

Ignatovsky Diffraction: Calculating Vector Fields in an Arbitrarily Tight Laser Focus

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Abstract

Extremely tight focusing produces a somewhat complicated vector field structure in the focus of a laser pulse. Accurately modelling this vector field requires an integral approach as introduced by Ignatovsky in the 1920s. The Ignatovsky model is an exact solution to Maxwell's equations, and correctly models the vector fields in a laser focus at all focal sizes. Several approximations for vector fields in a laser focus have been introduced and are now in wide use. These approximations provide significantly reduced computational requirements, but at varying costs in accuracy. We compare several of these models to the Ignatovsky model, and show that for most practical cases a model developed by Singh and Erikson in 1994 provides the most accurate results.

Ignatovsky Diffraction

We highlight the under-appreciated (and under-used) work of V. S. Ignatovsky [1] which models vector diffraction for a beam focused by a parabolic mirror or by a lens. Ignatovsky published his work in 1920. Unfortunately, Ignatovsky was executed together with his wife by the Soviets, but his work has influenced the development of vector diffraction in the microscopy community for nearly a century. In [2] we provide a streamlined and accessible derivation of Ignatovsky's results and demonstrate its practicality for use in high-intensity laser physics. For an azimuthally symmetric beam with uniform polarization, the diffraction integral collapses to one dimension, which can be performed numerically with reasonable efficiency.

Although some in the microscopy community have used Ignatovsky diffraction, many in the laser community have sought alternative vector models of a laser focus, apparently without the benefit of Ignatovsky's work. A variety of models have been offered, which often differ markedly from each other. A broad criticism that we make against many of these models is that they start from an *assumed field distribution* in the focal region and attempt to develop vector fields (consistent with Maxwell's equations) in the surrounding region. This approach is at odds with the fact that no experimenter directly controls the focal field distribution. Rather, experimenters typically diagnose and manipulate their incident beam to control the fields at the focusing optic before it converges, diffracts, and interferes to form the focal fields. Moreover, the ability to directly measure vector components of the fields in an intense focus is extremely limited. This makes Ignatovsky diffraction, where the incident field is defined at a focusing optic rather than inside the focus, much more natural and relevant to experimental work.

Other Models

For applications such as computing relativistic trajectories of charged particles in a tightly focused intense beam, one would ideally like a closed analytic formula that adequately represents the vector field components to avoid repeatedly evaluating the integrals used in Ignatovsky diffraction at various positions within the interaction region. We evaluate several of these models and compare them with the results calculated using the Ignatovsky model. We find that a paraxial vector model proposed by Erikson and Singh [3] best agrees with Ignatovsky diffraction (down to $f/2$ optics).

On the other hand, a frequently employed iterative scheme first introduced by Lax in 1975 [4], with the intent of improving beyond the paraxial limit, actually worsens agreement with Ignatovsky. We note also that the Lax expansion produces undesirable divergences in the far field, making that program suspect.

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References

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