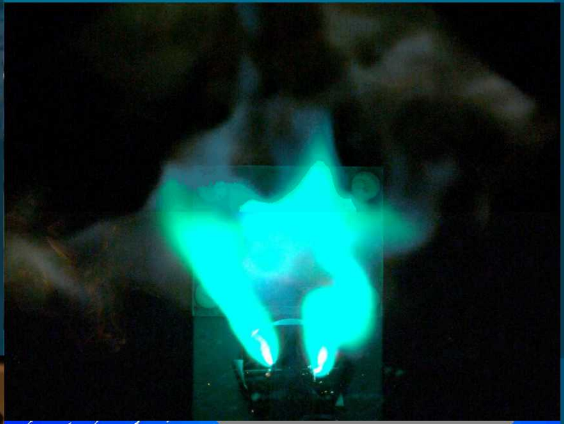
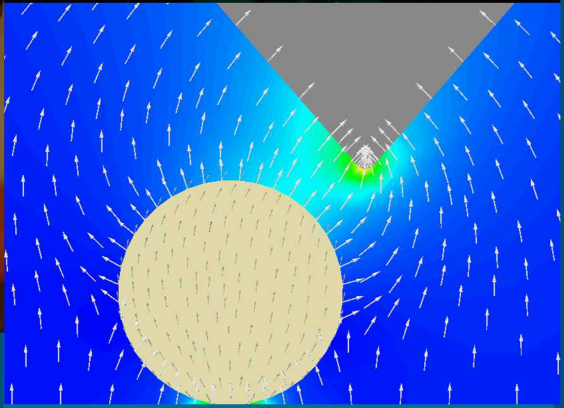
SAND2019-3467PE

# Electrical Breakdown Diagnostics and Coordinated Discharge Model Development





*Thanks to:*
*Paul Clem*
*Matt Hopkins*
*Chris Moore*
*Laura Biedermann*
*Danny Kotovsky*
*Andy Fierro*
*Ed Barnat*
*Beth Paisley*
*Roy Jorgenson*
*Becky Coats*
*Tom Swiler*
*Pin Yang*
*Derek Wilke*

PRESENTED BY

Rajan Tandon

Component Science, Engineering and Manufacturing Center

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# Introduction

Matt Hopkins:

"Sandia is interested in vacuum breakdown, low to high pressure gaseous breakdown, secondary emission characteristics, aging and environmental effects, and intended operation vs. failure mitigation.

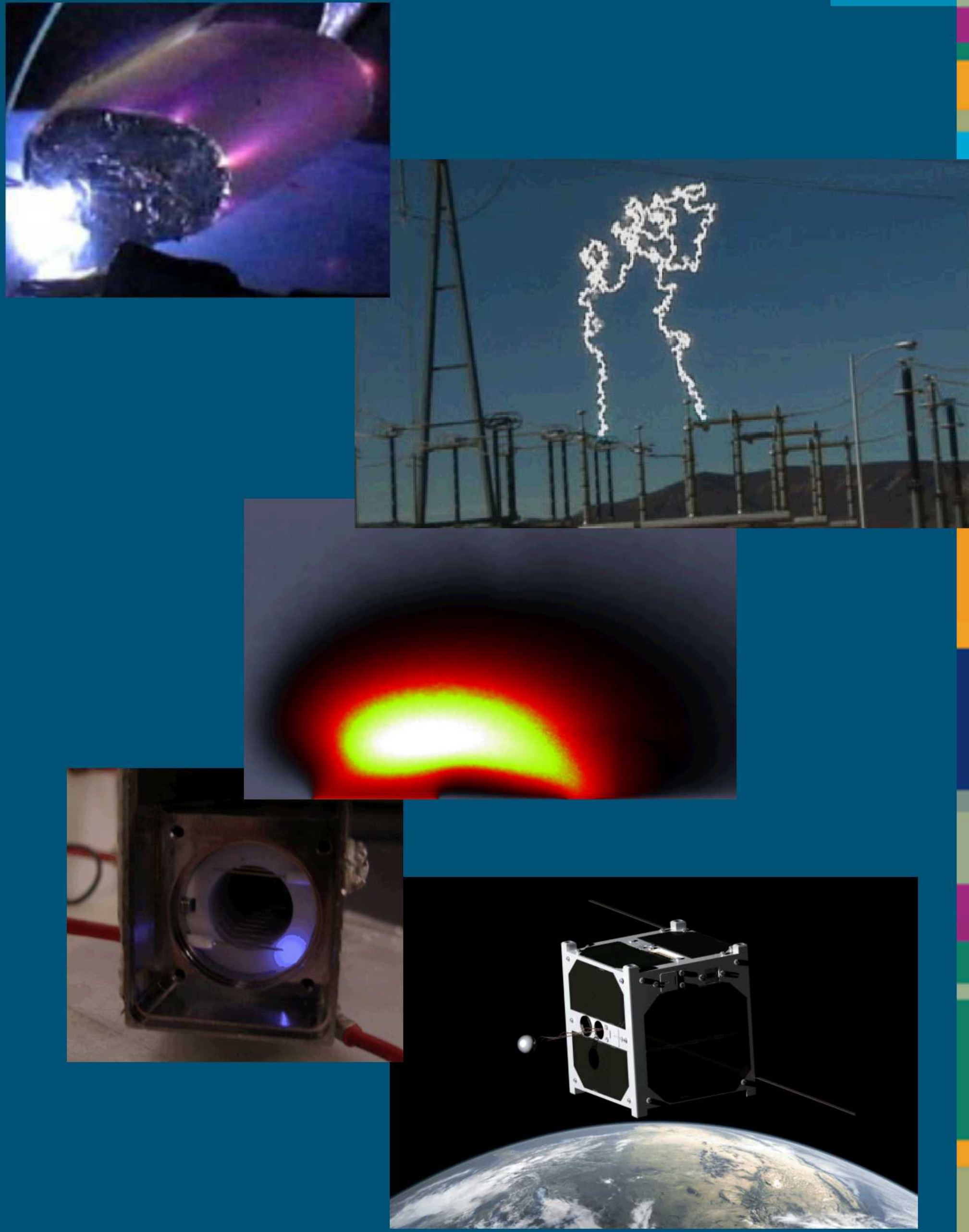
The broad goals of our work are to:

1) Develop diagnostic and measurement capabilities to characterize real surfaces for use in predictive modeling and simulation. Provide a scientific mechanistic description for discharge physics. Challenge hypothesized models with experiment. Remove calibration and fitting.

2) Develop computational tools for design, trade-off, failure diagnosis, etc."

For this talk:

- Examples and some lessons of component breakdown experiments
- Current efforts toward more complete electrical breakdown models



