Proof-of-principle experiment for a sub-femtosecond electron bunch length diagnostic

Maria Weikum

Gerard Andonian, Nicholas Sudar, Mikhail Fedurin, Mikhail Polyanskiy, Christina Swinson, Andrey Ovodenko, Finn O'Shea, Mark Harrison, Zheng-Ming Sheng, Ralph Assmann

Special thanks to the ATF, AXSIS & EuPRAXIA collaboration teams

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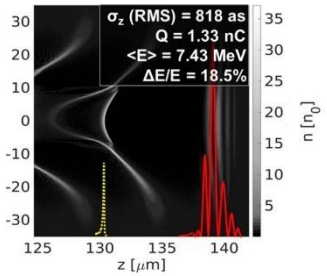
Overview

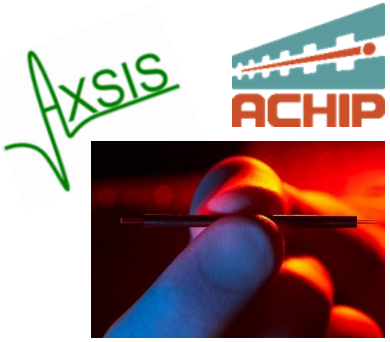
- Motivation
- How does the diagnostic work?
- Experimental setup at ATF
- Experimental results
- Application to ultrashort electron beams
- Summary & outlook

Motivation

- **Electron beam lengths towards the attosecond regime**

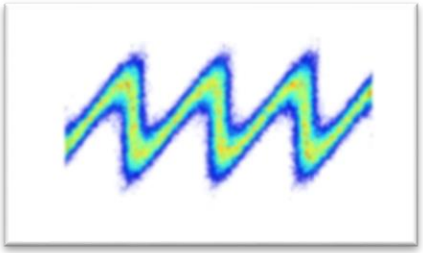


Plasma acceleration



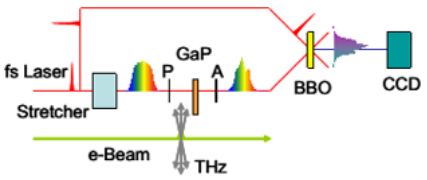
Dielectric acceleration

Bunch compression



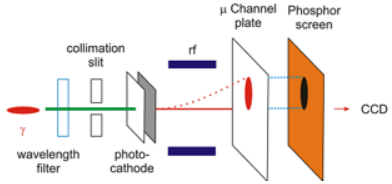
Microbunching

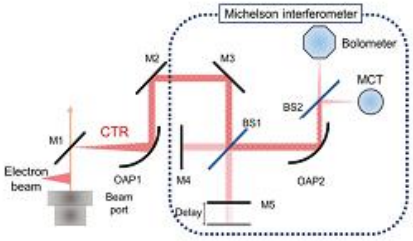
- **Experimentally established techniques: bunch length diagnostics limited to >fs level**



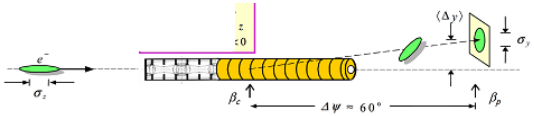
Electro-optical measurement

Streaking of electron radiation





Coherent transition radiation



Transverse deflecting cavity

+ novel concepts at sub-fs level: plasma TDS, THz TDS, …

How Does the Diagnostic Work?

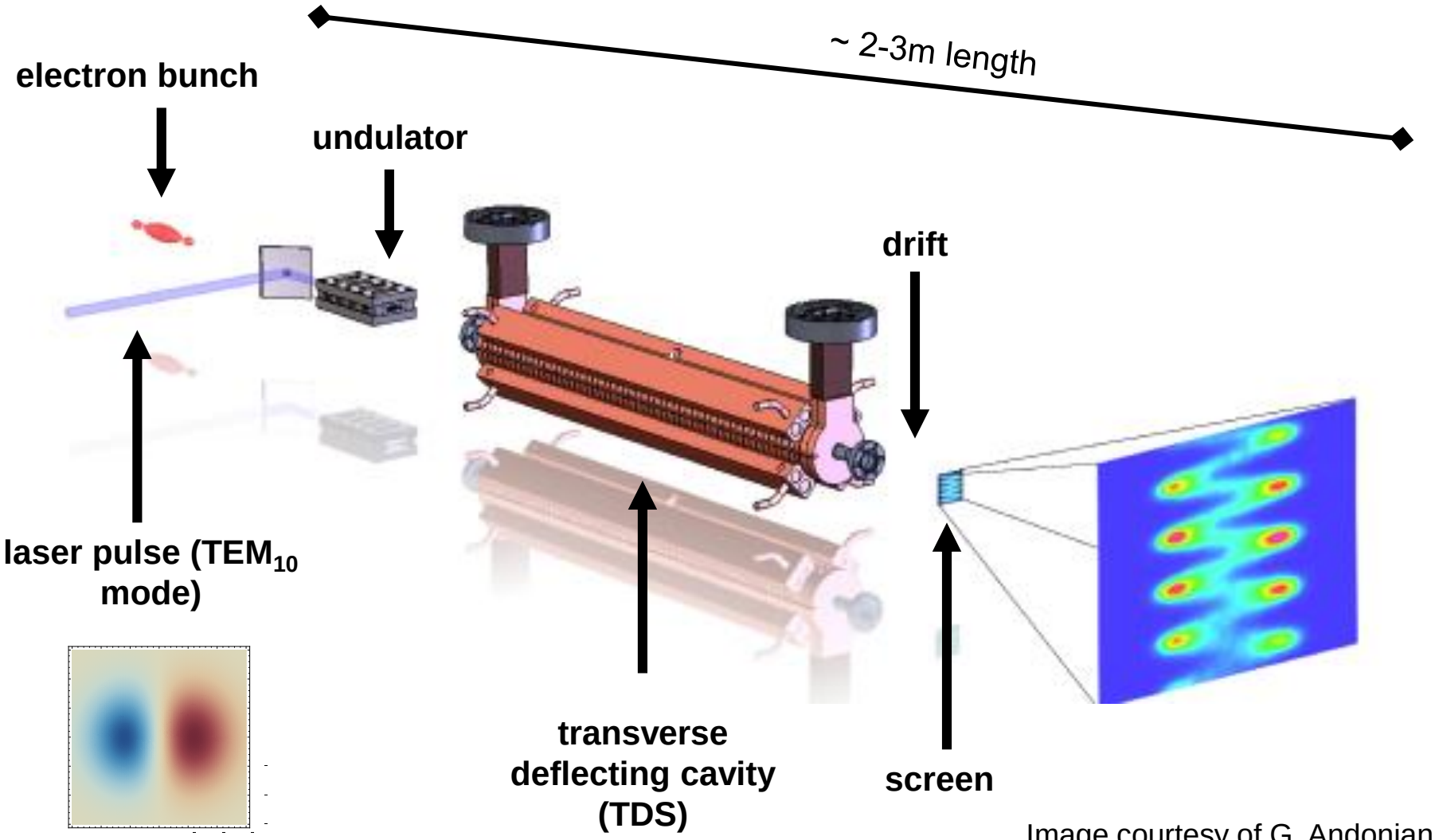


Image courtesy of G. Andonian

Andonian et al. Phys. Rev. ST Accel. Beams 14 (072802).

How Does the Diagnostic Work?

> Laser modulator (laser + undulator):

- energy exchange with laser field translates to angular modulation → transverse kick in horizontal direction Δx‘ with strength dependent on longitudinal position s_0:

$$x' = x'_0 + S_{LM} \sin(k s_0)$$

with $S_{LM} \propto \frac{K}{\gamma^2}\sqrt{P_L}$

> RF deflecting cavity (TDS):

