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Abstract:

A near back-scattering imaging diagnostic system has been implemented, qualified and fielded on the first quad of beams on the National Ignition Facility. This diagnostic images diffusing scatter plates, placed around the final focus lenses on the NIF target chamber, to quantitatively measure the fraction of light back-scattered outside of the incident cone of the focusing optics. The imaging system consists of a wide-angle lens coupled to a gated CCD camera, providing 3mm resolution over a 2m field of view. To account for changes of the system throughput due to exposure to target debris the system was routinely calibrated *in situ* at 532nm and 355nm using a dedicated pulsed laser source. The diagnostic and calibration methods will be described together with recent results from the NIF early light shots. Work performed under the auspices of the U.S. Department of Energy by UC/Lawrence Livermore National Laboratory under
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I Introduction

The National Ignition Facility (NIF) uses two diagnostics to study the laser coupling interaction in inertial fusion targets: the Full Aperture Back Scatter diagnostic (FABS), and the Near Backscatter Imaging diagnostic (NBI) [1]. Both diagnostics measure the laser energy backscattered from targets. An NBI system was used to measure light back-scattered outside the cone angle of the focusing optics on the Nova laser at LLNL, this diagnostic showed that under certain circumstances it is possible for an appreciable fraction of the incident laser light to be back-scattered outside the focusing lens [2,3]. For NIF experiments calculations with the laser-plasma interaction code pF3D [4] have predicted that a substantial fraction of the scattered light can be outside the final NIF lens for long plasma scalelengths that will be required for ignition scale hohlraums. This fraction of light cannot be measured by the FABS and requires an NBI system to test the code predictions and to fully characterize the laser plasma coupling.

Figure 1(a) shows an illustration of light distribution a pF3D calculation of laser light backscatter from a CO2 gas filled target at an electron temperature of 2keV, density = 0.05ncr = $0.05 \times 1 \times 10^{22} = 5 \times 10^{21}$ cm^{-3} and laser intensity of $3 \times 10^{15} Wcm^{-2}$[4]. The plasma density and composition were chosen to provide high levels of backscatter to test both the models and provide a good test of the diagnostic. This simulation shows that the 20% of incident light is backscattered over a wide range of angles with substantial light in between the quad beams and 50% of the total backscattered light outside the final lens assembly. This light could not be detected by a full aperture backscatter system and so a near backscatter imager is required to fully quantify the total backscatter. The relative fraction of light scattered outside the lens depends on the non-linear laser plasma interaction model used in pF3D, so a measurement of the fraction of light scattered through large angles will help constrain these models. It should be noted that the laser intensity and gas material chosen for this study produce much higher backscatter levels than the NIF point design at $I = 5 \times 10^{14} Wcm^{-2}$ and CH gas, which would produce total backscatter levels < 10%.

Fig. 1(b) shows the diagnostic NBI arrangement. The NBI system consists of two subassemblies as described in ref [1]. A brief summary of the system is as follows: Laser light backscattered from the target is incident on a 2 m x 2 m scatter plate located around the chamber wall laser entrance aperture. The scatter plate has four cut-outs to allow passage of incoming beams. Laser light scattered by the target strikes the scatter plate, which scatters light within the view of imaging cameras outside the chamber. The images of backscattered laser light are compared to calibration images taken when the scatter plate is illuminated with known laser energy. The backscattered energy is then measured by comparing target shot images to calibration images.

The NBI diagnostic uses two separate cameras to measure the energy from stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS) processes separately. SBS light has a bandwidth around a few nanometers of the incident 351.5 nm laser beams, and the camera response is essentially constant over this wavelength range. SRS scattered light may fall anywhere between 400-800 nm, depending on the target, and camera response varies significantly over this bandwidth. Hence, a relative spectral measurement of the Raman scattered light is also required to determine Raman backscatter energy (provided by FABS spectrally resolved data).

