Multi-bunch Plasma Wakefield Experiments

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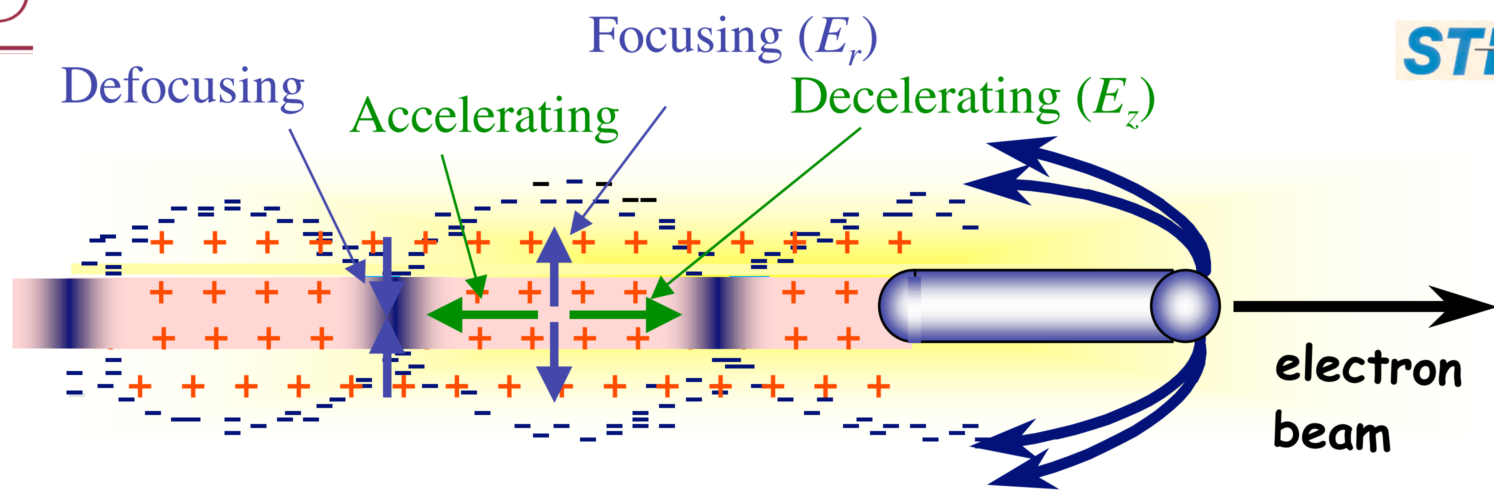
OUTLINE

- Introduction to the plasma wakefield accelerator (PWFA)
- Single bunch results
- Multi-bunch experiments (2-150)
- Two bunches at ATF
- Plasma source
- Experimental results / comparison with theory
- Summary / Conclusions

e^--BEAM-DRIVEN PWFA



- Plasma wave/wake excited by a relativistic particle bunch
- Plasma e^- expelled by space charge forces => energy loss + focusing
- Plasma e^- rush back on axis => energy gain

- Plasma Wakefield Accelerator (PWFA) = Energy Transformer

Booster for high energy accelerator?

Vol 445|15 February 2007|doi:10.1038/nature05538 nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

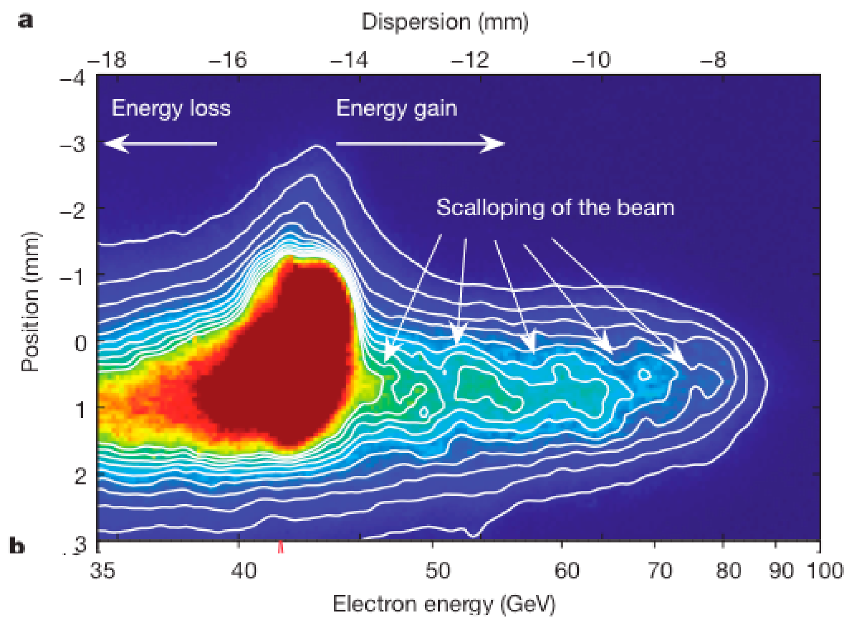


Figure 2 | Energy spectrum of the electrons. **a**, Energy spectrum of the electrons in the 35–100 GeV range as observed in plane 2. The dispersion

SLAC Beam:
E_0=28.5 GeV
σ_z≈20 μm
N=1.8x10^{10} e^-
n_e=2.7x10^{17} cm^{-3}
L=90 cm

42 to 84 GeV in 90 cm
Energy Doubling

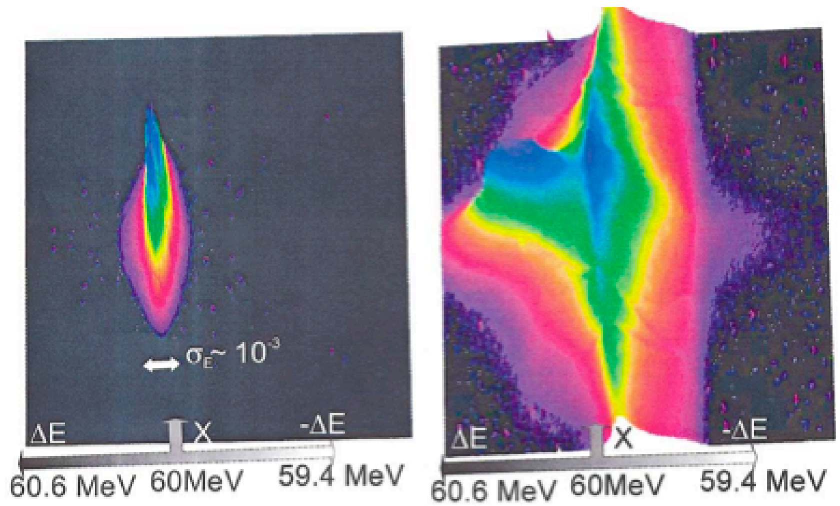
→ 100% ΔE/E

PREVIOUS PWFA AT BNL-ATF

VOLUME 91, NUMBER 1 PHYSICAL REVIEW LETTERS week ending 4 JULY 2003

Cohesive Acceleration and Focusing of Relativistic Electrons in Overdense Plasma

V. Yakimenko,[1] I.V. Pogorelsky,[1] I.V. Pavlishin,[1] I. Ben-Zvi,[1] K. Kusche,[1] Yu. Eidelman,[1] T. Hirose,[2] T. Kumita,[3] Y. Kamiya,[3] J. Urakawa,[4] B. Greenberg,[5] and A. Zigler[5]

