Workshops on X-band and high gradients: collaboration and resource

International workshop on breakdown science and high gradient technology 18-20 April 2012 in KEK

https://indico.cern.ch/conferenceDisplay.py?confId=165513

Addressed getting high gradients in rf accelerators – CLIC, FELS, medical accelerators, Compton sources, accelerating structures, photo-injectors, deflecting cavities, power sources, components etc.

The next one will be held in Trieste on 3-6 June 2012.

MEVARC3 – Breakdown physics workshop hosted this year by Sandia National Laboratory

Summary | Lodging & Location | Agenda

3rd International Workshop on Mechanisms of Vacuum Arcs (MeVArc 2012)

Monday, October 01, 2012 6:00 PM - Thursday, October 04, 2012 (Mountain Time)

Hotel Albuquerque at Old Town
1-866-505-7829
800 Rio Grande Blvd., NW
Albuquerque, New Mexico 87104
United States
Map and Directions

Vacuum arcs are a concern in essentially every vacuum electronic device. Sometimes they form the basis for device operation, but all too often they are the primary failure mode. They are often described as high voltage breakdown (HVB) and electrostatic discharge (ESD) as well. The purpose of this workshop is to bring together scientists and engineers to discuss the latest improvements in our understanding of vacuum arcs, including their initiation and evolution.

Register Now

Contact Information

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505-284-8861

Technical
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505-284-6376

Albuquerque International Balloon Fiesta
October 6-13, 2012

Specific topics include:

- High electric field gradient devices (e.g., accelerators)
- Effect of electrode material processing
- Material/electrode damage characterization
- Primary mechanisms for discharge
- Diagnostic methods for interrogating breakdown, surface structure, plasma constituents, etc.
- Modeling and simulation

We welcome new areas of investigation in addition to the above. The multidisciplinary nature of vacuum arcs and vacuum devices provides a rich environment for finding physics of shared interest from multiple sources.

Past workshops:

- 1st workshop, May 2010, CERN
- 2nd workshop, June 2011, Univ. Helsinki

Organizers:

- Matt Hopkins (mmhopki@sandia.gov), Sandia National Laboratories, USA
- Flyura Djurabekova (flyura.djurabekova@helsinki.fi), University of Helsinki, Finland
- Walter Wuensch (walter.wuensch@cern.ch), CERN, Switzerland
- André Anders (aanders@lbl.gov), Lawrence Berkeley National Laboratory, USA

http://www.regonline.com/builder/site/default.aspx?EventID=1065351
https://indico.cern.ch/conferenceDisplay.py?ovw=True&confId=208932

MEVARC3

Focused on the physics of vacuum arcs.

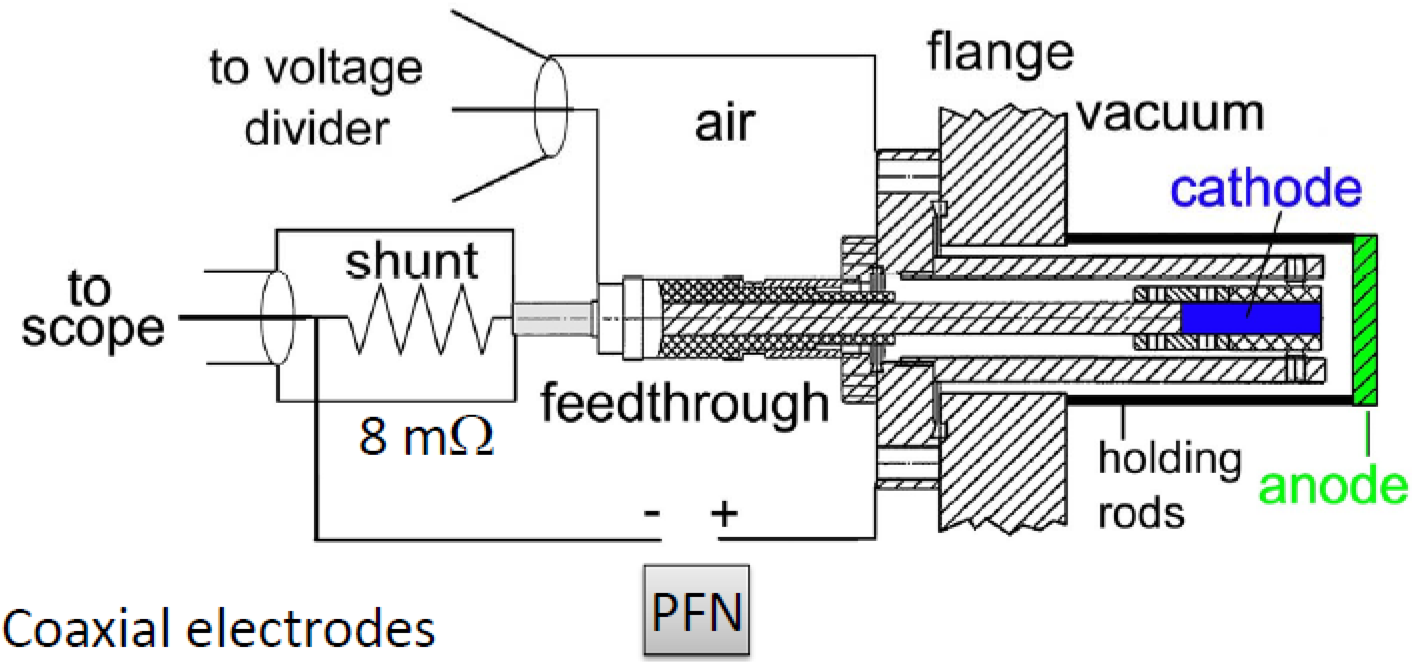
Representatives from many communities: accelerators, fast switches, satellites, micro-scale gaps, vacuum interrupters.

Many specialities: rf, plasma, material science, simulation and diagnostics

Many issues: breakdown, field emission, gas discharge, multipactor, dc and rf.

Next one planned for late 2013, early 2014

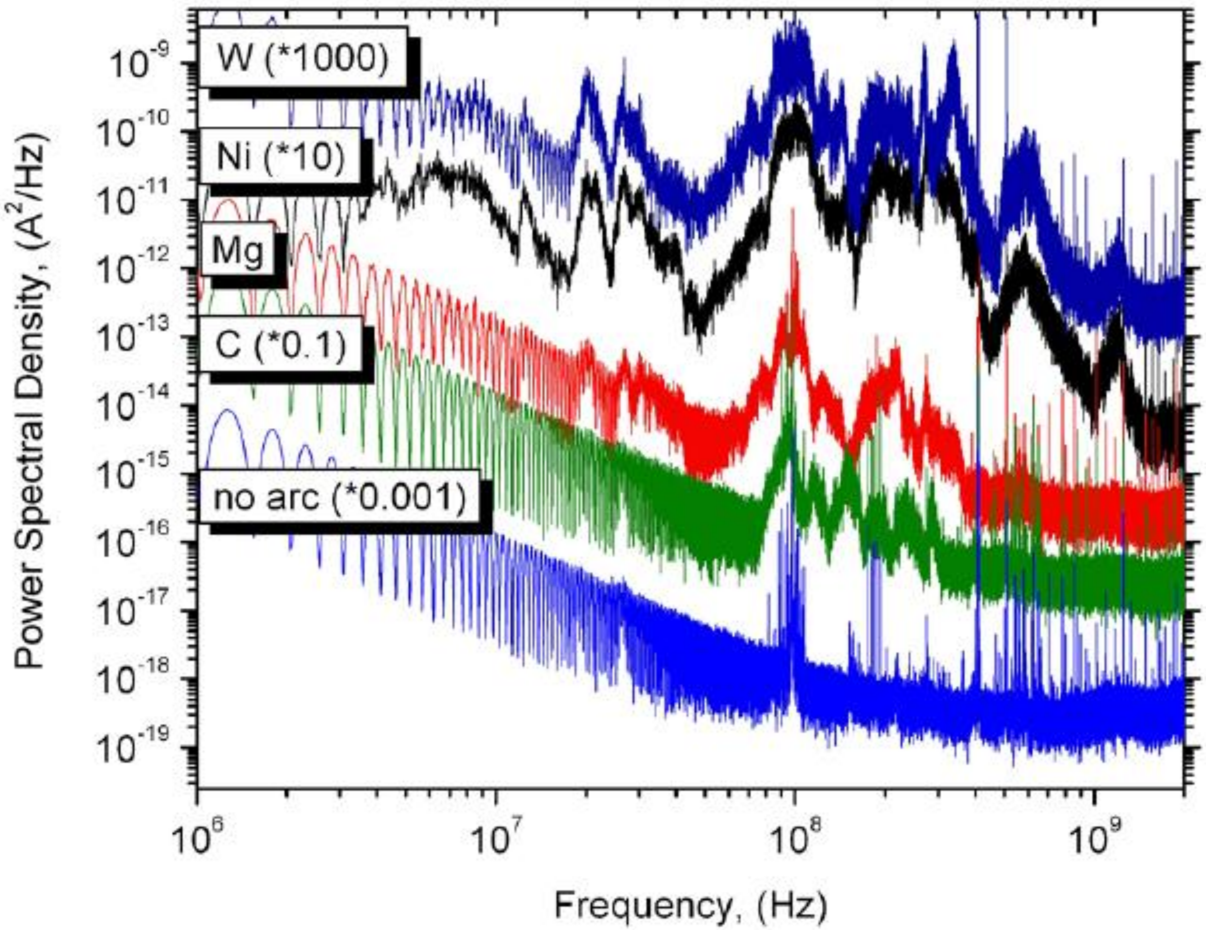
Experimental Setup For Arc Noise Measurements



- Coaxial electrodes
- fast digital oscilloscopes
- selecting only the “flat” potion of arc discharge pulse
- Fast Fourier Transform of each individual data set
- Repeat all steps 10 times and produce average

A. Anders, et al., Appl. Phys. Lett. 86 (2005) 211503.

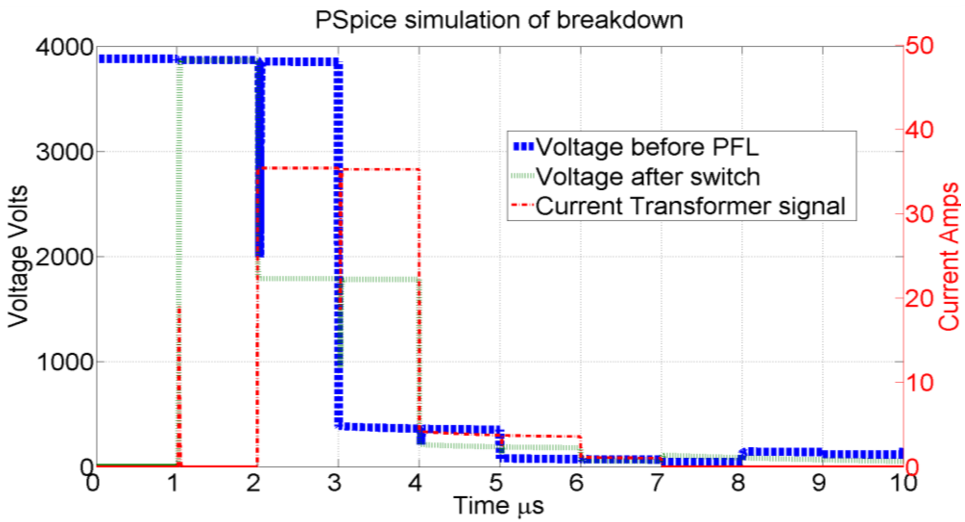
Power Spectrum of Arc Current for Different Materials

