Electro-optic detection of sub-ps electron bunches

(for wakefield acceleration experiments)

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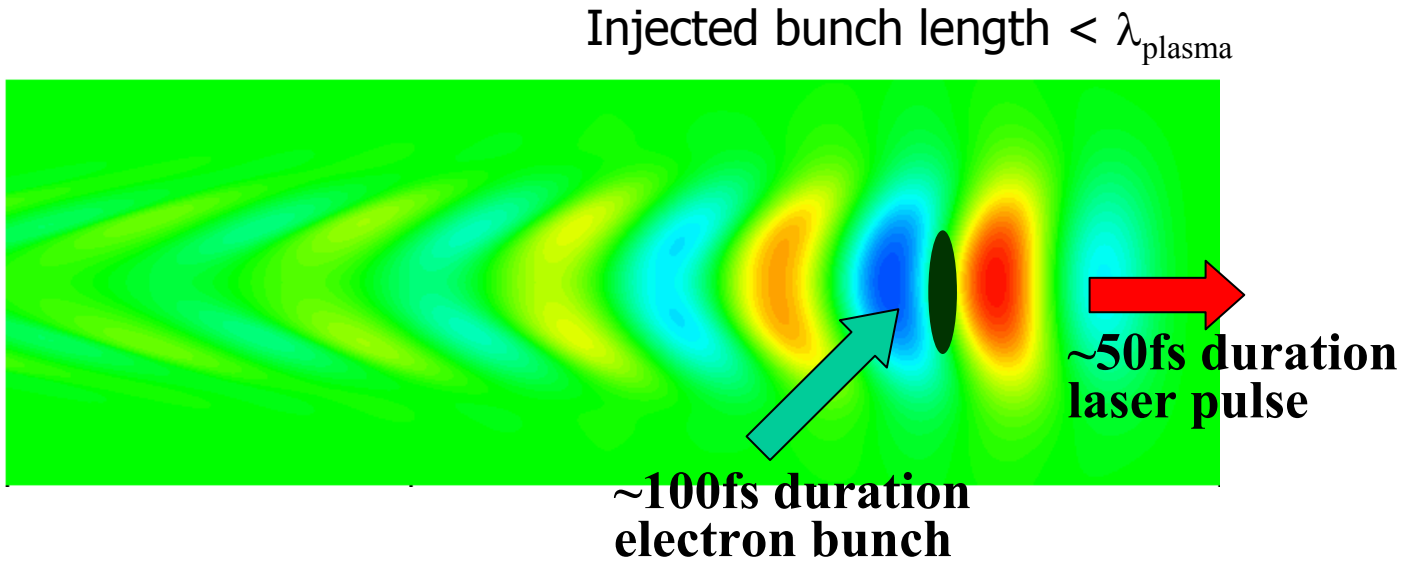
- Single-shot electro-optic detection
  - Spectral decoding
  - Envelope cross-correlation (“temporal decoding”)
- FELIX electron bunch measurements
  - synchronisation for injector
  - beam temporal profile
- Wake-field acceleration experiments

Why do we need an ultrafast electron bunch diagnostic?

Plasma wakefield acceleration



How to measure bunch synchronism?
Bunch duration? Temporal profile?

What is temporal structure of both injected and accelerated beam?

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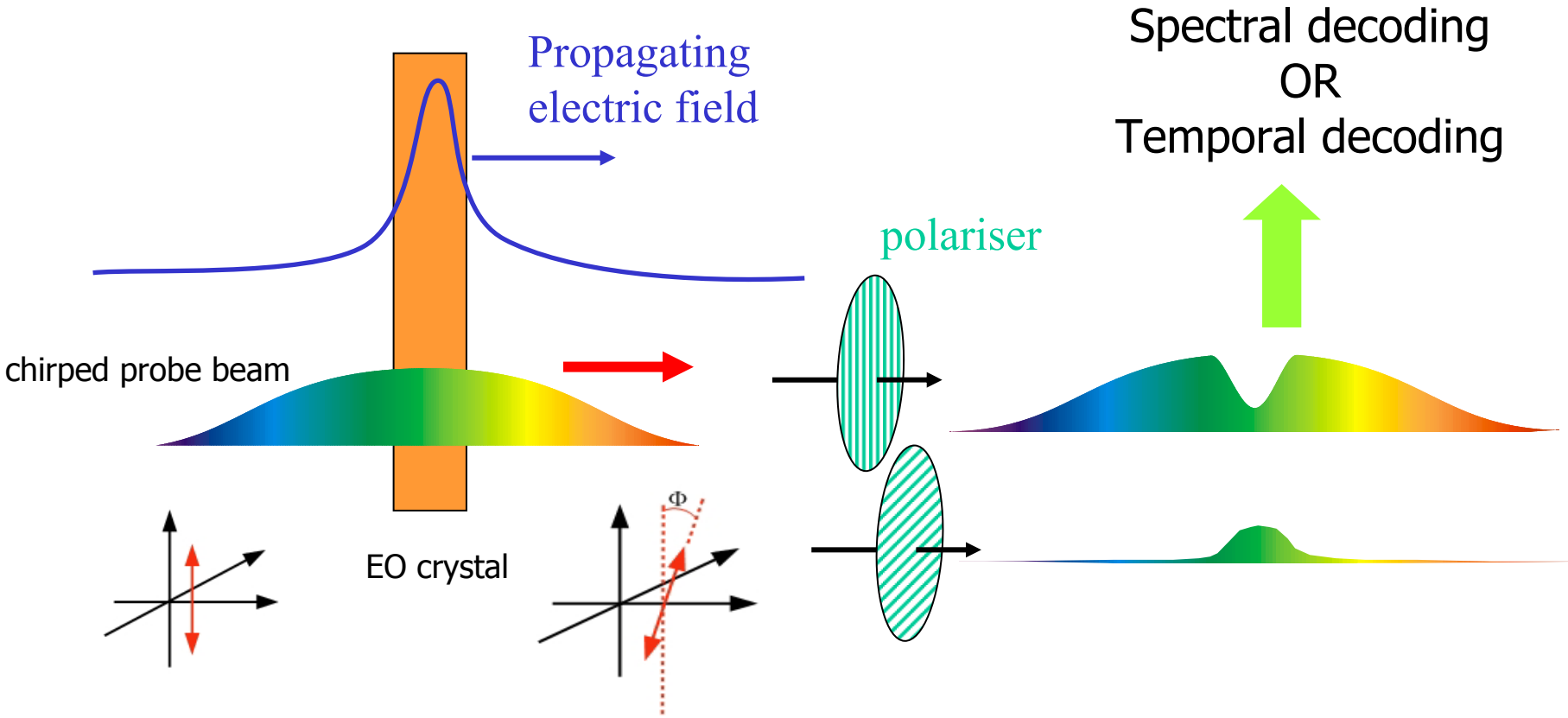
Single-shot EO measurement of Coulomb field



