New metrics for better standards

Systematic characterization of ring-shaped laser beams beyond ISO 11146

Johannes Roßnagel and Ruben Hartwig

The introduction of new parameters enables accurate and consistent characterization of ring-shaped beams.

Ring-shaped laser beams are increasingly used in material processing due to their efficiency advantages. However, conventional beam analysis methods are inadequate for describing their unique structure. This work introduces tailored parameters for plateau and single-mode ring beams, enabling reproducible and meaningful characterization – both in the focal plane and along the beam axis.

Ring-shaped laser beams have the potential to significantly enhance efficiency in various laser material processing applications, including welding, surface treatment, and additive manufacturing. Advances in laser fabrication, fiber production, and optical technologies have made ring beams widely accessible. As their adoption grows, it is essential to establish meaningful and comparable descriptions of their properties. Conventional analysis methods, such as the second-moment method or the 86-percent-method based on ISO 11146, are optimized for Gaussian beams and do not account for the substructure of ring beams, limiting their informational value. Moreover, there is currently no standardized framework or unified set of parameters for characterizing ring beams. It is crucial that the evaluation of ring beam parameters yields reproducible, comparable, and relevant metrics.

We distinguish between two types of ring beams: "plateau beams" and "single-mode ring beams", each used in different laser processing domains and exhibiting distinct characteristics. To address the specific requirements of both types, we analyze each with tailored algorithms.

Plateau beams are primarily used in welding and surface treatment. Typically generated using a two-zone fiber (core diameter: 50–100 µm; cladding diameter: 180–400 µm), these beams are a superposition of multi-mode radiation, resulting in a stepped intensity distribution in the processing plane, depending on the power contributions from the two fiber sections.

Single-mode ring beams are mainly employed in additive man-

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ufacturing and micromachining. Both the core and the ring exhibit Gaussian intensity distributions, approaching the diffraction limit, with a defined gap between them.

Relevant parameters

Since conventional beam definitions are inadequate for ring beams, a new set of parameters is required for accurate characterization. We describe the geometric features of the ring and core separately. Utilizing ISO 13694, which specifies parameters for flat-top beams, we define the following for plateau beams:

- **Diameter of ring:** Full width at half maximum (FWHM) of the ring structure
- **Diameter of core:** FWHM of the core region, assumed to be on the plateau
- **Decentering:** Distance between the geometric centers of the core and ring
- **Edge steepness:** Ratio of the area within the ring edge to the total beam area
- **Homogeneity:** Intensity variation within the plateau region
- **Inclination:** Slope of an inclined plane fitted to the plateau
- **Modulation:** Ratio of the maximum power density in the core to that in the plateau
- **Power share core:** Relative power contributions of the ring and core sections
- **Power loss:** Difference between the total beam power and the sum of core and ring contributions

These parameters provide a comprehensive geometric description of the beam. Laser parameters can be verified using power share and modulation, while the sharpest imaging location can be inferred from edge steepness. Notably, the sharpest image may differ from the beam waist. Misalignments in the optical system manifest as inclination or decentering between the core and ring. A donut-shaped beam (a ring with a central hole) is equivalent to a ring beam with negligible core amplitude.

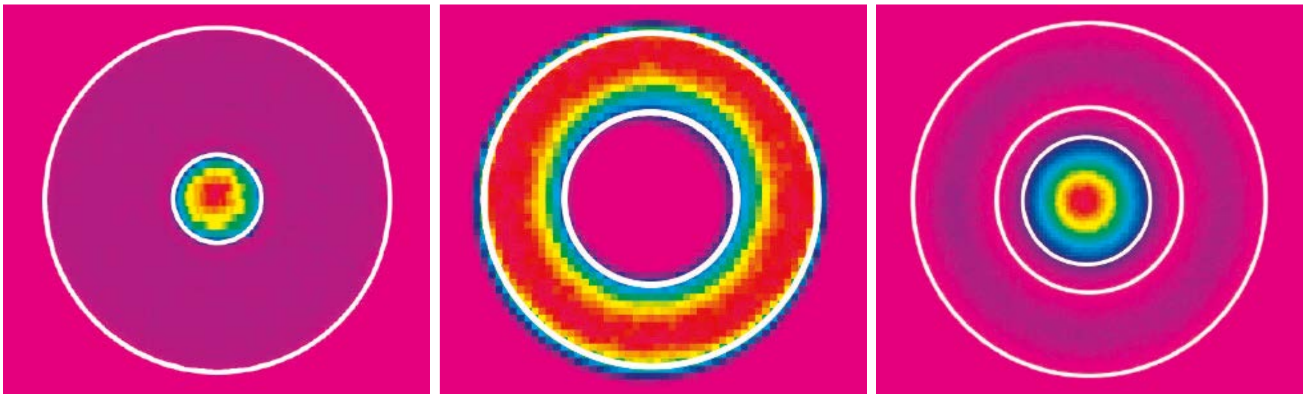
For single-mode ring beams, parameter calculation requires a slightly different approach. These beams consist of a separate core and ring, each with single-mode character in the radial direction. Gaussian fits are applied to cross-sectional intensity distributions passing through the center of gravity, yielding the width and center position for both the ring and core. Rotated fits at various azimuthal angles enable extraction of combined parameters, such as decentering, power shares, and statistical measures like the variation of ring width, diameter, and amplitude.

Caustic parameters

In caustic measurements, traditional parameters – such as beam quality, Rayleigh length, or waist diameter – are often not meaningful or can be misleading for ring beams. Most importantly, the ring and core features disintegrate within a fraction of a Rayleigh length. Thus, new parameters are needed to accurately characterize the process-relevant caustic properties of these beams.