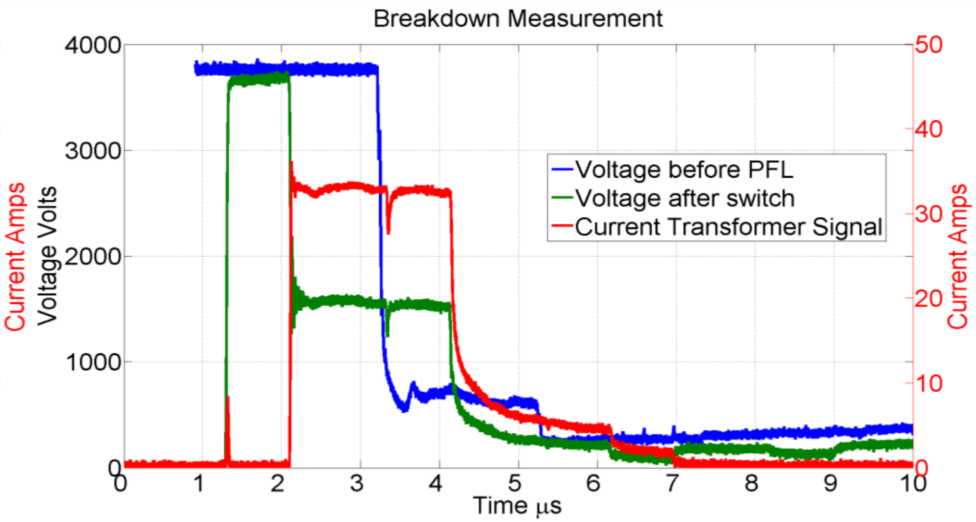


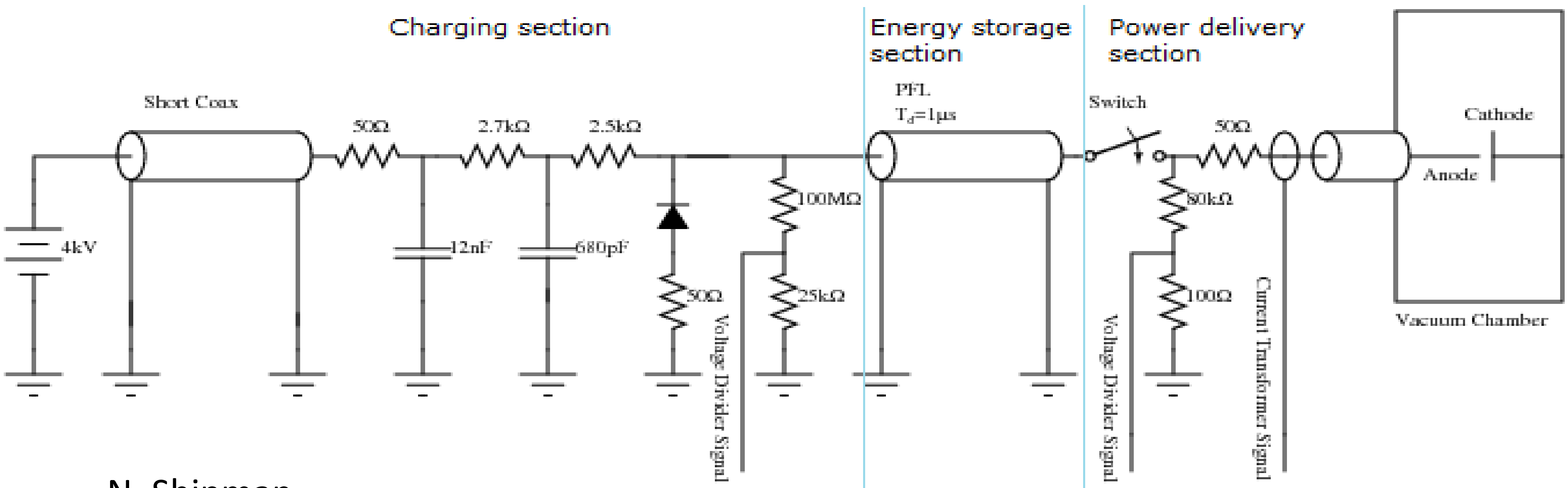
20 A

A. Anders, E. Oks, J. Appl. Phys. 99 (2006) 103301.

The High Rep Rate System

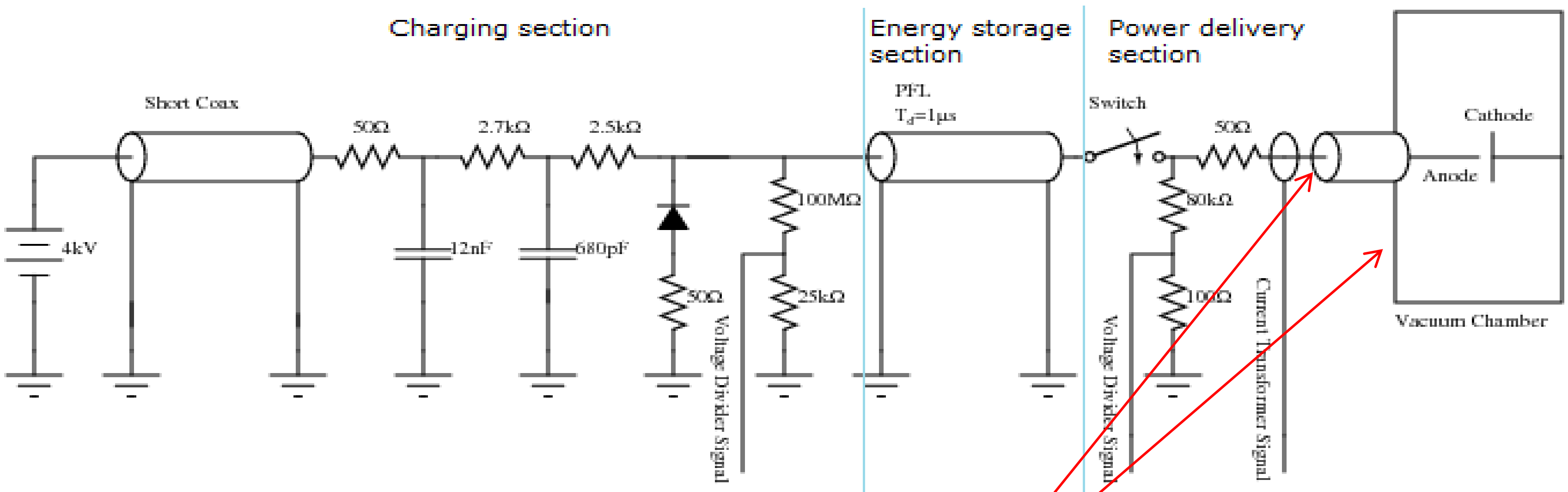


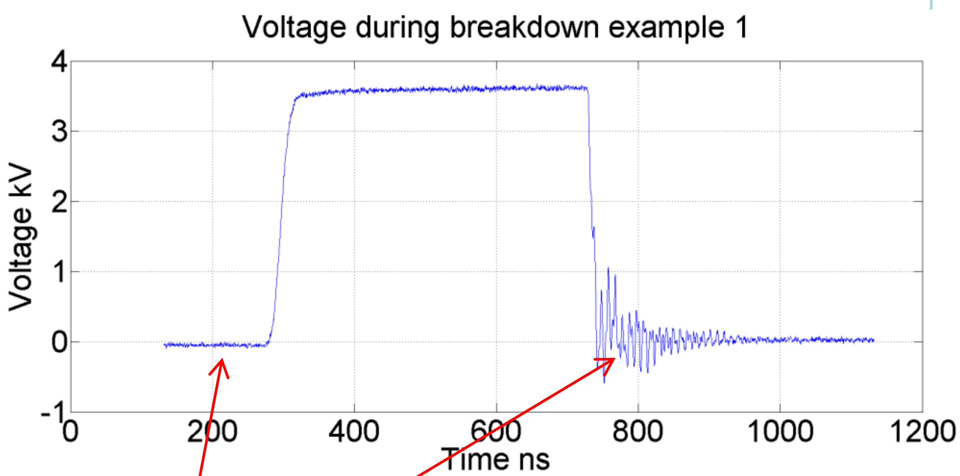




N. Shipman

Measured Burning Voltages



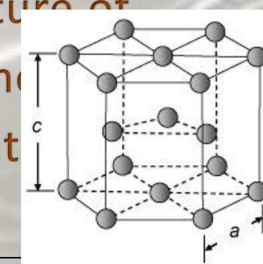


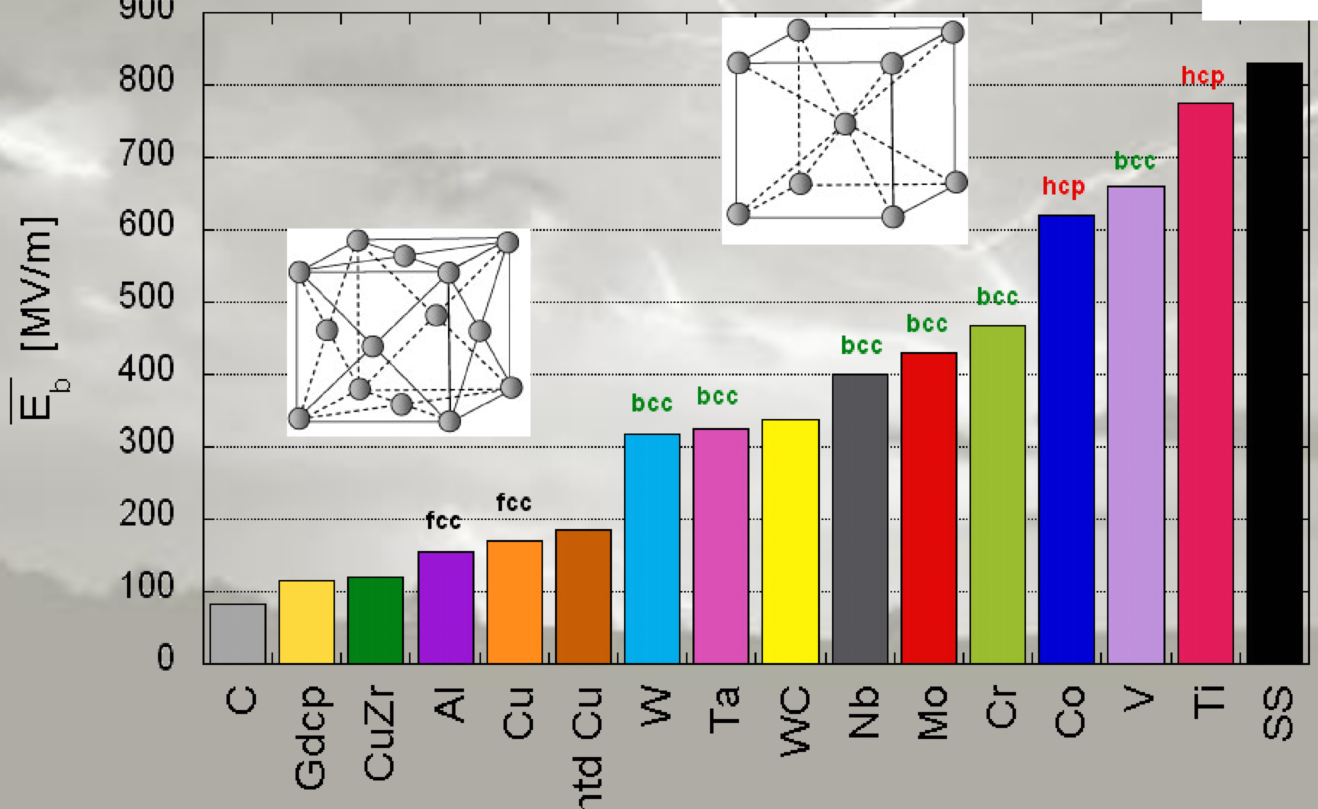
The burning voltage was measured across here.
It is the “steady state” voltage across the plasma of a spark during a breakdown at which point most of the voltage is dropped across the 50 Ohm resistor. It is a property of the material.

Subtract average voltage with switch closed from
Average voltage during breakdown after initial voltage fall.

What are the field emitters? Why do we look for dislocations?

- The dislocation motion is strongly bound to the atomic structure of metals. In FCC (face-centered cubic) the dislocation are the m and HCP (hexagonal close-packed) are the hardest for dislocat mobility.





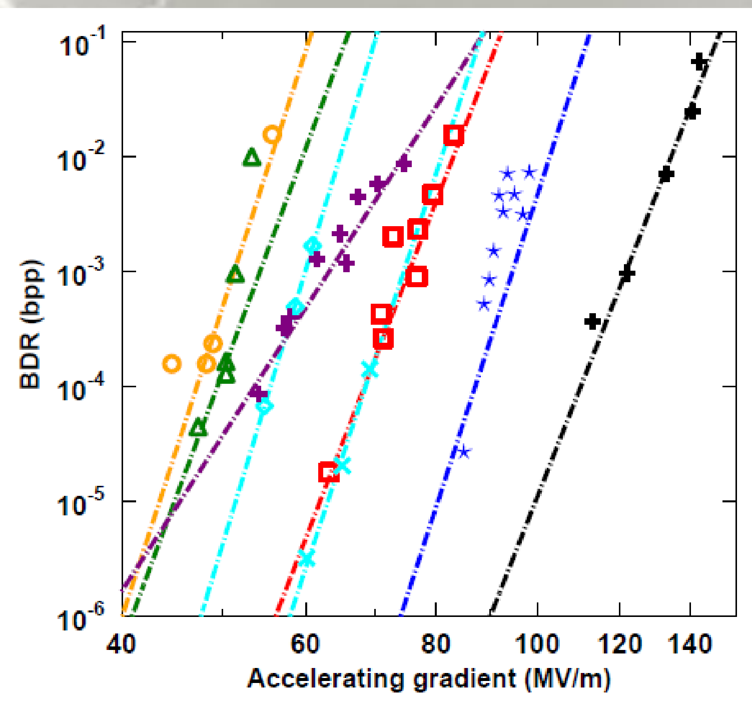
A. Descoeudres, F. Djurabekova, and K. Nordlund, DC Breakdown experiments with cobalt electrodes, CLIC-Note XXX, 1 (2010).