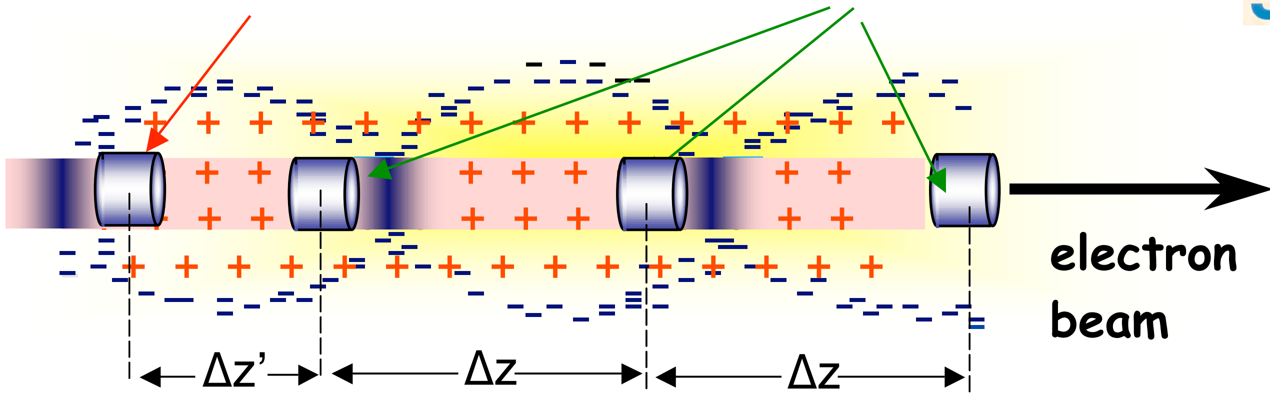


(a) (b)

FIG. 4 (color). Spectrometer images, showing intensity in a combined false-color and contour plot. Energy is shown on the horizontal axis and transverse size in the vertical axis: (a) plasma off, (b) plasma on, $\Delta t = 3\ \mu s$.

- ATF 300 pC, 1.3 ps: gain 0.6 MeV over 17 mm plasma at $n_e \approx 5 \times 10^{16}$ cm^{-3}
- Accelerating gradient: 35 MV/m
- Continuous energy spread

MULTI-BUNCH PWFA



- Bunch spacing/plasma density condition:

  $\Delta z = \lambda_p$ (resonance) $\sigma_z \ll \lambda_p$

  $\Delta z' \approx \lambda_p / 2$

Plasma wavelength: $\lambda_p = \dfrac{2\pi c}{\omega_{pe}}$ Plasma angular frequency, density n_e: $\omega_{pe} = \left(\dfrac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

- Wake fields add up (linear theory):

  $E_{z\ N\ bunches} = N \times E_{z\ 1\ bunch}$ (beyond energy doubling!)

- Maximize transformer ratio with "shaping"
- Finite energy spread, beam acceleration

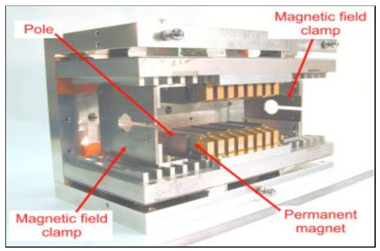
Experiment Overview

Electron Beam

$I_{peak} \approx 100$A
$E_0 = 45$ MeV
$Q = 300$ pC

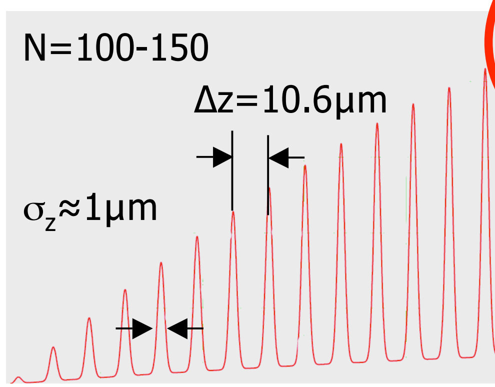
1500 µm

10µm IFEL Pre-buncher
⇒Velocity modulation
⇒$\Delta E/E \approx 1\%$

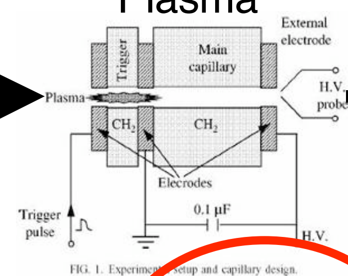


Multi-bunches
$I_{peak} \approx 600$A
$\sigma_r = 25$µm

2.5 m Drift



Ablative Capillary Discharge Plasma



$n_0 = 10^{19}$ cm^{-3}
Resonant for $\lambda_p = 10.6$µm

$$\frac{\Delta n_e}{2n_e} = \frac{\Delta\omega_{pe}}{\omega_{pe}} \propto \frac{1}{N}$$

