International Thermonuclear Experimental Reactor

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Metrology/Viewing System for Next Generation Fusion Reactors

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DISCLAIMER

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ABSTRACT

Next generation fusion reactors require accurate measuring systems to verify sub-millimeter alignment of plasma-facing components in the reactor vessel. A metrology system capable of achieving such accuracy must be compatible with the vessel environment of high gamma radiation, high vacuum, elevated temperature, and magnetic field. This environment requires that the system must be remotely deployed. A coherent, frequency modulated laser radar system is being integrated with a remotely operated deployment system to meet these requirements. The metrology/viewing system consists of a compact laser transceiver optics module which is linked through fiber optics to the laser source and imaging units that are located outside of the harsh environment. The deployment mechanism is a telescopic-mast positioning system. This paper identifies the requirements for the International Thermonuclear Experimental Reactor metrology and viewing system, and describes a remotely operated precision ranging and surface mapping system.

I. INTRODUCTION

The International Thermonuclear Experimental Reactor (ITER) is a fusion device planned to be built early in the next century. The performance and survival of plasma-facing components (PFC) located within the reactor's vacuum vessel depend on precise alignment and positioning with respect to the plasma edge. A remotely deployed and controlled three-dimensional metrology system is being developed to periodically verify the condition of in-vessel components and measure surface erosion. This metrology system has two basic functions: (1) frequent inspection to establish the dimensional status of in-vessel components and (2) extensive checking of in-vessel components and plasma-facing surfaces during scheduled maintenance shutdowns.

II. DESIGN REQUIREMENTS

The interior surface area of ITER is approximately 1500 m^2. In order to achieve acceptable mapping times, ten metrology systems will be required. Each system must be capable of acquiring in-vessel dimensional data accurately, under harsh environmental and radiological conditions. They must withstand gamma radiation levels at 3 x 10^4 Gy/h, while operating in a 200°C environment, in vacuum conditions. The undeployed system will be subjected to a cyclic magnetic field that peaks at 0.15 Tesla (T). In addition, there is a requirement to deploy the system into a constant magnetic field of 6.2 T. The system must also function duringscheduled maintenance activities when the vessel will be at atmospheric pressure.

III. DEPLOYMENT SYSTEM

The viewing/metrology deployment system is designed to support and deploy the laser scanner to survey and assess damage to the first wall surfaces. The deployment system and its supporting structure are located on top of the bio-shield at R=7380 mm from the reactor center. A series of openings in the bio-shield, cryostat, and vacuum vessel will allow a telescopic mast to be extended into the reactor. Figure 1a is a cutaway view of the deployment system mounted above the bio-shield; Fig. 1b is a cutaway of the reactor showing the mast fully depoyed.

During reactor operation, the mast will be stowed inside a vacuum container and isolated from the vacuum vessel by means of a shield lock mechanism at the vessel port, a vacuum isolation valve at the cryostat, and another shielding mechanism at the bio-shield. All of these components are designed to open and close in a specific sequence to preclude neutron streaming and control potential contamination. The deployment sequence is: (1) deployment system bake out, (2) evacuate mast containment, (3) open upper shield lock, (4) open vacuum isolation valve, (5) extend telescopic mast until it reaches vacuum vessel, (6) open lower shield lock mechanism, (7) extend 2nd stage of telescopic mast into vacuum vessel, and (8) position mast in tokamak and begin scanning.

A. Support Structure

The deployment system support structure is approximately 18 meters tall and designed to provide structural/seismic support for the telescopic mast and the two containment vessels. It is mounted directly to the bio-shield. This interface consists of a set of mating flanges, one mounted on the structure the other mounted at the bio-shield opening. In order to achieve the vacuum isolation required during mast deployment a mechanical seal system is used between the two flanges. A set of bolts is used to connect the two flanges and provide the necessary support for the deployment system.

