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by

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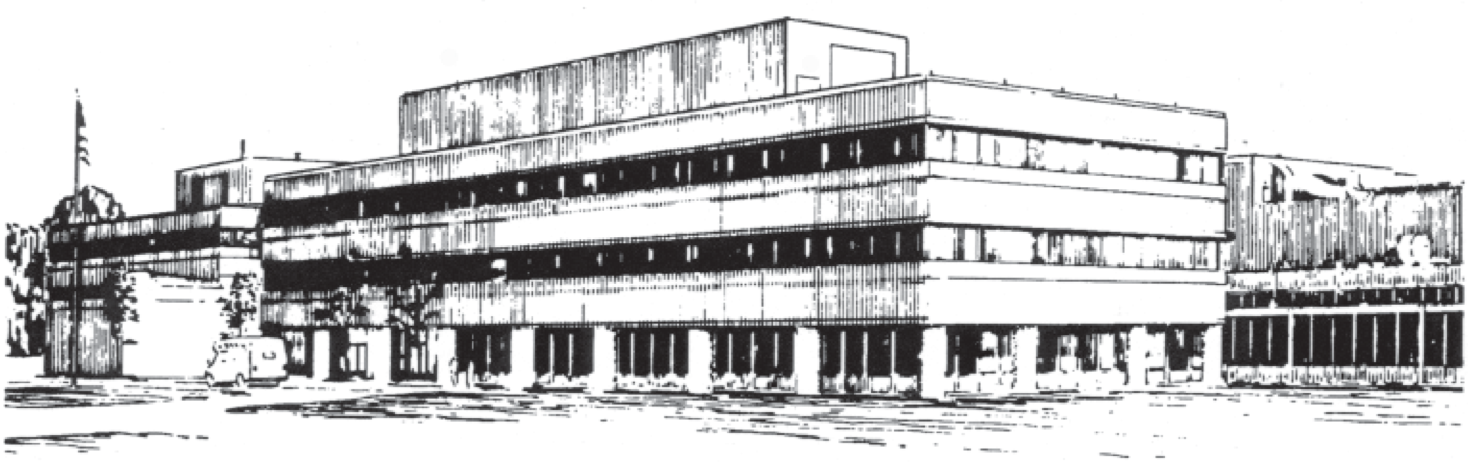

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Infrared camera diagnostic for heat flux measurements on NSTX

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Received

An infrared imaging system has been installed on NSTX at PPPL to measure the surface temperatures on the lower divertor and center-stack. The imaging system is based on an Indigo Alpha 160 x 128 microbolometer camera with 12 bits/pixel operating in the 7-13 μm range with a 30Hz frame rate and a dynamic temperature range of 0-700 °C. From these data and knowledge of graphite thermal properties, the heat flux is derived with a classic 1-d conduction model. Preliminary results of heat flux scaling are reported.

I. Introduction

The National Spherical Torus Experiment (NSTX is a low aspect ratio spherical torus (R=0.86m, a≤0.67m, $I_p \leq 1.5$ MA, $B_t \leq 0.6$ T) [1,2] capable of being operated in single-null, double-null, or center-stack limiter configurations. Thermal imaging on NSTX is required to measure changes in surface temperature of the center stack and lower divertor from which the heat flux absorbed by the plasma facing components may be inferred. Measurement of the surface temperature allows verification that the tiles do not exceed the upper design limit of 1200°C. Temperatures in excess of this value would require a reduction of the pulse length. In addition, the inferred heat flux profile may be compared with models of heat flow in the plasma edge, which can be used for future machine design.

II. Experimental Setup

Two compact Indigo ALPHA cameras with 12 bit dynamic range were installed on NSTX. The indigo Alpha is a 160 x 128 pixel microbolometer operating in the 7-13 μm range with a 30Hz frame rate which produces grayscale images with a dynamic temperature range of 0-700 °C and an efolding response time of ~ 20ms. To provide both magnetic shielding and electrical isolation to 2 KV, the cameras are surrounded by 0.010 cm of Kapton tape, an inner layer of 0.076 cm G-10, an inner layer of soft iron 0.635 cm thick, an outer layer of 0.0762 cm G-10, and finally an outer layer of soft iron

