A possible mechanism for enhanced field emission

with essential input from Yinon Ashkenazy and Jan Paszkiewicz

Background

As far as I know, everyone who makes field emission measurements on a macroscopic system needs a large – 30, 100 or more – correction factor to get I vs V data to fit to Fowler-Nordheim. We certainly do.

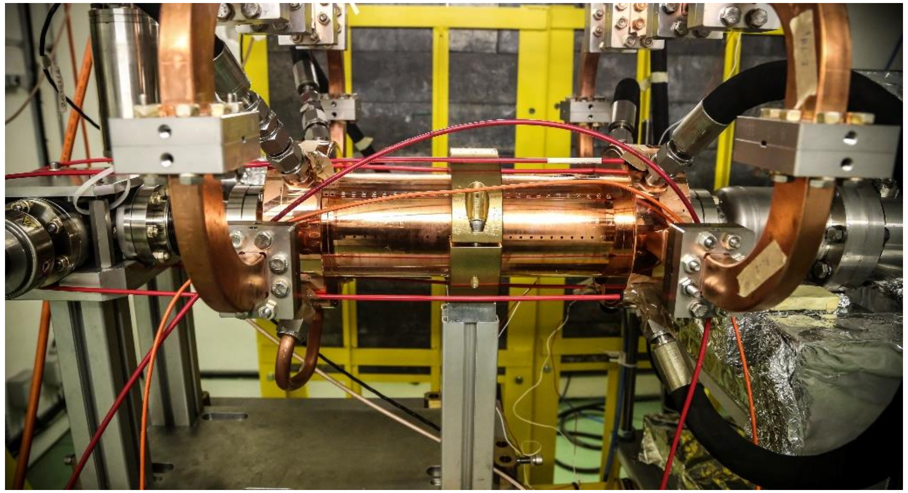
There are quite a lot of ideas about how this enhanced emission comes about. Tips, oxides, carbon and dust, and these may indeed dominate most systems - you know your systems better than I do!

I propose a mechanism for observed enhanced field emission which I believe dominates in our high field systems.

Introduction

CLIC 12 GHz high-gradient accelerating structures and associated dc systems have particular conditions:

- Surface electric fields in excess of 250 MV/m
- Over 50 structures and electrode sets tested
- Hundreds of millions of pulses per test, sometimes even billions
- Ultra-high vacuum
- Reproducible conditioning behavior
- Highly repeatable results – for example β around 30 every time in accelerating structures!
- Extensive microscopy



Presentations at MeVArc: D. Banon, J. Paszkiewicz, I. Profatilova, M. Jacewicz, A. Saressalo, L. Millar

All of which taken together, leads us to believe that we are working in a regime where the limiting surface field, and consequently the electron field emission mechanism, is given by the **intrinsic characteristics of copper**.

State-of-the-explanation

So if **intrinsic**, what can give enhanced field emission?

Two possibilities are **geometrical “tips”** and **suppressed work function**.

State-of-the-explanation

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Two possibilities are **geometrical “tips”** and suppressed work function.

But we never see tips. From SEM we are sure they would have to be smaller than 100 nm. But they are thermodynamically unstable below 20 nm or so. Narrow window…

They might be built up dynamically. Timescale is then less than 5 ns and the process would have to be very reproducible and evolve as conditioning proceeds. Hmmm.

Excellent work on tips being done. But I’m not convinced they’re there…

State-of-the-explanation

So if **intrinsic**, what can give enhanced field emission?

Two possibilities are geometrical “tips” and **suppressed work function**.

Suppressed work function can come from lattice defects, add-atoms and so on.

Experiments show effect around 0.5 eV

H. Chen, Y. Du, W. Gai, A. Grudiev, J. Hua, W. Huang, J. G. Power, E. E. Wisniewski, W. Wuensch, C. Tang, L. Yan, and Y. You, Surface-Emission Studies in a High-Field RF Gun based on Measurements of Field Emission and Schottky-Enabled Photoemission, Phys. Rev. Lett. 109, 204802 (2012).

