QUANTUM ACCELERATOR & WIGGLER USING EXTREME PLASMONS EXCITED IN NANOFABRICATED MATERIALS: E-339 AT SLAC*

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Abstract

Extreme plasmons that are nonperturbative excitations of quantum electron gas inherent in conductive, nanofabricated materials, open unprecedented PetaVolts per meter fields. PV/m fields enable concepts such as a collider on a chip, nano-wiggler based gamma-ray lasers, opening the vacuum using high-field polarizability etc.

This technique that relies on emergent properties of the conduction electrons is being prototyped as part of our experimental program using E339 at SLAC. In experiments, we controllably excite extreme plasmons that not only access large fields but also preserve the material structure from irreversible damage, making a quantum accelerator and PV/m plasmonics realizable. Numerous unexplored aspects of quantum dynamics underlying large-amplitude, collective oscillations of the quantum electron gas work in unison to allow access to quantum coherence limit, $E_Q = 0.1\sqrt{n_0[10^{24}\text{cm}^{-3}]}\ \text{PVm}^{-1}$, where n_0 is tunable using techniques in material science.

Here we present the experimental design and initial results that indicate the excitation of ten GV/m fields and material resilience over thousands of shots upon careful tuning of appropriately structured, doped semiconductors. A semiconductor tube that is closely matched and configured to collisionlessly interact with FACET-II beams sustains surface crunch-in plasmons critical for stable excitation as well as tunability that paves the way to significantly higher fields.

INTRODUCTION

Beam-matter interactions, particularly with high-intensity beams are well established to cause complete and irreversible damage to materials within a few shots primarily due to resistive or Ohmic heating [1, 2]. This has made it futile to explore beam-material interaction techniques.

Our experiment E-339 at the SLAC national lab titled *PetaVolts per meter plasmonics using engineered materials* has demonstrated a novel pathway to damage-free interactions. High-intensity particle beams directly interact with condensed matter systems that are specially fabricated with appropriately tuned electronic and ionic properties of materials to sustain extreme plasmons [3, 4]. This is observed in Fig. 1 where synthesized Si tubes remain undamaged after thousands of shots whereas Al tubes are damaged in a few.

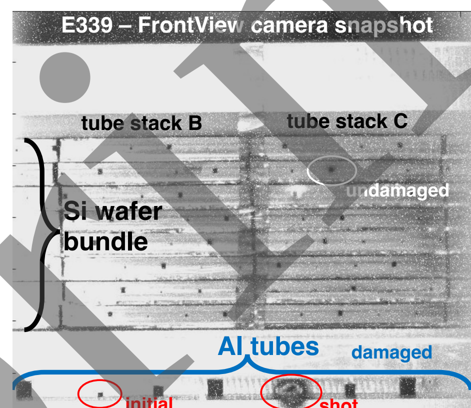

Figure 1: Front-view image of the plasmonic tube stack of E339 that is one of more than 10,000 continuous shots.

These observations are in stark contrast with many decades of experimental data [4]. The underlying physics is based upon controlled excitation of extreme plasmons. These plasmons rely on emergent behavior of ultradense quantum gas of conduction electrons undergoing coherent, collective oscillations. Specifically, thermal damage is mitigated by relativistically induced ballistic electron transport that is non-Ohmic. This transport is almost collisionless and is enabled by a combination of specialized materials, ultrashort excitation timescales, etc., put forth in [5].

As opposed to native metals such as Copper and Aluminum traditionally employed in accelerators, our work opens novel possibilities using artificially fabricated materials. Fabricated materials allow carefully synthesized ionic lattices and density controlled quantum electron gas of conduction electrons to uncover phenomena not possible with native materials.

Fundamentally distinct phenomena driven by extreme plasmons [5] that enable damage-less interactions have also recently led to observations that indicate ten GV/m field driven, high-gradient particle acceleration and gamma-ray production through excitation of extreme plasmons with currently accessible beams. This establishes *quantum accelerator & wiggler* on sound experimental footing with favorable scaling for shorter, more intense bunches a trend in accelerator physics.

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In our experiments, such plasmons are excited in tubes with walls made of nanofabricated, conductive materials, by ultra-relativistic, few nC electron beams of few tens of μm overall dimensions of the FACET-II facility at SLAC, typically with $Q_b = 2.1$nC, $\sigma_z = 30$μm and $\sigma_r = 30$μm.

The ability of nanofabricated materials to sustain extreme plasmons that have scaling laws that allow access up to PV/m fields opens transformative possibilities for the electromagnetic field frontier [6] that is critical for several research areas in addition to high-energy physics.

