Recent computational results for rf breakdown mitigations

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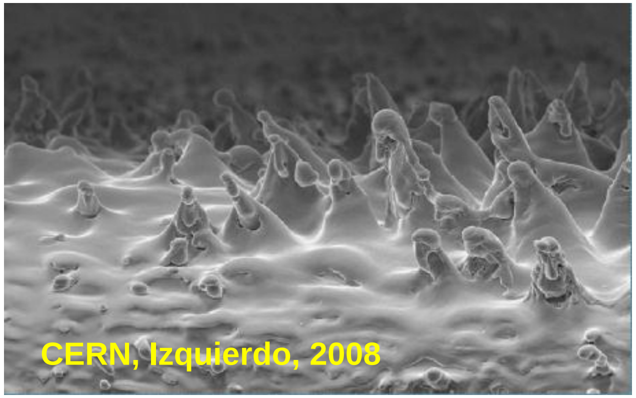
Outline

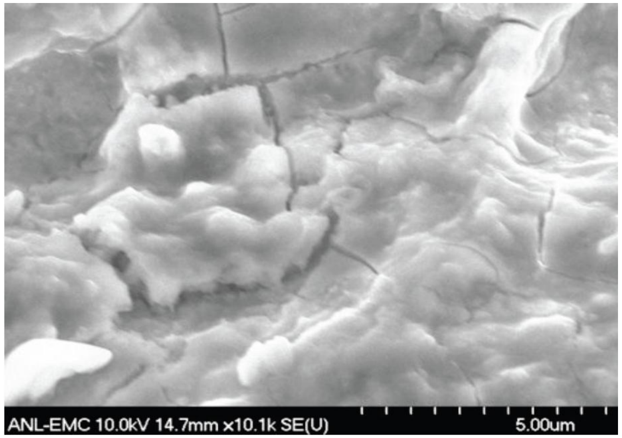
- Motivation - RF breakdown in cavities
- Field enhancements of tips vs cracks
- Schwirzke model of unipolar arc
- Plasma fueling by surface sputtering
- Plasma model of RF BD
- Modeling non-Debye plasma sheath
- Summary of the Arc model
- Other applications and future plans

