Measurements of Electron-Bunch Trains in a Laser-Plasma Accelerator

Olle Lundh[1,2], C. Rechatin[2], J. Lim[2], V. Malka[2], J. Faure[2]

[1]Lund University and Lund Laser Centre, Sweden
[2]Laboratoire d'Optique Appliquée, France

European Advanced Accelerator Workshop, June 3-6 2013, Elba

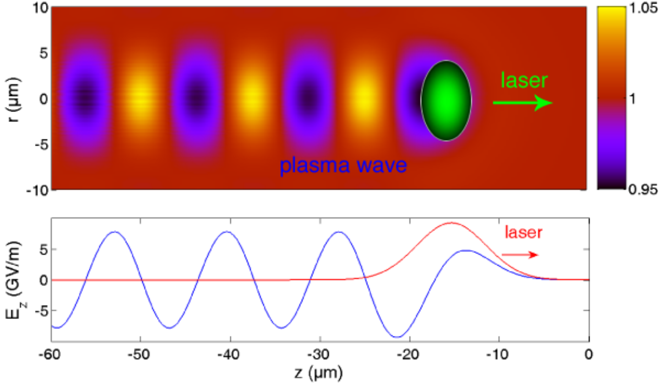
erc

Laserlab Europe

Vetenskapsrådet

Outline

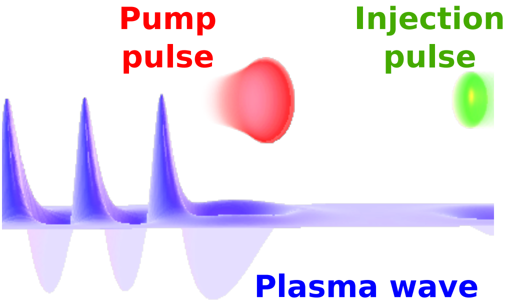
Laser-driven plasma wave



- Laser expels electrons, ions stationary $\Rightarrow$ Plasma wave oscillation
- Typical plasma wave period $\lambda_p \approx 10 - 20$ µm
- Self-injection by wavebreaking can give mono-energetic beams but only in a narrow parameter range

Image: C. Rechatin

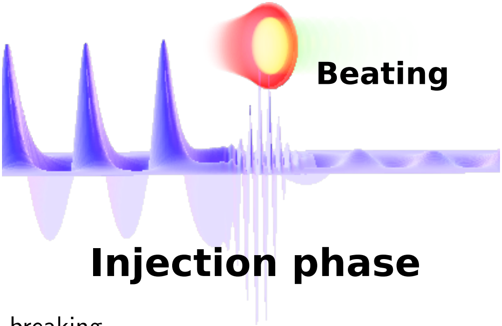
Injection by colliding laser pulses



- No wave breaking
- Electrons boosted in the beatwave and locally injected
- Electron beam parameters can be tuned

Esarey *et al, Phys. Rev. Letters*, **79**, 2682 (1997)
Kotaki *et al, Phys. Plasmas*, **11**, 3296 (2004)
Fubiani *et al, Phys. Rev. E*, **70**, 016402 (2004)
Faure *et al, Nature*, **444**, 737 (2006)

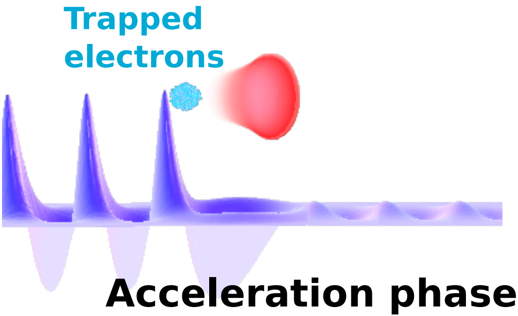
Injection by colliding laser pulses



- No wave breaking
- Electrons boosted in the beatwave and locally injected
- Electron beam parameters can be tuned

Esarey *et al*, *Phys. Rev. Letters*, **79**, 2682 (1997)
Kotaki *et al*, *Phys. Plasmas*, **11**, 3296 (2004)
Fubiani *et al*, *Phys. Rev. E*, **70**, 016402 (2004)
Faure *et al*, *Nature*, **444**, 737 (2006)

