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Development of CCD cameras for soft X-ray imaging at the National Ignition Facility

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Disclaimer

Development of CCD cameras for soft X-ray imaging at the National Ignition Facility

Target Diagnostics Physics and Engineering for Inertial Confinement Fusion II/SPIE Optical Engineering + Applications

August 27, 2013

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Lawrence Livermore National Laboratory

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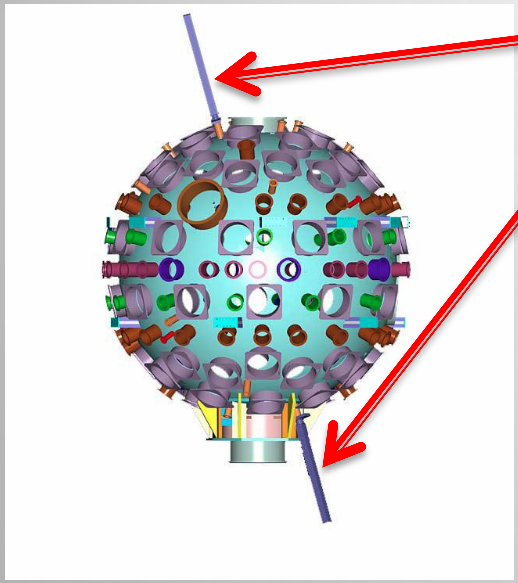
List of Collaborators

- LLNL
  - Alan Teruya, Nathan Palmer, Perry Bell, Marilyn Schneider
- National Security Technologies, Inc. (NSTec)
  - Michael Haugh, Ed Romano, Ken Jacoby, Michael Charest
- Spectral Instruments
  - Gary Sims, Kevin Toerne, Ken Rodenberg
- University of Arizona, Imaging Technology Laboratory
  - Michael Lesser

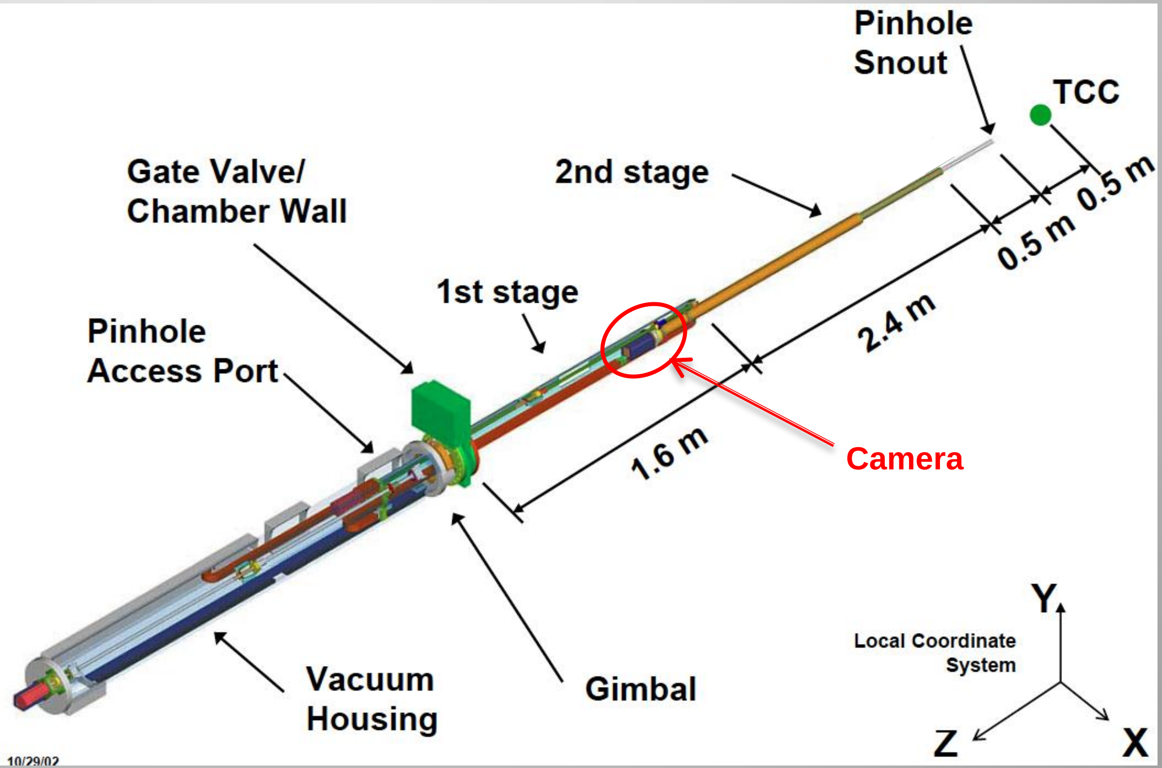
Outline

- Introduction to the Static X-Ray Imager (SXI)
- Requirements for a replacement charge-coupled device (CCD) camera for SXI
- Testing of a prototype camera and procurement of replacement CCD cameras
- Performance
  - Replacement camera with a front-illuminated CCD sensor
  - Replacement camera with a back-illuminated CCD sensor
- Future use in SXI

SXI provides X-ray pinhole images of the top and bottom of targets



- SXI-Upper located at port 018-123
- SXI-Lower located at port 161-326



- X-Ray pinhole images acquired using a CCD camera
- Image plate substituted on higher yield shots

