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** See annex of J. Pamela et al, "Overview of JET Results ",*
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INTRODUCTION

The surface temperature of the plasma facing components needs to be measured to operate large, additionally heated tokamaks in a safe manner and to calculate the power flux impinging on the different parts of the machine [1]. In the framework of JET-EP (Enhanced Performances), a new infrared thermography diagnostic is being developed. The objective is to provide a wide-angle view in the infrared range (3 to 5μm) for thermography of the main chamber and divertor, aiming at real time machine protection and analysis of the power flux deposition during normal operation and transient events such as disruptions and ELMs.

OPTICAL DESIGN

In order to image a large section of the tokamak in both poloidal and toroidal directions, the optical system has been designed with a field of view of 70 degrees, viewing the divertor, the inner wall, the outer poloidal limiters, the ITER-like ICRH antenna and the top limiter (Fig.1). The diagnostic is located in octant 8, in a lower limiter guide tube (horizontal port at 330mm below the equatorial plan. An important aim of the optics design is that it should be ITER-relevant. To this end, the optical components are mainly reflective, being the only kind which can sustain high neutron radiation. The diagnostic consists of an endoscope formed by a tube holding the front head mirrors, a Cassegrain telescope, and a relay group of lenses, the latter being connected to the camera body [2]. The design uses a concave aspheric mirror located behind a flat mirror equipped with a small aperture (Fig.2(a)). Both mirrors are made of stainless steel coated with gold. The combination of the aspheric (primary) and flat (secondary) mirrors allows to bend the beam with an angle of 40^o, collimate the beam in the endoscope tube and place the black hole (shown in figure 1) in an acceptable position in the image. The black hole in the field of view is due to the aperture located by purpose in the flat mirror allowing to protect the primary mirror from plasma radiation and to minimize the off-axis of the parabolic mirror in order to simplify the following optic. The Cassegrain telescope (Fig.2(b)) is composed of elliptic and hyperbolic mirrors, both made of Zerodur® glass (gold coated) and a field group made of 2 Silicon lenses. Finally, the image is magnified and transmitted to the detector with 4 Silicon and Germanium relay lenses (Fig.2(c)). The infrared camera is equipped with a MCT detector, working in the 3.6-5.1μm range and cooled at 80K by using a closed loop Stirling cooler. The Focal Plan Array (FPA) is formed by 640×512 pixels with a pitch size of 25μm

Additionally, a part of the photon flux is extracted in the Cassegrain telescope and transmitted via a 200mm lens to a CCD camera, giving the same field of view in the visible range. Only a small fraction of the light is used for the visible line: the part which would be lost due to the central occultation, therefore the f number is the visible range is large (f# ~10) while the f number in the IR range is about f# ~4.5.

Strong requirements apply to the shape and the positioning of the optical elements. The most critical tolerances apply to the Cassegrain, which requires a mirrors surface quality of about 100nm (0.3 fringe on interferometer test pattern) and a positioning precision of about 30μm. To fulfil these constraints, a strong connection between optical and mechanical design is absolutely mandatory and both merge in an opto-mechanical design. A 3D view of the diagnostic with the IR camera installed on the endoscope is shown on figure 3.

PERFORMANCES

The main specifications in the design of the IR thermography diagnostic are the spatial resolution, the dynamic range of the temperature measurement and the time resolution. The performance of the system in term of spatial resolution is due on one hand, to the optics, and on another hand to the number of pixels of the camera. In the present stage, commercial FPA detectors are limited to 640 lines by 512 columns. With a pitch size of 25µm, the limit in resolution for the camera is 20 cycles per millimetre. The system is diffraction limited for all the points in the field and all incident light is focused within the pixel size. The criterion retained for the space resolution of the optic is based on the Modulation Transfer Function (MTF) measurement. The theoretical MTF curve obtained with the optical code (Zeemax) is plotted on figure 4. The expected yield at 20 cycles per mm gives a resolution of 8 mm at a distance of 3 meters, with a contrast of 40%. For absolute temperature measurement with an error bar of 10% (MTF >80%), space resolution is reduced by a factor 2.

Thanks to the gold coating, the reflection on the mirrors is close to 98% ; taking into account the transmission of the lenses, the global transmission of the endoscope is larger than 60%. A large transmission factor is required, not only to get a high photon flux allowing to perform acquisition with short integration time, but also to minimize the parasitic flux emitted by the hot optics with an emissivity $\varepsilon = 1\text{-}R$, where R is the reflection or transmission coefficient for the mirrors or lenses, respectively. In that respect, the main source of stray light will be produced by the uncoated double sapphire window, located at the front of endoscope and at a temperature of 200^{o}C.

