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(54) Title: STRUCTURED LIGHT-BASED SENSOR DEVICES

(57) Abstract: Disclosed is a structured light sensor system. The system may include a beam structuring module configured to receive a laser beam from a laser source and output structured light towards a target volume. The beam structuring module designed to receive a laser beam and output a structured laser beam may comprise a spatial light modulator or a combination of axicons, or spiral phase plates, or other optical elements. This module directs the structured beam towards various optical components, which may consist of single or multimode optical fibers or free-space optics, including lenses, collimators, and mirrors, to precisely shape and guide the beam. The system may include optical element(s), including a focusing lens, configured to direct the structured light towards the target volume. The system may include additional optical element(s) configured to direct a non-reflection output response from the target volume towards a detector along a response optical path.



## STRUCTURED LIGHT-BASED SENSOR DEVICES

## CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority to US Provisional Patent Application No. 63/460,165, filed April 18, 2023, the contents of which are incorporated by reference herein in its entirety.

## STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Grant No. DE-AC02-09-CH11466 awarded by the Department of Energy. The government has certain rights in the invention.

## TECHNICAL FIELD

The present disclosure is drawn to the field of laser-based sensor devices and systems, and specifically for devices and system utilizing a laser beam to probe a target volume and receive non-reflective output from the target volume in response to the probe.

## BACKGROUND

This section is intended to introduce the reader to various aspects of art, which may be related to various aspects of the present invention that are described and/or claimed below. This discussion is believed to be helpful in providing the reader with background information to facilitate a better understanding of the various aspects of the present invention. Accordingly, it should be understood that these statements are to be read in this light, and not as admissions of prior art.

There are numerous optical diagnostic techniques used in industrial and research applications. Laser-induced fluorescence (LIF), including variations like Doppler-shift-based LIF or two-photon LIF, stands out as an exceptionally useful diagnostic in research environments with significant potential for industrial application. It is a non-invasive, active optical diagnostic technique that is commonly used for measuring the velocity distribution function (VDF) of ions or neutral species in low-temperature plasmas in a range of conditions, from weakly collisional low-pressure plasmas to collisional plasmas generated at elevated pressures. The principle of the LIF diagnostic is based on the optical pumping of a plasma

sample with laser light and analyzing the resulting fluorescence signal. By using a narrow linewidth tunable laser, this diagnostic method is able to provide high-resolution information about the velocity distribution function of plasma species. This makes LIF a versatile and valuable tool for plasma physicists and engineers studying plasma behavior in various applications. The VDF obtained from LIF can provide information about important parameters such as ion or atom temperatures and flow velocities.

However, adapting diagnostics from research to industrial use presents significant challenges and its capabilities are insufficient. For example, the semiconductor industry increasingly demands non-invasive, real-time, spatially resolved, species specific (*e.g.*, etching reactants as Cl, F, and their products SiCl, SiCl<sub>2</sub>, etc.) plasma diagnostics and metrology tools compatible with industrial reactors. This is essential as the industry moves toward extremely uniform, 'gentle' plasma conditions for atomic layer manipulation and 3D geometries on large-area wafers (a common size of which is a 300 mm diameter, but other sizes, such as 450 mm, etc., are known). Under such conditions, small deviations from the prescribed processing steps (*i.e.*, a recipe) may lead to unforgiving errors in production, significantly reducing yield of the manufacturing chain. Current diagnostics like mass spectroscopy or optical emission spectroscopy provide limited bulk plasma data, lack spatial and temporal resolution, and cannot be used as detectors serving as metrology tools. Active laser spectroscopy, not yet industry-adapted, offers high-fidelity, spatio-temporally resolved, species-specific plasma characterization. These advanced diagnostics provide critical insights into material processing, active processing control, and microchip defect minimization. However, their industrial implementation is impeded by challenges such as restricted optical access, complex geometries, space constraints, and harsh reactor environment.

## BRIEF SUMMARY

Various deficiencies in the prior art are addressed below by the disclosed compositions of matter and techniques.

In various aspects, a structured light sensor system may be provided. The system may include a laser source, configured to generate a laser beam. The laser beam may be configured to pass along a laser optical path towards a target volume (which may include, *e.g.*, a plasma, or other atoms or ions responsive to a structured laser beam as disclosed herein.). The laser source may include a single wavelength laser diode, a quantum cascade laser, a diode laser system, a dye laser, an optical-parametric oscillator, or a combination thereof, or may include

any appropriate laser source configured to generate a laser beam that can generate a response in the target volume. The laser source may include a tunable laser diode.

The system may include a beam structuring module configured to receive a laser beam from the laser source and output structured light.

5        There are many ways to generate structured light, including using, *e.g.*, spatial light modulators or a combination of axicons, spiral phase plates, etc.

      The beam structuring module may include a light modulator configured to receive the laser beam and output a modulated laser beam. The beam structuring module may include a single or multimode mode optical fiber with a collimator configured to receive the modulated  
10       laser beam and output a laser beam with a circular beam shape. The beam structuring module may include a plurality of axicons configured to receive the laser beam with the circular beam shape and output the structured light, where the structured light has an annular beam shape. The plurality of axicons may include two refractive axicons or two diffractive axicons. The plurality of axicons may include at least two coaxial and parallel axicon lenses. The system  
15       may include one or more optical elements configured to direct the structured light towards the target volume. The one or more optical elements may include a focusing lens. The system may include one or more additional optical elements configured to direct a non-reflection output response (such as fluorescent output) from the target volume towards a detector along a response optical path.

20       The beam structuring module may include one or more additional components. The additional components may include a spiral phase plate. The additional components may include a fiber grating. The additional components may include a digital micro-mirror. The additional components may include a combination of two or more of the above. Each additional component may be disposed in the laser optical path.

25       The beam structuring module may include a spatial light modulator. The light modulation may be performed by an optical chopper. The spatial light modulator may be something other than an optical chopper that similarly modulates the intensity of the laser beam, such as a mechanical beam shutter or MEMS optical shutter/chopper. The structured light sensor system may include a beam splitter disposed in the laser optical path.

30       The laser optical path and the response optical path in the vicinity of the target volume may vary. For example, the response optical path as it exits the target volume may be configured to be in a direction orthogonal to a direction of the laser optical path as it enters the target volume (*e.g.*, a more conventional approach). The response optical path as it exits the

target volume may be configured to be in a reciprocal direction a direction of the laser optical path as it enters the target volume (*e.g.*, at least a portion of the optical paths are confocal). The response optical path as it exits the target volume may be configured to be in a direction non-orthogonal and non-reciprocal to a direction of the laser optical path as it enters the target  
5 volume.

When the response optical path is configured to use the confocal approach, the structured light sensor system may include a bandpass filter disposed in the response optical path. The bandpass filter may be configured to differentiate between the structured light and the non-reflection output response. The center wavelengths and full width-half maximum  
10 values of the bandpass filter may vary. In some embodiments, the bandpass filter may have a center wavelength of 400-450 nm, and a full width-half maximum of 5-20 nm.

The detector may be, *e.g.*, a photodiode or photomultiplier tube, or may be some other appropriate detector for detecting the responsive output from the volume of space.

The structured light sensor system may include a first beam splitter disposed in the laser  
15 optical path. The first beam splitter may be configured to direct a portion of the laser beam or modulated laser beam towards a first light sensor operably coupled to an amplifier.

The structured light sensor system may include a dichroic mirror disposed in the laser optical path to receive the structured light (*i.e.*, downstream from the beam structuring module). The dichroic mirror may be configured to reflect a first wavelength (*e.g.*, a wavelength of the  
20 structured light) and to pass a second wavelength (*e.g.*, a wavelength of an output response). The focusing lens may be configured to receive output from the dichroic mirror, direct and focus the laser beam having the first wavelength to the target volume, receive fluorescent output from the target volume at the second wavelength, and direct the fluorescent output having the second wavelength along the response optical path through the dichroic mirror.

25 The structured light sensor system may include an iris disposed in the response optical path to receive the fluorescent output having passed through the dichroic mirror. The iris may be configured to cut off fluorescent light emitted by species which are excited along the laser optical path (outside the target volume).

The structured light sensor system may include a second lens configured to receive  
30 output from the iris and direct the fluorescent output towards the detector, the detector being operably coupled to an amplifier. In some embodiments, both the detector and the first light sensor are coupled to the same amplifier, which may be a lock-in amplifier where information from the first light sensor is used as a reference input, and information from the detector is used

as a signal input. The structured light sensor system may include at least one processing unit configured to receive information from the amplifier.

The structured light sensor system may include a second beam splitter disposed between the laser source and the first beam splitter. The second beam splitter may be configured to direct a portion of the laser beam towards a wavemeter.

The structured light sensor system may include at least one mirror between the laser source and the single mode optical fiber. The structured light sensor system may include a pinhole disposed in the response optical path between the second lens and the detector. The pinhole may have a diameter of 50-200  $\mu\text{m}$ .

The target volume may be a volume of space adjacent to a surface of a metal or a semiconductor. The target volume may be an ion source. The ion source may be a vacuum chamber comprising a housing defining a central volume of space, ions being within the central volume of space, where both the laser optical path and the response optical path pass through a window in the housing. The housing may include a plurality of ports configured as collection ports for conventional LIF diagnostics.

In various aspects, a method for structured light-based diagnostics using a structured light-based system may be provided. The method may include generating a laser beam. The method may include transforming the laser beam into an annular laser beam using at least two coaxial and parallel axicon lenses. The method may include directing the annular laser beam towards a target volume comprising one or more ions or atoms. The method may include receiving non-reflective output from the target volume. The method may include directing the non-reflective output (which may be, *e.g.*, fluorescent output from one or more ions within the target volume) towards a detector.

Transforming the laser beam may include receiving the laser beam at a spatial light modulator and outputting a modulated laser beam, receiving the modulated laser beam at an optical fiber with a collimator and outputting a laser beam with a circular beam shape, and receiving the laser beam with the circular beam shape at the at least two coaxial and parallel axicon lenses and outputting the annular laser beam.

The method may include directing a portion of the laser beam or modulated laser beam towards a first light sensor operably coupled to an amplifier, the amplifier being further coupled to the detector. In a preferred embodiment, a portion of the modulated laser beam is directed towards a first light sensor, and a fundamental component, arising due to laser beam amplitude modulation, is filtered out of output from the detector.

The method may include calibrating and testing the structured light-based system to ensure its laser light central wavelength, lineshape, delivered power, and power stability are each within its predetermined range.

