Coherent Ray-tracing for BREAD

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DOE SULI Poster Session, December 8, 2021 FERMILAB-POSTER-21-130-STUDENT

Axion Detection

The nature of dark matter is an outstanding question in fundamental particle physics, astronomy, and cosmology that has yet to be resolved. Modern-day axion experiments detect photons emitted from the Primakoff effect——an Axion-Photon-Mixing interaction induced by an external magnetic field. Recently proposed broadband searches use a dish antenna [1] coupled with a photosensor and are shown to be suitable for probing QCD axions in the THz regime, currently inaccessible to their traditional microwave cavity counterparts such as ADMX.

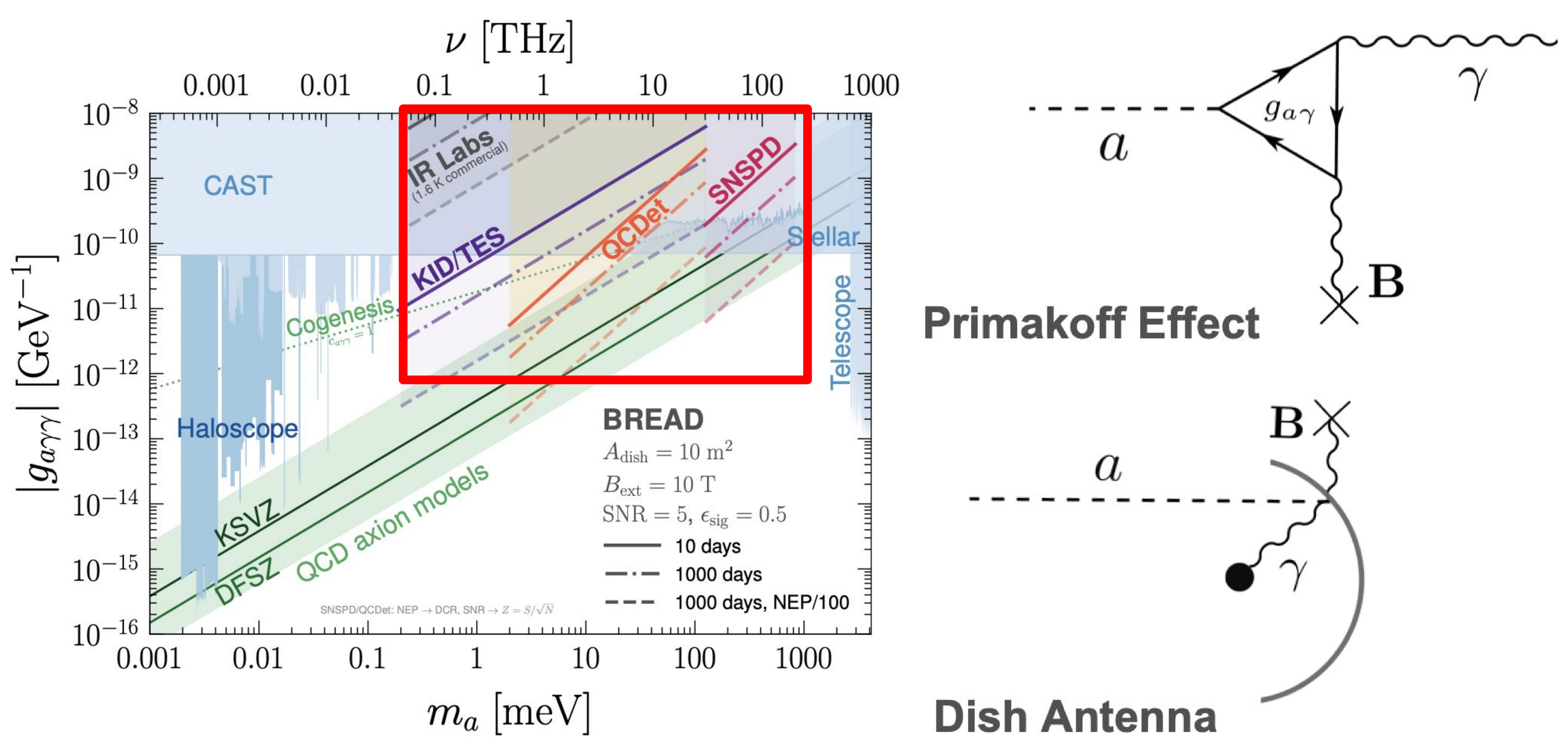

Fig. 1 Sensitivity Projections for BREAD [2] in the coupling vs. mass plane (left). Feynman diagrams representing axion-photon-mixing interaction (right).