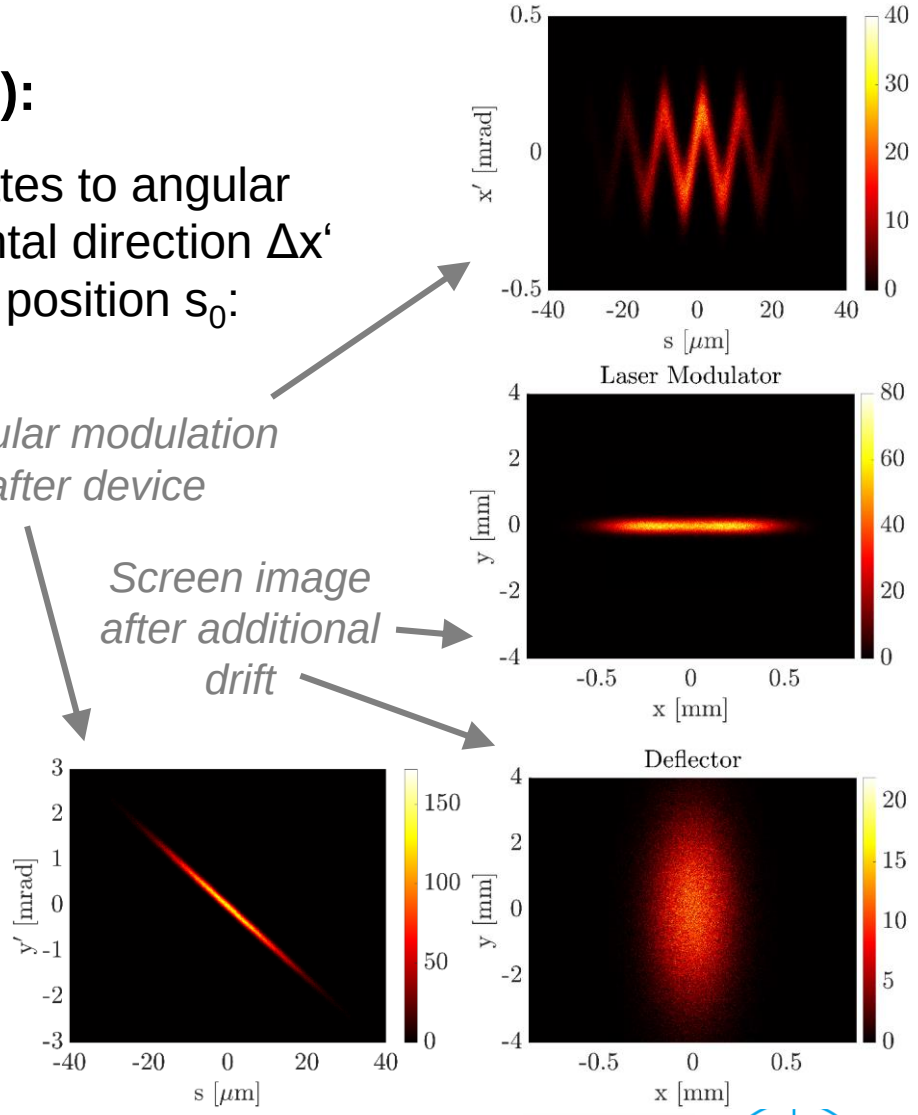
- transverse kick in vertical direction Δy‘ with strength dependent on longitudinal position s_0:

$$y' = y'_0 + S_{rf} \sin(k_{rf} s_0)$$

with $S_{rf} \propto \frac{V_{rf}}{\gamma}$

Angular modulation after device

Screen image after additional drift



Elegant (Sirepo) simulations [beta.sirepo.com]

How Does the Diagnostic Work?

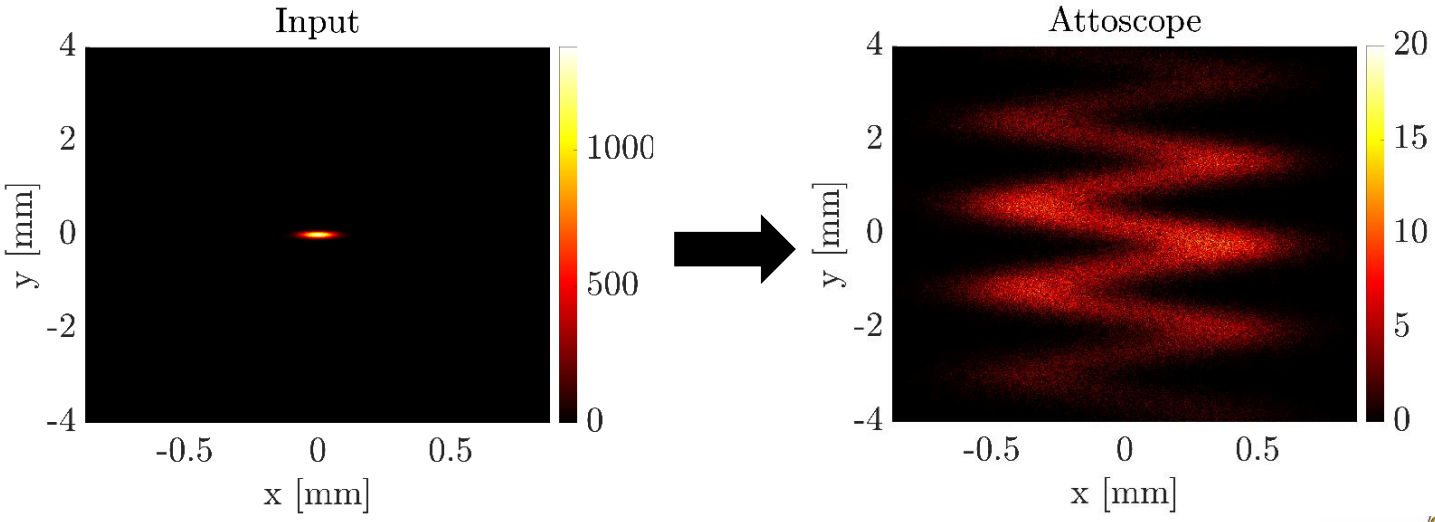
- Temporal resolution determined by laser modulator:

$$\Delta t_{LM} \propto \frac{1}{S_{LM} k} \quad \text{with } S_{LM} \propto \frac{K}{\gamma^2}\sqrt{P_L}$$

(for TDS: $\Delta t_{rf} \propto \frac{1}{S_{rf} k_{rf}}$ with $S_{rf} \propto \frac{V_{rf}}{\gamma}$)

→ significant improvement as $\frac{S_{LM} k}{S_{rf} k_{rf}} \gg 1$

- Laser modulator provides advanced streaking strength
- RF deflector ensures resolution of full beam profile over multiple laser wavelengths



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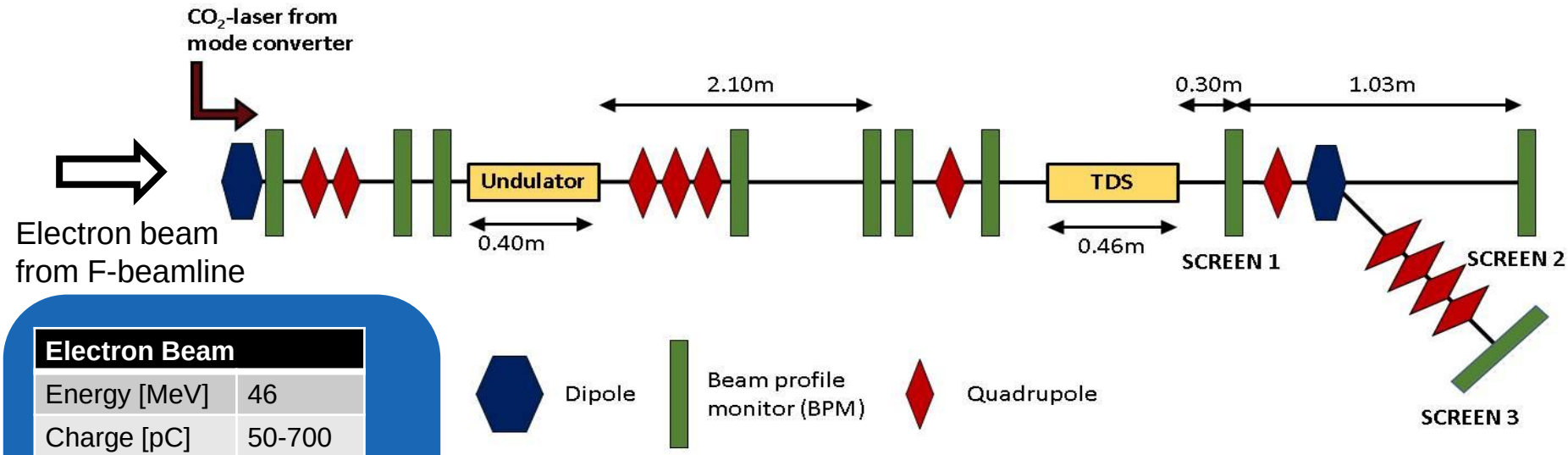
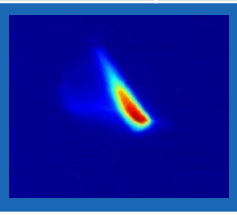
Experimental Setup at ATF (Brookhaven National Lab)



Electron Beam	
Energy [MeV]	46
Charge [pC]	50-700
Duration [ps]	0.05-2



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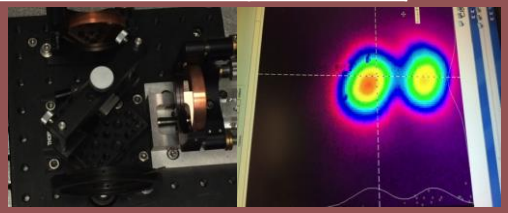
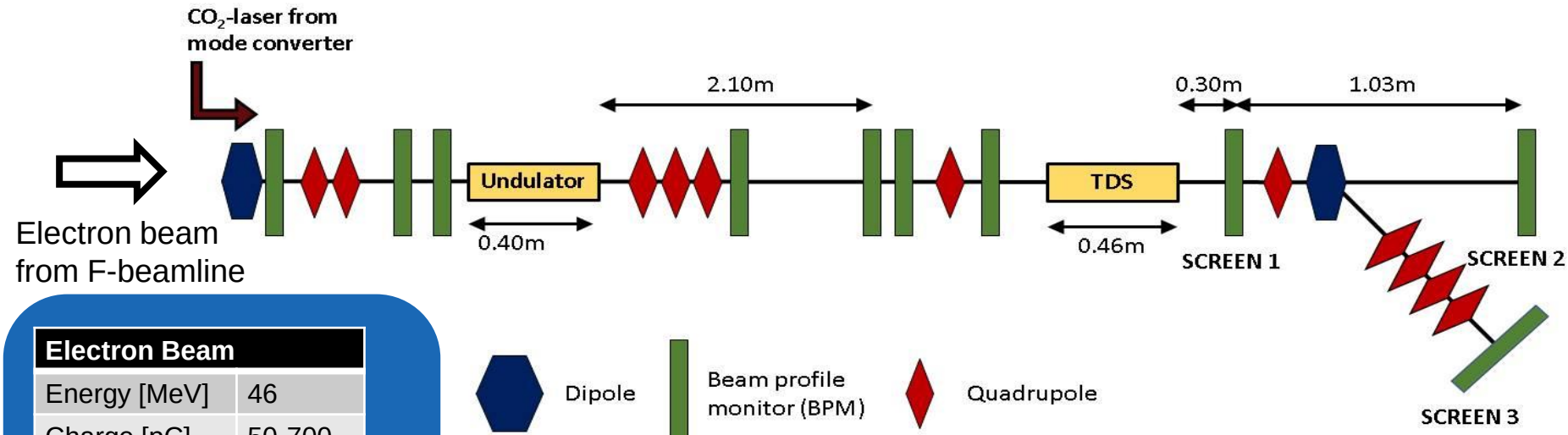
CO_2-Laser	
Power [GW]	5-150
Wavelength [µm]	10.3
Duration [ps]	3.5

