

Plasmonic accelerators for colliders with PetaVolts per meter gradients

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Plasmonic acceleration offers the potential to achieve PetaVolts per meter fields, that would transform the current paradigm in collider development in addition to non-collider explorations in fundamental physics. Plasmonic accelerators rely on collective oscillations of the free electron Fermi gas inherent in the conduction band of materials with a suitable combination of constituent atoms and ionic lattice structure. As the conduction band free electron density can be as high as 10^{22-24}cm^{-3} , plasmonic acceleration gradients can be of the order of $10\sqrt{n_0(10^{22}\text{cm}^{-3})}$ TVm⁻¹. Engineered materials not only allow highly tunable material properties but quite critically make it possible to overcome disruptive instabilities that dominate the interactions in bulk media. Due to rapid shielding by the free electron Fermi gas, dielectric effects are strongly suppressed. Because the ionic lattice, the corresponding electronic energy bands and the free electron gas are governed by quantum mechanical effects, comparisons with plasmas are merely notional. Based on this framework, it is critical to address various challenges that include stable excitation of plasmonic modes while accounting for their effects on the ionic lattice and the electronic energy band structure over femtosecond timescales. We summarize the ongoing theoretical and experimental efforts as well as map out strategies for the future. Plasmonic colliders can shape the future by bringing high energy physics at the tens of TeV to multi-PeV center-of-mass-energies within reach. In view of this promise, we invite the scientific community to help realize the immense potential of plasmonic accelerators and call for significant expansion of the US and international R&D program.

I. Grand challenge of ultra-high gradient acceleration

Our initiative on **plasmonic accelerators based future colliders** [[Plasmonic IEEE](#), [Plasmonic SPIE](#)], comes at a time and in the context of reinforced commitment by the worldwide high-energy physics (HEP) community to support basic research and development (R&D) on high gradient accelerators in recognition of their critical need for future colliders as well as fundamental discoveries, in general.

As radiofrequency (RF) acceleration technology has been a reliable workhorse of HEP since 1960s, it has undergone continual improvements and redesigns to optimize its size and economic viability. But, it has become apparent over the past several decades that this legacy technology has inherent limits on attainable energy in a practical layout for future colliders. The lack of its scalability is because the highest electromagnetic fields that RF cavities can support are limited to 100 MV/m. This limit on attainable electromagnetic fields and the acceleration gradient dictates that the only way forward in particle physics is to increase the infrastructure size and as a consequence the cost. Moreover,

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this limit on gradients for both acceleration and focusing severely limit the possibilities for exploration across the Energy, Intensity and Cosmic frontiers.

Consequently, past and ongoing strategic planning processes around the world have recognized the critical need for advanced accelerator R&D as summarized below (extracts from a few prominent reports are cited):

1. **2014 Particle Physics Prioritization Planning Panel (P5) report [P5 report]**: *“Recommendation 26: Pursue accelerator R&D ... with an appropriate balance among general R&D, directed R&D, and accelerator test facilities and among short-, medium-, and long-term efforts. Focus on outcomes and capabilities that will dramatically improve cost effectiveness for mid-term and far-term accelerators”*,
2. **2020 Update for European strategy for particle physics [EU HEP strategy report]**: *“3. High-priority future initiatives: A. the particle physics community should ramp up its R&D effort focused on advanced accelerator technologies...”*,
3. **2015 HEP Advisory Panel (HEPAP) sub-panel on accelerator R&D [HEPAP Acc sub-panel report]**: *“Long-term: Perform the exploratory research aimed at developing new concepts that will make possible the complementary accelerator facilities of possible science interest after the Next Step” and “R&D that provides higher performance at lower cost should be more heavily emphasized in the definition of the R&D programs.”*

This contribution to the proceedings of the US Community Study on the Future of Particle Physics or Snowmass 2021 process is aimed at bringing to the attention of the worldwide HEP community and the accelerator community, in particular, our initiative on a **plasmonic accelerator** and its potential to open access to **PetaVolts per meter** electromagnetic fields. Our work focusses on utilizing the promise of access to PV/m plasmonic fields for acceleration and focusing of particle beams.

We also highlight the strong alignment of **technological trends** towards micron and sub-micron level charged particle beam compression and diagnostic techniques with the PetaVolts per meter nano-plasmonics initiative [**CU Patent**] for future colliders and exploratory basic science and technology, in general.

II. Scope and structure

The scope of our work encompasses high gradient acceleration mechanisms that utilize the unique properties of condensed matter materials with periodic ionic lattice such as certain crystals and nanomaterials. Particularly, of importance are those properties that stem from the structure of the **ionic lattice** which inevitably gives rise to **electronic energy bands**.

Our scope is limited to mechanisms where there exists a strongly correlated ionic lattice and corresponding electronic energy bands. Under these conditions, quantum mechanical effects dominate. Specifically, our effort focusses on acceleration and focusing gradients as high as PetaVolts per meter that can be sustained by plasmonic modes of collective oscillations of the free electron Fermi gas [**Plasmonic modes**] inherent in conducting materials.

The scope of our work DOES NOT include:

- a. **Solid-state plasmas**: In solid-state plasmas the individual ions are uncorrelated as there is no ionic lattice. Solid-state plasmas are obtained by ablation of solids such as by interacting the solid with a high-intensity optical (near-infrared) laser. These plasmas have been experimentally studied in the past for laser-plasma ion acceleration in addition to being proposed for schemes such as channeling or solid-state plasma acceleration to guide and accelerate positively charged particles [**Channeling collider**].
- b. **Dielectric or insulating solids**: Dielectric or insulating materials have near zero electron density in the conduction band. The excitation of dielectrics relies on polarization of ionic sites which effectively generates high frequency electromagnetic radiation. It has been experimentally demonstrated that when free electrons are driven by high electromagnetic fields to transition into the conduction band of a dielectric material, the electromagnetic wave is rapidly shielded which puts an end to dielectric acceleration [**Dielectric strong damping**].