Dislocation-based model for electric field dependence

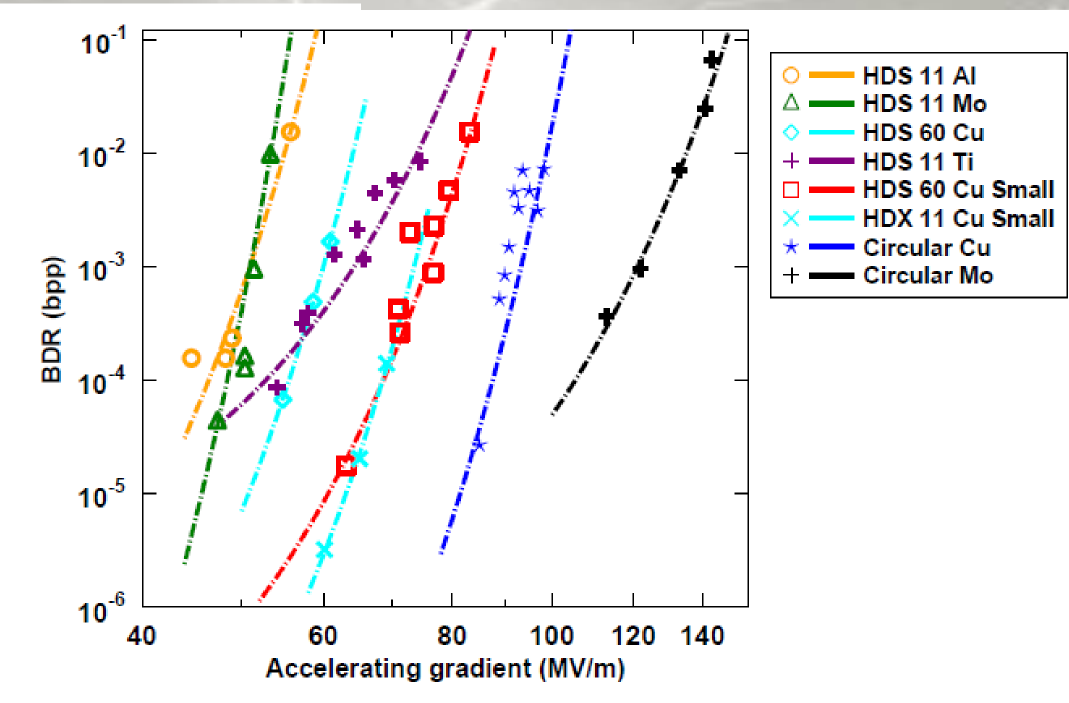
- Now to test the relevance of this, we fit the experimental data
- The result is:

$$BDR \propto c_0 e^{-(E^f - \varepsilon_0 E^2 \Delta V)/kT} = c_0 e^{-E^f/kT} e^{\varepsilon_0 E^2 \Delta V/kT}$$

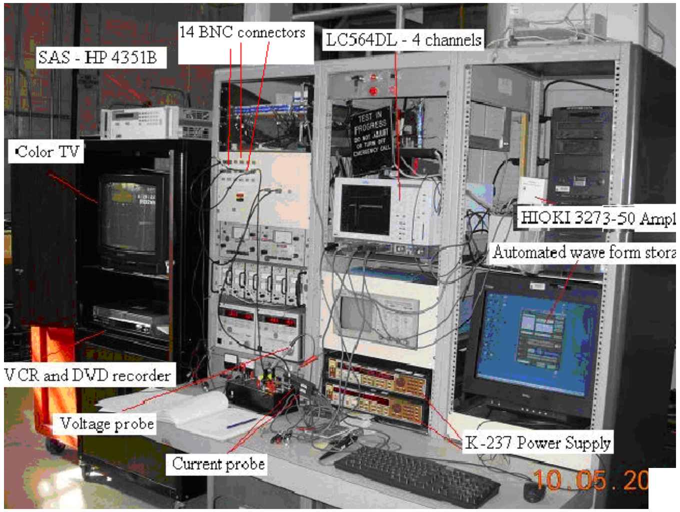
Power law fit

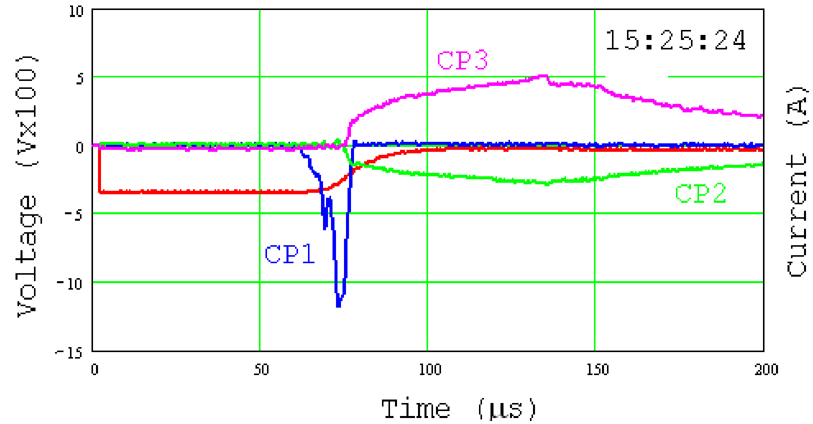


Stress model fit

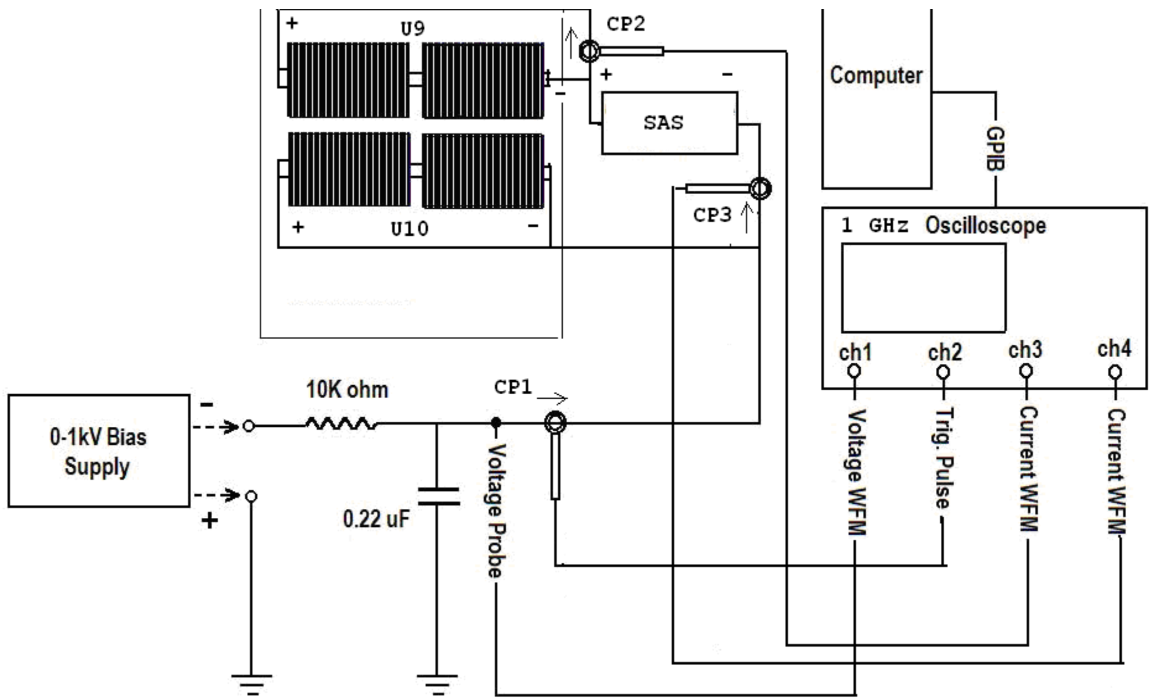


[W. Wuensch, public presentation at the CTF3, available online at http://indico.cern.ch/conferenceDisplay.py?confId=8831.] with the model.]





P=30 μTorr (Xe)

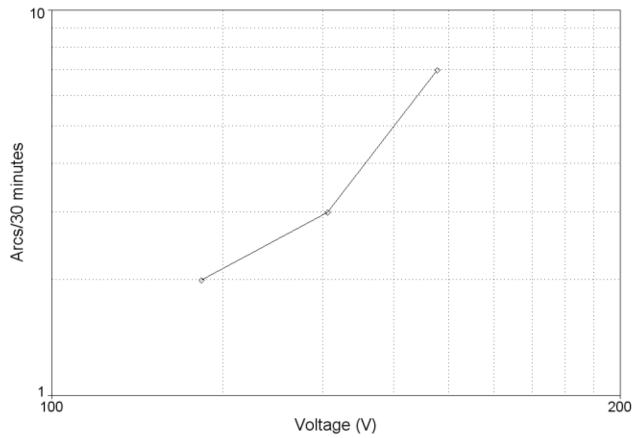


Arc in LEO plasma

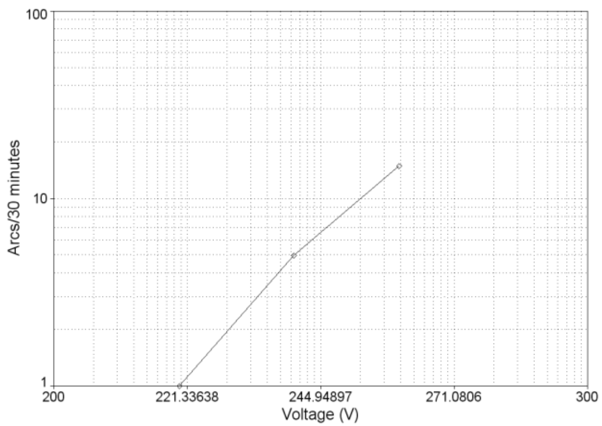
T_e=0.2-0.5 eV; n_e=10^5-10^6 cm^{-3}

Circuitry diagram for arc parameter measurements.

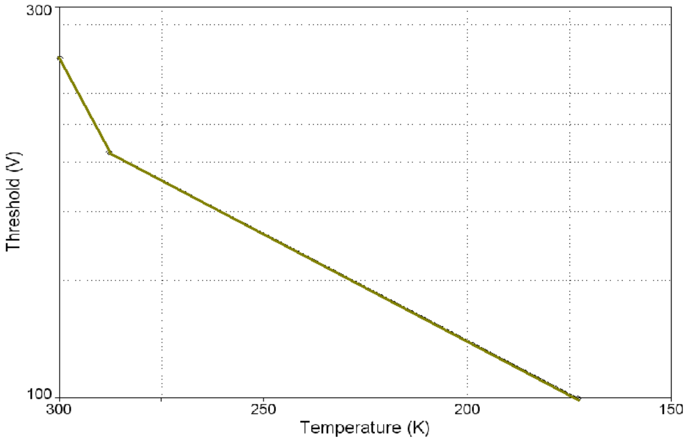
LEO



Arc rate vs. bias voltage at low temperature (-100 C).



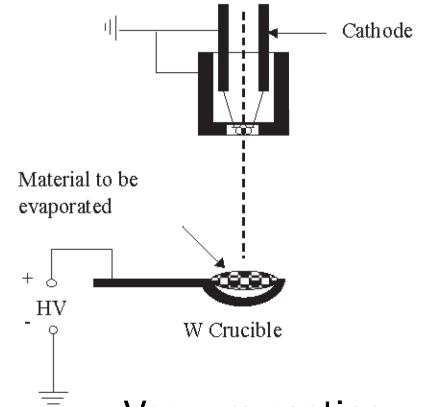
Arc rate vs. bias voltage at the temperature +10 C



Arc threshold vs. sample temperature

Applications and Model Requirements

We're interested in low temperature collisional plasma phenomena, and transient start-up of arc-based devices.



Vacuum coating

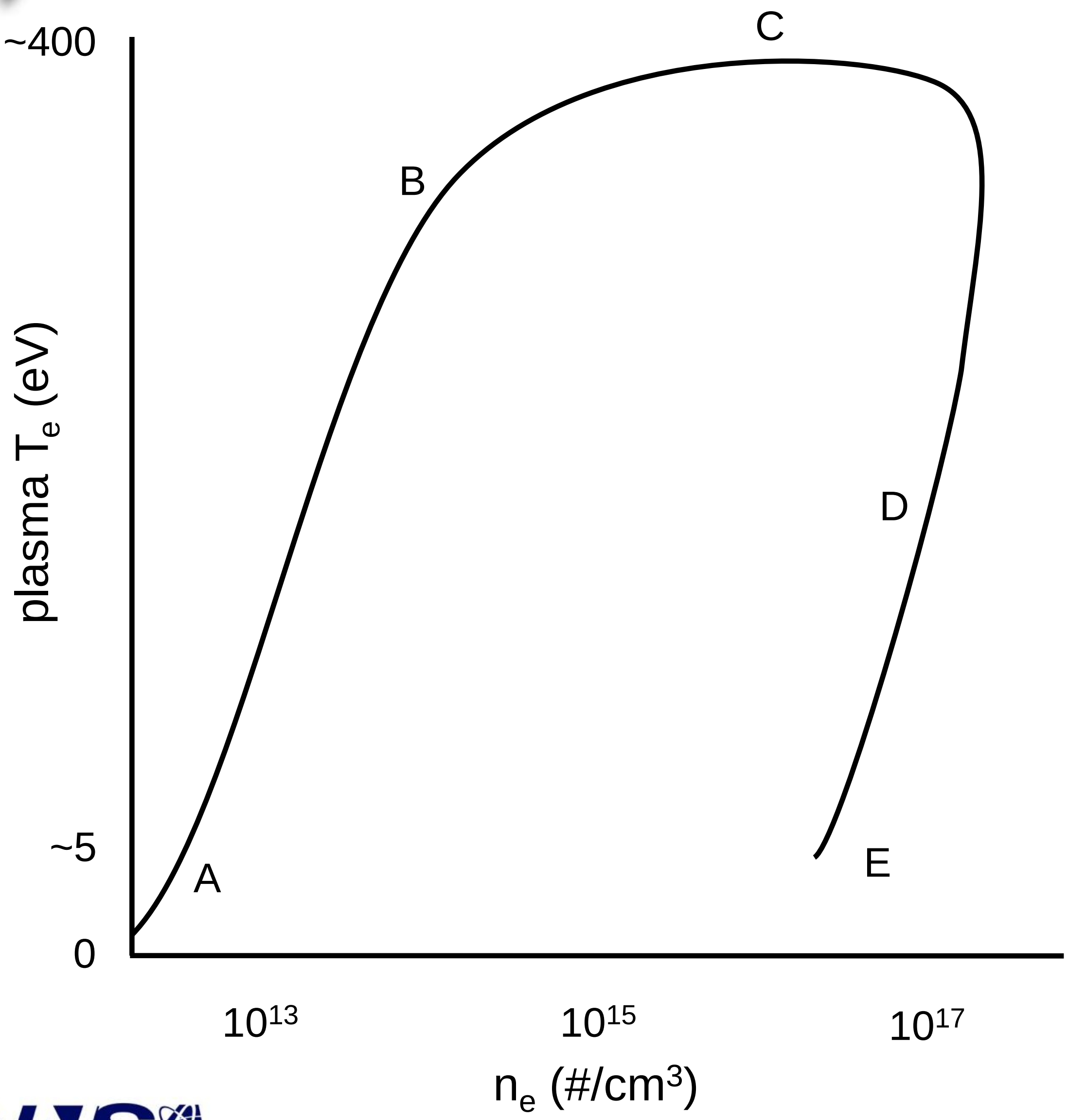
Examples:

- Vacuum arc discharge
- Plasma processing
- Spark gap devices
- Gas switches
- Ion and neutral beams

Our applications generally share the following requirements:

- Kinetic description to capture non-equilibrium or non-neutral features, including sheaths, particle beams, and transients.
- Collisions/chemistry, including ionization for arcs. Neutrals are important.
- Very large variations in number densities over time and space.
- Real applications with complex geometry.

