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
Plasma wave/wake excited by a relativistic particle bunch

Plasma e⁻ expelled by space charge forces  \(\Rightarrow\) energy loss + focusing

Plasma e⁻ rush back on axis  \(\Rightarrow\) energy gain

Plasma Wakefield Accelerator (PWFA) = Energy Transformer

Booster for high energy accelerator?
Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

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SLAC Beam:
\[ E_0 = 28.5 \text{ GeV} \]
\[ \sigma_z \approx 20 \text{ \mu m} \]
\[ N = 1.8 \times 10^{10} \text{ e}^- \]
\[ n_e = 2.7 \times 10^{17} \text{ cm}^{-3} \]
\[ L = 90 \text{ cm} \]

42 to 84 GeV in 90 cm

Energy Doubling

100% $\Delta E/E$

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Cohesive Acceleration and Focusing of Relativistic Electrons in Overdense Plasma


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, Δt = 3 μs.

ATF 300 pC, 1.3 ps: gain 0.6 MeV over 17 mm plasma at n_e ≈ 5 x 10^{16} cm^{-3}

Accelerating gradient: 35 MV/m

Continuous energy spread
Bunch spacing/plasma density condition:
\[ \Delta z = \lambda_p \text{ (resonance) } \sigma_z \ll \lambda_p \]
\[ \Delta z' \approx \lambda_p / 2 \]

Plasma wavelength:
\[ \lambda_p = \frac{2\pi c}{\omega_{pe}} \]

Plasma angular frequency, density \( n_e \):
\[ \omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \]

Wake fields add up (linear theory):
\[ E_z \text{ N bunches} = N \times E_z \text{ 1 bunch} \]
(beyond energy doubling!)

Maximize transformer ratio with “shaping”

Finite energy spread, beam acceleration
Electron Beam
- $I_{\text{peak}} \approx 100\, \text{A}$
- $E_0 = 45\, \text{MeV}$
- $Q = 300\, \text{pC}$

10$\mu$m
- IFEL
- Pre-buncher
- $\Rightarrow$ Velocity modulation
- $\Rightarrow \Delta E/E \approx 1\%$

Multi-bunches
- $I_{\text{peak}} \approx 600\, \text{A}$
- $\sigma_r = 25\, \mu\text{m}$

Ablative Capillary Discharge Plasma

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

$n_e = 10^{19}\, \text{cm}^{-3} \pm \text{a few \%}$

Laser Beam
- CO$_2$: $\lambda_0 = 10.6\, \mu\text{m}$, 200 ps
- $P_{\text{peak}} \approx 1$-2GW

2.5 m Drift

Components available on ATF beam line 1

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**Wakefield: Theory-Simulations**

- Theory: non-linear equations for $E_{\text{wake}}$, $p_z$, $n_e$
- Resonant plasma density: $n_0=1.0 \times 10^{19} \text{ cm}^{-3}$ over 1 mm plasma, 10.6 $\mu$m bunch spacing. $[0.01 \text{ e}/(mc\omega_p) = 3 \text{ GV/m}], \sigma_r=25 \mu$m
- $\approx 6.5 \text{ GeV/m}$ with good agreement between theory and simulation

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

Larger bunch spacing $\Delta z \leftrightarrow$ lower $n_e$

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

- Choice of $\Delta z \leftrightarrow$ 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?
Bunch spacing/plasma density condition:
\[ \Delta z = \lambda_p \text{ (resonance) } \sigma_z \ll \lambda_p \]
\[ \Delta z = \lambda_p / 2 \]

Plasma wavelength:
\[ \lambda_p = \frac{2\pi c}{\omega_{pe}} \]

Plasma angular frequency, density \( n_e \):
\[ \omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \]

Wake fields add up (linear theory):
\[ E_{z \text{ N bunches}} = N \times E_{z \text{ 1 bunch}} \] (beyond energy doubling!)

Maximize transformer ratio with “shaping”

Finite energy spread, beam acceleration

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Two-Bunch Generation

W. Kimura et al., AAC’06 Proceedings

Two-bunch Parameters:

- \( E_0 \approx 60 \text{ MeV} \)
- \( \Delta E \approx 1.8 \text{ MeV} \)
- \( Q_{\text{High}} = 300 \text{ pC} \)
- \( Q_{\text{Low}} = 200 \text{ pC} \)

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

**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 \( \sim 4\% \) FWHM.  
(b) At the high-energy slit located downstream of the chicane.  
(c) At the spectrometer at the end of the beamline.
**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**
  \[ \sigma_t \approx 144 \text{ fs} \]

- **Double Bunch**
  - Gaussian
  - \( \sigma_t^{\text{High}} \approx 144 \text{ fs} \)
  - \( \sigma_t^{\text{Low}} \approx 90 \text{ fs} \)
  - \( Q^{\text{High}} = 300 \text{ pC} \)
  - \( Q^{\text{Low}} = 200 \text{ pC} \)
  - \( \Delta \tau \approx 500 \text{ fs} \)

Use PWFA interaction to determine time sequence! (High=Driver, Low=Witness)
Plasma Density from $H_{\alpha}$ Stark Broadening

After $I=0$: \[ n_e = n_0 e^{-\alpha t} \]

\[ \alpha = 3 \text{ } \mu s^{-1} \]
\[ \alpha = 1.7 \text{ } \mu s^{-1} \]

FIG. 1. Experimental setup and capillary design.

Kaganovich et al., APL 1997

Vary discharge-beam delay to vary the plasma density
Plasma OFF

Plasma ON

$4 \times 10^{15} \text{ cm}^{-3}$

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

$1 \times 10^{16} \text{ cm}^{-3}$

$\lambda_p = 334 \mu m = \Delta z / 2$

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ENERGY LOSS / GAIN

2-bunch

\( n_e=4 \times 10^{15} \text{ cm}^{-3}, L=6 \text{ mm} \)

\( \lambda_p=530 \mu m > \Delta z \)

\( \Delta E_D \approx -1.1 \text{ MeV} \)

\( \Delta E_W \approx -1.3 \text{ MeV} \)

\( G \approx -200 \text{ MeV/m (L=6 mm)} \)
2-bunch
\( n_e = 1 \times 10^{16} \text{ cm}^{-3}, L = 6 \text{ mm} \)
\( \lambda_p = 334 \mu \text{m} \approx \Delta z \)
\( \Delta E_D \approx -0.9 \text{ MeV} \)
\( \Delta E_W \approx +0.9 \text{ MeV} \)
\( G \approx +150 \text{ MeV/m} \) (\( L = 6 \text{ mm} \))
**Energy Loss / Gain**

1-bunch (Low)

\[ n_e = 1 \times 10^{16} \text{ cm}^{-3}, \quad L = 6 \text{ mm} \]
\[ \Delta E_W \approx -1.0 \text{ MeV} \]
\[ G \approx -165 \text{ MeV/m} \ (L = 6 \text{ mm}) \]

Low energy is 2nd in time: **Loses by itself**

Gains with other bunch

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**Graphs:**

- Top graph: Illustration of plasma OFF and ON scenarios.
- Middle graph: Time evolution of electric field (E vs. Time).
Agreement with 2D model

Maximum accelerating gradient \((0.9+1.0)\text{MeV}/6\text{mm}=316\text{MeV/m}\)
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 $\approx 316$ 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 ($N\approx 150$)
- Multi-bunch ($N=1, \ldots, 5$) mask PWFA experimental program
  ($\Delta E/E<1$, and important for $> \text{ energy doubling}$!)
MOST IMPORTANTLY

Thank you to the ATF staff for making this possible!

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