Direct response time measurements on semiconductor (& metal?!) photocathodes

Measuring bunch lengthening during the photoemission process

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on behalf of the PITZ & INFN Milano cathode groups

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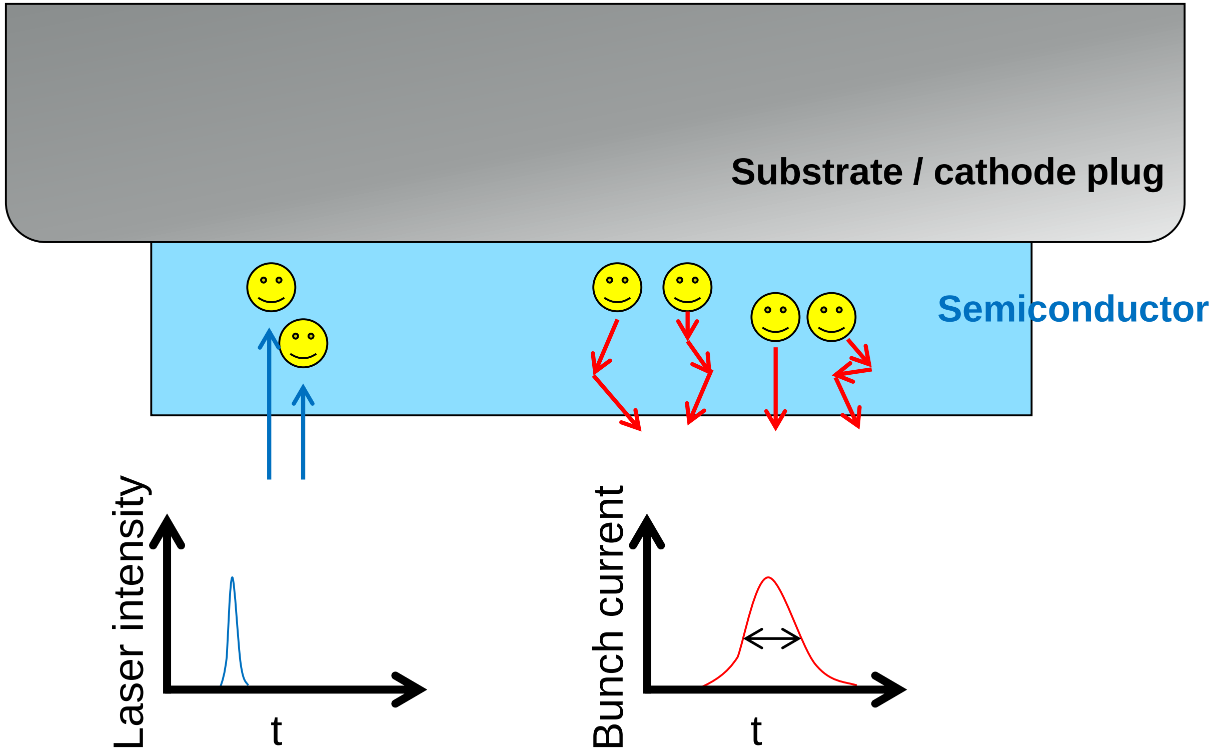
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Cathode response time measurements

Delay time of emitted electrons from semiconductors

- "*Spicer* 3-step model": Excitation, Transport, Emission
- Incident photon releases electron from cathode
- Varying delay until electron extraction
  - Penetration depth of photon
  - Path of electron in cathode (collision with phonons if $E < E_{exc}$)
- Smears out electron bunch time profile
  - Defines achievable accuracy of bunch shaping
  - Defines minimum bunch length
  - Allows to confirm emission model
  - Data on "green" cathodes needed
  - Literature data on e.g. Cs2Te not satisfying



<u>Response time definition here:</u> *Characteristic time scale of cathode contribution to bunch length*

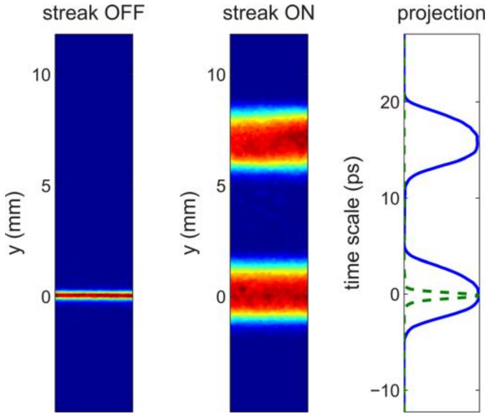
Results in literature

Measurement methods and results

- Direct measurement of Cs3Sb resp. time
  - Low resolution (~2ps) → only upper limit
- No direct measurement of response time in RF-accelerator reported for Cs2Te
  - Measurement with streak camera
- Measurement/"estimation" by measuring minimum separation between 2 short bunches in energy spectrum
  - "P2P RMS separation" of ~370 fs
- Monte-Carlo simulations

