Bunch Length Dependence of Plasma Wakefield Accelerators

A Proposal for a User Experiment
on the ATF User Facility at the
Brookhaven National Laboratory

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OUTLINE

- Motivation for this work

- Plasma Wakefield Accelerator (PWFA) scaling law

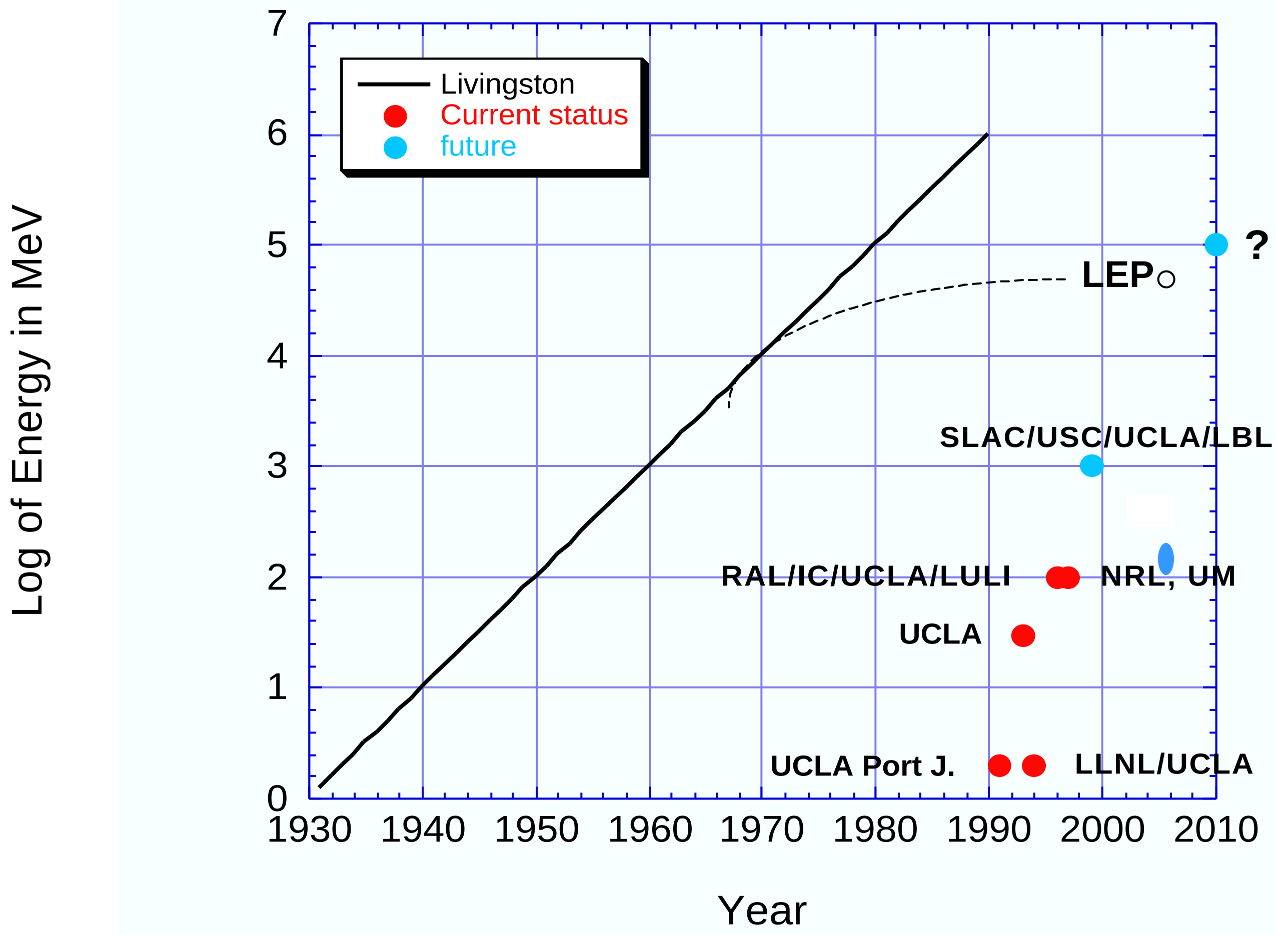
- Why ATF?

- Description of the experiment & plan

- Diagnostics and measurements

- Proposed schedule

MOTIVATION



PWFA?

PWFA KEY ISSUES

- Long plasma production
    - Meter long, homogeneous plasmas (E-157)

- Hose instability
    - Limits the propagation/acceleration length
    - Limits the accelerating gradient

- Transverse dynamics (E-157)
    - Betatron oscillations
    - e^- beam tail motion

- **Acceleration scaling law**

WHAT DO WE PROPOSE?