# There are different types of electrical breakdown

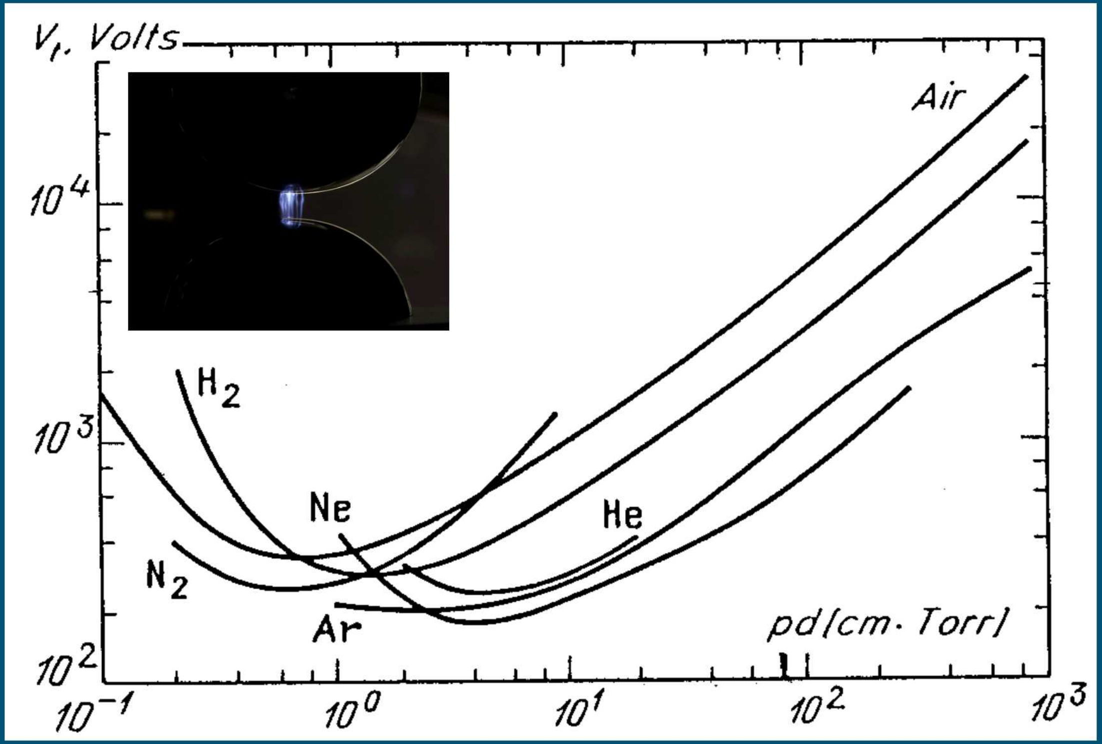
Gas

- High pressure
- Non-uniform fields
- Microwave

Vacuum

Solid

Liquid



Paschen curve

# How can electrical discharge be engineered?

Gas composition

Gas pressure

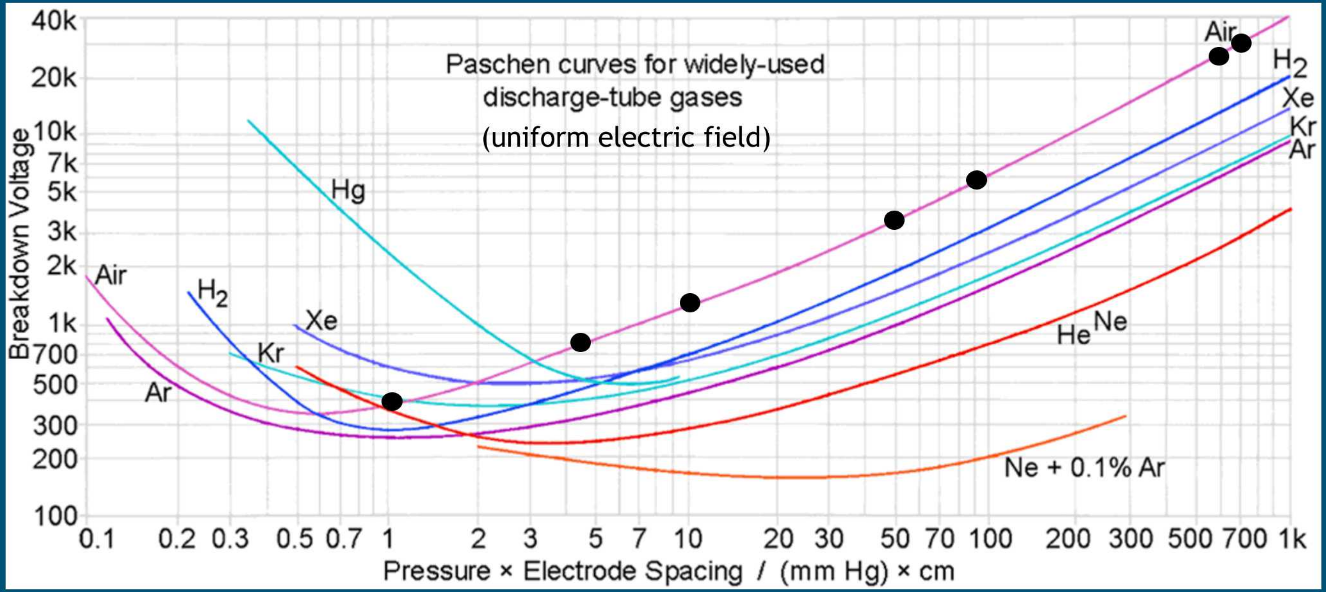
Electrical field level

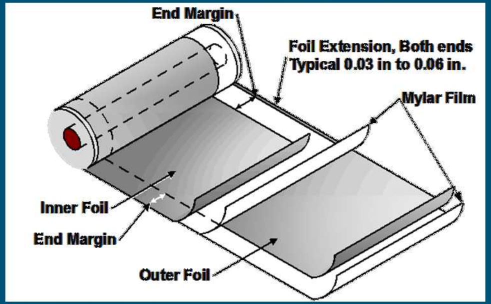
Electrical field gradients

Electrode properties

- Work function ($e^-$ emission)
- Photoemission
- Ion-induced secondary electron emission (SEE)
- Other material properties (roughness, alloy composition, crystallographic orientations, dislocation density, …)

# Example 1: High Voltage Breakdown Pressure Effects in Polymer Capacitors





For d (0.4”) ≈ 1 cm

| P | P*d | Vbreakdown |
|---|---|---|
| 760 Torr | 700 torr-cm | 30 kV |
| 650 Torr | 594 Torr-cm | 25 kV |
| 100 Torr | 91 Torr-cm | 6 kV |
| 50 Torr | 45 Torr-cm | 3.5 kV |
| 10 Torr | 9 Torr-cm | 1.2 kV |
| 5 Torr | 4.5 Torr-cm | 0.8 kV |
| 1 Torr | 0.9 Torr-cm | 0.4 kV |

Pressure effects on capacitors can affect reliability.

Potential causes of decreased voltage holdoff
- Pressure can change/drift over time
- Pressure inside capacitors not quantified

*Courtesy: Roy Jorgenson and Becky Coats*

# Effects of nonuniform fields on breakdown

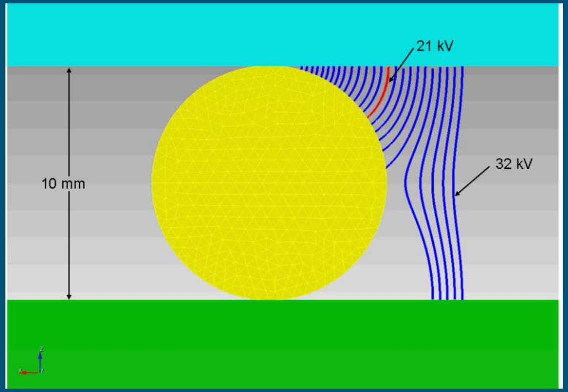
Many Sandia components depend on the physics of gas breakdown in nonuniform fields

Lightning arrestors enable lightning strike current surge protection via:

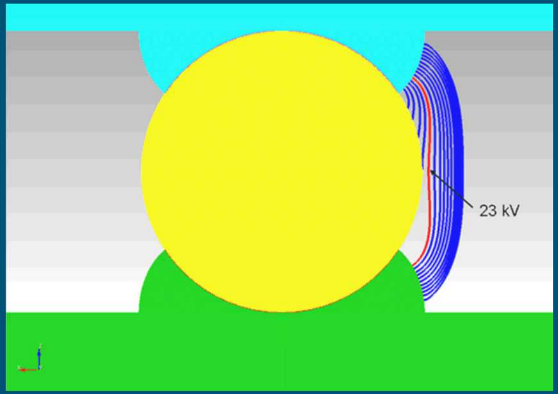
- Dielectric particles: nonuniform fields
- Engineered breakdown voltages
- Tolerance of multiple strikes

**Lightning Arrestor Connectors (LACs)**

**LAC Physics Models**



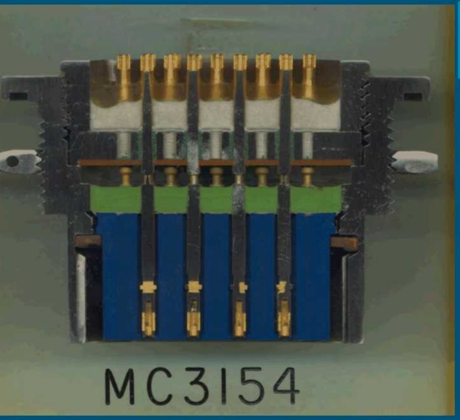
Breakdown causes a conductive high field region



Second breakdown path is modified (lower $V_{BD}$)

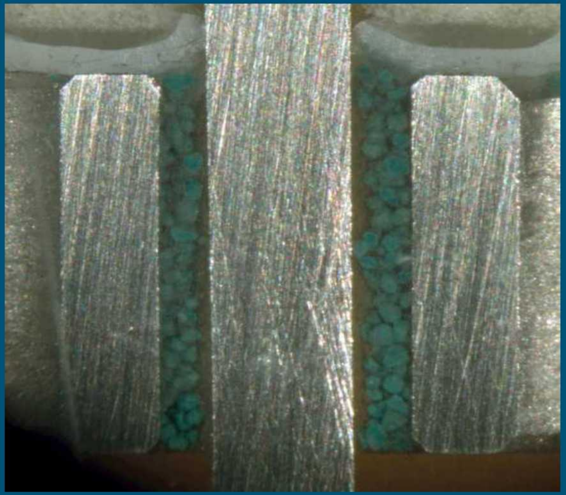
*Model/data: Laura Biedermann*

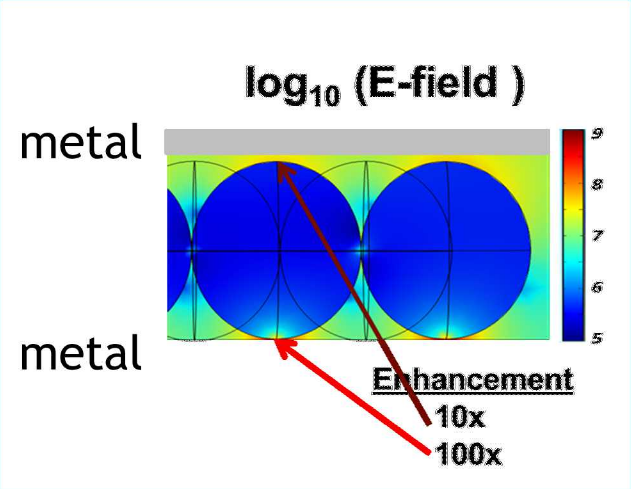
# Understanding of Fundamental LAC Physics

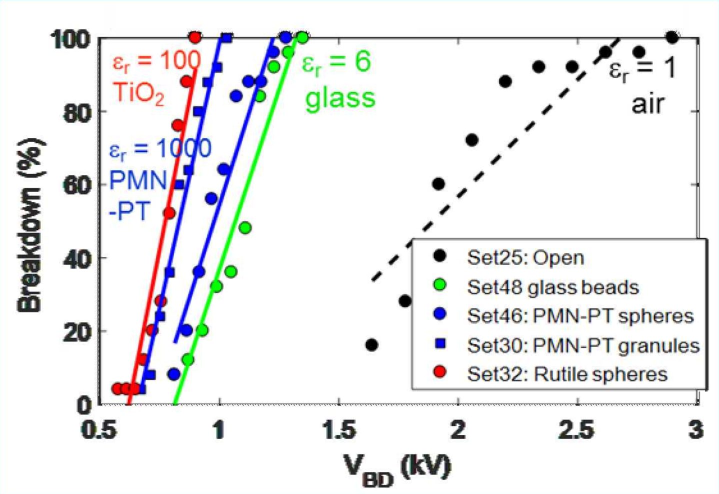


Developing physics-based models & experiments to explain and control LAC dielectric granule-stimulated arcing.