Dynamic range is extended by varied filtering of multiple pinholes

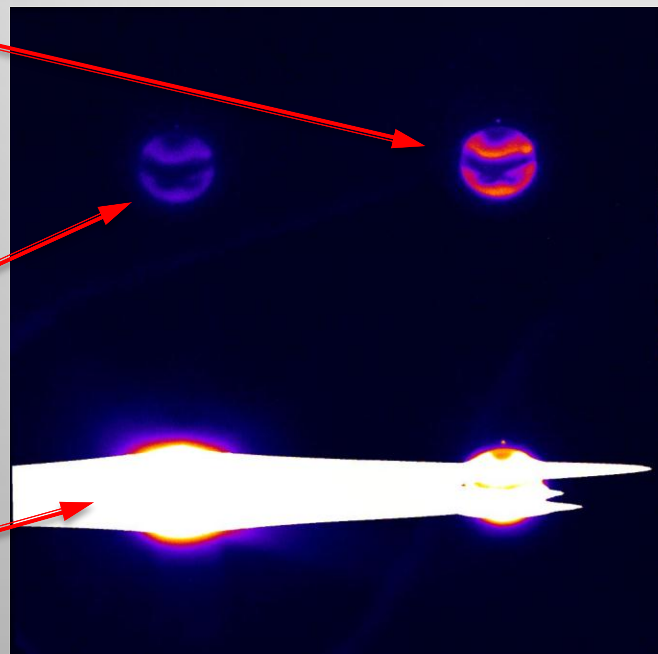
- SXI measures the clear aperture of the laser entrance hole (LEH) of the hohlraum

At least one pinhole/filter combination results in good contrast

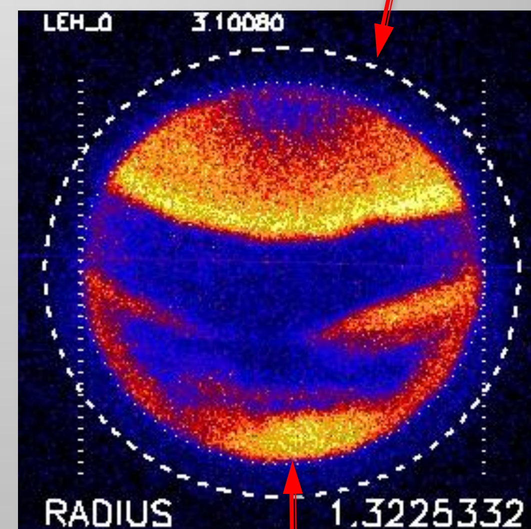
Higher filtering results in dim images

Less filtering results in bloomed images

SXI Camera Image with 4 Pinhole Images



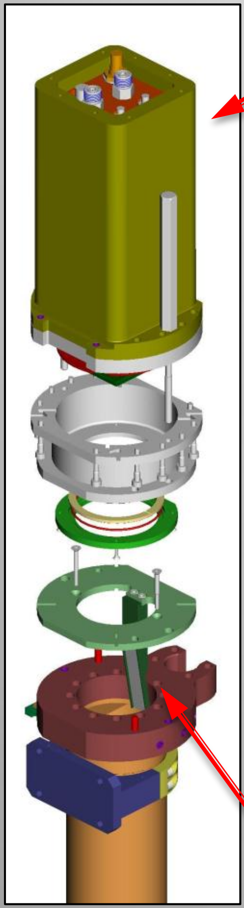
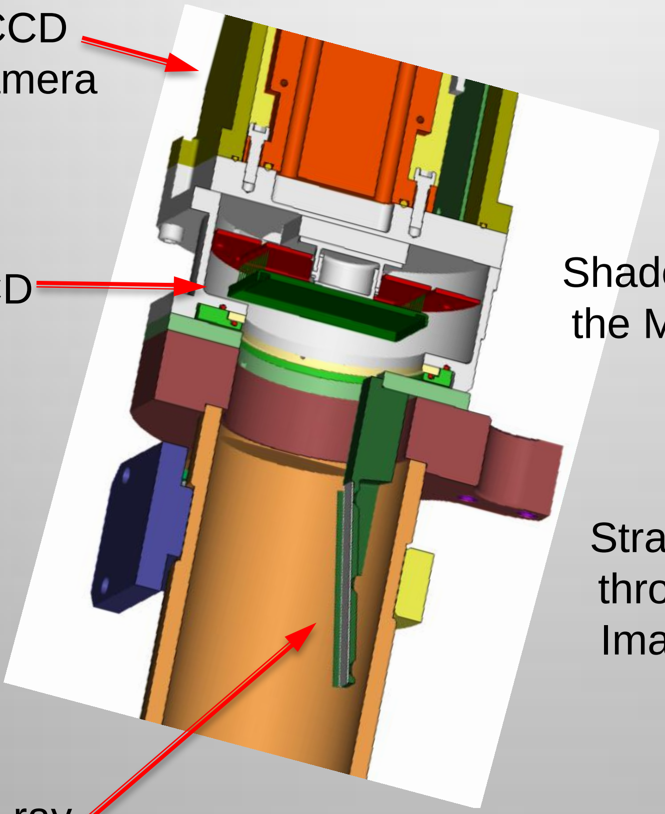
Initial LEH



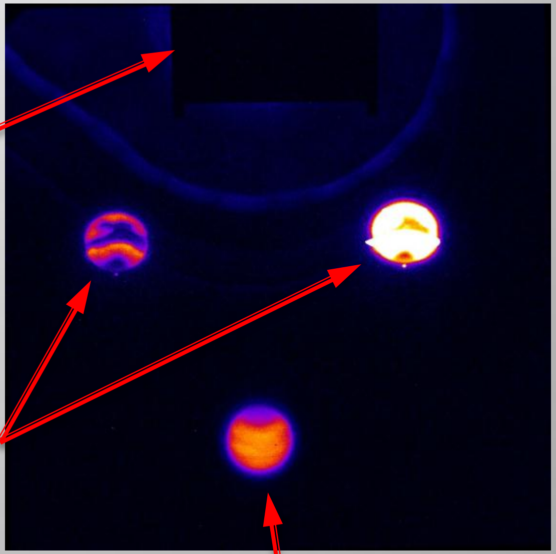
Measured clear aperture after generation of plasma from target walls

