THz ELECTRON-PULSE TRAIN DYNAMICS IN A MeV PHOTOINJECTOR

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Outline

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• Evolution of an ultra-short electron bunch
• Initial Phase Compensation:
  Generation of an ultra-short electron pulse
  Generation of ultra-short electron-pulse train
• Schemes of initial phase compensation
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Motivations

- Electron-pulse train:

  - Electron micro-bunches
  - Electron macro-bunch

Narrow-line coherent radiation

Radiation spectrum

\[
\omega / \omega_b \quad \omega_b / N_p
\]
A soft X-ray FEL with 10-time reduced size
(Fu-Han Chao et al., Proceedings, FEL2011)

**Beam:**
- Beam energy = 150 MeV
- Peak current = 3.3 kA
- Energy spread = 3x10^{-4}
- Emittance = 2-mm-mrad
- Initial bunching factor = 10 ppm

**Undulator:**
- Period = 5 mm
- Gap = 0.8 mm
- Undulator parameter = 0.4
- Length = 3 m

**Radiation:**
- Wavelength = 32.2 nm
- Power = 0.2 GW
Motivations

I. Bunch width $\gg$ period
II. Bunch width $\sim$ period
III. Bunch width $\ll$ period

Longitudinal distribution

- Bunch width $\gg$ period
- Bunch width $\sim$ period
- Bunch width $\ll$ period

Bunching factor spectra

- Bunching frequency (THz)
- Comb-like distribution
Electromagnetic fields in an RF accelerator

- The RF fields in a standing-wave accelerator are radial-dependent. The field components of the dominate mode are given by:

  Longitudinal field

  \[ E_z(r, z, t) = E_0 J_0(\eta_0 r) \cos(k_0 z) \sin(\omega t + \phi_0) \]

  Transverse fields

  \[ E_r(r, z, t) = E_0 k_0 r \frac{J_1(\eta_0 r)}{\eta_0 r} \sin(k_0 z) \sin(\omega t + \phi_0) \]

  \[ B_{\theta}(r, z, t) = E_0 \frac{\omega r J_1(\eta_0 r)}{c^2 \eta_0 r} \cos(k_0 z) \cos(\omega t + \phi_0) \]
Evolution of an ultra-short electron bunch

- **Assumptions:**
  1. Longitudinal distribution: $n_i(\phi) = \delta(\phi - \phi_0)$ at cathode.
  2. Transverse distribution: $n_i(r) = \exp\left(-\frac{r^2}{2\sigma_r}\right)$, $\sigma_r$: RMS bunch radius.
  3. No space charge effects.
Evolution of an ultra-short electron bunch

- PARMELA simulation results (w/o space charge effects)

\[ \frac{\Delta r}{\Delta \phi} = \text{const.} > 1 \]
Both the widths and radius of the accelerated electron bunch are broadened!

The transverse distribution of electrons is uniformly broadened by $M$ times during particle acceleration!
Initial Phase Compensation

The longitudinal phase spread of the accelerated electrons due to the non-uniform RF fields can be compensated!
Initial Phase Compensation

The longitudinal phase spread of the accelerated electrons due to the non-uniform RF fields can be compensated!
Generation of an ultra-short electron pulse

- Applications of ultra-short electron pulse:
  1. Coherent radiation
  2. Ultrafast electron diffraction (UED) or Ultrafast electron microscopy (UEM)

\[
\text{Power} \propto N^2
\]
Generation of ultra-short electron pulse train

- **Without initial phase compensation**: The non-uniform RF fields broaden the longitudinal bunch width of the electron micro-bunches and reduce the bunching factor of the accelerated electron-pulse train.

- **PARMELA simulation results (w/o space charge effects):**
  
  ![Graph 1](Cathode)

  - Radial position $r_f$ (mm)
  - Correction $\Delta \phi$ (deg.)
  - Bunching factor spectrum
  - Bunching frequency (THz)

  ![Graph 2](Accelerator exit)

  - Radial position $r_f$ (mm)
  - Correction $\Delta \phi$ (deg.)
  - Bunching factor spectrum
  - Bunching frequency (THz)
Generation of ultra-short electron pulse train

- **With initial phase compensation:** The debunching of electron micro-bunches can be overcome. An excellent bunching spectrum of an electron-pulse train can be retained at the accelerator exit.
Generation of ultra-short electron pulse train

No space charge eff.

Total charge: 5 pC

Total charge: 10 pC
Schemes of Initial Phase Compensation

1. Adjustable laser pulse front shaping
   - Ultrafast laser pulses with aberrations
   - Deformable mirror
   - Optical lenses
   - Planar pulse front (corrected laser pulses)
   - Curved pulse front

2. Slightly concave photocathode
   - Concave photocathode
   - Ultrafast laser pulses
Conclusion

- The non-uniform RF fields broaden the electron bunch width in both the longitudinal and transverse directions during particle acceleration.
- With the non-uniform RF fields, it is hard to retain the width of an accelerated electron pulse in the fs regime.
- We proposed to compensate the phase spread of the electrons by changing the initial phases of the electrons over $r$.
- With initial phase compensation, the longitudinal bunch width of the accelerated electron bunch could be retained in the fs regime when the space charge effects are not significant.
- It is possible to produce a periodic electron-pulse train with a high bunching factor for a bunching frequency at tens of THz.
Thank you for your attention!