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Thermal emittance and response time from NEA photocathodes

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LABORATORY FOR ELEMENTARY-PARTICLE PHYSICS

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Talk outline

- Theoretical maximum beam brightness
- Introduction to NEA cathodes
- Inelastic scattering mechanisms
- Diffusion model
- Thermal emittance & response time
- Temporal laser pulse shaping

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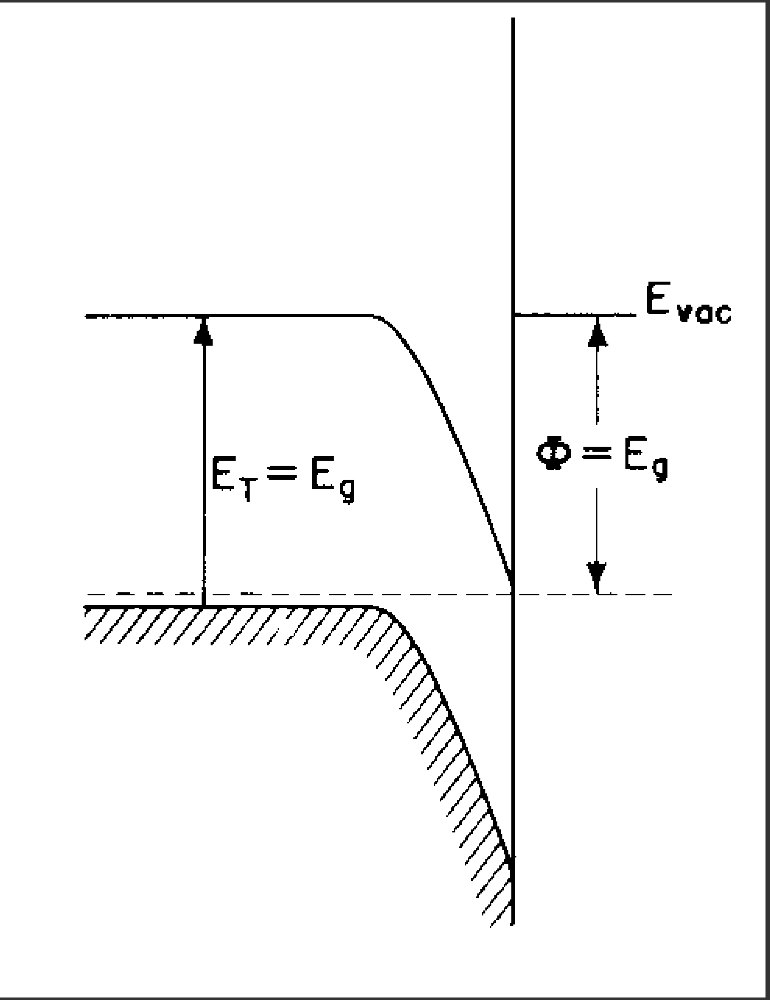
Theor. max brightness

- Assuming a pan-cake bunch at the cathode [$\sigma_t << (\sigma_x m/eE_{cath})^{1/2}$] max charge density that can be extracted $dq/dA = \varepsilon_0 E_{cath}$
- For Gaussian distribution of transverse momenta characterized by thermal energy kT, $\langle p_x^2 \rangle = mkT$
- Normalized average beam brightness (Δx, Δp_x … ellipse half-axes) $B_{n,avg} \equiv I_{avg}(mc)^2/(\pi\Delta x\Delta p_x\pi\Delta y\Delta p_y)$
- Max brightness per bunch:

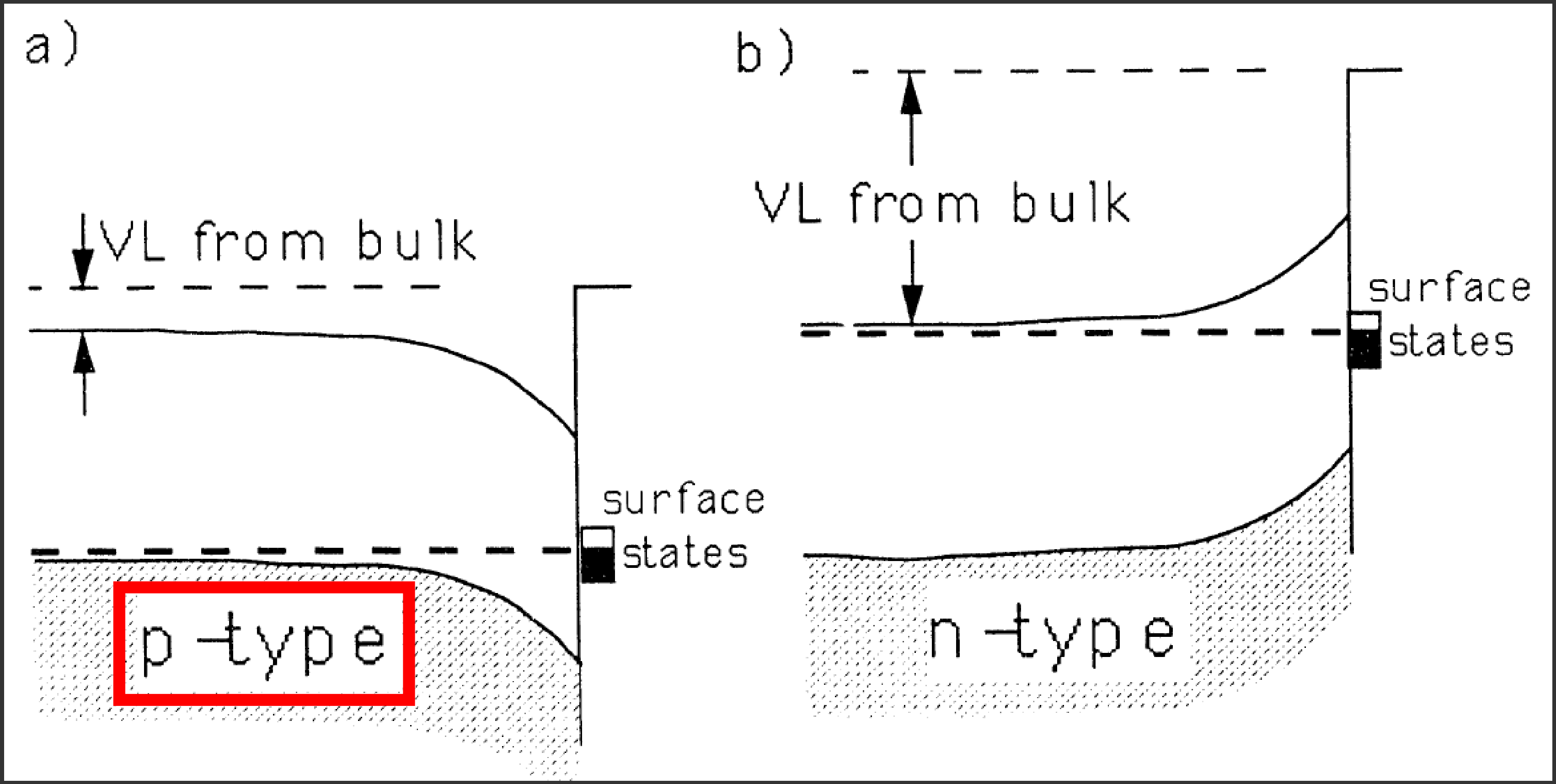
$$\frac{B_{n,avg}}{f} = \frac{\varepsilon_0 mc^2}{8}\frac{E_{cath}}{kT}$$

Negative Electron Affinity

- Defined as vacuum level E_{vac} relative to the bottom of conduction band
- Negative affinity means the vacuum level lies below the conduction band minimum $\Rightarrow$ very high QE
- *Surface condition* induces a *space charge*, which may bend the bands either up or down



NEA: doping


a)
VL from bulk
surface
states
p-type
b)
VL from bulk
surface
states
n-type

NEA: Cs monolayer

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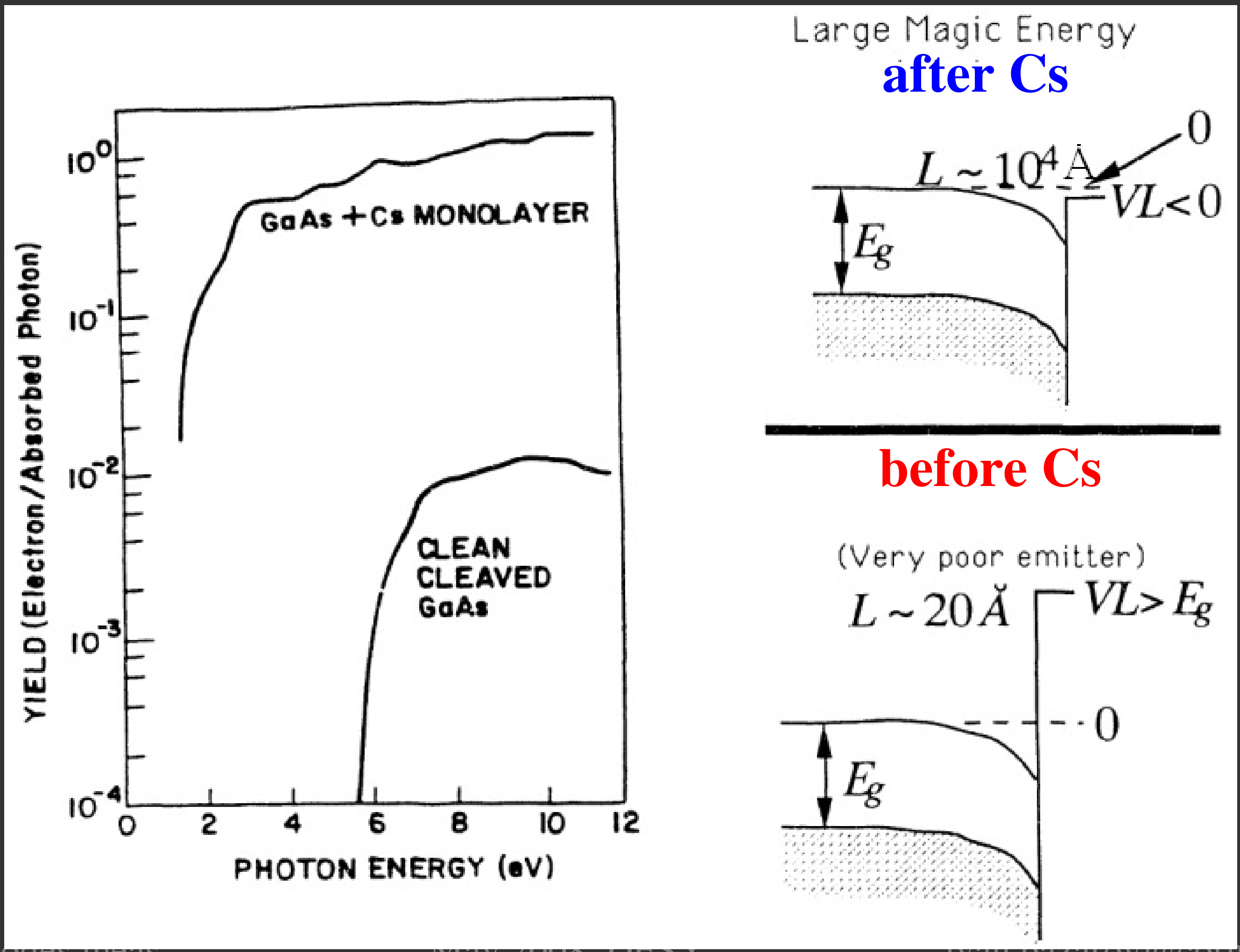
If thickness of a low work function material << mean free path
$\Rightarrow$ e^- can traverse the surface material without much loss
$\Rightarrow$ better quantum efficiency / reduced threshold



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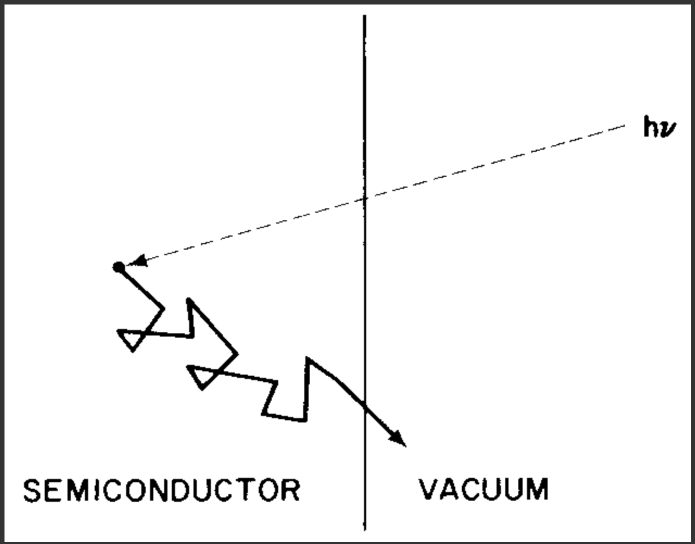
Spicer's 3-step model



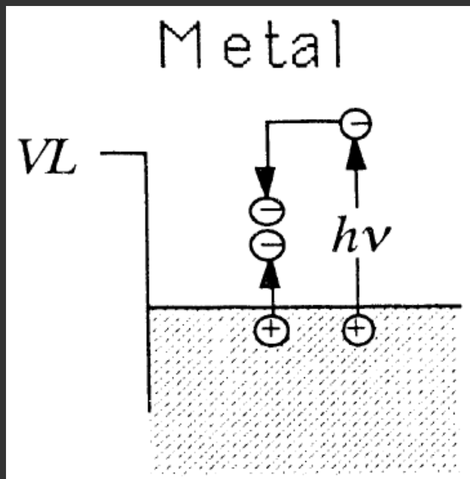
1. photon excites electron to a higher-energy state;
2. electron-phonon scattering (~0.01–0.05 eV lost per collision);
3. escape with kinetic energy in excess to E_{vac}

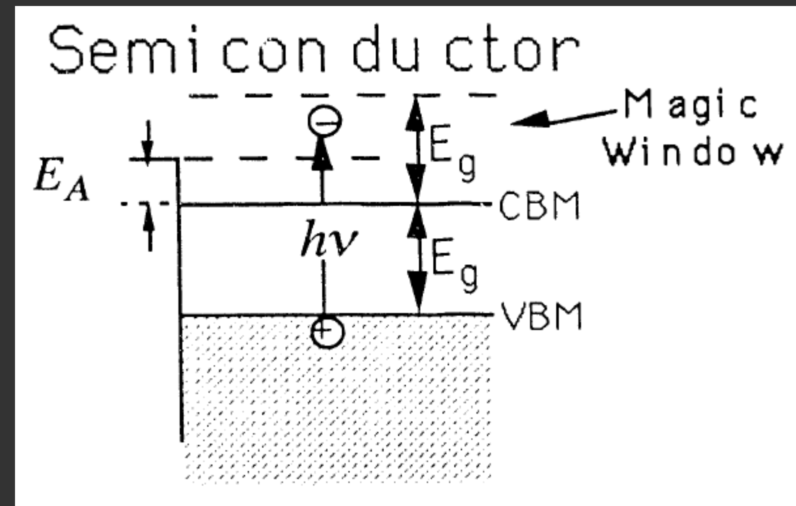
In GaAs the escape depth is long enough that a large fraction of electrons are thermalized to the bottom of the conduction band before they escape.

