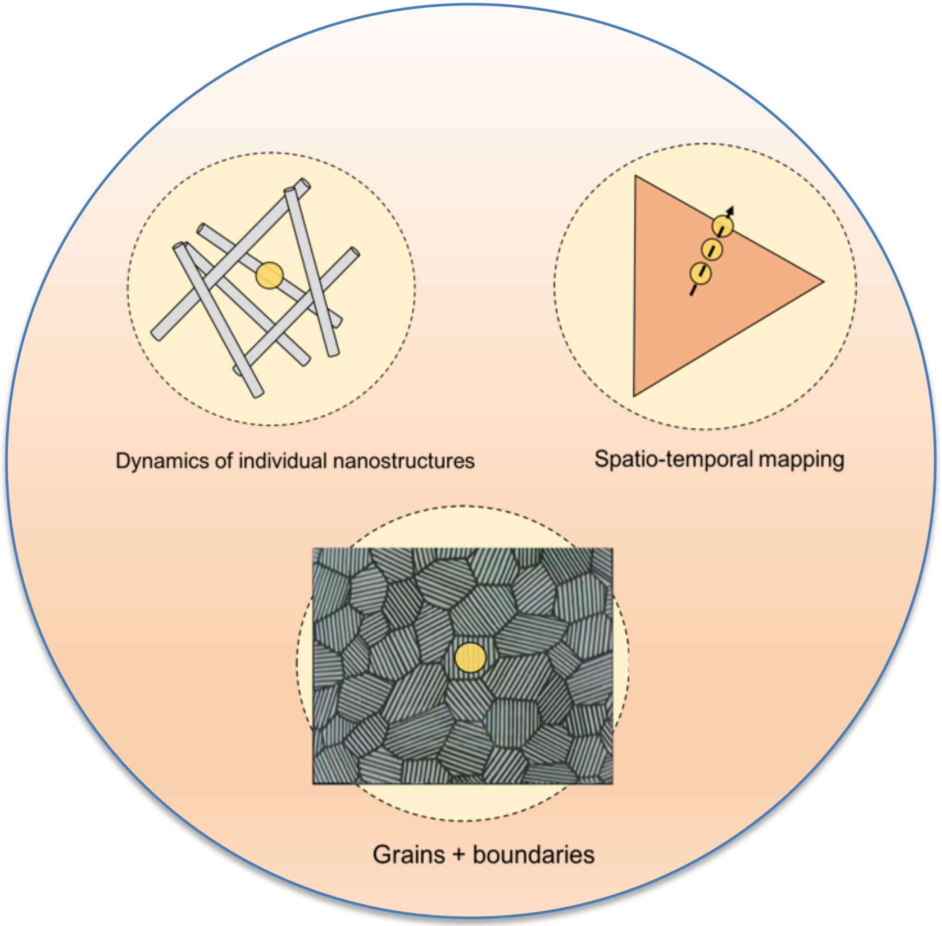
Laser-triggered nano-emitters for femtosecond pulse generation from flat surfaces

Daniele Filippetto
Oct 15th, 2018
P3 meeting

Frontiers in ultrafast science with relativistic beams

Goal: Ultrafast dynamics with high spatial resolution



Challenge: limited brightness

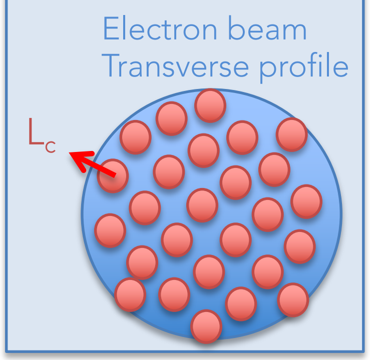
Degeneracy parameter (sub-ps beams)

$$\delta = N_e \left(\frac{\lambda_c}{2\pi\epsilon_n}\right)^2 \leq 10^{-4}$$

$$N_{e,\epsilon_n=100pm} << 10$$

$$L_c \frac{\sigma_{p_x}}{mc} = \frac{\lambda_c}{2\pi}$$

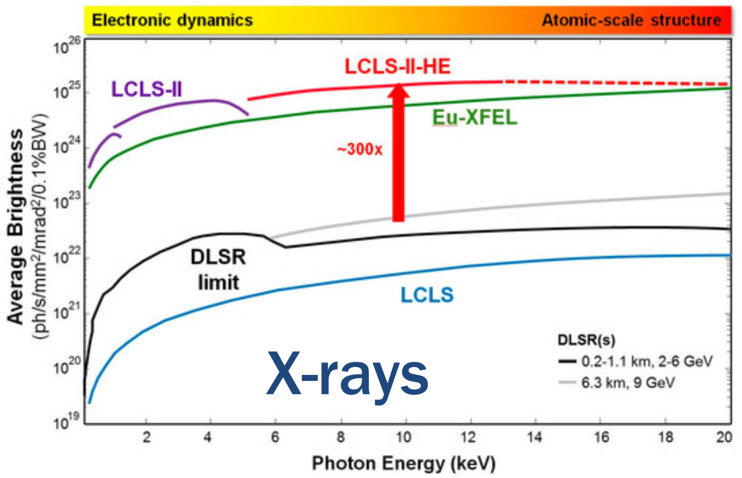
$$\sigma_x \frac{\sigma_{p_x}}{mc} = \epsilon_{nx}$$

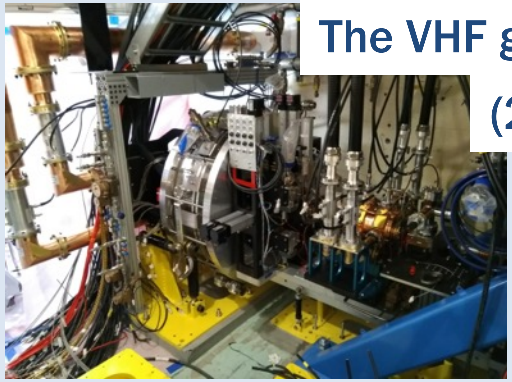


- Increase average N_e/s, new electron sources
  - higher flux, average brightness
- Increase δ, novel photo-emitters
  - nanoemitters, engineered cathodes with low MTE

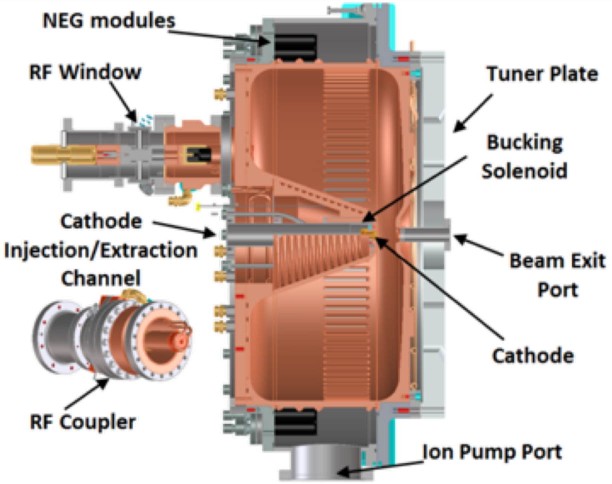
The LBNL High repetition rate VHF gun is a unique source of high brightness & high flux electron beams

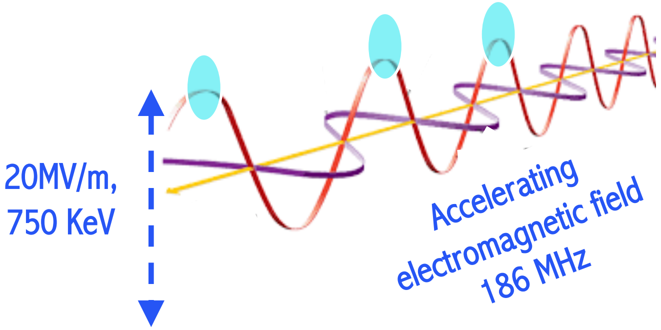
X-FEL R&D (2010-2016)





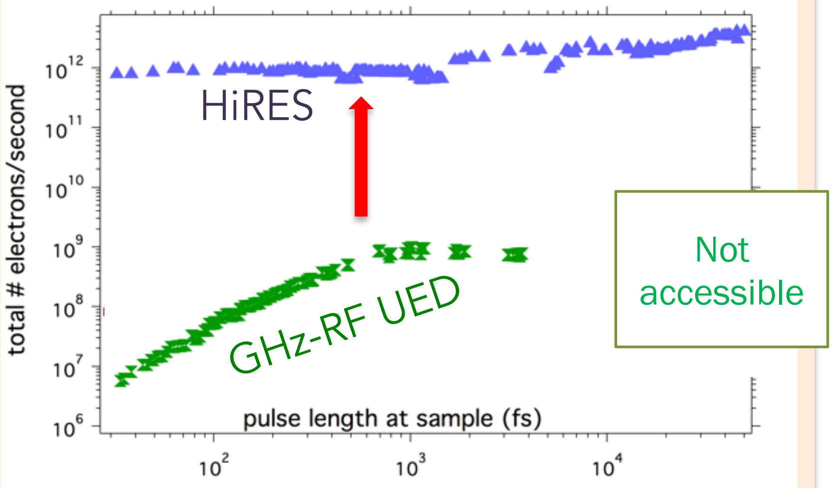
The VHF gun at SLAC (2016-today)

