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NANOPLASMONIC ACCELERATORS TOWARDS TENS OF TERAVOLTS PER METER GRADIENTS USING NANOMATERIALS [*]

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Abstract

Ultra-high gradients which are critical for future advances in high-energy physics, have so far relied on plasma and dielectric accelerating structures. While bulk crystals were predicted to offer unparalleled TV/m gradients that are at least two orders of magnitude higher than gaseous plasmas, crystal-based acceleration has not been realized in practice. We have developed the concept of nanoplasmonic crunch-in surface modes which utilizes the tunability of collective oscillations in nanomaterials to open up unprecedented tens of TV/m gradients. Particle beams interacting with nanomaterials that have vacuum-like core regions, experience minimal disruptive effects such as filamentation and collisions, while the beam driven crunch-in modes sustain tens of TV/m gradients. Moreover, as the effective apertures for transverse and longitudinal crunch-in wakes are different, the limitation of traditional scaling of structure wakefields to smaller dimensions is significantly relaxed. The SLAC FACET-II experiment of the nano^{2}WA collaboration will utilize ultra-short, high-current electron beams to excite nonlinear plasmonic modes and demonstrate this possibility.

NANOPLASMONIC ACCELERATOR

The quest for using crystals to access many TeraVolts per meter (TV/m) acceleration gradients was set forth in 1968 by experimental nuclear physicist and Nobel laureate, R. Hofstadter [1]. It was hypothesized that single-atom excited states across the length of the ionic lattice of a crystal would upon stimulation individually transfer their energy and accelerate the interacting particles. In 1980s, this quest was revived in theory using the mechanism of channeling of particles between the planes of a metallic lattice [2]. However, given several fundamental limitations such as uncontrolled energy loss and emittance growth due to beam collision with the ionic-lattice besides complete disruption of the beam due to filamentation, hosing etc., crystal-based acceleration has remained unrealizable in practice.

Consequently, over the past few decades great strides have been made towards tens of GV/m gradients using significantly different media of plasmas [3] and dielectrics [4], although these gradients are well below a TV/m.

Our work [5–8] has introduced and demonstrated a new concept on using plasmonic modes [9] in nanomaterials for experimental realizability of unprecedented tens of TV/m electromagnetic (EM) fields. This new mechanism can overcome several fundamental limitations and thereby holds the promise to open up an entirely new extreme field frontier. Specifically, a new class of nonlinear surface plasmons [10] in the crunch-in regime wherein the oscillating surface electrons collectively cross over in to the core vacuum region (as shown in Fig.1) are excited in nanomaterials [11–13] that have tunable structural and material properties.

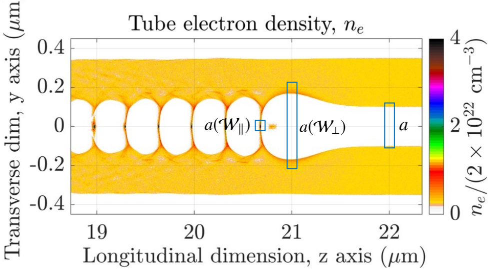

Figure 1: Electron density profile of the crunch-in surface plasmonic mode. These collisionless modes of oscillations of the Fermi electron gas (EG) in a tube (radius, r_t = 100 nm, wall EG density, $n_t = 2\times10^{22}$ cm^{-3}) are modeled using 3D Particle-In-Cell (PIC) simulations (details in [5]). The beam (see below) that excites this mode has a peak beam density, $n_{b0} = 5\times10^{21}$ cm^{-3}, waist-size σ_r = 250 nm ($\sigma_r = 2.5\times r_t$), bunch length σ_z = 400 nm.

Both the particle bunches (or clusters within a bunch), the one that excites the nonlinear surface plasmons with TV/m fields and the one that undergoes acceleration by extracting the plasmon field energy, propagate in the vacuum-like core region of nanomaterials such as tubes. This mitigates the limitations that arise due to collisions and defects in bulk crystals. Most importantly, in complete contrast with known surface waves the crunch-in process is the key to obtain strong electrostatic fields in surface waves which access the coherence or wavebreaking field limit [14].