Response time ~ $(10^{-4}$ cm$)/(10^{7}$ cm/s$)$ = ~10 ps

strong wavelength dependence!

Inelastic scattering





(1) Electron-electron scattering: occurs in metals, large energy loss per collision

(2) Electron-phonon scattering: slowly depletes excessive energy of excited electron

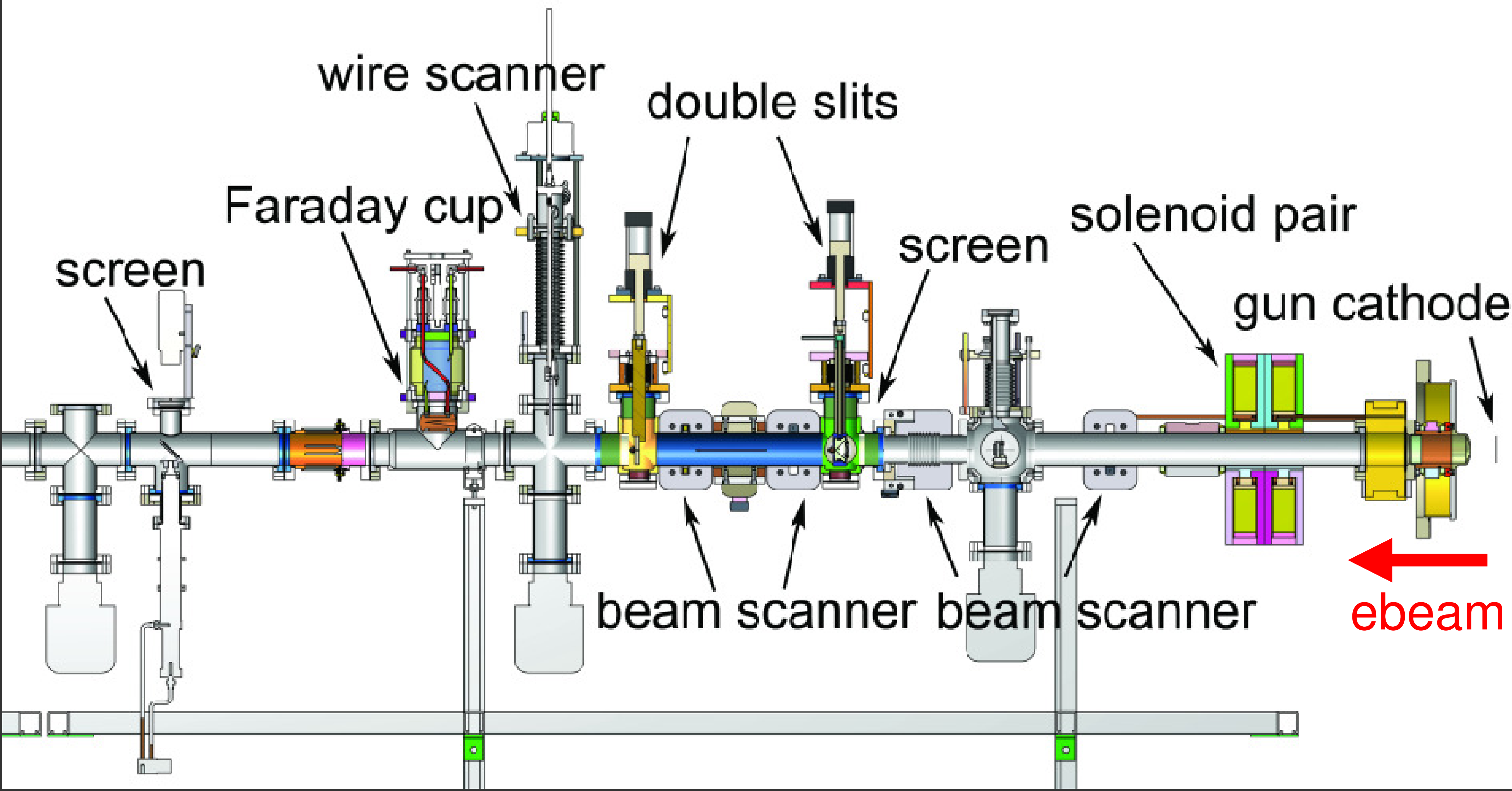
(3) "Magic window": in semiconductors, one needs excess KE > E_{gap} for e^-/e^- scattering. Thus, electrons excited with $E_{vac} < KE < E_{VBM} + 2E_{gap}$ have excellent chances of escape (high QE)

Thermal emittance meas.

$$\varepsilon_{n,th} = \sigma_{\perp}\sqrt{\frac{kT}{mc^2}}$$

- Thermal emittance was measured as a function of laser wavelength for GaAs and GaAsP(P = 45%)
- Emittance was measured by solenoid scan using a wirescanner for different laser spot sizes and profiles
- Essential to take data for various laser spot sizes, cross-check between various methods (e.g. solenoid scan and double-slits, viewscreen & wirescanner)
- See J. App. Phys. **103** (2008) 054901 for details

Setup (therm. emit.)



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Getting methods to agree

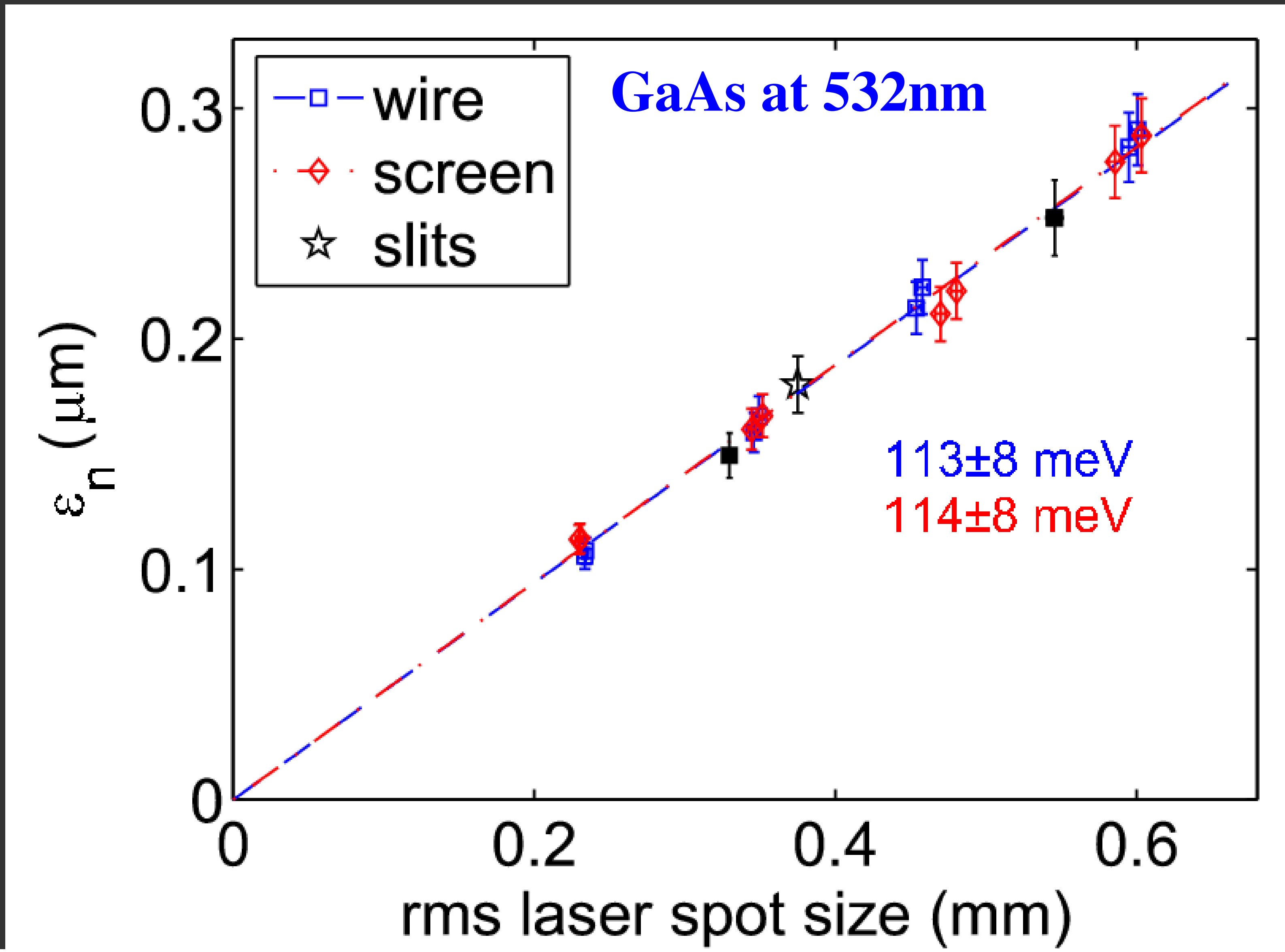
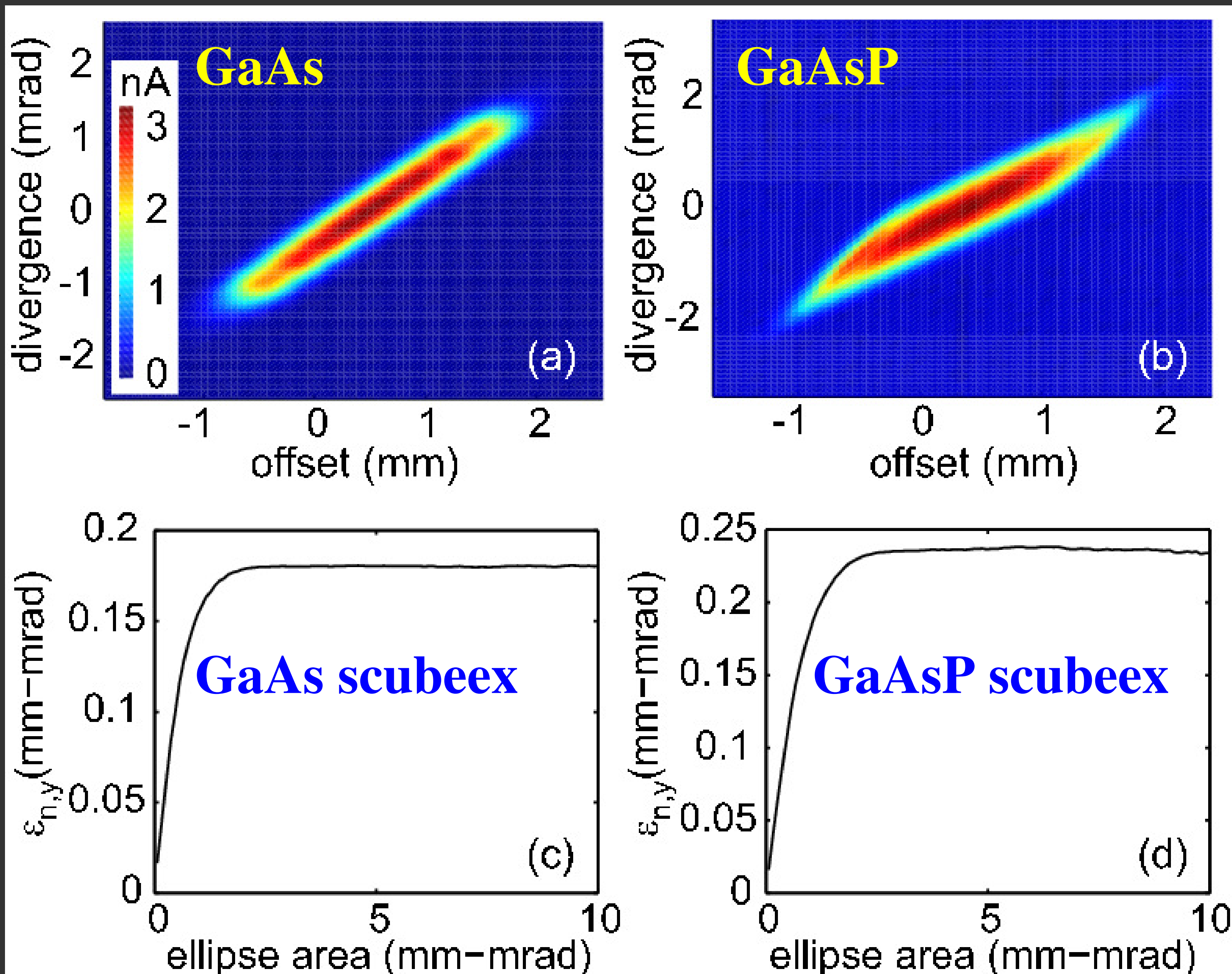
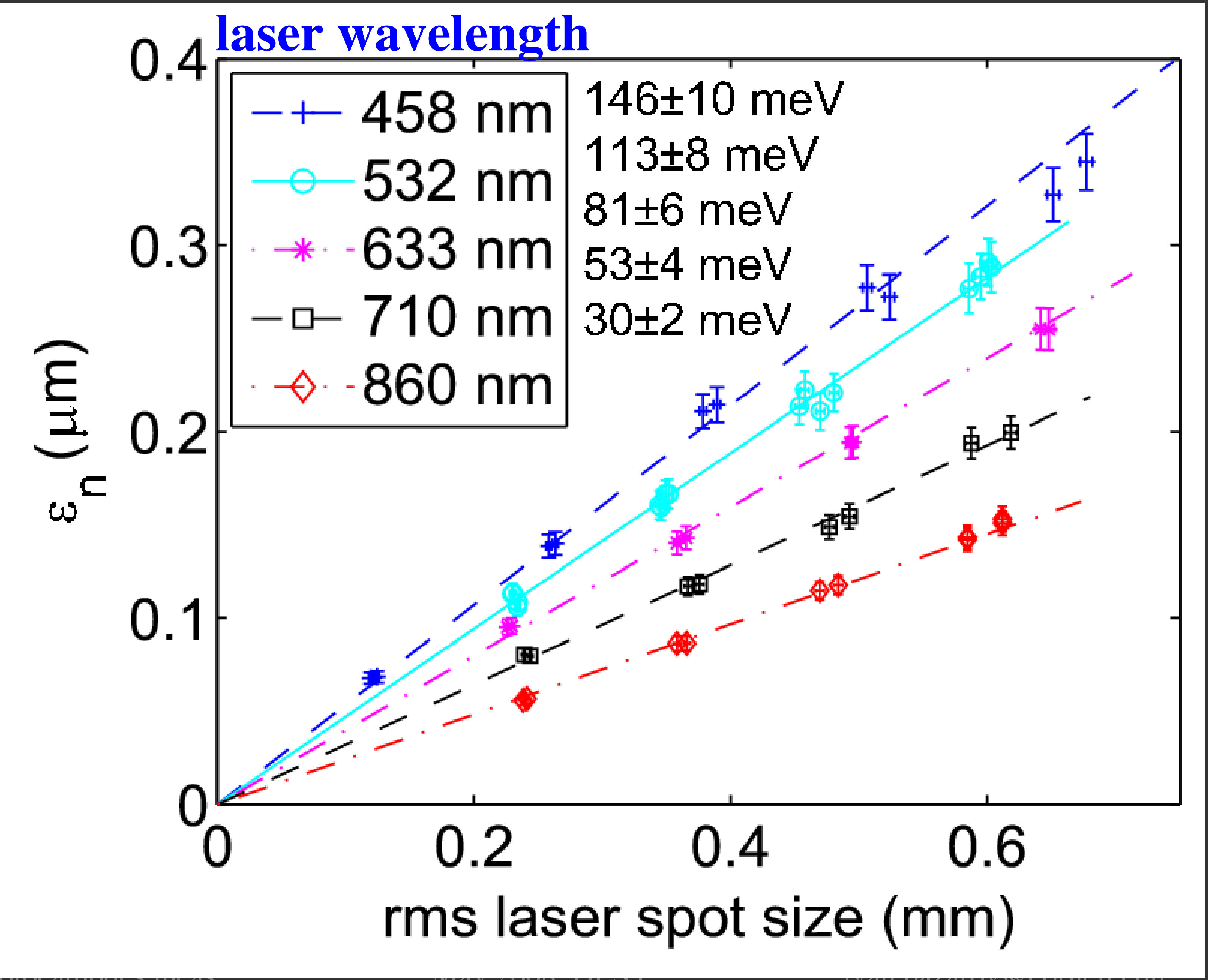


