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R. K. Kirkwood, C. A. Back, S. H. Glenzer,
B. J. MacGowan, D. S. Montgomery, and J. D. Moody

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Imaging Back Scattered and Near Back Scattered Light in Ignition Scale Plasmas

R. K. Kirkwood, C. A. Back, M. A. Blain†, D. E. Desenne†, A. G. Dulieu†, S. H. Glenzer, B. J. MacGowan, D. S. Montgomery*, and J. D. Moody,

Lawrence Livermore National Laboratory, University of California, L-473 P.O. Box 808, Livermore Ca. 94550,,

†Centre D'Etudes de Limeil-Valenton, France.

* presently at Los Alamos National Laboratory

Abstract

Diagnostics have been developed and fielded at the Nova laser facility that image scattered light in the vicinity of the final laser focusing lens. The absolute calibration of optical components exposed to the target debris have been achieved by a combination of routine in situ calibration and maintenance. The scattering observed from plasmas relevant to ignition experiments indicates that light scattered just outside the lens can be larger than that collected by the lens , and is a significant factor in the energy balance when the f number is high.

Introduction

Ignition of ICF plasmas requires efficient coupling of laser energy to the target. A significant loss mechanism is the scattering of laser light in the plasma created by ionization of the target material. In indirectly driven ignition scale targets [1] the laser beam must pass through a gas filled region before reaching the solid surface where it is converted to x-rays. A large scale (~ 2mm) low density (n ~ 0.1 critical) plasma forms in this region and scatters laser energy by both stimulated Brillouin (SBS) and stimulated Raman (SRS) scattering. These processes involve the stimulation and growth of ion acoustic waves and Langmuir waves, respectively, which can scatter a significant fraction of the incident energy. The gain for this process [2] is known to be peaked in the direction of direct back scatter when the plasma is homogeneous. Previous observations of light scattered from small scale length plasmas indicate that light is, in fact, scattered predominantly into or near the final focusing lens of the incident beam by both SBS [3] and SRS [4,5]. In addition, the detailed angular distribution of the scattered light can depend on the geometry of the target plasma [6]. As a result the diagnosis of both the total scattered energy and the angular distribution of the scattered energy is significantly complicated by the fact that the maximum scattering occurs in the direction of the final focusing lens of the beam. Access to this region is difficult because it includes the palth of the incident peam and its optics and support structures. None the less, both accurate determination of energy balance, and characterization of the angular distribution require continuous measurements in this entire region, including both light scattered into and near the final focusing lens of the incident beam (designated back scatter and near backscatter, respectively).

Recently, a diagnostic system was installed at the Nova laser facility [7] that is capable of angularly resolving scattered light, both inside and outside of the lens cone with either f/8 or f/4.3 lens configurations, which includes $\geq$90% of the solid angle with in 20° of the lens axis. In addition to producing an angularly resolved image of the time and spectrally integrated scattered light the system also provides temporal and spectral information of the light at selected angles. The imaging system consists of four cameras that image light in two different wavelength ranges, corresponding to SBS and SRS, in each of two different angular regions, corresponding to light scattered in the lens and, outside the lens within 20° of the lens axis. The light scattered into the lens is partially transmitted through the last turning mirror of the incident beam and focused by a second full aperture lens onto a scatter plate. The scatter plates are imaged by a pair of CCD television cameras in the Full Aperture Back Scatter (FABS) system, as shown in figure 1. An independent pair of cameras images an annular scatter plate surrounding the entrance hole of the incident laser beam in the target chamber, as viewed from a port located on the opposite side of the target chamber. This Near Back scatter Imager (NBI) views the scatter plate at a 38° angle with respect to the normal to the plate, as shown in figure 1, providing a clear image of the entire plate, while rejecting direct side scatter by insuring that the target is outside the field of view of both the camera and the vacuum window. Each pair of cameras consists of one camera that is filtered to be sensitive to UV light between 345 nm and 355 nm, and a second that is filtered to be sensitive to light between 400 nm and 700 nm. These spectral ranges correspond to SBS and SRS respectively when the incident beam has the nominal 351 nm wavelength. Spectral information is obtained using fiber optics located at various points in each scatter plate to collect light at a particular angle. The fibers are then placed at the image plane of a spectrometer and coupled to a streak camera, providing images of wavelength vs. time at 4 locations inside the lens and as many as 16 outside the lens. The spectrometers are 0.25 m for SRS measurements and 0.5m for SBS, providing spectra in the range of 400 nm to 720 nm and 350.5 nm to 352.5 nm respectively.