Effective polarisation rotation
proportional to coulomb field

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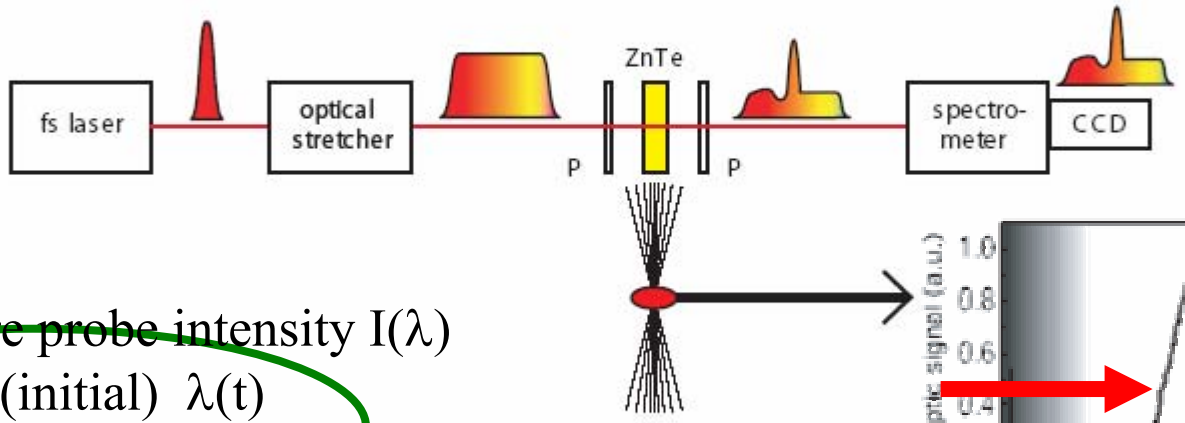
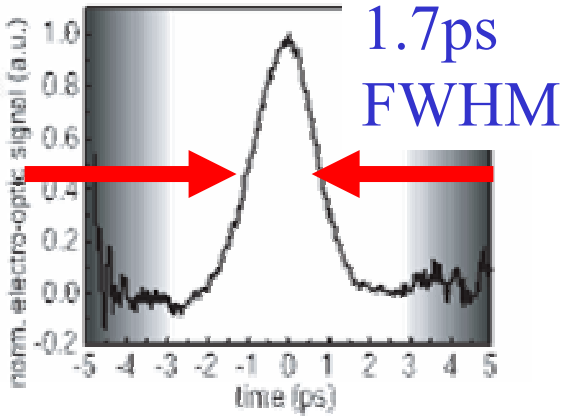
Electro-optic detection of the Coulomb field: 'Spectrometer method'

(Spectral decoding)



- ~~Measure probe intensity~~ I(λ)
- known (initial) λ(t)

⇒ infer I(t)



1.7ps FWHM

Not suitable for ultra short electron bunches (i.e. bunches <500fs FWHM)

Wilke et al. Phys. Rev. Lett. **88** 124801 (2002).

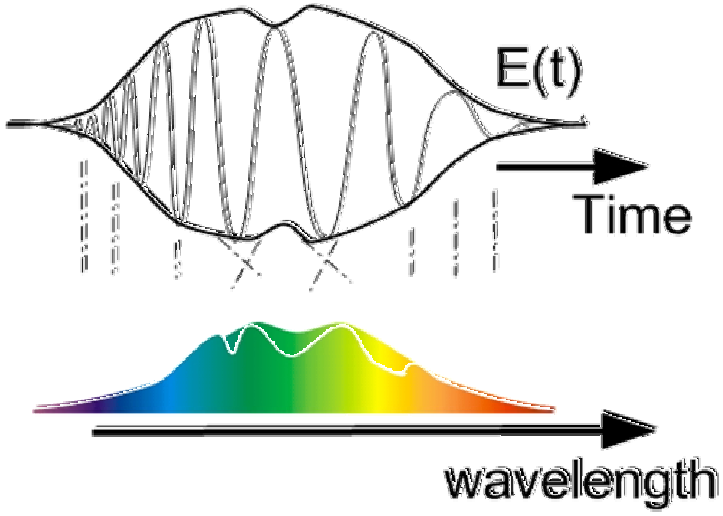
Time-resolution of spectral decoding.