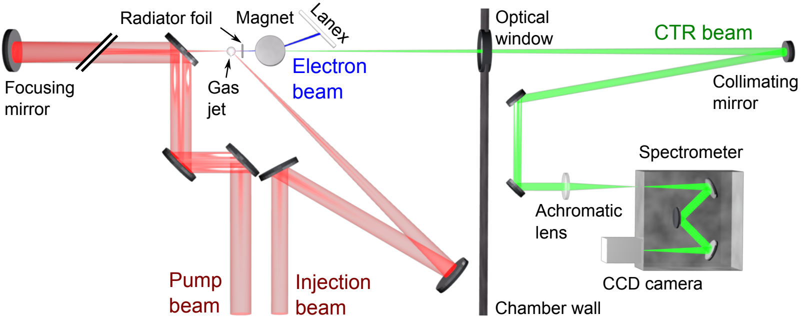
Injection by colliding laser pulses



- No wave breaking
- Electrons boosted in the beatwave and locally injected
- Electron beam parameters can be tuned

Esarey *et al*, *Phys. Rev. Letters*, **79**, 2682 (1997)
Kotaki *et al*, *Phys. Plasmas*, **11**, 3296 (2004)
Fubiani *et al*, *Phys. Rev. E*, **70**, 016402 (2004)
Faure *et al*, *Nature*, **444**, 737 (2006)

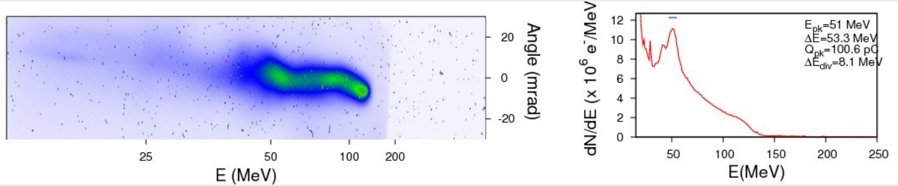
Experimental Setup



- **Pump laser:** 1 J, 30 fs, 4×10^{18} W/cm^2
- **Injection laser:** 100 mJ, 30 fs, 2×10^{17} W/cm^2

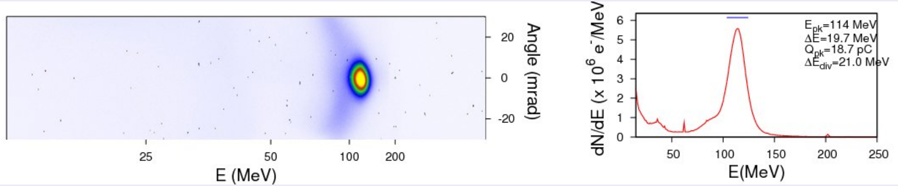
Typical electron beams

Self-injection



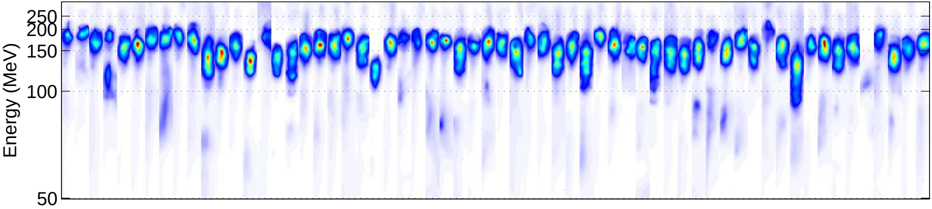
$n_e = 13 \times 10^{18}$ cm^{-3}

Colliding Pulse Injection



$n_e = 10 \times 10^{18}$ cm^{-3}

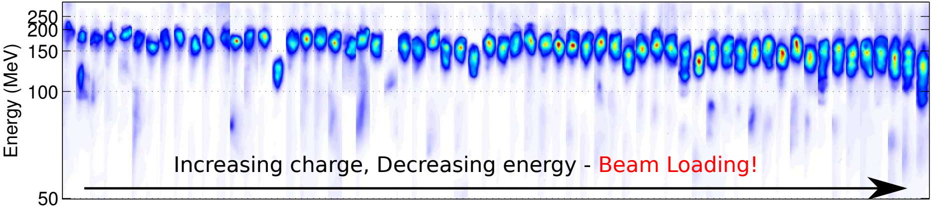
Colliding pulse injection – stability



62 consecutive shots with $a_0 = 1.3$, $a_1 = 0.3$, $n_e = 8.4 \times 10^{18}$ cm^{-3}

- $E = 160$ MeV (9% rms fluct.)
- $\Delta E = 30$ MeV (13% rms fluct.)
- $Q = 42$ pC (37% rms fluct.)
- $\Delta\theta = 5.4$ mrad (24% rms fluct.)