SXI-Upper includes a soft X-ray mirror channel

- 10° angle-of-incidence tungsten/boron carbide multilayer mirror is designed to reflect a 100 eV band around 870 eV

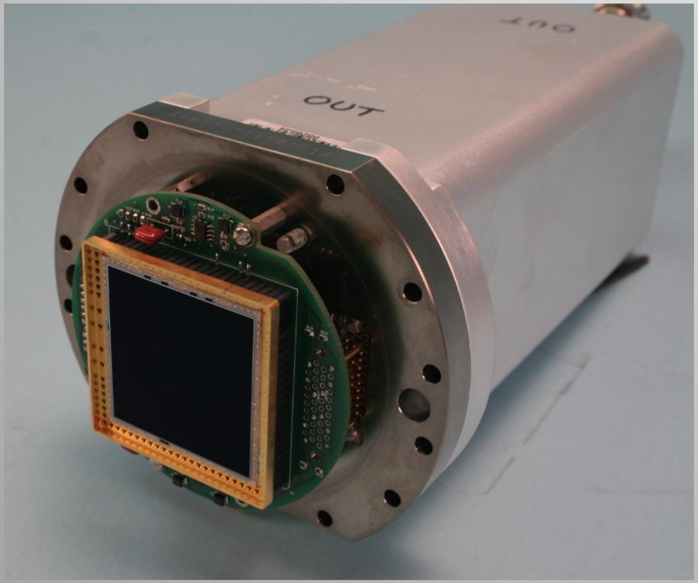



SXI-Upper Camera Image with 3 Pinhole Images



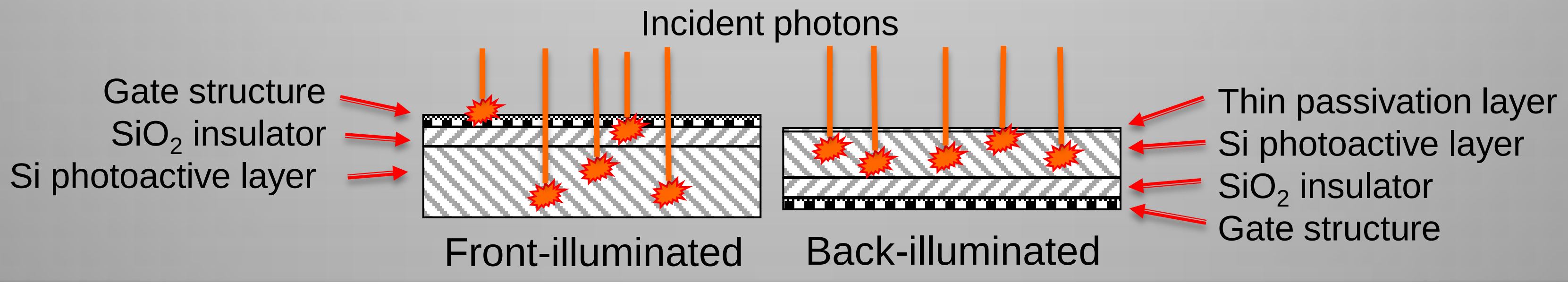
The current SXI camera records X-rays in the range of 700 to 8,000 eV

- Modified Spectral Instruments SI-800 in an LLNL-designed vacuum-immersible airbox housing
- CCD: Scientific Imaging Technologies, Inc. (SITe) 2,048 x 2,048, 49 mm x 49mm, 24 um pixel, back illuminated



