

# Excitation Of Wakefields In A Relativistically Hot Plasma Created By Dying Non-linear Plasma Wakefields

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**Abstract.** We study the various physical processes and their timescales involved in the excitation of wakefields in relativistically hot plasma. This has relevance to the design of a high repetition-rate plasma wakefield collider in which the plasma has not had time to cool between bunches in addition to understanding the physics of cosmic jets in relativistically hot astrophysical plasmas. When the plasma is relativistically hot (plasma temperature near  $m_e c^2$ ), the thermal pressure competes with the restoring force of ion space charge and can reduce or even eliminate the accelerating field of a wake. We will investigate explicitly the case where the hot plasma is created by a preceding Wakefield drive bunch 10's of picoseconds to many nanoseconds ahead of the next drive bunch. The relativistically hot plasma is created when the excess energy (not coupled to the driven  $e^-$  bunch) in the wake driven by the drive  $e^-$  bunch is eventually converted into thermal energy on 10's of picosecond timescale. We will investigate the thermalization and diffusion processes of this non-equilibrium plasma on longer time scales, including the effects of ambi-polar diffusion of ions driven by hot electron expansion, possible Columbic explosion of ions producing higher ionization states and ionization of surrounding neutral atoms via collisions with hot electrons. Preliminary results of the transverse and longitudinal wakefields at different timescales of separation between a first and second bunch are presented and a possible experiment to study this topic at the FACET facility is described.

**Keywords:** Relativistically Hot Plasma, Plasma Wakefield Collider, High repetition rate, Dying Plasma Wakefield, FACET.

## ELECTRON BEAM INTERACTION WITH RELATIVISTICALLY HOT PLASMA

High-energy high intensity electron beam interacting with appropriate density plasma can excite non-linear “blow-out” Wakefields. A trailing or witness bunch loaded in right phase of the Wakefields, where transverse focusing and longitudinal acceleration fields are both optimal, can maximally absorb the energy and accelerate high quality beam in the drive bunch generated Wakefields.

The trailing witness bunch or the bunch being accelerated cannot however absorb all the energy coupled by the drive bunch into the plasma Wakefields. The maximum energy transfer efficiency is of the order 30-40%. Hence, even in the cases where the witness bunch accelerates with optimal characteristics, there is excess energy left over in the plasma. This excess energy leads to different processes during the dying stages of the plasma wakefields. The ions that are left in the ion column created by ponderomotively-ejected electrons tend to diffuse out away from the axis. This leads to the possibility of existence of a hollow plasma channel. At later timescales, the plasma tends to thermalize with energy of electrons of the order of their initial ponderomotive force balance.

Facility for Accelerator Experiments and Test (FACET) at Stanford Linear Accelerator Center (SLAC) National Laboratory is a unique facility for advancing accelerator technology as well as the frontiers of science. The proposed experiments of studying the dying stages of the Plasma Wakefields accomplish both of these goals. It will explore the feasibility of running a plasma wakefield accelerator at high repetition rate, while at the same time explore new beam physics of relativistic beams interacting with extremely hot and possibly turbulent plasmas typically found only in astrophysical settings.

One of the main motivations for building FACET was that it would allow the development and testing of many aspects of a single stage of a future multi-stage Plasma Linear Collider (PLC) at the energy frontier. One of the first self-consistent designs for a high luminosity PLC is shown in Figure 1 with parameters given in Table 1.

