Microplasmas for Enhanced Thermionic Energy Conversion

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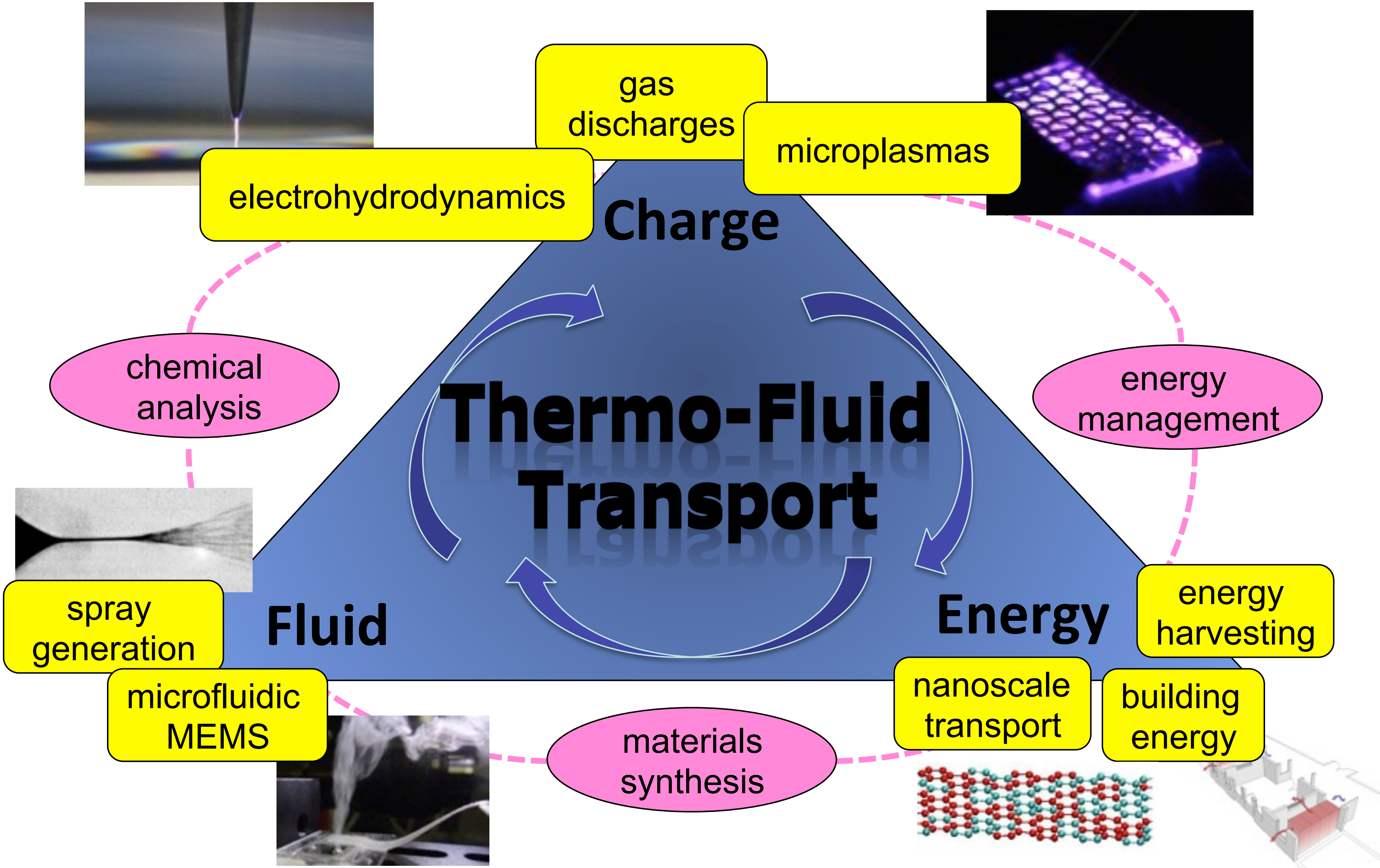
Small Scale Transport Research Lab



Thermo-Fluid Transport

Charge

Fluid

Energy

gas discharges

microplasmas

electrohydrodynamics

chemical analysis

energy management

spray generation

microfluidic MEMS

materials synthesis

nanoscale transport

energy harvesting

building energy

The Space Charge Challenge

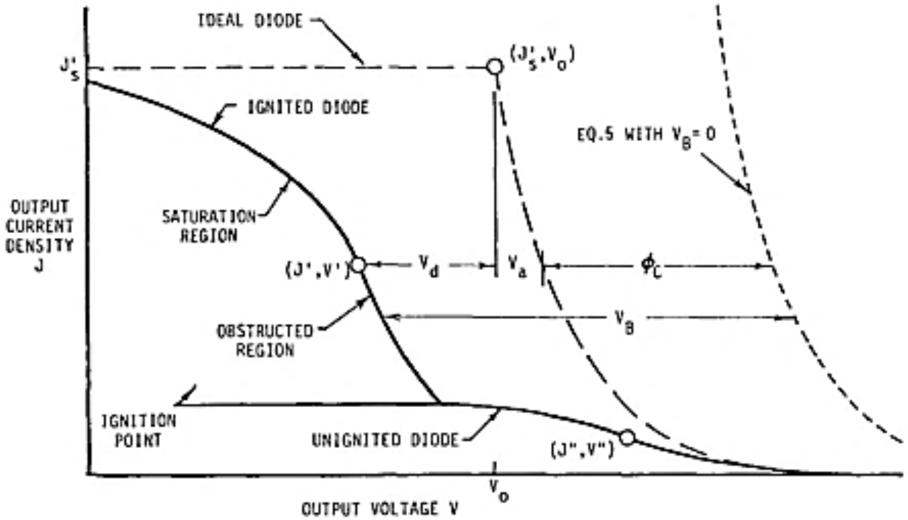
- Space charge can be a limiting factor thermionic emission and thermionic energy conversion (TEC)

- Two approaches to overcoming negative space charge:
  - Small electrode gaps to reduce electron residence time

    Practical Implementation: micron-scale electrode gaps or smaller
  - Introduce positive ions to ‘cancel’ negative electrons

    Practical Implementation: ignite a plasma (ionized gas) in the inter-electrode gap

Plasma-Enhanced TEC: Some History



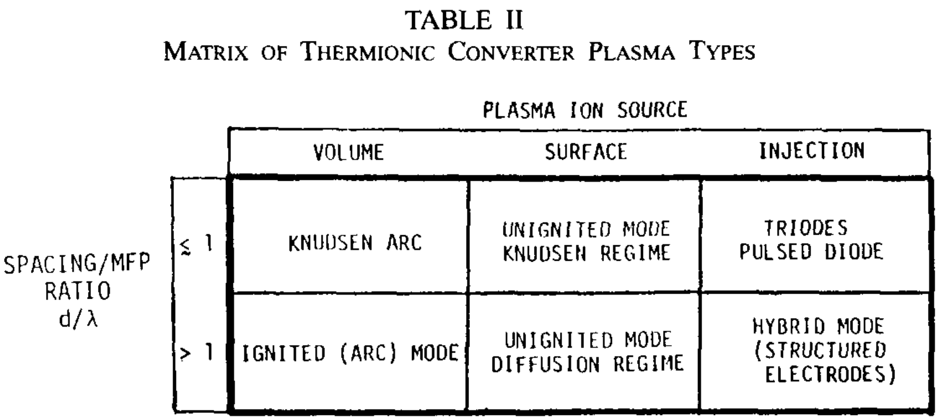


TABLE II

MATRIX OF THERMIONIC CONVERTER PLASMA TYPES

		PLASMA ION SOURCE		
		VOLUME	SURFACE	INJECTION
SPACING/MFP RATIO d/λ	$\lesssim 1$	KNUDSEN ARC	UNIGNITED MODE KNUDSEN REGIME	TRIODES PULSED DIODE
	> 1	IGNITED (ARC) MODE	UNIGNITED MODE DIFFUSION REGIME	HYBRID MODE (STRUCTURED ELECTRODES)

N. Rasor, IEEE Trans. Plasma Sci. 19, 1191 (1991)

- Plasmas have a long history of being incorporated into TEC in multiple modes
- Typically cesium plasmas are used because of low ionization energy (spontaneously ignite) and low work function (reduce cathode work function by adsorption) - require high temperatures > 1500 K to operate

Injected non-equilibrium plasmas *bring in new opportunities for taking advantage of unique plasma science (balancing ionization, collisions, and energy paths in plasma with power conversion)*

M. Shneider et al., AIAA 2006-3385 (2006); B. Pivtorak, AIAA (2007)

Microdischarges and Microplasmas

Microdischarges & Microplasmas

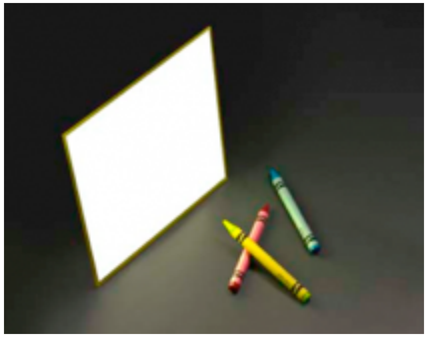
- gas discharges with a characteristic dimension less than 1 mm
- advantageous *pd* scaling enables stable operation at high *p* (1 atm)
- high pressure leads to new chemical pathways ➔ new applications

Effects of Confinement*

- **decreased electrode spacing ➔** affects charge density distribution & Debye length
- **increased surface-to-volume ratio ➔** affects energy balance and distribution

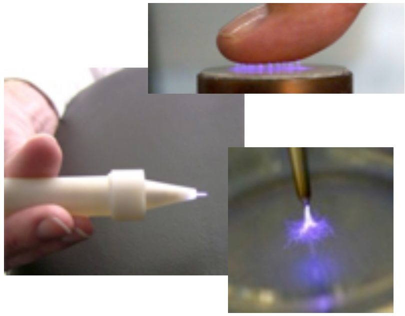
*Mariotti & Sankaran, *J. Phys D: Appl. Phys.*, 2011

