High charge yield from nanopatterned cathodes in S-band RF photoinjector

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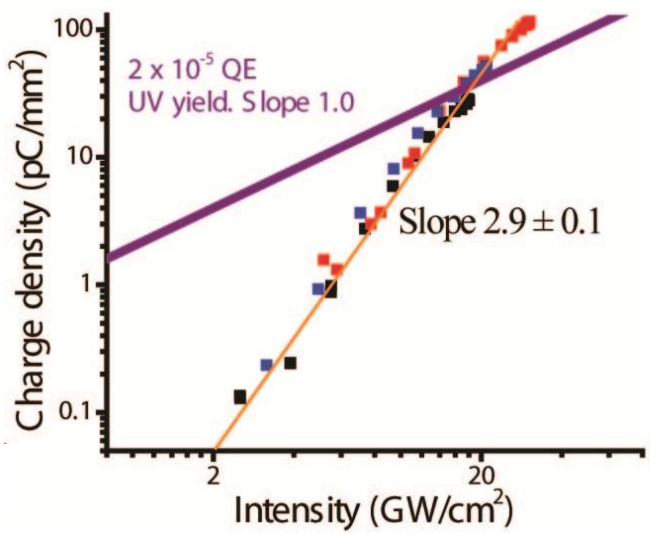
PPP workshop 2012

Background

- To generate high average power beams, cathode yield and drive laser power is still a major limitation.
- No need to struggle to get above work-function photons to initiate photoemission.
- Take advantage of the large charge yield from multiphoton photoemission.
  - Ultrashort laser pulses on cathode naturally married with 'blow-out' regime.
  - Avoid lossy non linear frequency conversion.
- How to enhance multiphoton photoemission?
  - By modifying reflectivity
  - By optical field enhancement
  - ❖ Surface plasmon excitation (Padmore, PPP 2010)

Musumeci et al. *PRL*,**100**:244801, 2010



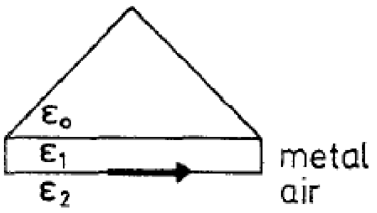
Outline

- Nano-plasmonics inside an RF photoinjector
- Reflectivity response
- High charge yield from nanopatterned cathodes tested in high gradient RF guns
- Damage threshold and limitations
- Nanopatterned beam dynamics

- Conclusions

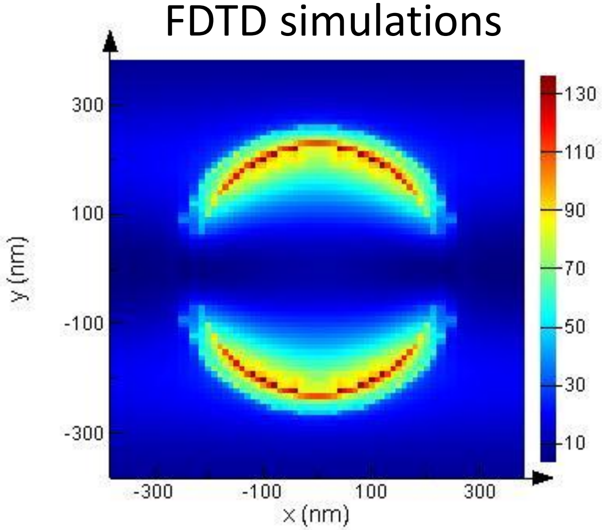
Surface plasmon assisted photoemission

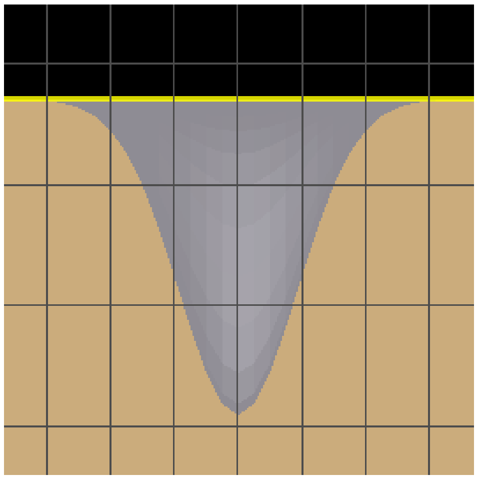
- The reflectivity of a metal can be controlled by coupling incident linearly polarized light with surface plasmon oscillations.
- Kretschmann geometry requires back-illumination.

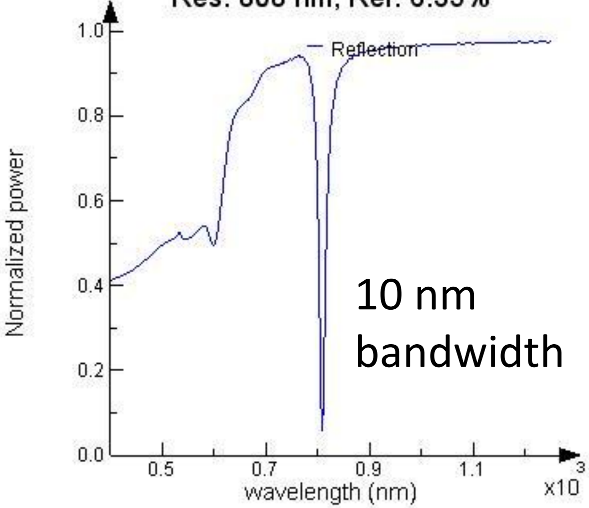


- The coupling can also be done by using periodic nanostructures such grids or arrays of holes.
- Low reflectivity corresponds to optical electric field enhancement.

FDTD simulations





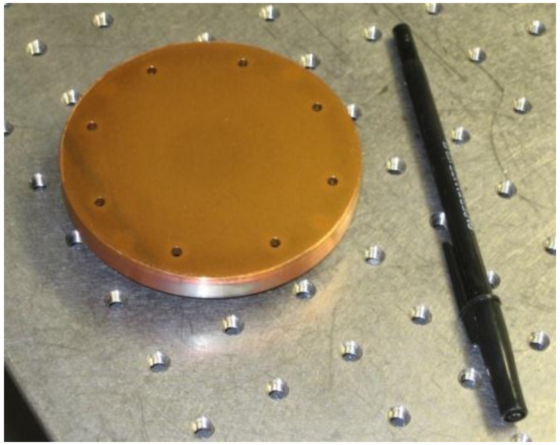


Nano-hole arrays using Focused Ion Beam technique

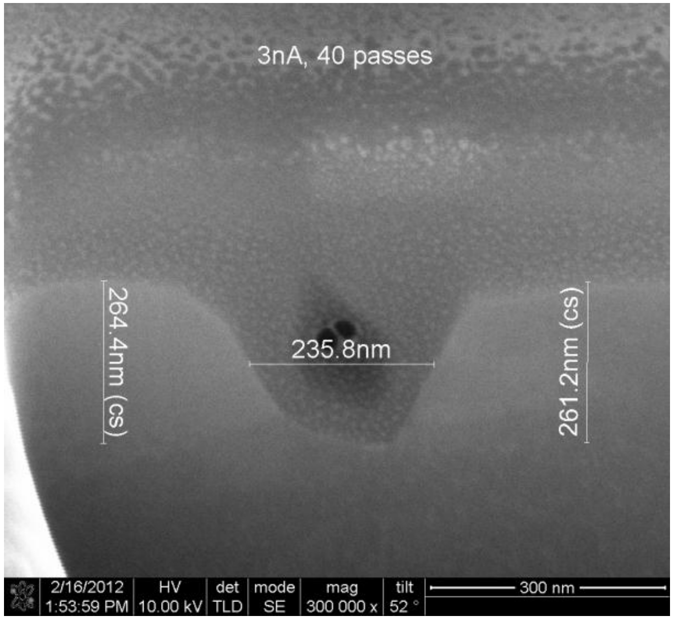
• most nano-fabrication techniques/machines work on small pieces (light, very thin, wafer-like)