FIG. 5: Comparison between different emittance measurement techniques for GaAs at 532 nm. Filled squares correspond to a Gaussian laser profile.

Double-slit check



GaAs


laser wavelength
458 nm
532 nm
633 nm
710 nm
860 nm
146±10 meV
113±8 meV
81±6 meV
53±4 meV
30±2 meV
0.4
0.3
0.2
0.1
0
εn (μm)
0
0.2
0.4
0.6
rms laser spot size (mm)

GaAsP

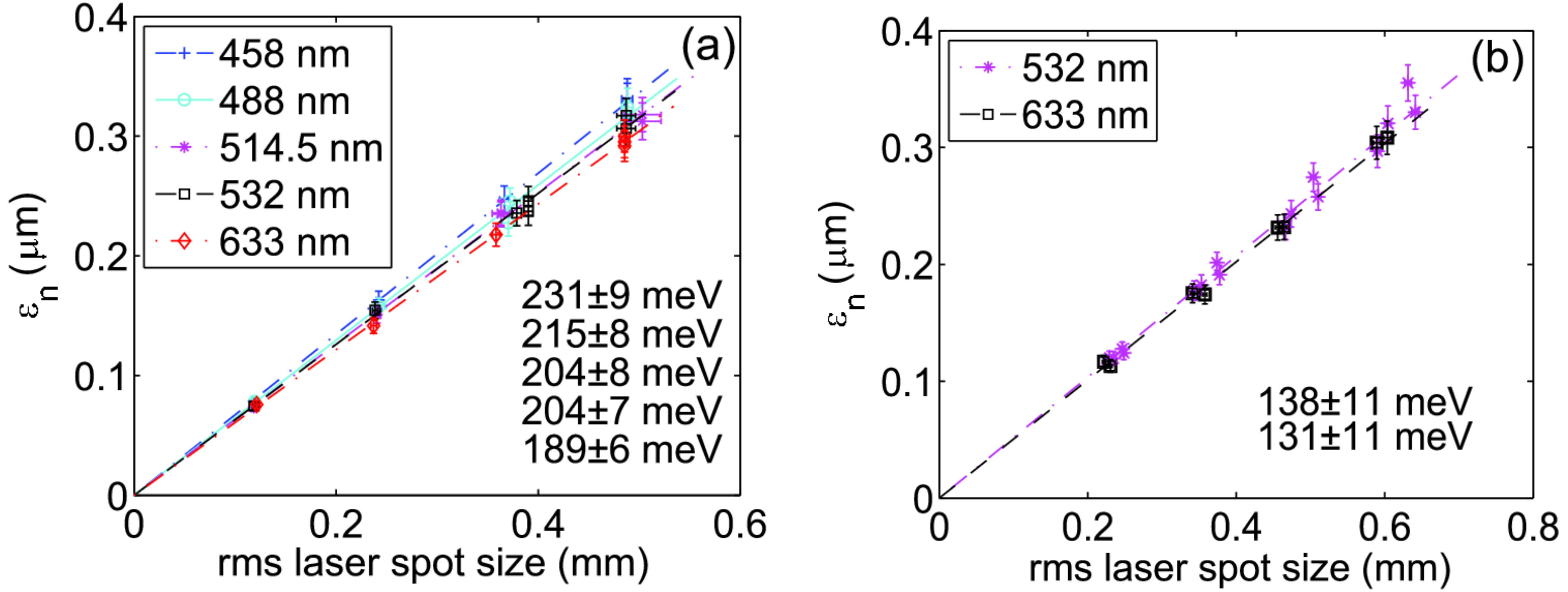
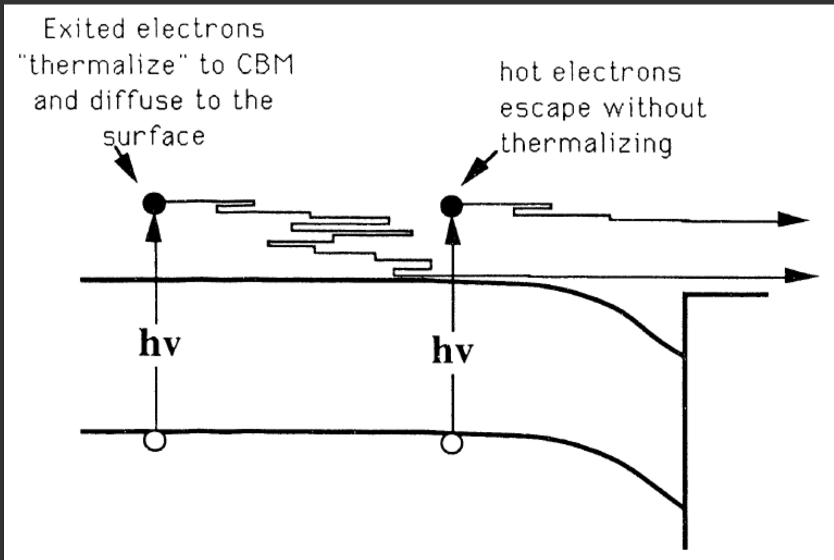


FIG. 7: Thermal emittance of GaAsP as a function of rms laser spot size. (a) QE = 6%. (b) QE = 1%.

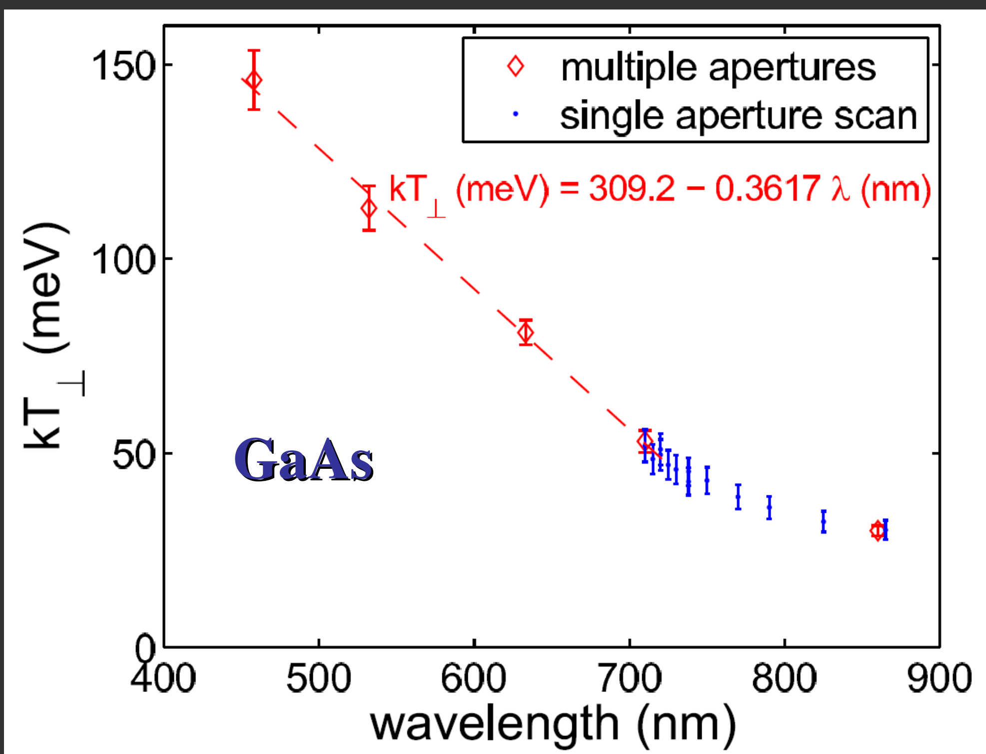
can see QE effect on thermal emittance for GaAsP!