Colliding pulse injection – stability



62 consecutive shots with $a_0 = 1.3$, $a_1 = 0.3$, $n_e = 8.4 \times 10^{18}$ cm^{-3}

- $E = 160$ MeV (9% rms fluct.)
- $\Delta E = 30$ MeV (13% rms fluct.)
- $Q = 42$ pC (37% rms fluct.)
- $\Delta\theta = 5.4$ mrad (24% rms fluct.)

Beamloading $\Rightarrow$ high peak current, short duration

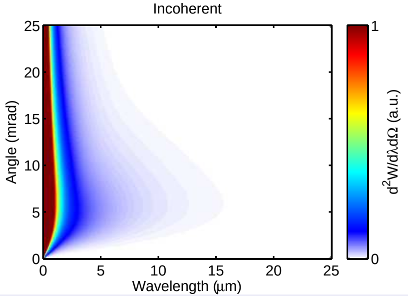
Transition Radiation

Single Electron

$$\frac{d^2 w}{d\omega d\Omega} = \frac{e^2}{4\pi^3 \epsilon_0 c} \left[\frac{\beta}{1 - \beta^2 \cos^2 \theta} \right]^2$$

$$\theta_{div} = 1/\gamma$$

Incoherent radiation



Transition Radiation

Single Electron

$$\frac{d^2 w}{d\omega d\Omega} = \frac{e^2}{4\pi^3 \epsilon_0 c} \left[\frac{\beta}{1-\beta^2 \cos^2\theta} \right]^2$$

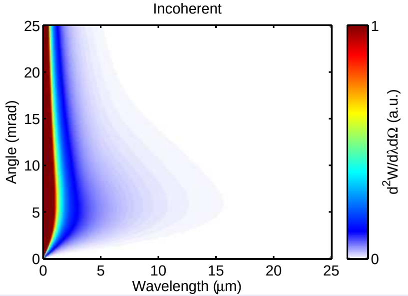
$$\theta_{div} = 1/\gamma$$

Ensemble of Electrons

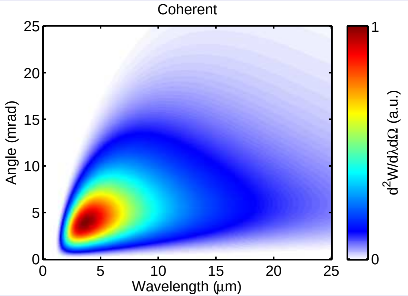
$$\frac{d^2 W}{d\omega d\Omega} = [N_e + N_e^2 F(\omega,\theta)] \frac{d^2 w}{d\omega d\Omega}$$

