APPLICATIONS OF THERMAL IMAGING TO TOKAMAK FUSION PLASMA RESEARCH

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1. INTRODUCTION

The global demand for energy continues to grow and there is an immediate need to find new sources of energy. Controlled thermo nuclear fusion offers significant potential advantages as a clean future source of energy in a scenario where there is increasing concern that the emission of green house gases from burning fossil fuels is producing tremendous climatic change by contaminating the environment. Fusion is foreseen as outstanding candidate for energy source as it has merits such as the abundance of fuel, safety and environmental advantages over present energy sources. The fusion process is safe as there are no avalanching or runaway reactions. Fusion is a clean energy source, as it doesn't produce any harmful green house gases and there are also no radioactive wastes, unlike fission. In fusion reactions two light nuclei fuse to give a heavier nuclei, neutrons and energy. At extremely high temperatures (100 million ^{o}K) at which fusion occurs, the fuel turns into **Plasma**, a hot, electrically quasi-neutral gas consisting of electrons and positively charged ions. This hot plasma is confined in a special device called a Tokamak. Tokamaks are the forerunner in the race to fusion energy. These fusion devices, where very hot plasmas as fuels are confined by magnetic fields, use variety of diagnostics for studying, monitoring and controlling such plasmas. Thermal Imaging or Thermography is one of the important non-destructive, non-invasive, non-perturbative tokamak plasma diagnostics. Thermal imaging is used for monitoring plasma – first wall interaction in tokamak components like limiters, divertors, RF antennas etc., both for safety and energy balance studies. Thermal imaging also aids in measuring plasma radiation losses by the way of bolometry. Besides the above, thermal imaging of tokamak plasmas in the infrared region gives important information about destructive high energy relativistic electrons that are at times generated in

tokamaks and hence facilitates in mitigating them. This paper will highlight some of these interesting applications to tokamak research.

Key words: IR thermography, Tokamak, Runaway Electrons, IRVB, PFCs

2. TOKAMAK: A DEVICE TO CONFINE PLASMA [1]

Since fusion grade plasma is extremely hot it is necessary to isolate it from the container vessel wall for the safety of in-vessel components. This isolation also reduces the conductive heat loss from plasma. Moreover, it helps in reducing impurities from the vessel wall contaminating the plasma, which otherwise will radiate and will ultimately cool the plasma. Out of several magnetic plasma confinement techniques, **Tokamaks** (toroidal’naya ***ka***_mera v_ ***ma***_gnitnykh_ ***k***_atushkakh_ or a toroidal chamber in magnetic coils) are most prominent and widely used technique for confining hot plasmas. In Tokamaks, magnetic field coils are arranged around the vacuum vessel to produce fields in shape of a torus. The charged particles follow the toroidal magnetic field lines as shown in Figure 1 and thus remain isolated from vessel wall. The basic components of Tokamak magnetic fields are illustrated in Figure 2. They are toroidal field, which is the primary mechanism for plasma confinement, poloidal field, which pushes plasma away from wall and maintains plasma shape and stability and the central solenoid, which is for driving plasma current and heating.

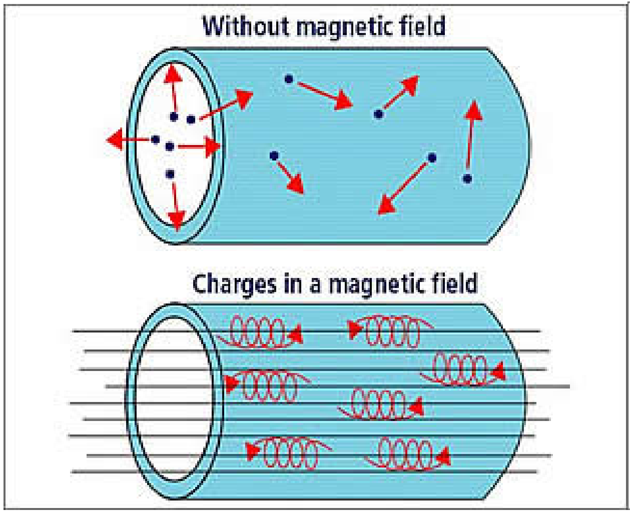

Figure 1: Charged particles spiral along the magnetic field [2]

