Optics design considerations for improving the sensitivity of the Infrared Imaging Video Bolometer on LHD

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Introduction

The InfraRed imaging Video Bolometer (IRVB) [1] is an inevitable diagnostic for LHD due to its capability of measuring two-dimensional radiation profiles from high temperature plasmas. Currently the IRVB diagnostic is being used for studying the localization of radiation structures near the n/m=1/1 resonant magnetic perturbation (RMP) X-points during plasma detachment [2] and also for three-dimensional tomography on LHD. Improvement in the sensitivity and signal to noise ratio (SNR) yields higher temporal resolution for the IRVB. Unfortunately the sensitivity decreases while SNR increases with the separation between the IRVB foil and the IR camera. The motivation is to improve the sensitivity and SNR simultaneously by the addition of a re-imaging infrared optics.

IRVB sensitivity

The IRVB has a thin 2.5μm platinum foil acting as a absorber of plasma radiation collimated by a pinhole camera geometry. The incident radiation results in a temperature rise of the foil which is monitored by an infrared camera placed outside the LHD vacuum vessel in a double walled soft iron magnetic shield box. The radiated power from the plasma falling on the foil can be estimated by numerically solving the 2D heat diffusion equation [3] considering spatiotemporal variation in the foil temperature obtained from the infrared camera. The noise equivalent power density (NEPD) [4] is a figure of merit for the IRVB which defines the sensitivity of the diagnostic and can be achieved by dividing the noise equivalent power (NEP) η_{IRVB} of the IRVB by the bolometer pixel area and is given by equation (1).

$$S_{Bolo} = \frac{\eta_{IRVB} N_{bol}}{A_f} = \frac{\sqrt{10} k t_f \sigma_{IR}}{\sqrt{f_{IR} N_{IR}}} \sqrt{\frac{N_{bol}^3 f_{bol}}{A_f^2} + \frac{N_{bol} f_{bol}^3}{5\kappa^2}} \quad \text{..........(1)}$$

This equation is expressed in terms of the noise equivalent temperature difference (NETD), σ_{IR}, of the IR camera operating at f_{IR} Hz and having N_{IR} detectors, f_{bol} and N_{bol} signify the bolometer frame rate and number of IRVB channels respectively whereas A_f is the area of the IRVB foil. k and t_f are the thermal conductivity and thickness of the foil respectively. This equation signifies that the IRVB sensitivity increases with the square root of the number of camera pixels and the camera frames being averaged over. The separation between the IR camera and the IRBV foil will reduce the number of pixels N_{IR} imaging the foil due to diverging field of view (FoV) which eventually reduces the IRVB sensitivity.

