IVeSC 2020

Sources and Blankers for Ultrafast Electron Microscopy

Pieter Kruit

Mathijs Garming, Lixin Zhang and Jacob Hoogenboom

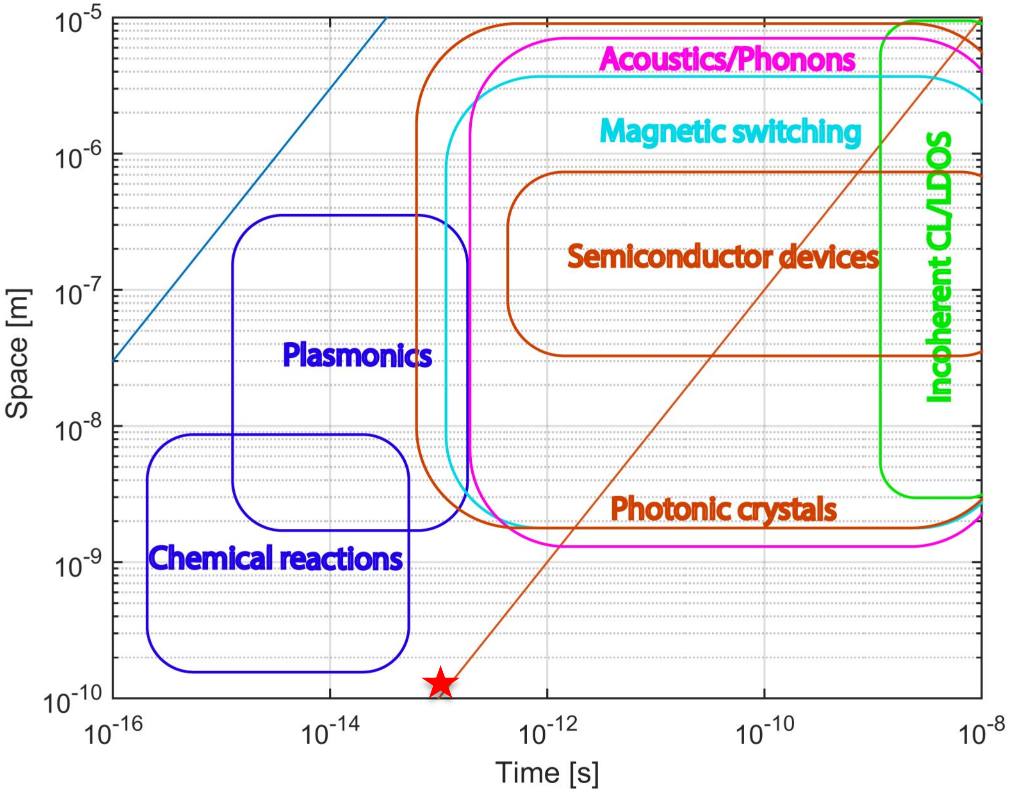
Department of Imaging Physics, Delft University of Technology, The Netherlands

TU Delft

UEM = Ultrafast Electron Microscopy

TEM allows 0.1 nm spatial resolution. Photo emission sources allow 100 fs pulses.

What if these are combined? ★



From Weppelman's thesis

TU Delft

Reminder: What is Brightness?