While the existing parallel efforts on R&D of plasma and dielectric accelerators have been duly recognized and well supported by funding agencies, our effort being at an early stage calls out for special attention and investment by the HEP community.

In order to bring out the promise of this effort, while also identifying its challenges and mapping out strategies for the future, the following sections are structured as follows.

- **Sec.III** introduces the fundamentals of plasmonic accelerators and the ultrafast dynamics of free electron Fermi gas.

- Sec.IV (contributed by J. Stohr) summarizes the certain fascinating findings of a past experiment that specifically studied the interaction of an ultrafast electron beam with conducting materials.
- Sec.V provides brief description of the plasmonic modes that enable acceleration and focusing of particle beams. The role of a strongly electrostatic surface plasmonic mode to mitigate well known disruptive effects of collision between particle beams and bulk materials is also briefly discussed.
- Sec.VI (contributed by G. White and G. Andonian), discusses novel techniques for extreme bunch compression, focusing and diagnostic for ultra-dense particle beams. This includes longitudinal compression towards $< 100\text{nm}$ bunch lengths and multi-MegaAmpere peak currents as well as focusing of the beam waists to the order of 100nm .
- Sec.VII (contributed by G. Mourou and T. Tajima) describes x-ray laser driven nanostructures which use the proposed high intensity keV-photon laser to drive carbon nanotubes.
- Sec.VIII, describes the challenges, possibilities and ongoing efforts to prototype plasmonic accelerators.
- Sec.IX, outlines a strategic plan for our future efforts.

III. Plasmonic accelerator fundamentals

Plasmonic accelerators [Plasmonic IEEE, Plasmonic SPIE] rely on the electronic energy band structure inherent in conducting materials due to an appropriate combination of suitable constituent atoms and ionic lattice structure. The electron energy band structure of conducting materials supports free electrons (electron not tied to any specific atoms) in the conduction band. In particular, electrons that occupy energies in the conduction band constitute a *free electron Fermi gas*.

The Fermi electron gas freely moves about the entire lattice. It is interesting to note that the free electron Fermi gas in conducting solids is the highest density collection of electrons that is accessible at a terrestrial lab. Upon external excitation, this electron gas undergoes collective oscillations [Plasmonic modes] and in the process excites collective fields which form the basis of the general field of plasmonics and plasmonic accelerators, in particular.

The strongly electrostatic surface plasmonic mode underlying a plasmonic accelerator which is sustained by relativistically oscillating Fermi electron gas is depicted in Fig.1 reproduced from [Plasmonic IEEE]. This figure is a snapshot in time of the evolving interaction between an electron beam (with its envelope at a given density in orange) and the free electron Fermi gas (darker colors representing a higher density) modeled using simulations that use the particle tracking approach to treat collisionless behavior of the conduction band free electron gas.

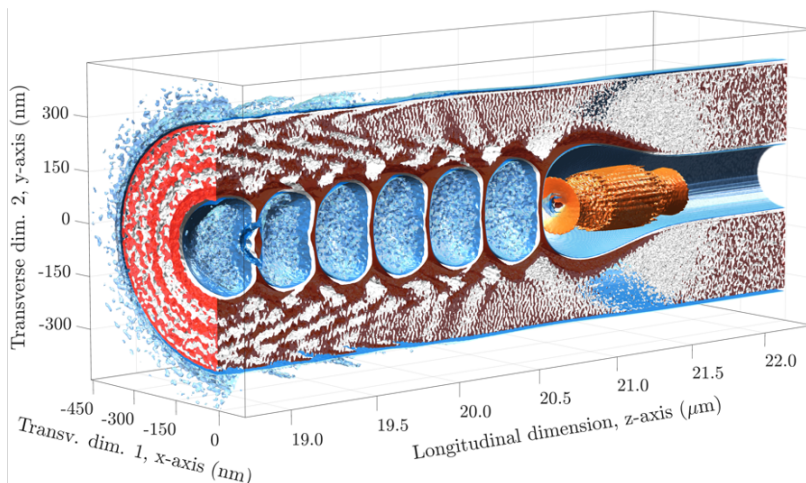


FIG. 1. Density profile of free electron Fermi gas of surface crunch-in plasmonic mode, reproduced from [Plasmonic IEEE], in a tube with equilibrium conduction band density, n_e in the tube walls of $n_t = 2 \times 10^{22}\text{cm}^{-3}$. The snapshot is at $20\mu\text{m}$ ($\sim 73\text{fs}$) of interaction of a $\sigma_z = 400\text{nm}$, $\sigma_r = 250\text{nm}$ beam with tube. The tube has a vacuum-like core of radius, $r_t = 100\text{nm}$ (nearly flat-top beam limit, $\sigma_r = 2.5 \times r_t$). The beam envelope (in orange) although initially larger than the tube has undergone self-focusing approaching ultra-solid densities.

The free electron Fermi gas is a quantum mechanical entity. The near-continuum energy levels that make up the conduction band and give rise to free electrons are entirely a consequence of two distinct quantum mechanical phenomena related to the electron wave-function in an ionic lattice:

- i. inter-atomic bonding due to orbital overlap of neighboring atoms, and
- ii. periodic potential exerted by the background lattice on electron wave-functions.

Due to their quantum mechanical origins and having a fixed energy (and dispersion relation), collective oscillations of free electron Fermi gas are treated as quasi-particles and labelled as plasmons.

Plasmonic accelerators rely on the excitation of the free electron Fermi gas by ultrafast sources with temporal duration that may perturb or distort the ionic lattice but cannot disrupt it. Modeling the transient modification of the ionic lattice and as consequence the electron energy band structure has been identified as a key challenge which is summarized in sec.VIII.

Over those timescales of interaction between a charged particle beam and the free electron Fermi gas, where the periodic ionic lattice structure and its corresponding quantum mechanical derivative of electronic energy band structure are still present, plasmonic processes are dominant and control the interaction. Especially because the free electron Fermi gas has the highest density and therefore (in accordance with Eq.1) the shortest response times to external excitations. Therefore, plasmonic processes are the fastest when considering electron dynamics.