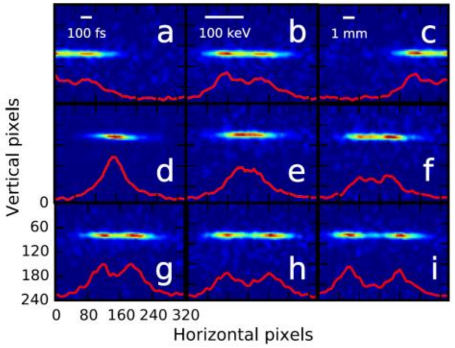
→ Expected Cs2Te cathode response shape: exponential & ~x00 fs scale

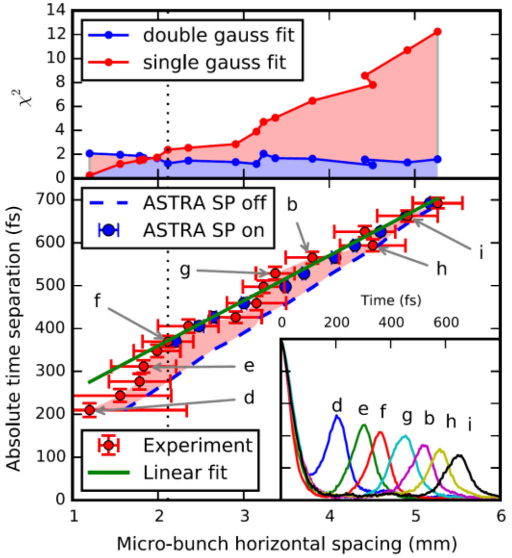
→ No direct measurement so far

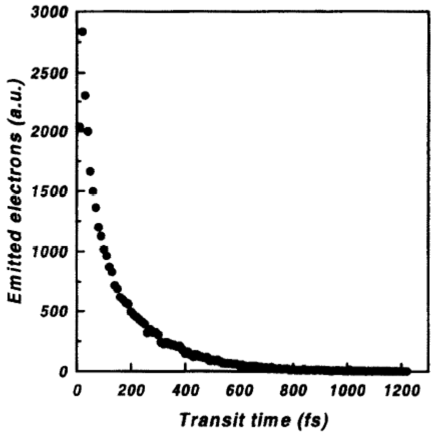


Cultrera *et al.* – *APL* **99,** *152110* (2011)

Aryshev *et al.* - *APL* **111,** *033508* (2017)







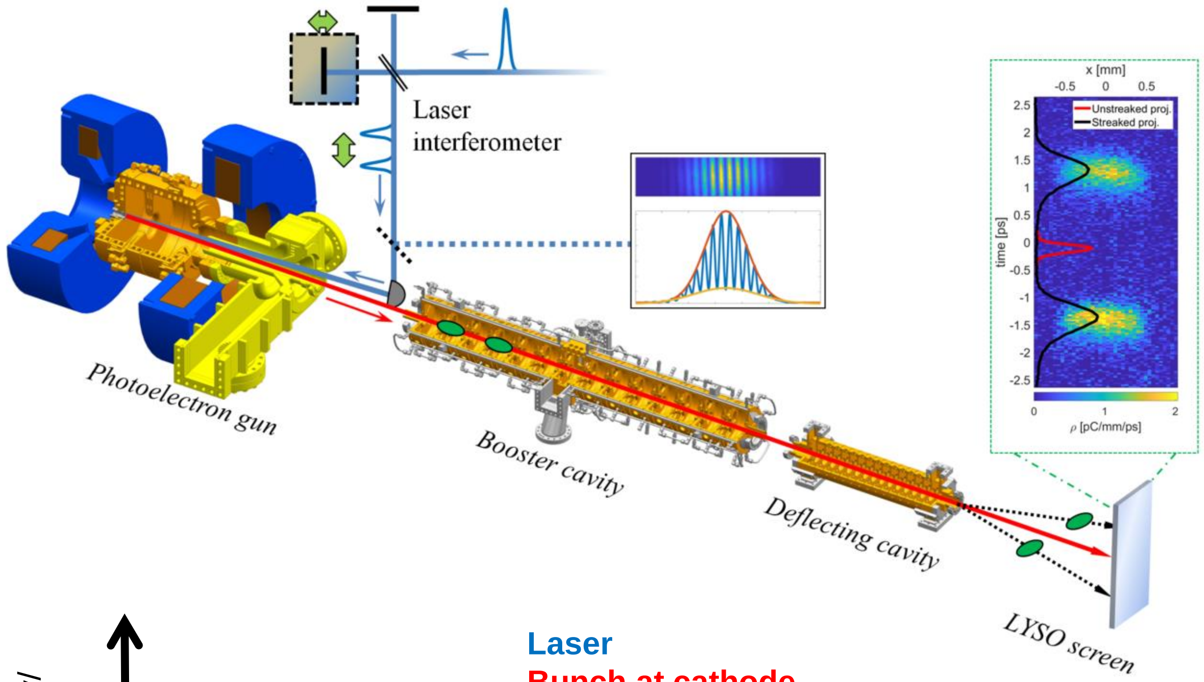
Ferrini *et al.* –*Solid State Comm.* **106**, *1* (1998)