Design of the Diagnostic

Implementation of the imaging diagnostic requires a large, well characterized diffusing surface to scatter the light for collection by the camera. The design of this plate is driven by two considerations. First, in the case of Nova experiments the scattered light in both SBS and SRS can reach intensities as high as 20 kJ/str., and second the first optical materials the light interacts with must not be significantly affected by the debris generated by as many as eight experiments per day. The first consideration has required that nonlinearities in the reflectivity of the scatter plates be included, while the second has required that materials be replaced or cleaned on a routine basis.

The highest fluences of scattered light are directed into the lens cone were they exit the vacuum chamber through a debris shield and the lens itself. Once outside the chamber the reflected light is removed from the path of the incident beam by the partially transmitting mirror, the full aperture lens, and a fresnel reflector, that reduce the intensity substantially before reaching the diffusers. Because of the chromatic aberration of the lens the SBS and SRS light are imaged on separate Spectralon diffuser plates that are each imaged by a CCD camera with 8 bit dynamic range. The debris shield that protects the laser focusing system also protects the reflected light system, and is replaced or cleaned every two weeks as part of the normal facility maintenance.

The light outside the lens cone is nearly as intense and cannot be brought out of the target chamber easily. As a result this light is directly incident on the NBI scatter plate which is also exposed to target debris. The NBI scatter plate is imaged by two cameras through a beam splitter/combiner and a vacuum window that is located on the opposite side of the chamber. Because the camera is placed off the normal to the plate by 38°, it is possible to place a shield that obstructs the path of debris from the target to the port, but does not obscure the view of the scatter plate. This shield has reduced the darkening and damage rate of the vacuum window substantially, so that maintenance is only required every few months. The scatter plate is constructed of bead blasted Al which has both a reasonably well characterized reflectivity and is easy to clean. Although other materials (such as Spectralon) may have better linearity than Al at high intensity they usually are not as compatible with the vacuum environment, or as easy to manufacture and clean.

The NBI scatter plate and imaging camera have been calibrated and had their response characterized up to 200 mJ/cm^2 (equivalent to 5 kJ/str.) using a 1 mJ calibration laser with two different pulse lengths, as shown in Figure 2. The scattered energy is found to be linear with incident energy up to a critical energy of about 20 mJ/str. and is well described by a power law between 20 mJ/str. and 200 mJ/str. Both the critical energy and the exponent of the power law are not strongly dependent on the pulse length or wavelength of the incident laser, indicating that the scattered energy provides a good measure of the time integrated incident power, provided nonlinearities are accounted for.

Calibration of the Diagnostic

The back scatter and near back scatter diagnostics are calibrated independently, and cross checked to demonstrate consistency. The back scatter diagnostic is calibrated by firing the incident laser beam when there is no target at the position of best focus, and a retroreflecter is at the far wall of the target chamber, shaped to reflect light back along the incident ray path and into the back scatter imager. The know reflection coefficient of the retroreflector and the standard incident energy diagnostics at the Nova facility are then used to determine the total back scattered energy, which is equated with the angularly integrated camera signal to obtain a calibration constant. This *in situ* calibration is quite accurate and reproducible ($\pm$ 5%) for determining the sensitivity of the in the lens diagnostics, but cannot be used to directly determine the sensitivity of the diagnostics which are out side the lens cone (NBI), and therefore out of the path of the incident and retroreflected beam. Limitations on beam positioning and focusing that are required by the Nova facility to insure laser integrity unfortunately make it difficult to divert the incident beam onto the NBI diagnostics directly. As a result the NBI diagnostics require an alternate calibration method.

