Multi-bunch Plasma Wakefield Acceleration at ATF

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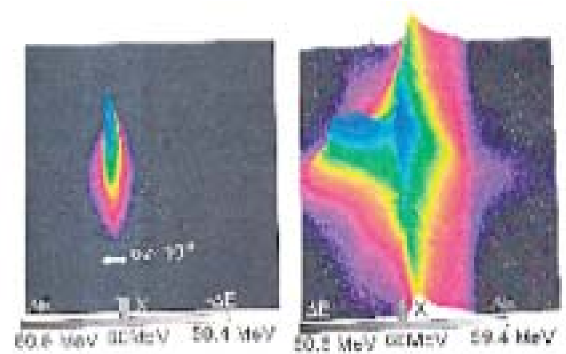
Background and Motivation

- Several recent PWA experiments have shown promise w/ single bunches
  - E-162 at SLAC: 280 MeV/1.4m, e- and e+
  - ANL: ~15 MeV/30cm, >50% beam energy extracted
  - ATF: .6 MeV/cm, focus and acceleration phases
- Realizations require multi-bunches
  - Afterburner: 2
  - NLC Afterburner: many

Building on Recent Success

- ATF Plasma Wakefield Experiment
  - Single bunch,
  - low plasma density



- ATF Stella Experiment
  - IFEL-modulated bunches at 10.6 μ

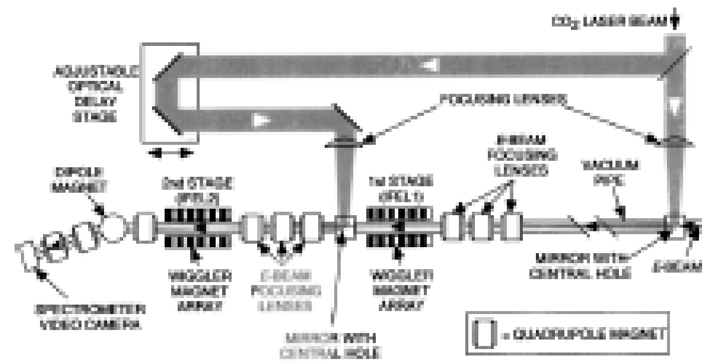
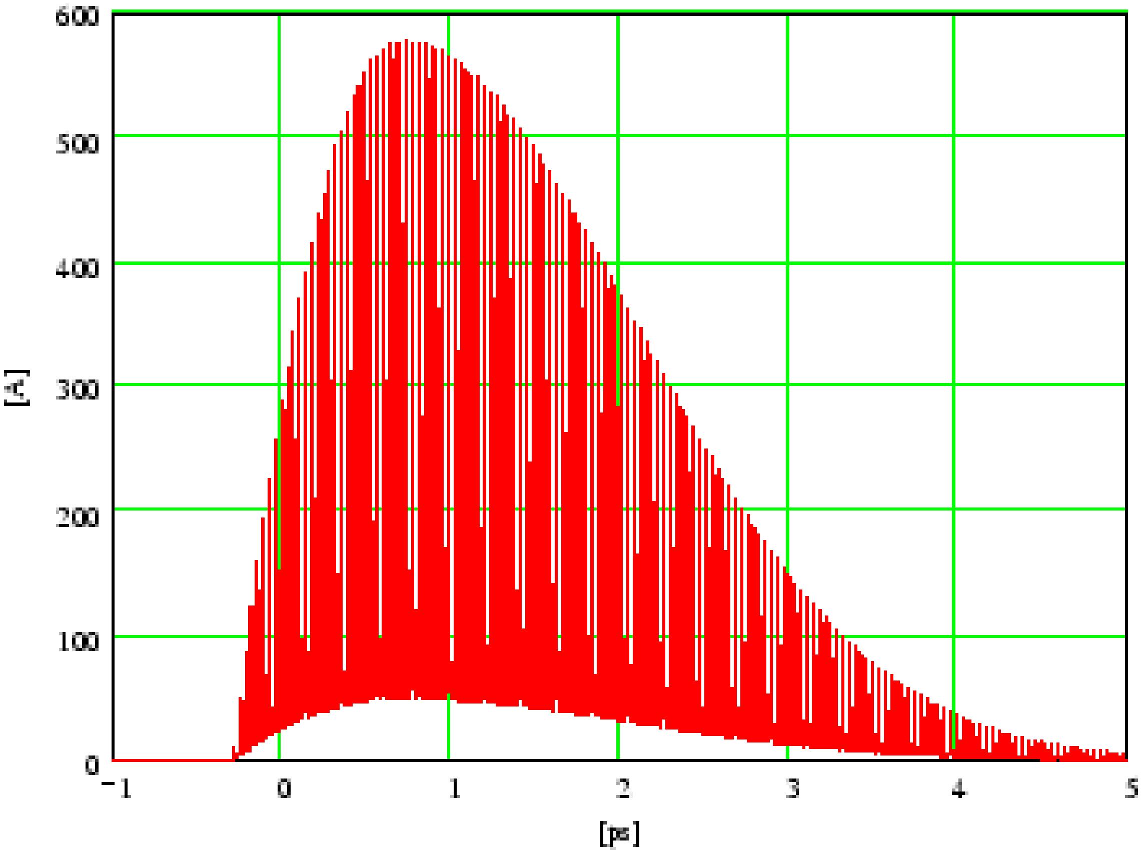


FIG. 1. Schematic layout for the STELLA experiment. For size reference, the distance separating the two IFELs is 2.3 m and the laser beams enter the beam line ≈6 m apart.