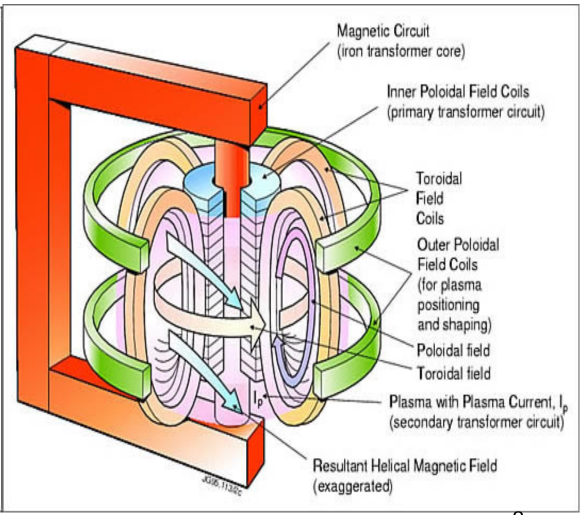

Figure 2 : Schematic of Tokamak [2]

Tokamak experiments are carried out all over the world to demonstrate the concept of the magnetic confinement. India is also involved in fusion research at the Institute for Plasma Research (IPR) and at Saha Institute of Nuclear Physics (SINP). IPR has indigenously built two tokamaks; the first named, ADITYA, which is a small size limiter tokamak and the other which is more advanced one named, Steady State Super-conducting Tokamak - 1 (SST-1).

3. TOKAMAK DIAGNOSTICS

Various parameters of plasma like temperature, density, radiation losses etc. need to be precisely known and measured non-destructively for understanding plasma behavior. Since plasma is confined in vacuum vessel measuring its extreme properties like high temperature and low density is difficult by conventional diagnostic methods. Radiations and particles leaving the plasma are measured by diagnostics. Plasma parameters can be deduced from the knowledge of cause of origin for such radiation and particles.

4. THERMOGRAPHY DIAGNOSTICS FOR TOKAMAKS

Thermal imaging is an important plasma diagnostics as it has an advantage of real time monitoring of the surface temperatures remotely. Thermal imaging has multiple uses in the field of plasma physics. It can be used for surface temperature monitoring of Plasma Facing Components (PFCs), measurement of particle flux and radiation flux from plasma in broad wavelength ranges (e.g. Infrared video bolometer) and for studying synchrotron radiation due to high-energy electrons that are occasionally produced inside the tokamak.

4.1 THERMAL IMAGING OF PLASMA FACING COMPONENTS (PFCS)

PFCs are first components inside the tokamak to come in contact with the hot plasma. They are important first wall components, which play crucial role in keeping plasma away from the tokamak wall. It also helps in protecting other in-vessel components from directly interacting with plasma and thus reducing impurity generation from the vessel wall. Thus PFCs define the edge of plasma. As PFCs come in direct contact with plasma their temperatures may reach as high as 1500 ºC during the plasma discharge. Real-time monitoring of these components help in estimating the temperature rise and plays important role in ensuring machine safety. The key PFCs in tokamaks are Limiters, Divertors, Baffle Plates and passive stabilizer plates.

Flux falling on PFCs can be calculated from time resolved measurements of temperature. This flux is one of the important components of power balance studies in tokamak. Power balance studies are done by comparing total output power from plasma with that of the total input power. One such technique for direct time resolved measurement of temperature is Infrared Thermography. Thermography has an advantage that it can be used from outside the tokamak, which reduces handling complexities unlike other conventional diagnostics.

Temperature monitoring of limiters in ADITYA tokamak has been done by Thermal Imaging technique. The poloidal limiter belt was viewed by IR camera through a CaF_2 window. The image acquisition of the limiter tile was done using MWIR camera working in 3-5µm wavelength range, having CMOS based Mercury Cadmium Telluride focal plane array with 320(H) X 240(V) pixels, which is cooled by Sterling cooler. Field of view of IR camera was 22°(H) X 16°(V). Software was used for data acquisition and camera control. Camera calibration was done in the laboratory. A typical infrared image of the poloidal limiter of ADITYA is shown in Figure 3.