REMOTE CONTROL AND DATA ACQUISITION SYSTEM

The diagnostic should be able to measure from operating temperature of 200^{o}C up to a maximum temperature of 2000^{o}C. Nevertheless, the photon flux follows a non linear dependence with the surface temperature ($\varphi = \sigma T^4$ over the full spectral range), limiting the dynamic range of the temperature measurements. In our case, the dynamic range is enhanced by using a multi integration time : three integration time are used and the corresponding frames are combined in a single thermal image. The acquisition of the raw data is performed in 14 bits and the reconstructed frame, with the full dynamic range, is stored in 16 bits. The pixel clock is set at 10MHz and with four parallel readout systems, we can achieve a frame rate of 100Hz with a full image size. The maximum frame rate can be increased up to 10kHz by reducing the image size to 128×8 pixels, located at any position in the field of view. With an image of 640×512 pixels and a frame rate of 100Hz, the data flux is about 65MB/s. The storage capability has been limited to 1GB per shot (~15s of acquisition). Data are first written locally on the diagnostic PC and then transmitted at the end of the pulse to Codas for storage. Additionally to the numerical data, an analog video output is available in real time in the JET control room. Both digital data and video signal are transmitted from the torus hall to the diagnostic hall through optical fibres (Fig.6). Control of the camera (integration time, duration, size and location of the image, etc) is performed from the control room by using an HTTP server protocol.

CONCLUSION

In the framework of the JET-EP program, a new infrared thermography and visible view diagnostic has been designed using mainly reflective optics. The wide-angle field of view will permit to observe a large fraction of the Plasma Facing Components (divertor, ITER-like ICRH antenna, inner, outer and top limiters). The endoscope and the infrared camera are in manufacturing phase and should be delivered at JET in summer 2005.

REFERENCES :

[1]. A.E. Costley et al, Diagnostics for ITER, Varenna, Aug. 1995

[2]. J.B. Migozzi, E. Gauthier, internal note CEA, DIAG/NTT-2004.017, CEA Cadarache