+ conversion to TEM_{10}-mode





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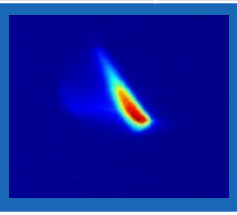

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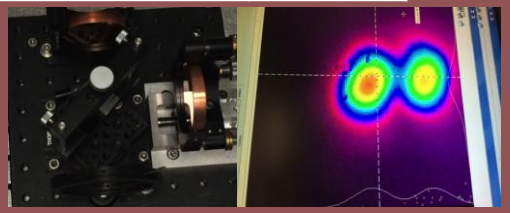
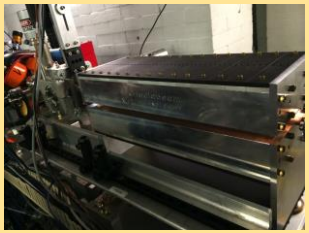
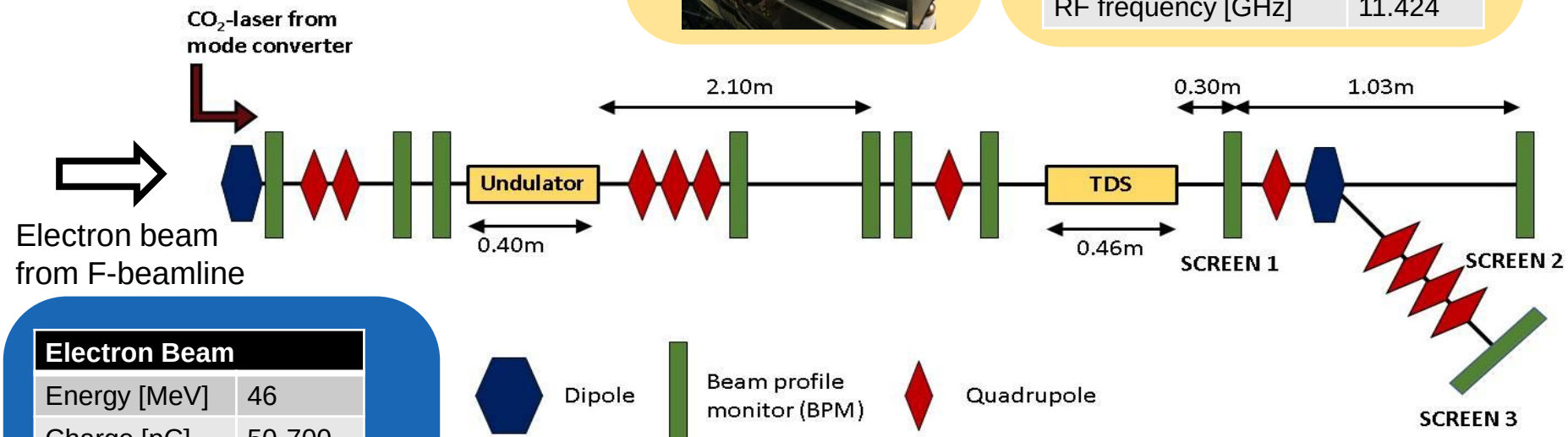


Undulator	
Peak field [T]	0.67
Period [cm]	4.0
K	2.5



RF Deflector	
Voltage [MV]	≤15
RF frequency [GHz]	11.424



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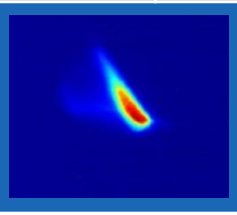
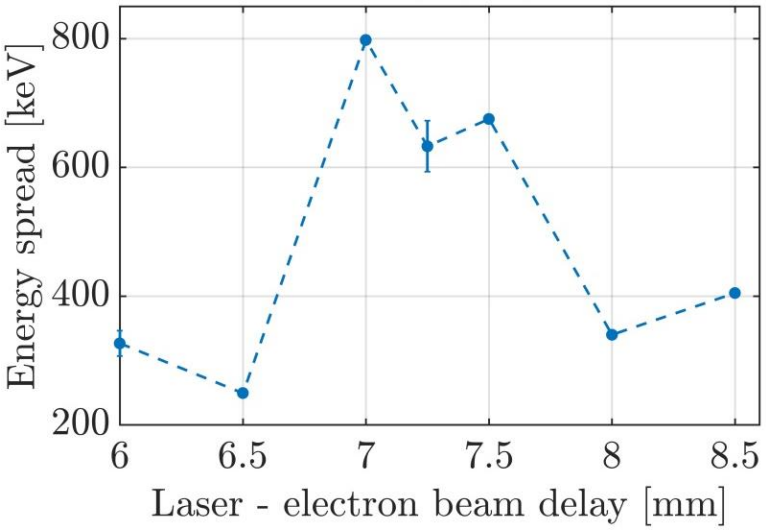
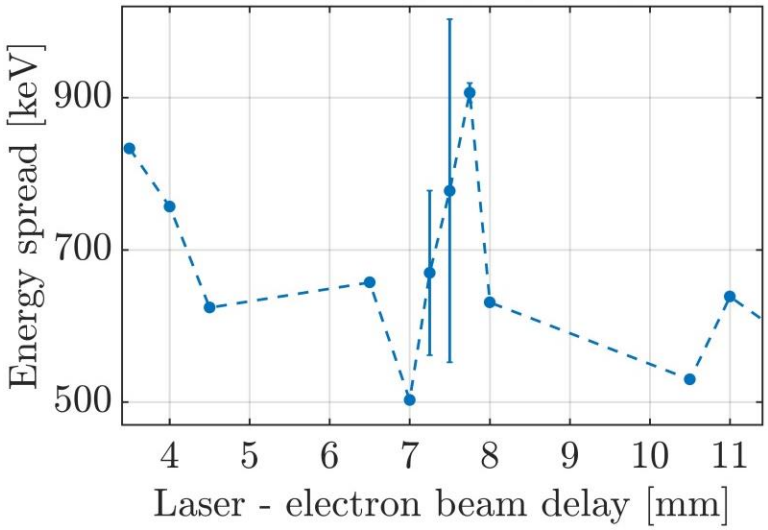


Experimental Results: Synchronisation

- Measure IFEL interaction between electron beam and laser in TEM_{00}-mode at spectrometer for tuning beam-laser fine timing





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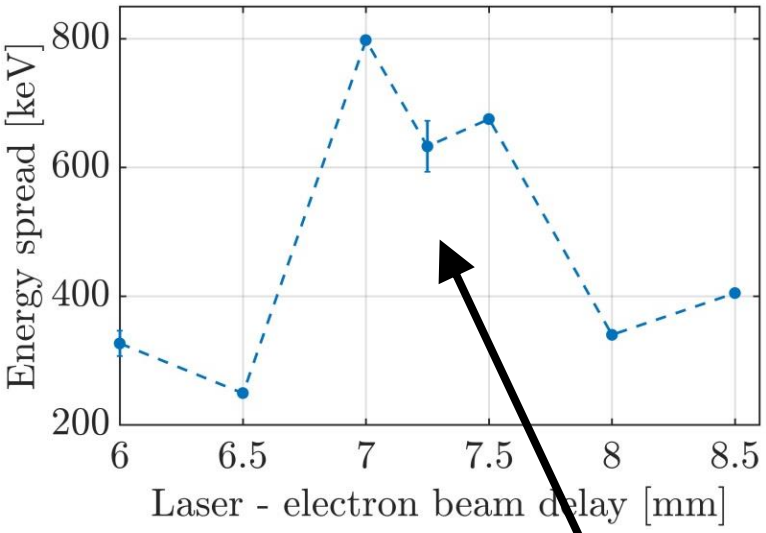
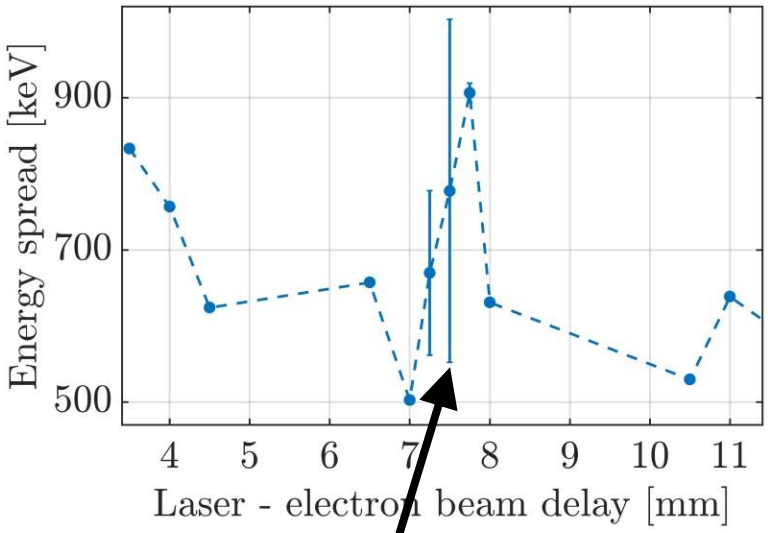