Theory also shows around 0.5 eV

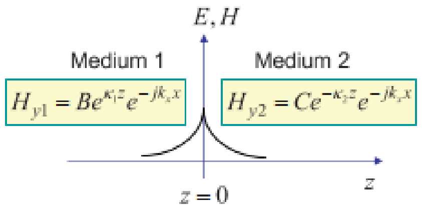
Heikki Toijala, Kristjan Eimre, Andreas Kyritsakis, Vahur Zadin, Flyura Djurabekova, Ab Initio calculation of field emission from metal surfaces with atomic--scale defects, arXiv:1907.12903

Compared to 4.5 eV - not enough for corrections of 30 to 100 and more!

Have we missed an effect?

Surface Plasmon Polaritrons

$\boxed{\mu_1 = \mu_2 = \mu_0}$



$\boxed{H_{y1} = B e^{\kappa_1 z} e^{-jk_x x}}$ $\boxed{H_{y2} = C e^{-\kappa_2 z} e^{-jk_x x}}$

$$\begin{cases} k_x^2 + k_{z1}^2 = k_1^2 = k_0^2 \varepsilon_{r1} \\ k_{z1} = -j\kappa_1 \end{cases} \qquad \begin{cases} k_x^2 + k_{z2}^2 = k_2^2 = k_0^2 \varepsilon_{r2} \\ k_{z2} = -j\kappa_2 \end{cases}$$

$$\boxed{k_x^2 - \kappa_1^2 = k_1^2} \qquad \boxed{k_x^2 - \kappa_2^2 = k_2^2}$$

Using now $\kappa_1^2 \varepsilon_{r2}^2 = \kappa_2^2 \varepsilon_{r1}^2$ (follows from $\zeta = -1$) $\boxed{\zeta = \frac{\kappa_2 \varepsilon_1}{\kappa_1 \varepsilon_2} = -1}$

$$(k_x^2 - k_1^2)\varepsilon_{r2}^2 = (k_x^2 - k_2^2)\varepsilon_{r1}^2$$

Rearranging $k_x^2(\varepsilon_{r2}^2 - \varepsilon_{r1}^2) = k_1^2 \varepsilon_{r2}^2 - k_2^2 \varepsilon_{r1}^2 = k_0^2(\varepsilon_{r1}\varepsilon_{r2}^2 - \varepsilon_{r2}\varepsilon_{r1}^2)$

The dispersion k_x vs. ω $\boxed{k_x^2 = k_0^2 \frac{\varepsilon_{r1}\varepsilon_{r2}(\varepsilon_{r2} - \varepsilon_{r1})}{(\varepsilon_{r2}^2 - \varepsilon_{r1}^2)} = k_0^2 \frac{\varepsilon_{r1}\varepsilon_{r2}}{\varepsilon_{r1} + \varepsilon_{r2}}}$

From:

Metamaterials and Plasmonics

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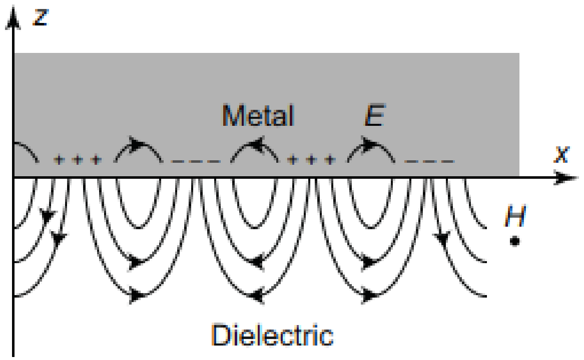
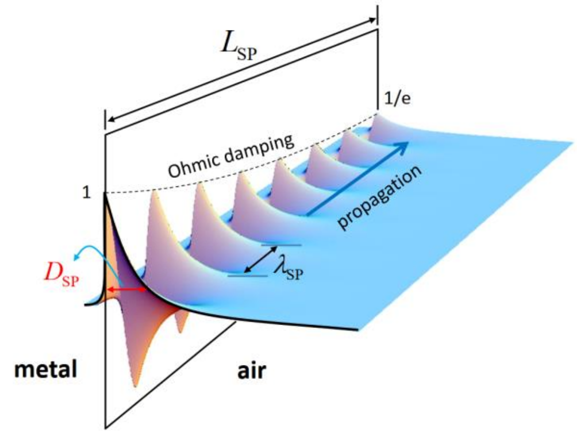
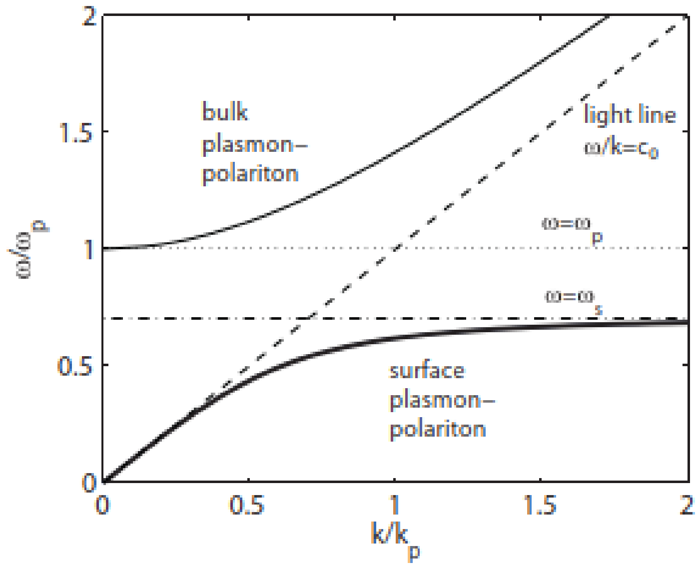
University of Oxford

MT 2015







Plasmons are waves confined to the metal surface. They wavelength of the order of 100 nm at optical frequencies.

Plasmons generally

- Plasmons exist, and there is a whole field studying them and using them.
- They have a dimension scale, wavelength order 100 nm, so similar to ours.
- They are notoriously difficult to observe due to the wavelength mismatch with light, so easy to miss.
- Turns out that excitation with electron beams is a standard technique!

Plasmons, optical transition radiation and electron beams

620 nm

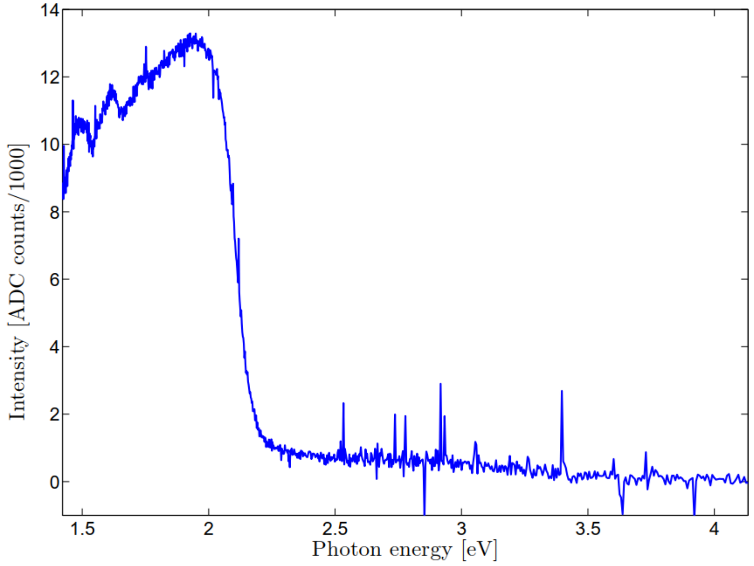
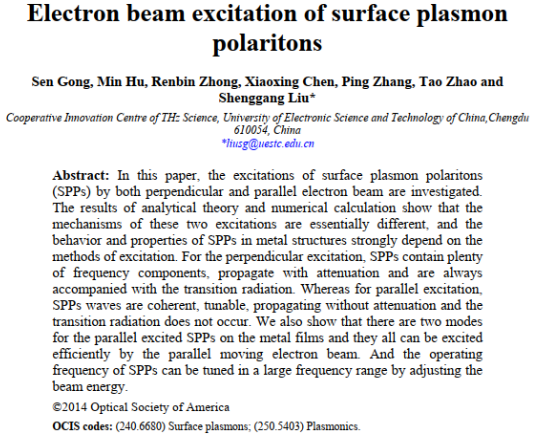


