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Ultra-Bright Electron Source Study for Accelerator Applications

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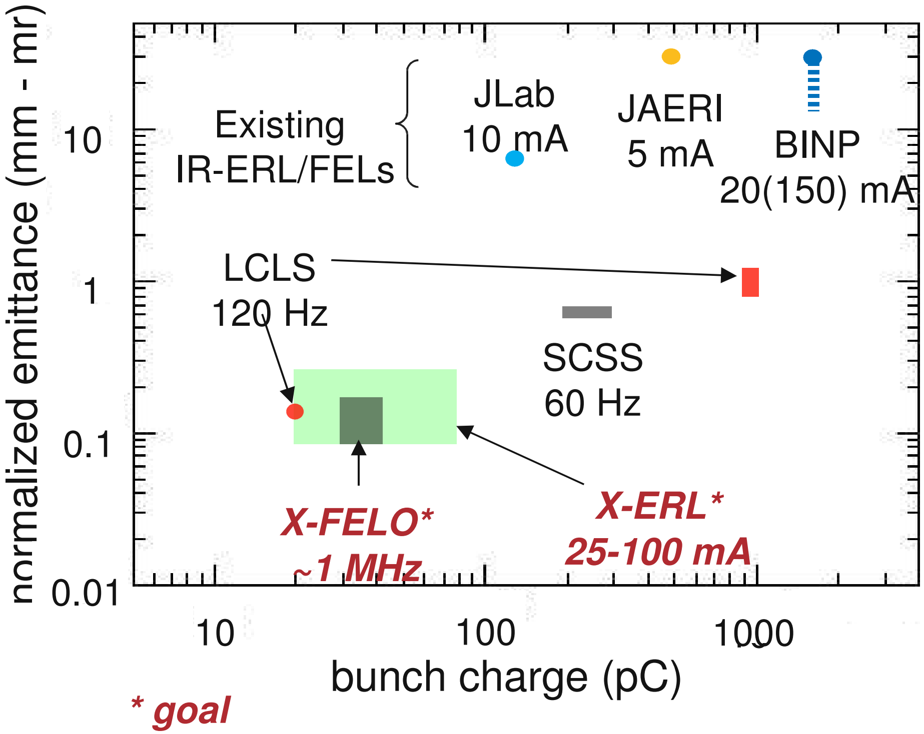
Outline

- Motivation: next-generation x-ray sources
- Electron "enhancement factor"
  - Enhancement = ultra-low emittance
- Experimental
  - Characterize emission distribution
- Theoretical
  - Optimize material properties to minimize emittance
- Summary

Ultra-Bright Electron Injector

- X-FEL and X-ERL requirements on low beam emittance and electron bunch repetition rate are *very* demanding on electron source
- Photoemission efficiency & wavelength response also important: smaller laser (cost) and/or higher rep rate (flexibility)



Low bunch emittance:

- **Photocathode emission physics and materials optimization**
- Laser pulse shaping
- Numerical multivariate optimization modeling

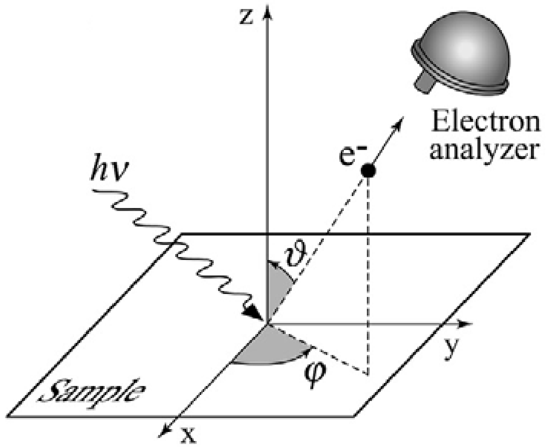
Low bunch emittance, high bunch rate:

- Thermionic cathode, VHF rf cavity design, and beam manipulation (K.-J. Kim et al.)

