Measurements of Short Bunches at SPPS and E-164X

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• Motivation

• CTR Interferometry*

• Bunch energy spectrum measurements

• Application to E-164X

• Conclusions

MOTIVATIONS

• Length of SLAC ultra-short bunches was never measured!

• In E-164X plasma wakefield acceleration (PWFA) experiment, the accelerating gradient increases as $1/z^2$ with matching plasma density increasing as $1/z$

• Bunch incoming energy spectrum and CTR energy varies significantly from bunch to bunch (especially at 1 Hz rep. rate)

• Outcome of E-164X …
• **Optical Transition Radiation (OTR)**
  - Spatial resolution \( \approx 100 \, \mu m \)
  - Energy resolution \( \approx 30 \, \text{MeV} \)

**EXPERIMENTAL SET UP**

- Li Plasma Gas Cell: \( H_2, \text{Xe}, \text{NO} \)
  - \( n_e \approx 0-10^{18} \, \text{cm}^{-3} \)
  - \( L \approx 2.5-20 \, \text{cm} \)

- Cherenkov Radiator
  - Spatial resolution \( \approx 100 \, \mu m \)
  - Energy resolution \( \approx 30 \, \text{MeV} \)

- Cherenkov (aerogel)

- X-Ray Chicane
  - Energy resolution \( \approx 60 \, \text{MeV} \)

- Coherent Transition Radiation and Interferometer

- Optical Transition Radiators
  - 1:1 imaging, spatial resolution \( \approx 9 \, \mu m \)

- Energy Spectrum “X-ray”

- Plasma light

- Imaging Spectrometer
  - 25m

- Injected Current
  - \( N = 1.8 \times 10^{10} \)
  - \( E = 28.5 \, \text{GeV} \)
  - \( \Delta E = 20-12 \, \mu m \)

**Since E-162:**

- Plasma Light

- X-Ray Diagnostic, e-/e+ Production

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Transition Radiation (TR) becomes Coherent (CTR) for $\frac{a}{z} > 1$, with intensity $\approx N^2/z$, $N$ the number of e-/bunch of length $z$.

- CTR spectrum extends from for $\frac{a}{z} < 1$ (i.e., broad spectrum in the IR/FIR).

- CTR spectrum amplitude given by the bunch form factor $f(\omega)$, i.e, the Fourier transform of the longitudinal charge distribution squared (neglecting transverse variations, in the forward direction of observation).

$$ I_{\text{total}}(\omega) = N I_e(\omega) \left[ 1 + \left( N \frac{1}{\omega} f(\omega) \right)^2 \right] $$

$\ll$ for $\frac{a}{2\pi c/z}$

$I_e(\omega) = |E(\omega)|^2$, the TR for a single electron

$$ f(\omega)^2 = e^{\left(\omega a z / c\right)^2} \text{ for } E_r(z) $$

(Gaussian bunch)

$$ n(z) = \frac{1}{\sqrt{2\pi a^2 z^2}} e^{-z^2/2a^2} $$

- CTR carries longitudinal bunch shape information at long $\frac{a}{z}$'s.

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• Radiation field in the 2 arms of the interferometer with a time of flight difference $\Delta = 2\Delta z/c$:

$E_{\text{ref.}} = RTE(t)$

$E_{\text{var.}} = TRE(t + 2\Delta / c)$

$T, R$ transmission and reflection coeff. of beam splitter

Note: $T = T(\omega)$, $R = R(\omega)$ !

• Intensity $I_D = (E_{\text{ref.}} + E_{\text{var.}})^2$ on autocorrelator detector:

$$I_D(t; \Delta) = 2 \int |RTE(t)|^2 \, dt$$

Background $+ 2 \int RT^2 E(t)E(t + 2\Delta / c) \, dt$

Interferogram/autocorrelation
For each $d_1$ or $\Delta z$, measure the energy: $S_D(\Delta z) = \iint I_D(t; \Delta z) \, dt \, ds$

Autocorrelation signal characteristics:
- Symmetric (even if the bunch shape is not)
- Background=“2”, peak=“2”+”2”, contrast of 2
- Extends to long wavelengths, i.e., to long delays (CTR)
- FFT(interferogram) => bunch spectrum
- requires multiple (similar) bunches

