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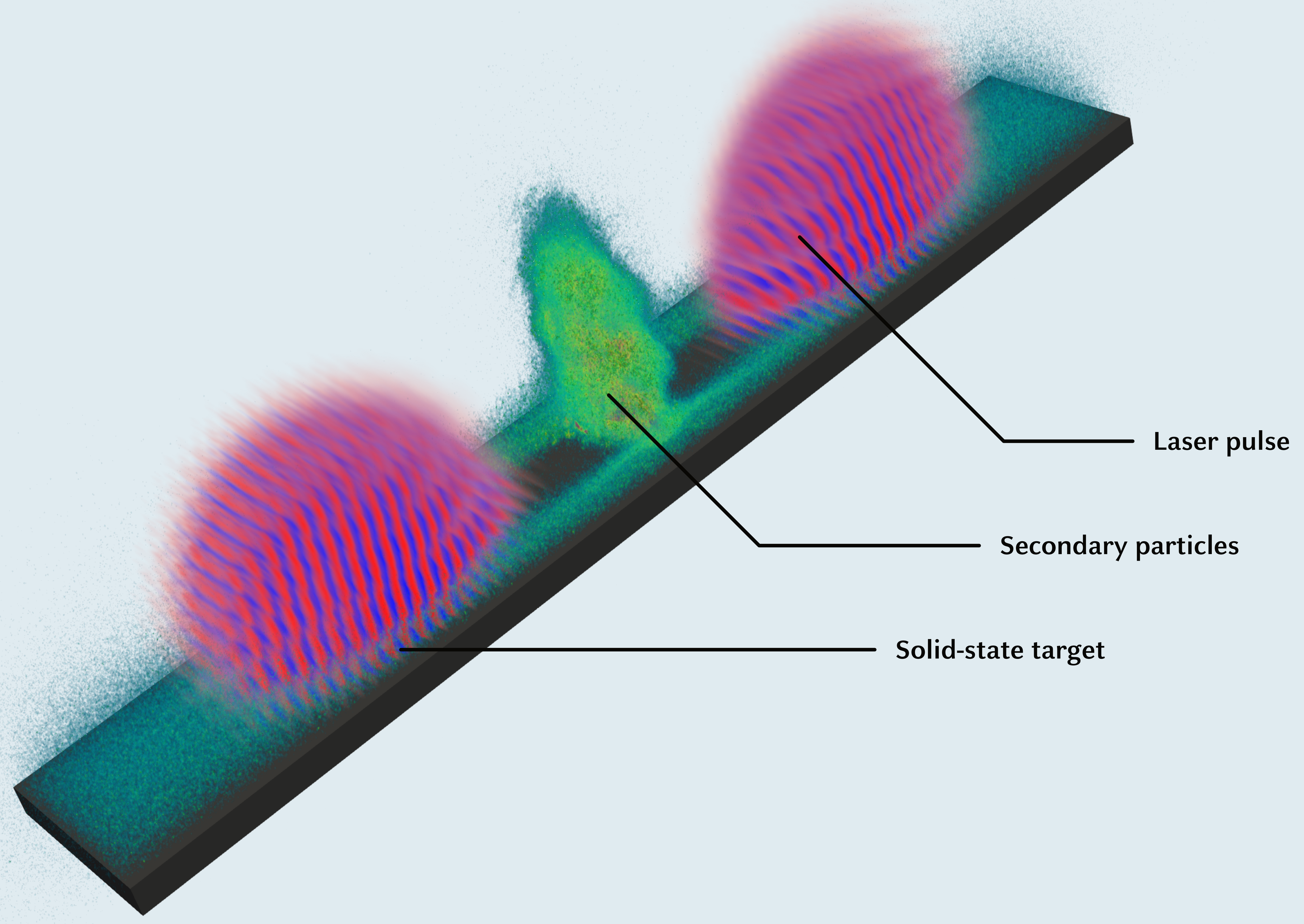
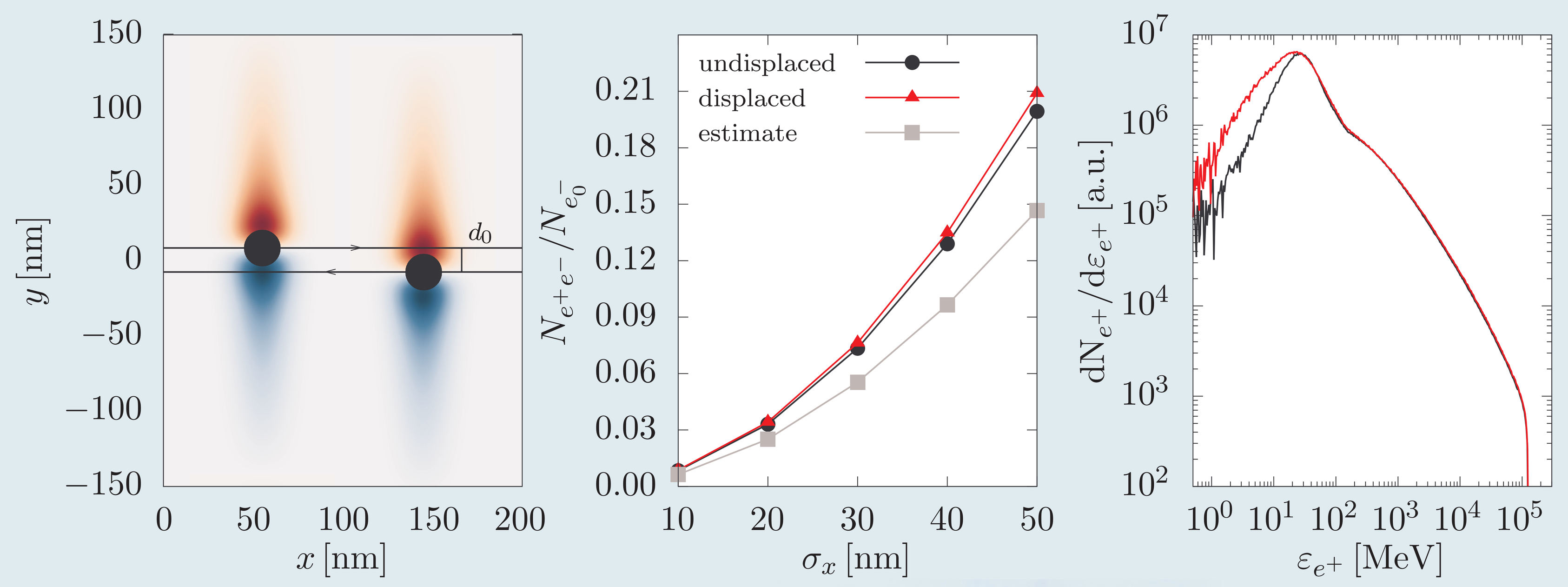
Beam-beam collisions and laser-solid interaction in the strong-field QED regime

