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PSI

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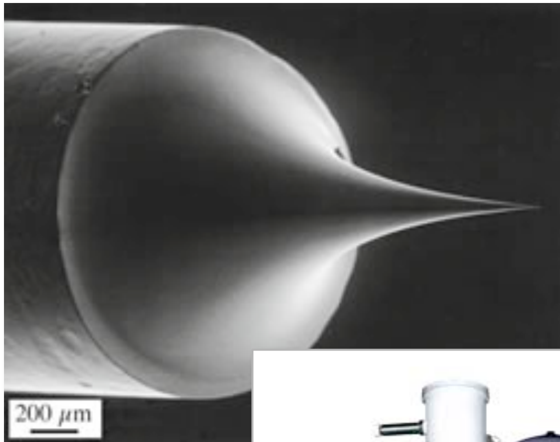
Focused tips arrays for production of cold electron beams

2016-10-19 Photocathode Physics for Photoinjectors (P3) 2016
Thomas Jefferson National Accelerator Facility, Newport News, Virginia USA

Field emitters…for accelerators?



FEG TEM: JEOL JEM 3200FS

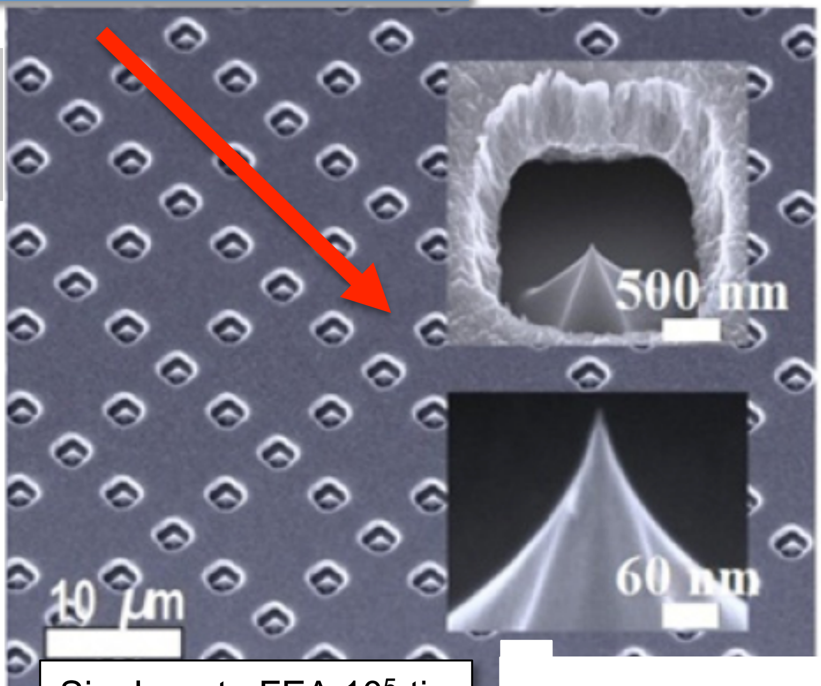
- Nanometer tip
- Small electron energy spread
- High current density
- Coherent e-source

for high resolution app.

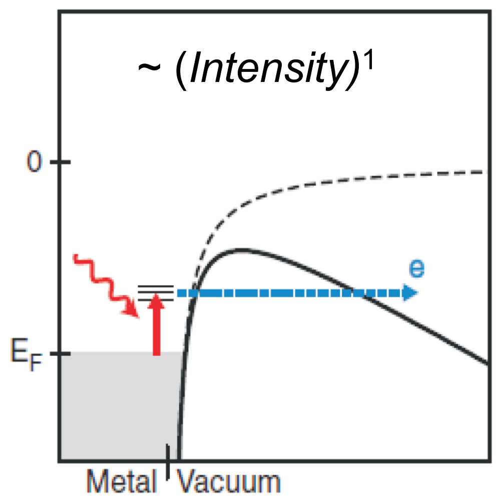
Field emitters…for accelerators?

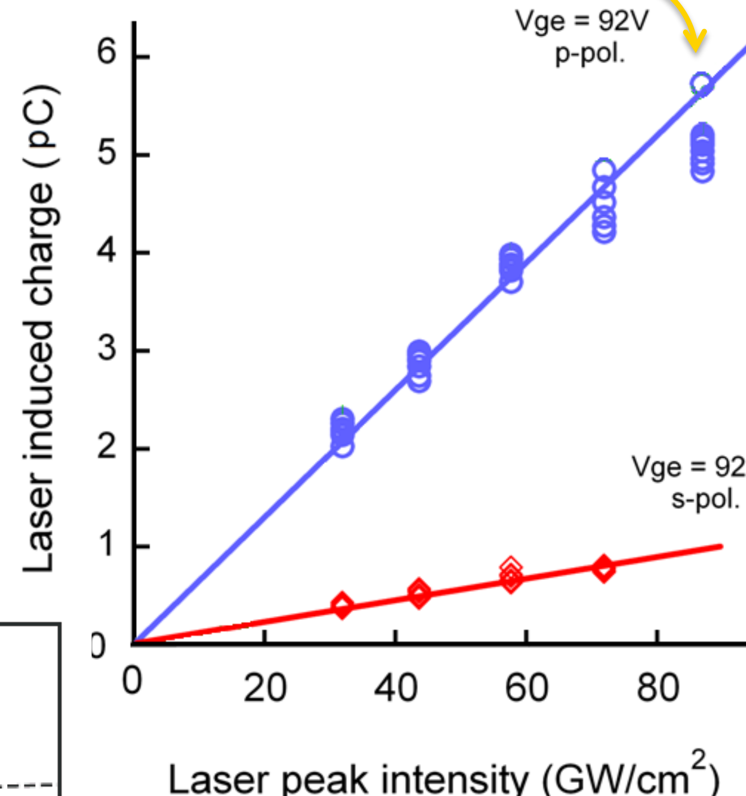
800 nm (1.6 eV), 50 fs

5 pC, 10^7 e^-, ~100 A?



