Evaluating radiation-induced noise effects on pixelated sensors for the National Ignition Facility

CASIS Workshop 2014

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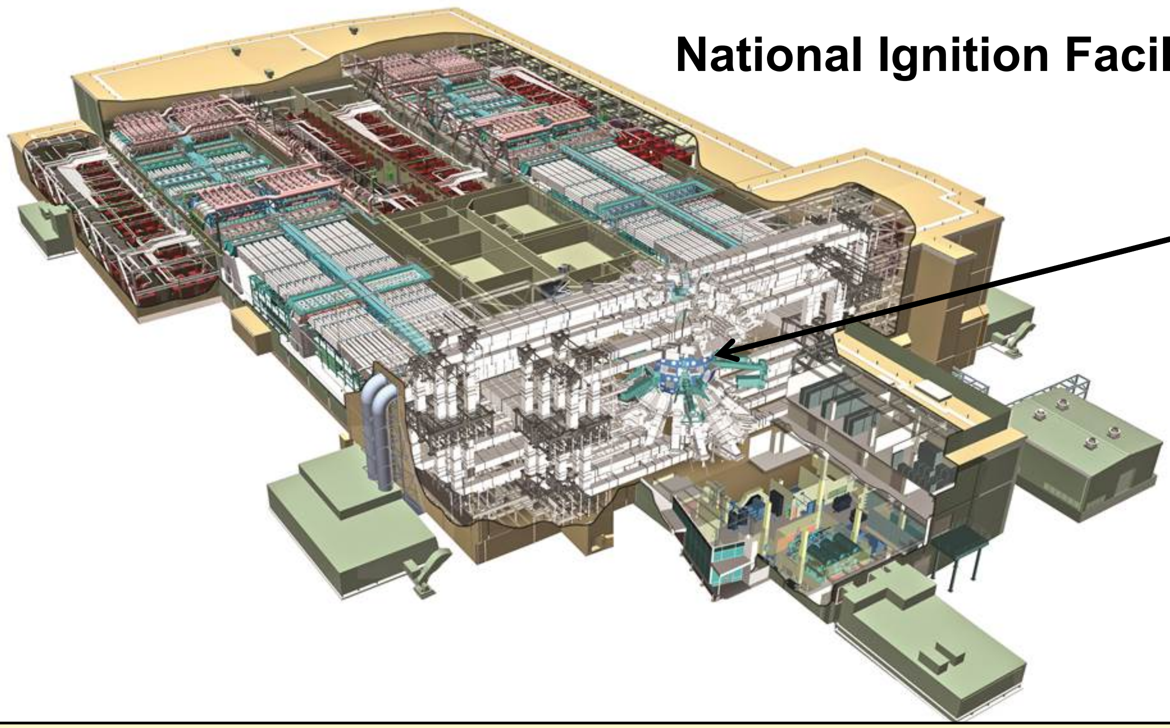
National Ignition Facility (NIF)

- The National Ignition Facility (NIF) is a 192 beam laser facility designed to support the Inertial Confinement Fusion (ICF) program.
- The facility was designed to have the capability of producing a deuterium-tritium (D-T) target shot in excess of 20 MJ of energy or 7.1E18 neutrons at 14 MeV.
- A (D-T) target shot will generate 14 MeV neutrons at Target Chamber Center that propagate through the chamber into the Target Bay with multiple scatters, resulting in a high fluence, broad energy band of neutrons.

National Ignition Facility



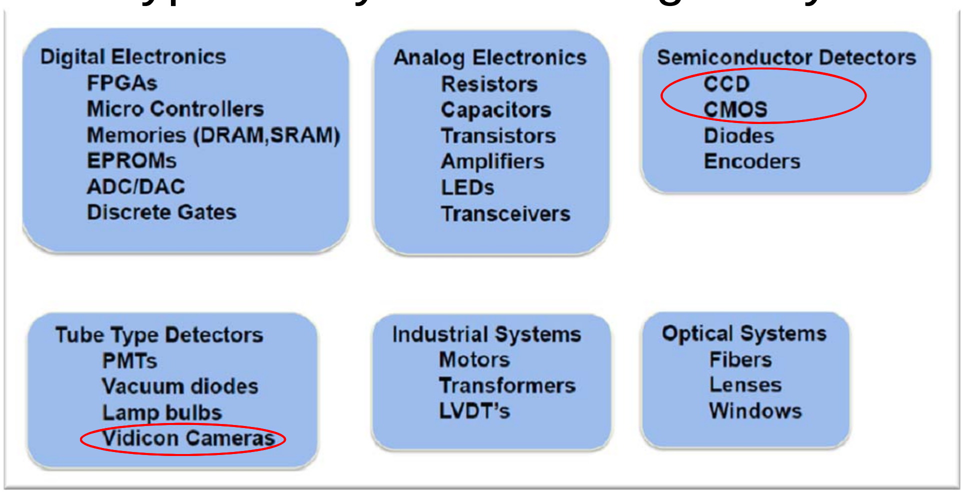
NIF Target Chamber

High fluence of 14MeV neutrons during a NIF yield shot is a very unique environment!