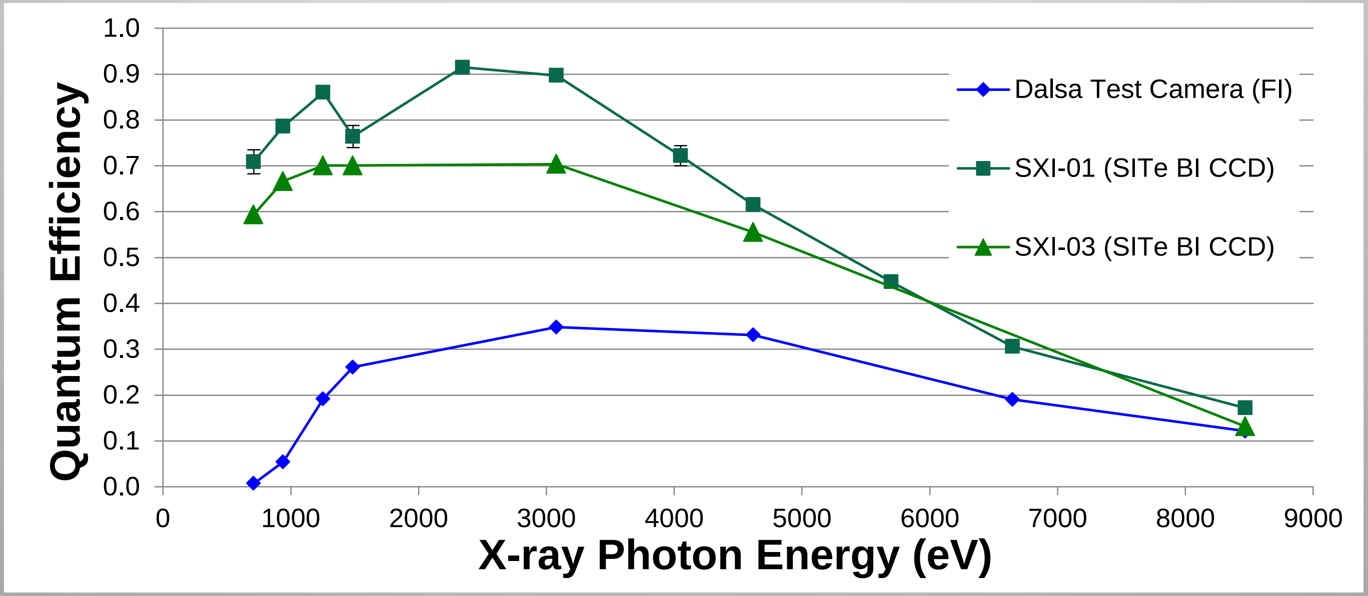
SXI had a need for new cameras

- Only three existing cameras – One spare for two diagnostics
- The CCD sensor is out of production and LLNL has no spares
  - The CCD manufacturer (SITe) is long out of business
- The new camera had to be a drop-in replacement – modification to the positioner hardware and utilities is cost prohibitive
- For SXI-Lower:
  - X-rays in 3-5 keV range
  - Front-illuminated CCDs have acceptable sensitivity
- For SXI-Upper:
  - X-rays in 800-900 eV range
  - Back-illuminated CCDs required, but none available off the shelf



A candidate CCD was identified

- Teledyne Dalsa IA-DJ-02084 CCD
  - 2084 x 2084 pixel, 50.2 mm x 50.2 mm, 24 x 24 um pixels, front illuminated
  - Full well capacity 170 ke- (typical), RMS noise 13 e-
- Spectral Instruments built a test camera using the 1044 x 1044 pixel version of the sensor for quantum efficiency (QE) evaluation
- Due to the front illumination structure, the QE was lower than the existing cameras, but was deemed usable in the 2 to 8 keV range if filtering was adjusted



New cameras were ordered for use in the SXIs

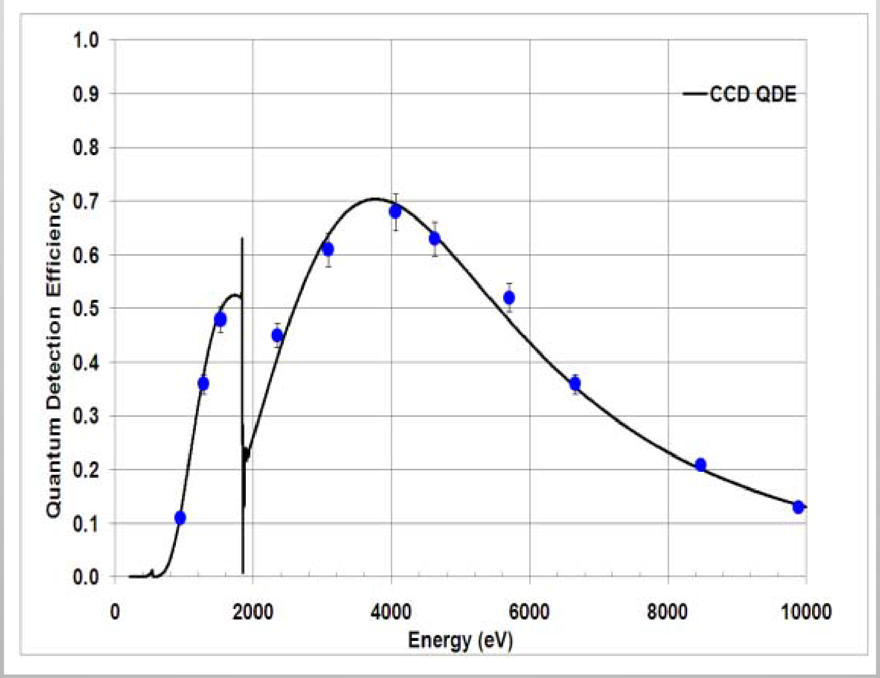
- Physical drop-in replacements for existing cameras
- Use gigabit optical fiber link, but same NIF control software
- 16-bit image depth
- Three cameras ordered for SXI-Lower (2 to 8 keV)
  - Off-the-shelf front-illuminated Dalsa CCD
- Two cameras ordered for SXI-Upper (700 to 900 eV)
  - SI purchased nine CCDs on the die from Teledyne Dalsa and contracted with the Imaging Technology Laboratory at the University of Arizona, Tucson, to develop a back-thinning process to convert them to back-illuminated
  - The process yielded three usable sensors

Front-illuminated Cameras

- Spectral Instruments built three cameras (SXI-05, -07, -08) with stock Teledyne Dalsa IA-DJ-02084 Class I or II grade CCDs
- Standard calibration measurements have been done on SXI-05 by NSTec
  - Quantum Efficiency
  - Camera Efficiency
  - Flat Field
  - Linearity and Dynamic Range