II The Imaging System

The NBI diagnostic uses intensified cameras to image the scatter plate. The intensifier captures an image of light scattered off the scatter plate while blocking both direct illumination from the target and multiple reflections inside the chamber. An intensifier gate width of 25ns is short enough to block direct target illumination and multiple scattering from the chamber, and long enough to capture the 1-3 ns pulse from the scatter plate. A relatively flat response function over the gate is desired, and this criterion was used to select the NBI cameras. The dynamic range and useful range of intensifier gain were also measured for various intensified cameras. A dynamic range of 200 was typical, and the responses were linear for gains up to 200. While high dynamic range is advantageous in our application, gain linearity is not as critical because there are many photons available, the gain will be fixed to a modest value and the gain curves for both cameras were fully characterized at the Bechtel calibration facility before the shot campaigns.

The two intensified cameras are packaged in a light tight enclosure located outside the target chamber. Filters located at the enclosure entrance select a wavelength range for each camera and attenuate the light intensity. The remaining light reflects off a turning mirror and passes through a focusing lens on its way to the camera intensifier cathode. For high target backscatter shots, attenuation up to10^8 is required to avoid camera saturation. For calibration, some of the ND filters are removed to maximize the camera signal.

III Timing of the imaging system cameras

Target backscatter is captured by turning the camera intensifiers on at a prescribed time relative to a fiducial signal generated by the main laser. The fiducial signal is referenced to the time laser light arrives at chamber center. The fiducial and intensifier gate monitor pulses are both recorded by an oscilloscope, and relative timing is adjusted to achieve the required temporal separation. Using the fiducial, proper timing can be achieved without firing a high power laser pulse. Timing was verified on a laser shot using an ET-2000 diode, which collects light from the scatter plate, and the diode trace is recorded along with the fiducial and monitor pulses. These settings were verified using the optical diode placed next to the cameras and tested on qualification shots for laser diagnostics. Fig. 2 shows a series of images taken from laser diagnostic shots where no target was present. In this case light can travel through the center of the chamber, reflect off the rear side of the chamber and back onto the first wall around the input beam tube. The chamber is 10m in diameter so the round trip time for light is approximately 60ns from input–far wall-back to input again. By altering timing of cameras by 30ns either side of to, light can be captured as the pulse enters the chamber (T = To – 32ns as shown in fig. 2(a)) and when it returns back at the FOA (T= To + 32ns as shown in fig.2(c)). For data collection the camera is set mid way between these two extremes (T = To fig 2(b)) (note that light is visible at To even when no target is present because a 30ns gate was set on the CCD camera, this gate with is wide enough to still detect light scattering around the beam tube as the pulse came into the chamber).

Using this technique over a number of shots the absolute timing error for the center of the gate was less than 1ns. The system gate width was then set to 25ns enough to capture all backscatter from the laser pulse whilst ensuring that light scattered from the beam tube before the shot and any light from the far side of the chamber after the shot were outside the gate width and did not contaminate the data.

IV The Scatter Plate Subassembly

The challenge of the scatter plate design is to select materials with uniform scattering properties across the 350-800nm wavelength range, with high laser damage threshold that are also compatible with the vacuum environment. A number of materials meet these requirements. From a laser damage point of view the main challenge is that the scatter plate also must not damage when subjected to up to 1 J/cm^2 backscatter of 351 nm light and the scatter plate and any window placed in front of it must last for hundreds of shots before accumulating noticeable damage. Spectralon, a product made by Labsphere, is a commonly used scatterer for optics applications. Its scattering properties are well characterized and available on the Labsphere web site [5]. The linearity of Spectralon vs. incident energy density was also independently tested using a 200ps doubled YLF laser at LLNL and compared with both Aluminum and Teflon [1]. Based on these results, Spectralon was chosen for the scatter plate. To illustrate the complete working system Fig.3 shows qualification images from the SBS and SRS cameras taken during shots were very low backscatter levels were expected.