EXTREME PLASMONS

Plasmons have been typically studied under perturbative excitation of the quantum gas of conduction electrons. Extreme plasmons are large-amplitude, non-perturbative coherent oscillations of this ultradense, nearly *ideal Fermi gas*. The amplitude of collective oscillation (density, $n_0 \simeq 10^{24}\text{cm}^{-3}$) is constrained by the breakdown in their mutual coherence that also limits the maximum electric fields (one-dimensional oscillations) to,

$$E_Q \simeq 0.1\ \mathscr{F}_Q(\vec{k},\vec{p})\ \sqrt{n_0[10^{24}\text{cm}^{-3}]}\ \text{PVm}^{-1}, \qquad (1)$$

where, $\mathscr{F}_Q$ is the quantum factor (to simplify many-body excited states of the quantum system [3]) dependent on collective density wavevector, $\vec{k}$ and momentum profile, $\vec{p}$.

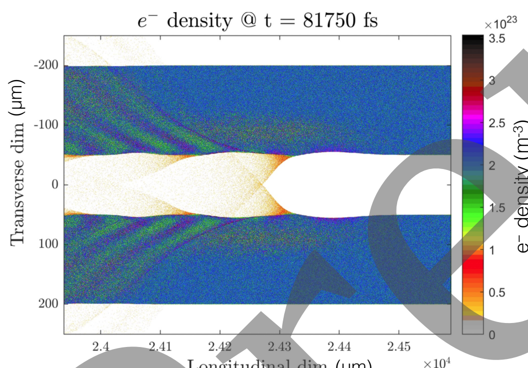

Figure 2: Simulation snapshot (after ≃24mm of interaction) showing conduction electron density of crunch-in plasmon excited in a doped Silicon tube by an electron bunch with about 1.5nC charge, 30-micron overall dimensions.

In consideration of factors underpinning realizability of the field in Eq. (1) as detailed in [3, 5, 7], *surface crunch-in plasmon* excited in a tube has been identified as suitable for sustained beam-material interaction. The electron density profile supporting this plasmon excited by an electron beam with FACET-II parameters is shown in Fig. 2. Radially oscillating conduction electrons crunch into the tube allowing strongly electrostatic accelerating as well as focusing fields.

This strongly electrostatic nature observed from simulations allows the crunch-in plasmons to attain the quantum coherence field limits. In these specific simulations, the tube is modeled to be made of doped Silicon (Si) with initial carrier concentration, $n_0 \simeq 10^{17}\text{cm}^{-3}$ comparable to the beam density of around $n_b \simeq 2 \times 10^{16}\text{cm}^{-3}$. The fields predicted for these conduction electron densities , $n_0 \simeq 10^{17}\text{cm}^{-3}$ from Eq. (1) are about 30 GV/m. However, as the simulations are carried out with realistic beams that have a minimum spot-size of about 35μm and square tubes with side of 100μm, the predicted plasmonic accelerating and focusing fields are around 20GV/m.

When collisionlessly excited to large amplitudes by intense particle bunches, collective dynamics of ultradense electrons manifests emergent phenomena. Specifically, the far-from-equilibrium dynamics driven by many-body interaction of the electrons initially at the Fermi level uncovers new phenomena due to emergence [5, 7, 8]:

1. *Relativistically induced ballistic transport* enables collisionless dissipation of collectively excited electrons. When conduction electrons attain relativistic velocities, their mean free paths get correspondingly longer. Even upon decoherence
2. *Conduction-band density tuning to optimize plasmon excitation* such that the bunch properties are matched to allow maximum energy transfer and minimize excitation of the ionic lattice.
3. *Strong oscillations across material-vacuum interface* due to large-amplitude, ultrashort limit of Fowler-Nordheim tunneling effect that enables focusing forces.
4. *Peak fields sustained by materials observed to 10s of GV/m* in contrast with the constrain of around 100 MV/m when excited by radiofrequency pulses.

Beam Excited Metallic and Dielectric Media

Resistive wake (RW) [9] is a good model to estimate fields (decelerating and defocusing) excited behind a charged particle bunch in tubes with metallic conductivities, $\sigma_m \simeq 10^7\text{Sm}^{-1}$ that are inversely proportional to conductivity: $E^{RW} \propto 1/\sqrt{\sigma_m}$. The RW model is not applicable to fabricated materials with synthesized lattices that allow controlled conductivities: $\sigma_{nanofab}/\sigma_m \ll 1$, as the estimates of the RW model blow up. Specifically, for E-339 samples with $\sigma_{nanofab} \simeq O(10)\text{Sm}^{-1}$, RW model estimates the transverse kick to be 800m after 4cm of interaction with a plasmonic tube with 50μm radius. This contradicts experimental observations. So, RW model that is collision-dominated is not applicable to extreme plasmons.