The initial calibration of the NBI imaging diagnostic was done in two independent ways which were then compared; the overall scatter plate reflectivity and camera response were calibrated in the calibration facility, and calibrated photo diodes placed at up to 20 locations in the plate were used to determine the plate reflectivity at different points *in situ.* The SBS camera was calibrated viewing the scatter plate illuminated with a 351 nm incident wavelength while the SRS camera was calibrated with a 527 nm incident wavelength. These calibrations were then corrected for the different distance between the camera and scatter plate in the calibration facility and in the target chamber, as well as for any changes in filtration. The SRS image is further corrected using a measured SRS spectrum from each shot and the camera and filter spectral response function as shown in figure 3. When the single point measurements made with the photo diodes are compared with the signals from adjacent regions of the plate in the camera images the agreement is typically within 30%, as shown in the SBS image of light scattered outside the lens from a hohlraum target in figure 4. Because of the good agreement obtained when the plate is carefully calibrated, and the relative simplicity of maintaining the calibration of the photo diodes, the image of the plate is now routinely normalized to the photo diode signals and the 30% uncertainty is taken to be the overall accuracy.

Maintaining the calibration of the NBI images is difficult because of darkening of the scatter plate and diode debris shields. The importance of this effect is dramatically illustrated by figure 5 which shows the calibration constant for the NBI imaging system determined by comparison with the photo diodes and by calibration of the scatter plate in the calibration lab. Note the period of 72 days from July 3 to September 15 during which the NBI scatter plate remained in the chamber while a normal schedule of experiments was carried our (~ 30 experiments per week). During this period the NBI camera calibration was determined by comparison of the camera images with data from photo diodes with a well characterized sensitivity mounted at eight locations in the plate. The calibration factor for the uncleaned plate was found to increase by a factor of ~ 6x consistent with darkening by target debris. To minimize the effect of darkening the plate is cleaned and the diode optics are now replaced and every two weeks during normal Nova operation resulting in a fairly constant calibration constant similar to that shown for the period of Sept. 18 to Oct. 27 in figure 5. One additional effect that is uncovered by the studies shown in figure 5, is the rapid darkening of the 351 nm reflectivity during the first day after cleaning. This effect is illustrated in the Sept. 18-29 data and has been observed whenever calibrations are made during the first day. Such darkening is probably the result of an Aluminum Oxide layer forming on the surface rather than darkening by actual target debris, and is one disadvantage of using the Al material. Because the effect is only important for one day out of the two week maintenance cycle and can be avoided by scheduling the cleaning well in advance of experiments, it does not out weigh the other advantages of the Al material for this application.

Measurements of Back Scatter from ICF targets

Experiment have been performed at Nova with a variety of gas filled targets designed to produce plasma conditions similar to those expected in the NIF [8]. The angular distribution of both the SRS and SBS scattering including both light inside and outside of the lens cone is shown in figure 6 for a gas filled hohlraum target illuminated by an f/8 beam with 351 nm wavelength. The hohlraum target is a Au cylinder with a hole at each end filled with a hydrocarbon gas, as described in detail in Ref. [8]. The laser beams are incident at a 50° angle with respect to the axis of the cylinder, enter the hole, and transit the gas to impinge on the inner surface of the wall. As show in figure 6 the asymmetric target geometry is found to cause an asymmetry in the back scattered SBS light, but not in the SRS light. The asymmetry in the scattered power is such that the scattered rays are at a slightly larger angle (θ) with respect to the axis of symmetry of the target than the incident rays, but remain in the plane of the gradients in the target (r, θ plane). While a homogeneous plasma would be expected to scatter both SRS and SBS directly back into the lens, there are a number of ways in which the inhomogenities in the hohlraum target can cause the observed deflection of the SBS. One effect is the steering of the incident beam by formations of filaments in the flowing plasma near the laser entrance hole [9].
This steering has been observed in similar experiments [10,11] and can deflect the incident beam by as much as several degrees. Direct back scatter from the deflected portion of the beam would appear off the axis of the incident beam similar to what is observed in figure 6. Additionally, as will be discussed in a future publication [12], including the dephasing effects [13] due to strong inhomogeneities in the flow velocity near the laser entrance hole can cause the SBS gain to increase in the direction of the observed asymmetry in figure

6. Similar measurements of the distribution of scattered light in gas filled hohlraum experiments shows that as much as 50% of the back or near back scattered *SBS* is not collected by the lens when the f number is 4.3, while as much as 96% is not collected by the lens when the f number is 8. Since as much as 8% of the incident energy is Brillouin scattered within 20° of the lens, the measurement of light outside the lens is important for determining energy balance in hohlraum targets.