Lighting



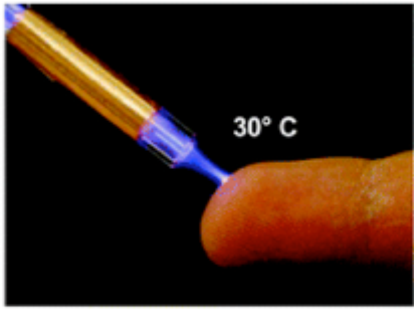
http://www.edenpark.com/

Medical and Dental



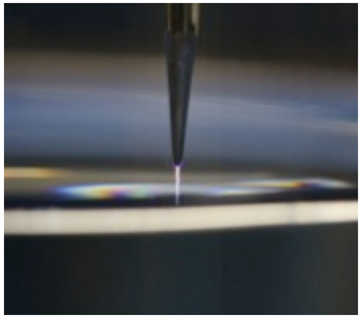
http://www.plasmainstitute.org/

Environmental and Chemical Analysis



Harper et al., *Anal. Chem.*, 2009

Plasma/Liquid

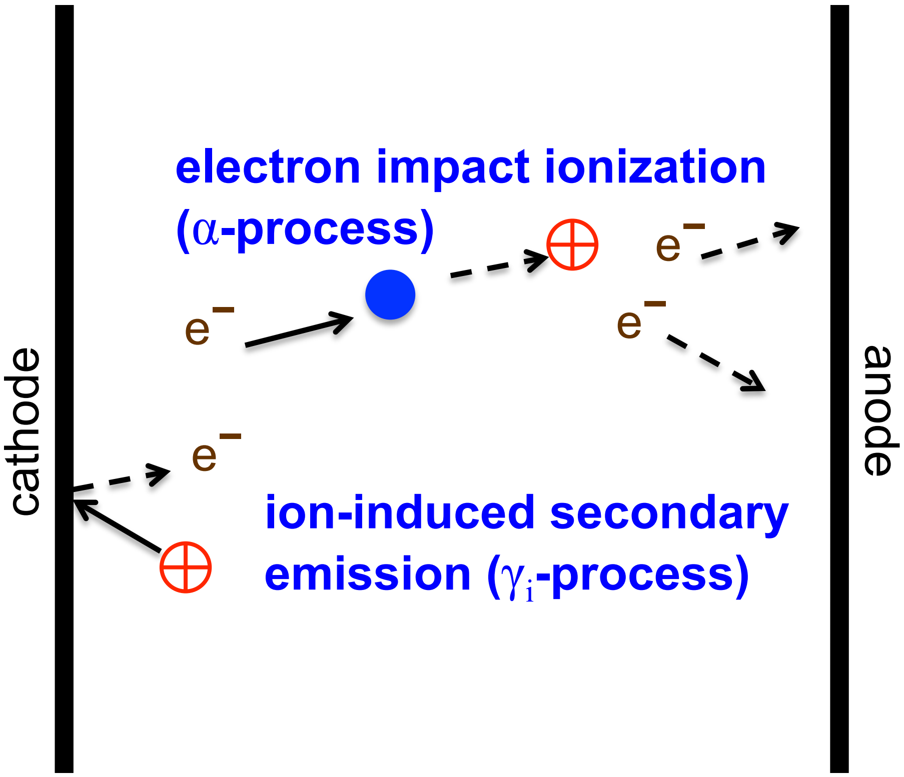


Witzke, Rumbach, Go, Mariotti, *J. Phys D: Appl. Phys,* 2012

Surface processes play an increasingly important role as scales decrease

Gas Breakdown

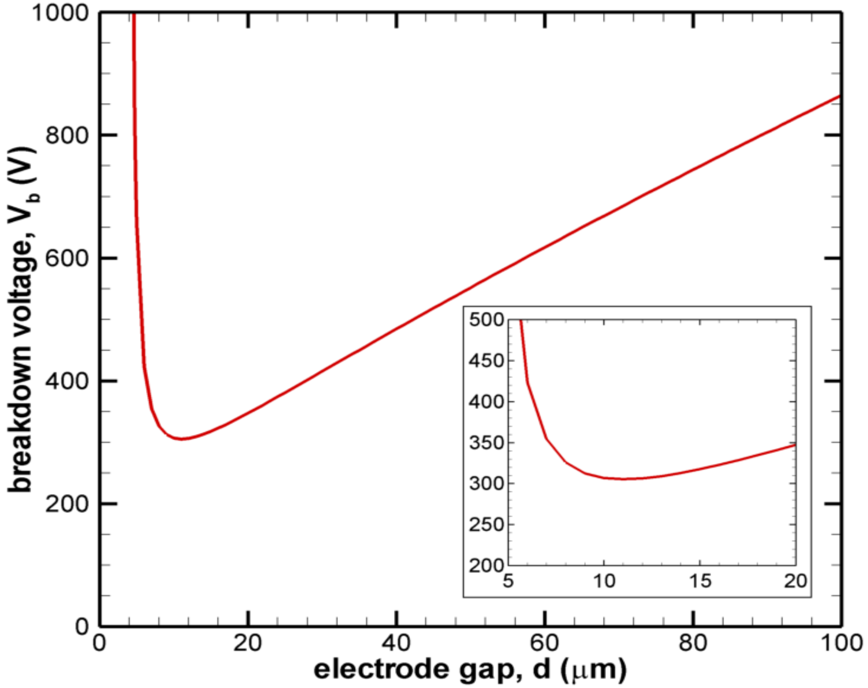
Charge Creation Processes



electron impact ionization (α-process)

ion-induced secondary emission (γ_i-process)

Paschen's Law (curve)



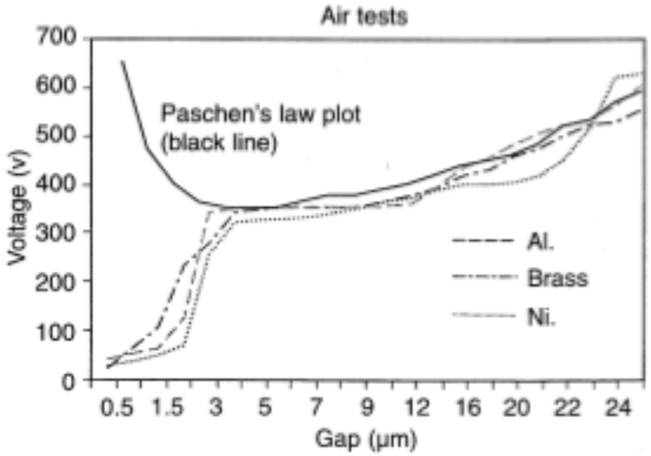
$$V_b = \frac{Bpd}{\ln(pd) + \ln\left(\frac{A}{\ln(1/\gamma_i + 1)}\right)} = f(pd)$$

MEMS and Anomalous Breakdown

Microsystem Technologies 6 (1999) 6–10 © Springer-Verlag 1999

Electric field breakdown at micrometre separations in air and vacuum

J.-M. Torres, R.S. Dhariwal



Arc erosion behaviour of silver electric contacts in a single arc discharge across a static gap

R.-T.Lee, H.-H.Chung and Y.-C.Chiou

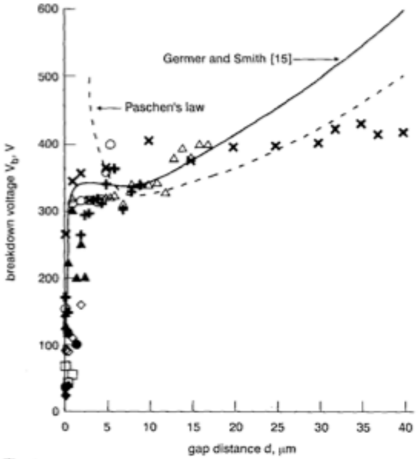


Fig.6 *Effects of supply voltage and gap distance on breakdown voltage*

Supply voltage:

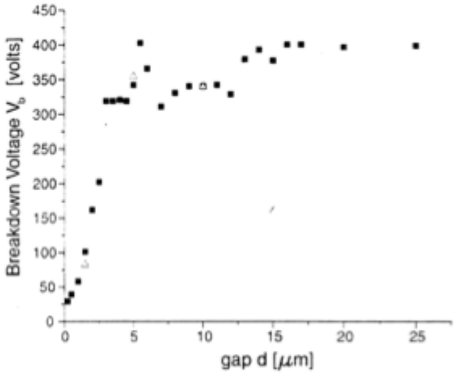
× 500V ○ 250V ● 100V

△ 400V ▲ 200V □ 60V

+ 300V ◇ 160V ◆ 40V

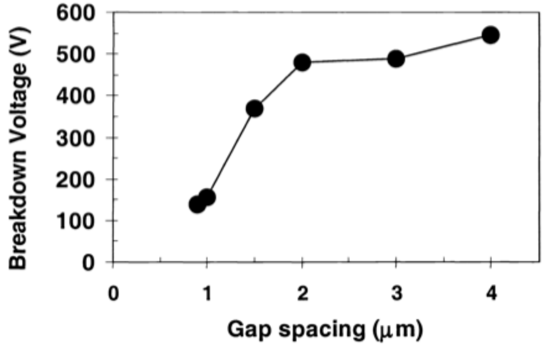
Electrical Breakdown in Atmospheric Air Between Closely Spaced (0.2 μm–40 μm) Electrical Contacts

