# Prospects for measurement of rapid equilibrium changes and electron fluctuations using a high repetition rate Thomson scattering diagnostic

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Recent technological developments make a laser Thomson scattering diagnostic, operating in the incoherent electron scattering regime, a good candidate to accomplish measurements of fast electron dynamics (i.e., fast equilibrium changes, turbulence, and electron fluctuations) in high temperature plasmas. Pulse repetition rates for current generation Thomson scattering diagnostics have been limited to about 100 Hz, with the possible exception of ''burst'' modes in which multiple laser systems provide a limited sequence of closely spaced pulses. To overcome this limitation in laser capability, we propose that recent advances in compact, high power, diode-pumped solid state lasers be applied to a fast Thomson scattering diagnostic for fusion research. To illustrate the possibilities, we present an overview of a diagnostic system designed for the Madison Symmetry Torus reversed field pinch. The operational goal for this single-laser system is to measure $\tilde{T}_e$, $\tilde{n}_e$, and $\tilde{p}_e$ with a measurement rate of at least 10 kHz and spatial resolution of 2 cm. If successful, the technique can be extended to higher temporal frequencies and much better radial resolution, and implemented on other fusion research devices.  [DOI: 10.1063/1.1532762]

## I. DIAGNOSTIC GOALS

Measurement of fast electron dynamics (i.e., fast equilibrium changes, turbulence, and electron fluctuations) in high temperature plasmas is one of the remaining frontiers of plasma diagnostics.[1] The Transport and Turbulence Subgroup at the 1999 Snowmass Fusion Summer Study reported, ''While ion transport appears to be fairly well understood in tokamaks, knowledge of electron particle and energy transport remains far more elusive.'' Oversimplifying the measurement problem, ions are able to emit discrete wavelength photons that carry information about the state of that ion to a detector, while electrons emit radiation only when accelerated (e.g., cyclotron or bremsstrahlung emission) and typically must be actively probed with a beam of particles or photons in order to obtain detailed information. In spite of this difficulty, substantial progress has been made in measurement of the turbulent electron density field in the tokamak edge. However, the other turbulent moments of the electron distribution function have typically only been measured in cool edge plasmas with material probes. In addition to electron turbulence, there is also a critical need for measurement of fast equilibrium changes (such as sawtooth crashes and confinement barrier transitions), and long wavelength disturbances such as pressure-driven magnetohydrodynamic (MHD) instabilities.

Ideally, the experimentalist would like to make direct measurements of the entire electron distribution function as it fluctuates in time and space. A laser Thomson scattering diagnostic, operating in the incoherent electron scattering regime, is a candidate to accomplish a good part of this goal. Several examples of the possibilities of this approach exist. The high spatial resolution Thomson scattering system on the Rijnhuizen Tokamak Project (RTP) tokamak was used to make initial measurements of $\tilde{T}_e$, $\tilde{n}_e$, and $\tilde{j}_e$ for $0.03<k<0.2\ \mathrm{mm}^{-1}$ from an ensemble of 47 discharges.[2] The six laser vertical Thomson system on ASDEX Upgrade has just been improved to allow ''burst'' mode operation with a minimum time delay between laser pulses of 100 ns and radial resolution of 2.7 mm.[3] This is an impressive achievement, but temporal resolution in these and similar systems[4] is limited to a burst train consisting of a single-digit number of laser pulses; the time delay between bursts is a substantial fraction of a second. Continuous pulse repetition rates for current generation Thomson scattering diagnostics have been limited to about 100 Hz. This situation can be improved by increasing the number of lasers operating in the diagnostic system, but space, cost, and complexity severely limit that path. This limitation in laser capability is the sole difficulty, as filter or holographic transmission grating spectrometers with avalanche photodiode (APD) detectors could easily handle much higher data rates.