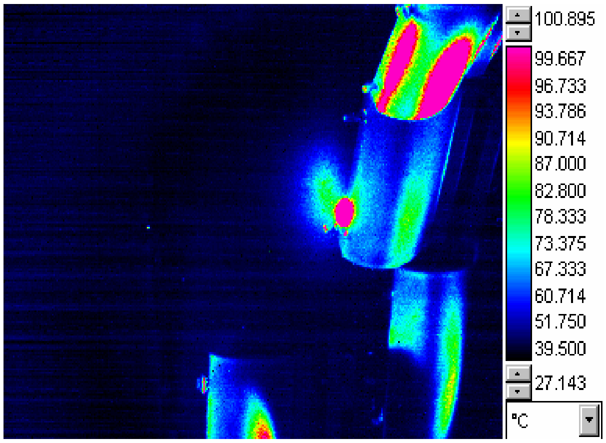

Figure 3 : Thermal image of ADITYA Limiter

The toroidal temperature distribution of the flux for a typical ADITYA discharge is shown in Figure 4. This profile clearly shows two peaks, which signify the electron and ion side of the plasma current. The rise in the temperature of the limiter with time during the discharge is shown as temporal profile in Figure 5.

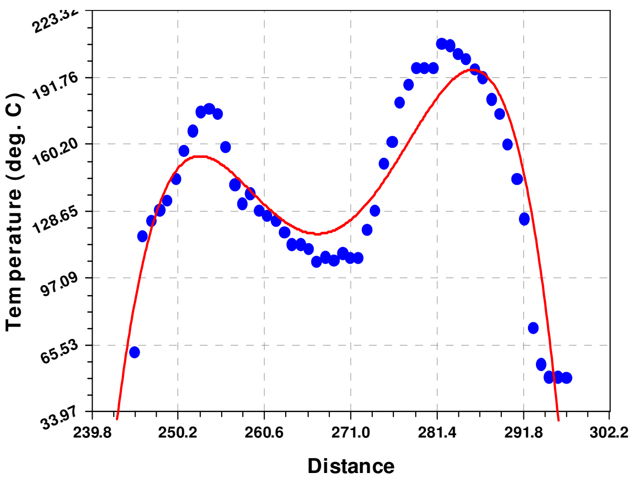

Figure 4: Toroidal temperature profile

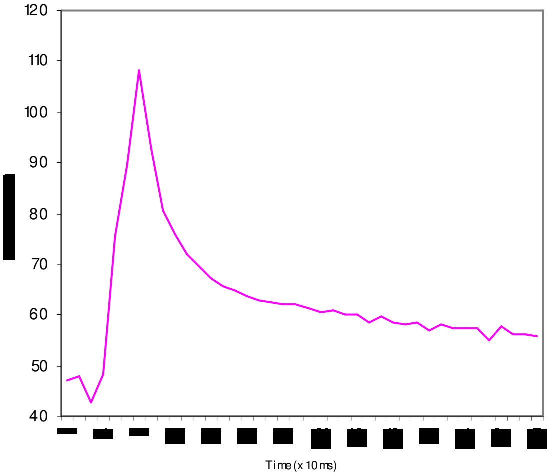

Figure 5: Temporal profile over ADITYA limiter

The tail of Figure 5 shows gradual cooling of the limiter after the plasma discharge. The flux falling on the limiters is estimated by solving the heat conduction equation with appropriate boundary conditions. The estimated power falling on the limiters from the plasma was found to be about 15 to 20 percent of the total input power. Remaining input power is assumed to be confined within the plasma or lost by other loss mechanisms like charge exchange neutrals and radiation in different wavelength regions.

Infrared thermography is planed for limiters and divertors of SST-1 tokamak also. The inboard and outboard limiters of SST-1 are viewed from a single view port. Inboard limiter is viewed directly while outboard limiter is viewed with the help of mirror on the inboard side. A typical infrared picture of inboard limiter and reflected outboard limiter from the mirror is shown in Figure 6.

