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Plasma wakefields: from accelerators to black holes

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In this lecture, we provide an overview of the Plasma Wakefield Accelerator (PWFA) [1] driven by relativistic charged particle beams (Fig.1). Together with the laser-driven Laser Wakefield Accelerator (LWFA) [2], these two schemes are complementary and have become the two major plasma-based accelerator concepts actively pursued worldwide, evidenced by the recent whitepapers [3,4] published by major international consortiums that chart the R&D roadmap in the next 20 years toward a full-scale plasma-based high energy collider. Considering the pros and cons between LWFA and PWFA, a Hybrid LWFA+PWFA concept was introduced [5] with the attempt to take the best of both schemes, which may become the future direction.

Several fundamental aspects in beam dynamics of plasma wakefield accelerators will be reviewed, which include the issues of beam loading [6], phase slippage, transformer ratio [7,8], and the universal beam self-induced plasma focusing that is charge-blind [9]. Plasma lenses based on this self-focusing effect would provide a focusing strength to high energy particle beams that is 3 to 4 orders of magnitude larger than that of the conventional focusing systems. The plasma focusing of high energy electron and positron beams has been experimentally verified as predicted [10]. For high energy colliders, there exist two challenging frontiers to be addressed. That is, the energy frontier and the luminosity frontier. The PWFA offers a solution to the former, while the plasma lens offers a solution to the latter.

In addition to the application to high energy physics, plasma wakefield principle has also been applied to addressing the challenging issues in other frontier fields of physics, such as astrophysics, cosmology, and gravity. In particular, it was proposed that plasma wakefields are responsible for the production of the observed ultra-high energy cosmic rays beyond 10^{20} eV [11]. Another exciting application is to accelerate laser-induced flying plasma mirrors as analog black holes in the laboratory to investigate the celebrated Hawking radiation and the associated black hole information loss paradox [12] (Fig.2). The international AnaBHEL (Analog Black Hole Evaporation via Lasers) Collaboration is currently pursuing such an experiment [13].

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Fig. 1: The particle beam driven Plasma Wakefield Accelerator (PWFA) is analogous to what happens in this photo. The mother duck exerts her energy to pump the water wakes, while the ducklings enjoy the free ride by sitting on the crest of the wake. In PWFA, a higher current charged particle beam injected into a plasma would excite the plasma wakefields, while a lower current beam trailing with a proper distance would pick up the energy and be accelerated.

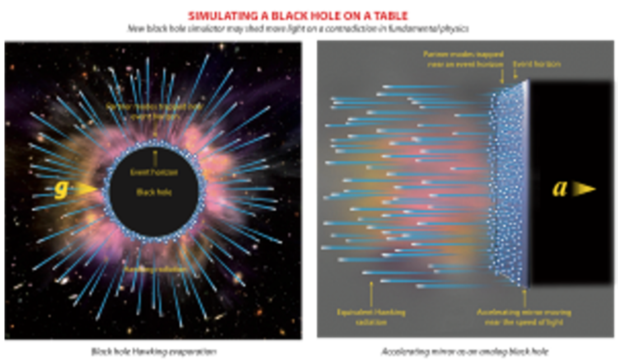

Fig. 2: Accelerating mirror as an analog black hole. Left: Black hole Hawking evaporation and the trapping of the partner modes near the horizon. Right: An accelerating mirror also has a horizon and can also emit Hawking particles and trap their partner modes. The analogy between these two systems may be appreciated via Einstein's equivalence principle.