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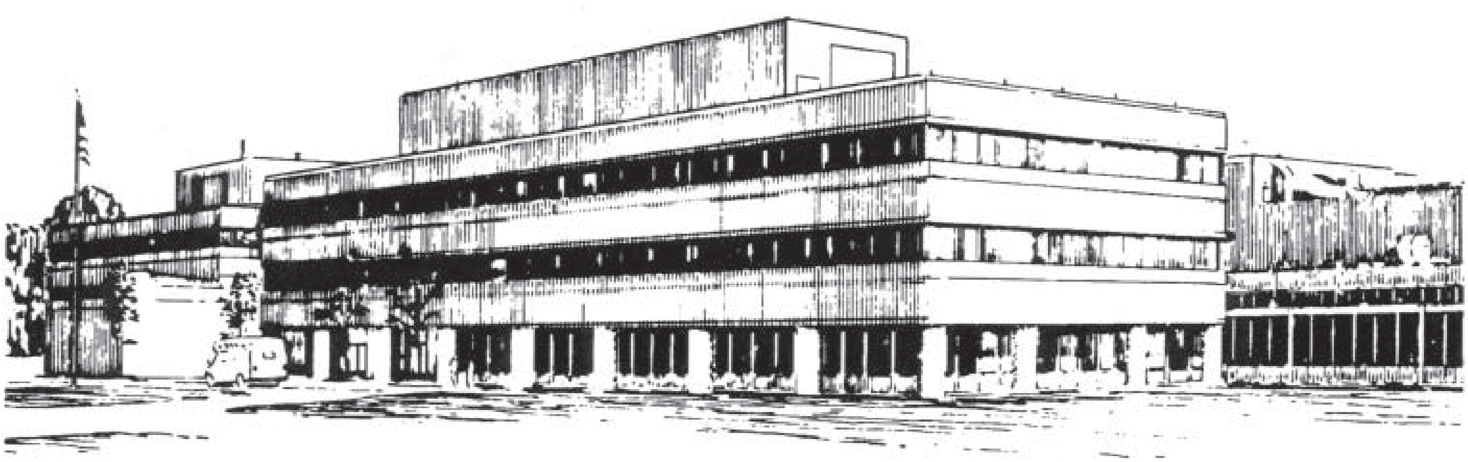

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ABSTRACT

Fast, two-dimensional, soft x-ray imaging is a powerful technique for the study of MHD instabilities in tokamak plasmas. We have constructed an ultra-fast frame rate soft x-ray camera for the National Spherical Torus Experiment. It is based on a recently developed 64 x 64 pixel CCD camera capable of capturing 300 frames at up to 500,000 frames per second. A pinhole aperture images the plasma soft x-ray emission (0.2-10 keV) onto a P47 scintillator deposited on a fiber-optic faceplate; the scintillator visible light output is detected and amplified by a demagnifying image intensifier and lens-coupled to the CCD chip. A selection of beryllium foils provides discrimination of low-energy emission. The system is installed on NSTX with a wide-angle tangential view of the plasma. Initial plasma data and an assessment of the system performance are presented.

I. INTRODUCTION

Soft x-ray (SXR) imaging is a powerful technique for the study of magnetohydrodynamic (MHD) instabilities in magnetically confined toroidal plasmas. It is usually performed with one-dimensional arrays of discrete silicon diodes viewing the plasma in a poloidal cross section. Such arrays yield two-dimensional information on the MHD mode structure when the plasma is rotating faster than the frequency of the instabilities of interest. Another approach, which has been used on the TEXTOR tokamak and the LHD stellarator, is to do two-dimensional imaging in the SXR region using a fast camera with a wide-angle toroidal view[1-3]. This approach has the potential advantage that very fast events, (such as sawtooth crashes), stationary MHD modes, and modes with high poloidal mode number can be observed[1]. However, the challenge is to construct a system with sufficient sensitivity that useful images can be obtained at frame rates of 100 kHz or more.

We have constructed an ultra-fast frame rate soft x-ray pinhole camera for the National Spherical Torus Experiment (NSTX). The system was completed and began operation in February 2004. This paper describes the system, efficiency and noise estimates, and presents some initial data.