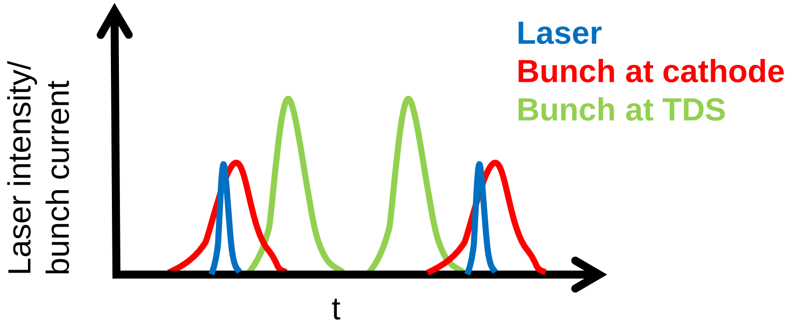
Measurement setup

The PITZ facility

- Measure bunch length of low charge, short bunch with high resolution TDS
- Identify RF-contribution to bunch length via two bunch probe beam
- Disentangle cathode response from laser shape
  → laser ~Gaussian, ~170fs RMS

- <u>Procedure:</u>
  - Measure double bunch time structure for
    - Different charges
    - Different gradients
  - Disentangle rf compression from signal
    - → direct calibration to "laser time"



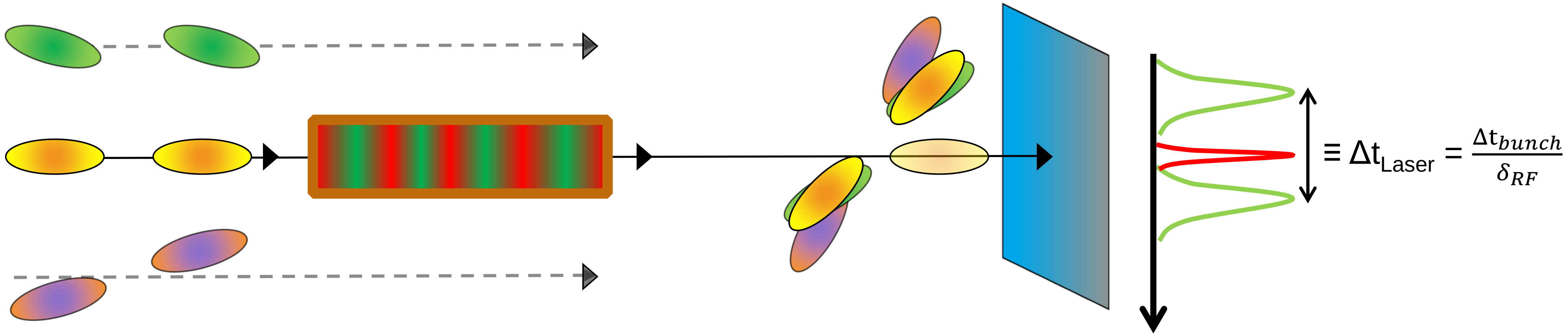


Error mitigation

Identify and avoid several sources of systematic errors

- Several error sources identified
  - x-y-correlations
  - bunch z-y-correlations
  - bunch pair z-y-correlations
  - laser pulse time delay calibration
  - statistical
  - space charge induced lengthening

- Error mitigation includes
  - avoiding x-y-correlations
  - averaging over different TDS slopes
  - averaging over different laser pulse “chronological” orders
  - high statistics
  - low bunch charge, large cathode laser spot