Comparison with Plasmas and Dielectrics

Plasmonics is by itself an active and well established field, however, in the context of physics of extreme fields it can be specifically differentiated from existing mechanisms of plasma and dielectric wakefields. Plasmonics relies on collective oscillations of Fermi electron gas (EG) that envelopes an ionic lattice at equilibrium, whereas plasma modes are excited in gasses whose atoms have to be first stripped off their outer electrons. Secondly, dielectric modes are driven in media by polarization of bound electrons (insulators) in contrast with collective modes of the free EG (metals, semimetals or semiconductors) underlying plasmons.

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CRUNCH-IN VS. CONVENTIONAL SURFACE MODES

The crunch-in surface plasmonic modes can be better understood against the background of known modes of surface electron oscillations that sustain EM waves. While surface electron oscillations commonly sustain EM modes in metallic RF cavities and beam or laser driven dielectric wakefields, these oscillations are well below the plasma frequency, $\omega_{\rm pe} = \left(4\pi {\rm n_0 e^2/m_e}\right)^{1/2}$ and therefore, cannot attain wavebreaking fields, $\rm E_{wb} = m_e\omega_{pe}c/e$. But, with its surface oscillations at $\omega_{\rm pe}$ the hollow-channel plasma wakefield mode is of direct relevance.

Beam-driven hollow-channel plasma wakefields [15] were shown to have certain favorable properties for acceleration and transport of charged particle beams compared to homogeneous gasses. These characteristics are:

(i) *Zero focusing fields* sustained by hollow-channel plasma wakefields (for emittance preservation) [15].
(ii) The accelerating fields are *purely electromagnetic*, because (a) they are the leakage (fringe) fields of the wall electron currents and, (b) surface electron perturbations are negligible compared to the channel radius [16].

Experiments on positron-beam driven hollow-channel plasma wakefield [17] have confirmed these characteristics by verifying zero focusing fields with peak gradient of around 220 $\rm MVm^{-1}$ ($\sim$ 0.01 $\rm E_{wb}$).

However, hollow-channel plasma wakefields have certain basic physics challenges such as deflecting fields [18] and beam break-up instability [16] apart from technological difficulties in the formation of a hollow structures in gasses.

Crunch-in Surface Modes

Apart from benefitting from nano-scale structured materials, there are several prominently desirable and defining characteristics specific to the crunch-in mode [12, 13]:

(i) *Strong focusing fields* in the walls and on the axis (on-axis wall electron accumulation phase favors positrons).
(ii) The longitudinal fields along the channel axis are *strongly electrostatic* and they approach $\rm E_{wb}$.

In the crunch-in mode irrespective of the charge [11] of the drive beam, compression of entire population of wall electrons and their oscillation as they crunch into the core leads to the excitation of predominantly electrostatic longitudinal and focusing fields (in Fig.2).

Being strongly electrostatic due to large-scale charge accumulation inside the core, crunch-in fields approach the wave-breaking limit, $\rm E_{wb}$ of the wall electron density.

It is to be noted that the crunch-in fields although sustained by a surface mode, are capable of focusing the beam. So, parametric dependence of conventional (transverse magnetic, TM) surface modes do not directly apply.

Nevertheless, when the relation between the cavity radius "a" and the amplitude of conventional surface wakes, transverse: $\mathcal{W}_\perp \propto a^{-3}$ and longitudinal: $\mathcal{W}_\parallel \propto a^{-2}$, accounts for the dynamic nature of the effective aperture (in Fig.1) of the crunch-in modes, $a(\mathcal{W}_\parallel) \ll a(\mathcal{W}_\perp)$ and $a(\mathcal{W}_\parallel) \rightarrow 0$ significant advantages become evident.