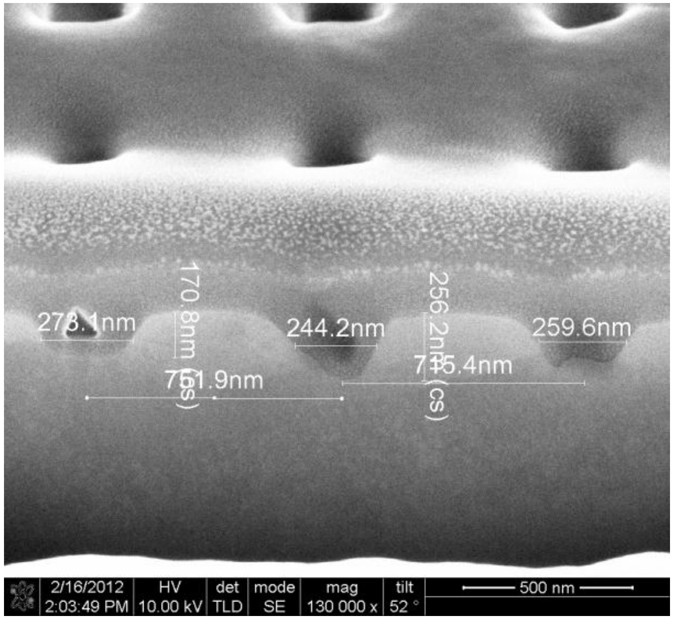
• larger pieces with FEI Nova 600 Dual-Beam FIB at UCLA

• Target nanostructures directly onto the gun cathode



test the operation parameters of the FIB (nA, passes)





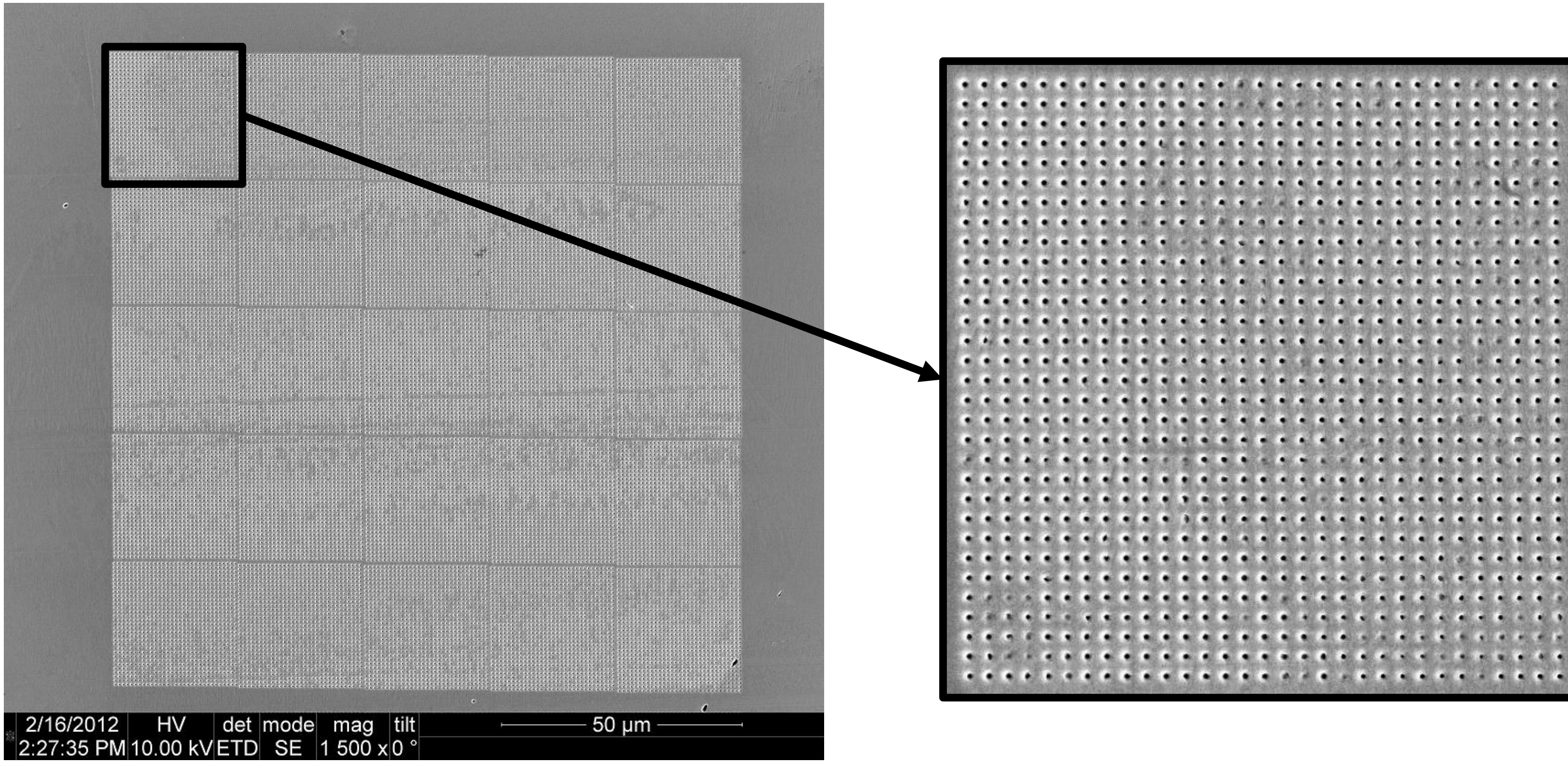
• target dimensions:

d=765 nm
h=244 +- 15 nm
w=185 +- 15 nm

• FDTD: ~0% at 800 nm, bandwidth 10 nm

• variations due to random orientation and sizes of the grains

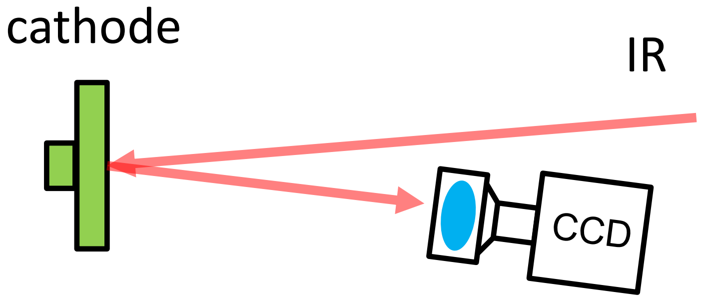
the final FIB-ed pattern



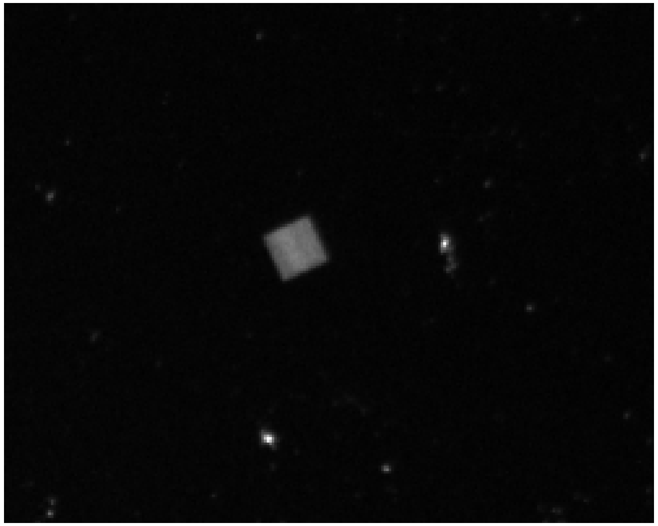
- specify the hole coordinates with a script file (limited to 1000 points each pitch)
- each pitch 25 um square, 5 × 5 pitches
- 125 um square pattern finished in 30 minutes
- ready for optical characterization and gun installation

Reflectivity measurements of the FIB-ed cathode

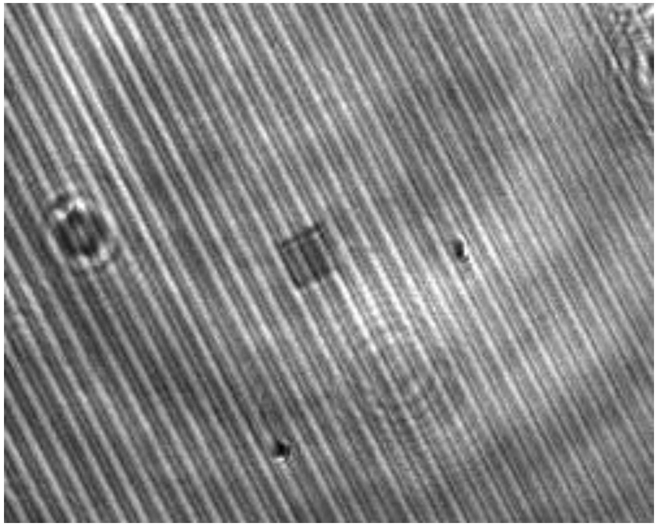
- Pattern visible to naked eyes
- imaged at near normal incidence (< 10 deg)
- with room light / 800 nm laser



scattered room light



reflected 800 nm laser

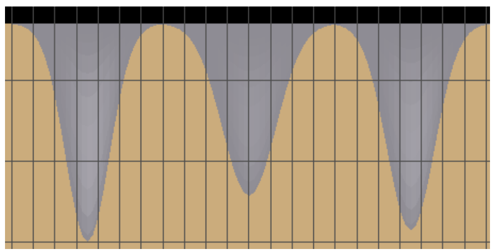


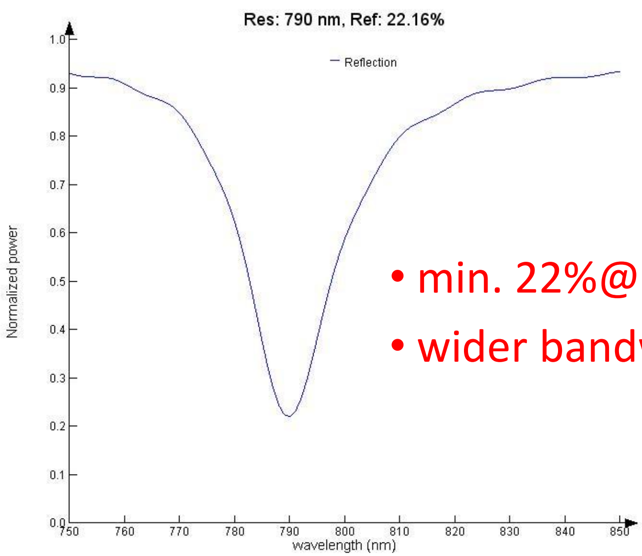
reflectivity of the flat surface 88%
reflectivity of the pattern 64%

Effect of pattern non-uniformity: simulations

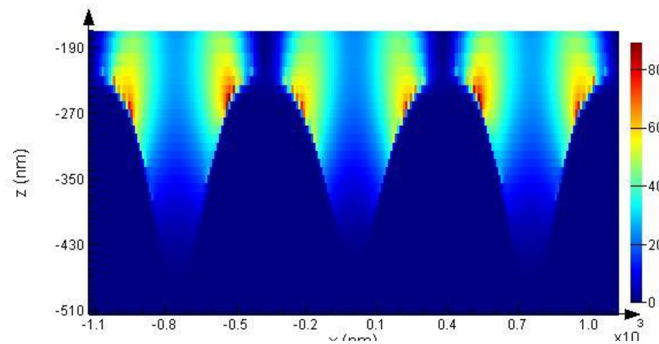
- FDTD: ~0% at 800 nm with d=765 nm, h=244 nm, w=185 nm, identical Gaussian shape
- large variations in the (test) fabricated structures
- run FDTD again using some of the SEM measured dimensions

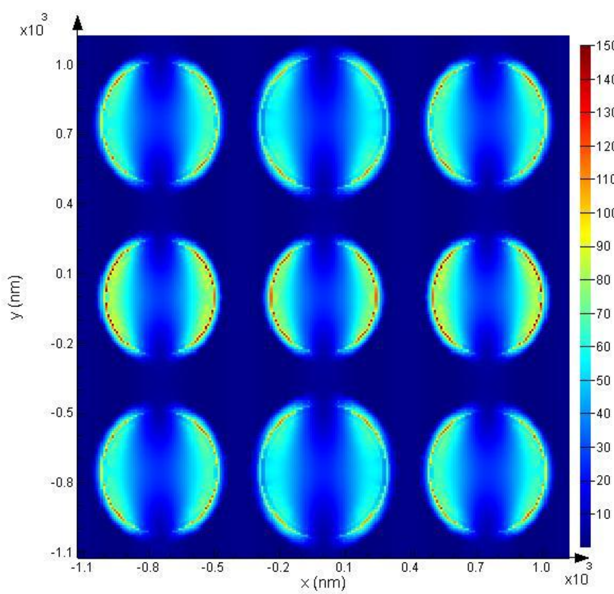
variation of the dimensions (cross section of the 3D model)