Ultra-Bright Photocathode Physics Study and Design

- Fundamental cathode emission properties determine lower bound on achievable electron source emittance *
- Intrinsic emittance depends on:
  – Emission momentum distribution
  – Surface roughness, nonuniformity
  – Surface chemistry, impurities (e.g., oxide layers)
  – Grain boundaries
  – Laser profile, energy, polarization
- Angle-resolved photoemission spectroscopy (ARPES), an important tool in surface science, is also promising as a tool to characterize photocathodes**

Physica Scripta T109, 61 (2004)
A. Damascelli



Basic ARPES geometry

* I.V. Basarov, B.M. Dunham, C.K. Sinclair, Phys. Rev. Lett. 102, 104801 (2009).
** D. Sertore et al., Proc. 2004 EPAC; W. Wan, CHBB Mini-workshop, DESY Zeuthen (2008).

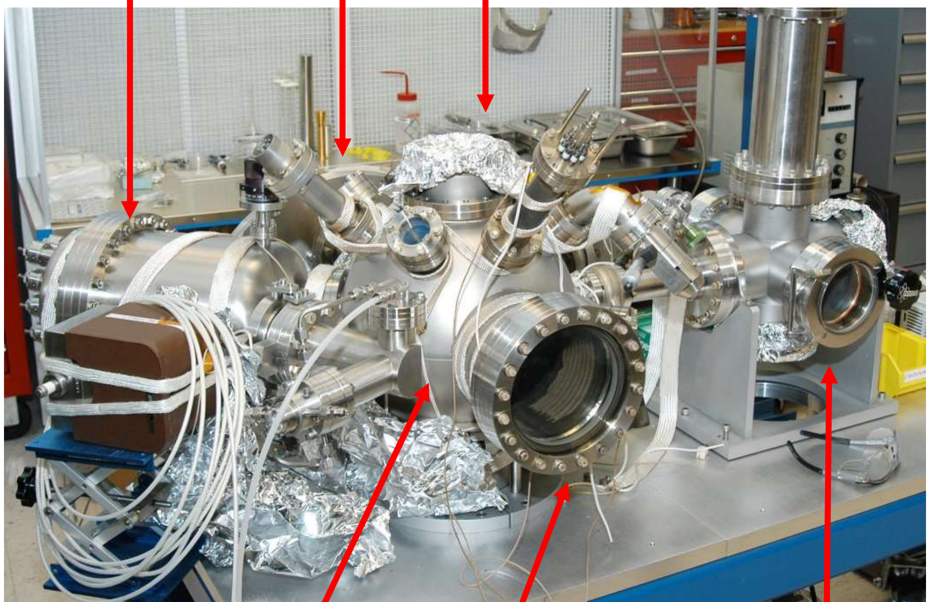
*Photocathode Surface Lab **

XPS system

Monochromatized x-ray source

Spherical electron analyzer

Dual-anode Al, Mg source



Analysis chamber

Sample intro chamber

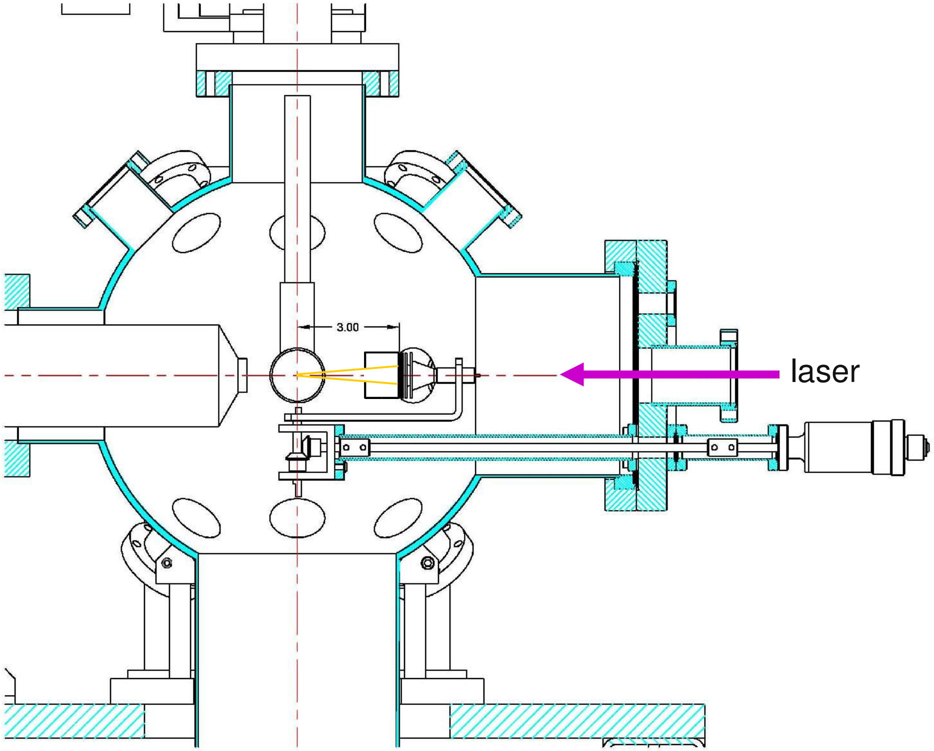
ARPES system: Mounting flange for photon input, TOF detector

- Existing UHV surface analysis chamber being upgraded to add ARPES**
  - Mu-metal analysis chamber
  - XPS to study surface chemistry *in-situ*
  - Heat/cool sample (1000C/140K)
- Eventual upgrade (2nd UHV chamber)
  - Scanning Auger (AES) and scanning electron microscopy (SEM) (1-2 μm resolution)
  - *In-situ* ion sputtering/ vapor deposition

* Courtesy R. Rosenberg (ANL)