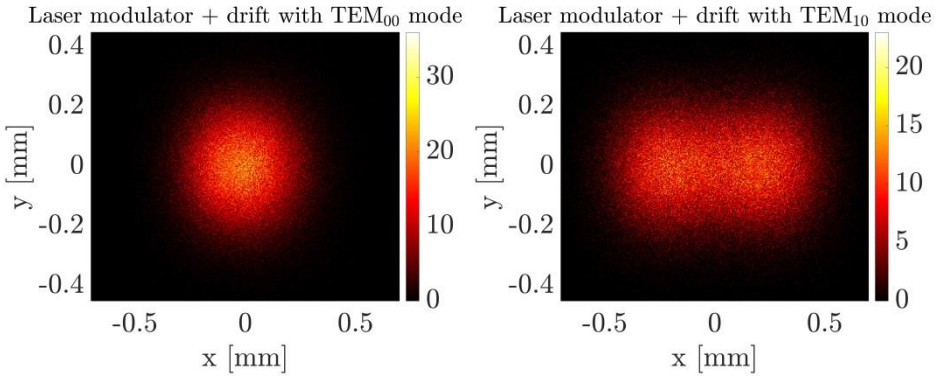


Strongest beam-laser interaction
= ideal timing between laser and electron beam

Experimental Results: Interaction with TEM_{10}-mode

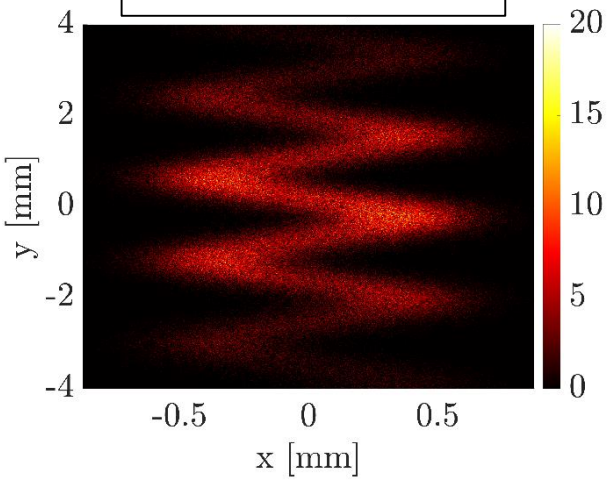
- TEM_{00}-mode induces energy modulation, but no transverse kick

→ need TEM_{10}-mode



Laser modulator: TEM_{00} TEM_{10}

SIMULATION



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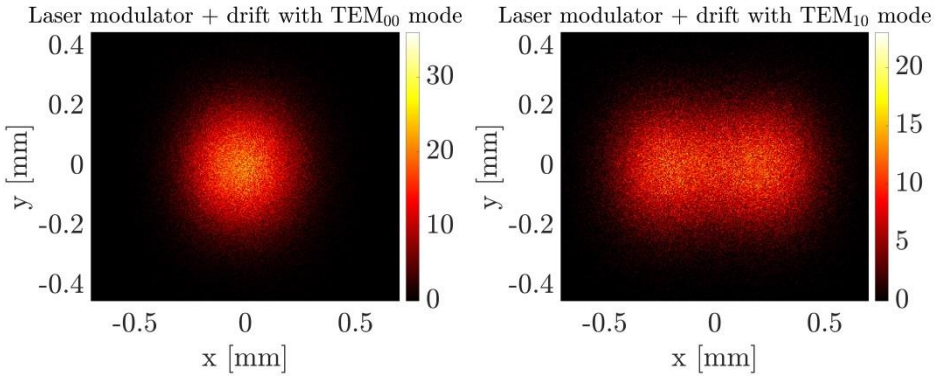

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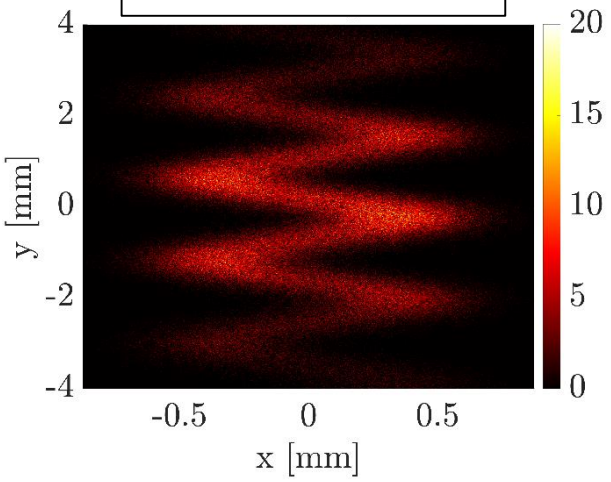

Realistic ATF setup:

→

Longer electron beam, limited streaking power, complex beam transport, etc.

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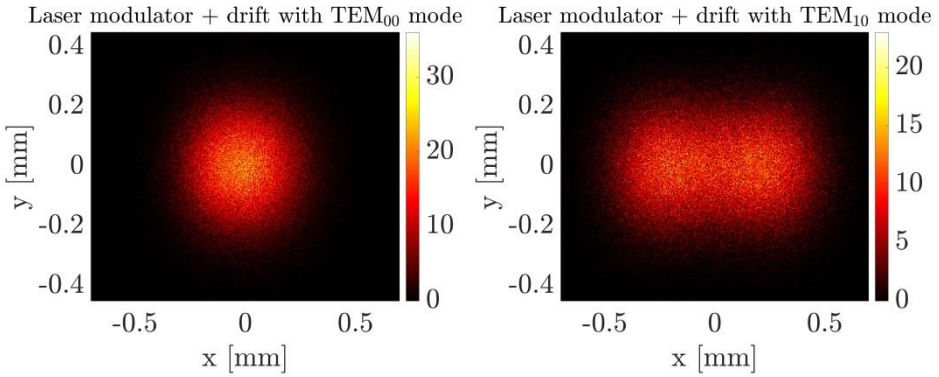

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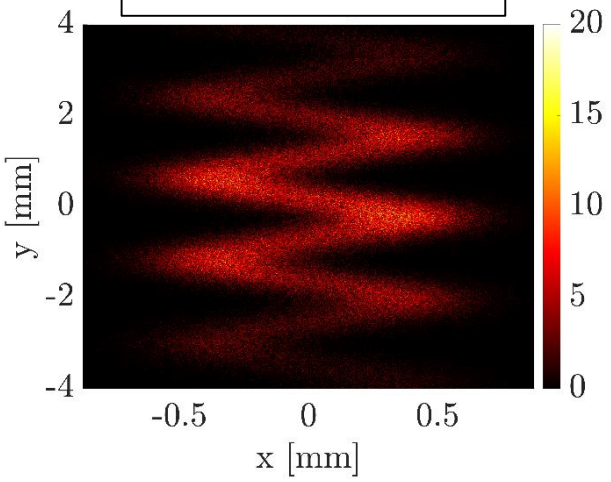

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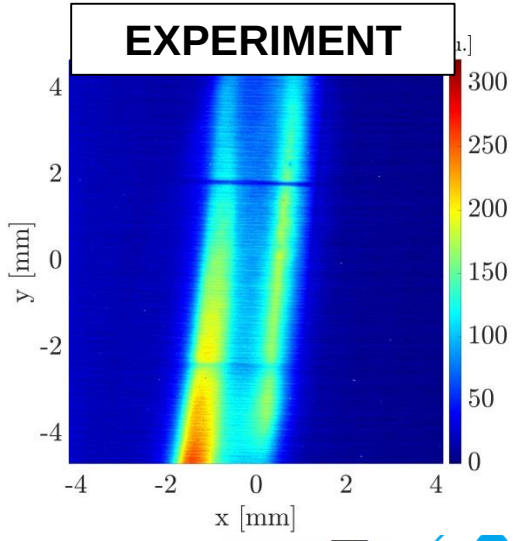
EXPERIMENT