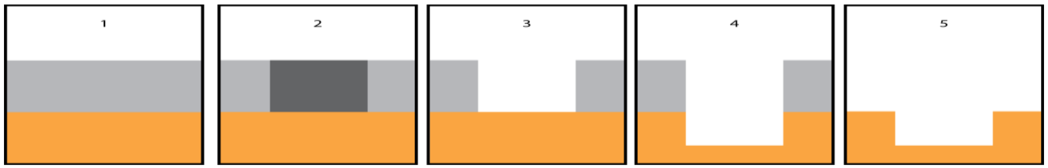
- min. 22%@790 nm
- wider bandwidth

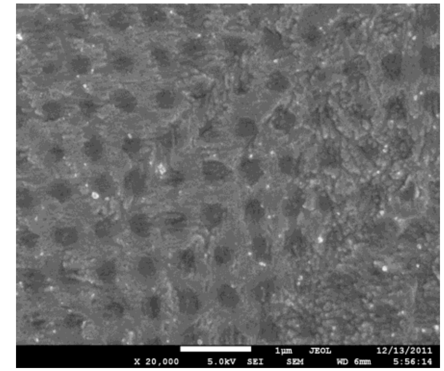




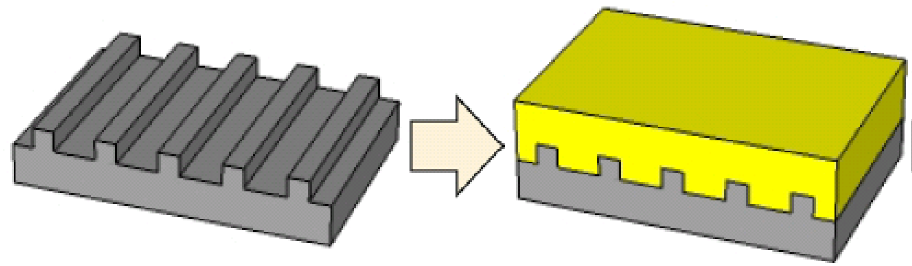
FIB is not the only way….

- E-beam lithography (UCLA- CNSI)

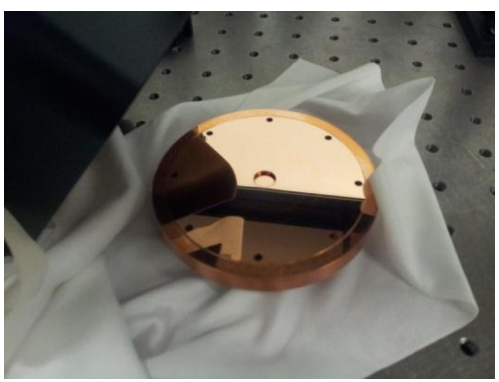




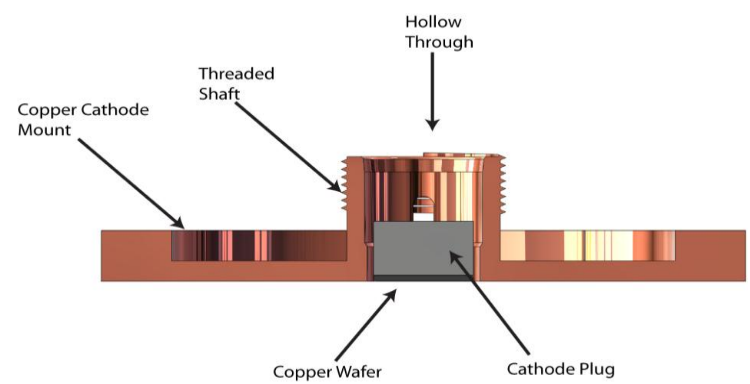
- UV lithography (Padmore group, LBNL)



- Need to interface with cathode flange



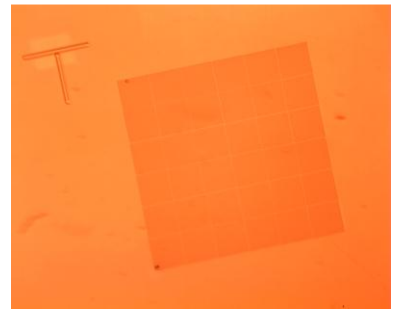
Cathode plug engineering to be compatible with nanofabrication techniques and single crystal wafers

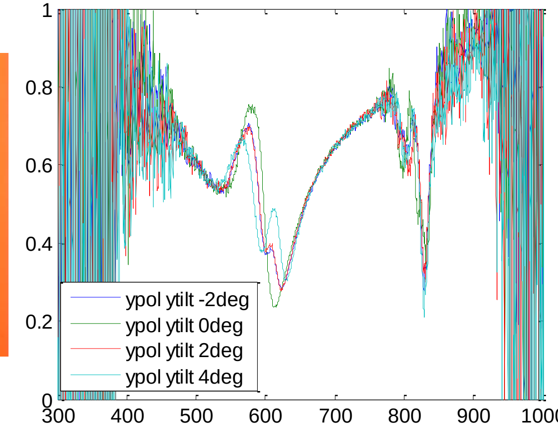


Successfully installed in RF gun!
Exciting opportunity for cathode testing ahead…

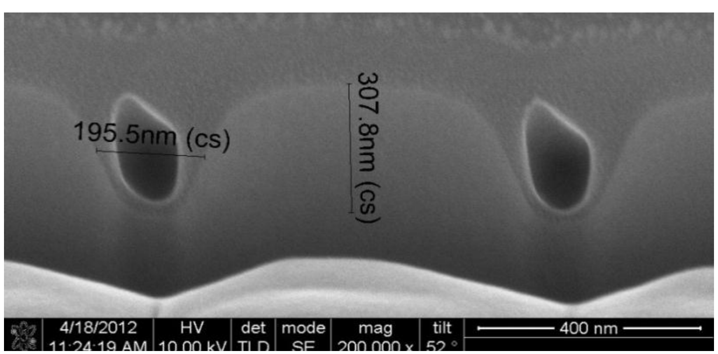
Single crystal samples

- FIB optimized for 100 grain orientation
- Much more uniform
- Measurements at LBNL
- Benchmark and calibrate FDTD simulations
  - 600 nm peak ?!
  - 840 nm peak (too long !)
- Last iteration: 710 nm spacing between nano-holes

