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

P. Musumeci and R. K. Li

UCLA Department of Physics and Astronomy

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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)

Background

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 as grids or arrays of holes.
- Low reflectivity corresponds to optical electric field enhancement.

![FDTD simulations](image.png)

![Normalized power](image.png)
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:
  \[ d = 765 \text{ nm} \]
  \[ h = 244 \pm 15 \text{ nm} \]
  \[ w = 185 \pm 15 \text{ nm} \]

- 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

scatterd 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
‘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...

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e- beam from flat surface

when laser hit the nanopattern
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.

<table>
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<th>Equation</th>
<th>( y = y_0 + A \sin(\pi(x-x_c)/w) )</th>
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<td>Adj. R-Square</td>
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<table>
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<th>Value</th>
<th>Standard Error</th>
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<td>( y_0 )</td>
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</table>

![Graph showing charge vs. waveplate angle with sine fit](image)

- Charge
- Sine fit
Damage threshold

- Definitely different than flat surface.
- For copper absorbed fluence threshold 50-60 mJ/cm²
- Increased laser absorption can cause significant damage
- Damage after $10^3$ shots at 25 mJ/cm² incident fluence
- Increase can be explained by field (intensity) enhancement
Charge yield measurements

- Measured charge density scales as $3^{rd}$ 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)
  - nano-holes are low-Q cavities
  - broad resonances

![Graph showing charge yield versus intensity](image-url)

**Flat copper surface**

**Slope = 3**

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.

![Graph showing normalized emittance vs beam charge](image)

60 um rms
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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?
    – Different substrates/metals
  • Sub-wavelength patterning initial beam distribution.
  • Nanostructures beam dynamics evolution
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?

Co-Chairs: X.J. Wang & P. Musumeci
Strong polarization dependence for some patterns

Shifted resonance.
Not clear if FIB has some issues.