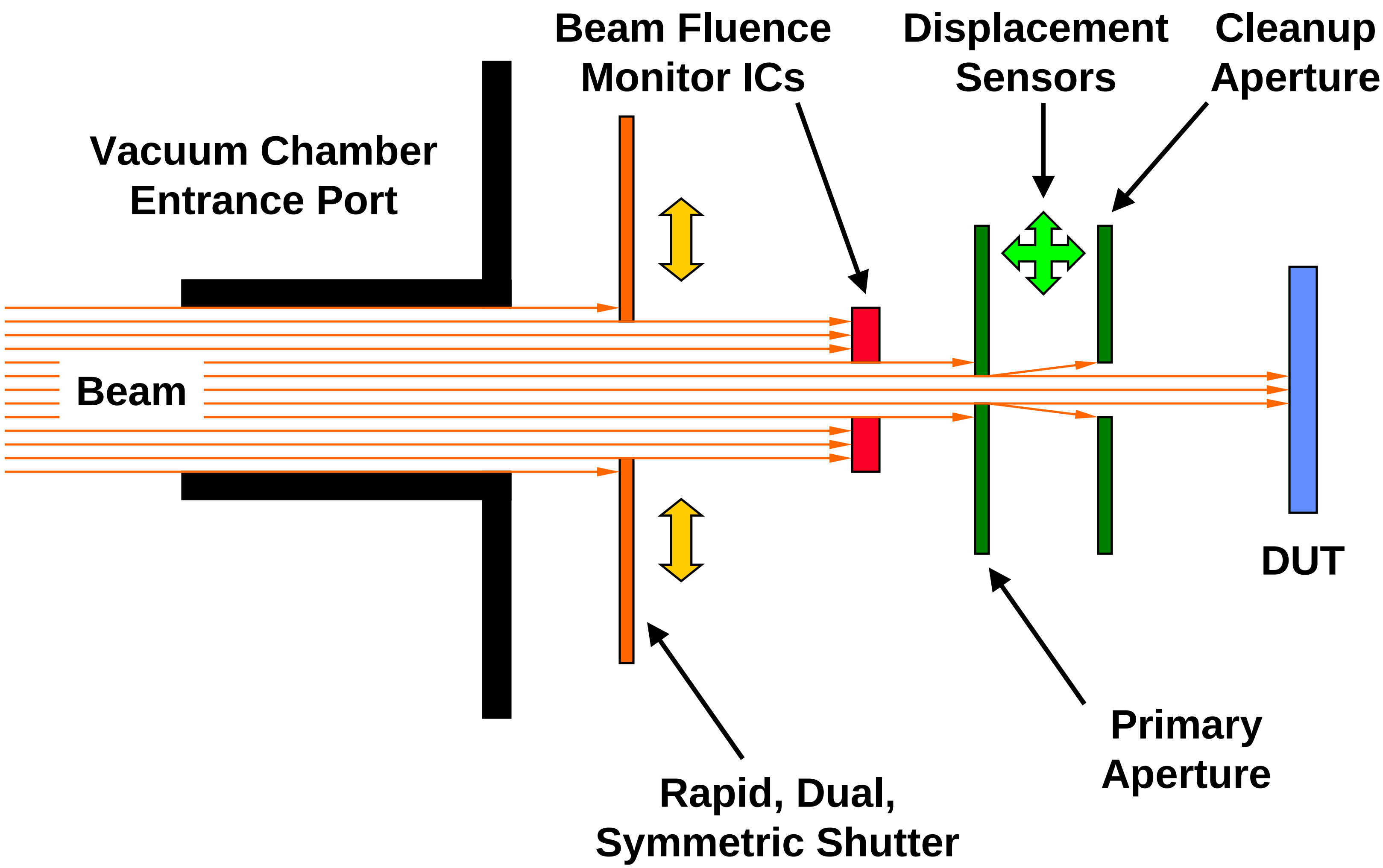
- Show photos of the actual apparatus
  - As presently installed at the Berkeley 88-inch cyclotron

- Present examples of recent measurments
  - SRAM scan
  - DSET propagation chain scan
  - PLL loss of lock raster scan

Milli-Beam Overview and Features

- Precise collimation for use at the LBL cyclotron
  - New hardware and software to raster scan complex ICs
  - Achieve spatial resolutions between 10 µm and 500 µm
- Hardware
  - Primary square aperture (2-orthogonal slits) stepped <1 µm precision
  - Secondary scattering cleanup aperture controlled from second stage
  - Displacement sensors provide error feedback signal for corrections
- Software
  - Computes coordinate transformations, sets beam position, controls run
  - Provide FPGA test board with positions for inclusion in error message
- Independent ICs for beam characterization and dosimetry
  - Homogeneous RAM for location and intensity profile measurement
  - Specially designed Beam monitor ICs placed upstream of aperture
  - At preset fluences: Stop data acquisition, step apertures, update FPGA test board with new position, resume data acquisition

Milli-Beam Schematic



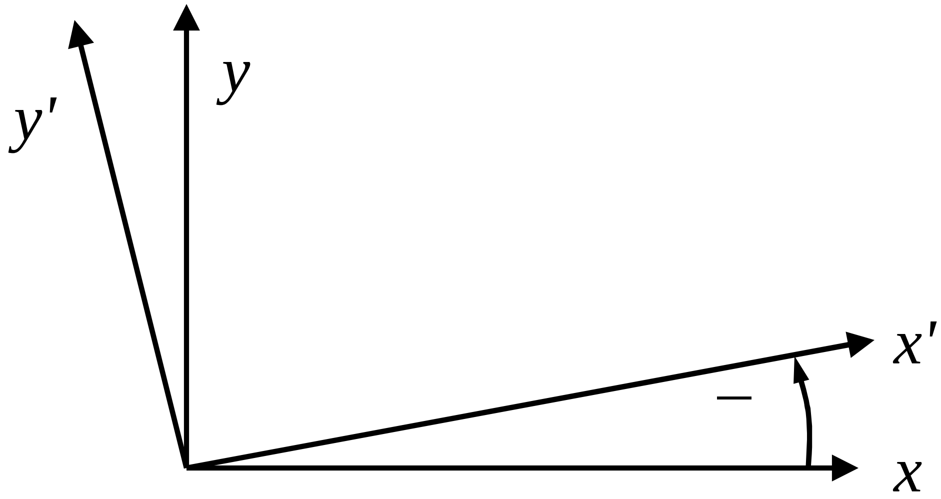
Physical Considerations

- Displacement and rotation of DUT w.r.t. calibration SRAM
- SRAM Y-axis rotation w.r.t. Milli-Beam Y-actuator
- Non-orthogonally of Milli-Beam X and Y acutuators
- Berkeley Stage Y-axis rotation w.r.t. Milli-Beam Y-actuator†
- Non-orthogonally of Berkeley X and Y acutuators†
- Dimensional scaling of each actuator†