$F(\omega,\theta) = |\mathcal{F}(f)|^2$, $f(\vec{x})$ = bunch shape

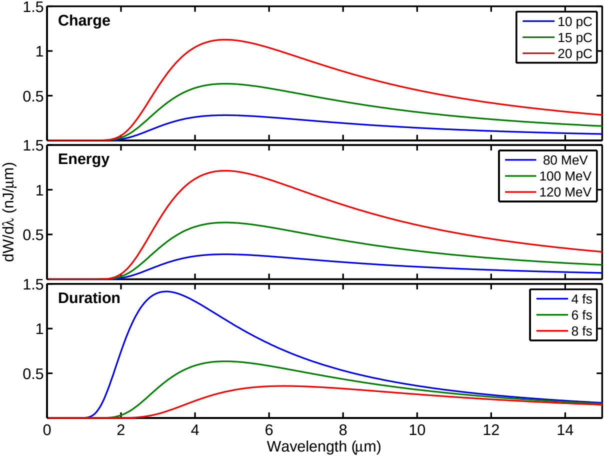
Incoherent radiation



Coherent radiation



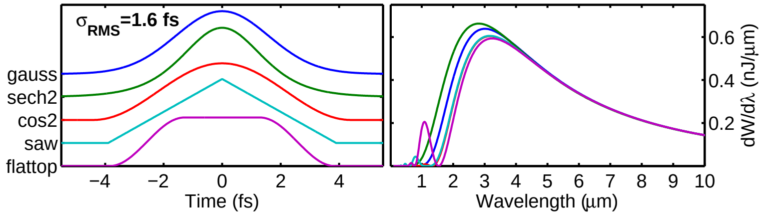
Influence of bunch parameters



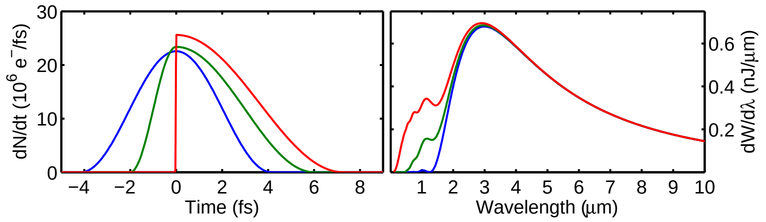
- Bunch length determines peak wavelength

Influence of bunch shape

Symmetric bunch



Asymmetric bunch



O. Lundh *et al*, *Nature Phys.*, **7**, 219–222 (2011)

Frequency-duration product

Shape	Function	Interval	τ/σ	$\sigma \cdot \omega$	$\sigma_{3\mu m}$ (fs)
Gauss	$\exp(-t^2/2\sigma^2)$	$\|t\| < \infty$	2.35	1.00	1.59
Cosine	$\cos^2(\pi t/2\tau)$	$\|t\| < \tau$	2.77	0.95	1.51
Sech	$\mathrm{sech}^2(\pi t/2\sigma\sqrt{3})$	$\|t\| < \infty$	1.94	1.10	1.75
Rectangle	1	$\|t\| < \tau/2$	3.46	0.91	1.45
Triangle	$1 - \|t/\tau\|$	$\|t\| < \tau$	2.45	0.95	1.51
Parabolic	$1 - t^2/2\tau^2$	$\|t\| < \tau\sqrt{2}$	1.58	0.90	1.43