Strategy: Use 1st stage of Stella to drive multi-bunch PWA

- Current profile from Stella stage 1:



Linear Plasma Wake Theory

$$E_z(r,\xi) = Z'(\xi)R(r) \qquad \xi = z - ct$$

$$Z'(\xi) = -4\pi \int_{\xi}^{\infty} d\xi' \rho_{\parallel}(\xi') \cos k_p(\xi - \xi')$$

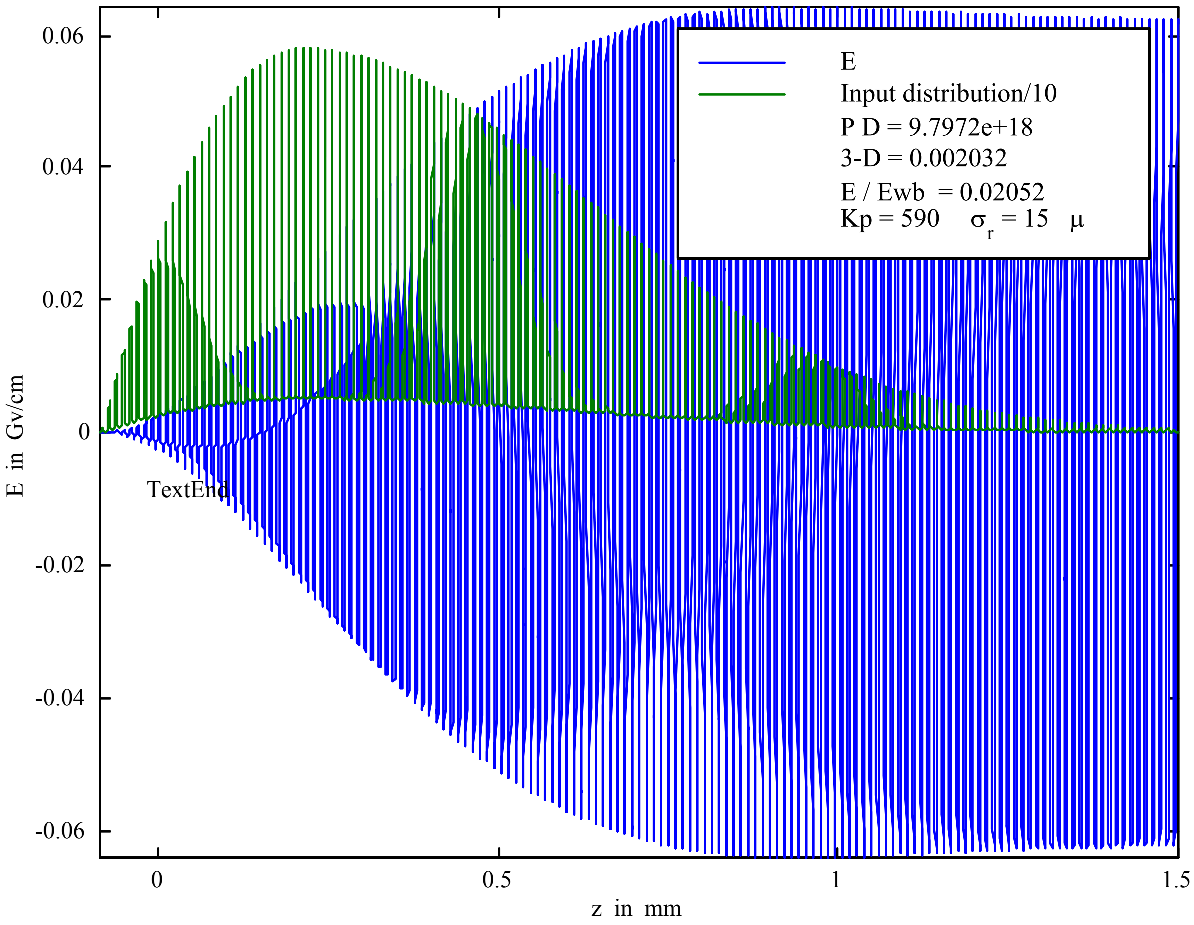
$$R(r) = \frac{k_p^2}{2\pi} \int_0^{2\pi} d\theta \int_0^{\infty} r' dr' \rho_{\perp}(r') K_0(k_p \,|\, \mathrm{r} - \mathrm{r}' \,|)$$

$\rho_b = \rho_{\perp}(r) * \rho_{\parallel}(\xi)$ $\rho_{\parallel}(\xi)$ **= profile from Stella**