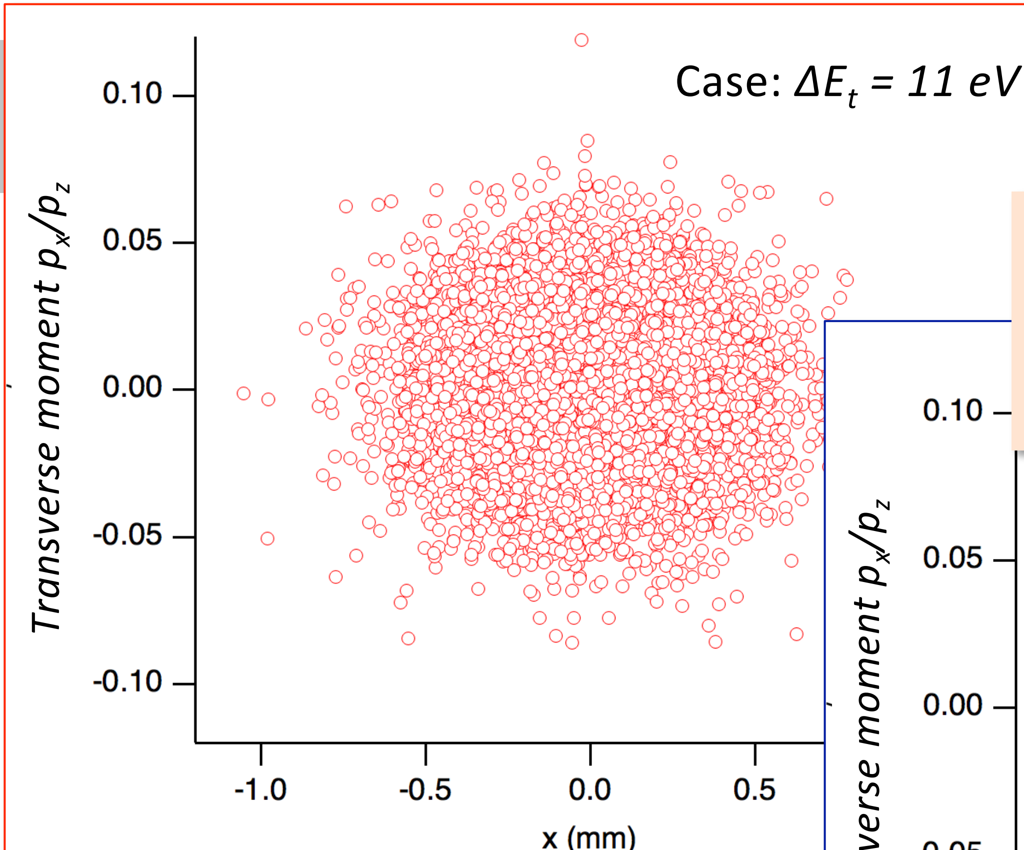
Single-gate FEA, 10^5-tip



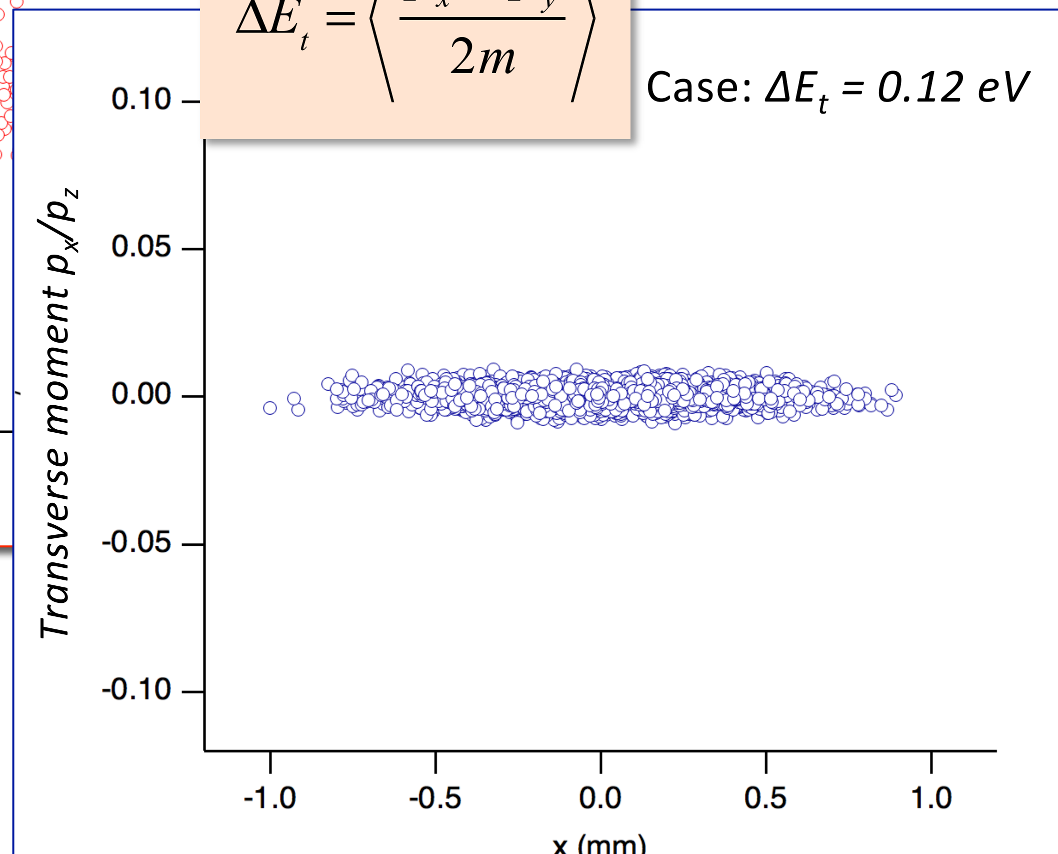


Emittance reduction

$$\varepsilon_x = \sqrt{\langle x^2 \rangle \langle (p_x / mc)^2 \rangle - \langle x (p_x / mc) \rangle^2}$$
$$= \beta\gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}$$



$$\Delta E_t = \left\langle \frac{p_x^2 + p_y^2}{2m} \right\rangle$$



Emittance reductio

$$\varepsilon_x = \sqrt{\langle x^2\rangle\langle (p_x/mc)^2\rangle - \langle x(p_x/mc)\rangle^2}$$

$$= \beta\gamma\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}$$

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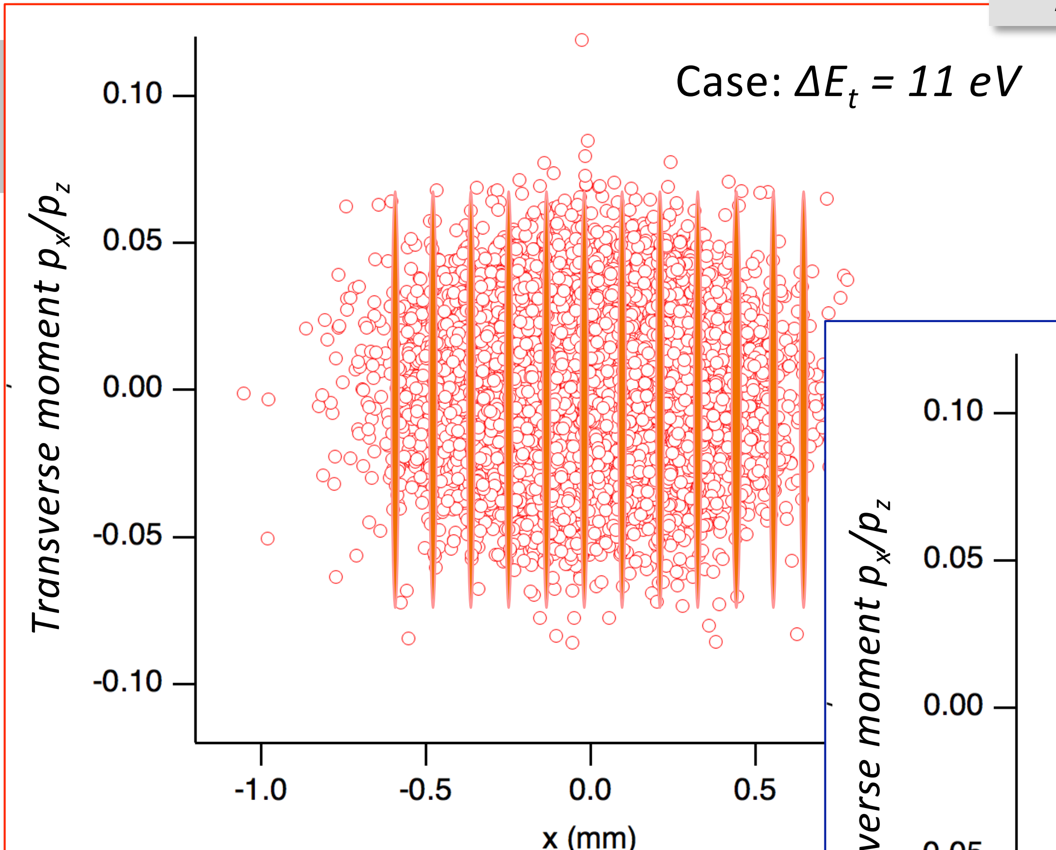
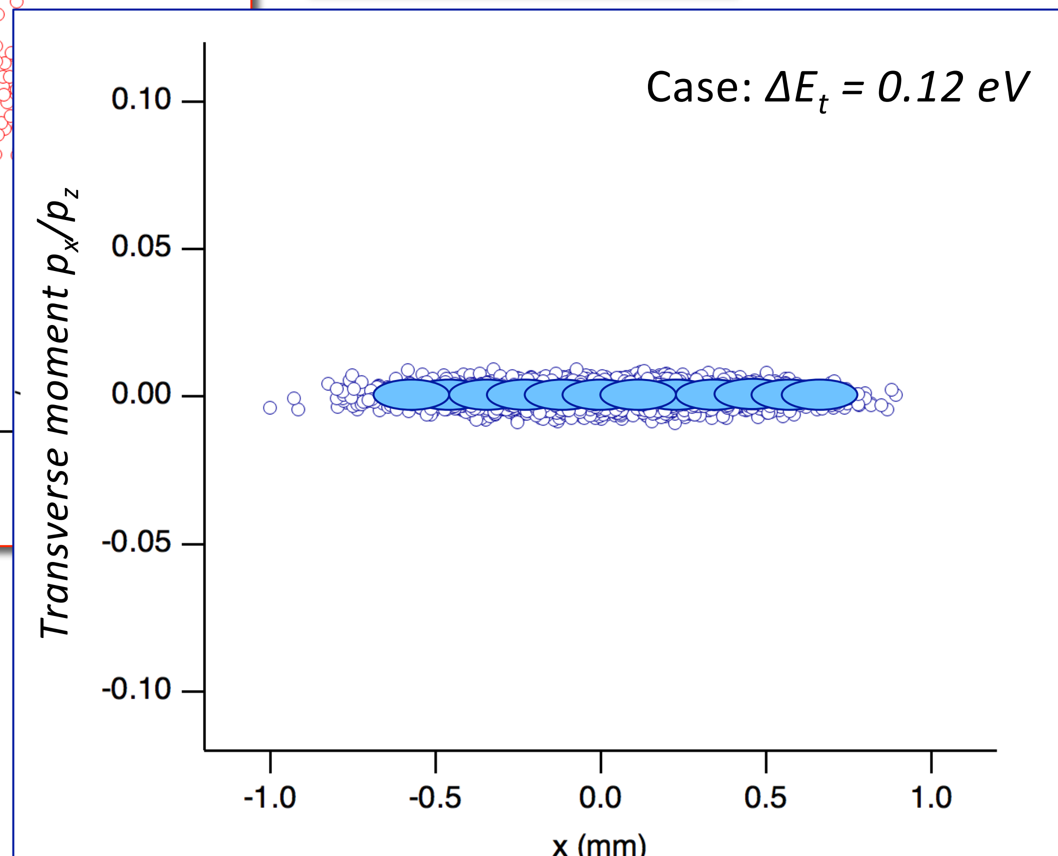
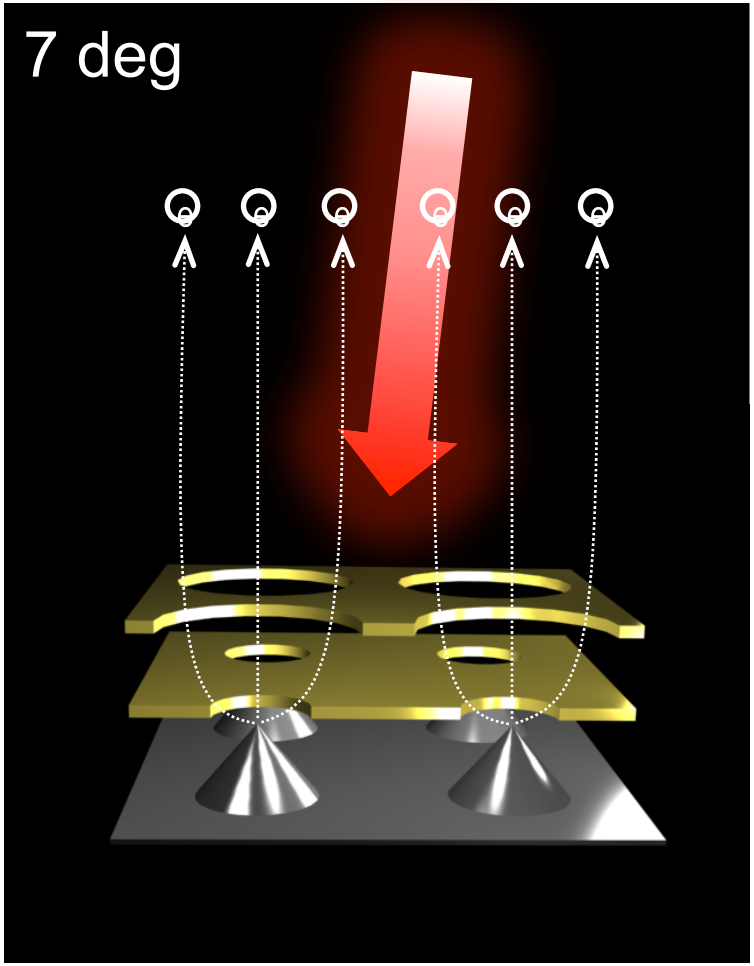
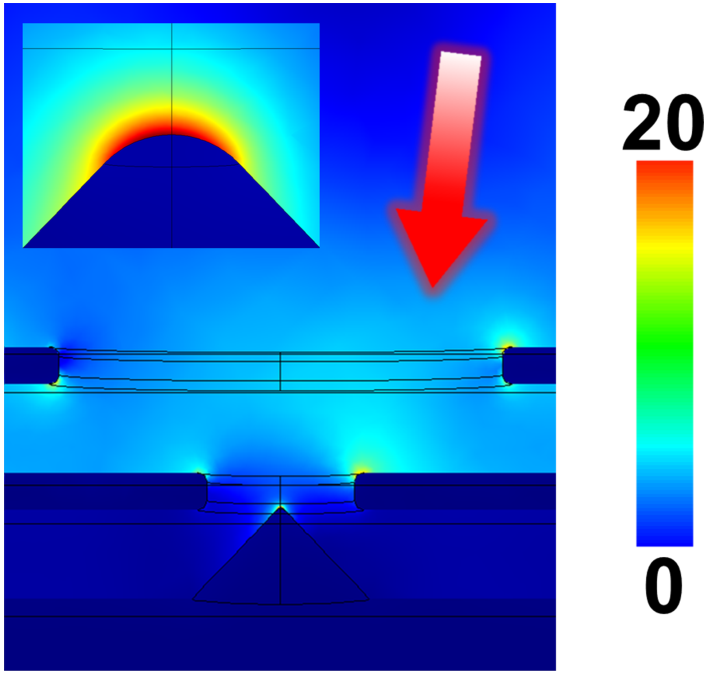