We present our results of studying quantum electrodynamical processes under extreme densities and strong electromagnetic fields utilizing large-scale particle-in-cell (PIC) simulations. This entails the study of potential experimental configurations like electron-electron beam collisions, and high-intensity lasers irradiating a solid-state target at an angle to produce an abundance of γ-photons whose decay leads to the creation of electron-positron pairs. Throughout, a novel solver for Maxwell's equations, capable of suppressing the numerical Cherenkov instability, is used.



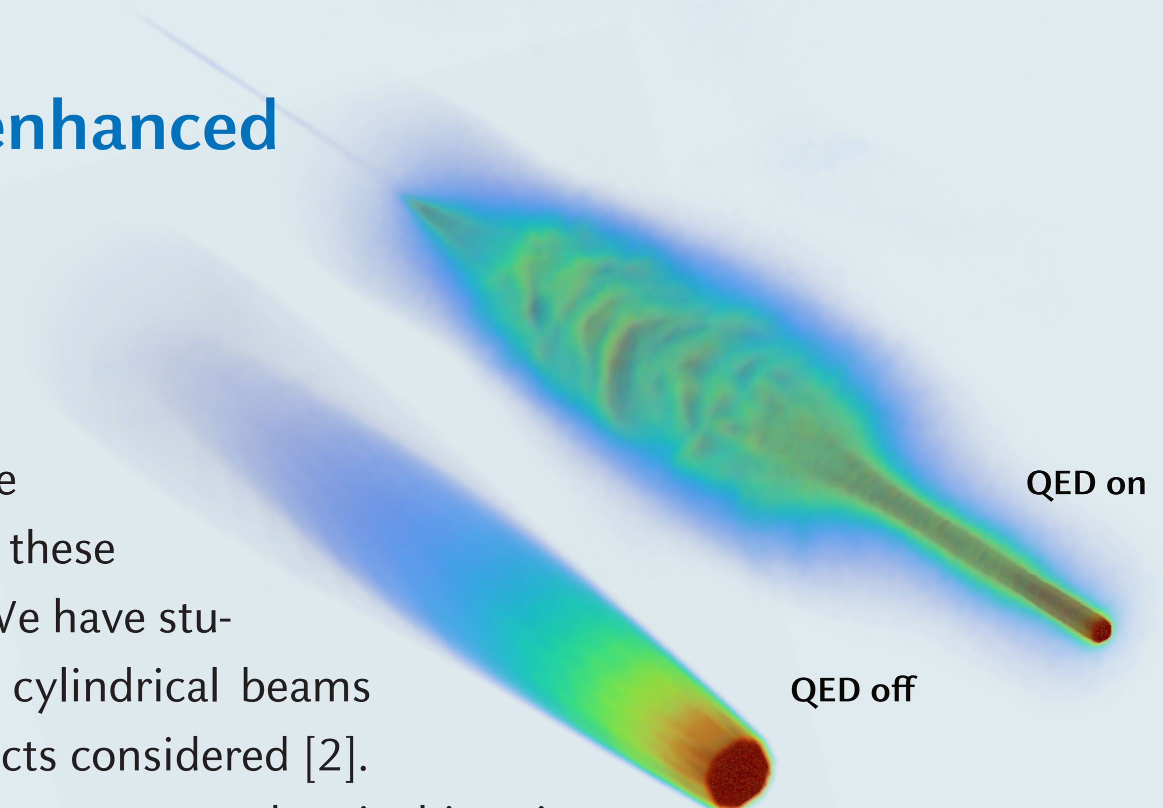
Shifted beam-beam collisions

Electron-electron and electron-positron beam collisions are theorized to be a feasible way of achieving the fully non-perturbative regime of QED. Introducing a transverse shift between the two