1.270 cm thick. The compact size of the Indigo Alpha (4.32 cm H x 4.32 cm W x 10.92 cm L) minimized the amount of magnetic shielding necessary. One camera was placed with a 15 deg field-of-view lens in a magnetic shield on the top of the machine with a view looking across the lower divertor, through a Zinc Selenide window with a typical IR transmission efficiency of 70%. A remote relay switch enabled power-cycling of the cameras to reduce baseline drift. Spatial calibrations were obtained using the known location of resolved tile features and the resolution was found to be ~ 0.7 cm/pixel. The second camera was installed at the midplane with a view of the center stack (Fig.1) through a similar Zinc Selenide window and a 25 degree field-of-view lens (spatial resolution ~ 1.1cm/pixel). We previously reported results[3] from the divertor camera using an 8-bit video frame grabber. Both cameras now use an Indigo digital interface unit (12 bit capability) and a National Instruments image acquisition (IMAQ) PCI board installed in a local Windows NT computer and are synchronized with experiment through an external electrical trigger to the IMAQ board. The NI IMAQ 1424 boards in use can capture up to 32 bits of data at a clock speed of 50 Mhz for a total acquisition rate of 200 Mbyts/sec with onboard memory of up to 80 MB and have 4 digital I/O lines. Data Acquisition is controlled by a Visual Basic (VB) application, which responds to an external trigger from the NSTX shot cycle, initializes the camera, and collects camera frames for a programmable length of time, usually about 2 seconds, during which the cameras are in a continuous free-running acquisition mode acquiring frames at 30 Hz. An accurate start time relative to the start of the NSTX shot cycle is found using a CAMAC 408 module to capture the Frame Start signal from the camera. Both cameras are controllable from a single PC, but it was determined that reliability was improved at one camera per PC. The VB application properly arranges pixels and puts them into MDSplus[4] (a local database storage structure) for later analysis. Temperature calibrations were obtained through an in-situ process in which pixel intensities were correlated with temperatures taken from thermocouples on the lower divertor and center stack during the NSTX shot cycle (~30-50°C). An additional in-situ calibration was completed during an NSTX vacuum vessel bake (to ~350°C) with gradual temperature changes over a larger temperature range, again correlating pixel intensities with temperatures taken from thermocouples on the lower divertor and center stack.

III. Analysis technique and Results

Typical grayscale images of the lower divertor (Fig. 2(a)) and center stack (Fig. 2 (b)) are shown with the analysis regions marked. The temperature is converted to heat flux using the known temperature-dependent thermal conductivity of the ATJ graphite tiles in the NSTX divertor and center-stack[5], and a 1-D conduction model of heat transport into the tiles as used at DIII-D[6]. Since the thermal characteristics of the inner and outer tiles of the divertor, and of alternating sets of tiles on the center-stack differ, separate heat-flux calculations are done for each of the labeled regions in Figs. 2 (a) and (b). Fig. 3 shows an example of the calibrated divertor temperature and heat flux profiles as a function of divertor tile major radius from the machine centerline. Two distinct peaks can be seen in both of the profiles. The peak at smaller major radius is within a few cm of the inner divertor strike point, and the outer peak is close to the outer divertor strike point. Note that the inner peak has a broad maximum. The full width-half max of these profiles is about 10 cm, i.e. well within the spatial resolution of the system. In contrast the outer divertor profile is narrow. In many cases, the full-width half-max of the profile is 2.2-2.5 cm, i.e. at the lower limit of spatial resolution with the 25 degree field-of-view lens. The typical ratio of the outer to inner peak heat flux is typically 5:1. Integrating under the heat flux profile yields the total power to the divertor target. Typically the outer to inner target power ratio is 3:1. Fig. 4 shows the results of a heat-flux scaling experiment performed with these cameras in high-confinement mode discharges.[7] Note that the peak heat flux increased non-linearly with the level of auxiliary heating power. The highest peak heat flux measured in NSTX to date has been 10 MW/m^2, with a profile width of 2.2cm limited by system spatial resolution.

III. Conclusion & Future Work

Future usage of the infrared imaging system on NSTX includes measurements of heat flux profiles on the center stack and lower divertor in various operation modes. Simultaneous operation of these cameras will allow some gross power balance studies, i.e. what fraction of power flows to the center stack vs. the divertor in various configurations. Future upgrades of the system include obtaining optics with better spatial resolution and a faster frame rate, which will be required to capture fast changes in heat flux due to edge-localized modes (ELMs), reconnection events, disruptions or other plasma phenomena.