5 The method may include determining a parameter (such as a density of velocity) of one or more atoms or ions in the target volume based on information from the detector (which may be modified by the amplifier, etc.). The method may include comparing the parameter to a predetermined target value or range.

#### BRIEF DESCRIPTION OF DRAWINGS

10 The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate embodiments of the present invention and, together with a general description of the invention given above, and the detailed description of the embodiments given below, serve to explain the principles of the present invention.

Figure 1A is a schematic illustration of a system.

15 Figure 1B is a cross-sectional side view of a target volume adjacent to a surface.

Figure 1C is a cross-sectional side view of a vacuum chamber.

Figure 2 is an illustration of a cross-section of a structured laser beam.

Figure 3 is a schematic illustration of a pair of axicon lenses.

Figures 4A and 4B are schematic illustrations of alternative embodiments of a system.

20 Figure 5 is a flowchart of a method.

Figure 6 is a schematic illustration of a plasma source showing an enclosed plasma volume with diagnostic orifice of less than 1 cm at the front side and three collection ports on the side, which may be used for conventional LIF.

25 Figure 7 is a schematic illustration of fluorescence light collection with a confocal design, showing the contour of the annular laser beam, a central region showing a collected cone of the fluorescence light, and a hashed zone showing the intersection of the fluorescence light cone and the laser beam hollow cone.

Figure 8 is a schematic illustration showing a depth of field for an annular beam.

30 Figure 9A is an illustration showing intensities of a cross section of an annular beam profile.

Figure 9B is a graph showing a confocal optics response function, with defined DOF lines.

Figure 10A is a graph showing argon ion velocity distribution functions (VDFs) at  $Z = 0.5$  (*see* Figure 6) obtained with conventional and confocal LIF setups (*see* Figures 1 and 4A).

Figures 10B and 10C are graphs showing a comparison of ion velocity (10B) and ion temperature (10C) distributions along the radial position obtained with conventional (dashed line) and confocal (solid) LIF setups.

Figure 10D is a graph showing a comparison of metastable density profile obtained with the confocal LIF (black circles) with the ion density measurements obtained with the biased Langmuir probe (white squares). Black dashed line shows density profile reconstructed from the deconvolution of the confocal LIF profile with the optical response function (*see* Figure 9B). Error bars are standard deviations from three repeated measurements.

It should be understood that the appended drawings are not necessarily to scale, presenting a somewhat simplified representation of various features illustrative of the basic principles of the invention. The specific design features of the sequence of operations as disclosed herein, including, for example, specific dimensions, orientations, locations, and shapes of various illustrated components, will be determined in part by the particular intended application and use environment. Certain features of the illustrated embodiments have been enlarged or distorted relative to others to facilitate visualization and clear understanding. In particular, thin features may be thickened, for example, for clarity or illustration.

## DETAILED DESCRIPTION

The following description and drawings merely illustrate the principles of the invention. It will thus be appreciated that those skilled in the art will be able to devise various arrangements that, although not explicitly described or shown herein, embody the principles of the invention and are included within its scope. Furthermore, all examples recited herein are principally intended expressly to be only for illustrative purposes to aid the reader in understanding the principles of the invention and the concepts contributed by the inventor(s) to furthering the art and are to be construed as being without limitation to such specifically recited examples and conditions. Additionally, the term, "or," as used herein, refers to a non-exclusive or, unless otherwise indicated (*e.g.*, "or else" or "or in the alternative"). Also, the various embodiments described herein are not necessarily mutually exclusive, as some embodiments can be combined with one or more other embodiments to form new embodiments.

The numerous innovative teachings of the present application will be described with particular reference to the presently preferred exemplary embodiments. However, it should be understood that this class of embodiments provides only a few examples of the many advantageous uses of the innovative teachings herein. In general, statements made in the specification of the present application do not necessarily limit any of the various claimed inventions. Moreover, some statements may apply to some inventive features but not to others. Those skilled in the art and informed by the teachings herein will realize that the invention is also applicable to various other technical areas or embodiments.

Structured light beams, characterized by tailored spatiotemporal structures (*e.g.*, Laguerre-Gaussian beams, beams with orbital angular momentum, etc.), offer solutions to diagnostic challenges in plasma spectroscopy. While these beams have driven innovations in optical communications, imaging, and microscopy, their potential in plasma spectroscopy is largely unexplored. For instance, structured light can enhance confocal spectroscopy methods, reducing optical access requirements while maintaining high spatial resolution and signal-to-noise ratio. This is particularly beneficial for LIF diagnostics in industrial plasma reactors. The technology's adaptability promises to bridge the gap between lab-based and industrial plasma diagnostics, especially in high-volume manufacturing settings. Moreover, its applications extend beyond microelectronics to fundamental plasma research, electric propulsion, and fusion technology, where optical access is similarly restricted.

In various aspects, a structured light sensor system may be provided. Referring to FIG. 1A, the system (100) may include a laser source (101) configured to generate a laser beam (102). The laser beam may be configured to pass along a laser optical path towards a target volume (122) (which may include, *e.g.*, atoms or ions (123) responsive to a structured laser beam as disclosed herein.).

The target volume may be any appropriate volume intended to be analyzed or diagnosed by the sensor. Referring to FIG. 1B, in some embodiments, the target volume (122) may be a volume of space adjacent to a surface (141) of a metal or a semiconductor (142). The surface may be planar, or may have one or more features (143), such as a depression or protrusion, such as an etched pattern. The target volume may be an ion source.

Referring to FIG. 1C, the ion source may be a vacuum chamber (151) comprising a housing (152) defining a central volume of space (153), ions (154) being within the central volume of space, where both the laser optical path (155) and the response optical path (156)

pass through a window (157) in the housing. The housing may include a plurality of ports (158) configured as collection ports for conventional LIF diagnostics.

The laser source may include a single wavelength laser diode, a quantum cascade laser, a diode laser system, a dye laser, an optical-parametric oscillator, or a combination thereof, or  
5 may include any appropriate laser source configured to generate a laser beam that can generate a response in the target volume. The laser source may include a tunable laser diode.

In some embodiments, the laser source may be configured or controlled so as to generate one or more laser beams with constant wavelength(s) while the system is operating and detecting responses. In some embodiments, the laser source may be configured or  
10 controlled so as to generate one or more laser beams with wavelength(s) that vary while the system is operating and detecting responses.

In some embodiments, the output wavelength(s) of the laser source may be determined based on the atoms or ions intended to be detected in the target volume. In a preferred embodiment, the laser wavelengths / frequencies and intensities may be selected such that they  
15 generated laser beam is configured to optically pump or excite atoms or ions in the target volume such that the atoms or ions then fluoresce as they relax. The selection of appropriate wavelengths for accomplishing this are well understood in the art, and any appropriate wavelengths may be utilized.

The system may include a beam splitter (103). The beam splitter may be configured to  
20 direct a portion of the laser beam towards a wavemeter (104). The wavemeter may be operably coupled to one or more processing unit(s) (105). As used herein, the term “processing unit” can refer to a single hardware processing unit or a plurality of hardware processing units that together (*e.g.*, collectively) may be programmed to perform the indicated actions. The hardware processing units may be implemented as virtual hardware processing units of a virtual  
25 programmable device hosted on a physical hardware device. Instructions (which may be included on a non-transitory storage device) may be provided that, when executed, program the processing unit(s) to perform an indicated action or may program any or all of the processing unit(s) to perform the indicated action. Where the processing unit is one or more multi-core processors, instructions that when executed program the processing unit to perform  
30 an action may program any or all of the multiple cores to perform the indicated action.

The processing unit(s) may be configured to determine one or more values based on received information (such as from the first light sensor, the detector, etc.). The processing unit(s) may, for example, utilize derivative spectroscopy techniques to improve performance.

For example, conventional LIF typically utilizes modulated laser intensity (IM), where the wavelength is scanned across an absorption line, while with wavelength-modulated (WM)-LIF, a laser wavelength is modulated and scanned across the absorption line. The detected signal is fed to a lock-in amplifier and processor(s), which can be configured to detect the  $n$ th harmonic. A velocity distribution function (VDF) can be modeled as a composite of several distributions:

$$f(v) = \sum_{k=1}^N \frac{c}{v_0^k} \left( \frac{M_i}{2\pi k_B T_i} \right)^{1/2} \exp \left( \frac{M_i c^2 (v - v_0^k)^2}{2k_B T_i (v_0^k)^2} \right) \quad (1)$$

where  $M_i$  is ion mass,  $k_B$  is the Boltzmann constant,  $T_i$  is the ion temperature, and  $v_0$  is the mean velocity. Signals may be fitted with a sum of Maxwellians (Eq. (1)) or their derivatives. For low noise information from the detector, the VDF and its derivative fitting yield comparable outcomes. In some embodiments, a bi-Maxwellian distribution may provide a best fit. For high noise information from the detector, a second derivative signal may identify multiple distributions reliably. Thus, in some embodiments, the system may utilize a second derivative of information received from the detector to determine one or more parameters.

The system may include a beam structuring module (106) configured to receive a laser beam (102) from the laser source and output structured light (118). The beam structuring module may include a spatial light modulator (107) configured to receive the laser beam and output a modulated laser beam (108). The spatial light modulator may be an optical chopper. The spatial light modulator may be something other than an optical chopper that similarly modulates the intensity of the laser beam, such as a mechanical beam shutter or MEMS optical shutter/chopper.

In some embodiments, a spatial light modulator may be configured to structure light (*e.g.*, it can replace axicons, spiral phase plates, etc.). A spatial light modulator may include a spatial light modulator that is configured to modulate a phase of light, an amplitude of light, or a combination thereof.

The structured light sensor system may include a beam splitter (109) disposed in the laser optical path. The first beam splitter may be configured to direct a portion of the laser beam (102) or modulated laser beam (108) towards a first light sensor (110) operably coupled to an amplifier (111). The first light sensor may be any appropriate detector for detecting the laser beam or modulated laser beam. The first light sensor may be a photodiode. The first light sensor may be a photomultiplier tube. The first light sensor may be a detector other than a photodiode or photomultiplier tube; such sensors are well understood in the art.

The beam structuring module may include a single mode optical fiber (113). A collimator (114) may be coupled to an end of the optical fiber. The optical fiber (and optional collimator) may be configured to receive the modulated laser beam (108) and output a laser beam with a circular beam shape (115).