Background: Dielectric granules (left) between pin and case cause 100X electrical field enhancement at metal-dielectric-air triple points (center); increasing granule permittivity $\varepsilon_r$ decreases both breakdown voltage and distribution (right).







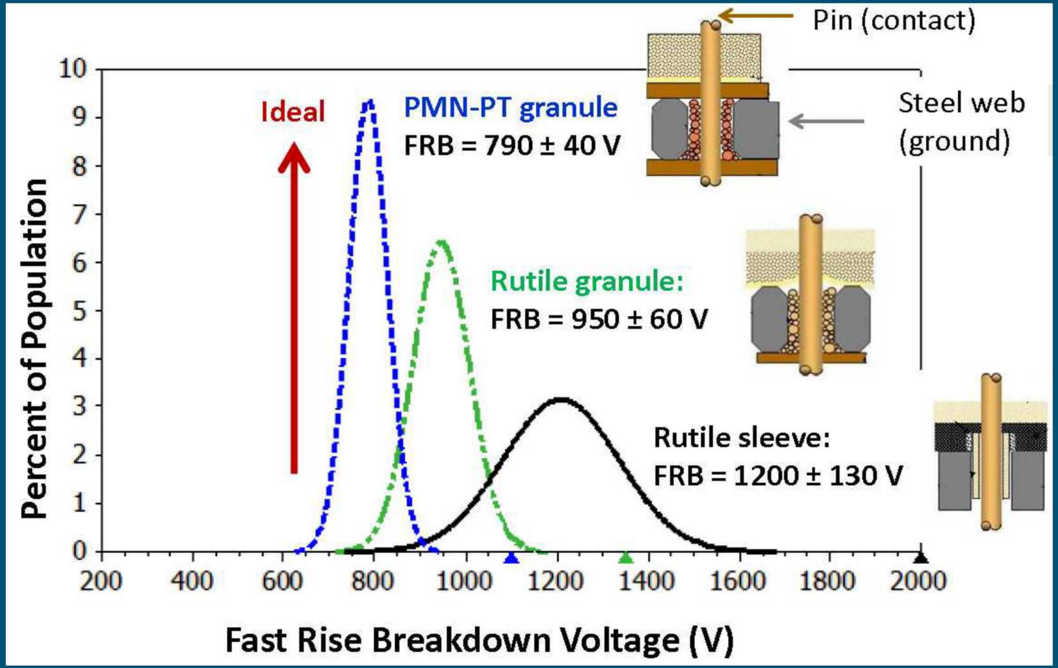
LAC/SL breakdown may be engineered with control of:

- Granule shape & permittivity → Field concentration
- Electron emission → Breakdown statistics

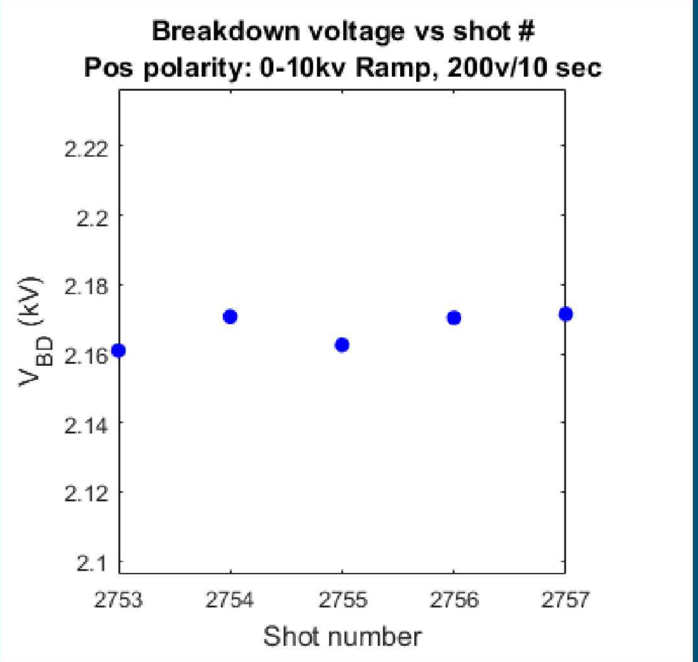
*In collaboration with Laura Biedermann*

# Efforts towards improved LAC performance and manufacturability

Lightning arrestor connectors protect against 20kV, 10kA lightning by designed breakdown. 5-6% variability is typical for fast rise breakdown



Engineered LACs show 0.2% variation by increasing permittivity and electron emission



<u>Aim:</u> increased safety basis for LAC-stronglink lightning protection architecture

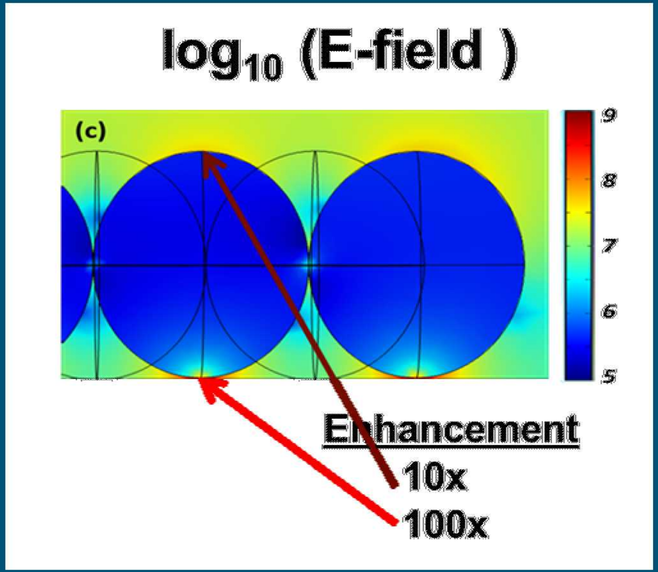
*In collaboration with Pin Yang and Derek Wilke*

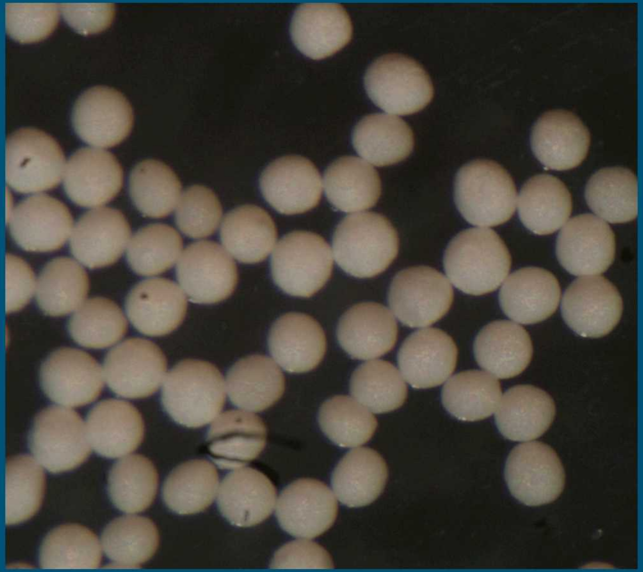
# Efforts towards improved LAC performance and manufacturability

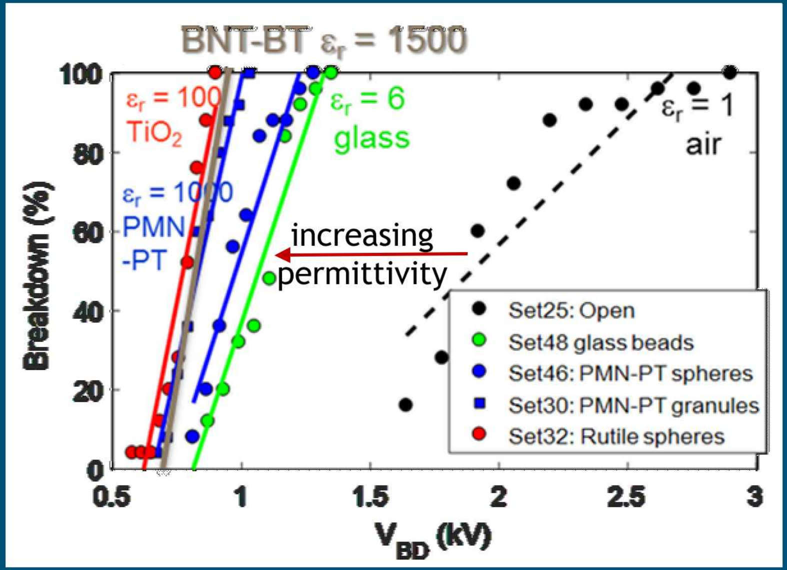
<u>Current efforts:</u>

- Spherical granules (more consistent shape, high yield, potentially better filling)

- New bismuth-based dielectric granules $Na_{1/2}Bi_{1/2}TiO_3$-$BaTiO_3$ (NBT/BT) to compare with historic $TiO_2$ and PMN/PT. Increasing granule permittivity decreases breakdown voltage and distribution.