Pros and cons of CTR Interferometry
- Simple and inexpensive (<$10k$)
- No sophisticated timing required
- Symmetric trace
- Multi-bunch measurement
- Requires knowledge of broadband response of the entire system
CTR MICHELSON INTERFEROMETER

- Interference signal normalized to the reference signal
- Motion resolution $\Delta z_{\text{min}} = 1 \, \mu\text{m}$ or $\approx 14 \, \text{fs}$ (round trip)
- Mylar: $R \approx 22\%$, $T \approx 78\%$, $RT \approx 0.17$

$e^-\Delta z\text{e}^-$

$1 \, \mu\text{m} \text{ Titanium Foil at } 45^\circ$

$\square_x = 60 \, \mu\text{m}, \, \square_y = 170 \, \mu\text{m}$

$N \approx 1.9 \times 10^{10} \, e^-$

Alignment Laser

Reference Pyro Detector

Variable Position Mirror $\Delta z$

Interferometer Pyro Detector

12.5 $\mu\text{m}$ Mylar
1mm HDPE Vacuum Window (3/4” dia)

12.5 $\mu\text{m}$ Mylar Beam Splitters $R \approx T \approx 0.17$

$1 \, \mu\text{m}$ Laser

$1 \, \mu\text{m}$ Titanium Foil at 45°

$R \approx 22\%$, $T \approx 78\%$, $RT \approx 0.17$

$N \approx 1.9 \times 10^{10} \, e^-$

$\Delta z_{\text{min}} = 1 \, \mu\text{m}$ or $\approx 14 \, \text{fs}$ (round trip)
• Trace is symmetric (even if the bunch shape may not be)
• Peak/background ratio = 2
• Large “dips” on either sides of the peak
• Modulation far from the peak
Interferometer “transmission” can be affected by: *(amplitude and phase)

- Water absorption in humid air
- Vacuum window size cut-off (long $l$)
- Interferometer optics aperture (long $l$)
- Pyro-electric detector resonances
- Beam splitter(s)/window Fabry-Perot resonances

BEAMSLITTER R & T, 45°

Thickness \( d \)

Index of refraction \( n \)

Angle of incidence 45°

\[
R(\square) = \frac{1}{1 - r} e^{i\square} \frac{1}{1 - r^2 e^{i\square}}
\]

\[
T(\square) = \left(1 - r^2\right) e^{i\square/2} \frac{1}{1 - r^2 e^{i\square}}
\]

\[
r_{\perp}(\square) = \frac{1}{1 + \sqrt{2n^2 - 1}}
\]

\[
r_{//}(\square) = \frac{n^2}{n^2 + \sqrt{2n^2 - 1}}
\]

Mylar: \( n=3, n=n(\square) \)?

- Include in a simple autocorrelation calculation
- Interferometer delay \( \Delta z \) or \( d \) => relative phase shift \( 2k\Delta z \)
Mylar Fabry-Perot

Simple model:
Gaussian, $\sigma_z=20 \mu m$, $d=12.7 \mu m$, $n=3$ Mylar window+splitters

- Fabry-Perot resonance: $\square=2d/nm$, $m=1,2,…$, $n$=index of refraction
- Signal attenuated by Mylar beam splitter: $(RT)^2$
- Modulation/dips in the interferogram
- Smaller measured width: $\square_{\text{Autocorrelation}} < \square_{\text{bunch}}$
CORRECTED GAUSSIAN WIDTH

NDR compressor voltage: 41.8 MV/m, 2-6BNS phase -19°

Autocorrelation:

\[ z \approx 9 \, \mu m \]

Gaussian Bunch

\[ z \approx 18 \, \mu m \]

or

\[ \approx 120 \, fs \]
FFTBR_{56} DEPENDENCY

- Measurable, but weak dependency
- Variations masked by beamsplitter transmission characteristics

- \( z \approx 17 \mu m \) or 114 fs (corrected)
- \( z \approx 13 \mu m \) or 86 fs
- \( z \approx 11 \mu m \) or 74 fs
MYLAR EFFECT
(Example)

Beam current profiles for PWFA

- Beamsplitter “filtering” masks beam profile features

\[ z_{za} \approx 108 \, \mu m \]
\[ \approx 47 \, \mu m \]
\[ \approx 47 \, \mu m \]
CTR AMPLITUDE DEPENDENCY
@ PEAK COMPRESSION

