Plasma turbulence imaging using high-power laser Thomson scattering

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The two-dimensional (2D) structure of plasma density turbulence in a magnetically confined plasma can potentially be measured using a Thomson scattering system made from components of the Nova laser of Lawrence Livermore National Laboratory. For a plasma such as the National Spherical Torus Experiment at the Princeton Plasma Physics Laboratory, the laser would form an ≈10-cm-wide plane sheet beam passing vertically through the chamber across the magnetic field. The scattered light would be imaged by a charge coupled device camera viewing along the direction of the magnetic field. The laser energy required to make 2D images of density turbulence is in the range 1–3 kJ, which can potentially be obtained from a set of frequency-doubled Nd:glass amplifiers with diameters in the range of 208–315 mm. A laser pulse width of ⩽100 ns would be short enough to capture the highest frequency components of the expected density fluctuations. [DOI: 10.1063/1.1319369]

I. INTRODUCTION

Plasma turbulence is one of the most difficult phenomena to understand in plasma physics. Compared with neutral fluid turbulence, there is still relatively little experimental information about the space-time structure of small-scale plasma density turbulence, which is probably the dominant turbulence in many magnetic fusion plasmas (here ''small scale'' refers to a range of turbulence wave numbers across the magnetic field of $k_{\perp} a \ll 1$, where a is the plasma size). Given the well-recognized importance of such turbulence for magnetic fusion plasma confinement,[1] it is important to improve our diagnostic ability in this area.

This article discusses the feasibility of making a significant improvement in diagnosing plasma density turbulence by applying the high-power laser equipment developed by the inertial confinement fusion (ICF) program at Lawrence Livermore National Laboratory (LLNL) to measure plasma density turbulence in a suitable magnetic fusion device. We propose to use the well-understood technique of Thomson scattering to measure the two-dimensional (2D) structure of density turbulence in an experiment such as the National Spherical Torus Experiment (NSTX) at the Princeton Plasma Physics Laboratory (PPPL), which has a large magnetically confined plasma suitable for such a study. This initial assessment shows that the required laser would need ≈1–3 kJ of energy in a pulse of width ⩽100 ns to make a single 2D image of the expected density turbulence in a NSTX discharge. This appears feasible using a laser built from components that could be obtained from the recently decommissioned Nova laser system at LLNL.

A schematic illustration of this concept is shown in Fig. 1. The laser would enter the plasma through a large window at the bottom of the machine in a beam with a radial width of ≈10 cm. The laser beam would exit through a window at the top, and stop in a specially constructed beam dump remote from the machine. A very small fraction of the laser light ($\approx 10^{-9}$) will be Thomson scattered by the free electrons in the beam path. The local intensity of the scattered light will be proportional to the local electron density. Therefore spatial fluctuations in the electron density in the radial versus

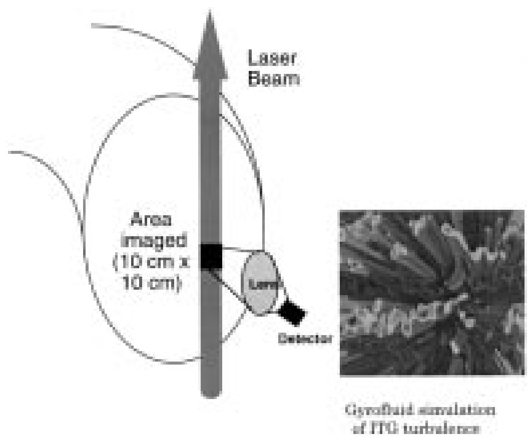

FIG. 1. Schematic illustration of a 2D Thomson scattering measurement of density turbulence in NSTX. The camera viewing along the magnetic field line would make a 2D radial vs poloidal image of the scattered light from electrons within the area imaged. At the right is a 3D rendering of a theoretical simulation of ITG density turbulence, which has short correlation lengths in the radial vs poloidal plane but a long correlation length along the magnetic field. The laser beam duration of ⩽100 ns is shorter than the turbulence autocorrelation time, so the instantaneous structure of the turbulence should be visible.

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TABLE I. Assumed NSTX parameters for 2D Thomson scattering.