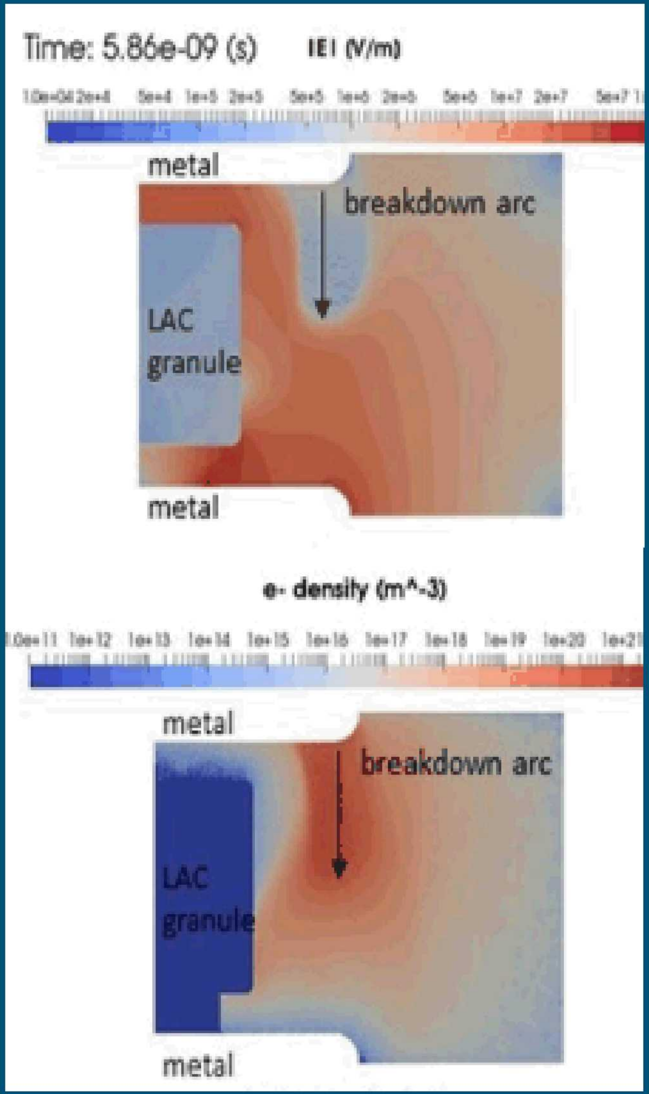


<u>Aim:</u> increased safety & reproducibility for lightning protection architecture

*Courtesy of Chris Moore and Ashish Jindal*

# Model development for discharge physics understanding

## Aleph models of LACs



**Dielectric feedback mechanisms**

Relative permittivity field enhancement

- Constant / frequency-dependent $\varepsilon_r$

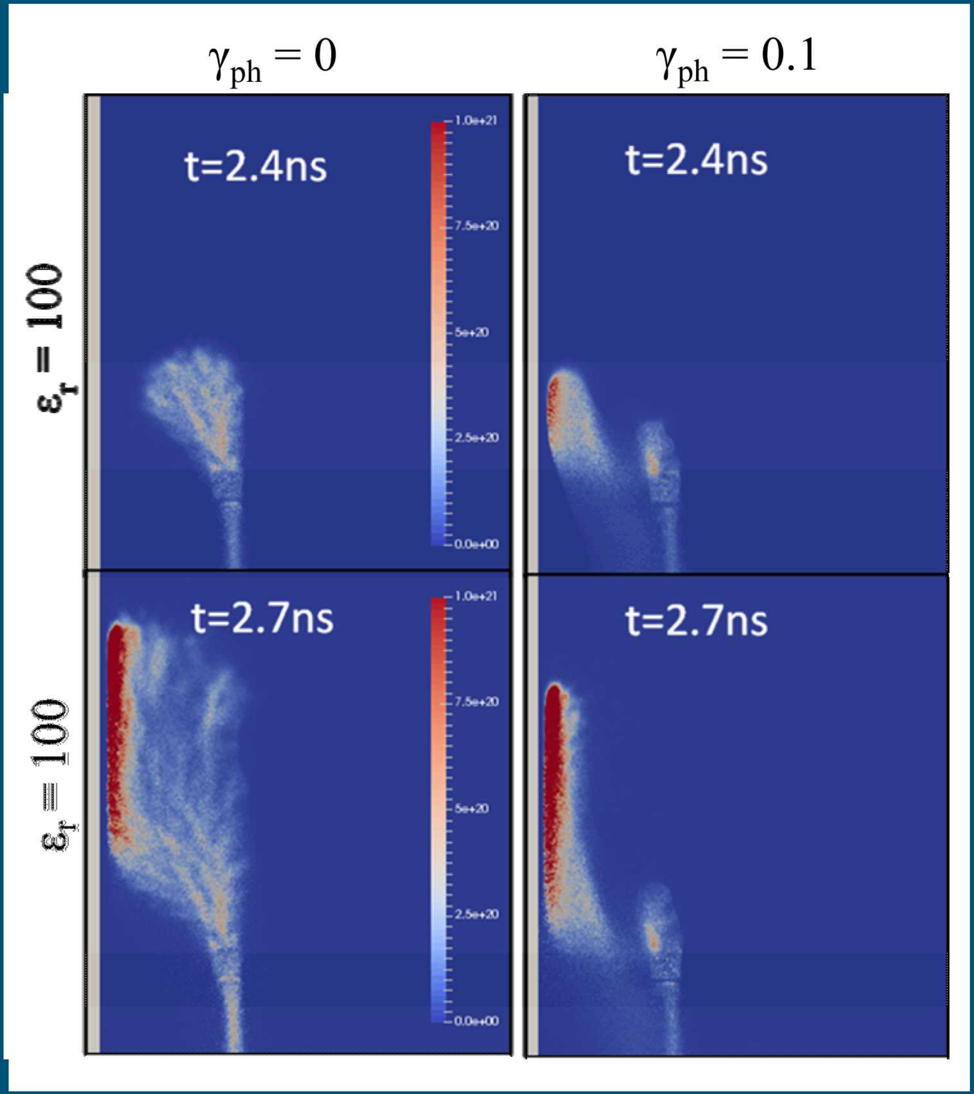
Source of electrons:

- Photon & ion-induced SEE

Surface charging

- Bleed-off rate important
- SEE yield altered by trapped charge

## Aleph dielectric photoemission effects



*Courtesy of Chris Moore and Matt Hopkins*

# Two LDRDs in progress on impacts of materials on discharge

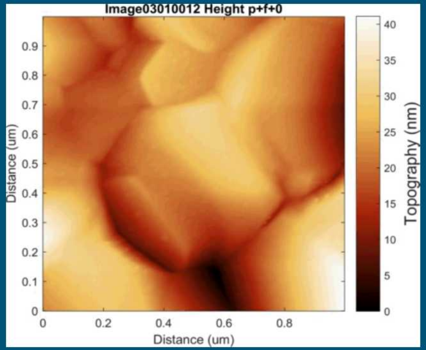
**Physics of Discharge Initiation from Complex Surfaces**
PI Chris Moore

- Goal: quantitatively predictive, vacuum field emission models on real surfaces
- Remove fitting parameter $\beta$ in the typical Fowler-Nordheim emission model,

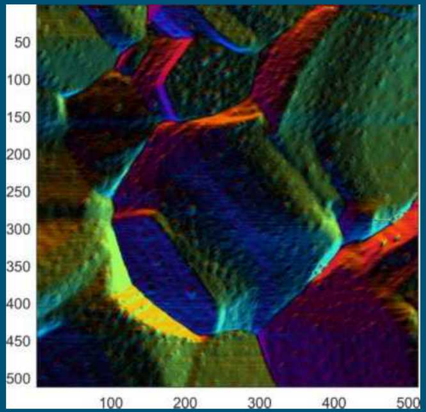
$$J_{FN}(E_s) = A_{\text{eff}}\, A_{FN} \frac{(\beta E_s)^2}{\varphi} \exp\left[-\frac{B_{FN}\varphi^{3/2}}{\beta E_s}\right]$$

1. Surface roughness affects height
2. Surface orientation modifies metal work function.
3. Conductors are not pure metal crystals; defects appear to matter.
4. Surfaces are not clean. Physisorbed and chemisorbed elements and compounds may drastically change emission behavior.

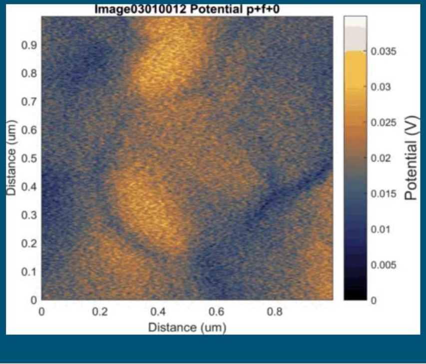
height



orientation



potential



*Courtesy of Chris Moore and Matt Hopkins*

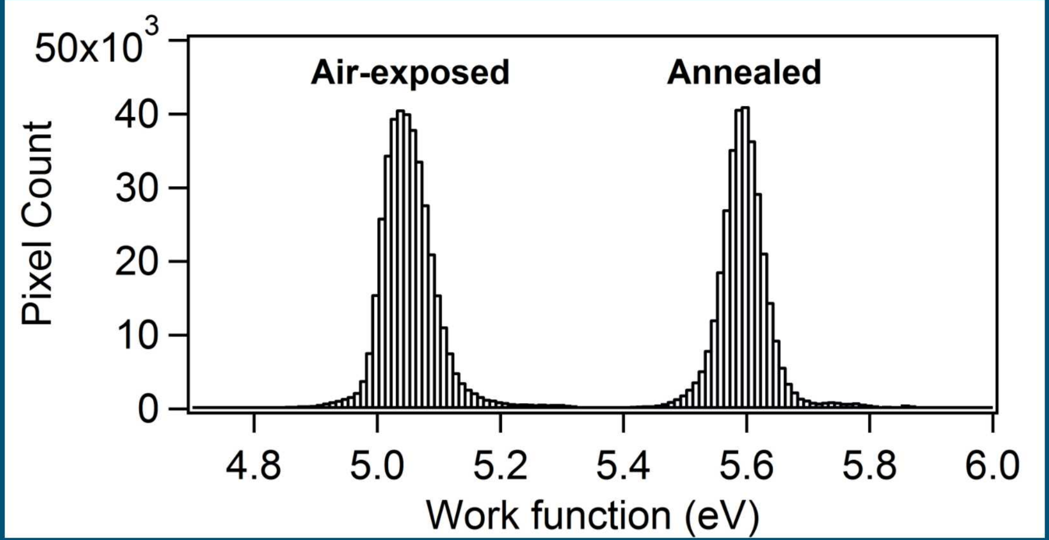
# Varying Apparent Work Functions

Employ photoemission electron microscopy (PEEM) to measure distributions of apparent work functions on same surfaces used in STM (Taisuke Ohta, Ezra Bussmann).