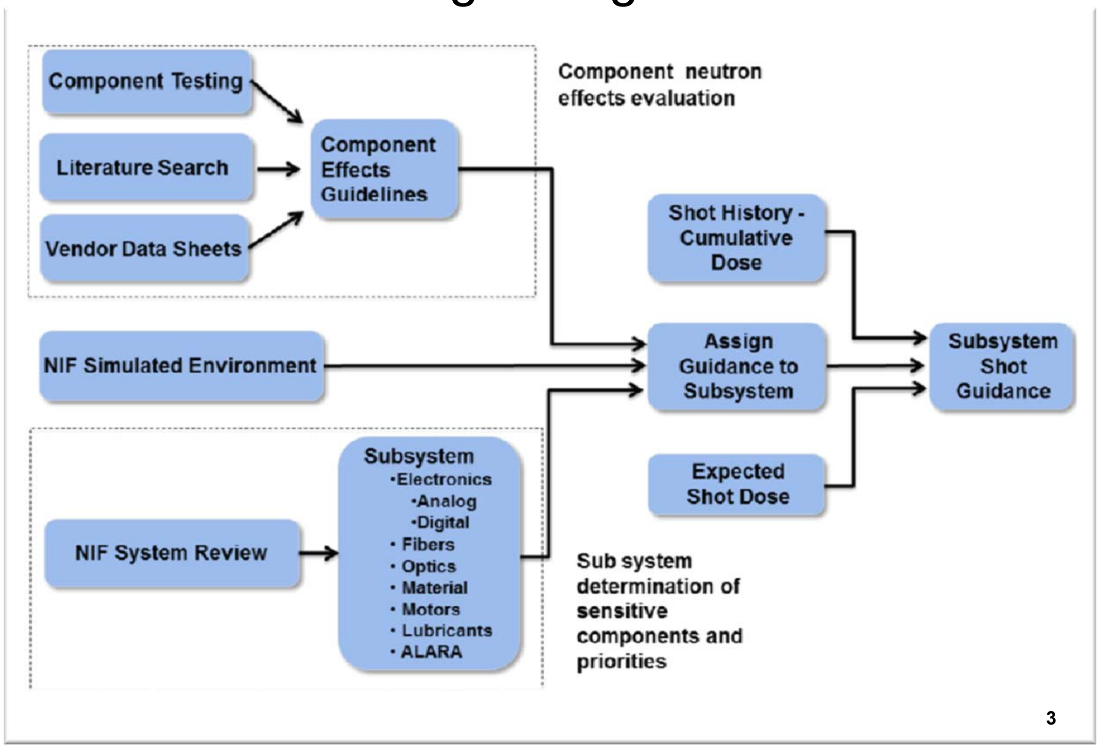
All Target Bay components exposed to high fluence 14MeV neutron radiation

- **Neutrons emanating from the target chamber scatter as the propagate outwards.**
  - **— When neutrons are absorbed, physical changes to the material or device can occur.**
- **Neutron Project IPT looks at effect on many different systems in the target bay.**
  - **— Gives guidance to system for yield shots.**

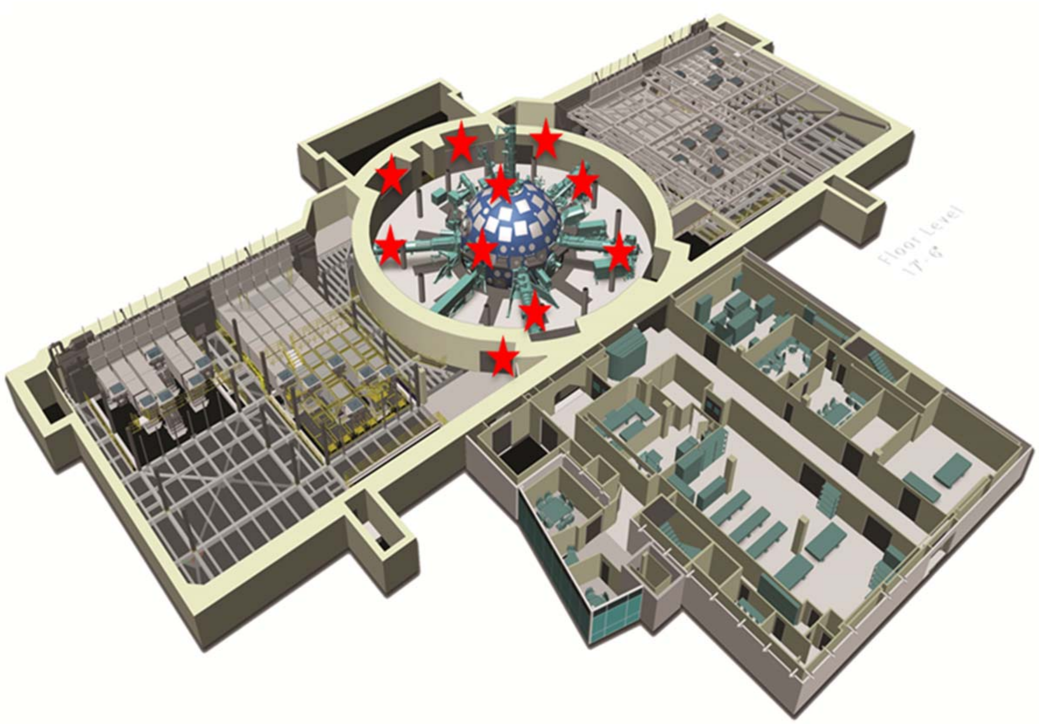
Types of systems in target bay:



Determining shot guidance:



NIF radiation can degrade many alignment and diagnostic cameras



Sectional view of the target bay at the equator

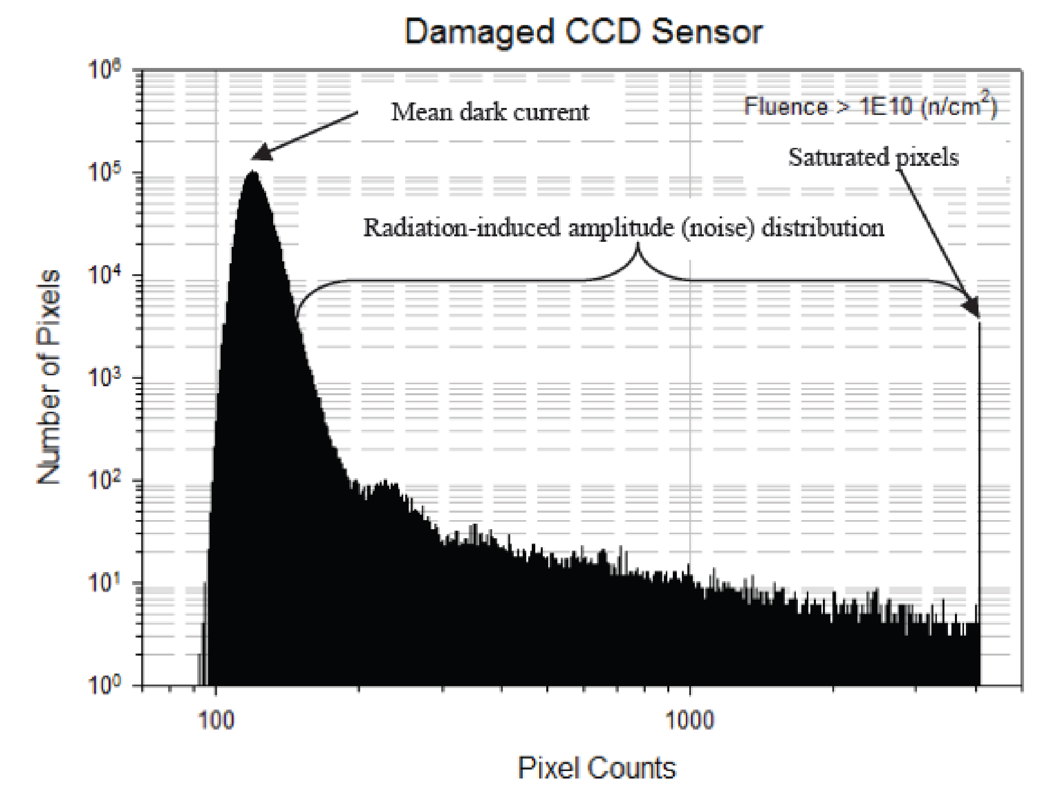
- **Camera systems exist on all levels of NIF**
- **Facility systems include:**
  - **Target Alignment Sensor (TAS)**
  - **Chamber Center Reference System (CCRS)**
  - **Chamber Interior Viewing System (CIVS)**
  - **Final Optics Damage Inspection System (FODI)**
- **Diagnostics systems include:**
  - **VISAR**
  - **Backscatter (FABS & NBI)**
  - **SXI**
  - **Gated Imagers**

The high fluence of 14MeV neutrons during a NIF yield shot degrades image quality (increased dark current) and can cause communication upsets in CCD/CMOS imagers. In this presentation we develop a new method to evaluate camera system exposed to neutrons.

NIF radiation increases dark current in cameras

- **Monitoring the performance of the camera is important to tracking its health and planning.**
  - **Background (dark field) images are captured before and after every high yield shot.**

A histogram of a 12 bit CCD sensor exposed to a cumulative fluence of greater than 1×10^{10} 14MeV neutrons/cm^2 shows the positive growth in dark noise.



A sensor exposed to 14 MeV neutrons exhibits short and long term damage that is manifested by "stars" (pixels with increased dark current).

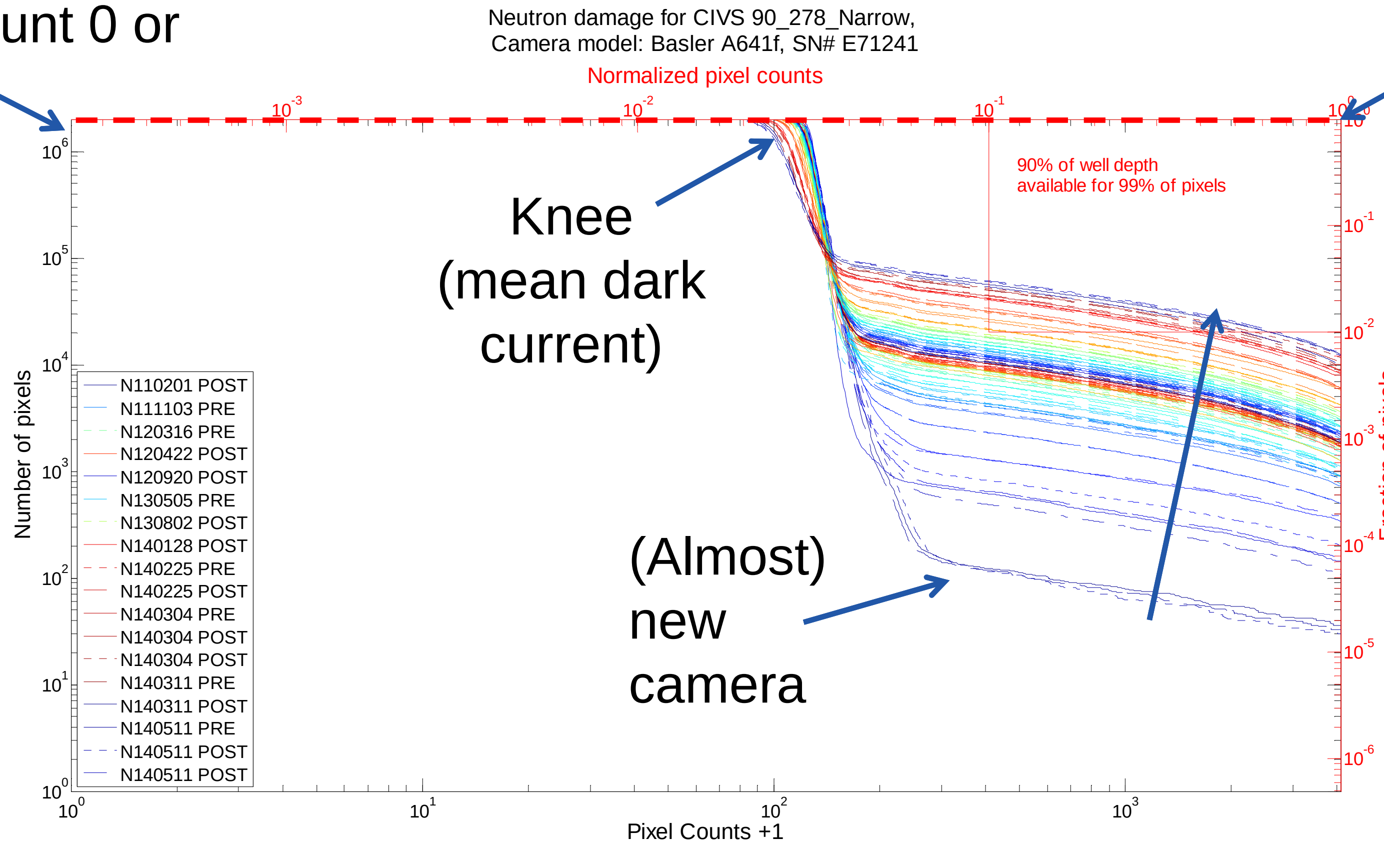
NIF

Normalized reverse sum histogram plot with same data

- **A normalized reverse sum histogram plot in log-log space shows changes well to small numbers of pixels.**
  - **This is the “inverse cumulative probability function” for the histogram of pixel ADC dark noise counts.**