5        The beam structuring module may include a plurality of axicons (shown here as first axicon (116) and second axicon (117)) configured to receive the laser beam with the circular beam shape (115) and output the structured light (118), where the structured light has an annular beam shape. As seen in FIG. 2, the annular beam shape (118) has a ring-shaped light section (201) within an otherwise dark (non-light) background (202) and a dark (non-light) middle section (203). The ring-shaped light section is defined by a ring thickness (204) and a beam diameter (205).

10        The plurality of axicons may include two refractive axicons or two diffractive axicons. Referring to FIG. 3, in a preferred embodiment, two diffractive axicons are utilized. In FIG. 3, a first axicon (301) is shown as having a first surface (302) that may line in a plane (303) orthogonal to the central optical axis (304) of the first axicon. A second axicon (305) is shown as having a second surface (306) that may line in a plane (307) orthogonal to the central optical axis (308) of the second axicon. The plurality of axicons may include at least two coaxial and parallel axicon lenses – that is, the two axicons may have a common central optical axis (309), and the plane (303) of the first surface (302) and the plane (307) of the second surface (306) may be parallel.

20        The beam structuring module may include one or more additional components (112). In FIG. 1A, the additional component is shown as a mirror. As shown, the structured light sensor system may include at least one mirror (112) between the laser source and a single mode optical fiber (113). However, any additional optical component for directing the laser beam or modifying the laser beam. For example, the additional components may include a spiral phase plate. In some embodiments, the spiral phase plate may be disposed upstream from the single mode optical fiber. In some embodiments the spiral phase plate may be disposed between the single mode optical fiber and the axicons. In some embodiments, the spiral phase plate may be disposed downstream from the axicons. The additional components may include a fiber grating. The additional components may include a digital micro-mirror (sometimes referred to as a digital micromirror device, DMD). In some embodiments, the DMD may be disposed upstream from the single mode optical fiber. In some embodiments the DMD may be disposed between the single mode optical fiber and the axicons. In some embodiments, the DMD may

be disposed downstream from the axicons. The additional components may include a combination of two or more of the above. Each additional component may be disposed in the laser optical path.

5 The system may include one or more optical elements configured to direct the structured light from the beam structuring module towards the target volume. That is, one or more optical elements may be disposed downstream of the beam structuring module (106) and upstream of the target volume (122).

10 The one or more optical elements may include a focusing lens (121). The focal length of the focusing lens may be any appropriate focal length, depending on the application. In some embodiments, the focal length is no more than 5 meters. In some embodiments, the focal length is no more than 3 meters. In some embodiments, the focal length is no more than 1 meter. In some embodiments, the focal length is no more than 0.5 meters. In some embodiments, the focal length is no less than 0.01 meters. In some embodiments, the focal length is no less than 0.05 meters. In some embodiments, the focal length is no less than 0.1  
15 meters. In some embodiments, the focal length is no less than 0.25 meters. In some embodiments, the focal length is no less than 0.5 meters. In some embodiments, the focal length is no less than 1 meter. In some embodiments, the focal length is no less than 3 meters. In some embodiments, the focal length is no less than 5 meters.

20 The structured light sensor system may include one or more optical elements configured to direct the output from the beam structuring module towards the target volume. As seen in FIG. 1A, this may include, *e.g.*, at least one mirror (119). However, in other embodiments, such as that shown in FIG. 4A, there may be no mirrors between the axicons and the target volume.

25 The structured light sensor system may include a dichroic mirror (120) disposed in the laser optical path (*see, e.g.*, light path (124) from the laser source to the target volume) to receive the structured light (*i.e.*, downstream from the beam structuring module (106)). The dichroic mirror is preferably before the focusing lens (121). The dichroic mirror may be configured to reflect a first wavelength (*e.g.*, a wavelength of the structured light output from the beam structuring module) and to pass a second wavelength (*e.g.*, a wavelength of an output  
30 response from an atom or ion (123) in the target volume (122)).

In some embodiments, the focusing lens may be configured to receive output from the dichroic mirror, direct and focus the laser beam having the first wavelength to the target volume, receive fluorescent output from the target volume at the second wavelength, and direct

the fluorescent output having the second wavelength along the response optical path (*see, e.g.,* response path (126) from the target volume to the detector) through the dichroic mirror.

The laser optical path (*see, e.g.,* light path (124)) and the response optical path (*see, e.g.,* light path (126)) in the vicinity of the target volume may vary. As shown in FIG. 1A, the response optical path (*see, e.g.,* light path (126)) it exits the target volume may be configured to be in a direction (127) reciprocal to a direction (125) of the laser optical path (*see, e.g.,* light path (124)) as it enters the target volume. That is, at least a portion of the two optical paths are confocal. However, other approaches are readily envisioned. For example, following a more conventional approach, and referring to FIG. 4A, the response optical path (*see, e.g.,* light path (126)) as it exits the target volume may be configured to be in a direction (127) orthogonal to a direction (125) of the laser optical path (*see, e.g.,* light path (124)) as it enters the target volume. Alternatively, referring to FIG. 4B, the response optical path (*see, e.g.,* light path (126)) as it exits the target volume may be configured to be in a direction (127) that is non-orthogonal and non-reciprocal to a direction (125) of the laser optical path (*see, e.g.,* light path (124)) as it enters the target volume.

The system may include one or more additional optical elements configured to direct a non-reflection output response (such as fluorescent output) from the target volume towards a detector along a response optical path. Referring again to FIG. 1A, the structured light sensor system may include an iris (128) disposed in the response optical path (*see, e.g.,* light path (126)) to receive the fluorescent output having passed through the dichroic mirror. The iris may be configured to cut off fluorescent light emitted by species which are excited along the parts of the response optical path that are confocal with the laser optical path (outside the target volume), such as those in portion (133) of the optical paths.

The structured light sensor system may include a bandpass filter (129) disposed in the response optical path. In some embodiments (as shown in FIG. 1A), there may be one or more optical elements between the target volume and the bandpass filter. In some embodiments (as shown in FIG. 4A), there may be no optical element between the target volume and the bandpass filter.

The bandpass filter may be configured to differentiate between the structured light and the non-reflection output response. The center wavelengths and full width-half maximum values of the bandpass filter may vary. The specific parameters may be based on the laser wavelengths, the chemistry of the target volume, etc. In some embodiments, the bandpass filter may have a center wavelength of 400-450 nm, and a full width-half maximum of 5-20 nm.

The structured light sensor system may include a second lens (130) configured to receive output from the iris (128) and/or the bandpass filter (129). The second lens may be configured to direct the output towards a detector (132). The structured light sensor system may include a pinhole (131) disposed in the response optical path between the second lens and the detector. The pinhole may have an opening with any appropriate diameter. In some embodiments, the diameter of the opening may be 50-200  $\mu\text{m}$ .

The detector may be, *e.g.*, a photodiode or photomultiplier tube, or may be some other appropriate detector for detecting the responsive output from the volume of space. This may be a detector configured to detect a fluorescent response. The detector may be operably coupled to an amplifier. In some embodiments, both the detector (132) and the first light sensor (110) are coupled to the same amplifier (*e.g.*, amplifier (111)), which may be a lock-in amplifier where information from the first light sensor is used as a reference input, and information from the detector is used as a signal input.

The structured light sensor system may include at least one processing unit (105) configured to receive information from the amplifier (111).

In various aspects, a method for structured light-based diagnostics using a structured light-based system may be provided. Referring to FIG. 5, the method (500) may include generating (501) a laser beam. This may be done using any appropriate laser source, as disclosed herein.

The method may include transforming (502) the laser beam into an annular laser beam using at least two coaxial and parallel axicon lenses. This may be done using a beam structuring module as disclosed herein. In some embodiments, transforming the laser beam may include receiving (503) the laser beam at a spatial light modulator and outputting a modulated laser beam, receiving (504) the modulated laser beam at an optical fiber with a collimator and outputting a laser beam with a circular beam shape, and receiving (505) the laser beam with the circular beam shape at the at least two coaxial and parallel axicon lenses and outputting the annular laser beam.

The method may include directing (506) the annular laser beam towards a target volume comprising one or more ions or atoms. This may be done using one or more mirrors and/or lenses, as disclosed herein.

The method may include receiving (507) non-reflective output from the target volume.

The method may include directing (508) the non-reflective output (which may be, *e.g.*, fluorescent output from one or more ions within the target volume) towards a detector.

The method may include directing (509) a portion of the laser beam (output from the step of generating (501) a laser beam) or a modulated laser beam (output from the step of receiving (503) the laser beam at a spatial light modulator and outputting a modulated laser beam) towards a first light sensor operably coupled to an amplifier, the amplifier being further  
5 coupled to the detector.

In some embodiments, a portion of the modulated laser beam may be directed towards a first light sensor, and the method may include filtering (510) out a fundamental component of output from the detector, arising due to laser beam amplitude modulation, based on information received from the first light sensor and the detector.

10 The method may include sending (511) output from the amplifier to one or more processing unit(s).

The method may include determining (512) a parameter of one or more atoms or ions in the target volume based on information from the detector (*e.g.*, the responsive output from the target volume detected by the detector). This may be done using the processing unit(s).  
15 The information from the detector may have been modified by the amplifier, etc., as understood in the art. The parameter may include, *e.g.*, a density of velocity of one or more atoms or ions in the target volume.

The method may include comparing (513) the parameter to a predetermined target value or range. For example, a quality control process could be configured to generate a warning or  
20 identify a failed part if the signal detected by the detector and sent to various processing unit(s) does not fall within a predetermined acceptable range (*e.g.*, between an upper and lower spec limit for the parameter). As an alternate example, a process could be configured to continue until the parameter meets a predetermined threshold value.

The method may include calibrating (514) and/or testing (515) the structured light-based system to ensure its laser light central wavelength, lineshape, delivered power, and power  
25 stability are each within its predetermined range.

#### Example 1

Referring to FIG. 6, a plasma source (600) was provided (not to scale), having a plasma  
30 volume (601) of about 100 cm<sup>3</sup> with the only diagnostic orifice (602) of about 1 cm located at the center of the front surface. The source has collection ports (603) for convention LIF, and one or more ions (604) within the plasma volume. The device is operated with argon gas at a pressure of about 10<sup>-4</sup> Torr (measured outside of the source). RF or thermionic cathodes (not

shown) can be used for electron production. An externally applied magnetic field is parallel to the central line (605) with a magnitude from 15 to 150 G and it is uniform within the plasma volume; at these levels Zeeman effect does not affect the shape of the argon ion velocity distribution function (VDF).