$n_e = 10^{19}$ cm^{-3} ± a few %

Energy Diagnostic for Bunching and PWFA

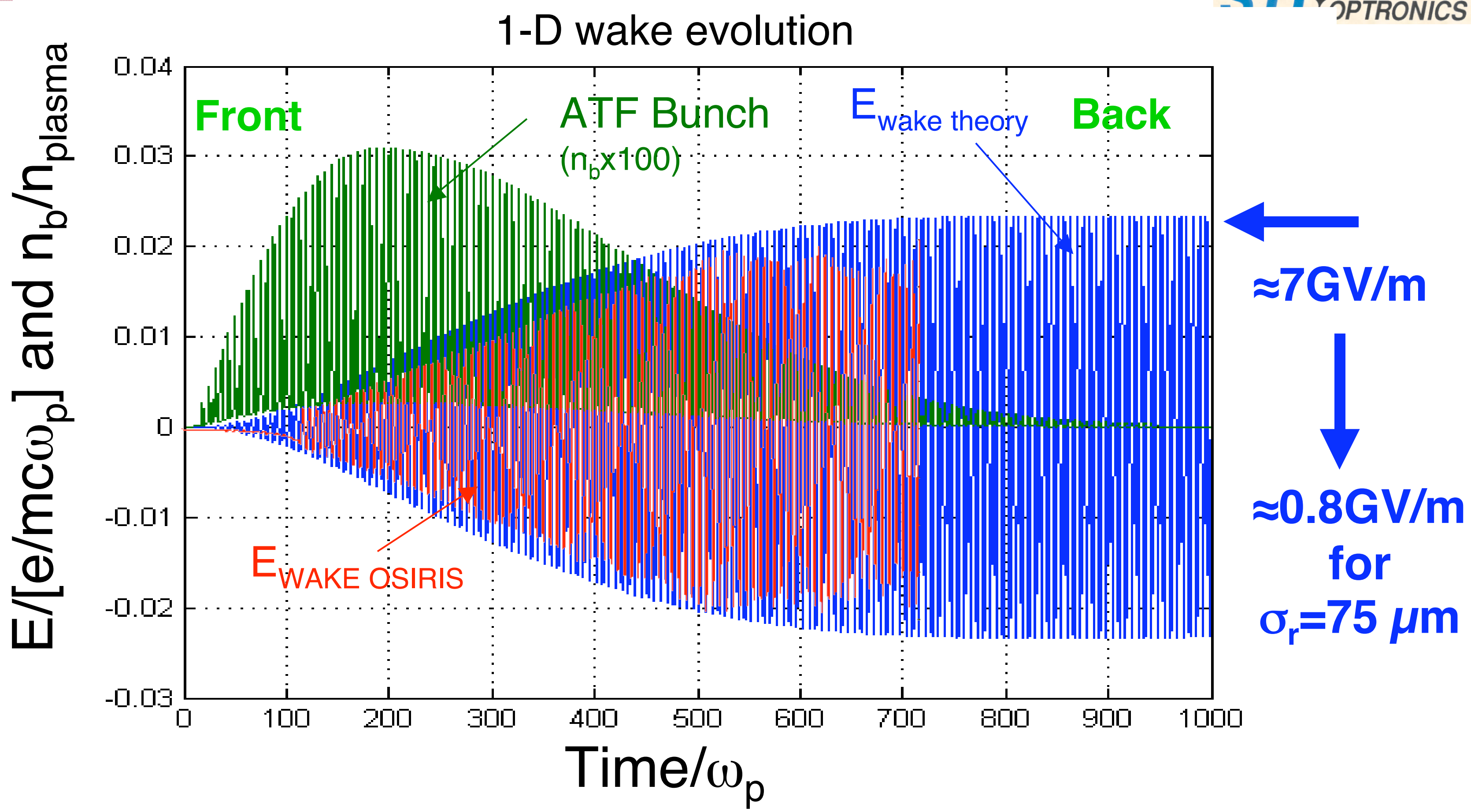
Laser Beam

CO_2: $\lambda_0 = 10.6$µm, 200 ps

$P_{peak} \approx 1$-2GW

➡ Components available on ATF beam line 1

WAKEFIELD: THEORY-SIMULATIONS



- Theory: non-linear equations for E_{wake}, p_z, n_e
- Resonant plasma density: $n_0=1.0\times10^{19}$ cm^{-3} over 1 mm plasma, 10.6 μm bunch spacing. $[0.01\ e/(mc\omega_p) = 3\text{GV/m}]$, $\sigma_r=25\mu$m
- ≈6.5 GeV/m with good agreement between theory and simulation

SOLUTIONS

- Difficult to reach 10^{19} cm^{-3} in capillary (D. Stolyarov, yesterday)

- Larger bunch spacing Δz <=> lower n_e

  This morning, W. Kimura: "Generation of Tunable Micro-bunch Train"

  Choice of Δz <=> choice of n_e
  Choice of number of bunches
  Generation of witness bunch
  Beyond energy doubling (application to high energy accelerator, ILC?)

- Two-bunch experiment

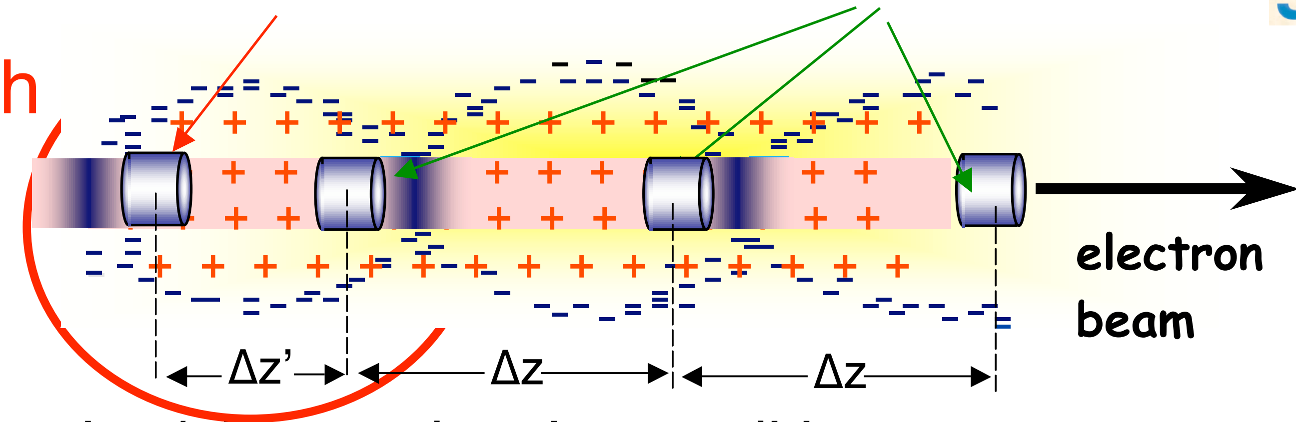
  Two-bunch parameters fixed (length, delay, charge, …)

  Vary plasma density n_e to vary relative phase of witness bunch in the accelerating structure

  Accelerating gradient varies with n_e

  Narrow energy spread?

MULTI-BUNCH PWFA



- Bunch spacing/plasma density condition:

  $\Delta z=\lambda_p$ (resonance) $\sigma_z \ll \lambda_p$

  $\Delta z=\lambda_p/2$

  Plasma wavelength: $\lambda_p = \dfrac{2\pi c}{\omega_{pe}}$ Plasma angular frequency, density n_e: $\omega_{pe} = \left(\dfrac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$

- Wake fields add up (linear theory):

  $E_{z\ N\ bunches} = N \times E_{z\ 1\ bunch}$ (beyond energy doubling!)