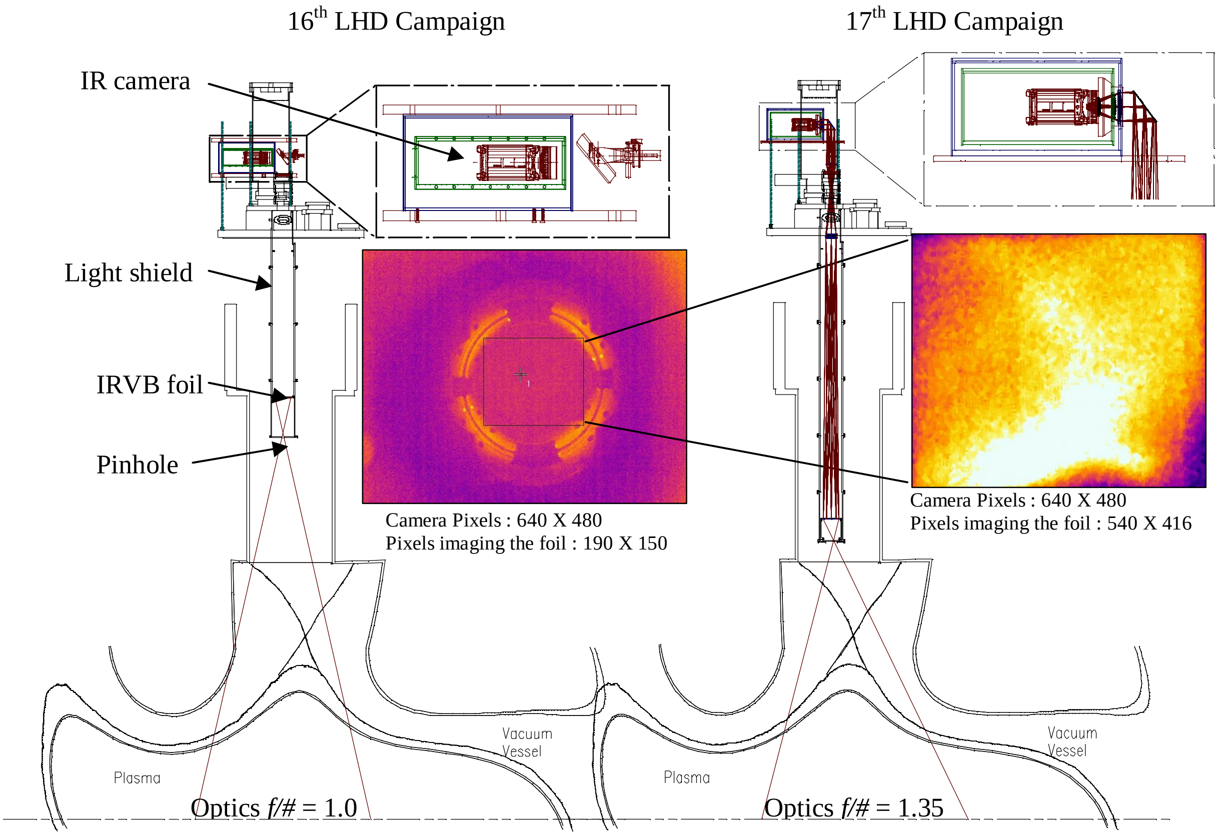

Fig. 1 (a) IRVB foil imaged with 15º X 11º IR objective (b) IRVB foil imaged with an IR periscope

The IRVB at the upper port of LHD uses a FLIR SC655 infrared camera having a microbolometer detector sensible to the spectral range from 7.5~12 µm. Since this particular camera does not need a sterling cooler it is suitable for the relatively higher magnetic field of the upper port of LHD. The NETD of this camera is 50 m°K. The detector has a 640 X 480 pixel focal plane array with a 17µm pixel pitch. Fig. 1(a) shows the IRVB installed on LHD for the 16th experimental campaign with an infrared objective having a 15° X 11° FoV and optics f-number (*f/#*) =1.0. The inset picture in Fig.1(a) shows the foil bounded by a rectangle. It is estimated that only 9% of the total number of camera pixels actually image the foil. Diagnostic requirements for the 17th experimental campaign require a wide IRVB FoV and higher SNR to improve its temporal resolution. Both these requirement can only be accomplished by lowering the foil towards the plasma mid-plane, which will result in increased SNR but reduced IRVB sensitivity. Adding infrared optics to the IRVB as shown in Fig.1(b) would increase the number of pixels imaging the foil to 73% and hence increase its sensitivity even though the separation between the IR camera and the foil is increased during the 17th experimental campaign to meet the diagnostics requirements.

Radiometric estimations

Since it is evident form equation (1) that the sensitivity of the IRVB depends on the NETD σ_{IR} of the IR camera, it is mandatory to study the effect of various optical parameters like *f/#* and transmission τ_0 that might affect σ_{IR}. The temperature rise of the IRVB foil can be estimated by considering the power incident on the foil through pinhole geometry and thermal properties of the foil. The effective power M_{eff} emitted by the heated foil in the infrared wavelength range 7.5~12μm can be estimated by multiplying the blackbody cooling term and the bandwidth factor obtained from the universal blackbody curve. The power reaching the infrared detector is given by equation (2) where A_d is the pitch of the detector. The NETD of the IR camera can be determined by equation (3) where ΔT is the foil temperature rise and NEP_{IRdet} is the noise equivalent power of IR detector.

$$P_{IR\,\det} = \frac{\tau_0 M_{eff} A_d}{4(f/\#)^2} \quad \text{………} (2) \qquad NETD\,(\sigma_{IR}) \approx \frac{\Delta T\ P_{IR\det}}{NEP_{IR\det}} \quad \text{…….} (3)$$