Work function $\varphi$ is certainly not constant.

$\varphi = 6.09$ eV for textbook Pt(111). Our polycrystalline Pt(111) is centered at $\varphi = 5.6$ eV.

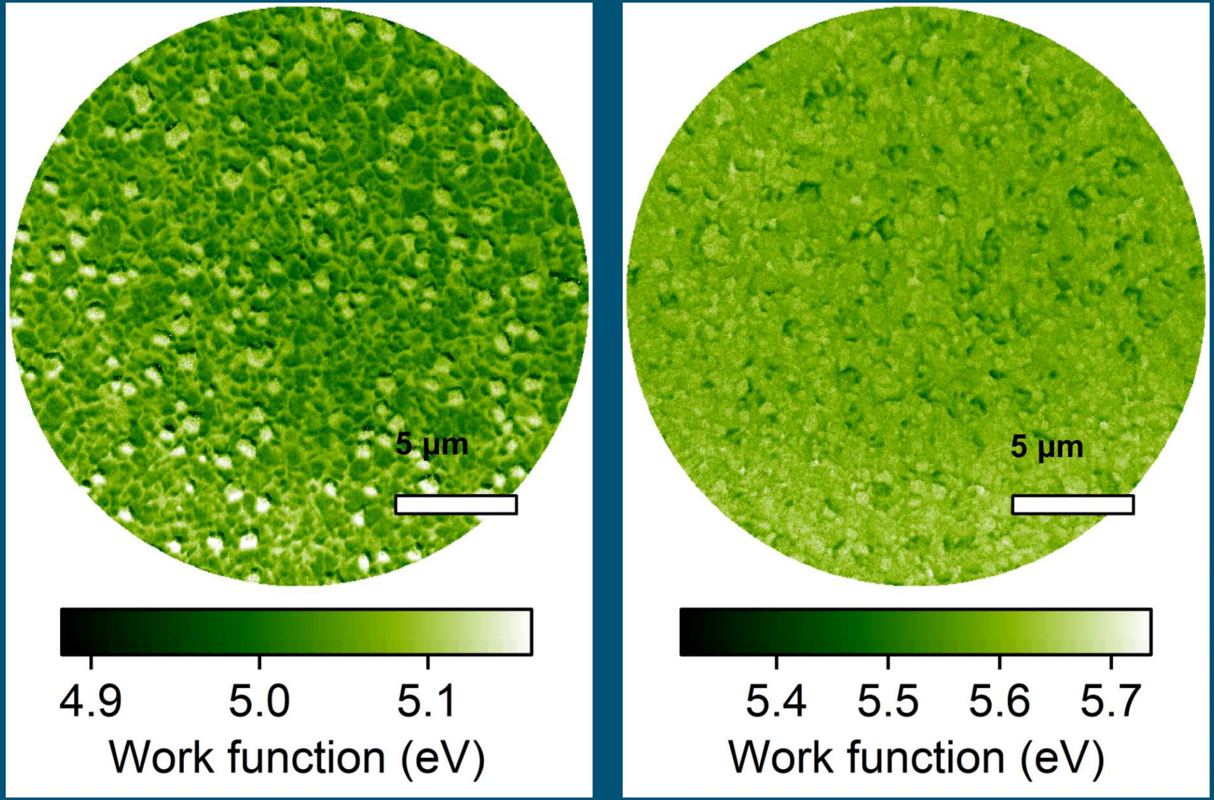
Air exposure drops another 0.5 eV.



Polycrystalline Pt (111) film surfaces

Air-exposed

Annealed



*Courtesy of Chris Moore and Matt Hopkins*

# Topography Influences Apparent Work Function

Found earlier work relating atomic step density to change in apparent work function. Atomic steps are like small dipoles.

$\varphi$ is inseparable from nm-scale topography. This further complicates the role of $\beta$.

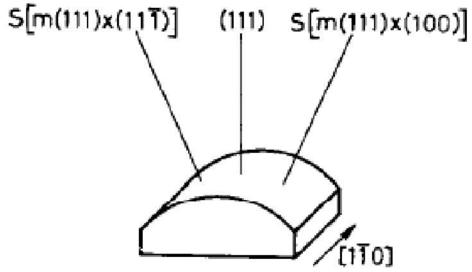
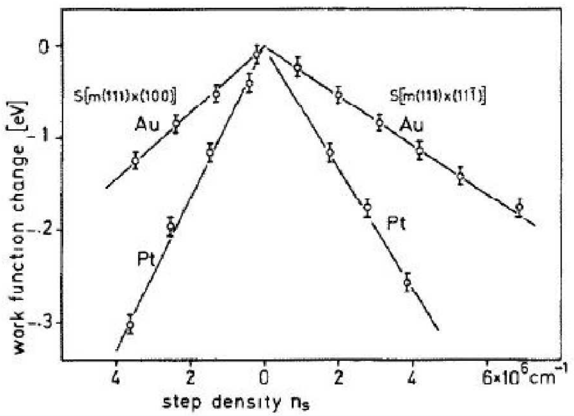
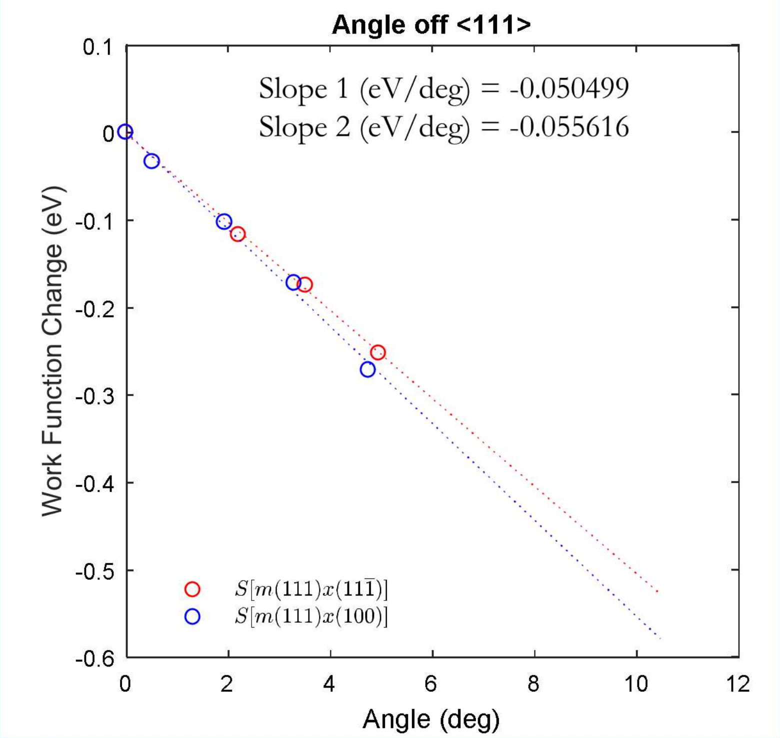
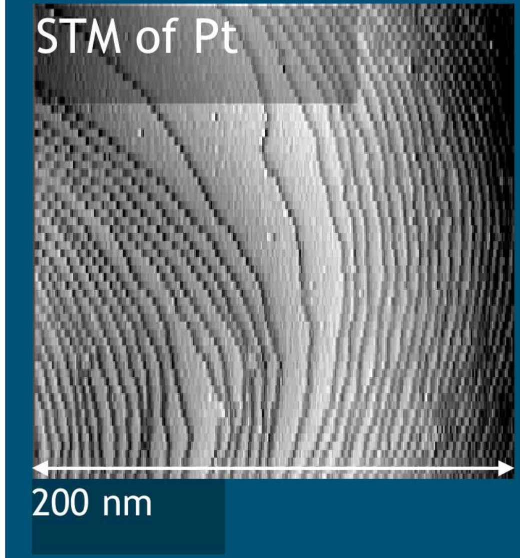


Fig. 1. Schematic representation of curved Pt and Au sample.