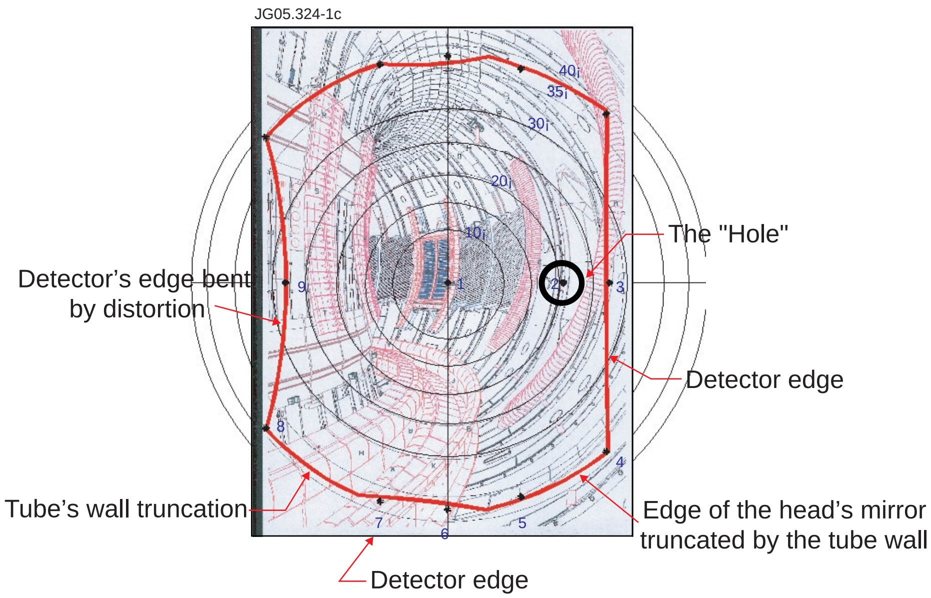

Figure 1: Field of view in the infrared and visible range

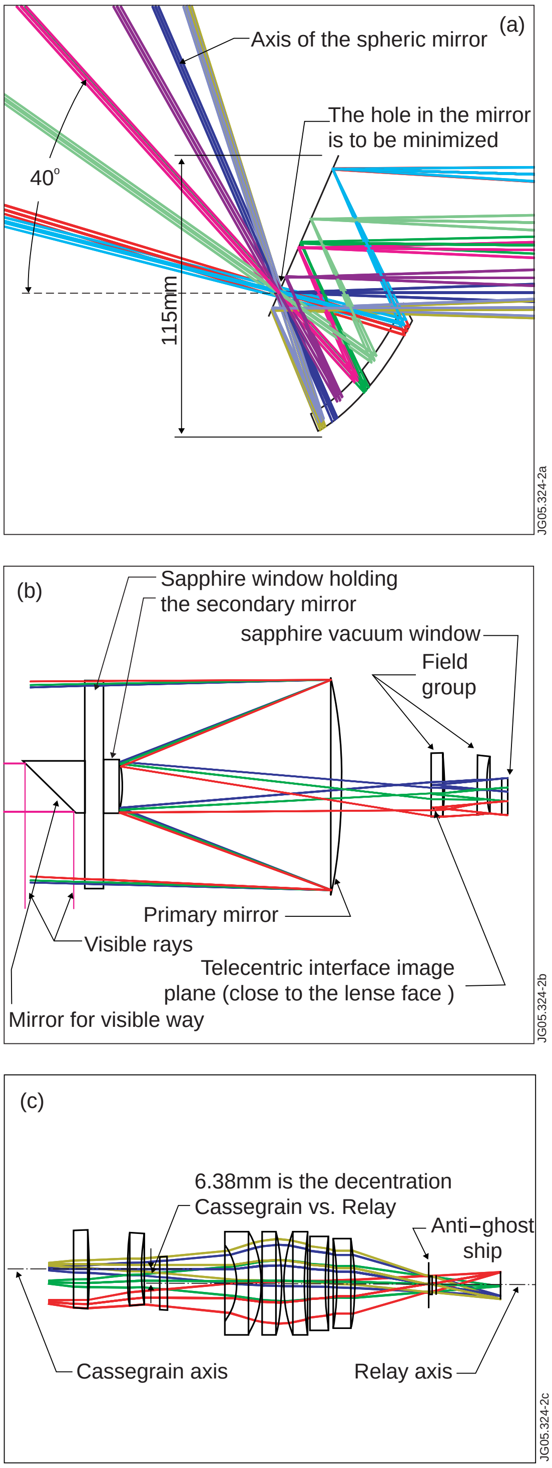

Figure 2: Optical design of the front mirrors (a), Cassegrain (b) and relay group lenses (c)