100% of pixels have count 0 or higher

100% of pixels are fully saturated

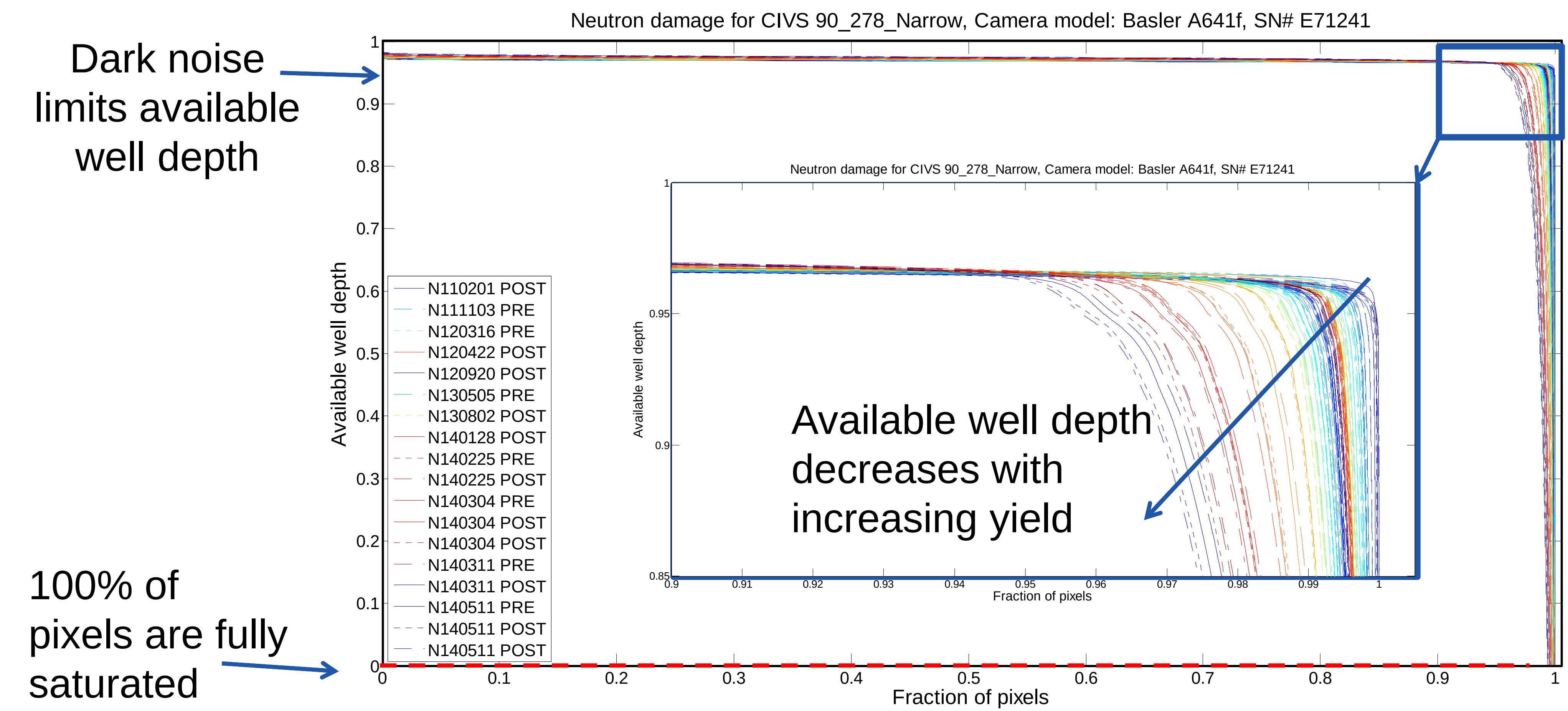


Dark current increases with increasing yield

Can we predict how these curves are going to move as the cumulative yield increases?

Available well depth decreases with increasing yield

- The histograms of pixel values in the dark field images can be plotted as curves of available well depth vs. fraction of pixels to provide information as to the health of the sensor through time.
- Every pixel has dark noise, so the available well depth can never be 100% (i.e. With a 12-bit camera and 100 counts of dark noise: $\frac{2^{12}-100}{2^{12}} = \frac{3996}{4096} = 98\%$)



How do we predict noise at a future date?

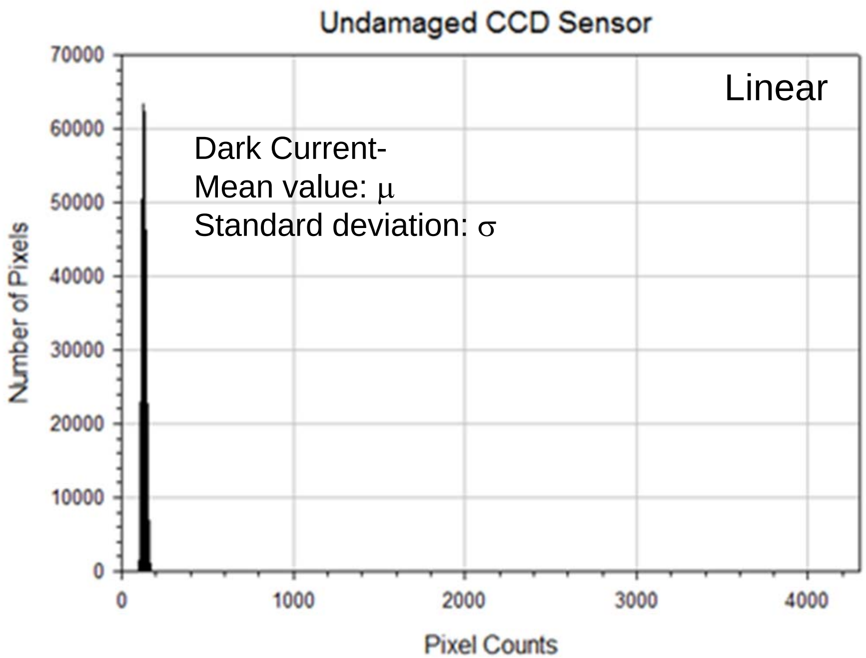
- Steps to predict the noise after additional neutron exposure:
  - Find a function that fits the observed data.
  - Determine how the fit coefficients depend on yield for the images captured so far.