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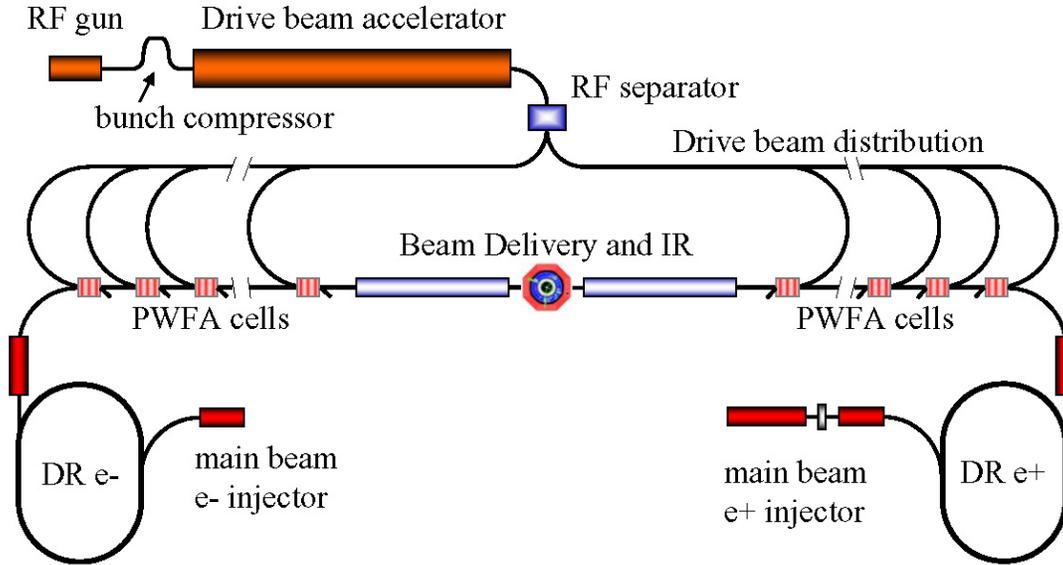


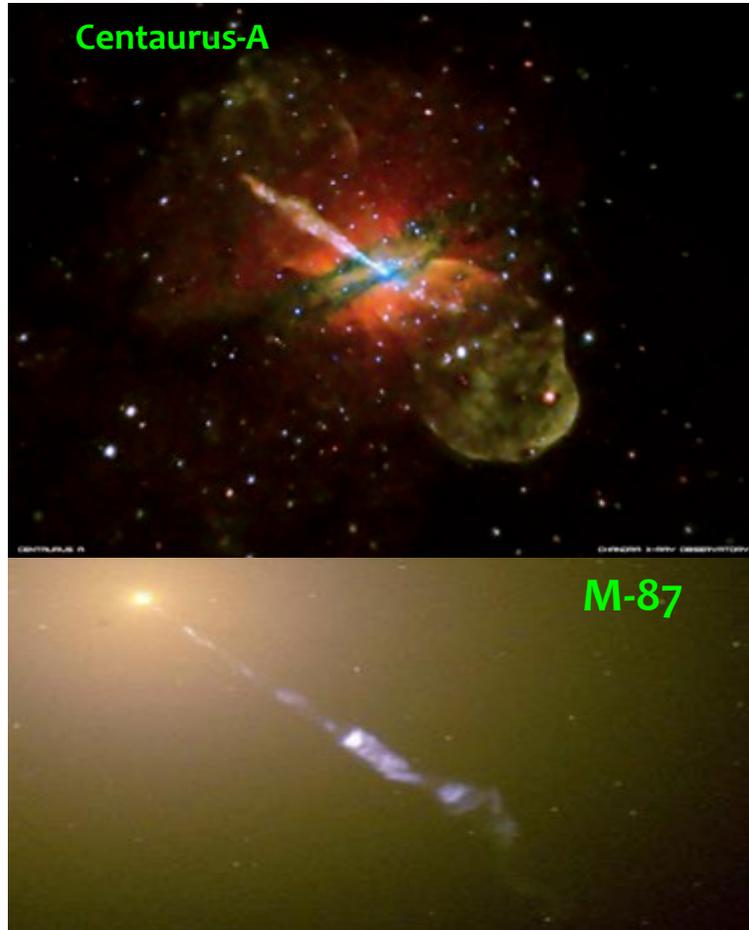
Figure 1: self consistent design of PLC

Main beam: bunch population, bunches per train, rate	$1 \times 10^{10}$ , 125, 100 Hz
Total power of two main beams	20 MW
Drive beam: energy, peak current and active pulse length	25 GeV, 2.3 A, 10 $\mu$ s
Average power of the drive beam	58 MW
Plasma density, accelerating gradient and plasma cell length	$1 \times 10^{17} \text{ cm}^{-3}$ , 25 GV/m, 1 m
Power transfer efficiency drive beam $\Rightarrow$ plasma $\Rightarrow$ main beam	35%
Efficiency: Wall plug $\Rightarrow$ RF $\Rightarrow$ drive beam	$50\% \times 90\% = 45\%$
Overall efficiency and wall plug power for acceleration	15.7%, 127 MW
Site power estimate (with 40MW for other subsystems)	170 MW
Main beam emittances, x, y	2, 0.05 mm-mrad
Main beam sizes at Interaction Point, x, y, z	0.14, 0.0032, 10 $\mu$ m
Luminosity	$3.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
Luminosity in 1% of energy	$1.3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$