SPP-enhanced tip-laser coupling



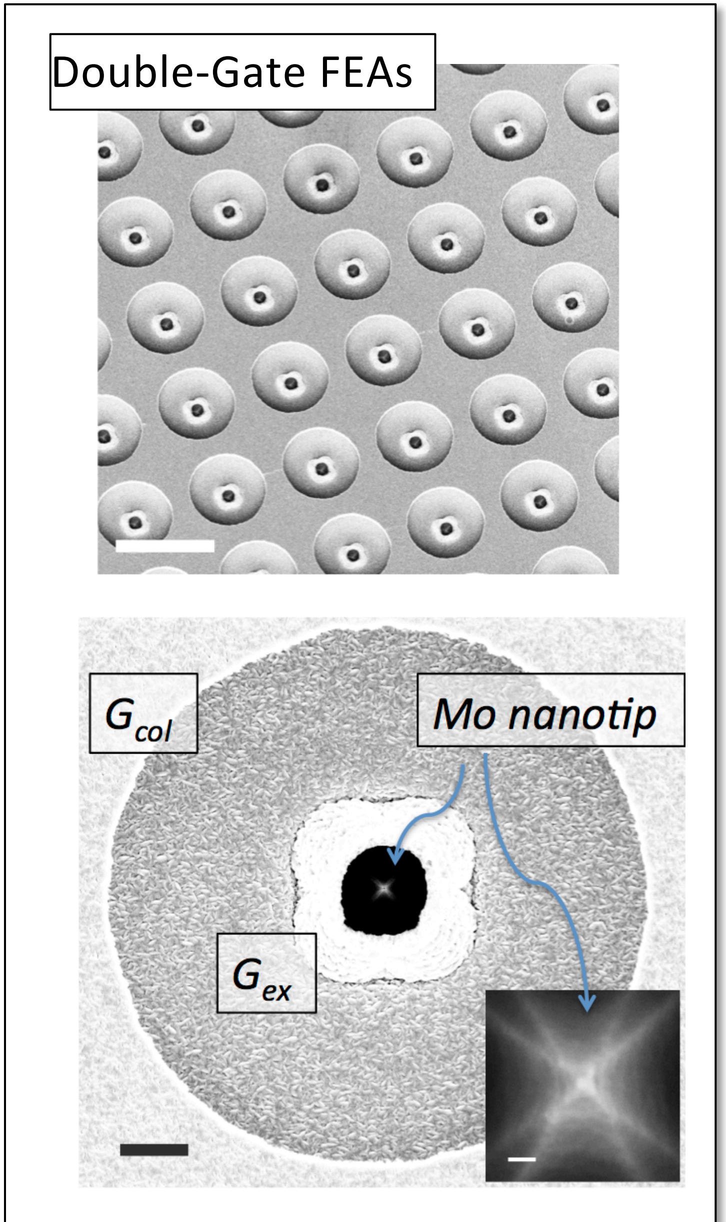


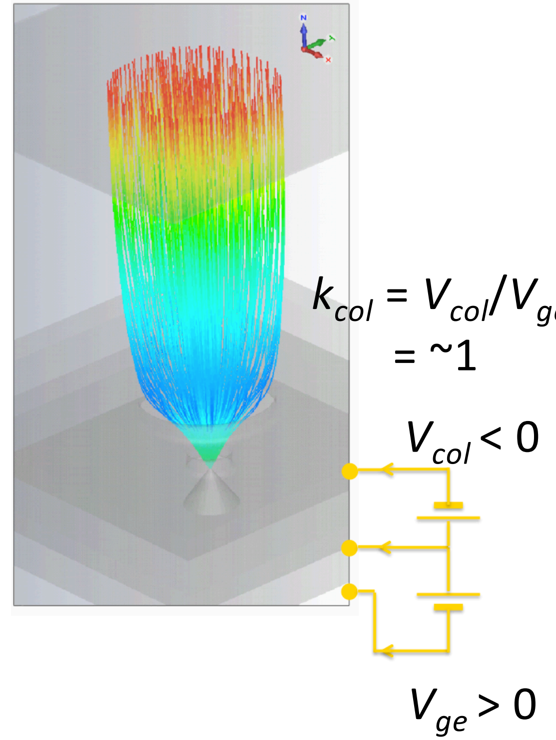
- 10^6 emitters, 1 µm-pitch, NIR (800 nm) excitation
- Copper double-gate struc. to support surface plasmon
- polariton => enhanced tip exitation

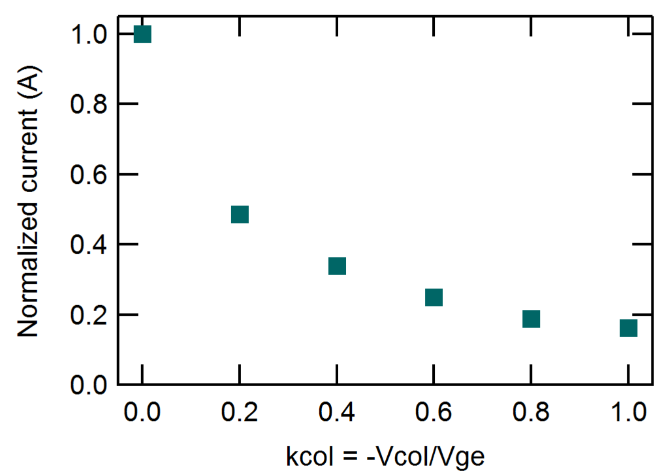
- Predicted electron yield ~ 10^{-5},
- Requiring NIR pulse energies of ~25 µJ for 200 pC.

(APL 2008/2009/2011-2, SciRep 2012, APEX 2013, JVST2015)

Field emitters…for accelerators?







FEA for accelerators?