We propose to measure the parametric dependencies of the PWFA gradient:

$Q=0\text{-}1nC,\ N_b=0\text{-}7\cdot10^9\ e^-$

$n_0=10^{13}\text{-}10^{15}$

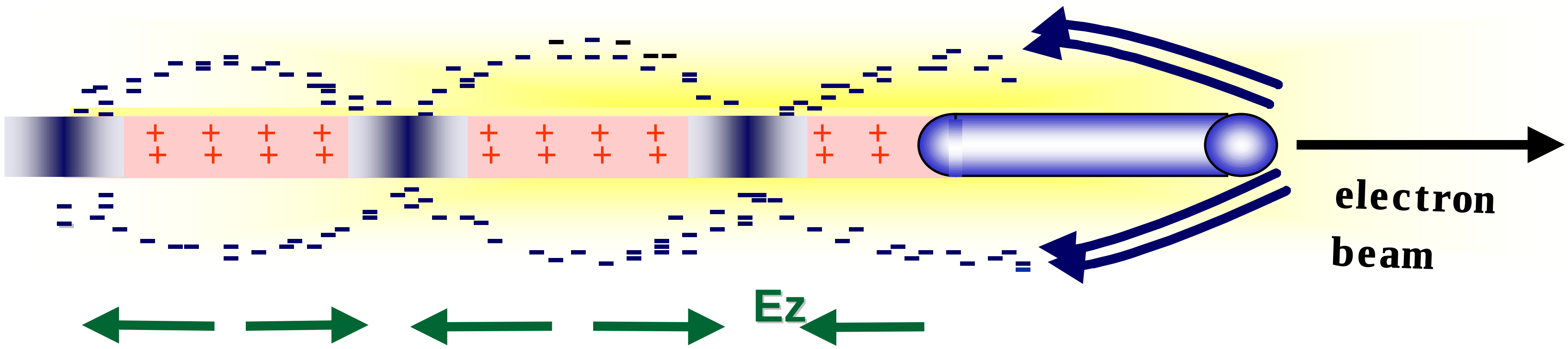
$$eE \approx 70\,MeV/m\left(\frac{N_b}{10^{10}}\right)\left(\frac{1.0}{\sigma_z(mm)}\right)^2 \quad \text{with} \quad \lambda_p \approx 4\sigma_z$$

$\tau=\sigma_z/c=1\text{-}10ps$

Never measured before!

Physical Principles of the Plasma Wakefield Accelerator

- Space charge of drive beam displaces plasma electrons



- Plasma ions exert restoring force => Space charge oscillations
- Wake Phase Velocity = Beam Velocity (like wake on a boat)
- Wake amplitude $\boxed{N_b/\sigma_z^2}$ $\left(\text{for } 4\sigma_z \approx \lambda_p \quad \frac{1}{\sqrt{n_o}}\right)$
- Transformer ratio $E_{zacc.}/E_{dec.beam}$

WAKE FIELD AMPLITUDE

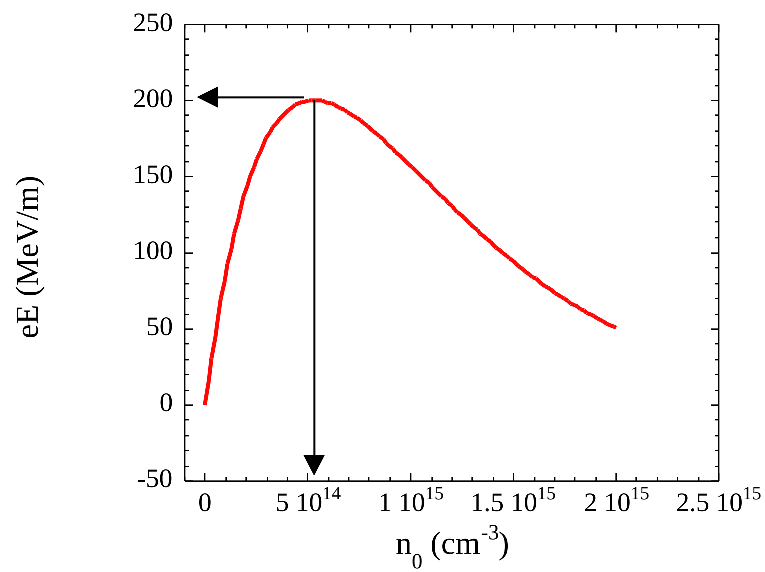
Linear Theory:* $$eE(eV/cm) = \sqrt{n_0(cm^{-3})}\,\frac{n_b}{n_0}\,\frac{k_p\sigma_z e^{-k_p^2\sigma_z^2/2}}{1+1/k_p^2\sigma_r^2}$$