†Only if need to move Berkeley Stage to bring DUT into Milli-Beam Range

Milli-Beam Coordinate Transformations (1 of 4)

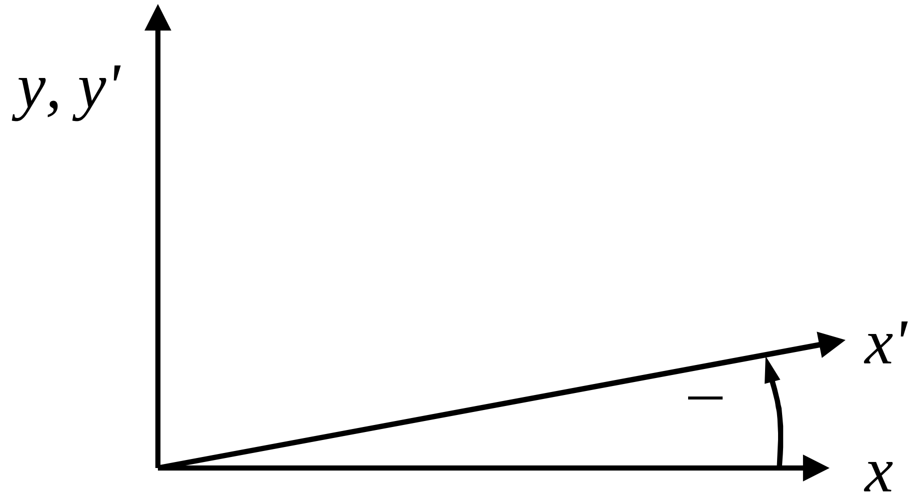
- Simple Rotation



$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{bmatrix} \cos\text{—} & \sin\text{—} \\ -\sin\text{—} & \cos\text{—} \end{bmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \cos\text{—} & -\sin\text{—} \\ \sin\text{—} & \cos\text{—} \end{bmatrix} \cdot \begin{pmatrix} x' \\ y' \end{pmatrix}$$

Milli-Beam Coordinate Transformations (2 of 4)

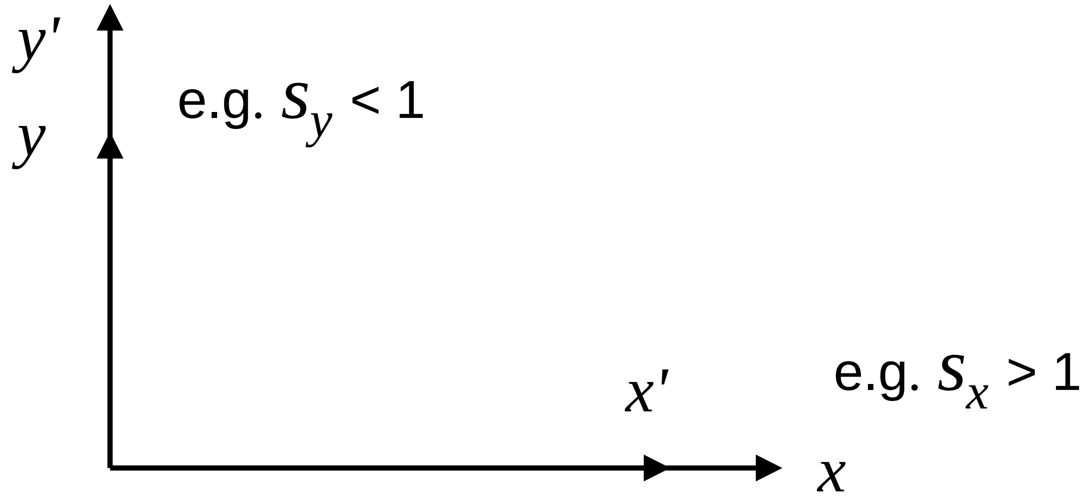
- **Non-Orthogonally Transformations**



$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{bmatrix} 1/\cos\theta & 0 \\ -\tan\theta & 1 \end{bmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} \cos\theta & 0 \\ \sin\theta & 1 \end{bmatrix} \cdot \begin{pmatrix} x' \\ y' \end{pmatrix}$$

Milli-Beam Coordinate Transformations (3 of 4)

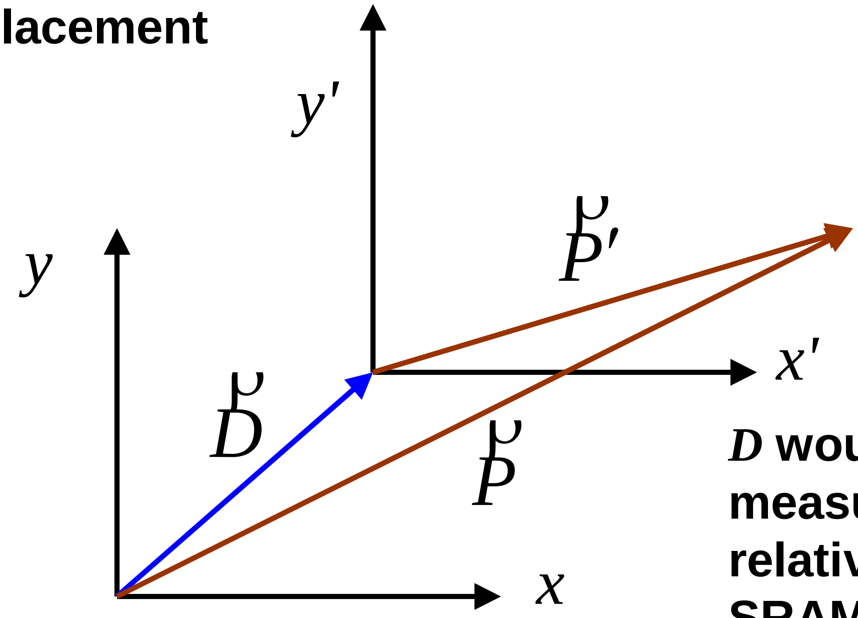
- Axis Scaling



$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{bmatrix} s_x & 0 \\ 0 & s_y \end{bmatrix} \cdot \begin{pmatrix} x \\ y \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix} = \begin{bmatrix} 1/s_x & 0 \\ 0 & 1/s_y \end{bmatrix} \cdot \begin{pmatrix} x' \\ y' \end{pmatrix}$$

Milli-Beam Coordinate Transformations (4 of 4)

- Simple Displacement



D **would typically measure DUT location relative to calibration SRAM location**

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} x \\ y \end{pmatrix} - \begin{pmatrix} X_D \\ Y_D \end{pmatrix} \qquad \begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} x' \\ y' \end{pmatrix} + \begin{pmatrix} X_D \\ Y_D \end{pmatrix}$$