To overcome this limitation in laser capability, we propose that recent advances in compact, high power, diode-pumped solid state lasers can be applied to a fast Thomson scattering diagnostic for fusion research. This laser development effort has been driven by a combination of industrial,

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defense, and inertial fusion energy applications, and thus this proposal represents an attractive and cost-effective transfer of technology to the magnetic fusion energy program. To illustrate the possibilities, we will present an overview of a diagnostic system designed for the Madison Symmetric Torus (MST) reversed field pinch (RFP). MST has a well-diagnosed plasma and exhibits interesting physics, including an improved confinement operating mode, large-scale resistive MHD activity, and magnetic relaxation phenomena. The operational goal for this system is to measure $\tilde{T}_e$, $\tilde{n}_e$, and $\tilde{p}_e$ with a measurement rate of at least 10 kHz and spatial resolution of 2 cm, using a single, compact laser. If successful, the technique can be extended to higher temporal frequencies and much better radial resolution, and implemented on other fusion research devices.

## II. SIMILAR WORK

To our knowledge, no one has constructed a laser Thomson scattering diagnostic operating in the incoherent electron scattering regime to measure electron turbulence. A proposal to perform plasma turbulence imaging using high-power laser Thomson scattering has appeared in the literature,[5] but the present proposal is fundamentally different. That work proposed use of the Nova laser to produce a single-pulse 1–3 kJ "plane sheet" beam to produce a snapshot two-dimensional (2D) image of spatial electron density fluctuations, providing a diagnostic capability with similarities to recent advances in beam emission spectroscopy.[6] The initial implementation of the diagnostic we are proposing nominally produces one-dimensional spatial measurement of both $\tilde{n}_e$ and $\tilde{T}_e$, but the time-series measurement capability will provide data from which 2D or even three-dimensional structures can be reconstructed. This was accomplished to a very limited extent on the RTP tokamak by double pulsing the Thomson scattering laser. The two pulses were timed to coincide with the passing of the tearing mode "*O*" and "*X*" points past the measurement points; the expected profile flattening and steepening was observed.[7] In MST the long wavelength helical tearing modes will continuously rotate past the measurement points; correlation of the fluctuations in $\tilde{n}_e$ and $\tilde{T}_e$ with magnetic fluctuation measurements will allow for spatial reconstruction of the $\tilde{n}_e$ and $\tilde{T}_e$ turbulent structures. Thus the ability to make local, time-series measurements of fluctuations should translate to a powerful spatial mapping capability.

The diagnostic in current operation that is most similar in capability to the proposed fast Thomson scattering system is correlation radiometry of electron cyclotron emission. Successful use of this technique was first reported on the W7-AS stellarator,[8] and has since been extended to measurement of the correlation between electron density and temperature fluctuations in W7-AS by simultaneous operation of a heterodyne reflectometer and correlation electron cyclotron emission (ECE).[9] Correlation ECE radiometry has been applied to or is being implemented on a number of tokamaks, most notably TEXT-U.[10] Future application of ECE radiometry is limited by several factors. Probably the most severe is the radiation cutoff that prevents viewing ECE in low-field magnetic confinement devices, although mode conversion of electron Bernstein waves offers diagnostic possibilities in overdense plasmas.[11] But even in tokamaks and stellarator, auxiliary current drive and heating, or the presence of suprathermal electrons, can significantly alter the electron distribution function and make interpretation of ECE spectra more difficult.[12] An incoherent Thomson scattering diagnostic is less sensitive to this problem, and does not suffer from radiation cutoff.

## III. EXAMPLE IMPLEMENTATION

The innovative aspect of the proposed diagnostic is the application of high-average-power diode-pumped solid state Yb:yttrium–aluminum–garnet (YAG) laser technology to a Thomson scattering system. Development of this laser technology is being driven by both industrial and inertial fusion energy applications.[13] Development work on diode-pumped Yb:YAG lasers is being done by various laboratories worldwide.[14–17] (Refs. 18 and 19 are good summaries of the current status of ytterbium solid state lasers). Yb:YAG improves on Nd:YAG by having a longer fluorescence lifetime and closer pump and emission peaks, thus making it a more efficient gain medium, especially for diode pumping. However, Yb:YAG is a three-level laser (unlike Nd:YAG) and thus requires a minimum pump level to bleach the lower level. At low pulse repetition frequencies, every shot requires this bleaching investment, but above kHz rates at high power Yb:YAG becomes highly efficient. Design scalings have predicted reasonably compact Yb:YAG lasers operating at 100 kW average power.[16]