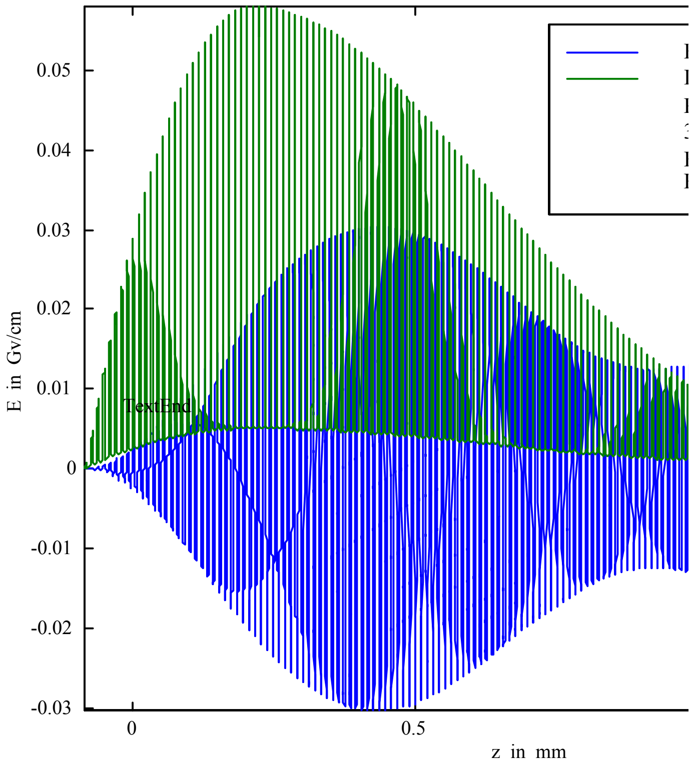
$k_p \sim 2\pi/10.6\mu\ (n_o/10^{19}\mathrm{cm}^{-3})^{1/2}$

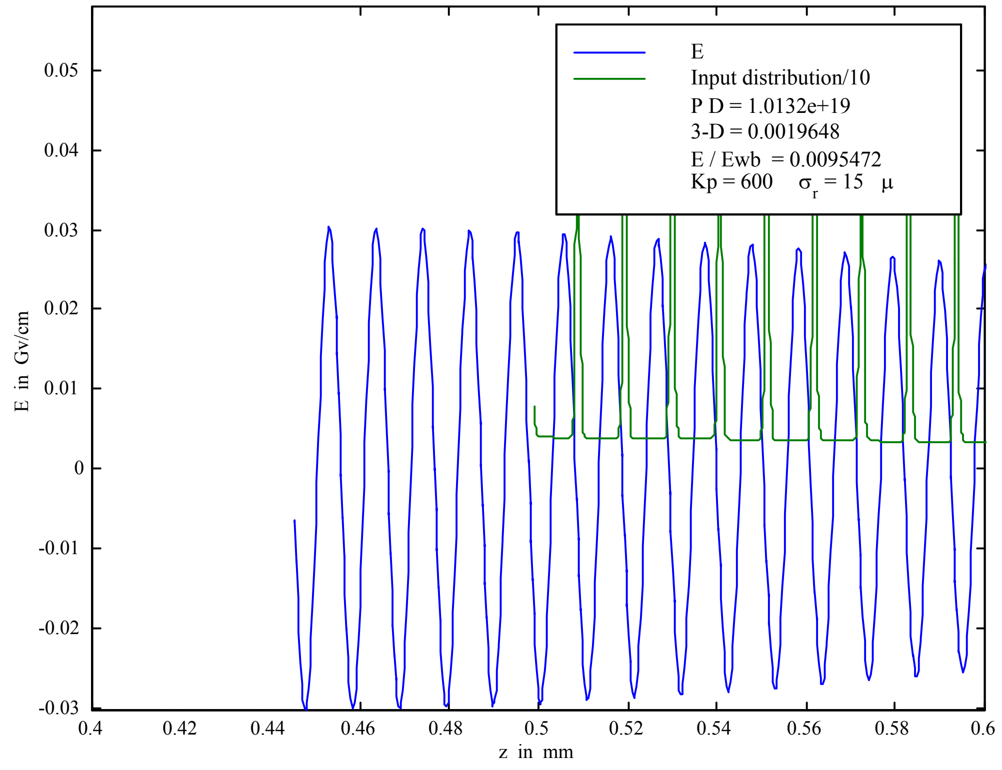
Linear Theory Results

Wake build-up at resonance:



3% detuning accelerates later bunches





Beam Evolution

- Transverse --Focusing strength in wake:

$$K = \frac{eE_o k_p}{\gamma mc^2 (k_p \sigma_r)^2}$$

=> $\lambda_\beta = 2\pi/\mathrm{sqrt}(K) \sim 3.6$ mm

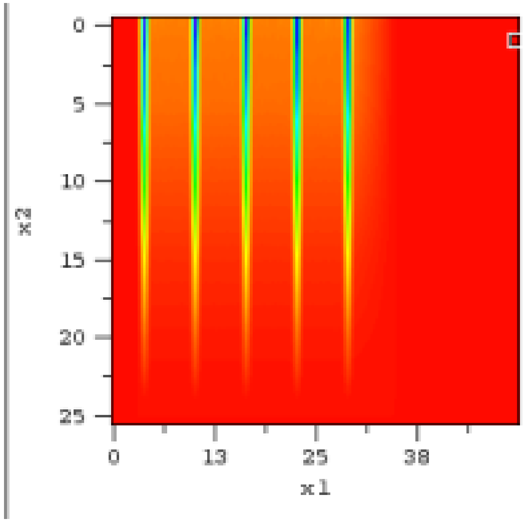
- Longitudinal--slippage/loss length
  - 50 MeV/cm wake => few mm