5 A laser beam (606) with the wavevector  $\vec{k}$  and frequency  $\nu$  was directed from the diagnostic orifice at the front of the device. Positive direction of the argon ion velocity  $\vec{v}$  was set towards the laser beam. Confocal measurements were performed at several positions (between  $Z = 0.0$  (inner front wall of housing around the plasma volume) to  $Z = 1.0$  (inner back wall of housing around the plasma volume)) within the source. Three collection ports were  
10 made on the side of the source to perform conventional LIF measurements. Operation of the plasma source was not affected by these ports.

LIF measurement was performed by sweeping the frequency of a tunable diode laser with a narrow linewidth over the absorption line of an argon ion which is broadened due to Doppler shift. By measuring of the emission intensity at different laser wavelengths, a VDF  
15 profile can be recovered. For an argon ion, a three-state scheme is used. An argon ion at a  $3d^4F_{9/2}$  metastable state is optically pumped by 664.553 nm (in vacuum) laser light to a  $4p^4D_{7/2}$  state, which decays to a  $4s^4P_{5/2}$  state by an emission at 434.929 nm. This transition was chosen over more commonly used  $3d^4F_{7/2} - 4p^4D_{5/2}$  (excitation at 668.614 nm, emission at 442.724 nm) as having better signal intensity for given experimental conditions.

20 A pair of diffractive axicons (DA), which were custom made by HOLO/OR for 670 nm wavelength, were used. Diffractive axicon results in very low residual intensities of the central region. The quality of the annular beam is sensitive to the input beam shape and beam collimation. To improve the performance of the DA element the laser beam was converted into the circular beam with Gaussian intensity profile by fiber coupling and follow-up collimation.

25 Light collection with the example confocal setup is illustrated in FIG. 7. Collimated annular laser beam (702) is focused with the lens (121). Fluorescence intensity is maximized in the region with maximum laser intensity at the focal distance (701). Fluorescence light, which is spread in all direction from the focal point, is collected with the same lens, forming, *e.g.*, the light cone (703) with a base and height. The base of this cone can be reduced, so it is  
30 not overlapped with the laser beam path. From FIG. 7, one can see that the spatial resolution is defined only by the overlap volume (704) between the laser beam, and collection cones. The contour of the overlap area is marked with hashed lines. However, due to nonuniform laser

intensity distribution, only fluorescence light from the shaded area is a main contributor to the detected signal.

The overlap volume can be controlled by the ring thickness and annulus radius. All fluorescence light, that is within the laser beam cone, can be collected without loss of the spatial resolution. This is distinct from approaches where spatial resolution is controlled by, *e.g.*, an obstruction disk, where higher spatial resolution can be achieved only by reduction of the collected fluorescence light.

The system was built around single-mode TOptica digital laser controller (DLC) DL PRO™ 670 tunable diode laser (TDL). The system design matches that shown in FIG. 1A. The diode laser is Littrow-type grating stabilized external cavity design and it has coarse tuning range between 660 to 673 nm and mode-hop free tuning range of 20 GHz. The output power is wavelength dependent and maximum value is about 23 mW. Short term wavelength stability is 600 kHz (over 5  $\mu$ s). The laser wavelength is controlled by scanning the voltage applied to the piezo actuator.

Part of the laser beam is sampled by a beam splitter (103) and is directed to a Bristol Instruments Model 621-A wavemeter, which has a built-in continuous calibration (single-frequency He–Ne laser, accuracy  $\pm 0.0002$  nm at 1000 nm). With this accuracy the achievable velocity resolution is  $\sim 60$  m/s. Main beam is modulated by a mechanical chopper (*i.e.*, spatial light modulator (107)), which is set to a frequency of 2 kHz. The modulated beam was sampled with a beam splitter (109) and the sampled beam is sent to a photodiode (PD) (*i.e.*, first light sensor (110)). Output of the photodiode provides the reference frequency for the lock-in amplifier (*i.e.*, amplifier (111)). The beam is then directed by a mirror (112) through a fiber launch system (FLS) Thorlabs MBT613D into a single mode fiber (113). This is to ensure the circular beam shape with Gaussian profile. The fiber output was collimated with F260FC-B collimator (114) providing 3 mm diameter beam.

The output beam is then passed through a pair of diffractive axicon lenses (HOLO/OR 670 nm) (*i.e.*, first axicon (116) and second axicon (117)), which are installed in XY adjustable mounts (133) (*e.g.*, mounts adjustable in the x and y directions) to ensure their coaxiality. Both diffractive axicons are installed on rotation stages (134) (*e.g.*, rotating around the Y axis) to ensure that they are parallel to each other. Beam quality after axicons was verified with a CMOS camera (not shown). Circularity, equal intensity distribution, and absence of light intensity within the ring were monitored.

After the axicons, an annular beam (with diameter of ~22 mm) was directed by a mirror (119) and a dichroic mirror (120) (shortpass, 490 nm cutoff) into a vacuum chamber. Beam focusing is achieved by a focusing lens (121) with the focal distance 300 mm.

The fluorescence light is collected by the same lens (focusing lens (121)) and the passed  
 5 through the dichroic mirror (120). The outer part of the collimated light cylinder was then cut by iris (128). This was to cut part of the fluorescent light from species which are excited along the laser beam path. Collected light is then passed through the bandpass filter 430/10 nm (Thorlabs FBH430-10) (*i.e.*, bandpass filter (129)) and then focused by a lens (*i.e.*, second lens (130)) into the 100  $\mu$ m pinhole (*i.e.*, pinhole (131)). After the pinhole the light is sent into  
 10 photomultiplier tube PMT (*i.e.*, detector (132)). PMT output is fed into the lock-in amplifier input and the fundamental component arising due to laser beam amplitude modulation is filtered out. Laser wavelength, and readings from wavemeter and lock-in amplifier outputs (signal and phase) are collected with in-house developed software.

The fluorescence excitation line shape can broaden if the transition is saturated due to  
 15 high laser intensity. LIF signal intensity was measured as a function of the laser power to ensure such line-shaped distortions are prevented. A linear relation between fluorescence signal and laser power was obtained.

#### Example 2

20 A simplified model for spatial resolution estimation is also disclosed. Spatial resolution or depth of field (DOF) is defined by the intersection between annular beam paths at the focus point. This is illustrated in FIG. 8, where an annular beam of radius  $R$  (801) and ring thickness  $\delta$  (802) is focused by lens (121) with a focus length  $f$  (701). From geometrical considerations the length of the depth of field (DOF) (803) can be found as

$$25 \quad DOF = \frac{4\lambda f}{\pi\delta} \frac{1}{\sin(\arctan(R/f))} \quad (2)$$

where  $\lambda$  is the laser wavelength. For the setup used in this work,  $R \approx 11$  mm,  $\delta = 1.5$  mm,  $f = 300$  mm,  $\lambda = 668$  nm, the theoretical DOF is 4.6 mm. Note that this is an upper limit due to the laser intensity being not uniformly distributed (Gaussian) along the DOF. Such nonuniformity will result in smaller effective spatial resolution. However, it is  
 30 important to notice that this is simplified model, which doesn't consider hyperbolic shape of focused laser beam and the effect of full volume of the overlap between the injection and the collection paths.

From Eq. (2) one can see that at fixed focal length the DOF can be minimized by increasing or annulus radius. For example, for an annular beam with  $R = 30$  mm and  $\delta = 3$  mm, it is possible to achieve  $\sim 1$  mm resolution. In the example setup the main limit for the spatial resolution improvement is the axion diameters, which is 25.4 mm and clear aperture is about 22 mm. By utilizing 2-inch optics (with a clear aperture of  $\sim 48$  mm) and further increasing ring thickness to 4 mm (*e.g.*, with fiber collimators available at Thorlabs) it is possible to achieve spatial resolution of 0.8 mm at  $f = 300$  mm.

To experimentally characterize the spatial resolution and the optical response function of the example system, a CMOS camera on a movable stage was installed at the focal point of the lens. The camera was moved along the optical axis ( $Z$ ) and beam profile images were collected. The origin value was selected as the lens focal point. Camera exposure was adjusted at each position to avoid pixels saturation. All images were then stacked together allowing for the laser beam profile visualization. An example of this is seen in FIG. 9A, showing cross-sections of the beam profile in the area around the focal point (here, roughly  $\pm 20$  mm along the  $z$ -axis from the focal point and roughly  $\pm 10$  mm in the radial direction).

Spatial resolution and optical response function were determined from the intensity profiles along the centerline at  $R = 0$  mm, which is shown in FIG. 9B. Conservatively, resolution was defined as a region which contains 95% of the laser beam intensity (dotted line in FIG. 9B). An experimentally-found value of 5.3 mm is close to the theoretical value of 4.6 mm obtained from Eq. (2). Resolution of the conventional method, defined as a region with 99.73% intensity is about 1.2 mm. If spatial resolution is defined as a region where only 68% of the laser beam intensity is contained, then the obtain value is 2.5 mm (dashed line in FIG. 9B).

### Example 3

Measurements were performed in eight locations  $0 \leq Z \leq 1$ . Focusing optics were installed on the translational stage with a micrometer, allowing for precise location control. Typical ion velocity distribution function (IVDF) profiles (FIG. 10A) were obtained with confocal and conventional LIF setups (*see, e.g.*, FIG. 1 and FIG. 4A). Both signals were normalized to maximum intensity. Signal-to-noise ratio was defined as  $SNR = \mu_{signal} / \sigma_{signal}$ , where  $\mu_{signal}$  is an average signal value and  $\sigma_{signal}$  is the noise standard deviation found after subtraction of the fitted function from the signal. For both methods the

obtained SNR values are very similar: SNR = 7 and SNR = 90 for conventional and confocal setups respectively. Ion temperatures and mean velocities were determined by fitting the IVDF profiles with

$$f(v) = \left( \frac{M_i}{2\pi k_B T_i} \right)^{1/2} e^{-\frac{M_i(v-v_0)^2}{2k_B T_i}} \quad (3)$$

- 5 where  $M_i$  is ion mass,  $k_B$  is the Boltzmann constant,  $T_i$  is the ion temperature, and  $v_0$  is the mean velocity. Error bars for ion temperature were defined as a standard deviation between three measurements. For ion velocity, the error bars were a combination of standard deviation of three measurements and wavemeter uncertainty, which is ~60 m/s. One can see that both methods result in very similar shapes of VDFs and close values for mean velocities and ion  
10 temperatures.