Fourier transform

$$E_{Opt}(t) \longrightarrow E_{Opt}(t)[1 + E_{Coul}(t)]$$ Time domain

$$\overline{E}_{Opt}(\omega) \longrightarrow \overline{E}_{Opt}(\omega) + \overline{E}_{Opt}(\omega) * \overline{E}_{Opt}(\omega)$$ Frequency domain

Mixing of optical spectrum with neighbouring frequencies
⇒ optical spectral modulation unreliable with resolution greater than modulation bandwidth



approximate temporal resolution based on bandwidth

$$\Delta\tau > (t_o t_{chirped})^{1/2}$$

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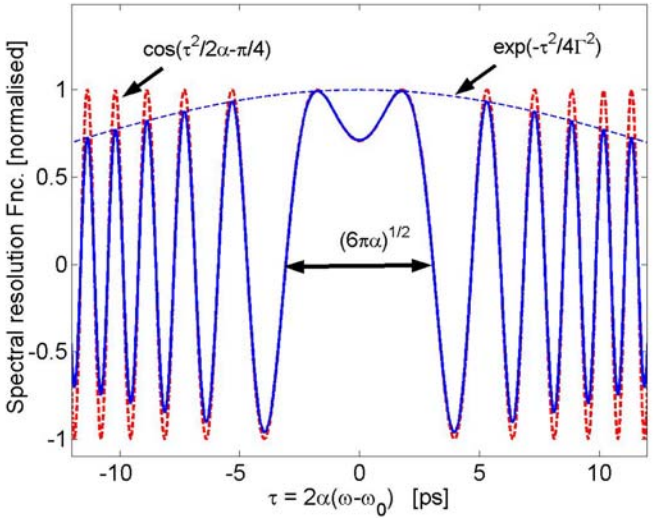
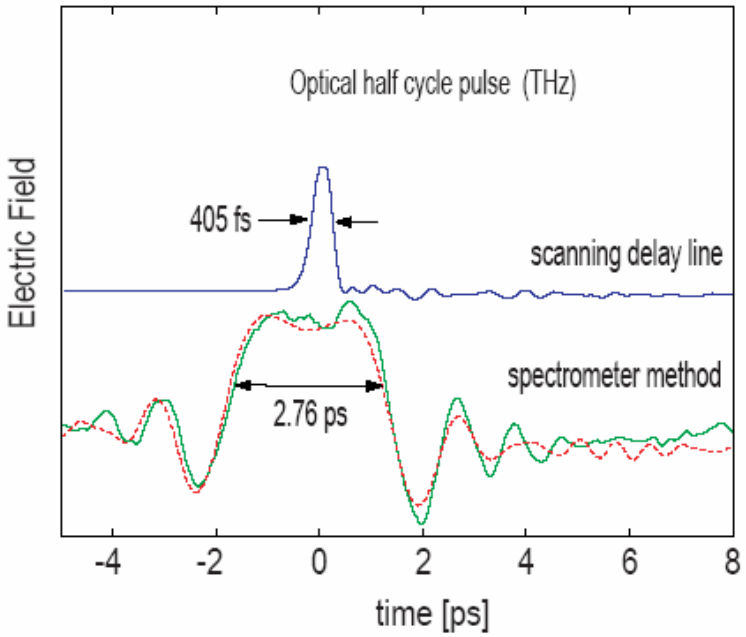
Time-resolution function NOT a smoothing function.
Can cause artifacts!!
CANNOT BE TREATED AS RMS TIME-RESOLUTION
Should be considered as temporal *limitation*

Time resolution function
(for balanced detection)



$$t_{res} \sim (t_0 t_{chirped})^{1/2}$$



Jamison et al. Opt. Lett. **18** 1710 (2003)

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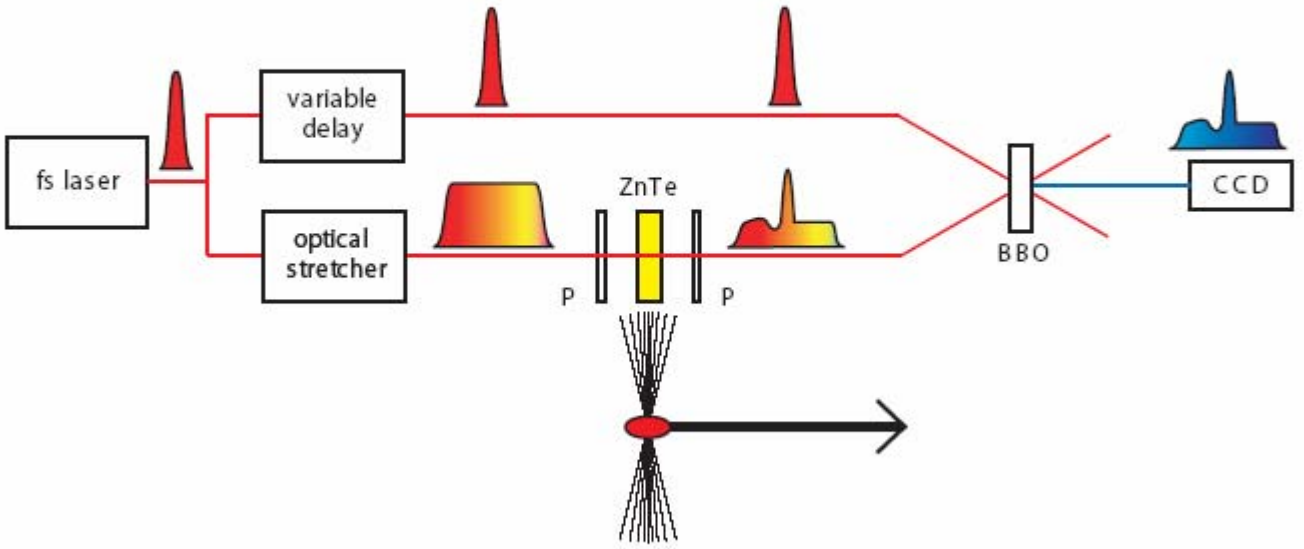
(Temporal decoding)

Electro-optic detection of Coulomb field: 'Cross correlation method'