K. Besocke, B. Krahlurban, and H. Wagner, *Surf. Sci.* **68**, 39 (1977).

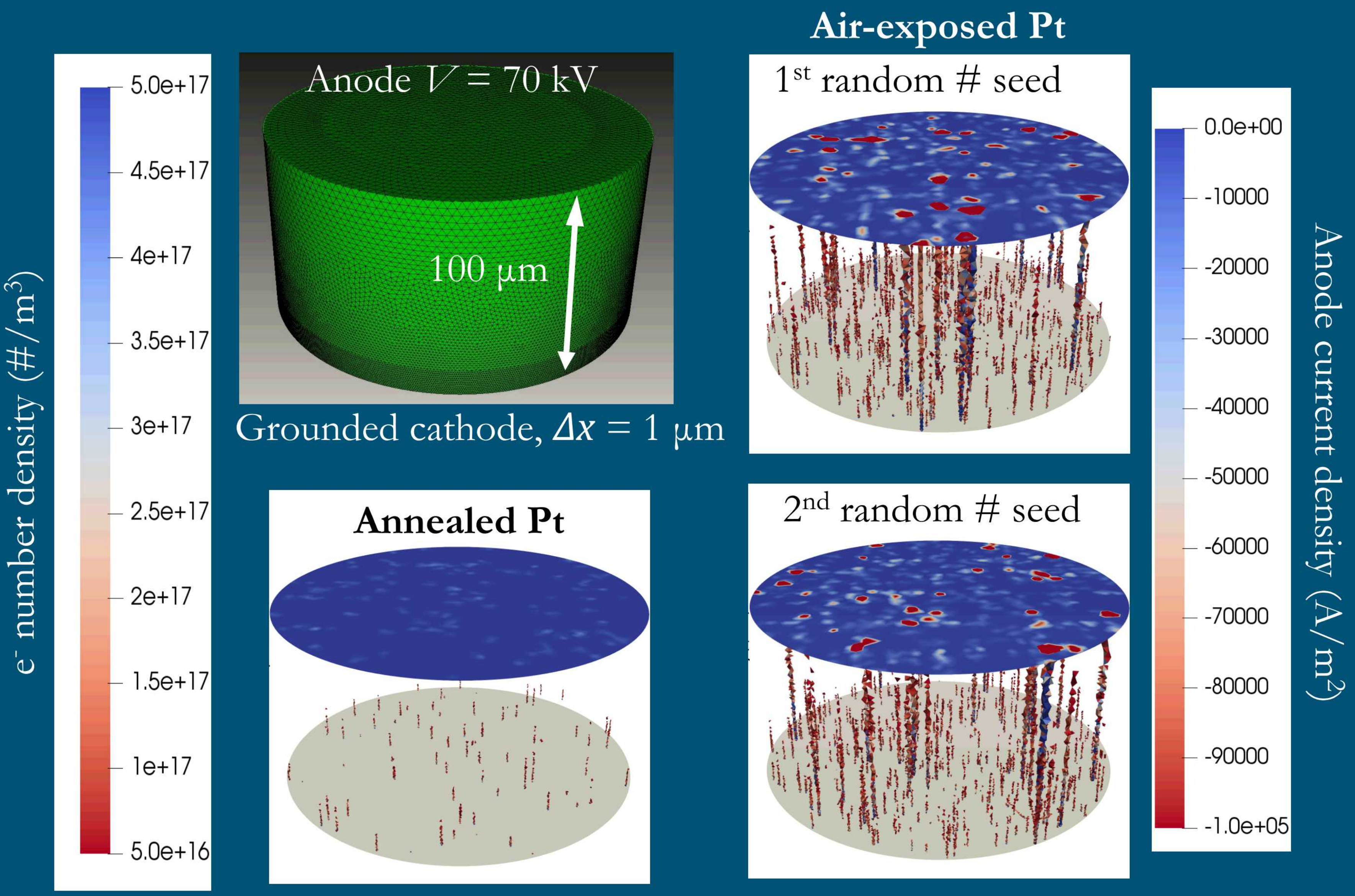
*Courtesy of Chris Moore and Matt Hopkins*

# Bridging to Practical Predictions of Electron Field Emission

Air-exposed Pt has significant variation in the initial field emission across the electrode due to variation in $\beta$ and $\varphi$.

Changing the random seed results in different distributions of initial emission sites. Important for understanding how parts fail.

A higher $\varphi$ for annealed Pt results in ~10x less emission.



Anode $V$ = 70 kV

Grounded cathode, $\Delta x$ = 1 μm

**Annealed Pt**

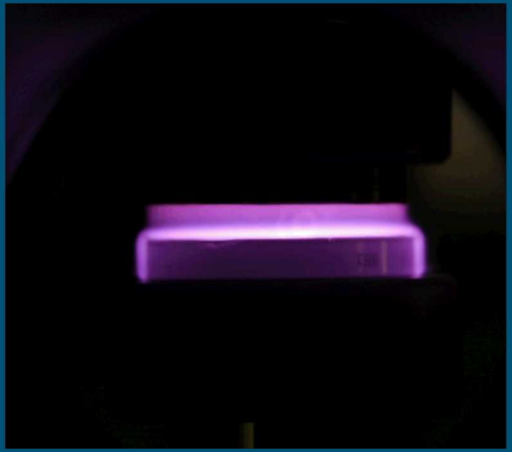
**Air-exposed Pt**

1st random # seed

2nd random # seed

# Discharge Feedback:

## Plasma ↔ secondary electron emission



Photons and ions created in the plasma cause photoemission and ion-induced secondary electron emission (SEE).

Technical gaps/science questions:

- Plasma determines fluxes of photons, ions and electrons to surface:
  - ➢ *directly measure plasma photo and ion energy spectra.*

- Photoemission yield $\gamma_{ph}$ and ion-induced SEE yield $\gamma_i$ for our materials/environments:
  - ➢ *measure the secondary electron generation rates at the surface.*
  - ➢ *physics of electron emission due to ion and photon surface impacts (yield model)*

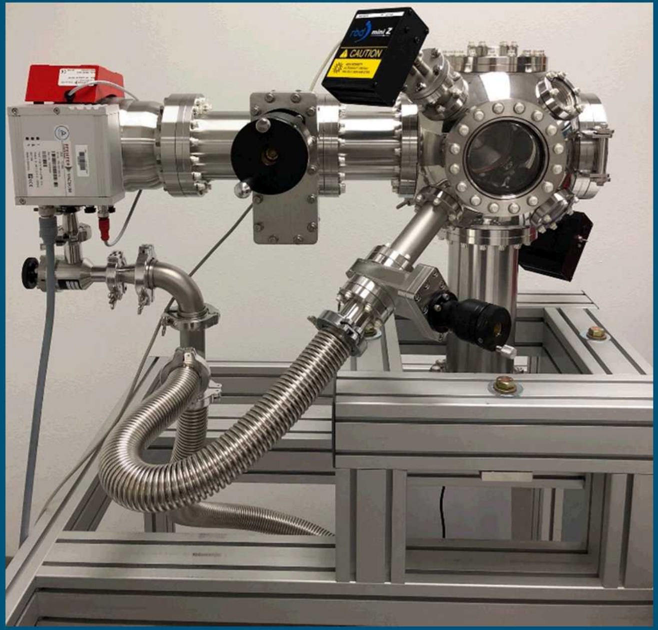
*Courtesy of Beth Paisley and Mike Brumbach*

# New metal SE yield measurement capability

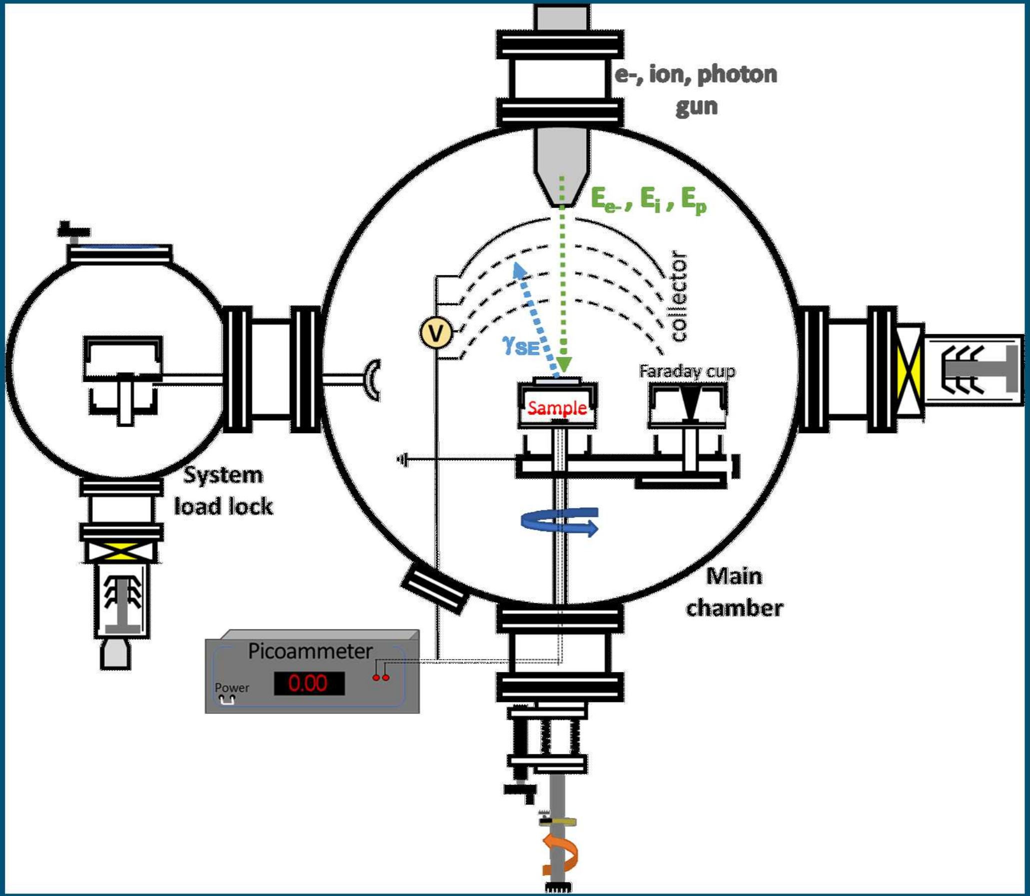
Secondary electron emission yield measurements of metals from: photons and ions.