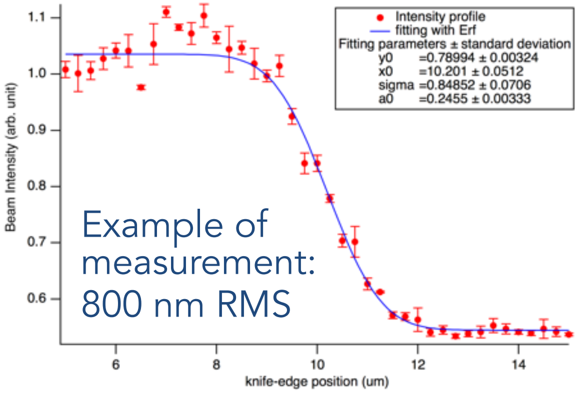




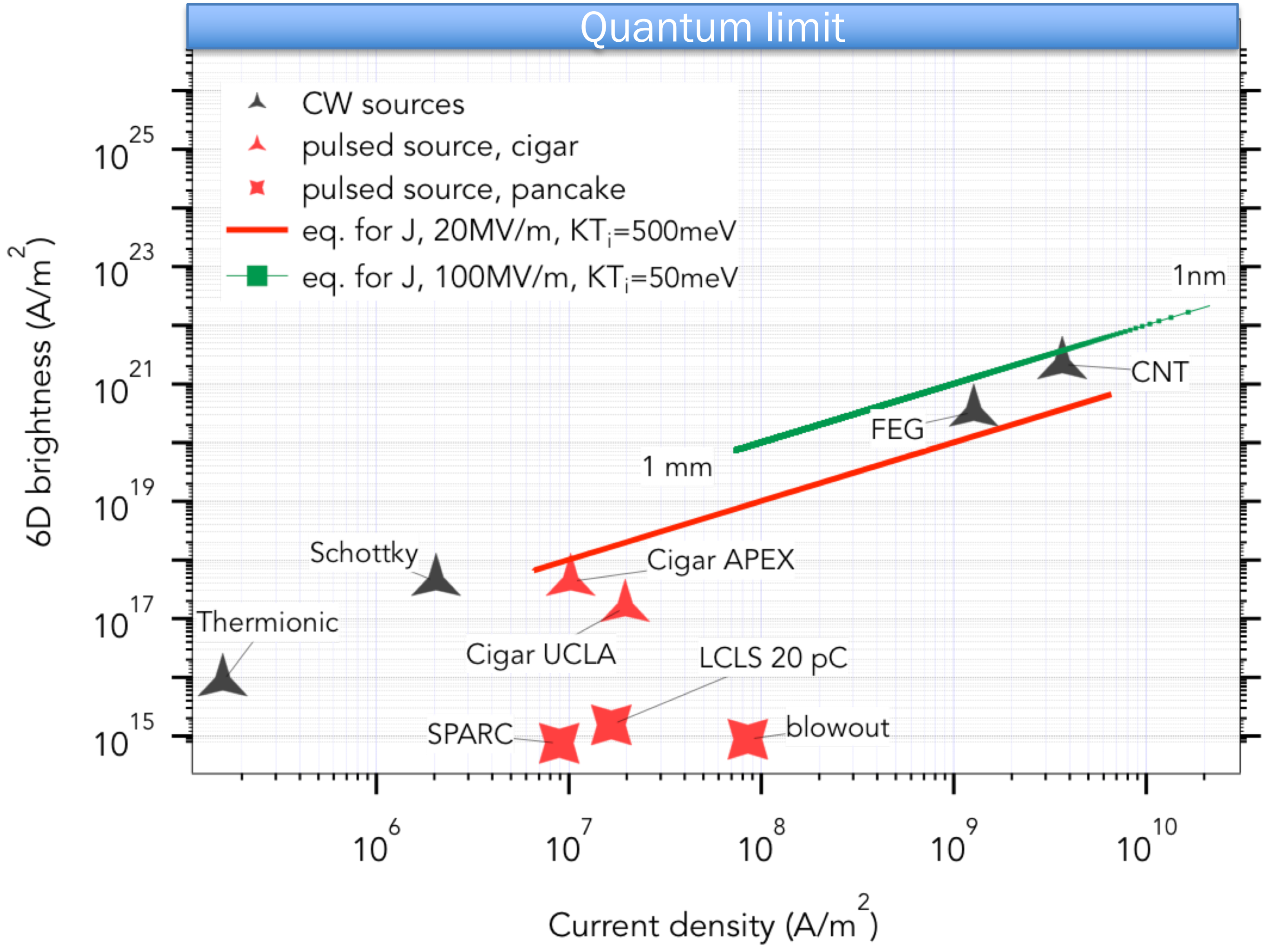
Nucl. Instr. & Meth A 599, 9 (2009)
Phys. Rev. ST Accel. Beams 15, 103501 (2012)
Phys. Rev. ST Accel. Beams 18, 013401 (2015)
Appl. Phys. Lett. 107, 042104 (2015)

MeV-UED R&D (2014-today)





Tip or flat?

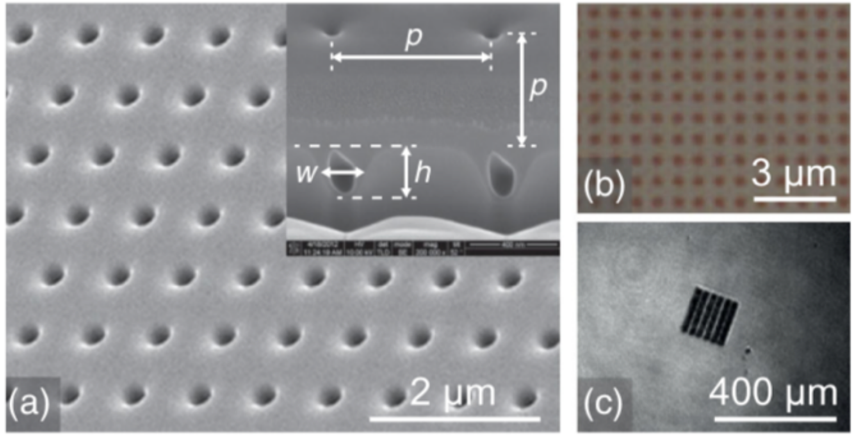


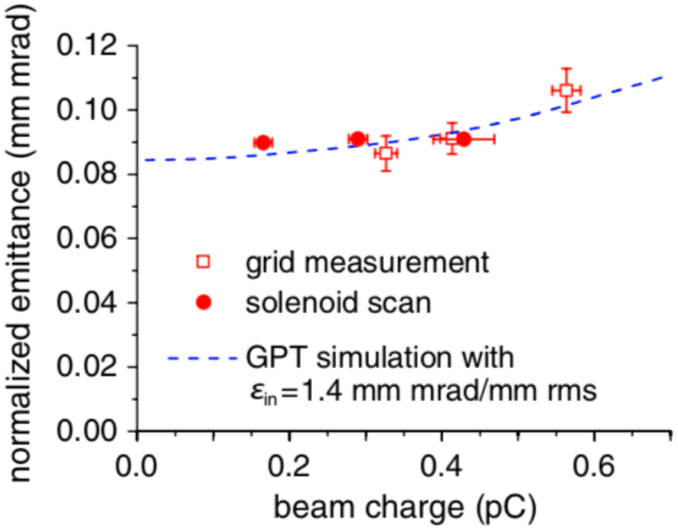
$$B_{6D} = \frac{Q}{\pi^3 \epsilon_n^2 \sigma_t \frac{\sigma_E}{mc^2}} = \frac{2\sqrt{2\pi}}{\pi^2} \frac{J}{\frac{\sigma_{p_\perp}^2}{(mc)^2} \frac{\sigma_E}{mc^2}}$$

$$J_{sat,2D} = \frac{I_0}{9\pi} \sqrt{\frac{2}{R}} \left(\frac{eE_0}{mc^2} \right)^{\frac{3}{2}}$$

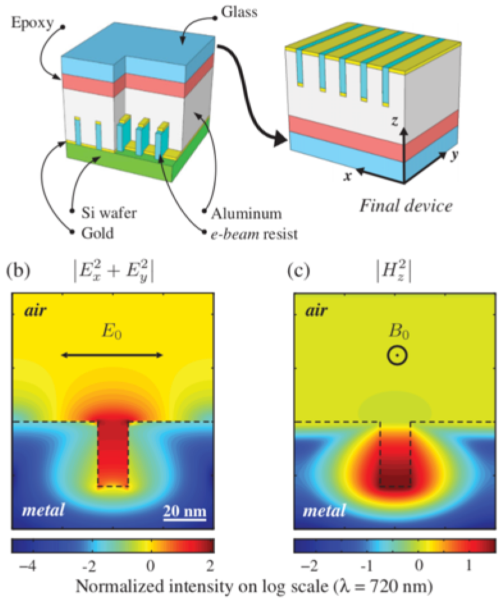
D. Filippetto et. al., PRSTAB 17, (2014) 024201