II. EXPERIMENTAL ARRANGEMENT

A schematic of the fast tangential SXR pinhole camera is shown in figure 1. (Details are given by Feder, *et al.*[4]) SXR photons pass through the pinhole and are converted to visible photons by a fast (80 ns decay time) P47 scintillator deposited on a fiber optic faceplate. A P47 layer thickness of 3.2 mg/cm^2 with a 50 nm aluminum overcoat is used to optimize efficiency for x-ray energies in the 1-6 keV range. Approximately 55% of the soft x-ray photons are absorbed at 6 keV, with more absorption at lower energies. A selection of five pinholes with diameters in the 1-5 mm range and beryllium foils with thicknesses in the 2.5-127 μm range are mounted on three remotely-controlled linear motion vacuum feedthroughs. Changing the pinhole diameter allows the signal or optical throughput to be optimized. Varying the beryllium foil thickness changes the cutoff energy of the transmitted x-ray photons. Visible photons emitted by the scintillator are transmitted by the fiber-optic-faceplate to an electrostatic image intensifier, which demagnifies the image by 6:1 to match the scintillator diameter (80 mm) to the size of the CCD chip (13.3 mm x 13.3 mm). The image intensifier demagnifies the image more efficiently than is possible with a lens system. A pair of f/0.95 lenses operating at near unity magnification efficiently couples the image from the intensifier output to the CCD chip. Because the diameter of the individual fibers in the fiber optic faceplates is much smaller than the pixel dimensions, any cross talk between fibers has a negligible effect on the image quality. The image intensifier is very sensitive to magnetic fields so it is enclosed in a three-layer magnetic shield[4].

The ultra-fast CCD camera is the model PSI-5 produced by Princeton Scientific Instruments, Inc. It utilizes a unique CCD chip design to allow frame rates of up to 500 kHz for 300 frames. This is achieved by storing all 300 frames on the CCD chip and then performing a standard slow (10 seconds) CCD readout into a control and data acquisition PC. The camera produces 64 x 64 pixel images and the dimensions of the light-sensitive area of each pixel are 202 μm x 62 μm. The pixels have a full-well capacity of 50,000 electrons and the readout noise is 46 electrons. Digitization is at 14 bits with a transfer function of 3.05 electrons per digitizer count.

The camera may be operated in either pre-trigger mode or in post-trigger mode. In pre-trigger mode, the camera takes 300 images after receiving a trigger pulse at a preset time during the discharge. In post-trigger mode, the camera operates in a streaming mode with the most recent 300 frames of data always present on the chip; the camera stops acquiring new frames when the trigger pulse is received. The post-trigger mode will be useful for MHD studies because the occurrence time of individual MHD events cannot be reliably predicted. The post-trigger will be obtained from a soft x-ray diode or Mirnov coil using a transient signal detection circuit. The camera is operated by a local PC which acts as a server for a web interface that can be accessed from another computer using a web browser. This makes remote control of the system convenient.

The camera has a wide angle (28º) tangential view of the NSTX plasma, as shown in figure 2. Space limitations did not allow the optical axis to be placed in the NSTX midplane so it is tilted downward at a 7º angle. This provides a view of nearly the entire plasma diameter and most of the vertical extent of the plasma. There is slight vignetting of the field of view by the top and bottom of the port structure. The entire diagnostic is heavy due to the weight of the magnetic shielding, and it will become heavier when lead and borated polyethylene radiation shielding is implemented to reduce neutron and gamma noise seen by the CCD camera. Thus, it is supported by a large, rigid support structure[4].

III. SYSTEM SENSITIVITY AND NOISE ESTIMATES

The overall sensitivity of the system is estimated to be 1.7 CCD photoelectrons per one keV x-ray photon. The contribution of the individual system components to the system sensitivity is given in Table I. The quantum efficiency of the P47 scintillator as coated was measured using a Fe^{55} source to be 6% at 5.9 keV x-ray energy. Using this value and the fact that the peak of the P47 emission occurs at 410 nm, 20 visible photons are produced per 1 keV input x-ray energy. We assume that 75% of the visible photons emitted by the scintillator layer are collected by the fiber optic faceplate. The fiber optic faceplate coupling efficiency of 50% assumes two coupled fiber optic faceplates with a numerical aperture of 1. The lens coupling efficiency is calculated assuming two f/0.95 lenses at unity magnification. The image intensifier gain and the CCD quantum efficiency given in Table I are measured values.