Figure 7.1: OTR light spectrum emitted by a copper spark gap in the dc setup. 20 µm gap, 4.25 kV, 10 accumulated spectra of 60 s integration time, 150 l/mm grating, 250 µm input slit width, CCD QE corrected. Huge grain (cm range) copper.

PhD thesis Jan Kovermann



Electron beam excitation of surface plasmon polaritons

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Abstract: In this paper, the excitations of surface plasmon polaritons (SPPs) by both perpendicular and parallel electron beam are investigated. The results of analytical theory and numerical calculation show that the mechanisms of these two excitations are essentially different, and the behavior and properties of SPPs in metal structures strongly depend on the methods of excitation. For the perpendicular excitation, SPPs contain plenty of frequency components, propagate with attenuation and are always accompanied with the transition radiation. Whereas for parallel excitation, SPPs waves are coherent, tunable, propagating without attenuation and the transition radiation does not occur. We also show that there are two modes for the parallel excited SPPs on the metal films and they all can be excited efficiently by the parallel moving electron beam. And the operating frequency of SPPs can be tuned in a large frequency range by adjusting the beam energy.

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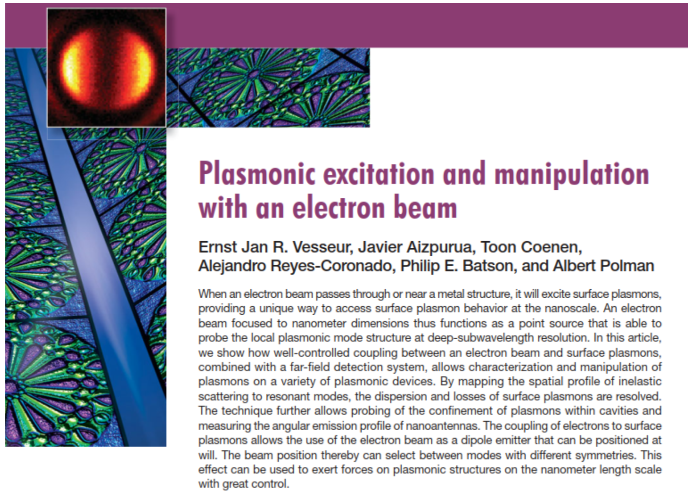
OCIS codes: (240.6680) Surface plasmons; (250.5403) Plasmonics.



Plasmonic excitation and manipulation with an electron beam

Ernst Jan R. Vesseur, Javier Aizpurua, Toon Coenen, Alejandro Reyes-Coronado, Philip E. Batson, and Albert Polman

When an electron beam passes through or near a metal structure, it will excite surface plasmons, providing a unique way to access surface plasmon behavior at the nanoscale. An electron beam focused to nanometer dimensions thus functions as a point source that is able to probe the local plasmonic mode structure at deep-subwavelength resolution. In this article, we show how well-controlled coupling between an electron beam and surface plasmons, combined with a far-field detection system, allows characterization and manipulation of plasmons on a variety of plasmonic devices. By mapping the spatial profile of inelastic scattering to resonant modes, the dispersion and losses of surface plasmons are resolved. The technique further allows probing of the confinement of plasmons within cavities and measuring the angular emission profile of nanoantennas. The coupling of electrons to surface plasmons allows the use of the electron beam as a dipole emitter that can be positioned at will. The beam position thereby can select between modes with different symmetries. This effect can be used to exert forces on plasmonic structures on the nanometer length scale with great control.