RF Breakdown examples

Severe damage

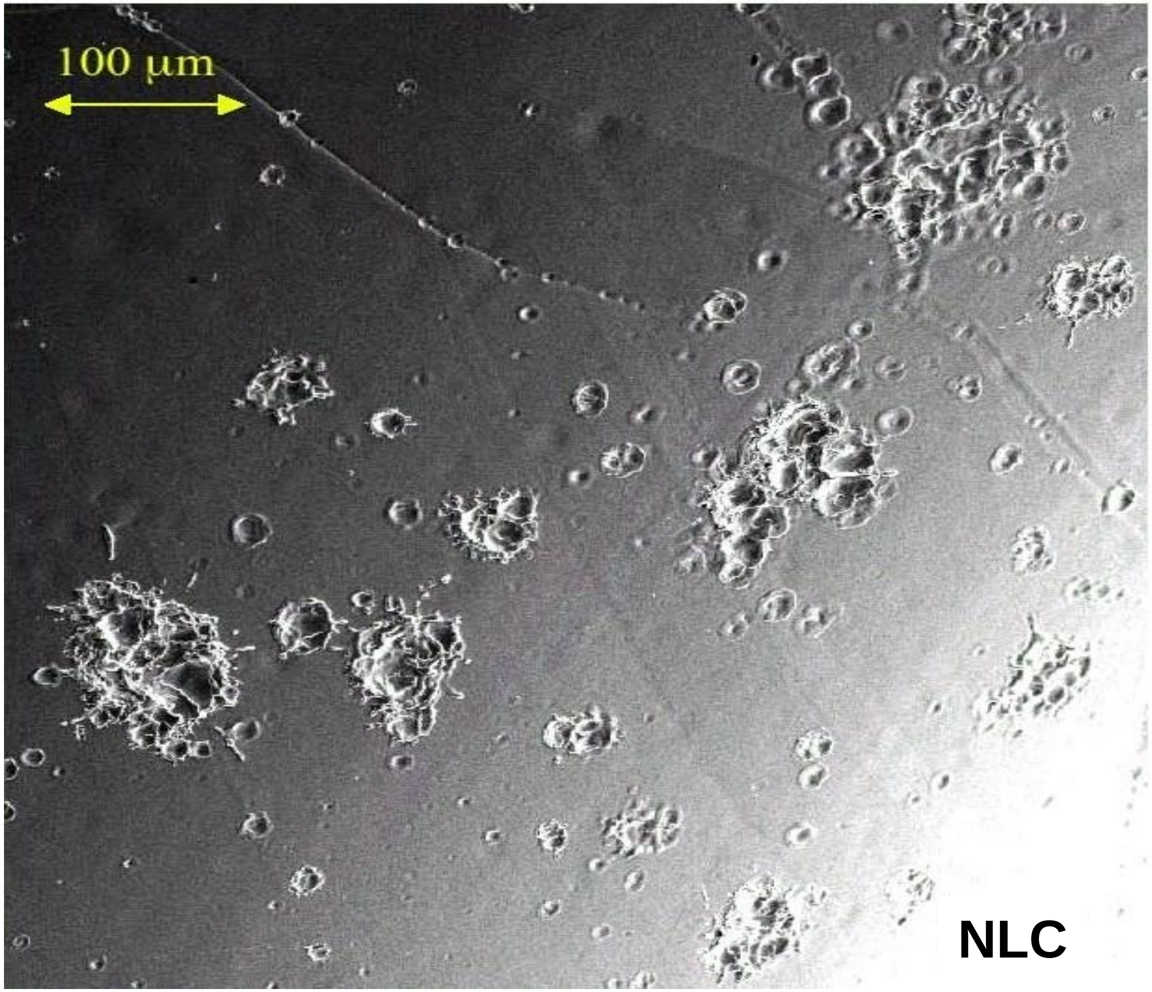


Cracks



Norem, 2011

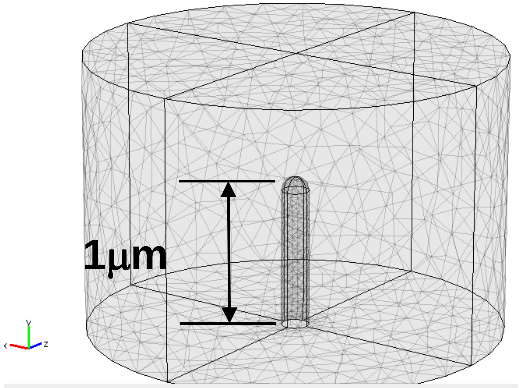
Moderate damage

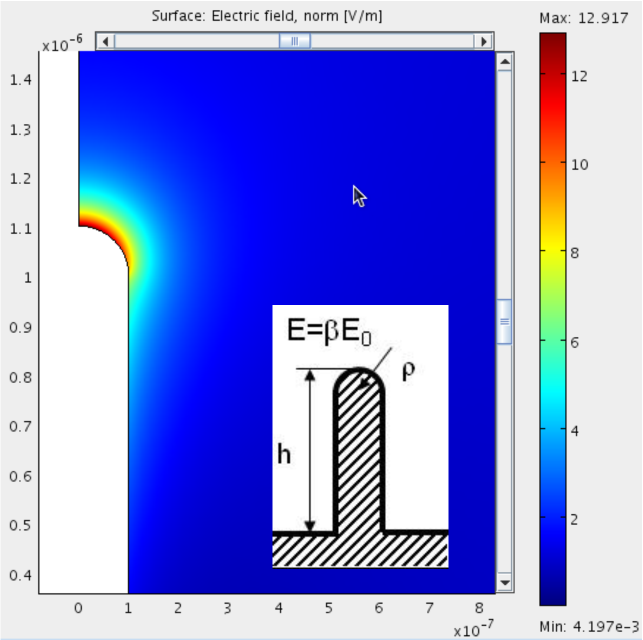


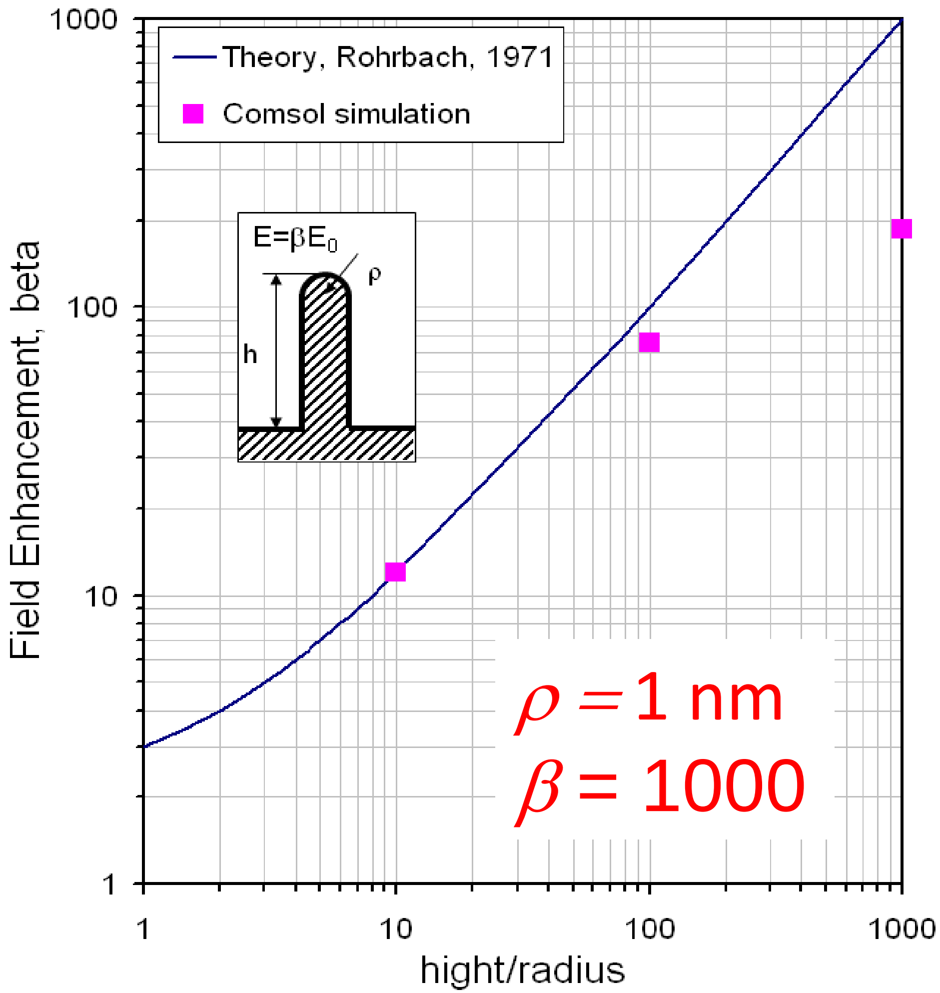
[From the 2001 Report on the Next Linear Collider]