Properties of plasmonic modes: As a consequence of the fact that the equilibrium density of free electron Fermi gas in conducting solids defines the limit of accessible electron density, its dynamics presents a unique set of properties.

The characteristic energy of a plasmonic quasi-particles depends only on the free electron density n_e in the conduction band of an ionic lattice, $\hbar\omega_{\text{plasmon}} (= 3.7\text{eV} \sqrt{n_e[10^{22}\text{cm}^{-3}]})$. For comparison, the photon energy of a near-IR optical ($\lambda_0 = 800\text{nm}$) laser is around 1.2eV.

The characteristic oscillation time of the free electron Fermi gas is,

$$2\pi\omega_{\text{plasmon}}^{-1}[\text{fs}] = 1.1 [n_e(10^{22}\text{cm}^{-3})]^{-1/2} \quad (1)$$

The characteristic spatial dimension or size of plasmons is dictated by their wavelength which depends upon the properties of the conducting condensed matter material that sustain them. The wavelength of plasmons is a function of the density (n_e) of the free electron Fermi gas in the conduction band,

$$\lambda_{\text{plasmon}}[\text{nm}] = 330 [n_e(10^{22}\text{cm}^{-3})]^{-1/2} \quad (2)$$

In a typical metallic nanostructure with conduction band electron density of 10^{22-24}cm^{-3} , the characteristic size of a plasmon (planar surface plasmon is longer) ranges from few hundred nanometers to a few nanometers.

If the free electron Fermi gas is undergoing relativistic oscillations with electron momentum of $\mathbf{p}_{\text{plasmon}}$ (and velocity, v_{plasmon}) approaching $m_e c$ as is the case in our work, then the time and spatial scales of plasmonic oscillations need to be modified (and elongated) by the average relativistic factor of electrons, $\gamma_{\text{plasmon}} = \sqrt{1 + \frac{\mathbf{p}^2}{m_e c^2}} = \frac{1}{\sqrt{1-\beta^2}}$, where $\beta = v_{\text{plasmon}}/c$, as follows:

$$\begin{aligned} 2\pi\omega_{\text{plasmon}}(\gamma_{\text{plasmon}})^{-1}[\text{fs}] &= 1.1 \sqrt{\gamma_{\text{plasmon}}} [n_e(10^{22}\text{cm}^{-3})]^{-1/2} \\ \lambda_{\text{plasmon}}(\gamma_{\text{plasmon}})[\text{nm}] &= 330 \sqrt{\gamma_{\text{plasmon}}} [n_e(10^{22}\text{cm}^{-3})]^{-1/2} \end{aligned} \quad (3)$$

Highly non-linear electron oscillations [**Dawson coherence limit**] of the electron gas approach the coherence limit of orderly collective electron oscillations which is defined in terms of the electric field amplitude that is sustained during oscillations. This coherence limit of the electric field is,

$$E_{\text{plasmon}}[\text{TV/m}] = 9.6 \sqrt{n_e(10^{22}\text{cm}^{-3})}. \quad (4)$$

While electric fields a few times the coherence limit are achievable, the electron oscillations become less orderly and coherent upon exceeding the limit in Eq.4.

Key enablers behind the emergence of plasmonic accelerators: There are two fundamental realizations that have enabled the emergence of ultra-high gradient plasmonic accelerator modules for a future collider:

- i. past experimental observation of the **absence of damage in conducting materials** for electron bunch lengths, $\sigma_{\parallel} \leq 10\mu\text{m}$ as summarized in section IV, and
- ii. **sub-micron bunch compression techniques** (discussed in sec.VI) that can match the spatial, Eq.2 and temporal, Eq.1 scales of plasmonic oscillations: (i) which can longitudinally compress the bunch through manipulation of the bunch phase-space correlations using magnetic lattices, (ii) bunch waist compression using permanent magnet quadrupole triplet systems.

In contrast with conducting media which have free electrons occupying the conduction band, insulators or dielectrics have near zero electron density in the conduction band. So, plasmonic modes can not be sustained in insulating materials.

Distinction from Dielectric or Insulating solids: (contributed by T. Katsouleas) Although there appear to be phenomenological similarities between the plasmonic modes in conducting media and the dielectric modes in an insulating dielectric because both are excited in a hollow solid tube, the physics of each is quite distinct.

Whereas plasmonic modes are supported by collective oscillations of free electron Fermi gas, dielectric modes are supported by polarization currents generated by the distortion of the electron cloud of ions in the lattice. Plasmonic oscillations are out of phase with the drive electric field while dielectric polarization currents are not. In dielectrics, polarization currents excite large amplitude Cherenkov radiation which supports the acceleration mechanism. In plasmonics, electrostatic plasmonic modes supported by large-scale charge separation between the free electron Fermi gas and ionic lattice sustain ultra-high gradients.

As a result the dispersion relation of each type of wave is quite different:

- $\omega = \omega_{\text{plasmon}}/\sqrt{2}$ for a plasmonic surface wave and
- $\omega = k c/n_{\text{dielec}}$ for a dielectric wave, where n_{dielec} is the index of refraction of the dielectric.

The resulting mode structure can be predicted from the intersection of the dispersion relations and the driver disturbance at $\omega = kv_b$ (where, v_b is the beam velocity) as in Fig.2a. From this we see that the surface plasmonic mode has but one wavenumber and frequency and gives rise to planar wave fronts and sinusoidal oscillations as seen in the cartoon of Fig.2b. On the other hand, the dielectric dispersion intersects the beam disturbance at the Cerenkov angle ($\cos(\theta_c) = 1/n_{\text{dielec}}$) at every ω and k . This supports the familiar Cerenkov cone type wavefront structure familiar in the wake of supersonic jets and illustrated in the cartoon in Fig.2c.