** K. Harkay et al., Proc. 2009 PAC (MO6RFP045)

ARPES Chamber

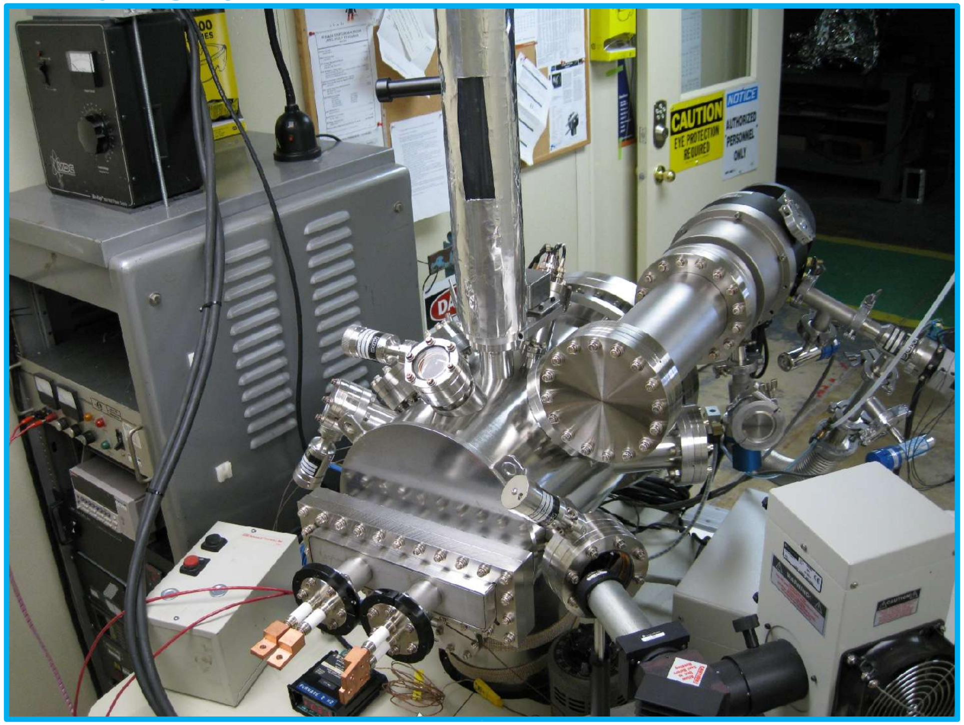


Design: R. Rosenberg

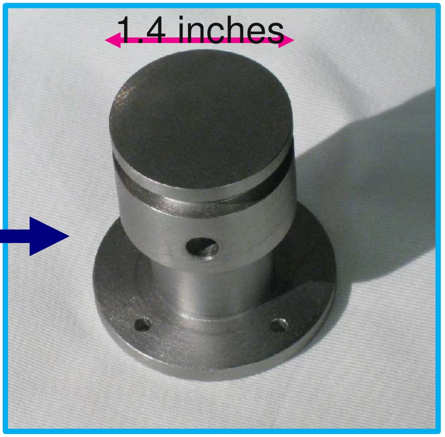
K. Harkay et al., Proc. 2009 PAC (MO6RFP045)

- Sample holder XYZ θ, sample current
- Vary photon incident angle and polarization
  - Nd:YAG laser, 3-ns pulse (1064, 540, 355, 266 nm)
  - UV flash lamp (1-μs), spectrometer
- MCP TOF electron detector inside vacuum on a rotating arm
  - Angular acceptance ~6 deg
  - Scan emission angle vs. photon incident angle
- Electron tracking underway (SIMION) to optimize design (EM fields)
- Eventual upgrades: fast laser, 2D MCP TOF detector, vacuum load-lock system, test fast MCPs

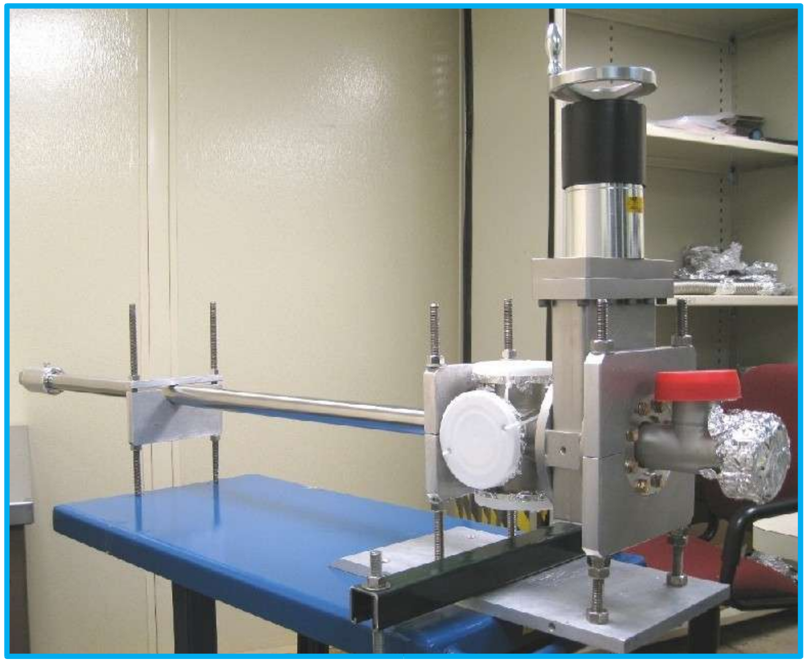
High QE Photocathode – Fabrication and Vacuum Transfer



Cs_2Te photocathode deposition system



Photocathode plug/substrate (Mo)



Cs_2Te UHV vacuum transfer system

Photocathode R&D status/plans

- Plan to start with existing cathodes (Cu, Cs_2Te*, diamond**); no facilities for *in-situ* cesiation (e.g. Cs:GaAs)
- UV ARPES chamber assembly underway; first measurements this year. Opportunity to compare intrinsic emittance results with
  - BNL, PITZ (msr'd in injector)
  - INFN, LBNL (ARPES labs)
  - others
- Preliminary theoretical calculations under way; suggest a design method for ultra-high brightness cathodes
- Novel material designs that predict small emittance to be investigated experimentally
- Fabrication of novel cathodes to be discussed with: Argonne Materials Science Division, APS X-Ray Science Division, others from this workshop