FE multi-physics simulation

- **Comsol simulation vs analytical theory of field enhancement**

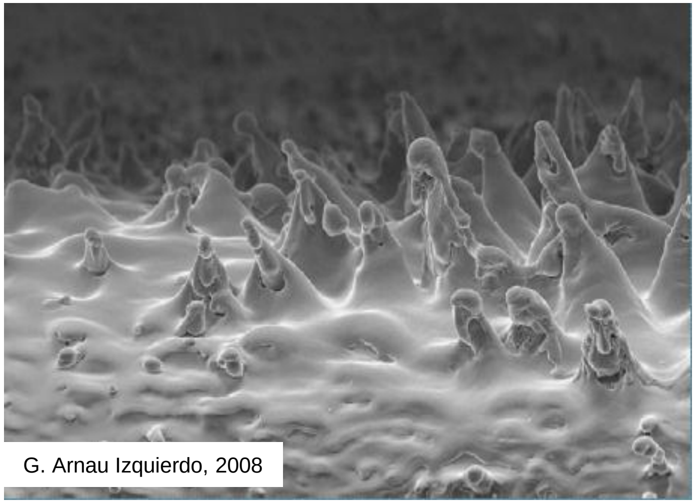




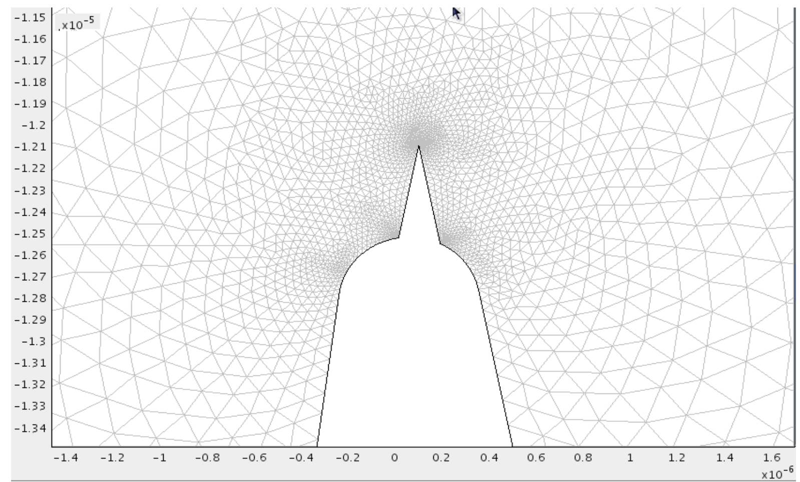


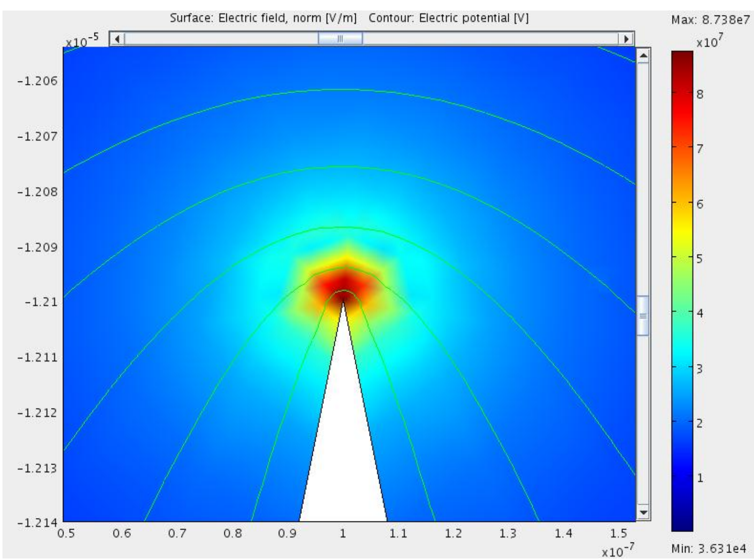
Field Enhancement by cones

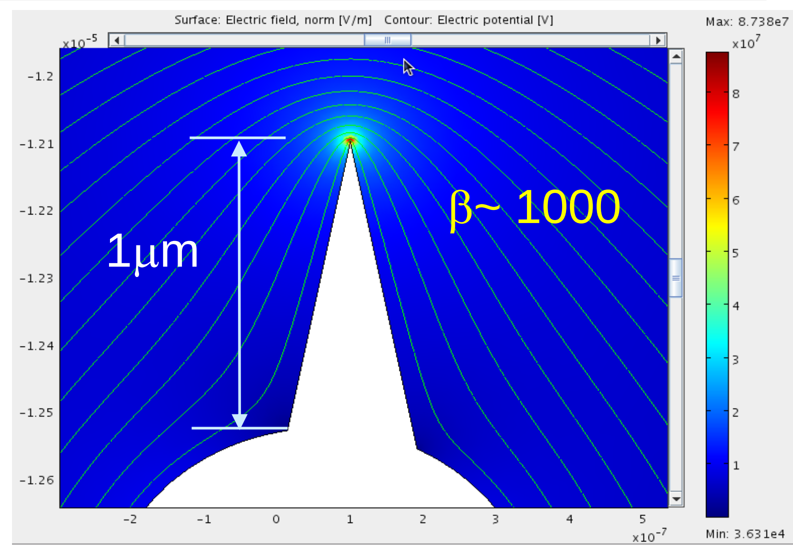
- **Comsol simulation of field enhancement at sharp cones**