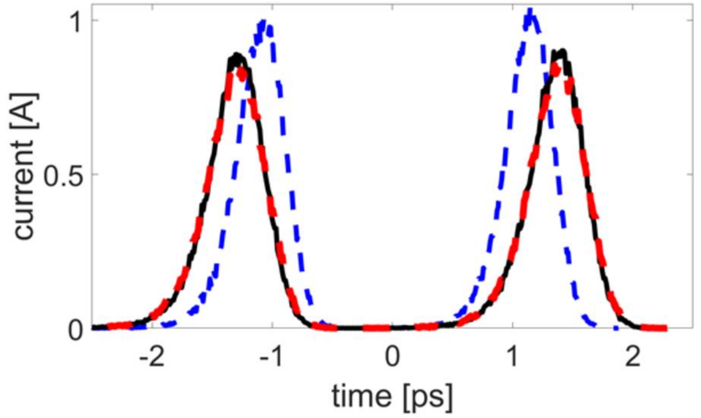


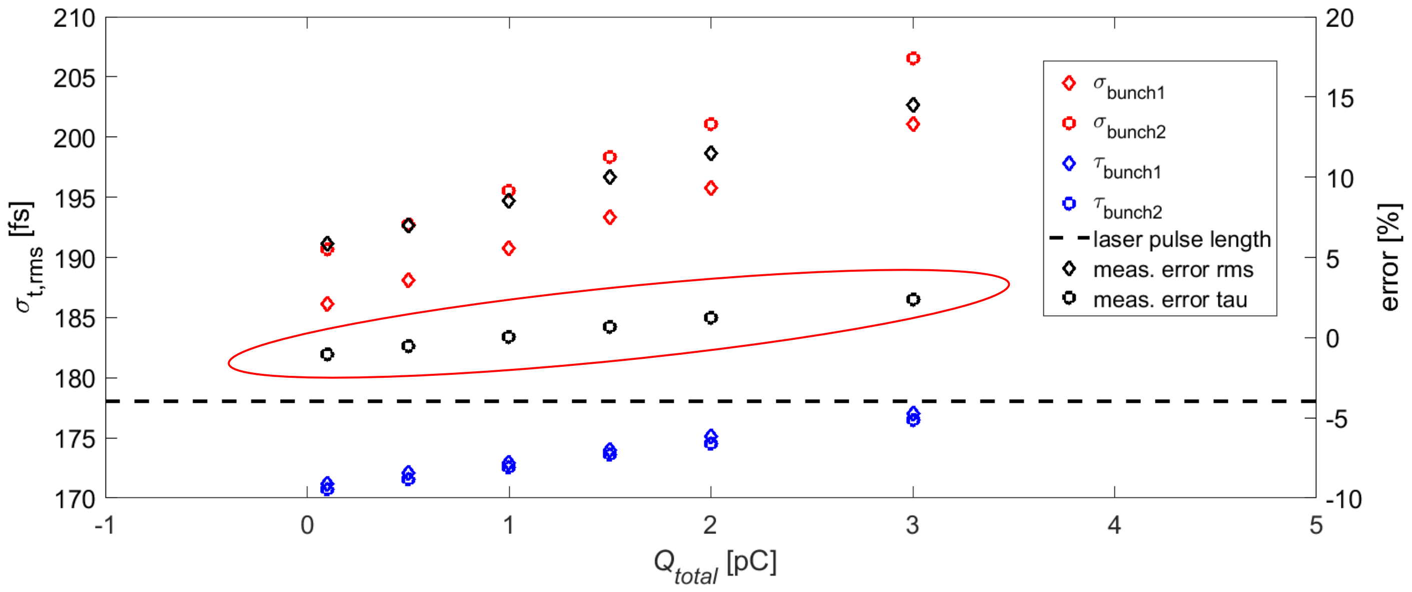
ASTRA simulations & error estimation

Start to end simulation of measurements

- Simulated beam transport of exponential response time in ASTRA
- S2E simulation of full measurement
- Resp. time error much lower than RMS bunch length measurement
- Simulated resp. time error <2.5% !!
- Additional laser stage positioning error ~5%

