

# A scalable multipass laser cavity based on injection by frequency conversion for noncollective Thomson scattering<sup>a)</sup>

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A scalable setup using injection by frequency conversion to establish a multipassing cavity for noncollective Thomson scattering on low density plasmas is presented. The cavity is shown to support  $>10$  passes through the target volume with a 400% increase in energy on target versus a single-pass setup. Rayleigh scattering experiments were performed and demonstrate the viability of the cell to study low density plasmas of the order of  $10^{12}$ – $10^{13}$   $\text{cm}^{-3}$ . A high-repetition, low-energy, single-pass Thomson scattering setup was also performed on the University of California, Los Angeles Large Plasma Device and shows that the multipass cavity could have a significant advantage over the high-repetition approach due to the cavity setup's inherently higher signal per shot. © 2010 American Institute of Physics. [doi:10.1063/1.3460626]

## I. INTRODUCTION

Thomson scattering has been an important noninvasive, nonperturbative plasma diagnostic for many decades.<sup>1–3</sup> However, due to the small Thomson cross-section ( $\sigma_{\text{th}} = 6.65 \times 10^{-25}$   $\text{cm}^2$ ), Thomson scattering is challenging at low densities ( $<10^{14}$   $\text{cm}^{-3}$ ). In the absence of a more energetic laser (or if laser-induced plasma heating is a concern<sup>5</sup>), one can compensate by integrating the signal from repetitive measurements using a high-repetition laser<sup>6–8</sup> or by sending each laser pulse multiple times through the scattering volume.<sup>9–11</sup>

We present here a new multipassing cavity configuration for using the laser pulse multiple times per shot to perform noncollective (incoherent) Thomson scattering sampled over a time proportional to the cavity's length. Like other multipassing schemes that use Pockels or Herriot cells,<sup>9–11</sup> our setup allows low density plasmas to be studied by averaging a Thomson signal over several passes. Unlike these other schemes, our setup uses laser frequency conversion to trap the beam in the cavity.<sup>12</sup> It has the advantage that the input laser energy is only limited by the optics' damage thresholds, that the laser beam size is only limited by the size of the optics, and that the probe beam passes through the same scattering volume and is collected at the same scattering angle (within alignment errors) every cycle of the cavity. This configuration is thus scalable for large diameter, high energy applications such as turbulence diagnostics in tokamaks,<sup>13</sup> where time scales of interest are longer than the cavity sampling time.

## II. EXPERIMENTAL SETUP

The overall design of the multipass system is shown in Fig. 1. The cell is seeded with the University of California, Los Angeles PHOENIX Nd:glass laser, a 1064 nm, 40 mm beam that provides 20 J in 5 ns. The seed laser is frequency doubled inside the cavity, which acts like a spherical resonator.

The cavity is bounded by two 532 nm flat mirrors at 0° incidence. To prevent incoming 1064 nm light from being back-reflected toward the laser, the cavity mirrors are mounted orthogonal to each other, and the seed beam enters the cell through a 532 nm mirror, angled at 45° relative to the main beam, located equidistant with the second cavity end mirror from the first focusing lens. This arrangement allows  $\approx 90\%$  of the seed beam to enter the cavity while reducing the total back-reflected light by a factor of  $10^6$ , low enough to operate the glass laser without a large-aperture Faraday isolator. A type 2 potassium dihydrogen phosphate (KDP) crystal frequency doubles the seed beam to 532 nm (with an efficiency up to 50%) and is located between the angled mirror and a dichroic mirror. The dichroic mirror, also angled at 45° relative to the main beam and fielded before the first focusing lens, reflects 1064 nm light unconverted by the KDP crystal out of the cavity while transmitting 532 nm light. The two  $f/20$  focusing lenses are placed equidistant from the target and outside the chamber. Antireflective windows coated for 532 nm allow the probe beam to enter and exit the target chamber.

