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ABSTRACT
Two new bolometer cameras, for horizontal and vertical views of the plasma cross section, are under construction for the Enhanced Performance Phase of JET, to begin in 2005. These cameras replace previous cameras in operation and represent a substantial upgrade in capabilities: More viewing chords over a larger viewing angle, higher detectable energy range, higher sensitivity, lower noise level and therefore lower detectable signal (~1μ W/cm^2 for τ = 2ms vs. ~70μ W/cm^2 for τ =20 ms). The detectors are essentially the same as those in use on ASDEX-Upgrade (gold energy-absorbing layer, mica substrate, gold meander), whereby the absorber layer has been increased in thickness from 4 to 8μ in order to extend sensitivity to 8keV. Each camera is comprised of 24 channels, with a particularly fine spatial resolution in the divertor region of ~8cm. Definition of the lines-of-sight is attained by a collimator arrangement for the vertical camera and use of pinholes for the horizontal camera. Salient design features of these cameras are described.

INTRODUCTION
It is of primordial importance for the success of the fusion program to determine the absolute level of radiation emanated by a plasma $P_{rad}(t)$ as well as the spatial distribution of the radiation zones over the plasma cross section $P_{rad}(r,t)$. This is effected by means of bolometer- cameras that measure emitted radiation over fans of lines-of-sight defined by individual bolometer arrays within the cameras in combination with collimating structures. At least two cameras (vertical and horizontal views) are necessary to permit a tomographic reconstruction of the radiation zones. Two entirely new cameras have now been prepared to fulfill this task during the JET Enhanced Performance Phase, due to begin in the summer of 2005.

The vertical camera (KB5V) interrogates the radiation along 24 chords, with 8 of the channels (δr ~8cm) dedicated to the divertor region where localized radiation patterns occur (Fig.1). The other 16 channels cover the entire plasma. An additional 8 channels in reserve can be activated as a backup to determine P_{rad}. KB5V replaces the vertical camera of KB1 where only 10 channels were still operative (out of 14 from 1984 [1]), and which was designed for limiter operation (radiation primarily from inside periphery of the plasma) as opposed to divertor (radiation from x-point and target plates at bottom of torus). KB5V is also much closer to the plasma, thereby allowing a larger field of view. The lines-of-sight for KB5V are determined by the individual bolometer apertures in connection with a collimator block (Fig.3).

The horizontal camera (KB5H) has a total of 24 channels, again with 8 concentrated on the divertor region (δr~8cm) (Fig.1). Here a more simple pinhole structure is used to define the lines-of-sight. This camera replaces the two horizontal cameras of KB1 (only 20 channels) which have continued to function but needed to be replaced as a result of re disposition of port use on JET.

Miniaturized metal resistor bolometers are employed as detection elements, similar to those on Tore-Supra [2], RFX [3-4], JET [5] and ASDEX-Upgrade [6]. The detector element consists of a 20μ muscovite mica substrate, on one side of which an 8 μ gold layer is deposited (absorber) and on the other are two interwoven gold meanders (resistors). When the absorber heats due to impinging plasma radiation, the meander resistances change. These changes can be related to the energy input. In order to compensate for temperature drifts as well as electromagnetic disturbances a 2^{nd} reference bolometer is employed which is optically shielded from plasma view. The two reference meanders and two measurement meanders are coupled in a Wheatstone bridge circuit such that the output voltage is proportional to momentary temperature excursion of the measuring absorber. Four such units are combined to form a bolometer head consisting of a 3mm AlMg3 front plate (area 20x33mm) with four defining apertures (each 1.3x3.8mm), the mica substrate and a 3mm back anodized pressure plate of AlMg3. The cameras contain 8/6 (KB5V/H) such heads. These are produced by IPT [7]. IPT also modified the existing JET spare electronic units used to power the bolometers. PINK GmbH [8] had responsibility for manufacturing the camera assemblies.

1. TECHNICAL DETAILS

The bolometer heads are identical to the last-generation units in ASDEX-Upgrade with exception of the thicker absorbing gold layer. Together with modifications in the electronics they represent a considerable improvement over the KB1 cameras: For KB5 a higher bridge voltage is used (40Vp-p instead of 10Vdc), effecting a proportionate increase in signal level. Special low-noise twisted-pair cables are employed for signal and AC voltage transmission. These are either on a PEEK basis (~2m long in the secondary vacuum region between the feedthroughs in the bulkhead and feedthroughs to air) or with PTFE (HABIA cable type SML 50, of length 32 or 42m). Use of synchronous demodulation techniques with a carrier frequency of 50kHz and an improved shielding concept has permitted a dramatic decrease in the detection limit (S/N = 1) to ~1μ W/cm^2 for an integration time constant $\tau = 2$ms vs. 70μ W/cm^2 for $\tau = 20$ms. Thus, whereas the inherent response time of the bolometer foil is not better, the lower noise level should permit a faster useful temporal response. Consequently the data sampling frequency has been increased from 4 to 10kHz. Further, all 48 bolometer signals are made available to the Real Time Control system [9] for feedback/ control purposes, with a maximum sampling bandwidth of 5kHz.