* Z. Yusof, http://www.hep.anl.gov/eyurtsev/psec

** J. Smedley, T. Rao, private discussion at ERL09

Emittance: Theoretical Estimate

At the surface, the emittance is

$$\epsilon_{x,rms} = x_{rms} p_{x,rms} / (m_e c)$$

For uniform emission from a disk,

$$x_{rms} = \frac{1}{2} R$$

For uniform distribution in the transverse momentum space,

$$p_{x,rms} = \frac{1}{2} P_r = \frac{1}{2} \hbar k_{max}$$

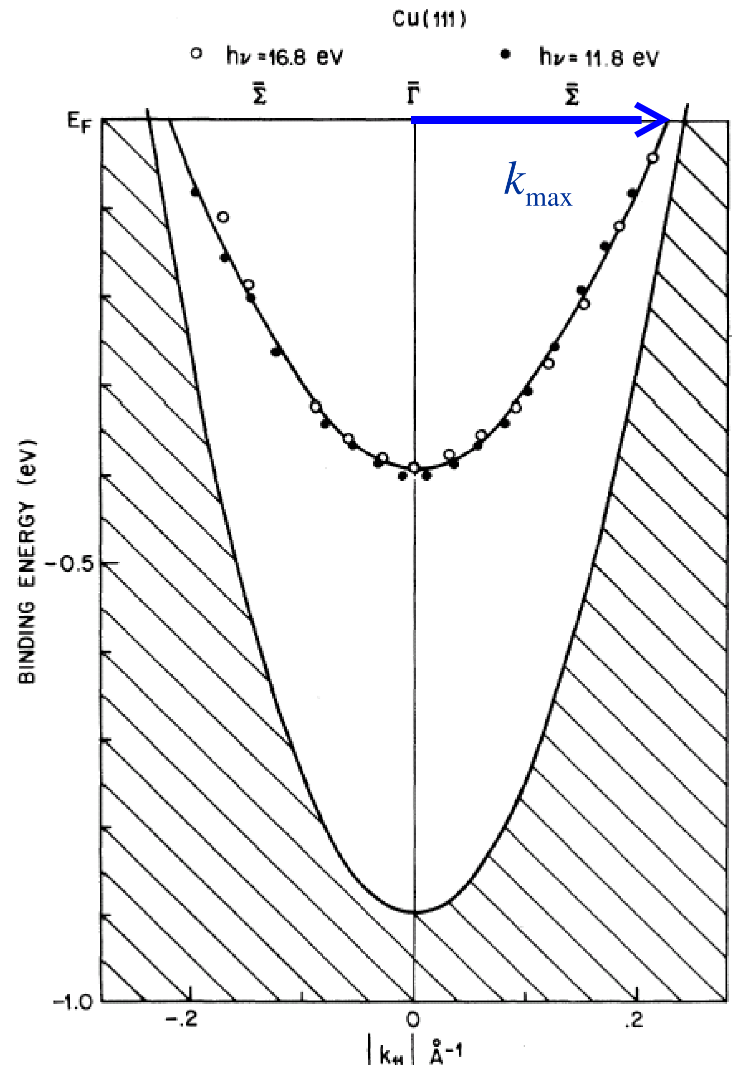
$$\epsilon_{x,rms} = \frac{1}{4} R \cdot \hbar k_{max} / (m_e c)$$

For Cu(111), $k_{max} = 0.225\ \mathring{A}^{-1}$, $R = 1$ mm

$$\epsilon_{x,rms} = 2.2 \times 10^{-7} \text{ m rad}$$

For Ag(111), $k_{max} = 0.125\ \mathring{A}^{-1}$, $R = 1$ mm

$$\epsilon_{x,rms} = 1.2 \times 10^{-7} \text{ m rad}$$



S.D. Kevan, PRL 50, 526 (1983).