Plasmonic-enhanced multiphoton photoemission: Nano-holes and nano-grooves





R. Li, et al., PRL 110, 074801 (2013)



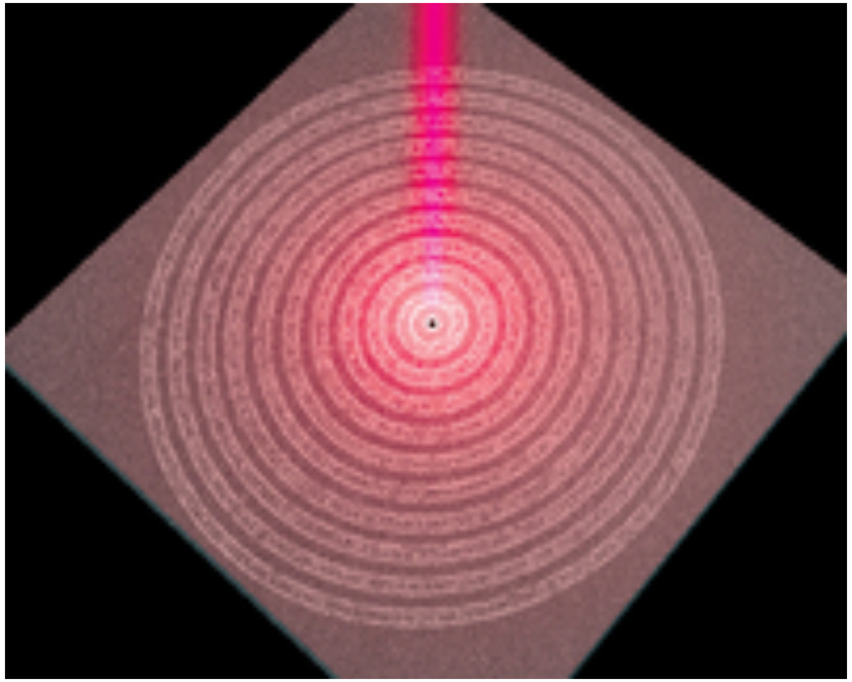
A. Polyakov et al., PRL 110, 076802 (2013)

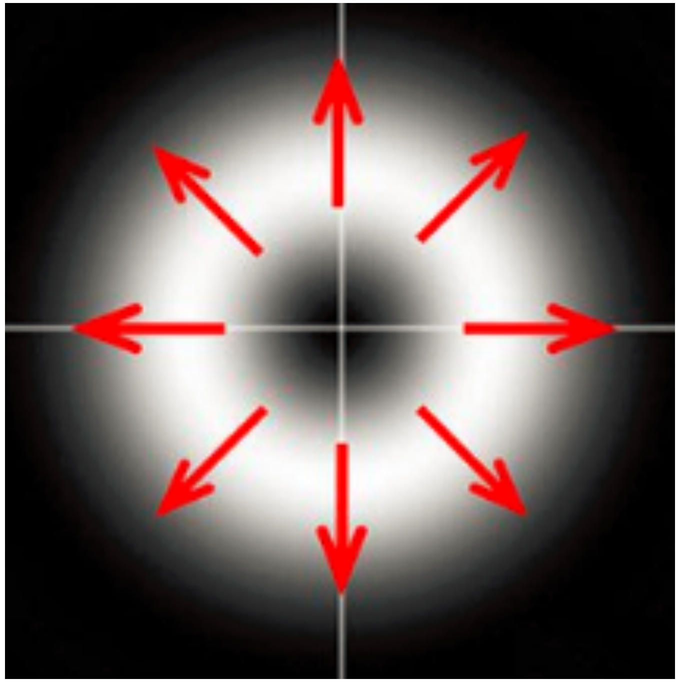
<u>Transverse momentum spread is increased compared to flat cathodes</u>

Plasmonic-enhanced multiphoton photoemission: plasmonic lenses

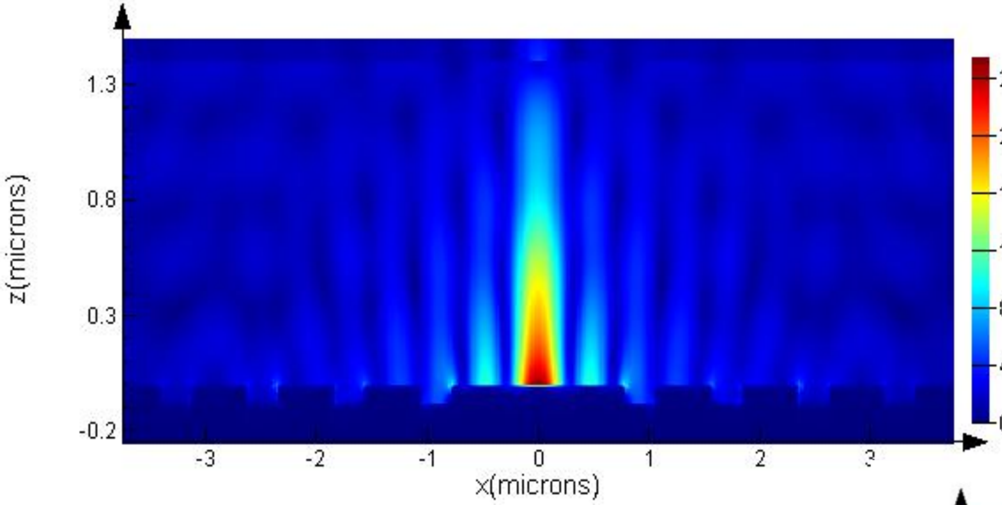
SPPs travel along the surface to interfere constructively at the center.

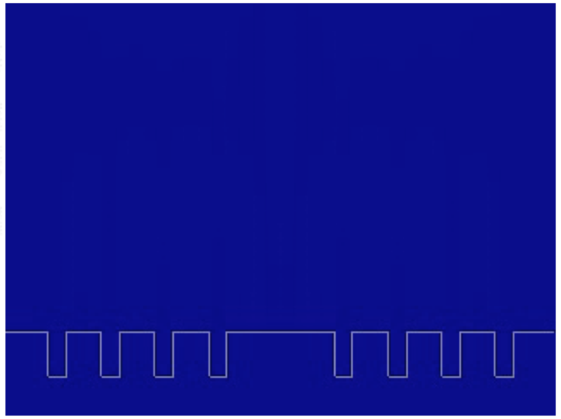
The central spot caused by the interference occurs in a flat region with subwavelength dimensions

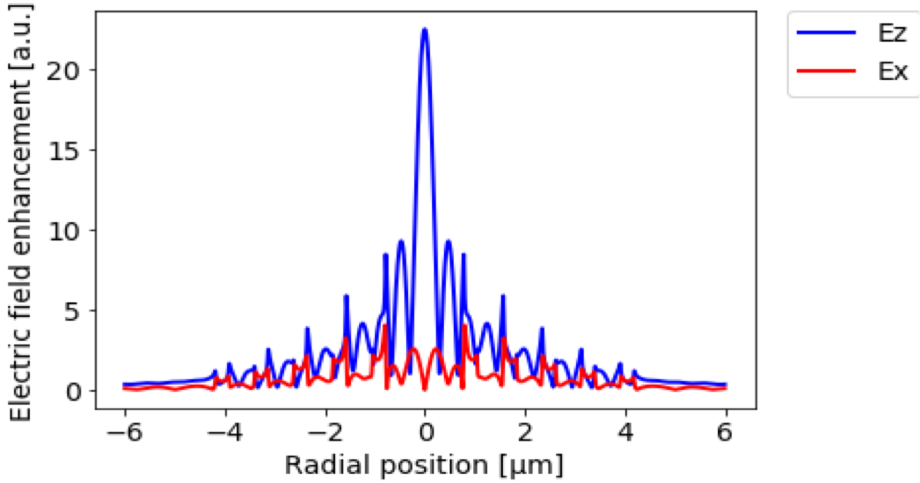


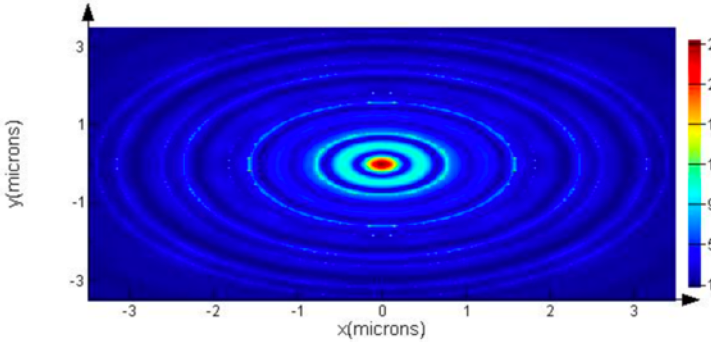


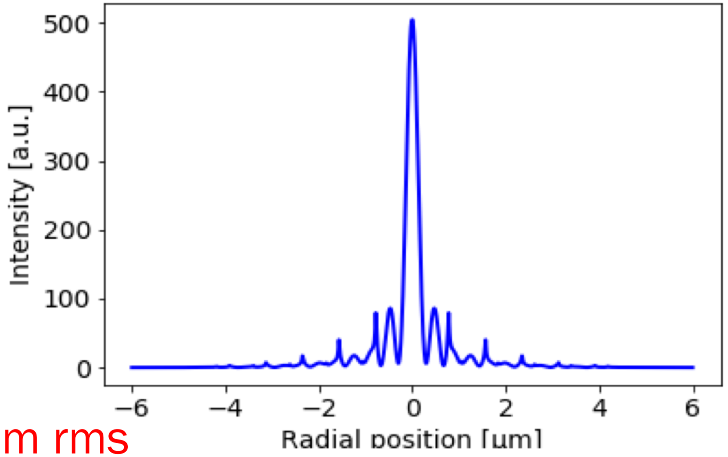
Bull's eye simulations











Optimum groove geometry for 1030 nm:
90X260X950 nm (HxWxD)
Max enhancement depends on number of rings:
Larger rings:

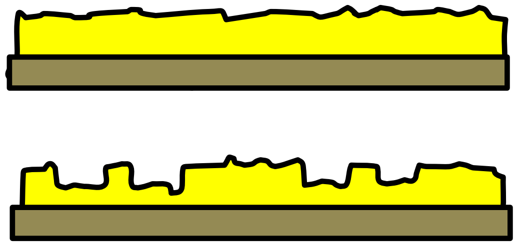
- higher enhancement
- Narrower bandwidth
- Limited by SPP propagation length

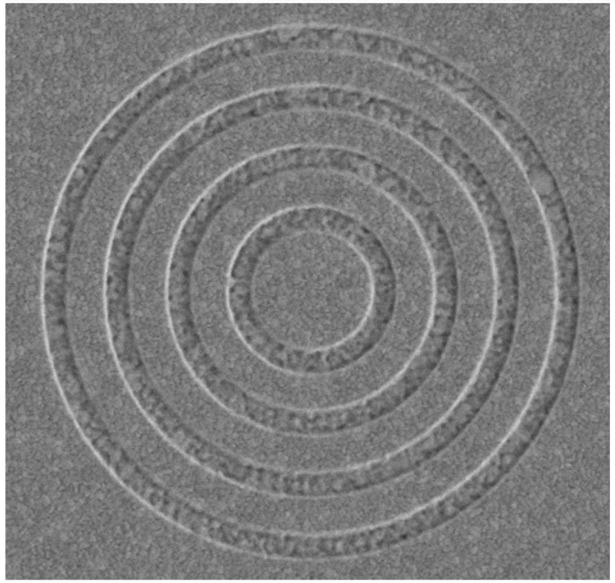
- 3rd order photoemission area: 87nm rms
- 4th order photoemission area: 63nm rms