B. Containment Vessels

Two containment vessels house the telescopic mast and provide the required double containment. The inner vessel is designed for ultra high vacuum atmosphere and provides the support points for mounting the telescopic mast and its components. Support points are used to transfer load from the mast to the support structure. Vacuum rated feed through openings are used to route all necessary cables and coolant lines into the telescopic mast. A double door isolation mechanism is mounted at the lower end of the inner vessel at the bio-shield level. The double-door arrangement is designed to prevent the spread of contamination when the deployment system is removed.

C. Telescopic Mast

The telescopic mast delivers the laser sensor into the tokamak during viewing and inspection campaigns. It will position the sensor at various elevations and provide all necessary power and coolant to run the sensor head which is mounted at the tip of the deployment mast-second stage. The telescopic mast is composed of three circular concentric tubes. The outer tube is stationary and supports the two movable tubes as well as the drive unit and the cable reels which are mounted at the top. Tracks and guide rollers are installed between the tubes to provide the necessary alignment and guide the mast during deployment. The mast tubes are driven by two sets of redundant cables which are reeled and unreeled by the drive.

D. Shielding Mechanisms

During reactor operation, port openings must be shielded to prevent neutron streaming and minimize damage to the magnets. Primary shielding is required at the vacuum vessel ports just above the shielding blanket. This is achieved by using a shield lock mechanism which is composed of a series of stationary and rotating disks. During mast deployment the moving disks will rotate to align the openings and provide access for the mast to pass through the shield lock assembly. This shielding mechanism is designed to provide an equivalent shielding thickness of one meter at all times. Figure 2 shows the major components of the shield lock system. Additional shielding is also required at the bio-shield. A similar shield mechanism is used at this level except it has a larger opening to accommodate the first stage of the telescopic tube.

IV. LASER RADAR METROLOGY SYSTEM

A. Background

A lightwave signal from the laser source sweeps linearly in frequency with time. Lightwave signals which have traveled to the target and through the local oscillator fiber optic loop will have a delay which results in a constant beat frequency when the two signals are mixed at the detector. This beat frequency is proportional to the path length difference between the target path and the local oscillator path. A block diagram of the main components of the sensor is shown in Fig. 3.

This laser metrology system is being designed to interface with a vertical deployment mast via a fixed umbilical. Fiber optic connections, cooling fluid, and power signals will be provided by the deployment system to the sensor interface. The sensor package will be completely self contained with all umbilical connections vacuum rated. The connection of the sensor package to the deployment mast will be designed as a hands-on operation for a rad-worker, wearing anti-contamination clothing.

The sensor is based on a design proposed by Coleman Research Corporation, and modified by Oak Ridge National Laboratory (ORNL).[1] Coleman's previous work in this area has yielded a precision laser radar system with a wide field of view, extremely high range resolution, and a high degree of programmability. ITER requirements, however, demand that a totally different sensor head and additional components be added to the current computer system in order to meet the ITER operational scenarios.

An additional challenge is to develop the metrology system for operation in the magnetic field inside the torus. The sensor is to be used with the reactor field coils energized, hence electromagnetic devices such as motors for driving the system cannot be used in the vicinity of the sensor head. This affects the sensor drive and positioning components. Operation in a magnetic field requires that electric drive motors must be placed remotely from the sensor, located in the first stage of the telescopic mast, and the position sensors must not be electromagnetically based, or they must also be placed remotely from the sensor. Figure 4a shows a configuration that cannot operate in a magnetic field, i.e. it has local motors; Fig. 4b is a configuration with motors located out of the magnetic field. Figure 4b is the present mechanical configuration.

B. Operation

The sensor will be capable of 20 meter range measurements with a range precision of approximately 10 micrometers. The design concept supports a field of view that is +/- 185 in azimuth and 100° in elevation. This is accomplished by sweeping a 7° azimuth x 100° elevation scan around the vertical axis of the sensor mast. Sensor resolution will be programmable from approximately 1 point per one centimeter square to approximately 1 point per ten centimeters square.