$$B = \frac{dI}{dA\,d\Omega}$$

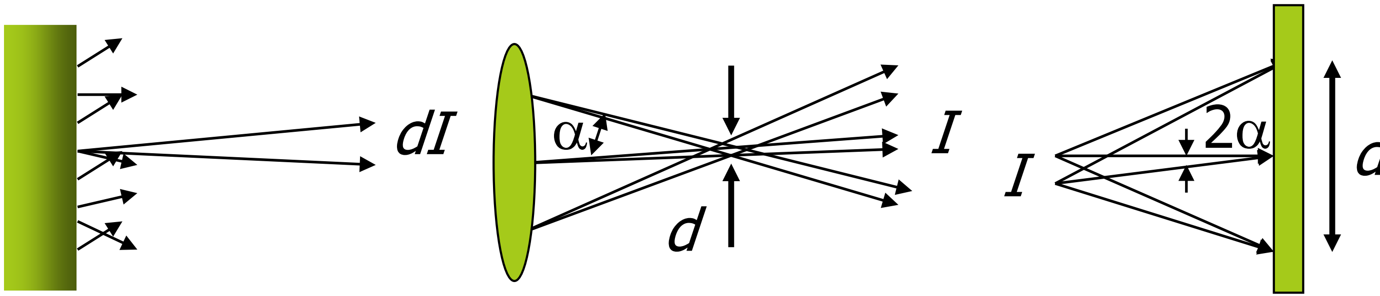
Differential Brightness

$$B = \frac{I}{\frac{\pi}{4} d^2 \cdot \pi\alpha^2}$$

Practical Brightness

$$B_r = \frac{I}{\frac{\pi}{4} d^2 \cdot \pi\alpha^2 \cdot V}$$

Reduced Brightness



At the cathode

In a probe

on the TEM sample

$$\boxed{B_r = \frac{eJ}{\pi E_t}}$$

$$\boxed{B_r = \frac{I}{\frac{\pi}{4} d^2 \cdot \pi\alpha^2 \cdot V}}$$

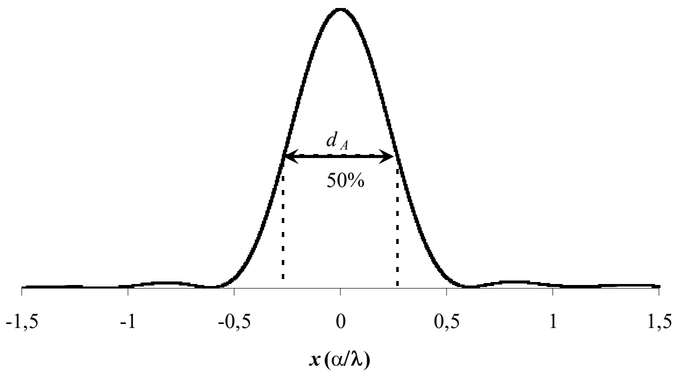
Resolution in Electron Microscopy is always limited by Diffraction.

Current in diffraction limited operation is

$$I_\Lambda \approx 10^{-18} B_r$$

Emittance of a coherent electron beam is order of

$$d_c \cdot \alpha \approx \lambda = \frac{1.226\times10^{-9}}{V^{1/2}}$$



Now add current with $d_g = d_c$ and we find

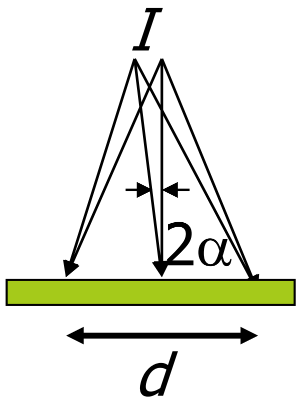
$$I_\Lambda = B_r \frac{\pi}{4} d_A^{\,2} \cdot \pi\alpha^2 \cdot V \approx 10^{-18} B_r$$

Conclusion: Typical probe currents close to the limits of resolution are always about 10^{-18} x B_r

UEM
source requirements

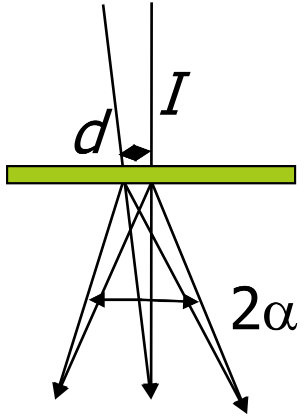
For TEM at
- 0.1 nm
- 100 fs

For diffraction at
- Coherence 5 nm
- Area d = 200 µm
- 100 fs



High resolution TEM:
10^8 electrons per image

$$B_r T = \frac{qN_{im}}{\pi^2 \varepsilon_{im}^2 V_r} \approx 5 \times 10^3$$



Large area Diffraction:
10^6 electrons per pattern

$$B_r T = 6.7 \frac{N_{diff}\, q}{r_{ill}^2} = 10^{-4}$$

Zhang, L., Hoogenboom, J. P., Cook, B. & Kruit, P. Struct. Dyn. 6, (2019)

UEM
source requirements for:

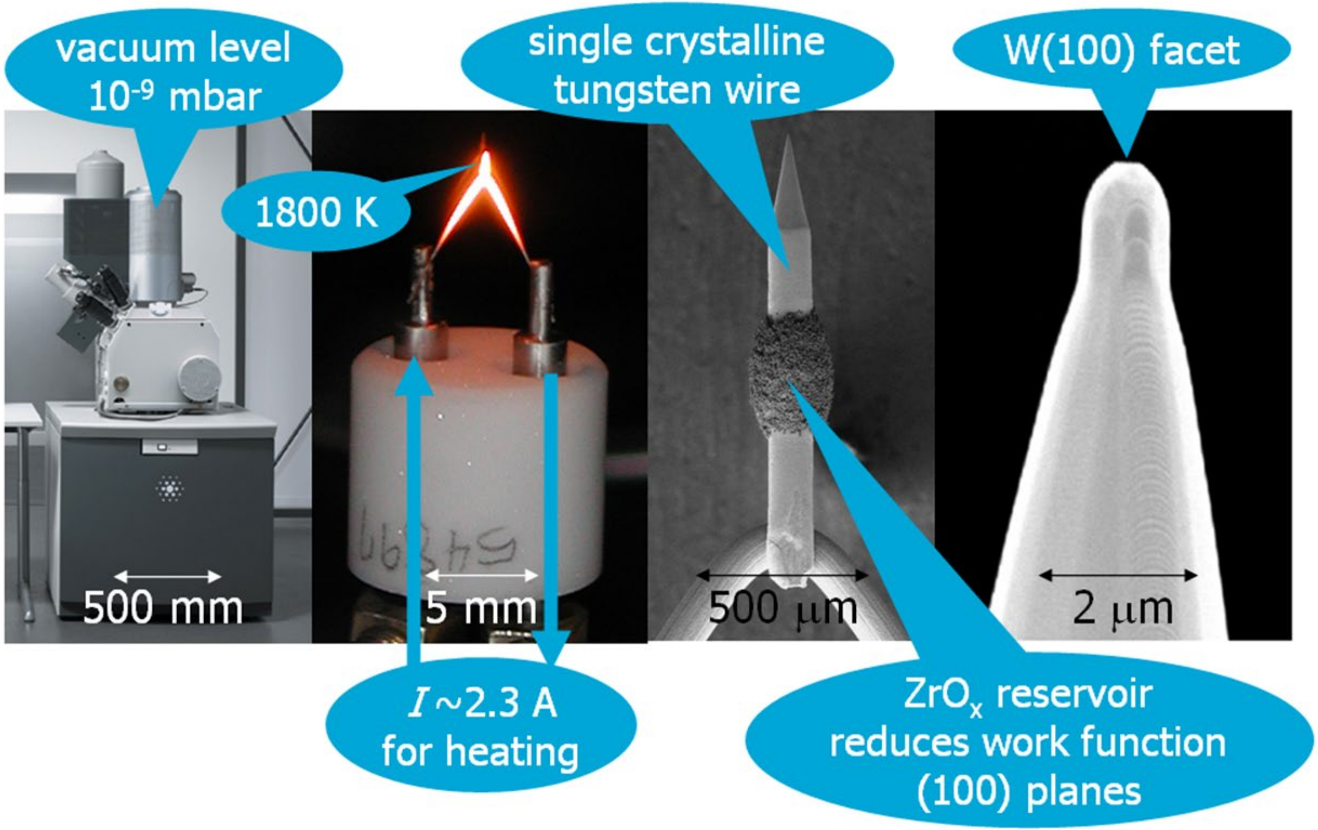
- 0.1 nm
- 100 fs

TABLE I. Approximate reduced brightness B_r required to operate in the various modes of imaging and diffraction with a time resolution of $\tau = 100$ fs. For imaging, the spatial resolution is $d_{res} = 0.1$ nm with 1 megapixels per image, $V_r = 100$ kV, $N_{im} = 10^8$. For diffraction, the illuminated area has a radius of 100 μm and $N_{diff} = 10^6$. For the repeated mode, we assume 10^4 electrons per pulse, and for the stroboscopic mode, we assume 1 electron per pulse. Note that the total illumination times for single-shot, repeated, and stroboscopic modes then become 100 fs, 1 ns, and 10 μs, respectively, for imaging, and 100 fs, 10 ps, and 100 ns for diffraction. HREM: high resolution electron microscopy. LAD: large area diffraction.