Mean ion velocities and ion temperatures along Z direction were compared with conventional LIF measurements performed at 3 positions. Results are shown in FIGS. 10B and 10C. One can see that overall flow velocities between two methods agree within the uncertainty. Ion temperature measurements shows good agreement as well. General trends  
15 for both quantities are similar between confocal and conventional LIF measurements. The difference between velocities can be explained with steep plasma gradients within the source. Regions with higher velocities correspond to lower plasma densities. Due to nonlocality of confocal measurements, regions with lower velocities, but higher densities contribute more to the obtained velocity distribution functions (VDFs). Therefore, the extracted velocity is lower.

20 Integration of ion VDF obtained at different spatial locations will yield the metastable ion density profile. This profile was compared with ion density profiled measured with the biased Langmuir probe along the beam path. Normalized profiles are shown in FIG. 10D. As one can see, LIF profile (black circles) is wider than density profile obtained with the probe measurements (white squares). The “true” density profile can be recovered if the optics  
25 response function is known (*see* FIG. 9B). The reconstructed profile obtained as a deconvolution of the LIF profile with the optics response function is shown as a black dashed line in FIG. 10D. One can see that the reconstructed profile closely follows the one measured with the probe; thus, confirming the determined spatial resolution of the example system.

In one preferred embodiment, the system may utilize a single-wavelength laser diode  
30 with a relatively wide linewidth, which can be finely controlled through current or temperature adjustments. This design simplification eliminates the need for mechanical components like intensity modulators, thereby reducing complexity and cost. The laser launch and collection

optics may be fiber-coupled, separate from the control and detector electronics, allowing for flexible diagnostic installation on vacuum chambers. The diagnostic aims to spatially resolve signals from target species in a target volume, providing critical process parameters such as densities or velocities that can be compared with pre-determined benchmarks to ensure manufacturing quality.

Various modifications may be made to the systems, methods, apparatus, mechanisms, techniques, and portions thereof described herein with respect to the various figures, such modifications being contemplated as being within the scope of the invention. For example, while a specific order of steps or arrangement of functional elements is presented in the various embodiments described herein, various other orders/arrangements of steps or functional elements may be utilized within the context of the various embodiments. Further, while modifications to embodiments may be discussed individually, various embodiments may use multiple modifications contemporaneously or in sequence, compound modifications and the like.

Although various embodiments which incorporate the teachings of the present invention have been shown and described in detail herein, those skilled in the art can readily devise many other varied embodiments that still incorporate these teachings. Thus, while the foregoing is directed to various embodiments of the present invention, other and further embodiments of the invention may be devised without departing from the basic scope thereof.

As such, the appropriate scope of the invention is to be determined according to the claims.

What is claimed is:

1. A structured light sensor system, comprising:
  - a beam structuring module configured to receive a laser beam from a laser source and output structured light, the laser beam being configured to pass along a laser optical path towards a target volume, the beam structuring module comprising a spatial light modulator configured to receive the laser beam and output a modulated laser beam, a single mode optical fiber with a collimator configured to receive the modulated laser beam and output a laser beam with a circular beam shape, and a plurality of axicons configured to receive the laser beam with the circular beam shape and output the structured light, the structured light having an annular beam shape;
  - one or more optical elements configured to direct the structured light towards the target volume, the one or more optical elements include a focusing lens; and
  - one or more additional optical elements configured to direct a non-reflection output response from the target volume towards a detector along a response optical path.
2. The structured light sensor system of claim 1, wherein the plurality of axicons includes two refractive axicons or two diffractive axicons.
3. The structured light sensor system of any one of claim 1-2, wherein the beam structuring module further comprises a spiral phase plate, a fiber grating, a digital micro-mirror, or a combination thereof, each disposed in the laser optical path.
4. The structured light sensor system of any one of claim 1-3, further comprising a beam splitter disposed in the laser optical path.
5. The structured light sensor system of any one of claim 1-4, wherein the target volume comprises a plasma.
6. The structured light sensor system of any one of claim 1-5, wherein the non-reflection output response is a fluorescent output.

7. The structured light sensor system of any one of claim 1-6, wherein the response optical path as it exits the target volume is configured to be in a direction orthogonal to a direction of the laser optical path as it enters the target volume.
8. The structured light sensor system of any one of claim 1-6, wherein the response optical path as it exits the target volume is configured to be in a direction non-orthogonal and non-reciprocal to a direction of the laser optical path as it enters the target volume.
9. The structured light sensor system of any one of claim 1-6, wherein the response optical path as it exits the target volume is configured to be in a reciprocal direction a direction of the laser optical path as it enters the target volume.
10. The structured light sensor system of claim 9, further comprising a bandpass filter disposed in the response optical path, the bandpass filter configured to differentiate between the structured light and the non-reflection output response.
11. The structured light sensor system of claim 10, wherein the bandpass filter has a center wavelength of 400-450 nm, and a full width-half maximum of 5-20 nm.
12. The structured light sensor system of any one of claim 1-11, wherein the spatial light modulator is an optical chopper.
13. The structured light sensor system of any one of claim 1-11, wherein the spatial light modulator is an element other than an optical chopper.
14. The structured light sensor system of any one of claims 1-13, wherein the detector is a photodiode or photomultiplier tube.
15. The structured light sensor system of any one of claims 1-13, wherein the detector is a detector other than a photodiode or photomultiplier tube.
16. The structured light sensor system of any one of claim 1-15, further comprising the laser source.

17. The structured light sensor system of claim 16, wherein the laser source comprises a single wavelength laser diode, a quantum cascade laser, a diode laser system, a dye laser, an optical-parametric oscillator, or a combination thereof.
18. The structured light sensor system of claim 17, wherein the laser source comprises a tunable laser diode.
19. The structured light sensor system of claim 16, wherein the laser source comprises a laser source other than a single wavelength laser diode, a quantum cascade laser, a diode laser system, a dye laser, an optical-parametric oscillator, or a combination thereof.
20. The structured light sensor system of any one of claims 16-19, further comprising:  
a first beam splitter disposed in the laser optical path, the first beam splitter configured to direct a portion of the laser beam or modulated laser beam towards a first light sensor operably coupled to an amplifier;  
a dichroic mirror disposed in the laser optical path to receive the structured light, the dichroic mirror configured to reflect a first wavelength and to pass a second wavelength, where the focusing lens is configured to receive output from the dichroic mirror, direct and focus the laser beam having the first wavelength to the target volume, and receive fluorescent output from the target volume at the second wavelength and direct the fluorescent output having the second wavelength along the response optical path through the dichroic mirror;  
an iris disposed in the response optical path to receive the fluorescent output having passed through the dichroic mirror, the iris configured to cut off fluorescent light from species which are excited along the laser optical path; and  
a second lens configured to receive output from the iris and direct the fluorescent output towards the detector, the detector being operably coupled to the amplifier.
21. The structured light sensor system of claim 20, further comprising a second beam splitter disposed between the laser source and the first beam splitter, the second beam splitter configured to direct a portion of the laser beam towards a wavemeter.
22. The structured light sensor system of claim 21, wherein the amplifier is a lock-in amplifier, information from the first light sensor is used as a reference input, and information from the detector is used as a signal input.

23. The structured light sensor system of any one of claims 20-22, further comprising at least one mirror between the laser source and the single mode optical fiber.
24. The structured light sensor system of any one of claims 20-23, further comprising a pinhole disposed in the response optical path between the second lens and the detector.
25. The structured light sensor system of claim 24, wherein the pinhole has a diameter of 50-200  $\mu\text{m}$ .
26. The structured light sensor system of any one of claims 20-25, wherein the target volume is an ion source, the ion source being a vacuum chamber comprising a housing defining a central volume of space, ions being within the central volume of space, where both the laser optical path and the response optical path pass through a window in the housing.
27. The structured light sensor system of claim 26, wherein the housing comprises a plurality of ports configured as collection ports for conventional LIF diagnostics.
28. The structured light sensor system of any one of claims 20-27, further comprising at least one processing unit configured to receive information from the amplifier.
29. A method for structured light-based diagnostics using a structured light-based system, comprising:
- generating a laser beam;
  - transforming the laser beam into an annular laser beam using at least two coaxial and parallel axicon lenses;
  - directing the annular laser beam towards a target volume comprising one or more ions or atoms;
  - receiving non-reflective output from the target volume; and
  - directing the non-reflective output towards a detector.
30. The method of claim 29, wherein transforming the laser beam comprises:
- receiving the laser beam at a spatial light modulator and outputting a modulated laser beam;

receiving the modulated laser beam at an optical fiber with a collimator and outputting a laser beam with a circular beam shape; and

receiving the laser beam with the circular beam shape at the at least two coaxial and parallel axicon lenses and outputting the annular laser beam.

31. The method of claim 30, further comprising directing a portion of the laser beam or modulated laser beam towards a first light sensor operably coupled to an amplifier, the amplifier being further coupled to the detector.

32. The method of any one of claims 29-31, further comprising calibrating and testing the structured light-based system to ensure its laser light central wavelength, lineshape, delivered power, and power stability are each within its predetermined range.

33. The method of any one of claims 29-32, wherein the non-reflective output is fluorescent output from one or more ions within the target volume.

34. The method of any one of claims 29-33, further comprising determining a parameter of one or more atoms or ions in the target volume based on information from the detector.