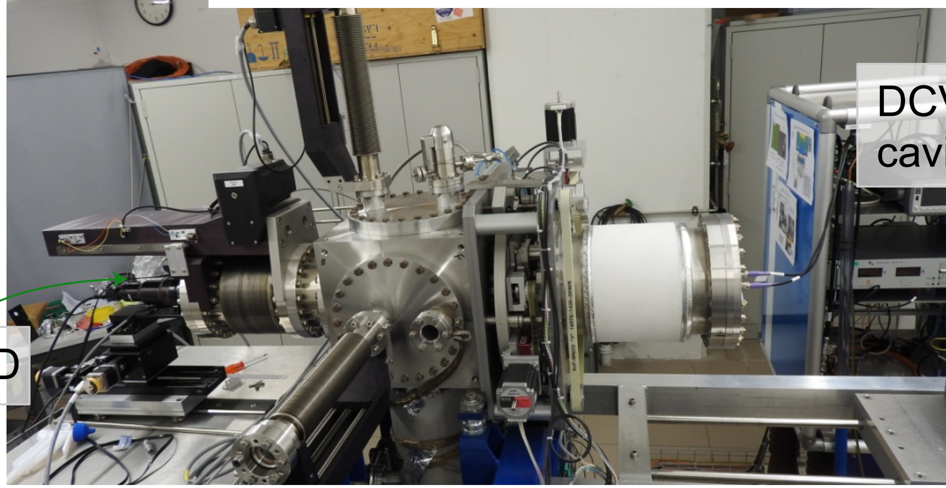
I. Challenges of double-gate FEAs

- Quenching of emission current by "collimation"
  => "engineered" gate structure
  (APL 2011, JAP 2012/2013, JVST 2015-1/2015-2)
- Non-uniformity of the tip-sharpness
  => Ne conditioning for selective blunting (APL 2011-1, JAP 2013)

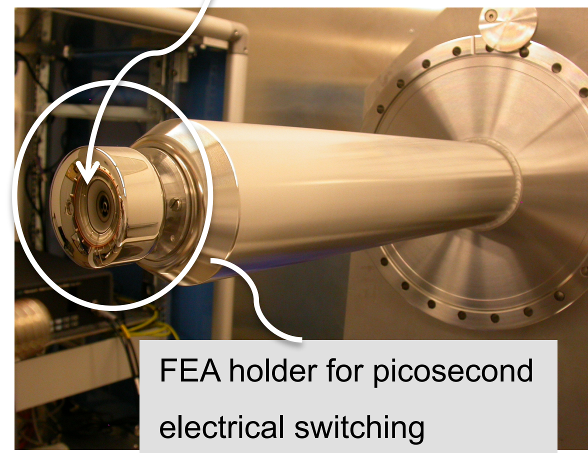
II. Requirement for accelerator applications?

- High current & short pulse
  => Field emission of NIR exited (single) FEA,
  w/surface-plasmon enhancement
  (APL 2008/2009/2011-2, SciRep 2012, APEX 2013, JVST2015)
- High gradient compatibility
  => Tested (w/single-gate FEA) up to ~30 MV/m (JVST 2011, PoP 2011)
- Emittance => Is it small?

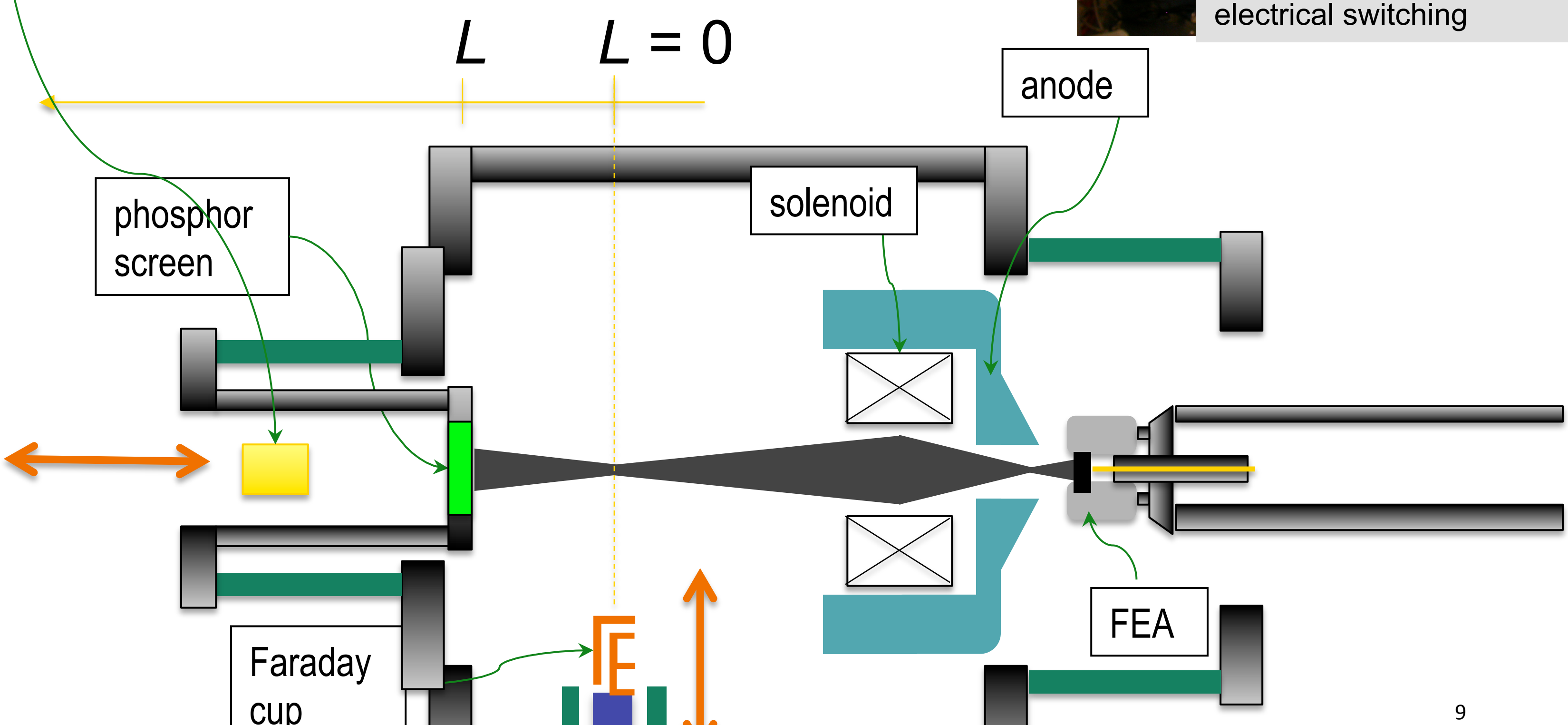
FEA characterization in a dc gun



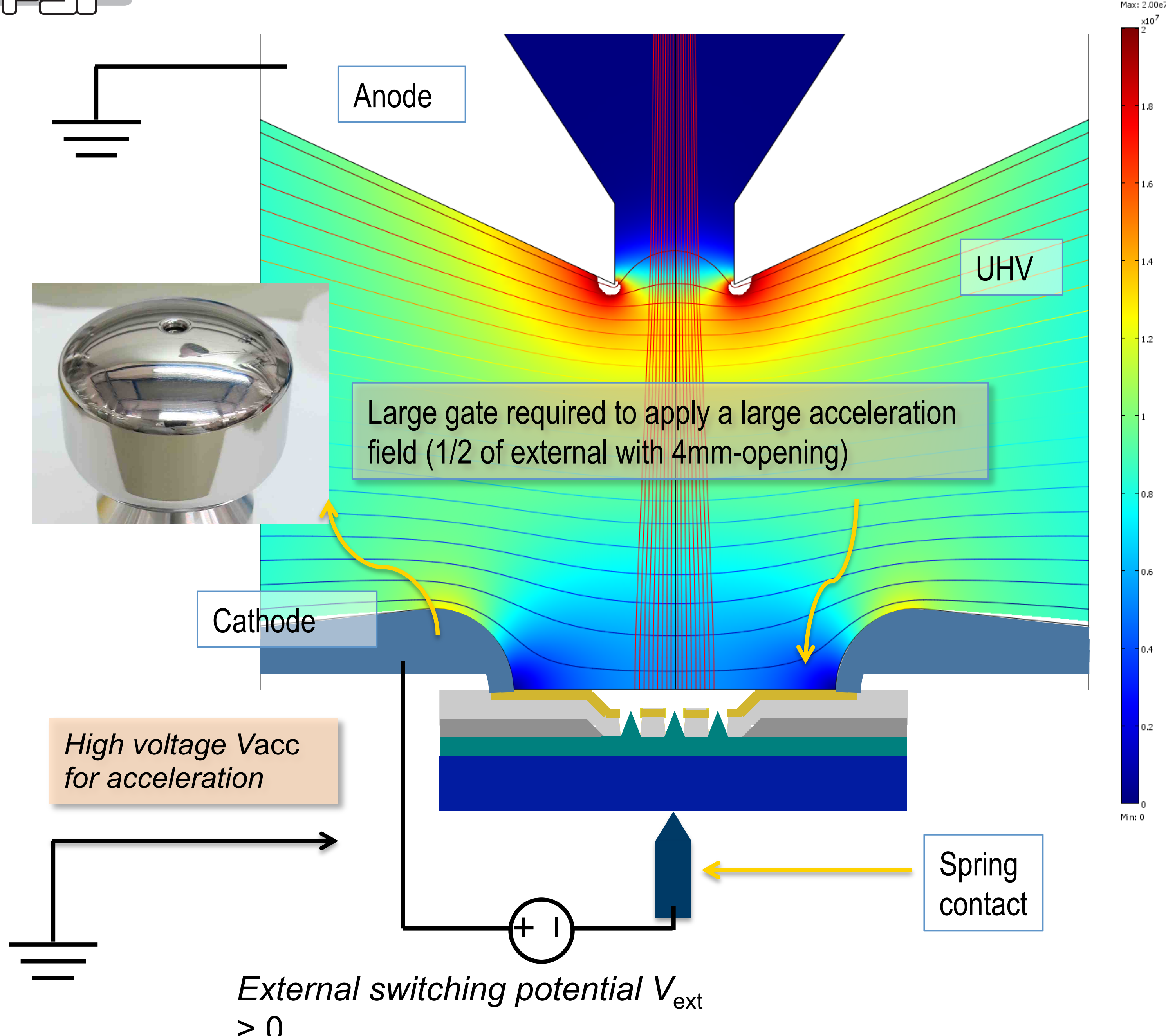
FEA sees the acceleration from the 4 mm-opening of the holder