Conclusions

A system capable of imaging energy scattered both in and outside the final laser focusing lens, has been installed and routinely operated on the Nova laser facility. It has been shown that the calibration of the optical components operating in the harsh environment of the target chamber, can be maintained by a combination of routine maintenance and in situ calibration. Measurements of scattered light from targets relevant to ignition experiments indicate that the light scattered outside of the lens makes a significant contribution to the overall energy balance when the f number of the beam is large.

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Figures

Figure 1 — Schematic of the FABS and NBI imaging systems operating on one beam of the ten beams in the the Nova laser facility.

Figure 2 — The reflectivity of the scatter plate has been characterized in the lab for the experimentally relevant energy densities and with different pulse lengths and wavelengths. Note the mild non linearity above a critical intensity that is well described by a power law.

Figure 3 Spectra of SRS light measured from a 0.1 critical density 'gasbag' target is corrected with the camera response function.

Figure 4 A line out of the image of SBS light scattered outside the lens is compared with signals from diodes mounted in adjacent positions.

Figure 5 Histogram of the calibration constant of the NBI imaging system during a period when the scatter plate was darkened by debris from the target plasma (July 3 through Sept. 15), and a period when the plate was cleaned bi-weekly (Sept. 18 through Oct. 27) demonstrating the effectiveness of maintenance.

Figure 6 Composite image of light scattered both into and outside the lens as measured by the FABS/NBI diagnostic. SBS and SRS are measured separately for a 351 nm beam incident on a gas filled hohlraum target.

