Generation of Multi-bunch Trains with Sub-picosecond Separation for PWFA (and Other?) Applications

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OUTLINE

- Motivation
- Mask idea
- Where and how?
- Results
- Summary and Future
MOTIVATION

$e^-$ ENERGY DOUBLING $E_0=42$ GeV


Tremendous progress with PWFA
Need to accelerate a particle BUNCH
Explore high transformer ratio scheme, beyond energy doubling

$E_0$ $2E_0$

Energy doubling of $e^-$ over $L_p \approx 85$ cm, $2.7 \times 10^{17}$ cm$^{-3}$ plasma
Unloaded gradient $\approx 52$ GV/m ($\approx 150$ pC accel.)
Bunch spacing/plasma density condition:
\[ \Delta z = \lambda_p \text{ (resonance)} \]
\[ \sigma_z << \lambda_p \]
\[ \Delta z' \approx (m+1/2) \lambda_p \]

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):
\[ E_z N \text{ bunches} \approx N \times E_z 1 \text{ bunch} \]

Maximize transformer ratio with “shaping”

Finite energy spread \( \Delta E/E \ll 1 \), beam acceleration
PURPOSE & REQUIREMENTS

PWFA
✓ Equidistant drive bunch train
✓ Witness bunch
✓ Variable charge

Witness bunch acceleration, large transformer ratio experiments, beyond energy doubling

FEL
✓ Variable delay
✓ Variable energy
✓ Variable charge

Pump-probe experiments

Stability in time and energy
MULTIBUNCH GENERATION

Correlated energy chirp from linac

Emittance selection: scattered electrons are lost

Choose microbunches spacing and widths with mask and beam parameters: N, Δz, σz, Q

Nguyen, NIMA 96
P. Emma, PRL 04

To Plasma FEL, …
Beam size at the mask: \[ \sigma_x = \sqrt{\frac{\beta_x \varepsilon_N}{\gamma_0} + \left( \frac{\eta_{\text{mask}}}{E_0} \right)^2} \]

= 1.372 cm

127 \mu m << 1.372 cm

Number of \( \mu \) bunches: \[ N_b = \frac{\sigma_x}{D} = \frac{\eta_{\text{mask}} \Delta E}{E_0} \]

= 10 to 11

\( D = 1270 \mu m \)

\( L_z = 1650 \mu m \)

\( R_{56} = 4 \text{ cm} \)

\( Q_0 = 500 \text{ pC} \)

\( d = 500 \mu m \)

\( \beta_x = 1.9 \text{ m} \)

\( \varepsilon_N = 1 \text{ mm-mrad} \)

\( \eta_{\text{mask}} = 1.372 \text{ m} \)

\( \gamma_0 = 117 \)

\( \Delta E/E_0 = 1\% \)

Mask transparency

\( T = \frac{(D - d)}{D} \)

Bunch chirp:

\( \Delta E / E_0 \)

\( \Delta z = \frac{L_z'}{N} \approx \frac{L_z + R_{56} \Delta E / E_0}{\eta_{\text{mask}} \Delta E / E_0} \)

= 200 \mu m

\( \mu \) bunches charge:

\( Q_{mb} = T \frac{Q_0}{N_b} = \frac{Q_0(D - d)}{\eta_{\text{mask}} \Delta E / E_0} \)

= 30 \text{ pC}

\( \mu \) bunches current:

\( I_{mb} = \frac{Q_0 C}{L_z'} = \frac{Q_0 C}{L_z + R_{56} \Delta E / E_0} \)

= 73 A
ATF BEAM LINE

- CTR/time diagnostic
- Dogleg
- Experiment
- Energy/space diagnostic
- Mask
- Gun Linac
ATF BEAM PARAMETERS

MAD Results

Dogleg configured for large dispersion $\eta_x$ and small beta function $\beta_x$ at mask location

Energy Slit Location

Mask Location

$E_0=50$ MeV
$\varepsilon_N<2$ mm-mrad
$Q=350$ pC
$\tau_{in}\approx5.5$ ps
$\Delta E/E_0=\pm1\%$
$R_{56}=+4$ cm
$\tau_{out}\approx5.5\pm1.3$ ps
Mask Principle

Energy Slit

\[ \Delta E/E_0 \approx 1\% \]