→ Main error source: signal to noise ratio

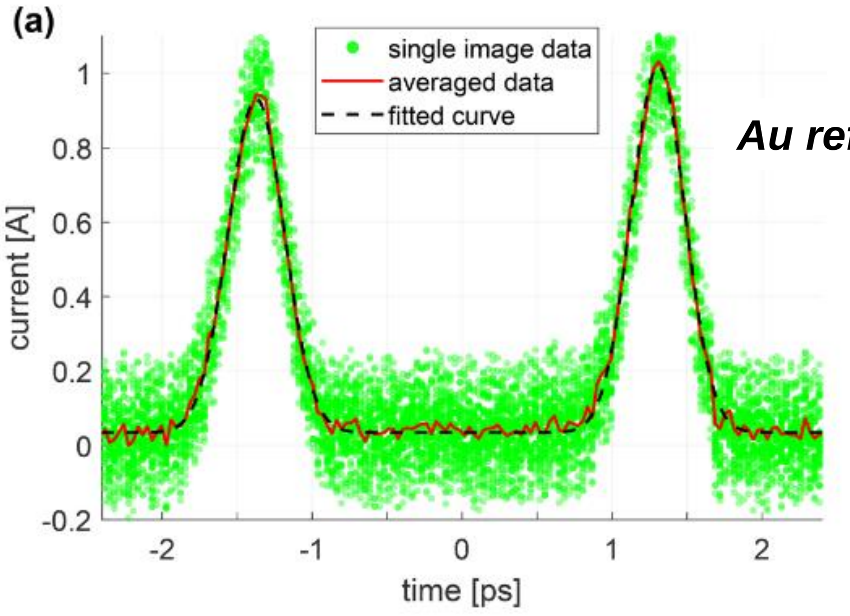




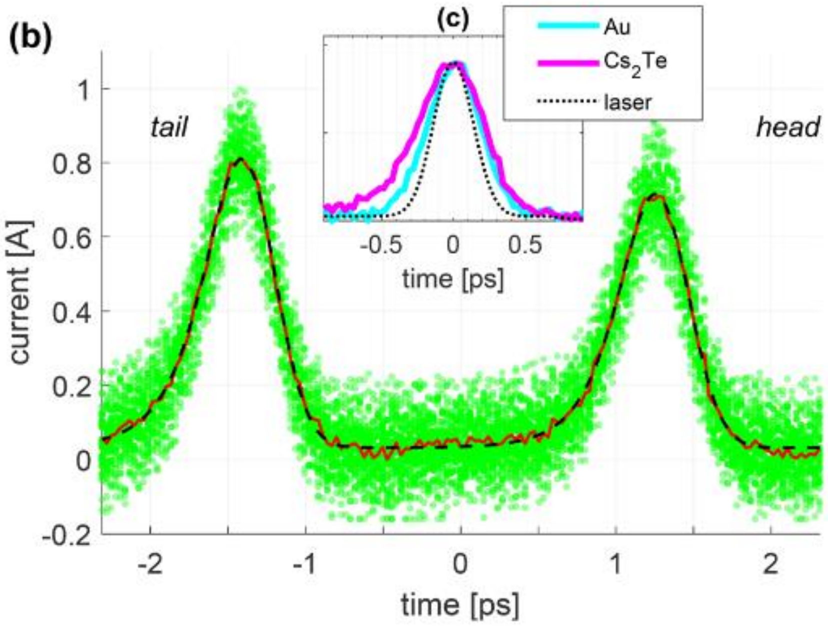
Cs2Te response time

Measurement results for Cs2Te

- Convoluted exponential Gaussian long. bunch shape
- Bunch charge scan → no space charge influence
- Measured various Cs2Te cathodes
- Shortest measured resp. time: 184 ± 42 fs
- Longest measured resp. time: 257 ± 41 fs
- Gaussian RMS length ~185 fs
  → reasonable agreement w/ laser transform limit ~170 fs
- Transient grating measurement of laser pulse length ~113 ± 7 fs (~130fs incl. res./disp.)
  → discrepancy to be resolved (see below..)



Au reference meas.

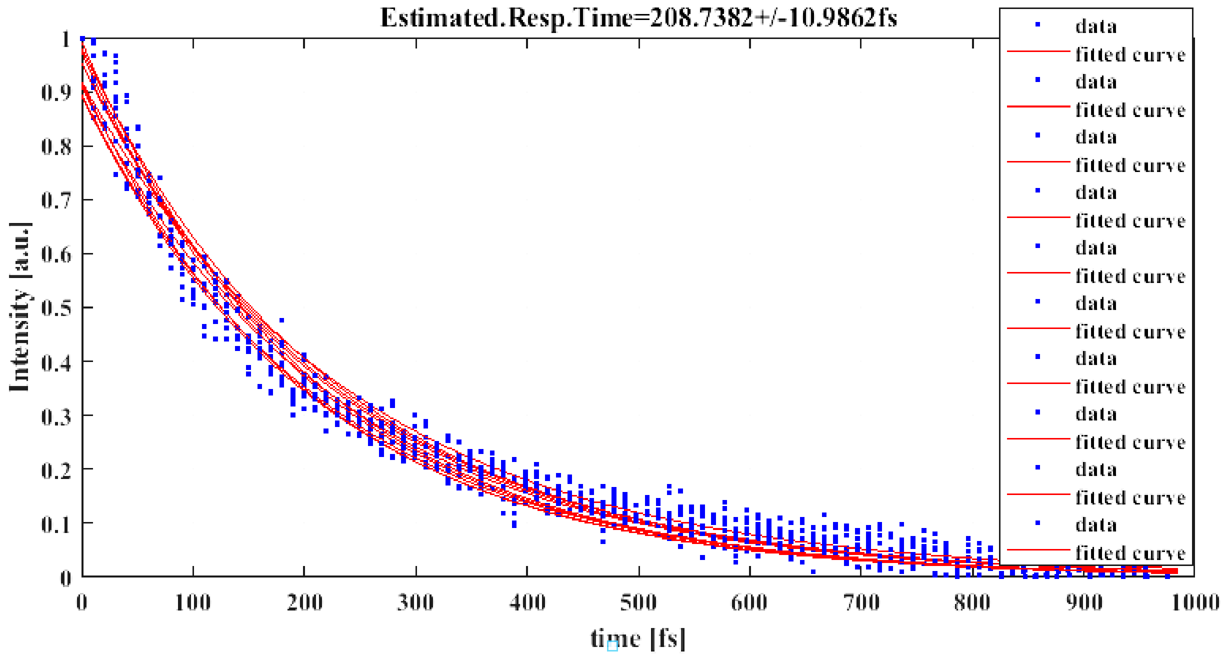


(1.02 ± 0.49) pC

Simulations

Modelling excitation & transport in the cathode

- 1-to-1 photoemission modeling based on Spicer's three-step model
- Initial electron exciting conditions based on **density of states**
- **Electron-phonon** scattering; **mean free path 3 nm** (literature data, INFN)
- Ionization energy @ room temperature
- Emission angle dependency