FEA holder for picosecond electrical switching



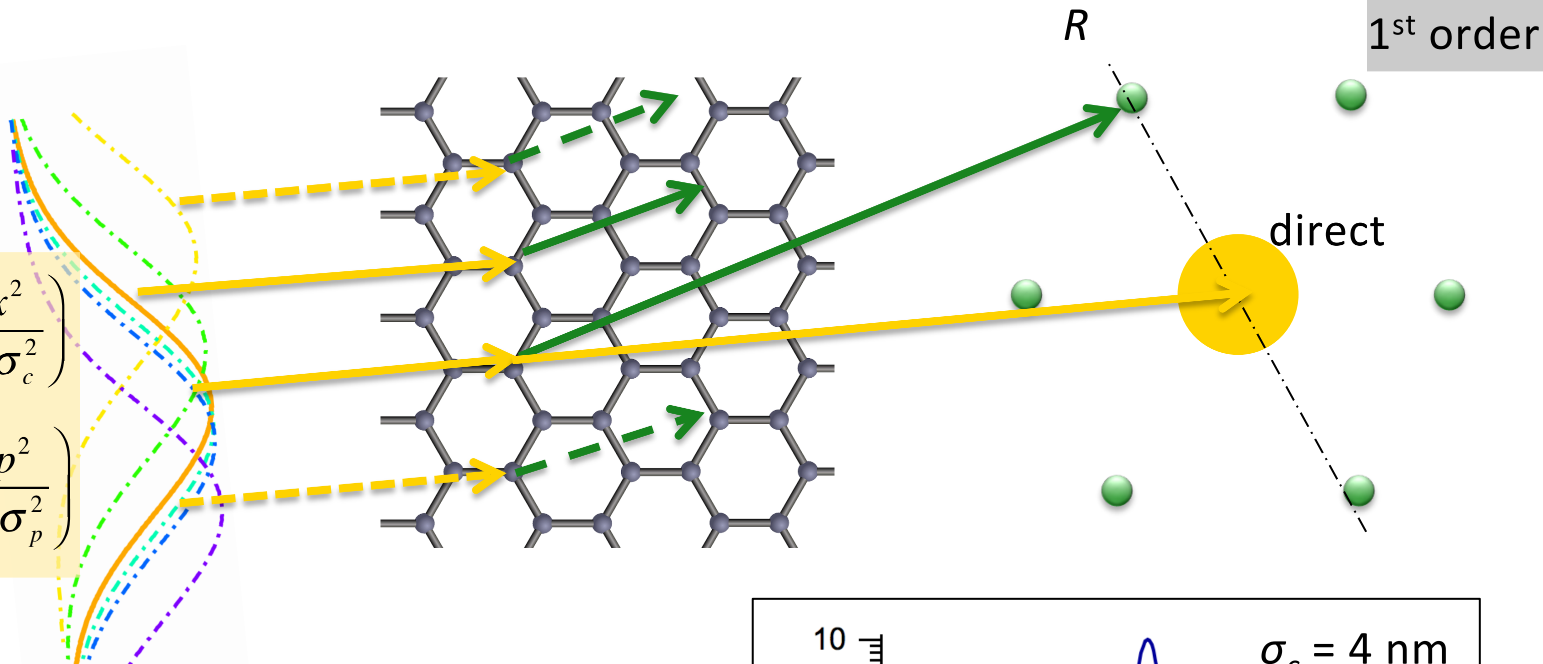
FEA integration to DC gun



Is FEA beam coherent?...test with diffraction

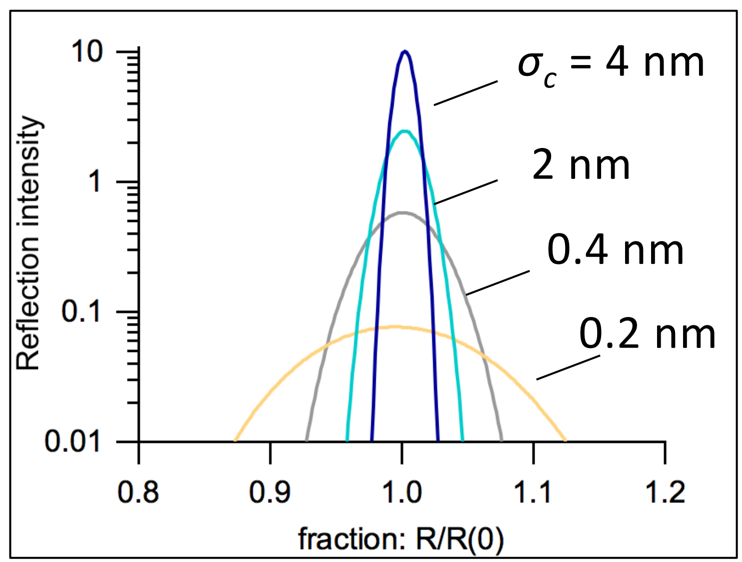
$$\exp\left(-\frac{x^2}{2\sigma_c^2}\right)$$

$$\sim \exp\left(-\frac{p^2}{2\sigma_p^2}\right)$$



Use graphene as coherence ruler:

***Longer** coherence length*
(σ_c = rms coherence length)
=> Sample more lattices
*=> **Sharper** diffraction spot*



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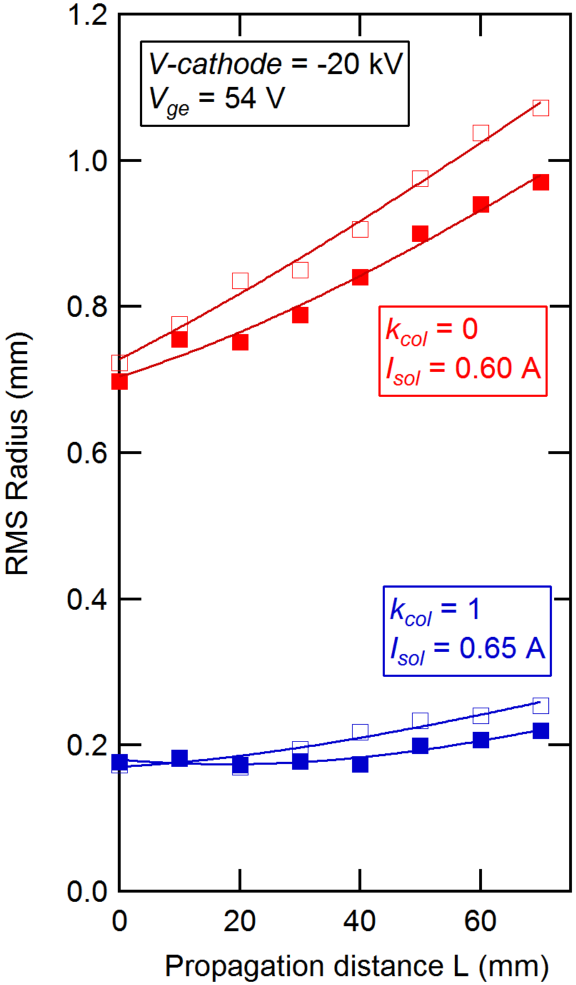
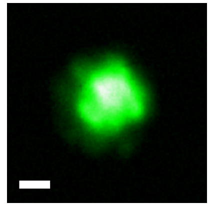
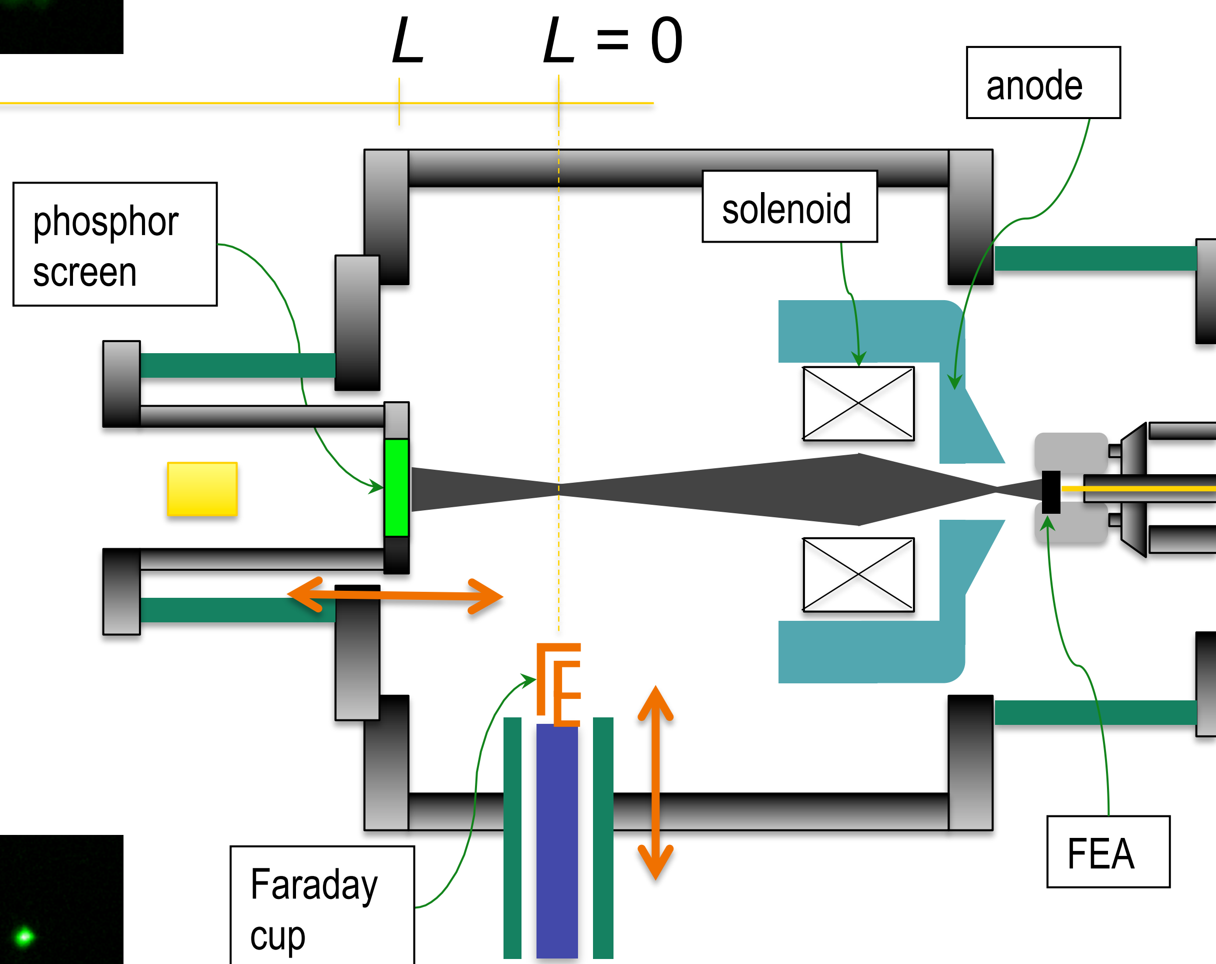
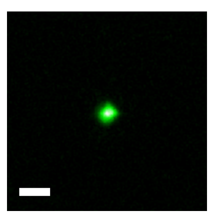
L-scan