*S. Lee *et al.*, Phys. Rev. E, May 2000

The maximum gradient is given by:

$$\boxed{eE \quad 70\,MeV/m\left(\frac{N_b}{10^{10}}\right)\left(\frac{1.0}{\sigma_z(mm)}\right)^2}$$

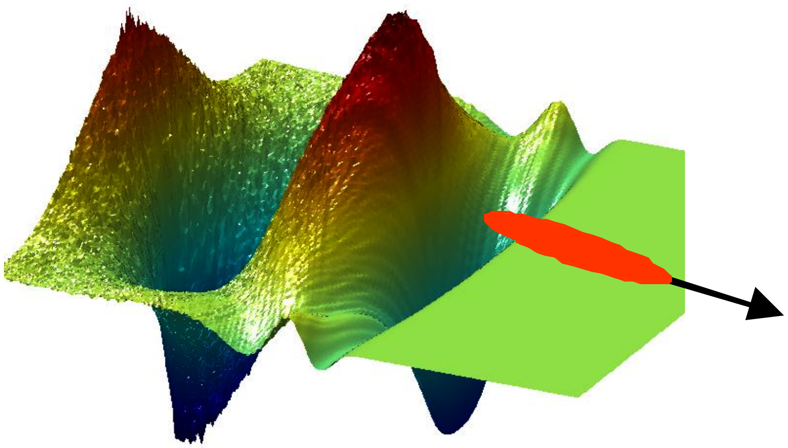
and scale as $1/\sigma_z^2$!



with a plasma density corresponding to: $2\sigma_z \quad \frac{\pi}{c\omega_p}$ or $\lambda_p \quad 4\sigma_z$

ACCELERATING STRUCTURE

2-D non-linear PIC numerical simulation

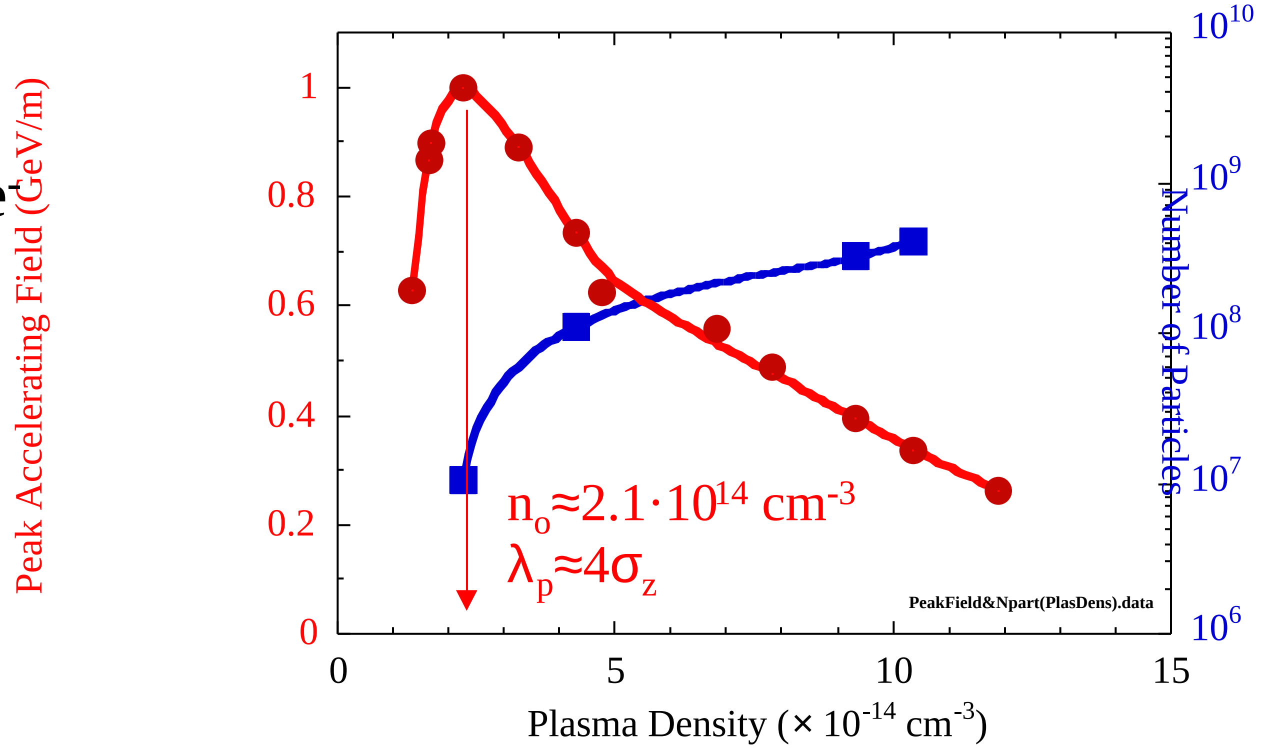


E-157 PWFA : $n_e=2\cdot10^{14}$ cm^{-3}-> f=127GHz

WAKE FIELD AMPLITUDE

2-D non-linear PIC simulation for E-157:

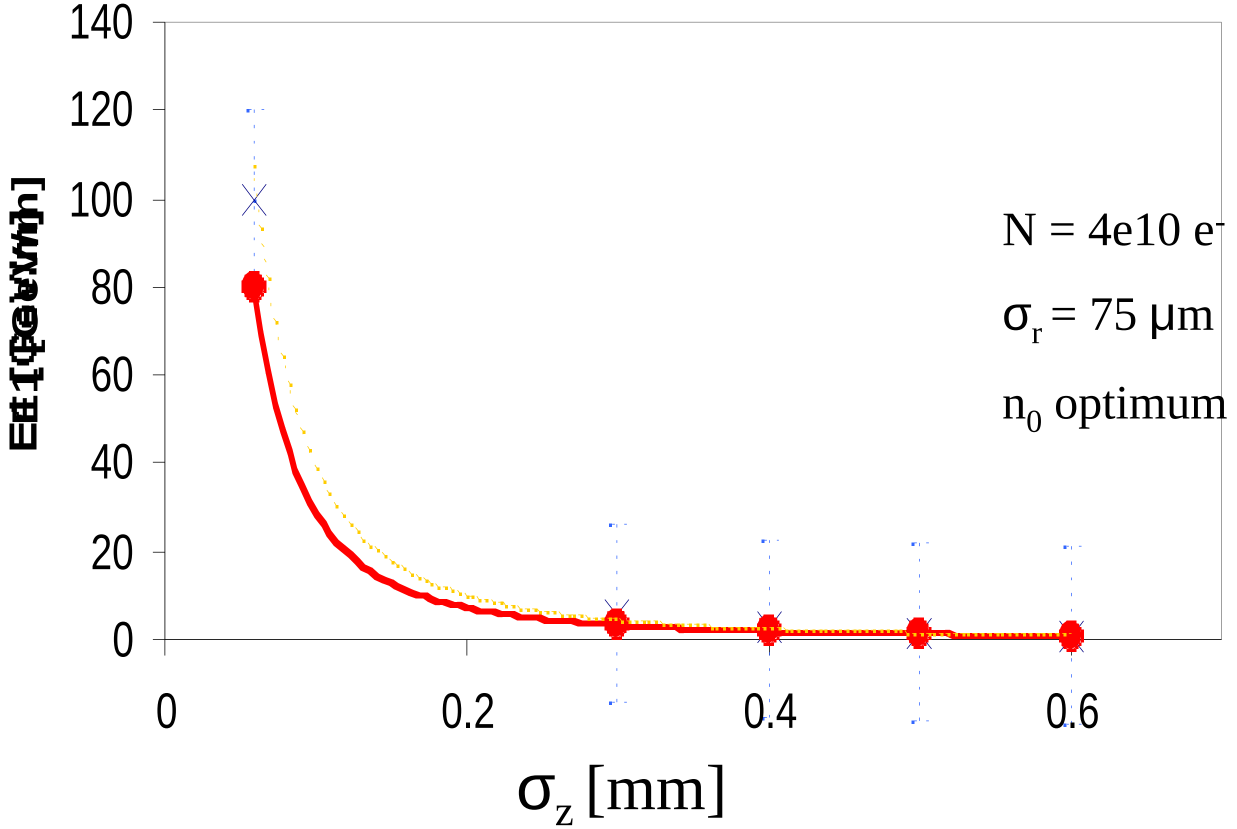
$N_b=4\cdot10^{10}$ e^-
$\sigma_z=0.6$mm
$\sigma_r=70\mu$m
$\gamma=60000$



Check!