Plasma Properties Through Breakdown



A: Initial injection of e-
(no plasma yet)

B: Cathode plasma grows

C: Breakdown

D: Relax to steady operation
(ΔV drops to ~50V)

E: Steady operation
(ΔV ~50V, I ~100A)

Model parameters:

$\Delta x \sim \lambda_D \sim (T_e/n_e)^{1/2}$

$\Delta t \sim \omega_p^{-1} \sim n_e^{-1/2}$

National Nuclear Security Administration

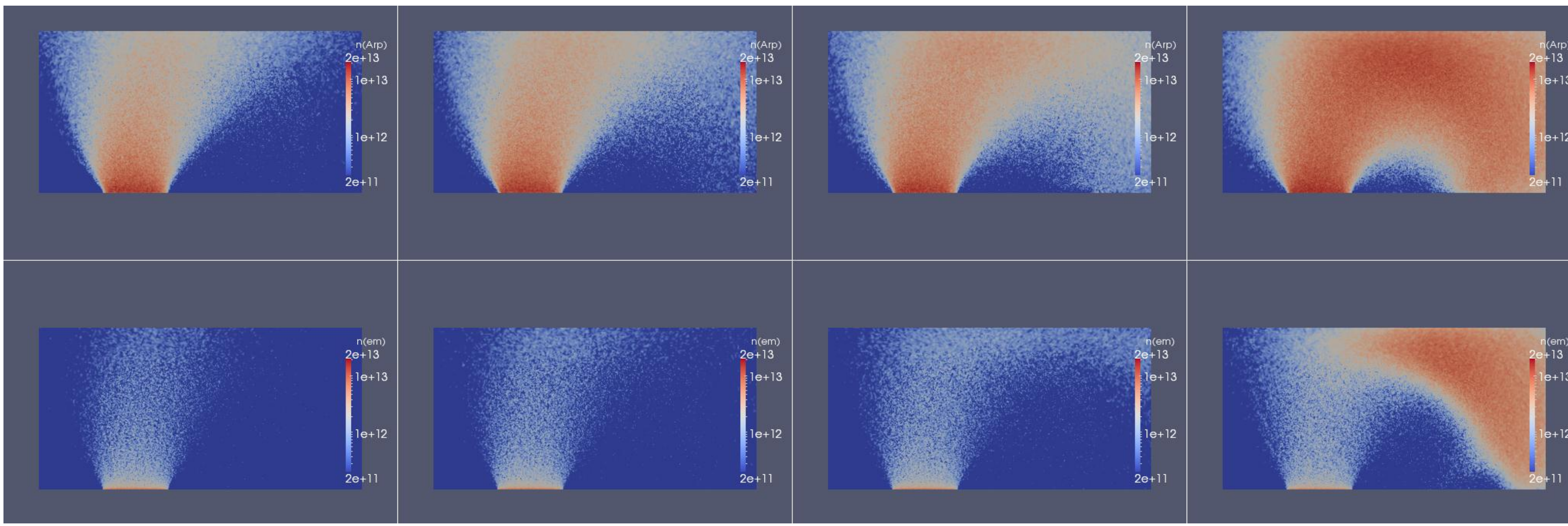
Sandia National Laboratories

Comments on Hierarchical Time Stepping

Performance Impact

- Using kinetic time, converged to 53,800 Xe+ and 30,800 e-, after 1:32.
- Using hierarchy time, converged to 53,600 Xe+ and 30,900, after 0:17.
- Hierarchical time stepping achieves 5.5x speed up, or 82% time savings.

Limitation: Need to keep time factor small (N<10) for "physical" solution.



N=1 N=3 N=5 N=10

Electron fountain ionizing argon at 1 torr, 300 K, using different time factors. N = 10 is clearly too large.

National Nuclear Security Administration

Sandia National Laboratories

Emission model

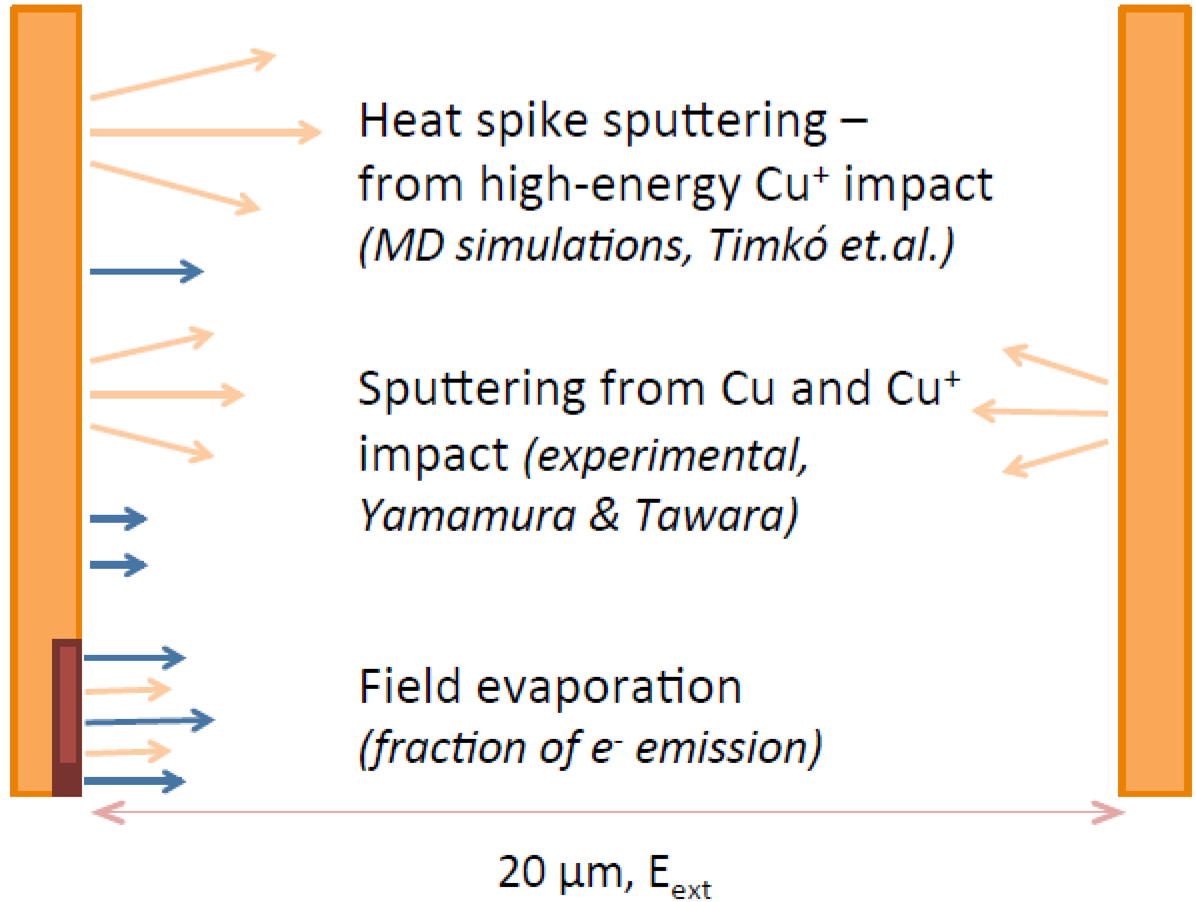
Electrons

SEY from Cu impact *(constant)*

Injection from "flat" surface with β_f

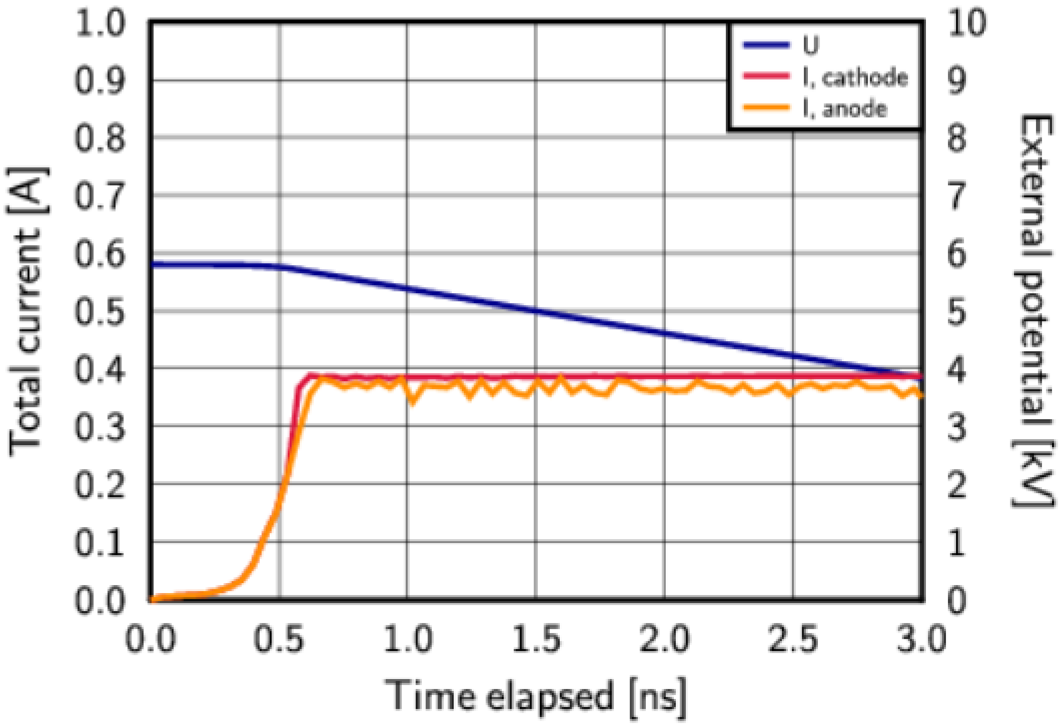
Injection over R_{em} *(calculated from J_{FN} through R_{tip} with β_0)*