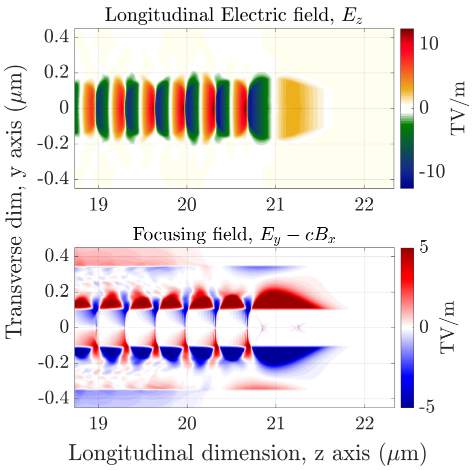

Figure 2: Longitudinal and focusing fields of the crunch-in surface plasmonic mode from the compression and crunching in of the EG into the core region (parameters of Fig.1).

EXPERIMENTAL DEMONSTRATION

In this section we briefly discuss the experimental plan of the nano^{2}WA collaboration to demonstrate nanoplasmonic accelerator and light-source using the beam at SLAC FACET-II facility. The layout of our experiment using the "picnic-basket chamber" is outlined in Fig.3.

FACET-II Beam Parameters

Table 1: FACET-II 10GeV Electron Beam Parameters

Parameter	**KPP** sec.4.3 of [19]	**simulated** sec.4.9 of [19]
Bunch charge	2 nC	2 nC
Norm. emittance	20 µm-rad	3.75 µm-rad
Bunch length	20 µm	3.1 µm

The key performance parameters (KPP) of the 10 GeV electron beam according to the FACET-II technical design report (TDR) [19] are in Table 1. The peak bunch density with KPP is $\rm n_{b0}[KPP] \simeq 10^{17}\ cm^{-3}$ (Gaussian approximation) and from simulated parameters in sec. 4.9 of [19] it is $\rm n_{b0}[simulated] \simeq 1.8 \times 10^{19}\ cm^{-3}$.

Moreover, FACET-II conceptual DR (sec. 3) [20] models the use of permanent magnet quadrupole triplets (PMQ-T) to focus the beam waist to less than 500 nm. Furthermore, simulations of sub-micron bunch compression [21] have reported bunch lengths as short as $\sim$ 400 nm (non-Gaussian profiles). Using above sub-micron level focusing and compression, the achievable $\rm n_{b0}$ is around $\simeq 5 \times 10^{21}\ cm^{-3}$.

The crunch-in regime utilizes tunneling of the Fermi EG across the surface. The Fowler-Nordheim tunneling field threshold which is around a GV/m, is just within the reach of objective KPP beam parameters. But, the radial fields of the simulated KPP and the sub-micron beams can readily excite tunneling and thereby the crunch-in regime.

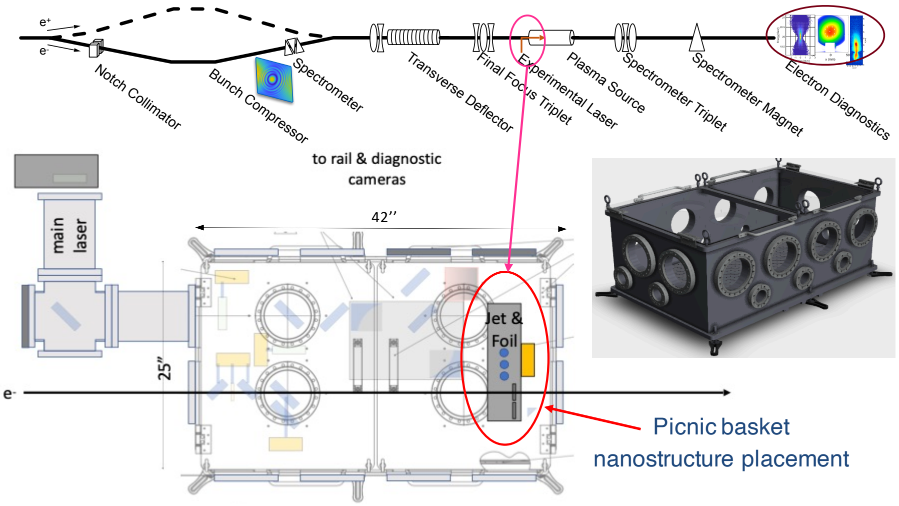

Figure 3: Layout of the nano^{2}WA experiment using the FACET-II experimental area design [22].