Since in the past some JET bolometers have experienced RF interference from Lower Hybrid heating, it was important to validate the shielding capability of the bolometer heads and grounding system foreseen for KB5. Tests on Tore-Supra under normal operating conditions at the PLH~3MW level revealed no RF influence on the bolometer signals [10].

Although the bolometer heads represent a standard product item, stringent and extensive tests were specified: a) Baking cycle at 160°C for 6 hours with monitoring of bolometer properties. At ambient, 80 and 160°C: b) calibration of the bolometer foils to determine the response time τ_{bolo} and sensitivity S_{bolo}, and c) noise level for a 1kHz bandwidth and amplifier gain of 5000. The p-p noise level is less than 20mV. Neither τ_{bolo} nor S_{bolo} exhibit a clear temperature dependence. The values averaged over all KB5 bolometers are: τ_{bolo} = ~202±29ms in vacuum, ~99±7ms in air, and S_{bolo} ~8.3±0.8V/W in vacuum, ~3.6±0.2V/W in air . The temperature coefficient of the meanders is dR/dT(1/R)~2.1 10^{-3} /°C, with

R~1200-1400 Ohm/meander. These are typical values for mica-based bolometer foils of the specified characteristics. However, the 160°C baking tests yielded several surprises: a) some foils lost bolometer channels beginning at around 140°C, b) others showed a continuous increase in resistance after attaining a steady-state temperature, part of which was retained after cooling to room temperature. The failure of individual channels was found to be due to microcracks in the mica substrate, which could finally be related to use of a more brittle mica mistakenly delivered to the foil manufacturer [11]. This problem was rectified late in the production phase. The ”irreversible drift effect” is not understood. Possibly there is a connection to the type of mica initially used. In any case, the effect is not evident at operational temperatures expected for JET.

Since the cameras are mounted close to the plasma, within a vessel heated to 220°C during operation and 340°C during bakeout, active cooling is necessary. The bolometer heads are mounted within massive heat sinks, attached to a bulkhead which is cooled via brazed watercarry stainless steel tubes on the secondary vacuum side. Figure. 2 shows the frontal arrangement for KB5H. In a test setup at PINK GmbH it is found that for a surrounding wall temperature of 240°C and a water flow rate of 4l/min the bulkhead and heat sinks can be maintained at 35°C for cooling water at 20°C ($\delta\tau_{water}$~1-2°C). As a backup, cooling by air is foreseen. Here, for a fore/backpressure of 7/5.3 bar a temperature of ~60°C can be maintained, with δT_{air}~11°C. The temperatures are registered via Pt100 resistors placed in the bulkhead and heat sinks, to be used as monitors during operation on JET.

The close proximity of KB5V to the plasma implies that the forward structures immersed in the toroidal field B_t are subject to strong eddy currents in the case of termination of a 6MA plasma current within 1ms (worst case scenario), generating potentially extreme material stresses. The associated torque about the vertical axis of KB5V arising from dB/dt~350T/s, with B_t ~3.7T, dictated choice of materials and major mechanical features of the collimatorbulkhead interface. Figure. 3 shows a 3D view of the bulkhead (containing the 8 bolometer heads) and collimator. Both are made of Inconel 625 in order to reduce eddy currents and to avoid the decrease of the elastic stress limit otherwise associated with stainless steel at increased temperatures. The castellation of the flange-collimator interface is necessary to carry the worst-case torque force. Further, the cooling blocks are made of AlMg3 rather than copper, again to reduce the magnitude of eddy currents. These precautions are not necessary for KB5H, for whose position neither the flux changes dB/dt nor B_t are of magnitude large enough to produce forces of consequence.