These numbers allow us to estimate the noise on the signal for various values of the x-ray flux incident on the scintillator area (0.45 mm^2) that corresponds to one pixel. The statistical noise is determined by the number of photoelectrons produced in the input photocathode of the image intensifier, which has a quantum efficiency of 11.5%. The relevant values for noise estimates are: 0.9 intensifier photoelectrons per 1 keV x-ray photon incident on the scintillator, and 2.0 intensifier photoelectrons per photoelectron in a CCD pixel. Using these values and the overall sensitivity of the system, we find that one pixel saturates at ~30,000 1 keV x-ray photons incident on the scintillator and the signal-to-noise ratio at this signal level is 160, determined by signal statistics. At 9800 x-ray photons/pixel, or 1/3 of saturation, the readout noise equals the statistical noise. At higher signal levels, the noise is dominated by statistics, while readout noise dominates at lower signal levels. A signal-to-noise ratio of one occurs at 90 x-ray photons/pixel, or 0.5% of saturation. Thus, the system has a large useful dynamic range, although large signals are required to produce statistics-dominated noise. This could be improved by reducing the readout noise of the CCD chip or by increasing the scintillator quantum efficiency.

IV. EXAMPLES OF DATA

In this section we show two examples of images from NSTX discharges, one taken at 20 kHz frame rate and the other at 100 kHz frame rate. A 3 mm diameter pinhole and 7.6 μm beryllium foil were used in both cases. The data were taken by triggering the camera at a preset time, as it is not yet setup to use post-trigger mode. Note that two 1 keV x-rays incident on the scintillator area equivalent to the sensitive area of one pixel produce one digitizer count.

Figure 3 shows an image obtained at a frame rate of 20 kHz immediately before an internal reconnection event (IRE), a large sawtooth-like event common in NSTX discharges[5]. The signal is large (~12,000 digitizer counts/pixel in the most intense part of the image) and the image has low noise. The core x-ray emission drops significantly during the IRE. This is illustrated in figure 4, which compares the time evolution of the signal in a pixel (row 12, column 35) in the most intense part of the image with the signal from a soft x-ray diode with a radial view in the plasma midplane. It is clear that the signals are very similar.

It is desirable to study individual MHD events such as IREs at frame rates of 100 kHz or higher if the signal levels are sufficient. This is difficult when operating in pre-trigger mode because 300 frames correspond to a short time window at high frame rates and IREs do not occur at reproducible times. (Post-triggering of the camera will be implemented in the near future.) Thus, we do not yet have images of an IRE at a frame rate higher than 20 kHz. As an example of operation at higher frame rates, figure 5 shows an image obtained at 100 kHz frame rate. The peak signal is lower (~550 digitizer counts/pixel) than in the previous case but the image quality should still be useful for MHD studies.

The images shown in figures 3 and 5 are not well centered on the CCD chip. This is due in part to a misalignment of the chip with respect to the image intensifier that has been corrected since these data were taken. However, even with good alignment, the plasma image is shifted from the center of the CCD chip in both the vertical and horizontal directions. This may be due to the effect on the intensifier of the residual magnetic field inside the magnetic shield. We are working to correct this problem.

In conclusion, we have demonstrated that good quality SXR images can be obtained at high frame rates. We plan to begin studies of MHD phenomena once commissioning of the system is complete.

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FIGURE CAPTIONS

FIG. 1. Schematic of the fast tangential SXR pinhole camera.

FIG. 2. Horizontal field of view of fast tangential SXR pinhole camera.