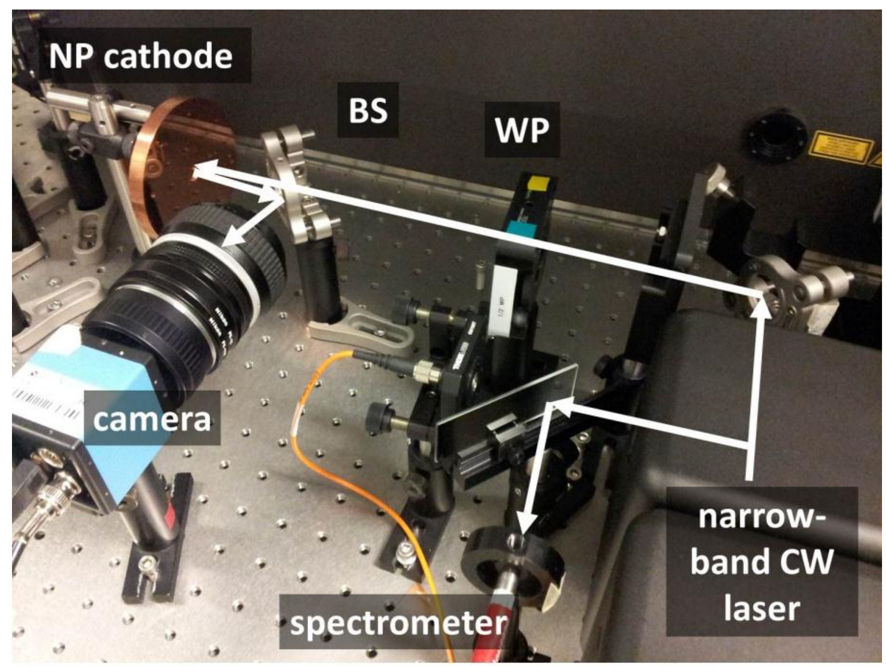


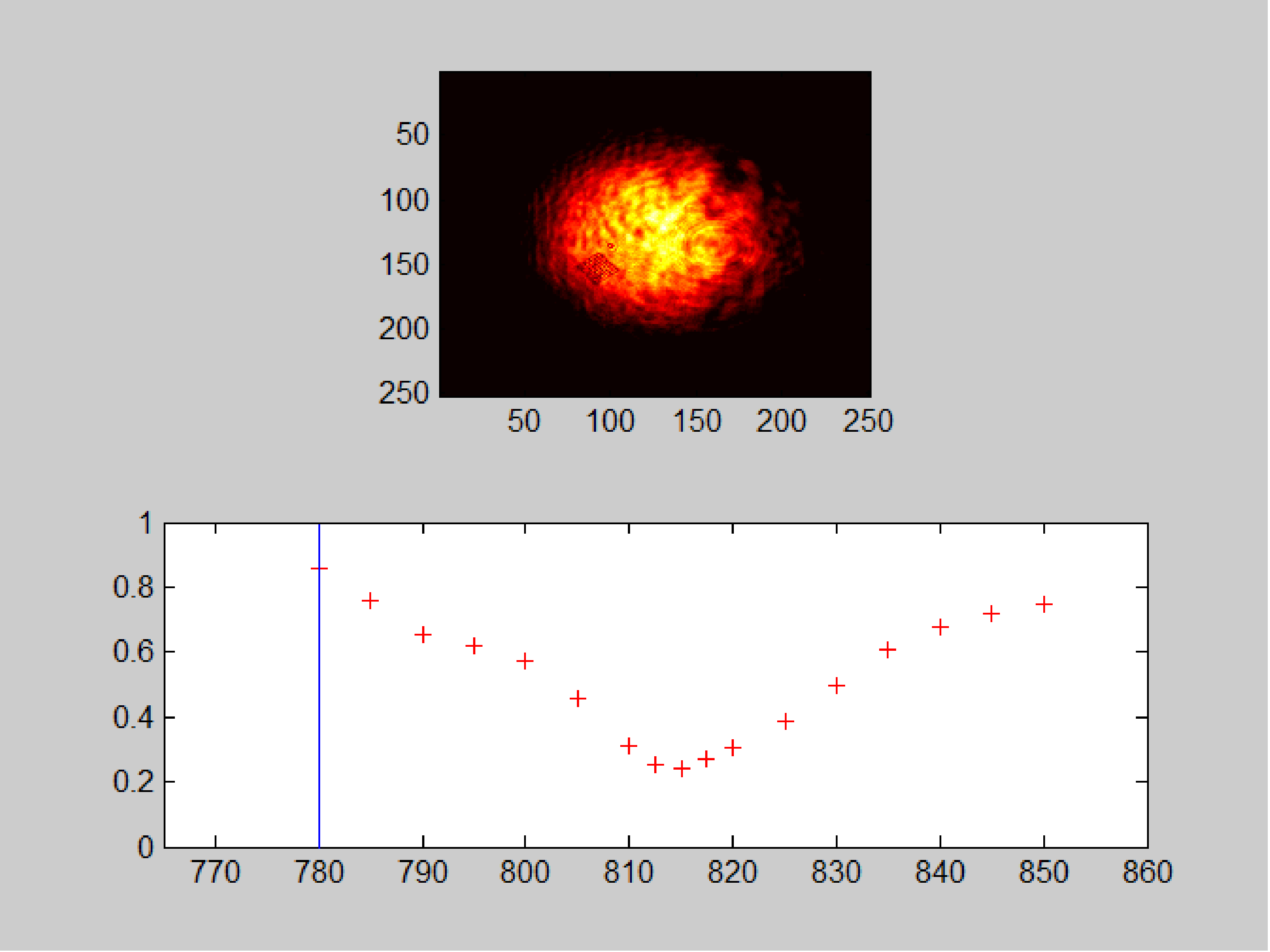


Single crystal SEM image



Measurement scheme

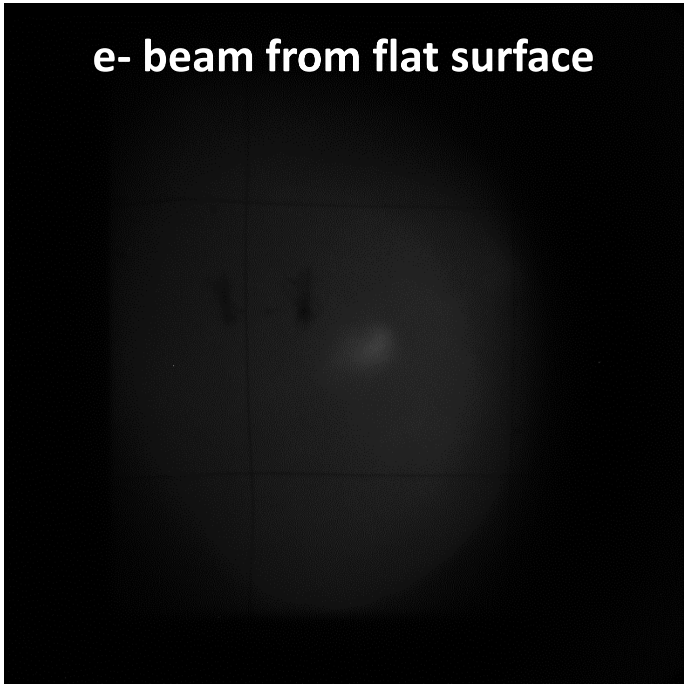


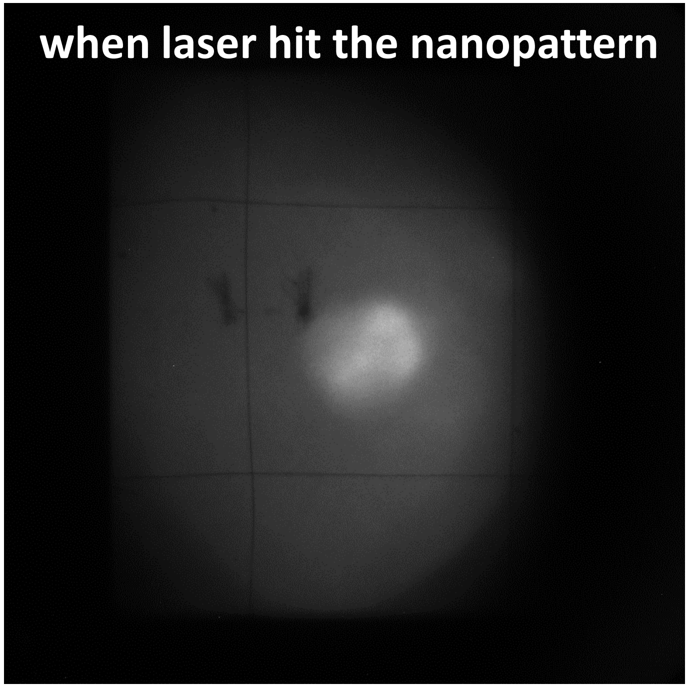


50
100
150
200
250
50
100
150
200
250
1
0.8
0.6
0.4
0.2
0
770
780
790
800
810
820
830
840
850
860

