











interference region of the BDW pulse is not moving at this tilt angle. Its phase (and pulse) fronts are perpendicular to the  $z$ -axis and move along this axis. Its Poynting vector, indicating the direction of energy flow, also lies along the  $z$ -axis. However, the energy flux is not superluminal. The superluminal pulse's velocity should not, of course, be confused with the signal velocity. As is well known, Maxwell's equations, or the wave equation for electromagnetic fields, does not allow superluminal signaling.

To further study the formation and evolution of the boundary-wave pulse, the propagation of an ultrashort pulse was computed in detail behind an opaque disk 1mm in diameter. In the simulations a smaller disk diameter was used in order to reveal the subtleties of the formation of the boundary wave pulse. Figure 4(a) ([Media 1](#)) shows the incident and diffracted pulse propagation in the laboratory reference frame where  $z = 0$ mm is the location of the disc. The simulations show the creation of the Arago spot at the moment when the expanding ring torus of the boundary-wave pulse becomes an expanding spindle torus. In the close vicinity after the disc, speeds much greater than  $c$  can be seen, where the boundary wave pulse literally jumps out of it. Due to the discrete color scale of the animations, the expanding spindle torus shape of the BDW pulse seems discontinuous during the first few picoseconds of the spot evolution, albeit it is only low in intensity in these particular directions.

The Bessel-like radial pattern is depicted in greater detail in Fig. 4(b) ([Media 2](#)) where only the field near the axis' center is shown. This time we use a reference frame that is moving with the incident plane-wave pulse. The origin of the frame  $z = 0$ mm is bound to the plane-wave pulse moving at velocity  $c$  to the right. The fringe pattern in the axial region of the boundary-wave pulse stretches during the propagation as the angle of intersection between the elementary wavelets decreases continuously. Correspondingly, the pulse velocity decreases as the fringe periodicity increases. Since the expansion rate of the spindle-torus is constant (equal to  $c$ ), the spot on the axis propagates superluminally, decelerating toward the limiting value  $c$ . Interestingly, the first seconds of the video also reveal the back-diffracted pulse, which follows from the direct evaluation of Eq. (1). This backward propagating contribution is expected since the spherical waves generated at the boundary of the disk are emitted at all angles in the  $x$ - $z$  plane. Of course, the intensity of the backward-moving pulse quickly decreases towards negative values of  $z$  and practically ceases to exist within the first millimeter of propagation.

#### 4. Conclusions

In summary, we have performed direct spatiotemporally resolved measurements of pulsed light fields behind basic types of diffracting screens and have interpreted the results using the boundary diffraction wave theory. The latter provides a one-dimensional integral expression for the diffracted field, which enabled us in a computationally simple way to simulate the evolution of the diffracted field. We believe that time-resolved measurements and a time-domain treatment of diffracting waves not only turn out to be fruitful in modern physical optics, especially in micro- and meso-optics, but also promote the understanding of diffraction phenomena.

#### Acknowledgements

R. T. and P. B. were supported by Georgia Research Alliance and NSF SBIR grant #053-9595, the other authors were supported by the Estonian Science Foundation.