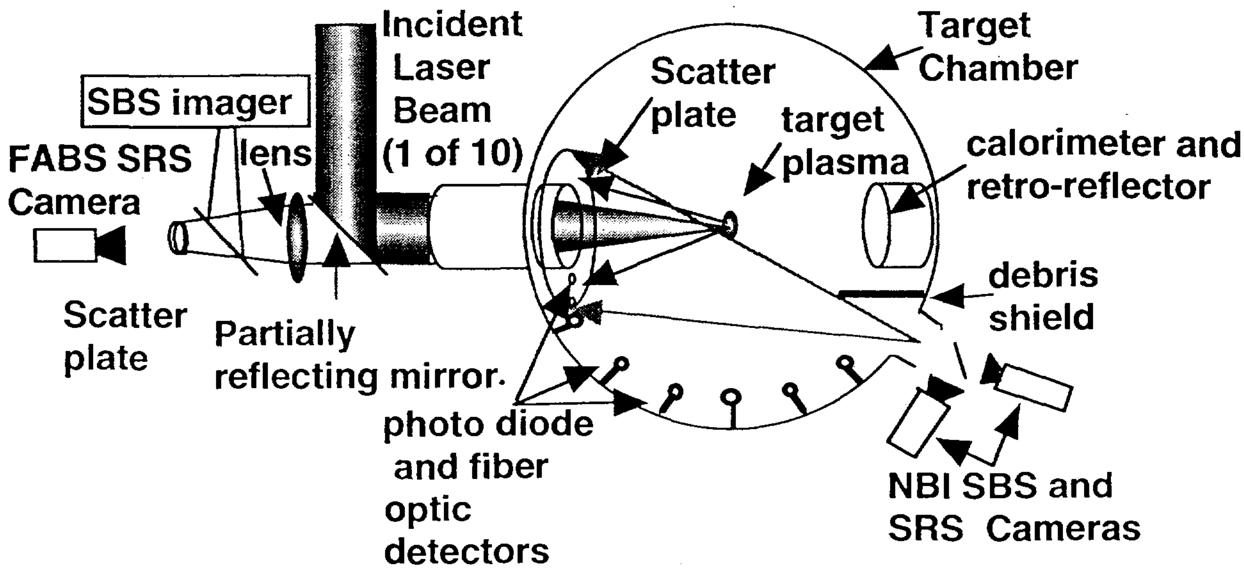
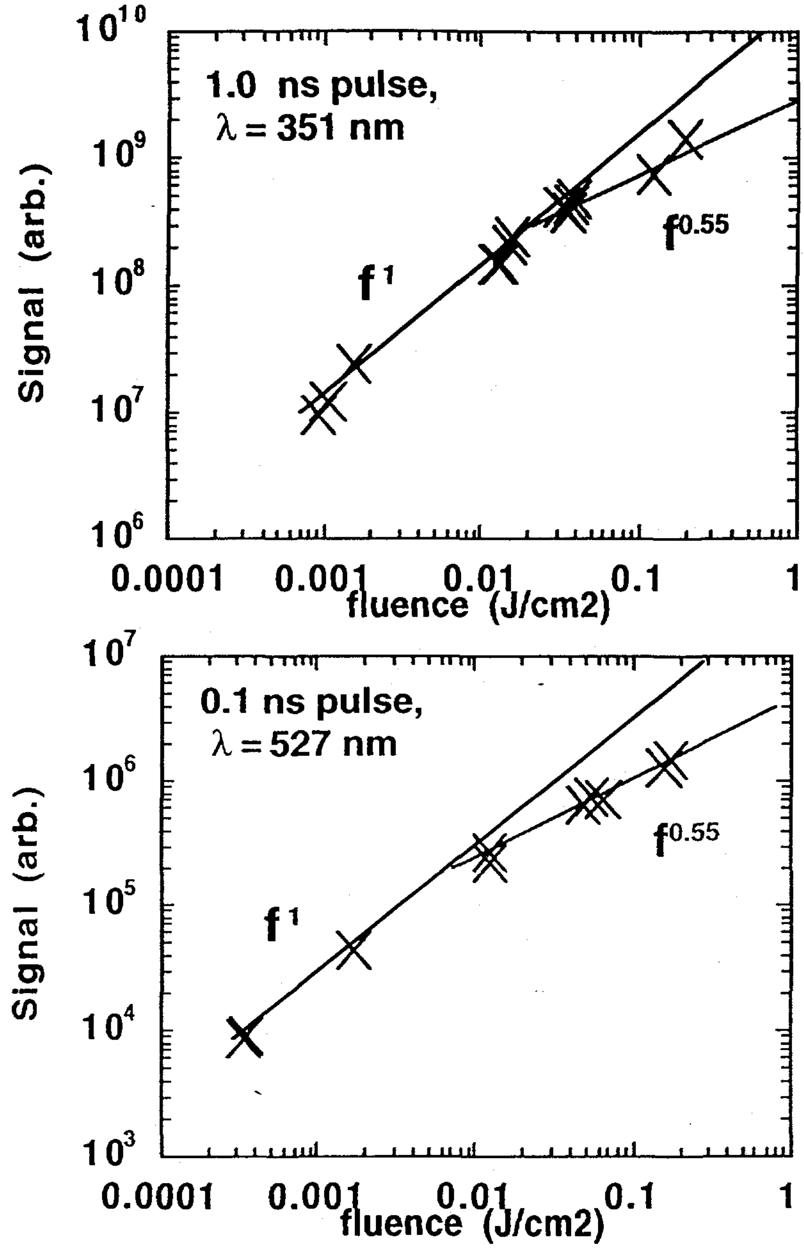

Incident
Laser
Beam
(1 of 10)
Target
Chamber
SBS imager
Scatter
plate
target
plasma
calorimeter and
retro-reflector
FABS SRS
Camera
lens
debris
shield
Scatter
plate
Partially
reflecting mirror.
photo diode
and fiber
optic
detectors
NBI SBS and
SRS Cameras

figure 1



1.0 ns pulse,
λ = 351 nm
Signal (arb.)
fluence (J/cm2)
f 1
f0.55
0.1 ns pulse,
λ = 527 nm
Signal (arb.)
fluence (J/cm2)
f 1
f0.55