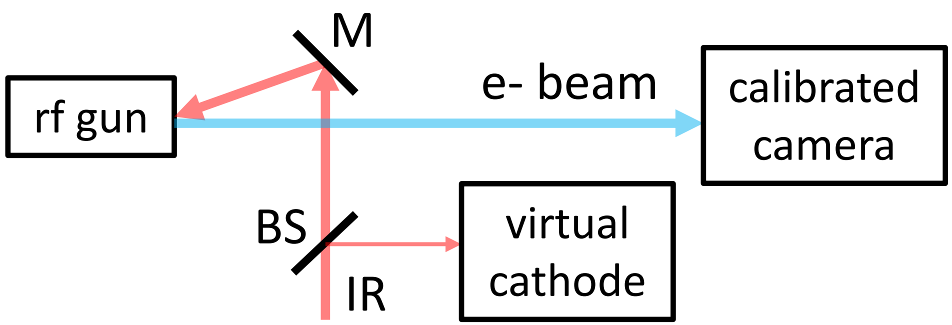
‘Warm’ test of the FIB-ed cathode

- Installation into the photocathode rf gun
- RF tuning procedure (pulling the cathodes toward the back)
- static vacuum 1e-9 torr
- increase the rf power for surface conditioning
- dark current (field emission) level comparable with regular flat cathode
- Exciting moment: shine the laser and scan across the cathode…

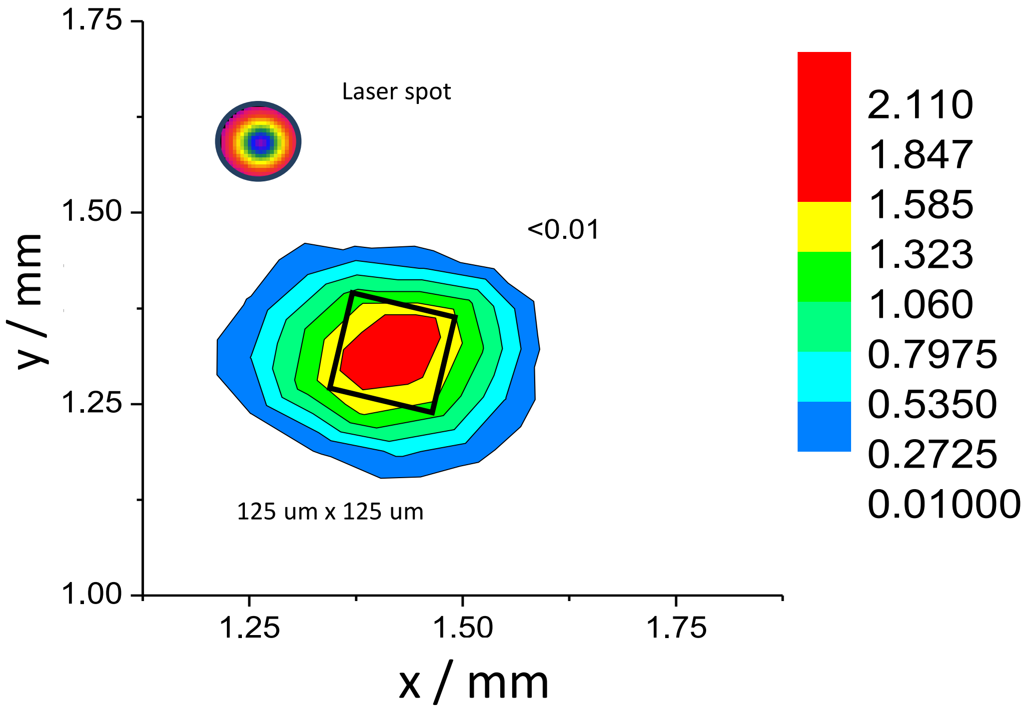




Charge Yield map



- virtual cathode: position and intensity of the IR laser on the cathode
- calibrated camera: e- beam charge

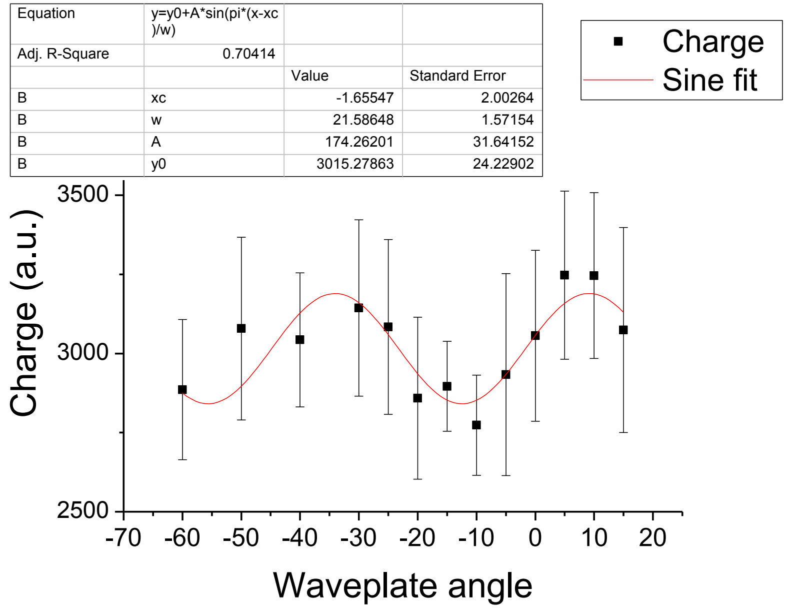


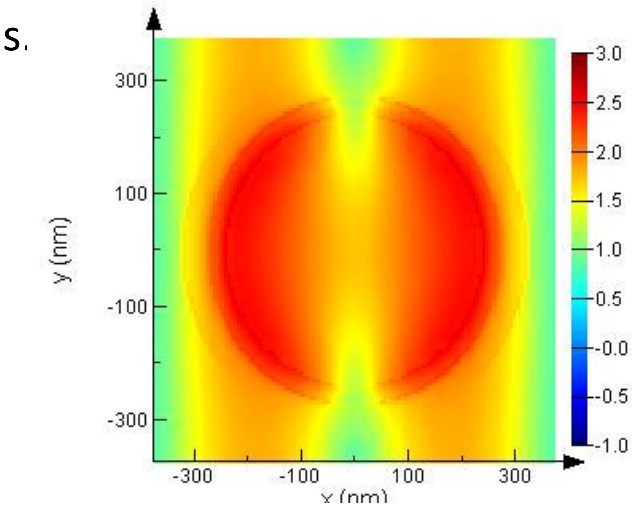
- charge yield ratio 500
- can not be totally explained by the reflectivity: $(1-0.64)^3/(1-0.88)^3 = 27$
- expected as the simulation show field enhancement around each nanohole

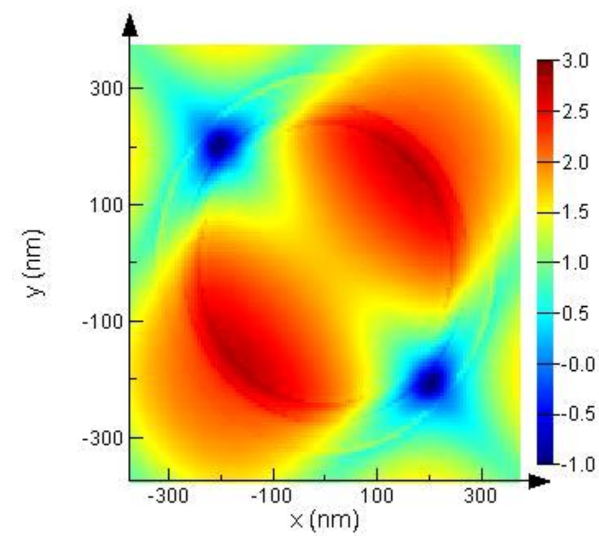
Polarization dependence

- Interesting question: does polarization matter?
- Spacing between holes is different at 45 degrees.
- Small effect due to incident angle on cathode being 5 degrees
- Measurements (taking into account mirror reflectivity) confirm simulation prediction.
- No polarization dependence.