Table 1: PLC design parameters

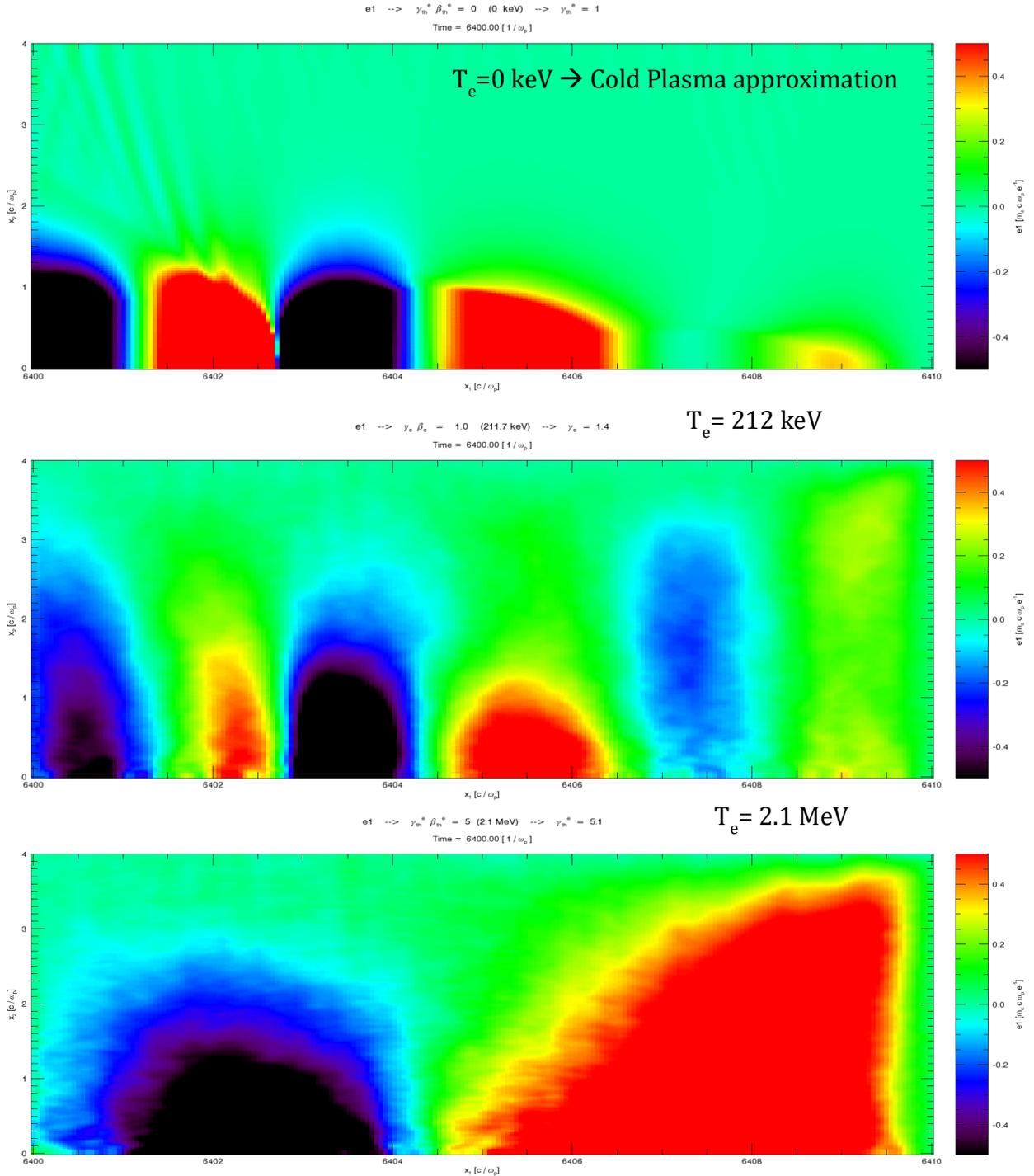
The design is for collision energy of 1 TeV in the center of mass with 20  $e^+$  and  $e^-$  plasma stages, each of approximately the energy of the FACET plasma Wakefield experiments (E-200). To achieve luminosity above  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$  requires each plasma stage to repeat every 4 nanoseconds. In such a short time, the plasma will be strongly affected by the thermalization of the wake from the previous pulses. Open questions include what will be the temperature and density profile of such plasma? Will the unabsorbed wake energy from the previous pulse(s) heat the plasma to relativistic temperatures (i.e.,  $k_B T_e$  of the order or greater than 0.5 MeV, thermal velocities near the speed of light)? Can wakes be excited and used for acceleration in such plasma and how will they differ from the cold plasma wakes studied thus far? How long must one wait for the plasma to cool, diffuse, recombine, etc. before it can be re-used effectively? This experiment will be the first to explore high repetition rate plasma acceleration and answer these questions.