Final Form of the Transformation

- Transformation to compute Milli-Beam raster scan movements

$$\begin{pmatrix} x_m \\ y_m \end{pmatrix} = \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{O_{-}} \cdot \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{R_{-}^{-1}} \cdot \left\{ \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{R_D^{-1}} \cdot \begin{pmatrix} x_{dut} \\ y_{dut} \end{pmatrix} + \begin{pmatrix} x_D \\ y_D \end{pmatrix} \right\}$$

$$\begin{pmatrix} x_D \\ y_D \end{pmatrix} = \begin{pmatrix} x_{D_o} \\ y_{D_o} \end{pmatrix} + \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{R_{-}} \cdot \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{R_g^{-1}} \cdot \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{O_g^{-1}} \cdot \underbrace{\begin{bmatrix} \times & \times \\ \times & \times \end{bmatrix}}_{S_g} \cdot \begin{pmatrix} ¢x_b \\ ¢y_b \end{pmatrix}$$

¯ → **SRAM w.r.t. Milli-Beam;** D → **DUT w.r.t. SRAM**

¨ → **Berkeley w.r.t. Milli-Beam;** b → **Berkeley stage movement**

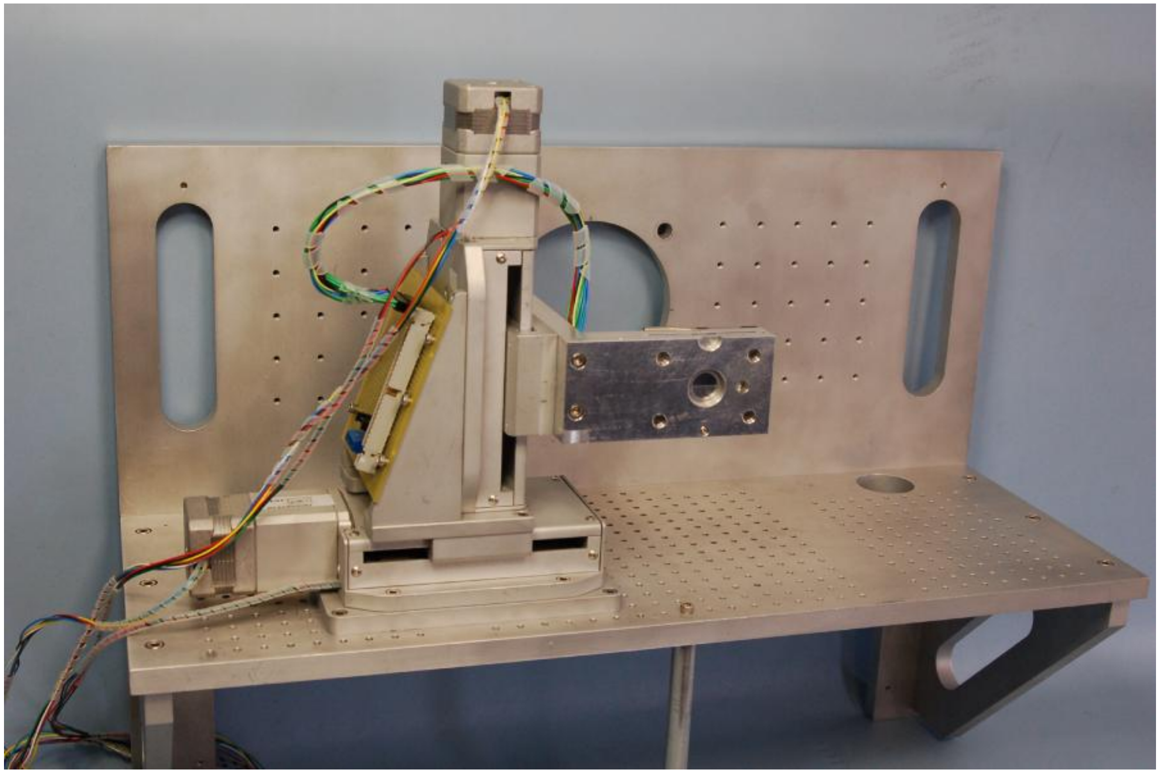
- Inverse transformation used to compute DUT location, along with an estimate of the variance, for each Milli-Beam raster position

Beam Fluence Monitor

- Four special ICs
  - Mounted just upstream of the Milli-Beam Primary Aperture
  - Incorporates several chains of RS flip-flops
  - Electrically selectable cross section
  - Extremely small dead time

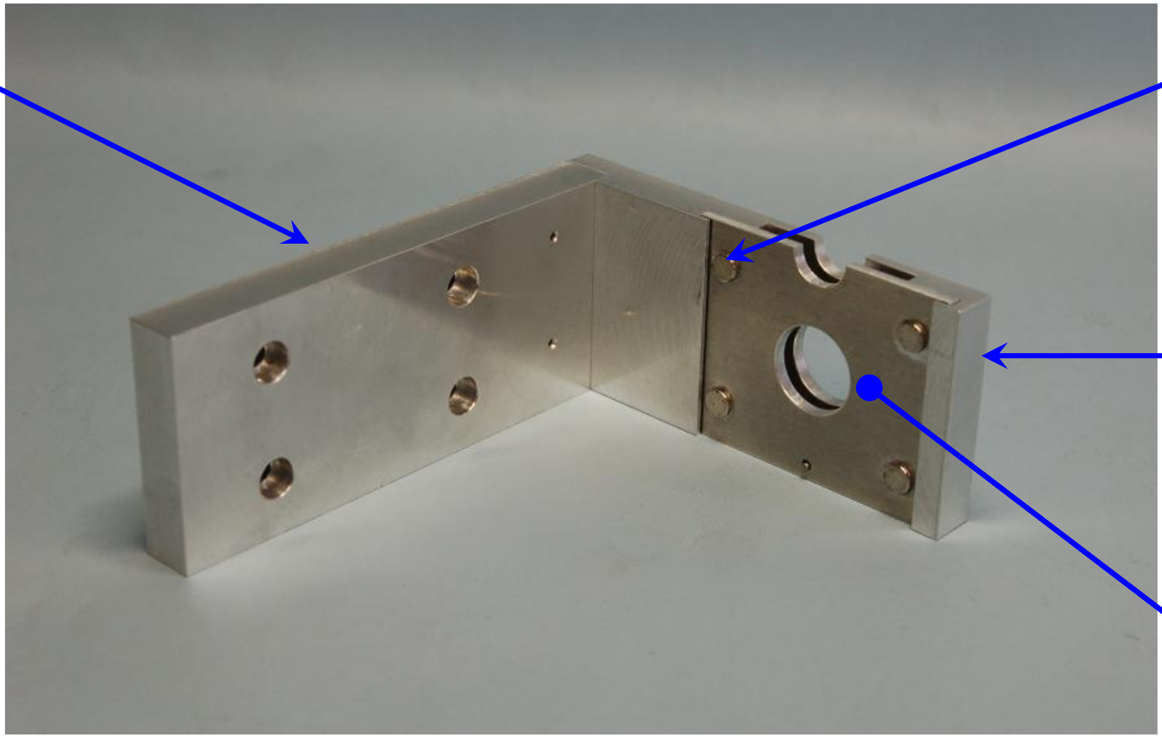
- Calibrated to an accuracy of better than 1%
  - Independent of the Berkeley scintillator system
  - Aperture of know size (as measured on a 90 nm SRAM)
  - Particle detector counts individual heavy-ions through aperture
  - Beam monitor IC events measured as a function of LET