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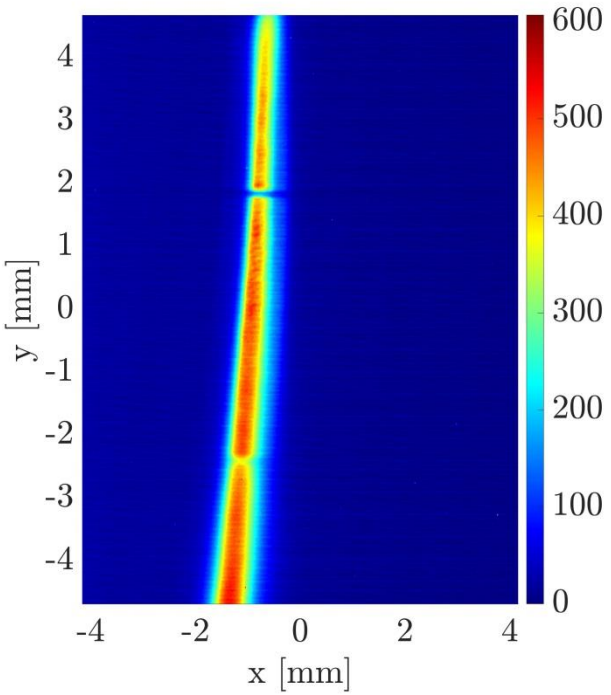
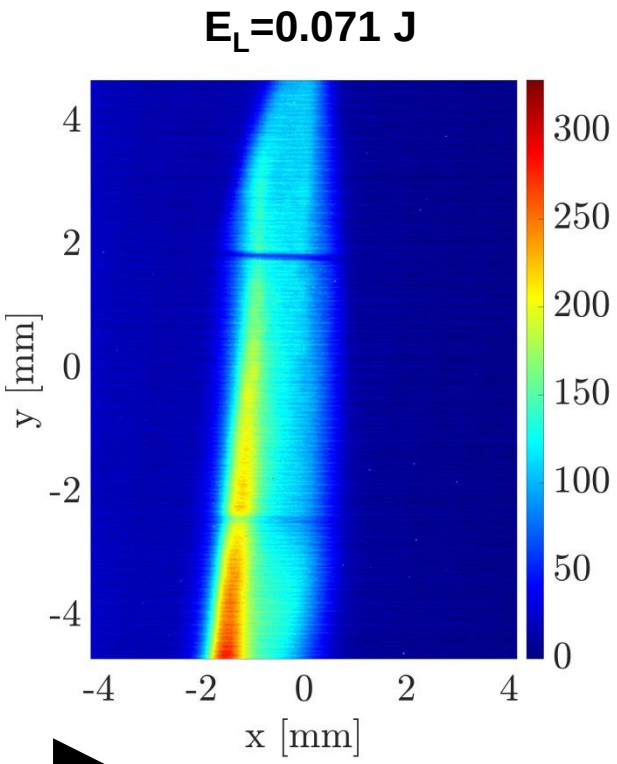
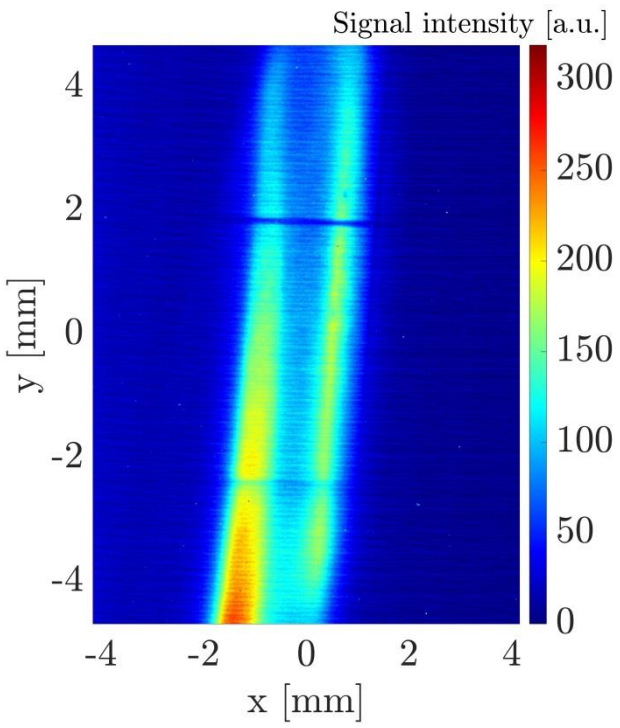
Transverse beam distribution at screen 1
(0.3m after deflector)



E_L=0.0 J



E_L=0.071 J

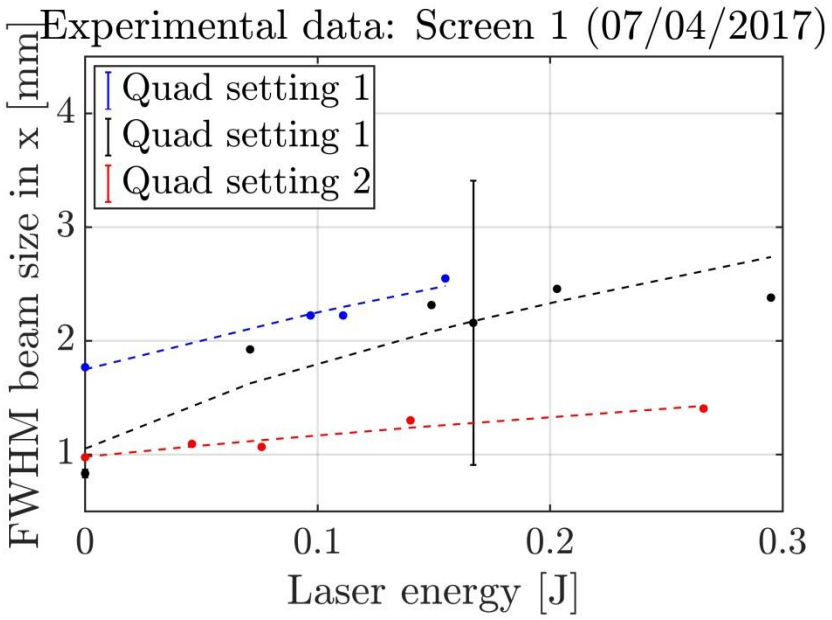


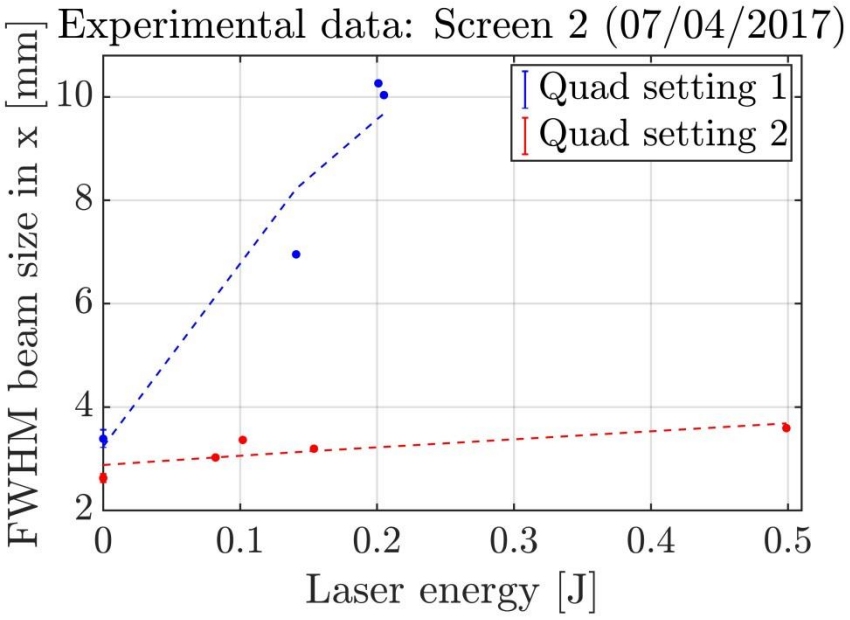
E_L=0.203 J

Increasing laser energy

Experimental Results: Interaction with TEM_{10}-mode

- Horizontal beam spread scales approx. with $\sqrt{E_L}$, but strength of streaking depends on beam focusing behind the laser modulator
- Too strong focusing reverses laser streaking → qualitatively consistent with simulation results