We propose development and construction of a 1030 nm Yb:YAG laser system as the source for a fast Thomson scattering diagnostic for the MST reversed field pinch. The technical approach follows a previously demonstrated Yb:YAG system in which good beam quality at high average power was achieved through a resonator design utilizing a large diameter fundamental mode that almost filled the rod.[14] In this approach, the laser rod itself acts as a spatial filter. This limits the number of transverse modes beyond the fundamental that are supported by the cavity without incurring large diffractive losses. Figure 1 shows a schematic drawing and photograph of a dual-rod Yb:YAG system with a 90° rotator located between the rods for birefringence compensation. This tabletop-size system is serving as the base line for the presently proposed Thomson scattering source.

The laser shown in Fig. 1 produced over 1 kW of continuous wave output power, and in a *q*-switched mode produced 532 W of output power at a kHz pulse repetition frequency (53.2 mJ/pulse). For *q* switching, two acousto-optic *q* switches were symmetrically located in the cavity near the end mirrors. In the *q*-switched mode of operation, the measured pulse width was 77 ns, the measured beam quality was $M^2 = 2.2$, and the pump-light to laser-light conversion efficiency was 17%. The only substantial difference between the already demonstrated laser technology and the technology being proposed here is in the diode pump arrays. Since the development of the laser shown in Fig. 1, LLNL has developed an advanced laser diode package,[20] called the

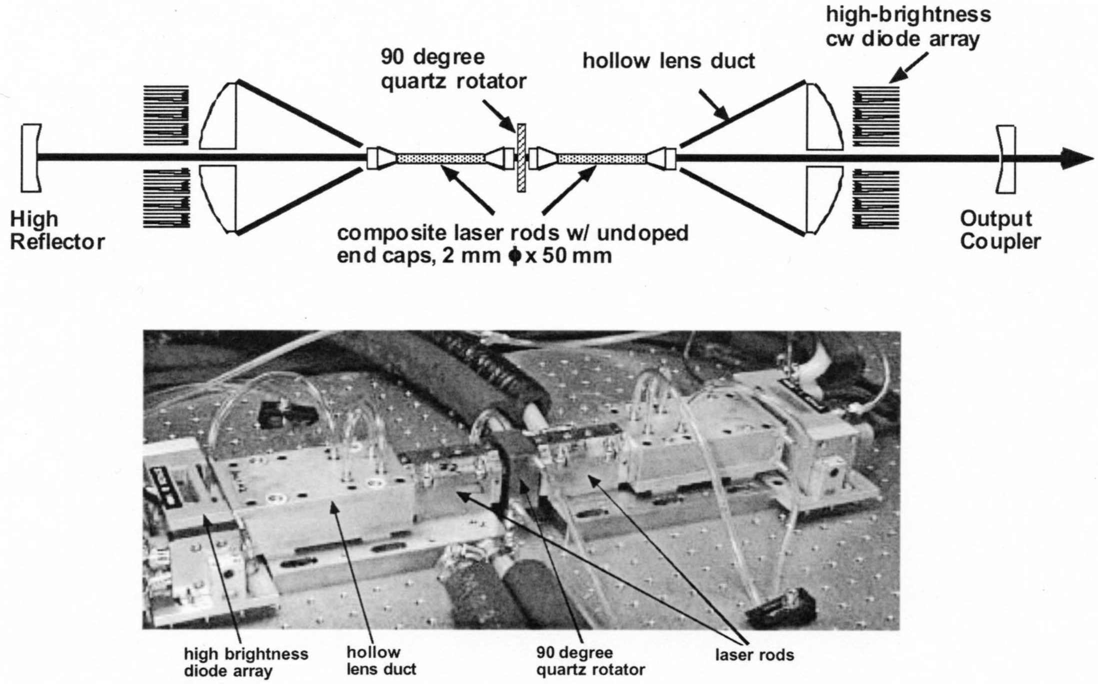


FIG. 1. Schematic diagram and photograph of a dual-rod Yb:YAG laser with birefringence and bifocusing compensation, developed at Lawrence Livermore National Laboratory.