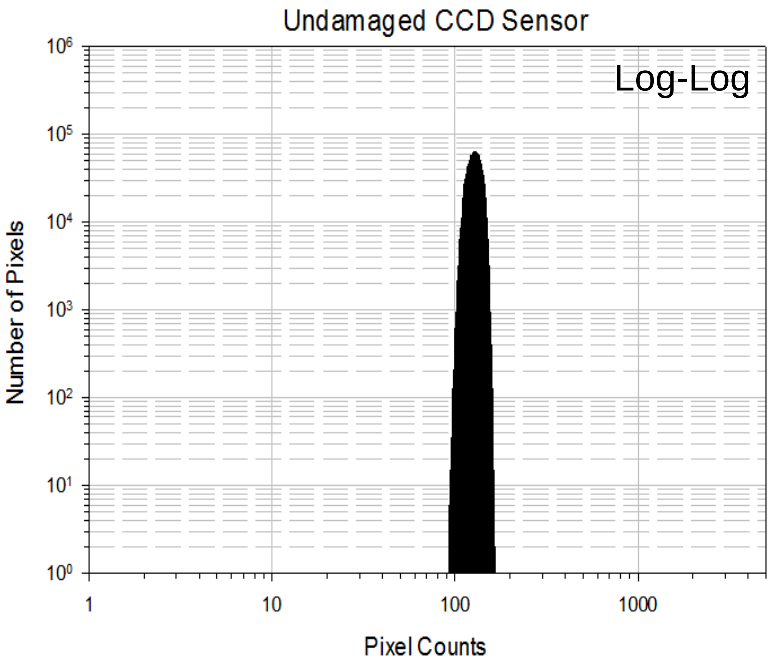
- You will see in the slides to come:
  - For a new camera, the pixel dark current follows one distribution function.
  - During a yield shot, some fraction of pixels are affected by neutrons, and will subsequently follow a different distribution.
  - The total distribution of pixels is a weighted distribution of the two functions:

$$f_{Total} = af_{undamaged} + (1-a)f_{damaged}$$

  - This weighting factor a is linearly dependent on yield.

Histogram of undamaged sensor





$$f_{Gauss}(x;\mu,\sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- **A histogram representation of an undamaged 12 bit CCD sensor dark field image where the horizontal axis represents the pixel intensity values in counts. The same data is displayed in each graph; however the plot on the right is shown in log-log space.**

For an undamaged sensor the dark current can be represented by a Gaussian function. The mean value of the dark current is μ, with standard deviation σ.

Gaussian function and the normalized reverse sum histogram.

The reverse sum histogram for a Gaussian distribution with no radiation damage is:

$$RSH_{Gauss}(x;\mu,\sigma) = 1 - \Phi(x;\mu,\sigma)$$

where Φ(x;μ,σ) is the cumulative probability distribution function for a Gaussian equation

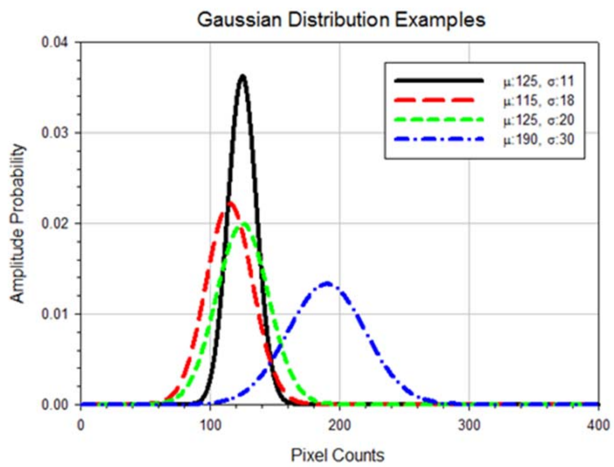
$$\Phi(x;\mu,\sigma) = \int_{-\infty}^{x} f_{Gauss}(x';\mu,\sigma)\,dx' = \frac{1}{2}\left[1 + \operatorname{erf}\left(\frac{x-\mu}{\sqrt{2\sigma^2}}\right)\right]$$

The error function above is given by the following equation

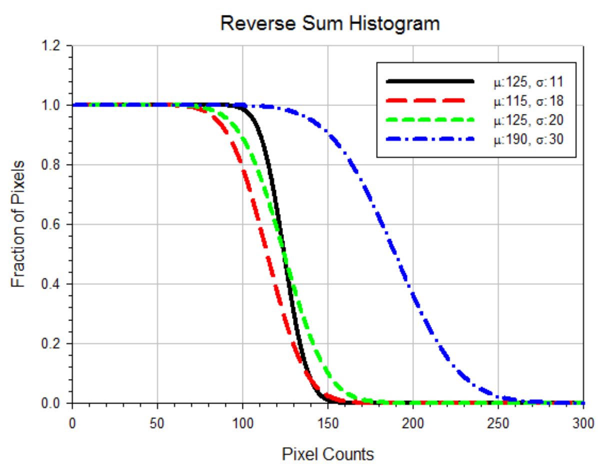
$$\operatorname{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-t^2}dt$$

Gaussian function represents undamaged pixel dark current in counts. A reverse sum histogram for this function can be described as the Error function.