This shock-like cone propagates out to the outer conducting wall boundary of the dielectric whereupon it is reflected back toward the axis, giving rise to an accelerating spike on the axis as in Fig.2c. It is clear from this picture that these two modes differ considerably. In the first, the accelerating field is nominally sinusoidal (in the linear regime) and the location of the accelerating peak is controlled by the free electron Fermi gas density in the tube. In the second, the accelerating field is a single spike and its location is determined by the outer radius of the dielectric and the dielectric constant of the tube.

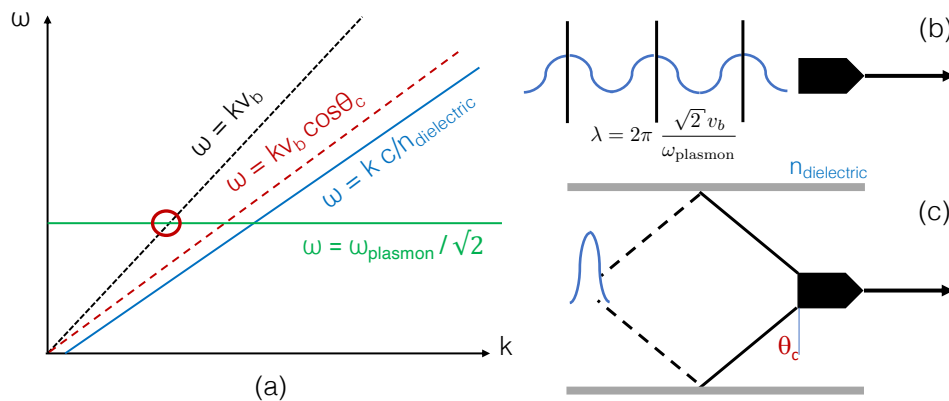


FIG. 2. Dispersion relation for surface plasmon and dielectric modes in (a) and their overlap with the drive particle bunch which determines the spatial and temporal profile, (b) of the surface plasmon mode, (c) of the dielectric mode.

Distinction from Plasmas: It is quite critical to note that our initiative does NOT deal with solid-state plasmas or gaseous plasmas. In solid-state plasmas, produced by ablation of solids the ionic lattice is completely disrupted with the constituent ions entirely losing their mutual correlations. By definition, solid-state plasmas therefore, do not have an energy band structure. Solid-state plasmas have been utilized for laser-plasma ion acceleration, but, due to their thermal characteristics may not be controllable for consistent properties desired from acceleration modules underlying a collider.

Due to highly randomized nature of ions in gaseous plasmas, the properties of plasma oscillations significantly diverge from that of plasmonic modes especially at solid densities. Using one simplified example, the characteristics of electron-electron collision with increase in the density of a gaseous plasmas are ineffectual for a **quantum mechanical electron gas** due to strict requirements set by the **Pauli exclusion principle**.

IV. Past ultrafast experiments with conducting materials

contributed by J. Stohr

A set of past experiments [Stohr FFTB 2003, Stohr FFTB 2009] that studied the interaction of conducting materials (Iron/ Cobalt alloys) with ultrafast electron beam of Final Focus Test Beam [FFTB bunch compression] at the Stanford linear accelerator center (SLAC) sets the precedent to answering several questions about plasmonic accelerator in addition to beam-driven plasmonics, in general.

The findings of these experiments are directly relevant and provide a strong experimental basis for the initiative on plasmonic accelerators. This is because these past experiments on ultrafast magnetic switching are also based upon femtosecond excitation [Stohr Springer series 2006] of metallic alloys that possess free electron Fermi gas.

Experiments conducted on ultrafast magnetic switching using the FFTB electron bunch at the SLAC laboratory observe fascinating phenomenon in a metal, namely **the lack of heating**, when the field strengths are increased well into the GV/m regime while the field pulses are shortened to less than 100 fs. These experiments studied the response of the same $\text{Co}_{70}\text{Fe}_{30}$ thin film samples of dimensions and geometry described in [Stohr FFTB 2003].

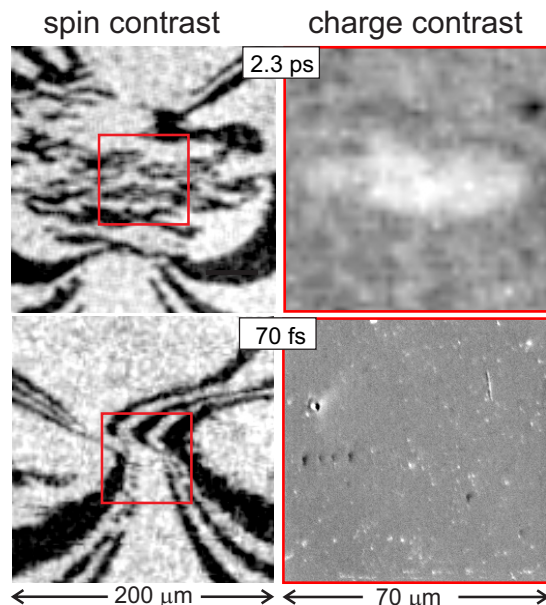


FIG. 3. A comparison of the sample images obtained with Scanning Electron Microscope (SEM) with spin polarization (SEMPA), on the left, and conventional SEM pictures of the structure, on the right, zooming in on the region where the beam hit. It is evident from this comparison that for the shorter electron pulses, $\sigma_{\parallel} \leq 100\text{fs}$ no topological deformation is seen.

Fig.3 a comparison of material damage for the two field pulses of different length and strength illustrated using spin sensitive transmission electron microscopy in Fig.3(a) and conventional transmission electron microscopy in Fig.3(b).

By examination of the magnetic patterns written into the ferromagnetic film by the fields of the electron bunch we find that only the longer electric fields of 2.3 ps and magnitude $\leq 0.6\text{GV/m}$ heat the sample above its Curie temperature of $T_C \leq 1200\text{K}$, while no such heating is observed for the shorter 70fs pulse with fields up to 20GV/m .