Nanomaterial Samples

The 3D PIC based proof of principle [5] is modeled in a single tube to effectively utilize computational resources while also elucidating the details. With the beam waist-size (σ_r) much larger than the tube radius (r_t), $\sigma_r = 2.5 \times r_t$, this model is in the "flat-top beam" limit (a nearly flat radial profile within the tube core). Therefore, this model applies to a wide beam overlapping with an array of tubes.

The nanomaterial sample can thus be a bundle of many thousands of tubes where each tube has an overall width (wall and core) of around a micron, resulting in a centimeter-scale wide macroscopic sample. A train of such finite length samples will make the length variable. Apart from mechanical stability, such a macroscopic sample will allow translation to a fresh region of the sample, in case of damage.

For sub-10^{19} cm^{-3} beams: Semi-metal based nanomaterials that have been characterized to have 10^{18-19} cm^{-3} free carrier densities are suitable for sub-10^{19} cm^{-3} beams. For instance, rolled up graphitic layers and fullerene tubules are well known semi-metals. In such semi-metals the beam to Fermi EG density ratio, n_b/n_t [5] is comparable making the crunch-in regime accessible.

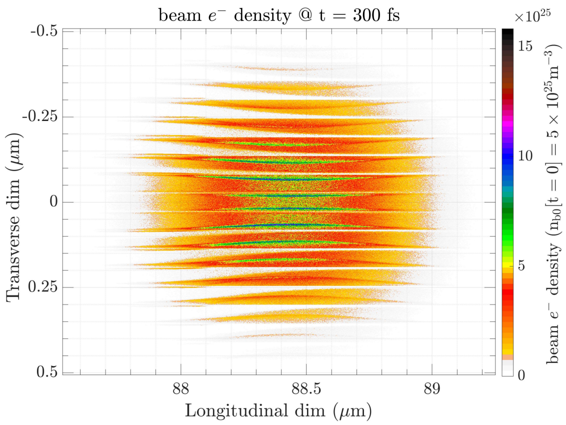

Figure 4: Focusing of a $n_{b0} = 5 \times 10^{19}$ cm^{-3} beam in a tube array (2.5D PIC) with core size of $r_t = 20$ nm and a few nm wall thickness with $n_t = 2 \times 10^{22}$ cm^{-3}.

For ≥ 10^{19} cm^{-3} beams: Nanoporous metals with variable filling fraction deposited on the inside surface of micro fibers or other nanomaterials are usable with ≥ 10^{19} cm^{-3} beams. The self-focusing effect demonstrated in [5], allows beams even with densities around 0.01 times the apparent wall electron density to excite high amplitude crunch-in mode and access tens of TV/m gradient.

Near-term Experiments

Our near-term experiments will focus on the primary effect of the beam on nanomaterials as well as the effect of the plasmonic modes on the beam. Ion-wake [13] and understanding of relaxation of the plasmonic oscillations as they couple to the phonon and other ion modes is being modeled. The effect of the beam driven plasmonic modes in an array of tubes on the beam itself have been modeled using 2.5D PIC simulations with setup as detailed in [6].

The results of the beam undergoing focusing inside the core region of the tube are shown in Fig.4. The beam focusses inside the vacuum-like core region and therefore (i) this is in contrast with the conventional surface modes only sustaining deflecting fields and (ii) this is not filamentation.

Bending of the beam in crunch-in focusing fields: Lastly, in 2.5D simulations we observe using the parameters in Fig.4 that when the beam has tens of milli-radians of angular misalignment relative to the tube core axis, the crunch-in fields bend the beam to align it with the axis.

DISCUSSION

Our TeraVolts per meter nanoplasmonics initiative promises to open a new extreme field frontier with far-reaching application including nanoplasmonic accelerators, light-sources, nonlinear quantum electro-dynamics (QED) tests and so on. The nano^{2}WA collaboration shall experimentally demonstrate TV/m nanoplasmonics at the FACET-II user facility and pursue its unprecedented applications.

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