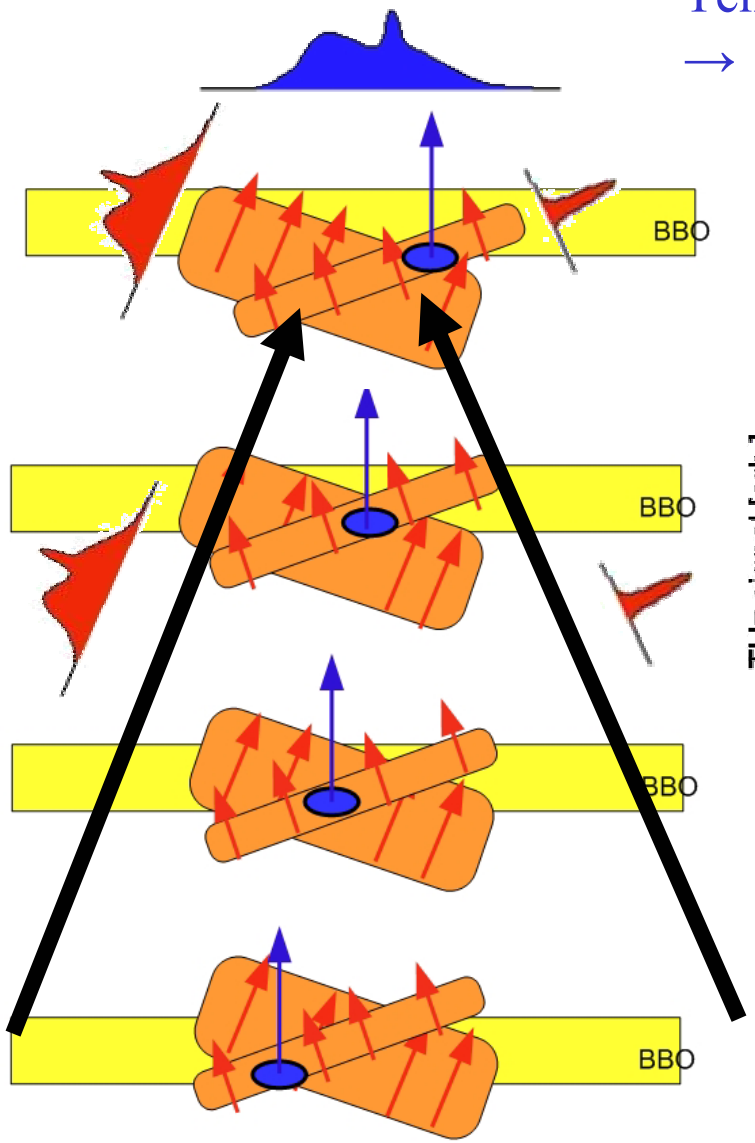


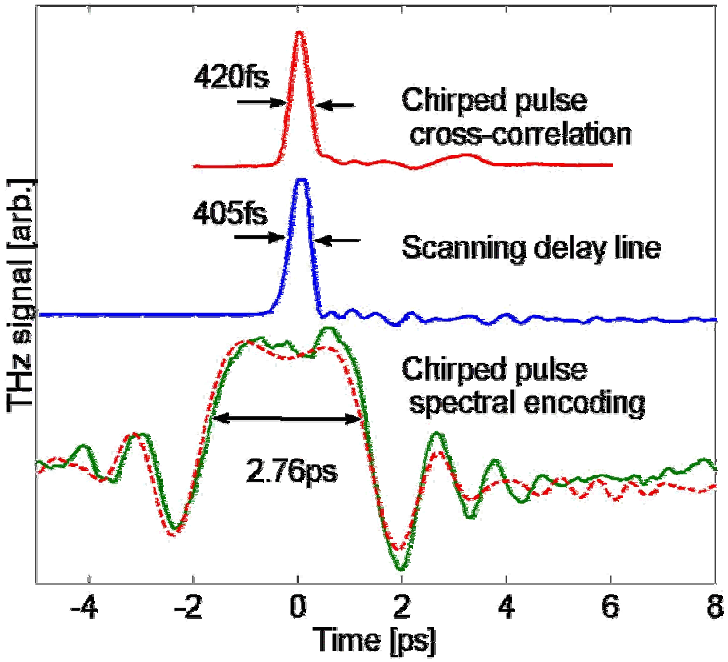
Temporal to spatial mapping of optical probe pulse

- Avoids problems of inseparability of frequency-time
- *Decoding* time-resolution ~ 30fs

Single-shot "temporal decoding" of optical probe

Temporal profile of probe pulse
→ Spatial image of SHG





Jamison et al. Opt. Lett. **18** 1710 (2003)