Fabrication processes

Focused ion beam milling

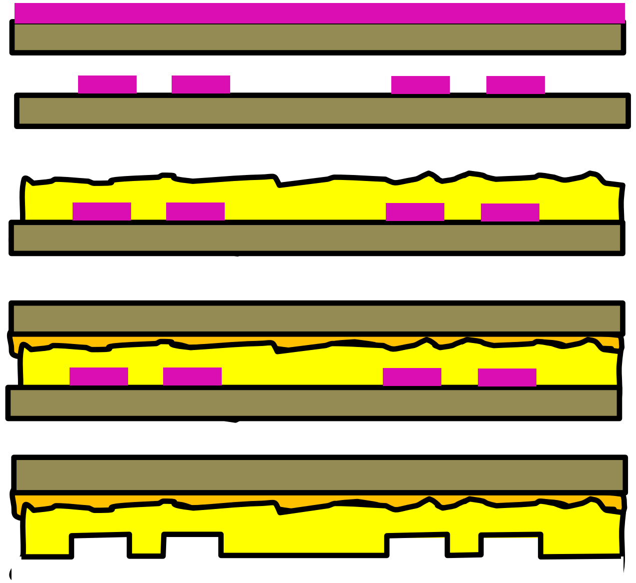
1. Evaporate gold
2. FIB mill

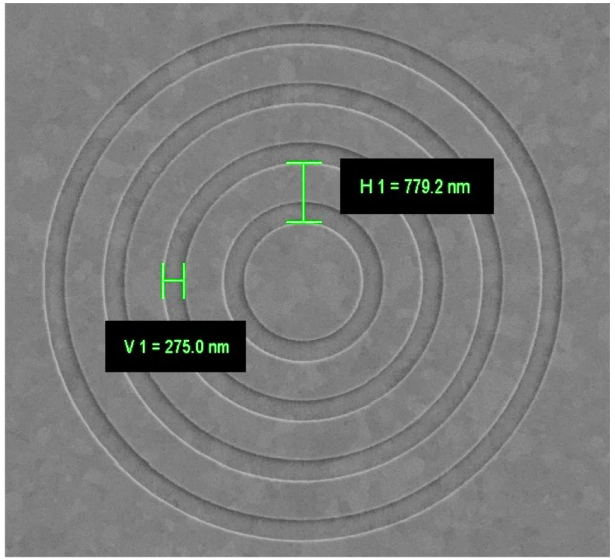




E-beam lithography + template stripping

1. Spin coat e-beam resist
2. E-beam exposure
3. Evaporate gold
4. Apply/cure epoxy
5. Peel off

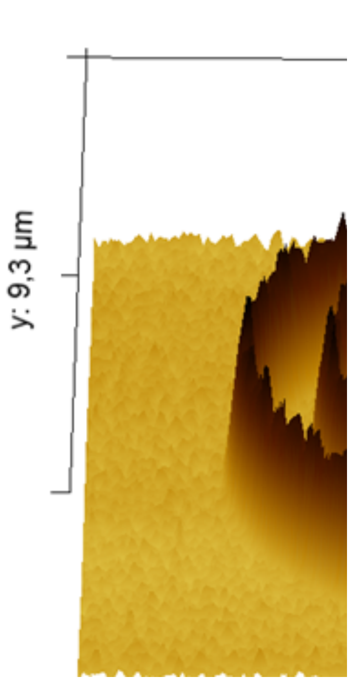


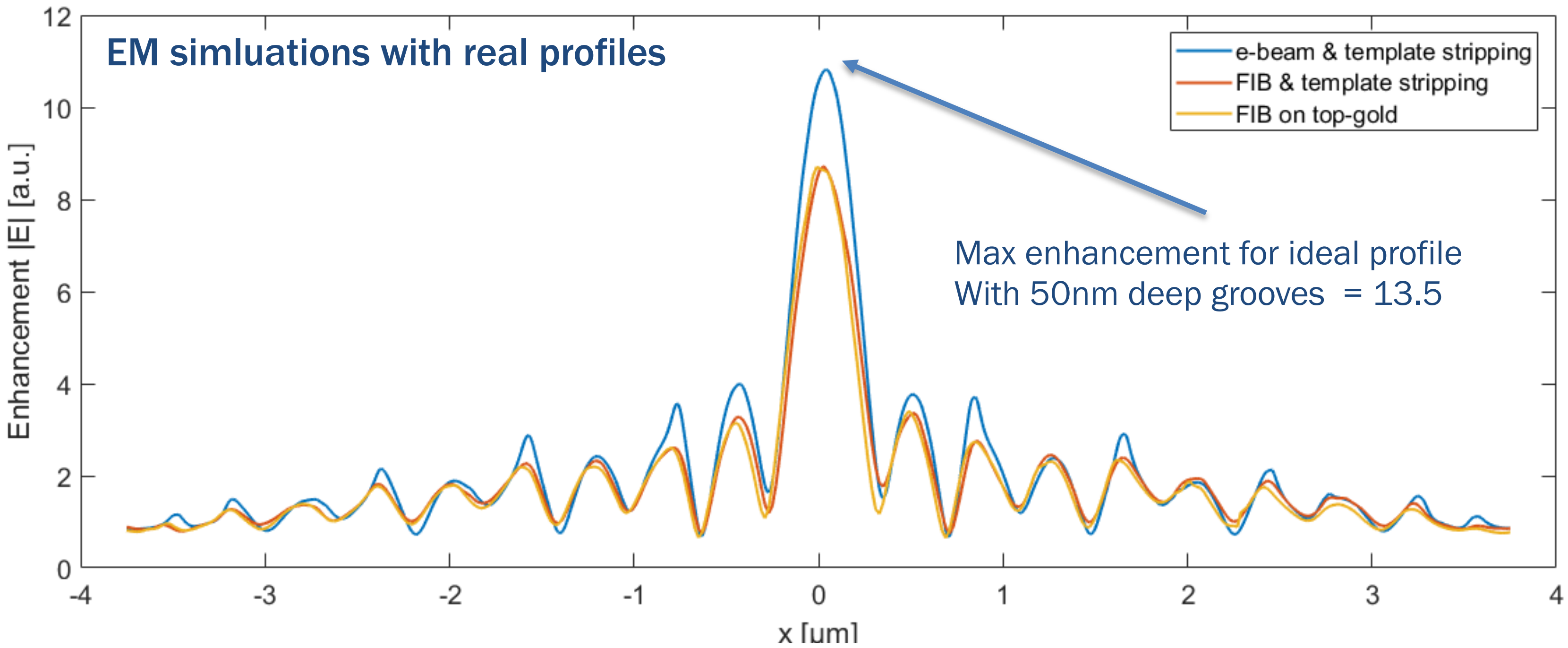


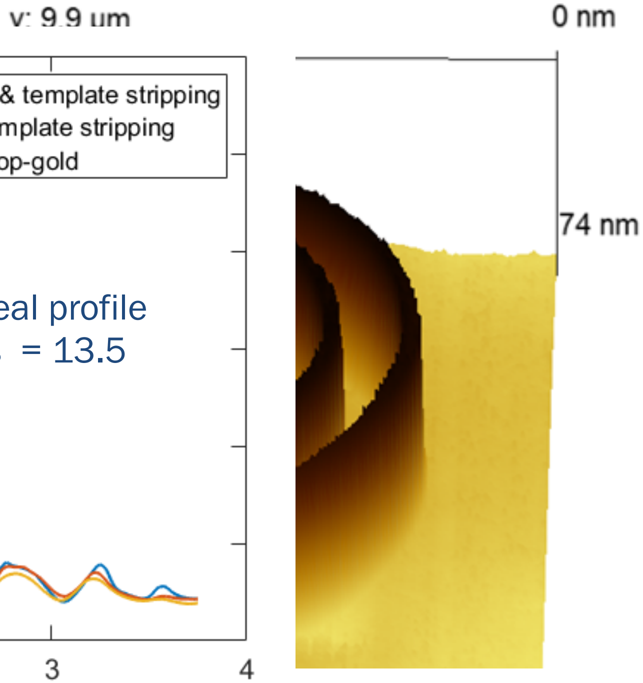
EBL process yields smoother surfaces

FIB

EBL



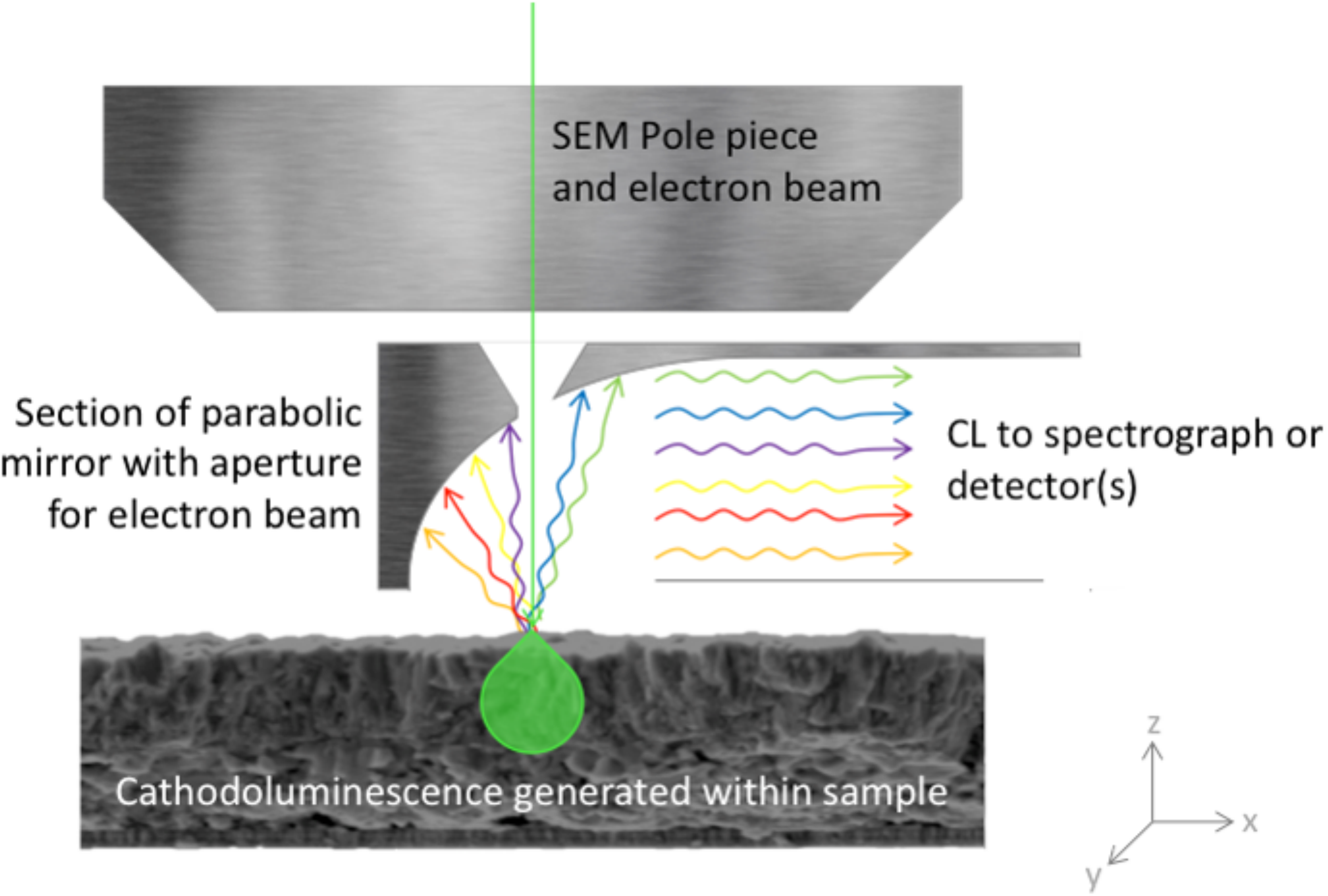




Rms roughness
Center: 1.41 nm
Grooves: 3.64 nm

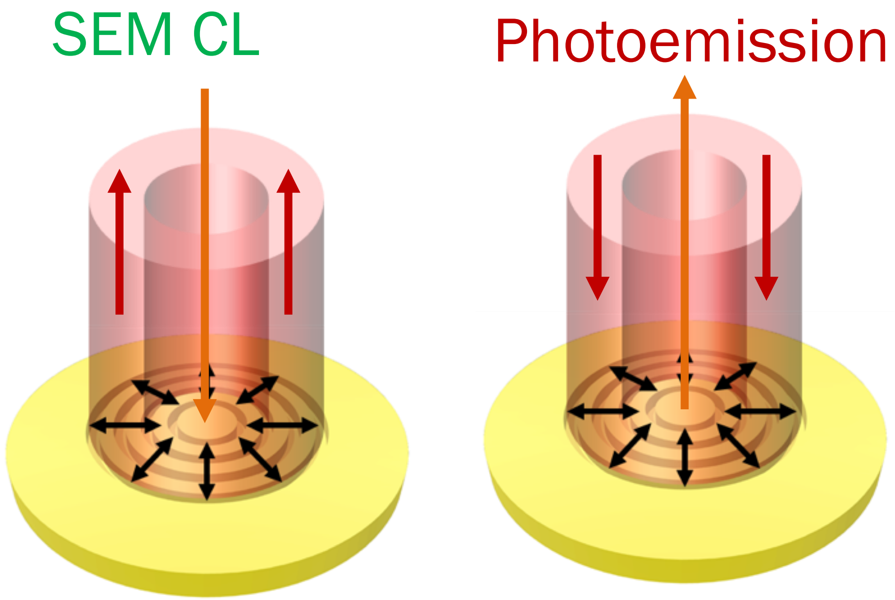
Rms roughness
Center: 0.30 nm
Grooves: 0.57 nm