Paul G. Slade, *Fellow, IEEE*, and Erik D. Taylor, *Member, IEEE*

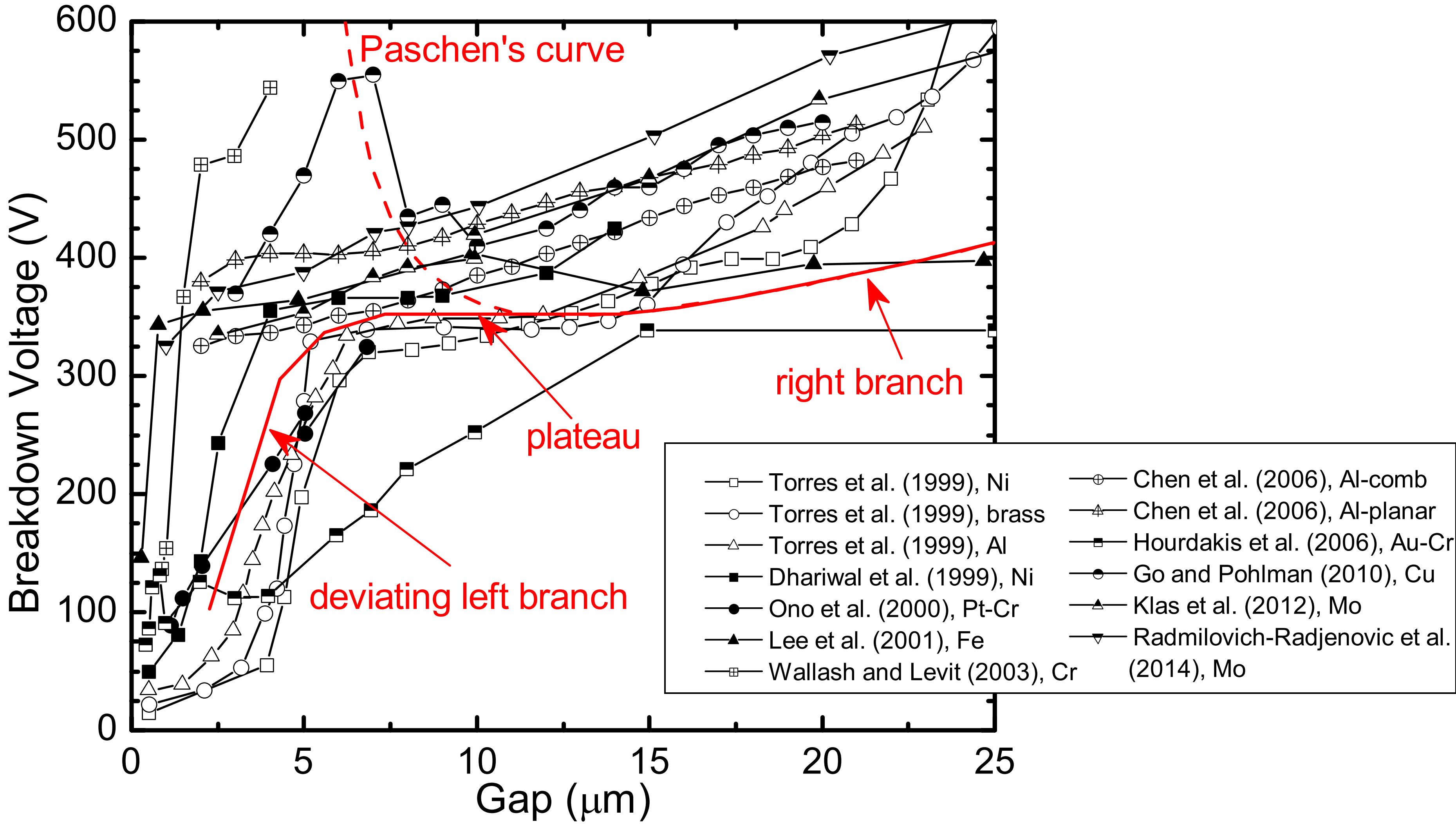


Electrical breakdown and ESD phenomena for devices with nanometer-to-micron gaps

Al Wallash[*a] and Larry Levit[b]



Modified Paschen's Curve

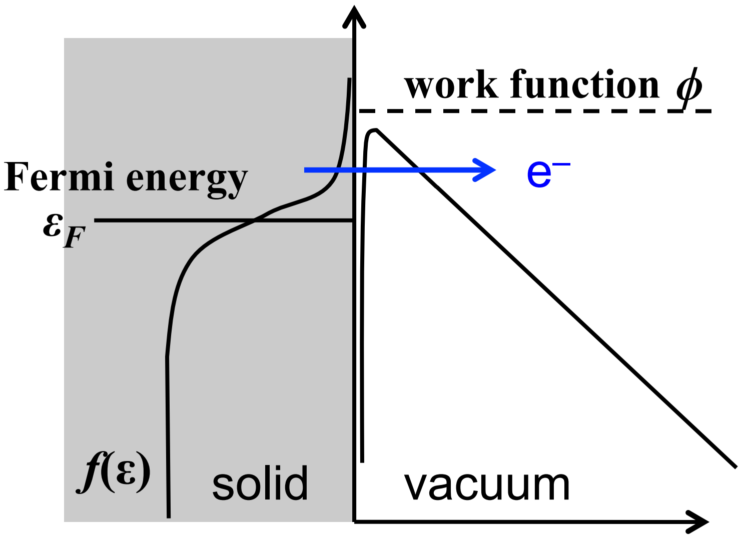


Go and Pohlman, *J. Appl. Phys.* (2010)

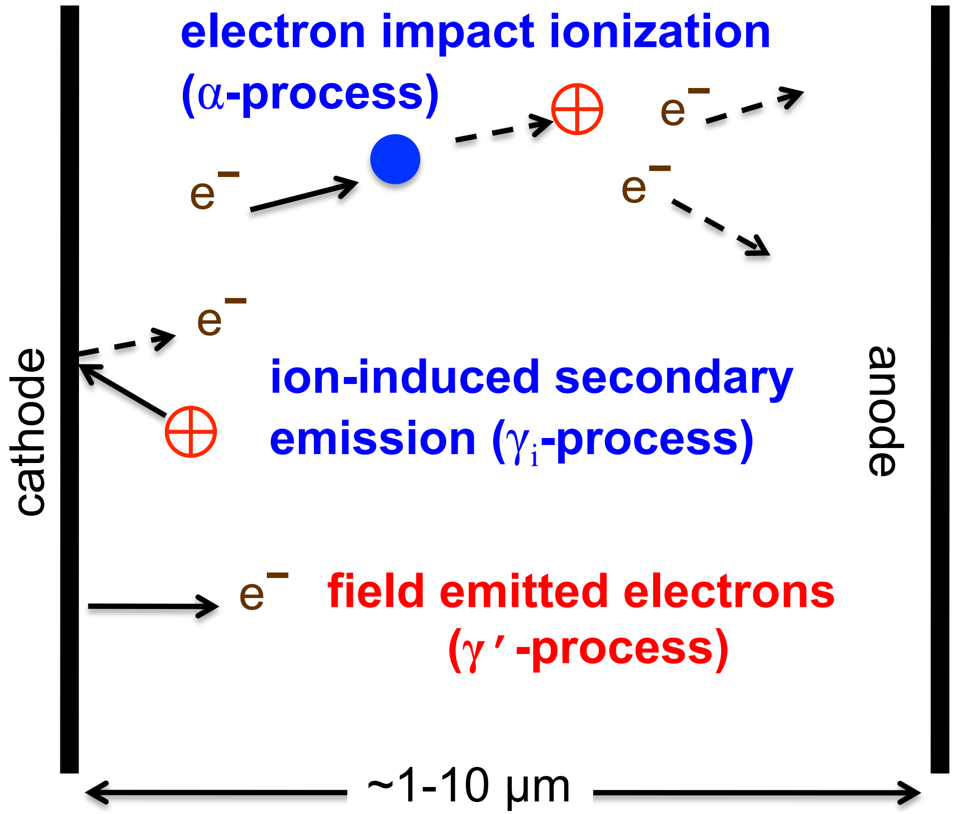
Go and Venkattraman, *J. Phys. D*: *Appl. Phys.* (2014)

Microscale Induces Electron Field Emission

At very high electric fields – electrons can be directly emitted from the surface of a metal via a quantum mechanical effect called **field emission**



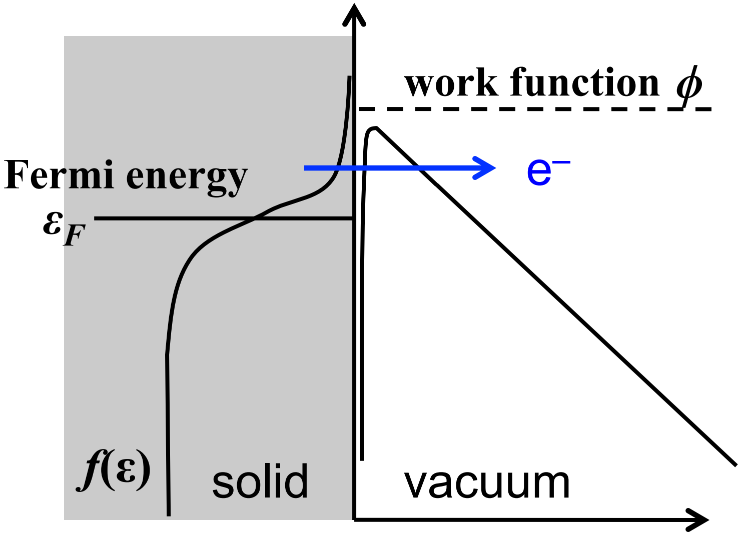
Charge Creation Processes


electron impact ionization (α-process)

ion-induced secondary emission (γ_i-process)

field emitted electrons (γ'-process)

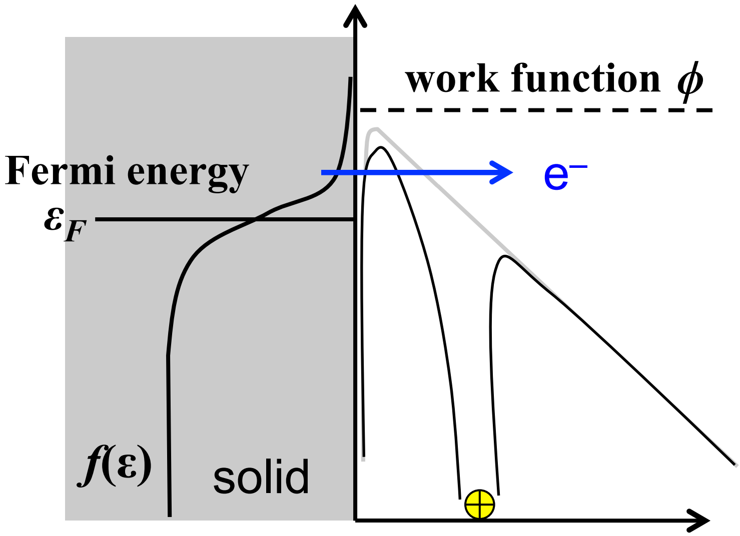
Ion-Enhanced Field Emission



Fowler-Nordheim Equation (1928)

$$j = \frac{A_{FN}[\beta E]^2}{\phi \tau^2(y)} \exp\left[\frac{-B_{FN}\phi^{3/2}v(y)}{\beta E}\right]$$