- Maximize transformer ratio with "shaping"
- Finite energy spread, beam acceleration

TWO-BUNCH GENERATION

W. Kimura *et al.*,
AAC'06 Proceedings

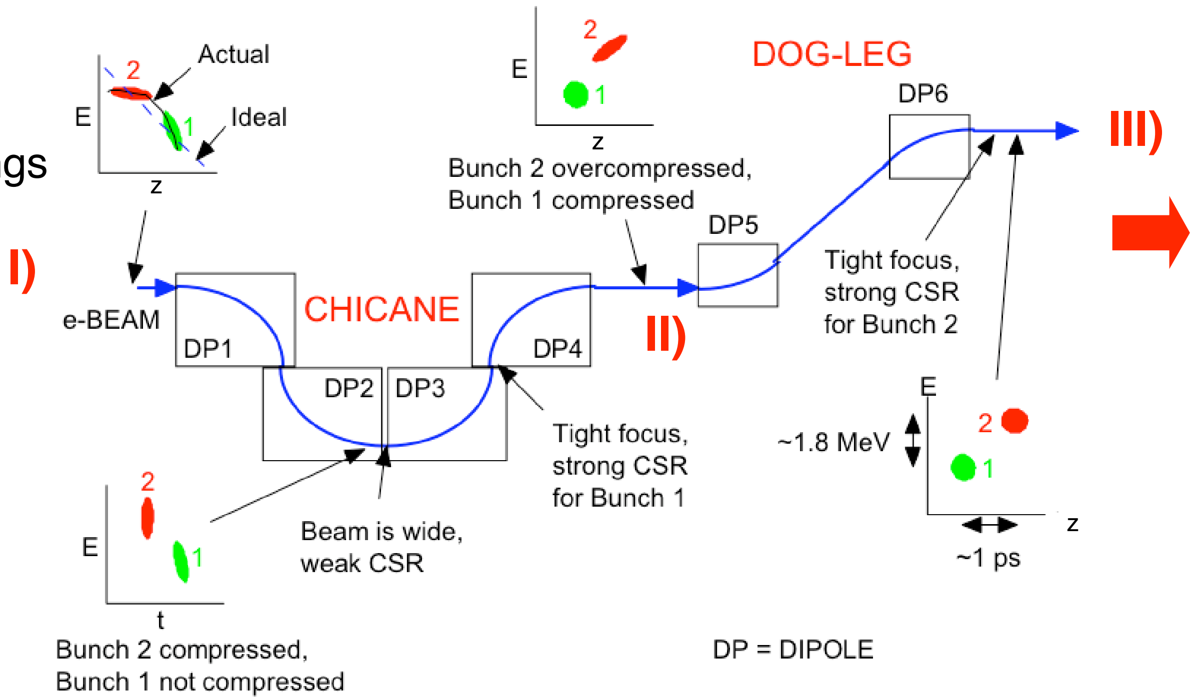
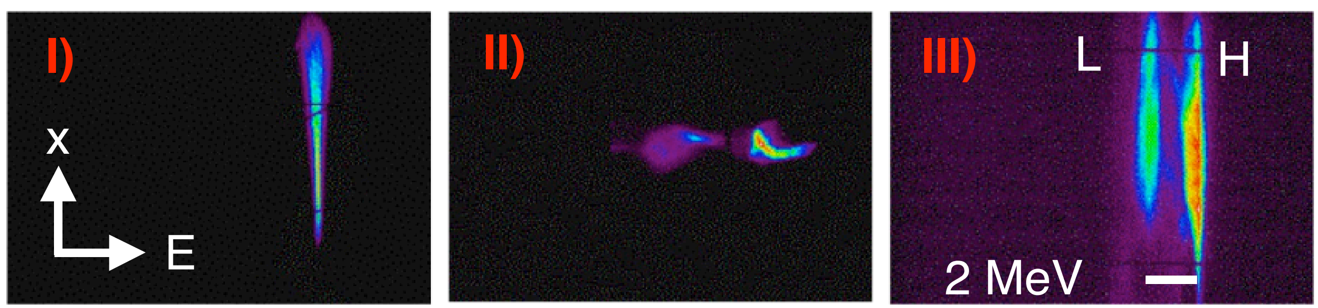


FIGURE 2. Cartoon of chicane/dogleg system showing a possible scenario for the double-bunch formation process.



(a) (b) (c)

FIGURE 3. Raw energy spectrums of double-bunch *e*-beam. Energy dispersion increases to the left. (a) Before the chicane and without compression. Energy spread is ~4% FWHM. (b) At the high-energy slit located downstream of the chicane. (c) At the spectrometer at the end of the beamline.

Two-bunch Parameters:

$E_0 \approx 60$ MeV
$\Delta E \approx 1.8$ MeV
$Q_{High} = 300$ pC
$Q_{Low} = 200$ pC

TWO BUNCHES IN TIME

Coherent Transition Radiation (CTR) Interferometry
Bunch Auto-correlation Trace

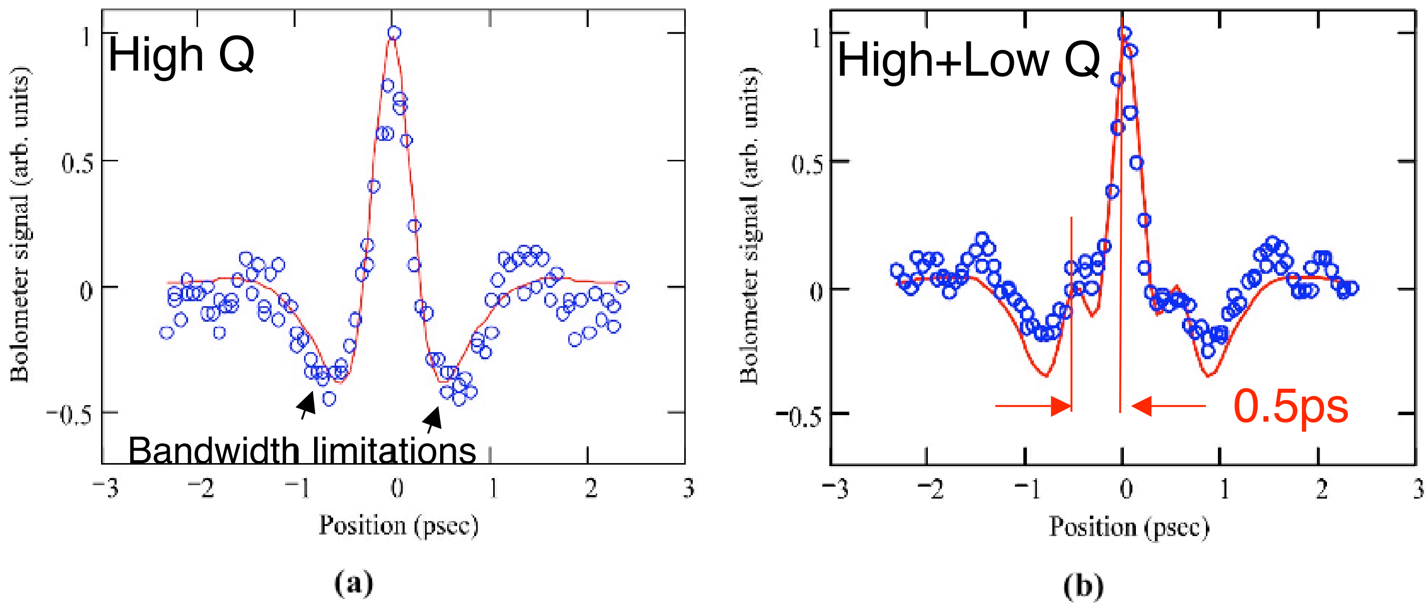


FIGURE 7. Example of raw data from CTR interferometer (circles) and the curve fits to the data (solid line) calculated from the autocorrelation integral [2]. (a) Single bunch. (b) Double bunches.