Example Gaussian probability distributions for undamaged pixels



A



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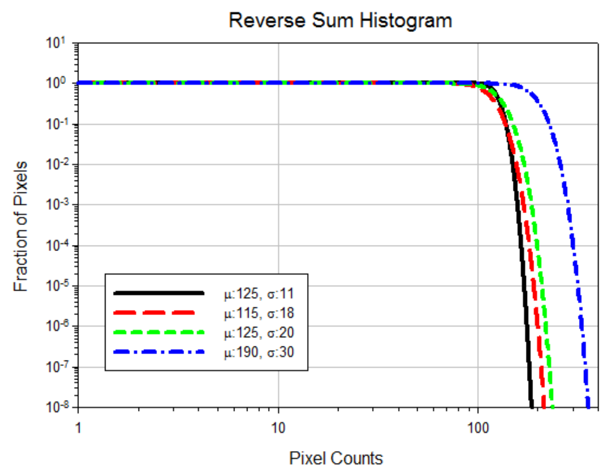


C

A. Gaussian probability distribution functions which represent the dark current in undamaged CCD pixels
B. Normalized reverse sum histograms on linear plot
C. Normalized reverse sum histograms on a log-log plot

Example Gaussian probability and the associated normalized reverse sum histograms for undamaged pixels representing the sensor dark current. The mean and standard deviation are chosen to describe a typical undamaged sensor.

Equations describing a damage curve after being exposed to neutrons

- **When a sensor is exposed to neutrons, more pixels have more dark noise**
  - **There are exponentially fewer pixels of very high ADC counts than pixels lower counts (true for the values above the mean dark noise)**
- **The probability distribution function for just the damaged pixels is a well-described by an exponential function convolved with a Gaussian**

Ex-Gauss function is described as:

$$f_{ExGauss}(x;\mu,\sigma,\tau)=\frac{1}{2\tau}\left[e^{\left(-\frac{x}{\tau}+\frac{\mu}{\tau}+\frac{\sigma^2}{2\tau^2}\right)}\right]\left[1+\operatorname{erf}\left(\frac{-\sigma^2+x\tau-\mu\tau}{\sqrt{2}\sigma\tau}\right)\right]$$

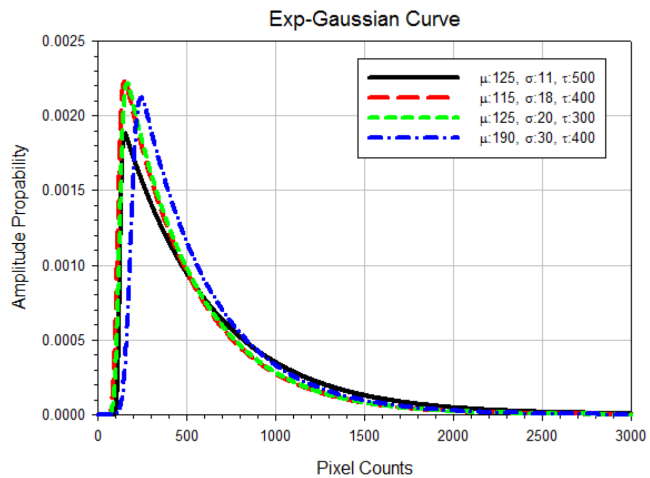
x- represent the dark current amplitude
μ- mean dark current
σ- standard deviation of the Gaussian
τ – is the exponential decay coefficient

The reverse sum histogram for the Ex-Gauss is:

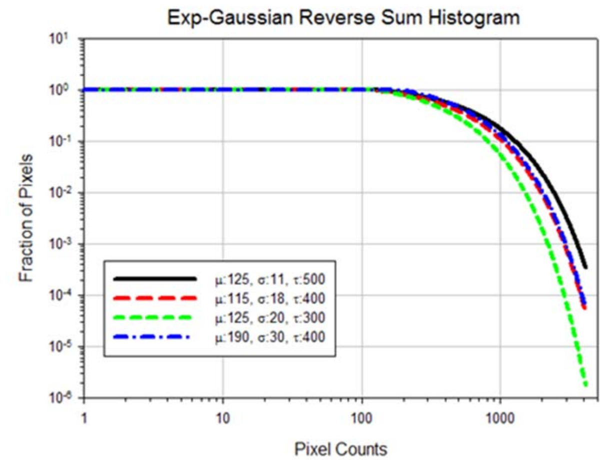
$$RSH_{Exp-Gauss}(x;\mu,\sigma,\tau)=1-\Phi(u;0,v)+e^{-u+v^2/2+\ln\left(\Phi(u;v^2,v)\right)}$$

Where $u = (x-\mu)/\tau$, $v = \sigma/\tau$ and $\Phi(x;\mu,\sigma)$ is the cumulative probability for a Gaussian discussed earlier

Example of Ex-Gauss probability distributions for damaged pixels



A



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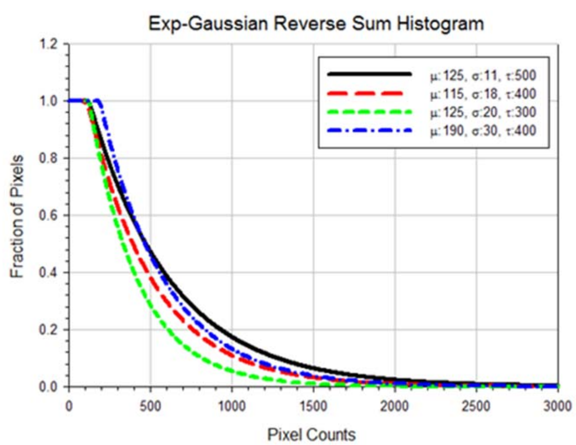


B

A. An exponentially modified Gaussian probability distribution function representing sensors with damaged pixels.

B. Normalized reverse sum histograms for this function displayed linearly.

C. Normalized reverse sum histograms for this function displayed in log-log.

- The sample values chosen for the mean, standard deviation and exponential decay are typical of those found describing the damaged pixels for our CCDs.