G. Arnau Izquierdo, 2008







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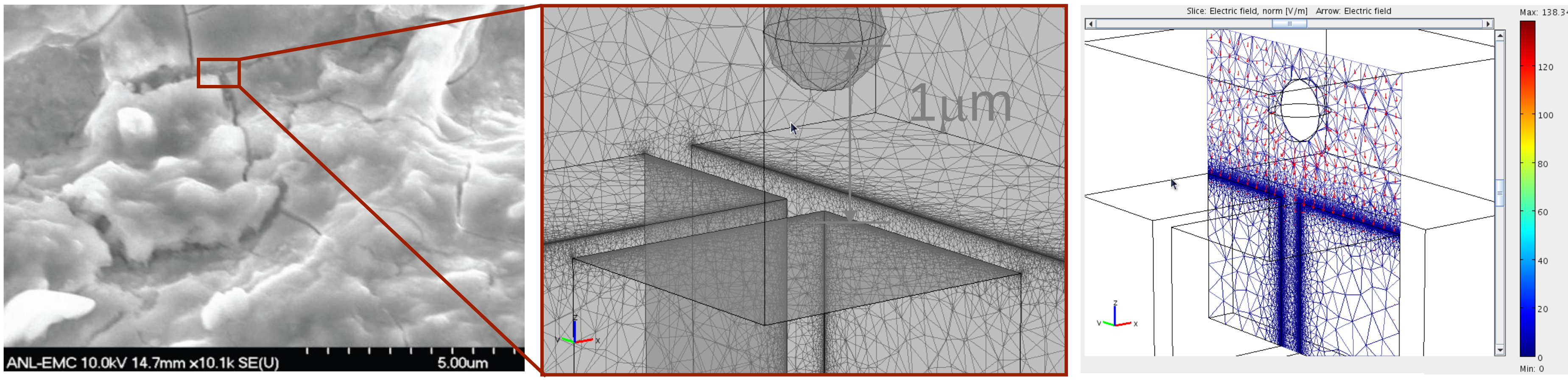
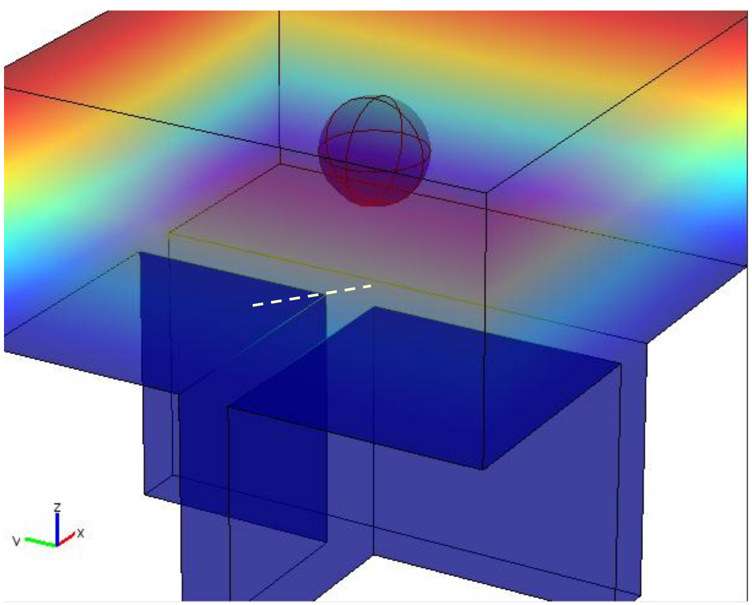
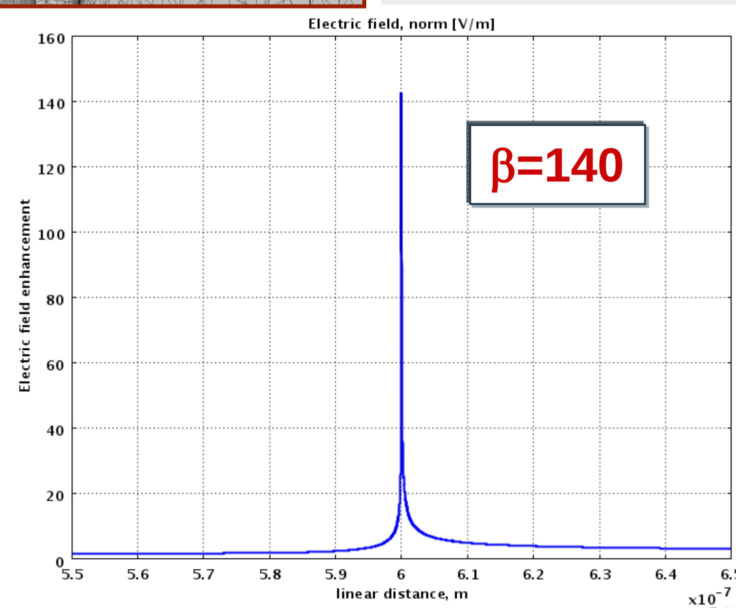
Triple junction E-fields

