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Study of an Erosion Monitor for the ITER Divertor Target Plates

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Introduction

A FM (frequency modulated) laser radar system installed in the divertor port is being studied as a means to measure the erosion of the divertor plates in ITER. The depth of amount will be measured as a change in the distance between the divertor target and a reference point.

The optical distance (L) is expressed by the equation, $L = v_c \Delta t /2$. Here v_c is the speed of light in the medium. The round trip time is given by $\Delta t = f_{IF}/(\Delta F/\Delta T)$, as shown in Fig. 1. Here f_{IF} is the intermediate frequency of the light-wave, which is measured by the optical heterodyne technique. This remote metrology technique has been applied for the inspection system of the first wall in TFTR and NSTX [1]. For the measurement of erosion in ITER, the accuracy of the measurement must be improved to better than 5 x 10^{-7} to meet the accuracy requirement of 12 μm from an optical distance of 15 – 20 m to the divertor targets.

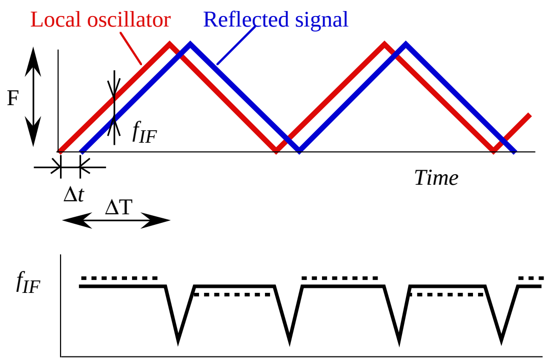

Fig. 1 FM laser radar measurement

Optical Design and Heterodyne Detection of Back-scattered Light

For the FM laser radar measurement, a laser beam, whose wavelength varies in time, is emitted from a tunable laser source. Sources in the visible wavelength with power P_{LS} = 1~ 40 mW, tunable frequency range ΔF= 100 GHz with repetition frequency $1/\Delta T$ = 1 kHz are commercially available. In order to obtain spatial profiles of the divertor target erosion, the direction of the emitted laser beam must be scanned to measure the distance to multiple points. Since accurate control of the beam direction is required, the optical components for beam scanning are located outside the neutron bio-shield. In the design, the laser beam from the tunable laser source is expanded to a Gaussian beam diameter ϕ = 50 mm and then focused by a lens (f = 15.4 m). This weakly focused beam is reflected by a scanning mirror, which is driven piezoelectrically and is capable of steering around the two orthogonal axes with a resolution of 1 μ radian, corresponding to an accuracy of 0.3 mm on the divertor target. Beams reflected off the scanning mirror are relayed by flat mirrors into the divertor cassette and then spread over the divertor targets by a spherical mirror, as shown in Fig. 2. The aperture of the optics to the targets must be as small as possible to minimize the potential coating of the mirror. A small radius spherical mirror (**M** ; R = 0.16 m) is used to achieve this. In addition, a shutter will be integrated in the mirror box. The spot size of the Gaussian beam on the target decreases as a function of the initial beam diameter before the focusing lens, the radius of the spherical mirror and the inverse wave-length of the laser beam. Efforts in the optical design have been directed towards minimizing the beam spot size on the target so that good spatial resolution and high signal intensity on the receiver are possible. A beam spot size on the target with Gaussian beam diameter ϕ_s = 2.0 mm has been obtained for the visible wavelength (λ = 650 nm).

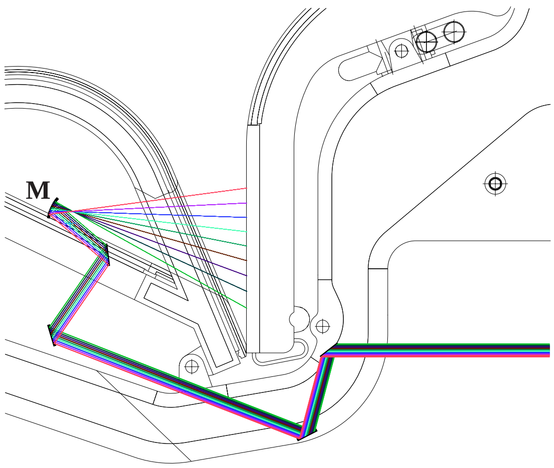

Fig. 2 Optics of viewing the outer targets

In order to estimate the feasibility of real- time measurement during ITER pulses, the effect of the divertor plasma on the laser radar measurement has been calculated. Both the beam deflection due to the divertor plasma (10^{-5} of the beam spot size) and the change in the effective path length (10^{-3} of the required accuracy) were found to be negligibly small.