Equation	y=y0+A*sin(pi*(x-xc)/w)		
Adj. R-Square	0.70414		
		Value	Standard Error
B	xc	-1.65547	2.00264
B	w	21.58648	1.57154
B	A	174.26201	31.64152
B	y0	3015.27863	24.22902



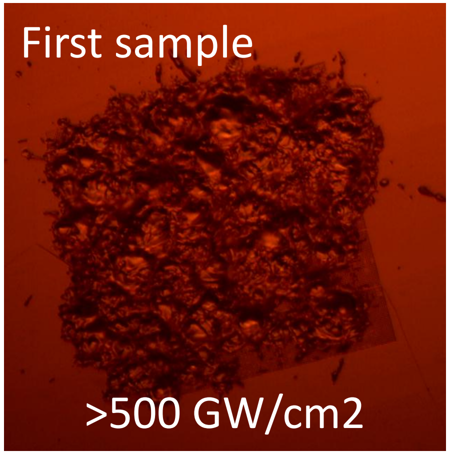


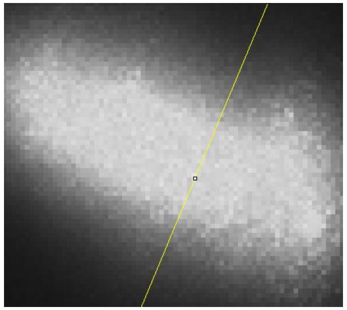


Damage threshold

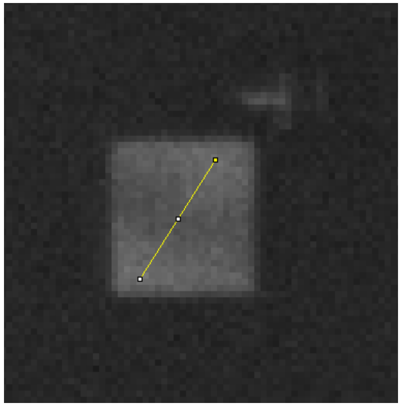
- Definitely different than flat surface.
- For copper absorbed fluence threshold 50-60 mJ/cm^2
- Increased laser absorption can cause significant damage
- Damage after 10^3 shots at 25 mJ/cm^2 incident fluence
- Increase can be explained by field (intensity) enhancement

bright field zoom x50





Laser spot



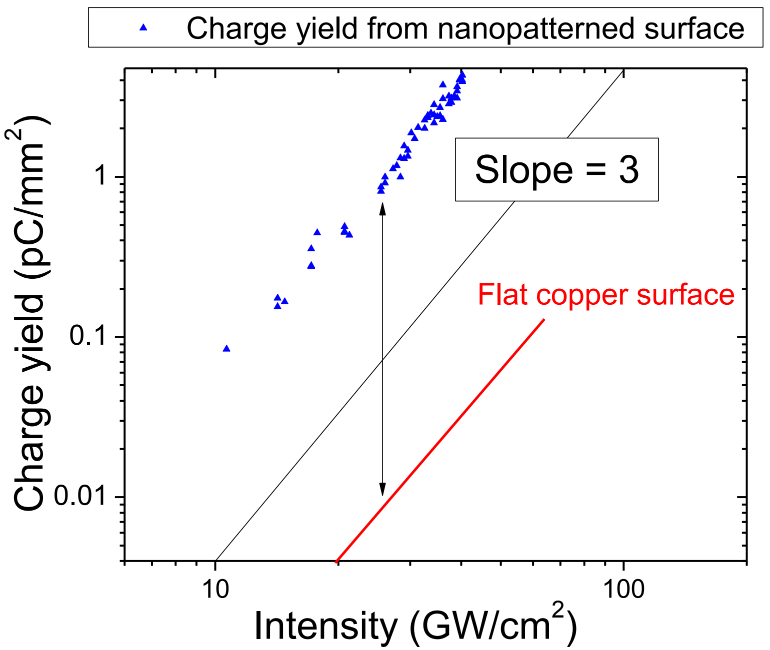
Damaged pattern

Charge yield measurements

- Measured charge density scales as 3rd power of laser intensity

  - indicating a 3-photon process

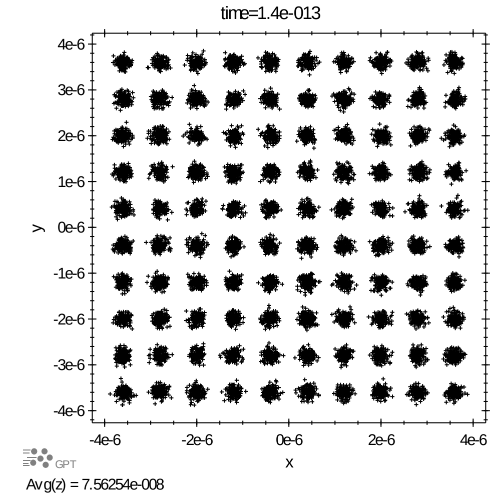
- 35 MV/m extraction field. (30 degrees phase at 70 MV/m peak)
- Saturation due to the virtual cathode limit could be affected by non uniform surface charge density at emission plane
- e-beam bunch length comparable with the same charge beam from a flat area. (measured by RF deflector)
  - nanoholes are low-Q cavities
  - broad resonances