Focused beam (by solenoid)
[un-collimated, kcol = 0]





Focused beam
[collimated, kcol = 1]

Reduction of transverse emittance

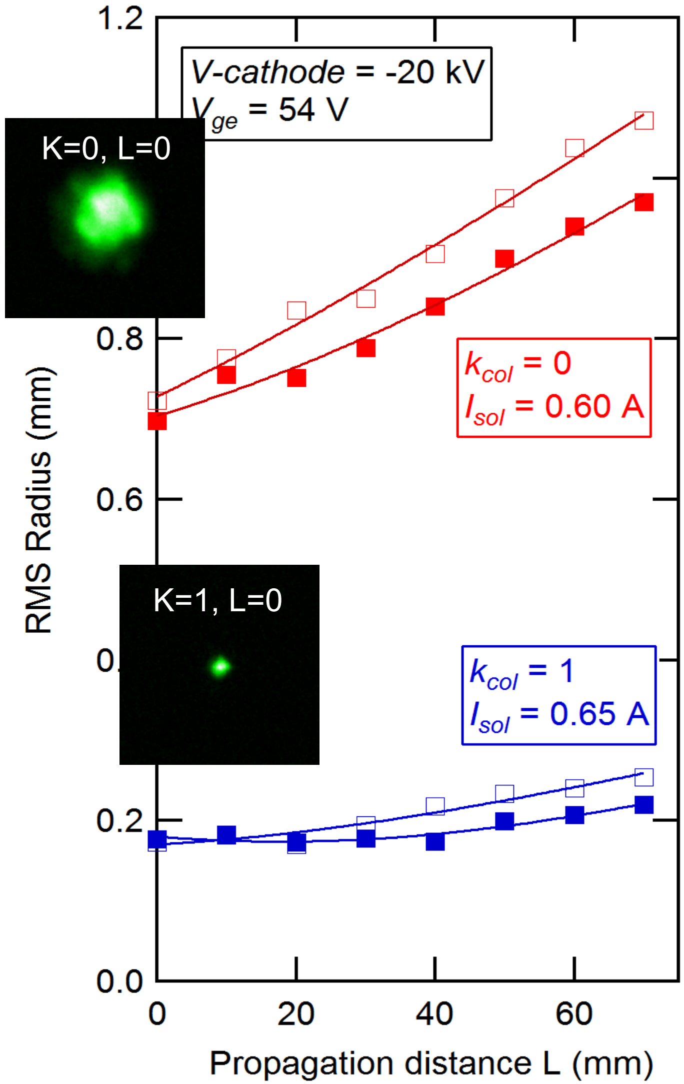
$$\sigma_x^2(L) = \left\langle x^2 \right\rangle_0 + 2\left\langle xx' \right\rangle\Big|_0 L + \left\langle x'^2 \right\rangle_0 L^2$$

$$\varepsilon_x = \beta\gamma\sqrt{\left\langle x^2 \right\rangle\left\langle x'^2 \right\rangle - \left\langle xx' \right\rangle^2}$$

$$\gamma = 1/\sqrt{1-\beta^2} = 1.04 \qquad \text{(20 kV)}$$

$$\beta = v_{long}/c \sim 0.27$$

$$\varepsilon_x = R_{rms}\left(v_{x,rms}/c\right)$$



Uncollimated Beam (k=0)

ε = 1.2 μm

Collimated beam (k=1)

ε = 0.1 μm

Reduction of transverse emittance

$$\sigma_x^2(L) = \langle x^2 \rangle_0 + 2\langle xx' \rangle\big|_0 L + \langle x'^2 \rangle_0 L^2$$

$$\varepsilon_x = \beta\gamma\sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle xx' \rangle^2}$$

$$\gamma = 1/\sqrt{1-\beta^2} = 1.04 \qquad \text{(20 kV)}$$

$$\beta = v_{long} / c \sim 0.27$$

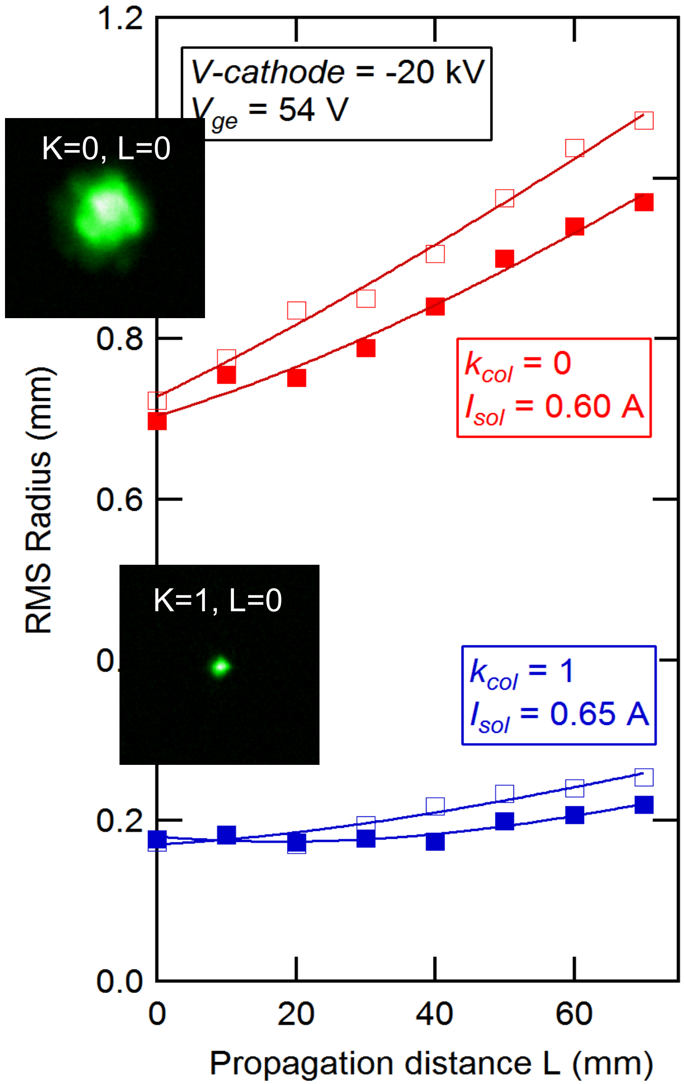
$$\varepsilon_x = R_{rms}\left(v_{x,rms}/c\right)$$

$$E_t = \frac{m}{2}\left(\upsilon_{x,rms}^2 + \upsilon_{y,rms}^2\right)$$

11.8 eV (k = 0)

0.13±0.06 eV (k = 1)