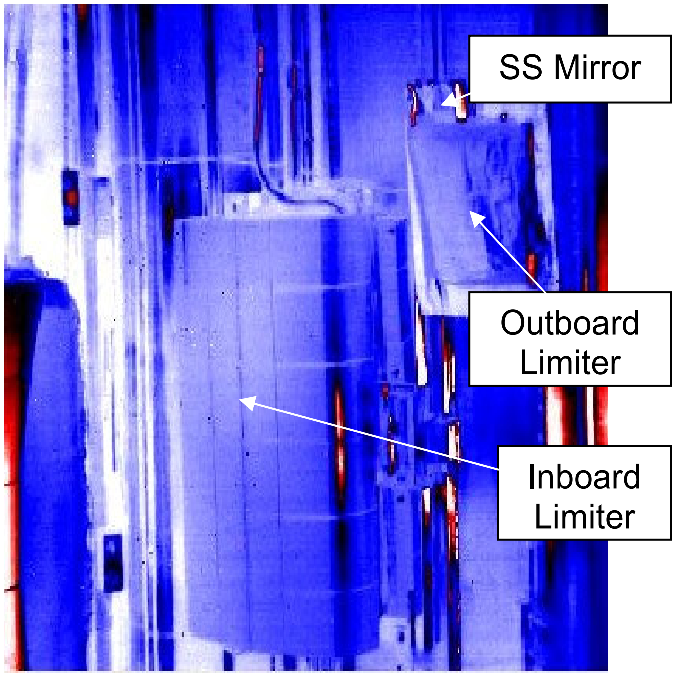

Figure 6: Thermal image of SST-1 Limiter

4.2 SYNCHROTRON RADIATION FROM RUNAWAY ELECTRONS [3,4,5,6]

Plasma current is driven by induced electric field by transformer principle. Electrons are accelerated by this electric field but they experience friction due to collision with ions and other electrons, which provide drag force to accelerating electrons. This force is inversely proportional to square of electron velocity. Hence a small amount of electrons are successful in acquiring enough energy to overcome this drag force and escape from the thermal bulk. These electrons are termed as “run-away” electrons.

Figure 7: Damage in JET Tokamak by Runaways

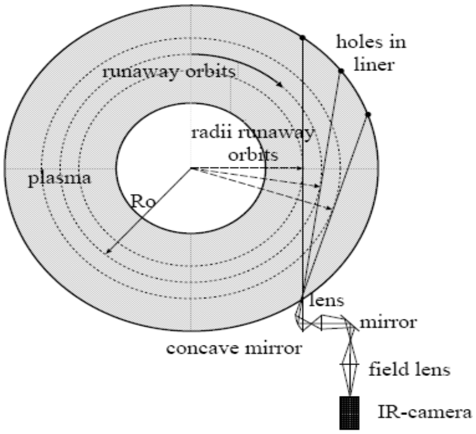

Figure 8: Conceptual design for viewing Runaways [5]