Scattered light from the target is collected with an  $f/4$  lens at a 90° angle relative to the probe beam, focused with an  $f/6$  lens onto a 0.75 m SPEX™ spectrometer, with a 1200 grooves/mm grating blazed at 532 nm, and image-relayed onto a Princeton Instruments MAX intensified charge-coupled device (ICCD) camera. The spectrometer has

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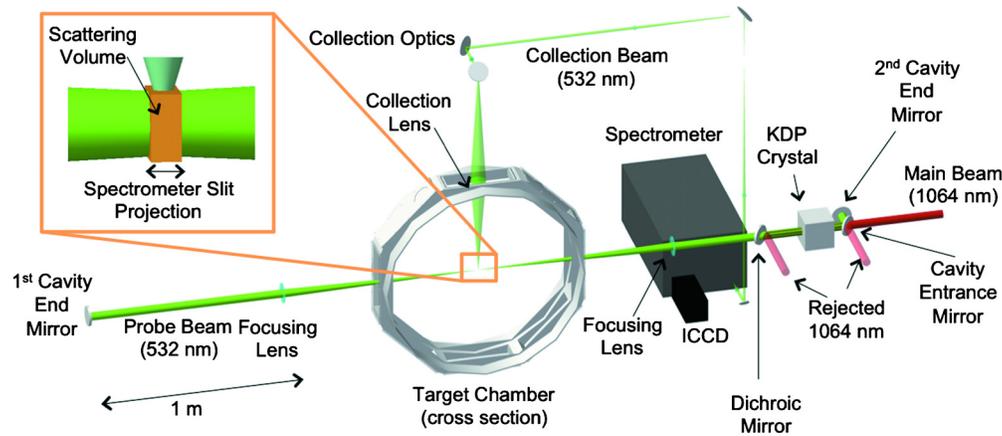


FIG. 1. (Color online) Schematic layout for multipass cavity.

a resolution of  $2 \text{ \AA}$  for a  $50 \text{ }\mu\text{m}$  slit width. The camera has a  $512 \times 512$  pixel array with an effective pixel size of  $24 \times 24 \text{ }\mu\text{m}^2$  and a  $130 \text{ \AA}$  field of view. Steep  $[\Delta\lambda(6 \text{ OD}-50\% \text{ transmission})=1.7 \text{ nm}]$  longpass or short-pass filters mounted immediately before the focusing collection lens block stray light at the laser line by a factor of  $10^6$ . The collection beam path between the filters and the ICCD is completely enclosed to prevent stray light contamination and the entire spectrometer/ICCD setup (including filter and focusing collection lens) is enclosed in a light-tight box.

A CCD camera placed in the path of rejected 1064 nm and leaked 532 nm light from the dichroic mirror, with a filter to block 1064 nm light and crosshairs placed next to each cavity end mirror, facilitated cavity alignment. The cell alignment was found to be stable at least over the course of a day.

Photodiodes were placed at the leaks of the cavity end mirrors to gauge the performance of the cell. Each diode recorded the time and amplitude of the light as it made alternating passes through the cell (either from the first cavity end mirror to the second cavity end mirror or vice versa), tracking how many passes the cell supported and how efficiently the light was transmitted. Figure 2 shows the performance of the cell after combining the information from both diodes. The cell supported  $>12$  passes (six round trips) with a travel time of  $13.7 \pm 0.2 \text{ ns}$  and a loss of  $\approx 30\%$  each pass. The total energy on target was then  $\sim 4\times$  the input energy

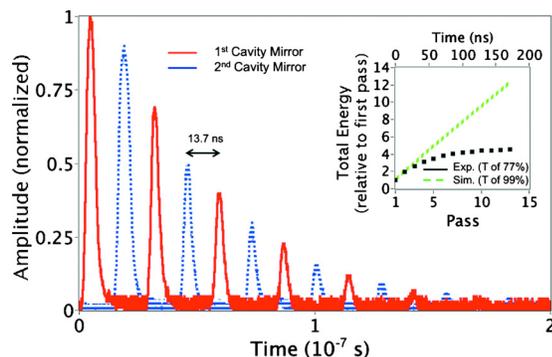


FIG. 2. (Color online) Interlaced diode signal from leaks of first cavity mirror (solid line) and second cavity mirror (dotted line). Inset shows total energy on target (square points) for a KDP crystal transmission of 77% and the simulated total energy on target (dotted line) for a crystal transmission of 99%.