Moreover, the interaction of relativistic beams with relativistic plasmas is of interest for understanding the physics of astrophysical jets (Figure 2). In recent years, new observational facilities for astrophysics have revealed that such jets are ubiquitous in nature, emerging from objects ranging from pulsars to supernovae and galactic nuclei. Their interaction with surrounding hot plasma gasses exhibits self-focusing, hosing, radiation generation and other phenomena that can be studied in this proposed experiment.



**Figure 2: Astrophysical Jets from gravitationally compressing hot plasmas in Galaxies**

To illustrate the physics that may occur in high rep-rate plasma Wakefield stage, we perform 2-D particle-in-cell simulations (with cylindrical symmetry assumptions) with the well-benchmarked code OSIRIS. Figure 3 shows real space iso-contours of longitudinal plasma longitudinal Wakefield  $E_x$  in a cold plasma for typical E-200 experimental parameters as well as corresponding wakes in plasmas of increasing temperature from 0 to a few MeV. At relativistic temperatures, the mass of plasma electrons increases, lowering the plasma frequency ( $\omega_{pe} = \sqrt{\{4\pi n_0 e^2 / \gamma_e m_e\}}$ ) where  $\gamma_e$  is the Lorentz factor of the hot electrons) and correspondingly increasing the plasma wavelength ( $\lambda_p = 2\pi c / \omega_{pe}$ ) and wake radius (proportional to the skin depth  $c / \omega_{pe}$ ). The Wakefield amplitude is also reduced in accordance with the lower  $\omega_{pe}$ , and the “spike” in electric field (at the back of the bubble) characteristic of cold plasma wakes of large amplitude is lower because thermal pressure of the relativistic electrons prevents the density from compressing to the same degree.



**Figure 3: Longitudinal Wakefields  $E_x$  in Hot plasma (electron temperature in eV) in a real-space Cross-section (iso-contours on one side of the axis)**

The actual temperature that the plasma could reach in a high-rep accelerator depends on a number of factors including how well the wake energy is absorbed through efficient beam loading. As an upper limit, one can estimate that when the wake energy thermalizes due to plasma instabilities and mode couplings, the kinetic energy of the oscillating electrons in the wake (as well as some of the field energy) will become random thermal energy. Roughly

the quiver velocity of electrons in the wake approaches  $\rightarrow c \times E_x [\text{V/cm}] / \sqrt{(n_0 [\text{cm}^{-3}])}$ . For FACET the latter ratio is of order 1 ( $E_x \sim 10 \text{ GV/m}$ ;  $n_0 \sim 10^{17} \text{ cm}^{-3}$ ), so we may expect temperatures of several hundred keV to MeV after the wake thermalizes.

The thermalization of a large amplitude plasma wake is complex and little studied. Previous PIC simulations have shown that the wake decoheres on a timescale of 10's of plasma periods or a few times  $10^{-3} / \sqrt{(n_0)} \sim 10$  picosecond scale. The resulting hot plasma electrons will expand outward driving so called ambi-polar diffusion of the ions at a speed typically near the sound speed  $c_s \sim \sqrt{(T_e/M_i)}$ , where  $T_e$  is the electron temperature and  $M_i$  is the ion mass. For MeV electrons and Rubidium ions, this is a few mm/ns. This will lead to a typically parabolic channel of lowered plasma density on axis on a nano-second timescale. However, as the plasma expands it cools, slowing the process and eventually allowing recombination to occur (microsecond timescale).

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