BRoadband Experiment for Axion Detection

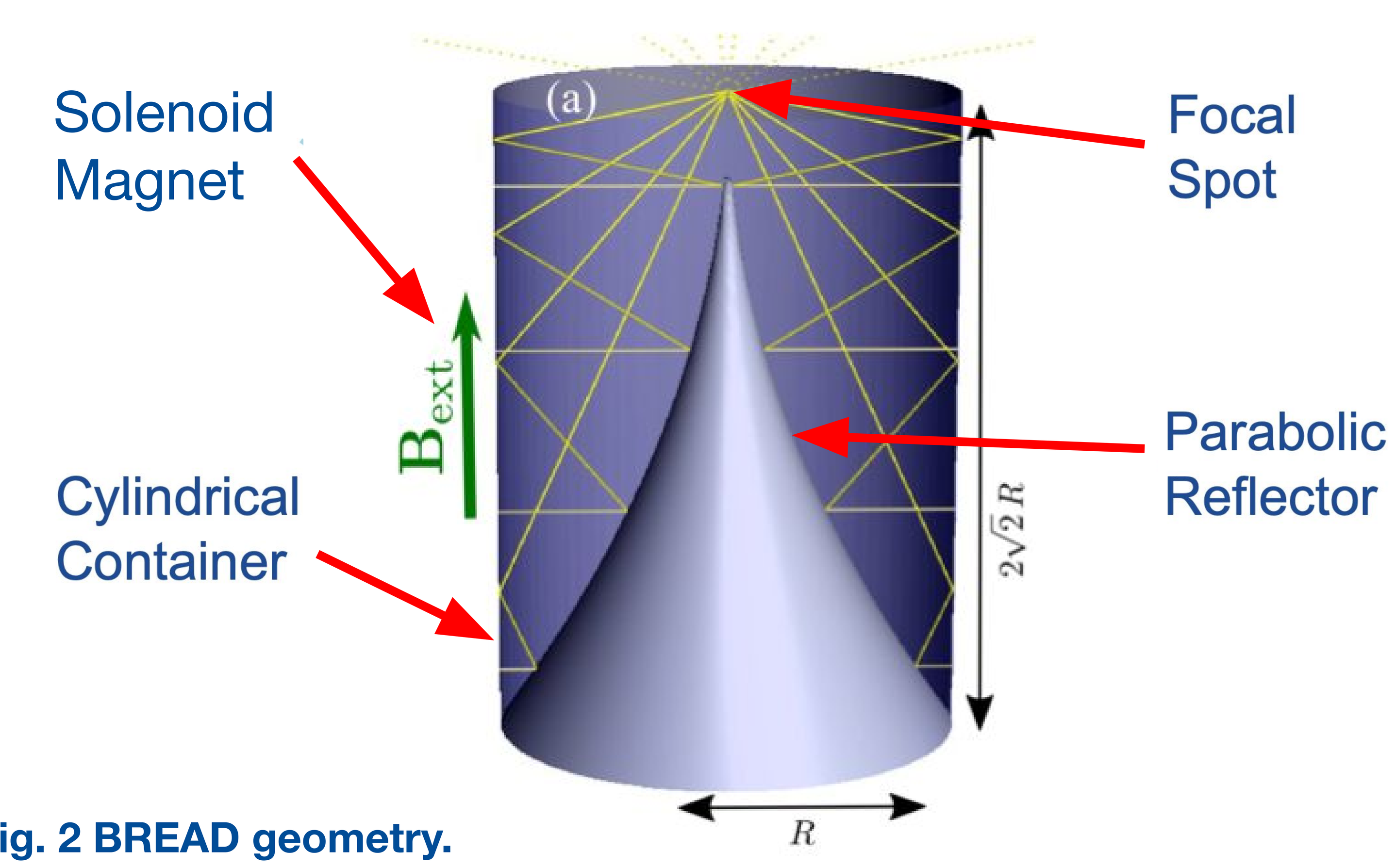

Fig. 2 BREAD geometry.