As in previous work the experiments were carried out using the Stanford Linear Accelerator and by use of a special electron bunch compressor the Gaussian shaped bunch length could be shortened from several picoseconds to below 100 femtoseconds. We used bunches with longitudinal Gaussian rms widths, σ_t of 2.3 ps and 70 fs, as indicated in Fig.3. As a result of relativistic field contraction, the fields are entirely parallel to the surface of the sample oriented perpendicular to the direction of bunch propagation. Our 10nm thick polycrystalline $\text{Co}_{70}\text{Fe}_{30}$ thin film sample with uniaxial in-plane magnetic anisotropy was deposited onto a 0.5 mm thick [110]-MgO substrate with intervening buffer layers consisting mainly of 30nm $\text{Cr}_{80}\text{Mg}_{20}$ and capped with a 1.5 nm thick layer of Pt to prevent corrosion.

The magnetic pattern written by the 2.3 ps pulse exhibits the formation of stripe domains along the horizontal easy axis which are characteristic for a sample that has been heated to a temperature above the Curie temperature $T_C = 1200\text{K}$ and then cooled in the absence of a magnetic field. In addition, conventional SEM images revealed non-magnetic changes of the sample surface near the beam impact area, as shown on the right in Fig. 3. In contrast, the magnetic pattern written by the 70 fs pulse, shown underneath, has sharp domain walls and is clearly written by the

magnetic beam field as discussed in the earlier results with 2.3 ps pulse [Stohr FFTB 2003]. Also, no non-magnetic SEM contrast indicative of beam “damage” was observable.

The pulsed E-field leads to current flow and Joule heating. Since the peak E-field of the beam scales as N_e/σ_t and the pulse energy scales with N_e^2/σ_t (where, N_e is number of bunch particles and σ_t is the bunch length), the shorter pulse is expected to produce more heat. This is at odds with our experimental observation.

It is surmised that these puzzling observation can be explained by the non-linear response of the electrons in a metal when the fields become extremely large. The relativistic and nonlinear electron response driven by GV/m electric fields of the beam results in processes that do not follow the conventional Ohm’s law.

V. Strongly electrostatic and relativistically oscillating plasmons

Surface plasmon: For preservation of the essential properties of a particle beam, it is critical to mitigate its direct collision with the ionic lattice. Random collisions between particles and the ionic lattice not only result in loss of energy of the individual particles of the beams but can also disrupt the beam, as a collective entity, through a wide-range of instabilities. These instabilities include filamentation, hosing and several others which can rapidly grow and completely disrupt the beam. Our effort on plasmonic accelerators, therefore, utilizes a surface plasmon where the beam propagates through vacuum surrounded by conducting walls.

Conventional surface modes: It is well known that the Transverse Magnetic (TM) mode which is a purely electromagnetic mode sustains zero focusing forces on a beam inside a metallic cavity or tube. In fact contrary to focusing forces, charged particle beams propagating inside hollow cavities are well known to excite strong deflecting forces if not perfectly aligned to the axis of the cavity.

Whereas the conventional metallic cavities that form the basis of modern particle particle accelerators and light sources utilize electron currents in the metallic walls that oscillate only at the radiofrequency (rf), plasmonic accelerators utilize collective oscillations at spatial and temporal frequencies, Eq.1 and 2, dictated by the density of the free electron Fermi gas itself.

Purely electromagnetic surface wave mode: Besides metallic cavities, existing works on excitation of the TM mode by a charged particle beam in a hollow tube of gaseous plasma have also analytically demonstrated that there are zero focusing forces [Katsouleas PRL 1998], we quote:

“The focusing force is zero inside the channel for a very relativistic particle.”

Experiments on purely electromagnetic surface wave mode: Experiments on excitation of TM mode by a charged particle beam in a hollow tube of gaseous plasma have confirmed the above theoretical result [Hollow-channel expt 2016], we quote:

“We find that when the positron beam propagates on-axis through the channel, there are no significant changes in the spatial profile, indicating the absence of the transverse focusing forces within the channel, thus demonstrating the merit of using hollow channel plasmas for PWFA.”

The crunch-in regime [Crunch-in PRAB, Crunch-in IPAC] is known to violate the conditions imposed by the purely electromagnetic TM mode.

Strongly electrostatic surface crunch-in mode: The strongly electrostatic surface crunch-in plasmonic mode, in contrast with the TM mode, sustains strong focusing forces. As the free electron Fermi gas is driven by beam fields larger than tens of MV/m, the free electron gas gains relativistic momentum. With relativistic momentum, the kinetic energy of plasmonic oscillations increases beyond the surface potential. The oscillating electron gas can thus breach the surface potential. Further details of relativistic plasmonic oscillations and the surface crunch-in process are in [Plasmonic IEEE, Plasmonic SPIE].

The density structure of the free electron Fermi gas oscillating to sustain the surface crunch-in mode is demonstrated in Fig.1 and the corresponding field structure is shown in Fig.4. Due to the highly nonlinear and relativistic nature of plasmonic oscillations in our work, crunch-in plasmonic mode is demonstrated using particle-in-cell simulations of metallic free electron Fermi gas density of $n_t = 2 \times 10^{22} \text{cm}^{-3}$. The beam density is $n_b = 5 \times 10^{21} \text{cm}^{-3}$. These simulations demonstrate that the surface crunch-in plasmon supports strong focusing fields (E_r) in addition to longitudinal field (E_z).

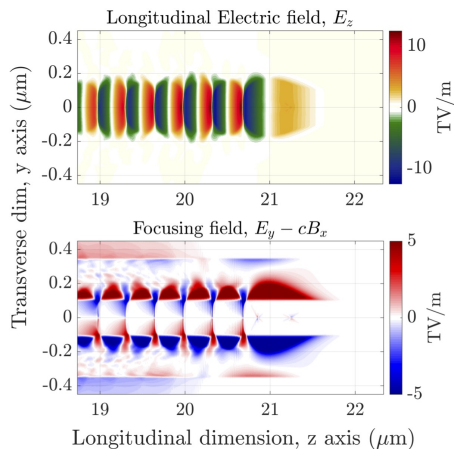


FIG. 4. Longitudinal (top, E_z) and Focusing (bottom, $E_y - cB_z$) fields of the surface crunch-in plasmonic mode from 3D PIC simulations in cartesian geometry. The tube and beam parameters are exactly the same as in Fig.1.