Plasma major radius	$R_o = 0.85$ m
Plasma minor radius	$a = 0.68$ m
Radius of measurement	$R \approx R_o + a/2 \approx 1.3$ m
Density at this location	$n = 3 \times 10^{13}$ cm^{-3}
Electron temperature at this radius	1 keV
Estimated turbulence size scale	$\lambda \approx 1-10$ cm
Estimated turbulence magnitude	$\tilde{n}/n \approx 1\%$
Estimated viewing area	10 cm $\times$ 10 cm
Estimated turbulence time scale	$\leqslant 1$ μs

poloidal plane can be measured by making a 2D image of the scattered light as viewed approximately along the magnetic field line, thus integrating over the width of the laser beam in the direction parallel to the magnetic field (in which the fluctuations are constant). If the laser pulse width is shorter than the turbulence autocorrelation time (eddy turnover time), an image of the small-scale density turbulence will be produced.

Similar scattering techniques are used in fluid turbulence experiments,[2] but a plasma scattering experiment is more difficult due to the $\geqslant 10^6$ times lower density of plasma with respect to neutral fluids. However, this measurement in a magnetic fusion plasma is important because the results could be directly compared with the recent three-dimensional (3D) gyrokinetic and gyrofluid simulations of toroidal plasma turbulence, such as that illustrated in Fig. 1.[3] A comparison between the measured 2D density turbulence structure and these models would be a significant test of the validity of these models, even if this structure could only be measured at one point in time per discharge.

II. SIMULATION OF THE EXPECTED 2D IMAGES

The main technical difficulty in this diagnostic arises from the very small cross section for incoherent Thomson scattering, $\sigma_{\mathrm{TS}} = (8\pi/3) r_e{}^2 \approx 6.6 \times 10^{-25}$ cm^2. Although small, this cross section is completely understood, making Thomson scattering measurements the most reliable method for plasma density and temperature measurements in magnetic fusion research.[4] In this section we estimate the laser energy needed to produce 2D images of plasma density turbulence in NSTX and show a simulation of such an image.

The assumed plasma and turbulence parameters for NSTX are shown in Table I, as estimated from previous experimental studies on tokamak plasmas.[1] The plasma density in the region of interest is typically $n = 3 \times 10^{13}$ cm^{-3} with a local density fluctuation level of $\approx 1\%$ rms and a range of spatial scales from $\lambda_\perp \approx 1-10$ cm. The structure of these fluctuations is generally isotropic and turbulent across the magnetic field but very elongated along the magnetic field ($\lambda_{\mathrm{parallel}} \gg 1$ m), as illustrated in Fig. 1.

First we give a rough estimate of the laser energy required to resolve these density fluctuations using Thomson scattering. The fraction of scattered photons is $F = \sigma_{\mathrm{TS}} n L$, where L is the vertical distance along the laser path length. For an incident laser beam with P photons/cm in the radial direction, the total number of photons per cm scattered into a detector subtending a solid angle Ω str. is thus $N_{\mathrm{tot}} \approx F P \Omega / 4\pi$. For imaging a 1 cm vertical $\times$ 1 cm radial area of the NSTX plasma, $F \approx 2 \times 10^{-11}$, $P \approx 3 \times 10^{18}$ photons/cm for a 1 J/cm green laser, and $\Omega/4\pi \approx 2 \times 10^{-3}$ (corresponding to *f*/6). Thus the total number of scattered photons from this area reaching the detector is $N_{\mathrm{tot}} \approx 10^5$ per Joule/cm of laser energy. We now assume a total photon-to-photoelectron detection efficiency of $\approx 3\%$, which includes both the losses in the optics and the detector photon counting efficiency. Thus the number of photoelectrons detected is $\approx 3 \times 10^3$ per Joule/cm of laser energy. For an assumed laser of 1 kJ energy over a beam width of 10 cm, this implies 3×10^5 photoelectrons will be detected from the plasma area of 1 cm $\times$ 1 cm. This corresponds to a statistical fluctuation level of $\leqslant 0.2\%$, which should be small enough to measure the $\approx 1\%$ density fluctuations.

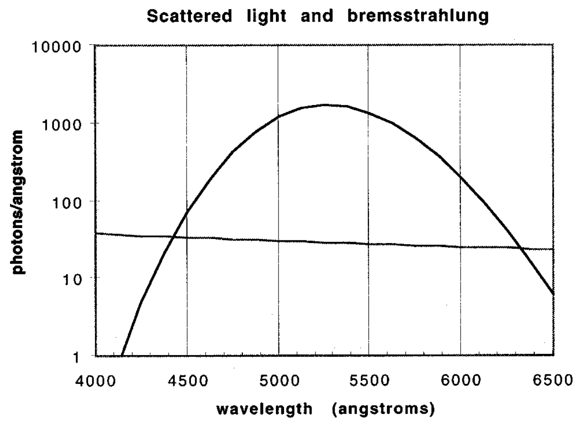

FIG. 2. Calculated spectrum of the laser light scattered at 90° to the laser beam by a 1 cm $\times$ 1 cm area of a NSTX plasma with $n = 3 \times 10^{13}$ cm^{-3} and $T_e = 1$ keV, compared with the plasma bremsstrahlung spectrum (straight line). The estimated signal/noise level for a density measurement within this area is S/N$\approx$430 for a 1 kJ laser beam spread over a radius of 10 cm radially.