Cathodoluminescence spectromicroscopy

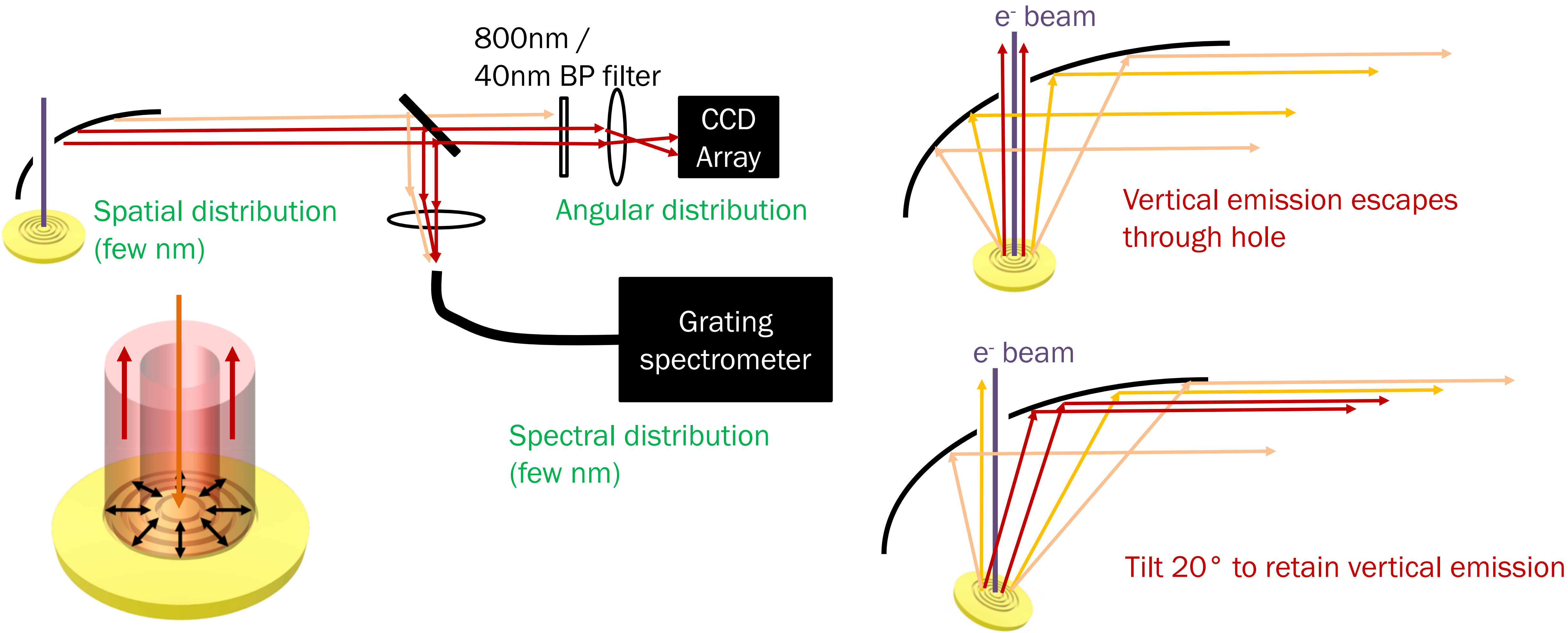


SEM Cathodoluminescence (CL)

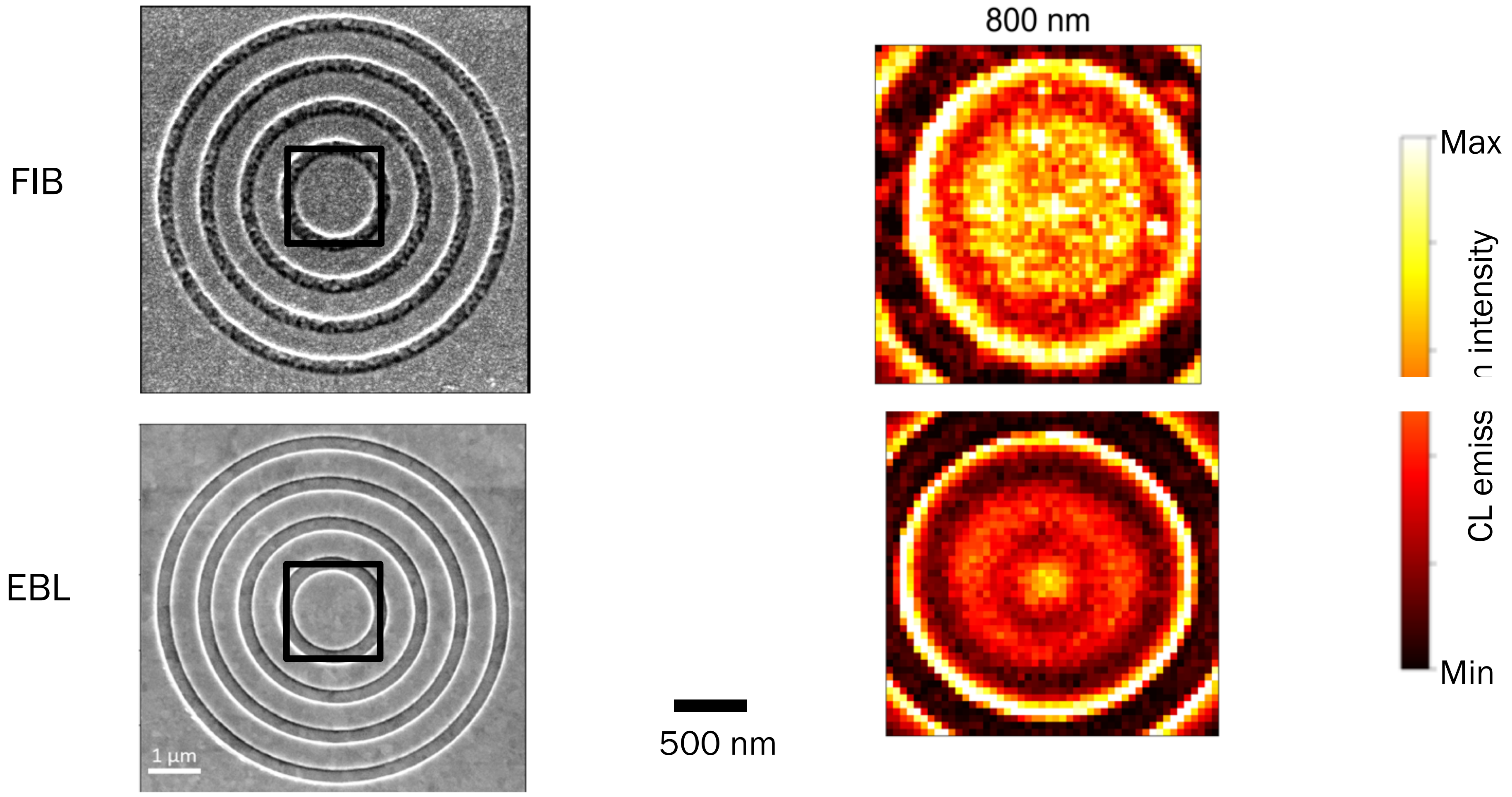
- Map of SPPs modes
- SEM spatial resolution (several nm)
- Hyperspectral
- Angle-resolved



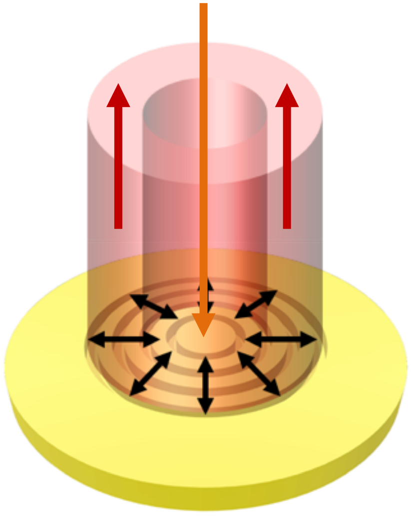
CL setup

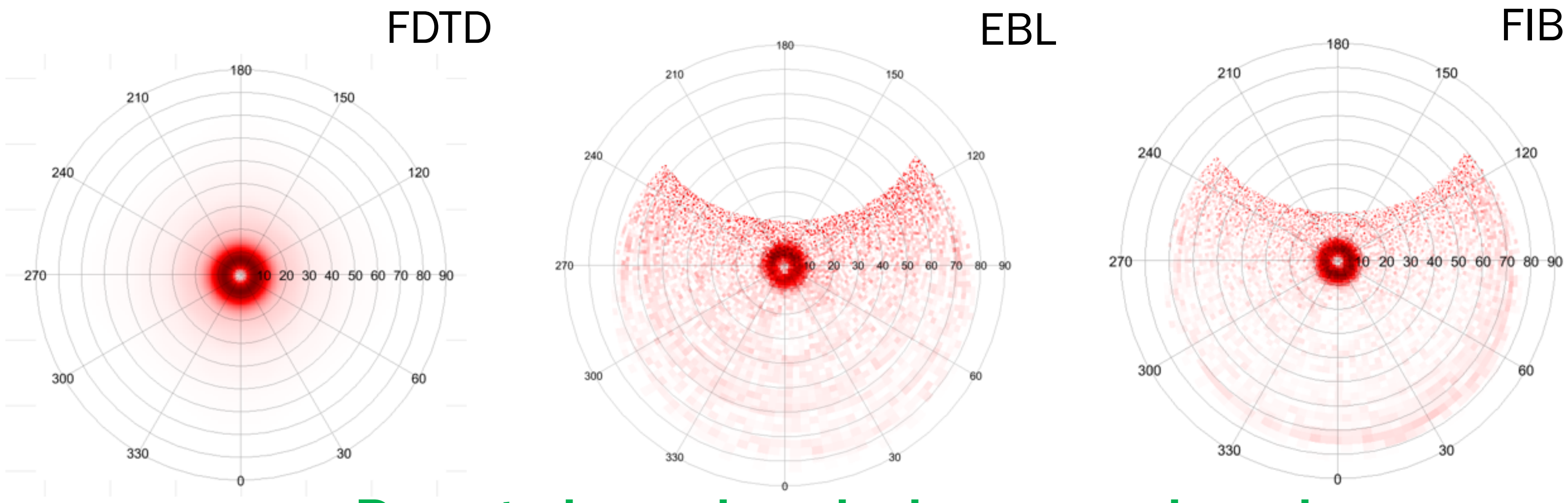

800nm /
40nm BP filter
CCD
Array
Spatial distribution
(few nm)
Angular distribution
Grating
spectrometer
Spectral distribution
(few nm)
e- beam
Vertical emission escapes
through hole
e- beam
Tilt 20° to retain vertical emission