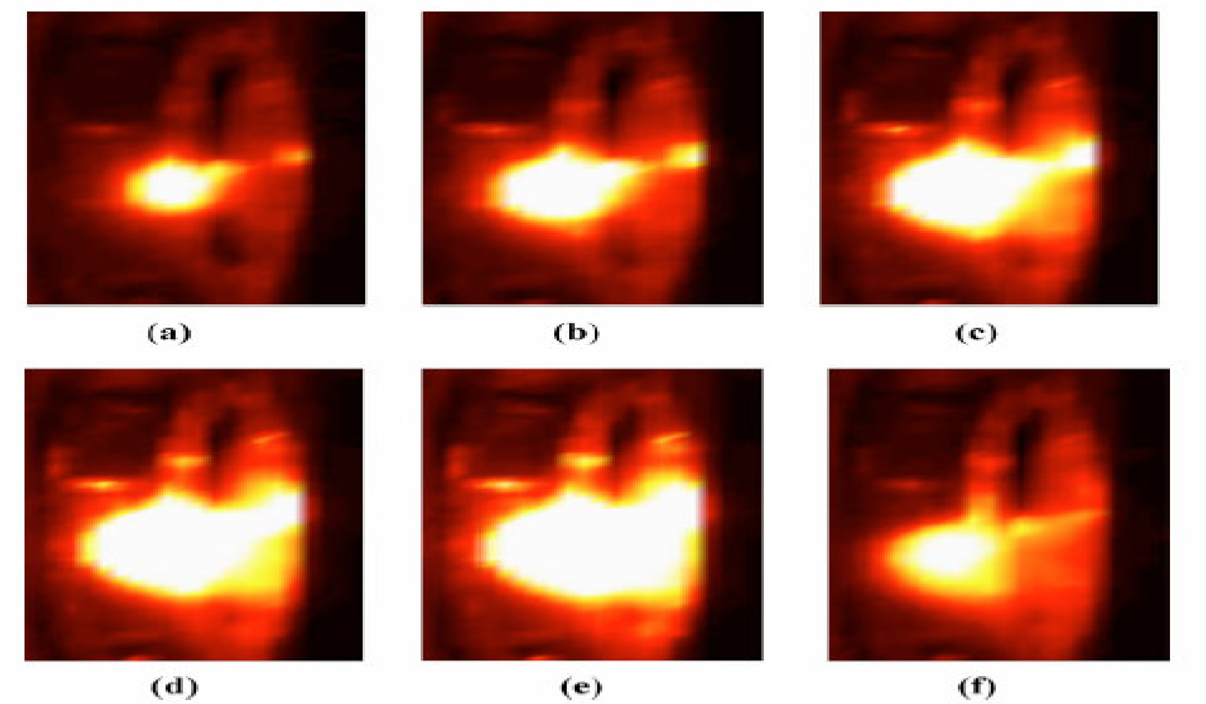

Figure 9: Synchrotron Radiation observed with IR camera at HT7 tokamak [5]

These electrons occasionally reach to energies as high as few tens of million electron volts. Such energetic electrons when lost from the plasma create considerable damage to the in-vessel components. Figure 7 shows the damage done by run-away electrons on the vessel wall of Joint European Torus (JET) tokamak. These electrons gain even more energies (~ 100 MeV) during plasma disruptions as magnetic field rapidly decays transferring huge amount energy to electrons. Hence the study of run-away electrons is essential for machine safety considerations. There are several methods for runaway detection. Low energy runaway electrons are detected by electron cyclotron emission (ECE) measurements. Runway electrons are usually detected by measuring hard x-ray (HXR) radiation. When runway electrons strike on the vessel walls or plasma-facing components, this gives rise to X-rays. However, this detection of HXR cannot measure the runaway electrons directly. It only measures those runaways that are no longer confined. It is well known that accelerated charge particles emit electromagnetic radiation. For relativistic electrons in a magnetic field this is called synchrotron radiation. The synchrotron radiation measurement with thermal imaging camera provides a tool to detect runaways when they are still confined within the plasma and measure different runaway parameters like number of runaways, runaway energy etc. Figure 8 shows the experimental setup schematic for observation of synchrotron radiation. Here an IR camera is placed tangential to the electron approach direction. Figure 9 shows the synchrotron radiation observed in HT7 tokamak[5]. The pictures clearly depict the sequence from generation to extinction of runaway synchrotron radiation.

4.3 INFRARED VIDEO BOLOMETER 7,8,9

Bolometers are used for measurement of heat flux. They are used to measure energy loss due to plasma radiation in fusion research. Conventional bolometers are either semiconductor bolometers or metal foil bolometers. Each bolometer gives one spatial channel of data. Conventionally many such bolometers are interconnected to form an array, increasing wiring and mounting complexities. This demands a robust diagnostic, which fits well into the access constraints, having good sensitivity, low noise, allowing several data channels, less wiring complexities and essentially radiation-hard. Infrared imaging Bolometers has all the merits listed above. In such bolometers a thin metal foil is sandwiched between two identical masks having either holes or rectangular cutout in the centre of the mask. The mask decides the type of infrared video bolometer. The mask with holes in it as shown in Figure 10 is termed as Segmented mask Infrared Bolometer (SIB) whereas the other one with rectangular cutout as shown in Figure 11 is known as Infrared Imaging Video Bolometer (IRVB).