ACCELERATING FIELD (E_1) vs. BUMNCH LENGTH

2-D cylindrical, non-linear simulation



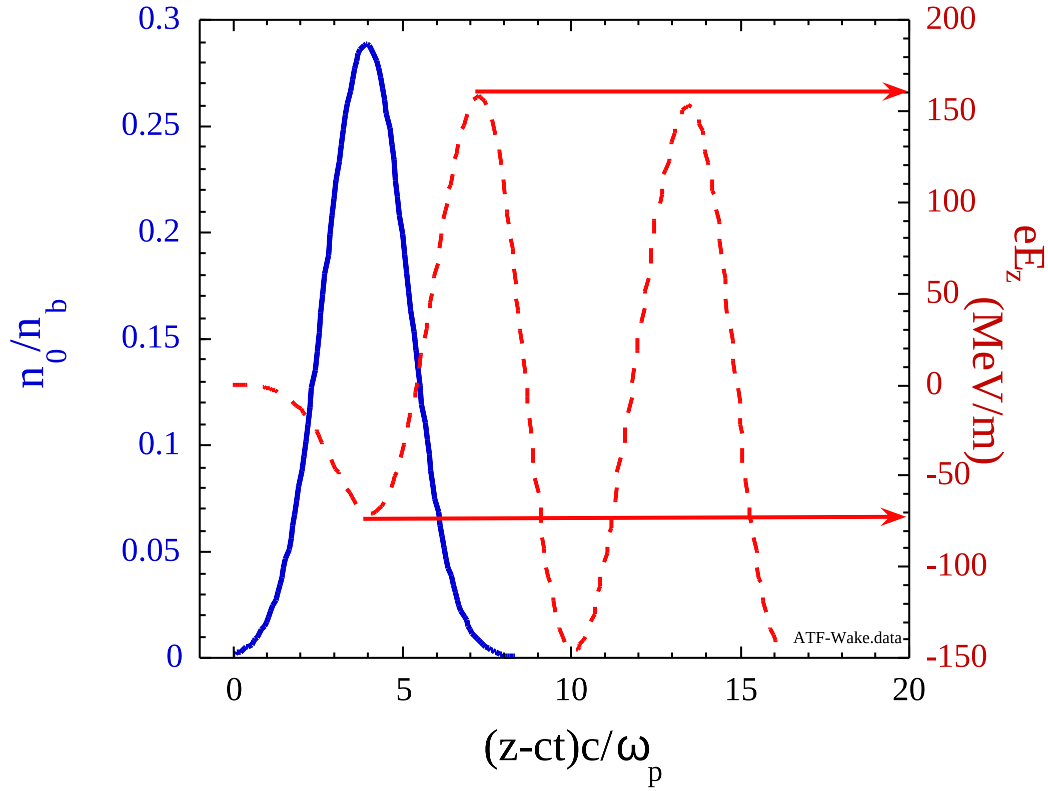
Numerical simulations confirm linear result: $eE \quad 1/\sigma_z^2$

Check!

SIMULATION FOR ATF

2-D fully non-linear simulation (NOVA code)

Q=1nC, σ_z=300µm, σ_r=100µm, $n_0=2\cdot10^{14}$ cm^{-3}



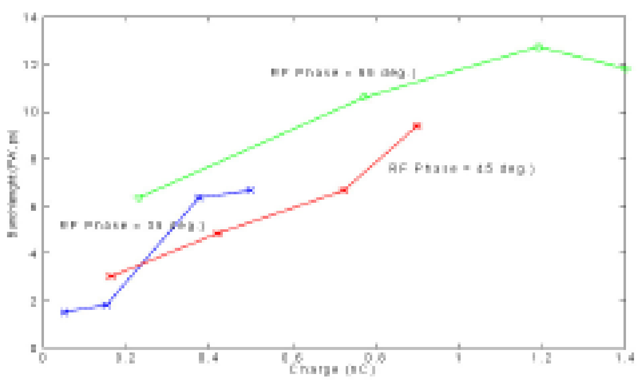
eE≈160MeV/m, $\delta n/n_0=0.12$

WHY ATF?

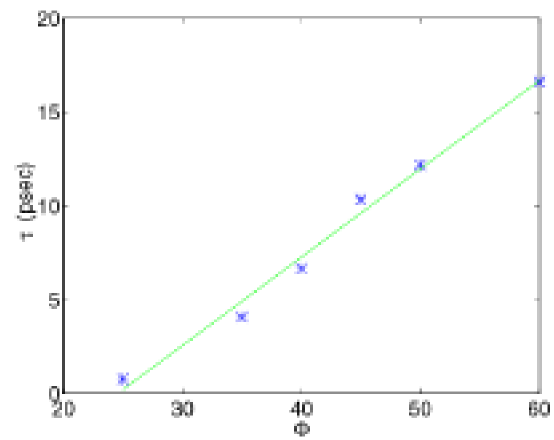
- High quality e^- beam

- High current e^- beam

- Variable e^- bunch length (σ_z)