*theoretically require fields ~1000 V/μm but practically as low as 10-100 V/μm

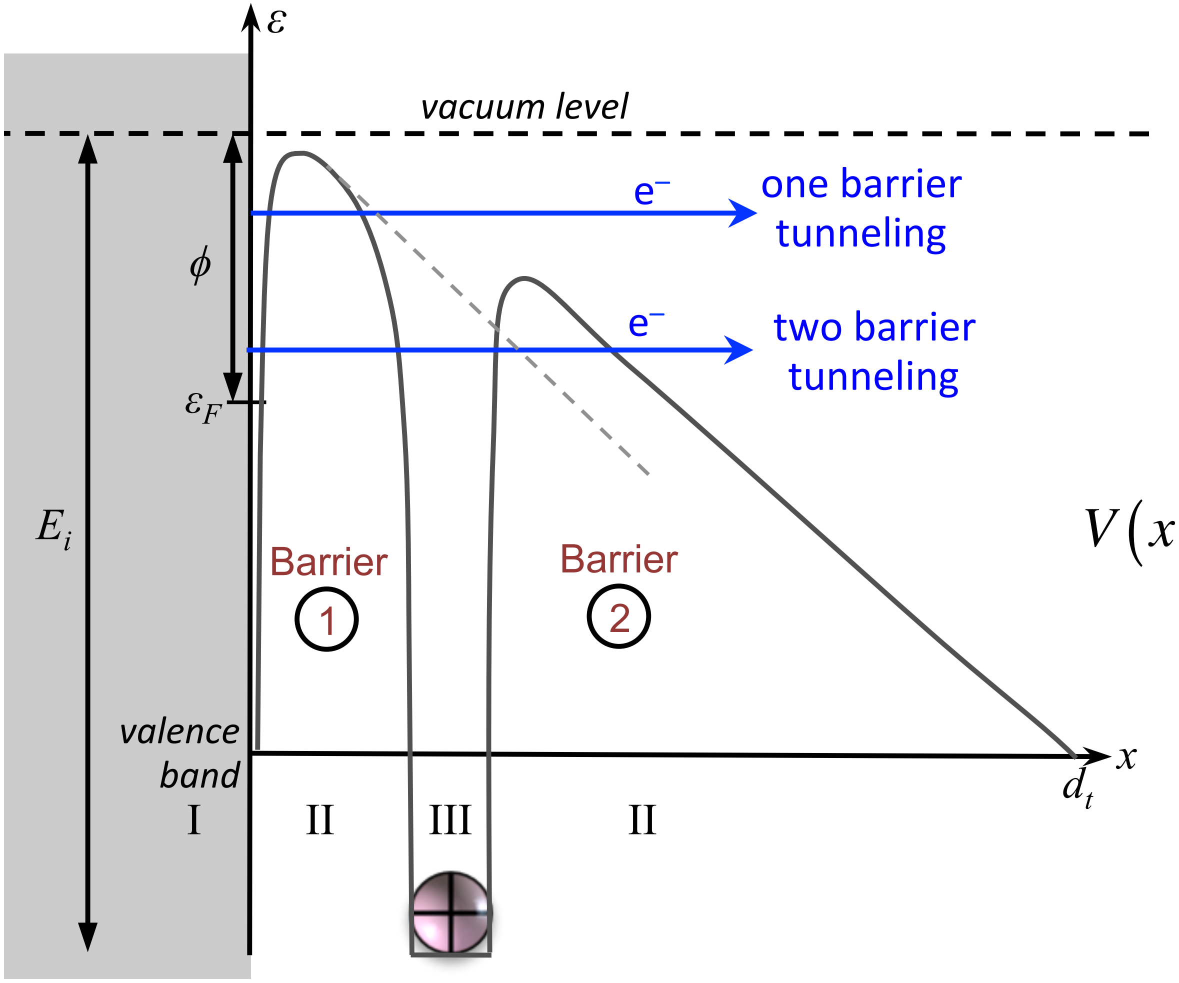


0th-order ion enhanced field emission

$$j = \frac{A_{FN}[\beta E + E_{ion}]^2}{\phi \tau^2(y)} \exp\left[\frac{-B_{FN}\phi^{3/2}v(y)}{\beta E + E_{ion}}\right]$$

*the ion's potential thins the potential barrier making it easier for an electron to tunnel from the cathode

Quantum Mechanics of IEFE

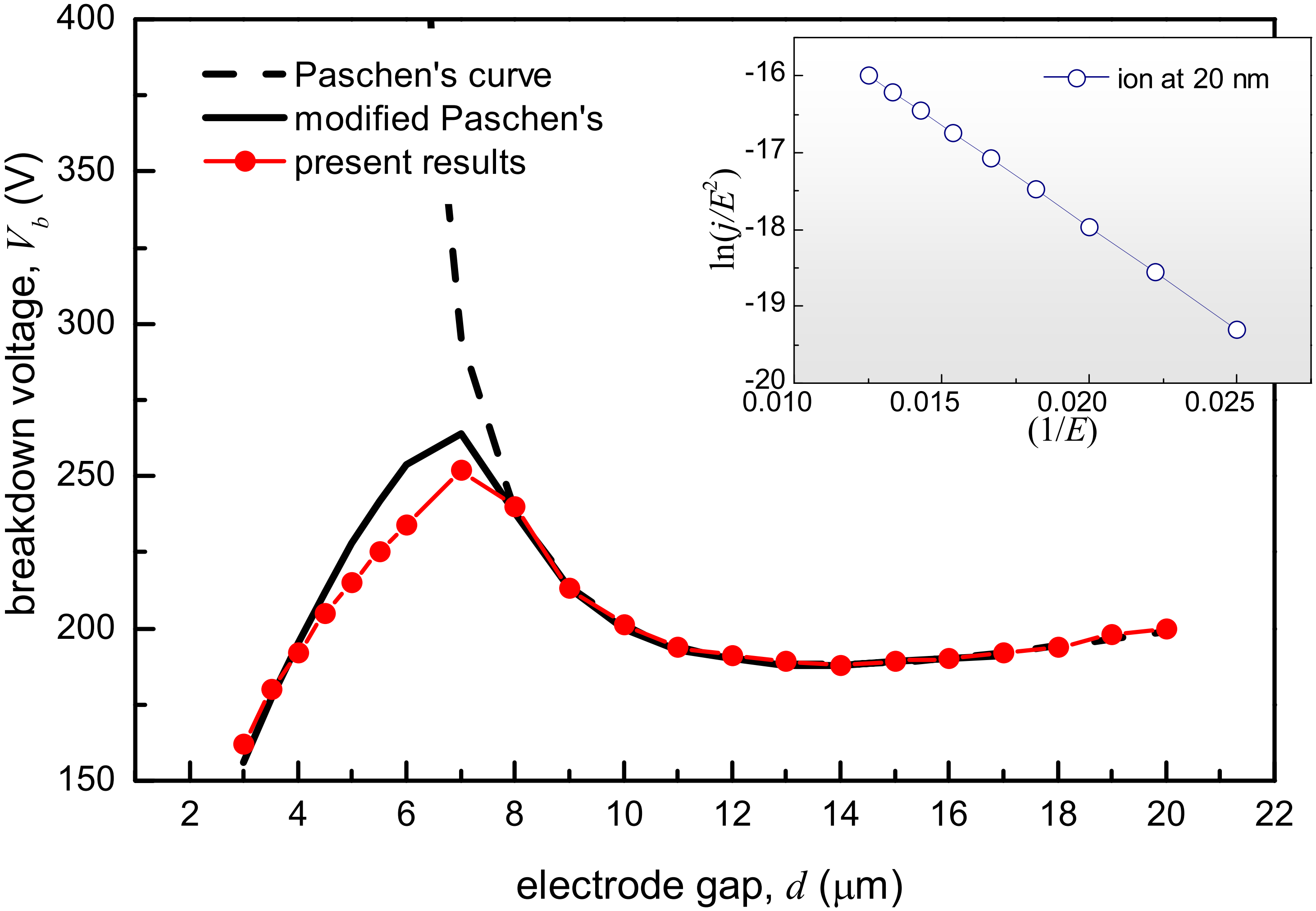


$$\frac{\hbar^2}{2m}\frac{d^2\Psi}{dx^2}+\varepsilon\Psi = V(x)\Psi$$

$$V(x)=V_{electron}(x)+V_{app}(x)+V_{ion}(x)$$

$$T(\varepsilon)=\frac{|\text{outgoing}|}{|\text{incoming}|} \longrightarrow j=q\int N(\varepsilon)T(\varepsilon)\,d\varepsilon$$

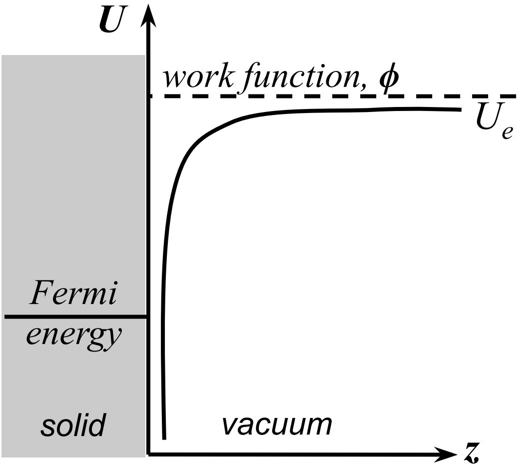
IEFE Causes Deviation from Paschen' Curve



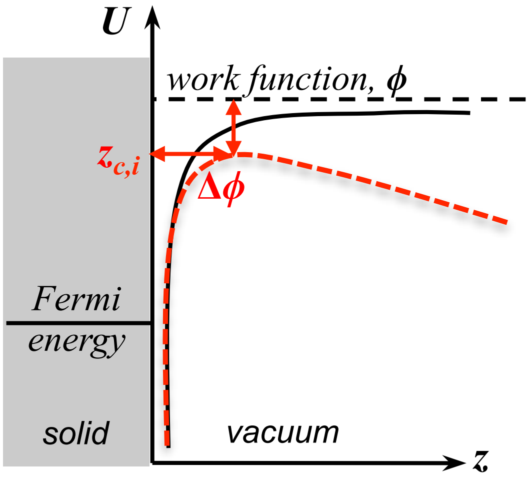
Ion-enhanced field emission manifests itself in a global effect (breakdown)

Tirumala and Go, *Appl. Phys. Lett.* (2010)
Li and Go, *J. Appl. Phys.* (2014)