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics

BREAD will consist of a **cylindrical container** immersed within a **solenoid magnet** that generates a magnetic field parallel to the barrel's surface. Through the Primakoff effect [Fig. 1], emitted radiation from the barrel's inner wall will reflect off of the novel, **parabolic reflector** and be focused onto a photosensor located at the parabola's vertex, the **focal spot**.

Why coherent ray-tracing?

When evaluating the sensitivity of detecting DM-to-γ:

I. $\lambda_{DM} << R$ [Incoherent emission]
Focal spot is blurred on a scale ~ v_{DM} R. Diffraction effects may be ignored.

II. $\lambda_{DM} >> R$ [Coherent emission]
Rays coherently accumulate at the focal spot, and diffraction effects need to be accounted for.

Recently, a full-wave simulation in COMSOL has been used to simulate the large wavelength limit [II.], but this is computationally expensive for higher axion masses since the γ wavelength becomes smaller. Thus, the λ_{DM}~R case was studied with coherent ray-tracing in FRED [3].

Gaussian Beam Decomposition

Essentially, any wavefront can be decomposed into a set of Gaussian beams, of which the analytical solutions to Maxwell's Equations are well known. FRED initializes secondary rays that trace the optical system and their fields are added at the analysis plane.

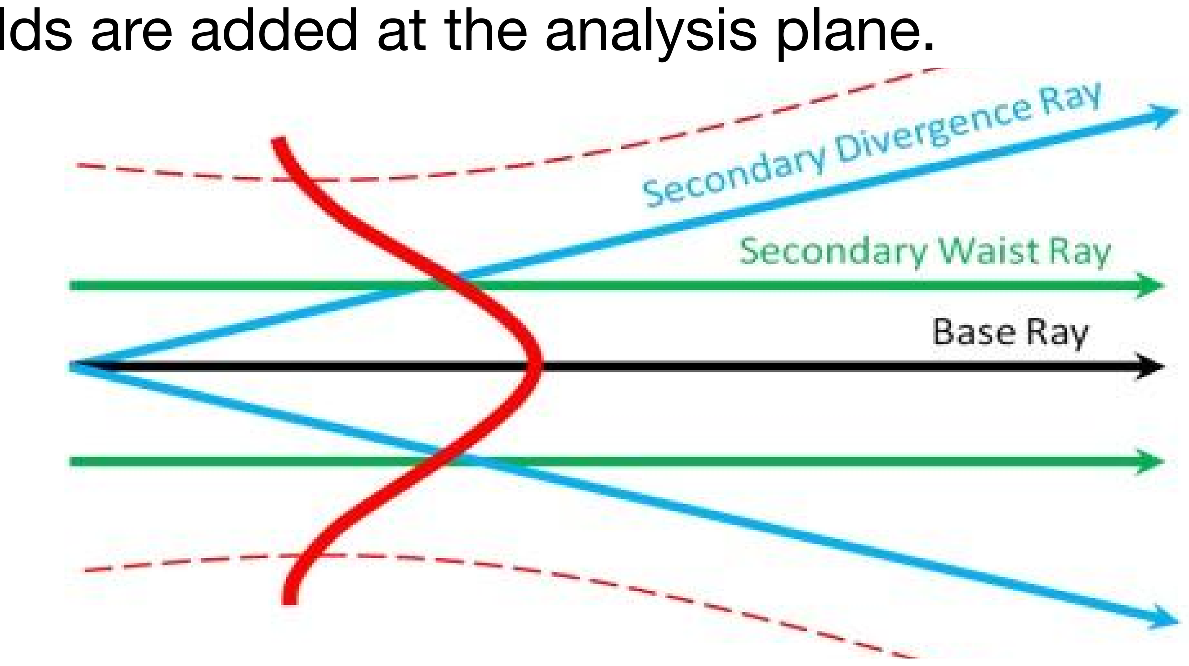

Fig. 3 Representation of a Gaussian beam in FRED coherent ray tracing simulation.

