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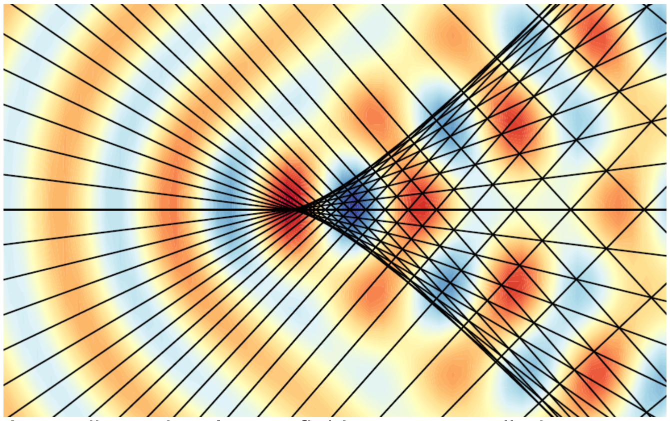
Fixing Ray Optics for Wave Simulations

Ray optics is indispensable for simulating waves in fusion plasmas but breaks down near so-called caustics. Now, researchers have found a way to fix this.



A two-dimensional wave field near a so-called cusp caustic calculated using ray optics. The corresponding rays used for calculating the field are shown as black lines.

The Science

Future magnetic fusion reactors will rely on precise heating of plasmas with radiofrequency (RF) waves, which impart energy to charged particles via resonant interactions. To ensure high heating efficiency, the propagation of RF waves must be calculated with fidelity. Direct solution of the governing equations, namely Maxwell's equations, is often too slow to be practical, so approximate "geometrical-optics" theory, or ray optics, is used instead. But ray optics breaks down in regions called caustics where either the wavelength becomes too large or the electromagnetic field does not locally resemble a plane wave, as shown in the figure. Today, the field structure near caustics is found in simulations by solving Maxwell's equations directly, which is a bottleneck. Now, researchers at PPPL have introduced a new formulation that reinstates ray optics near caustics and thus can help speed up simulations.

The Impact

The new theory makes it possible to calculate complex patterns of high-frequency fields entirely by means of ray optics. This opens a path toward speeding up simulations of RF waves in fusion plasmas. In the future, this will help facilitate the optimization of magnetic fusion devices.

Summary

To efficiently calculate electromagnetic wave fields near caustics, researchers have developed an extension of traditional ray optics called metaplectic geometrical optics. The basic idea is best illustrated on a wave field that has a caustic near a reflection point, or a cutoff. Traditional ray optics assumes that the wavelength is small, so it fails near the cutoff, where the wavelength is infinite. By applying the so-called metaplectic transformation, one can rewrite the wave equation in a form that has no cutoff, at least locally, and then ray optics works just fine.

But how far from the original cutoff should the transformation be applied? The lack of a good answer to this question has kept the overall method impractical, so it was never used for applied calculations. Now, researchers have found a way to transform the wave equation continuously, both eliminating the singularities at caustics and allowing for fully automated and fast simulations. This new approach is now being used for developing more flexible ray-based algorithms to aid the design of RF systems for fusion experiments.

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Publications

N. A. Lopez and I. Y. Dodin, “Restoring geometrical optics near caustics using sequenced metaplectic transforms”, to appear in *New Journal of Physics.* [DOI:10.1088/1367-2630/aba91a]
N. A. Lopez and I. Y. Dodin, “Pseudo-differential representation of the metaplectic transform and its application to fast algorithms”, *The Journal of the Optical Society of America A* **36**, 1846 (2019). [DOI:10.1364/JOSAA.36.001846]