ε/σ = 0.5 μm/mm-rms



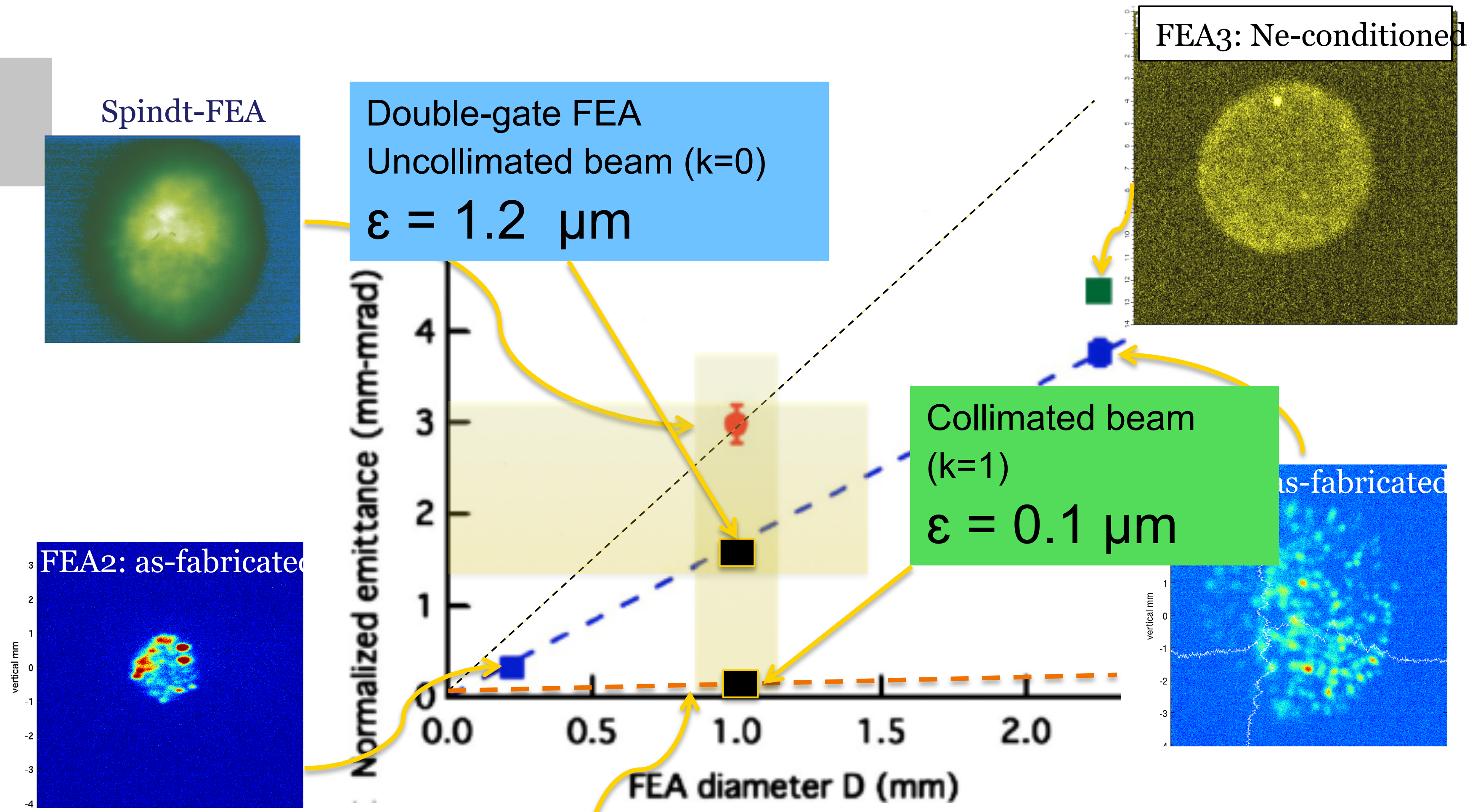
Uncollimated Beam (k=0)

ε = 1.2 μm

Collimated beam (k=1)

ε = 0.13 μm

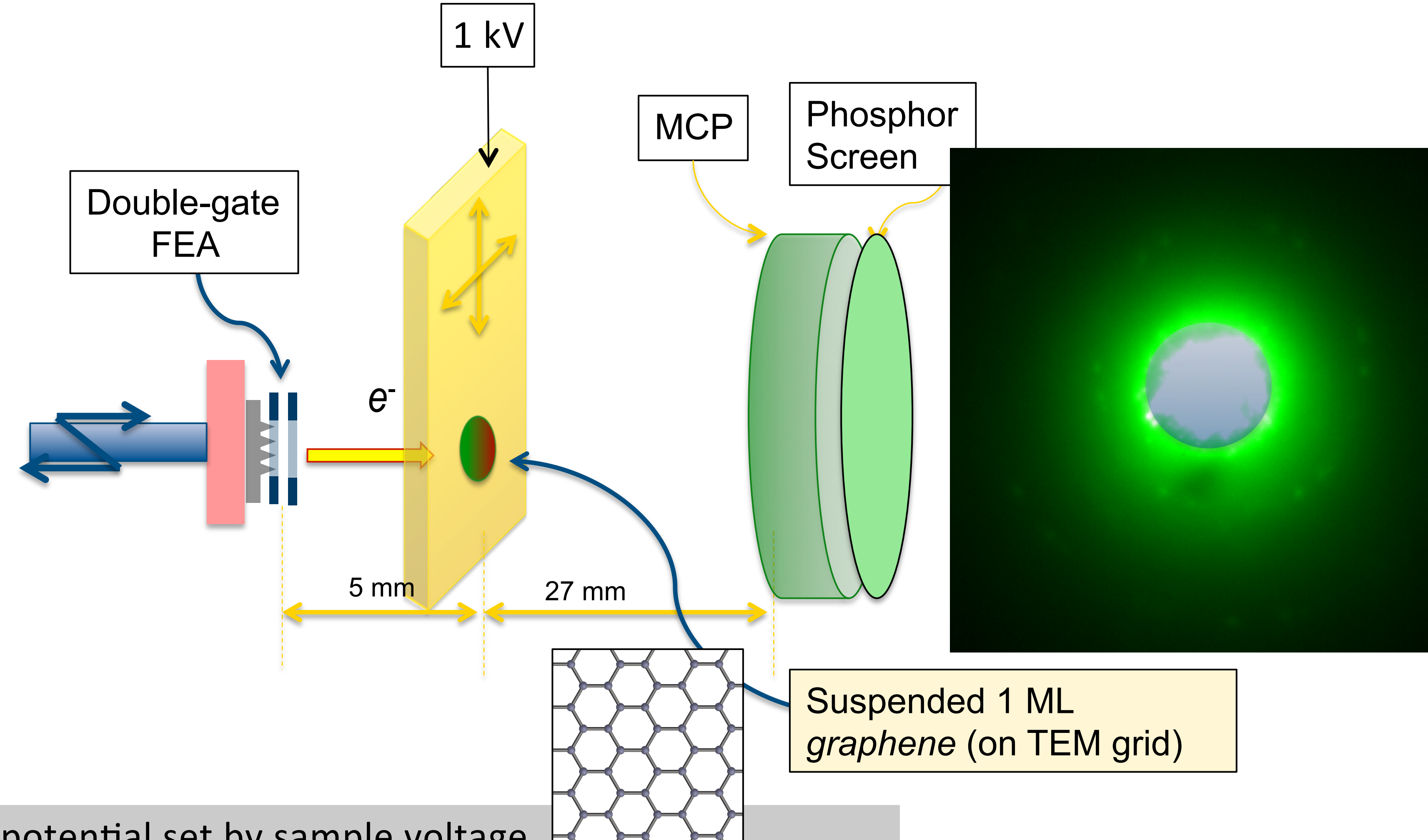
Reduced emittance: Double-gate FEA?



Target: below ~0.1 μm (for D = 1 mm)

$$\varepsilon = R_{rms}\left(v_{t,rms} / c\right)$$

Is FEA beam coherent?...test with diffraction



- Beam potential set by sample voltage
- No additional optics ~ ***relying on the small velocity spread of collimated double-gate FEA beam***