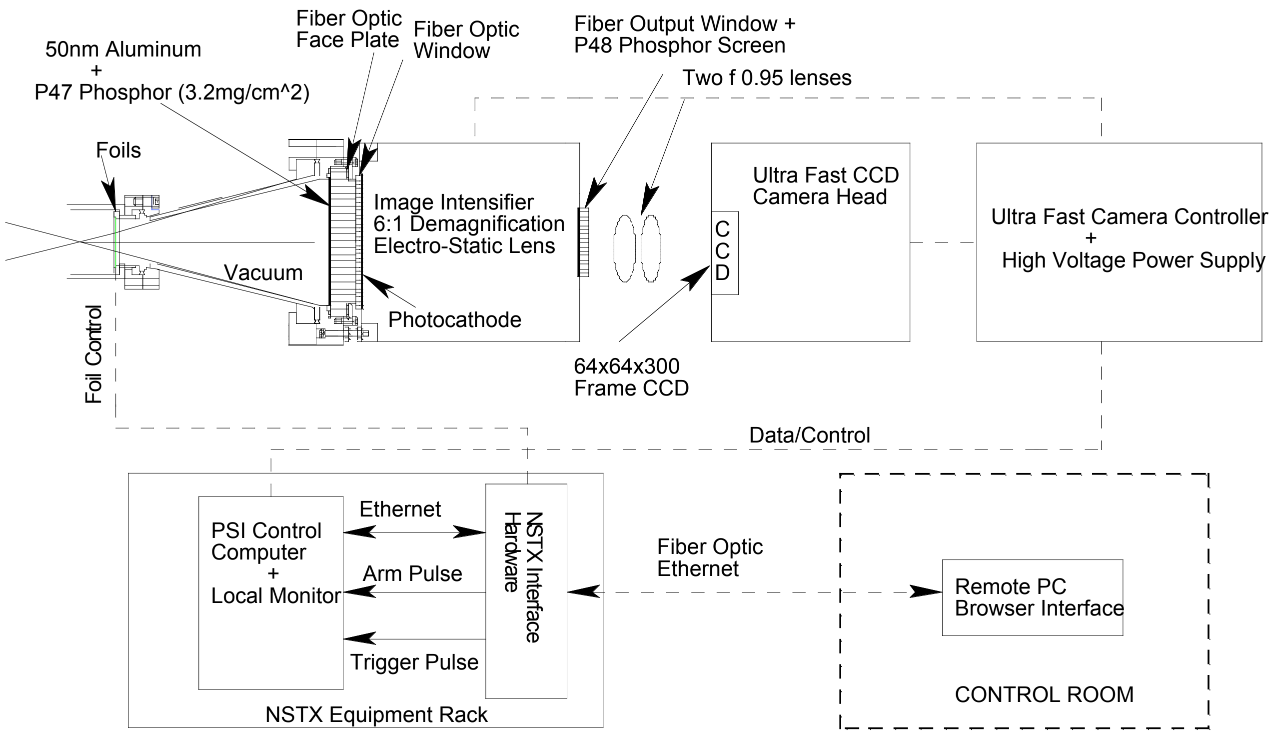
FIG. 3. Image taken at at 20 kHz frame rate.

FIG. 4. Time evolution of signal in SXR camera core pixel (dashed line) during internal reconnection event with SXR diode signal (solid line) shown for comparison.

FIG. 5. Image taken at 100 kHz frame rate.

Table I. Efficiency of System Components

P47 phosphor	20 visible photons/ 1 keV x-ray photon
Scintillator emission collection efficiency	0.75
Fiber optic faceplate coupling loss	0.5
Intensifier gain	5.4 output photons/ input photon
Lens transmission	0.277
CCD quantum efficiency at 410 nm	0.5
CCD fill factor	0.305
Overall sensitivity	**1.7 CCD photoelectrons/1 keV x-ray photon**



50nm Aluminum
+
P47 Phosphor (3.2mg/cm^2)
Fiber Optic
Face Plate
Fiber Optic
Window
Fiber Output Window +
P48 Phosphor Screen
Two f 0.95 lenses
Foils
Image Intensifier
6:1 Demagnification
Electro-Static Lens
Ultra Fast CCD
Camera Head
Ultra Fast Camera Controller
+
High Voltage Power Supply
C
C
D
Vacuum
Photocathode
Foil Control
64x64x300
Frame CCD
Data/Control
Ethernet
PSI Control
Computer
+
Local Monitor
Arm Pulse
Trigger Pulse
NSTX Interface
Hardware
Fiber Optic
Ethernet
Remote PC
Browser Interface
CONTROL ROOM
NSTX Equipment Rack