IV Energy Calibration

The camera and scatter plate are calibrated together in order to determine the net response to target backscatter. Laser pulses of known energy from a Minilite II YAG laser are directed onto the scatter plate, and images of the scattered light from these pulses are captured by the NBI SRS and SBS camera systems. The pulses come from a laser inside the NBI camera enclosure. A calibration function is generated from the images, and when applied to target shots this function determines the target energy back scattered. Frequency conversion crystals provide output wavelengths at 532 or 355 nm, in 3 ns pulses. The 532 nm wavelength is used to calibrate one camera for SRS, and 355 nm is used to calibrate the other for SBS. Each pulse contains a few mJ of energy spread over about a 10 mm spot. Mirrors are then installed to direct calibration laser light through one of the camera viewing ports and onto the scatter plate. Only one camera is calibrated at a time because the 2” turning mirror blocks the other cameras view. The calibration laser timing is synchronized with the camera’s intensifier gate to capture the scattered light. A calibrated calorimeter monitors the pulse energy that is incident on the spectralon, this used to calculate the absolute sensitivity of the NBI system.

The last turning mirror is motorized in order to scan the scatter plate point by point with calibration pulses. A continuous calibration function is generated from interpolation of the point map. The continuous function is applied to the intensity profile captured from a target shot to calculate backscattered energy. Pulses at 355 nm are adequate to calibrate the narrow bandwidth (few nm) of Brillouin backscatter. For the camera observing Raman backscatter, the calibration pulse response observed at 532 nm pulses must be extrapolated over the Raman bandwidth. This can be done using the wavelength response curve provided by the camera manufacturer, and a relative measurement of the target shot’s Raman spectra. The FABS diagnostic measures the relative spectral intensity of Raman scattered light, and this distribution is applied to the NBI image of Raman backscatter.

An example image of the calibration map for the SBS camera is shown in fig.4 (a). The response of plate was found to be constant within 10% across the plate as shown in fig 4(b). The response in the vertical cross region was slightly different to the rest of the plate. There were two reasons for this; 1) the calibration laser spot was larger than the width of the vertical cross and so not all the light was reflected back into the imaging system. 2) There were 3 small damage marks on the vertical cross region, which had lower reflectivity than the rest of the plate. These issues did not affect the calibration to first order as the surface area of the vertical cross represented a very small fraction of the total plate area and the correction was negligible.

V Operation

Fig. 5 shows an NBI image from the SBS camera of backscatter from a vacuum hohlraum shot during the NIF early light campaign with 8kJ of 351nm light in a 1ns pulse [6]. From previous hohlraum data on the Nova laser [2,3] backscatter levels around 1% were expected from this target. These expectations were confirmed with the NBI system. The absolute levels were 90J backscattered across the whole plate from the 8kJ pulse.

This representing 0.6% of the incident laser energy. The system was also used to measure backscatter from gas filled pipes (NIF gas filled hohlraum facsimiles). Here the gas fill and density were intentionally chosen to give backscatter levels in range 10-30% to test the accuracy of the laser plasma interaction models. The NBI data confirmed these predictions and showed the importance of using phase plates, SSD and polarization smoothing to accomplish low backscatter levels. This work is currently being prepared for publication elsewhere.

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VI References:

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VII Figure Captions

1. Figure 1. (a) A pF3D calculation of backscattered light intensity around the port – total backscatter is 20%; with 10% inside, and 10% outside the lens. (b) The diagnostic arrangement. The imaging systems view the scatter plate from the opposite side of the chamber. One camera is filtered for SBS the other for SRS.
2. Relative timing of the framing cameras was set using NIF timing fiducial and verified using a photodiode located next to the cameras. System shots fired without targets were used to differentiate light coming from the beam tube as pulse entered the chamber and from back reflections from far side of chamber. These signals can be seen on the diode traces and the framing camera images.
3. Picture of scatter plate taken by SBS and SRS camera during Dante qualification shots. Backscatter levels measured by FABS extremely low: ~mJ/cm2 on plate in range
4. (a) Calibration image showing discrete laser spots of known energy projected on plate by pulsed calibration laser.