As these plasmonic oscillations are sustained at the coherence limits which are dictated by the density of the free electron Fermi gas, n_e , they support electromagnetic fields at the coherence limit in Eq.4. This is modeled to be possible by exciting novel high amplitude modes of plasmonic oscillation with dense particle beams. It is important note that in the crunch-in mode, just like the beam which excites the plasmonic mode, the accelerated bunch does not interact with the background ionic lattice. Due to this negatively charged as well as positively charged particles can be accelerated with equivalent efficacy. Apart from the injection of an electron within the plasmonic mode, it is also possible to inject ultrashort positron bunch as well as positive and negative muons. Ultrashort bunches of exotic particles, such as positrons [Plasma positron source] and muons [Plasma muon source], may be obtained from a plasma-based accelerator.

Crunch-in mode breaks the scaling of purely EM modes: (contributed by T. Katsouleas) It follows from the Panofsky-Wentzel theorem at a given frequency that when the longitudinal field of a charge in a structure increases with miniaturization as $1/a^2$, where a is the transverse structure dimension, the transverse field amplitude increases as $1/a^3$. These transverse fields lead to head-tail instabilities that severely limit the amount of charge that can be accelerated in miniaturized devices. Moreover, transverse misalignment between the beam axis and the axis of symmetry of the structure excites higher-order mode that further deflect the beam off-axis.

On the other hand, this scaling can be overcome when the transverse aperture is dynamic as in a plasmonic crunch-in surface mode. In that case the head of an electron beam strongly drives out the free electron Fermi gas which as part of their oscillation trajectory go across the surface and re-converge on the axis behind the driver. The aperture behind the beams can be vanishingly small and result in large accelerating fields, while the aperture seen by the beam and associated with the transverse fields is much larger. These dynamic structures can overcome the scaling limitation described above that otherwise limits fixed structures.

The study of the above regime of plasmonic mode in micro to nano-scale tubes will reveal the new physics of plasmonic surface modes. Plasmonic modes potentially offer extreme gradients and an alternate and potentially more direct path to achieving milestones such as staging, positron acceleration and control of emittance growth.

VI. Extreme bunch compression, focusing and diagnostics for plasmonics

contributed by G. White and G. Andonian

VI.1. Extreme compression of particle beams to greater than 100kA peak bunch current (contributed by G. White)

Recent advances in bunch compression has opened up the possibility of producing sub-micron bunch lengths with MegaAmpere (MA) peak currents. For example, ongoing upgrades at the SLAC FACET facility are expected to

provide the possibility for $> 200\text{kA}$ pulses with $< 1\mu\text{m}$ rms bunch length in the near future.

Taking the next logical step and compressing electron bunches into the $< 0.1\mu\text{m}$, $> 1\text{MA}$ regime would support the development of revolutionary new applications across a range of fields including plasmonic accelerators for future colliders.

To reach the regime of multi-MA peak current compression, in addition to a next-generation high-brightness source (not discussed here), various non-linearities present in the bunch compression process need to be considered in order to preserve both longitudinal and transverse emittance.

One of the most limiting physical processes is that of Coherent Synchrotron Radiation (CSR) which causes transverse emittance growth of many orders of magnitude, in addition to strongly limiting the final achievable peak current in the regime considered. To compensate for the CSR emittance degradation, chicane designs more complex than the standard 4-bend chicane need to be considered. Multi-bend chicanes, quadrupole and sextupole loaded chicane/arc/wiggler options are considered here and preliminary performance estimates for a quadrupole and sextupole loaded multi-bend arc lattice are shown. Although performance at the required level has not yet been demonstrated, significant improvements with these new lattice designs are shown. Finally, a discussion of other relevant processes in this novel, ultra-high peak current regime is discussed.

Design Parameters, Constraints and General Considerations

- We consider a bunch compressor design capable of compressing an electron bunch to peak currents $\gg 100\text{kA}$ with $\ll 1\text{mm} - \text{mrad}$ transverse emittance growth.
- Source should be a next-generation photo-injector with transverse emittance $< 0.1\text{mm} - \text{mrad}$, $0.1\text{-}2\text{ nC}$ charge and few 100A initial peak current. Typical injector energies are $\sim 100\text{MeV}$.
- Probably more like $> 2\text{nC}$ initial charge to allow for collimation of tails as part of compression scheme.
- Precise charge is dependent on use case, most demanding is a collider which requires $> \text{nC}$ bunch charge and the smallest transverse emittances, $< 0.05\text{mm} - \text{mrad}$
- Multi-stage compression will be required to achieve compression ratios $> 1000\times$
 - E.g., FACET-II uses 3 compression stages at 0.3, 4.5, 10 GeV
 - Removes need for excessive energy spread
- Final compression stage should be at final energy
 - Helps with CSR, where $\Delta\epsilon_n/\epsilon_n \sim 1/\sqrt{\gamma}$
 - Adverse surface effects expected at high compression (I^2R pulse heating)
 - Allows use of wakefield chirp in final accelerating section
 - * Demands final compression stage should have +ve R56 (requires quadrupole loaded optics) to make use of wakefield chirp
 - * This also helps with non-linearities from compression system (T566. . .) due to partial self-cancellation from rf curvature
- We consider a final energy of 30 GeV here as a good compromise between CSR mitigation, whilst maintaining a reasonable system length (which scales strongly with energy due to Incoherent Synchrotron Radiation growth in bends).

NB: Convention used here is **-ve R56** requires **higher energy at tail** of bunch, **+ve R56** requires **higher energy at head** of bunch.

Initial compression stages reduce the initial bunch length to $20\mu\text{m}$ rms, where the peak current is a 12 kA, similar to the largest values used at FEL facilities, where at low charge emittance preservation has been experimentally demonstrated ($< 200\text{pC}$ charges). The final compression stage required to compress the electron bunch to $< 1\mu\text{m}$ in length requires careful design to mitigate emittance growth effects and is the subject of this note.