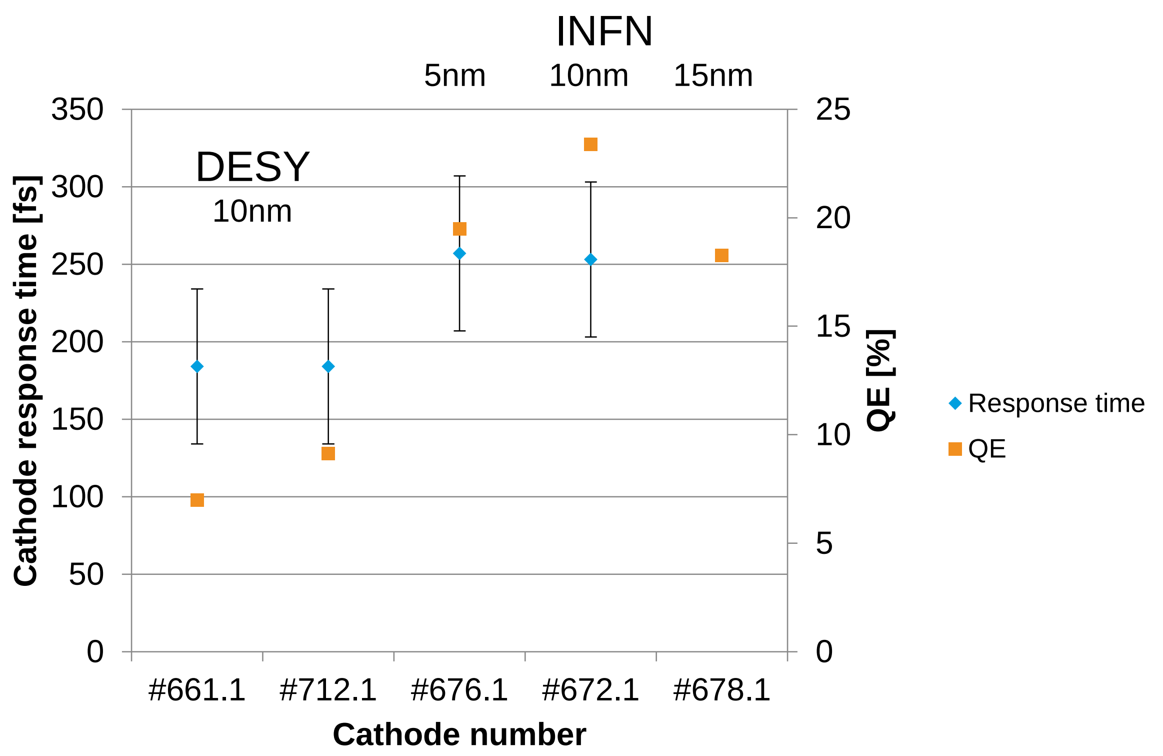


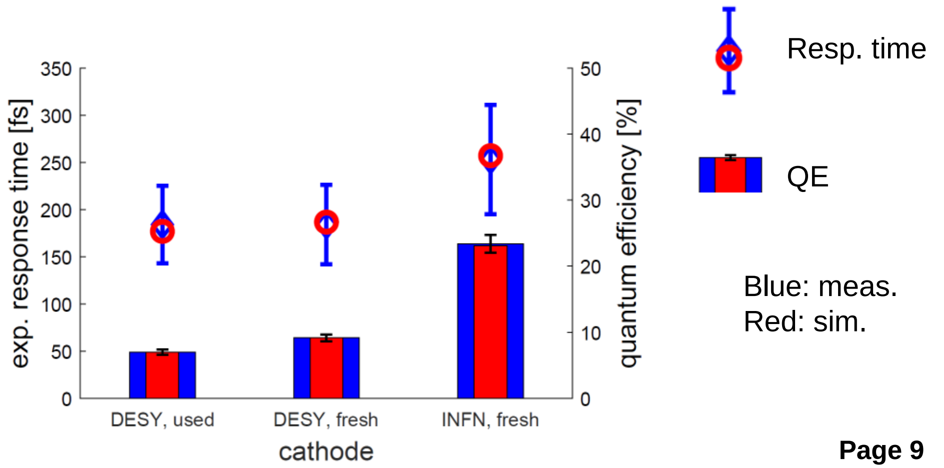
10 simulations, MFP = 3 nm, ΔE = 8 meV

Summarised measurements

Information gathered so far

- Errors contain statistical variation and systematic uncertainty
- No aging effect on cathode response time
- INFN & DESY cathodes inconsistent
  → similar production procedure!?!
- No QE dependence found in either cathode batch
- Cs2Te thickness studies not conclusive
  → more measurements and cathodes to come