- Single Bunch: $\sigma_\tau \approx 144$ fs
- Double Bunch (Gaussian): $\sigma_{\tau\ High} \approx 144$ fs, $\sigma_{\tau\ Low} \approx$ 90 fs; Q_{High}=300 pC, Q_{low}=200 pC; $\Delta\tau \approx 500$ fs

- Use PWFA interaction to determine time sequence! (High=Driver, Low=Witness)

PLASMA

Ablative Capillary Discharge

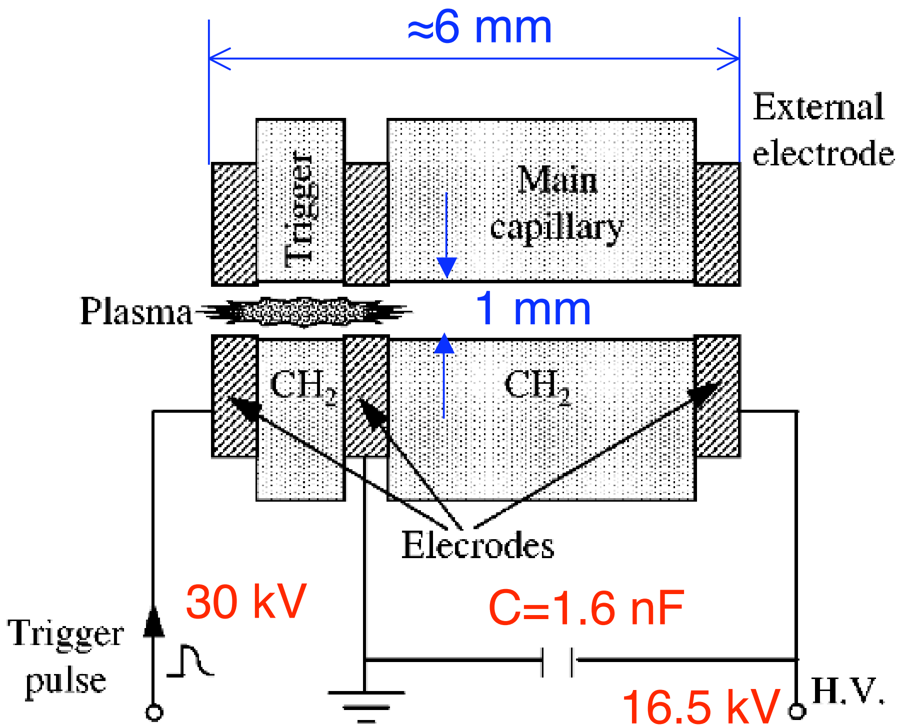
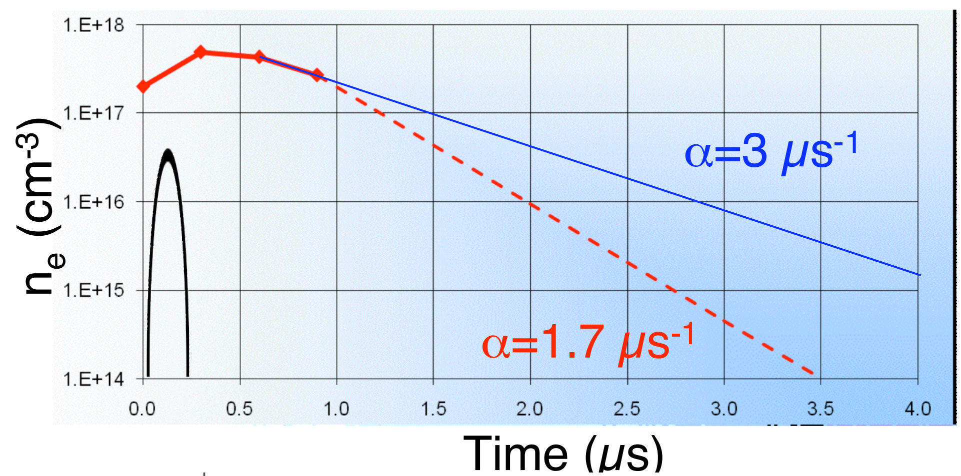


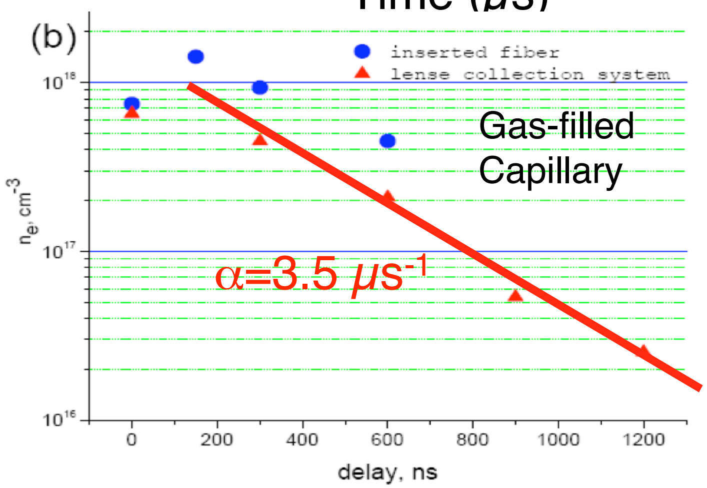
FIG. 1. Experimental setup and capillary design.