Four types of bunch compression optics: We now consider 4 styles of compression optics for use in the final compression stage: a simple 4-bend chicane; a minimal extension to provide CSR canceling- a 5-bend chicane; a double chicane with quadrupole optics between; and finally, a quadrupole (and sextupole) loaded arc or wiggler system.

- i. **4-bend chicane:** A classic 4-bend chicane is used for compression in (at least the later stages) many existing FEL facilities. It is simple to install and operate and has some nice features, such as automatic achromaticity to second-order, transversely. It is included here mainly for comparison purposes. As shown in Figure 1, the chicane system needs to be quite long at our 30 GeV design energy. The R_{56} of a chicane is also -ve, requiring it to “fight” the chirp induced in the rf structures of the final acceleration stage. There is no mechanism for canceling the CSR emittance growth (predominantly generated in the final 2 bend magnets).
- ii. **5-bend chicane:** Adding an additional bend to the chicane provides the minimum required additional free parameters to partially self-cancel emittance dilution due to CSR (e.g., see [5-bend chicane]). For our case, this design suffers from the problems outlined in the 4-bend chicane case (wrong sign R_{56} , long footprint). Additionally, realistic simulations (such as [5-bend chicane]) show expected performance of CSR cancellation at about the $\sim 10\%$ level which for the most demanding cases (particle collider) would not be sufficient.
- iii. **Dogleg or zig-zag chicane:** In order of increasing complexity, the next design to consider would be a double-chicane configuration (e.g., as considered in [CSR compensation]). This directly cancels the CSR degradation in the first chicane by introducing a second chicane and carefully tuning the optics to arrange for the CSR cancellation, including a quadrupole-based lattice between chicane pairs. Although, from simulation studies, more performant in CSR cancellation than the 5-bend chicane design: For our high-energy requirement, this design suffers again from having the wrong R_{56} sign and more so from system length.
- iv. **Arc or Wiggler compression lattice:** To achieve the desired +ve R_{56} compression in our final compressor design, we need a quadrupole-loaded lattice such as an arc or wiggler (depending on whether net-bending is a desired feature or not).

To demonstrate the idea, we constructed a basic model of a wiggler system designed to perform the tasks of our final compressor. In this model, CSR kicks are generated at the center of each bend magnet according to Equation 1 and sextupole kicks are generated at the center of each quadrupole magnet location such that the sum of kicks (Equation 3) cancels the effects of the CSR kicks leading to recovery of emittance dilution. Although useful for demonstrating the concept, this model is too simplistic. The nature of the CSR interaction in reality is more complex, and the sextupoles generate further chromatic and geo-chromatic distortions when fully considered with a realistic electron beam. To fully evaluate the effectiveness for such a lattice design, we have generated a strawman model for the final bunch compressor, based around the parameters laid out in Table 1. This design is implemented within a full 6D particle tracking model (Lucretia) which properly treats the passage of the electron beam through the lattice, including a full treatment of the CSR radiation, including transient effects as the beam enters and leaves each bending magnet. A 1-d line-charge kick model of CSR is used. This is appropriate due to the “Derbenev Criterion” being fulfilled for all bend magnets in the design:

VI.2. Permanent Magnet Quadrupoles for high-field focusing (contributed by G. Andonian)

Excitation of the strongly electrostatic longitudinal fields in the crunch-in modes requires very dense drive beams within the core of the conducting nano-structures. Beam densities on the order of 10^{17}cm^{-3} to 10^{21}cm^{-3} are required to explore the different regimes of nano-plasmonic acceleration, which corresponds to transverse spot sizes on the sub-micron scale for intense beams. In order to produce conditions optimal for crunch-in mode formation, an appropriate focusing scheme must be implemented. Furthermore, in realistic experimental scenarios where regions are constrained by spatial limitations, the focusing system should be compact and robust.

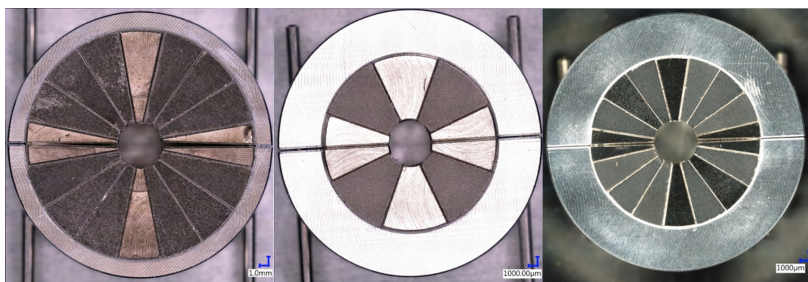


FIG. 5. Examples of different permanent magnet quadrupoles in the Halbach geometry, produced for ultrafast electron microscopy at the Brookhaven National Laboratory. Photographs courtesy of J. Penney.

Permanent magnet quadrupoles are ideal candidates for such applications as they are able to provide very high gradients (in excess of 700 T/m [Adjustable PMQ]) in a compact form factor, without the need for external cooling that electromagnetic counterparts require. However, quadrupoles only offer focusing in one dimension, while defocusing the beam in the other. Hence, the simplest configuration of permanent magnet quadrupoles for overall focusing requires a triplet configuration. The triplet system is tunable by the relative reconfiguration of quadrupole locations, and higher order moments can be tuned out by magnetic shimming as needed.

Current applications of permanent magnet quadrupoles are varied across the accelerator physics landscape, including final focus systems for inverse Compton scattering [Adjustable PMQ], beam-break up mitigation for extended energy exchange in wakefield interactions, and high quality imaging in ultrafast electron microscopy [TEM aberrations]. Advances in material development and higher levels of sophistication in fabrication techniques also allow for control of higher order modes, such as in the Halbach configuration [Rare Earth Magnet]. Technological advances in permanent magnet quadrupole integration into existing beamlines, applied in-vacuum or out-of-vacuum with hybrid split-designs [PMQ BNL UEM], offer further flexibility for use within the strict constraints in nano-plasmonic acceleration.