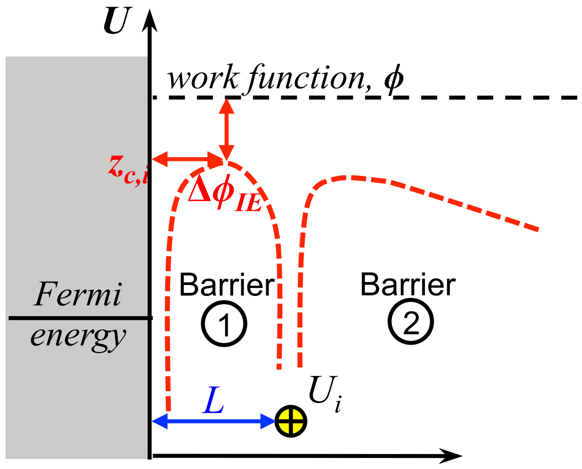
Ion-Enhanced Thermionic Emission



Thermionic Emission



Schottky Emission



Ion-Enhanced Schottky Emission

$$j_{TE} = AT^2 \exp\left(-\frac{\phi}{k_B T}\right)$$

$$j_S = AT^2 \exp\left(-\frac{(\phi-\Delta\phi)}{k_B T}\right)$$

$$j_{IESE} = AT^2 \exp\left(-\frac{(\phi-\Delta\phi_{IE})}{k_B T}\right)$$

$$j_S = j_{TE} \exp\left(\frac{\left(Eq^3/4\pi\varepsilon_0\right)^{1/2}}{k_B T}\right)$$

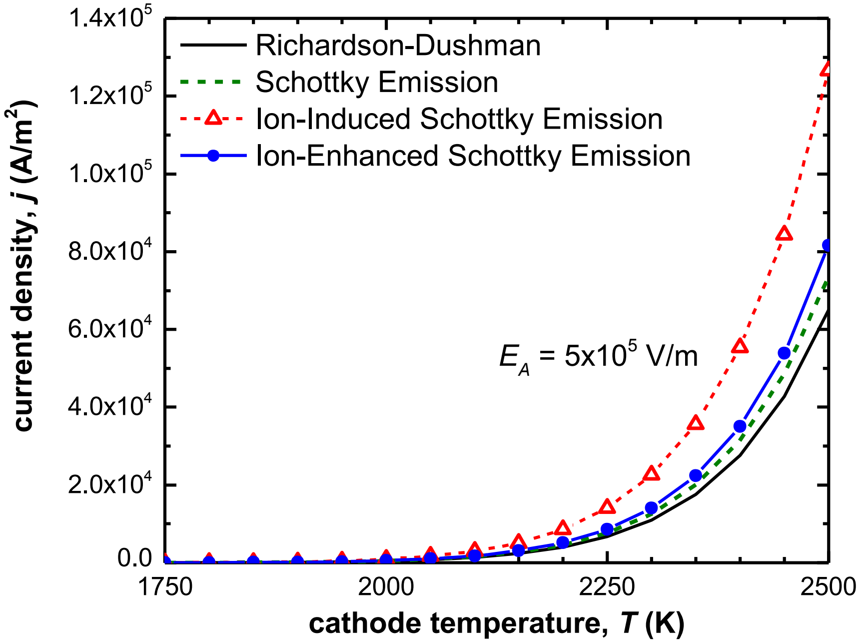
$$j_S = j_{TE} \exp\left(\frac{f\left(E_A, L\right)}{k_B T}\right)$$

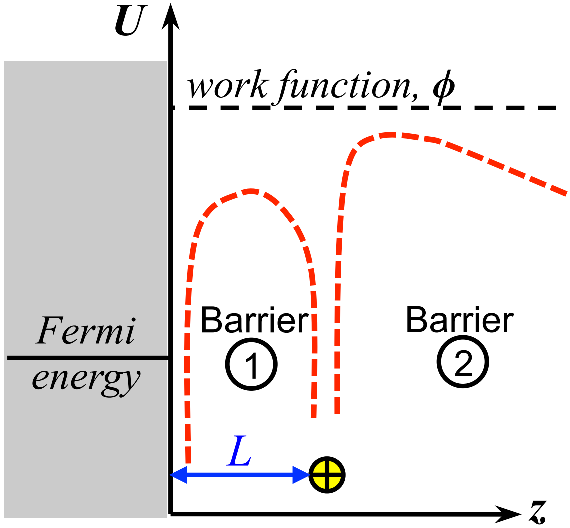
Go, *J. Phys. D: Appl. Phys.* (2013)

Ion Enhances Emission Current

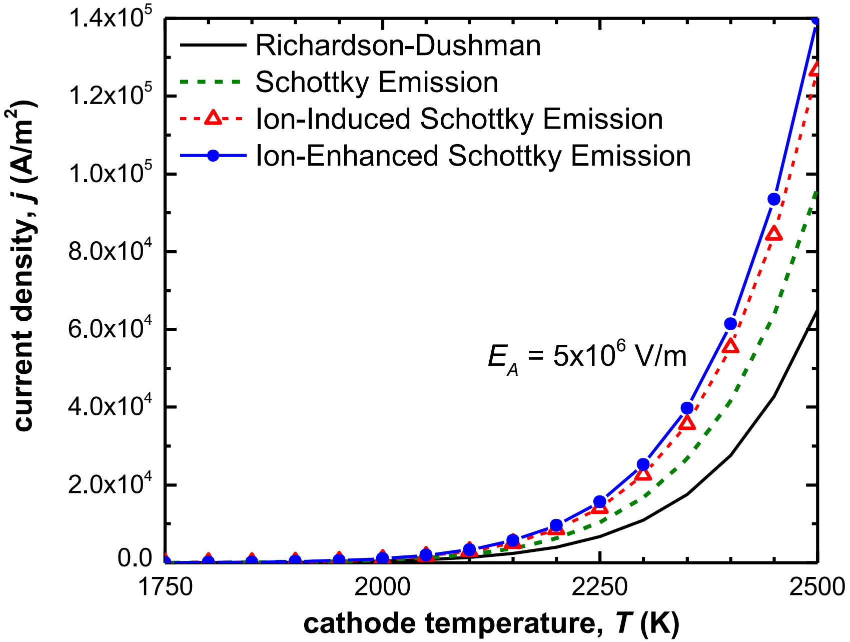
L = 15 nm

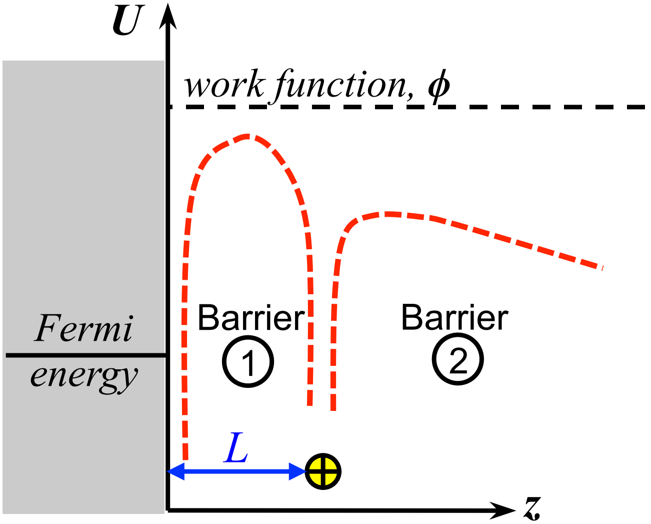
low electric field





high electric field



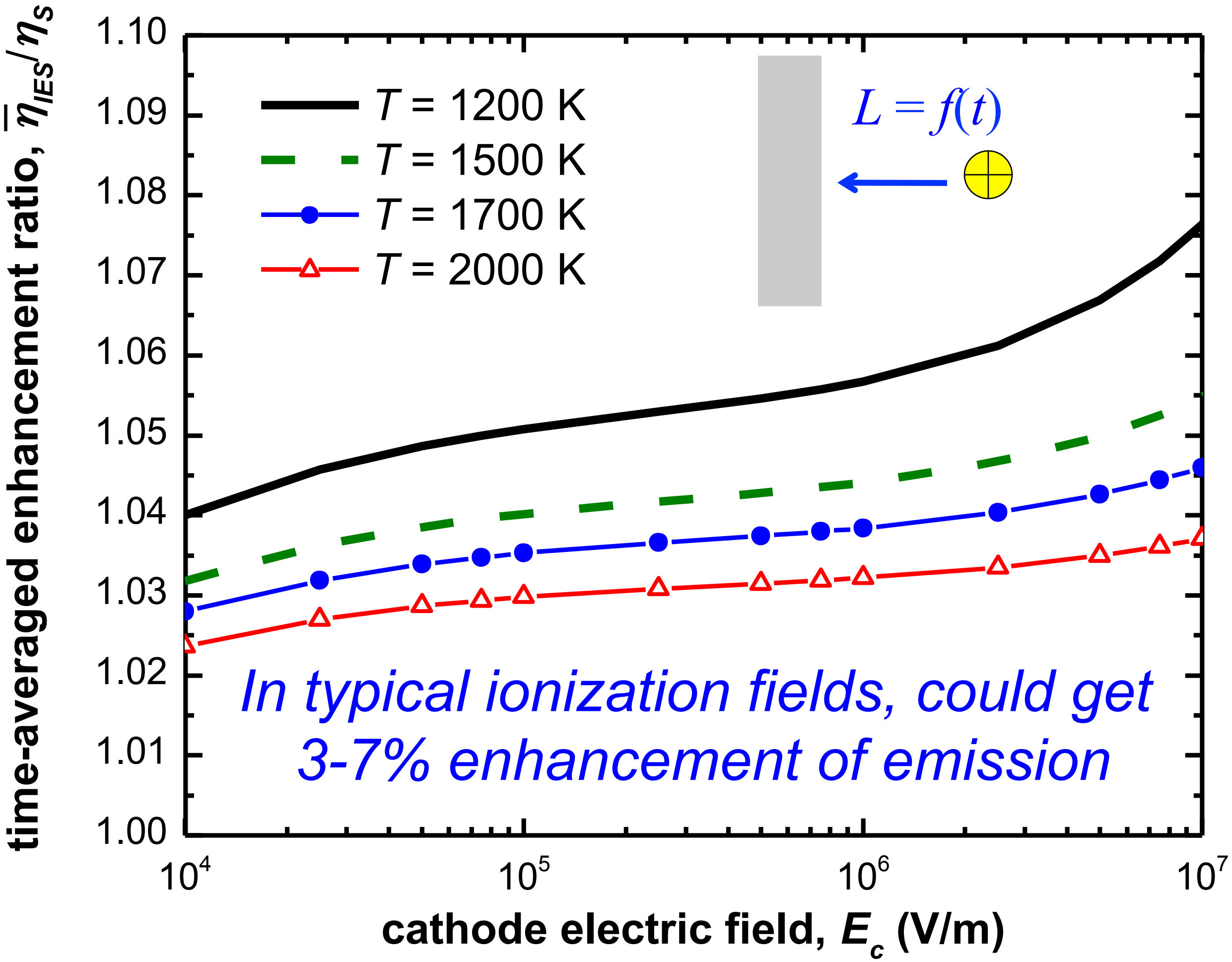


UNIVERSITY OF NOTRE DAME

Go, *J. Phys. D: Appl. Phys.* (2013)