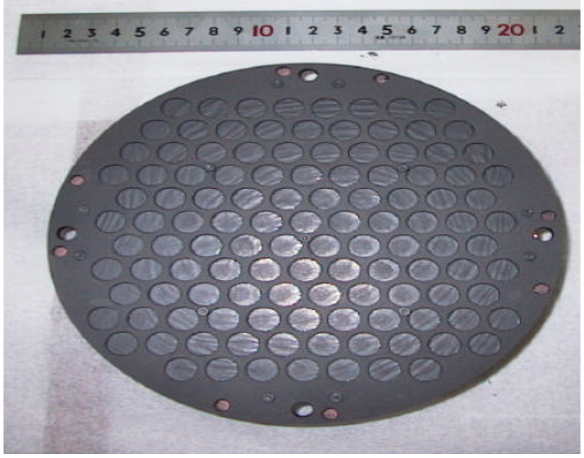

Figure 10: Segmented Infrared Bolometer (SIB) [7]

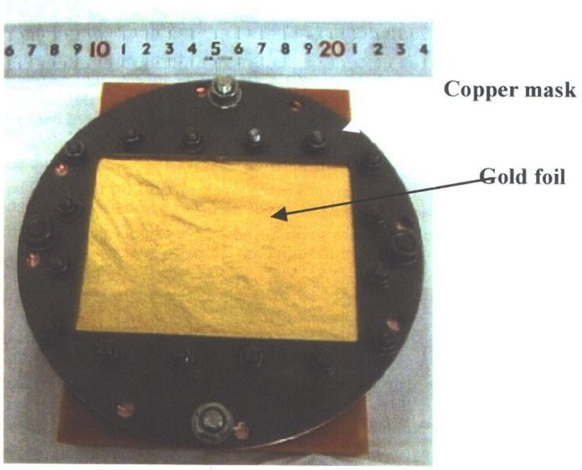

Figure 11: Infrared Imaging video Bolometer (IRVB) [7]

The plasma radiation falls on this metal foil through a pinhole and is converted into heat energy. This change in the foil temperature is monitored by infrared camera from outside the vacuum vessel. The rear side of the metal foil facing the camera is coated with carbon paint to increase the emissivity of the foil. The schematic of such an imaging bolometer is shown in Figure 12. The foil is made as thin as possible with a material having low thermal conductivity for high sensitivity. The material of the foil can be chosen depending on the photon energy to be measured. The mask is made of a material of high thermal conductivity, as mask has to be cooled to act as a heat sink for metal foil, which prevents it from melting during long pulse discharges. This also helps in preventing lateral heat flow from spilling onto adjacent pixels in case of SIB. The pinhole shell is also cooled to eliminate stray IR radiation from the housing. The flux falling on the foil can be estimated by solving the heat conduction equation with appropriate boundary conditions. Figure 13 shows typical IRVB image of a limiter observed tangentially in Large Helical Device (LHD). Figure 14 shows a CCD image of the limiter. It is clearly observed that the hot regions are very well identified in the IRVB image.

In case of SIB each hole in the mask serves as individual pixel. It has an advantage that the mask provides support to the foil and thus makes it robust. Since the pixels are well defined it can be easily calibrated. But SIB suffers from shadowing of the foil by the mask. There are thermal energy losses due to thermal contact by the edge of the pixel to the mask. One of the merits of IRVB is flexibility in number of channels that can be determined after the experiment. There is no shadowing effect and no thermal energy losses as in case of SIB. Images from IRVB are easy to interpret, as there is no shadowing by the mask. But calibration of IRVB is complicated as there are no separated spatial channels. The metal foil can be easily damaged, as it is weakly supported.