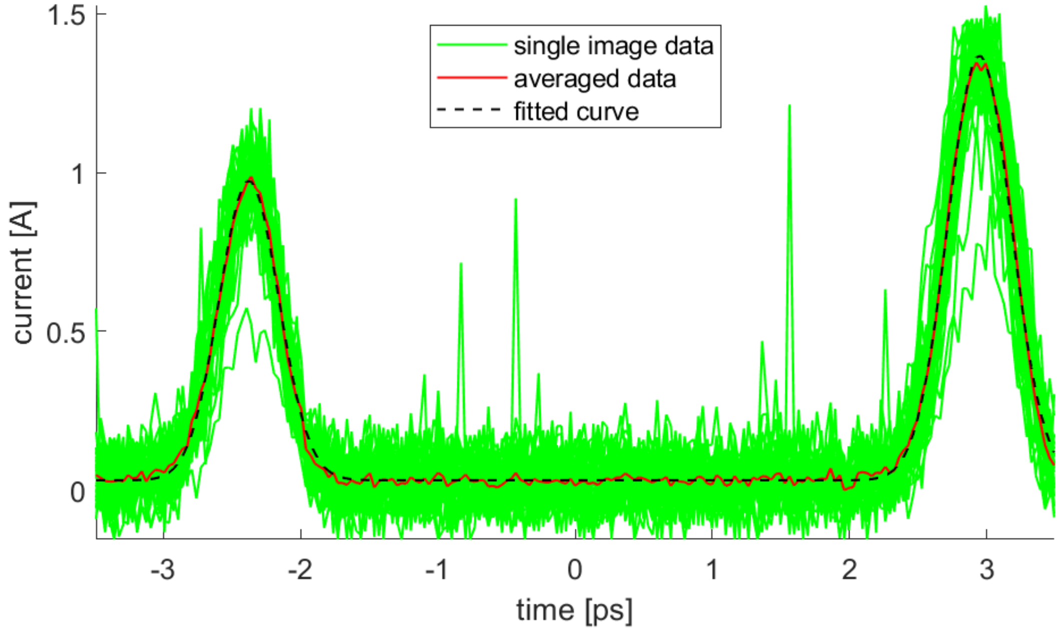


CsKSb measurement

First response time for CsKSb cathode

- Cathode prepared at INFN Milano
- Measurement @PITZ after several hours of cathode usage
  → QE had dropped: ~2.5% → ~0.4%
- Measured exp. component < 100 fs
- Unexpectedly short, ~measuring degraded surface layer?
- Repeat w/ fresh cathode…