A more detailed simulation of this Thomson scattering process has been done taking into account the electron temperature, the assumed scattering angle (90° to the laser beam), and the detection solid angle and efficiency used above. A typical scattered spectrum is shown in Fig. 2, along with the expected visible bremsstrahlung background spectrum calculated for this plasma assuming a $Z_{\mathrm{eff}} = 3$. The result is that by integrating over the scattered spectrum, the expected signal/noise (S/N) level for a density measurement made within a 1 cm $\times$ 1 cm area is S/N$\approx$430 at a laser energy of $E = 100$ J/cm, which is approximately consistent with the rough estimate above. The ratio of signal-to-bremsstrahlung signal is also $\geqslant 10$ over most of the linewidth, assuming a detector gating time of 100 ns.

The conclusion from this analysis is that the expected density fluctuations in NSTX can be imaged using a laser with $\geqslant 1$ kJ/pulse in a 2D configuration such as is illustrated in Fig. 1. This laser energy can be contrasted with the conventional NSTX Thomson scattering system,[5] which uses a frequency doubled Nd:yttrium–aluminum–garnet laser with an energy ≈ 1.5 J/pulse in a single line passing through the plasma. That system is expected to have a few-% statistical accuracy for measuring density in a cm-sized region. Thus it

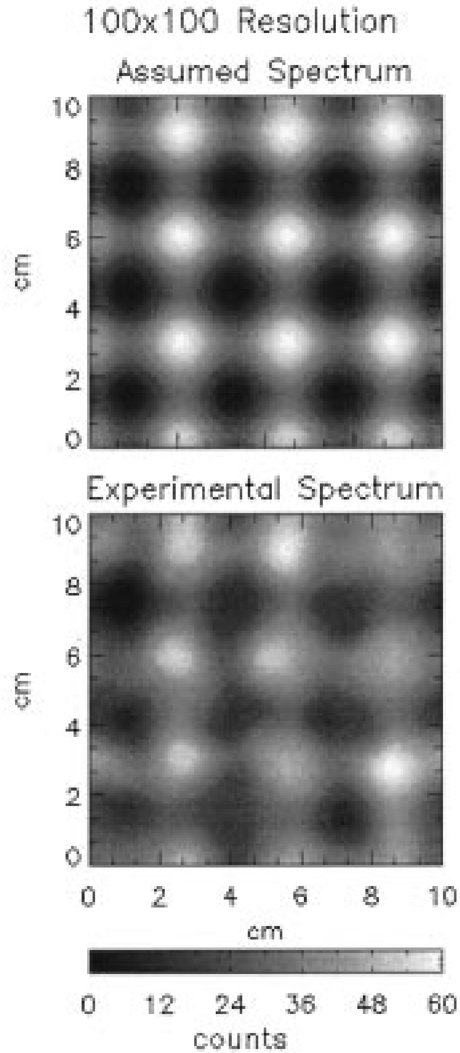

FIG. 3. Simulation of expected 2D image for an assumed 3 cm wavelength density fluctuation in NSTX. The top shows the assumed spatial structure of the 1% density fluctuations in a 10 cm $\times$ 10 cm area. The bottom shows the expected image after taking into account the statistical fluctuations expected for a 2 kJ laser scattering system. The average plasma density has been subtracted from both these images.

is not surprising that a kJ-class laser is needed to measure cm-scale density fluctuations to $\approx 0.2\%$ accuracy over a 10 cm $\times$ 10 cm region.

The quality of the 2D imaging which can be expected from a kJ-class laser Thomson scattering system in NSTX is illustrated in Fig. 3. The assumed ''theoretical'' spatial density fluctuation spectrum (top) was a coherent mode with a 3 cm wavelength in both directions perpendicular to the magnetic field. The amplitude of this perturbation was assumed to be 1% of its mean value (the mean is subtracted out in both parts of this figure). The ''experimental'' spectrum (bottom) was obtained by (a) binning this theoretical image in a set of 100 $\times$ 100 pixels, (b) randomly changing the number of counts in each pixel by the expected statistical noise level (proportional to the square root of the amplitude in each pixel), and (c) smoothing the results over 10 $\times$ 10 pixels (1 cm $\times$ 1 cm) to simulate the experimental image. The case shown in Fig. 3 corresponds to a signal level of 3×10^5 counts/cm^2, i.e., to a total laser energy corresponding to ≈ 1 kJ in the NSTX case. The conclusion of this analysis is that such a laser should be able to make a reasonably clear image of the expected density turbulence in NSTX.