VI.3. Advanced ionization diagnostics for intense beams (contributed by G. Andonian)

The generation of the crunch-in modes in nano-plasmonic acceleration requires the delivery and transport of high intensity beams through small apertures. Traditional diagnostics for transverse beam profile and centroid for alignment would not be sufficient due to damage from the intense beams. Alternative methods, preferably non-destructive are required to parameterize drive and witness beams through nano-plasmonic structures.

An exciting new diagnostic tool for high intensity beams operating in a minimally intercepting topology is the gas sheet ionization monitor. The concept is based on the generation of a thin neutral gas sheet, or curtain, that is propagated perpendicular to the drive beam. As the beam passes the neutral gas sheet, the particles are ionized, leaving a footprint of the initial beam distribution. The ionization distribution is then imaged using a series of electrostatic lenses and a micro-channel plate. The ion distribution is then back-convolved using a reconstruction algorithm to determine the initial beam profile at the point of ionization. Such methods have been used at low energy [Gas jet BPM] and also proposed for high intensity beams at SLAC FACET [High intensity BPM]. The technique is ripe for modern machine learning methods to extrapolate beam profile information where conventional techniques are not viable.

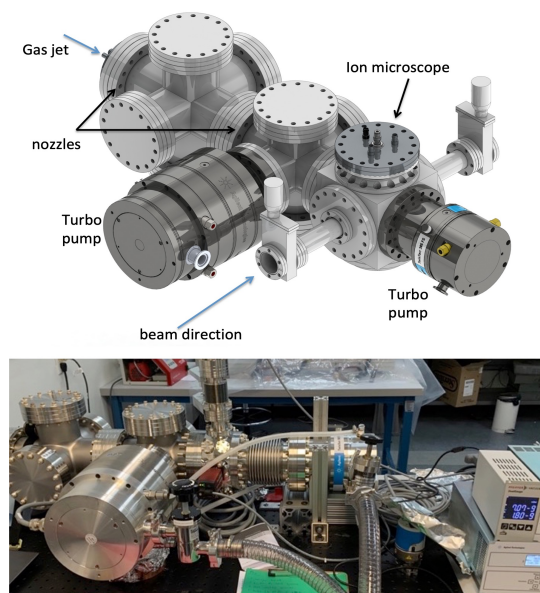


FIG. 6. Gas film ionization beam profile monitor for dense beams.

VII. X-ray laser driven Carbon Nano-Tubes (CNTs)

contributed by G. Mourou and T. Tajima

The recent invention of the Thin Film Compression technique opens the way to introduce the availability of the single-cycled laser pulse and thus the Relativistic Compressed X-ray laser pulse [[Xray laser](#)], which fits the need for X-ray laser driven nanostructured wakefield acceleration (WFA) possibility [[Xray crystal acc](#)]. This technology and arrangements allow the level of accelerating gradient on the order of TeV /cm.

Although the energy level and time duration of x-ray or optical energy in the pre-pulse of the yet to be prototyped x-ray laser remains uncharacterized, it is critical to note that plasmonic processes are only relevant if this radiation energy ahead of the main x-ray pulse does not completely ablate the target and dismantle the ionic lattice.

Acceleration of muons (instead of electrons or hadrons) channeling between the planes in crystals or inside carbon nanotube (CNT) with high charge carrier density holds the promise of the maximum theoretical accelerating gradients of 1-10 TeV/m allowing envisioning of a compact 1 PeV linear crystal muon collider [[Xray CNT acc](#)]. The choice of muons is beneficial because of small scattering on solid media electrons, absence of beamstrahlung effects at the IP, and continuous focusing while channeling in crystals, i.e., acceleration to final energy can be done in a single stage. Muon decay becomes practically irrelevant in such very fast acceleration gradients as muon lifetime quickly grows with energy. Initial luminosity analysis of such machines assumes a small number of muons per bunch $O(1000)$, a small number of bunches $O(100)$, high repetition rate $O(1 \text{ MHz})$ and ultimately small sizes and overlap of the colliding beams $O(1 \text{ Angstrom})$.

Another important path is nanostructures such as carbon nanotubes. The use of concavity of nanostructures such as CNT allows to eliminate collisions of the accelerated particles with the “background medium particles” and to serve to conduct electrons with self-focusing force. This leads to the potential of on the order of TeV/ cm accelerating gradient possibility. Nanostructures help also the “confinement” of the driving pulse of X-rays or charged particle beams. Furthermore, the introduction of such ultrahigh accelerating gradient opens up a path of non-luminosity paradigm of doing extreme high-energy physics, by stacking 1000 nano-fibers would lead to PeV over 10m. Recall that the gamma photon wavelength at PeV is so short that the vacuum texture may be explored by such photons. In such experiments, we do not require the luminosity and thus the equipment and power necessary may be greatly reduced over the collider construct.

VIII. Plasmonic accelerators: Challenges, possibilities and ongoing efforts

- modeling distortion of the ionic lattice due to plasmonic modes ?
- modeling changes to the electron energy levels due to lattice distortions under plasmonic fields

IX. Strategic plans for future efforts

- non-collider scientific discoveries ?
- PeV electron beam
- nano-Wiggler for coherent gamma-ray laser
- dedicated user facility or specific time allocation at an existing user facility ?
- integration of plasmonic nanomaterials research
- development of specialized and unconventional diagnostics for ultra-solid beams of photons and particles

contributed by F. Zimmermann

- path to highest energy colliders
- high energy accelerators for dark sector searches

- nano-wiggler for coherent-gamma-ray laser for gamma-gamma collider?
- applications, e.g. medical applications ? miniature accelerators for nano-surgery, and/or diagnostics inside the human body?
- can the plasmonic accelerator be brought into connection with crystalline beams ? e.g. acceleration of crystalline beams
- possibly application to beam-based inertial fusion and solving the world's energy problems

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