The sensor head steers the rangefinder laser beam, focuses the beam, and provides feedback on beam direction. The sensor interfaces with the remotely operated deployment mast. The next element is the rotary joint to steer the beam in the azimuthal direction and provide coarse positioning. Fine sweeping is provided by the acousto-optic (AO) device within the sensor. Below the rotary joint is the main sensor body which houses the focusing optics, the acousto-optic cell for beam steering and the nodding mirror.

A polarization maintaining (PM) optical fiber carries the beam to the sensor head. The beam is focused and the focused beam goes into the AO crystal where it is swept from side to side. The beam then passes through a wedge window and then to the nodding mirror. The wedge window is provided to angle the beam so that the nodding mirror can scan straight down.

C. Radiation Effects on Sensor Components

Little data exists on compatibility of certain crucial components of the sensor in the high radiation environment. The AO scanner and the polarization maintaining fiber fall into this category. In the AO device, the effect of high gamma radiation on the TeO_2 crystal was not known. Samples of the TeO_2 crystal and the PM fiber were tested under high gamma radiation at the High Flux Isotope Reactor (HFIR) facility at ORNL.

Although the radiation produced noticeable discoloration (radiation induced browning), there was no noticeable effect on the transmission characteristics of the crystal in the wavelength range of interest. Identical results were obtained for a second crystal. Therefore, it was concluded that the basic TeO_2 crystal is sufficiently rad-hard for ITER application. Future plans include the radiation of a complete AO device that will include the lithium niobate electro-acoustic transducer. The conclusions from the fiber irradiation were: (1) there was degradation in laser transmission with radiation dose, but, the deterioration can be readily compensated by gain adjustments, and (2) although we did not succeed in collecting sufficient data for a plot, the ratio of the two polarization components measured at two discrete intervals was constant, suggesting that the polarization did not change with radiation.

D. Magnetic Field Effects

Preliminary estimates have been made regarding the effects of operating the device in steady magnetic fields of up to 6.2 T. The direction of the field is toroidal, and therefore is orthogonal to the direction of probe deployment. The force on the boom during insertion is in the axial direction (only about 100 N for an insertion velocity of 1 m/min) and can be further reduced by reducing the insertion velocity. The j x b forces acting on the electrical leads of the AO device also appear not to be problematic. The primary problem is to design a remote actuating device for adjusting and monitoring the mirror position that can operate reliably. The operation of some of these crucial components will be tested in the High-Field (Magnetic) Test Facility at ORNL.

V. SENSOR MEASUREMENTS

Several different material types are currently being considered for first wall use in ITER. Since the range accuracy of most laser based ranging systems is highly dependent on the surface material type, several materials proposed for ITER were analyzed for their effect on range measurements. The materials chosen were beryllium, tungsten, and a carbon fiber composite (graphite). Each material was placed in a rotary stage and moved through a range of angles between 0 and 90 degrees with approximately 100 measurements made at each angle. The standard deviation of the highest quality range measurements were found to be acceptable.[2]

Further ranging tests were made with the Coleman system on a heat-damaged beryllium tile from the ORNL ISX-B fusion reactor. A photo of the tile used is shown in Fig. 5. The damage can be clearly seen at the apex of the tile's top surface. Using a scan pattern of 100 X 100 points, and measuring at a distance of 4.6 meters, a surface mesh of the range measurement data yields a graph as shown in Fig. 6. Additional testing will be done to assess range precision as a function of angle of incidence.

CONCLUSIONS

A remotely operated deployment mast and a frequency modulated, coherent laser radar system are being developed for remote metrology of plasma facing surfaces in the ITER (a 1500 MW fusion reactor that is currently in the design phase). The work to date shows that the system is capable of providing both qualitative and quantitative information regarding plasma facing surface conditions. Encouraging results were obtained from the testing of certain crucial components for radiation tolerance. Although the device is being developed for metrology and inspection of the internals of a fusion reactor, it can be applied to a variety of other applications involving precision measurements and observation on components in areas not accessible for humans.