Bunch length vs. charge and phase
for a 2 mm diameter laser spot size



- TW synchronized CO_2 laser for plasma production/diagnosis

EXPERIMENTAL PLAN

Multi-TW
ATF CO_2 laser
$I>10^{14}$ Wcm^{-2}
over a few cm

ATF e^- beam
0.1,1ps ≤ τ ≤ 10ps
Q ≤ 1nC

H gas cell
0.01T≤P≤1T
or
Li source
ArF laser

Diagnostics:
- Thomson scattering
- Plasma light
- Radiation at f_p

Q=1nC	eE (MeV/m)	n_e (cm^{-3})
τ=1ps	160	$7.8\cdot10^{14}$
τ=10ps	1.6	$7.8\cdot10^{12}$

Plan: Vary n_e for each σ_z (or τ), and Q (or N_b)

PLASMA SOURCE

- Field ionized H or He static fill
  - requires CO_2 laser pulse with $I>10^{14}$ W cm^{-2} over a few cm (TW ATF upgrade)
  - fully ionized
  - plasma density determined from gas pressure

- Lithium plasma source
  - requires ArF Excimer laser
  - large dimensions plasma

THOMSON SCATTERING

- Laser light scatters on the plasma wake (grating)

- Scattered power: $$\frac{P_{scatt}}{P_{inc.}} = \left(\frac{\pi}{2}\frac{n_0}{n_{crit}}\frac{\delta n}{n_0}\frac{L}{\lambda}\right)^2$$ (at k-matching)

- Compare to the UCLA Mars case:

$\delta n/n_0=0.3$ (eE=3GeV/m, $n_e=10^{16}$ cm^{-3}), $\lambda=0.5\mu m$, $n_0/n_{crit}\approx 2.2\cdot 10^{-6}$, $L\approx 200\mu m$

$\delta n/n_0=0.1$ (eE=160MeV/m, $n_e=2\cdot 10^{14}$ cm^{-3}), $\lambda=10.6\mu m$, $n_0/n_{crit}\approx 7.8\cdot 10^{-5}$, $L\approx 2cm$

$$\frac{P_{scatt}}{P_{inc.}} \approx 30 \left.\frac{P_{scatt}}{P_{inc.}}\right|_{UCLA}$$

- Frequency shift: $\omega_s=\omega\pm\omega_p$ or 130GHz @ $n_e=2\cdot 10^{14}$ cm^{-3}

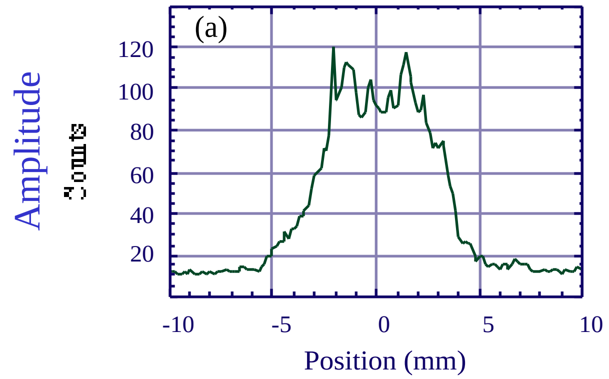
Spectrograph can resolve $\Delta\nu \approx 10$GHz

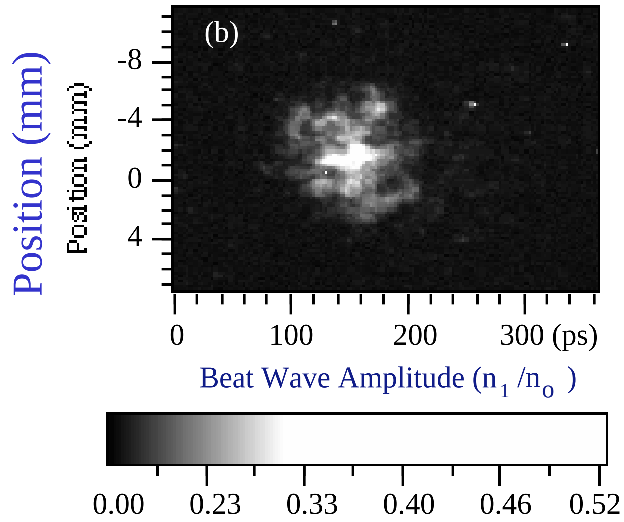
THOMSON SCATTERING

Mars Laboratory, UCLA:
space and time resolved Thomson scattering

Parameters:

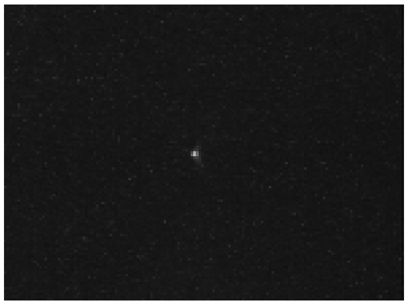
$n_e \approx 10^{16}$ cm^{-3}
$\lambda = 0.5 \mu m$
$L \approx 200 \mu m$