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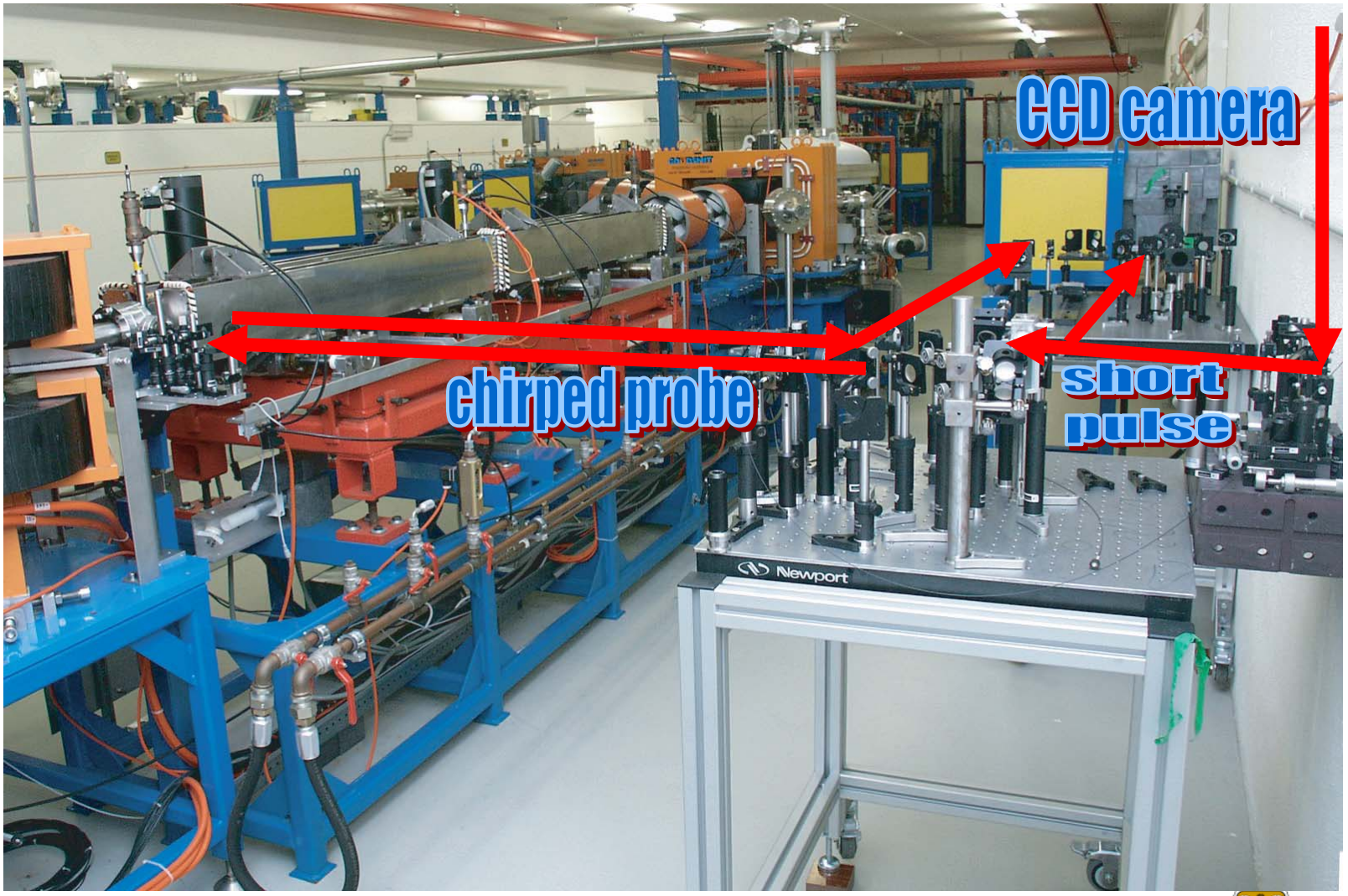
30-50MeV electron beam measurements

FELIX FEL facility, Rijnhuizen, Netherlands



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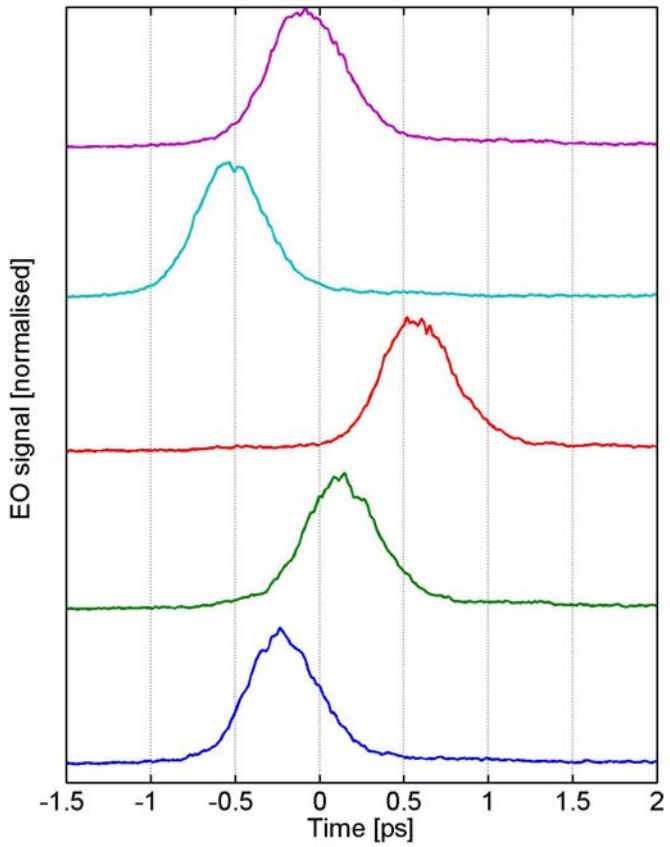
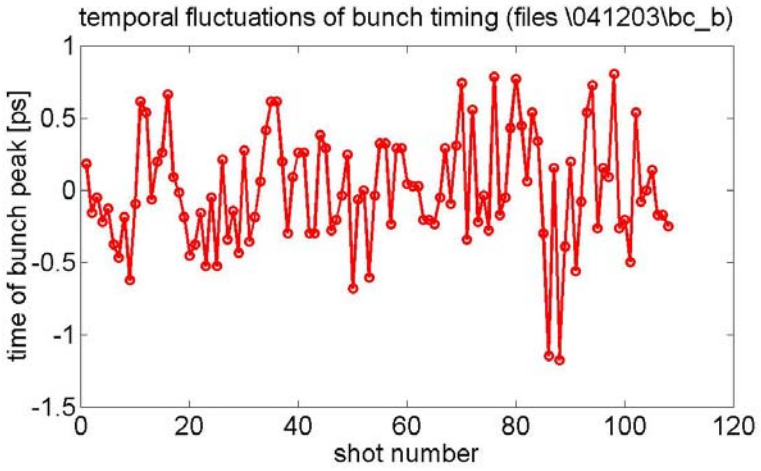
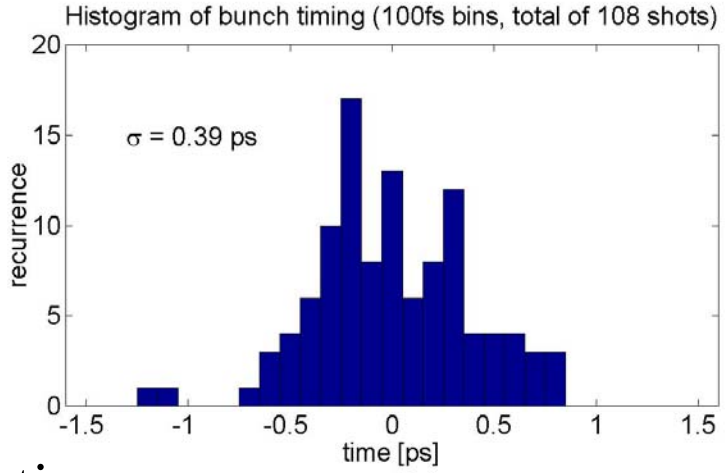
synchronisation for injection…

bunch timing jitter (temporal decoding)