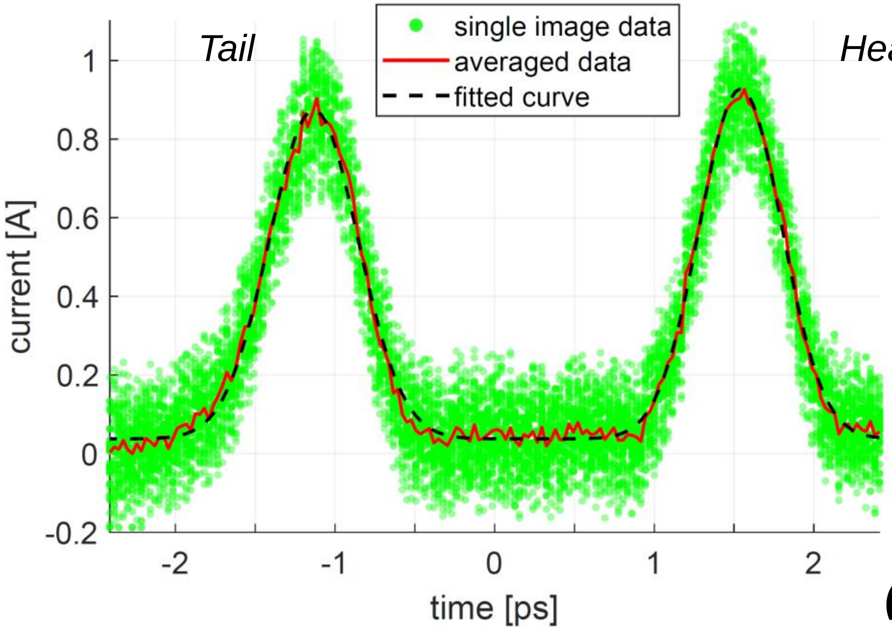
Cath. 147.1



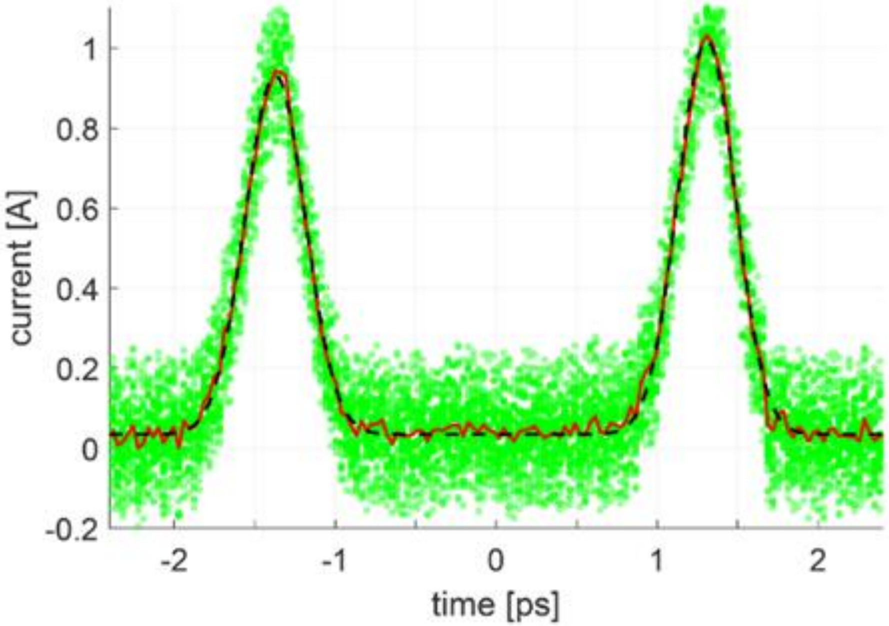
Reference measurements

Measured Mo & Au cathodes as reference

- Mo and Au cathodes gave similar results
- ~Gaussian bunch shape
- RMS lengths of 237 fs – 271 fs (±50 fs)
  - longer than Gaussian w/ Cs_2Te
  - >> laser pulse length
- Mo not polished, found production error for Au cathode
- new Au cathode was measured: 183 ± 10 fs
  → Gaussian lengthening much reduced
- Fitted exp. time constant: 93 ± 17 fs
  → similar error as Gaussian fit → resolution limit
- Systematic studies missing..



(1.34 ± 0.67) pC

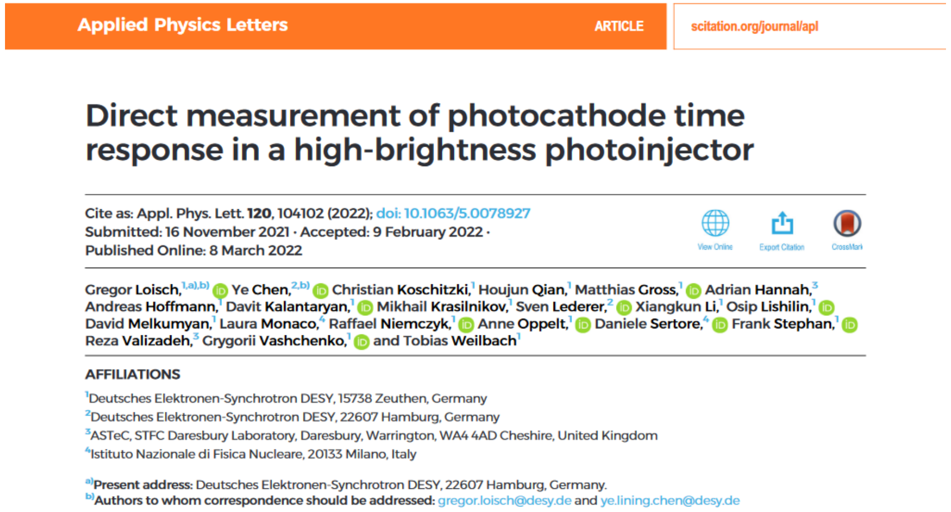


Summary

Status and possible future studies

- First time **Cs2Te cathode response directly measured**
- Measurement **procedure established** & in routine usage
  (>~45 fs RMS symmetric resolution)
- **Cs2Te cathode exponential response time ~185-257 fs** (depending on cathode)
- Emission process **simulation results show reasonable agreement**
- Measured metal response ~too slow → possibly roughness, systematic studies needed
- INFN Milano & DESY cathodes consistently different (similar production procedure..)
- Available & future data could **enable/inform advanced cathode preparation**
  - Deposition techniques
  - Other materials (CsKSb…)
  - Cathode thicknesses / Minimum achievable response time
  - ….

Thank you for your attention!



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Direct measurement of photocathode time response in a high-brightness photoinjector

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