- **Comsol simulation of field enhancement at triple crack junction**







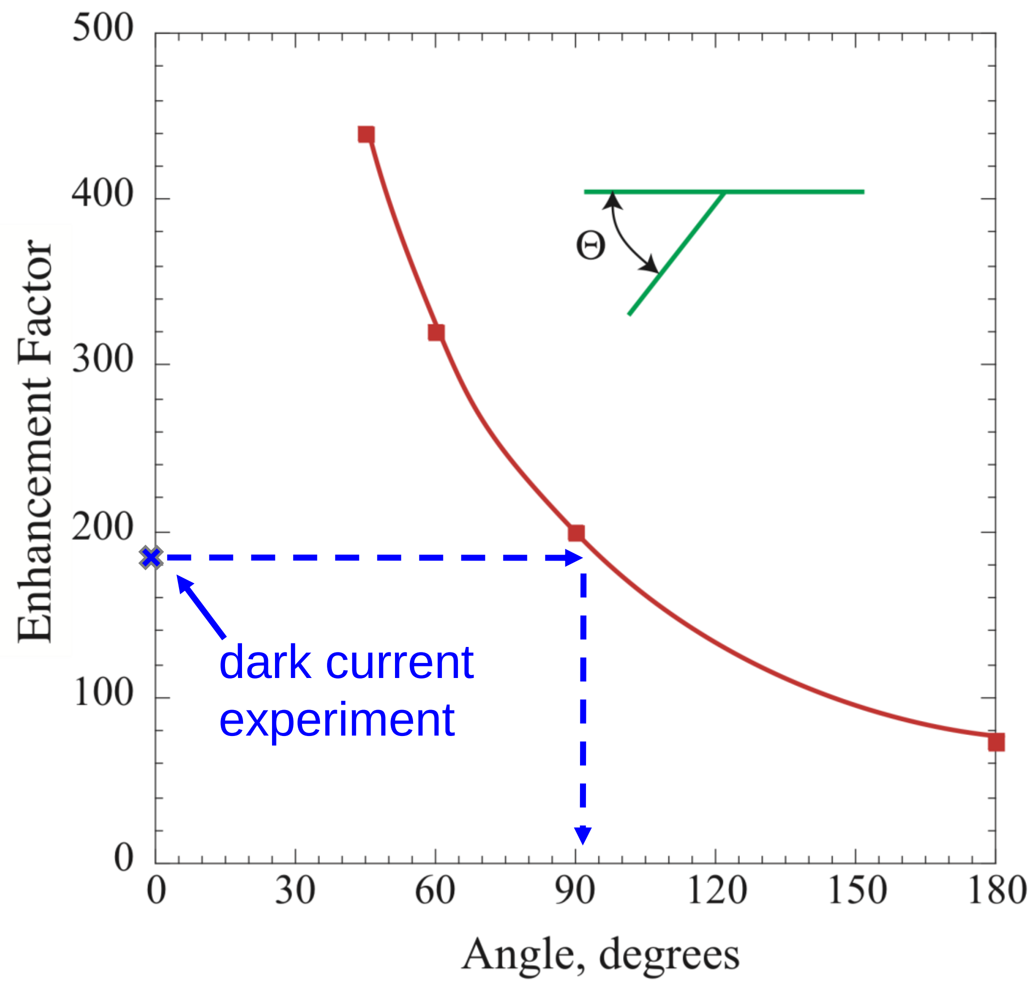
E-field enhancement junction

Experimental enhancement factor obtained from dark current measurements:

$\beta_{exp} \approx \mathbf{184}$

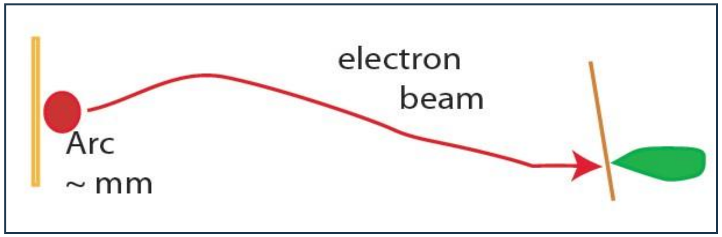
is close to values for a triple junction:

$\theta = \mathbf{90^\circ}$

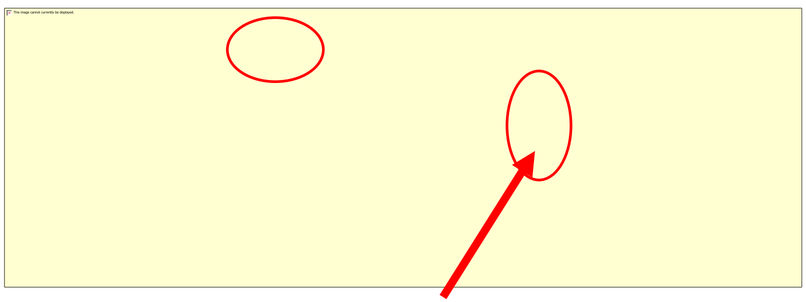


Dark current experiment

X rays show that cavities break down at E_{local} ~ 7–10 GV/m

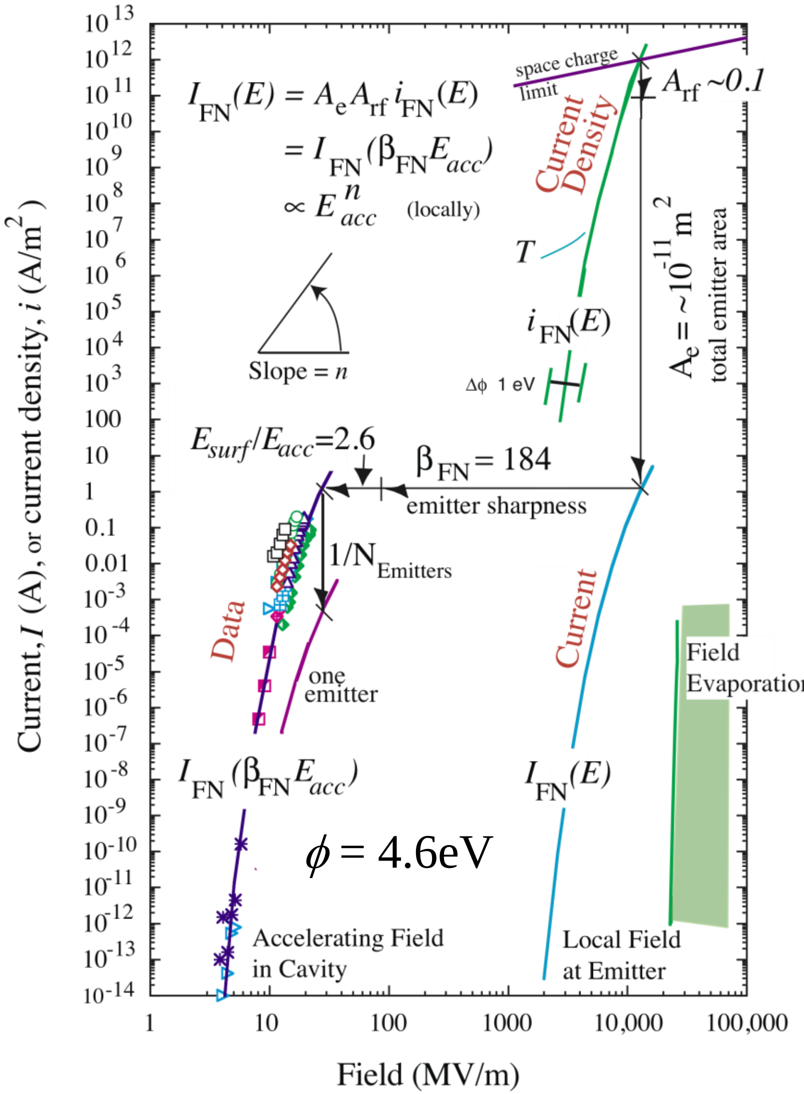


Fowler-Nordheim field emission (1928)



***β* – Local Field Enhancement**

β=184



[Norem, PR STAB (2003)]

Schwirzke model of Unipolar Arc model in Tokamaks

Heating occurs via ion bombardment.
Plasma fueling:
- **Evaporation of surface atoms**
- **Tip explosion by high electric field**