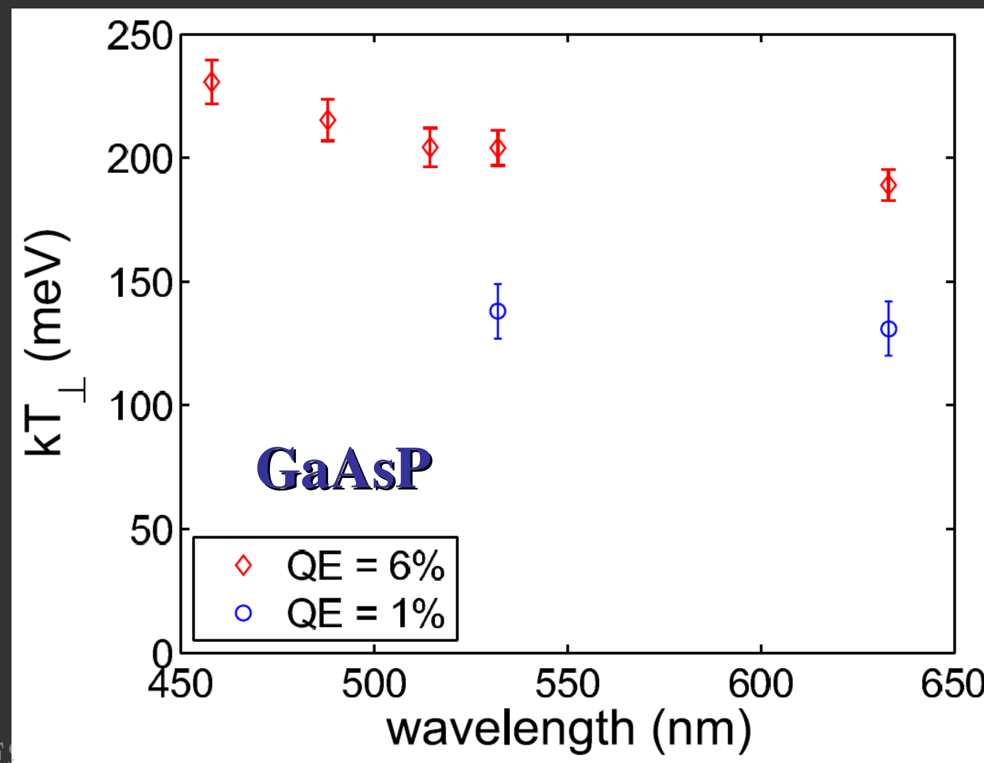
kT vs. wavelength



relates spot size to emittance

$$\varepsilon_{n,th} = \sigma_{\perp}\sqrt{\frac{kT}{mc^2}}$$





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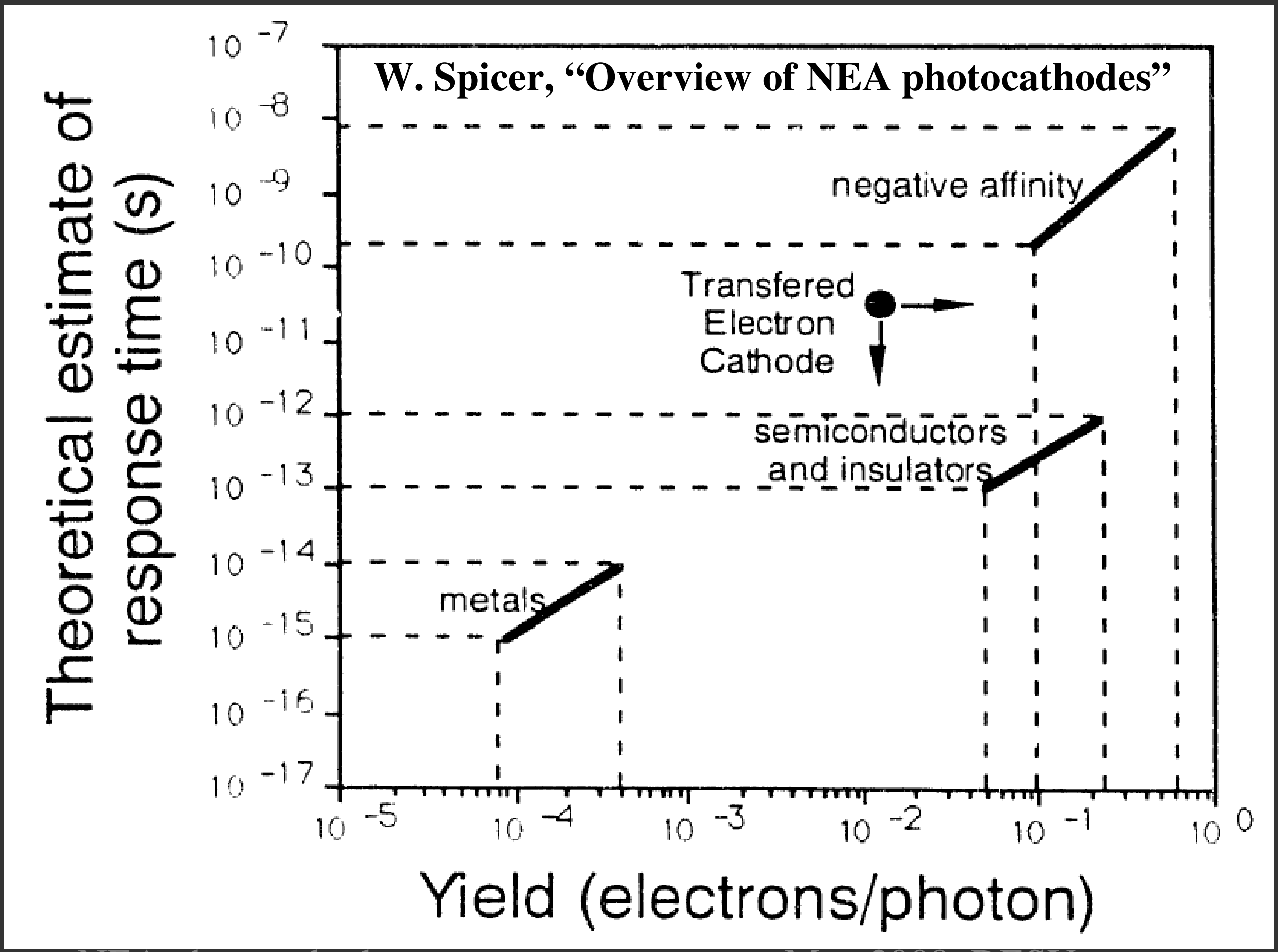
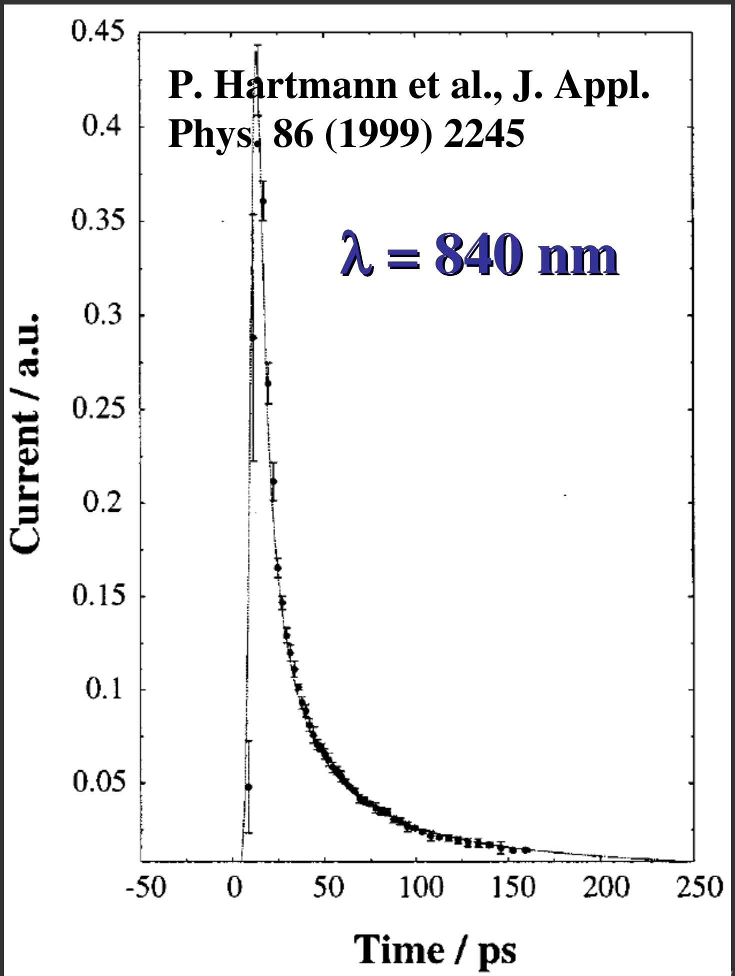
Conclusions (I)

- When GaAs excited near the bandgap, electrons come out essentially thermalized (kT ~ 30 meV)
- Shorter wavelength ⇒ smaller thermalized fraction ⇒ larger kT
- GaAsP has larger kT than GaAs despite smaller $h\nu_{ph} - E_{gap}$
- GaAsP shows QE dependence for kT, GaAs does not show such dependence within the uncertainty of the measurement

Temporal response

- Traditionally, it was believed that NEA cathodes are slow (~10s of ps); indeed, long emission tails were measured from GaAs for λ ~ 850nm





Diffusion model

$$\frac{\partial c(h,t)}{\partial t} = D\frac{\partial^2 c(h,t)}{\partial h^2}$$

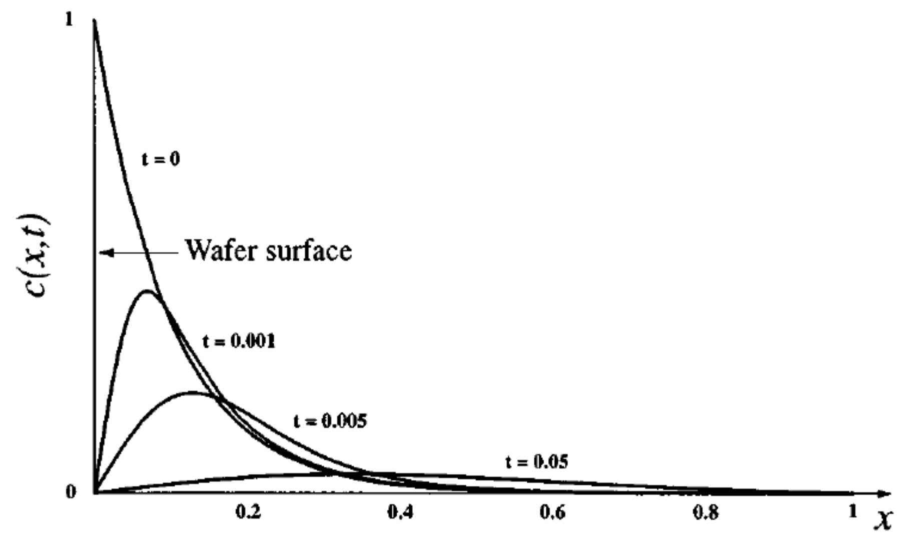
subject to:

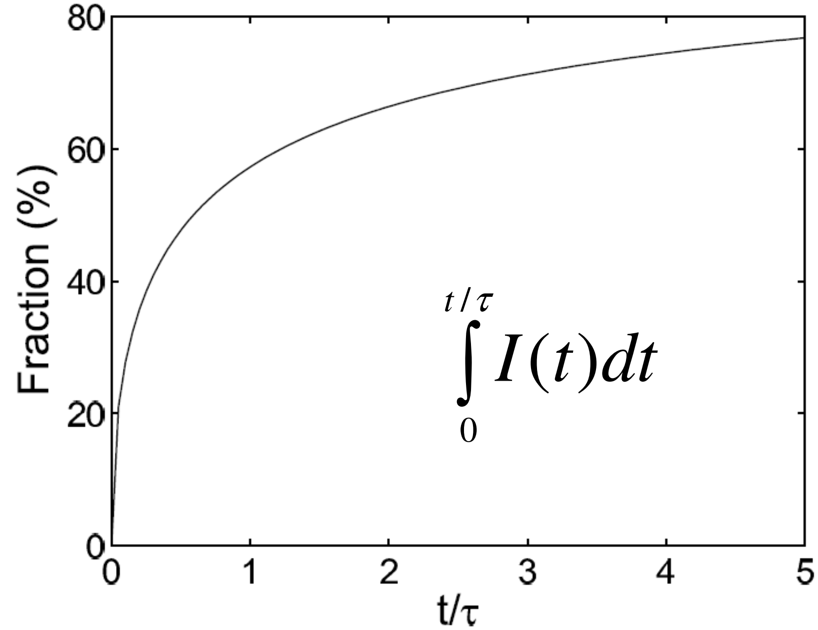
$$c(h,t=0) = c_0 e^{-\alpha h}$$
$$c(h=0,t) = 0$$

$$I(t) \propto \frac{\partial}{\partial t}\int_0^\infty c(h,t)dh.$$

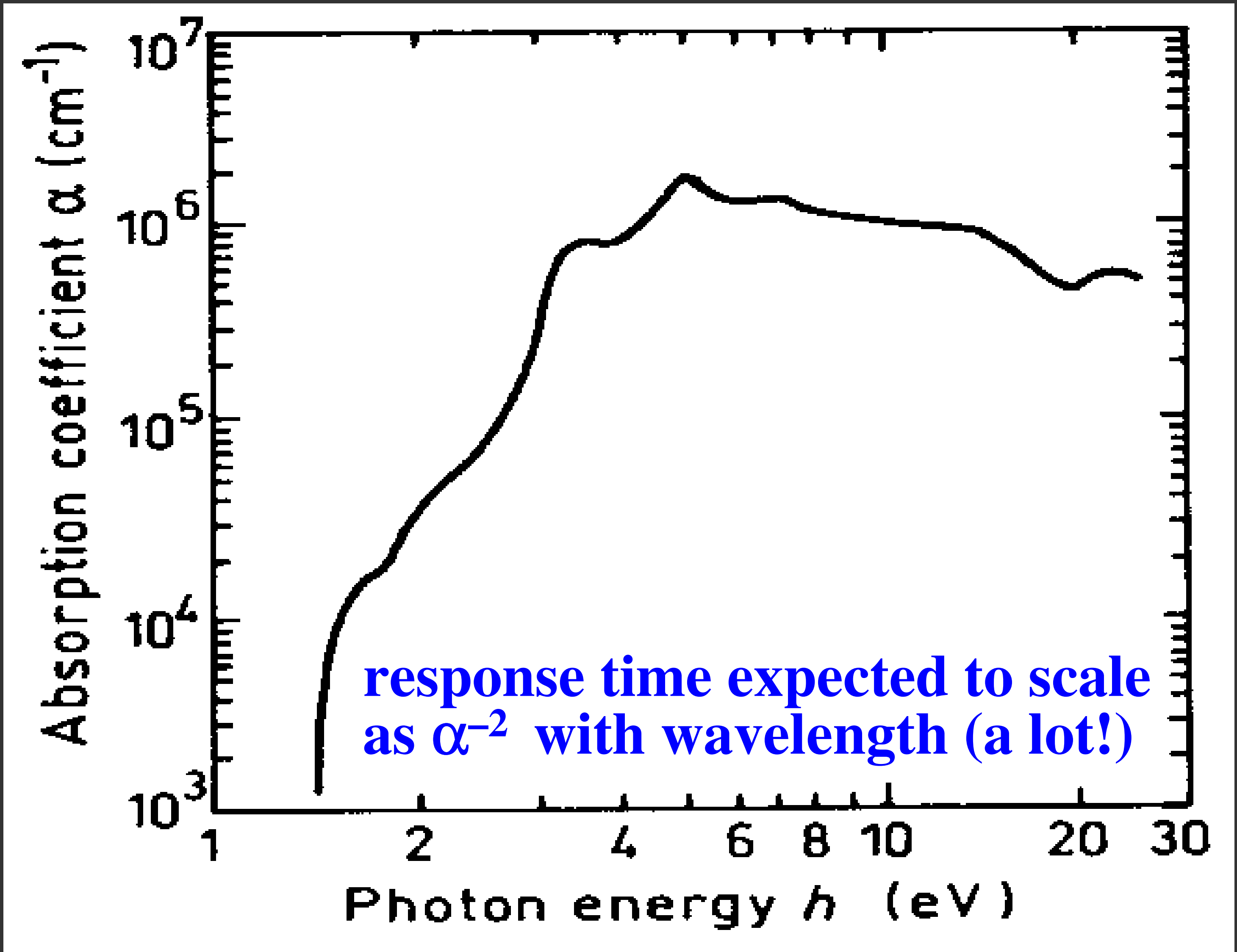
$$I(\kappa) \propto \frac{1}{\sqrt{\pi\kappa}} - \exp(\kappa)\,\mathrm{erfc}(\sqrt{\kappa})$$

$$\kappa \equiv t/\tau,\ \text{where}\ \tau \equiv \alpha^{-2}D^{-1}$$





GaAs absorption



response time expected to scale as α^{-2} with wavelength (a lot!)