Complete Milli-Beam Assembly



Aperture Mounting Assembly

Bracket to Mount to Stage



Neodymium Magnets (4)

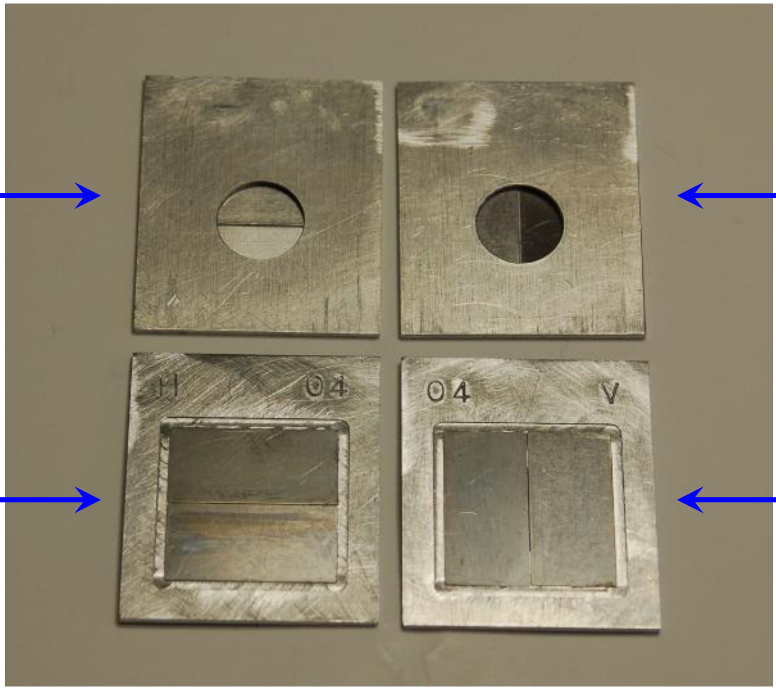
Slit Holder

Pressure Plate

Aperture Construction

Outside View
Horizontal Slit

Inside View
Horizontal Slit

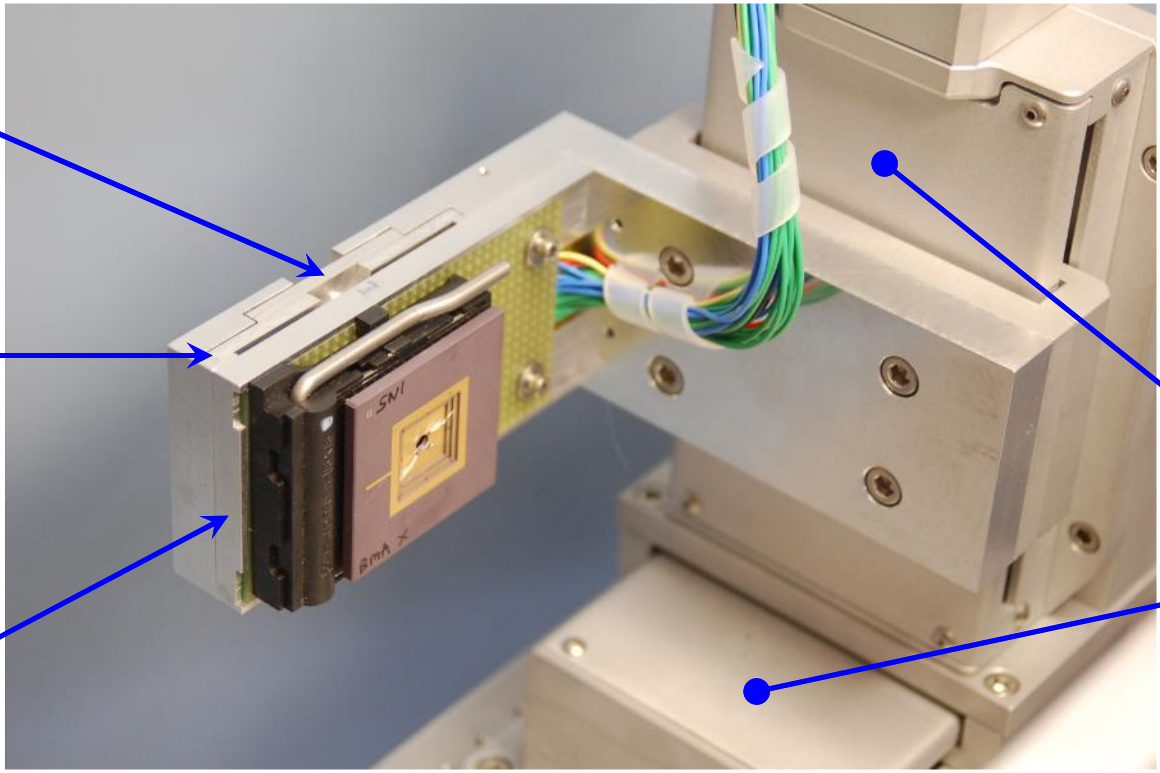


Outside View
Vertical Slit

Inside View
Vertical Slit

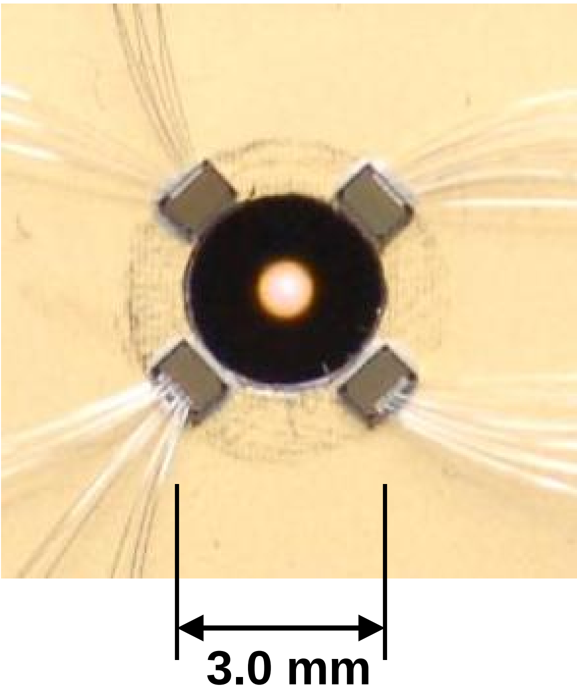
Fold to Assemble:

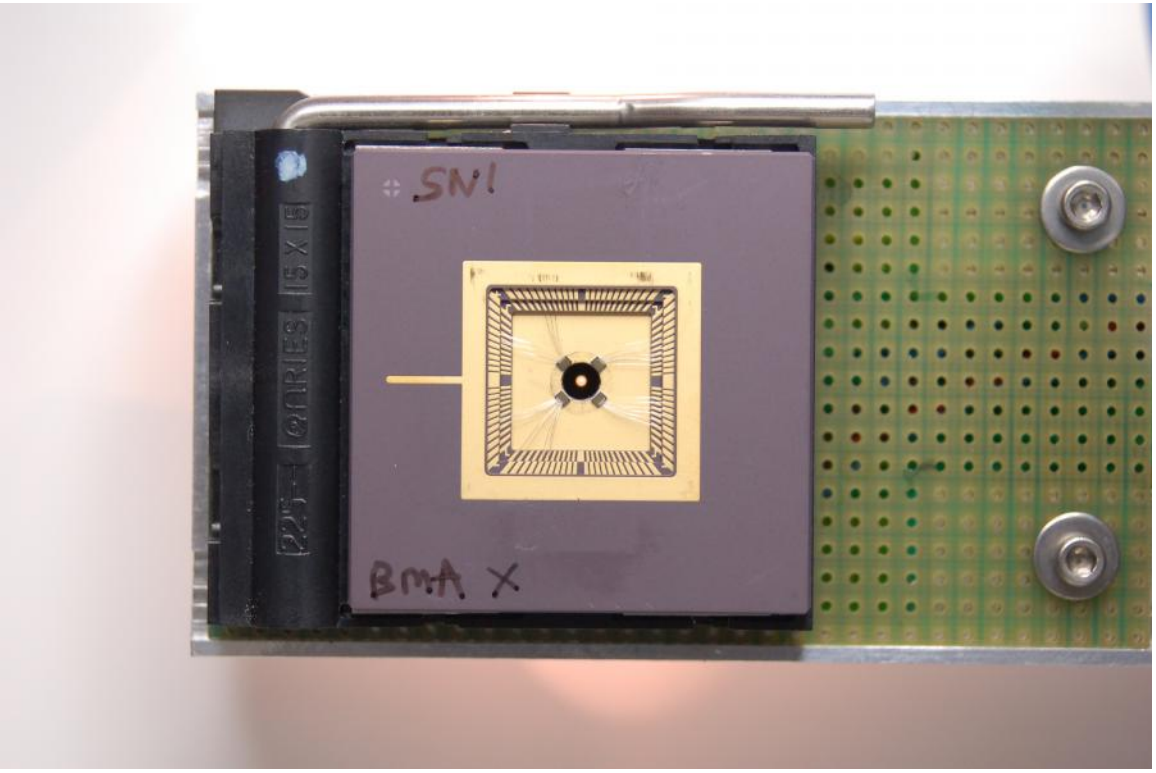
Beam Monitor in Relation to Primary Aperture