35. The method of claim 34, wherein the parameter is a density or a velocity.

36. The method of claim 34 or 35, further comprising comparing the parameter to a predetermined target value or range.

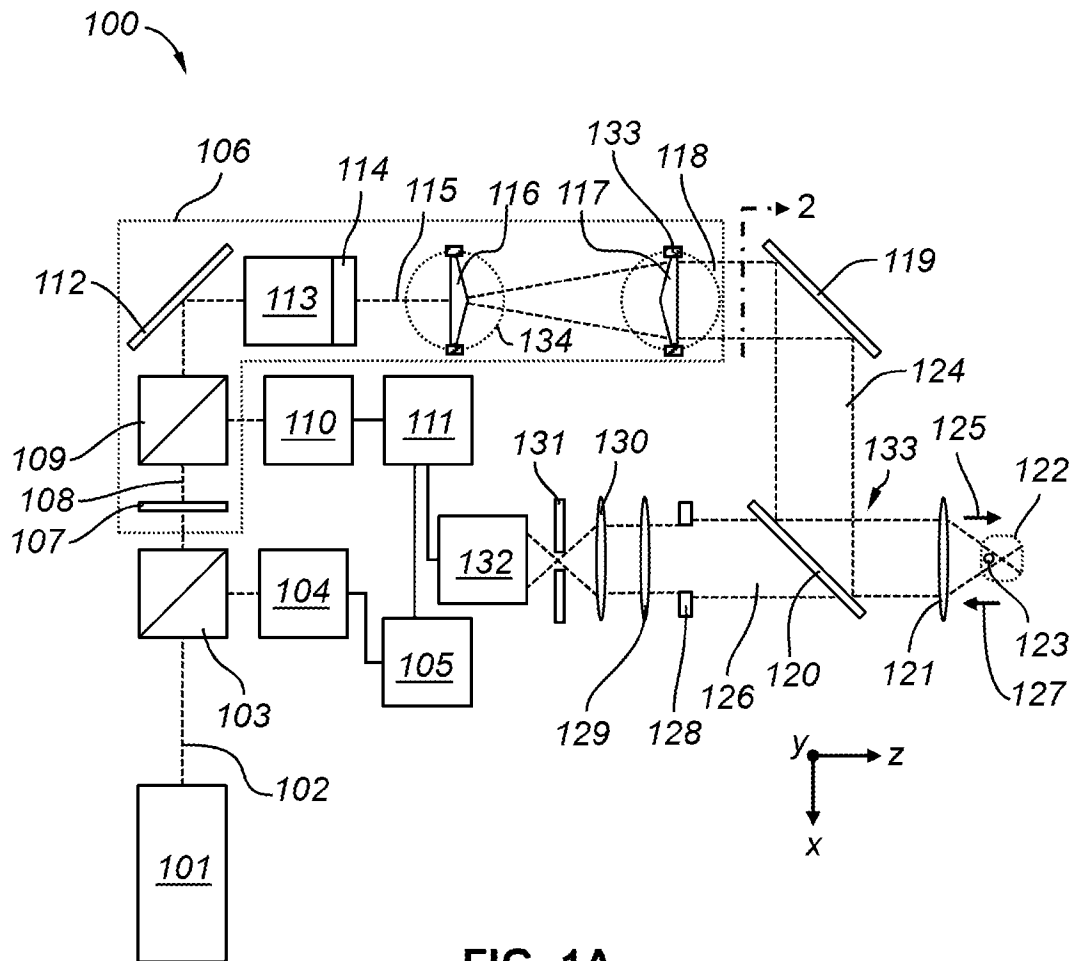


FIG. 1A

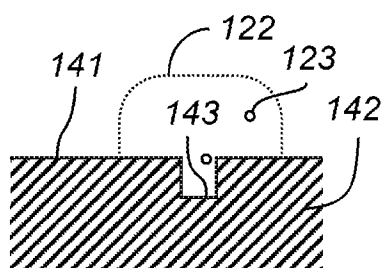


FIG. 1B

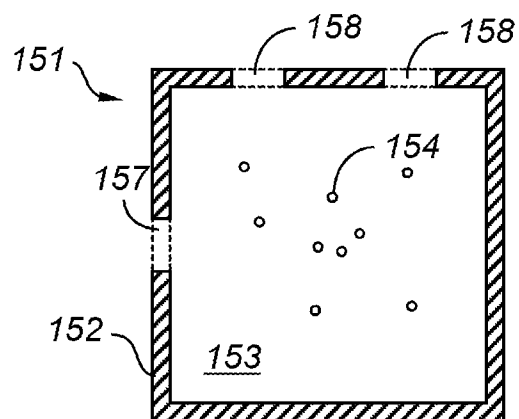


FIG. 1C

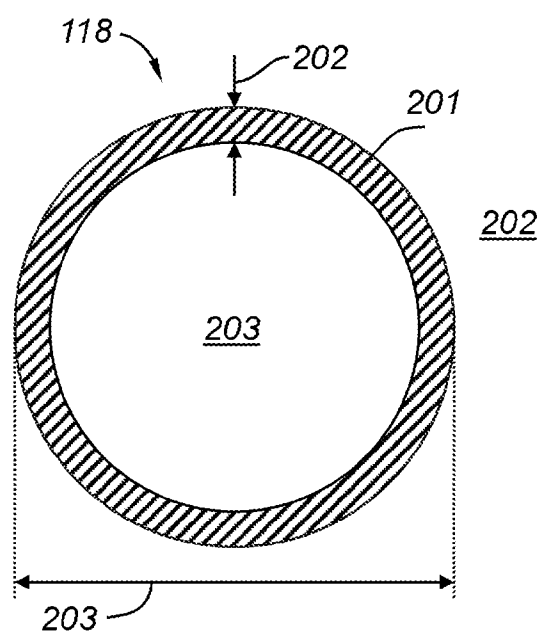


FIG. 2

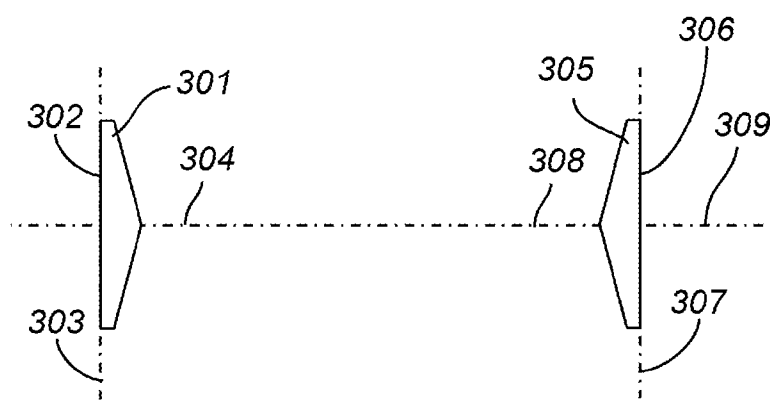


FIG. 3

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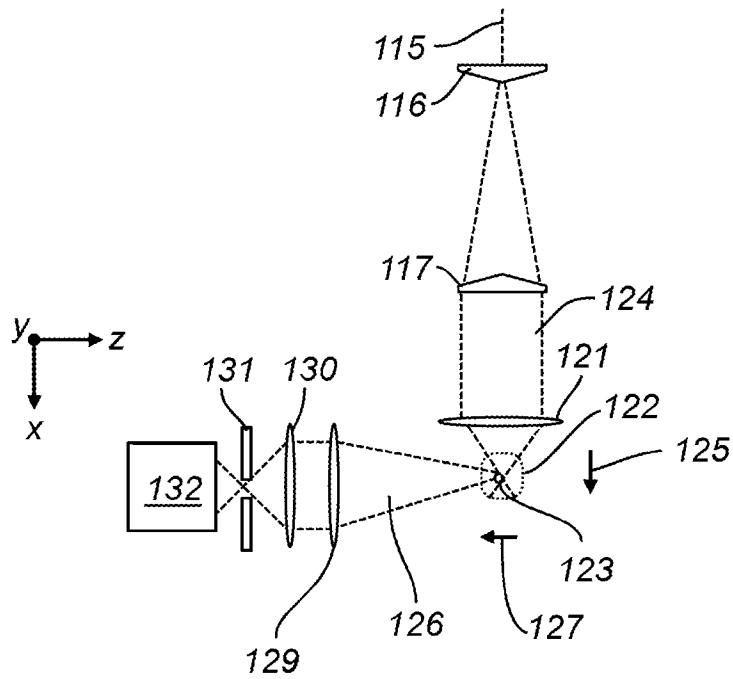


FIG. 4A

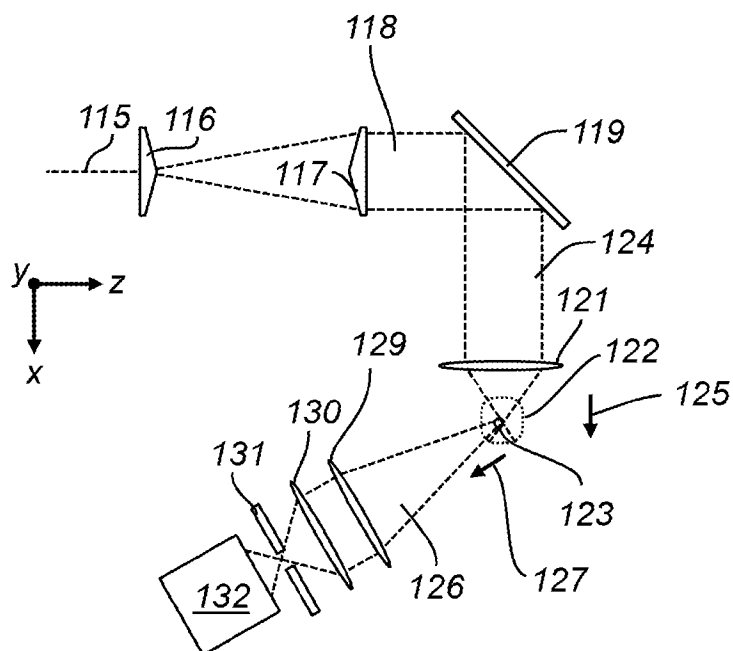


FIG. 4B

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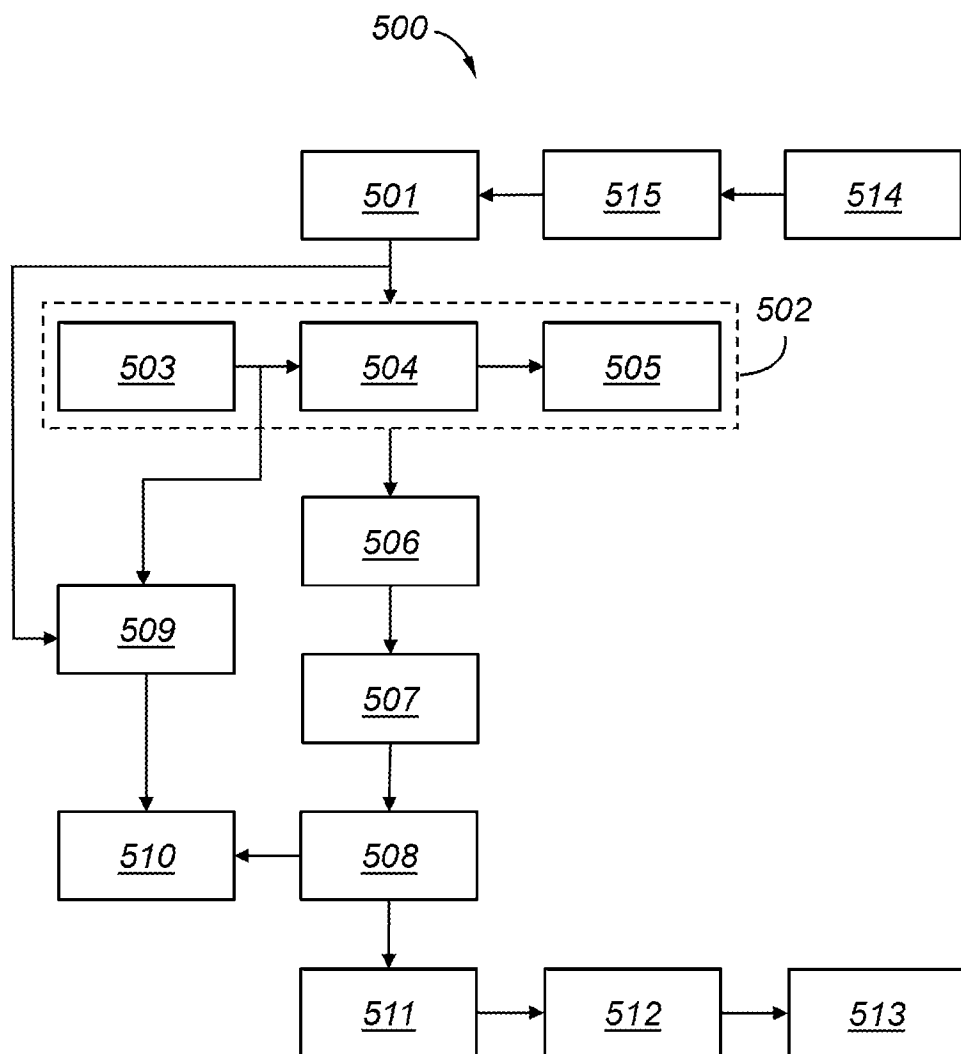