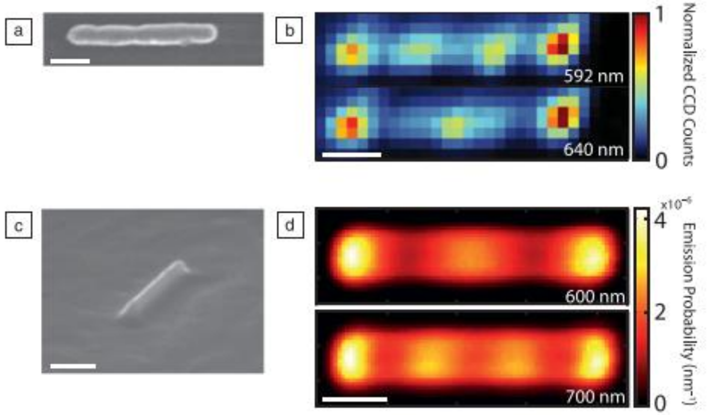
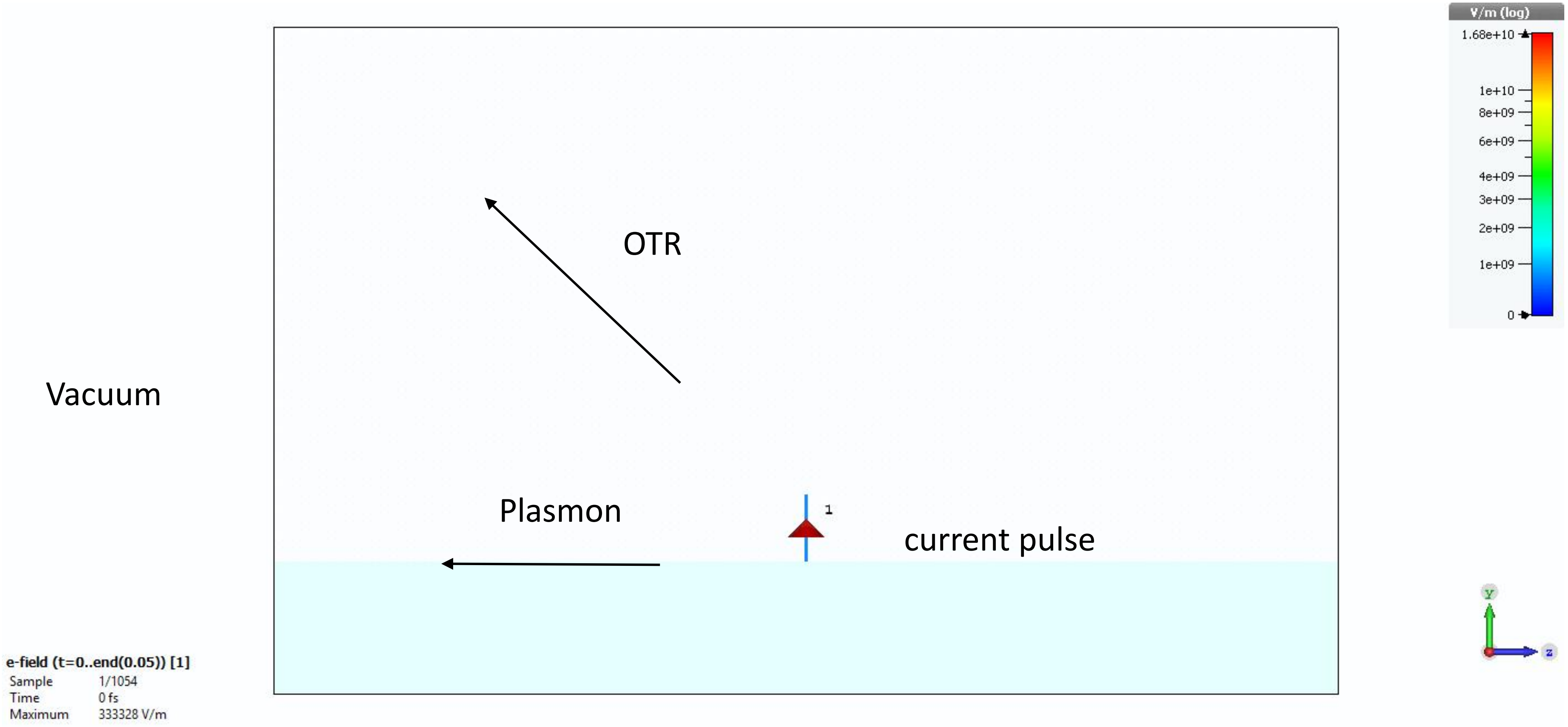