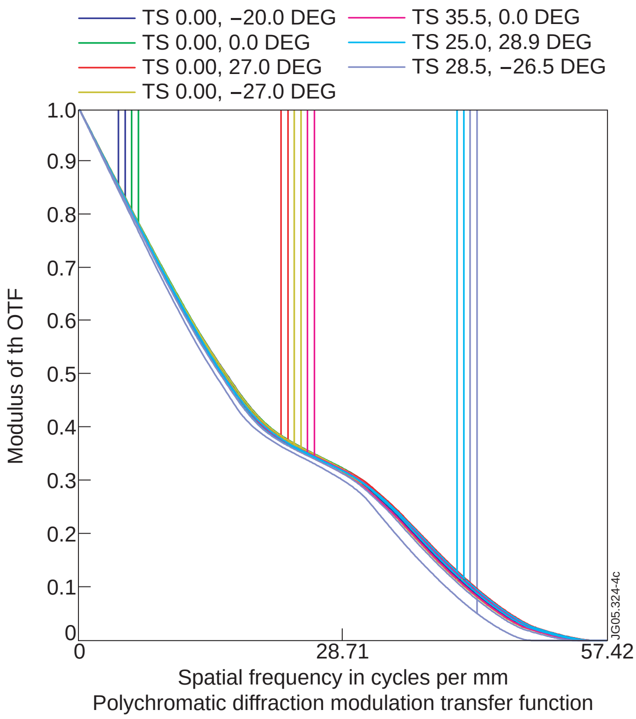

Figure 3: MTF curves of 9 points in the FOV

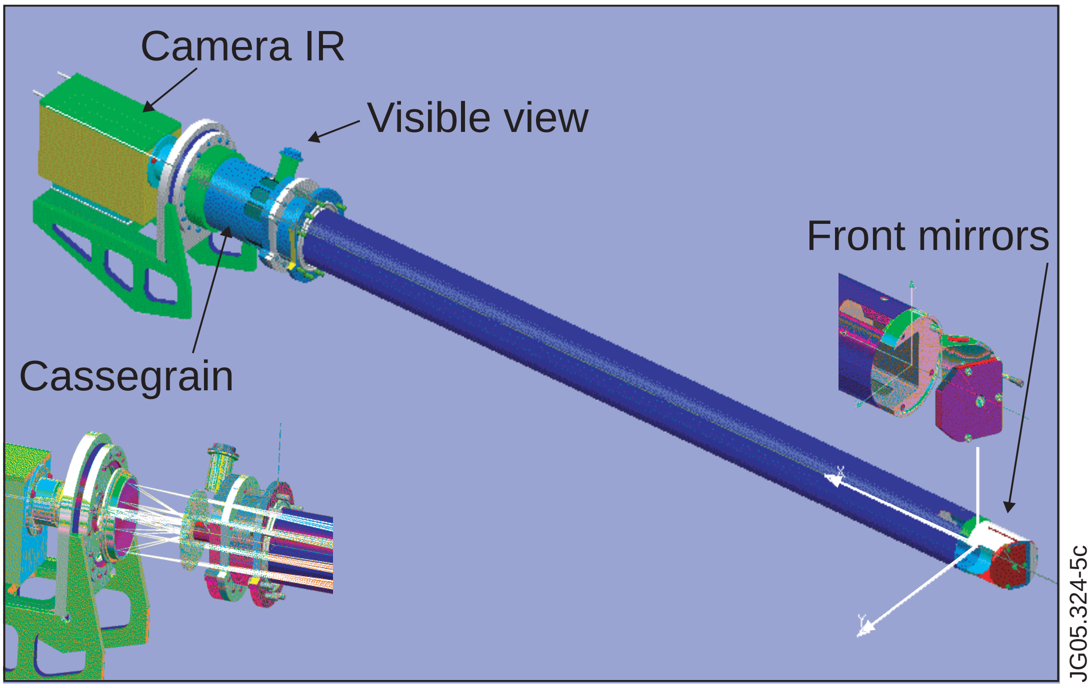

Figure 4: 3 D View of the opto-mechanical design

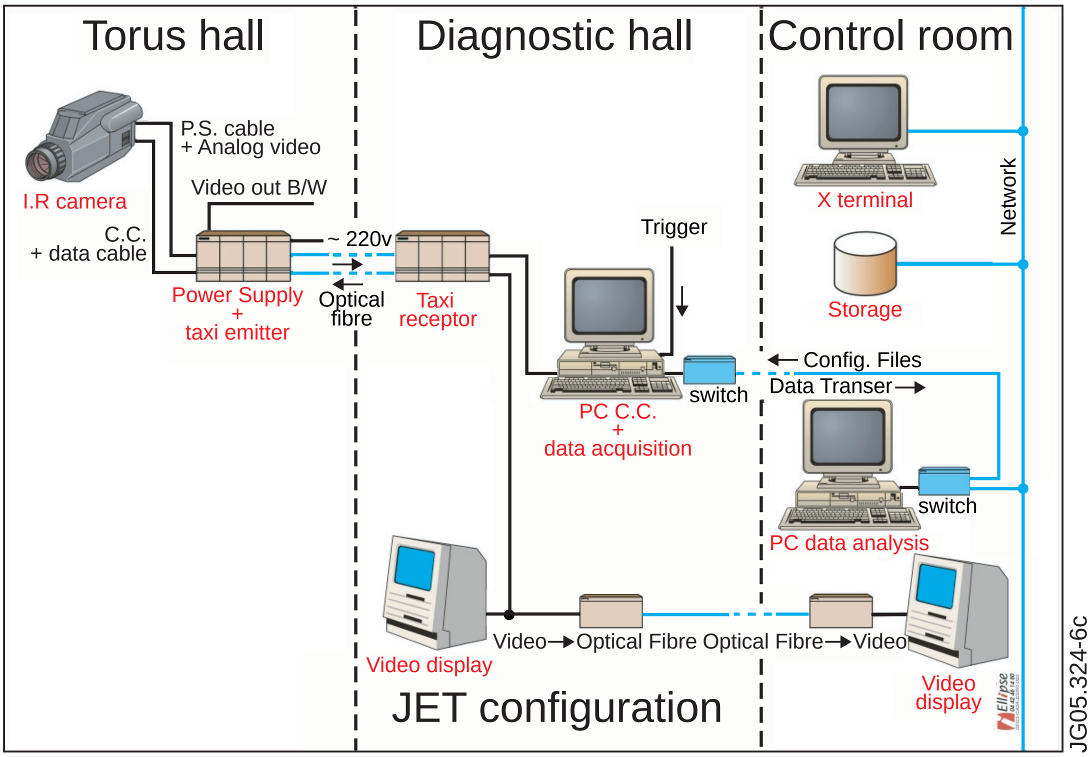

Figure 5: Schematic View of the data acquisition system