(after frequency doubling) over  $\approx 160 \text{ ns}$ . The most lossy component of the cavity was the KDP crystal with a measured transmission of  $\sim 77\%$ . Improvements in the transmissivity of the doubling crystal (e.g., 99%; see Ref. 14) would result in  $>3\times$  more energy on target for a similar number of passes (see Fig. 2 inset).

### III. RAYLEIGH SCATTERING VALIDATION

To estimate the expected Thomson scattering signal from a low density plasma and to validate the performance of the multipass setup, we used the cavity to Rayleigh scatter off air at various chamber pressures and ICCD exposure times. For a given gas density  $n_r$ , we can estimate the plasma electron density  $n_{th}$  that would give an equivalent Thomson scattering signal using  $n_{th}=n_r(\sigma_r/\sigma_{th})$ , where  $\sigma_r$  and  $\sigma_{th}$  are the Rayleigh and Thomson scattering cross-sections, respectively.<sup>2</sup>

For the Rayleigh scattering measurements, a 300 mJ, 532 nm, 5 ns pulse beam was injected into the multipass cell, and scattered light was collected with a  $f/6$  lens. Figure 3 shows a series of ICCD images for chamber pressures between 150–760 torr and ICCD exposure times between 10 and 125 ns. The images have a  $24 \text{ \AA}$  field of view. The first cavity pass is clearly visible at higher pressures, and the second cavity pass is clearly visible at later times (later passes have signals less than the stray light signal). The first and second pass centroids are separated by  $800 \text{ }\mu\text{m}$ , corresponding to an  $\approx 40$  arcsecond pointing error.

At a chamber pressure of 150 torr, the Rayleigh signal was approximately equal to the background RMS noise, representing the limit on the resolution of our system. Since for air  $\sigma_r/\sigma_{th}=1/401$ ,<sup>2</sup> a pressure of 150 Torr corresponds to a

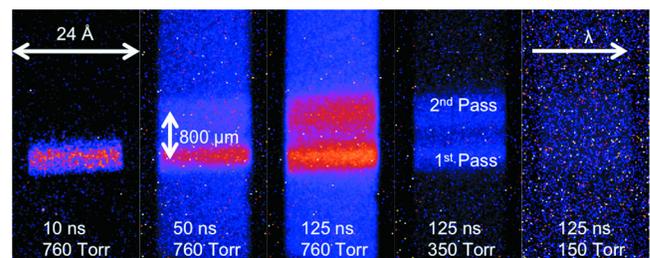


FIG. 3. (Color online) Chamber pressure and ICCD exposure time series for Rayleigh scattering using the multipass cavity.

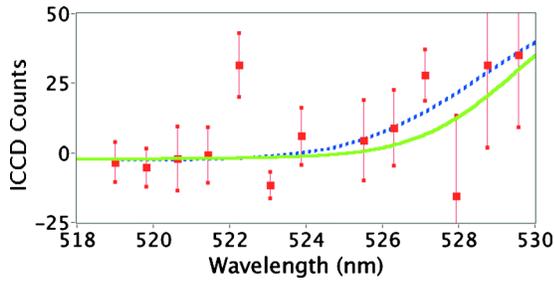


FIG. 4. (Color online) Background-subtracted experimental data per laser pulse and best electron temperature fit (dotted line) for LAPD Thomson scattering. Also shown (solid line) is a simulated Thomson spectrum for an electron temperature of 5 eV, normalized to the amplitude of the fit.