- Amplitude variations are clear(er)
- Amplitude related to bunch current profile

Gaussian Bunch:

\[ E_{\text{CTR}} \approx \frac{N^2}{\sigma_z} \]
e\textsuperscript{-} BUNCH MANIPULATION

\begin{itemize}
  \item Energy spectrum <-> phase space <-> current profile
  \item \( z \) does not fully describe the bunch shape
\end{itemize}

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SLC ENERGY SPECTRUM MONITOR USING SYNCHROTRON RADIATION

J. Seeman, W. Brunk, R. Early, M. Ross, E. Tillmann and D. Walz
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305

• Measure incoming bunch energy spectrum using "x-ray chicane" (C. Barnes PhD)

X-Ray Spectrometer Schematic

Spectrometer Chicane Magnet

Scintillate Detector
EXPERIMENTAL SET UP

- X-ray Chicane
  - Energy resolution ≈ 60 MeV

- Optical Transition Radiation (OTR)
  - 1:1 imaging, spatial resolution ≈ 9 µm

- Cherenkov (aerogel)
  - Spatial resolution ≈ 100 µm
  - Energy resolution ≈ 30 MeV

Since E-162:

- Energy Spectrum "X-ray"
- Coherent Transition Radiation and Interferometer
- Optical Transition Radiators
- Imaging Spectrometer
- X-Ray Diagnostic, e-/e⁺ Production
- Cherenkov Radiator Dump
- Plasma Light

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**BUNCH COMPRESSION & ENERGY SPECTRA**

- Pyro amplitude is ambiguous
- Energy spectra are not
- They are complimentary
- Clear correlation between Energy spectrum and E-164X outcome

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E164X:
A Plasma Wakefield Acceleration Experiment


*Stanford Linear Accelerator Center*

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• 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

• Linear scaling:
\[
E_{\text{acc}} \propto 110 (\text{MeV/m}) \frac{N/2 \cdot 10^{10}}{(\Box_z / 0.6 \text{mm})^2} \approx \frac{1}{\Box_z^2} @ k_{pe}\Box_z \approx \sqrt{2}
\]

• Plasma Wakefield Accelerator (PWFA) = Transformer Booster for high energy accelerator

• At \(n_e = 2.6 \times 10^{17} \text{ cm}^{-3}\): \(f_{r}\approx 4.5 \text{ THz}\) accelerator
  \(E_{\text{acc}} \approx 40 \text{ GV/m, } B_{\parallel} \approx 8 \text{ MT/m}\)
Energy loss correlates with CTR energy ($1/z$)

Peak energy gradient 3.4 GeV/10 cm! (or 34 GeV/m!)

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$n_e \approx 2.55 \times 10^{17} \text{ cm}^{-3}$

$L \approx 10 \text{ cm}, \ N \approx 1.8 \times 10^{10}$

$\langle \frac{1}{z} \rangle \approx 2.55 \times 10^{-17} \text{ cm}^{-3}$

Peak energy gradient 3.4 GeV/10 cm! (or 34 GeV/m!)

$\mathbf{U\ C\ L\ A}$
Results

- Energy gain reaches $\approx 3+1$ GeV or $\approx 40$ GeV/m
- $\approx 7\%$ of charge or $\approx 200$ pC with $E>E_0$
- Energy gain depends on the details of the incoming beam $(x,y,z)$

$\rho \approx 2.55 \times 10^{17}$ cm$^{-3}$, $L \approx 10$ cm

$N \approx 1.8 \times 10^{10}$

$E_{\text{gain}} \approx 3 \text{ GeV}!$

$U \ C \ L \ A$

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CONCLUSIONS

• First and only(?) measurement of SLAC short bunches
• CTR interferometry shows bunches as short as 74 fs, but …
• Beam splitter Fabry-Perot alters the measurement and CTR has limitations: multiple bunches, symmetric
• Short bunch confirmed by ionization of Li, NO, Xe, and H$_2$
• Measure single bunch energy spectrum to retrieve profile/current distribution
• CTR interferogram and amplitude, and bunch spectrum are key for E-164X and future E-…
• CTR interferometer can be improved: thinner Mylar splitter, vacuum box, …
• Retrieve/incorporate bunch current profiles: in CTR and E-164X, work in progress …