Aug 31th, 2020

# 2021 snowmass Letter of Interest: Laser-driven acceleration mediated by metallic nanostructures

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Laser-driven acceleration of electrons has been strongly pursued in the last few decades as a possible avenue to access to GV/m-scale accelerating gradients, reducing the size and the cost of the next generation of particle accelerators. Different coupling mechanisms to obtain synchronous interaction of longitudinal accelerating field with a traveling electron beam starting from an inherently transverse electromagnetic mode of the laser have been proposed, namely laser-driven plasma wakefield acceleration (LWFA) in an ionization channel [1] and near-field acceleration via dielectric laser-driven acccelerator (DLA) structures [2]. Both methods have been successfully demonstrated to different degrees and are primary subjects of current research.

The use of metallic surfaces to achieve strong field enhancement at optical frequencies for electron acceleration has not received much attention early on, mostly because of the higher losses in the metals with respect to dielectric systems [3], limiting the use of high energy laser pulses and high average power. In particular the ability to run at very high repetition rate is a key feature of any acceleration mechanism based on optical near-field modulation which aims at applications in high energy physics and beyond. This is because the size of the acceleration bucket and the sub-wavelength extent of the acceleration region pose severe limitation on the amount of charge that can be accepted and loaded in these kind of accelerators.

Nevertheless, as a quick look at the burgeoning field of plasmonics can confirm, metals offer much stronger control of the electromagnetic field at the subwavelength scale due essentially to the much higher index of refraction available, they are not affected by characteristic dielectric problems such as non-linearities or beam charging. In addition, owing to the latest advancements in nanotechnology, imprinting of nanoscale structures on atomically flat metal surfaces [4] has become readily available (for example via Electron Beam Lithography or Focused-Ion-Beam techniques). The high degree of precision achieved in nanopatterning translates in the ability of engineering the electromagnetic field amplitude, phase and polarization profiles in space and time accurately [5], optimizing for field enhancement, polarization, particle acceleration and focusing, and phase matching. Finally, the increasing computing power enabled high fidelity time-dependent electromagnetic simulations of near-field profiles for broadband sources, which can be used in conjunction with machine learning or other optimization techniques to refine geometries and even find new ones. Hence, we feel the potential of this technology should be revisited.

Laser field impinging on nano-structured metallic surfaces can excite traveling waves confined at the metal-dielectric interface, called surface plasmon polaritons (SPP). Mediated by SPP, whose wavelength can be much shorter than that of the excitation pulse, the optical field energy can be transported and concentrated in areas of sub-wavelength size, leading to large local field enhancement.

Realization of SPP nano-cavities has been experimentally demonstrated to generate very large field enhancements [6]. Here the nanostructure is acting as a high-Q Fabry-Perot resonator for the SPP waves [7], matching the speed of the (slow) surface plasmon along the surface of the structure with the incident laser wavelength. The optical energy is efficiently stored in the cavity, relaxing the requirements on laser energy. On the other hand, the strong local power density may result in damage of the structure and needs to be further investigated.

An alternative path is to make use of non-resonant structures[8][9], a similar approach to the one followed by the DLA community [10]. The intrinsically low quality-factor Q of the geometry results in lower field enhancement, but also decreases the energy density stored locally and, therefore, the potential for structure damage. In this configuration SPP waves travel along the surface until they are either absorbed by the surface through electron scattering or are radiated into the vacuum through surface defects. Interference between traveling SPP can also be exploited to generate large field enhancements in specific areas of the structure, not necessarily spatially coincident with a nanoscale feature. In particular, high intensity fields, or "hot-spots" can be generated in the vacancies between the nano-structures, thus reducing the potential for structural damage [9]. The nanopatterned superstructure, also called "metasurface", composed by all the single nanopatterns along the surface, is used to obtain constructive interference of SPP waves launched at different positions and/or times, resulting in large field-enhancement factors [4], while at the same time avoiding local energy confinement leading to damage.

Metasurface-Laser-Acceleration (MLA) holds the promise for large gradients in excess of 1GV/m, with modest requirements in terms of laser energy and high wall-plug efficiency [8]. Key advantages in the quest for the next acceleration technology include the high field enhancement factor and consequent relaxed requirements on laser systems, the large number of degrees of freedom for tuning field amplitude and phase in time and space, and the availability of reliable and high precision instrumentation for nanofabrication on plasmonic material. A plasmonic-based accelerator working at MHz repetition rate would be able to reach luminosity values of interest for high energy physics applications. These advantages make MLA technology competitive with other high gradient acceleration techniques.

**References**

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