Before simulating the BREAD geometry we validated the coherent ray tracing in FRED using the analytically well-understood case of a single-slit experiment [Fig. 4].

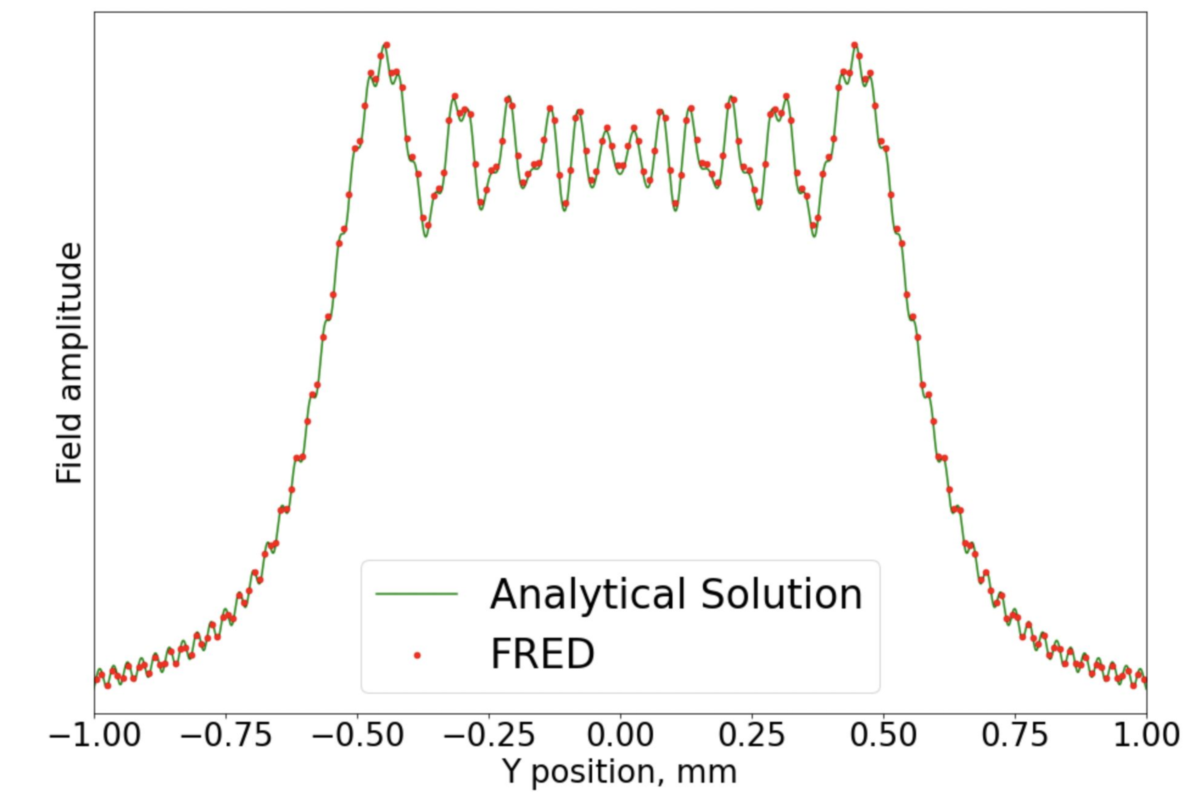

Fig. 4 Diffraction pattern 50 mm behind a 60 μm x 1.3 mm single slit along the long direction of the slit at a wavelength of 0.63 μm.

