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Whispering gallery effect in relativistic optics

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In this Letter we demonstrate, that a relativistic laser pulse, confined in a cylindrical target, under specific conditions may perform multiple scattering along the internal target surface. This results in the confinement of the laser light, leading to a very efficient interaction. Such propagation of the laser pulse along the curved surface is an example of the well known "whispering gallery" effect [1], although nonideal due to laser-plasma coupling. In the relativistic domain its important feature is a gradual intensity decrease, leading to changes in the interaction conditions.

The effect was observed at the LFEX laser facility [2] in the Institute of Laser Engineering (ILE) of the Osaka University, when an intense laser beam (the total energy ≈ 700 J, the pulse duration ≈ 1.5 ps, the focal spot diameter $\approx 60\,\mu$m, the wavelength 1053 nm, the intensity $\approx 9.7\times10^{18}$ W/cm^2, the contrast $\gtrsim 10^9$, the divergence angle of the focused optical beam $\approx 5.7°$) interacts with a dense surface plasma, generated inside a cylindrical-like shaped target (made from a copper foil of a $10\,\mu$m thickness, with a diameter of $500\,\mu$m at 0° decreasing down to $400\,\mu$m at 360°, so with a $100\,\mu$m slit entrance for the laser beams, the target length along the axis $500\,\mu$m), shown in Fig. 1. Those cylindrical-shaped, or "snail" targets were recently proposed for optical generation of super-intense quasistatic magnetic fields [3]. It was shown in numerical studies, that the laser pulse, entering the curved target in the shape of a cylinder with an entrance slit, experiences multiple reflections, and then is finally locked in the target internal volume. According to this physical description, if the surface was an ideal material which permits total internal reflection,

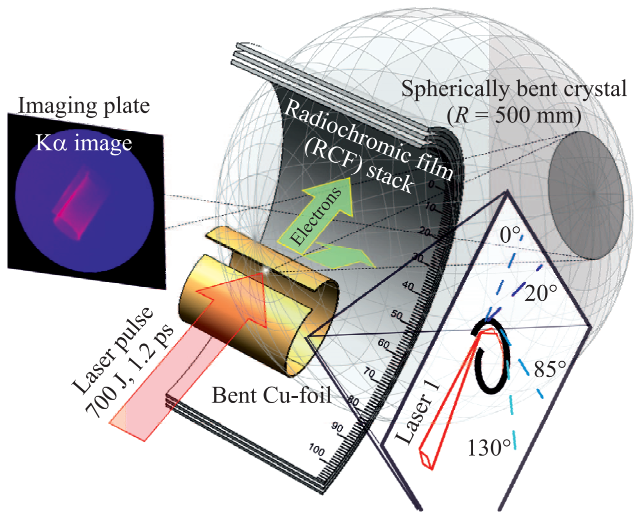

Fig. 1. (Color online) A sketch of the experimental setup, registered Kα image and a simplified scheme of the beam propagation. The laser pulse enters the slit at grazing incidence. The target material is copper, to allow the Cu-Kα imaging of the hot electrons with the use of a spherically bent crystal, shown behind the target. A curved large-angle radiochromic film (RCF) stack is placed around the target to detect large-angle particle signal

the Q-factor (quality factor) for corresponding whispering gallery modes would be high. Instead, in our situation, the multiple reflections lead to a very high absorption and energy deposition, which in turn may result in many interesting accompanying effects. The one considered in the original work [3] was magnetic field generation, and deals with very strong current generation along the target surface.

Two main diagnostics were used to demonstrate the effect of multiple successive surfing reflections of the laser beam inside the cylindrical target. The first one

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was based on the Cu-Kα emission due to the material heating by laser-accelerated electrons, and the second was performed by the radiochromic film (RCF) stack, positioned around the interaction zone. In the RCF images, we detected several regions at different angles with an increased electron dose deposition. The observed electron signal may be explained by the interaction of the laser beam with a surface at grazing incidence (see, e.g. [4, 5]). Thus we may deduce, that the set of observed maxima at $\{\approx 20^\circ; \approx 85^\circ; \approx 130^\circ\}$ relates to the laser beam internal reflections. These internal reflections evidence that the laser pulse propagates along the target surface. According to the geometry of our setup, it propagates at least over a half-sphere (due to technical limitations, the RCF stack is limited to a maximum angle of 150°), which is almost 1 mm of the interaction length. Because of strong coupling, the intensity of the beam gradually decreases, though it is high enough to generate relativistic electrons at each of the observed reflections.

A simplified geometry of the interaction is shown in the inset of the Fig. 1 using geometrical optics. It appears to be qualitatively consistent with the observed sequence of the angles, which demonstrates a quasi-regular sequence, though not ideally equidistant. In an ideal "whispering gallery" effect, for a cylindrical target, perfect reflection, and a zero-width laser beam without divergence it is expected that the sequence of reflections would be regular. In our case, besides experimental uncertaintes, the used target was not an ideal cylinder, but a figure with a radial dependence on the azimuthal angle. Also note, that we observe an electron signal, not the signal of the reflected laser beam. Gradually along the target surface, the laser intensity decreases, and the interaction conditions change. This would result in different conditions for escaping electrons, and in the signal decreasing with angle growth. As a possible scenario, we may remind, that in the case of a curved surface, electron guiding [4, 5] would allow electron acceleration in the generated surface fields up to a certain energy [6]. The strength of these fields, in the relativistic case, depends strongly on the laser intensity, which drops down for consequent reflections. As a result, the guiding structure becomes weaker, and electrons, accelerated at each next interaction point, should escape with a smaller angle. Indeed, the observed sequence of electron peaks proposes an angular distance between the second, the third, and the fourth maxima ($\approx 65^\circ$ and $\approx 45^\circ$), which gradually decreases. The change of interaction conditions along the propagation is an important feature of the considered effect in the relativistic optics domain.

The considered target possesses a possibility to catch a relativistic beam in a small volume and to obtain a very high-energy density state. The physics of this interaction is very rich. Taking into account the grazing incidence, for the experimental parameters we may estimate the focal spot to be $\sim 60 \times 120\,\mu$m, extended at least three times. With such nontrivial interaction conditions, we already observed very efficient electron acceleration [6], and strong current and magnetic field generation. A rough estimate, with the laser energy ~ 700 J and $\sim 20{-}30\,\%$ energy conversion efficiency into electron energy, results in $\sim 100{-}200$ J in relativistic electrons. With the electron charge of 0.1 mC and the pulse duration of ~ 1 ps this corresponds to ~ 100 MA electric current, or a magnetic field in the range of tens of kT, in accordance with the predictions of numerical studies [3]. This in turn entails possibilities for a number of consequent effects. Some of these effects, such as the strong quasi-static magnetic field generation up to several kiloteslas and electron acceleration at curved surfaces with a very high energy cutoff were already studied in literature [3, 6], while the others are yet to be discovered.

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