FIG. 1

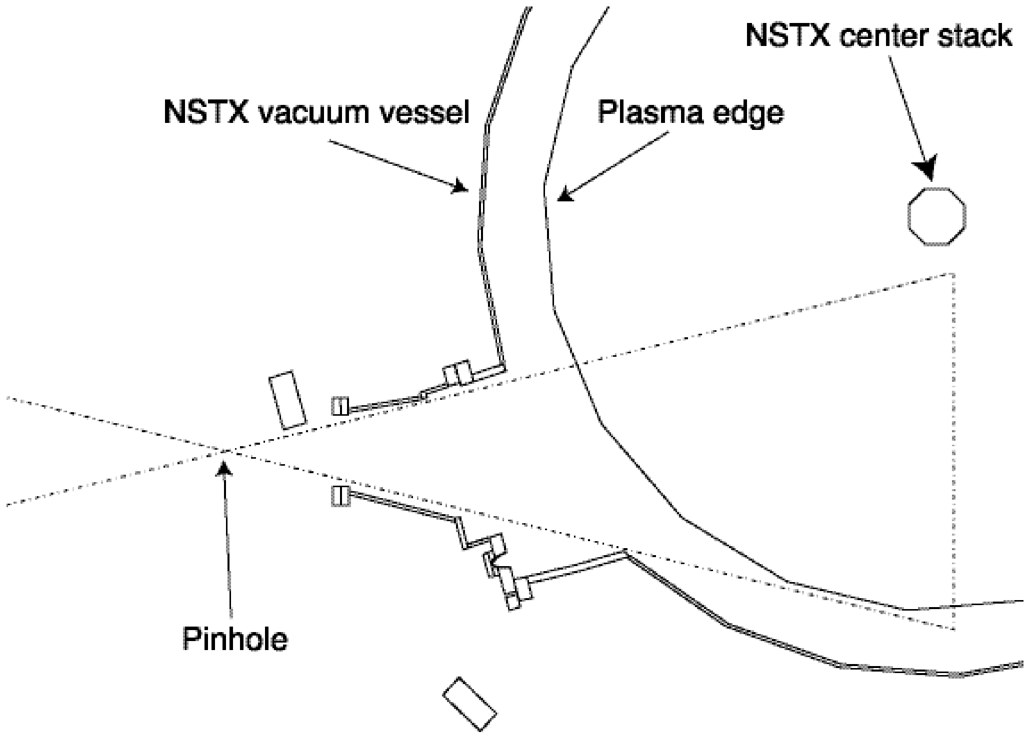
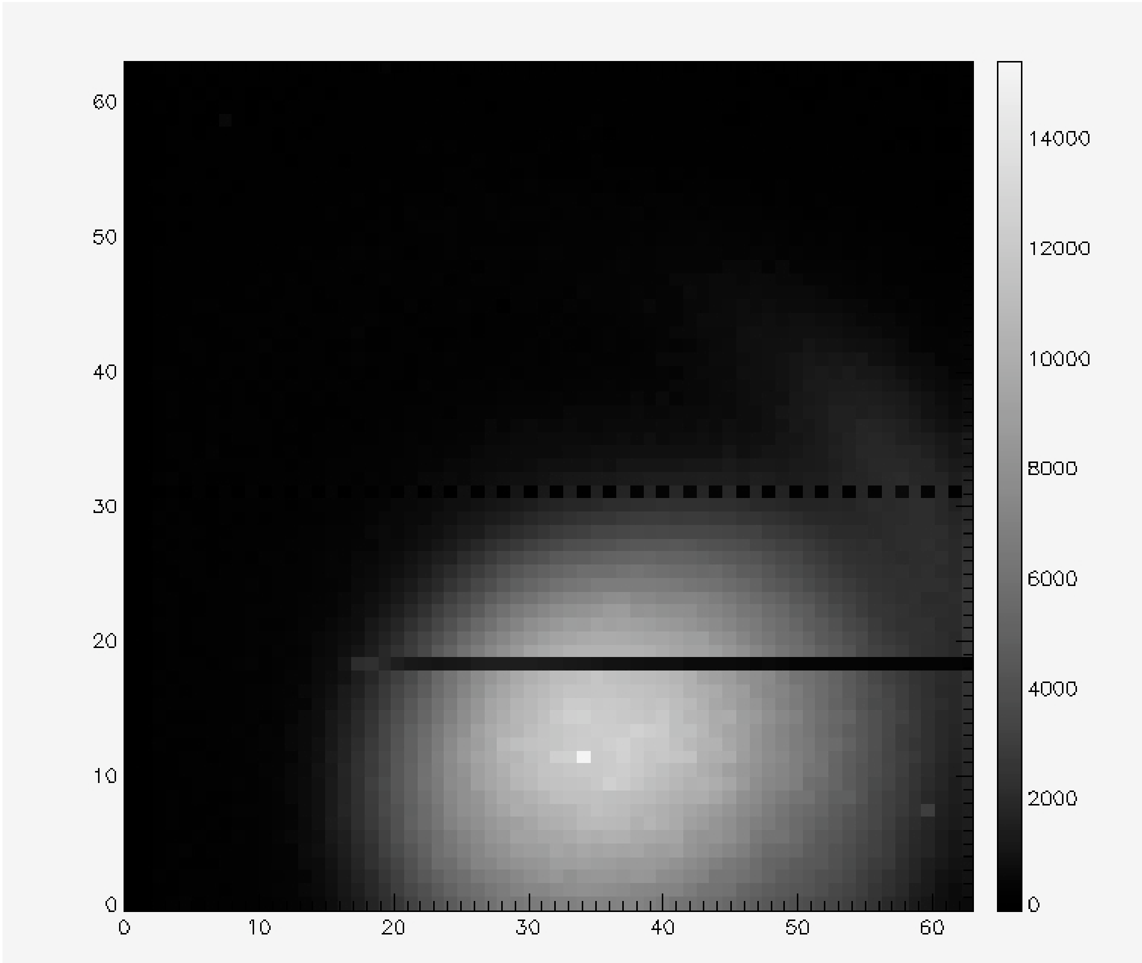