Net Enhancement Over Lifetime of Ion

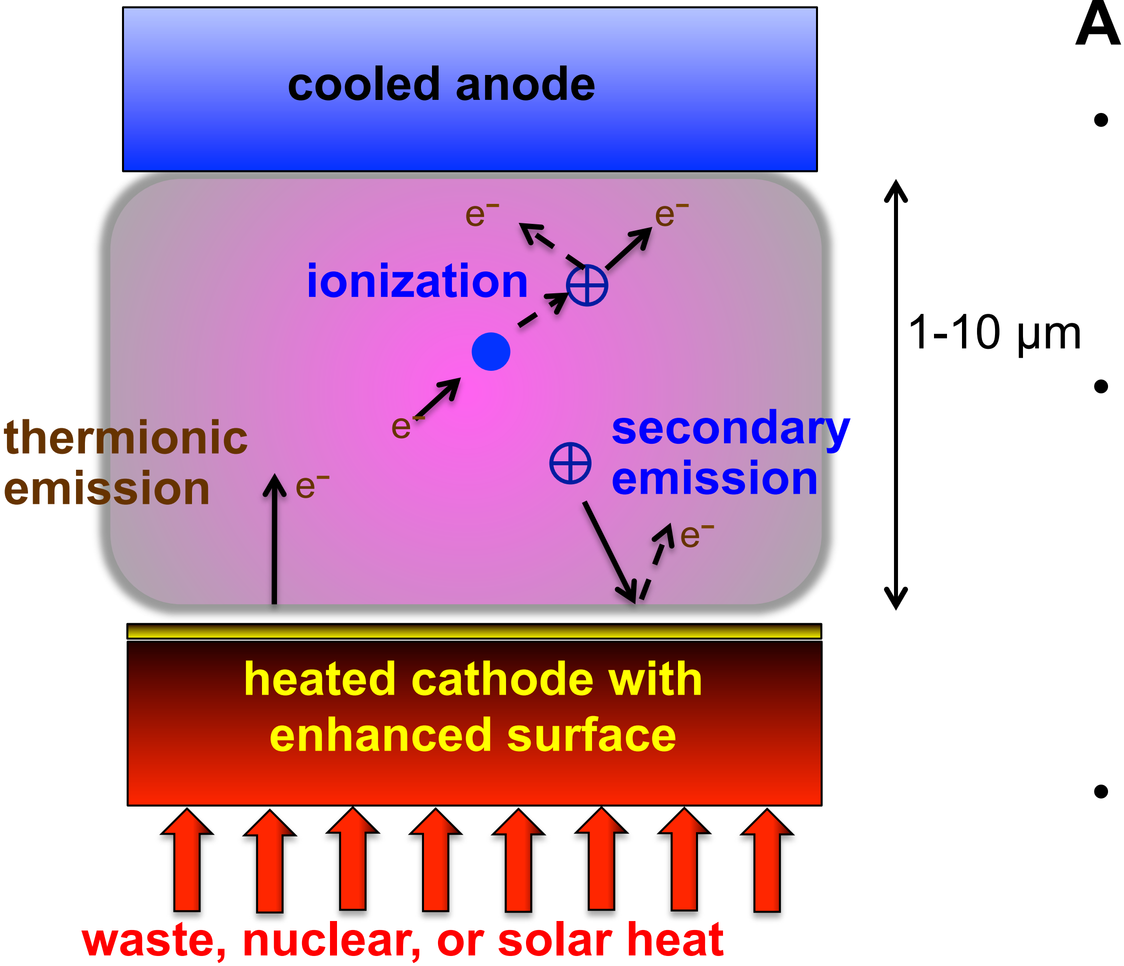
$$\overline{\eta}_{IES} = \frac{1}{T_c}\int_0^{T_c} \exp\left(\frac{1}{k_B T}\left[qE_c z_{c,i}(t) + \frac{q^2}{16\pi\varepsilon_o z_{c,i}(t)} + \frac{q^2}{4\pi\varepsilon_o}\left(\left[\left(z_{c,i}(t)-\left(L_0-\mu E_c t\right)\right)^2\right]^{-1/2} - \left[\left(z_{c,i}(t)+\left(L_0-\mu E_c t\right)\right)^2\right]^{-1/2}\right)\right]\right)dt$$



In typical ionization fields, could get 3-7% enhancement of emission

Go, *J. Phys. D*: *Appl. Phys.* (2013)

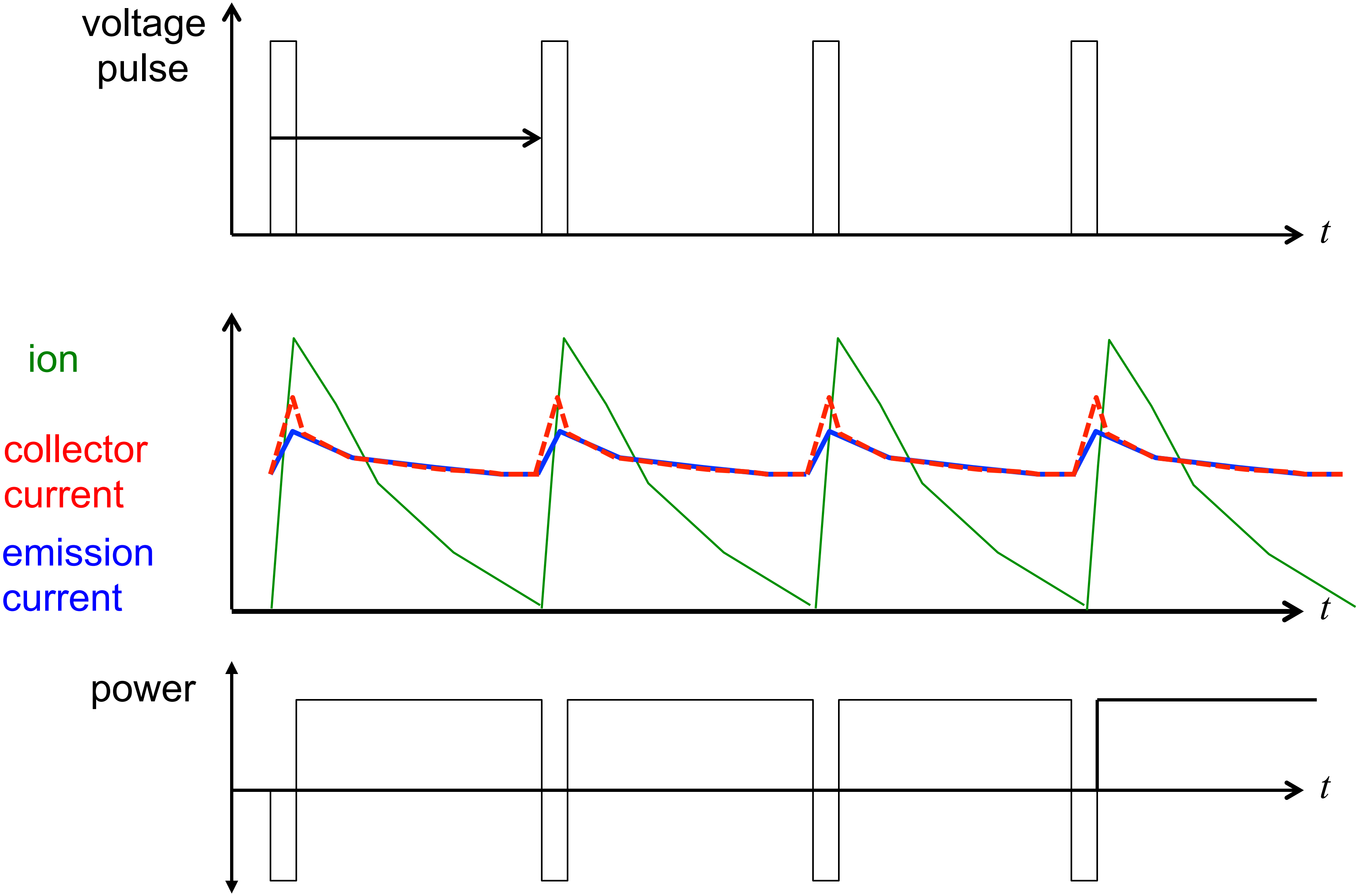
Microplasma-Enhanced TEC: Concept



Advantages (conceptually)

- reduced electrode gap mitigates negative space charge
- ionization enables build-up of positive space charge to mitigate space charge limitation and potentially enhance thermionic emission
- practical advantages of higher pressures

Potential Operating Concept



Questions/Areas of Study

Fundamental

- Quantum mechanics of IETE – how accurate is Schottky equation?
- Relationship between emission, current, and ionization – what role do the bias potential and pressure play?
- Impact of thermionic emission on the state of the microplasma – does it impact breakdown, sheath dynamics, etc.?
- TEC operating mode – what is the balance between emission, ionization, and transport?

Practical

- Cathode/anode materials – what materials balance good emission properties & robustness?
- TEC design – what is the optimal electrode configuration (cylindrical/ planar)?
- Gas and pressure – what gases and what pressures are realistic for integration into specific applications?
- TEC operation – how will the TEC be operated and what is it ultimate efficiency?