FIG. 5

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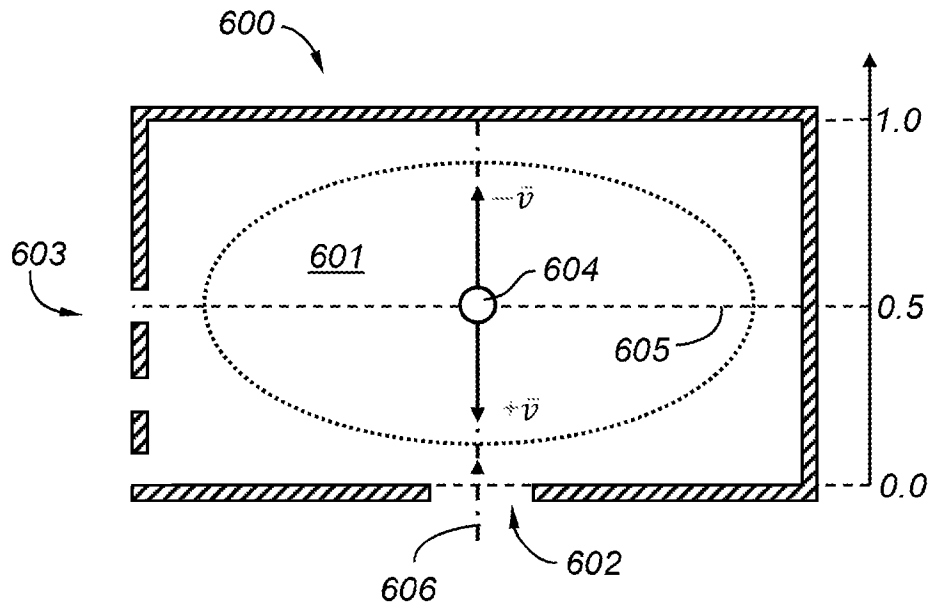


FIG. 6

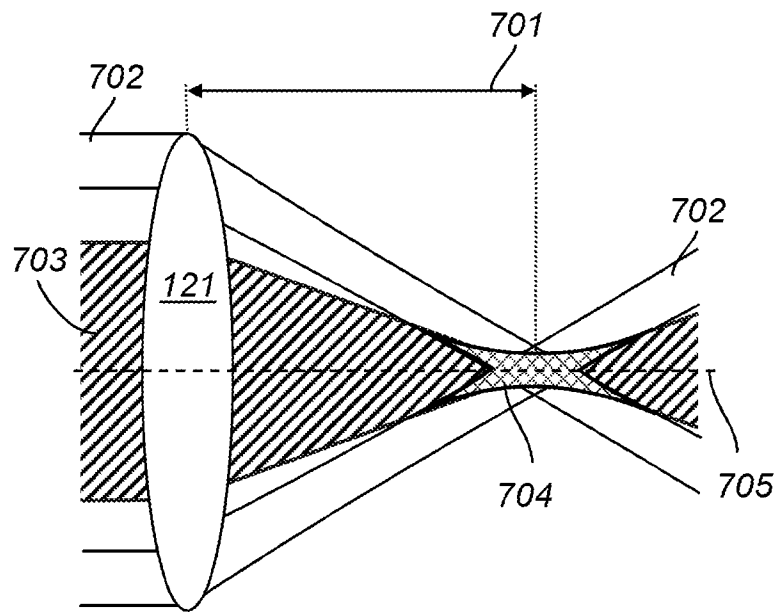


FIG. 7

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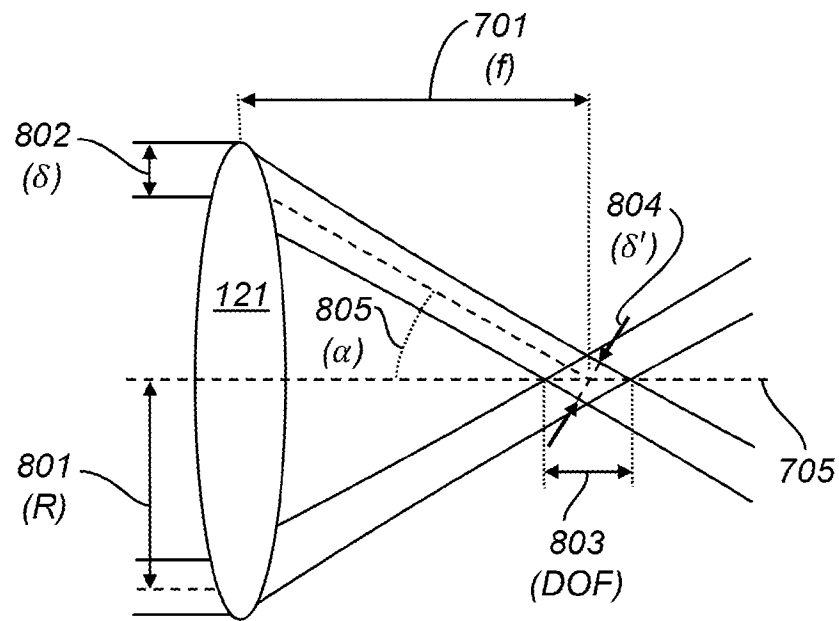
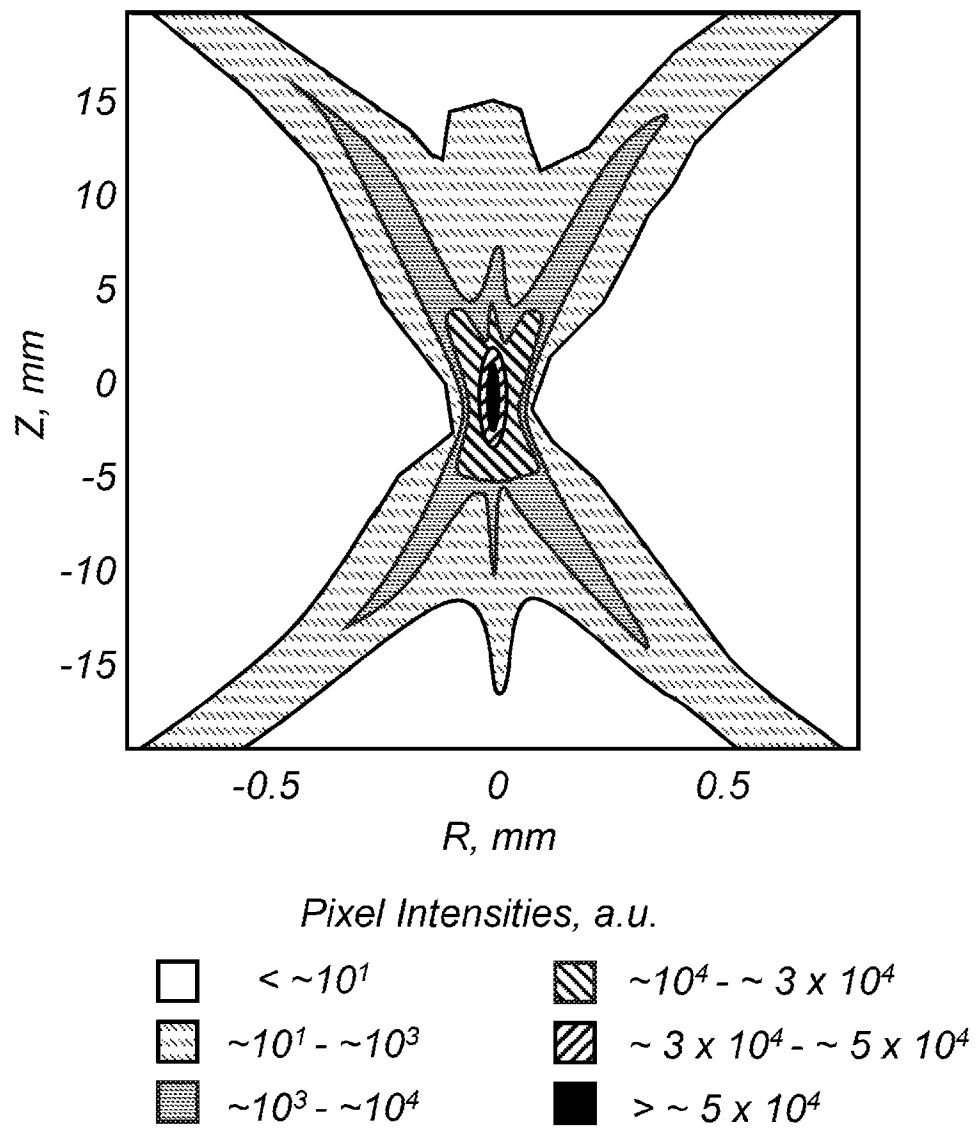
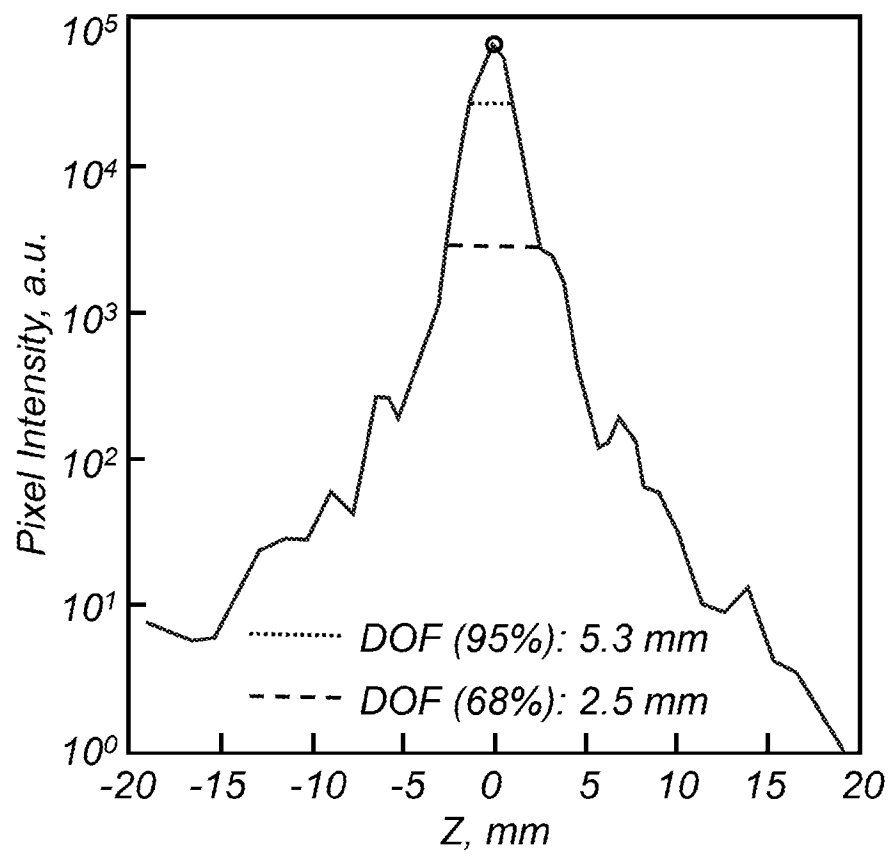