Bunch timing jitter ~ bunch duration

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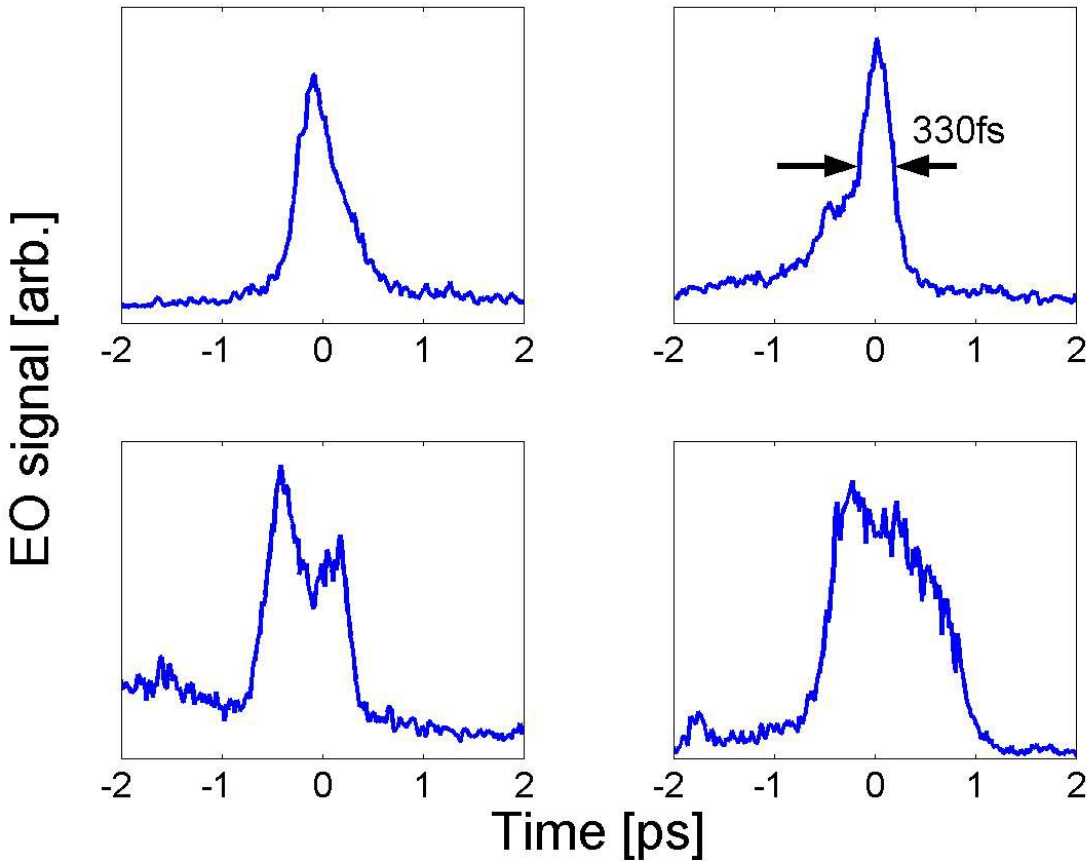
Real time bunch profile modification…

(FELIX, December 2003)



Bunch profile modified by changing the buncher and accelerator phase.

Measurements not time-resolution limited

However, still need further improvements in time resolution

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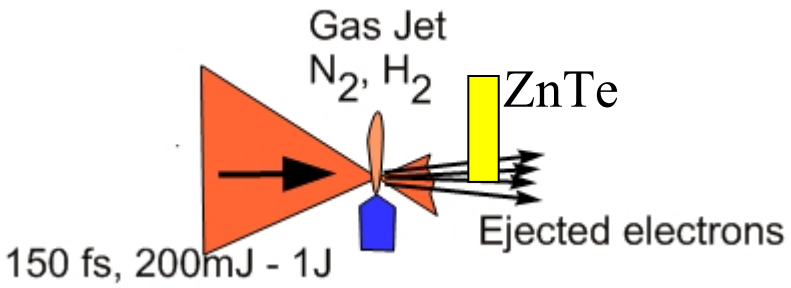
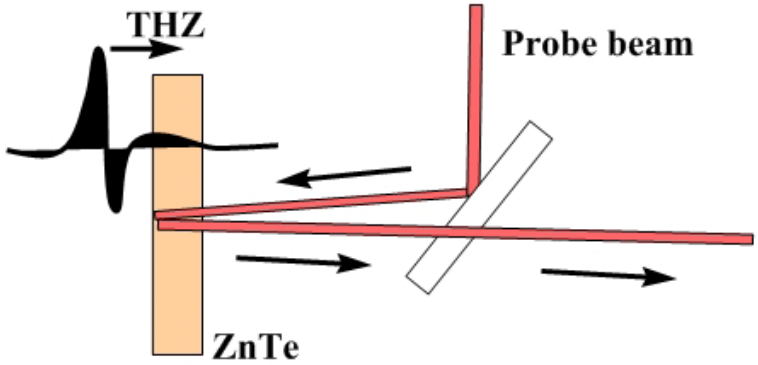
Electrons emitted from gas jets

Max-Plank Quant. Opt., Garching (ATLAS laser)



- Direction emission of electrons
- Exponential energy spectrum, ~1-5 MeV width
- ~100pC charge

ZnTe Reflection geometry….