★	Single shot	Repeated	Stroboscopic
B_{rHREM} [A/(m^{2}srV)]	5×10^{16}	5×10^{12}	5×10^{8}
I_{HREM} (A)	1.6×10^{2}	1.6×10^{-2}	1.6×10^{-6}
B_{rLAD} [A/(m^{2}srV)]	1×10^{9}	1×10^{7}	1×10^{3}
I_{LAD} (A)	1.6	1.6×10^{-2}	1.6×10^{-6}

Zhang, L., Hoogenboom, J. P., Cook, B. & Kruit, P. Struct. Dyn. 6, (2019)

Workhorse in Electron Microscopy: The Schottky emitter



TU Delft

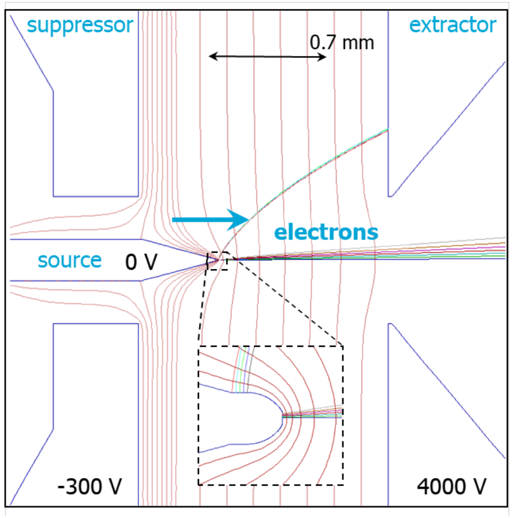
Workhorse in Electron Microscopy: The Schottky emitter

UEM
source requirements for:
- 0.1 nm
- 100 fs

Longer τ relaxes requirement B

TUDelft

Schottky emitter



$I_{total} = 10^{-4}$ A

$I_{facet} = 10^{-5}$ A

B_r = 1-5 x 10^8 A/m^{2}srV

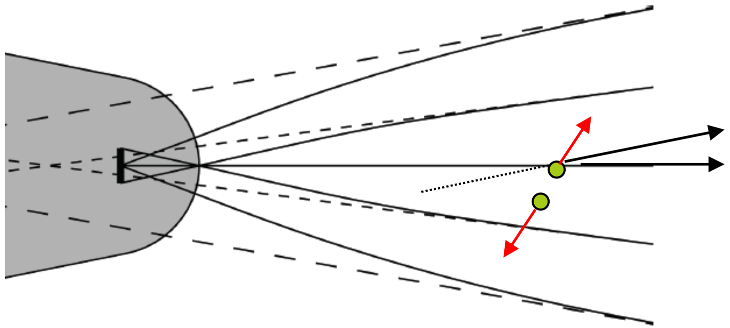
I_{coh} = 1-5 x 10^{-10} A

	Single shot	Repeated	Stroboscopic
B_{rHREM} [A/(m^{2}srV)]	5×10^{16}	5×10^{12}	5×10^{8}
I_{HREM} (A)	1.6×10^{2}	1.6×10^{-2}	1.6×10^{-6}
B_{rLAD} [A/(m^{2}srV)]	1×10^{9}	1×10^{7}	1×10^{3}
I_{LAD} (A)	1.6	1.6×10^{-2}	1.6×10^{-6}

Ultimate limit to Brightness of emitter:

Stochastic Coulomb Interactions

1. Trajectory displacement causes reduction of brightness
2. Boersch effect increases energy spread

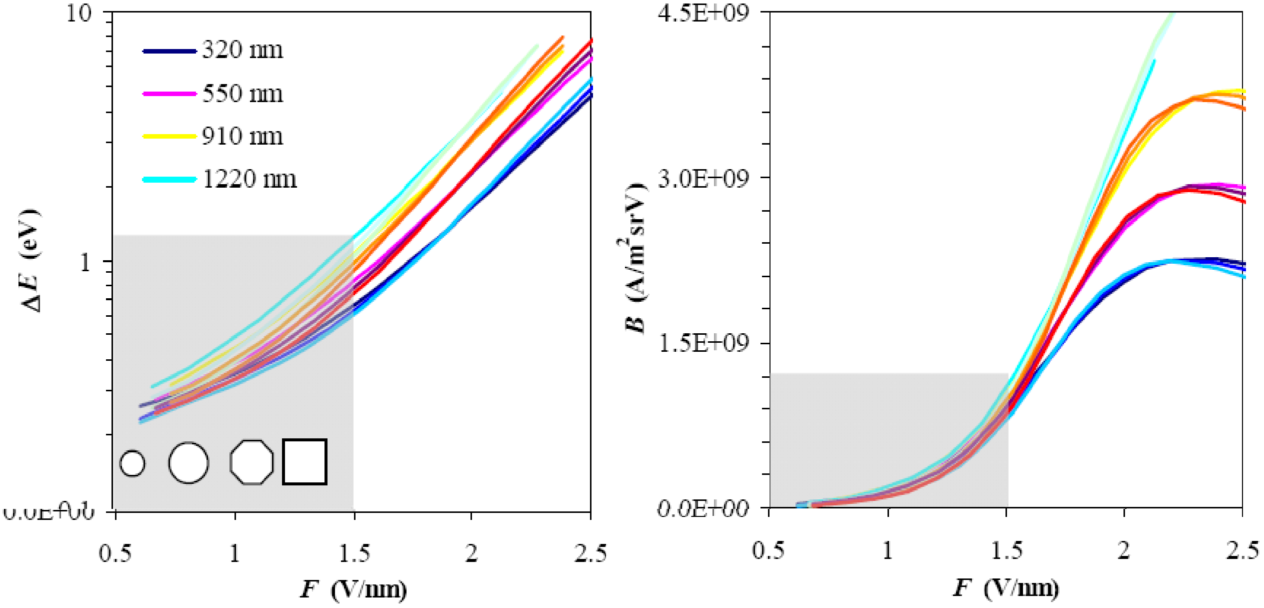


TU Delft

Coulomb Interactions in continuous beams

Coulomb interactions in Schottky sources:

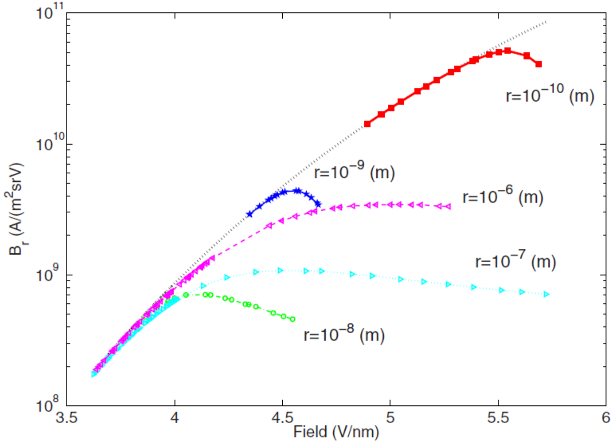
Just the emitter region (first few mm’s)



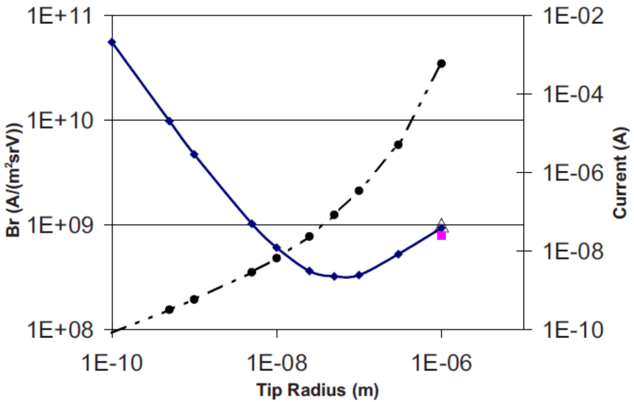
Bronsgeest, M. Physics of Schottky electron sources (2014). doi:10.4032/9789814364805.