Mapping the plasmonic interference

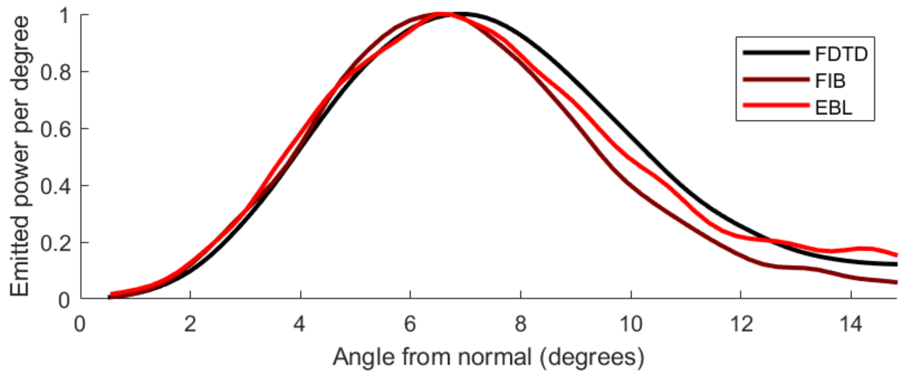


Far field measurement by angle-resolved CL





Donut-shaped emission reproduced

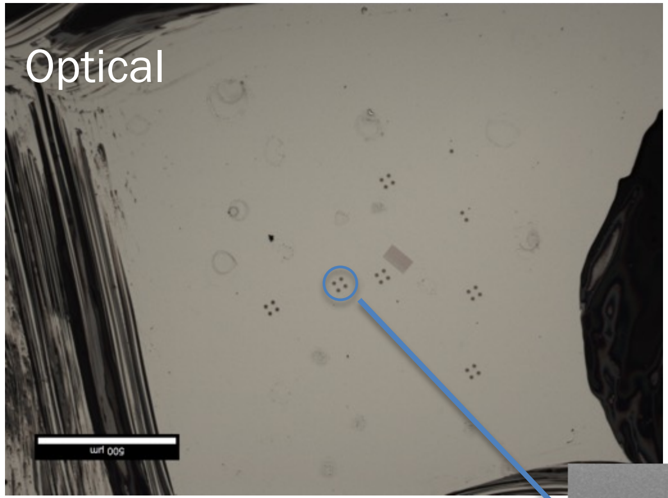


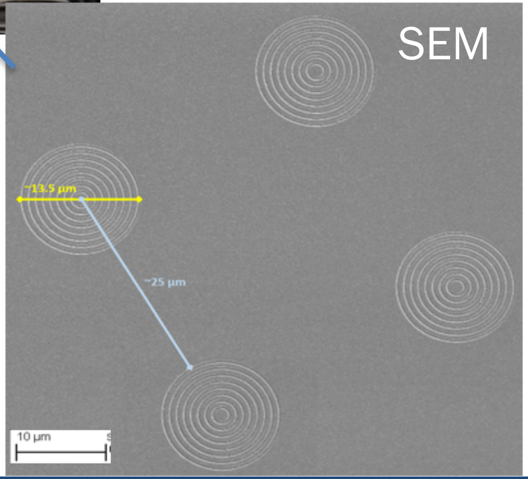
Angular distribution similar to model

$\Theta_{peak,EBL} \sim 6.6°$ $\Theta_{peak,FIB} \sim 6.5°$ $\Theta_{peak,FDTD} \sim 7°$

First attempt of characterization of photoemission from BE

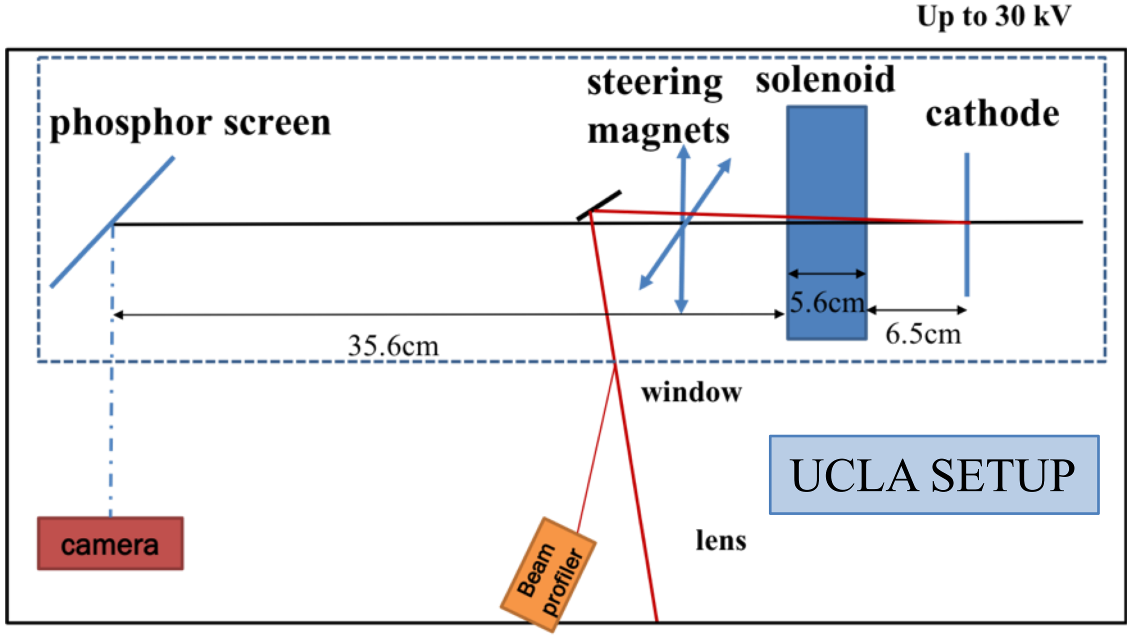
FIB sample for 800 nm



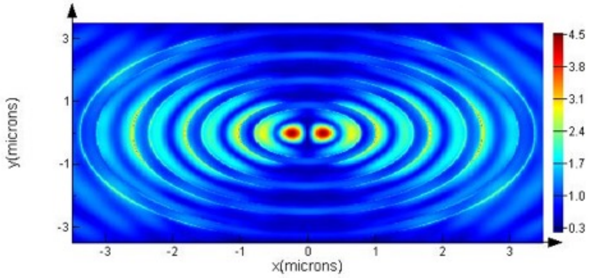


500 µm

Dan Durham, LBNL/UCB
Xinglai Shen, UCLA
Rafi Hessami, UCLA



Enhancement under linear polarization



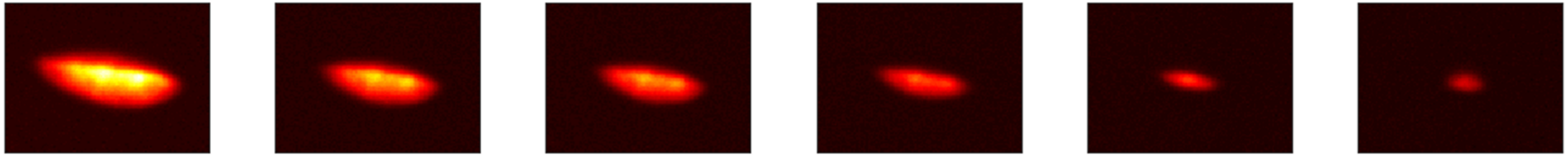
Parameters:

- Acceleration voltage: 26 kV
- Laser pulse energy: 0.1 – 10 µJ
- Rep rate: 500 Hz
- Spot size: 100 µm
- Pulse length: 50-100 fs
- Linear polarization

4-photon photoemission from gold at 800 nm

Electron bunches on screen for varying laser pulse energy

1.8 μJ | 1.6 μJ | 1.4 μJ | 1.2 μJ | 1.0 μJ | 0.82 μJ



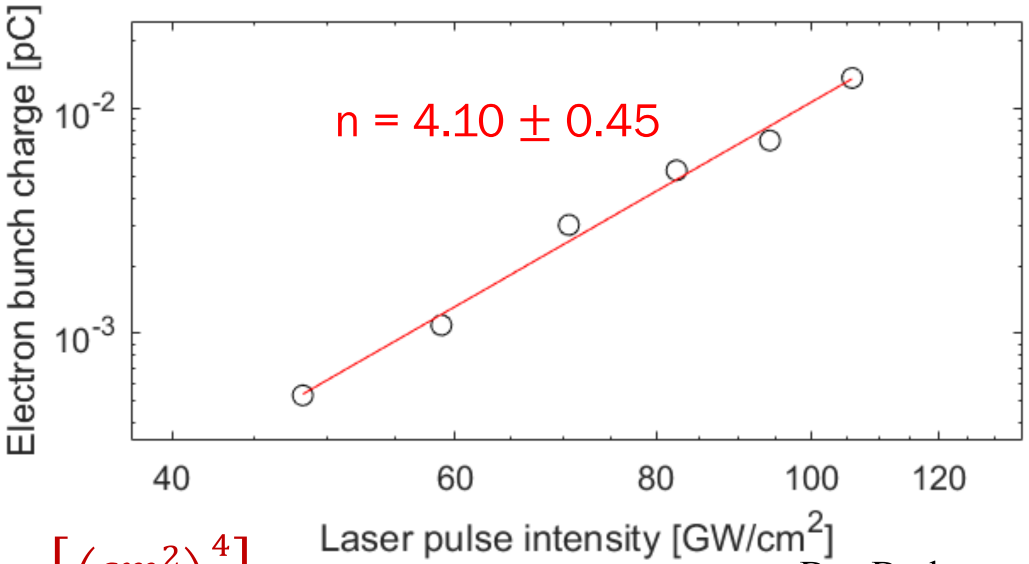
J = CI^n for n-photon photoemission

$$C \approx a_n \left(\frac{4\pi m_e e}{h^3}\right)\left(\frac{e}{h\nu}\right)^n (1-R_\nu)^n(\mathrm{nh}\nu - e\Phi)^2$$