A simple pinhole camera construction was not possible for KB5V due to lack of the space necessary to achieve the desired wide field of view and spatial resolution for the given detector spacing of each bolometer head. Thus an optimized collimator was designed [12] where each channel has its own bounding aperture. These can be seen in Fig.3. The masks placed within the collimator do not limit the viewing cone, rather they serve to prevent optical cross-talk between channels. For KB5H the slits defining the viewing cones for each set of bolometers are arranged at appropriate distances and width such that the chord pattern illustrated in Fig.1 is achieved. Hereby, the lines-of-sight are not all in one poloidal plane. Rather, they are placed so as to avoid viewing inner-limiter plasma contact surfaces. Both the collimator and pinhole are blackened internally with Aquadag (18% No. 5-1543-0-131-20 from Acheson Industries Ltd.) to reduce internal reflections.

To assure an accurate tomographical reconstruction of plasma radiation patterns it is essential to have precise knowledge of the viewing chords within the plasma vessel. On JET this is normally achieved by documenting the position of each camera-torus interface flange via photogrammetry and then merging the CAD model of the JET interior/exterior with that of each camera. Naturally, this assumes the correctness of both the camera and JET models. The camera geometry was checked at PINK with a special dimensional verification system whereby first the exit slits of each bolometer and then the defining apertures of the collimator/pinhole were measured within the same coordinate system and put into relationship with the camera's primary vacuum flange. In addition, each camera has also undergone an ptical mapping of each viewing cone via a point source of light from a Hg-Xenon lamp moved across the exit aperture at various distances. These measurements are placed into relationship via photogrammetry with the beams from three diode lasers attached to the front end of each camera. On JET the positions of these laser spots on the vessel walls will be observed via a CCD camera attached to the remote control boom, thereby allowing a very accurate cross-check between the situation expected from existing CADs models and that actually extant.

SUMMARY

Two new bolometer cameras using detectors almost identical to those of ASDEX-Upgrade have been prepared for installation on JET in the fall 0f 2004. Each camera has 24 chord views, optimized for divertor operation. At least in the laboratory the minimum detectable signal is more than two orders of magnitude better than the older bolometer systems from 1984. Lower Hybrid RF tests on Tore-Supra have shown that these bolometers remain undisturbed. All 48 bolometer signals will be made available to the Real Time Control System.

REFERENCES

[1]. K.F.Mast et al., "Bolometric Diagnostics in JET", Rev. Sci. Instrum."**56** (1985) 969

[2]. K.F. Mast, J.C. Vallet et al., "A Low Noise Highly Integrated Bolometer Array for Absolute Measurement of VUV and Soft X Radiation", Rev. Sci. Instrum."**62** (1991) 744

[3]. K.F.Mast et al., "Fast Bolometric Diagnostic in the RFX Reversed Field PinchExperiment", Rev. Sci. Instrum."**63** (1992) 4714

[4]. A.Murari, K.F.Mast et al., "Multichord Calibrated Bolometer Array for the RFX Experiment", Rev Sci Instrum. **66** (1995) 665

[5]. R. Reichle, et al., "Bolometer for ITER," in *Diagnostics for Experimental Thermonuclear Fusion Reactors*, Plenum Press, New York, 1996, pp. 559-570

[6]. J.C.Fuchs, K.F.Mast et al., "Radiation Distribution and Power Balance in the ASDEX Upgrade LYRA Divertor", ECA **Vol. 22C** (1998) 1510-1513

[7]. IPT-Albrecht GmbH, Ing.-Büro für Physikalische Technik, Emmendingen, Germany

[8]. PINK GmbH Vakuumtechnik, 97877 Wertheim, Germany
[9]. E.Joffrin, et al., "Integrated Scenario in JET Using Real Time Profile Control", Plasma Phys. Control. Fusion **45** No 12A (2003) A367-A383
[10]. J.C. Vallet, private communication
[11]. Dr. Johannes Heidenhain GmbH, 83301 Traunreut, Germany
[12]. L.C. Ingesson and D.J. Wilson, "Optimization of Apertures and Collimators for Multi- Channel Plasma Diagnostics," Rev. Sci. Instrum. **73** (2002) 2890