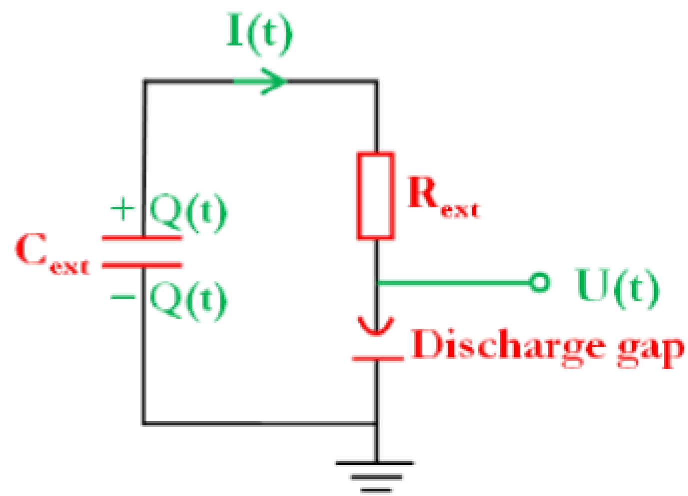
Neutrals



Current-voltage characteristics

- Current reaches maximum value ≈ 0.4 A
- Voltage decreases as capacitor is drained
- Plasma self-maintaining as long as energy is available





$$Q(t_{i+1}) = Q(t_i) - I(t_i)\Delta t$$

$$U(t_{i+1}) = Q(t_{i+1}) / C_{ext} - R_{ext} I(t_i)$$

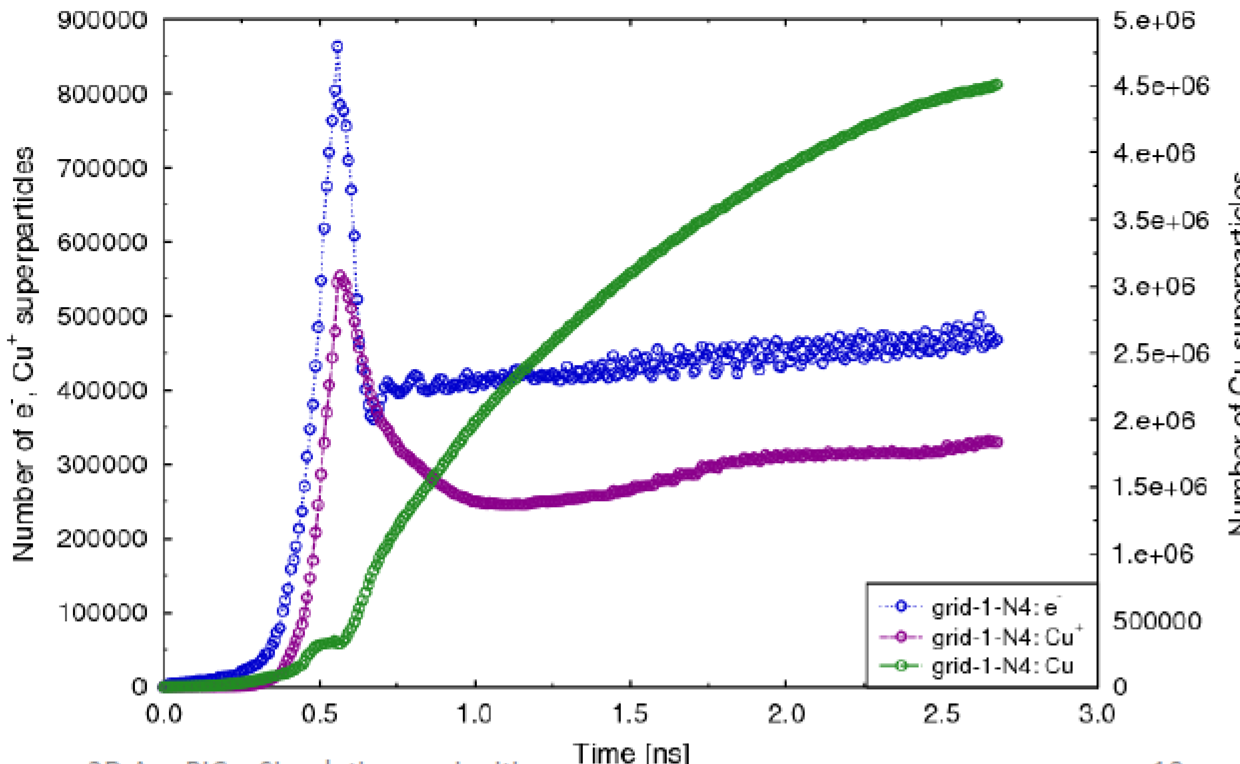
Here $R_{ext} = 0$

Why is the plasma current so low?

- Experimentally measured currents ≈ 10 -100 A
- Because of the field emission model
  - FN emission set to cut-off at 12 GV/m (≈ end of validity range)

- Need to improve emission model

- How?
  Thermionic effects?
  - How define T?
  - Shape of tip?

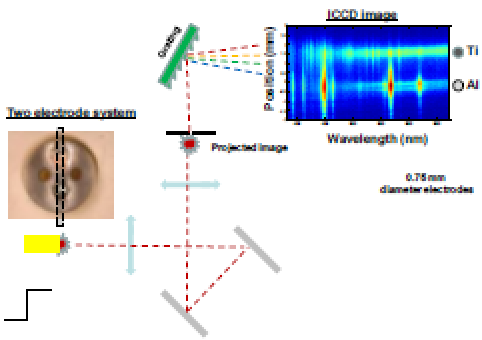


A wide range of diagnostic techniques are needed to study arc physics

- A wide range of techniques can be utilized to probe aspects of plasma generated in an arc
  - Our challenge is to match the right tool to the right job
- Tools can consist of
  - "Global" current and voltage
  - Semi-localized optical emission and ion beam spectroscopies
  - Localized laser induced fluorescence, absorption and or scattering

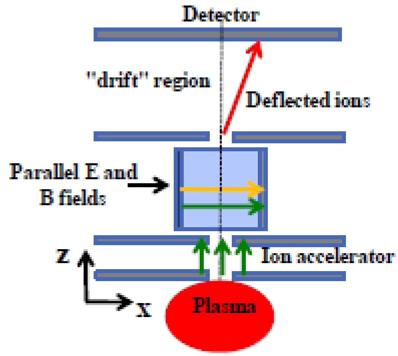
Optcial diagnostics

"Near the source"



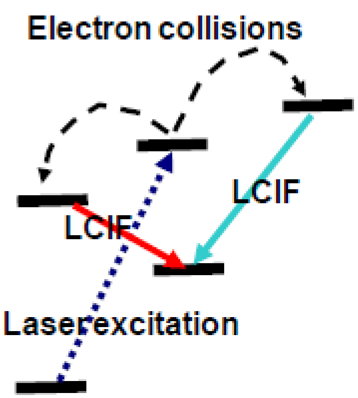
Ion-based diagnostics

"Downstream"



Laser spectroscop

"Bridge the gap"

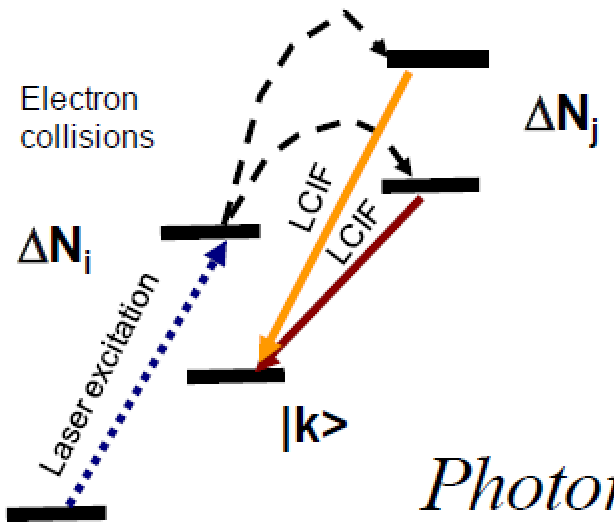


Emphasis is placed on laser based diagnostics

Sandia National

LCIF is based on redistribution of excited state by plasma electrons

- Laser excitation populates an intermediate state
  - Relaxation processes deplete the excited state
- Portion of excited state population gets redistributed into "uphill" states
  - Driven by interaction with energetic plasma species (electrons)



Electron- coupled interaction

$$\Delta N_j \sim K_{ij}^{e} n_e \times \Delta N_i \times \Delta t$$

Change in upper state due to excited state

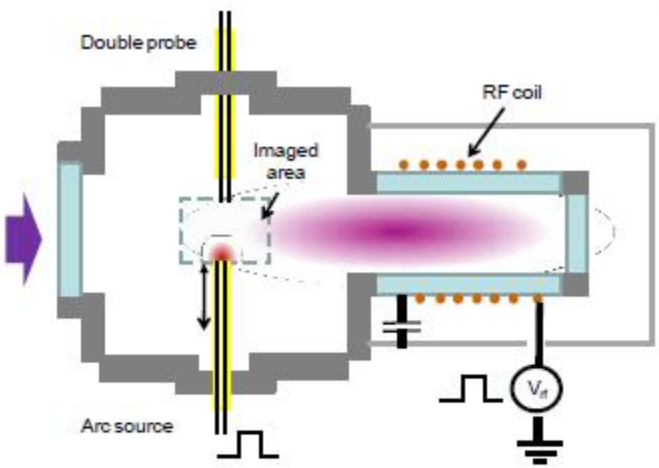
$$Photons\ emitted \sim A_{jk} \times \Delta N_j \times \Delta t$$

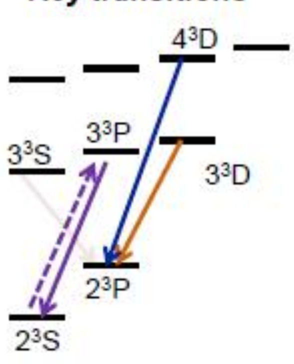
Detected light

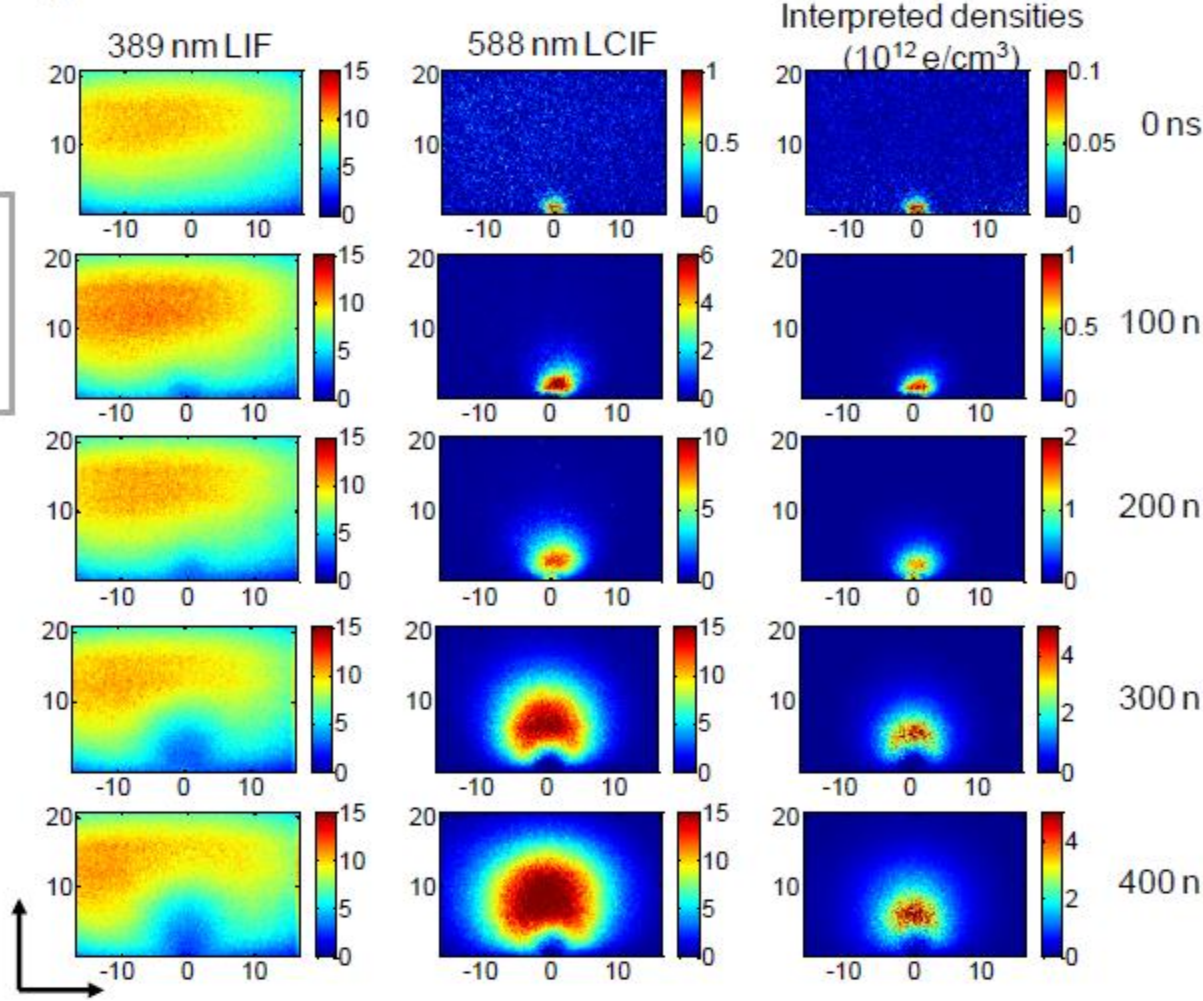
LCIF looks for changes in emission of neighboring "uphill" states after laser excitation

LCIF captures transient phenomenon

- **Examine generation of arc**
  - Low pressure (30 mTorr) helium after glow
  - Time steps of 100 ns, 50 ns gates