Transmitted

Mask

Wire Mesh

Wires Direction

W wires: Diameter \( d = 500 \ \mu m \)
Periodicity: \( D = 1270 \ \mu m \)

Mask transparency: \( T = (D-d)/D = 0.6 \)

Scattering:

\[ \theta_0 \approx \frac{13.6 \text{MeV}}{\beta cp} \sqrt{\frac{x}{X_0}} \]

\[ \epsilon_s = \left( \epsilon^2 + \sigma_x^2 \theta_0^2 \right)^{1/2} \gg \epsilon \]

Energy loss \( \approx 3\% \)

For stainless Steel \( x > 10 \ \mu m \)
MULTIBUNCHES IN ENERGY

Energy Spectrometer Image/spectra

Select # of bunches with energy slit (aperture)

Charge per microbunch determined by incoming bunch profile (here)

N=6

N=7

$\Delta E/E_0 \approx 0.5\%$
CTR INTERFEROMETRY

CTR:

\[ I_{tot}(k) = I_{incoh} + I_{coh} = N_e I_e + N_e (N_e - 1) I_e |F(k)|^2 \]

Incoherent \(\ll\) Coherent

Autocorrelator signal:

\[ S(\Delta z) = \int_{-\infty}^{\infty} dt \left( \frac{1}{2} E(t) + \frac{1}{2} E(t - \frac{\Delta z}{c}) \right)^2 \]

\(F(k)\) = Fourier transform of the bunch shape

Autocorrelation (cross term):

\[ A(\Delta z) = \int_{-\infty}^{\infty} dt E(t) E(z - \frac{\Delta z}{c}) \]

Bunch shape

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Multibunches in Time

Coherent Transition Radiation (CTR) Interferometry

- Autocorrelation leads spacing $\Delta z$
- $N$ microbunches $\Rightarrow 2N-1$ peaks
- Control $N$ and $\Delta z$ (I mean $\Delta t$!)

$\Delta z = 434 \mu m$

$\Delta z = 226 \mu m$

$\Delta E/E_0 \approx 1.5\%, 3.5\%$


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Autocorrelation Trace

Calculated

Bolometer response: ??->1000 µm
Filtering effect of the various apertures and windows

including filtering reproduces features of measured trace
Filtering affects bunch width measurement, but not µbunch spacing measurement!
BUNCH CONTRAST

\[ T(x_0; x_{w,i}, d, \sigma_x) = 1 - \frac{1}{2} \sum_i \left[ \text{erf}\left( \frac{x_{w,i} + d/2 - x_0}{\sqrt{2}\sigma_x} \right) - \text{erf}\left( \frac{x_{w,i} - d/2 - x_0}{\sqrt{2}\sigma_x} \right) \right] \]

Beam betatron size:
\[ \sigma_x = \sqrt{\frac{\beta_x \epsilon_N}{\gamma_0}} \]

Wire positions:
\[ D = x_{i+1} - x_i \]

Contrast decreases as \( \sigma_x/d \) increases

Present experiments: \( \sigma_x/d \approx 0.2 \)

Convolution function mask and beam betatron size

\( \sigma_x/d: \)
- 0.01
- 0.1
- 0.2
- 0.364

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Train for PWFA

Mask with non-equidistant “wires”

Measurement in energy plane

Generate “ideal” spacing for resonant PWFA

Charge modulation optimization possible

Plasma density must be adjusted for resonant excitation

D=1.56 mm

d=0.8 mm

Δz=150-400 µm, Δz’=225-600 µm

λ_p = plasma wavelength
Select number of drive bunches (high energy slit).

Witness bunch appears with drive bunch spacing on energy spectrometer CSR? See proposal by Alexei Fedotov
Summary / Conclusion

- Simple method to produce picosecond bunch train
- Proof-of-principle with wire mesh
- Stability in time and energy guaranteed by mask
- Number of µbunches and their spacing can be selected
- Bunch train pattern can be tailored for specific applications
  - Bunch spacing non-periodic, # bunches, length of bunches, charge, …
- Train length can be varied through bunch compression
- Application to PWFA experiments at ATF: train of drive bunches + witness bunch
- Influence, study of CSR effects

Thank you!

AND

Thank you **very much** to every one at ATF!