ACKNOWLEDGMENTS

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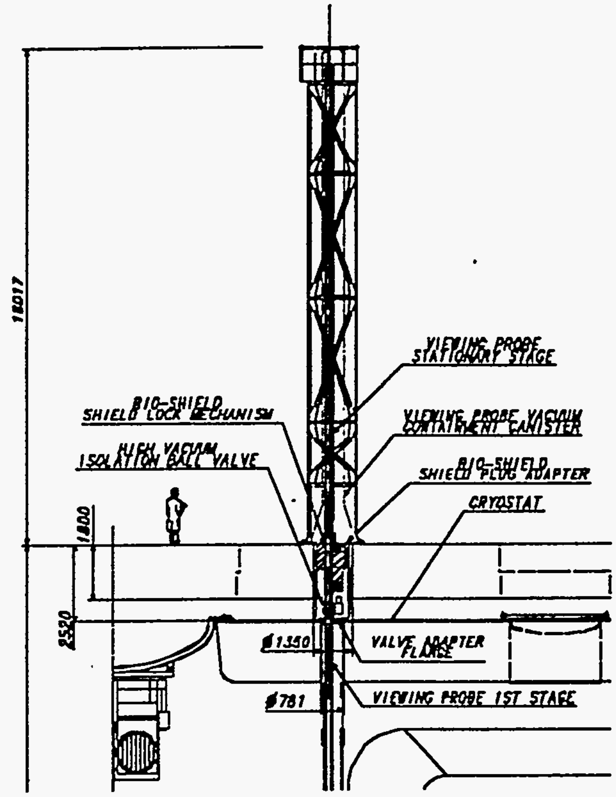


Fig. 1a. Cutaway view of the Metrology System installed above the bio-shield floor.

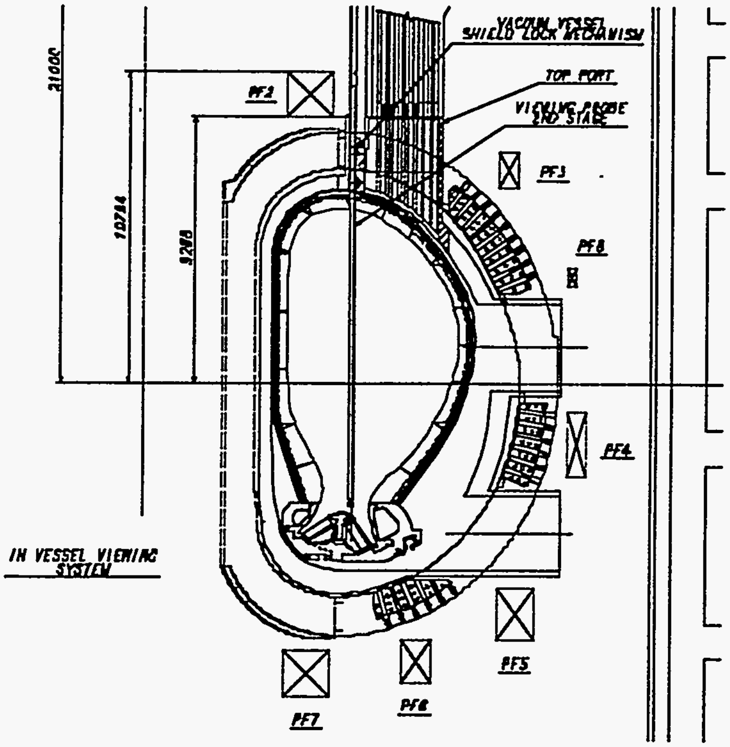


Fig. 1b. Cutaway view of the reactor showing the mast fully deployed.