Thomson scattering electron density of  $\approx 10^{16} \text{ cm}^{-3}$ . Since the Thomson signal scales linearly with laser energy,<sup>1</sup> using the full beam energy ( $\sim 10 \text{ J}$ ) should increase the Thomson signal by a factor of  $10^2$ , while installing longpass/shortpass filters should reduce stray light by at least a factor of  $10^2$ . The overall effect is to increase the signal relative to background by a factor of  $10^4$ , allowing us to measure our target electron densities of  $10^{12} - 10^{13} \text{ cm}^{-3}$ .

#### IV. THOMSON SCATTERING ON THE LAPD

With the goal of providing a performance comparison for the multipass setup, we performed Thomson scattering using a high-repetition, low-energy, time-averaged approach on UCLA's Large Plasma Device (LAPD), a 1 m diameter, 20 m long cylinder machine that pulses at 1 Hz to produce uniform magnetized He plasmas of densities of the order  $10^{12} \text{ cm}^{-3}$  and electron temperatures around 5 eV (Ref. 15) [a scattering parameter  $\alpha = (k\lambda_D)^{-1} \approx 0.01$ , with  $\lambda_D$  as the Debye length and  $k$  the magnitude of the scattering vector  $\mathbf{k}$  (Ref. 1)]. We used a single-pass setup with a 1 Hz, 300 mJ, 532 nm, 8 ns probe beam, and a  $f/3$  collecting lens. The spectrum was situated on the ICCD such that stray light at the laser line was cut (i.e., only wavelengths up to or larger than the laser line were imaged) and the ICCD exposure was set between 3 and 10 ns to minimize the collection of stray light and background plasma emissions. Additionally, to maximize our signal versus detector noise, we setup the ICCD to bin in both pixel directions to achieve a  $16 \times 1$  array of superpixels.

We were able to measure an electron temperature of  $6.3_{-4.1}^{+5.8} \text{ eV}$  by averaging the Thomson signal over 100–1000 shots and fitting a Gaussian curve (i.e., a simple noncollective Thomson spectrum) to the data (Fig. 4).<sup>1,4</sup> This agrees well with the LAPD electron temperature.

However, the small Thomson signal per shot warrants further investigation. Assuming Poisson statistics, we can compare the SNR of the averaged repetitive measurement approach to the multipass cavity using

$$\text{SNR} = N_{\text{th}} / \sqrt{N_{\text{th}} + N_{\text{b}}}, \quad (1)$$

where  $N_{\text{th}}$  is the mean Thomson signal and  $N_{\text{b}}$  is the mean background signal for a laser energy  $E$ . For an integer multiple  $n$ , the ratio  $R$  of the  $\text{SNR}_{\text{m}}$  from one multipass cell shot using a laser energy of  $n \cdot E$  (i.e.,  $N_{\text{th}} \rightarrow n \cdot N_{\text{th}}$ ) to the  $\text{SNR}_{\text{r}}$  from  $n$  repetitions with laser energy  $E$  (i.e.,  $N_{\text{th}} \rightarrow n \cdot N_{\text{th}}$ ,  $N_{\text{b}} \rightarrow n \cdot N_{\text{b}}$ ) is

$$R = \frac{\text{SNR}_{\text{m}}}{\text{SNR}_{\text{r}}} = \sqrt{\frac{(N_{\text{th}} + N_{\text{b}})}{(N_{\text{th}} + N_{\text{b}}/n)}}. \quad (2)$$

For large  $n$ ,  $R$  limits to  $\sqrt{1 + N_{\text{b}}/N_{\text{th}}}$ , which is always  $> 1$  as long as some background noise exists. This implies that under the same conditions, the multipass cavity always has an advantage over a low-energy, averaged measurement approach. Assuming similar LAPD conditions as above ( $N_{\text{th}} \sim 30$  counts,  $N_{\text{b}} \sim 650$  counts for  $E = 300 \text{ mJ}$ ), we expect the multipass cell to have  $\sim 5 \times$  the SNR of the corresponding averaged repetitive measurements (i.e.,  $R \approx 5$ ). This will be tested in an upcoming experiment on the LAPD.