Coulomb Interactions in continuous beams

For tip diameters 10^{-10} to 10^{-6} m



Brightness versus extraction field for cold field emitters



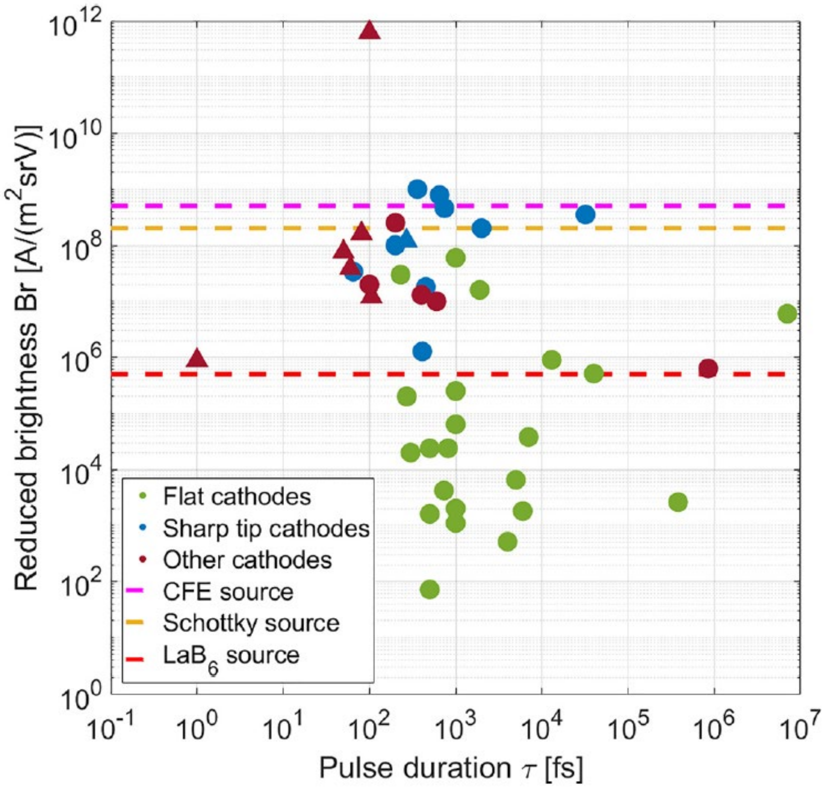
Solid line is brightness at 10% reduction by CI. Dashed line is current at 10% reduction.

Beams from small tips are in Pencil beam regime.
Beams from larger tips are in Holtsmark regime

TUDelft

Cook, B., Verduin, T., Hagen, C. W. & Kruit, P. J. Vac. Sci. Technol. B. 28, (2010).

Literature study shows that the best pulsed electron sources just reach the brightness of continuous sources.



Reduced brightness calculated for each photoemission source versus the reported pulse duration.

Circles indicate experimental results, and triangles represent theoretical or simulation work.

Zhang, L., Hoogenboom, J. P., Cook, B. & Kruit, P. Struct. Dyn. 6, (2019)

TU Delft

Single photo-electron pulses could have higher brightness without the Coulomb limitation

For pulse duration in which only a single electron is emitted:

$$\tau \leq \frac{e}{I_{em}}$$

there should be no Coulomb interaction.

Example:
for 50 nm tips, I = 5.10^{-8} A
is 1 electron every 3.2 ps
So 1 electron per 6 fs is 500 x larger Br: > 10^{11} A/m^{2}srV

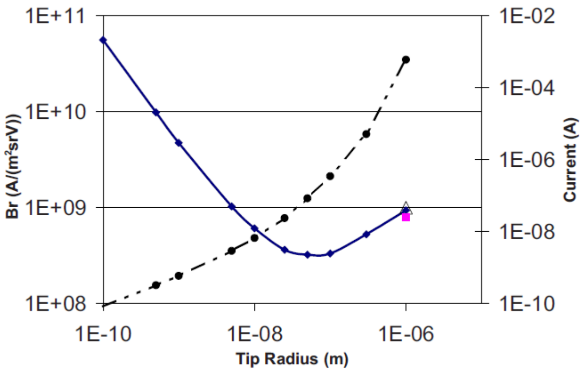
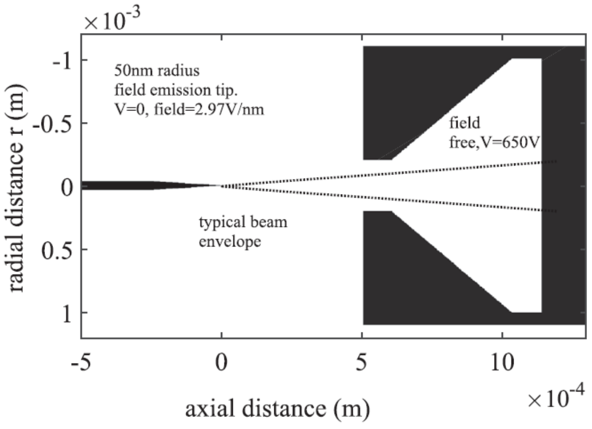
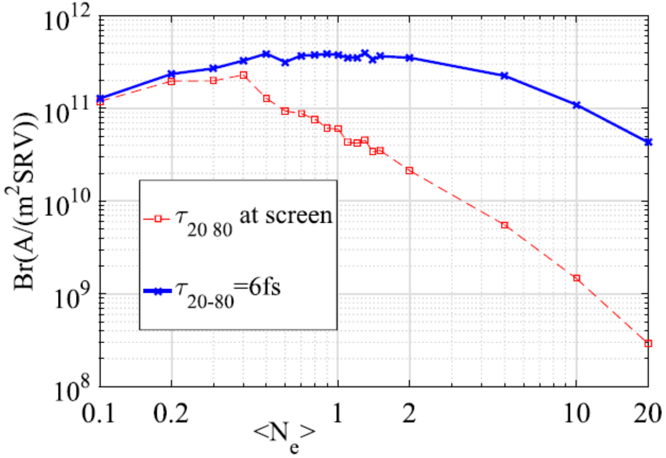