Spatial-temporal maps of arc expansion are illustrated with LCIF

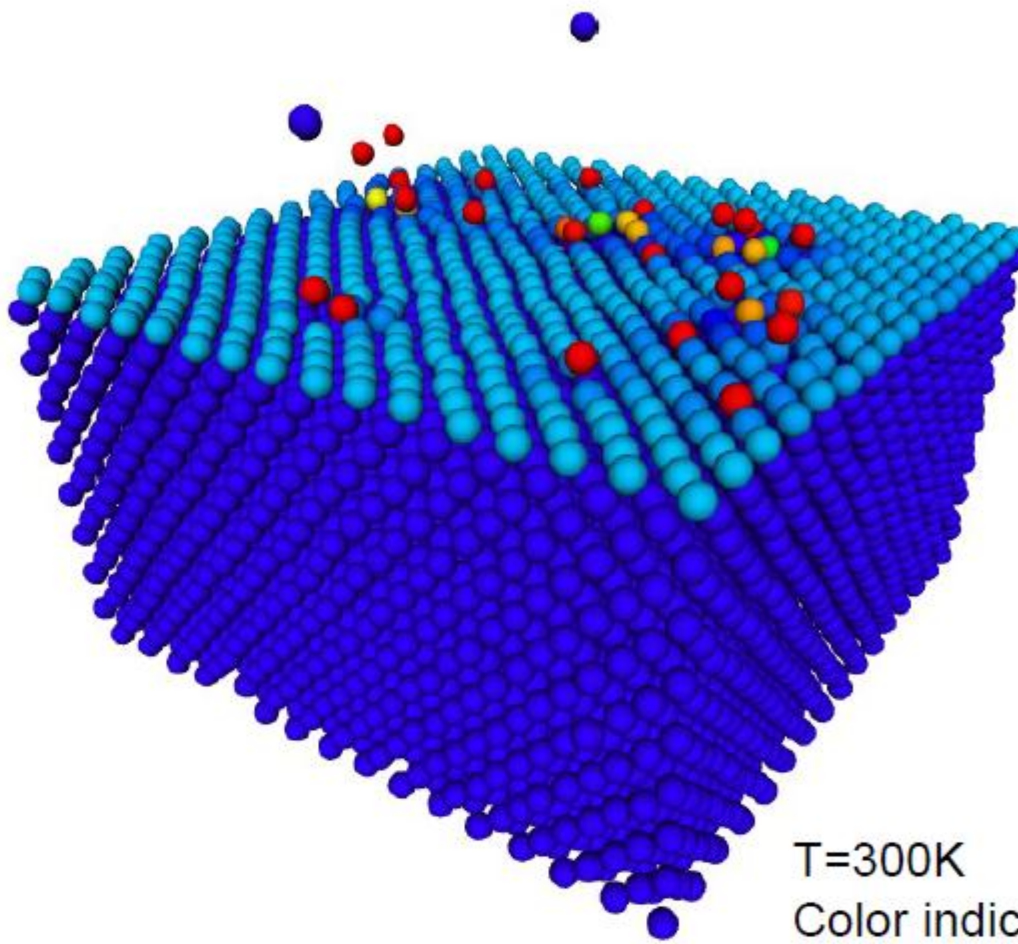
What is APT?

- Method to determine the structure and chemical composition of a sample in 3D
- Very high resolution (~nm)
  - Atomic resolution is the ultimate goal
- Destructive method

(Cameca SAS)

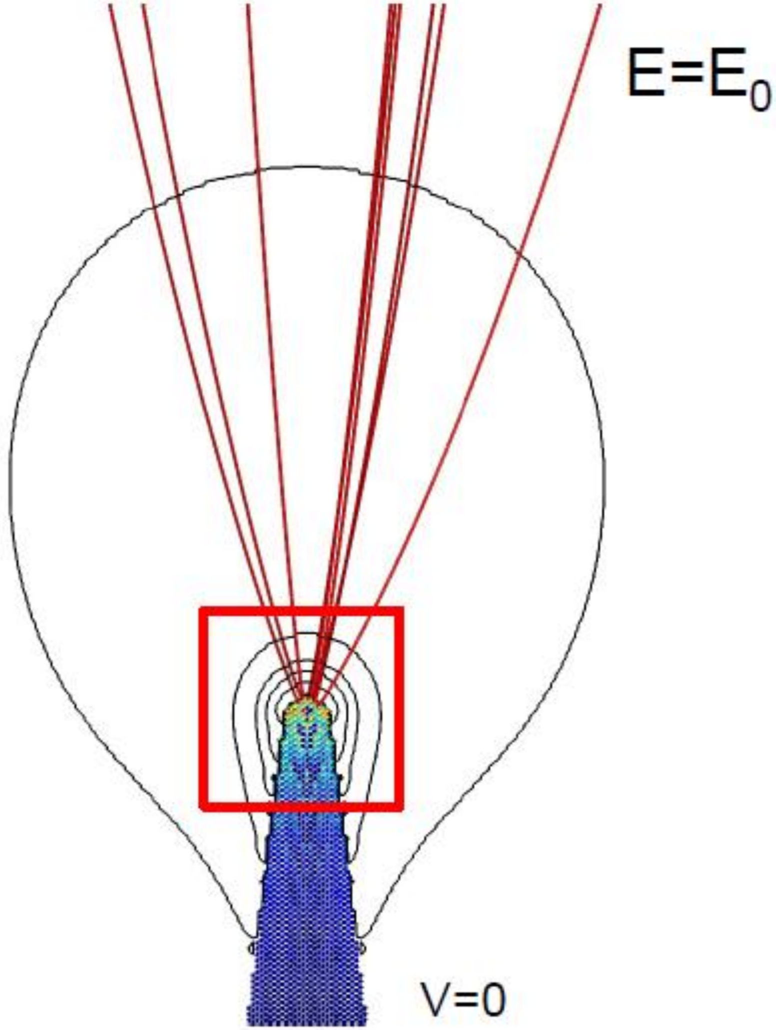
Simulating evaporation

- In principle the hybrid ED&MD code is all that is needed to simulate field assisted evaporation



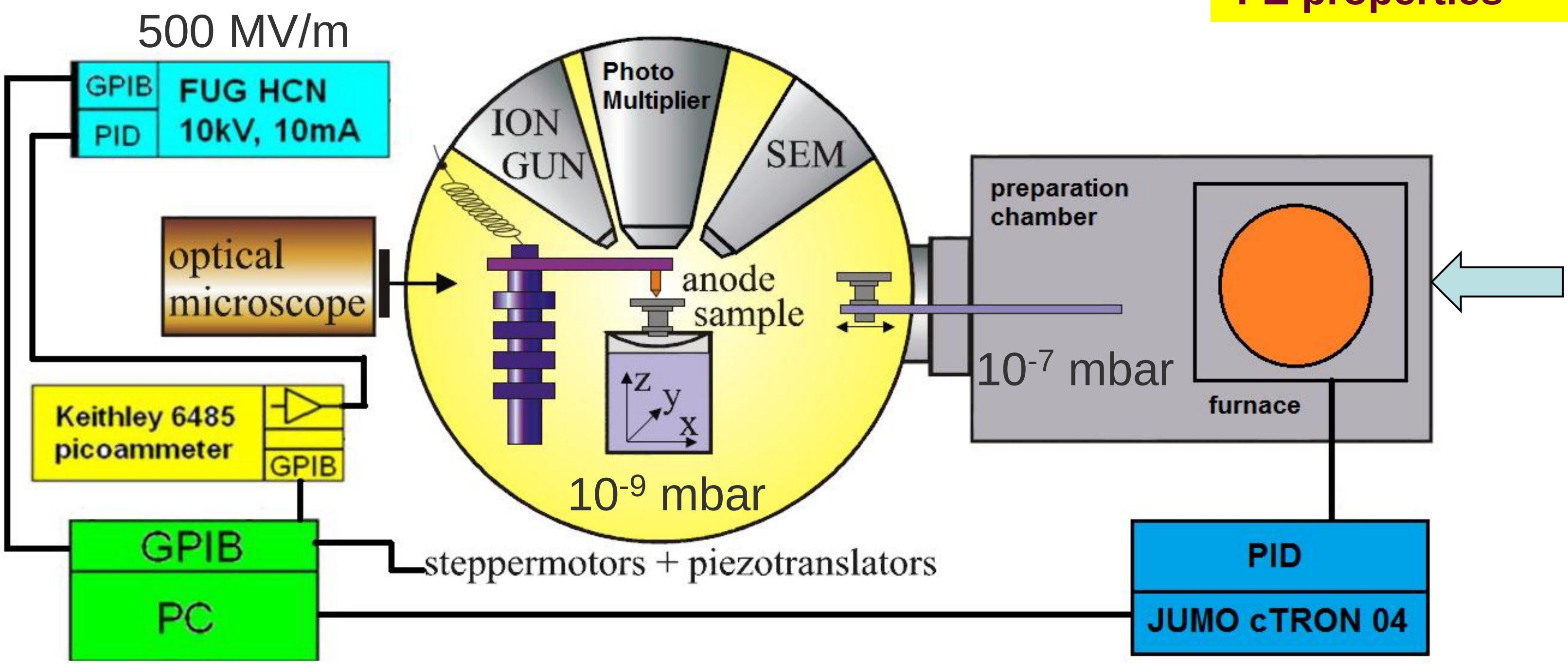
T=300K
Color indicates charge

Reconstruction - trajectories



FE & SEM measurement techniques

Field emission scanning microscope (FESM): → **- localisation of emitters**
- FE properties



- Regulated V(x,y) scans for FE current I=1 nA & gap Δz $\Rightarrow$ emitter density at $E=U/\Delta z$
- Spatially resolved I(E) measurements of single emitters $\Rightarrow$ E_{on}, β_{FN}, S
- Ion bombardment (**Ar,** E_{ion}= 0 – 5 kV) and SEM (low res.)
- In-situ heat treatments up to 1000°C

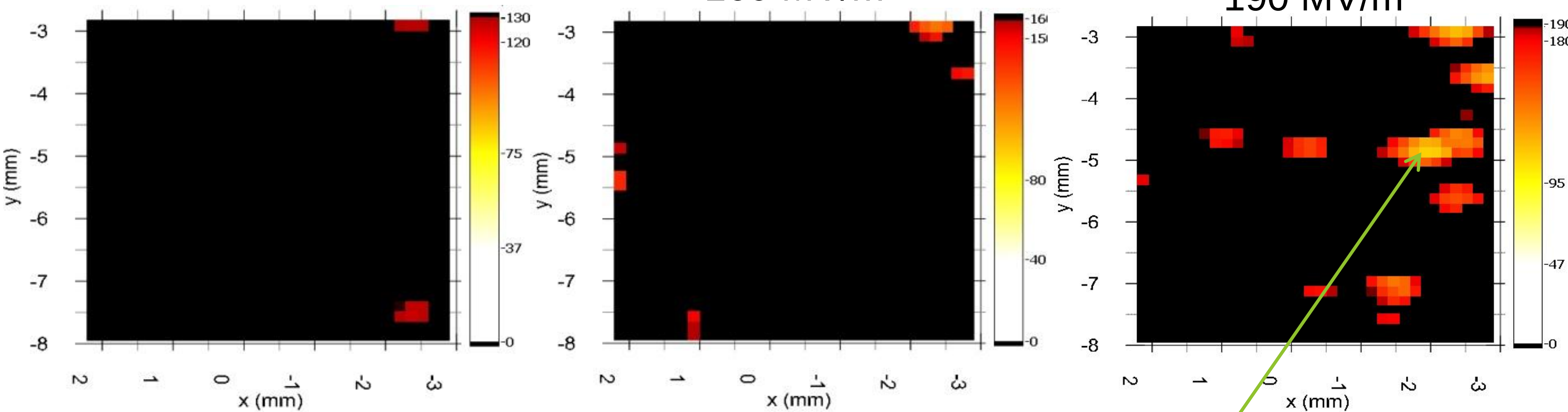
Ex-situ SEM + EDX → **Identification of emitting defects**

Correlation of surface features to FE properties (positioning accuracy ~ ±100 µm)