[Assuming $(\mathrm{nh}\nu - e\Phi) =$ 0.8 eV

ϕ ~ 5.4 eV for Au in literature [Michaelson, J. App. Phys. 48 1977]

R_ν ~ 98 % for Au in literature [Bass & Stryland, *Handbook of optics*, 2000]



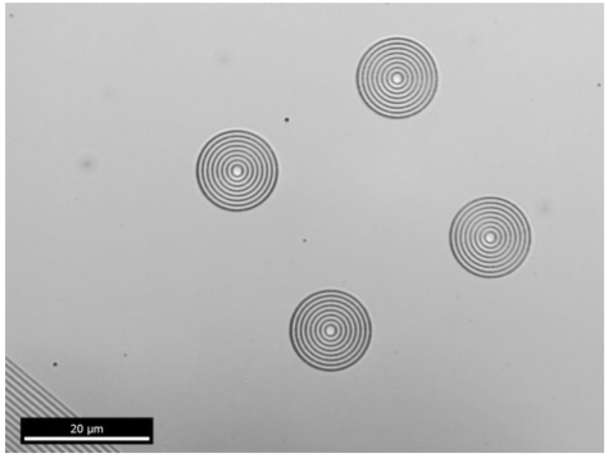
$$a_4 = 10^{-42.97 \pm 0.85}\left[\left(\frac{cm^2}{A}\right)^4\right]$$

Dan Durham,
Xinglai Shen
Rafi Hessami, UCLA

Spatial variation in signal

- Manual scan for initial test
- Charge measured at a few points of interest

SEM image after test



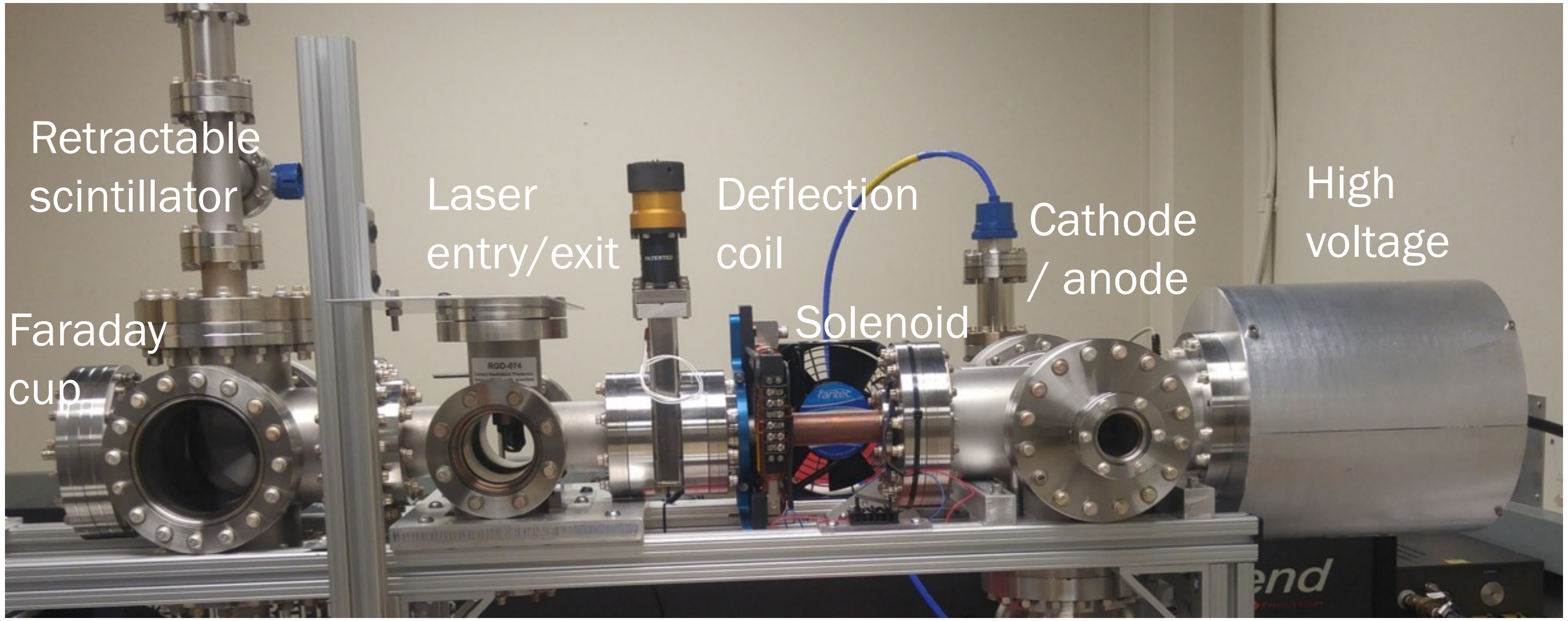
Next:

- Automatic scan of entire area with smaller beams
- Laser energy tailoring and higher repetition rates
- Radial Vs azimuthal polarization

Dan Durham
Xinglai Shen
Rafi Hessami, UCLA

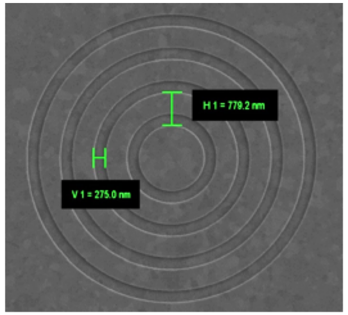
LBNL setup is coming online

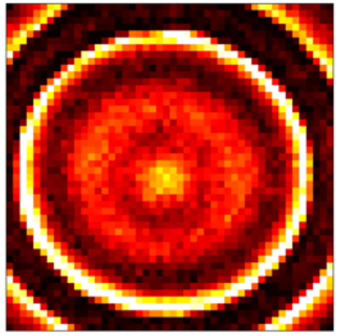
- A 30kV gun has been fabricated and recently commissioned
- Nano-photo-emitter test bed
- Ultrafast fiber laser at 1030nm available for tests (1uJ at 1MHz)

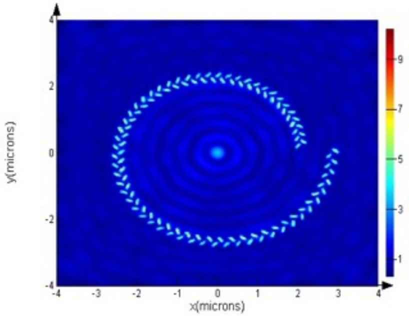


Conclusions

- R&D on nano-photo-emitters are ongoing and could further increase the electron beam tranverse coherence and decrease the focal spot.
- The final goal is to use such cathodes for ultrafast science at the nanoscale
- Collaboration team between ATAP and Molecular Foundry/UCB enable access to nanofabrication and characterization tools
- First cathodes fabricated are currently being tested for photoemission
- New designs for cathodes in transmission, and with simpler alignment.

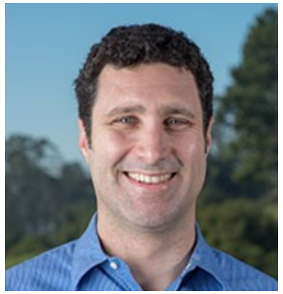






Nano-Team and collaborators

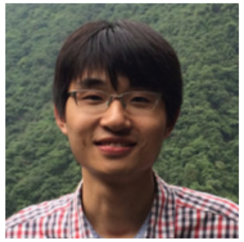
Daniele Filippetto
(Project leader/LBNL)



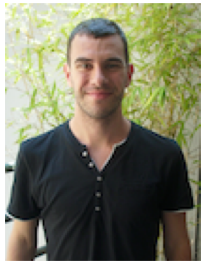
Andrew Minor
NCEM director
(MF/UCB)

Stefano Cabrini
(NanoFab Facility director
(MF/LBNL)

Dan Durham
(UC Berkeley/LBNL)



Fuhao Ji
(LBNL)



Fabrizio Riminucci
(La Sapienza/LBNL)

SAPIENZA
UNIVERSITÀ DI ROMA

- *UCLA cathode tests at 800 nm (Xinglai Shen, P. Musumeci)*
- *University of Rome "La Sapienza" , design and test of novel nanostructured photoemitters*
- *STROBE*
- **DOE Office of Science, *Basic Energy Sciences***