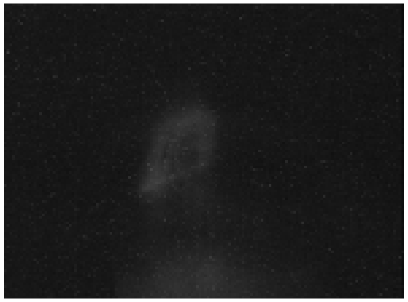


PLASMA LIGHT FROM WAKE DISSIPATION

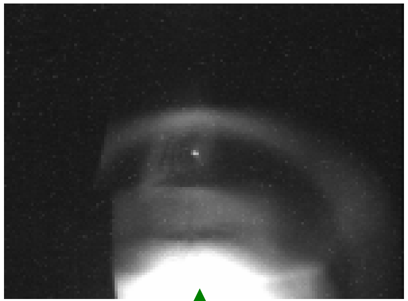
(Preliminary E-157 result*)



e⁻ Beam Only

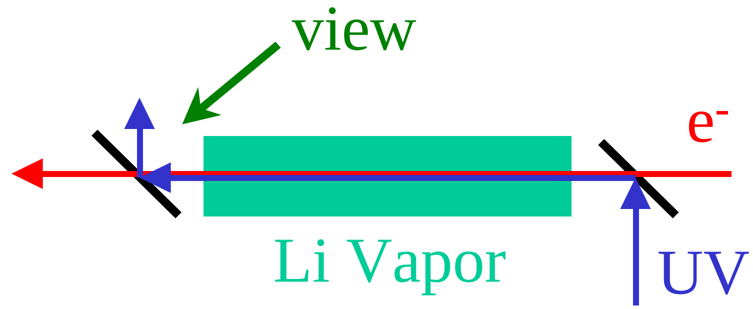


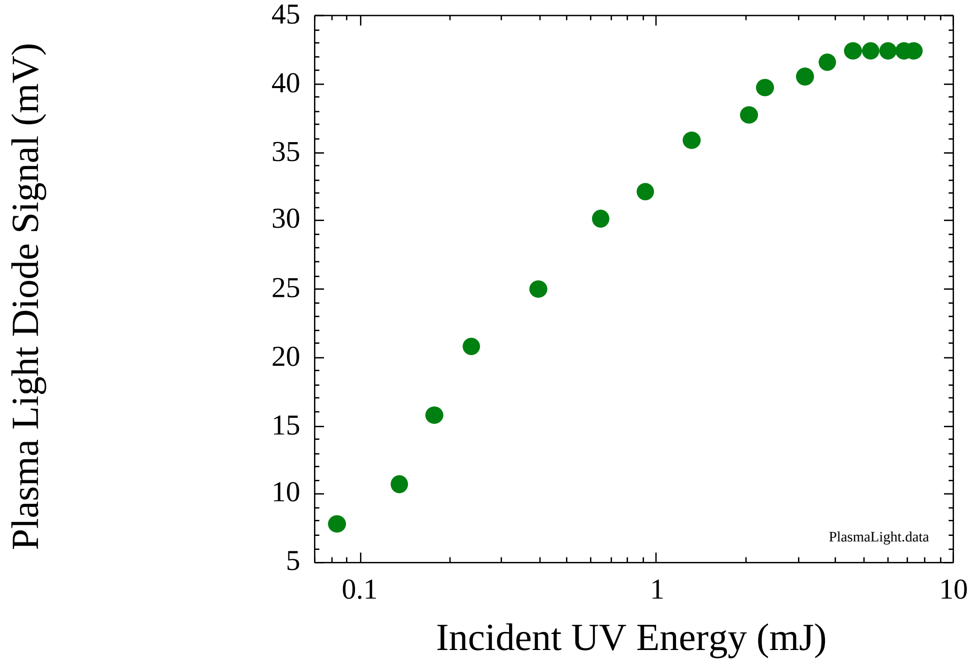
Laser/Plasma Only



e⁻ Beam + Plasma

Plasma Light





* P. Catravas *et al.*, in prep.