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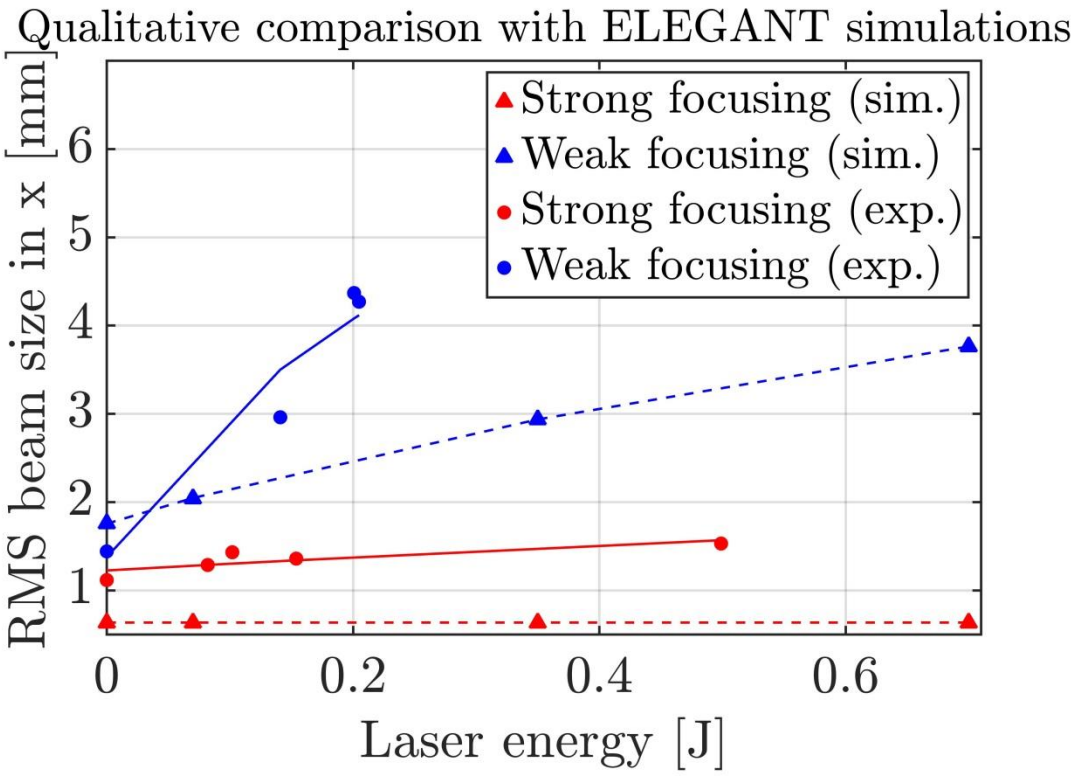
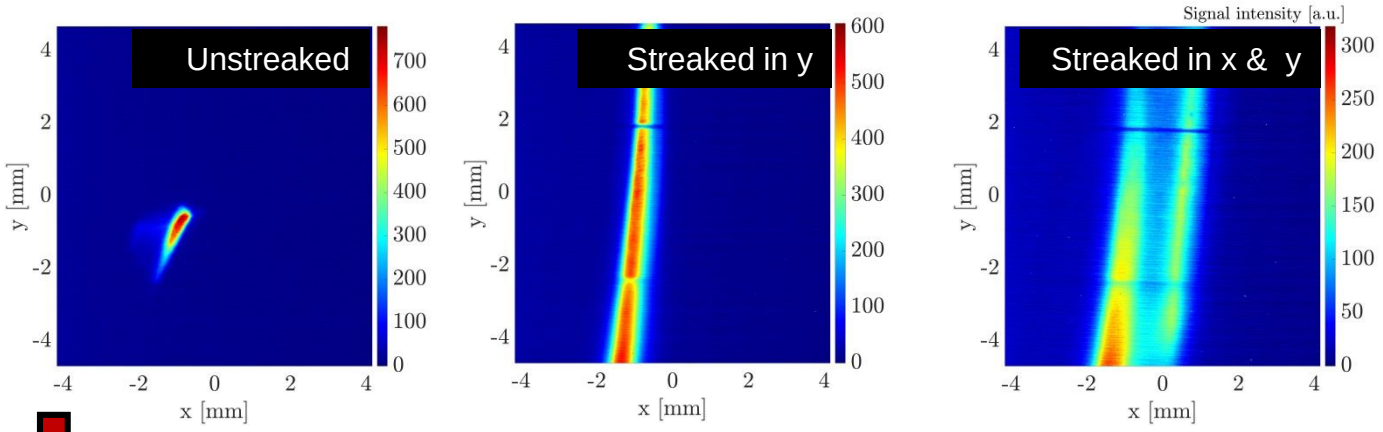


Experimental Results: Why is pattern not visible?



Transverse beam distribution at screen 1 (0.3m after TDS)

Good streaking, but full sinusoidal pattern not visible

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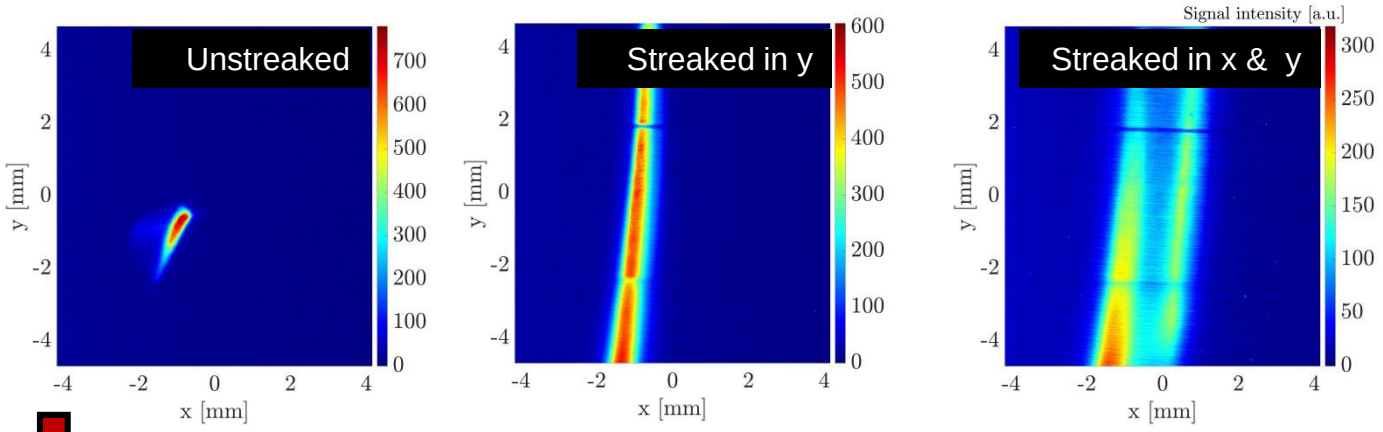

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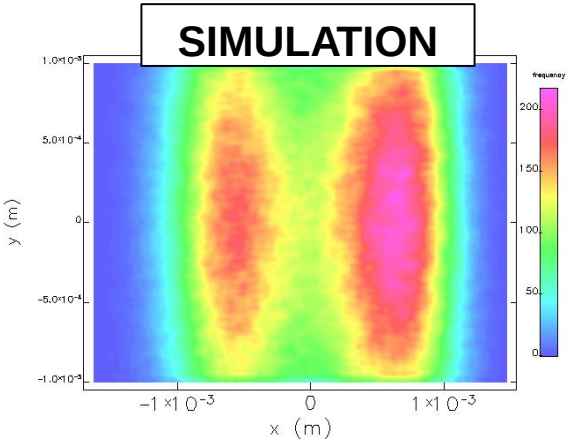

Courtesy of G. Andonian

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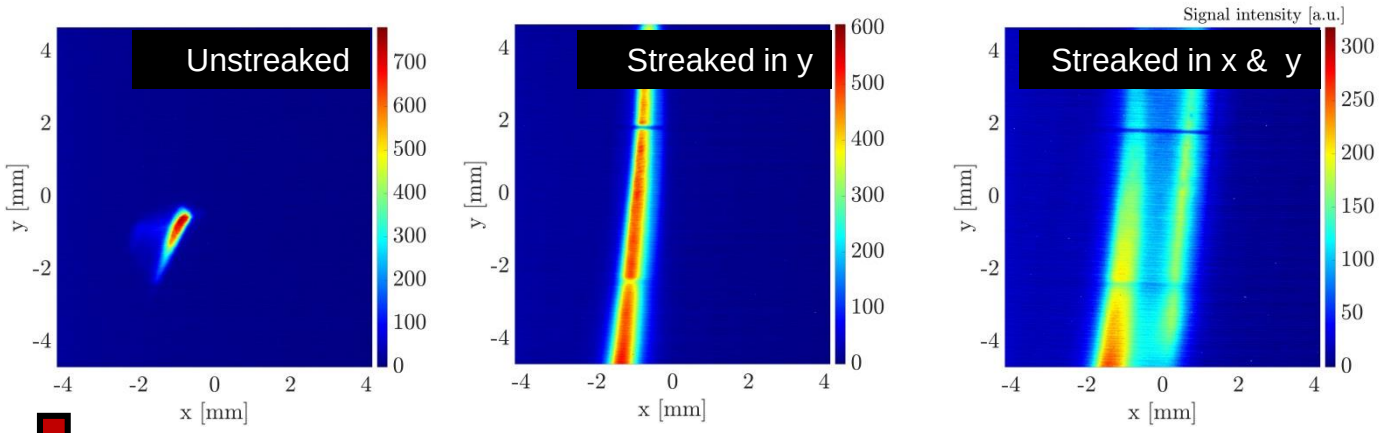

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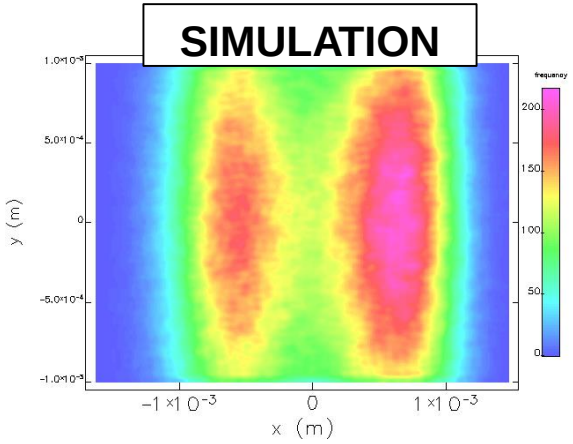
> Possible reasons:

1) Signal washed out due to large intrinsic beam size in y



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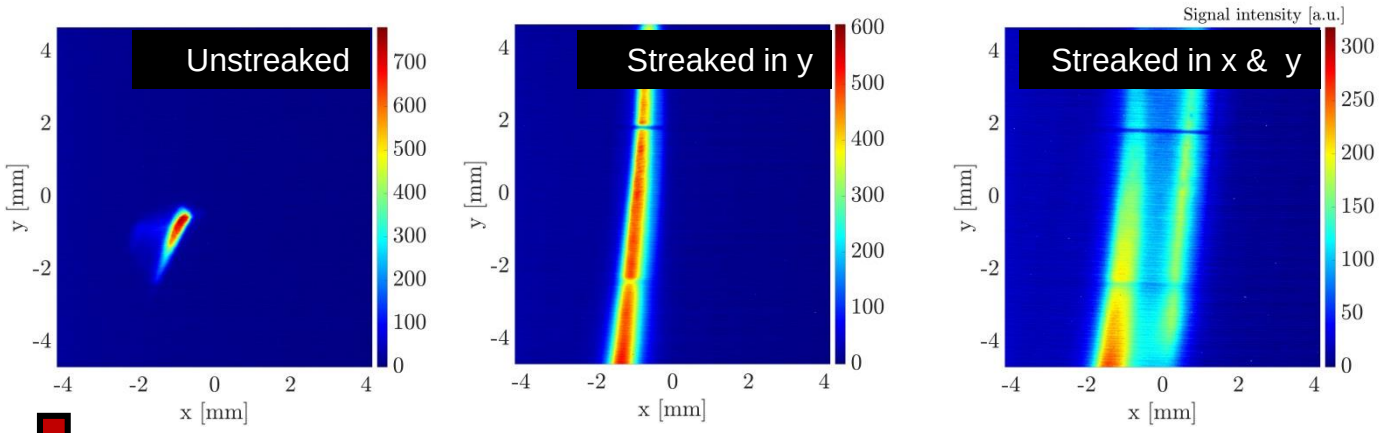

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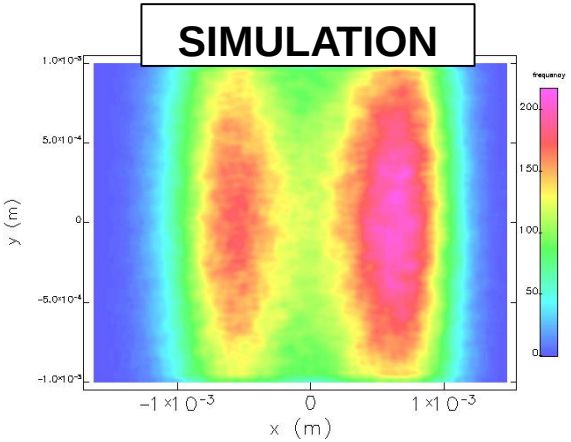
2) Resolution of imaging screen not good enough:

   approx. 5pixel / laser wavelength on screen (assuming V_{rf}=6MV)



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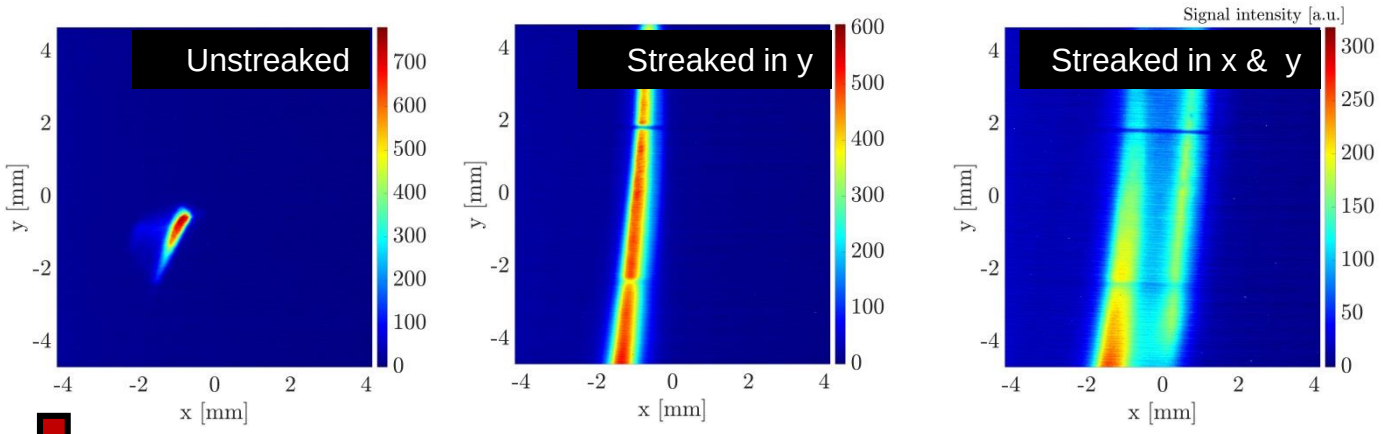

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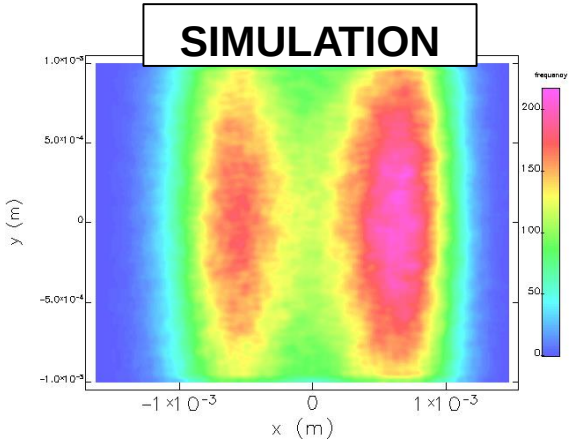


Courtesy of G. Andonian

Possible solution: increase in RF streaking voltage

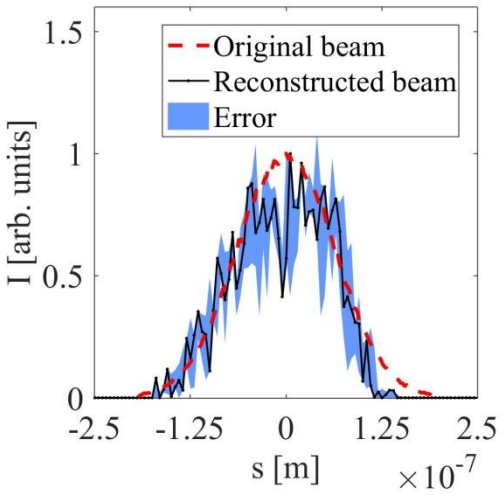
Application to Ultrashort Beams

- RF deflector optional for bunch lengths < λ/2
- Major limitations to effective resolution:

  1) Washing out of screen pattern due to **large transv. emittance or energy spread**

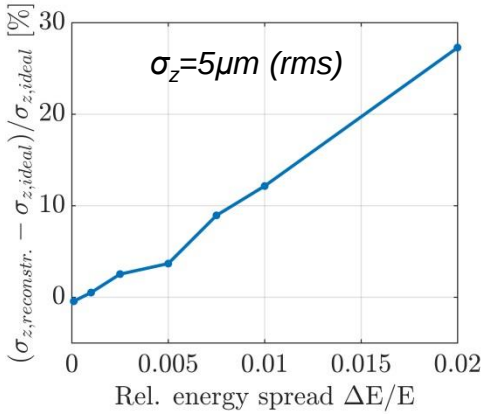
  2) Bunch length change in device due to **large energy spread or space charge forces** (→ important e.g. for novel accelerators!)

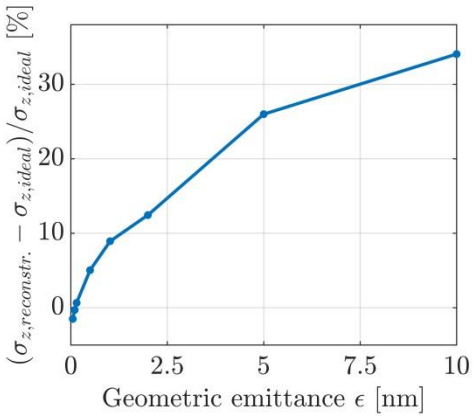
- Example designs for AXSIS and SINBAD sub-fs electron beams with successful bunch length reconstruction in simulations

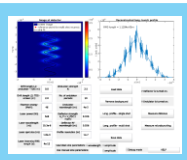


Example: SINBAD beam (courtesy J. Zhu)	
Beam energy	150 ± 0.4 MeV
RMS duration	210 as
Emittance in x,y	0.72, 0.66 nm
Laser power	350 GW
Undulator peak field	1.354 T

<5% error in bunch length reconstruction





elegant +  own reconstruction tool

Weikum et al. J. Phys.: Conf. Ser. 874 (012079).