   (b) Response across plate from calculated from calibration images in Joules/count. The plate response = 7.2 e-12 (J/count) ± 10% across the 2m field of view. The vertical cross shows slightly lower response because the calibration spot is larger than the cross thickness.
5. NBI SBS image from a vacuum hohlraum illuminated with 8kJ laser light at 351nm in a 2ns pulse. Total measured SBS backscatter on plate was 75J for this shot, equivalent to less than 0.6% of beam energy delivered to hohlraum

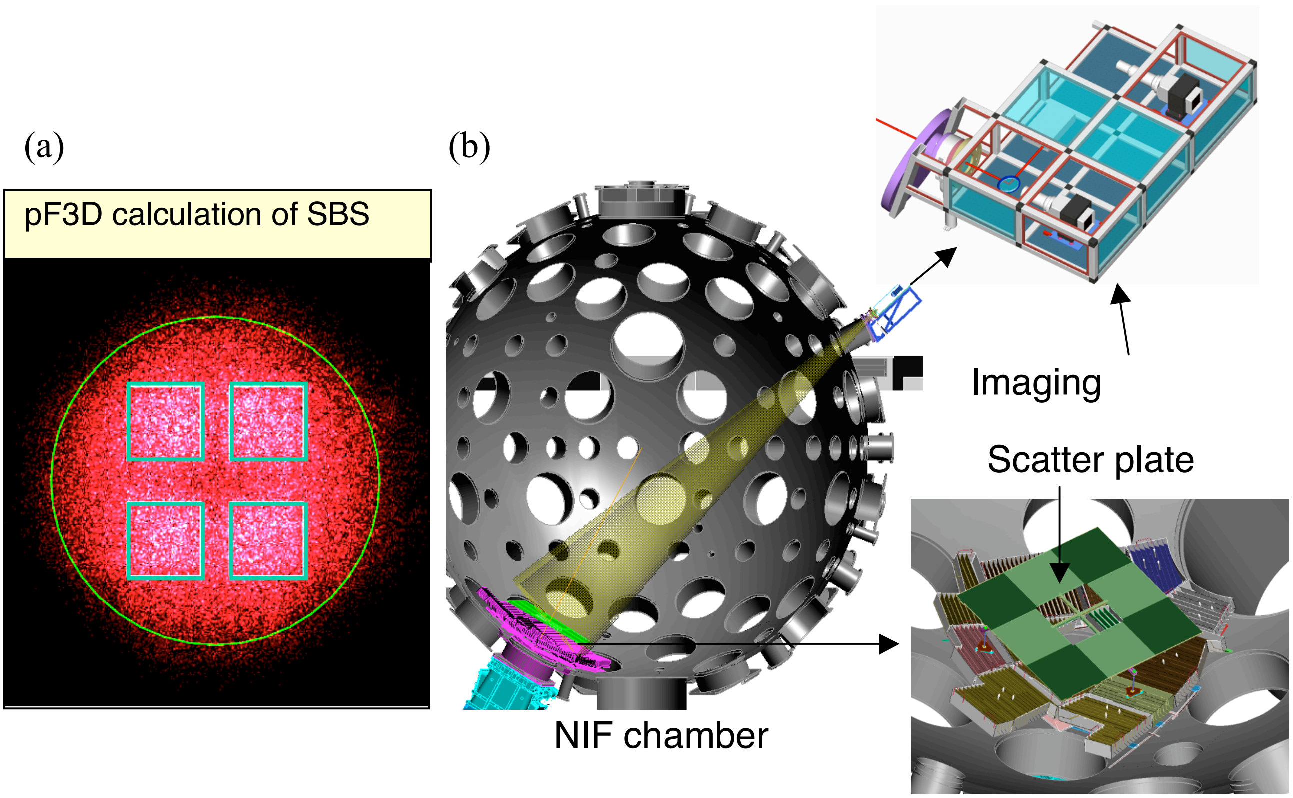

(a)