Beam does not evolve in mm scale experiment

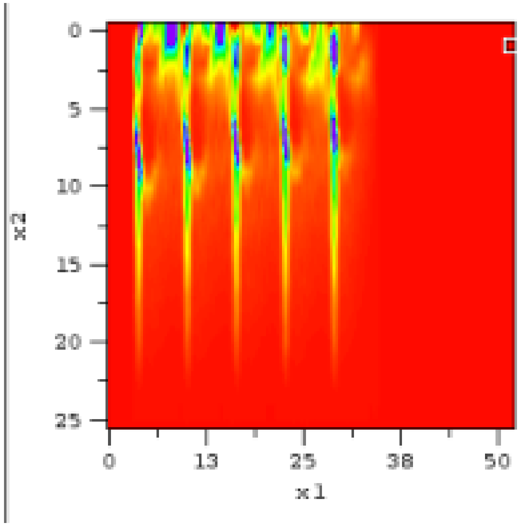
Beam evolves strongly in cm scale experiment

Self-consistent particle-in-cell Simulations

- 2-D OSIRIS
  - First 30 bunches (.5 ps rise) of Stella beam
  - 10^6 particles followed thru 1.5 mm of plasma
  - 32 processors at USC HPC

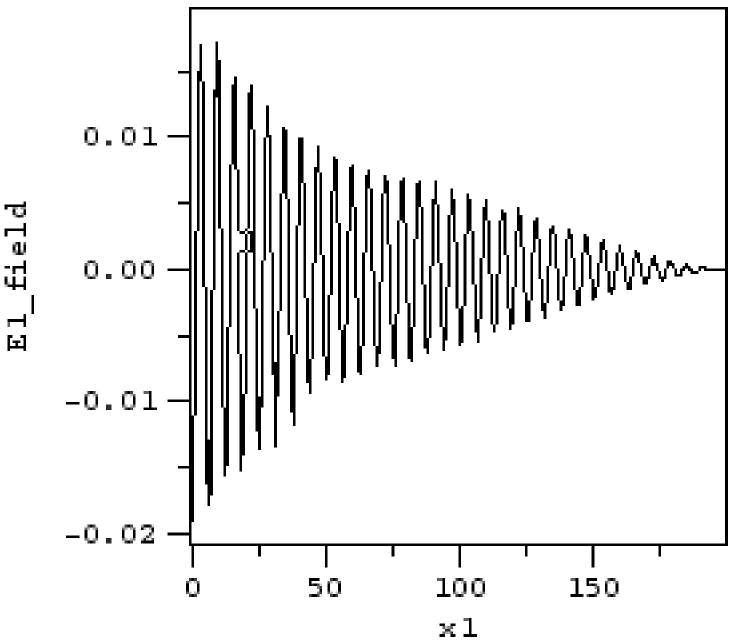


Initial bunch density

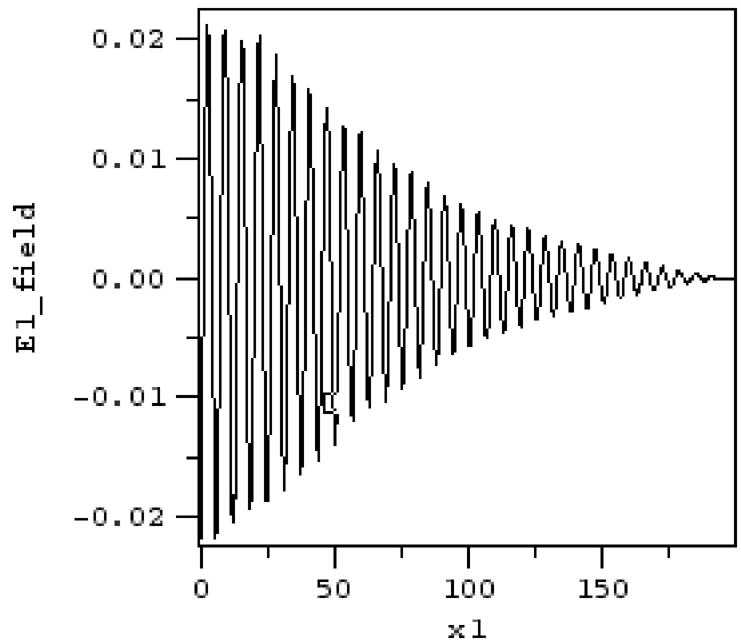


Final bunch density

Wakefield Evolution

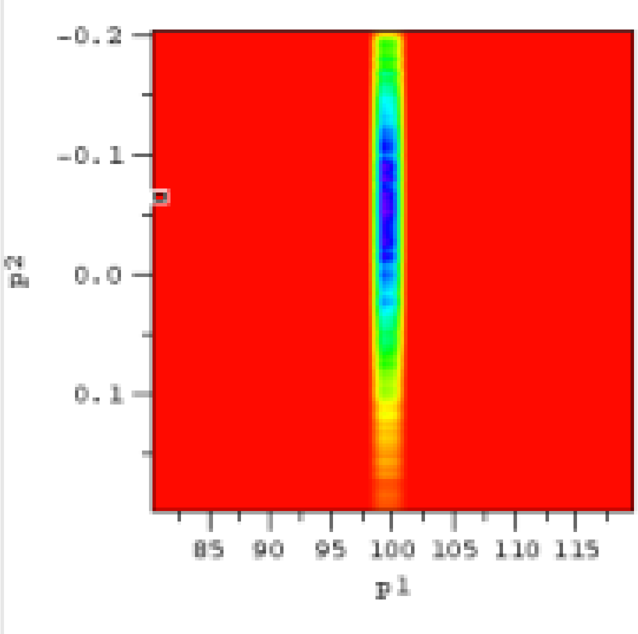


Initial wakefield ($eE/mc\omega_p$)