figure 2

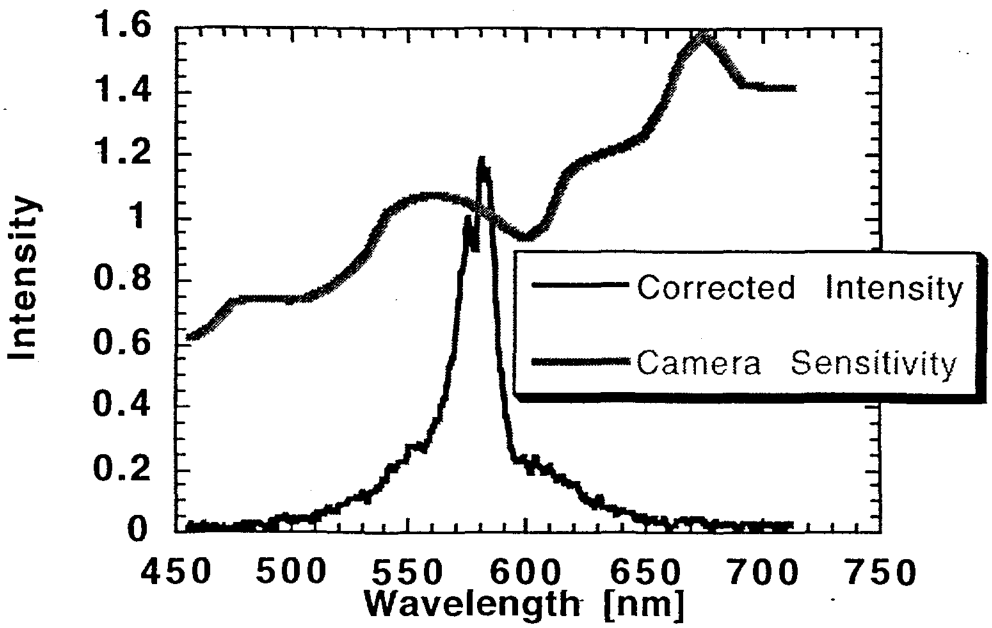

1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Intensity
450 500 550 600 650 700 750
Wavelength [nm]
Corrected Intensity
Camera Sensitivity