Dielectric ($\text{Re}(\epsilon_r) > 0$) wakes [10] are excited in insulator tubes of conduction electron free walls, with conductivity, $\sigma_d = 0$ and $\text{Im}(\epsilon_r) = 0$. With $\sigma_d = 0$, beam-field penetration is large. Cherenkov radiation is produced by significantly overlapping fields of the beam propagating at speed exceeding the phase velocity of electromagnetic wave, $v_b > c/\sqrt{\epsilon_r}$. However, in a plasmonic media with conduction-band electron density at equilibrium, the beam fields are shielded from interaction with the media in addition to a large attenuation coefficient disallowing propagation [8]. Furthermore, as plasmonic tubes do not have a confining metal scalding, even if Cherenkov radiation is produced it cannot possess an accelerating field per Lawson-Woodward theorem.

E-339 EXPERIMENTAL SETUP

E339 is setup in the so-called picnic-basket (PB) vacuum chamber that is located at the interaction point (IP) experimental area of the FACET-II beamline just downstream of the final-focus triplet magnet as shown in Fig. 3. Being located close to the final focus allows the plasmonic samples to interact with a tightly focused beam before it diverges.

Plasmonic tubes, an array of which have been engineered in appropriately doped semiconductor sample (conductive media samples, in general) are brought into the path of the beam using a computer-controlled stage and made to collisionlessly interact with the beam inside the picnic basket chamber. Different plasmonic tubes with square cross-sections of sides measuring 200, 100 and 75 micron have been setup. These tubes are fabricated in Phosphorus-doped, n-type Silicon with free electron Fermi gas density of 10^{17}cm^{-3}.

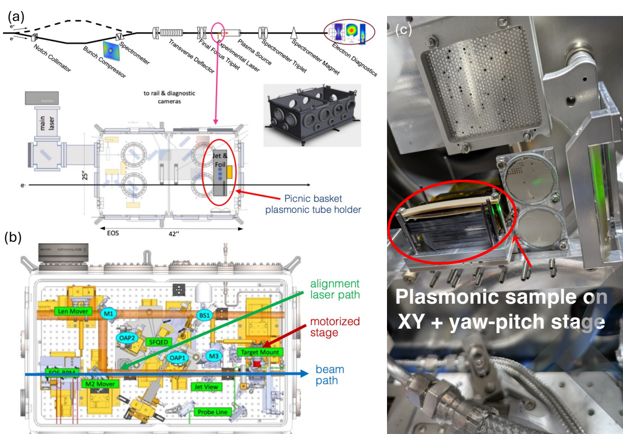

Figure 3: Experimental design of E-339 at SLAC: (a) a high-level diagram showing the relative placement of the PB chamber and the location of plasmonic samples. (b) a close-up of the picnic-basket chamber. (c) plasmonic stack integrated into the vacuum-chamber.

Alignment of these tubes to the beam vector is achieved in two stages. A HeNe laser gets moved and aligned to the beam vector. The symmetry and brightness of the diffraction pattern formed by the HeNe laser exit mode out of plasmonic tubes is used. The first stage of alignment is conducted during the planned tunnel access with PB chamber open. This allows direct optical access to the E-339 sample and HeNe laser for coarse alignment. The second stage is with closed and vacuumed-down PB chamber from the control room after HeNe and e-beam have been aligned. Second stage involves remote fine adjustments of the XY and pitch-yaw stage by monitoring the exit mode.

Under tube alignment and a two-bunch configuration, we have observed $\simeq$ 0.3-0.5 GeV energy gain of FACET-II electron beam (trailing bunch) in just 40mm-long plasmonic tube. This provides the first indications of unprecedented excitation of 10GV/m fields of extreme plasmons in synthesized materials. Furthermore, the signatures of the accelerated bunch exiting at different angles as well as gamma-ray production demonstrate the presence of strong focusing fields of the order of 10GV/m. These unprecedented observations of E-339 open pathways to fields as high as PVm^{-1} that are not accessible using other techniques.

CONCLUSION

While extreme plasmons have remained unexplored, E-339 at SLAC is pioneering studies of their underlying physics using the intense, ultrashort beams accessible at the FACET-II facility. The facts that were put forth in the theoretical model of nanoplasmonic accelerator and wiggler in 2020 have been experimentally validated since the first experimental shots were taken in November 2024. The ongoing campaigns using upcoming beamtime allocations hold the potential to transform the *electromagnetic field frontier*. A quantum accelerator and wiggler will not only open new pathways in accelerator physics but also in high-energy physics and photon sciences.

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