Due to sub μm-scale roughness of the surface of the target materials, light is back-scattered isotropically in a half sphere. It is reasonable to assume for this process a diffuse reflection rate γ_D = 0.01, that is 1 % of the incident laser power scattered, for carbon fiber composite (CFC) tiles. A very small fraction of the light scattered from the illuminated area A_s, which is viewed with the focusing lens with a solid angle Ω_s, is relayed back to the receiver and then focused on to the detector surface by the detection optics. Fig. 3 shows a schematic diagram of the collection of the back-scattered light from the divertor targets and the optical heterodyne detection.

Optical heterodyne detection is a technique to combine the beam of the returned light with a fraction of the laser beam source and to measure the intermediate frequency f_{IF} as the beat component of the electric field on a photo detector surface. In order to obtain high signal intensity for f_{IF}, the two wave fronts and polarization vectors must be carefully aligned on the photo detector surface. This requirement for stringent alignment poses a fundamental limitation on the available intensity of the signal on the detector. Antenna theory for optical heterodyning [2] states that the effective aperture multiplied by the solid angle of detection, $A_d\Omega_d$, is essentially the wavelength of light squared, λ^2. Since $A_d\Omega_d = A_s\Omega_s$, the ratio of returned power on the detector to the incident beam power to target, R_s is given by, $R_s = \gamma_D\lambda^2 / (2\pi A_s)$. In the designed optics, $R_s = 2 \times 10^{-10}$. The power focused on the detector P_d is given by $P_d = R_s\eta_{tr}^2 P_{LB}$. Here η_{tr} is the transmission coefficient of light in the optics and P_{LB} is the laser beam power sent from the tunable laser source toward the divertor targets (Fig. 3).

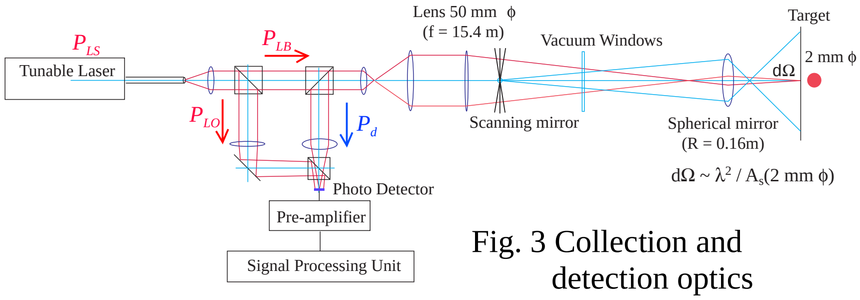

Fig. 3 Collection and detection optics

Signal to Noise Ratio and Statistical Analysis of Errors

In order to achieve both high time and space resolution, it is important to have a high signal to noise ratio SNR, in both the detection and signal processing stages. When the local oscillator power is high, shot noise in the detector, determined by the randomness in the production of photo electrons, dominates other noise sources such as thermal noise in the detection circuit and phase noise of the laser light. The signal to noise ratio, *SNR*, is then given by, $SNR \sim \gamma_{het}\eta P_d /(3h\nu\, f_B)$. Here η, $h\nu$ and f_B are the quantum efficiency of Si APD detector, photon energy and bandwidth of measurement, respectively. The heterodyne efficiency γ_{het} is a parameter that indicates how efficiently the beam profiles of both the returned light and the laser source are overlapped on the detector. A detailed calculation shows that the maximum γ_{het} is 0.44 for the optimized detection optics. The bandwidth of measurement depends not only on f_{IF} but also on the signal processing scheme. As shown in this equation, f_B must be decreased to obtain high *SNR* in the signal processing stage.