Starting from the beam waist, we analyze the propagation of the power density distribution along the beam axis. As described, ring beam parameters are examined in individual measurement planes around the beam waist. The evolution of these parameters along the axis leads to two new caustic parameters: feature focus location and feature depth.

Feature focus location indicates the axial position where the dominant beam feature attains its minimum size (see "feature depth"). Due to optical misalignments or inhomogeneous fiber emission angles, the sharpest image of the ring feature may differ from the beam waist as defined by ISO 11146. The diameters of the core and ring at their respec-



Plateau beam, Donut beam and single mode ring beam evaluated according to the new set of ring beam parameters. The white circles show the diameter of ring and core. These new parameters reflect the characteristics of the beam.

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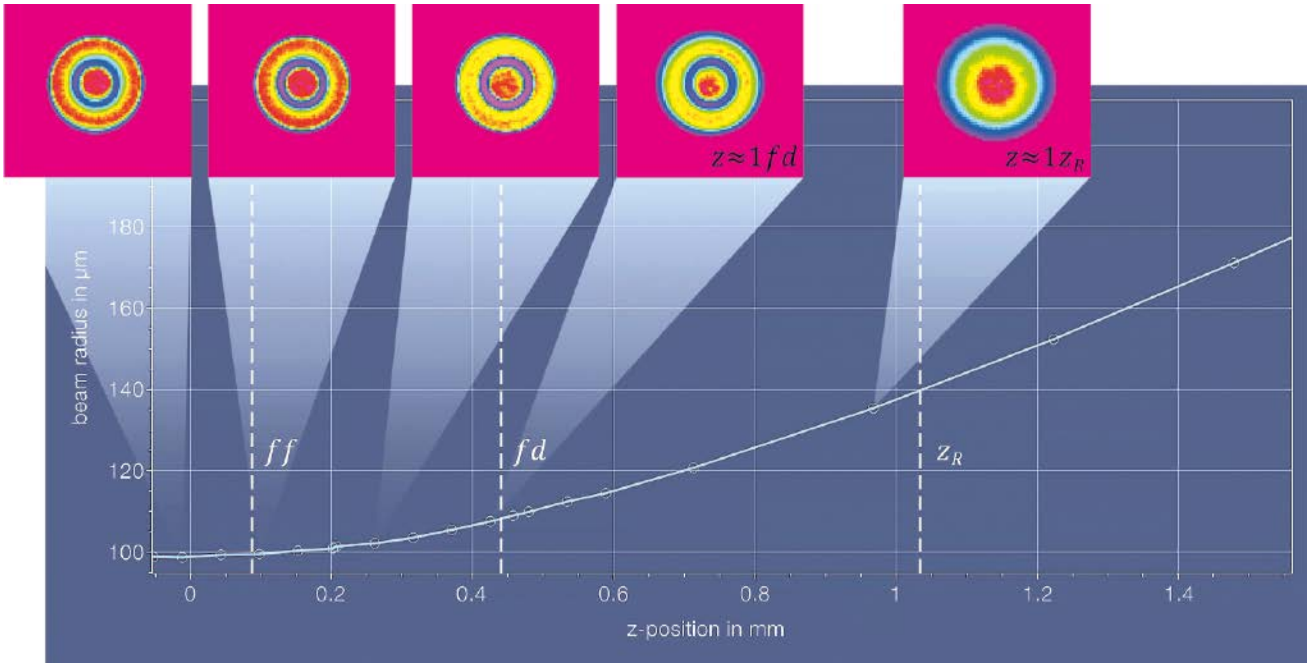

Measurement of a ring beam caustic following the measurement strategy with increased axial resolution. The z-positions of the feature focus (ff = 0.09 mm) and of the feature depth (fd = ff ± 0.35 mm) are indicated, much shorter than z_R = 1.06 mm. The displayed intensity distributions at various axial positions illustrate the evolution of the beam shape along the propagation axis.

tive feature focus locations are referred to as feature focus diameters.

Feature depth is analogous to the Rayleigh length for ring beams. It describes the axial distance over which the ring feature of the beam is maintained to a certain extent. According to ISO 11146, the Rayleigh length is defined as the distance at which the beam diameter increases by a factor of $\sqrt{2}$ relative to the waist. For ring beams, this concept is adapted to define the feature depth. While Gaussian beams are characterized by their beam diameter, we need to find another descriptive feature for ring beams. Plateau beams exhibit differing beam quality in the ring and the core: the core tends to lose its shape more rapidly than the ring. Conversely, in single-mode ring beams, this behavior is inverted, with the ring losing its shape more quickly than the core. The feature depth is thus defined as the shortest axial distance after which the width of either the ring or the core increases by $\sqrt{2}$, measured symmetrically around the feature focus location. Typically, the feature depth is significantly shorter than the Rayleigh length and provides a useful metric for process window optimization.

Given the shorter feature depth compared to the Rayleigh length, higher axial resolution is required – more than prescribed by ISO 11146. Specifically, at least five axial positions within one feature depth on either side of the feature focus should be measured. This enables clear separation of the ring and core regions and allows for a ring-beam-specific analysis.

Conclusion

This work demonstrates that conventional evaluation techniques are insufficient for a meaningful description of ring beams. The introduction of these new parameters provides an accurate, comparable and relevant characterization of ring beams both in the focal plane and across the full caustic. This framework lays the groundwork for discussions on establishing an ISO standard for ring beams beyond ISO 11146.

Authors

Dr. Johannes Roßnagel and Ruben Hartwig, Primes GmbH, Pfungstadt, Germany

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