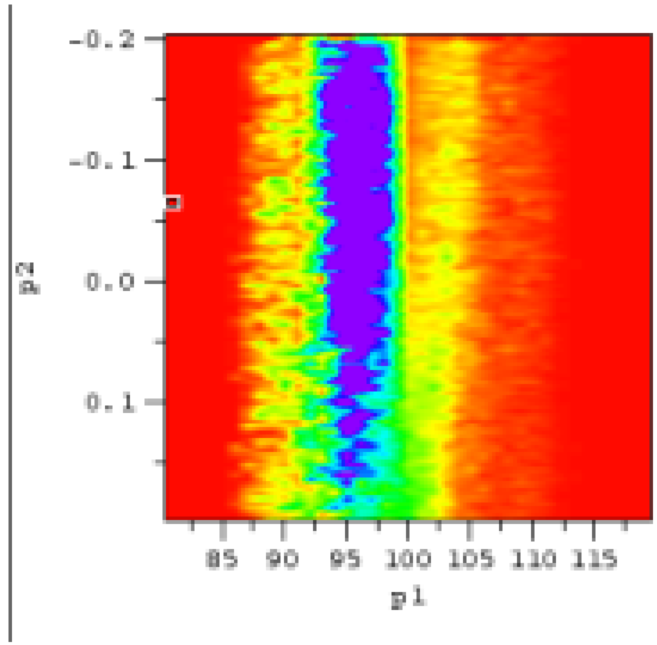


Final wakefield

OSIRIS Simulated Diagnostic

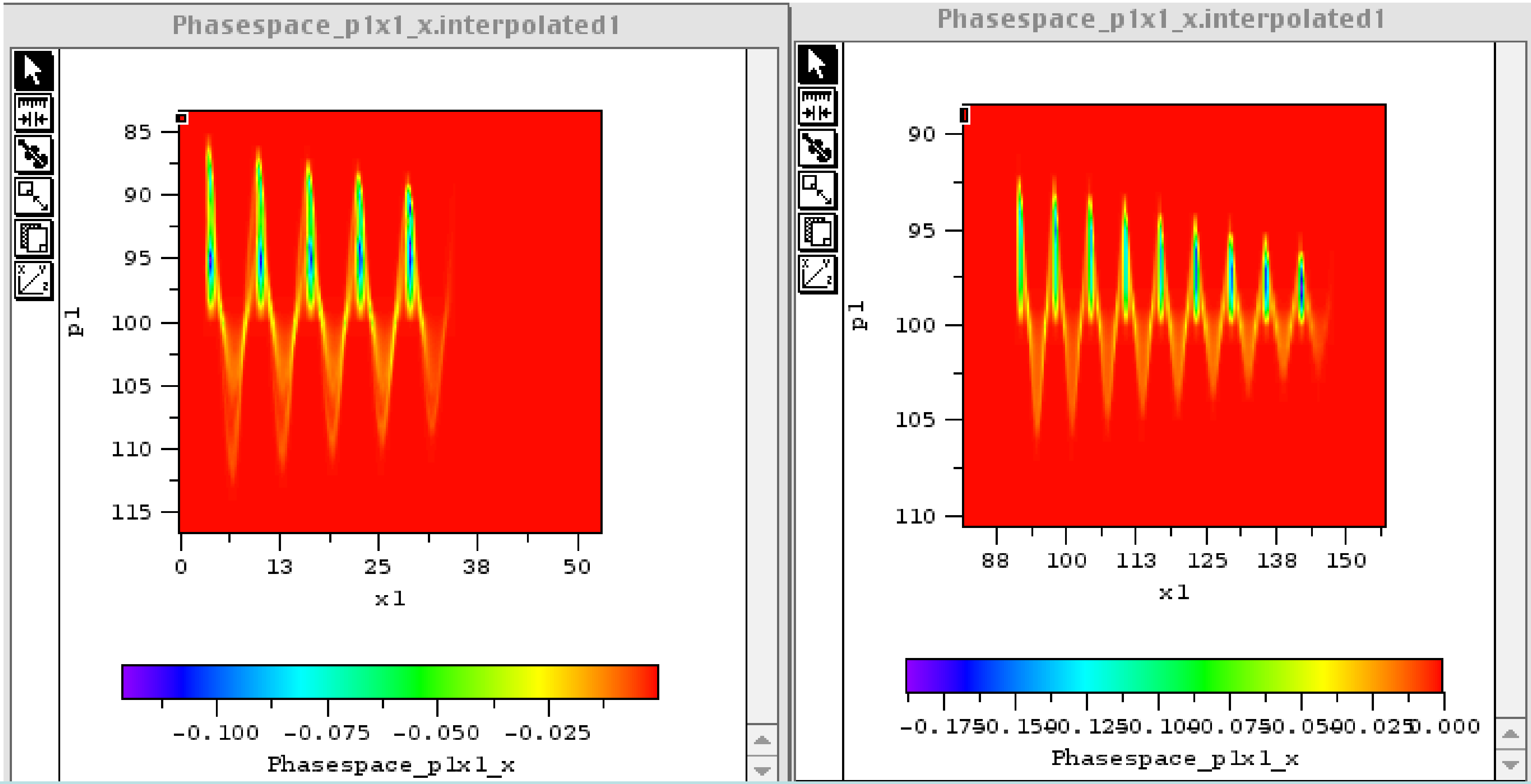


Initial beam momentum distribution (p/mc)



Final beam momentum distribution