View as Seen by the Heavy-Ion Beam

Zoomed View of Die

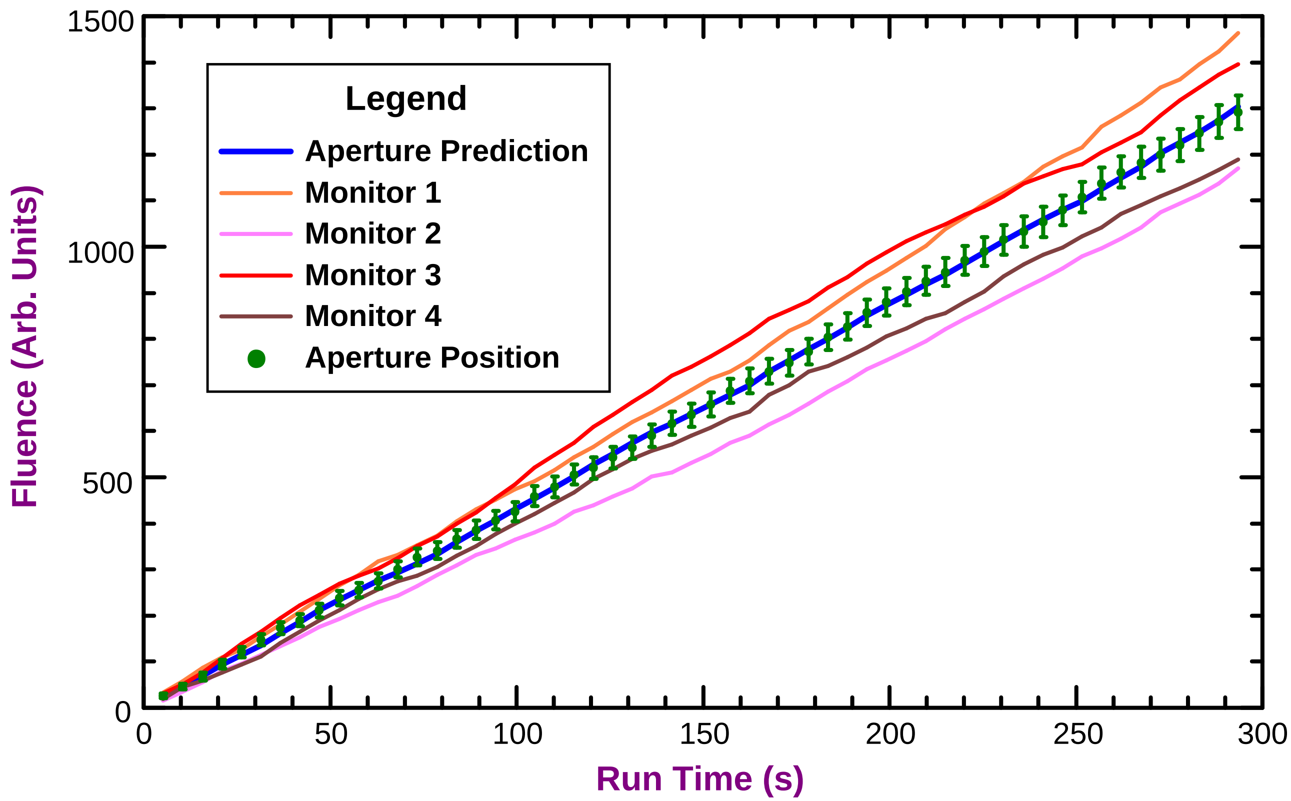




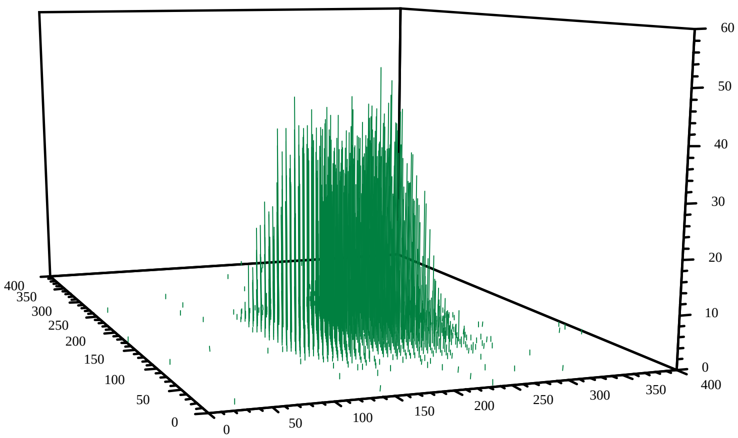
PGA, ZIF Socket, PERF Board

Beam Fluence Monitor Accuracy

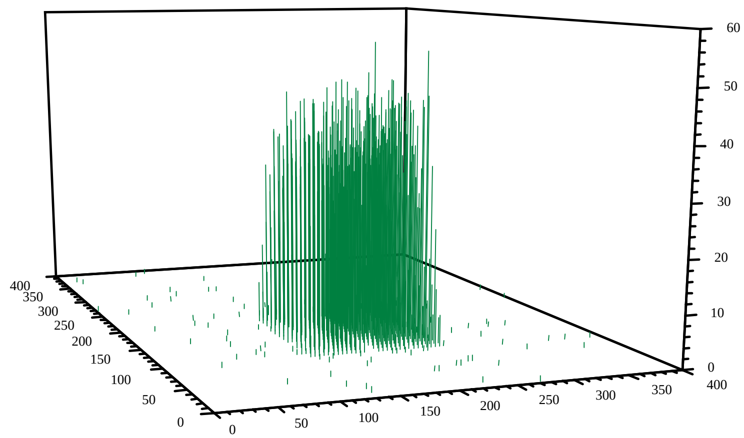
- Average the 4 monitor chip counts to predict beam flux at aperture



Milli-Beam Intensity Profile Measurement

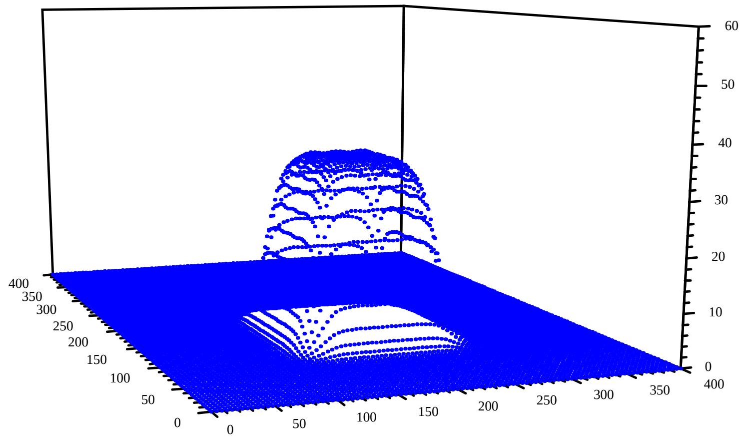


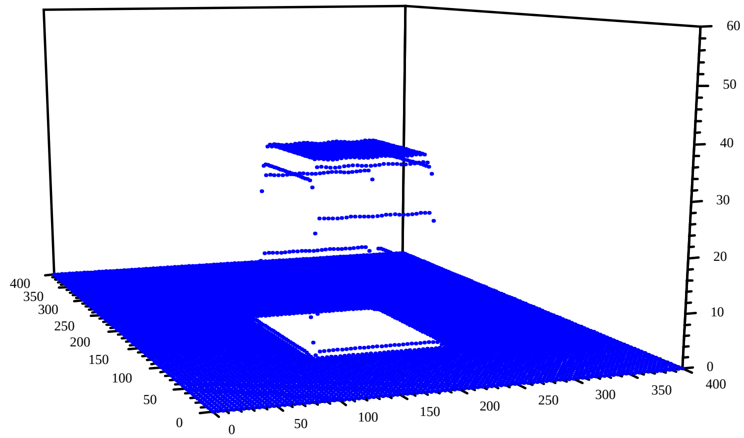
- 100 µm square aperture
- Located 40 cm to SRAM
- Edge washout due to angular spread



- 100 µm square aperture
- Located 5 cm to SRAM
- Sharper edge definition

LSQ Fits to the Intensity Profile Function

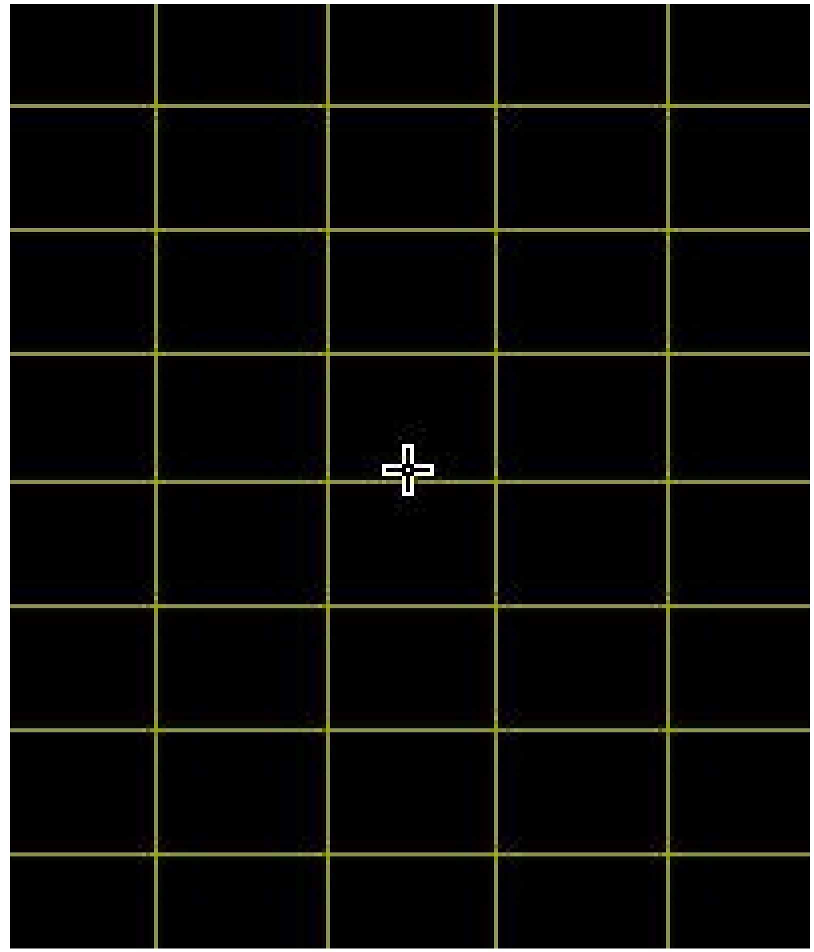




- **2-d Convolution of a Gaussian product z(x)ěz(y) with an x-y-z box**
- **Center, width, length of aperture determined to < 1 µm accuracy**
- **Gaussian $\pm_x$ and $\pm_y$ determined to <0.1 µm accuracy**
- **± values again match distance times tangent of 0.0025°**
- **± at 5 cm distance measured to be ~2 µm in x and y directions**