FIG. 8

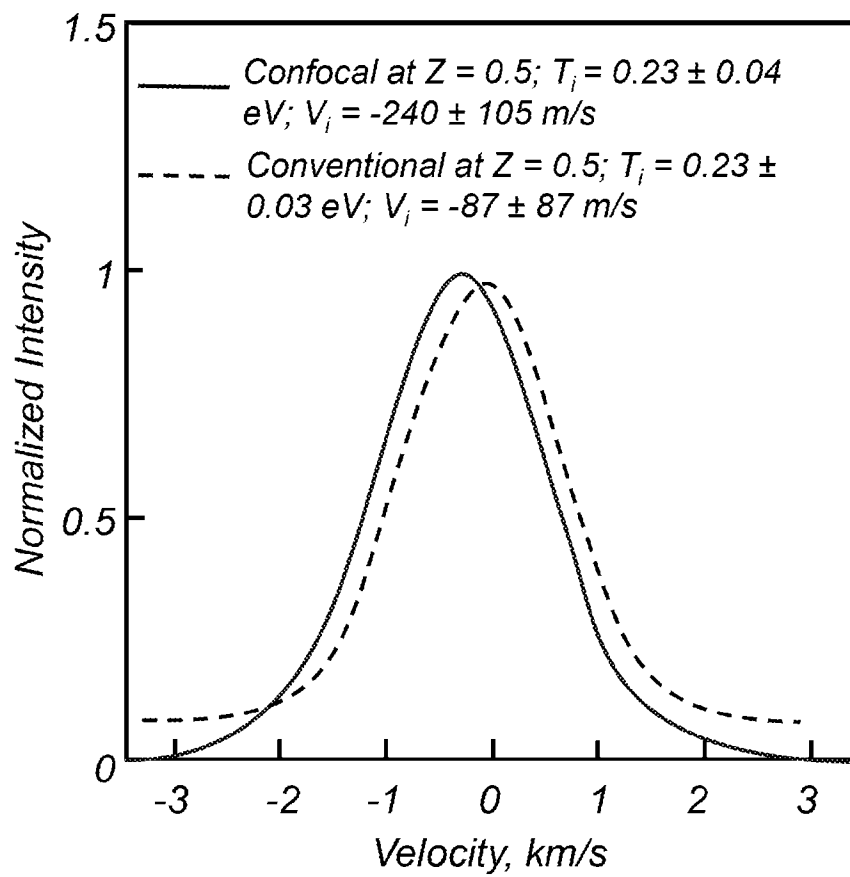
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**FIG. 9A**

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**FIG. 9B**

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**FIG. 10A**

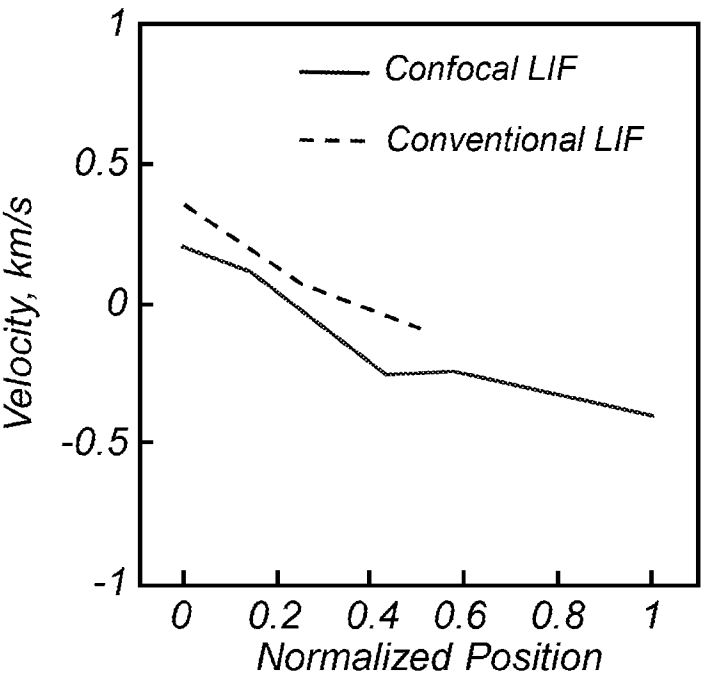


FIG. 10B

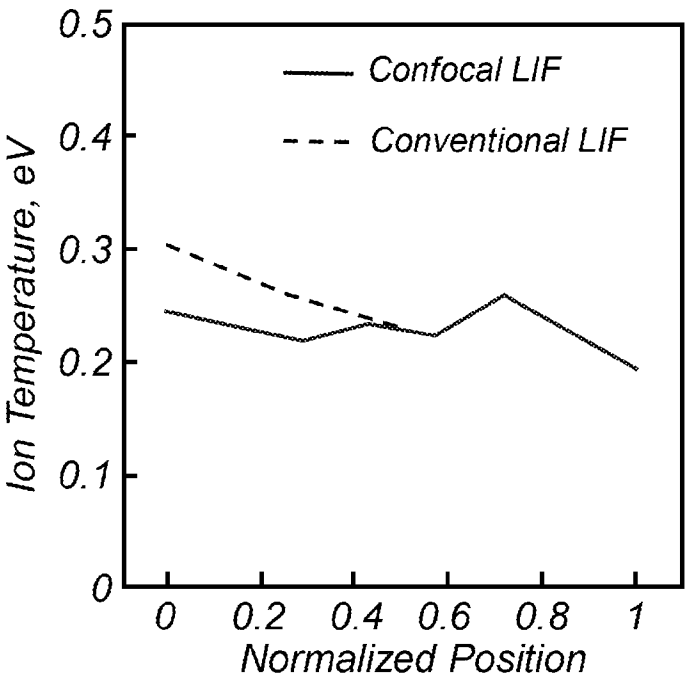


FIG. 10C

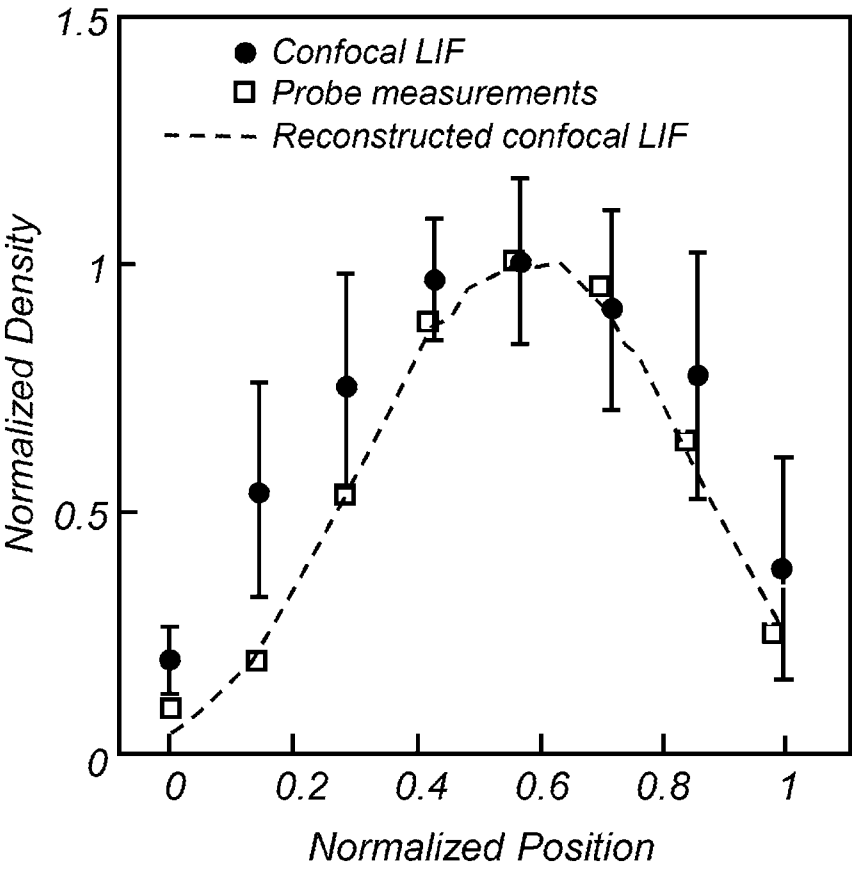


FIG. 10D