Photo-electron emission in 6 fs pulses gives highest brightness at an average of a single electron per pulse.



Set-up for calculations

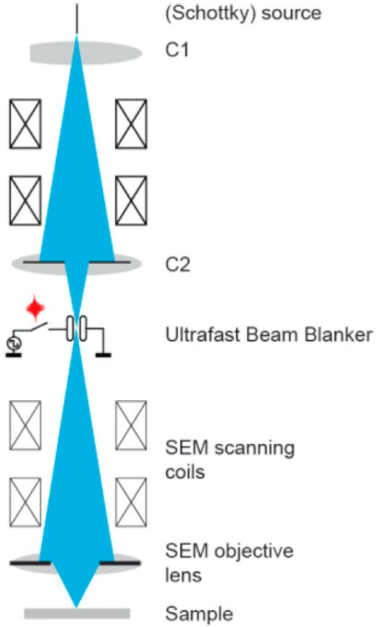


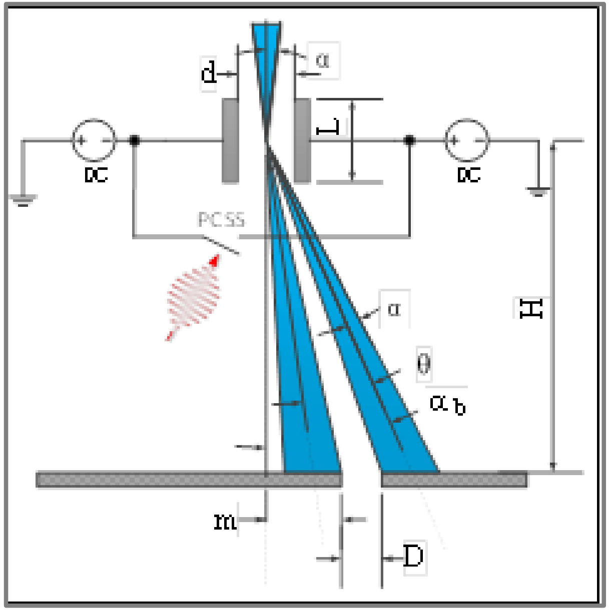
Brightness versus number of randomly emitted electrons in a 6 fs pulse. The red line takes into account that the pulse increases in duration by energy spread.

TU Delft

Cook, B. & Kruit, P. Appl. Phys. Lett. 109, 1–5 (2016).

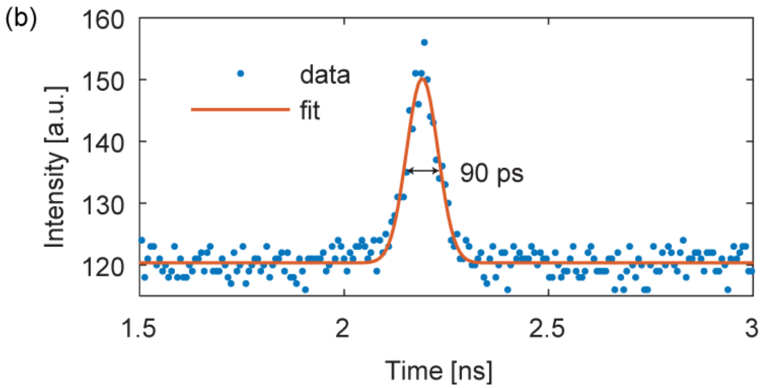
If the highest brightness in a photo-emission pulse is equal to the brightness of a continuous beam, a laser-triggered blanker should give the same quality pulse.