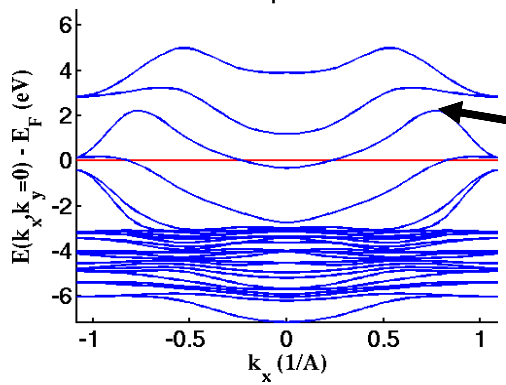
*Surface model analysis via Density Functional Theory**

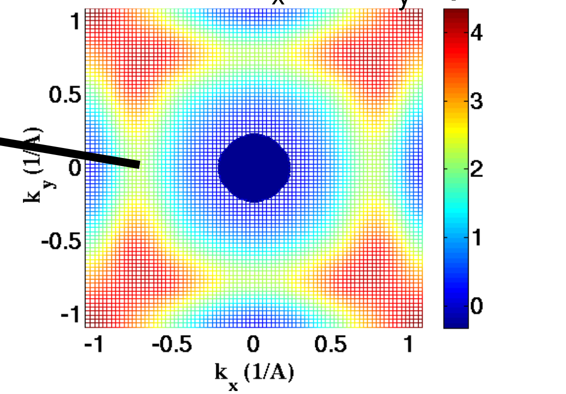
- Surface slab, crystal orientation, compute 2D EDCs
- Comparison to measured work function (<10%), computed EDCs (~10%) (e.g., S.D. Kevan)
- ARPES spectra: emission probabilities vs. photon energy, polarization, ϕ, band structure
- Preliminary results for Cu(001)
- Emittance to be estimated via 3-step model

k_x vs. energy bands relative to E_f

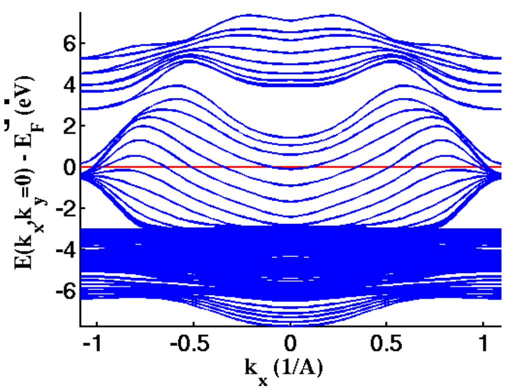
Lowest-energy (relative to E_f) surface bands in k_x vs. k_y space

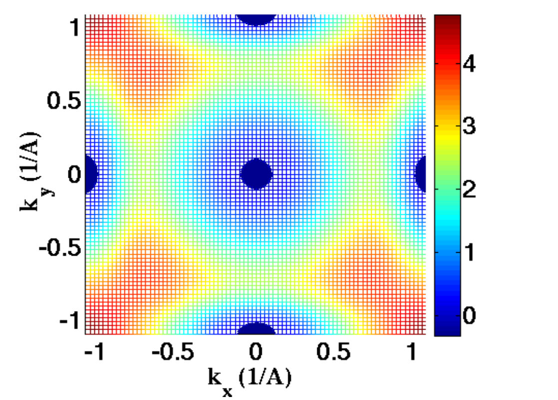
Ag(001)4L; DFT(PBE)





Ag(001)16L; DFT(PBE)





* K. Nemeth

Potential low-transverse-emittance layered structure

- Preliminary idea from surface catalysis systems (J. Chem. Phys. 127, 144713 (2007)).