FIG. 2



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50
40
30
20
10
0
0
10
20
30
40
50
60
14000
12000
10000
8000
6000
4000
2000
0

FIG. 3

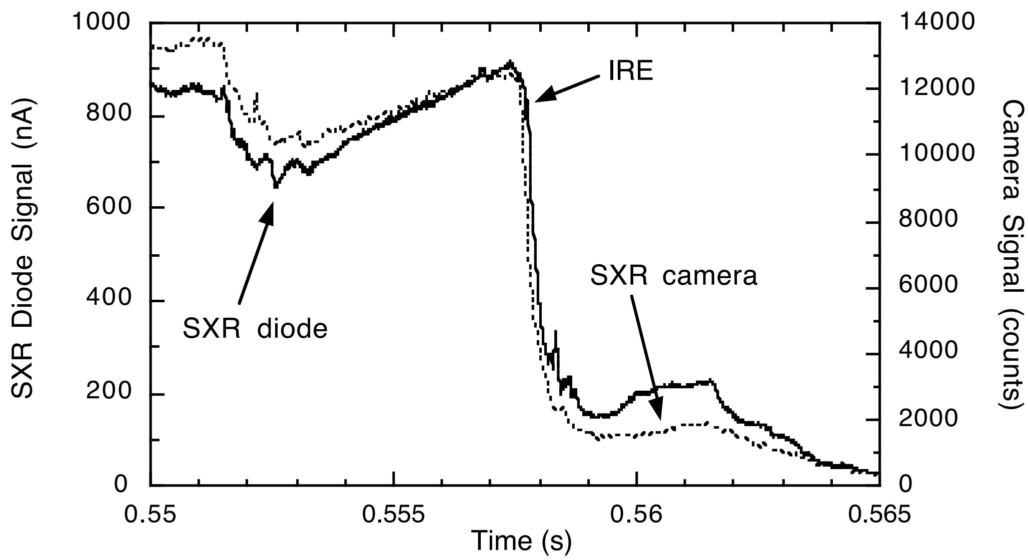
1000
800
600
400
200
0
14000
12000
10000
8000
6000
4000
2000
0
0.55
0.555
0.56
0.565
Time (s)
SXR Diode Signal (nA)
Camera Signal (counts)
IRE
SXR camera
SXR diode