(b)
pF3D calculation of SBS
Imaging
Scatter plate
NIF chamber

Figure .1

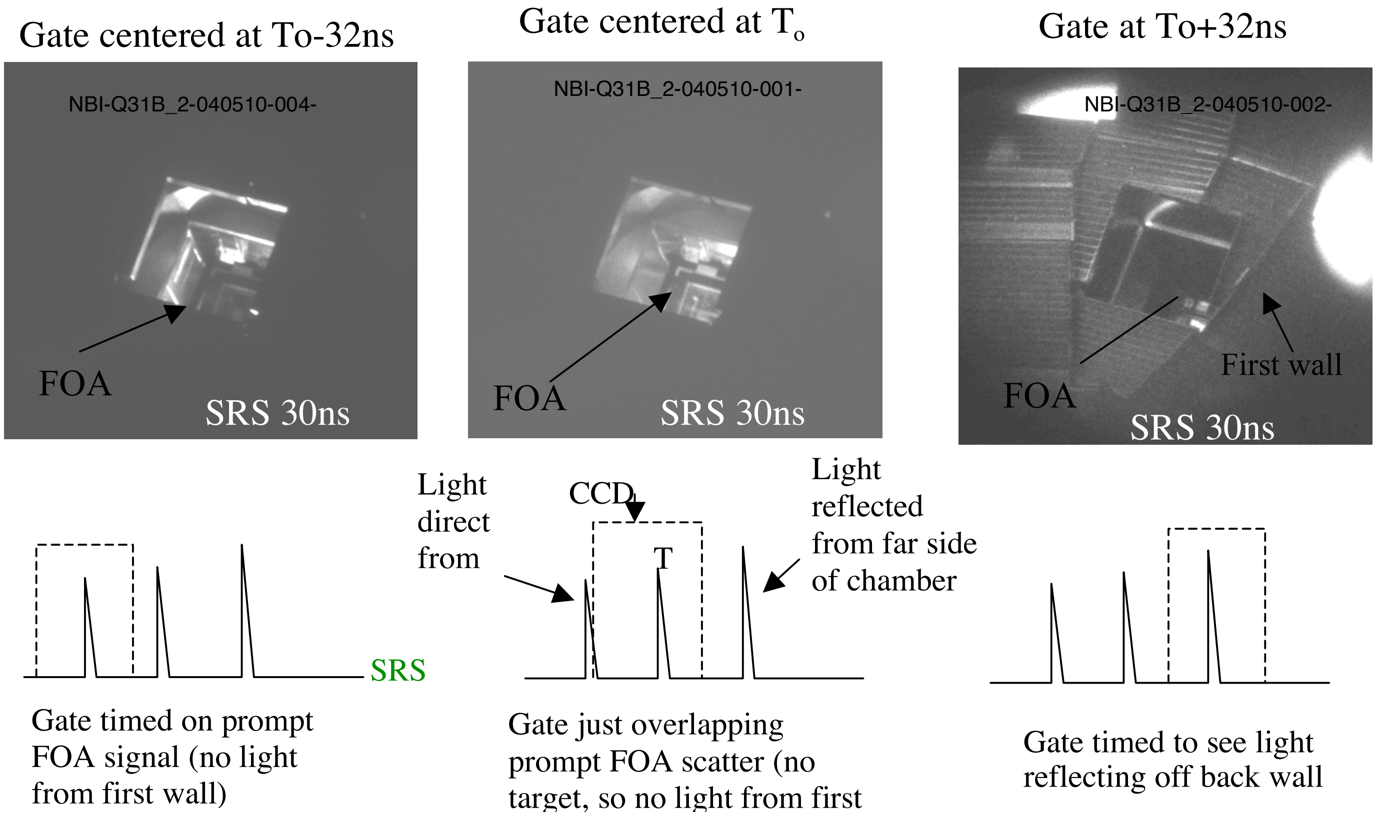

Gate centered at To-32ns
NBI-Q31B_2-040510-004-
FOA
SRS 30ns
Gate centered at T_o
NBI-Q31B_2-040510-001-
FOA
SRS 30ns
Gate at To+32ns
NBI-Q31B_2-040510-002-
First wall
FOA
SRS 30ns
SRS
Light direct from
CCD
T
Light reflected from far side of chamber
Gate timed on prompt FOA signal (no light from first wall)
Gate just overlapping prompt FOA scatter (no target, so no light from first
Gate timed to see light reflecting off back wall