ω peak frequency

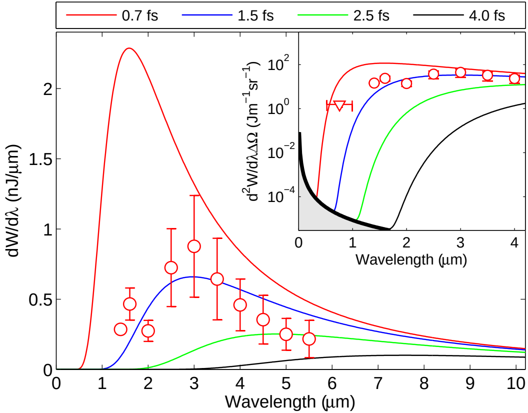
τ FWHM duration

σ RMS duration

$\sigma_{3\mu m}$ RMS duration giving peak at 3 μm

O. Lundh *et al, Nature Phys.*, **7**, 219–222 (2011)

Infrared OTR spectrum



Measurement of the bunch duration

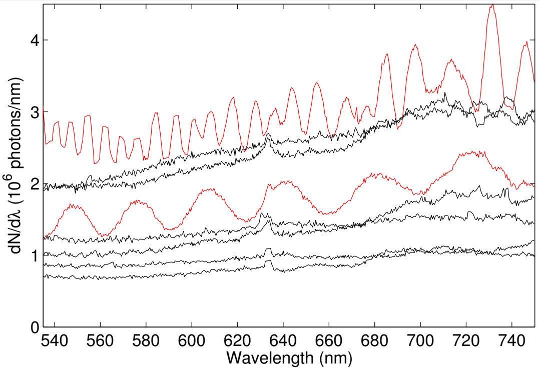
$\sigma_{rms} \approx 1.5$ fs

$I_{peak} \approx 4$ kA

$\tau_{fwhm} = 3 - 5$ fs, depending on bunch shape

O. Lundh *et al, Nature Phys.*, **7**, 219–222 (2011)

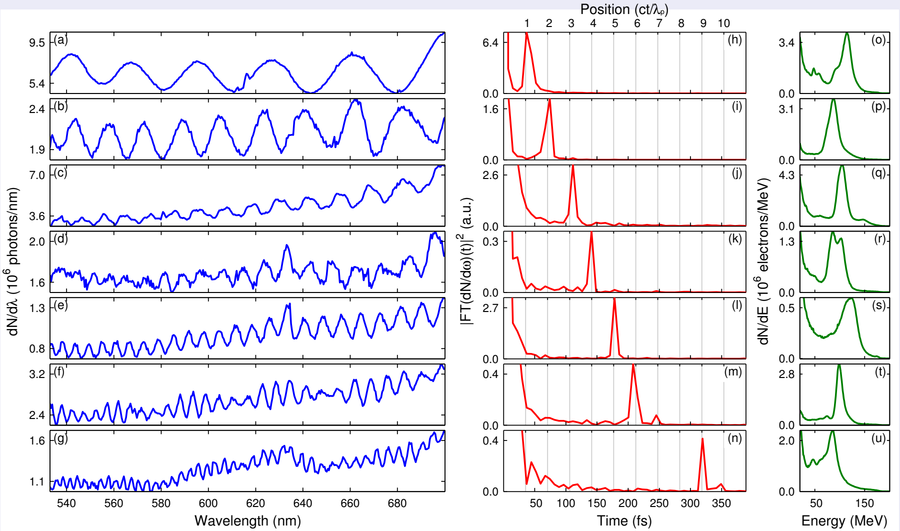
Visible OTR spectrum



- $n_e = 10^{19}$ cm^{-3}, $\lambda_p = 10.6\ \mu$m
- Some shots show spectral oscillations
- Interference between CTR from multiple bunches
- Modulation $\cos(\omega T)$ give separation in time T

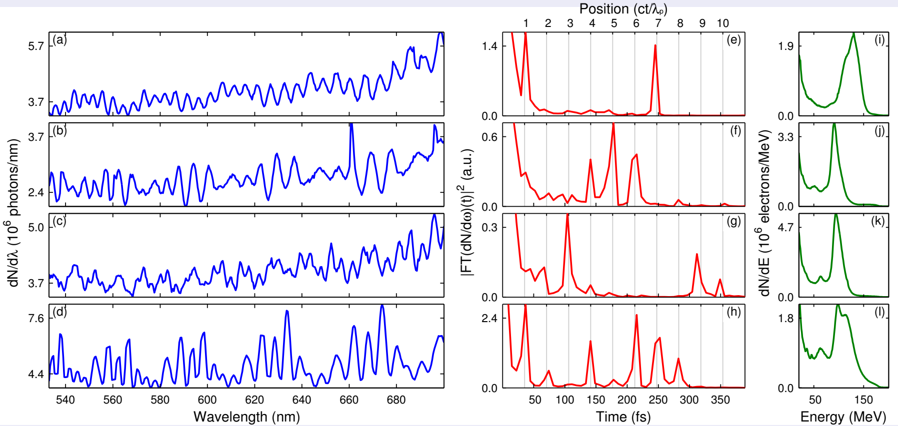
- One oscillation, $\Delta\omega = \omega_1 - \omega_2 = 2\pi c(\lambda_1^{-1} - \lambda_2^{-1}) = 2\pi/T \Rightarrow cT \simeq \lambda_0^2/\Delta\lambda$
- Ex. 1: $600^2/34 = 10.6\ \mu$m$= 1.0\lambda_p$
- Ex. 2: $600^2/7 = 51.5\ \mu$m$= 4.9\lambda_p$