Theoretical Impact of E/N & Pressure

In general, as pressure (and gas density) increase, collisional effects decrease the current collected at the anode

basic scaling

$$\frac{j_{anode}}{j_{emit}} \propto N^{-k} \qquad \frac{j_{anode}}{j_{emit}} \propto \left(\frac{E}{N}\right)^{k}$$

$$0.5 \le k \le 1.0$$

additional scaling

$$\frac{j_{anode}}{j_{emit}} \propto \left(\frac{E}{N}\right)\left(\frac{V^{1/2}}{d^{2}}\right) \qquad \frac{j_{anode}}{j_{emit}} \propto \left(\frac{E}{N}\right)^{1/2}\left(\frac{V}{d^{2}}\right)$$

low *p* high *p*

Ingold, *J. Appl. Phys.* (1969)

As sufficient voltage, electrons generate ions through collisions with neutral molecules and increase the current collected at the anode

$$\frac{j_{anode}}{j_{emit}} \propto \exp(\alpha d) \quad \text{where} \quad \alpha \sim AN\exp\left(-\frac{BN}{E}\right)$$

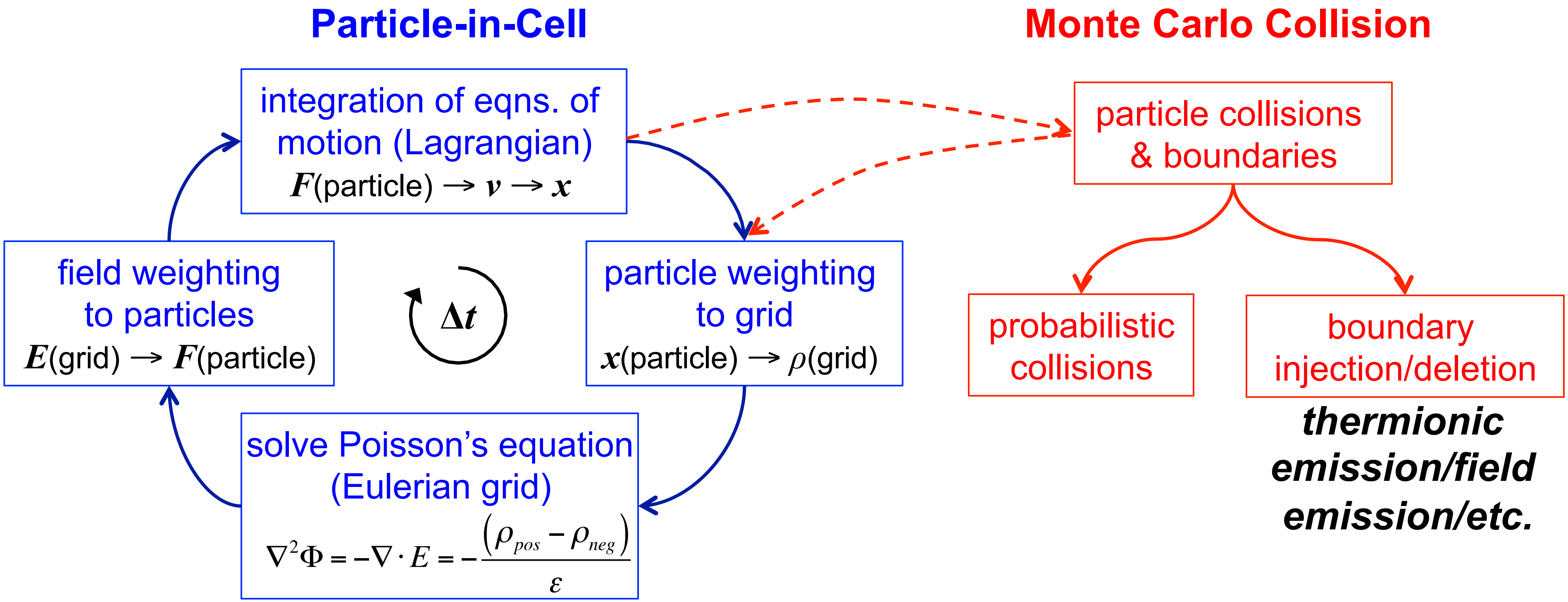
Initial study aimed at resolving impact of number density and applied voltage on collected thermionic current and ionization

Simulations to Study Role Particle Dynamics

Particle-in-cell/Monte Carlo collision (PIC/MCC) simulations

- particle based, Lagrangian approach to modeling transport and reactions
- direct solution to Boltzmann transport equation to provide particle distributions
- appropriate for conditions where electron population is highly non-Maxwellian

1d3v
1 field component
3 velocity components



Particle-in-Cell

Monte Carlo Collision

integration of eqns. of motion (Lagrangian)
$F(\text{particle}) \rightarrow v \rightarrow x$

particle weighting to grid
$x(\text{particle}) \rightarrow \rho(\text{grid})$

solve Poisson's equation (Eulerian grid)

$$\nabla^2\Phi = -\nabla\cdot E = -\frac{\left(\rho_{pos}-\rho_{neg}\right)}{\varepsilon}$$

field weighting to particles
$E(\text{grid}) \rightarrow F(\text{particle})$

Δt

particle collisions & boundaries

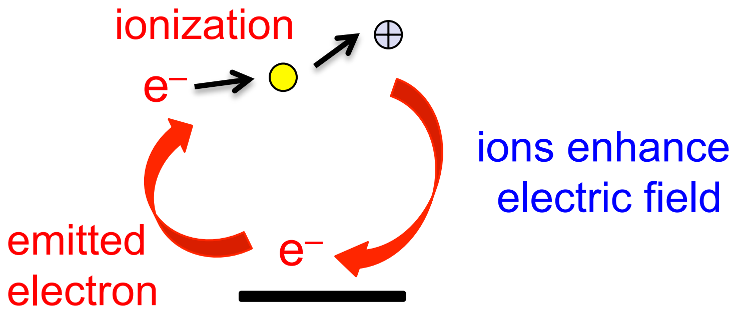
probabilistic collisions

boundary injection/deletion

thermionic emission/field emission/etc.

Li, Tirumala, Rumbach, & Go, *IEEE Trans. Plasma Sci.* (2013)