figure 3

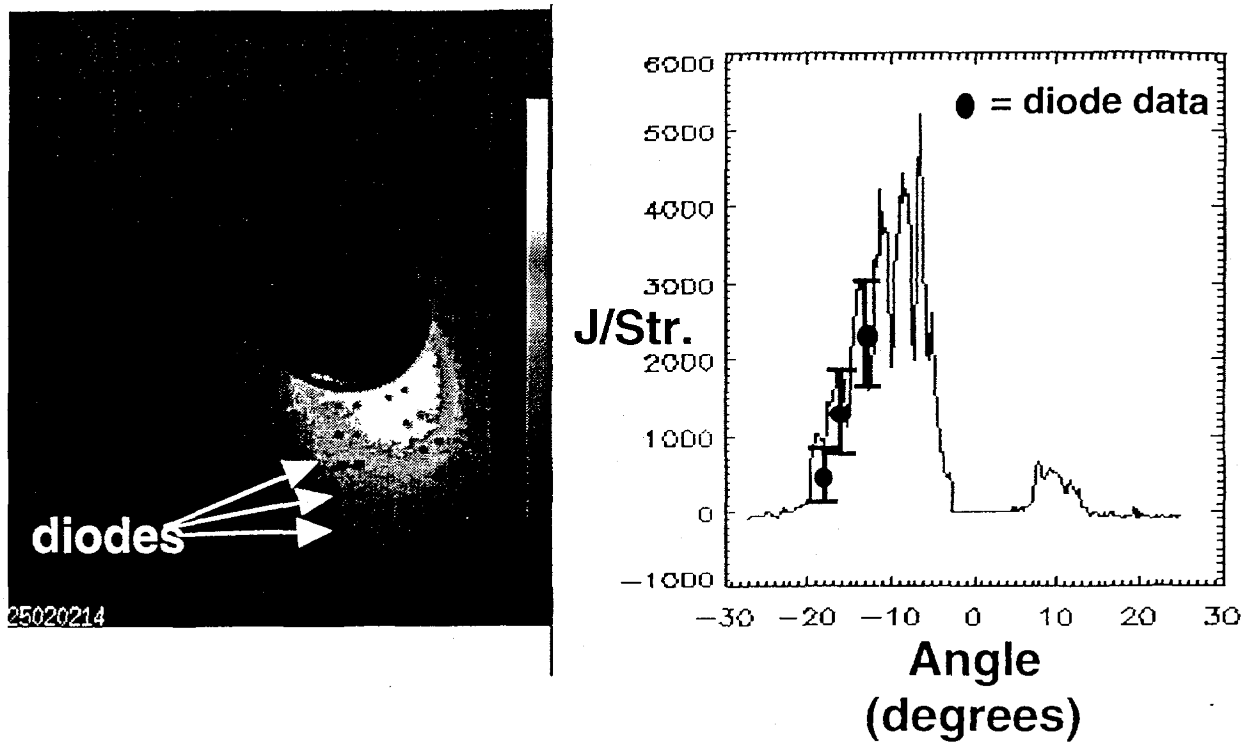

diodes
25020214
● = diode data
J/Str.
6000
5000
4000
3000
2000
1000
0
−1000
−30
−20
−10
0
10
20
30
Angle (degrees)

figure 4

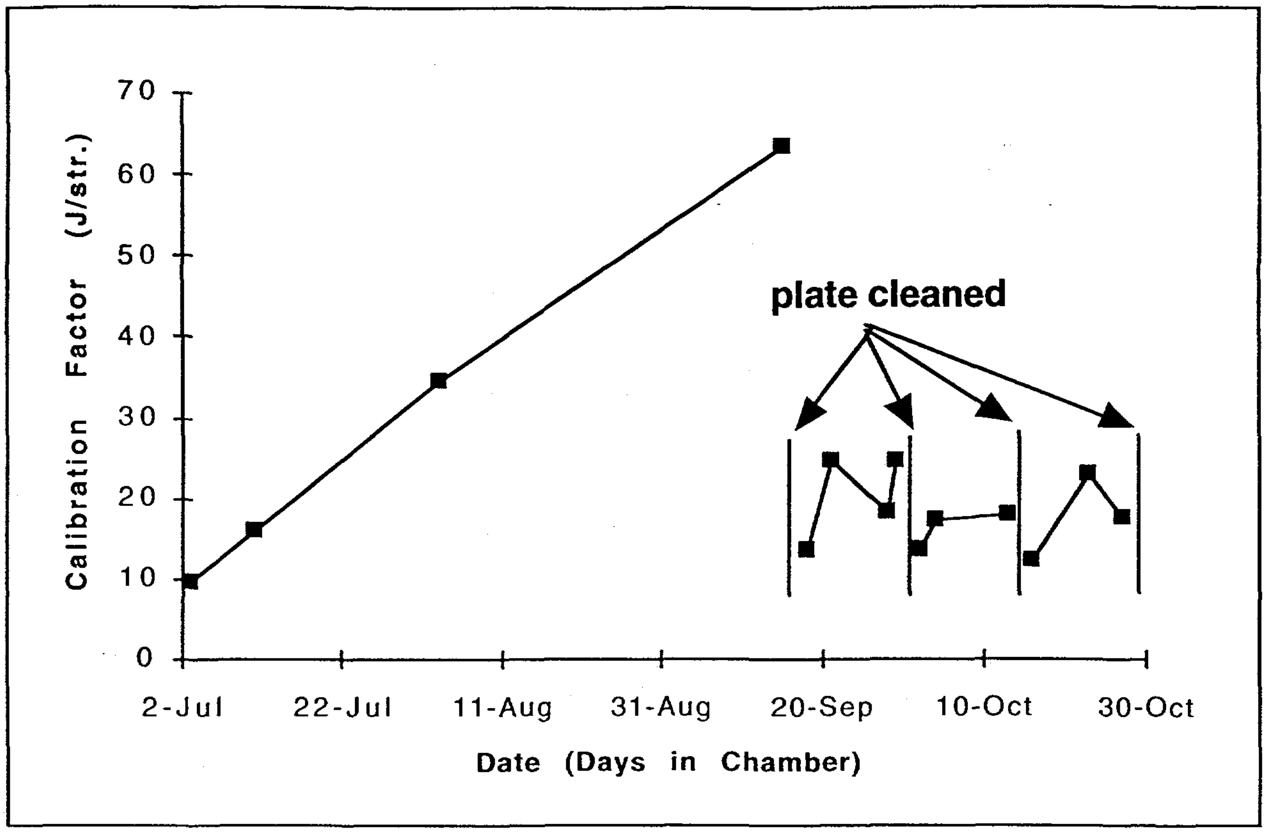

70
60
50
40
30
20
10
0
Calibration Factor (J/str.)
plate cleaned
2-Jul
22-Jul
11-Aug
31-Aug
20-Sep
10-Oct
30-Oct
Date (Days in Chamber)