III. HIGH POWER LASER SYSTEM

The $\approx 1-3$ kJ laser required for this diagnostic can be made using potentially available components from the Nd: glass Nova laser, which was operated at LLNL at a maximum energy level of 40 kJ/pulse (351 nm).[6] Laser components from LLNL have already been used to design a 2 kJ laser diagnostic for use on the Z-facility at Sandia National Laboratory.[7] This is about 10–100 times more laser energy per pulse than has been used in the highest-power laser Thomson scattering systems previously used in tokamaks.[8,9]

The requirements on the laser system for the present Thomson scattering diagnostic are relatively modest compared with the typical requirements for ICF experiments. The Nd:glass frequency would most likely be doubled to 526 nm to facilitate detection of the scattered signals using high spatial resolution charged coupled device (CCD) detectors (see Sec. IV). The pulse duration should be <100 ns pulse to reduce background light. The laser linewidth will easily be orders of magnitude smaller than the width of the scattered spectrum (Fig. 2). The beam needs a single pass propagation distance of ≈ 10 m to propagate through a device like NSTX, and a far-field spot size of ≈ 1 cm inside the plasma to achieve the desired spatial resolution. Note that the toroidal extent of the laser beam can be well over 10 cm, since the camera is viewing turbulent filaments which are highly correlated in the toroidal direction. The laser profile versus radius would need to be measured accurately to calibrate the scattered signals versus radius.

It would be highly desirable but not necessary to make several pulses per shot with a time separation comparable to the turbulence autocorrelation time (≈ 10 μs), in order to measure the dynamics of the turbulence. This could be achieved in principle by dividing the available laser energy into multiple pulses, since the Nova glass amplifiers have an energy storage time of several hundred microseconds. However, there is a trade-off between the number of such pulses per shot and the energy in each pulse, such that the highest spatial resolution would be obtained with a single laser pulse. A single 2D image obtained with a repetition rate of 1 high-power laser pulse per hour should be sufficient for the initial research goals of this diagnostic.

These requirements could be met by a laser constructed using Nova components similar to those outlined in Table II. The designs are based on laser amplifiers of aperture size 208–315 mm, which are potentially available for this purpose. The generic laser system design using Nova disk amplifiers, as illustrated in Fig. 4, can produce a 1200–3000 J pulse at 526 nm, the second harmonic of the Nd:glass laser wavelength. This system design uses four laser passes through the glass amplifiers, and assumes frequency doubling with 75% conversion efficiency. It should be stressed

TABLE II. Preliminary summary of potential main cavity laser amplifier configurations using Nova components (with angle-multiplexed four-pass arrangement).

Amplifier size (mm)	208[a]	315
Beam diameter (mm)	180	273
Disks per amplifier unit	3	2
Disk thickness (mm)	32	43.2
Single pass gain per amplifier	2.2	1.75
Small signal gain (cm^{-1})	0.068	0.054
Stored energy density (J/cm^3)	0.32	0.25
Stored energy per amplifier (J)	1182	1924
Damage limit (J, est. at 20 ns)	1600	15 000
Number of amplifiers in four-pass	3	4
Four-pass small signal gain	1804	2294
Total stored energy (J)	3545	7695
Gain saturation energy (J)	1527	3502
Available 1ω output energy (J)	1600	4000
2ω output at 75% conversion (J)	1200	3000

[a]The 208 mm amplifiers are currently unavailable due to heavy demand, but may become available at a later date depending on project funding availability.

that a detailed conceptual design for this laser system would be required to make a final determination of the laser requirements, identify all components, and make accurate cost and schedule estimates before implementation could begin.