colliding beams, the maximum field strength experienced by the respective beams can be optimized [1]. PIC simulations show an increase of 4.4% in pair yield at a bunch length of 10 nm. With these parameters, 33% of the electrons reach the fully non-perturbative regime.



Beamstrahlung-enhanced disruption

In beam-beam collisions, the particles are subject to betatron oscillations. Depending on the application, minimizing these oscillations is of interest. We have studied the collisions of two cylindrical beams with and without QED effects considered [2].



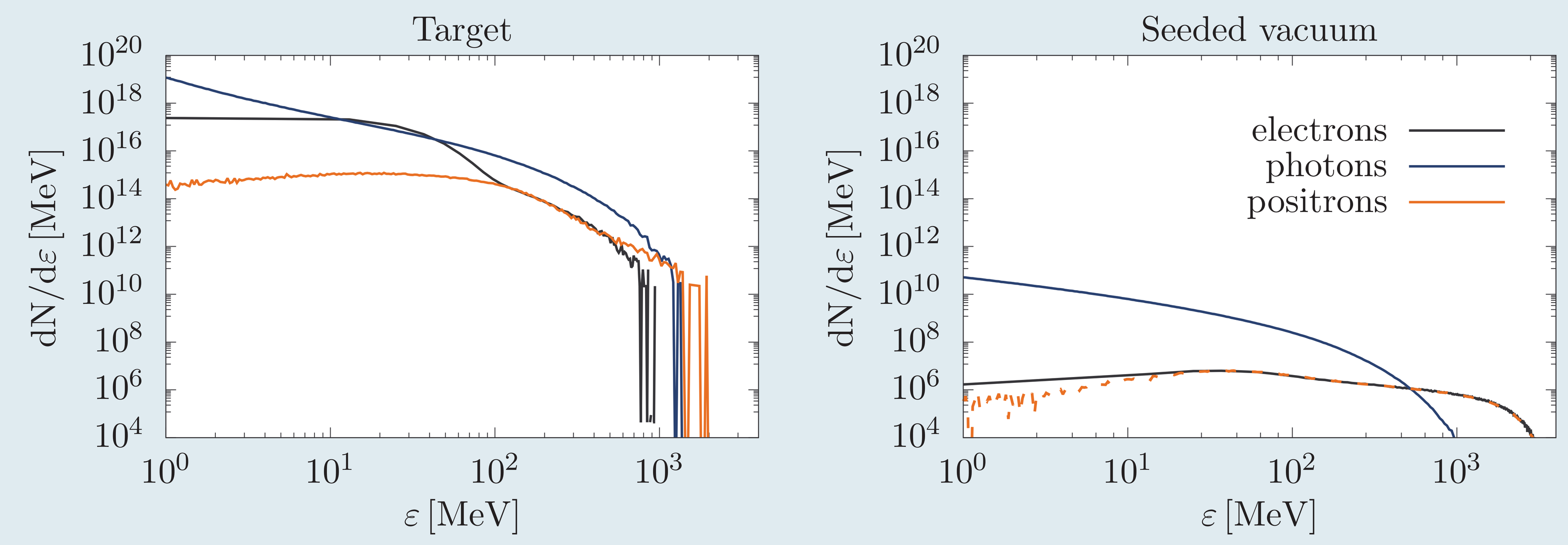
Taking radiation reaction into account, the pinching time can be improved upon. Further, the QED effects can act as a seed for a kink instability during the collision. In the quantum regime, an analytical estimate for the disruption time is obtained:

$$\frac{D}{D_0} \approx 30.8 \left(\varepsilon_b[100\,\mathrm{GeV}]\; n_e[10^{21}\,\mathrm{cm}^{-3}]\; r_b[\mu\mathrm{m}]^4\right)^{1/3}$$

This parameter quantifies the (de-)focusing of the beams and is in good agreement with our particle-in-cell simulations.

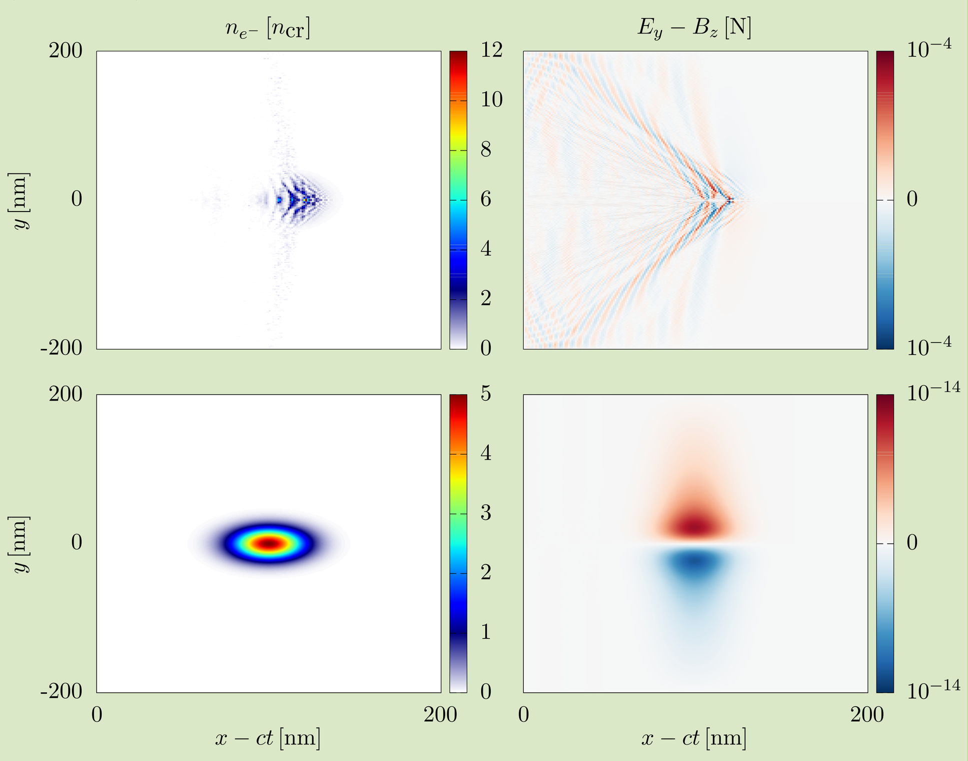
Grazing-incidence laser pulses

Using a linearly *p*-polarized laser pulse at grazing incidence on a solid-state target, electrons are extracted and accelerated from the target [3]. The electrons then interact with a counter-propagating pulse. During the electrons' interaction with the strong electromagnetic fields, photons are emitted which can decay into electron-positron pairs. As this happens repetitively, an electron-positron plasma is created. A comparison with the „seeded vacuum" shows that using the solid-state target significantly more secondary particles can be produced via QED effects.



The rhombi-in-plane (RIP) solver

Compared to the commonly used Yee Maxwell solver, RIP is able to suppress the numerical Cherenkov instability. For an ultra-relativistic electron bunch propagating through vacuum, particles lose ca. 90% of their energy. This does not occur for the simulation using RIP, making this solver very useful for QED-related simulations [4].



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References
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[2] A. Samsonov et al., *New J. Phys.* **23**, 103040 (2021)
[3] M. Filipovic and A. Pukhov, *arXiv:2206.15180* (2022)
[4] M. Filipovic et al., *PRAB* **25**, 054405 (2022)