''SiMMs'' package for silicon monolithic microchannels. This development substantially reduces the cost of the laser diode arrays. The proposed laser system will require approximately 3.2 kW of diode arrays for pump excitation, a small fraction of the 80 kW of SiMMs packaging that has already been successfully demonstrated.

The laser we are proposing will be designed to meet the following specifications:

(1) burst mode operation with a burst duration of 100 ms every 2–3 min;
(2) pulse duration $<100$ ns;
(3) 10 kHz$\leqslant$pulse repetition frequency $\leqslant 20$ kHz during burst on time;
(4) pulse energy $\geqslant 50$ mJ;
(5) beam quality ($M^2$) generated by the laser shall be such that a 1-mm-diam spot 50 cm from a beam entry point on the containment vessel can be generated, and that over a 50 cm span the beam remains less than 2 mm in diameter; and
(6) laser light should be linearly polarized.

The beam quality description given in the fifth specification above can be quantified as an $M^2$ requirement of 5.3. With this $M^2$ value, and a 3.6-mm-diam input beam spot at the entrance port to the containment vessel, a simple 50 cm focal lens at the entry port can be used to generate the necessary beam divergence profile.

With only a simple optical management system at the output of the laser, it can be argued that the dual-rod 1030 nm Yb:YAG system shown in Fig. 1 has met all the required laser specifications for the Thomson scattering diagnostic. The optical management system at the output of the laser would be required to address the linear polarization requirement given in specification (6). The laser light from the system shown in Fig. 1 was unpolarized due to the stress-induced birefringence in the laser rod. However, the demonstrated beam quality for the laser in Fig. 1 was $M^2 = 2.2$, which is more than two times better than that required to achieve a 1 mm spot size at a focus, 50 cm from an entry port [specification (5)]. This opens up the possibility that the output radiation from the laser can be split apart into two orthogonal linearly polarized beams and then recombined into a single composite spot. Simple optical recombination in which one of the split off beams has its polarization rotated by 90° and then is juxtaposed next to the other beam results in a composite single beam having linear polarization at roughly twice the beam quality of the original unpolarized laser beam. Thus the composite beam will be linearly polarized and have a beam quality sufficient to generate the 1-mm-diam spot as required by specification (5) above. However, for the Thomson scattering diagnostic it will probably be straightforward to generate linearly polarized light directly out of the laser without any need for beam splitting and recombining. As explained below, this is because the Thomson scattering laser runs at a substantially lower average power than the continuously running system that we have already demonstrated.

In many respects, the laser system proposed for application to a Thomson scattering diagnostic on the MST RFP is less demanding in terms of its specifications than the already demonstrated system in Fig. 1. This is because the system in Fig. 1 operated continuously at the 10 kHz and 53 mJ/pulse operating point, but the present system is only required to operate at this pulse format in a burst mode (100 ms every

2–3 min). This burst mode operation opens up a new operating window resulting from the relationship between the thermal diffusion time needed to establish steady state temperature gradients in the 2-mm-diam Yb:YAG rod and the burst mode duty cycle. As a very rough estimate of the time taken to establish steady state thermal gradients in the 2-mm-diam YAG rods to be used, we simply consider the thermal diffusion time in YAG:

$$\Delta t = \frac{\rho c}{\kappa} \Delta x^2,$$

where $\rho$ is the 4.56 g/cm$^3$ density of YAG, $c$ is the 0.59 J/g °C heat capacity of YAG, and $\kappa$ is the 0.01 $W_{th}$/cm °C thermal conductivity of YAG. Taking $\Delta x$ to be the 1 mm rod radius gives a thermal diffusion time of 2.7 s. This thermal diffusion time, which is much longer than the burst mode on time (100 ms), and much shorter than the burst mode off time (2–3 min), offers up interesting possibilities that suggest laser design could be simplified and laser performance exceeded relative to the already demonstrated continuously running system. These possibilities for simpler systems and better performance obtain because thermal gradients will not have a chance to establish themselves in the laser rod during the burst on time, and the gradients that do establish themselves after a burst is completed will have substantially decayed away before the next burst begins. This means the laser rod will essentially be starting from a cold cavity configuration for every burst and be operating in a near heat capacity mode. Simplifications over the continuously running design will come in several ways. Since thermally induced gradients will not establish significantly during the burst on time, thermal lensing in the laser rod will not be an issue. Additionally, it will not be necessary to correct for stress-induced birefringence, and so design considerations associated with bifocusing compensation that were important for the continuously running system will not have to be addressed in the Thomson scattering system. We are proposing to carefully consider the possibility of exploiting these conditions in the design phase of the laser. Based on our preliminary estimates, it does appear that a single rod pumped at each end will be adequate for the Thomson scattering laser.

The light collection and detection systems of this diagnostic do not require the same level of innovation as the laser. Implementation on the MST RFP is eased by a machine design that provides good diagnostic access (no discrete toroidal field coils), although porthole size is limited to 11.5 cm diameter. Scattered light collection will be done with a custom six-element lens similar to that used for the MST equilibrium profile measurement Nd:YAG Thomson scattering system. The lens translates entirely in vacuum through a valve to view the laser scattering volume in MST. The focal plane of the lens is outside the vacuum and is easily accessible. Fiber optic bundles will lead from the focal plane to filter polychromators designed and built by General Atomics.[21] All eight channels of each of the polychromators will be populated, four on the short wavelength side of the 1030 nm laser line, three on the long wavelength side, and one covering the laser line to enable Rayleigh scattering density calibration. Avalanche photodiode detectors will be used on each of the polychromator channels. The output of the APD modules will be directly digitized at a rate between 0.5 and 1.0 GHz, with the digitizer gated on for approximately 500 ns around each laser pulse. This digitization scheme captures both the signal and background with a single channel, and has become cost competitive with current pulse integrating digitizers such as the LeCroy 2249A. Direct digitization increases the system flexibility and provides a better operational record for troubleshooting and data analysis.

An eight channel polychromator is not sufficient to allow inversion of a non-Maxwellian electron velocity distribution function, but is sufficient to measure the small shift of the center of the scattered spectrum.[22] This shift is proportional to the directed electron velocity ($j_k$). Although not one of the goals of this diagnostic, it may be useful at some point to attempt ensemble average equilibrium measurements of the component of $j_e$ directed along the scattering $k$ vector.

## IV. ESTIMATED PERFORMANCE OF THE PROPOSED DIAGNOSTIC

To set the context for the fluctuation measurement performance that should be obtained from the proposed fast Thomson scattering diagnostic, we have carried out a simple moment analysis estimate of the expected uncertainties in $T_e$ and $n_e$. The most important parameter in this estimate is $N$, the total number of Thomson scattered photoelectrons collected per pulse of the laser. This can be calculated from $N \approx N_I(\eta T) n_e r_0^2 L(\Delta\Omega)$, where $N_I$ = number of incident photons in laser pulse; $n_e$ = electron density $\approx 1.5 \times 10^{19}$ m$^{-3}$; $r_0$ = classical electron radius = $2.82 \times 10^{-15}$ m; $L$ = length of observed scattering volume $\approx 0.02$ m; $\Delta\Omega$ = observation solid angle $\approx 0.03$ sr; $\eta$ = quantum efficiency of detector $\approx 0.4$; and $T$ = transmission of the optical system $\approx 0.2$.