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[4]MDSplus Manuals List. http://www.mdsplus.org

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[7]R. Maingi, et. al., "H-mode Research in NSTX", *Nucl. Fusion* in press, 1/03. , Maingi, R. et al. "Recent Results from the National Spherical Torus Experiment", *Plasma Phys. Contr. Fusion* in press, 1/03.

Fig. 1 – NSTX cross-section, showing approximate IR camera fields of view.

Fig. 2ab – Grayscale images of the lower divertor (left) and center stack, showing tile features and analysis regions.

Fig. 3 – temperature increase profile and heat flux profile as a function of divertor tile major radius

Fig. 4 – Divertor heat flux profiles at several different NBI powers. The profile width is reduced as the peak heat flux increases.

Fig.1

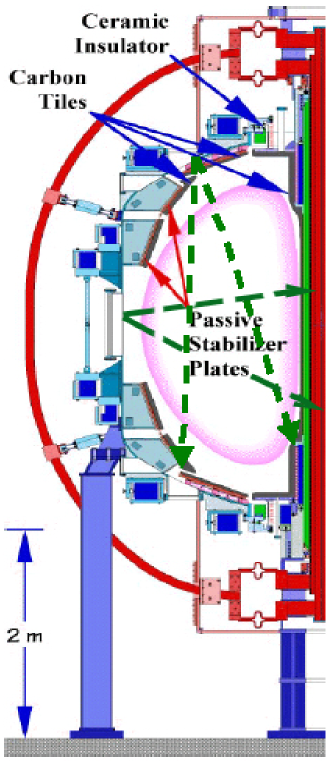

Ceramic
Insulator
Carbon
Tiles
Passive
Stabilizer
Plates
2 m

Fig. 2 (a) (b)

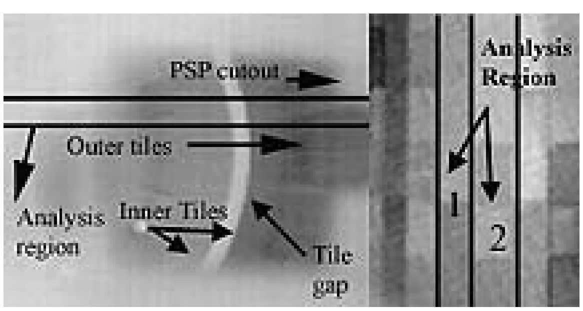
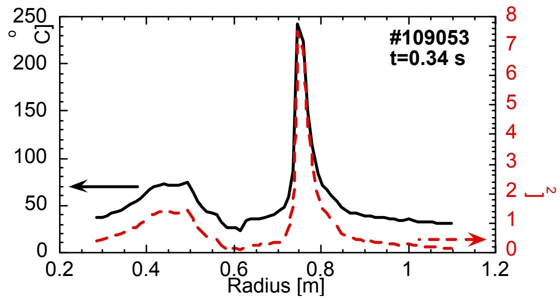
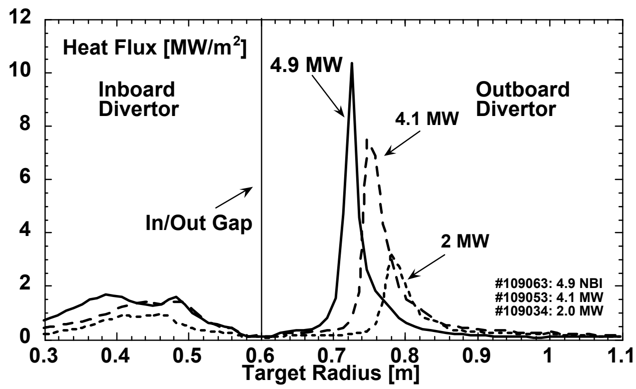

PSP cutout
Outer tiles
Analysis
region
Inner Tiles
Tile
gap
Analysis
Region
1
2

Fig. 3



#109053
t=0.34 s
Radius [m]

Fig. 4



Heat Flux [MW/m2]
Inboard Divertor
Outboard Divertor
4.9 MW
4.1 MW
2 MW
In/Out Gap
#109063: 4.9 NBI
#109053: 4.1 MW
#109034: 2.0 MW
Target Radius [m]

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