Figure 2

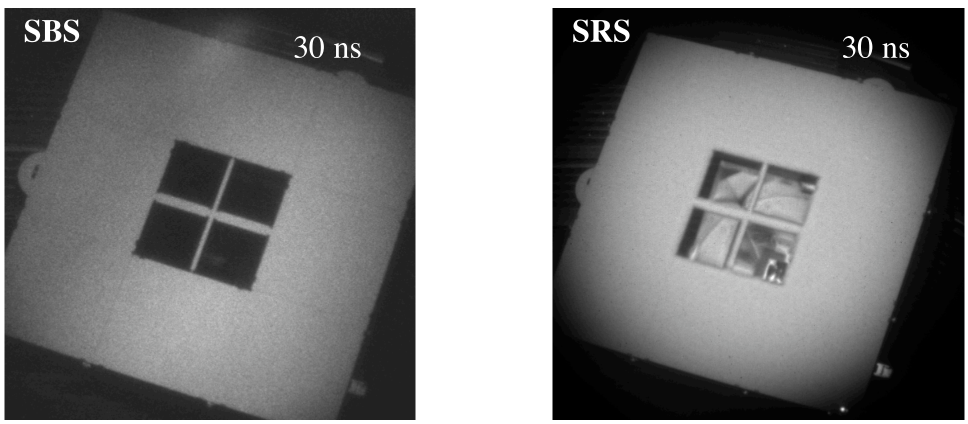
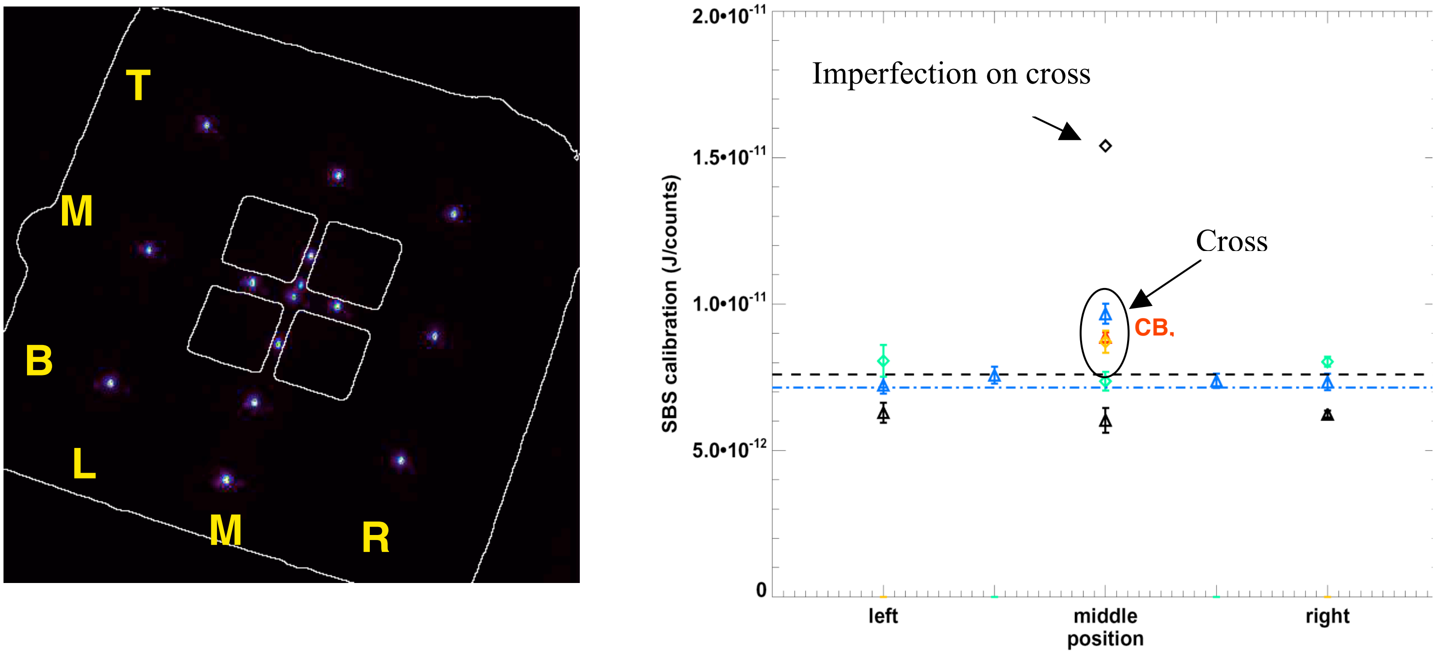