Front-illuminated Camera – QE

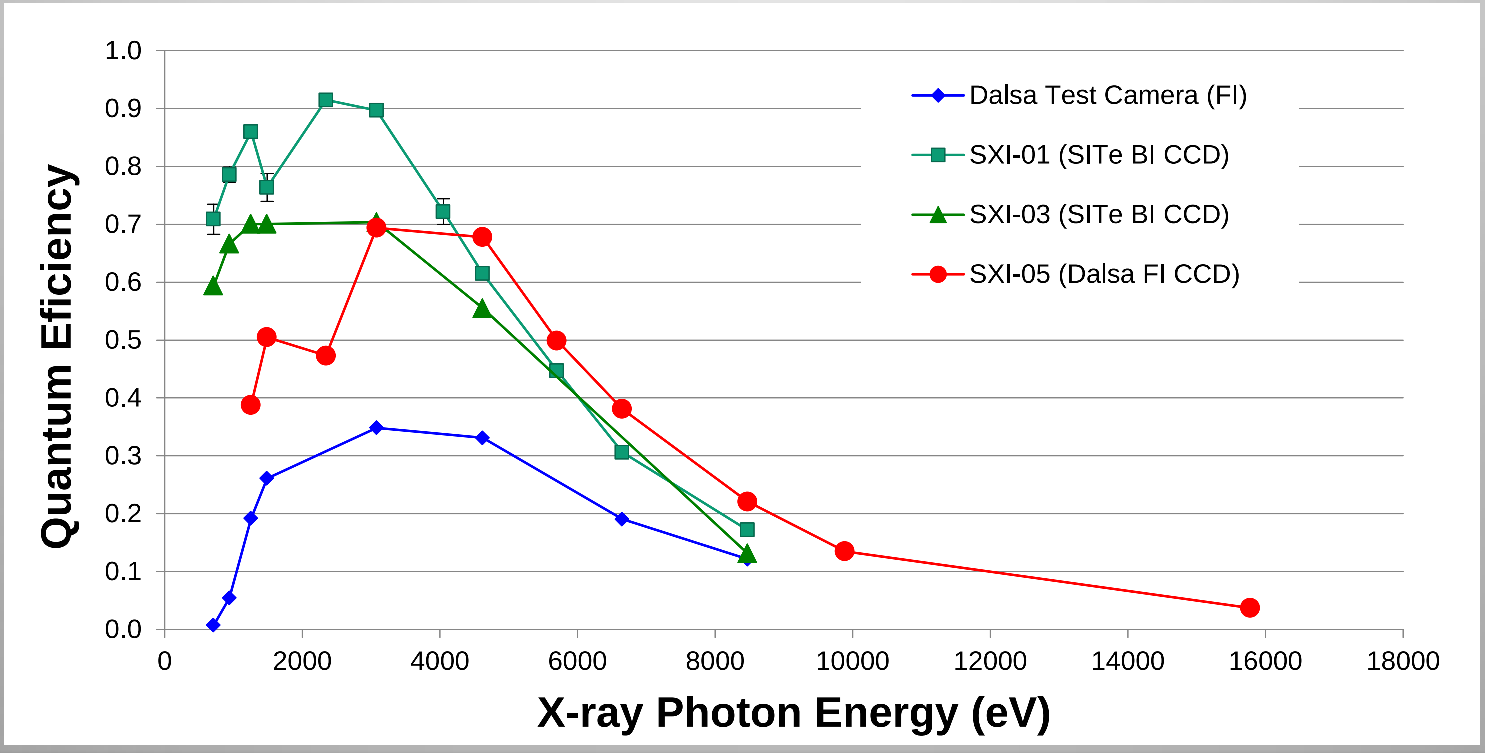
- QE measurements fit well to a model for CCD image sensors developed by Dunn and Steel[1] using estimates of the thickness of the active detection region (19 µm) and the electrode gate structure (3 µm)



[1] J. Dunn, and A. B. Steel, "Absolute determination of charge-coupled device quantum detection efficiency using Si K-edge x-ray absorption fine structure", Rev. Sci. Instrum. 83, 10E120 (2012)

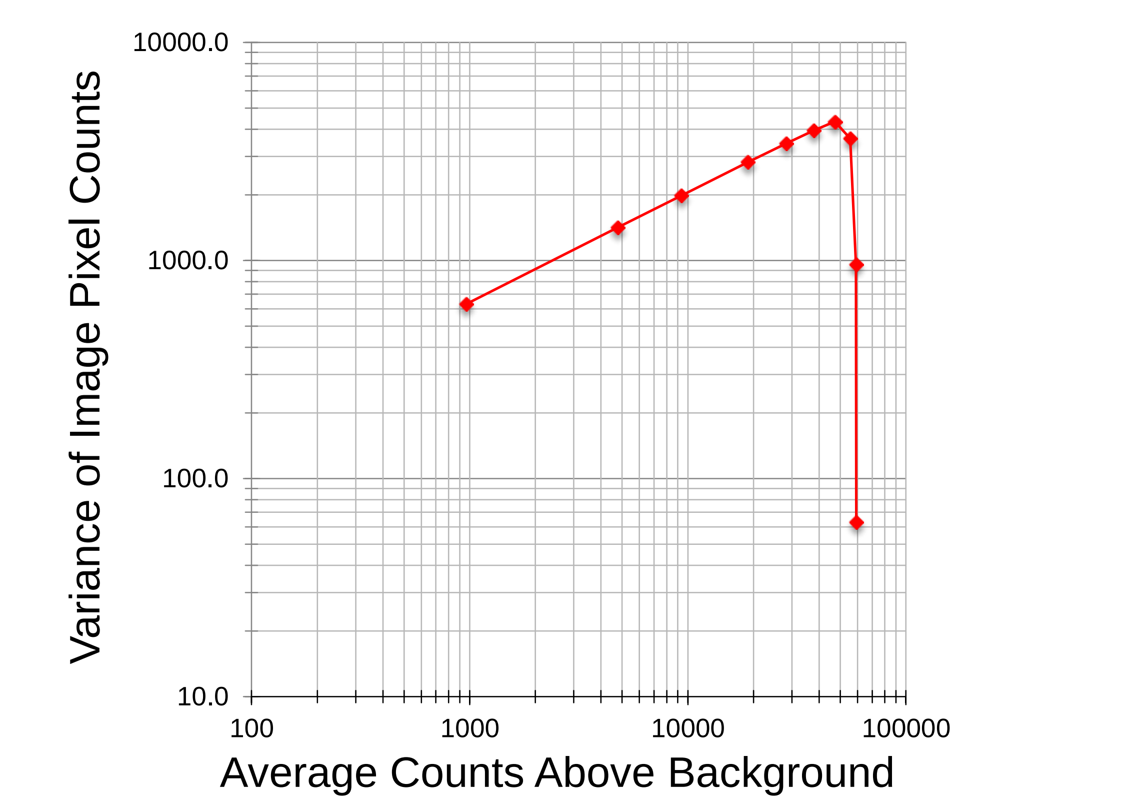
Front-illuminated Camera – QE Comparison

