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STUDY OF A CW, 2-D THOMSON SCATTERING DIAGNOSTIC SYSTEM

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ABSTRACT

We describe a new approach to Thomson scattering diagnostic that relies upon a high power CW laser cavity and a rf signal detection technique, instead of the more usual pulsed high energy laser. The new system has three major elements: an ultra long (~150 m) laser resonance cavity that includes the plasma region; an array of CW diode lasers of high power and high modulation frequency that pumps and maintains the average cavity energy (~10 mJ); and a lock-in detection system of narrow frequency bandwidth (~2 kHz). The resonance cavity consists of a pumping chamber for power input from diode lasers, and many relay chambers (~30) distributed across the plasma cross section for Thomson measurement. The cavity has a low energy loss (~2% round trip) and zero output power. It is estimated that S/N of the new system is ~100 times better than the present DIII-D pulsed system due to the increase in usable laser energy and the improved background signal rejection.

I. INTRODUCTION

High energy lasers of very short pulse duration have been Thomson scattering diagnostic's main probing tool since its early days [1]. The purpose of the pulsed lasers is to generate a lot of Thomson photons in a duration as short as possible, so that the Thomson signal will not be overwhelmed by the fluctuation in the plasma background light. Usually the intense laser light makes only one pass through the plasma, so much valuable laser light gets thrown away just after one application. An interesting question is then whether or not a method can be found to turn those laser photons around for repetitive uses?

However, even though laser photons can be reused 10 times, that is, 10 Thomson measurements within a time less than 1 µs (light travels fast), it is likely that the measurements are too closely packed to be of great interest to the study of long duration plasma discharges. It would be ideal if the laser photons can be sustained indefinitely, that is, like a true CW operation, with the photon loss to be replenished by newly created photons.

A solution to the above requirements will be studied in this paper. The repetitive use of laser photons means all photons have to travel back and forth in a closed oscillator cavity and the cavity space has to include the plasma region being measured. For the cavity to be operated in the CW mode, the laser rod has to be pumped continuously to compensate the cavity energy loss.

Unlike the pulse operation, there is no short gate in the CW operation to limit the collection of plasma background radiation. However, there exists another powerful method to reduce the background fluctuation. If the cavity energy is modulated at a high frequency, the signal detection can be limited to a narrow frequency bandwidth, thereby excluding most of the background light. This method is essentially the same method used in radio communication for extracting weak signals from a noisy background.

It is clear that the scheme differs in many ways from the present operation of Thomson diagnostic. The new scheme can be characterized to have three major elements: (1) a closed laser oscillator cavity that includes the plasma region to be measured; (2) CW operation that requires the cavity energy to be maintained and modulated at a high frequency; and (3) a narrow frequency bandwidth for signal detection, plus the use of signal processing techniques like Phase-Lock and Sample-Average.

II. A CLOSED, CW OSCILLATOR CAVITY THAT INCLUDES THE MEASURED PLASMA REGION

As an example, Fig. 1 shows the cavity setup CW–1D to include a region of DIII–D plasma. A closed oscillator means it provides no output power (end mirrors' reflectivity may reach ~99.995%). The cavity is divided into a pump chamber and a measurement chamber, with 7.5 m length each. It takes $\mathcal{T}_1$ = 100 nS for a photon to make a round trip and passes through the plasma region twice. If a pack of photons starts with initial energy E_c and the cavity loss at δ% per round trip, the total energy passing through the plasma E_{TOTAL} can be obtained by summing the pulse train as, $E_{TOTAL}/E_c = 200/\delta$. That is, by bouncing photons in a closed cavity with 2% loss per round trip, the gain in laser energy for Thomson measurement over the single pass is 100.

The power required to maintain the cavity energy at P_c can be expressed as, $P_c = E_c \times \delta/(100 \times \mathcal{T}_1)$. That is, about 200 W of laser photons per sec is required to sustain the cavity energy at 1mJ level. With the present day's pumping efficiency at about 15%, this translates into 1–2 kW of diode laser power. It is certainly within the capability of present technology, a good example being the Yb:YAG laser setup in LLNL [2].