Coherent Ray-tracing for BREAD

We ran simulations using the BREAD geometry [Fig. 2] with R=1m as proposed by the concept paper [2]. We resolved the field distribution at the focal spot, as seen previously in full-wave simulations. While preliminary results have shown to be promising, we find the electric field distribution resolved at the focal spot is azimuthally asymmetric, contrary to the azimuthal symmetry of the problem [Fig. 5]. Nevertheless, the obtained field distribution is qualitatively similar to the field distribution obtained in COMSOL before. The reason for the asymmetry is under investigation. Further open questions are also being investigated by the BREAD simulation group, such as surface perturbations and focal spot calibration.

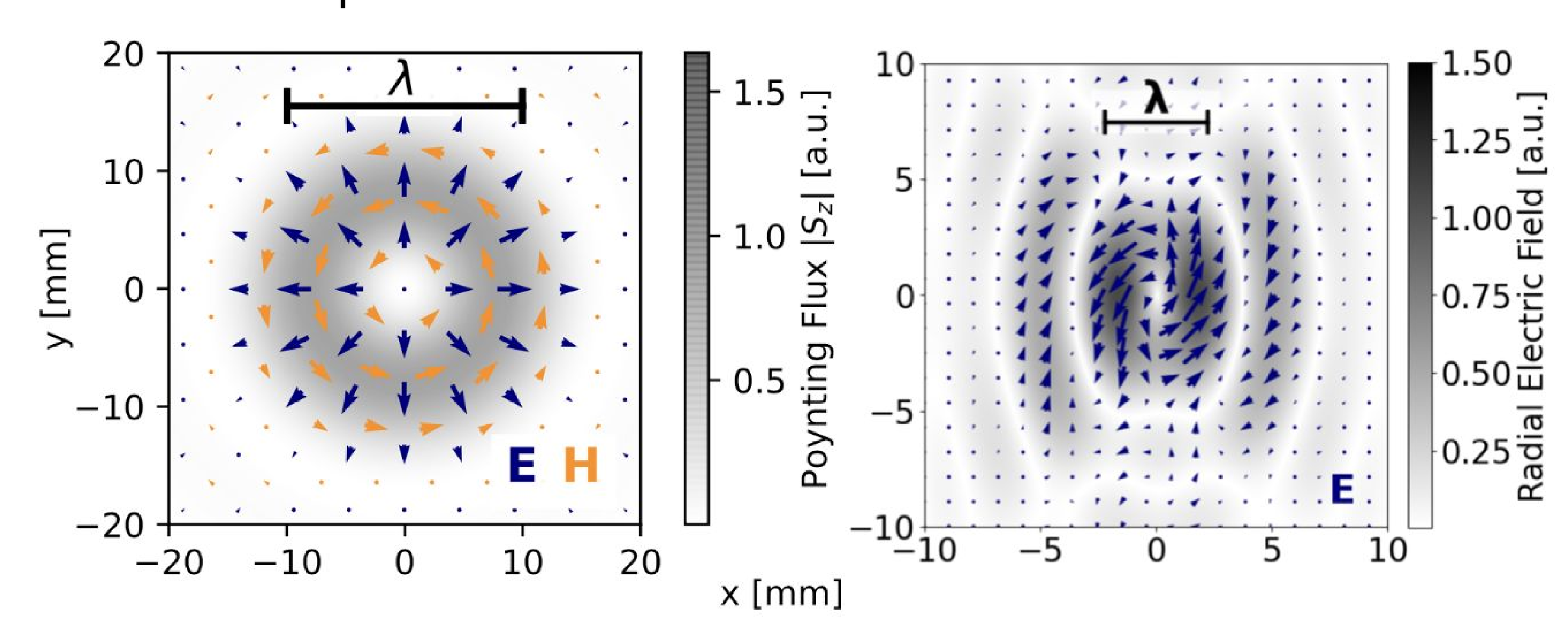

Fig. 5 Field distribution at the focal spot in COMSOL (left) and FRED (right).

References

[1] Horns et al, arXiv: 1212.2970
[2] BREAD Collaboration concept paper, Liu et al, arXiv: 2111.12103
[3] FRED by Photon Engineering, https//photonengr.com/fred-software/