figure 5

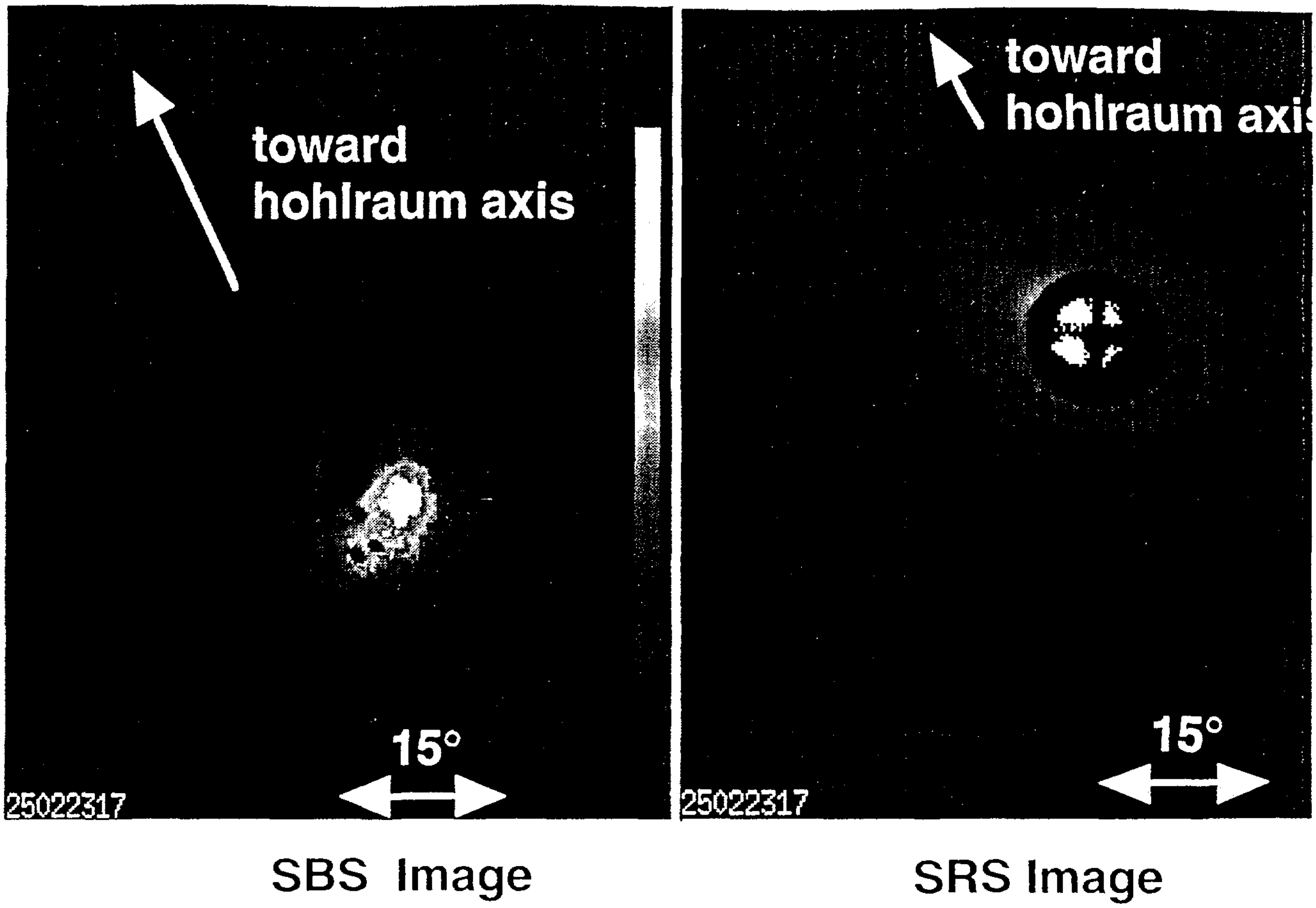

toward
hohlraum axis
15°
25022317
toward
hohlraum axi
15°
25022317
SBS Image
SRS Image

figure 6