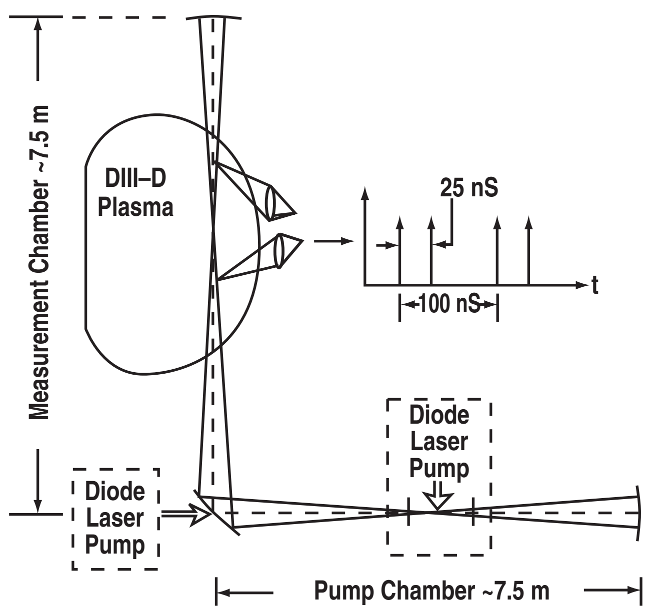

Fig. 1. A laser oscillator cavity for Thomson measurement with DIII-D geometry, CW-1D.

Since the laser pulse passes through the plasma region twice in one round trip, the laser energy per Second available for measurement can be expressed as, $\varepsilon\,(\mathrm{J/s}) = 2\times E_\mathrm{c}/\mathcal{T}_1$. For E_c at 1 mJ, $\varepsilon = 20{,}000\ \mathrm{J/s}$. This is more than 350 times larger than that provided by the DIII–D core Thomson system (4 YAG at 20 Hz each with 0.7 J/pulse). The example shows clearly the advantage of having a closed oscillator cavity that includes the plasma region for Thomson diagnostic.

For the convenience of picturing what to expect, we have assumed the laser photons stay as a pack; that is the cavity longitudinal modes stay locked. It is not essential to have mode-locking since the non-lock case can always be decomposed as two traveling waves traveling in opposite directions. The cavity configuration is likely to be between the Con-Focal and Con-Centric for stability. The preferred transverse mode is TEM_{00}. Since it is a long, long cavity, we assume that mechanical stability is a major concern and Piezo-positioners with feedback control are required to compensate for the alignment drifts.

III. NOISE (FLUCTUATIONS) AND CW SIGNAL PROCESSING

There are two types of noise power spectral density: $1/f$ and flatband (white noise). $1/f$ noise is not a concern in our case since the modulation frequency f_o is sufficiently high (>>1 kHz). As to the origin of the white noise, it can be shown mathematically (Carson's Theorem [3]) that a train of randomly occurring events of impulse function form gives rise to a flatband frequency spectrum. The white noise includes, for instance, Johnson (thermal) noise, shot noise and bremsstrahlung radiation. So long as the plasma background radiation (bremsstrahlung included) is in a quasi-equilibrium state, it should be possible to assume the spectral density as $\sigma_B^2 = B \times \Delta f$, where B is the emission density and Δf the frequency bandwidth. Among various noise sources, the background fluctuation is the dominant source in DIII–D Thomson measurement.

With the cavity energy at 1 mJ, one may feel instinctively the energy seemingly too low to overcome the background fluctuation. Figure 2 shows the block diagram of a possible signal processing arrangement. The two most important elements are the bandpass filtering and the sample average. It is fair to say that the essence for detection in the CW operation is to minimize Δf, thereby excluding noise as much as possible. Multiple sampling improves S/N also, since $S \propto m$ and $N \propto \sqrt{m}$, with m being the number of samples.

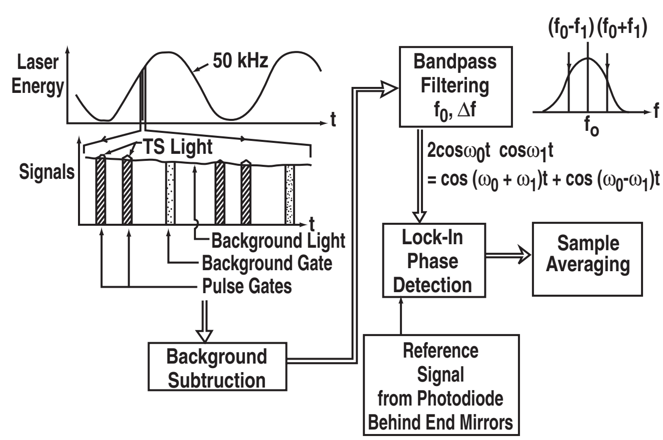

Fig. 2. A block diagram for CW signal processing. The two important elements re the bandpass filtering and the sample averaging. The cavity is assumed to be mode locked. Mode locking is not a necessary condition for the CW operation.