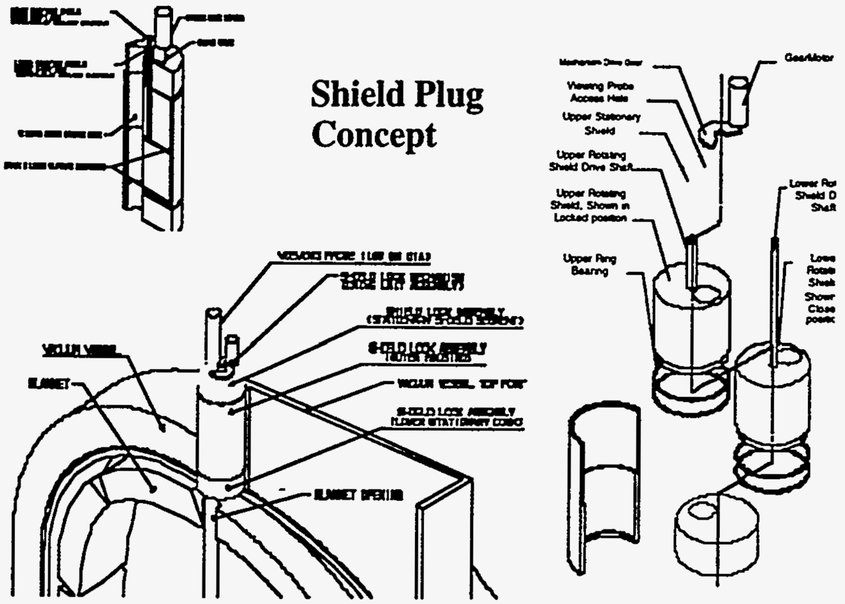


Fig. 2. The major components of the Shield Lock System

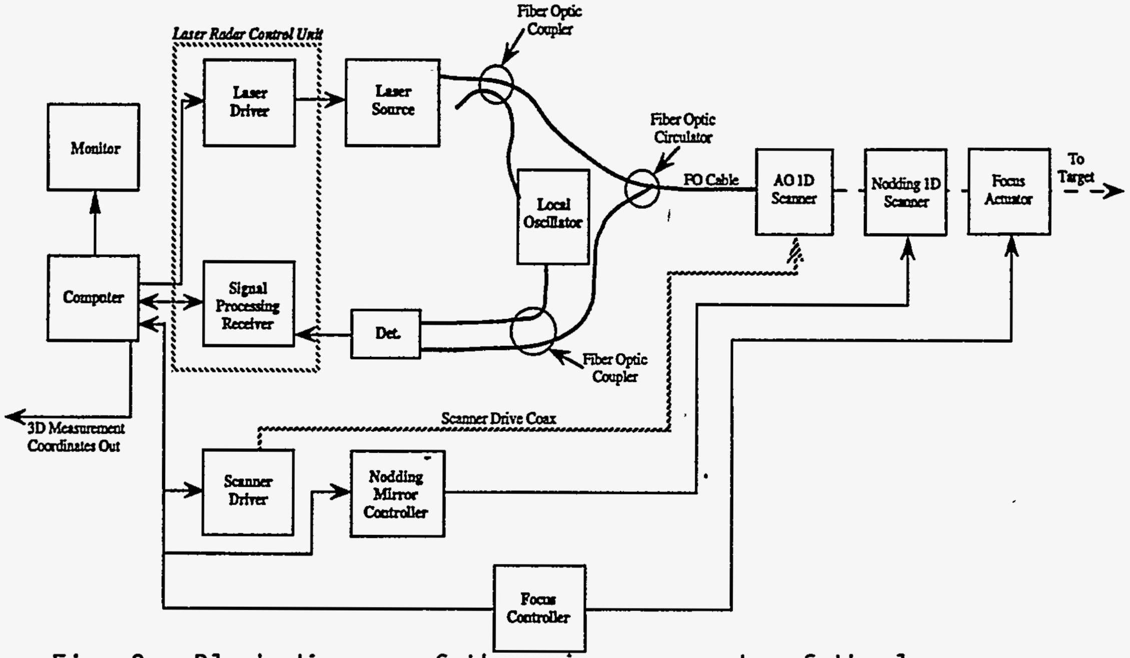