- QE of the camera with a front-illuminated CCD is closer to that of the existing cameras than was expected based upon the test camera
  - Higher QE above 5 keV because of thicker epitaxial Si
  - Lower QE below 2 keV due to electrode gate structure



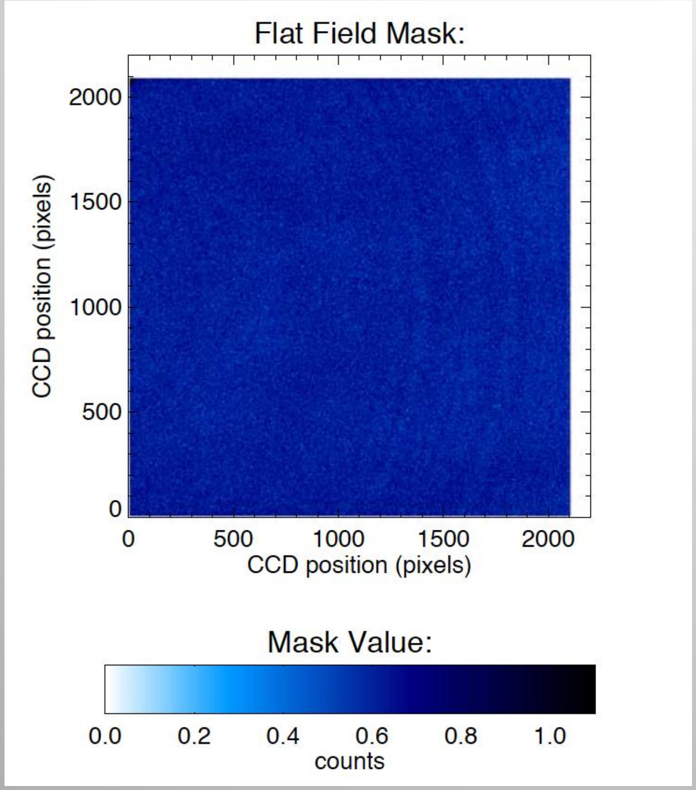
Front-illuminated Camera – Dynamic Range

- Deviation from linear at ~ 45,000 counts
- Bias image noise ~ 10 counts
- Dynamic range ~ 4500:1

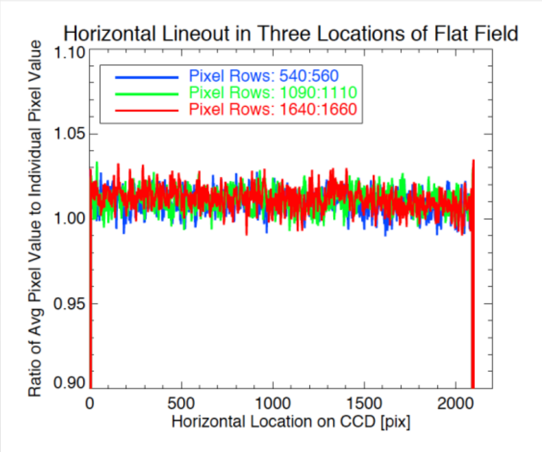


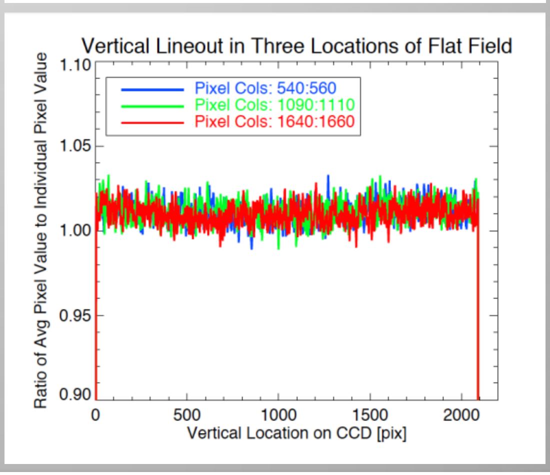
Front-illuminated Camera – Flat Field (8470 eV)

- Flat field masks show variation across the CCD of only a few percent



(Uniform illumination from 8470 eV X-ray source)