K. Nemeth

Ag(001)16L;
DFT(PBE)

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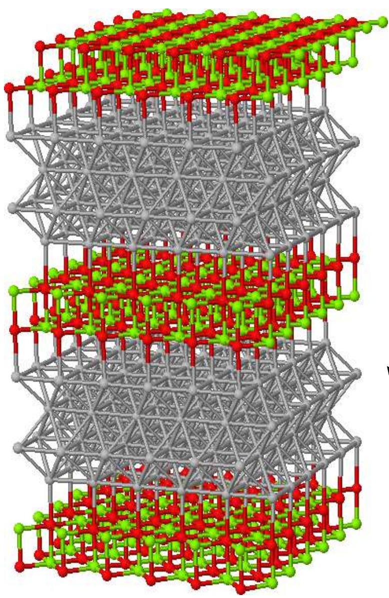
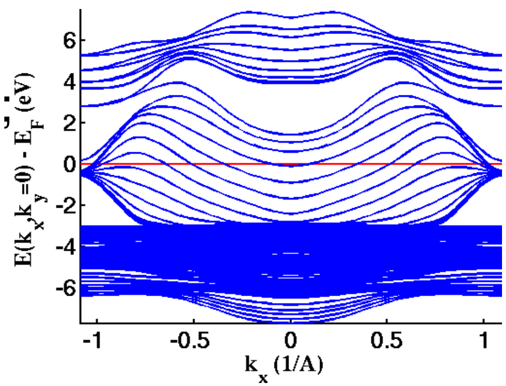
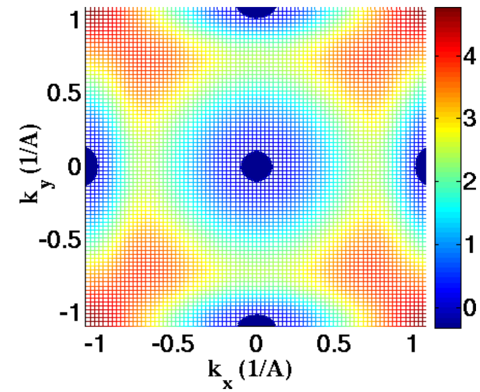
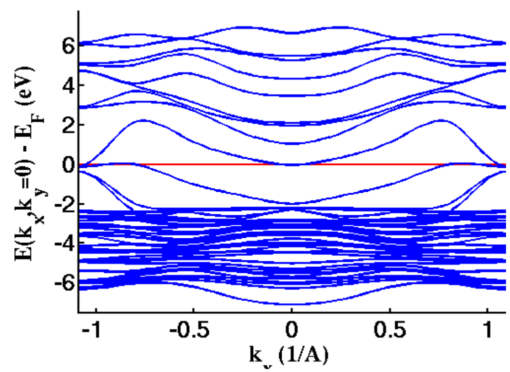
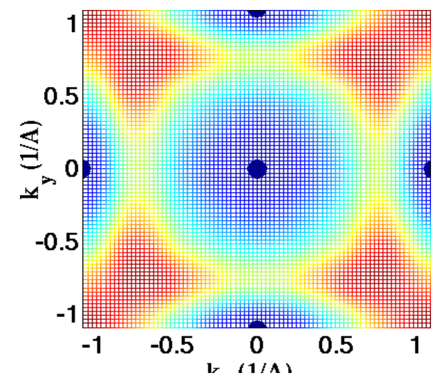
Lowest-energy (relative to E_f) surface bands in k_x vs. k_y space











MgO(100)2L-Ag(100)4L-MgO(100)2L; DFT(PW91)
Work function reduced by ~1 eV relative to pure Ag(001)

Summary

- Photoemission characterization using UV ARPES under development; chamber assembly underway
- Potential materials design methods being explored theoretically to optimize (minimize) emittance for next-generation x-ray source
- Prediction of ARPES spectra, emittance, and QE to be done
- Fabrication of promising designer cathodes needs to be developed; properties to be characterized (also lifetime, grain boundaries, etc)
- Other efforts:
  - High QE photocathodes (Z. Yusof, J. Noonan, M. Virgo, et al.): Cs_2Te, GaN
  - Plasmon-enhanced photocathodes (W. Wan, H. Padmore et al. (LBNL)
- Potential overlapping interests with fast PMT effort: test MCPs, cathode characterization/design

Collaborators: Yuelin Li, Karoly Nemeth, Richard Rosenberg, Marion White (ANL), Linda Spentzouris (IIT)

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