STUDYING THE BASICS OF PLASMA PHYSICS USING LONG RANGE PLASMA

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Abstract

Plasma wakefield acceleration (PWFA) is a burgeoning field, attracting much attention as an option to extend acceleration gradients from the present 100 MeV/m level to the TeV/m level. The effort will be expended to resolve the question of the long-term behaviour of the disturbances left behind in the plasma and the time it takes to reach equilibrium after the wakefield interaction occurs. The present limitations on gradient arise from material electromagnetic breakdown thresholds. Methods for exploring the beam's longitudinal and transverse phase space qualities have been developed in the context of an increasing worldwide effort. UCLA Large plasma device (LAPD) laboratory, with its diagnostics, permits the spatio-temporal resolution of electron density, magnetic field, and electro-magnetic signals in the plasma over long-time scales. We aim to explore intense electron beams for wake excitation available at the LAPD, commissioning the SAMURAI photoinjector and its electron beam production.

INTRODUCTION

The UCLA MITHRA (Megavolt InTense High-gradient Research Accelerator) laboratory houses a hybrid photoinjector projected to be capable of producing 250 pC beams with hundreds of Amperes of peak current and 1mm-mrad emittance. The LAPD plasma column, located beneath the MITHRA bunker, presents an opportunity for an experimental collaboration: with the construction of a vertical 180 degree bend section, electron bunches produced and accelerated at MITHRA can be injected into the LAPD plasma column to produce excitations. As the plasma is strongly magnetized by focusing solenoids, such data would be valuable for research into settings such as the behavior of ions in space plasmas and signal propagation in the Earth's ionosphere.

The aim of the projects is to explore the decay of the wave excitation on a long (100s of nsec) time scale, using the copious diagnostics of LAPD (including electromagnetic signals at the sub-100 GHz level, characteristic of the wave-excitation and collapse). This is the first time such a thing can be done in a magnetized plasma, and also for such impressive time scales. In order for this to be most interesting, we need an effective excitation. Magnetization provides an interesting amount of guiding for a 25 MeV electron beam in a 1 Tesla field, we are talking about an equilibrium beta of around 16 cm, which can control the beam head erosion somewhat.

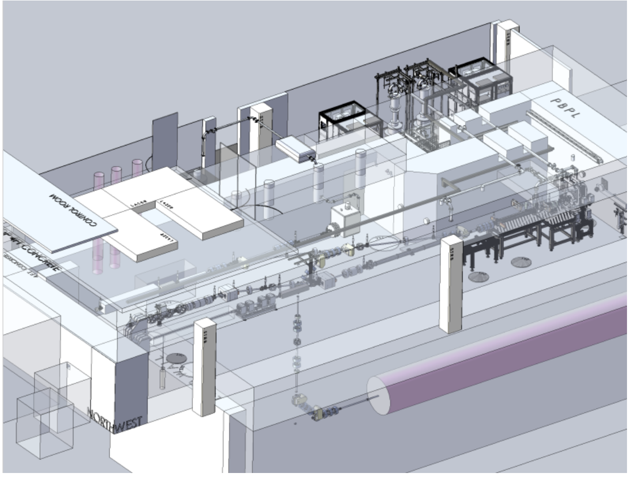

Figure 1: Schematic of U-bend connecting the MITHRA beamline to the LAPD plasma column in the basement of UCLA's STRB.

Figure 1 illustrates the schematic of U-bend connecting the MITHRA beamline to the LAPD plasma column in the basement of UCLA's STRB. The present study considers the transport of an electron beam that has undergone emittance compensation and acceleration through the first booster linac. This corresponds to a final energy 20-30 eV, depending on the choices of phase in the traveling wave section of the photoinjector and downstream booster linac. The deleterious effects of dispersion and coherent synchrotron radiation (CSR) on the beam are considered as it makes it's journey through a sequence of bending magnets, before a sequence of quadrupoles is used to match the beam to the plasma column. The corresponding excitations are explored in PIC simulations.

SIMULATION SETUP

The generation and acceleration of the electron bunch is performed in the General Particle Tracer (GPT) code, with 3D space-charge and image-charge effects taken into account. We assume a 0.95 mm transverse laser spot and 1.81 ps tri-Gaussian laser pulse illuminating the cathode and releasing 250 pC of charge. The electron gun in question operates in S-band, and consists of a 1.6 cell standing wave (SW)

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cavity coupled to a traveling wave (TW) section that effects the bunch compression mechanism. In order to minimize the effects of CSR as the beam propagates, we choose to operate the TW section closer to crest than the nominal case. This reduces the peak bunch current to only 80 A or so, but increases its uniformity and minimizes break-up of the longitudinal phase space, providing a mean energy of 33 MeV. This allows us to better preserve the beam emittance and longitudinal profile. The latter is particularly important, since it would be difficult and expensive to introduce a bunch compression apparatus inside LAPD as shown in Fig. 2.