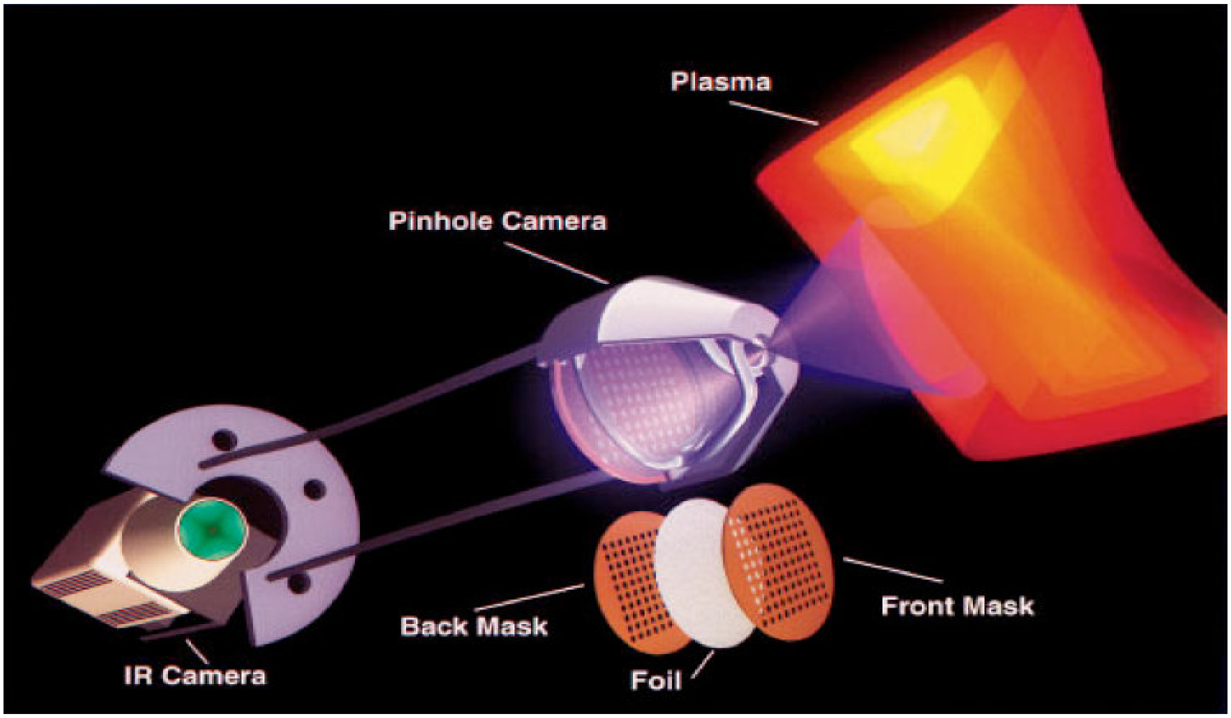

Figure 12 : Schematic for Infrared imaging video Bolometer [9]

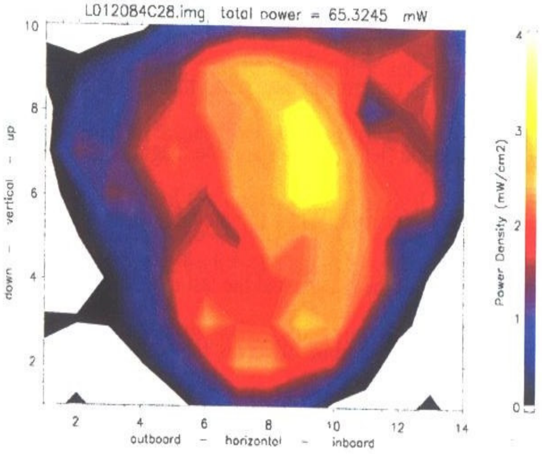

Figure 13 : IRVB image of limiter in LHD [7]

Figure 14 : CCD camera picture of limiter in LHD [7]

5. SUMMARY

Looking at the above sited applications of Infrared thermography in fusion research it can be concluded that thermography can play a crucial role as a prominent plasma diagnostics. It has vital applications in temperature measurement, flux estimation, power balance calculation, transport studies, deriving runaway parameters and mitigation of disruptions. It has applications in safety monitoring and can actively contribute to plasma discharge operations control by providing rapid feedback.

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