#### V. SUMMARY

We have developed a new multipass cavity configuration for performing noncollective Thomson scattering on low density plasmas that can be easily scaled to large laser energies and shown the viability of this configuration by Rayleigh scattering off air. If optics with proper optical damage properties are chosen, the cell could theoretically focus  $\sim 85 \text{ J}$  on target using a 1 J input laser by using a highly transmissive frequency doubling crystal. We have also shown that our multipass cavity should have a significant advantage over using a high-repetition, low-energy laser to average a Thomson signal from many shots because of the inherently low signal per shot in the high-repetition approach.

#### ACKNOWLEDGMENTS

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- <sup>1</sup>D. E. Evans and J. Katzenstein, *Rep. Prog. Phys.* **32**, 207 (1969).
- <sup>2</sup>A. DeSilva, G. Goldenbaum, H. R. Griem, and R. H. Lovberg, *Methods of Experimental Physics* (Academic, New York, 1971), Vol. 9, Part 1, pp. 61–113.
- <sup>3</sup>S. H. Glenzer and R. Redmer, *Rev. Mod. Phys.* **81**, 1625 (2009).
- <sup>4</sup>K. Muraoka, K. Uchino, and M. D. Bowden, *Plasma Phys. Controlled Fusion* **40**, 1221 (1998).
- <sup>5</sup>S. H. Glenzer, W. Rozmus, V. Y. Bychenkov, J. D. Moody, J. Albritton, R. L. Berger, A. Brantov, M. E. Foord, B. J. MacGowan, R. K. Kirkwood, H. A. Baldis, and E. A. Williams, *Phys. Rev. Lett.* **88**, 235002 (2002).
- <sup>6</sup>M. D. Bowden, T. Okamoto, F. Kimura, H. Muta, K. Uchino, K. Muraoka, T. Sakoda, M. Maeda, Y. Manabe, M. Kitagawa, and T. Kimura, *J. Appl. Phys.* **73**, 2732 (1993).
- <sup>7</sup>T. Hori, M. Kogano, M. D. Bowden, K. Uchino, and K. Muraoka, *J. Appl. Phys.* **83**, 1909 (1998).
- <sup>8</sup>S. G. Belostotskiy, R. Khandelwal, Q. Wang, V. M. Donnelly, D. J. Economou, and N. Sadeghi, *Appl. Phys. Lett.* **92**, 221507 (2008).
- <sup>9</sup>C. J. Barth, C. C. Chu, and A. J. H. Donné, *Rev. Sci. Instrum.* **66**, 501 (1995).
- <sup>10</sup>M. D. Bowden, Y. Goto, H. Yanaga, P. J. A. Howarth, K. Uchino, and K. Muraoka, *Plasma Sources Sci. Technol.* **8**, 203 (1999).
- <sup>11</sup>M. Y. Kantor, A. J. H. Donné, R. Jaspers, H. J. van der Meiden, and T. Team, *Plasma Phys. Controlled Fusion* **51**, 055002 (2009).
- <sup>12</sup>I. Jovanovic, M. Shverdin, D. Gibson, and C. Brown, *Nucl. Instrum. Methods Phys. Res. A* **578**, 160 (2007).
- <sup>13</sup>S. J. Zweben, J. Caird, W. Davis, D. W. Johnson, and B. P. Le Blanc, *Rev. Sci. Instrum.* **72**, 1151 (2001).
- <sup>14</sup>Y. Fei, B. H. Chai, C. Ebberts, Z. Liao, K. Schaffers, and P. Thelin, *J. Cryst. Growth* **290**, 301 (2006).
- <sup>15</sup>W. Gekelman, H. Pfister, Z. Lucky, J. Bamber, D. Leneman, and J. Maggs, *Rev. Sci. Instrum.* **62**, 2875 (1991).