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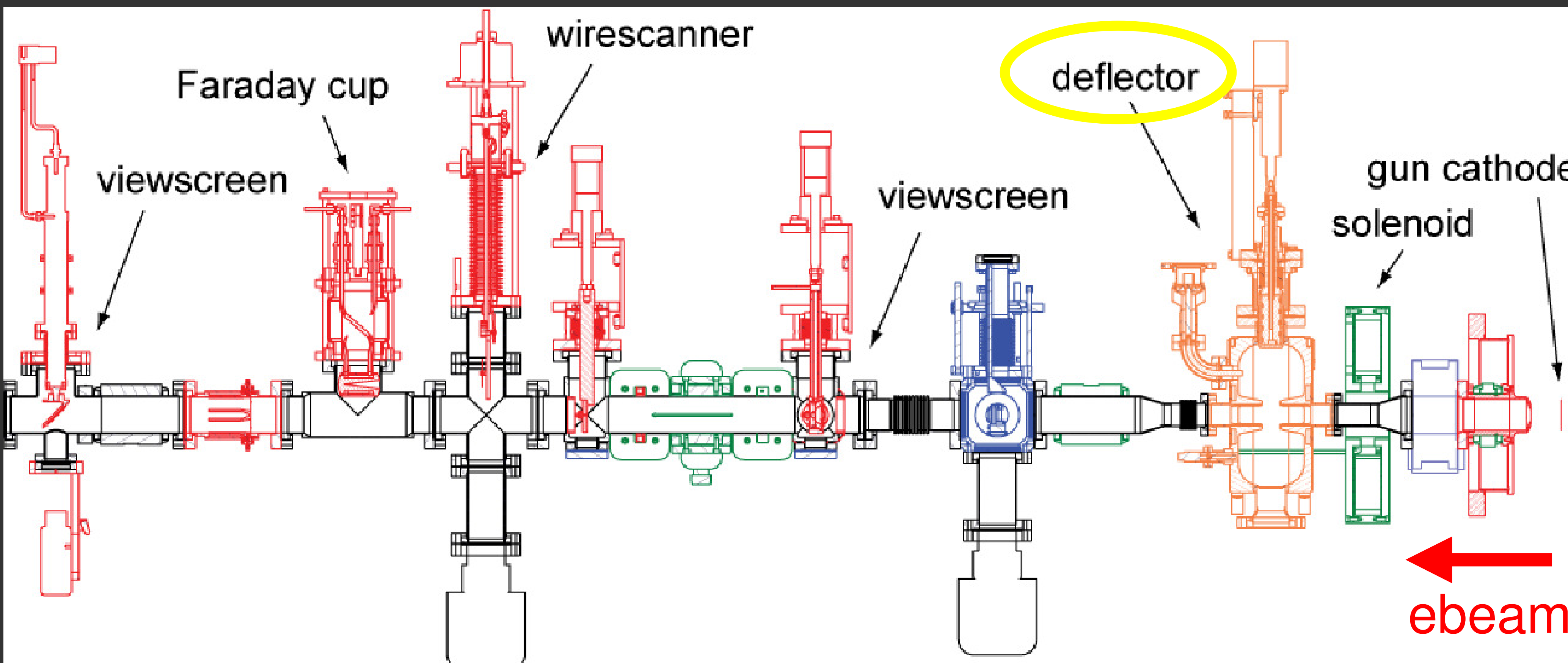
Temp. response meas.

- Temporal response directly measured for GaAs and GaAsP for 520 nm (1 ps rms laser pulse)
- Measured indirectly using space charge effect for both photocathodes at 860, 785, 710, and 460 nm (~100 fs laser pulse)
- See Phys. Rev. ST-AB **11** (2008) 040702 for details

Setup (temp. response)

- RF synchronized to laser (1.2 ps rms jitter measured)
- Overall time resolution: 1.5 ps rms



Indirect method (I)

- If solenoid is turned off, shorter response time $\Rightarrow$ more space charge $\Rightarrow$ larger spot size

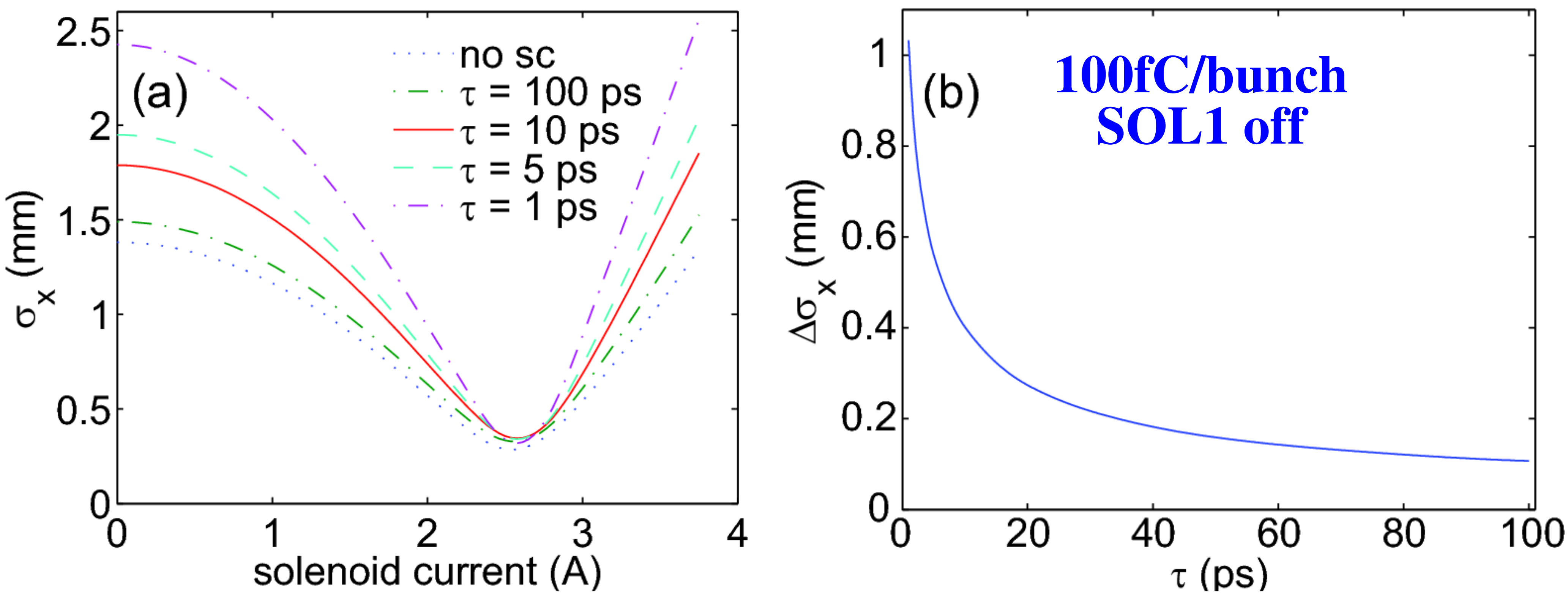
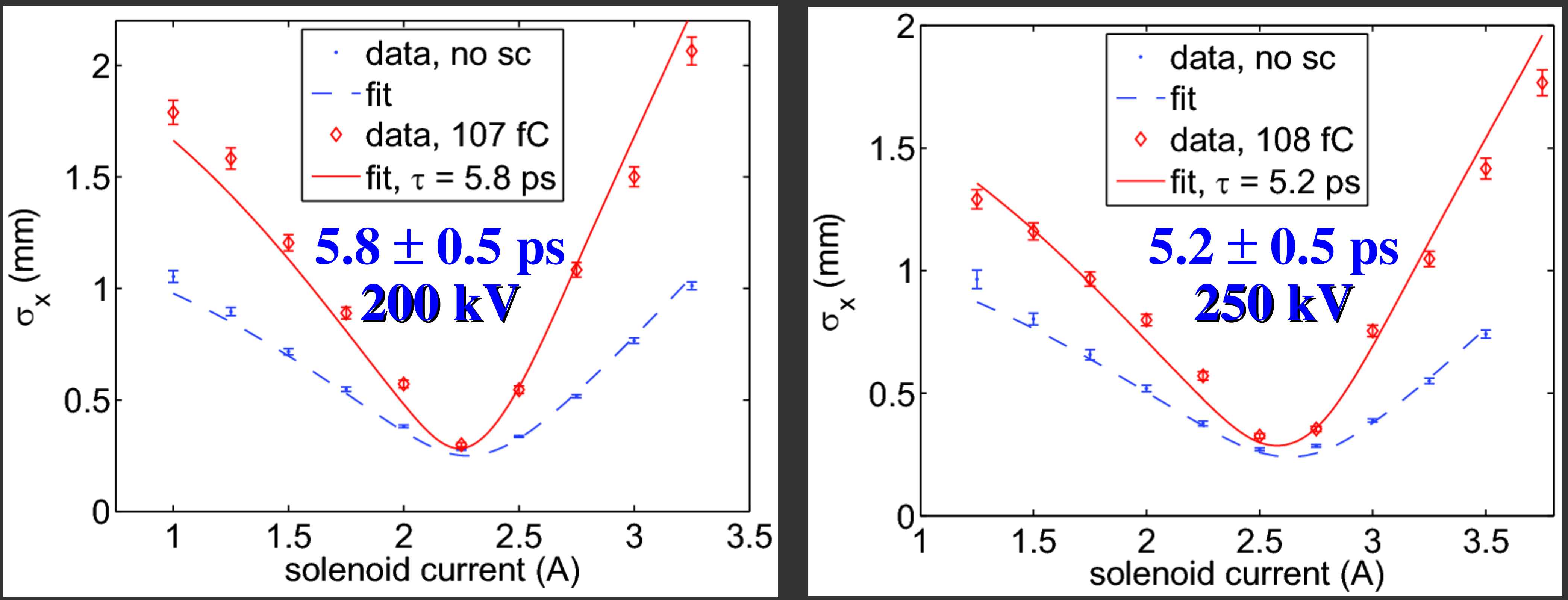