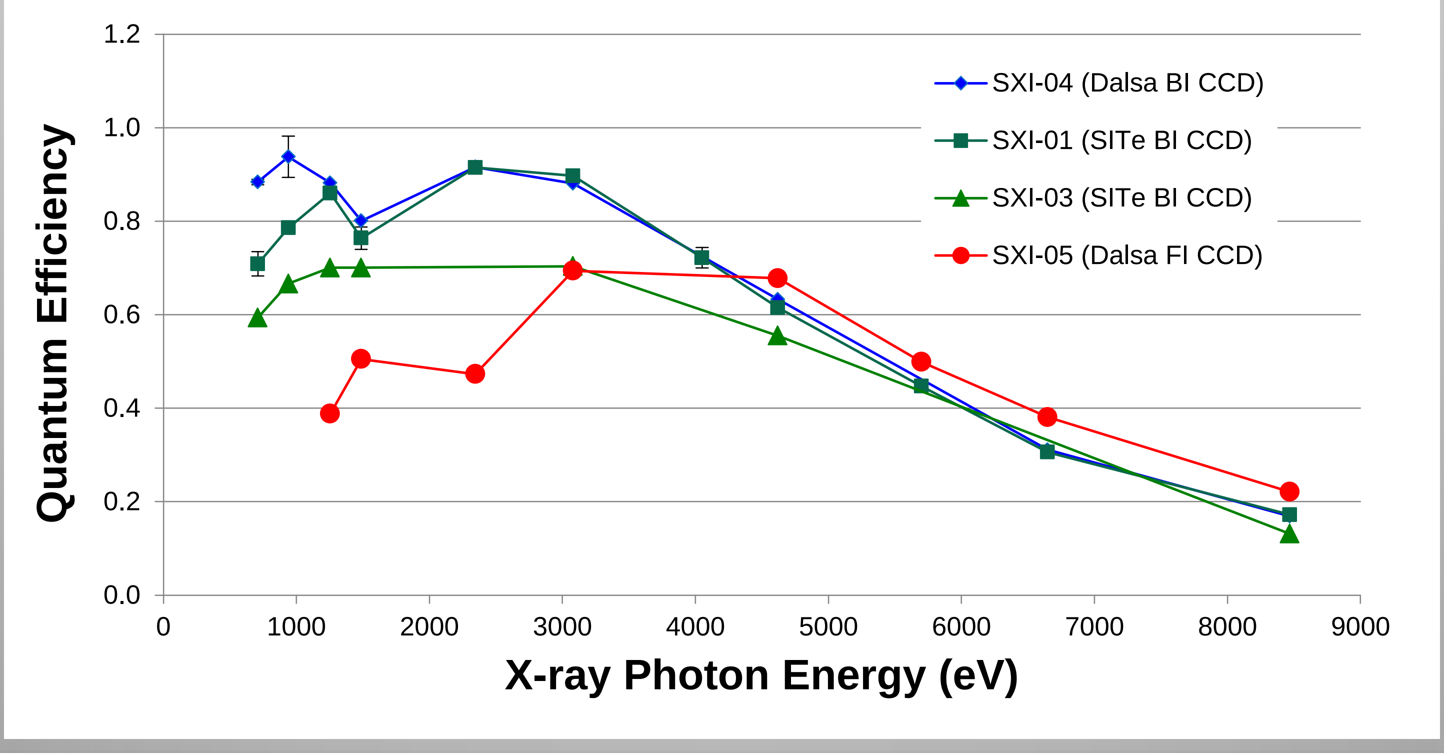


Back-illuminated Cameras

- Two cameras were built (SXI-04, -06) using two of the three usable back-thinned CCDs
- These cameras exhibit higher read noise and more bad pixels than the front-illuminated cameras
  - Longer traces on sensor circuit board to account for reversal of bond pads when sensor was flipped => More sensitive to power supply noise and other EMI
  - Some pixels damaged during the back-thinning process
- QE and flat field measurements have been done – still need to measure dynamic range

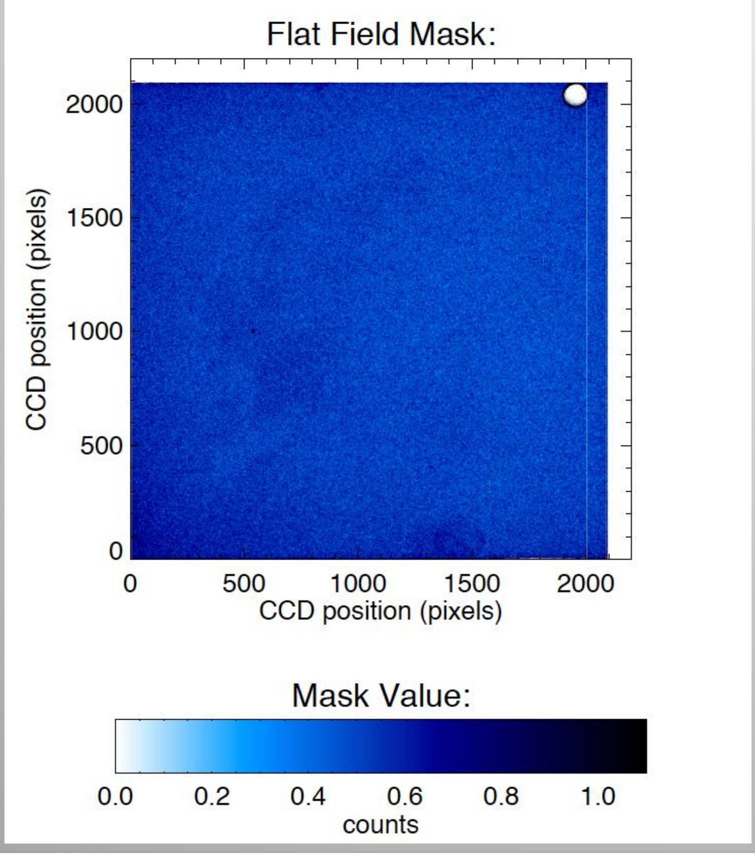
Back-illuminated Camera – QE

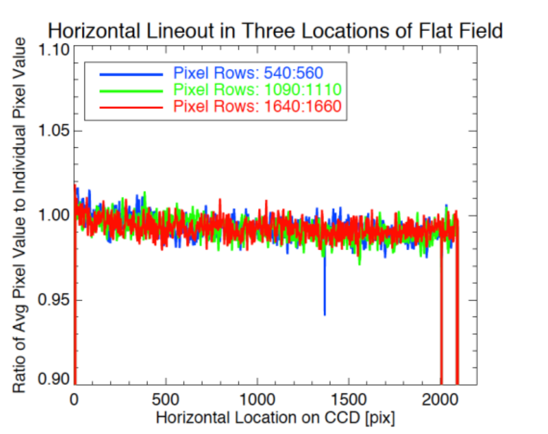
- As expected the QE at lower X-ray energies (below 3 keV) is higher than the front-illuminated CCD where the gate structure blocks photons
- Above 4 keV the front-illuminated CCD has higher QE due to it having a thicker layer of Si to capture photons
- Performance of the back-illuminated Dalsa CCD camera is similar to the existing SITe CCD cameras