Two electron bunches



O. Lundh *et al*, *Phys. Rev. Lett.*, **110**, 065005 (2013)

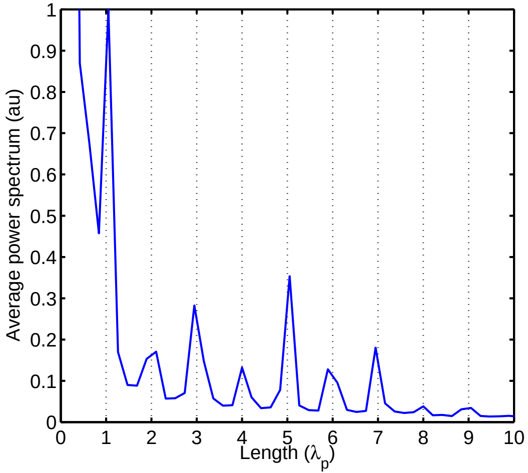
Multiple electron bunches



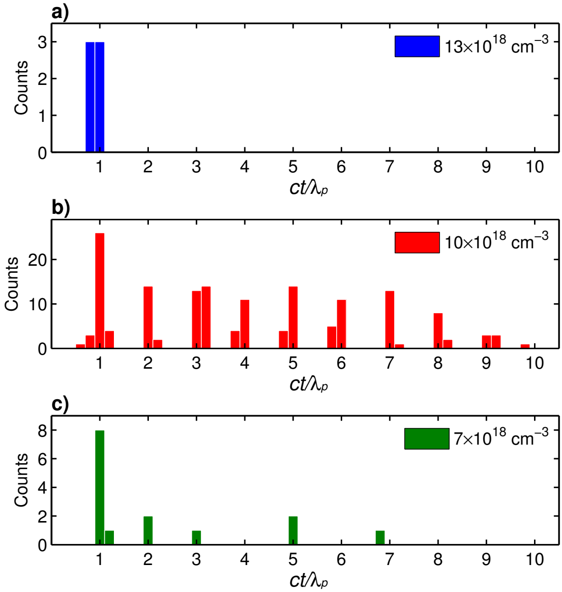
- Peaks in Fourier Transform always coincide with $n \cdot \lambda_p$
- No apparent signature of multiple bunches in e-spectrum

Fourier transform: average over all measurements

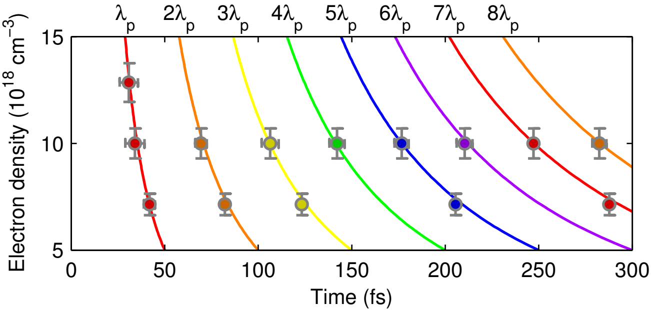
$n_e = 10 \times 10^{18}$ cm^{-3}, $\lambda_p = 10.6$ µm
114 measurements, 61 with interferences



Influence of plasma density



Influence of plasma density



Injection	n_e (cm^{-3})	λ_p	$N_{interferences}$	cT_{max}/λ_p	**Charge**
SI	13×10^{18}	9.3	10%	1.1	**91 pC**
CPI	10×10^{18}	10.6	56%	9.9	**27 pC**
CPI	7×10^{18}	12.5	42%	6.9	**34 pC**

O. Lundh *et al, Phys. Rev. Lett.*, **110**, 065005 (2013)

Fringe visibility and the wavelength

Normalized bunch distribution

Two bunches, rms duration σ_1 and σ_2, charge N_1 and N_2 and separation T.

$$f(t) = \frac{N_1}{\sqrt{2\pi\sigma_1^2}} \exp\left(-\frac{t^2}{2\sigma_1^2}\right) + \frac{N_2}{\sqrt{2\pi\sigma_2^2}} \exp\left(-\frac{(t-T)^2}{2\sigma_2^2}\right)$$

Fourier Transform

$$\hat{f}(\omega) = N_1 e^{-(\omega\sigma_1)^2/2} + N_2 e^{-(\omega\sigma_2)^2/2}$$