The values shown for these parameters are what could be expected for an implementation on MST. The uncertainty in density measured by Thomson scattering is proportional to $1/\sqrt{N}$, and the uncertainty in temperature is $\sim\sqrt{2}$ times larger. Two other mechanisms add to the measurement uncertainty: the excess noise generated by the avalanche process in the APD, and the background light emitted by the plasma in the wavelength region of measurement. A good quality APD will have low dark current and an excess noise factor $F$ of 3 or less, so we assume $F = 3$. (Electronic noise added by the amplifier and digitizer following the APD is not accounted for here, but that can be minimized by good design.) In MST, we typically record continuum emission in the near infrared (NIR) about five times bremsstrahlung, so that has been folded into the estimate of background photoelectron in Table I. Other estimates going into the figures in the table are a total spectral bandwidth of 100 nm for collection of Thomson scattered light, and a spectrometer étendue of 0.014 cm$^2$ sr (reasonable for standard 3-mm-diam APD detectors, but could be increased substantially by large area APDs). Note that a quantum efficiency of 0.4 for the APD detectors is conservative; for example, Perkin-Elmer NIR-enhanced APDs are specified to be 0.4 at 1064 nm, rising to nearly 0.8 at 950 nm.

TABLE I. Estimate of measurement uncertainties using a 50 mJ laser pulse energy in the proposed high repetition rate Thomson scattering system.

| Pulse energy at 1030 nm | Photons/ pulse from laser | Photoelectrons/ pulse $N$ | Background photoelectrons in 100 ns | $\Delta n_e$ | $\Delta T_e$ |
|---|---|---|---|---|---|
| 50 mJ | $2.6\times10^{17}$ | 1480 | 2000 | 12% | 17% |

These simple analytic uncertainty estimates are very encouraging. They are conservative by design; the moment analysis estimate does not assume a fitting function, and so does not add any information to the problem. A simple Monte Carlo simulation, assuming a Gaussian fitting function, produced substantially lower estimated uncertainties, $\leqslant$8%. More sophisticated Thomson scattering data analysis techniques, such as a maximum likelihood method,[23,24] may produce even lower uncertainties. Therefore, we can conclude, with a very high degree of certainty, that with a 50 mJ Yb:YAG laser similar to that demonstrated at LLNL, measurements with $\leqslant$17% single-pulse uncertainty will be achieved at $\geqslant$10 kHz. However, much more can be done with this diagnostic, as ensemble averaging and statistical correlation techniques dramatically lower the achievable uncertainty for electron turbulence measurements.

The key to reducing the statistical uncertainty of a measurement of a fluctuation quantity is to acquire many time-series samples. Over 100 such samples can be obtained in a single day of MST operation. Plasmas are routinely produced in MST with excellent reproducibility in relevant mean parameters (current, temperature, density, magnetic field profile) and in magnetic fluctuations (amplitude and spectra). Ensemble averages of correlated fluctuating quantities have been obtained for many years as part of the transport studies in MST. For the proposed Thomson scattering diagnostic, each time-series sample will have a duration of about 20 ms (the equilibrium flattop portion of a MST discharge) and contain 200 datapoints (at $f_{\text{pulse}}=10$ kHz). For fluctuations that are propagating in the poloidal and toroidal directions, as is the case for the tearing mode fluctuations in MST, the time average is equivalent to an average over a magnetic surface. As will be shown below, even with pessimistic assumptions, an ensemble averaged quantity will be precisely measurable in one MST run day.

The first step in fluctuation analysis of data from a high repetition rate Thomson scattering diagnostic on MST will be to perform a correlation analysis (e.g., the correlation of temperature and magnetic fluctuations). A correlated quantity such as $\langle\tilde{B}\tilde{T}_e\rangle$ is rich in physics content, and is simpler to measure because the tearing modes in MST produce a clean, low-noise $\tilde{B}$ that averages out uncorrelated noise from the correlated quantity. A simulation predicts that data from only 20 MST discharges will be sufficient to characterize a 1% fluctuation to a precision of 0.1% (e.g., 0.3 eV uncertainty on a 3 eV fluctuation of a 300 eV equilibrium). Correlation analysis techniques are well developed on MST, having been successfully applied to many measurements, including spectroscopic measurements of $\tilde{v}$ and interferometric measurements of $\tilde{n}_e$.[25,26] On MST, this Thomson scattering diagnostic will have the capability to capture the characteristics of the electron turbulence associated with tearing mode activity. This will enable first-time measurements of the structure of such turbulence and the transport caused by it.