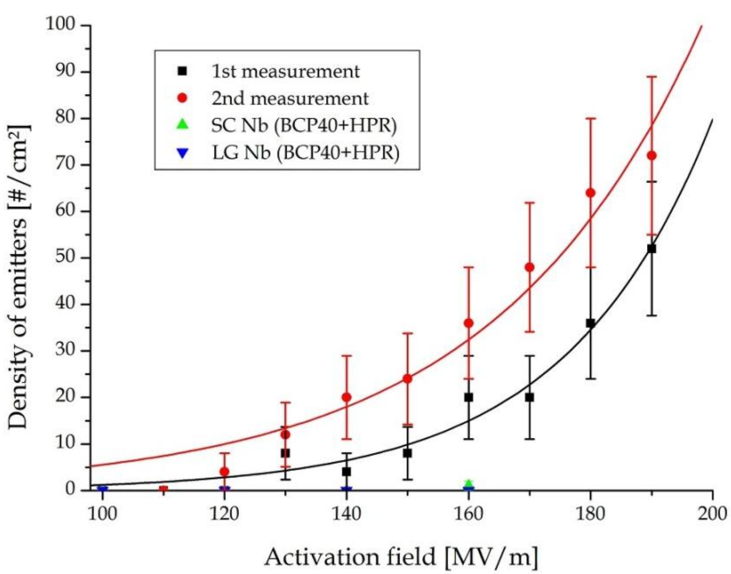
FESM results

Regulated E(x,y) maps for I = 1 nA , Δz ≈ 50 µm of the same area

130 MV/m   160 MV/m   190 MV/m



E_{on} = 120 MV/m

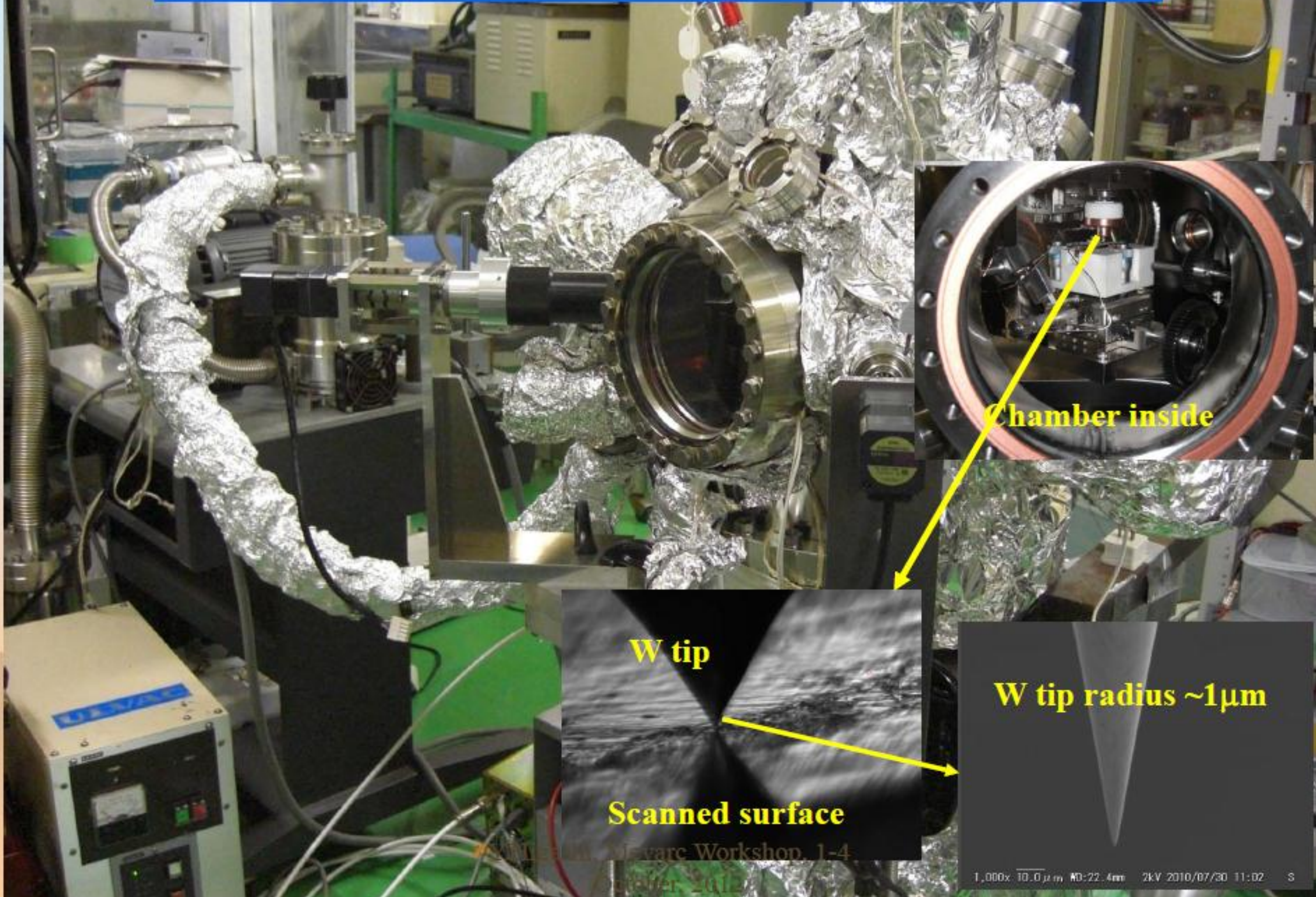


- **EFE starts at 130MV/m and not 500MV/m**
- Emitter density increases exponentially with field
- Activated emitters: $E_{act}=(1{,}2 – 1{,}4)\cdot E_{on}$

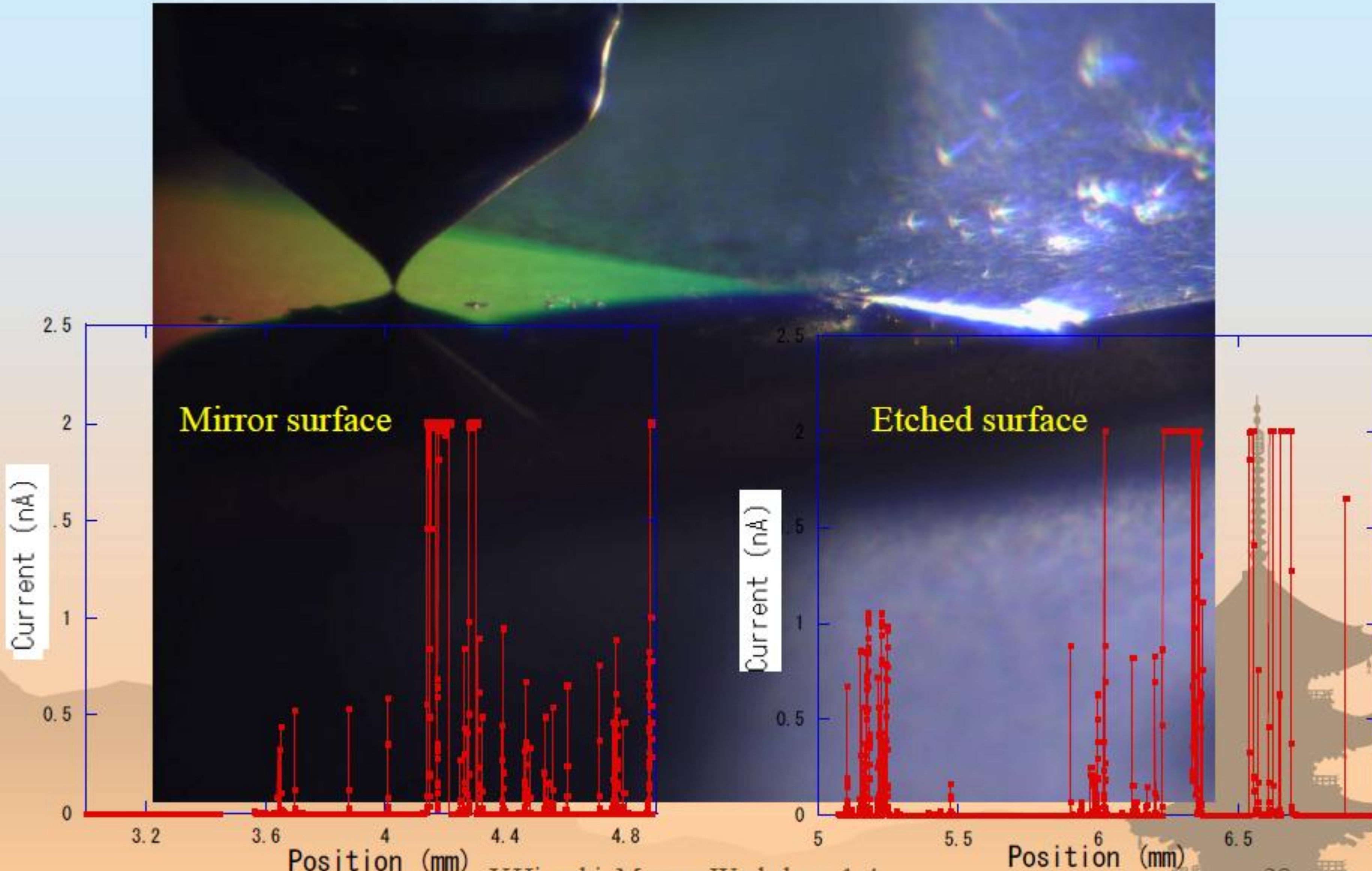
→ 2nd measurement: shifted to lower fields