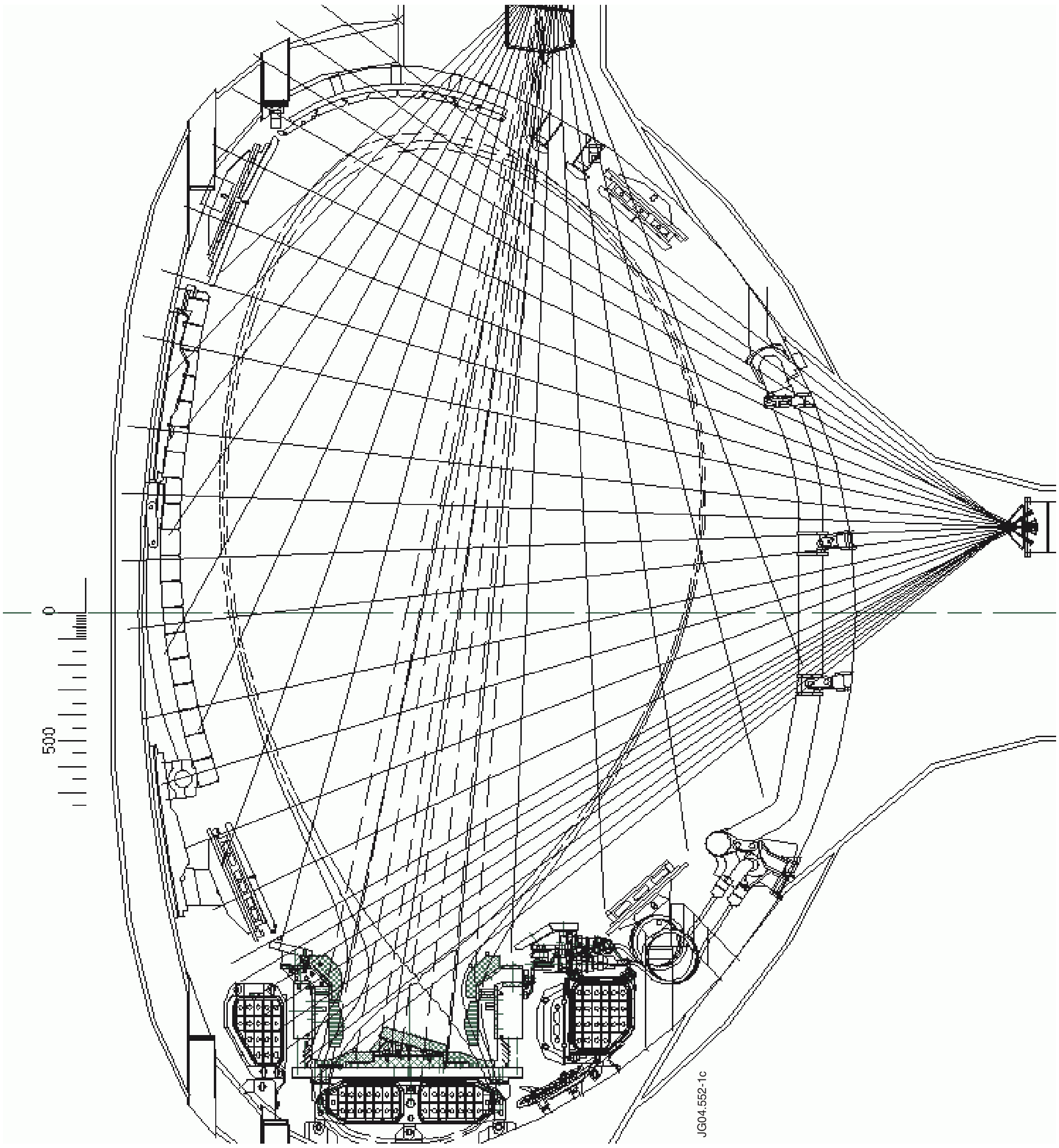

Figure 1: Cross section of JET (R=3m, a~1m) showing the lines-of-sight for the vertical KB5V and horizontal KB5H bolometer cameras. An additional 12 channels in the divertor region (KB3 – not shown) are necessary to completely cover the X-point and divertor regions.