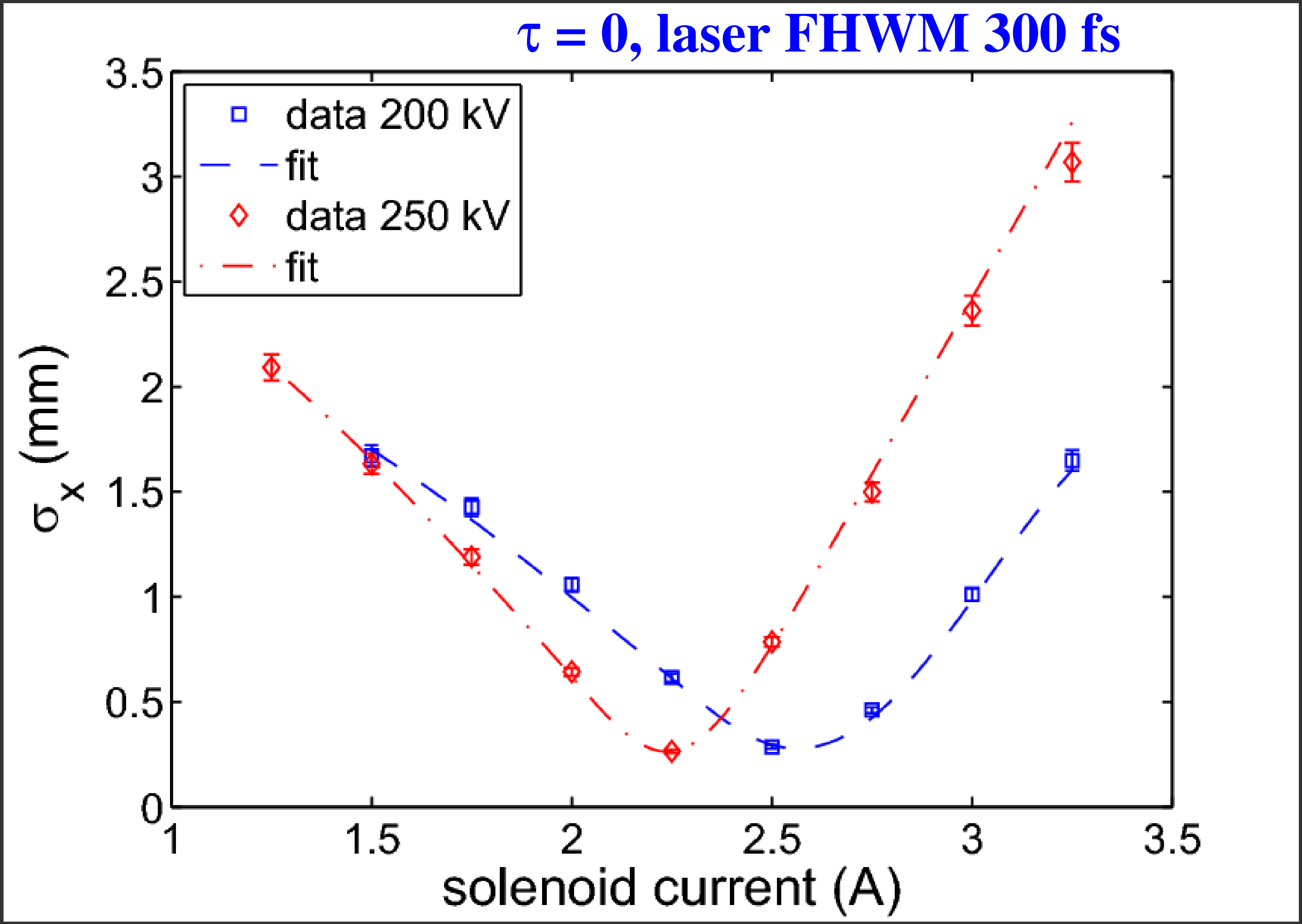
FIG. 11: Calculated dependence of the transverse beam size of the beam at the location of the wire scanner for different values of parameter τ. Charge per bunch 100 fC, gun voltage 250 kV, $k_B T_\perp$ 150 meV, initial rms laser spot size 120 μm. (a) Solenoid scan. (b) Change of the spot size relative to the case of negligible space charge for unpowered solenoid as a function of parameter τ.

Indirect method: 710 nm

- Used Astra with preprogrammed temporal profile (diffusion model + convolution with laser profile) to fit observed data (only one variable parameter)



Indirect method: 460 nm



Indirect method results

TABLE I: Results of data fitting for GaAs response time.

Wavelength (nm)	τ (ps)	Comment
860	76±26	$V_{gun} = 200$ kV
860	69±22	$V_{gun} = 250$ kV
785	11.5±1.2	$V_{gun} = 200$ kV
785	9.3±1.1	$V_{gun} = 250$ kV
710	5.8±0.5	$V_{gun} = 200$ kV
710	5.2±0.5	$V_{gun} = 250$ kV
520	≤1	upper estimate placed
460	≤0.14	upper estimate placed

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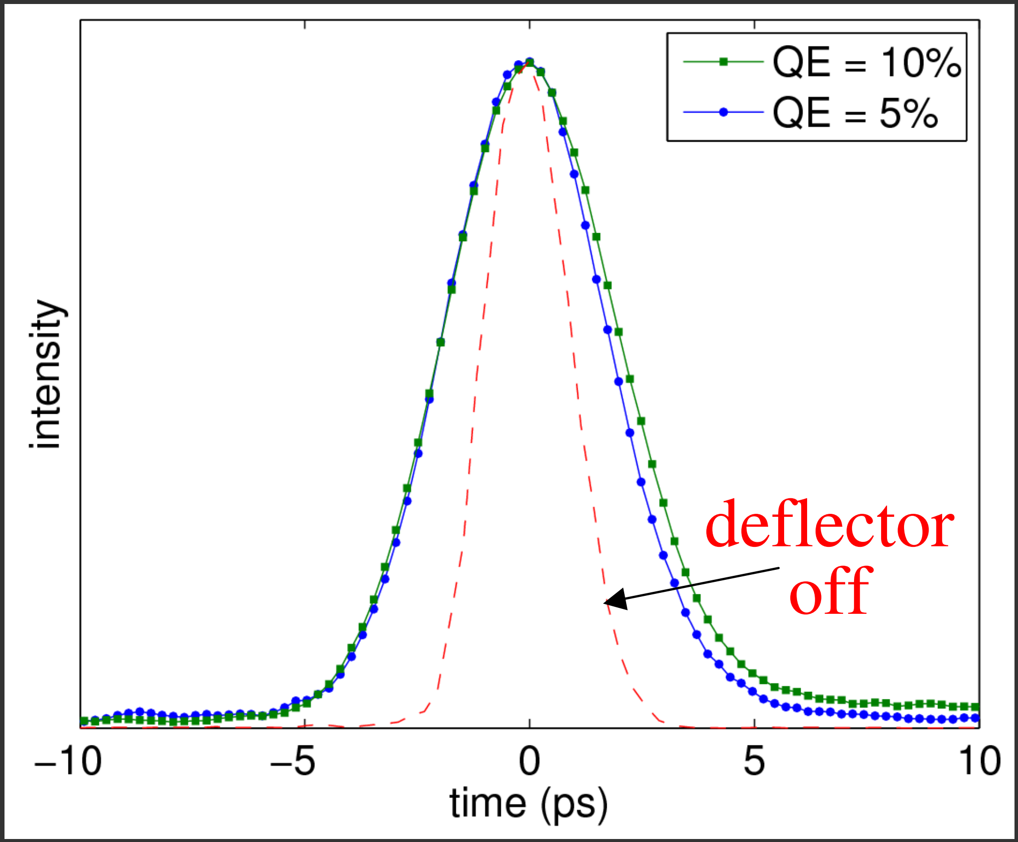
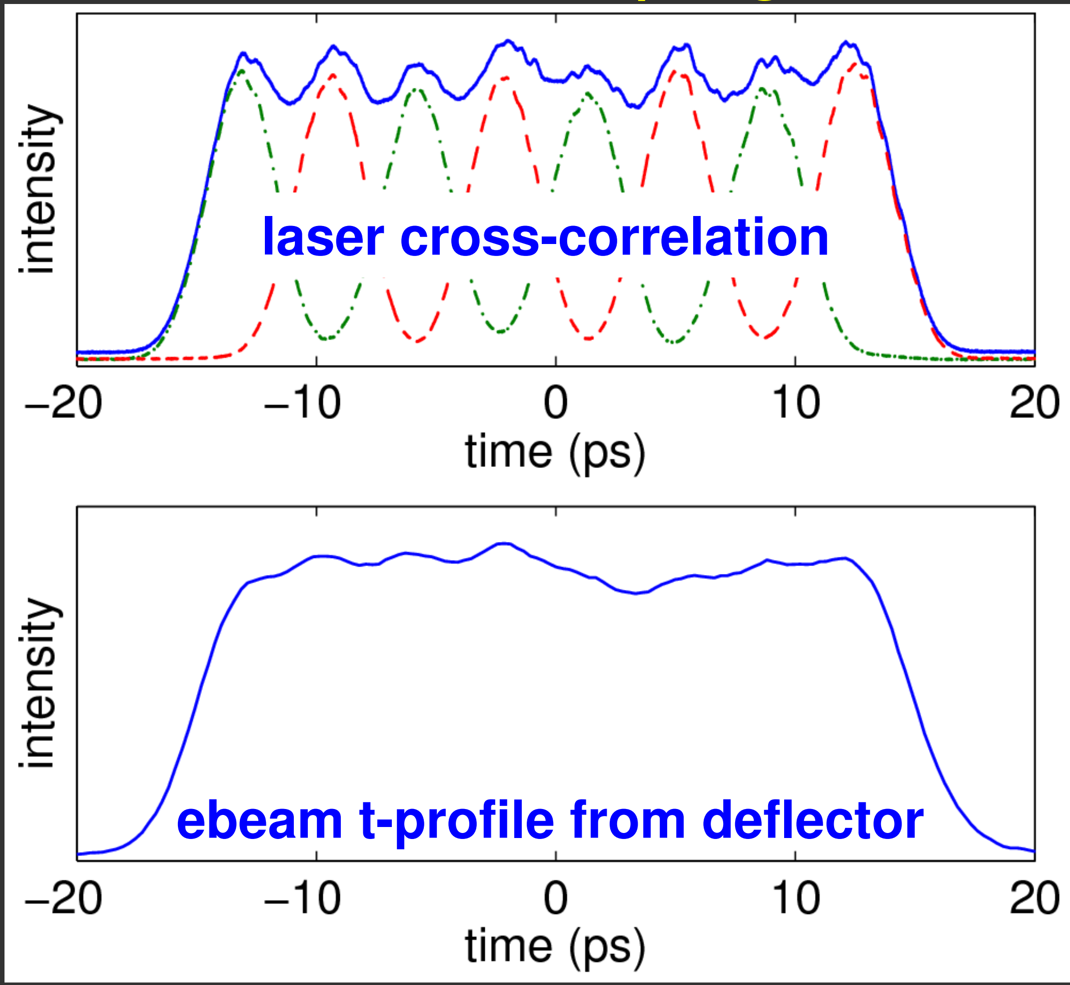
Direct meas.: GaAs

response: 1ps rms laser



laser shaping



Direct meas.: GaAsP

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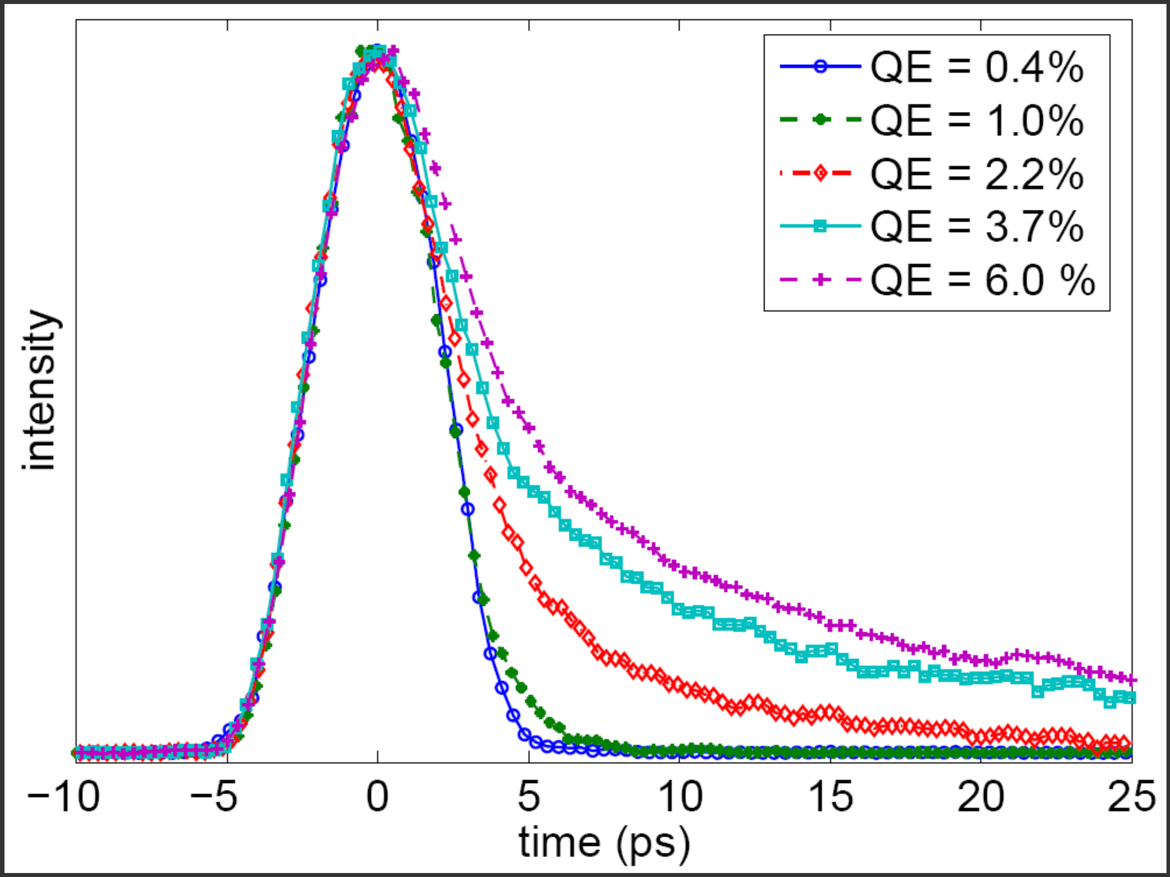
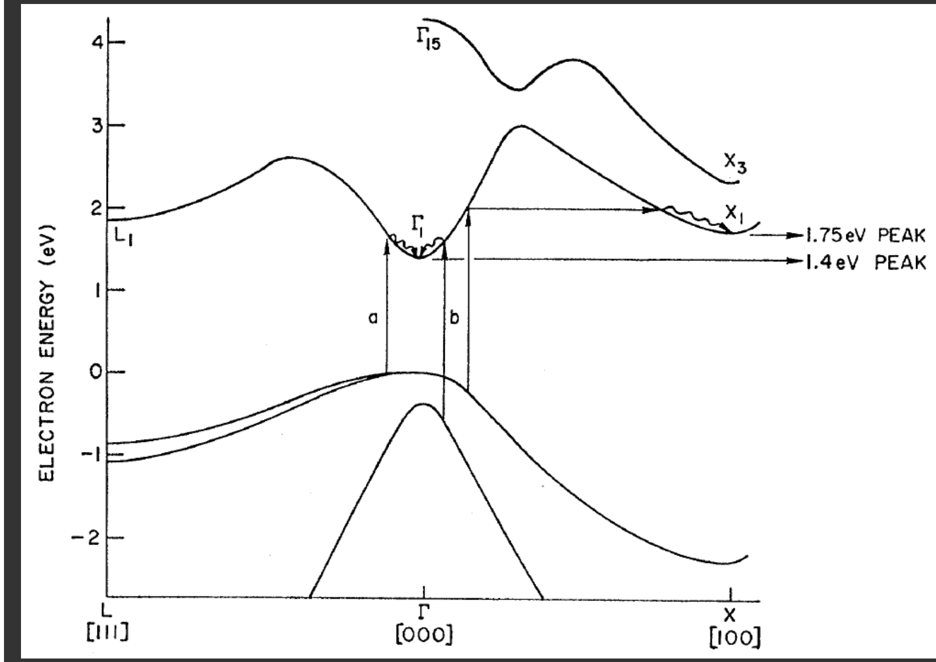
Strong QE dependency