Kaganovich *et al.*, APL 1997

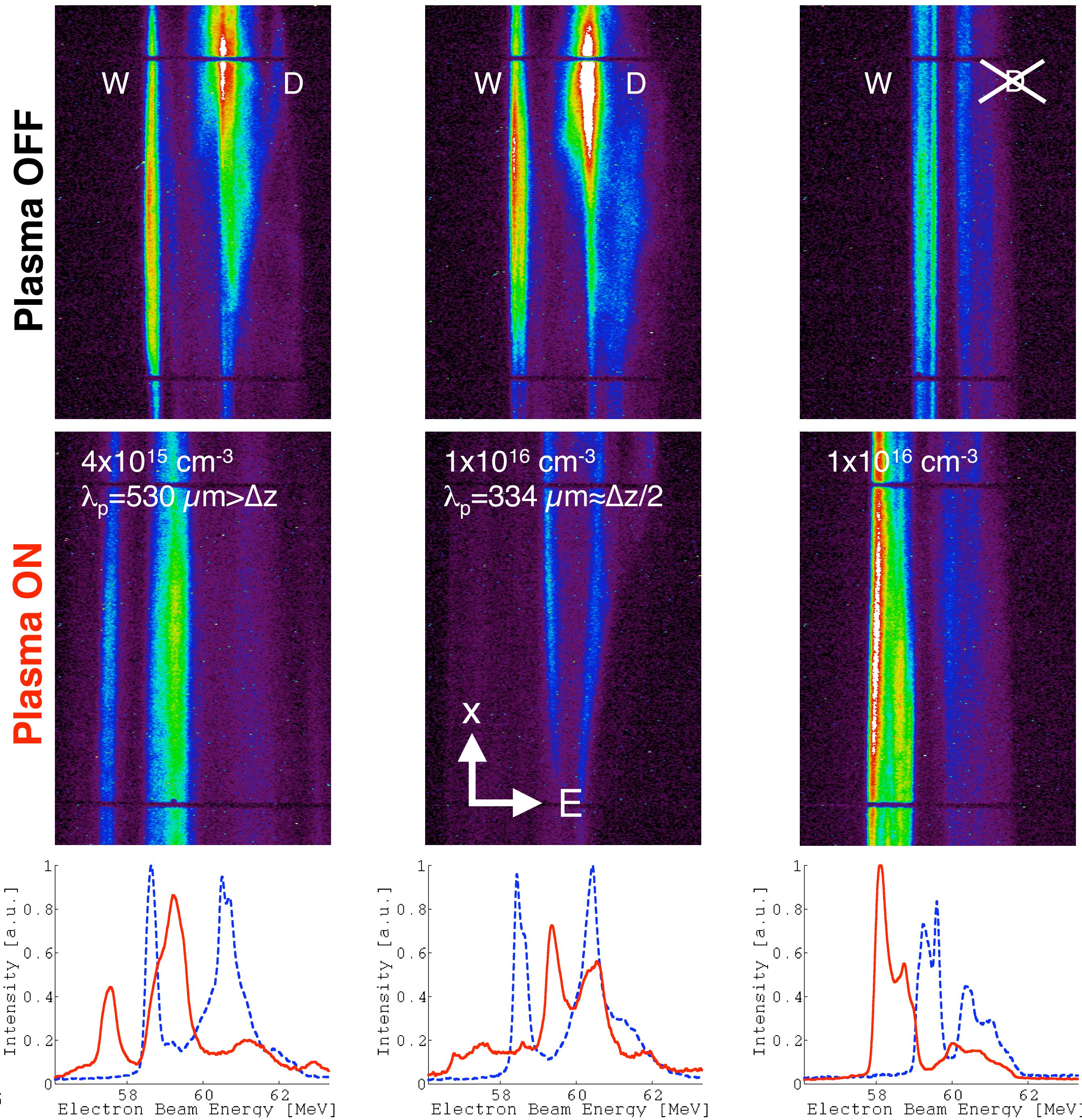
Plasma Density from H_α Stark Broadening

After I=0: $n_e = n_{e0} e^{-\alpha t}$

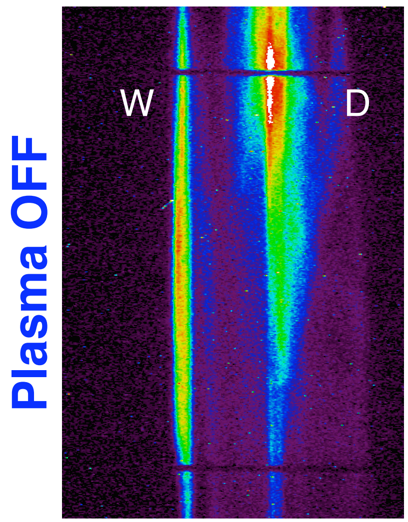


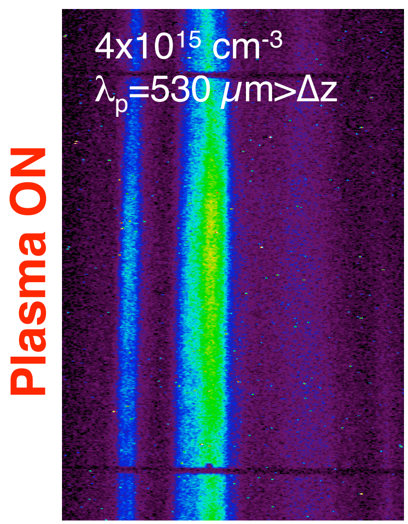


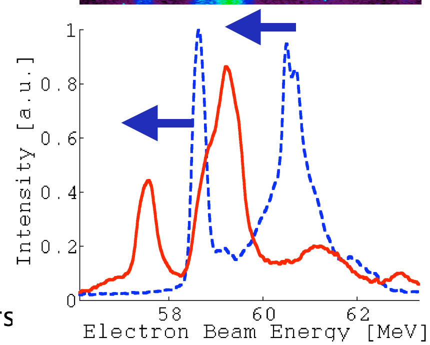
➡ Vary discharge-beam delay to vary the plasma density


Plasma OFF
Plasma ON
W
D
4x10^15 cm^-3
λp=530 μm>Δz
1x10^16 cm^-3
λp=334 μm≈Δz/2
x
E
Intensity [a.u.]
Electron Beam Energy [MeV]

Energy Loss / Gain







2-bunch

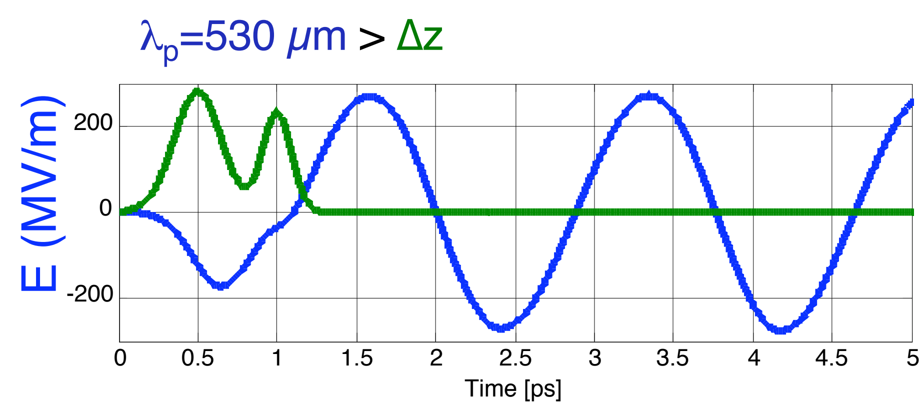
$n_e=4\times10^{15}$ cm^{-3}, L=6 mm

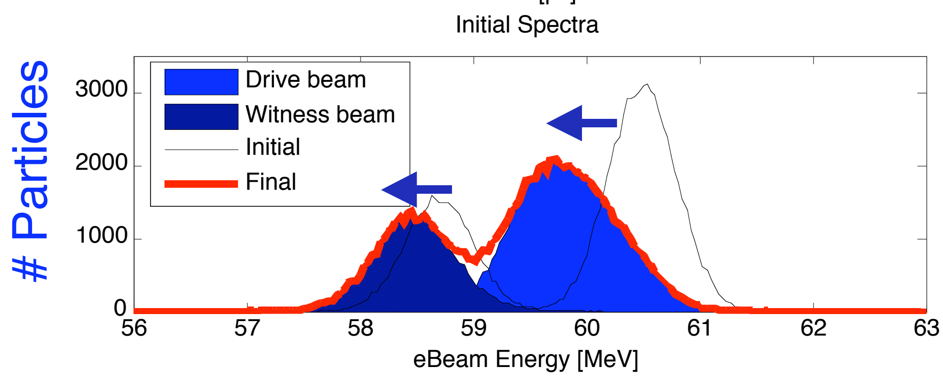
$\lambda_p=530\ \mu m > \Delta z$

$\Delta E_D \approx -1.1$ MeV

$\Delta E_W \approx -1.3$ MeV

G≈-200 MeV/m (L=6 mm)