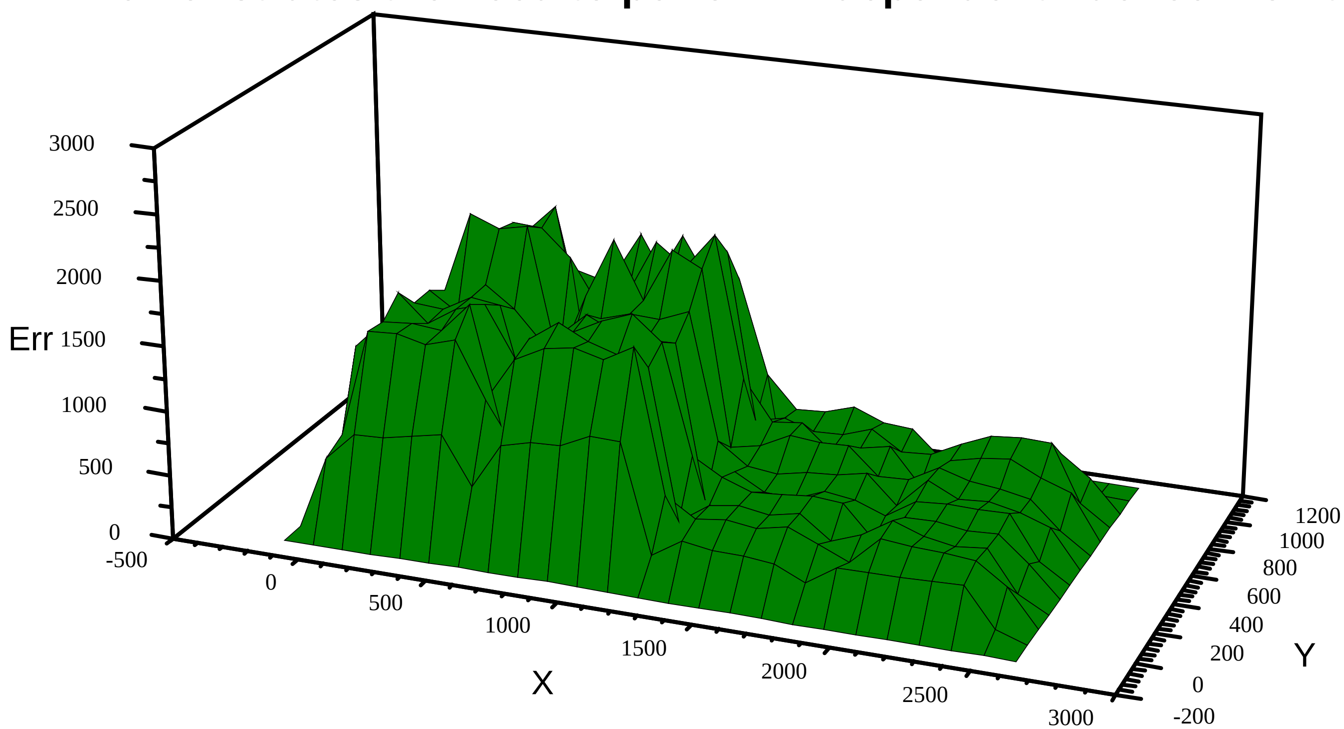
Example of a Raster Scan

- **114 µm x 101 µm aperture**
  - **As determined from LSQ fit**
- **5 cm from SRAM**
- **>>1 x 10^6 Ar ions/(cm^2-sec)**
  - **10x normal beam intensity**
- **Use aperture size for step size**
  - a**x step = 114 µm**
  - a**y step = 101 µm**
- **Scan in a serpentine pattern**
  - **~1.5 seconds/step**
  - **~300 errors at each position**



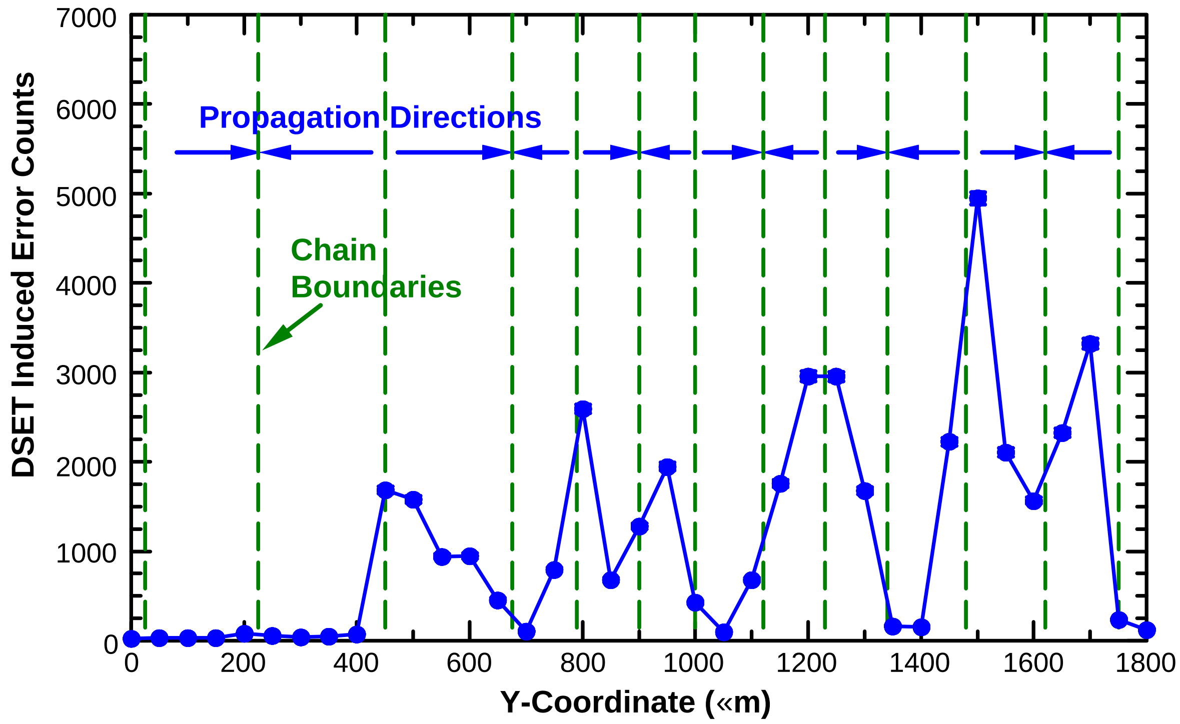
SRAM Raster Scan Data Example

- Scan an SRAM on one of our earlier test chips
  - Two different cell designs – hardened layout on right half
  - Decode locations clearly seen in center of each array
  - Variations outside of statistical uncertainties due to beam fluctuations
  - Demonstrates the need to perform independent fluence monitoring