PIC/MCC Tracks Dynamic Interactions



ionization

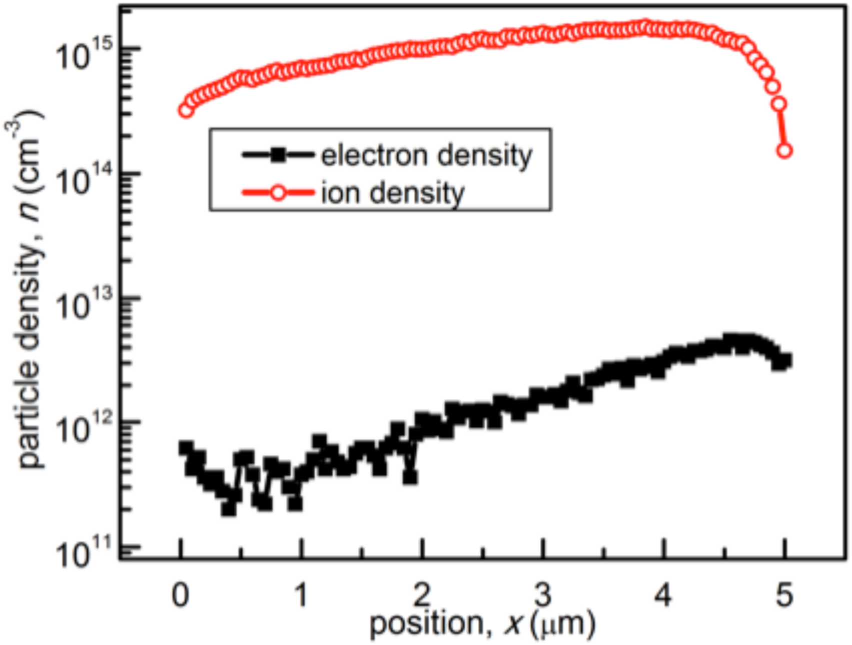
e⁻

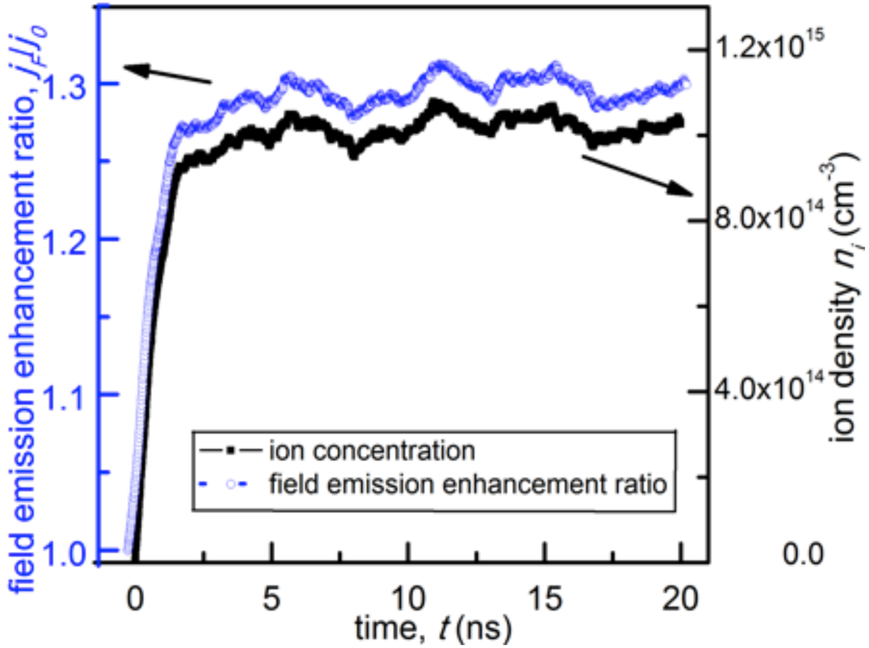
ions enhance electric field

emitted electron

e⁻

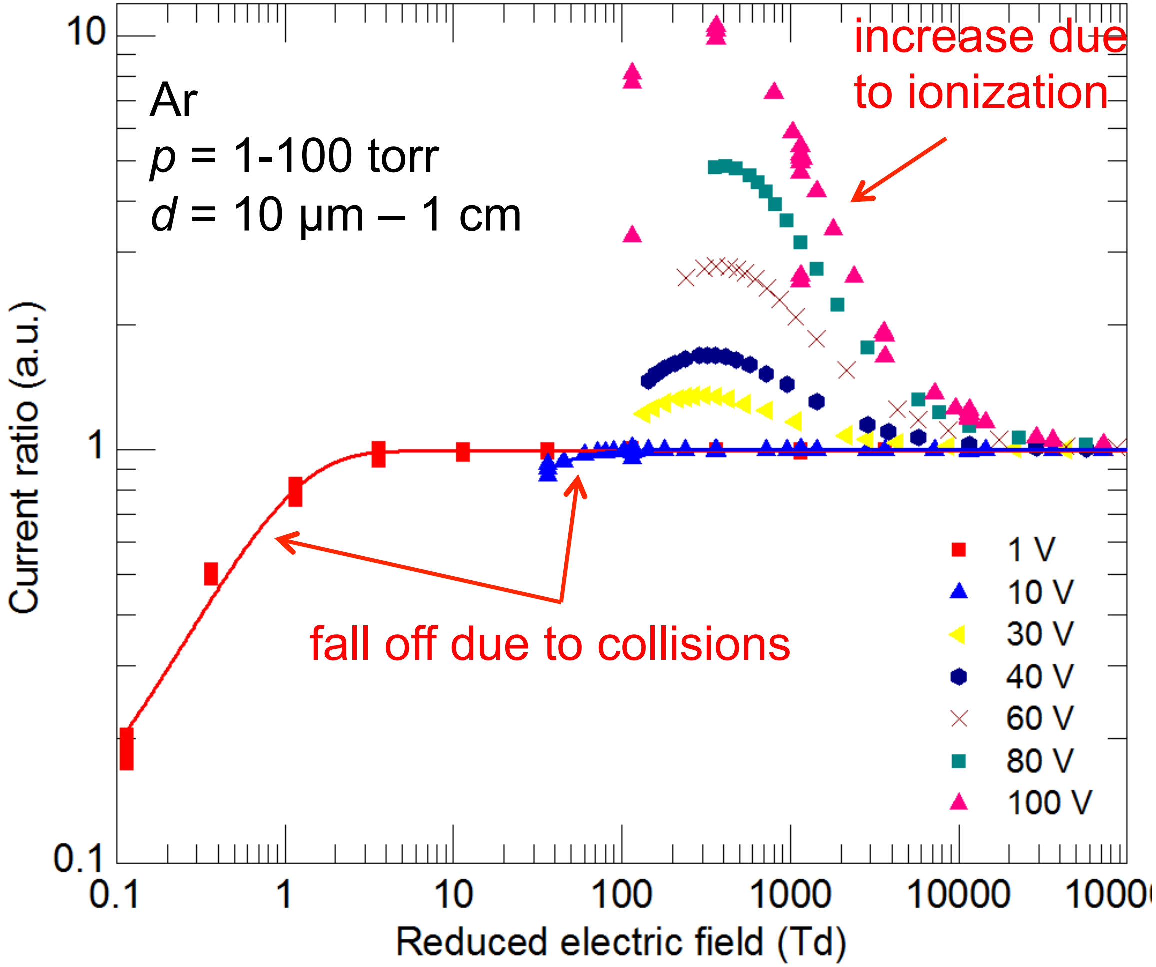
5 μm gap, 760 torr, Ar, applied voltage is 98% of breakdown voltage





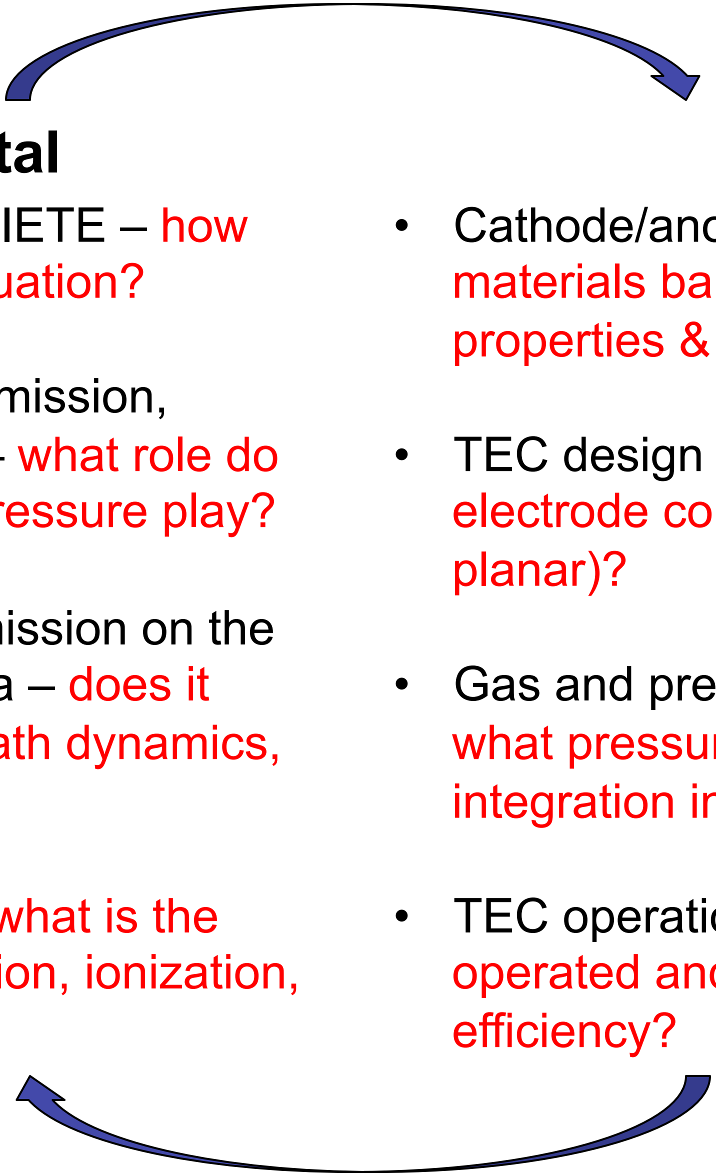
Li, Tirumala, Rumbach, and Go, *IEEE Trans. Plasma Sci.*, 2013

Preliminary Results Suggest Optimal Points



Balance: Energy input/ionization/current/transport/thermal loss with overall efficiency and energy conversion

Questions/Areas of Study



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Go Research Group

Current Students

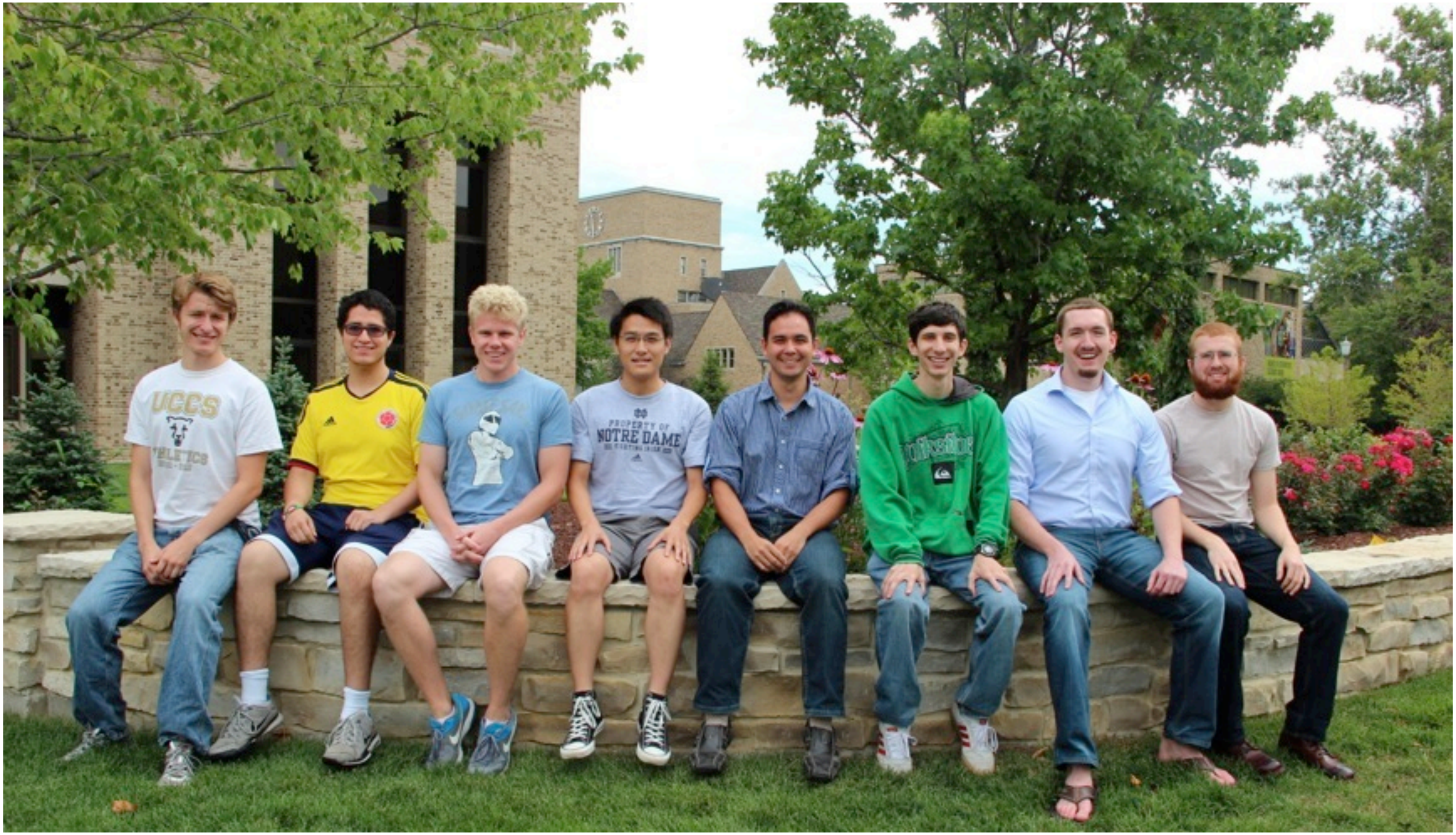
- Dr. Mridul Mandal (post-doc)
- Jay Li
- Paul Rumbach
- Danny Taller
- Michael Johnson
- **John Haase**
- **Xi Tan**
- Francisco Herrera
- **Nate Griggs (u)**
- John Kearns (u)

Collaborators

- Prof. Hsueh-Chia Chang
- Prof. Tengfei Luo
- Prof. Jason Hicks
- Prof. David Bartels
- Prof. Mihir Sen
- Prof. Aimee Buccellato
- Dr. Paul Brenner
- Prof. Norm Dovichi
- Dr. Carlos Gartner
- Prof. Mohan Sankaran (CWRU)
- Prof. Rohan Alkolkar (CWRU)
- Prof. Dan Lacks (CWRU)

Former Visitors/Post-Docs/Students

- Dr. Jenny Ho (visiting scientist)
- Dr. Ming Tan (post-doc)
- Dr. Nishant Chetwani (post-doc)
- Dr. Alejandro Guajardo-Cuéllar (Ph.D.)
- Dr. Rakshit Tirumala (Ph.D.)
- Katie Isbell (M.S.)
- Sajanish Balagopal (M.S.)
- 25+ undergrads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