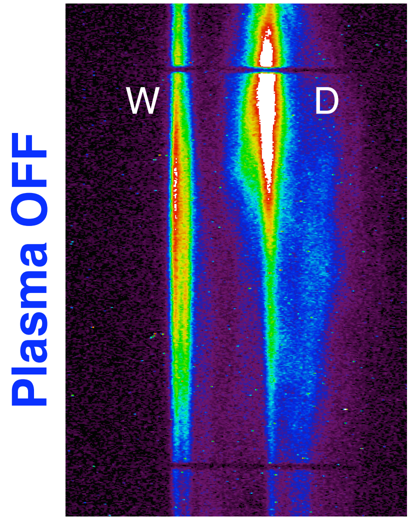


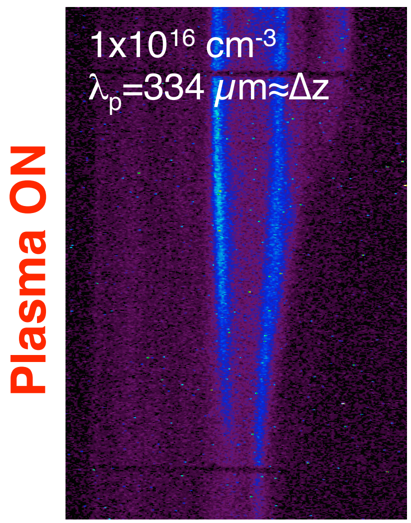
USC

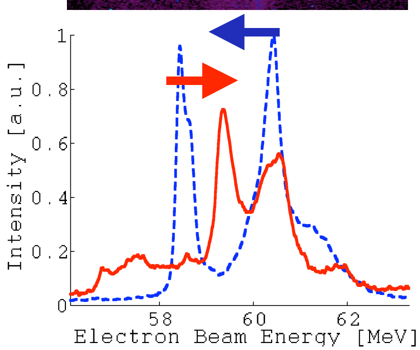
ENERGY LOSS / GAIN

BROOKHAVEN NATIONAL LABORATORY

STI OPTRONICS







2-bunch

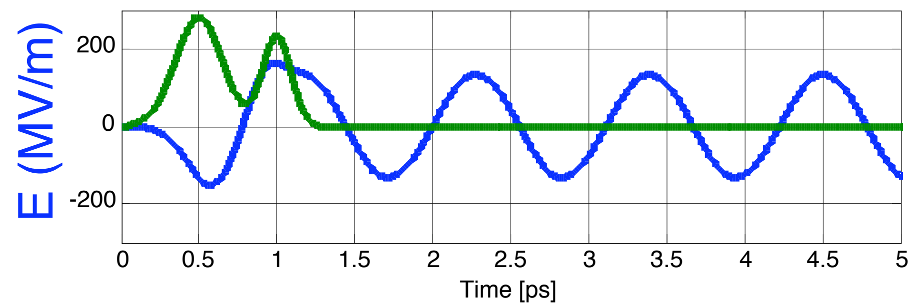
n_e=1x10^{16} cm^{-3}, L=6 mm

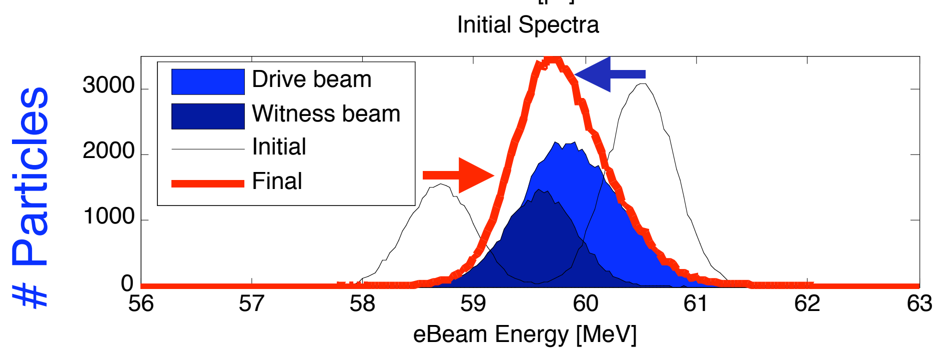
λ_p=334 μm≈ Δz

ΔE_D≈-0.9 MeV

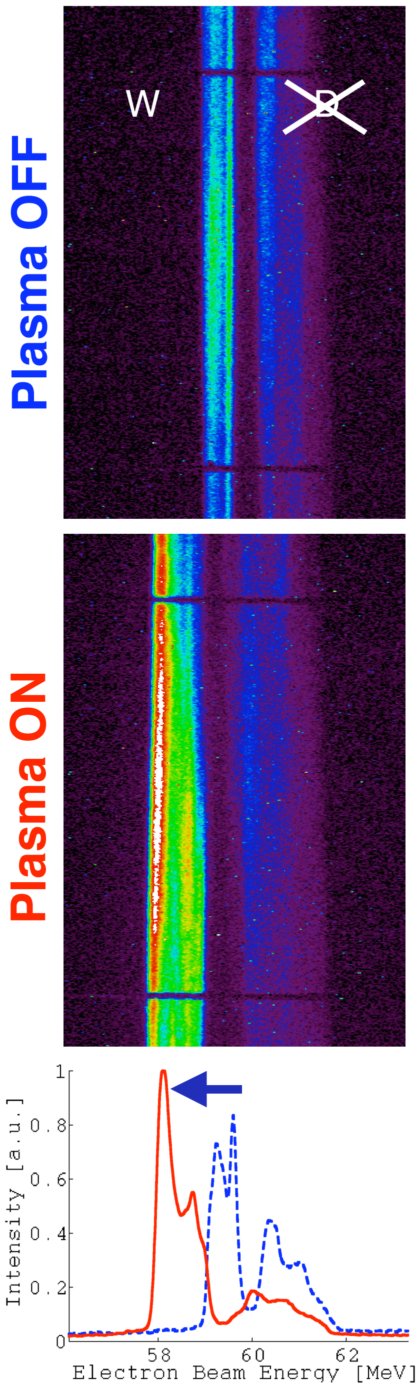
ΔE_W≈+0.9 MeV

G≈+150 MeV/m (L=6 mm)





Energy Loss / Gain



1-bunch (Low)