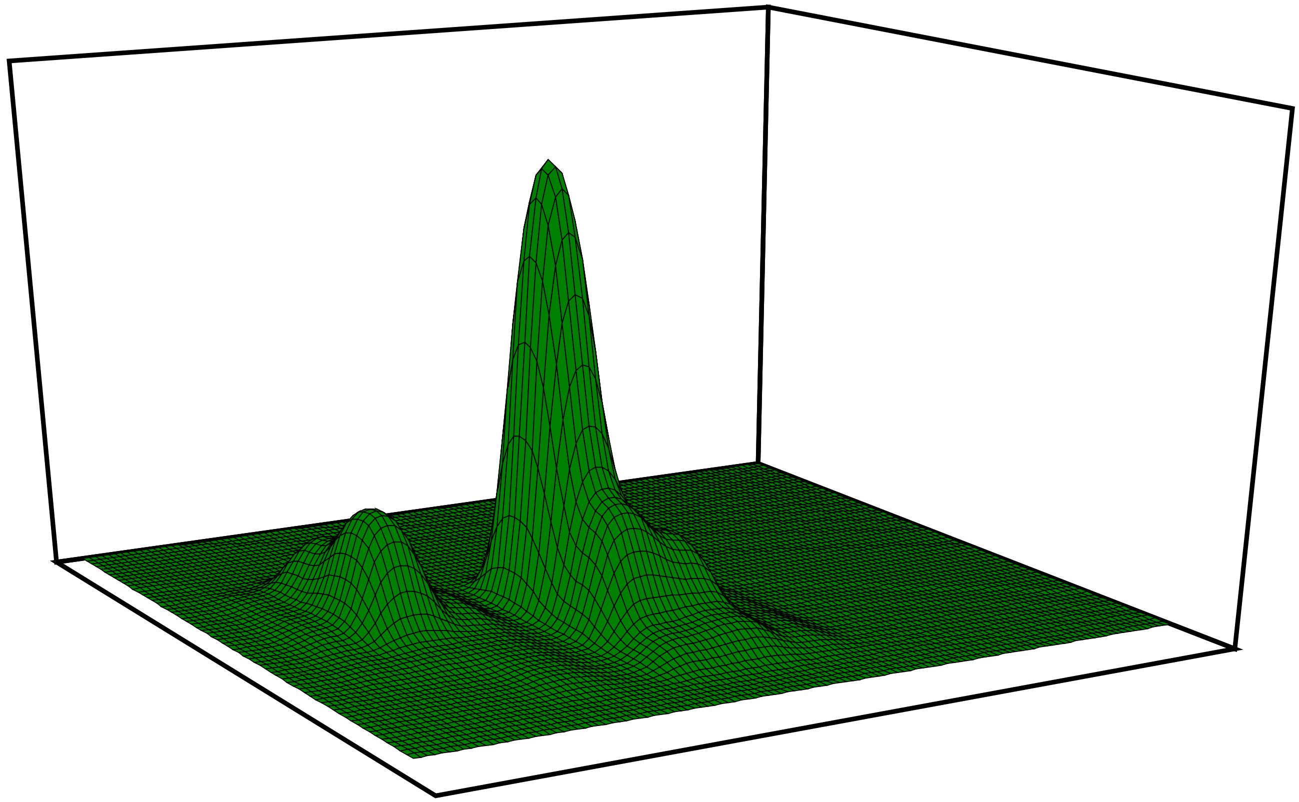
Propagation Chain Slit Scan Example

- Scan a clocked prop-chain test circuit from a DSET test chip
  - 12 different chains, propagate in y direction along an x serpentine
  - Scan a 50 µm wide slit in 50 µm steps along y-direction
  - Pulse broadening can be clearly seen from the data

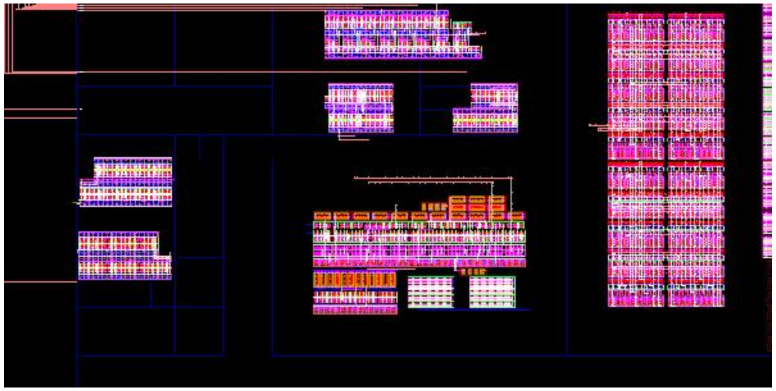


Raster Scan of a Commercial PLL Design

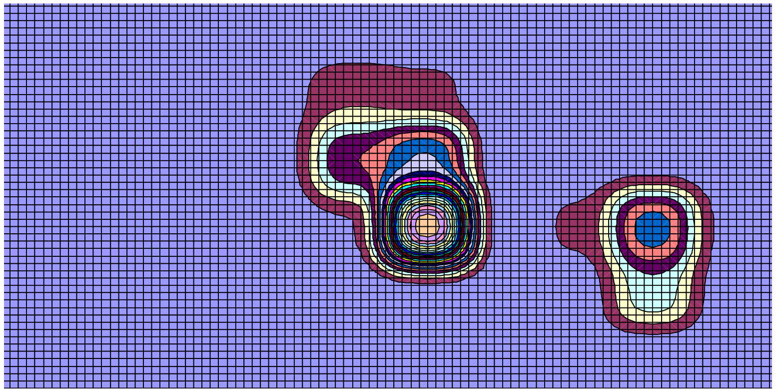
- Scan a 100 µm square beam over the PLL circuitry
  - Better approach than trying to test standalone circuit components
  - Monitor lock signal and measure recovery time
  - Correlate observed errors to specific circuits (CP, VCO, PSD, /N, òM)



Correlate PLL Errors to Physical Layout



Design Layout



Milli-Beam Error Contours

Summary

- New test methods
  - Full characterization of SRAM MBUs
  - True 90° heavy-ion irradiation
  - Accurate Milli-Beam raster scanning
- Versatile data acquisition system
  - FPGA-based mother board with inexpensive daughter cards
  - VHDL test programs to record detailed descriptions of each error
  - LabView user interfaces to control raster scans and provide real-time visualization
- Test specific data analysis
  - Perl scripts to parse and post-process data log files
  - Reduced data readied for graphical display and least squares fitting
  - Proper treatment of data uncertainties
  - Curvature matrix based least squares parameter extraction
  - Extraction of parameter variance
  - Correct propagation of errors when using extracted parameters