Possible explanations:
- Surface oxide
- adsorbates

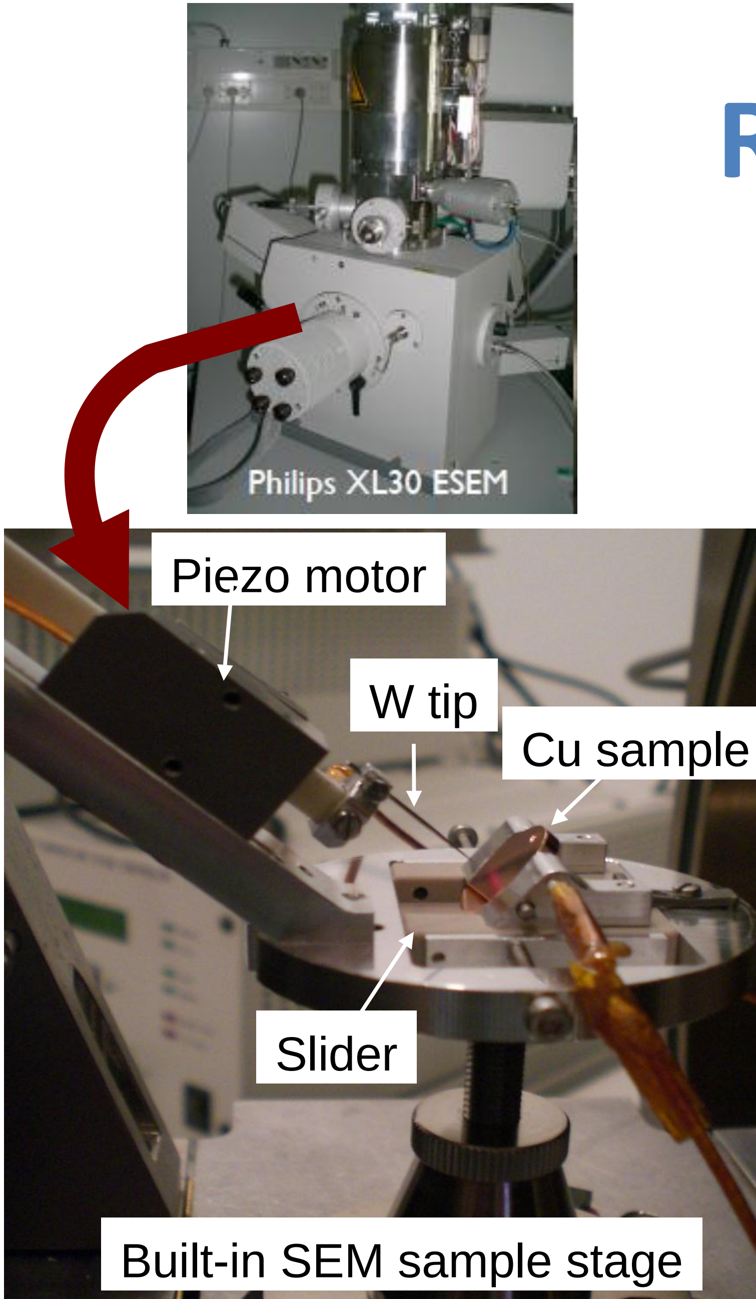
Scanning Field Emission Microscope

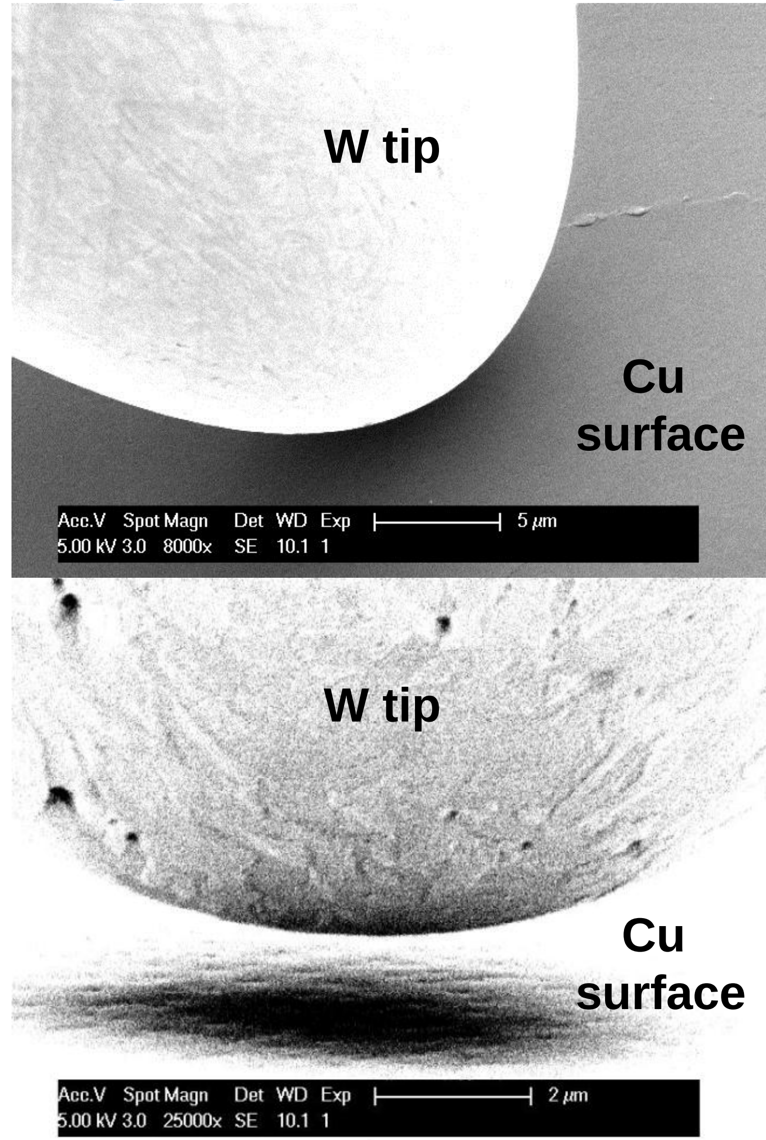


Measured field emission distributions

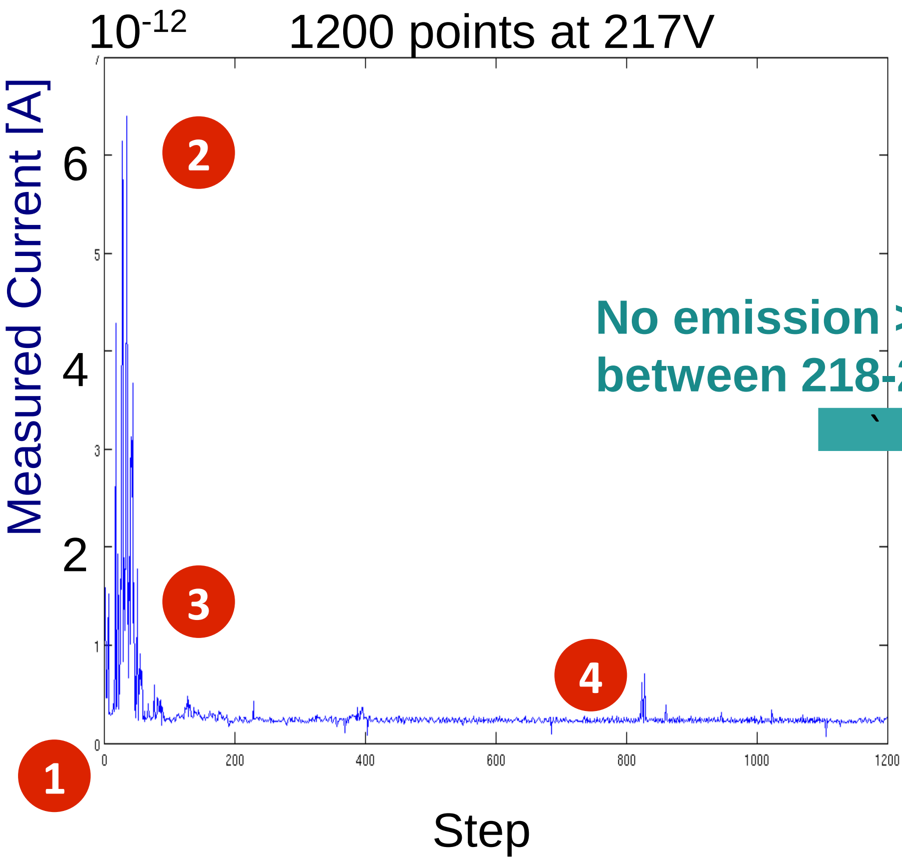


Real life

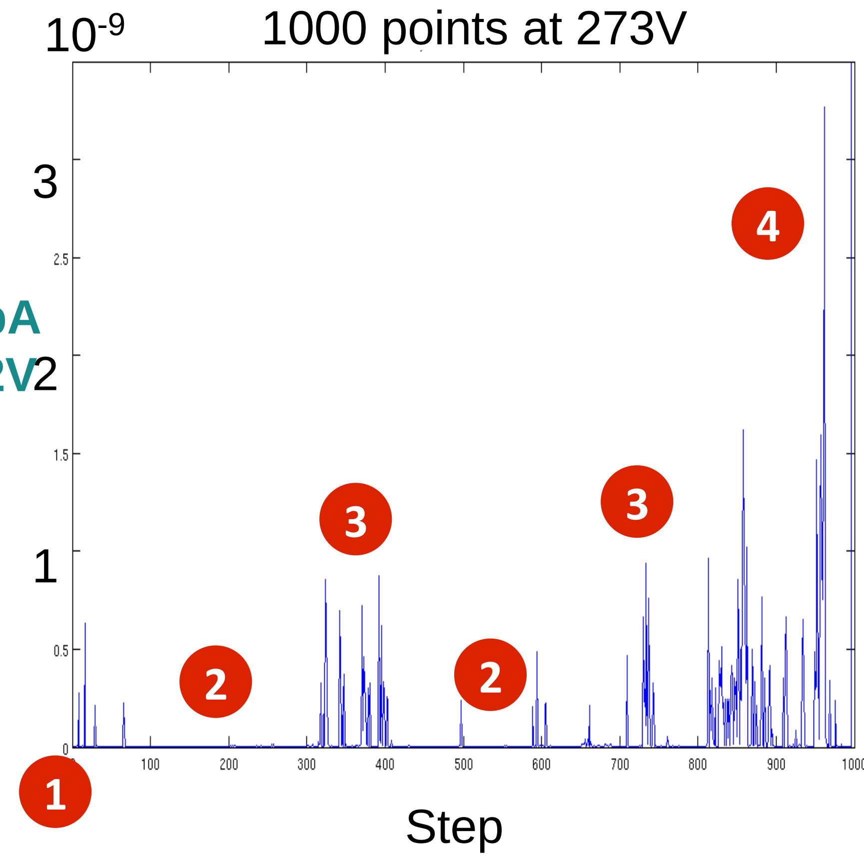

Philips XL30 ESEM
Piezo motor
W tip
Cu sample
Slider
Built-in SEM sample stage


W tip
Cu surface
Acc.V Spot Magn Det WD Exp 5 µm
5.00 kV 3.0 8000x SE 10.1 1
W tip
Cu surface
Acc.V Spot Magn Det WD Exp 2 µm
5.00 kV 3.0 25000x SE 10.1 1

Emission stability measurement



No emission >1pA between 218-272V



1. Measured current exceeded 1pA
2. Up to 6 pA
3. Decreased to the bg-level
4. Stayed at the bg-level

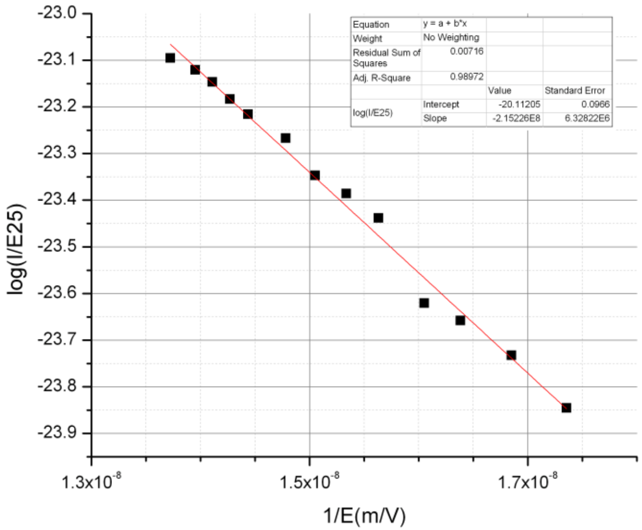
1. Measured current exceeded 1pA
2. Decreased to the bg-level
3. Spikes ~1nA
5. Emissions > nA then exceeded 10nA

Electron emission

Fowler Nordheim Law (RF fields):

$I_{FN}(\beta, \phi_0, A_e, E_0)$

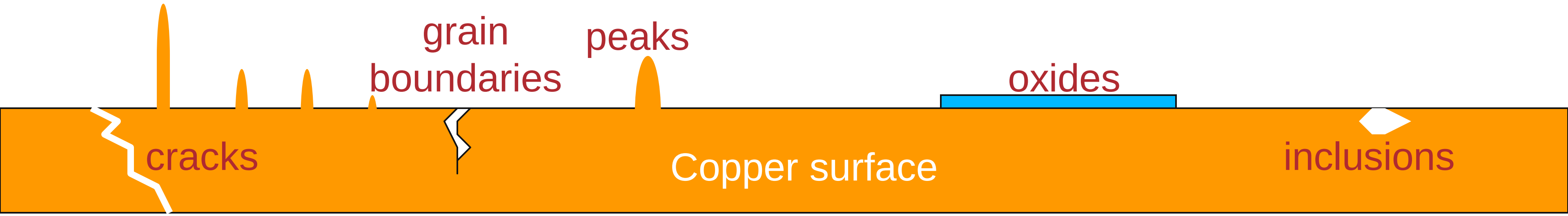
$$\bar{I} = \frac{5.79\times10^{-12}\exp(9.35\varphi_0^{-0.5})A_e(\beta E_0)^{2.5}}{\varphi_0^{1.75}}\exp\left(\frac{-6.53\text{x}10^{9}\,\varphi_0^{1.5}}{\beta E_0}\right)$$



1. High field enhancements (β) can field emission.
2. Low work function (ϕ_0) in small areas can cause field emission.

typical picture ➔
geometric perturbations (β)

alternate picture ➔
material perturbations (ϕ_0)

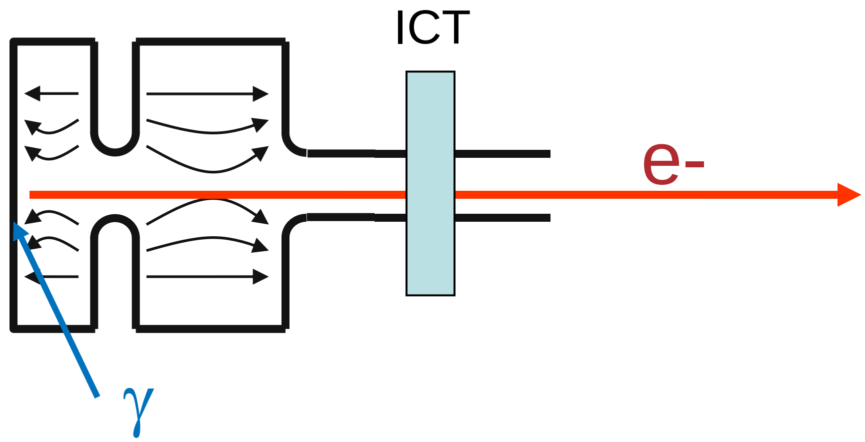


(suggested by Wuensch and colleagues)

Schottky Enabled Photo-electron Emission Measurements

Data 2010-10-04

First results from Tsinghua



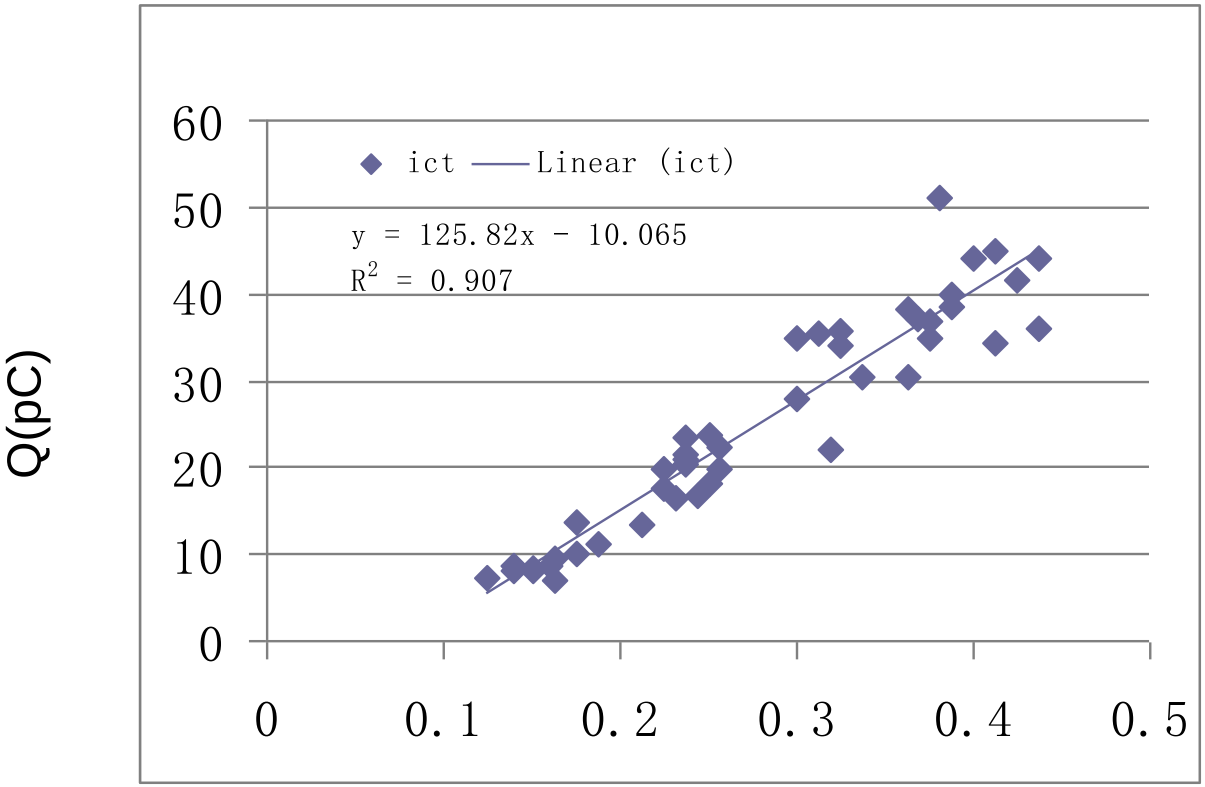
- **Experimental parameters**
  - work function of copper = ϕ_0 = 4.65 eV
  - energy of λ=400nm photon = hν= 3.1 eV
  - Laser pulse length
    - *Long = 3 ps*
    - *Short = 0.1 ps*
  - Laser energy ~1 mJ (measured before laser input window)
  - Field (55 – 70 MV/m)

Should not get photoemission

First results from Tsinghua

Data 2010-10-04

→Long Laser Pulse (~ 3ps)
→E=55 MV/m@ injection phase=80 ➔ 55sin(80)=54



laser energy (mJ)
photocathode input window

$Q \propto I$
single photon emission