Final Phase space of selected bunches



Energy gain and loss can be seen even at resonance

Experimental Design

Adapts ATF PWA setup of Yakimenko et al.:

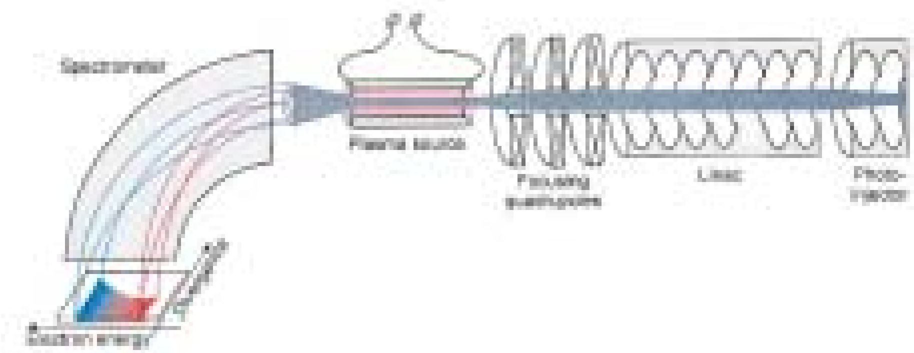
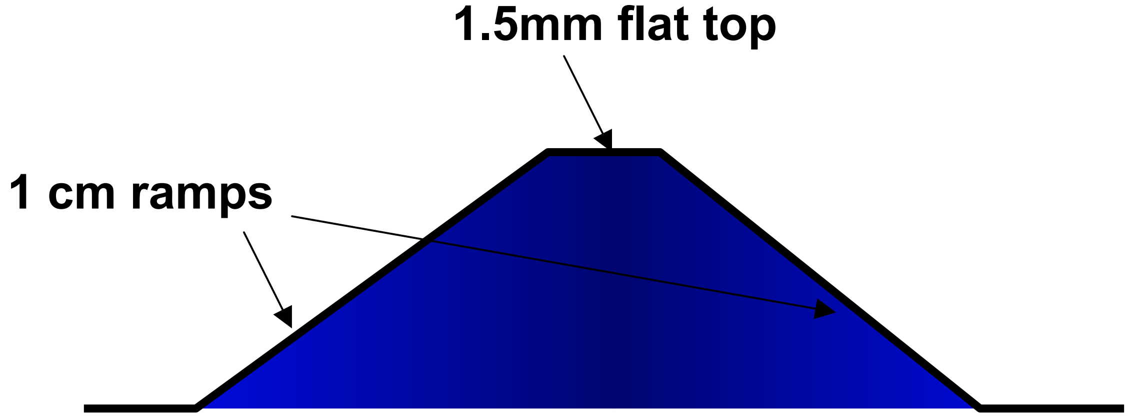