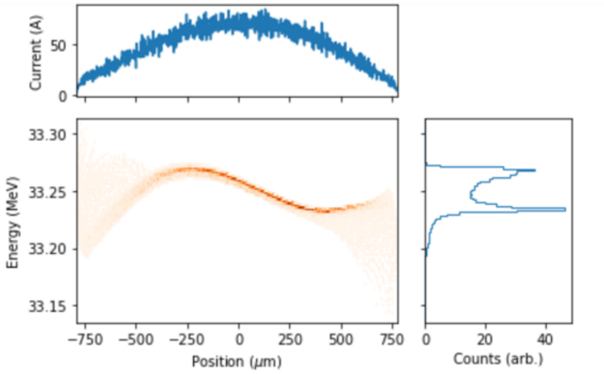

Figure 2: Beam LPS post-acceleration.

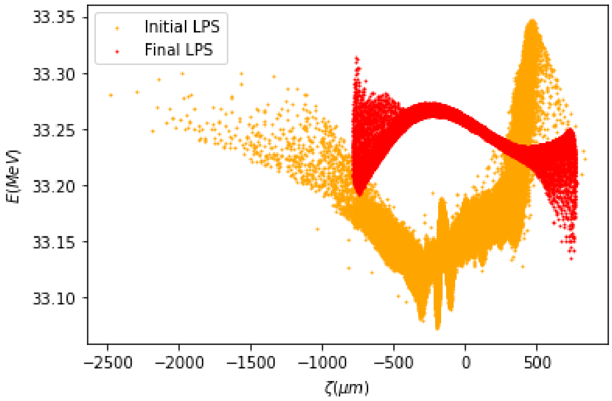

Figure 3: Comparison of LPS before and after ELEGANT tracking.

After acceleration, the beam distribution is tracked using ELEGANT, using a 1D CSR model. This model is valid when the beam parameters and bend radius R satisfy $\sigma_y(R\sigma_z^2)^{-1/3} \ll 1$, the so-called Derbenev criterion; for our simulation, this quantity does not exceed 0.06. A 20 degree horizontal dogleg is followed by four 45 degree vertical bend magnets, as well as a sequence of focusing quadrupoles. The results are shown in Fig. 3. The optics are chosen to ensure $\eta = 0, \eta' = 0$, with optimizations minimizing deleterious effects of dispersion and coherent synchrotron radiation (CSR) on the beam as it makes its journey through the aggressive bending magnets. A set of focusing quadrupoles is used to match the beam to an assumed plasma density of $n_p = 4e13\text{cm}^{-3}$, corresponding to $\beta \approx$0.96 mm The final beam parameters are shown in Table: 1; of particular relevance is the post-focusing beam density $\rho_{rms} = N_{bunch}/(\sigma_x\sigma_y\sigma_z)$ which must significantly exceed the ambient plasma density to induce a blowout.

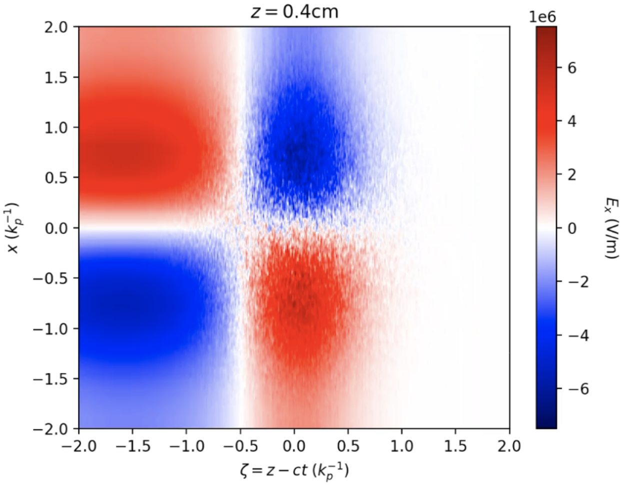

Figure 4: Electric field at Z= 0.4 cm calculated using OSIRIS code.

In order to gain better insight into the experimental results, we conducted 3D-PIC simulations using the `OSIRIS` code. We chose `OSIRIS` based on its ability to handle highly non-linear and kinetic processes that occur during high-intensity particle and laser interactions with the plasma. As the relativistic beam propagates, it expels all plasma electrons out of its way and thus generates in its wake a positively charged cavity. The fields in this cavity, also known as wakefields, reach values of 100 MV/m if the gas density is in the range $10^{13} - 10^{14}$ cm^{-3} as shown in Fig. 4. A significant challenge with PWFA is accelerating a beam while keeping energy spread and emittance growth small even for a longer propagation length. We investigate propagation of high-intensity charged particle beams in plasma.

The simulation box size was -8 k_p^{-1} in the transverse direction and 100 k_p^{-1} in longitudinal direction and 8 macroparticles per cell. The code used a static window approach, where the simulation box moves at the speed of light, and the pulse is initialized near the leftmost edge of the window. `OSIRIS` also incorporates the ability to launch EM waves into the simulation, either by initializing the EM field of the simulation box accordingly or by injecting them from the simulation boundaries. The mapping of trapped electrons and accelerating fields throughout the ionized gas was constantly simulated.