Since changes in ν_c are negligible under controlled conditions of temperature and humidity, the standard deviation of the error in the erosion measurement σ_ε is given by, $\sigma_\varepsilon^2 = \sigma_\varepsilon(f_{IF})^2 + \sigma_\varepsilon(\Delta F/\Delta T)^2$. Here $\sigma_\varepsilon(f_{IF})$ is the error of the intermediate frequency measurement, and $\sigma_\varepsilon(\Delta F/\Delta T)$ is the fluctuation in the sweep rate of the carrier frequency. The fluctuations in the swept frequency of the light from a tunable laser using a Littman-Metcalf cavity (chosen for the design), are estimated to be larger than 3×10^{-6} in the bandwidth f_s (~ 1kHz) of the retroreflector. Therefore $\sigma_\varepsilon(\Delta F/\Delta T)$ is given by, $\sigma_\varepsilon(\Delta F/\Delta T) = 3 \times 10^{-6} (f_s \Delta T)^{-1/2}$.

One possible signal processing scheme is frequency counting. The standard deviation of the error in the frequency measurement by this scheme can be derived as;

$$\sigma_\varepsilon (f\,;\Delta T) = \frac{1}{\Delta T}\left(\frac{1}{\pi f\sqrt{3\,SNR}} + \frac{1}{f_c}\right)$$

Here f is frequency to be measured and f_c is the clock frequency of the frequency counter. The first term represents trigger errors and the second term represents the quantization errors of ΔT. Since for the chosen optical design parasitic frequencies due to multi-reflections in the optics are at least $2.5 \times 10^{-2} f_{IF}$ away from f_{IF}, the bandwidth of the measurement must be lower than $1.0 \times 10^{-2} f_{IF}$. In this case all the parasitic components will be removed by down-conversion of f_{IF} and low-pass filtering. The down-converted frequency represents an increment from the reference point distance. When $f_B = 1.0 \times 10^{-5} f_{IF}$, the dynamic range of the distance is limited to 1 mm.

Finally, we calculate the time resolution to achieve the required accuracy of the erosion measurement. The standard deviation σ_ε is shown as a function of ΔT in Fig.4. In this figure, $\gamma_{het}\eta_{tr}^2 P_{LS}$ is scanned. In this calculation, the parameters L = 18 m, $P_{LB} = P_{LS}/2$, $R_s = 2 \times 10^{-10}$ and $\gamma_B = 5 \times 10^{-4}$ have been assumed. In conclusion, the required accuracy of 5×10^{-7} is achievable with time resolution 2ΔT = 60 ms for each point of measurement, in the best case when $\gamma_{het}\eta_{tr}^2 P_{LS}$ = 10 mW. In the chosen optics, $\eta_{tr}^2 R_s$ is a linear function of the signal amplitude. Therefore, if $\eta_{tr}^2 R_s$ is reduced by a factor of 10, for example γ_D = 0.001 instead of 0.01, P_{LS} must be increased by the same factor to compensate this reduction.

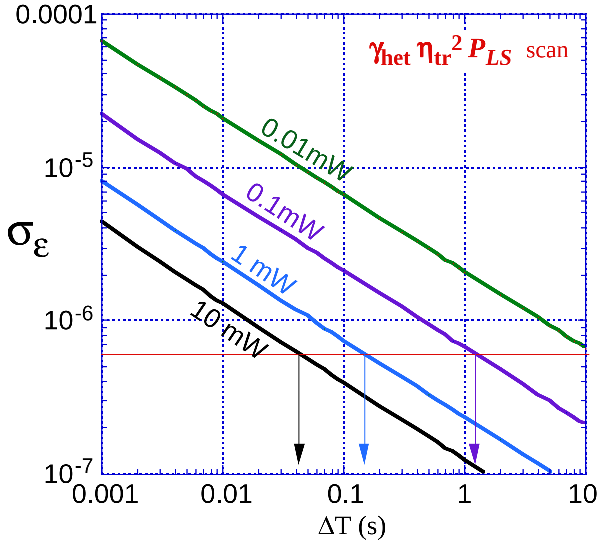

Fig. 4 σ_ε vs ΔT plot

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