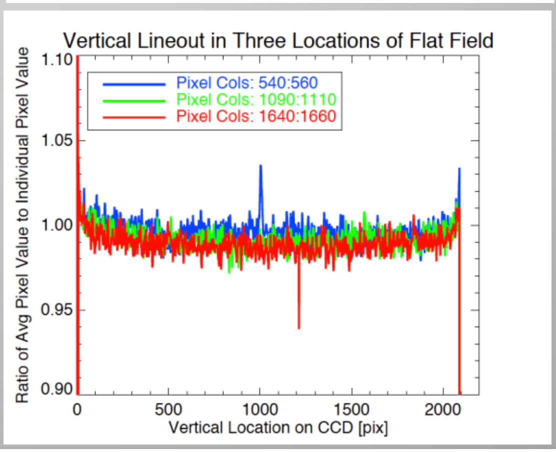


Back-illuminated Camera – Flat Field (1254 eV)

- At lower energy (1254 eV) any nonuniformity in the passivation layer or any contamination on the surface causes variation in the flat field
- Circular defect in the corner is a less sensitive spot damaged during the etching process. Otherwise, variation is only a few percent.

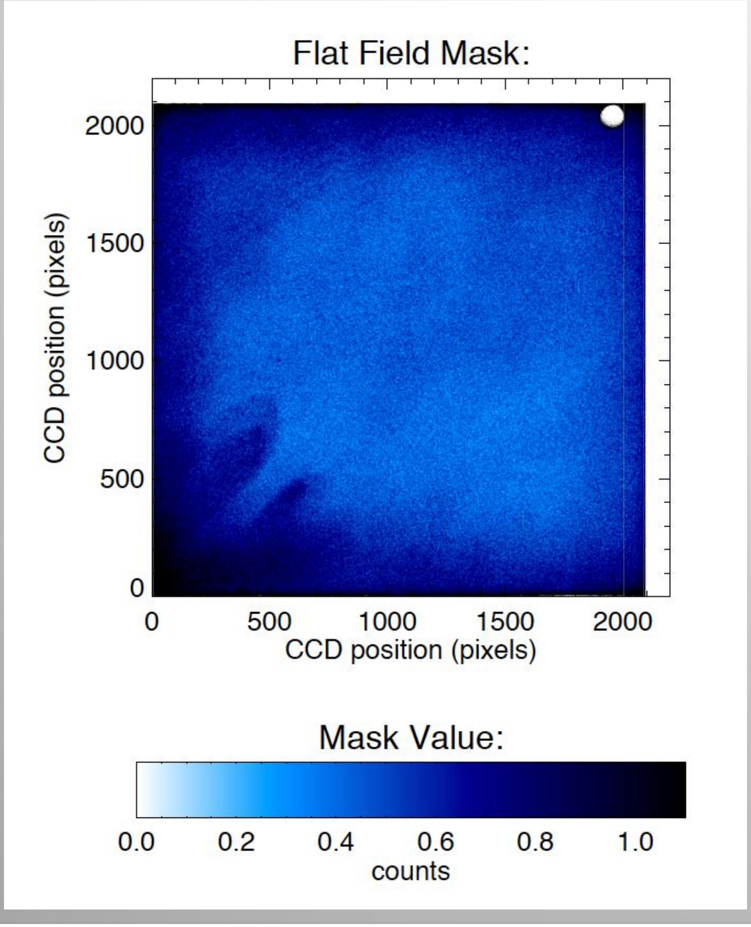


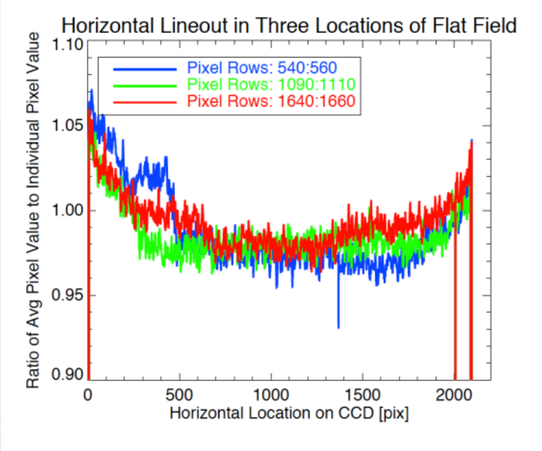


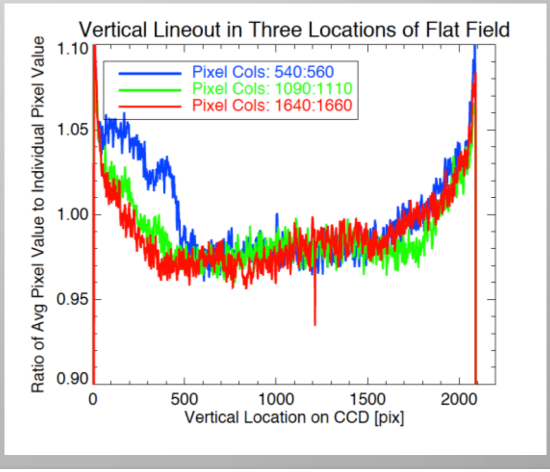


Back-illuminated Camera – Flat Field (8470 eV)

- At higher energy (8470 eV) the flat field varies due to nonuniformity in the thinning of the Si. Sensor is thicker in the center, thinner around the edges.
- Variation across the sensor as much as 10%







The cameras are suitable for use in SXI and are being prepared for fielding

- The replacement cameras use existing cables and utilities
  - 28 VDC Power
  - Multimode 62.5/125µm communication fibers
  - Cooling water
  - Trigger via coax. cable
- Control computers with upgraded gigabit optical fiber link boards have been installed at NIF
- Cameras are undergoing testing to pass NIF cleanliness standards and require final calibration