In Fig. 5 numerical simulation for drive beam evolution in plasma OSIRIS code are explored. It may also be noted that the transport and CSR effectively impart a negative R56, slightly compressing the core of the beam while inducing a energy chirp of 45 keV (rms). This beam distribution, along with a description of the ambient plasma and magnetization is then fed into the PIC-code OSIRIS. Beam-plasma Interac-

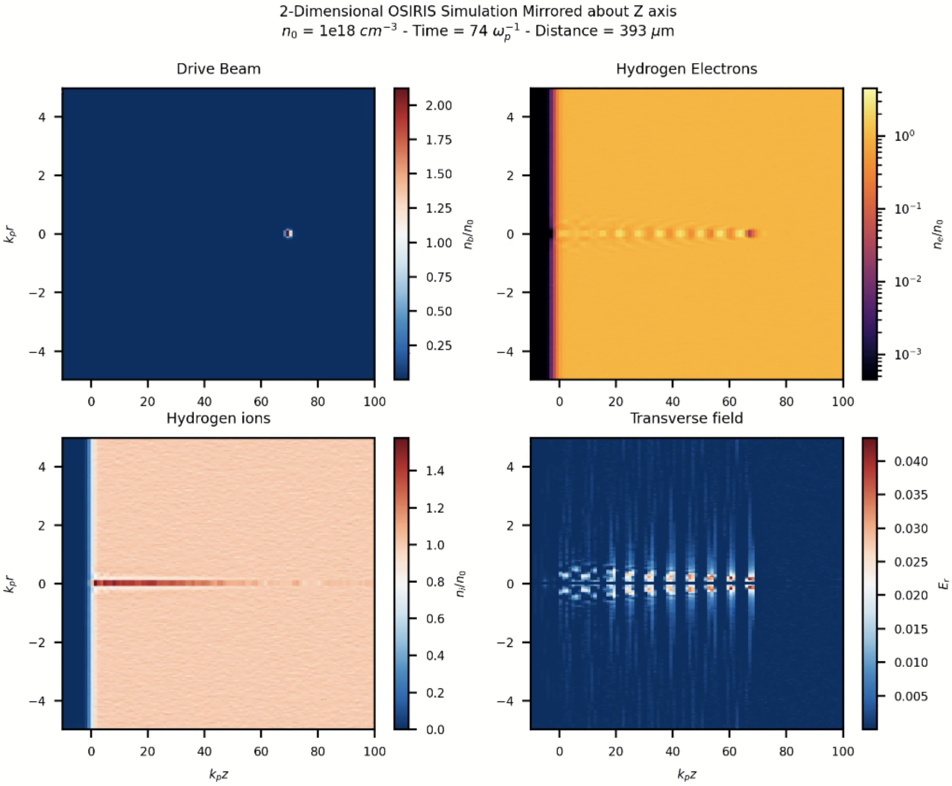

Figure 5: Numerical simulation for drive beam evolution in plasma OSIRIS code.

Parameter	Unit	Value
Charge	pC	100
RMS Laser Spot Size (Pre-Cut)	µm	950
RMS Laser Spot Size (Post-Cut)	µm	672
Injection Phase	°	40
Laser Length	ps	1.81
Peak Cathode Field	MV/m	45
γ (const)		64.90
ϵ_x, ϵ_y (initial)	µm	0.99, 0.98
ϵ_x, ϵ_y (final)	µm	1.45, 4.49
σ_t, σ_γ (initial)	ps, pct	1.2, 0.05
σ_t, σ_γ (final)	ps, pct	1.05, 0.129
ρ_{rms} (initial	cm^{-3}	1e12
ρ_{rms} (final)	cm^{-3}	6e14

Table 1: LAPD beam parameters.

tion in the LAPD using computational modelling has been previously explored at UCLA [1–4]

CONCLUSION

This report has investigated the excitation of long-range plasma waves in the LAPD with high brightness electron bunches produced in the nascent MITHRA accelerator facility. It was shown that the transport of a 250 pC bunch from MITHRA with acceptable losses due to CSR, longitudinal space-charge and dispersion is feasible, despite the sharp bends and relatively low beam energy involved.

While we considered single-bunch operation at a fixed parameter set, real experiments will likely require multi-bunch operation, as well as perturbation of the nominal operating parameters. Future work would require us to investigate the MITHRA gun repetition rate, multi-bunch interactions and bunch-structure interactions, and stability of the plasma response with respect to perturbations. Optimizing the final blow-out response with respect to variations in bunch charge, injection phase, and spot size will also prove beneficial.

LAPD is particularly useful for studying turbulence and other complex plasma phenomena, as well as for testing plasma-based technologies and devices. The LAPD is equipped with a variety of diagnostic tools and instruments, including magnetic probes, Langmuir probes, microwave interferometry, and optical emission spectroscopy. These tools allow researchers to measure plasma properties such as density, temperature, and flow velocity, as well as to study the behavior of plasma waves and instabilities.

ACKNOWLEDGEMENT

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