Plasma potential

$$U_f = \left(kT_e/2e\right)\ln\left(M_i/2\pi m_e\right),$$

$$\lambda_D = \sqrt{\varepsilon_0 kT_e/2n_e e^2},$$

$$E_f \approx \frac{U_f}{\lambda_D} \approx (n_e kT_e)^{1/2} \times 5.12$$

$$n_e \approx 4\times10^{22}\ m^{-3}$$

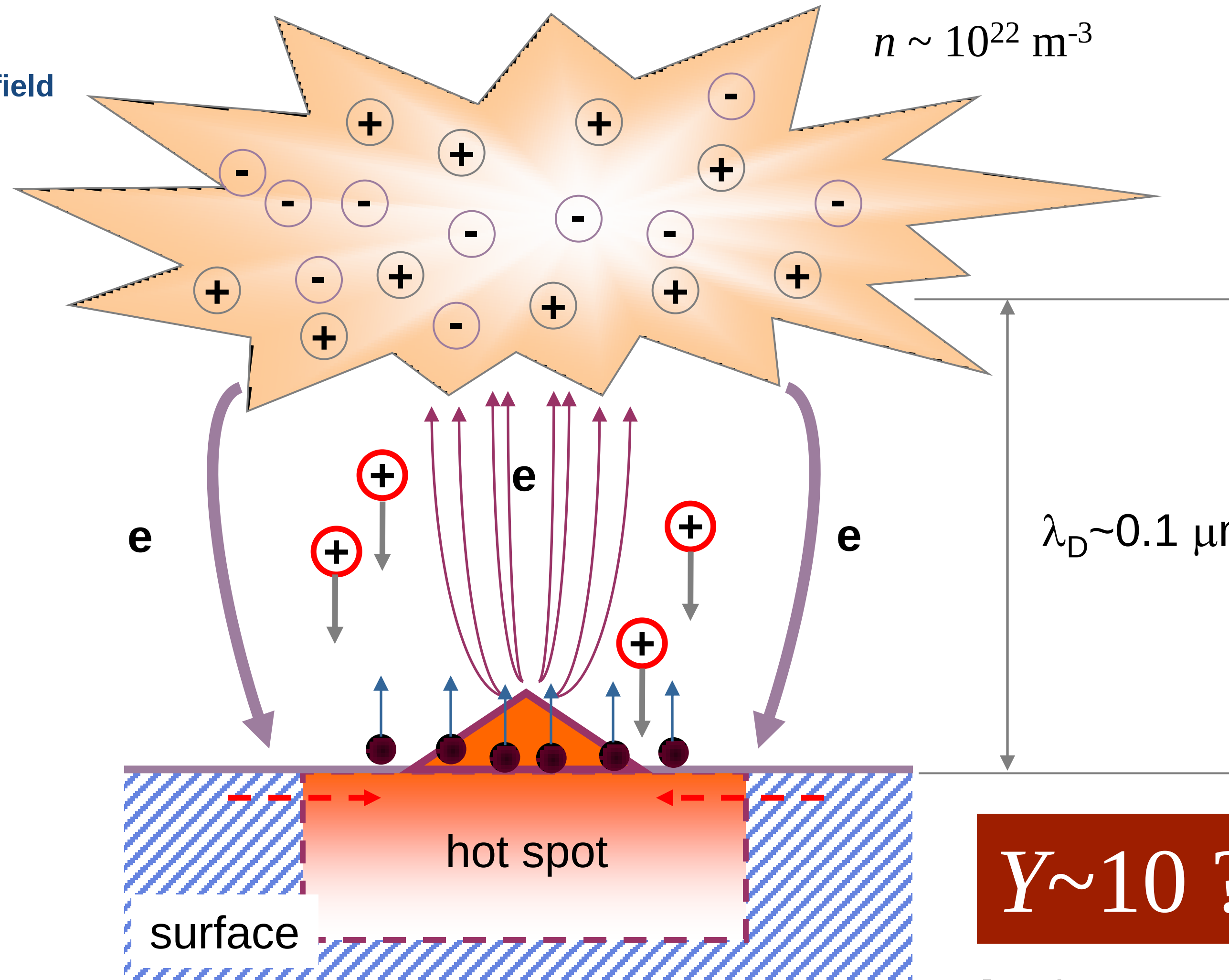
$$kT_e \approx 18\,eV, U_f \approx 26.4\,V$$

$$\lambda_D \approx 1.6\times10^{-7}\,m,$$

$$E_f \approx \beta\frac{U_f}{\lambda_D} \approx 3.6\times10^{10}\ V/m$$

$$\tau \approx \lambda_D\left(2M_i/eU_f\right)^{1/2} \sim 1ps$$

[Schwirzke, JNM 1984]