IV. POSSIBLE IMPLEMENTATION

There are many technical issues to be resolved before this diagnostic could be implemented on a magnetic fusion energy (MFE) device like NSTX. Some of these are:

(a) the vacuum and optical integrity of the windows must be maintained, which requires a laser energy limit of about 5 J/cm^2 at the windows;

(b) the beam dump must be capable of absorbing the laser pulse without damage or scattering of light back into the plasma;

(c) the laser beam must be handled safely, and requires a large clean area near the machine;

(d) the detector and laser wavelength need to be optimized for the desired spatial resolution and S/N ratio, e.g., a high resolution image might use a photocathode/CCD detector at a laser wavelength of 532 nm, while a low resolution (e.g., 10×10) image could be made at a higher S/N level using an array of avalanche photodiodes at 1064 nm; and

(e) a realistic evaluation needs to be made of the cost and schedule, including the laser systems, interface with the machine, and detection system.

It should be noted that this diagnostic could in principle be used on any MFE device similar in size and accessibility to NSTX. However, the implementation of this diagnostic would obviously be considerably more costly and time consuming than for a conventional Thomson scattering system of much lower energy.

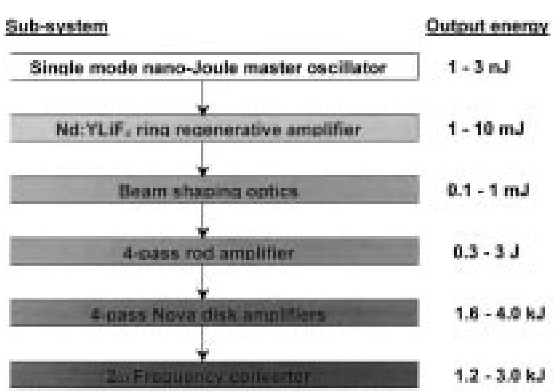

FIG. 4. Generic laser system design using Nova disk amplifiers to produce a 1200–3000 J pulse at 526 nm, the second harmonic of the Nd:glass laser wavelength. Two options are considered, one with a final frequency-doubled laser energy of $\approx$1200 J and another with a laser energy of $\approx$3 kJ.

V. SUMMARY

This article described a diagnostic to measure the 2D structure of plasma density turbulence in a MFE fusion plasma using high-power laser Thomson scattering. It appears feasible to construct the required $\approx 1-3$ kJ pulsed laser source with components developed for the Nova program at LLNL. This system could also make multiple images within the laser energy storage time of several hundred microseconds, but only at lower spatial resolution. Considerably more analysis is needed before a practical system could be implemented on a device such as NSTX.

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[1] A. J. Wootton, B. A. Carreras, H. Matsumoto, K. McGuire, W. A. Peebles, C. P. Ritz, P. W. Terry, and S. J. Zweben, Phys. Fluids B **2**, 2879 (1990).
[2] U. Frisch, *Turbulence* (Cambridge University Press, Cambridge, 1995).
[3] G. D. Kerbel, T. Pierce, J. L. Milovich, D. E. Shumaker, A. Verlo, R. E. Waltz, G. W. Hammett, M. A. Beer, and W. Dorland, Int. J. Supercomput. Appl. **10**, No. 213 (1996).
[4] I. H. Hutchinson, *Principles of Plasma Diagnostics* (Cambridge University Press, Cambridge, 1987), Chap. 7.
[5] D. Johnson, N. Bretz, B. LeBlanc, R. Palladino, D. Long, and R. Parsells, Rev. Sci. Instrum. **70**, 776 (1999).
[6] J. K. Lawson, D. R. Speck, C. Bibeau, S. C. Burkhart, M. A. Henesian, C. W. Laumann, T. L. Weiland, and R. B. Wilcox, Appl. Opt. **31**, 5061 (1992); C. Bibeau, D. R. Speck, R. B. Ehrlich, C. W. Laumann, D. T. Kyrazis, M. A. Henesian, J. K. Lawson, M. D. Perry, P. J. Wegner, and T. J. Weiland, *ibid.* **31**, 5799 (1992); P. J. Wegner, M. A. Henesian, D. R. Speck, C. Bibeau, R. B. Ehrlich, C. W. Laumann, J. K. Lawson, and T. L. Weiland, *ibid.* **31**, 6414 (1992).
[7] R. Adams, A. Anderson, R. Aragon, J. Auerbach, B. Behrendt, D. Boomquist, J. Caird, E. Dawson, G. Edwards, and A. Erlandson *et al.*, Report for UCRL-ID-134409, Lawrence Livermore National Laboratory, Livermore, CA, 31 May 1999.
[8] M. N. A. Beurskens, C. J. Barth, N. J. L. Cardozo, and H. J. van der Meiden, Plasma Phys. Controlled Fusion **41**, 1321 (1999).
[9] M. Yu. Kantor and D. V. Kourprienko, Rev. Sci. Instrum. **70**, 780 (1999).