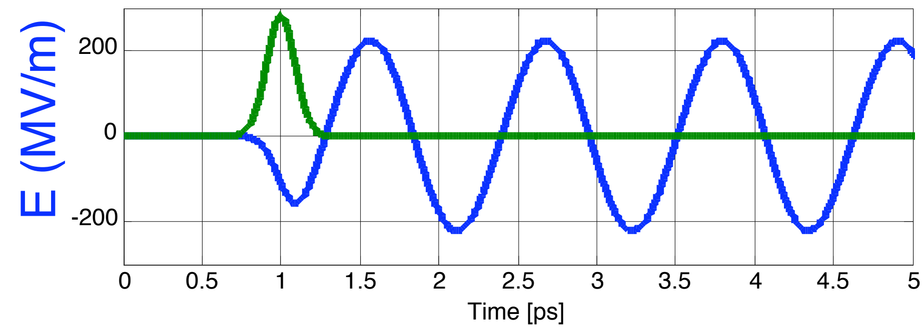
$n_e = 1 \times 10^{16}$ cm^{-3}, L=6 mm

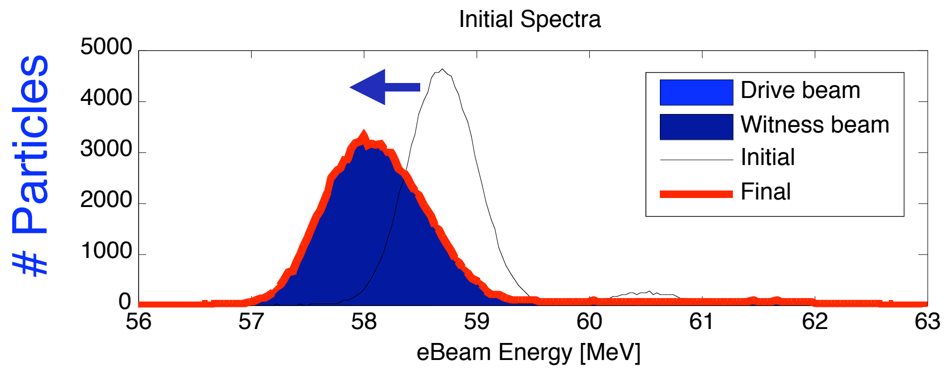
$\Delta E_W \approx -1.0$ MeV

G≈-165 MeV/m (L=6 mm)

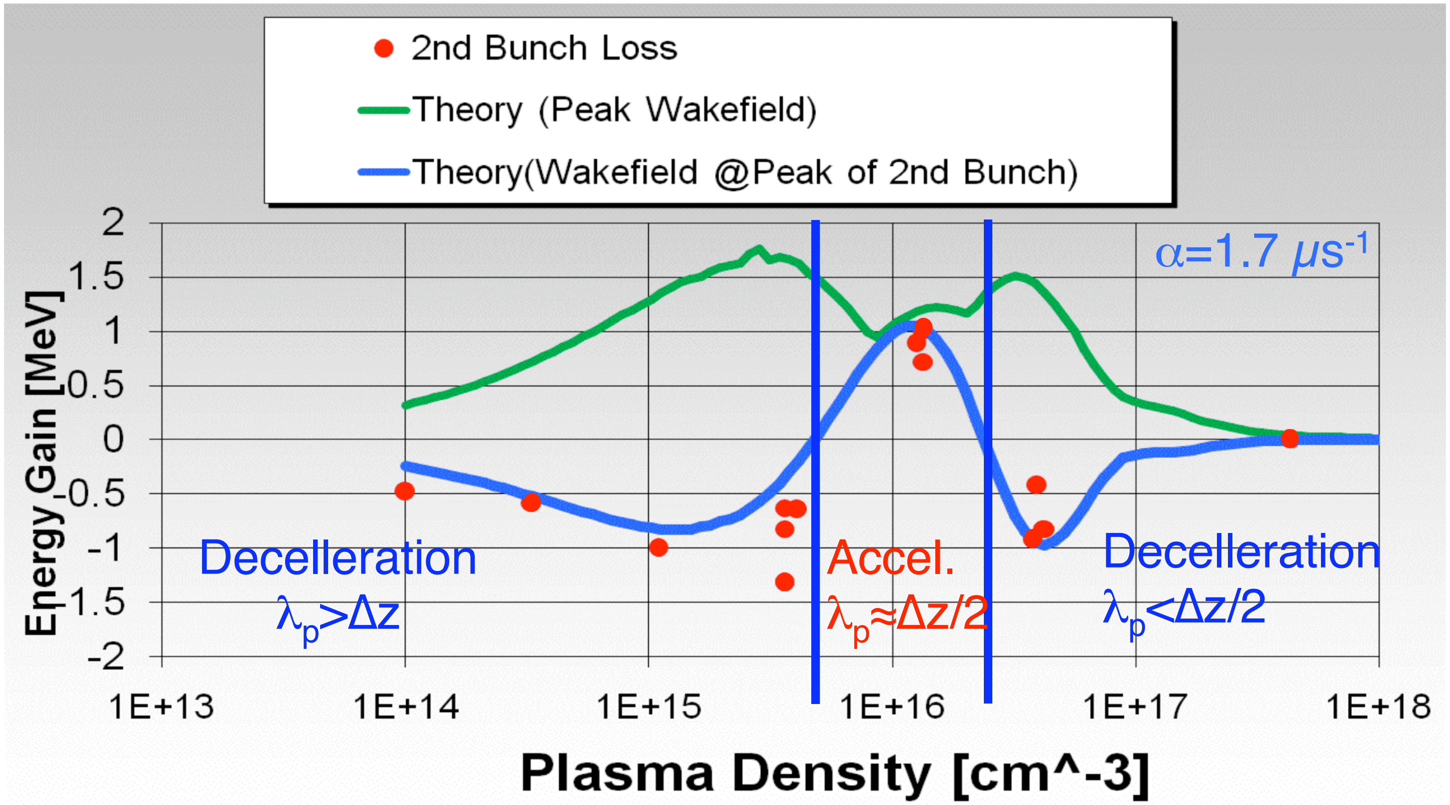
Low energy is 2nd in time: Loses by itself

Gains with other bunch





EXPERIMENT / THEORY



- Agreement with 2D model
- Maximum accelerating gradient (0.9+1.0)MeV/6mm=316MeV/m

SUMMARY / CONCLUSION

- Used beam break-up for two-bunch PWFA experiment at ATF
- Varied n_e to vary the wakefield "phase" between the 2 bunches
- Measured peak energy gain of 1 MeV over 6 mm
- Unloaded wakefield ≈316 MV/m (unloaded)
- Energy gain/loss in good agreement with theory
- PWFA as beam/plasma diagnostic

More to come …

- Reach $n_e=10^{19}$ cm^{-3} for multi-bunch PWFA experiment (N≈150)
- Multi-bunch (N=1, …, 5) mask PWFA experimental program ($\Delta E/E<1$, and important for > energy doubling!)

MOST IMPORTANTLY

Thank you
to the ATF staff
for making this possible!