THz frequency components of signal

- cancel during counter-propagating path
- sampled during co-propagating path

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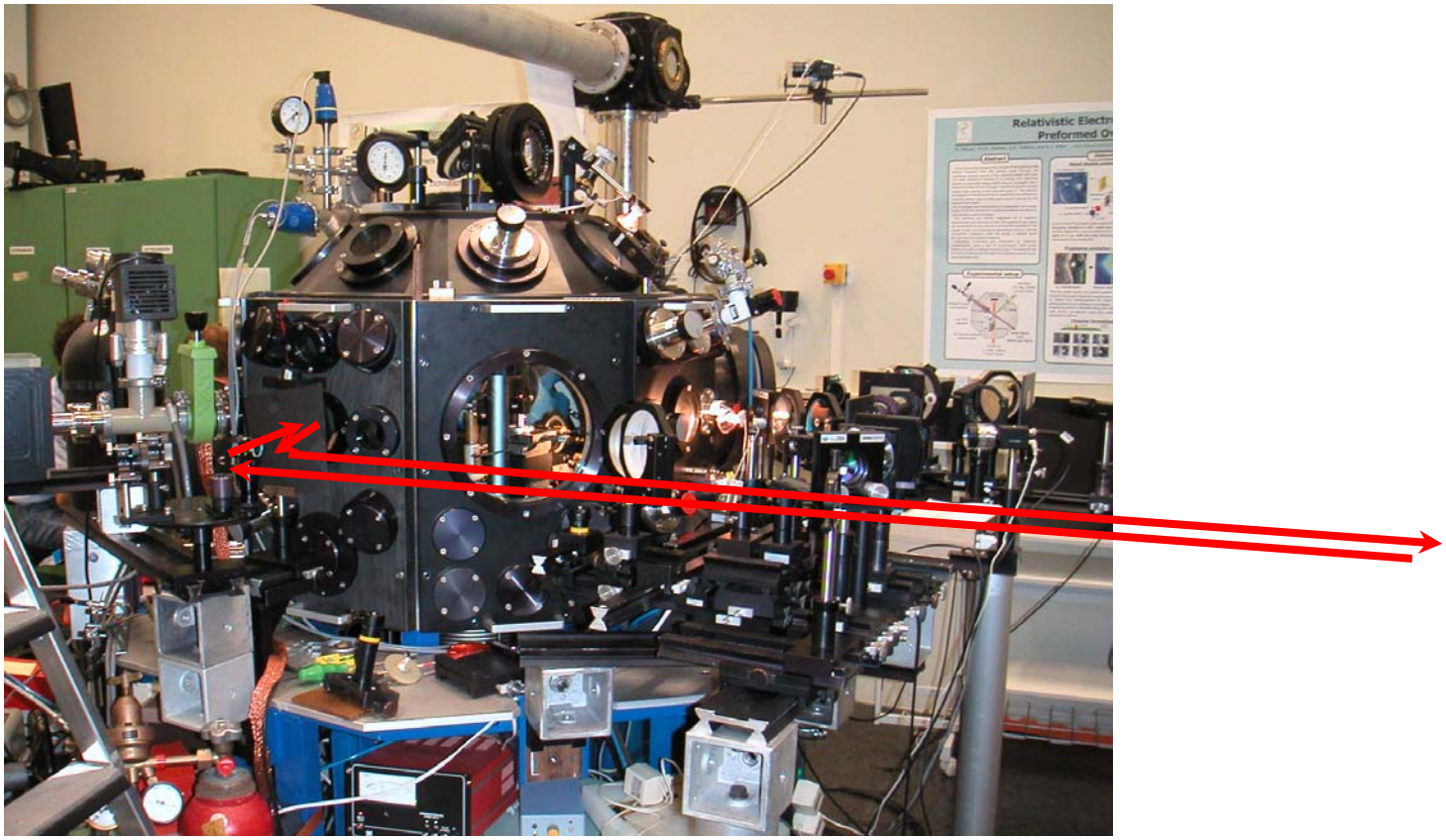
ATLAS experiments….



1Joule, 150fs (8nm bandwidth)
Focused to 5μm diameter

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Time of flight spread in electron bunch…

Shielding of (retarded) Coulomb fields by plasma…

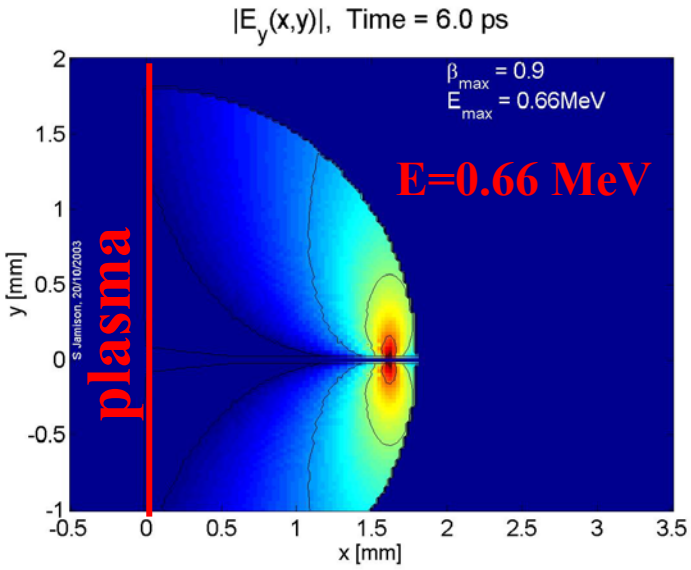
Coulomb field divergence of low energy electrons…