Figure 4. Standing plasmon waves on optical nanoantennas. (a) Scanning electron micrograph of a polycrystalline Au nanoantenna. (b) Cathodoluminescence emission from the antenna in (a) at 592 and 640 nm. Reprinted with permission from Reference 31. ©2007 American Chemical Society. (c) Single-crystalline Au ridge nanoantenna. Reprinted with permission from Reference 32. ©2008, American Institute of Physics. (d) Cathodoluminescence emission at 600 and 700 nm. Reprinted with permission from Reference 39. ©2012, American Chemical Society. Scale bars: 200 nm. CCD, charge-coupled device.

CERN dc system a few years back, light spectrum generated during field emission, copper electrodes. Attributed to OTR (Optical Transition Radiation).

Plasmons, optical transition radiation and electron beams



OTR

Vacuum

Plasmon

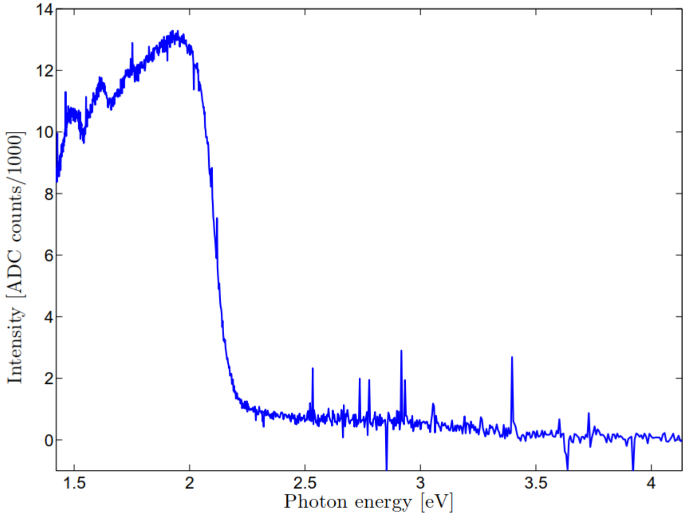
current pulse

e-field (t=0..end(0.05)) [1]
Sample 1/1054
Time 0 fs
Maximum 333328 V/m

Copper (Drude model)

Simulation by Jan Paszkiewicz

Anode and cathode



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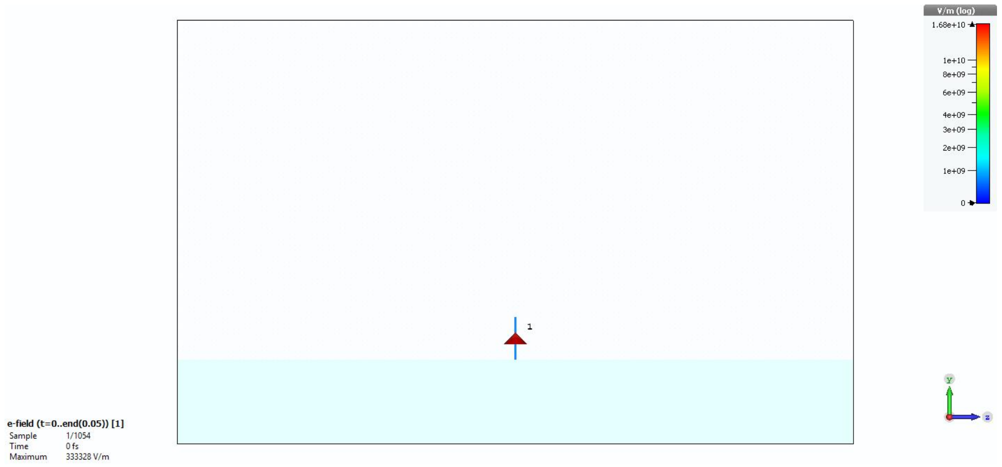