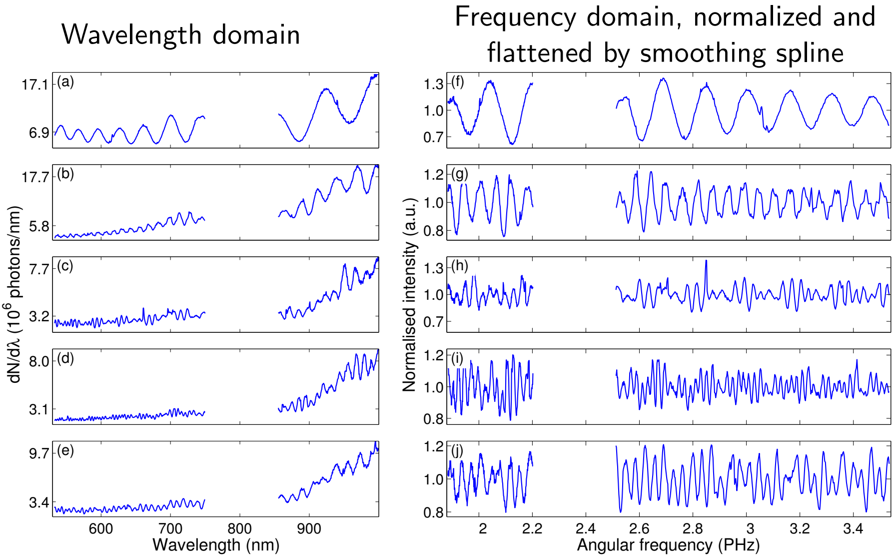
Form factor

$$F(\omega) = |\hat{f}(\omega)|^2 = N_1^2 e^{-\omega^2\sigma_1^2} + N_2^2 e^{-\omega^2\sigma_2^2} + 2N_1N_2 e^{\frac{\omega^2}{2}(\sigma_1^2+\sigma_2^2)} \cos\omega T$$

Fringe visibility

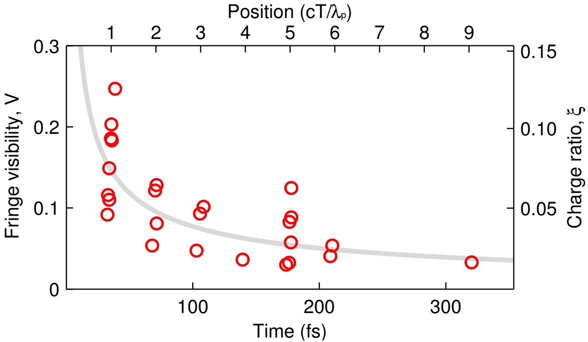
$$V = \frac{F_{max} - F_{min}}{F_{max} + F_{min}} = \frac{2\xi}{1+\xi^2}, \text{ where } \xi = (N_2/N_1) e^{\frac{\omega^2}{2}(\sigma_2^2-\sigma_1^2)}$$

Measured fringe visibility is nearly constant



Estimating the bunch charge

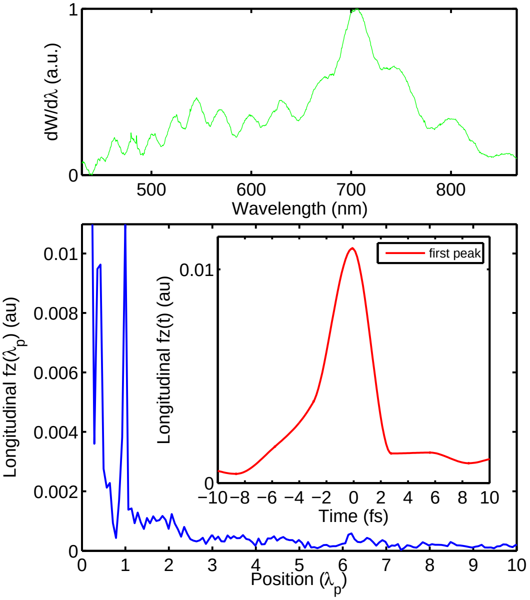
$$V = \frac{F_{max} - F_{min}}{F_{max} + F_{min}} = \frac{2\xi}{1+\xi^2}, \text{ where } \xi = (N_2/N_1)e^{\frac{\omega^2}{2}(\sigma_2^2 - \sigma_1^2)}$$



- Only data suggesting only two bunches included (one peak)
- Majority of the charge in the first bunch

O. Lundh *et al, Phys. Rev. Lett.*, **110**, 065005 (2013)

Estimating the duration?



YES

Works for smooth, symmetric bunch shapes (e.g. Gaussian)

NO

Not for assymetric shapes (complete CTR spectrum needed)

Conclusion

CTR is a powerful and simple diagnostic that gives crucial information on the temporal distribution of the electron beam.