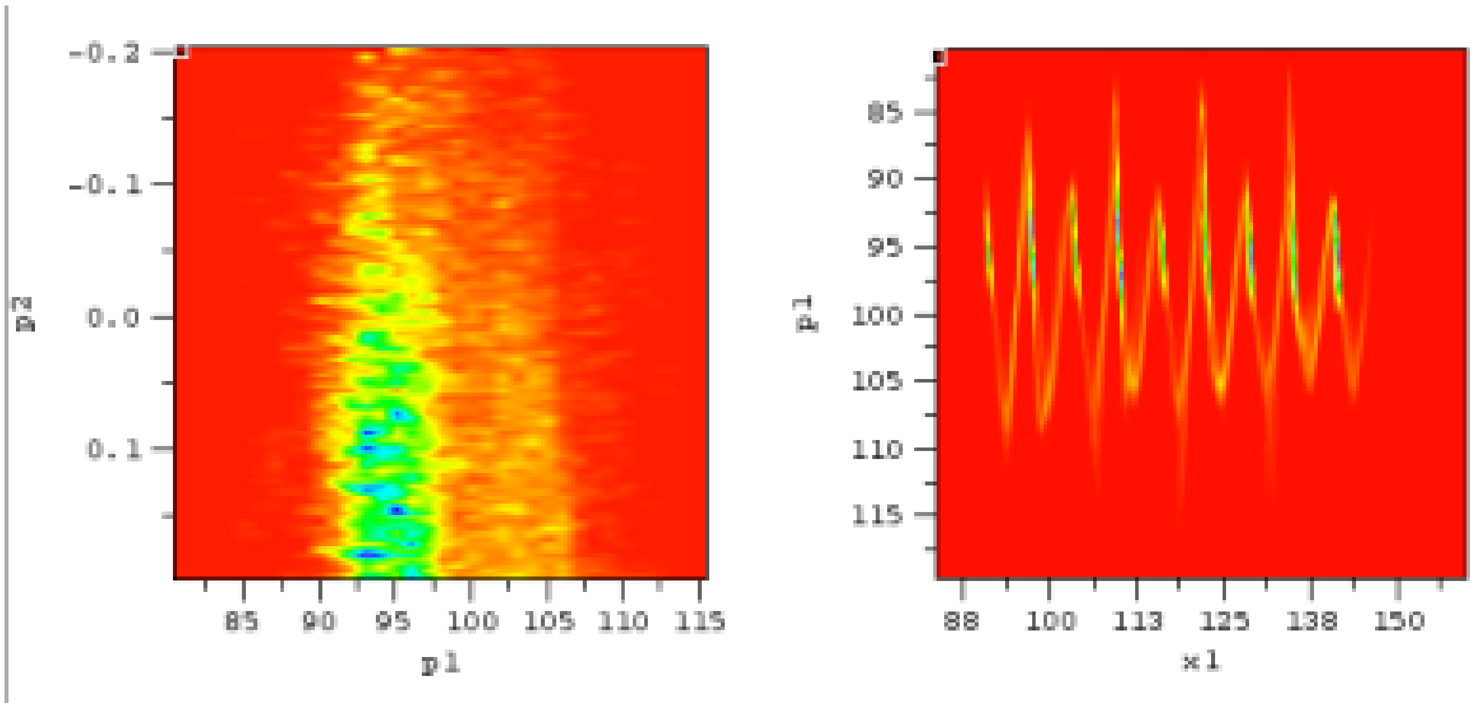
FIG. 1 (color). Schematic diagram of the plasma and electron beam interaction experiment.

- Plasma moved to second stage Stella IP
- Capillary discharge increased from 10^{16} to 10^{19} cm^{-3}

Modeling Plasma Density Gradients



Final energy distribution & phase space



Long non-resonant regions cause small reduction

Plasma Source

Requirements: $n_{e,\,opt}\approx 8\text{-}10\times10^{18}$ cm^{-3}, $\Delta n_e/n_e\approx 1\%$ $L\approx 5$ mm

-Double discharge capillary
(Yakimenko *et al.*, PRL 2003,
Kaganovich *et al.*, APL 1997)

$L\approx 17$ mm $n_e>10^{19}$ cm^{-3}

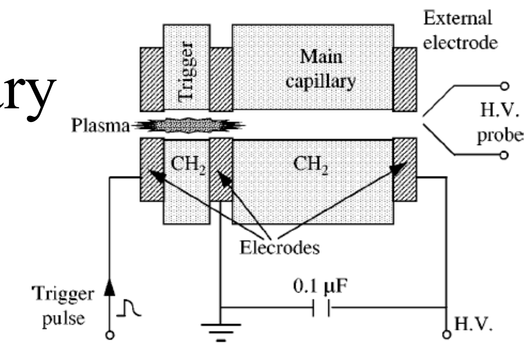


FIG. 1. Experimental setup and capillary design.

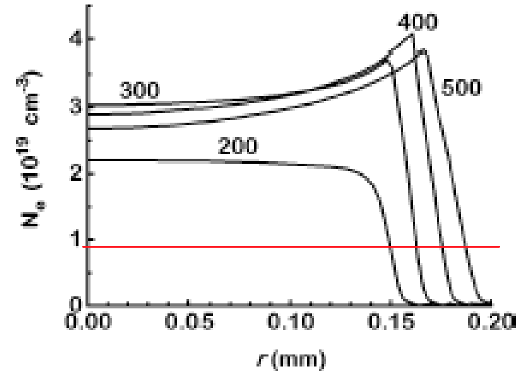


FIG. 2. Electron concentration distribution in the main discharge (I_{max}=0.6 kA, $\tau_{1/2}$=1 μs, diam=0.3 mm, initial density of C+2H plasma=8·10^{-4} g/m^3). Numbers near the curves indicate the time in nanoseconds measured rom the beginning of the discharge.