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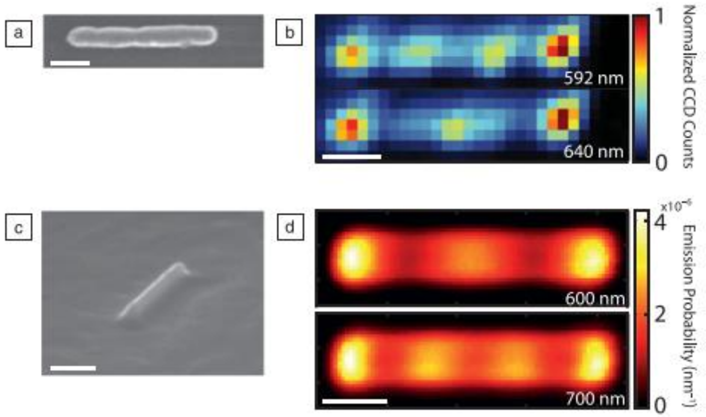

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OTR spectrum depends on electron beam energy so what we saw was most likely dominated by anode. But because plasmon is localized to metal surface, it doesn't care if current goes in or out so excited on both anode and cathode.

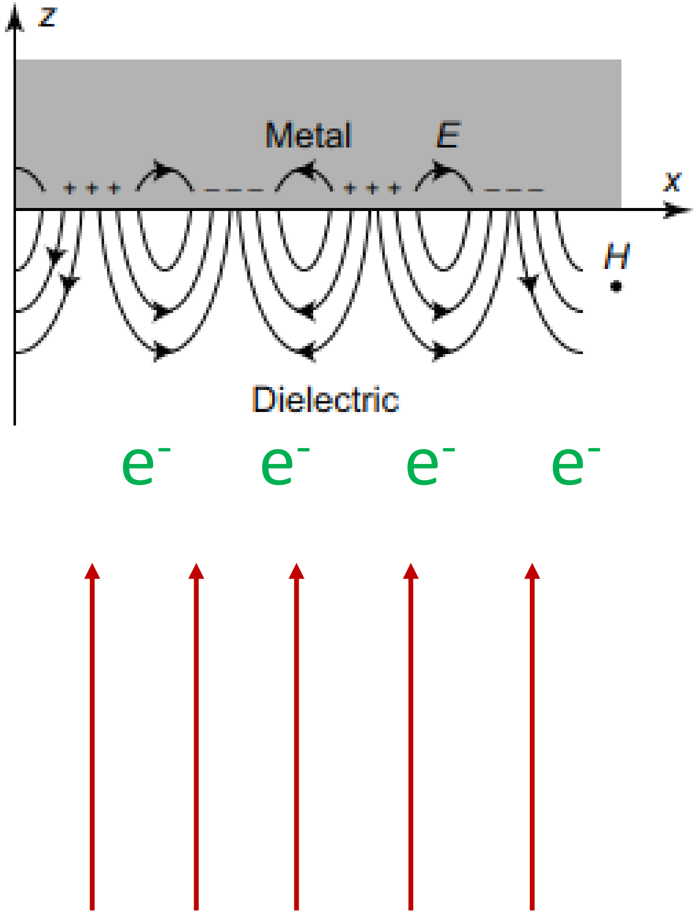
The big question: are plasmons playing an *important* role in field emission?

Do these elements interact?

Significantly?

Enough to modify expected field emission?

It’s far from proven, but I propose that the correction to Fowler Nordheim field emission in intrinsic-dominated systems is caused by **plasmon resonances**.