Design Specifications

The area to be imaged is 155 X 115 mm^2 which will cover the actual foil area of 130 X 100 mm^2 leaving enough tolerance for any installation misalignments. The magnification factor turns out to be 0.0707 which leads to an effective focal length of 114mm for the re-imaging optics. The detector with a 17μm pitch can resolve a spatial frequency of 29.4 cycles/mm. For this optics to be diffraction limited its *f/#* should approach 0.7 and the corresponding spatial resolution at the foil location approaches 0.24mm. The required spatial resolution at the foil location is 1mm (which is smaller than the 5mm bolometer pixel size) that allows for the binning of 3x3 pixel cluster which results in the effective pixel pitch of 51μm. The corresponding *f/#* for this optics configuration to be diffraction limited turns out to be 2.0 for a wavelength of 10μm. The estimation with *f/#*=2.0 results in 1.5 times poor sensitivity as compared to *f/#*=1.0 objective used for 16th experimental campaign. Hence an intermediate *f/#*=1.35 is chosen which achieves better performance as far as the sensitivity is concerned. The IRVB sensitivity improves 1.4 times with a periscope albeit the NETD estimate for this periscope with *f/#*=1.35 and effective transmission τ_0 = 89% (which results from a gold plated mirror and six anti reflection coated lens elements of germanium and zinc selenide) decreases by a factor of 2.

Evaluation of optical performance

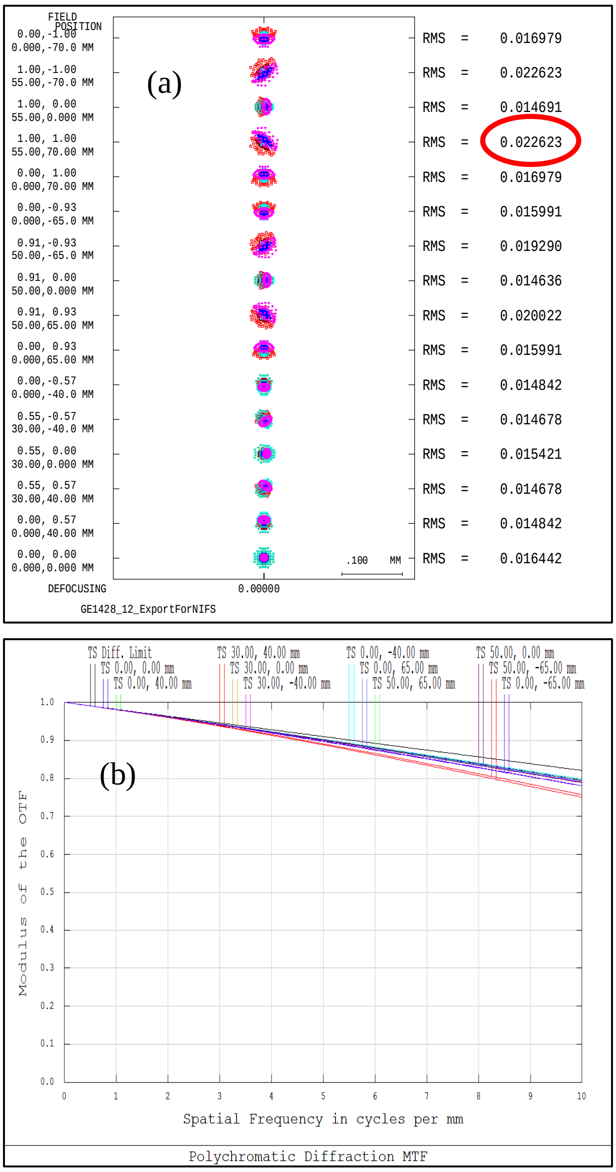

Fig. 2 (a) Polychromatic geometrical spot diagram
(b) Polychromatic diffraction MTF

Optical performance can be evaluated by spot diagram and modulation transfer function (MTF). The spot diagram in figure 2(a) gives the distribution of polychromatic rays originating from an infinitesimal point on the foil traced through the optics. The effective spatial resolution can be computed as the root-sum-squared value of RMS spot size, pixel size (51μm) and size of the airy disk (2.44*λ**f/#*), all parameters projected individually at the foil. The spatial resolution for the largest RMS spot size of 0.0226 mm is found to be 0.85 mm which is less than the targeted value of 1 mm in the previous section. The MTF plot shown in figure 2(b) signifies the ratio of object contrast and resulting (due to optics) image contrast at different spatial frequencies. The plot shows contrast better than 70% for a spatial frequency of 9.8 cycles/mm corresponding to a 51μm pixel pitch. The ensquared energy is > 80% and distortion <1% which signifies a well optimized design.

Conclusion

Addition of the reimaging optics to the IRVB simultaneously improves the sensitivity and SNR by a factor of 1.4 and 4.3 respectively even though the NETD of the IR camera becomes poorer by a factor to 2. The sensitivity of the IRVB can be improved further by using faster (lower *f/#*) optics.

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