P concentration 45%



Two valleys: Γ (direct) and X (indirect) involved in the process

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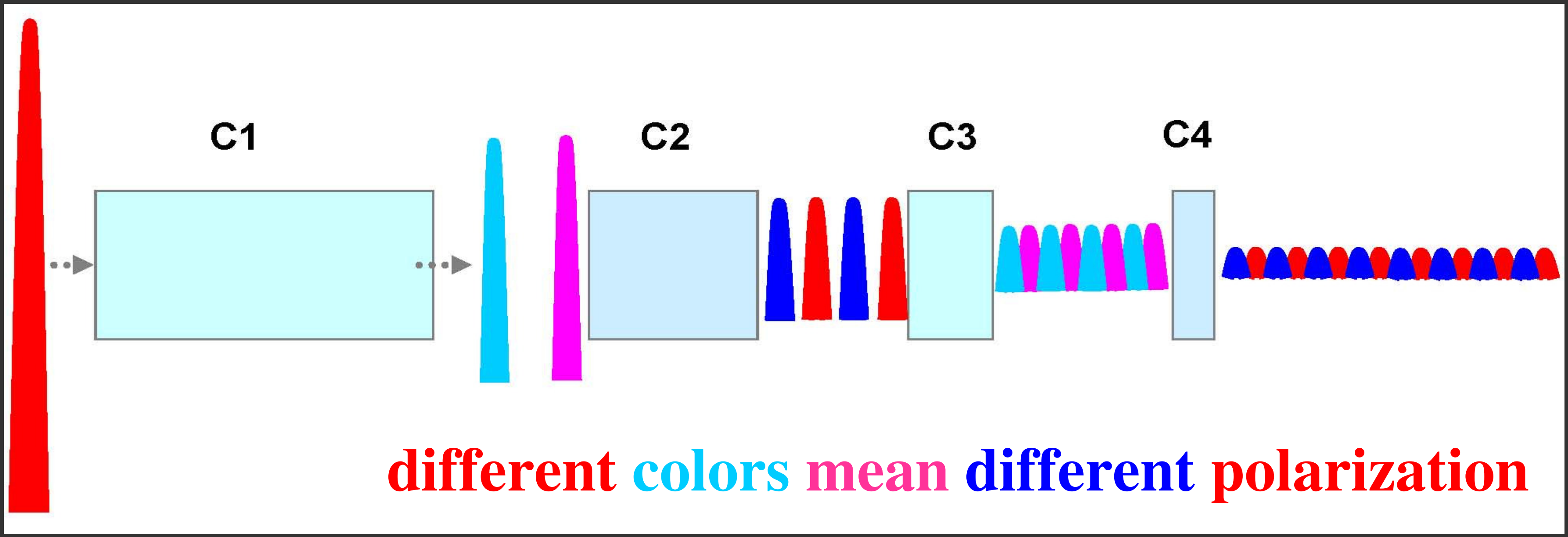
Conclusions (II)

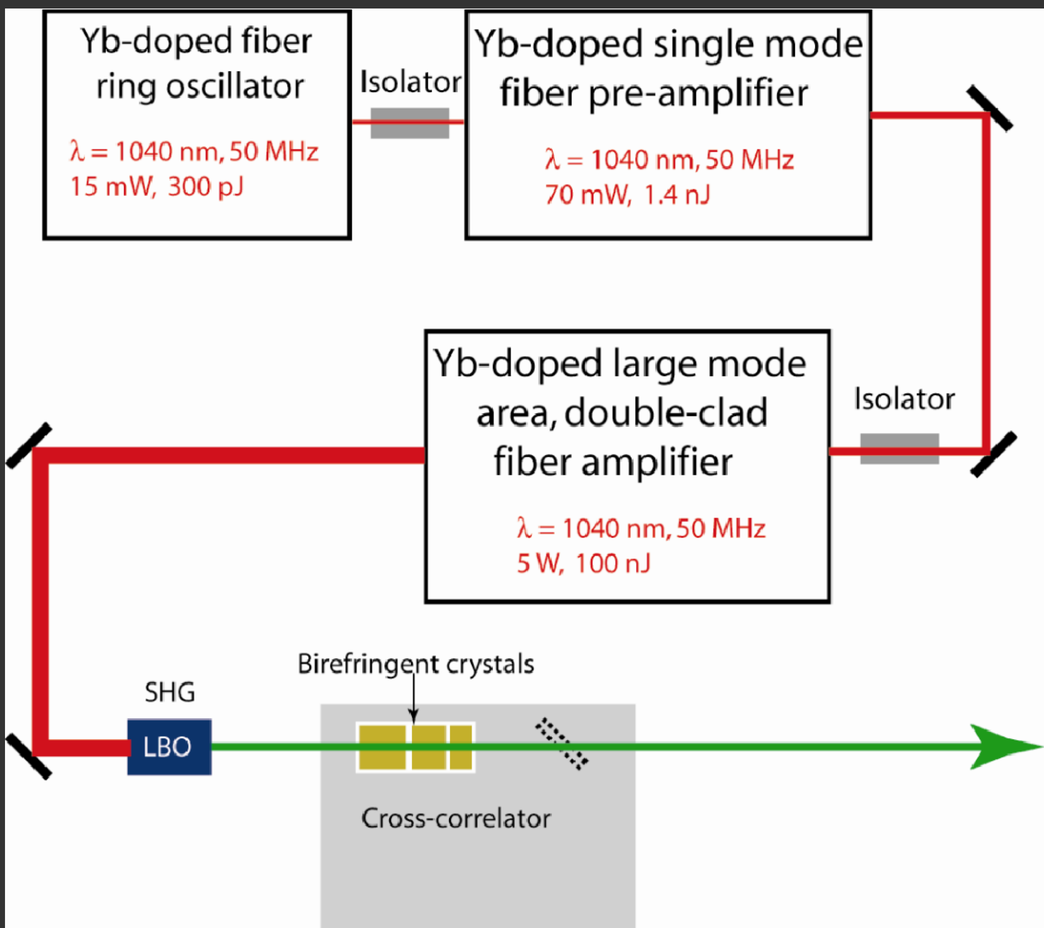
- GaAs is a prompt emitter (on ~1ps scale) at 520 nm
- GaAsP has longer tail (strong QE dependency) in addition to its larger thermal emittance
- This is thought to be due to emission from X CBM
- Also, have performed measurements on Cs:GaN photocathode at 260nm. Prompt emitter (on ~1ps scale). Thermal emittance data is work in process.

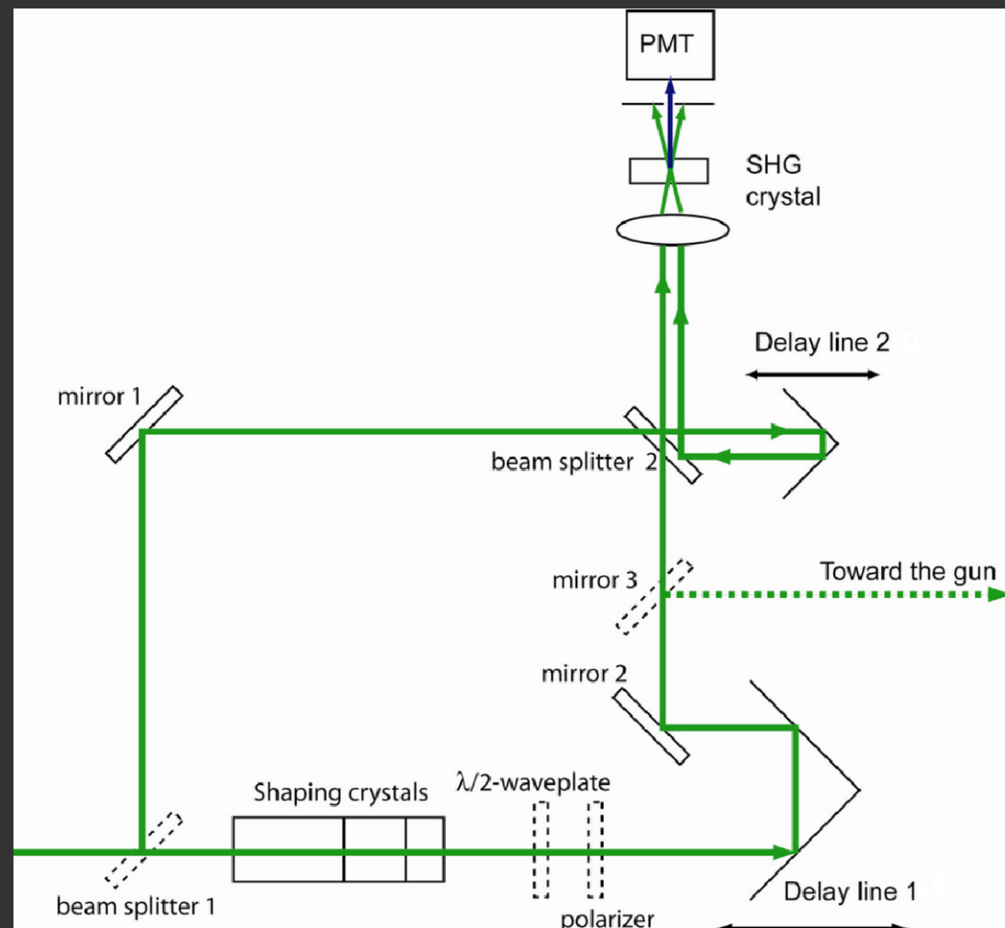
Temporal shaping



- Use birefringent crystals to shape short laser pulse (very efficient)

Laser setup


Yb-doped fiber ring oscillator
λ = 1040 nm, 50 MHz
15 mW, 300 pJ
Isolator
Yb-doped single mode fiber pre-amplifier
λ = 1040 nm, 50 MHz
70 mW, 1.4 nJ
Yb-doped large mode area, double-clad fiber amplifier
λ = 1040 nm, 50 MHz
5 W, 100 nJ
Isolator
SHG
LBO
Birefringent crystals
Cross-correlator


PMT
SHG crystal
Delay line 2
mirror 1
beam splitter 2
mirror 3
Toward the gun
mirror 2
Shaping crystals
λ/2-waveplate
beam splitter 1
polarizer
Delay line 1