Parameters describing sensor pixel damage based on reverse sum histogram

- **The total probability distribution function is the sum of the Gaussian and exponentially-modified Gaussian functions for the observed statistics. Each function separately describes the undamaged and damaged pixels.**

- **A weighting factor (0≤ a ≤1) changes that fraction of pixels that follow each distribution, so the net probability distribution function can be described by the following equation:**

$$f_{Total}(x;\mu,\sigma,\tau,a) = af_{Gauss}(x;\mu,\sigma) + (1-a)f_{ExGauss}(x;\mu,\sigma,\tau)$$

- **The four parameters (μ,σ,τ,a) represent the pixel parameters of the graph in relation to well depth capacity and pixel damage population in relation to neutron yield.**

The reverse sum histogram for this function is then:

$$RSH_{Total}(x;\mu,\sigma,\tau,a) = aRSH_{Gauss}(x;\mu,\sigma) + (1-a)RSH_{Exp-Gauss}(x;\mu,\sigma,\tau)$$

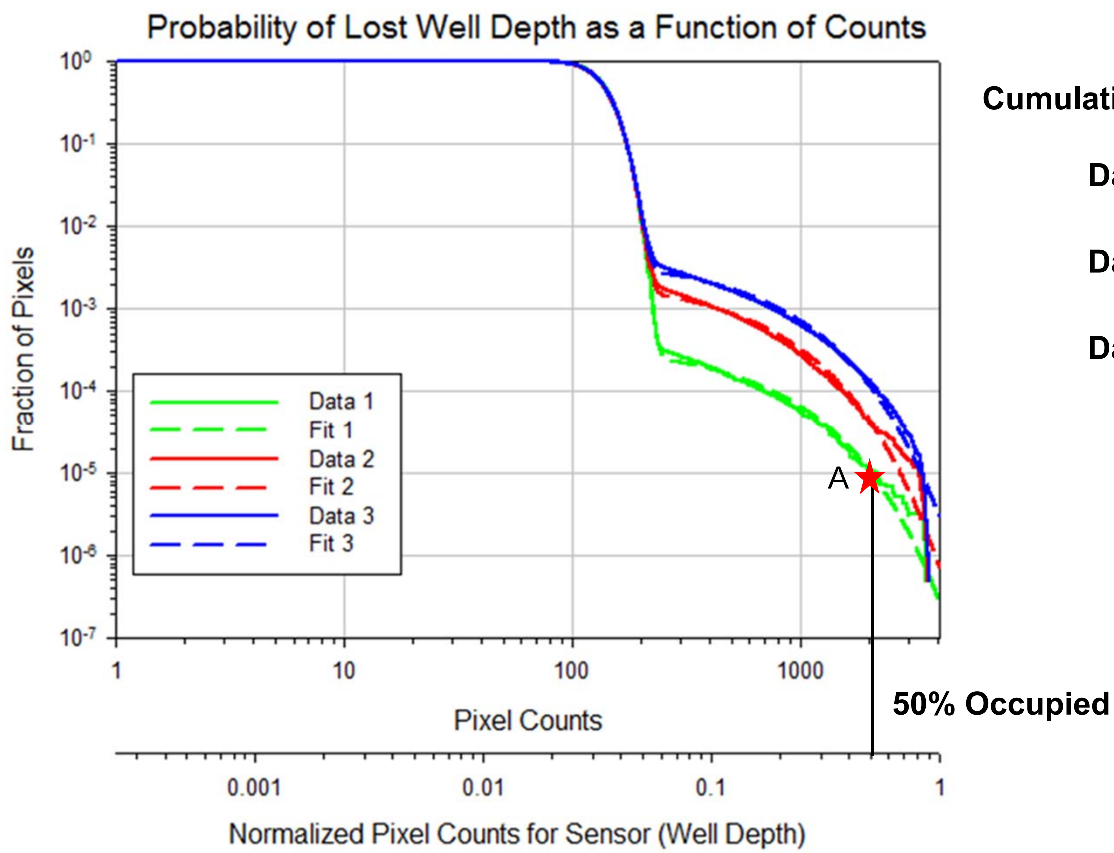
Plot describing probability of lost well depth as a function of counts for different cumulative yields

Fit values are: (μ,σ,τ,a) =

1- (138.4,28.1,567.9,0.99971)

2- (137.8,28.2,506.4,0.99822)

3- (138.1,28.2,565.7,0.99674)



Cumulative Yields

Data 1 - Yield: 1.1E15

Data 2 - Yield: 4.3E15

Data 3 - Yield: 7.6E15

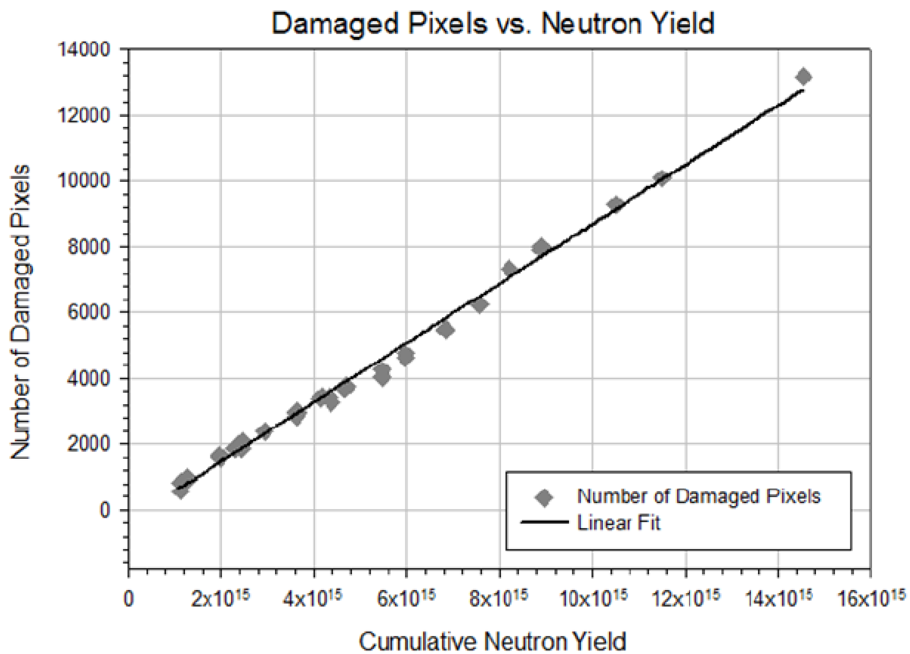
Reverse sum histogram data with best fit curves for three images taken after increasing yields. Point "A" represents at least 50% of the well depth is occupied for 0.001% of the pixels in the array.