New capability will be used on platinum to quantify SEE

Enduring SNL capability for SEE electrode measurements



SEE measurement schematic

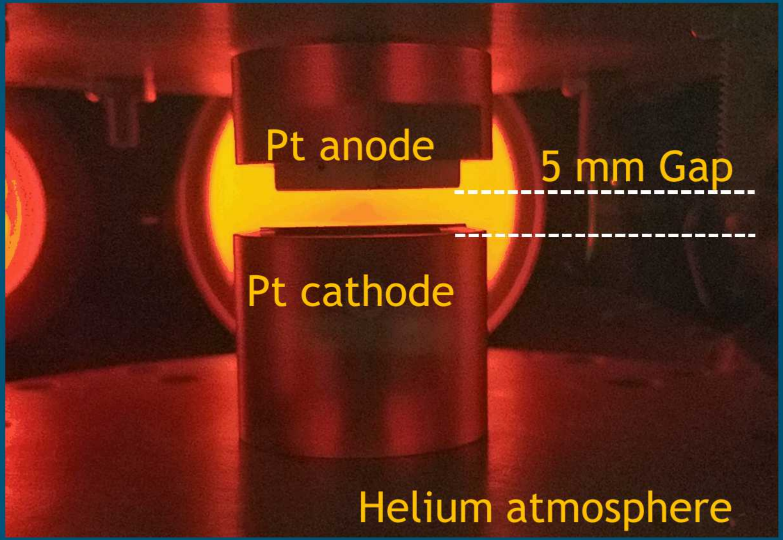


<u>Sources:</u>

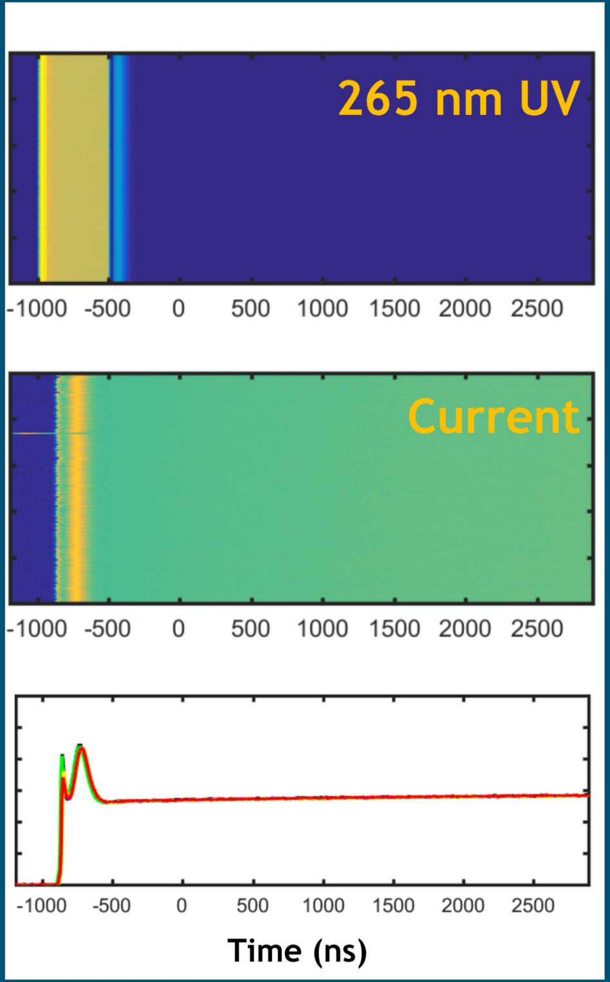
- $\gamma_i$ : He gas ion gun with E = 5 eV - 1 keV
- $\gamma_{ph}$: He lamp ($\lambda$ = 58.4 nm & 30.4 nm).

# 1D He discharge experiments

*Courtesy of Ed Barnat*



volume illuminated with UV to reduce experimental jitter

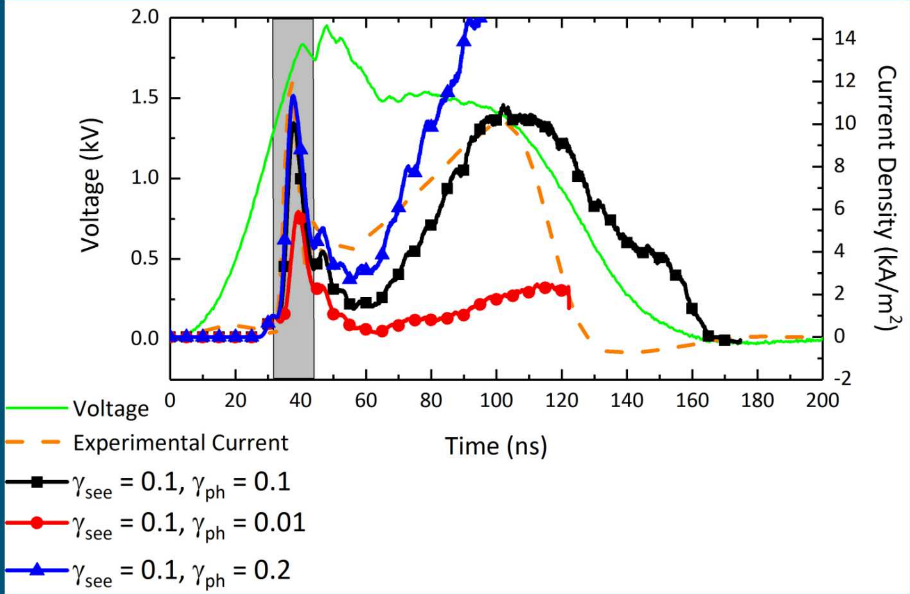


photoemitted electrons from the cathode seed predictable breakdown processes

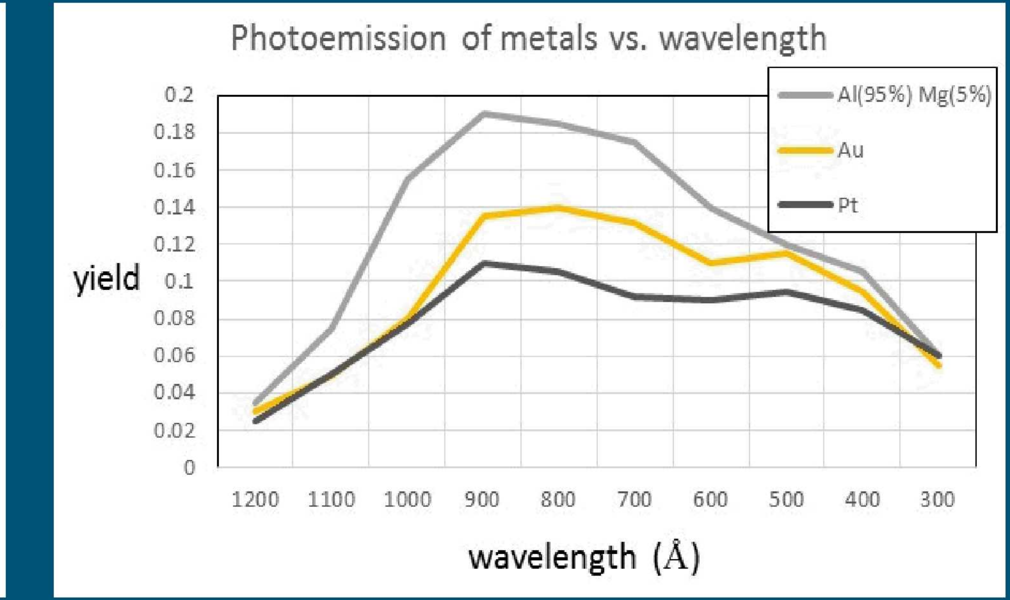
# 1D Simulations: metal photoemission affects discharge current

*Courtesy of Andy Fierro*

## Effect of photoemission yield



## Metal photoemission yields

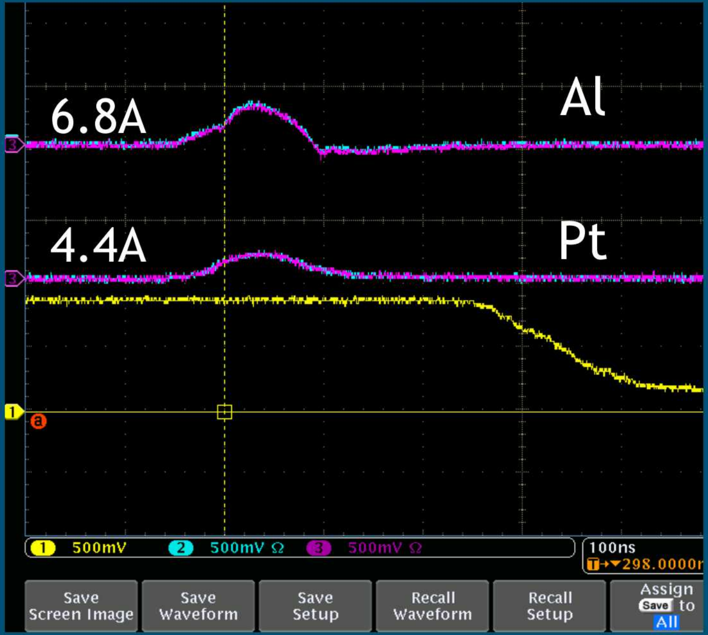


Varying photoemission yields predicts very different discharge currents:
Aluminum > steel ≈ gold > platinum

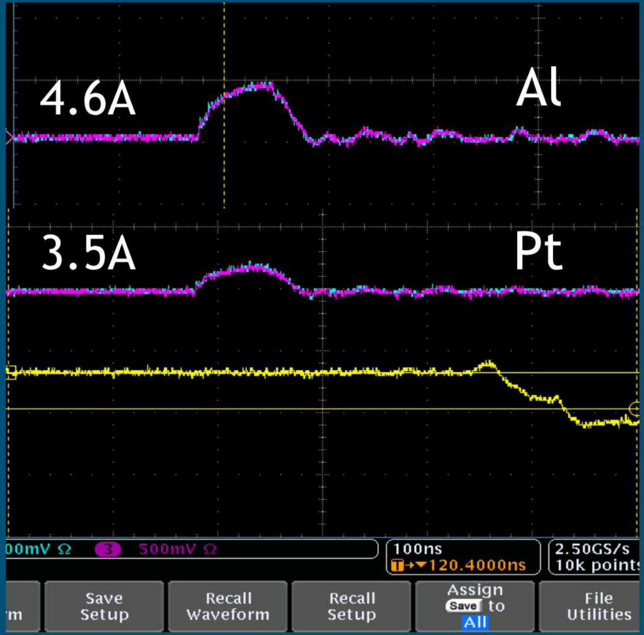
Ongoing experiments: investigating roles of different materials on breakdown