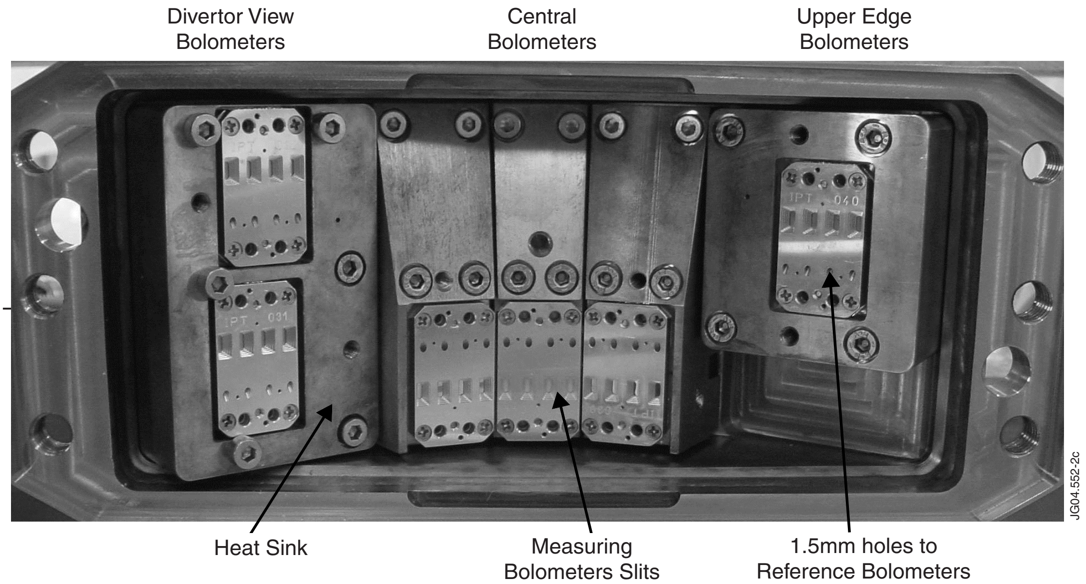

Figure 2: View of the six KB5H bolometer heads embedded in their copper heat sinks. The four slits of each head form the exit apertures of the measuring bolometers. The small holes opposite allow for neutral pressure equilibrium for the reference bolometers which are hidden from view by the AlMg3 front plates. The pinhole structure is mounted directly on this flange.

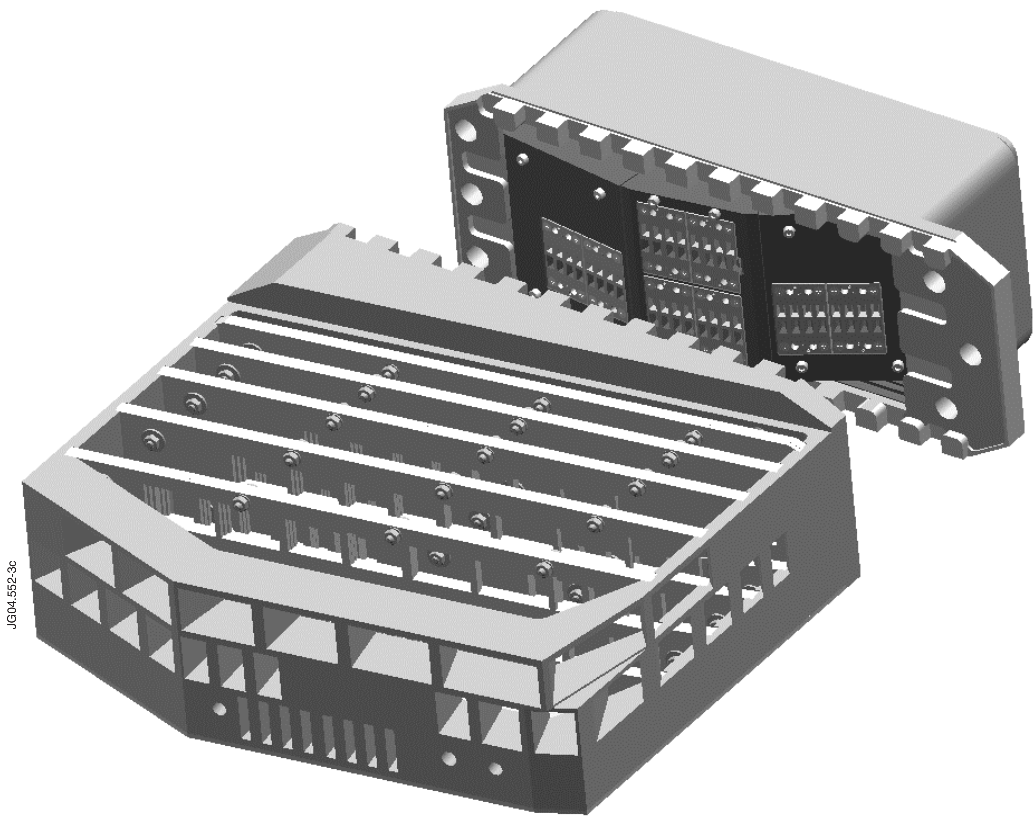

Figure 3: 3D view of collimator block (lid removed) and bulkhead. The exit slits for the 8 backup channels (top row), the 16 medium resolution channels (middle) and 8 fine divertor resolution channels (bottom) can be seen. The 8 bolometer heads are visible on the cooled bulkhead. The castellation between the collimator and bulkhead flange (both Inconel) is needed to handle the forces associated with sudden plasma disruptions.