Plot to predict the sensor pixel damage as a function of neutron yield

- **With the best fit parameters (μ, σ, τ, a) known, the fourth parameter "a", which describes the weighting between undamaged and damaged pixels has a linear dependence on yield.**
- **This parameter "a" can be used to describe the number of damaged pixels by the equation:**

$$n_{damaged}(a) = n_{total}(1 - a)$$

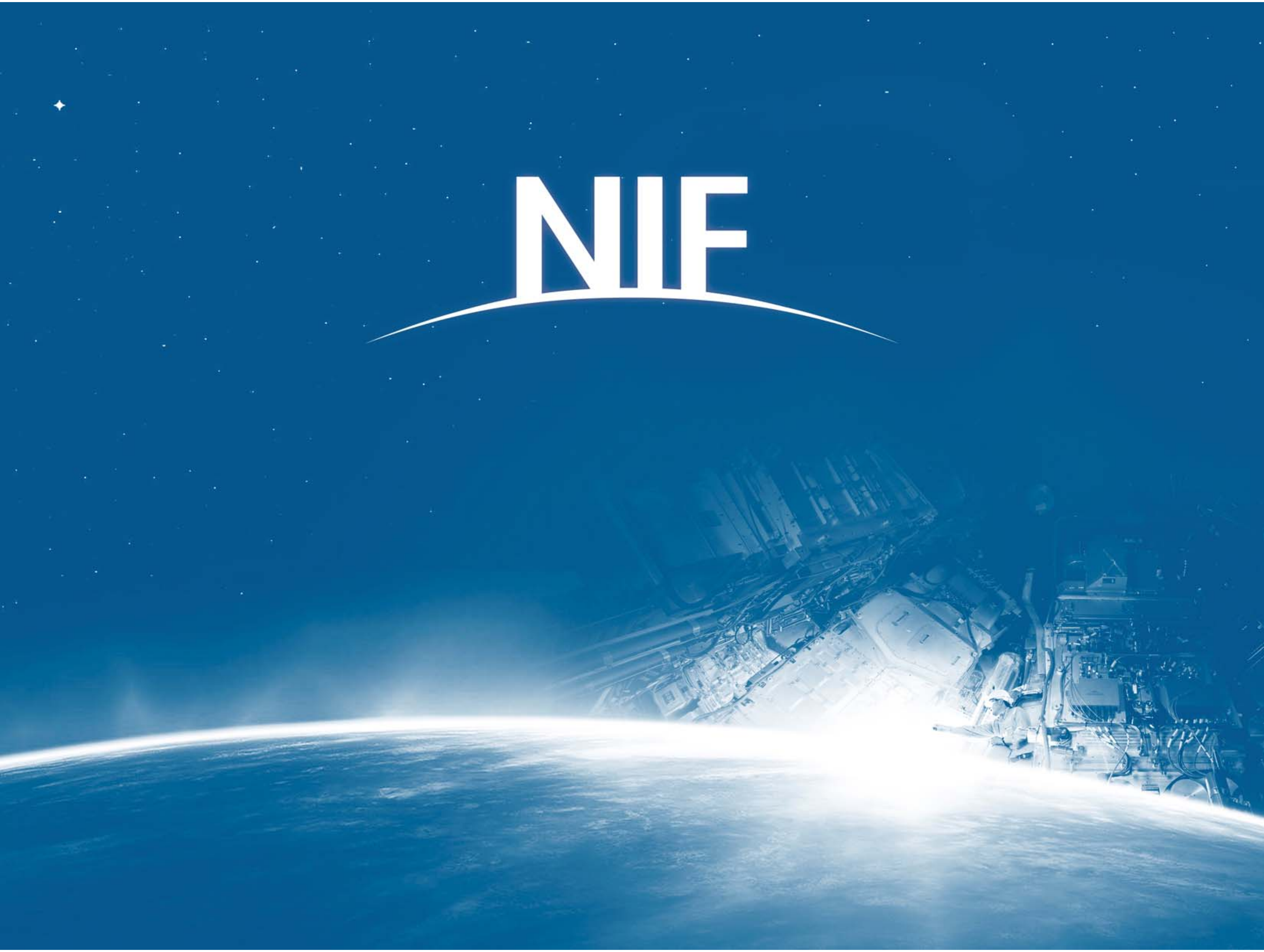
- **A plot can be generated describing the linear representation of damaged pixels vs. shot yield**



The plot of damaged pixels as a function of yield can now be used to predict future camera damage. For this camera, the slope is 90.8 damaged pixels per 1E14, 14 MeV neutron yield.

Summary

- We have described a series of algorithms for a two dimensional representation of graphic data that allow for the succinct visual evaluation of an image sensor performance when exposed to a neutron radiation field.
- Several figures-of-merit can be easily track over time leading to a quantitative relationship between exposure to radiation damage and the performance of the imaging sensor array.
- Also we have implemented a novel technique that allows for the prediction of future image sensor performance based on the response function of existing radiation exposures.
- Information that can be extracted from the plot include but not limited to dark current and well depth values based on pixel population, charge transfer efficiency failures, and radiation damage performance effects over time.


NIF

Test Program

	Radiation		Rate	Notes
Ohio test accelerator	14MeV neutron (nearly mono energetic)	CW	10 Rads/day (very slow)	Test instrumentation, electronics subsystems and components
LLNL gamma test well	Gamma (wrong energy)	CW	1.54kRad/min at source (wet) 1.5kRad/hour in the dry well	Cobolt-60 source
LLNL NIF test well	14MeV neutron	Pulsed	10 Si Rads/shot at 1E16 Yield at TCC	Unshielded in target chamber, 4.5m from TCC
LLNL NIF operation	**14MeV neutron**	**Pulsed**		**Shielded by target chamber, >6m from TCC**