PLASMA RADIATION AT f_p

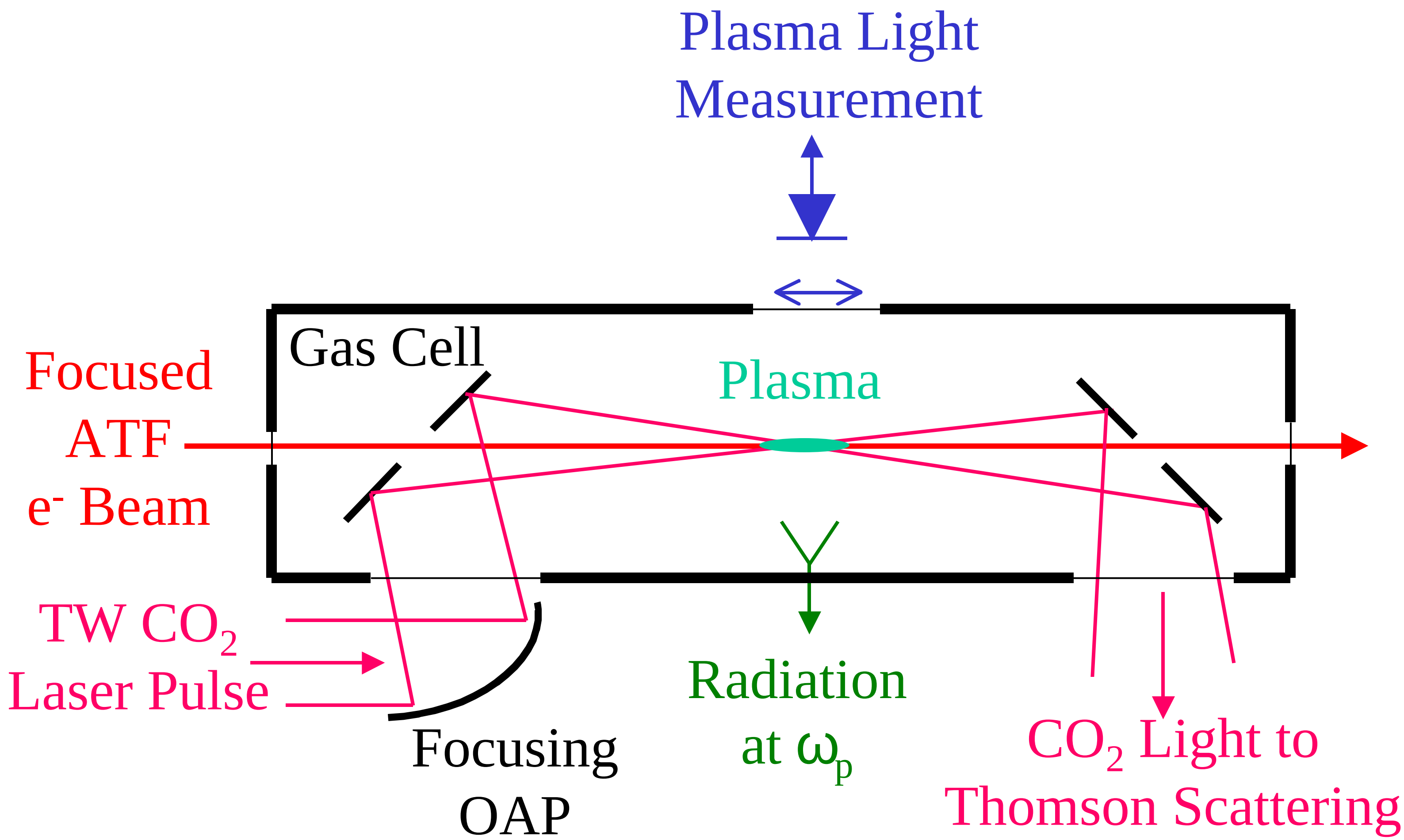
- With n_e in the 10^{14} cm^{-3} range, $f_p \approx 100GHz$ range

- Plasma waves do not couple efficiently to vacuum modes

- Large amplitude plasma waves are excited

- Detect leakage of plasma radiation at f_p

SCHEMATIC OF THE EXPERIMENT



PROPOSED SCHEDULE

- Experiment extends over 2-3 years, with 1 or 2 runs/year

- Each run is 3-4 weeks

- Each run is preceded by >4 weeks of off line preparation

- However, will accommodate ATF schedule

EXPERIMENTAL PLAN

- Use unique ATF capabilities to measure the wake amplitude scaling with respect to the e^- bunch length ($eE \quad 1/\sigma_z^2$)

- Use a field-ionized H plasma or a lithium plasma source

- Measure wake amplitude as a fct of σ_z, N_b, and n_0 using:

    - Thompson scattering of CO_2 laser pulse
    - Plasma light produced by dissipation of the wake
    - Radiation at ω_p from the plasma (μwave)

- Parameters:

    - $Q \leq 1$nC
    - σ_z=1ps eE=160MeV/m $n_0 \approx 7.8 \cdot 10^{14}$ cm^{-3}
    - σ_z=10ps eE=1.6MeV/m $n_0 \approx 7.8 \cdot 10^{12}$ cm^{-3}