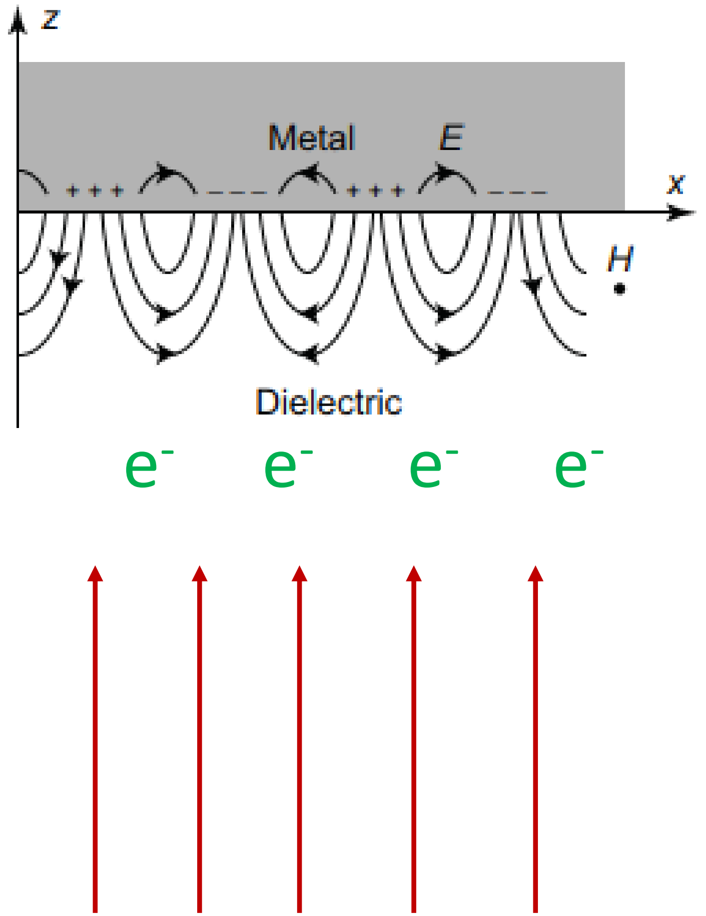
Plasmons

Field emitted electrons

External electric field

How might plasmons result in enhanced emission?

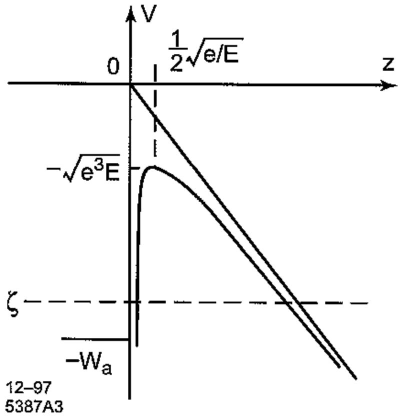
1. Spontaneous (thermally driven?) emission excites initial plasmons
2. Plasmon causes local increase in charge density, leading to increased field emission.
3. Etc. Requires mechanism for positive feedback, this is tricky.
4. Excitation grows to steady state value given by Q of plasmon resonance, and giving observed enhanced emission.



Plasmons

Field emitted electrons

External electric field



Generally – plasmons mean that the source of electrons for field emission is not an ideal current source, but rather one like a transmission line, or alternatively an effective inductance and capacitance. This means there are resonances.

How we will proceed

- Plasmons may provide a very high resolution diagnostic tool for investigating our high-field surfaces. We would like to learn how to measure them and manipulate them.
- Plasmons must be excited in our field emitting systems. We will investigate this experimentally.
- Plasmons may contribute to enhanced field emission. Investigating the first two points are essential steps to addressing this question.

Experimental:

- Implement interferometric techniques to excite and detect plasmons in our samples. First just as samples and later under high fields. Yinon and colleagues at the University of Jerusalem.
- Measure light emission from pulsed dc system at CERN with new focus. Two metal anode/cathode pairs, voltage vs field dependencies etc. Part of Ruth Peacock's PhD.
- etc.

Theoretical:

- Mathematical model for field emission to plasmon coupling to investigate positive feedback mechanism.
- Clarify how increased charge density affects field emission, try to make a quantitative estimate of level of emission enhancement.
- etc.

Thanks for your attention!