The time resolution of the measurement is related to the number of samples necessary to qualify as one measurement; that is, $\mathcal{T}_{\mathrm{R}} = m \times \mathcal{T}_1 / 2$. It is clear also that a shorter time resolution requires a higher bandwidth to work with, hence we define the minimum frequency bandwidth Δf_{o} as $1/(\pi \times \mathcal{T}_{\mathrm{R}})$. For the setup to be consistent, it requires $\Delta f \geq \Delta f_{\mathrm{o}}$.

If the laser photons stay as a pack (mode locked), one can even try the gating and background subtraction as we do in the present Thomson operation. However, they are not essential for the CW signal processing.

IV. CW–1D: A S/N COMPARISON WITH DIII–D

A S/N comparison can be made between the setup shown in Fig. 1 (CW–1D) and the present DIII–D Thomson system, if we let S/N to be expressed as,

$$S/N \propto \frac{m \times E_c}{\sqrt{2m \times B \Delta f}} \quad . \tag{1}$$

For DIII–D, we have $m = 1$, E_c = 1 J and Δf ~10 MHz. For CW–1D, we assume $E_c = 10^{-3}$ J, $\mathcal{T}_1 = 10^{-7}$ s, $m = 2\mathcal{T}_R/\mathcal{T}_1$, and $\Delta f = \Delta f_o = 1/(\pi \times \mathcal{T}_R) = 2/(m\pi \times \mathcal{T}_1)$. The parameter γ, the ratio of the S/N estimates, is obtained as,

$$\gamma = \frac{(S/N)_{CW-1D}}{(S/N)_{DIII-D}} \sim 2 \times 10^4 \times \mathcal{T}_R \quad . \tag{2}$$

Figure 3 shows how γ varies with the time resolution $\mathcal{T}_R$ of the CW measurement. For γ = 1, CW–1D to have a comparable S/N as DIII–D, it will needs 1000 samples and Δf ~ 5 kHz. The time resolution to qualified as one measurement in this case is 50 µs, an improvement of about 250 over the 12.5 ms interval in the present DIII–D core Thomson system.

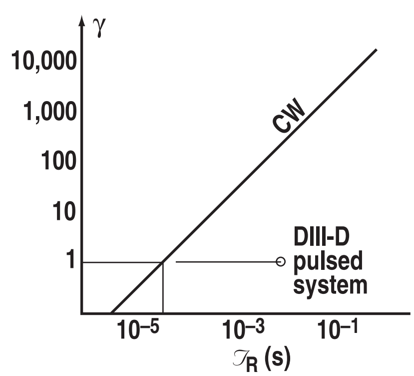

Fig. 3. γ-the ratio of (S/N) between CW-1D and DIII-D, as a function of $\mathcal{T}_R$, the sample time duration chosen for one measurement or simply the time resolution.

V. CW–2D: SETUP AND S/N COMPARISON

Using an optical relay arrangement, the measurement chamber can be duplicated to cover the entire plasma cross section, as shown in Fig. 4, the CW–2D case. For a cavity with 30 chambers, the cavity will be extended to about 150 m long and the round trip time 1 μs. However, the cavity loss may not increase much since relay mirrors close to the perfect reflectivity will be employed. For about the same level of pumping power as 1–D, the cavity can be run at 10 mJ energy level since the round trip time is 10 times longer than before.

The light collection cone $(F/\# \sim 25)$ will be much reduced over the 1–D case $(F/\# \sim 5)$. Instead of forming an image, the collection optics will collimate the light to pass along a series of large size filter panels, each covering a different wavelength range. Behind the filter panel, the light will form a 3–D image with arrays of SiAPD distributed to follow the image of the laser path.