Blanker on a standard aperture stick

First result: 90 ps
Goal: 1 ps

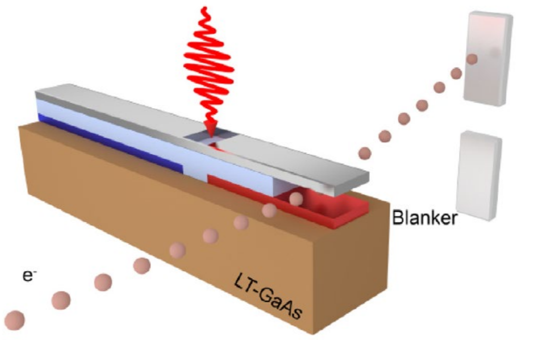


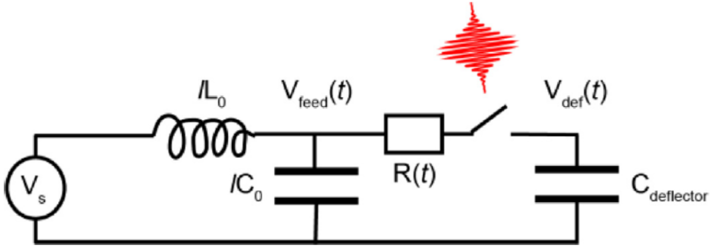
Moerland, R. J., Weppelman, I. G. C., Garming, M. W. H., Kruit, P. & Hoogenboom, J. P. Opt. Express 24, (2016).

TUDelft

Directly laser triggered blanker

Goal: 1 ps

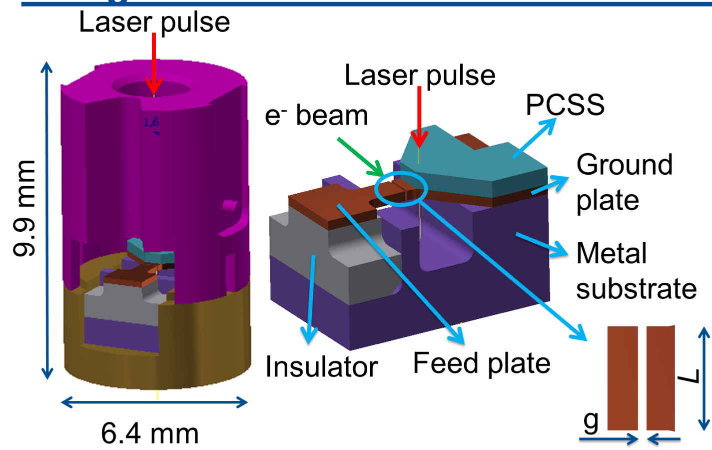




The switch is photo-conductive material

Weppelman, I. G. C., Moerland, R. J., Hoogenboom, J. P. & Kruit, P. Ultramicroscopy 184, (2018).

Design of the micro-fabricated fast beam blanker



In the design of this fast beam blanker, the capacitance and bright resistance are the important factors. We design a pair of deflector plates with a total capacitance of C=229 *fF.*

Length of deflector plates:
L=600 μm;
Gap between deflector plates:
g=50 μm

Image from Lixin Zhang, Mathijs Garming, Jacob Hoogenboom & Pieter Kruit, MNE 2018

Conclusions

Sources and Blankers for Ultrafast Electron Microscopy

- Source brightness is the key to UEM
- Coulomb Interactions limit the brightness
- Single electron emitters have no Coulomb Interaction
- One direction: very short single electron pulses
- ps pulses: blankers as good as photo-emitters

Pieter Kruit

Mathijs Garming, Lixin Zhang and Jacob Hoogenboom

Department of Imaging Physics, Delft University of Technology, The Netherlands

TU Delft