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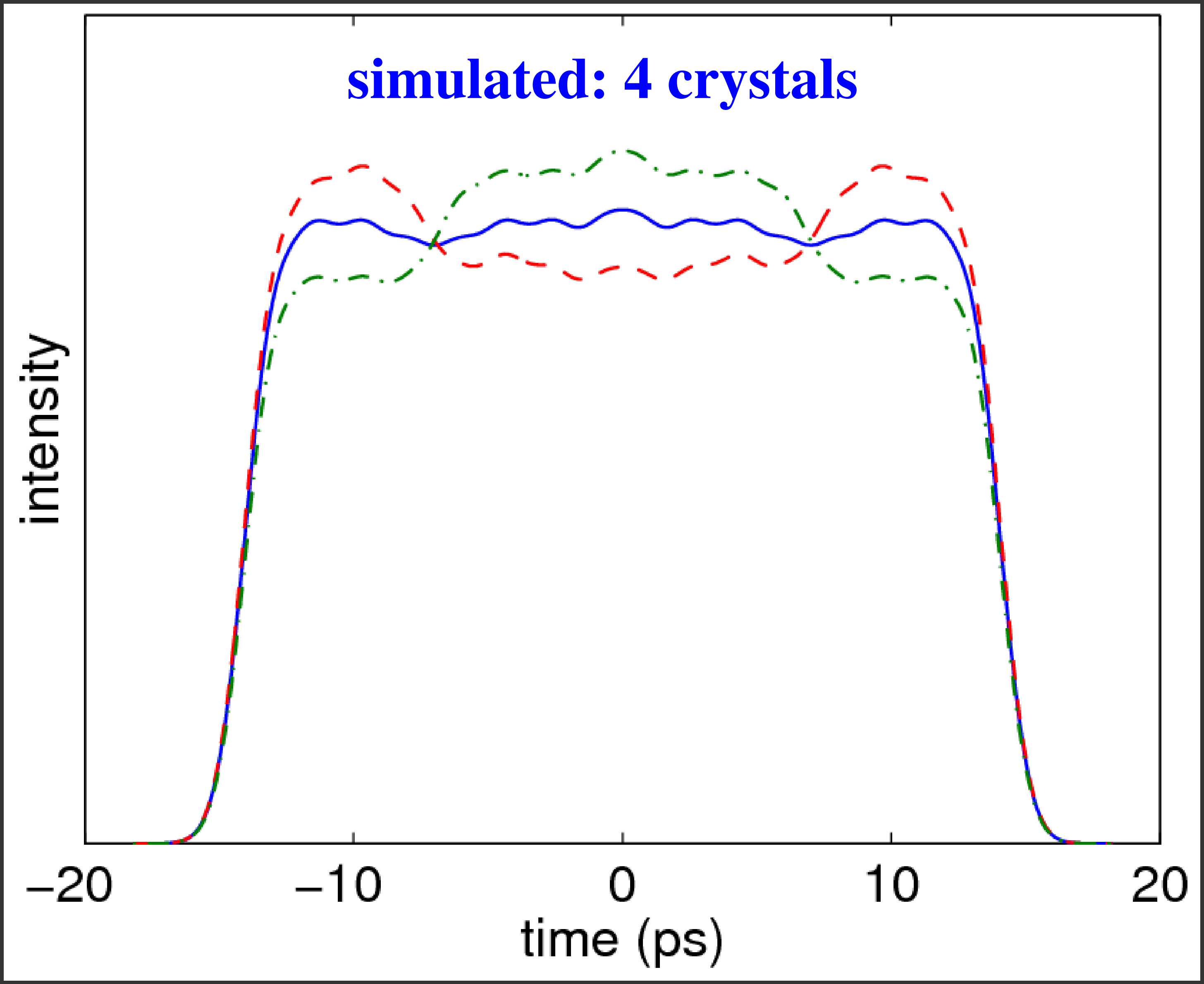
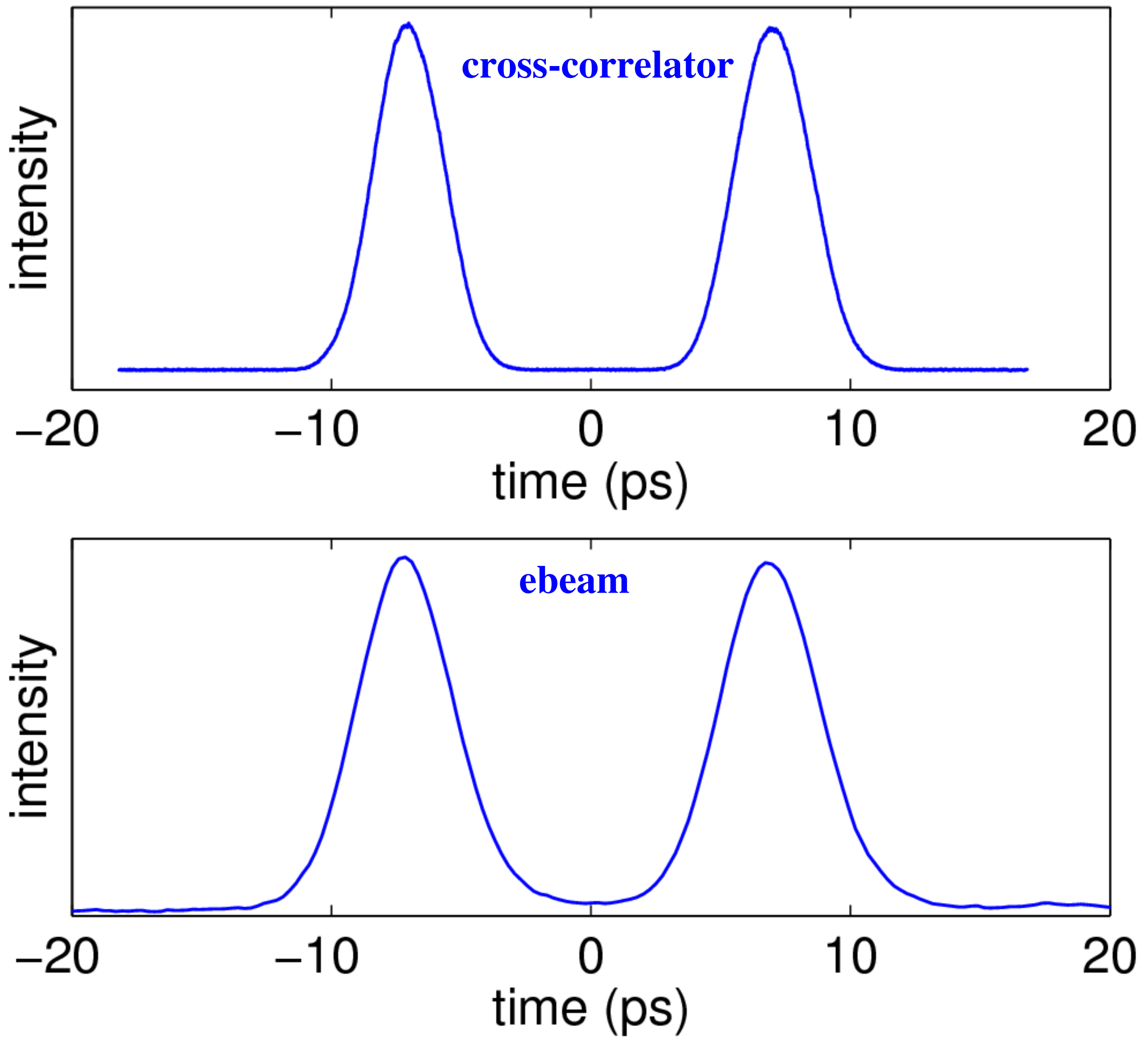
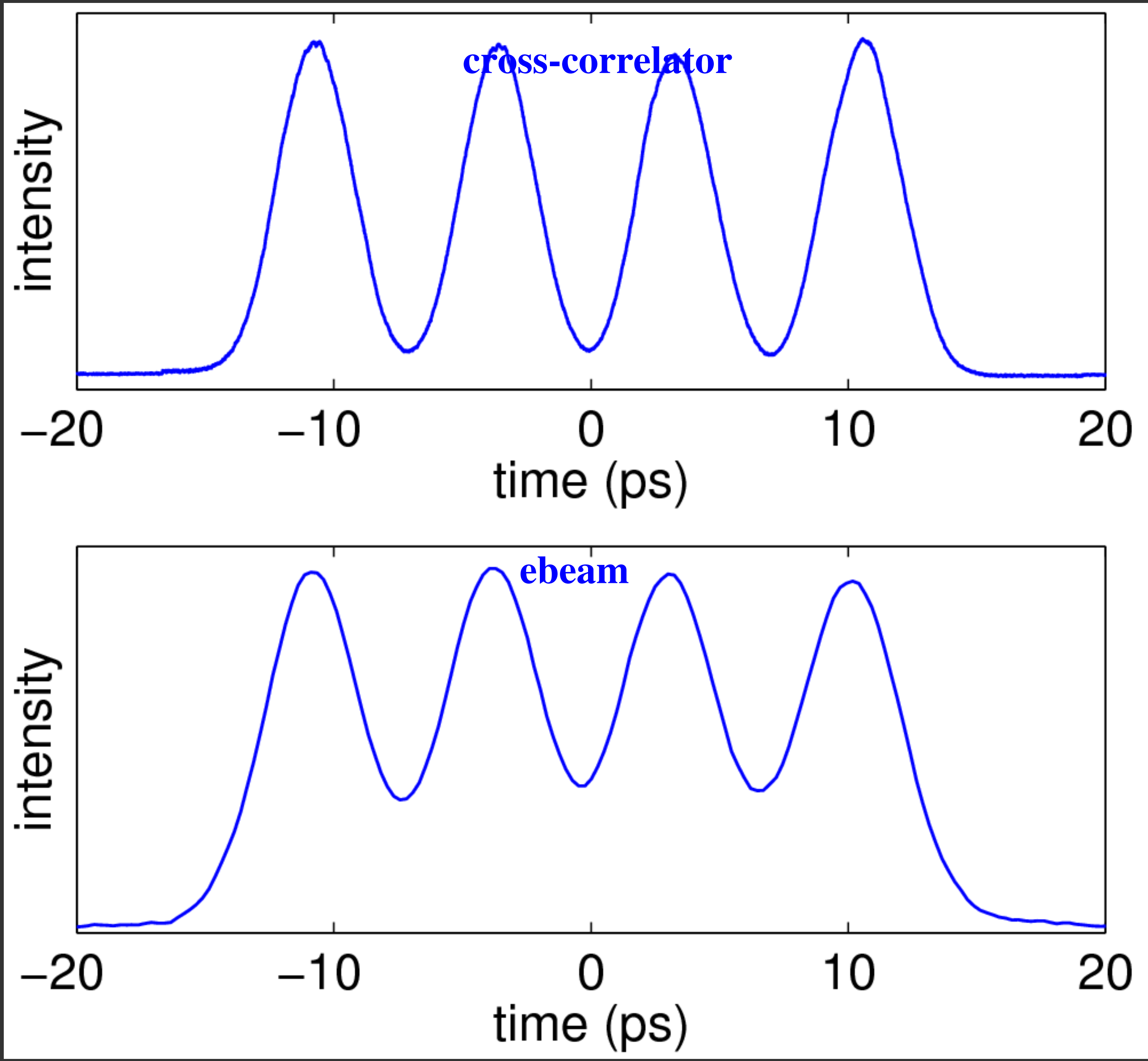
Pulse stacking



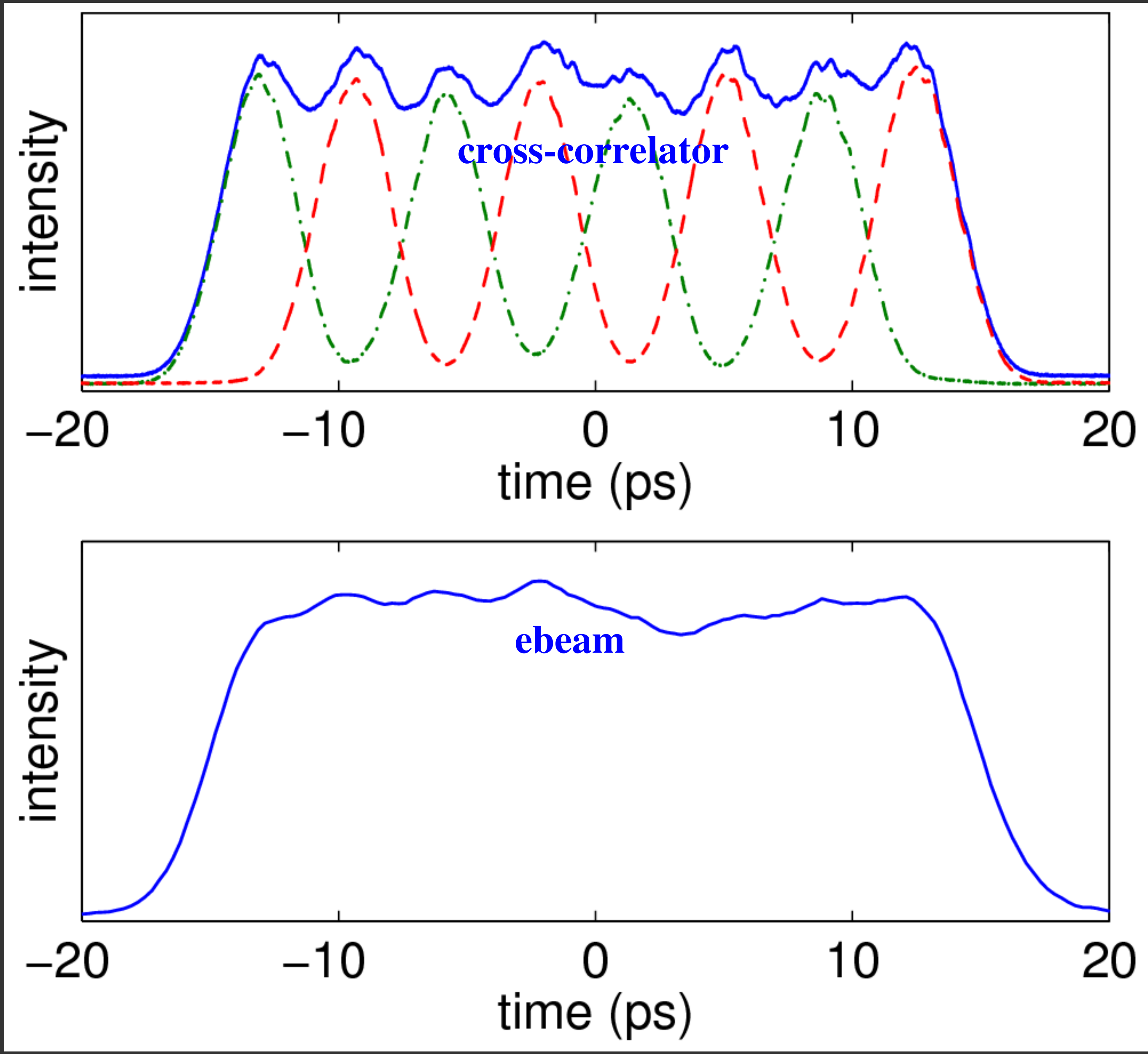
Ebeam vs. laser: 1 cryst



Ebeam vs. laser: 2 cryst



Ebeam vs. laser: 3 cryst



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Summary

- Essential properties of NEA photocathodes have been measured in wide range of laser wavelengths
- GaAs is the superior choice of what we have tried so far; at 520 nm the temporal response is ~ps or shorter; thermal emittance is 0.48 mm-mrad per 1mm rms laser spot (4mm diameter spot)

Acknowledgements

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NSF for $$$