Figure 3



T
M
B
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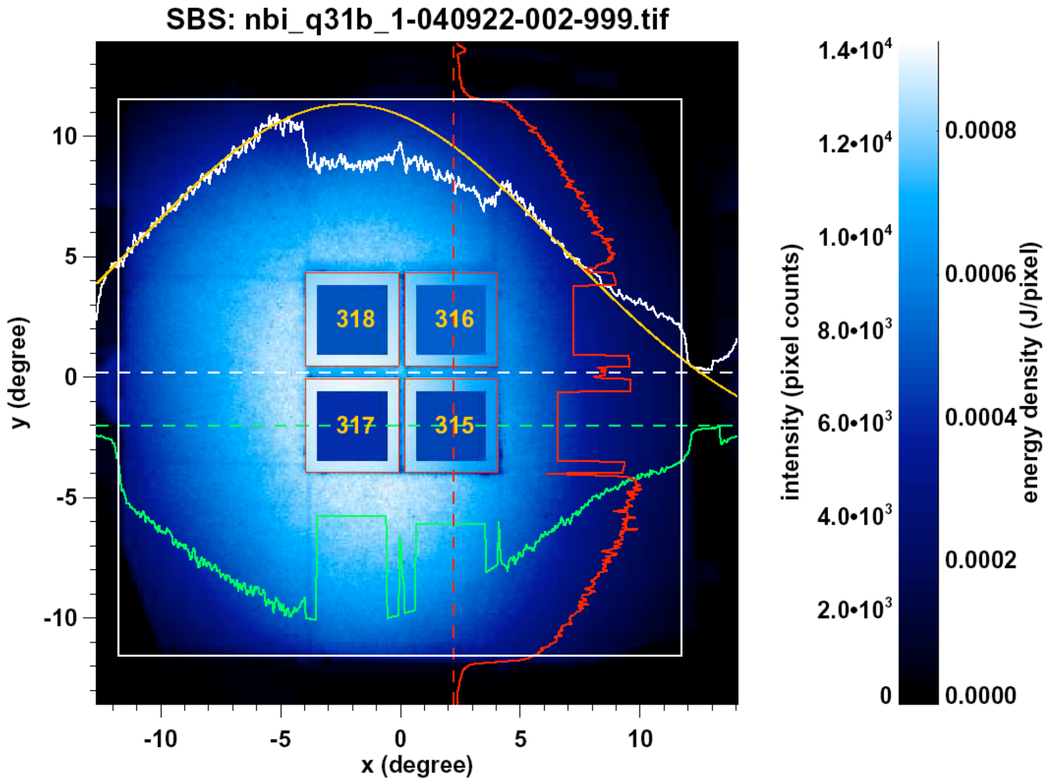
M
R
2.0•10^-11
1.5•10^-11
1.0•10^-11
5.0•10^-12
0
SBS calibration (J/counts)
Imperfection on cross
Cross
CB.
left
middle
position
right

Fig.4



SBS: nbi_q31b_1-040922-002-999.tif
y (degree)
x (degree)
318
316
317
315
intensity (pixel counts)
energy density (J/pixel)

Figure 5