-H_2-filled capillary
(Spence *et al.*, PRE2001)

$L\approx 3\text{-}5$ mm $n_e\approx 5\times10^{18}$ cm^{-3}

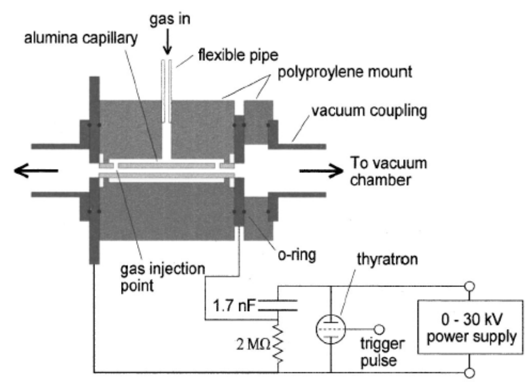


FIG. 1. Schematic diagram of the gas-filled slow capillary discharge, and the associated discharge circuit.

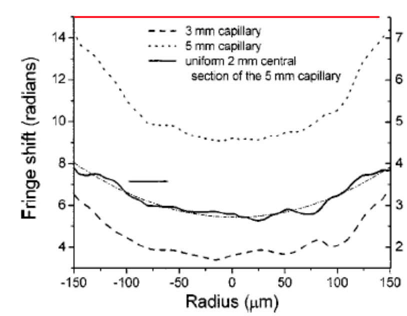


FIG. 2. Fringe shifts measured for 3-mm- and 5-mm-long capillaries. The calculated fringe shift caused by the uniform 2-mm-long central section of the 5-mm capillary is also shown, along with a parabolic fit, as described in the text. The right-hand axis shows the deduced electron density for the central 2-mm-long section.

- Supersonic gas jet (Malka *et al.*, Science 2003)

  - requires $I>10^{14}$ W/cm^2 laser intensity for ionization

Personnel

- USC 
  - PIs: Katsouleas and Muggli
  - Grad Students:
    - 1 student (experiments)
    - Suzhi Deng (simulations)
  - Educational outreach
    - Reid Maeda, UG (linear theory calculations)
    - Bill Qullinan, LA Middle School Teacher (“)
- BNL+
  - V. Yakimenko, I. Pogorelsky, key Stella participants

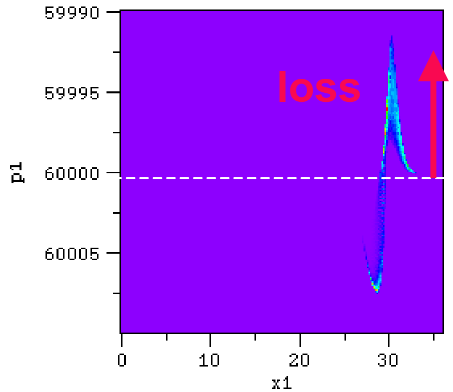
Summary

- Multi-bunch wakefields can lead to energy exchange of several MeV in a mm scale plasma
- Multi-bunch PWA viability can be demonstrated
- Multi-bunch issues can be explored
  - Phasing and resonance
  - Self-modulation enhancement
  - Hosing and other instabilities can be explored

Class homework: **A multi- bunch plasma afterburner for a linear collider**

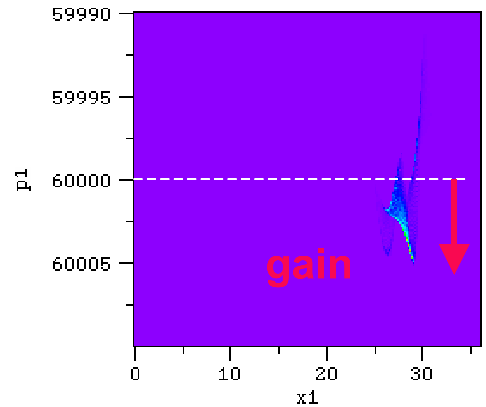
EE 590
MOHAMMAD KAZEMI
University of Southern California, Fall 2002

Bunch 1



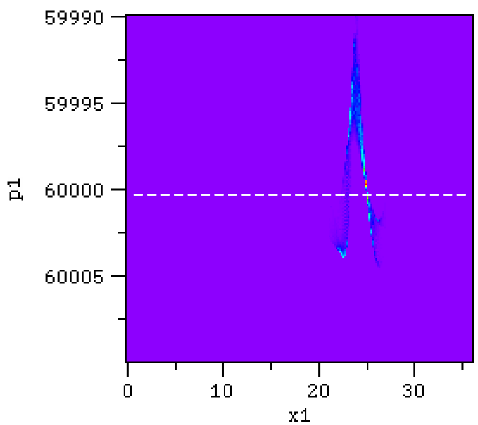
a)

Bunch 2

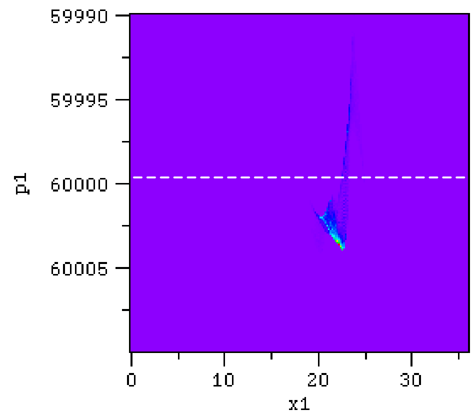


b)

Bunch 3



Bunch 4



Longitudinal phase space -- 2-D OSIRIS simulation, e+