FIG. 4

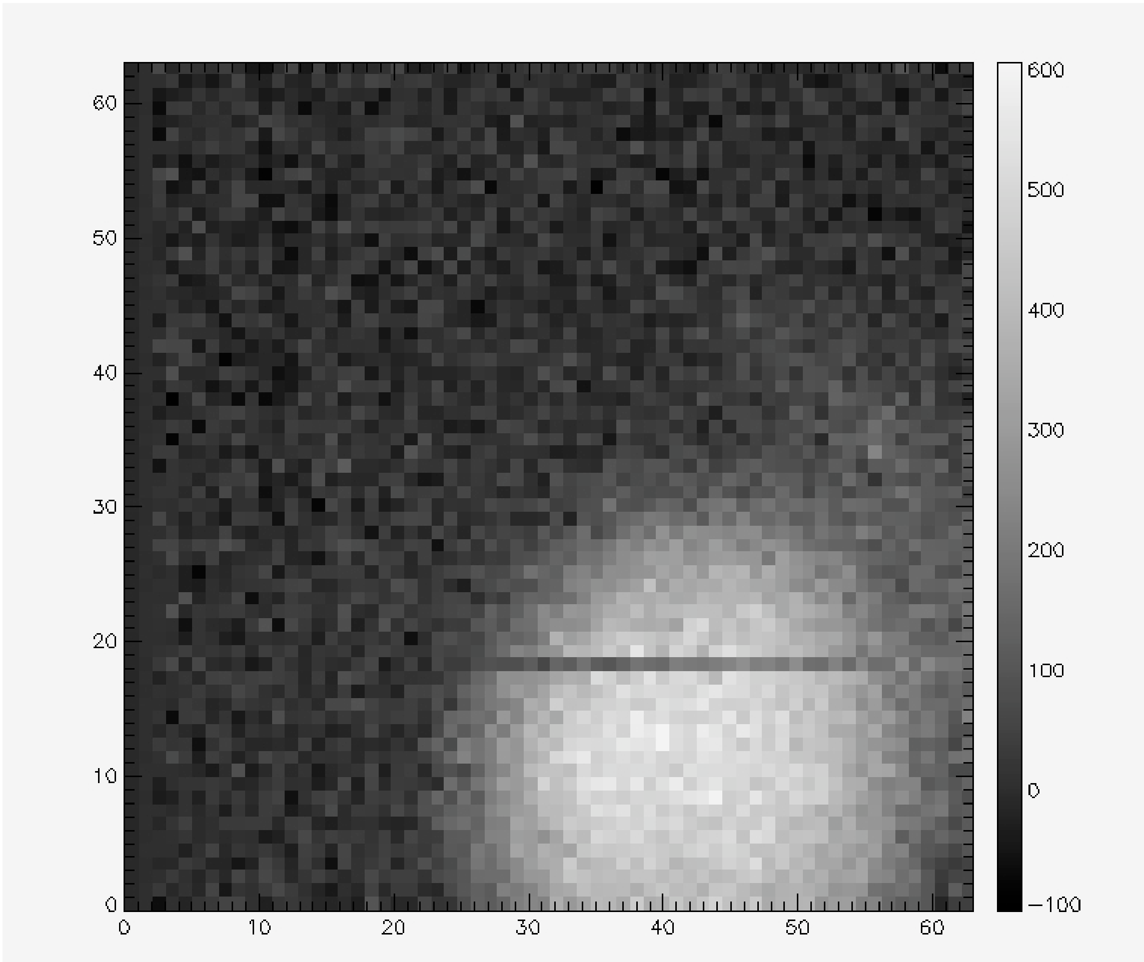

FIG. 5

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