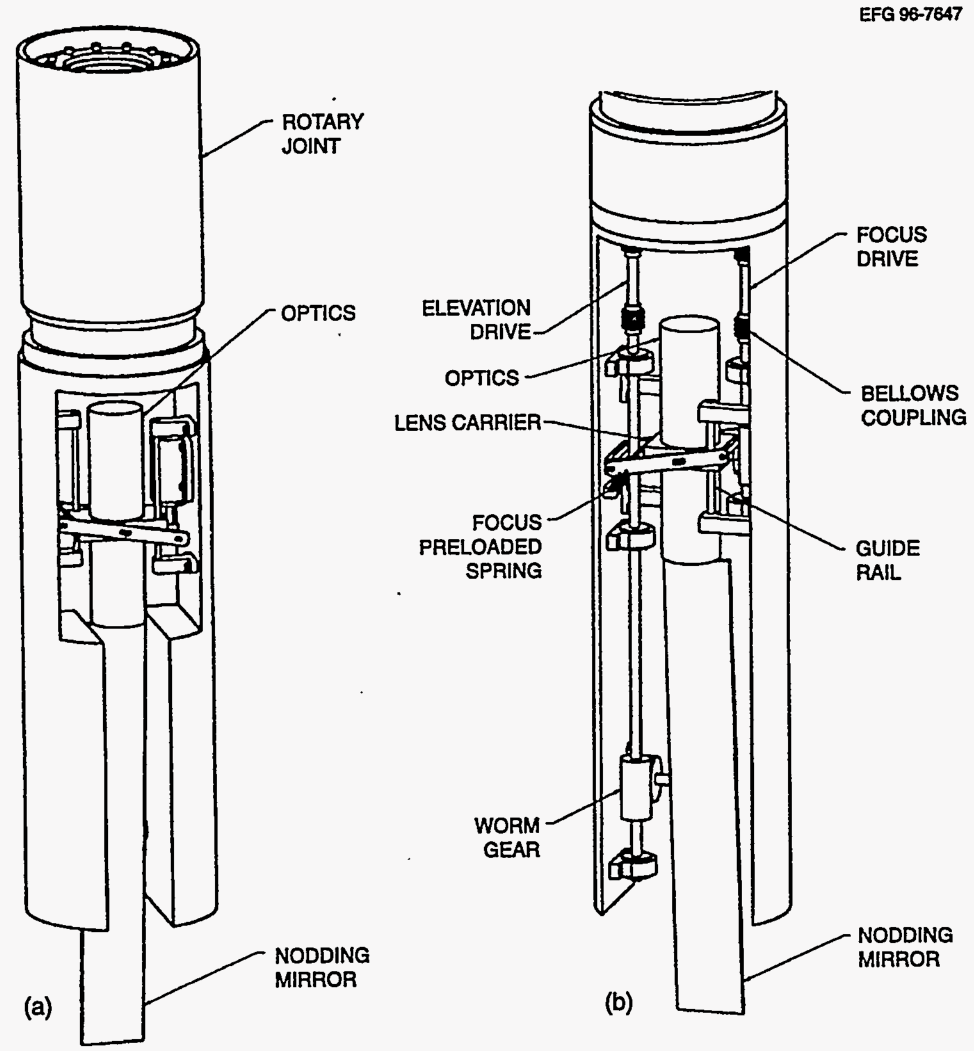


Fig. 3. Block diagram of the main components of the laser sensor.