Summary & Outlook

- **Bunch length diagnostic with sub-femtosecond resolution through streaking with laser modulator** and resolving beam pattern with RF deflector in orthogonal direction
- **Proof-of-concept experiment at ATF at Brookhaven National Laboratory**: GW CO_2-laser + Linac + MV X-band deflector
- **Laser-electron beam interaction** is shown through spread of beam in energy and horizontal direction, **full streaking pattern planned to be resolved in next experimental run**
- Improvements for follow-up experiment:
  - Optimise screen resolution and RF streaking voltage
  - Deconvolve effects of beam transport from laser streaking
  - More statistics
- **Potential future application to ultrashort beams from novel accelerators** (e.g. AXSIS, EuPRAXIA, …)

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+ ATF staff

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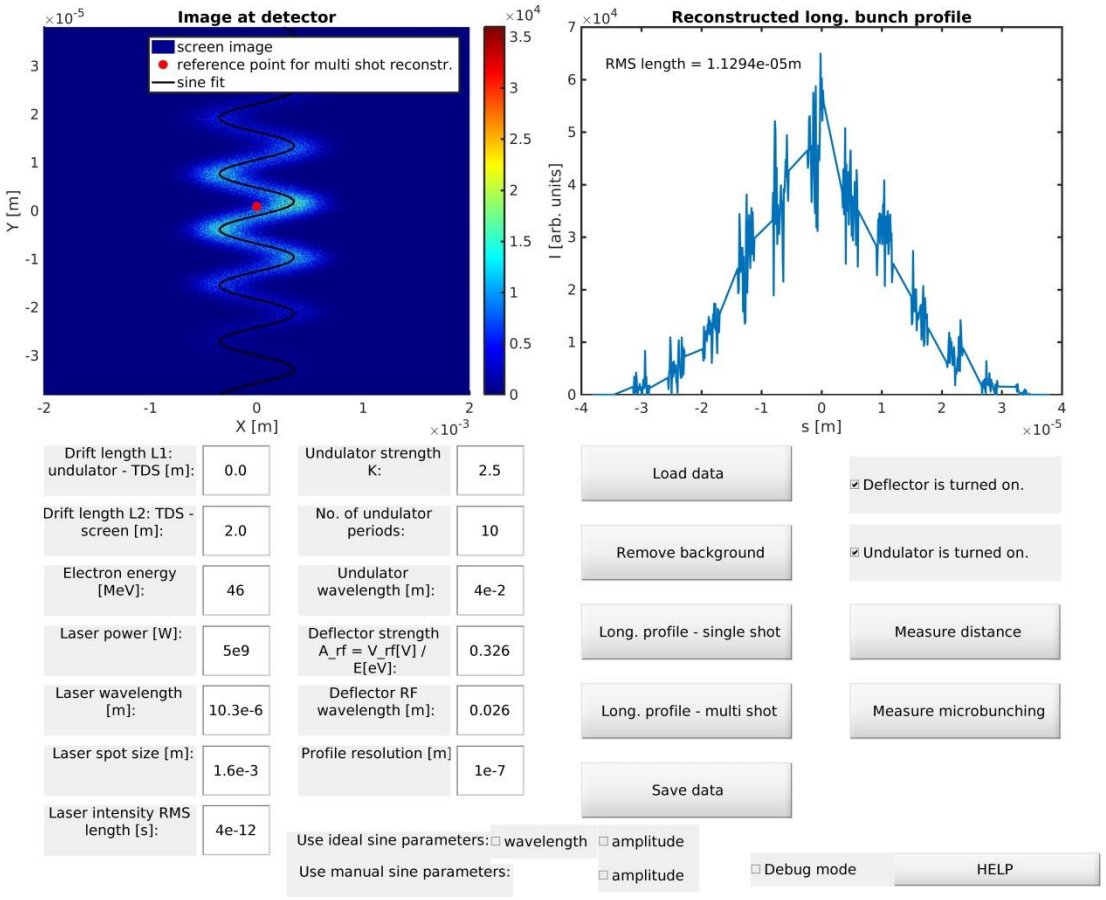
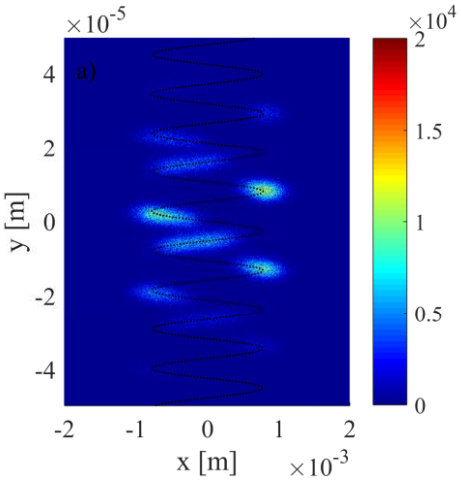
Thank you for your attention!

Questions?

Backup Slides

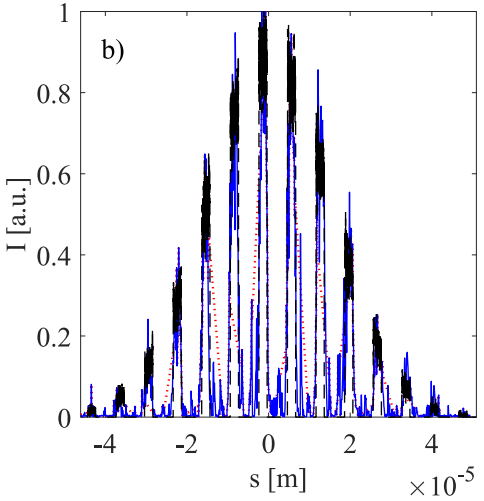
Development of a bunch profile reconstruction tool





Simulated screen image of a microbunched beam

Reconstruction of this beam (black) using a single (red) / multiple (blue) shots

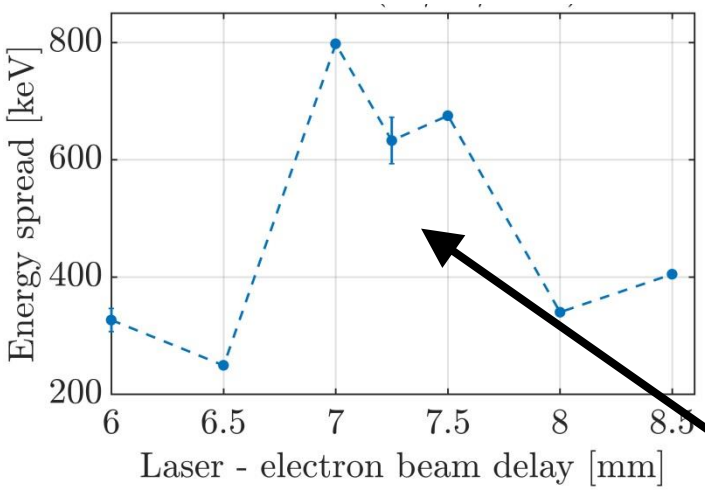


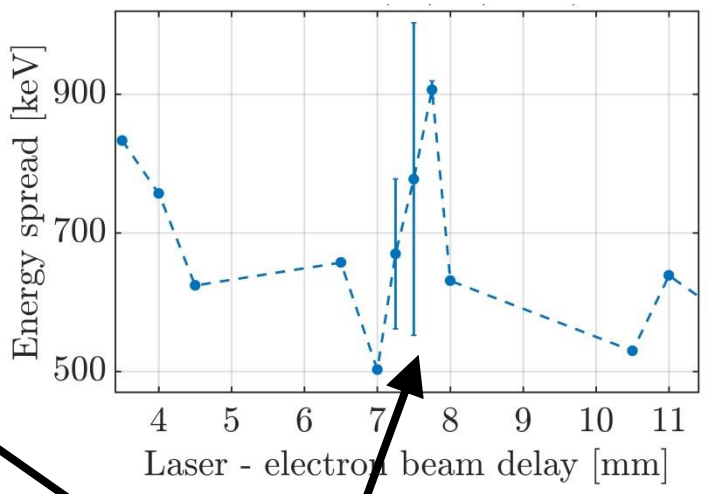
MATLAB GUI for reconstruction of long. beam profile from screen image:

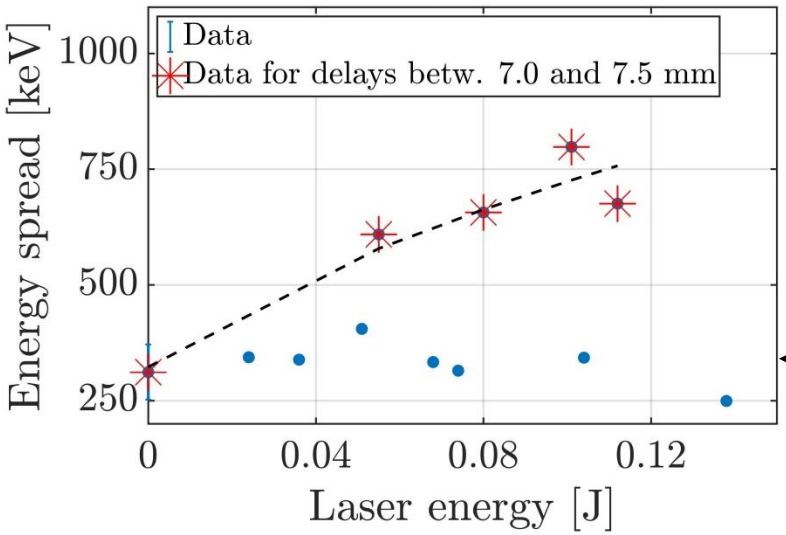
- Reconstruction based on single or multiple shots
- Estimation of RMS beam length and microbunch features

Experimental Results: Synchronisation

- Measure IFEL interaction between electron beam and laser in TEM_{00}-mode at spectrometer for tuning beam-laser fine timing







Strongest beam-laser interaction
= ideal timing between laser and electron beam

Dependence on laser energy for beam spread at correct delay setting

University of Strathclyde Glasgow

DESY