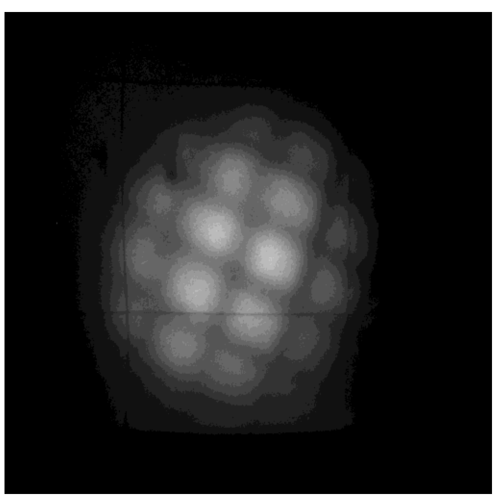


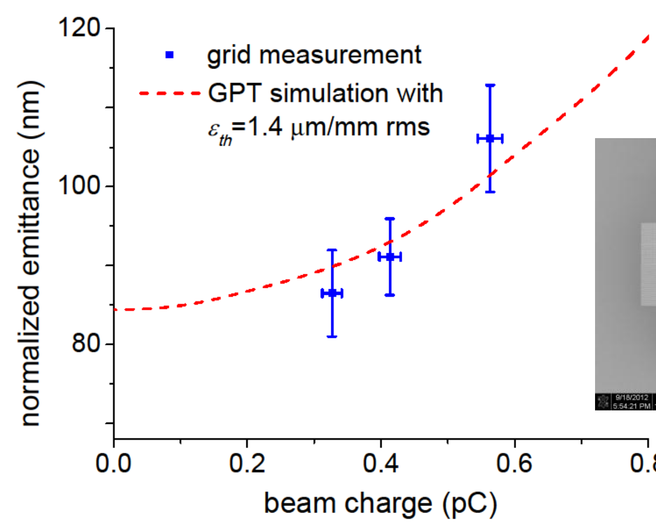
in – vacuum mirror not calibrated yet…

Beam dynamics from nanopatterned cathodes

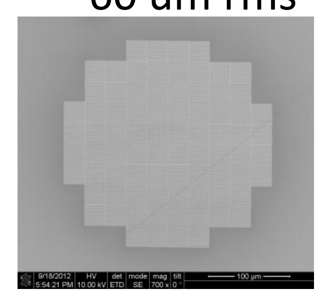
- Thermal emittance measurements
  - Grid images look blurry.
  - Emittance analysis give somewhat (~1.5 times) larger values when compared to flat surface thermal emittance
- Nanopatterned beam simulations.
  - Can the structure be preserved?
  - Can we demonstrate that emission is mostly from hole region?
  - Multi-scale simulation problem. Requires ad-hoc numerical algorithms.







60 um rms



Acknowledgements

- H. To (nanopatterned fabrication)
- C. M. Scoby, J. T. Moody, E. Threkheld, D. Cesar, K. Roberts, E. Curry (Pegasus Team)
- LBL H. Padmore, A. Polyakov

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- Funding agencies: DOE-BES, DOE-HEP, JTO-ONR

Conclusion and discussion

- Nanoplasmonics meets high brightness electron sources

- Significant increase in multiphoton charge yield with respect to flat surface
  - Reflectivity
  - Local intensity enhancement
- First RF photoinjector test successful
- Beam properties measured
- Damage threshold limitation

- Applications of nanopatterned cathodes
- Increase absolute charge yield ?
  - Optimize structures. Nanogrooves.
  - Different substrates/metals
- Sub-wavelength patterning initial beam distribution.
- Nanostructures beam dynamics evolution

Save the date

- When: 12/12/12 – 12/14/12
- Where: University of California, Los Angeles
- What: Workshop on Ultrafast Electron Sources for Diffraction and Microscopy applications

http://home.physics.ucla.edu/UESMD_2012/

The goal is to convene together people from the accelerator and instrument development community with some of the application guys and define the capabilities and limits of the technique in order to trace a path on how progress in UED can really make an impact in material studies and ultrafast science. Which of the beam characteristics should we push more? What processes or material studies will take most advantage from the unique properties of the source? What are the limits (and the requirements) in temporal resolution?

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Co-Chairs: X.J. Wang & P. Musumeci

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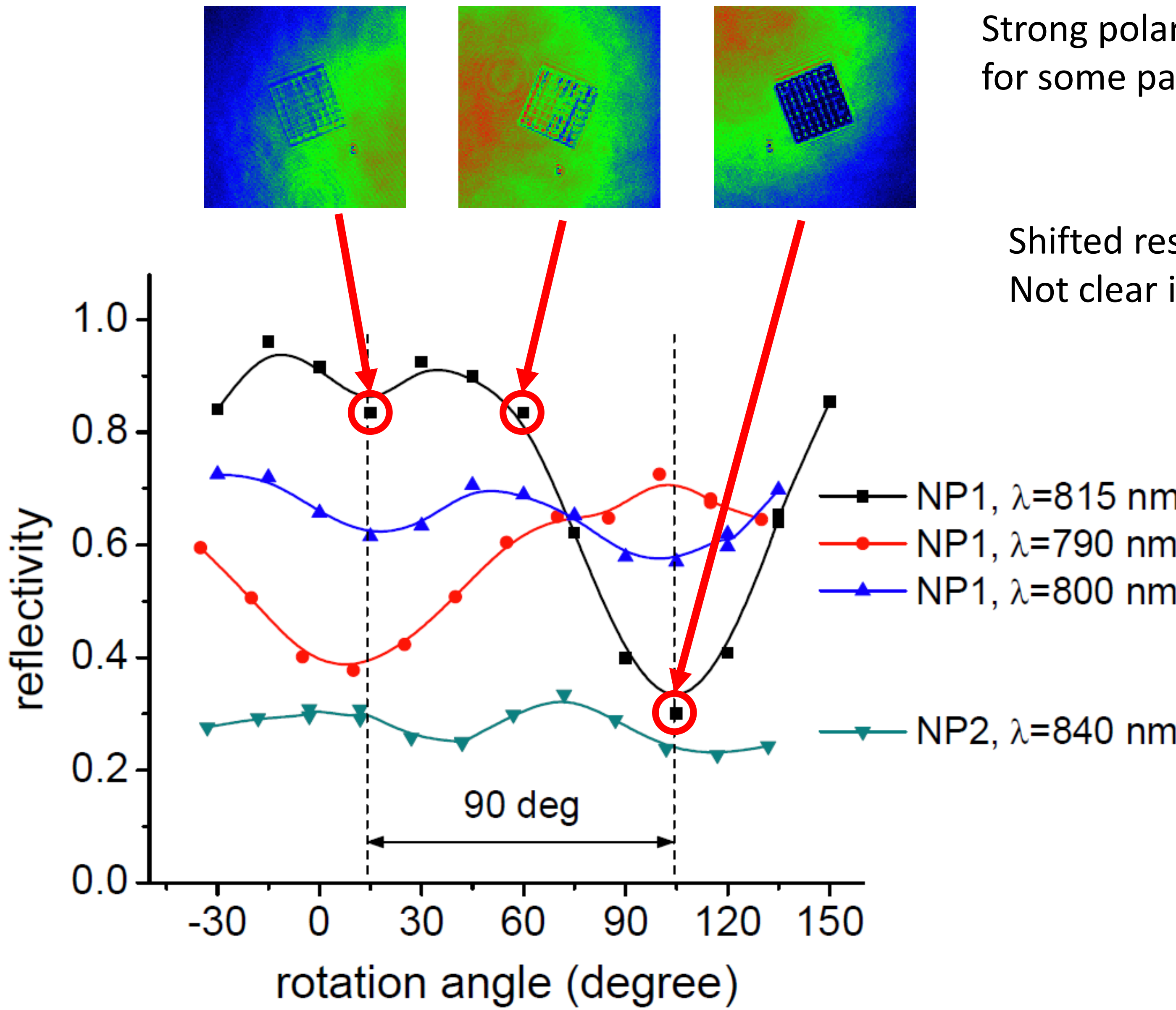
UCLA Department of Physics and Astronomy



Strong polarization dependence for some patterns

Shifted resonance.
Not clear if FIB has some issues.