However, suppose the temperature fluctuations are uncorrelated with other fluctuating quantities. From a physics viewpoint this would be unexpected in MST, and would provide the severest test of this Thomson scattering diagnostic. In order to estimate the uncertainty in an ensemble averaged quantity such as $\langle\tilde{T}_e\rangle$,[27] we first estimate the "fluctuation uncertainty," $\delta_{\tilde{T}_m^2}$, in a single time point measurement of $\tilde{T}_m^2=(\tilde{T}_e+\sigma_T)^2$, where $\tilde{T}_e$ is the actual physical fluctuation amplitude and $\sigma_T=51$ eV is a conservative estimate of the randomly distributed measurement uncertainty (Table I) for $T_e=300$ eV (typical in a standard MST discharge)

$$\delta_{\tilde{T}_m^2}=\sqrt{2\tilde{T}_e^2\sigma_T^2+\sigma_T^4}.$$

For an ensemble of $M$ time samples, the ensemble-averaged uncertainty is

$$\sigma_{\sqrt{\langle\tilde{T}_e^2\rangle}}\approx\frac{\delta_{\tilde{T}_m^2}}{\sigma_T\sqrt{M}},$$

where the approximation is valid when $M$ is large and the $\delta$ uncertainties at each time sample are similar. With $M=2\times10^4$ (one day of MST operation) and $\tilde{T}_e=3$ eV (1% of equilibrium $T_e$) the statistical measurement precision for $\langle\tilde{T}_e\rangle$ is 0.36 eV. Instrumental noise in the diagnostic will have to be understood and measured for such uncorrelated fluctuation measurements to be meaningful. If necessary, we can go beyond individual test and monitoring systems and test the instrumental noise and performance of the diagnostic system *in situ* by recording a Raman scattered signal from molecular hydrogen (no plasma, just $H_2$ in the vacuum vessel). In this application the Raman scattering signal is a "fluctuation-free" test bogey (no density or temperature fluctuations in a room temperature gas) that will enable us to quantify instrumental noise and cross-channel correlations that could disrupt fluctuation measurements. Thus, we are confident that the proposed diagnostic will be able to measure even uncorrelated electron fluctuations to approximately 0.1% of equilibrium $T_e$ at a fluctuation bandwidth of 5 kHz (the Nyquist limit due to the sampling frequency). Since MST plasmas are reproducible both shot to shot and day to day, detailed measurement of the spectral and spatial characteristics of electron turbulence will be within the capability of the proposed diagnostic.

## V. PERFORMANCE EXTENSION

Further development of diode-pumped Yb:YAG lasers to higher frequency and pulse energy is an obvious first step to extending the performance of a high repetition rate Thomson scattering diagnostic. Technical prospects for such development are good, but two other steps could also be taken to improve the capability of this diagnostic. The first is a photon recycling system of the type proposed by Barth, Chu, and Donné.[28] In such a system photons from a laser pulse are captured in a ring cavity by means of a polarizing beamsplitter and electro-optical switch. One arm of the cavity passes through the plasma, increasing the scattered photon yield by up to a factor of 10. Similar systems have been implemented and shown to function as expected,[29] so implementation on the proposed system should not be difficult, although the 77 ns pulse duration of the Yb:YAG would require a fairly large ring cavity.

A second step to extend diagnostic capability would require multiple (e.g., 10) Yb:YAG lasers installed such that their beams pass through the plasma closely spaced ($\approx$1 mm spacing) and tangent to flux surfaces, a scheme similar to that of the ASDEX vertical Thomson scattering system.[3] By phasing the firing of the lasers such that beams 1–10 follow each other at close intervals ($\approx$200 ns between each beam), a ''snapshot'' of the detailed radial structure of $T_e$ and $n_e$ could be taken at a 10 kHz rate. Adding this capability does not require an increase in the number of polychromators , as the data from each of the 10 spatial points is temporally multiplexed and recorded by the GHz digitizers on the polychromator channels. Thus, this could be a cost-effective way to capture the detailed structure of plasma turbulence at millimeter scale lengths.

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