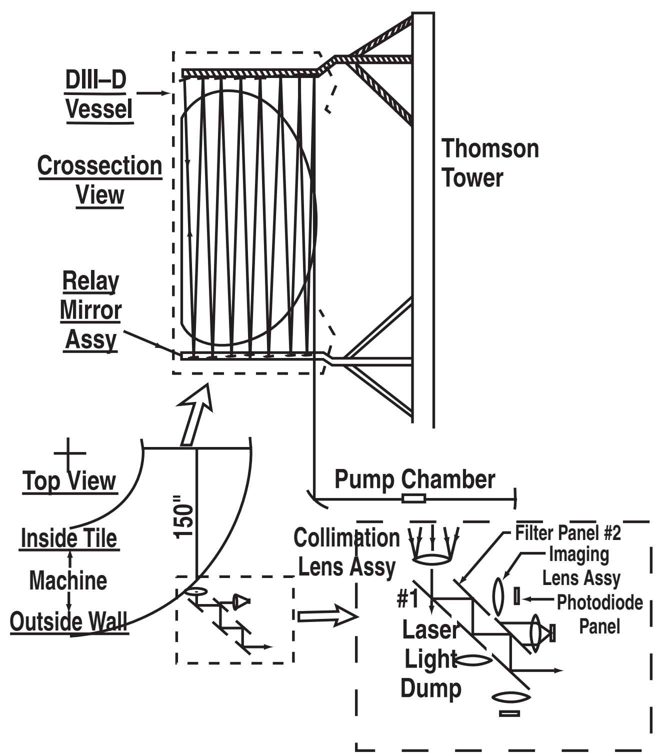

Fig. 4. A CW-2D arrangement, including relay measurement chambers, collection optics, filter panels and detector panel.

With the significant reduction in the light collection (background light included), the electronic noise (ignorable in the 1–D case) becomes comparable to the background fluctuation. The electronic noise includes the photo-detector's shot noise, the pre-amp's voltage and current noise, and Johnson noise of the resistive components. Its magnitude ranges about 20 photo-electron level at the photo-detector input for a bandwidth of ~10 MHz, as observed in DIII–D. By taking into account the light collection effect, we redefine $\sigma_B^2 = \alpha^2 B\Delta f$, where $\alpha = 1/(f/\#)$. We assume the electronic noise $\sigma_A = (1/10)\,\sigma_B\,(f/\# = 5)$, that is, one tenth of σ_B at $f/\# = 5$ as observed typically in DIII–D. And again, the S/N is expressed as

$$S/N \propto \frac{mE_c\alpha^2}{\left[2mB\Delta f\left(\alpha^2 + \frac{1}{2500}\right)\right]^{1/2}} \quad . \tag{3}$$

For DIII–D: $m = 1$, $E_c = 1$ J, $\alpha = [1/5]$, $\Delta f = 10^7$ Hz. For CW–2D: $E_c = 10^{-2}$ J, $\alpha = [1/25]$, $\mathcal{T}_1 = 10^{-6}$ s, $m = 2\times10^6\,\mathcal{T}_R$, $\Delta f = 2\times10^6/m\pi$. The ratio γ can be estimated as

$$\gamma = \frac{(S/N)_{CW-2D}}{(S/N)_{DIII-D}} \sim 10^4 \times \mathcal{T}_R \quad . \tag{4}$$

As shown in Fig. 5, for the CW–2D (10 mJ cavity energy and 1 µs round trip time) to have a comparable S/N as DIII–D $(\gamma = 1)$, it will need 100 samples and $\Delta f \sim 2.5$ kHz. The time resolution qualified for one measurement is 100 µs in this case, only a factor of 2 longer than that of 1–D.

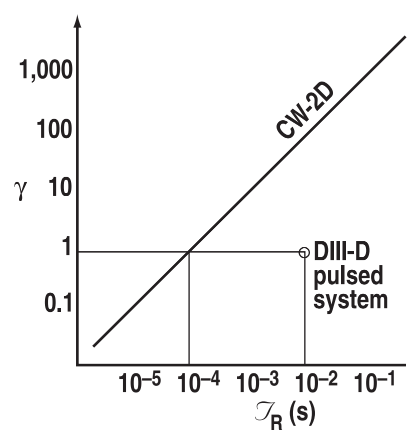

Fig. 5. γ-the (S/N) ratio between CW-2D and DIII-D as a function of the resolution time chosen for CW-2D.

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