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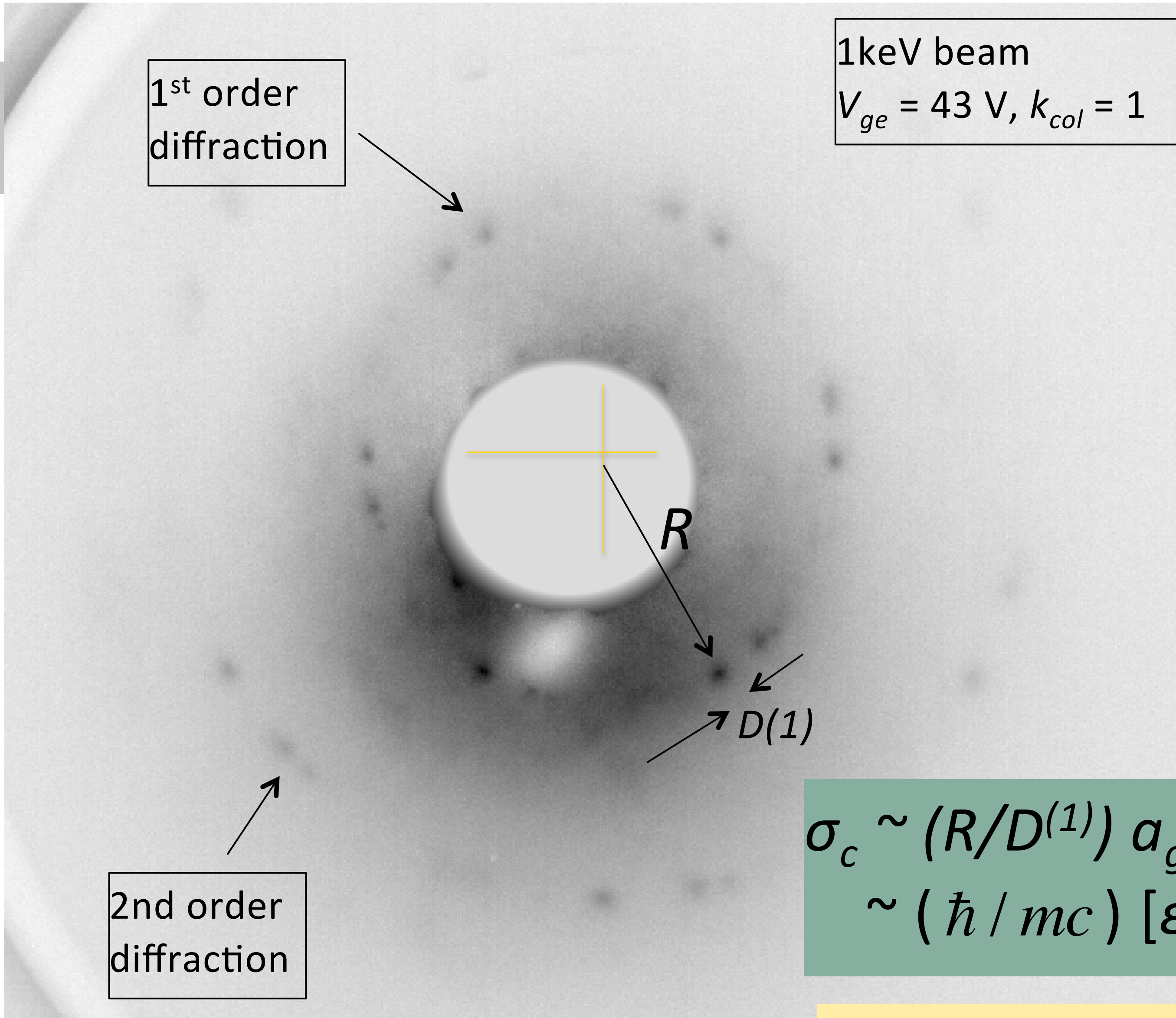
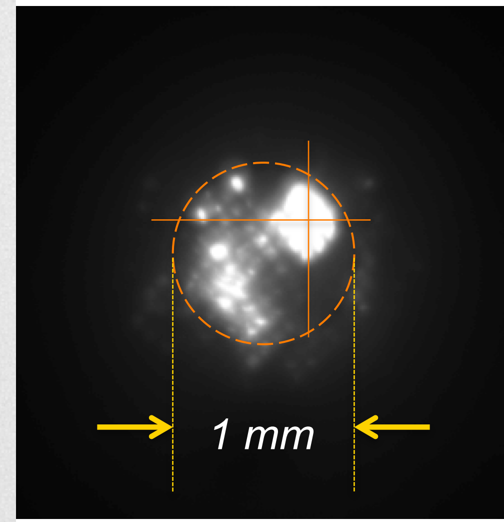
E-diffraction from monolayer graphene



Direct beam



$\sigma_c \sim (R/D^{(1)})\, a_{gp} = 0.8\ nm$

$\sim (\hbar / mc)\, [\varepsilon_x/\sigma_x]^{-1}$

⇔ ε/σ = 0.5 μm/mm-rms

Ideal emittance of field emission beam?

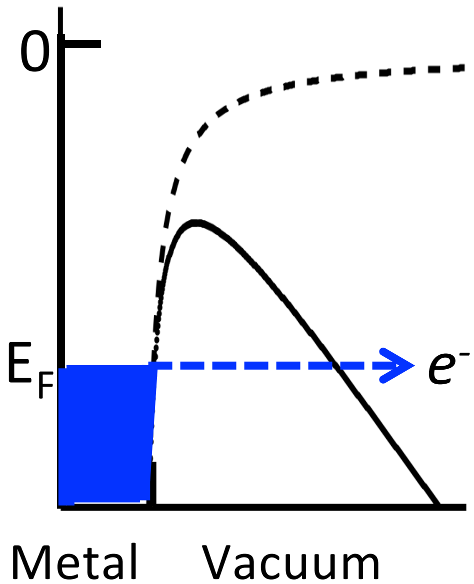
Transmission

$$\ln T(E) = -G(E) \approx -G_F + \frac{E - E_F}{d_F}$$

Field emission current (density)

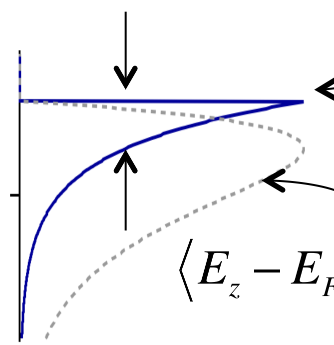
$$J = \int j(E)\,dE$$

$$j(E) \approx j_0 e^{E/d_F} / \left(1 + e^{E/k_B T}\right)$$



Average *total* energy

$$\langle E - E_F \rangle = \frac{\int (E - E_F)\, j(E)\,dE}{\int j(E)\,dE} \approx -\pi p d_F \cot \pi p$$



Average *normal* energy

$$\langle E_z - E_F \rangle = \frac{\int (E_z - E_F)\, j(E)\,dE}{\int j(E)\,dE} \approx -d_F \left[1 + \pi p d_F \cot \pi p\right]$$

Average *transverse* energy

$$\langle E_t \rangle = \langle E \rangle - \langle E_z \rangle \approx d_F = \frac{2}{3} \frac{F_{tip}}{\tau_F b \phi^{1/2}}$$

= 0.1-0.2 eV at F_{tip} = 2-5 GV/m

Intrinsic transverse emittance

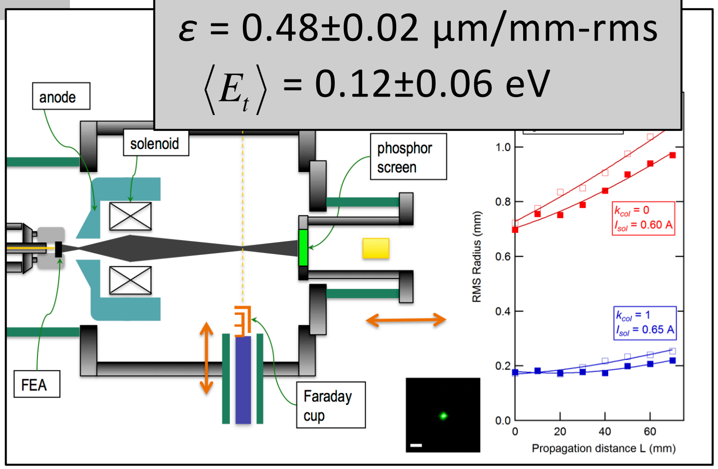
$$\varepsilon / \sigma_s = \sqrt{\frac{d_F}{mc^2}}$$ = 0.45-0.63 µm/mm-rms at F_{tip} = 2-5 GV/m

Summary

Beam measurement

ε = 0.48±0.02 μm/mm-rms

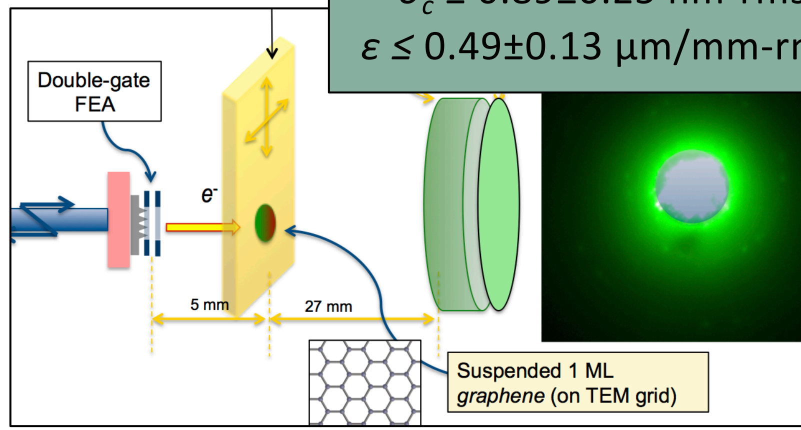
$\langle E_t \rangle$ = 0.12±0.06 eV



Low-energy electron diffraction

$\sigma_c \geq$ 0.89±0.25 nm-rms

$\varepsilon \lesssim$ 0.49±0.13 μm/mm-rms

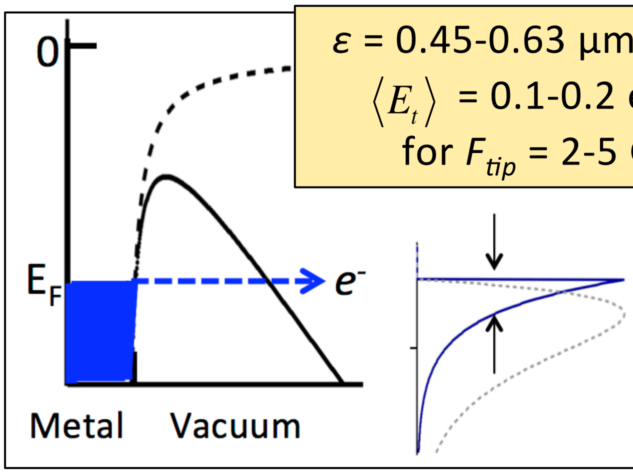


Electron distribution model (theory)

ε = 0.45-0.63 μm/mm-rms

$\langle E_t \rangle$ = 0.1-0.2 eV

for F_{tip} = 2-5 GV/m



- Definite advantage of our double-gate FEA for applications that demands low phase space volume e-beam.
- Competitive emittances as the state-of-the-art photocathode excited by UV
- All metal nanotip array: importance of small voltage dispersion (no ballast resisters)

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Vacuum Nanoelectronics group

Laboratory for Micro- and Nanotechnol.

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- Anna Mustonen, Dr. (former student)
- Prat Das Kanongo, Dr. (former PD)
- Youngin Oh (former PD)
- Mahta Monshipouri
- Chiwon Lee (also at MPI)
- Jens Gobrecht (LMN lab head)

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