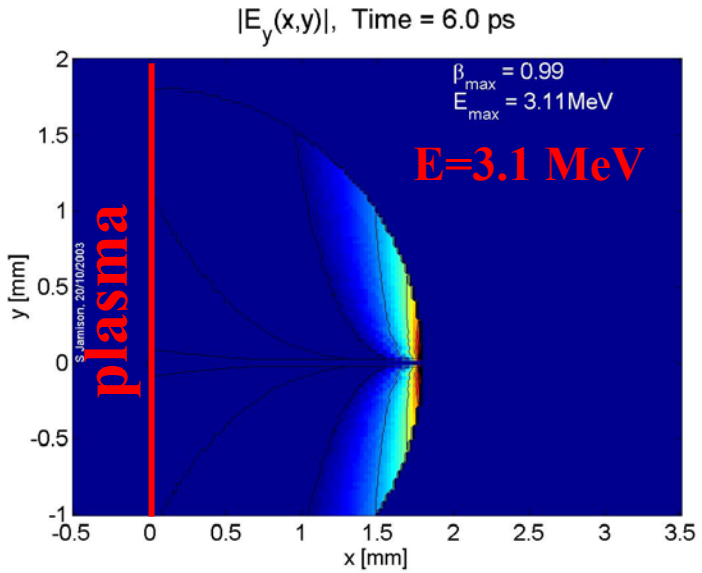
Transition radiation (?)…

$E = 0.6\ MeV \rightarrow \beta = 0.9$

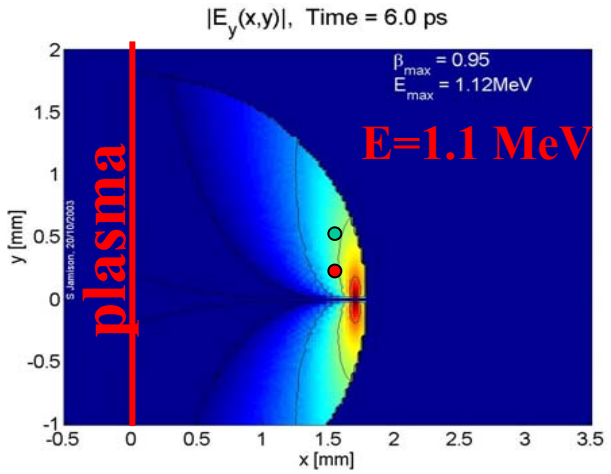
$E = 3.0\ MeV \rightarrow \beta = 0.99$

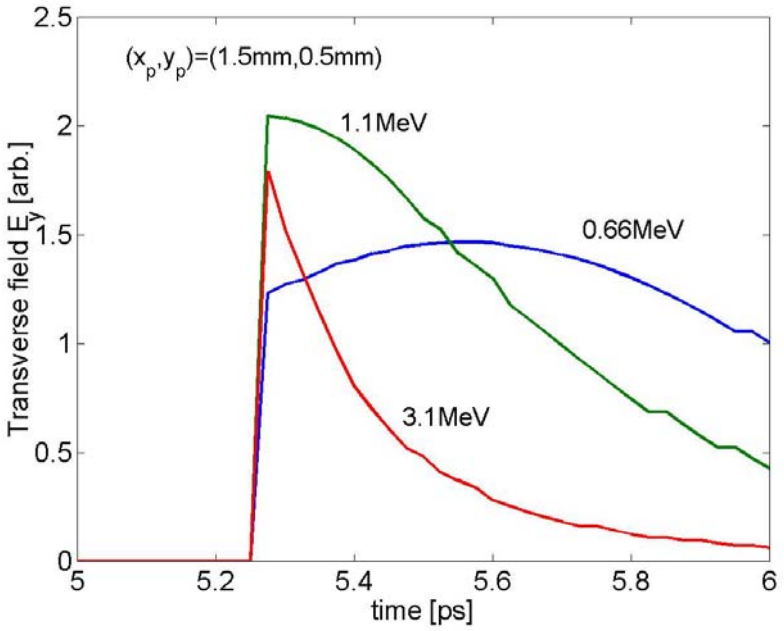
Time of flight separation of 330fs after 1mm propagation!!

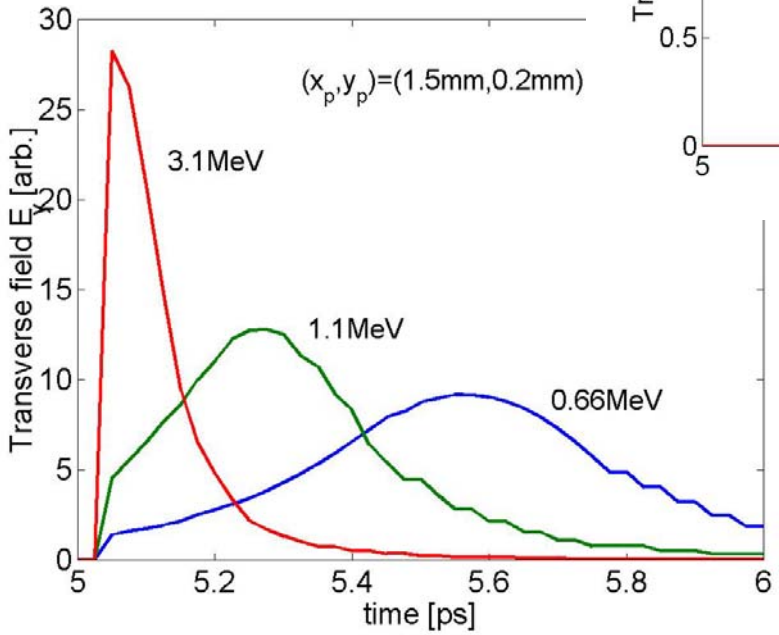




Calculated fields at different radial distance….







Summary….

- Identified artifact problem with EO spectral decoding
- Demonstrated temporal decoding (cross-correlation)
- Observed electron emission from gas jets (spectral decoding)
- Technique for monitoring injector timing jitter and bunch shape
- Challenges remain in getting sub-100fs resolution….

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