EFG 96-7647
ROTARY JOINT
OPTICS
NODDING MIRROR
(a)
FOCUS DRIVE
ELEVATION DRIVE
OPTICS
LENS CARRIER
BELLOWS COUPLING
FOCUS PRELOADED SPRING
GUIDE RAIL
WORM GEAR
NODDING MIRROR
(b)

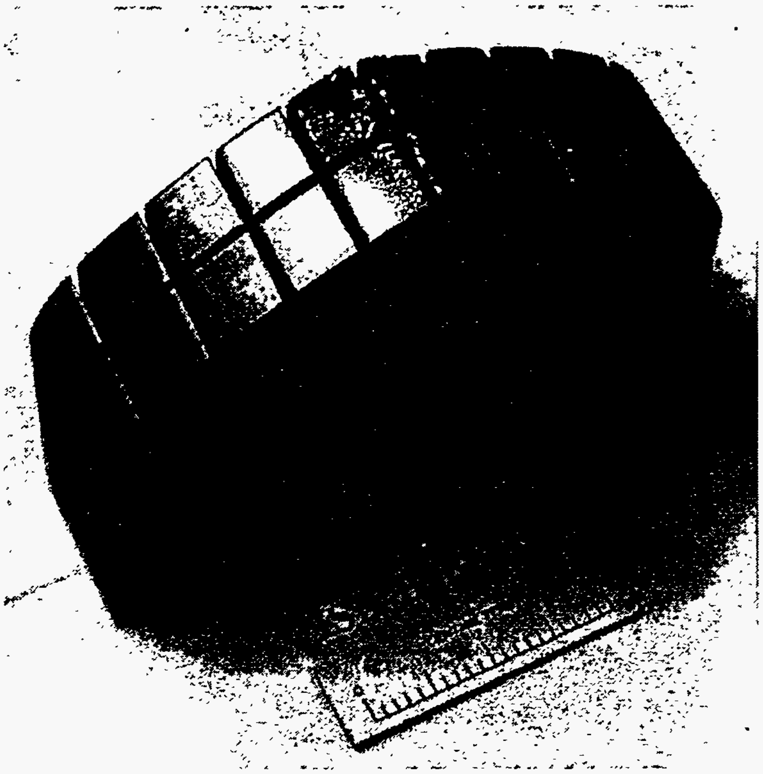


Fig. 5. Plasma damaged beryllium tile from ESX-B.

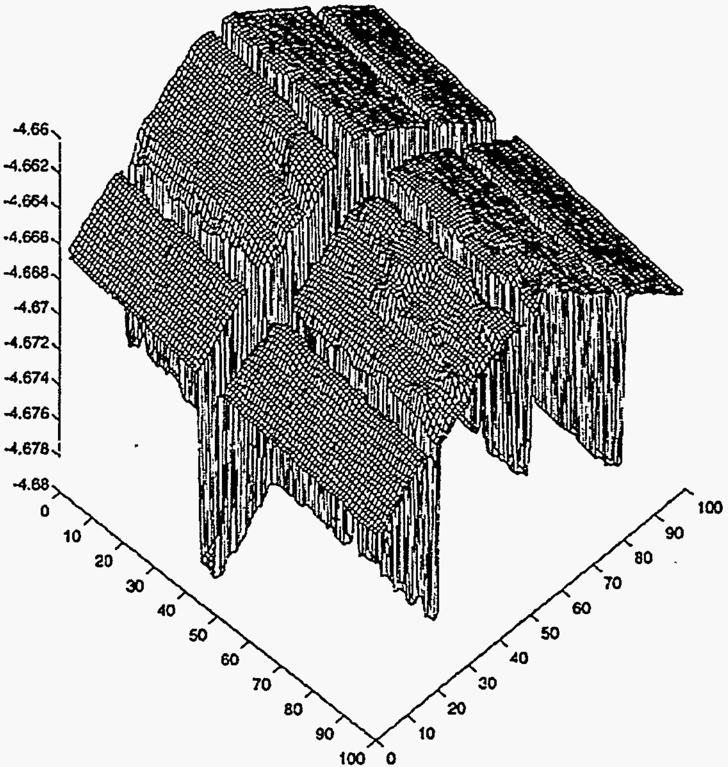


Fig. 6. Surface mesh of range measurement data taken at 4.6 meters.