# ID Experiments: Pt vs. Al discharge in He and air

He discharge



Air discharge



Aluminum appears to display 30-55% higher secondary electron current than platinum

Ongoing experiments:

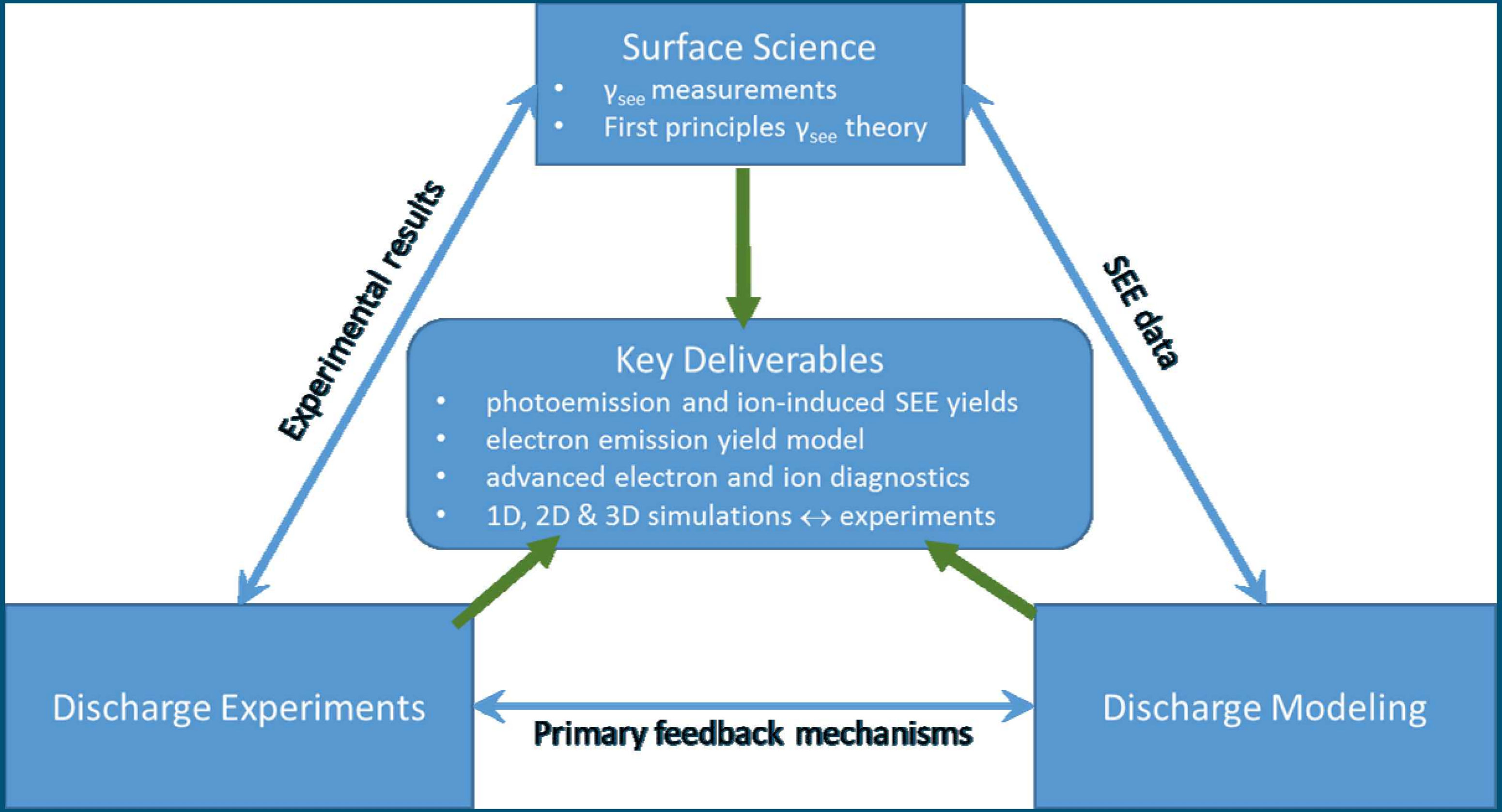
- Investigating roles of different metals on breakdown behavior in atmospheric and reduced pressure conditions
- Do thin surface coatings (1-5 nm) cause similar differences?

# The AMPPED LDRD goals are to

Quantify secondary electron emission (SEE) yields ($\gamma_{ph}$ and $\gamma_i$) for metal surfaces

Model, measure and confirm dominant discharge evolution processes

Incorporate these processes in Aleph/EMPIRE science-based modelling tools to predict electrical discharge and electrical discharge effects



**Surface Science**

- $\gamma_{see}$ measurements
- First principles $\gamma_{see}$ theory

**Key Deliverables**

- photoemission and ion-induced SEE yields
- electron emission yield model
- advanced electron and ion diagnostics
- 1D, 2D & 3D simulations ↔ experiments

Discharge Experiments

Discharge Modeling

# A Large Multi-Disciplinary Effort

Materials scientists
Morgann Berg
Ezra Bussmann
Taisuke Ohta
Elizabeth Paisley
Sean Smith
Michael Brumbach
David Scrymgeour
Laura Biedermann

Atomic scale modeling
Weng Chow
Harry Hjalmarson
Peter Schultz

Plasma/discharge modeling
Matt Hopkins
Chris Moore
Andrew Fierro
Ashish Jindal
Jeremy Boerner
Stan Moore

Plasma/discharge diagnostics
Edward Barnat
Ben Yee
Danny Kotovsky

prior projects over many years ...

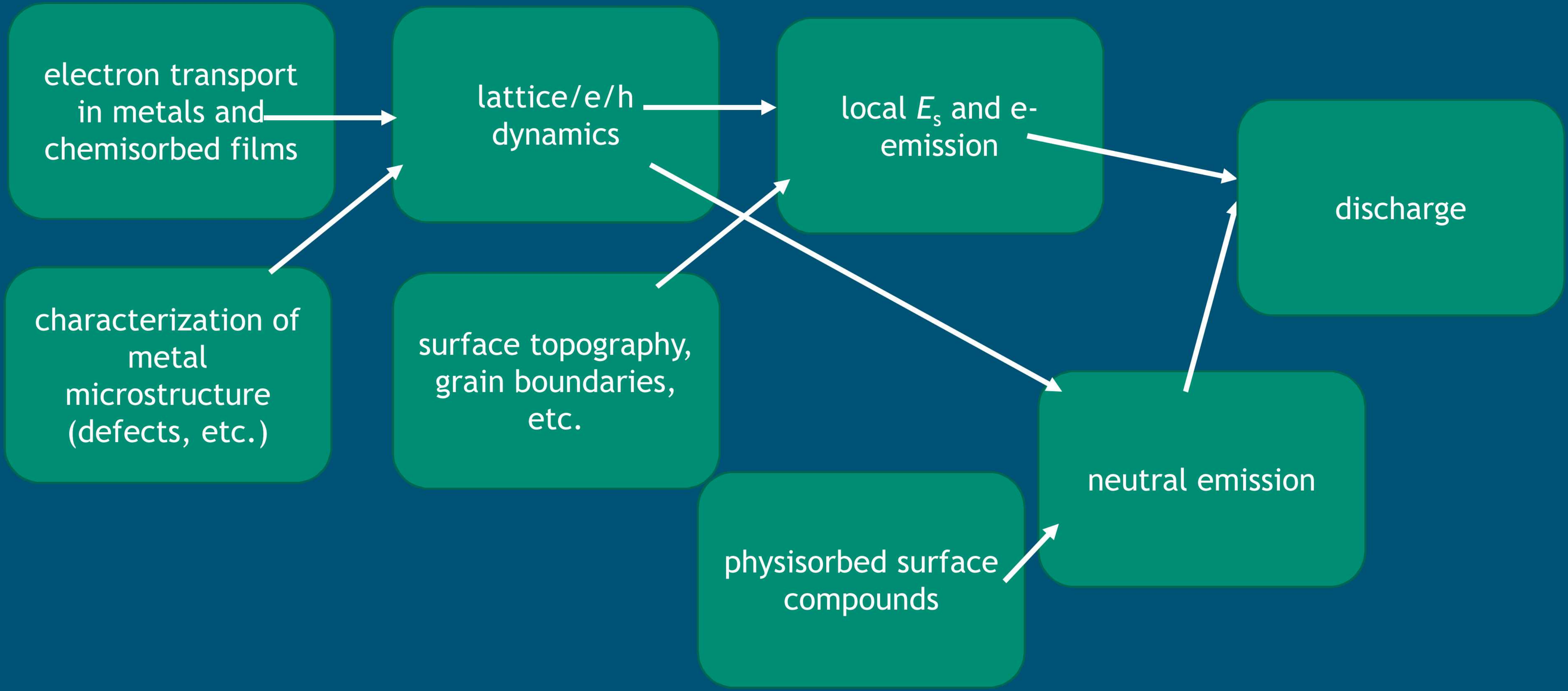
Talk topics:

Sources of initiating electrons
Uniform/nonuniform electrical fields
Gas ionization/pressure effects
Secondary electron processes

Wanted for future analysis:

Practical surfaces
Operating conditions (P, gas)
Electrical conditions
Aging mechanisms

# model hierarchy



electron transport in metals and chemisorbed films

lattice/e/h dynamics

local $E_s$ and e-emission

discharge

characterization of metal microstructure (defects, etc.)

surface topography, grain boundaries, etc.

neutral emission

physisorbed surface compounds