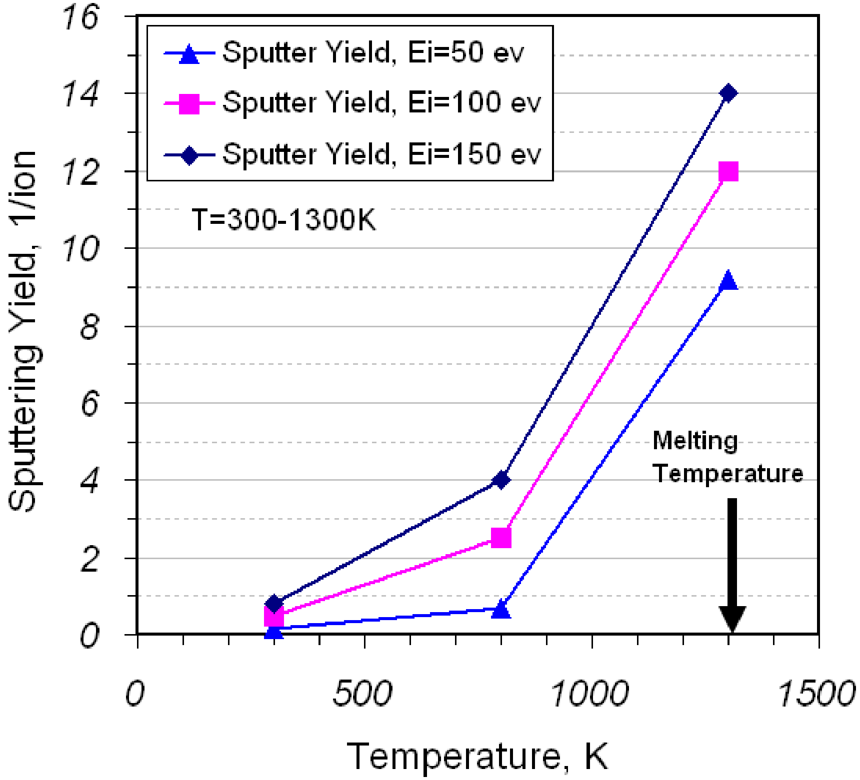


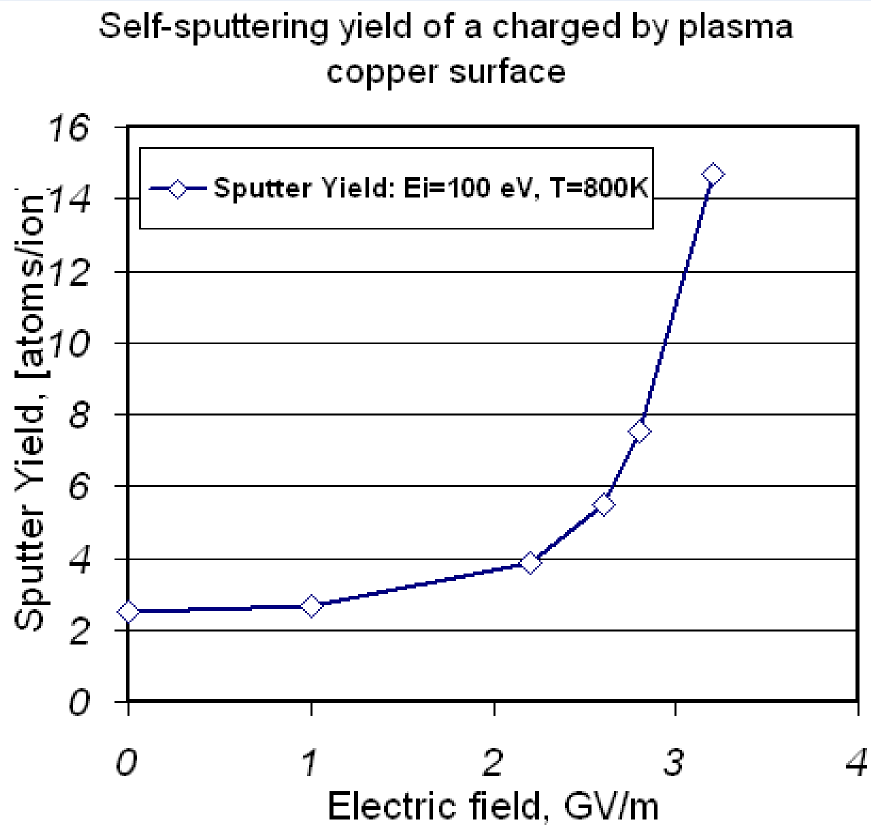
[Robson, Thonemann, 1959]

Y~10 ?

[Anders, 1994]

Self-sputtering at high T and E





- **Self-sputtering is the mechanism for fueling unipolar surface plasma.**
- **Unipolar model requires Y > 10 typical at low ion energies.**
- **MD predicts very high sputtering yields for high surface *T* and *E*.**
- **Erosion rates on the order of ~ 1 m/s.**

[Insepov et al, NIMB, 2010]

Unipolar Arcs via self-sputtering

- **Typical parameters for self-sustained self-sputtering**

Superdense glow discharge in pseudospark (hollow Mo cathode filled with H_2)

Heating occurs via ion bombardment.
Plasma fueling:

- Evaporation of surface atoms
- Tip explosion by high electric field

$$n_c \sim 10^{21}\, m^{-3},$$

$$\lambda = \left(\frac{v_e e}{j_e^{\sec} \sigma} \right)^{-1} \leq 1mm$$

$$d_c = \left(2\varepsilon_0 U_c / e n_e\right)^{1/2} \sim 50 \mu m,$$

$$E_c \approx \beta \frac{U_c}{d_c} = \beta \left(\frac{e n_e U_c}{2\varepsilon_0} \right)^{1/2} \sim 10^9\, V/m,$$

$$\beta \sim 20,\ U_c \sim 2\, keV$$

$$n_e \geq n_e^{cr} = \frac{2\varepsilon_0}{e U_c} \left(\frac{E_c^{cr}}{\beta} \right)^2,$$

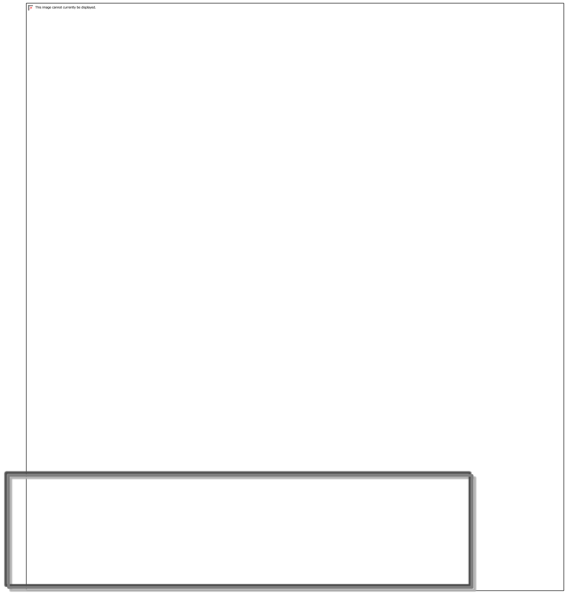
$$\boxed{E_c^{cr} \approx 10\,\text{GV/m},\ n_e^{cr} \approx 5 \times 10^{19}\, m^{-3}}$$

[A. Anders et al, J. Appl. Phys. (1994)]

RF breakdown on Copper surface

Heating via ion bombardment.
Plasma fueling:

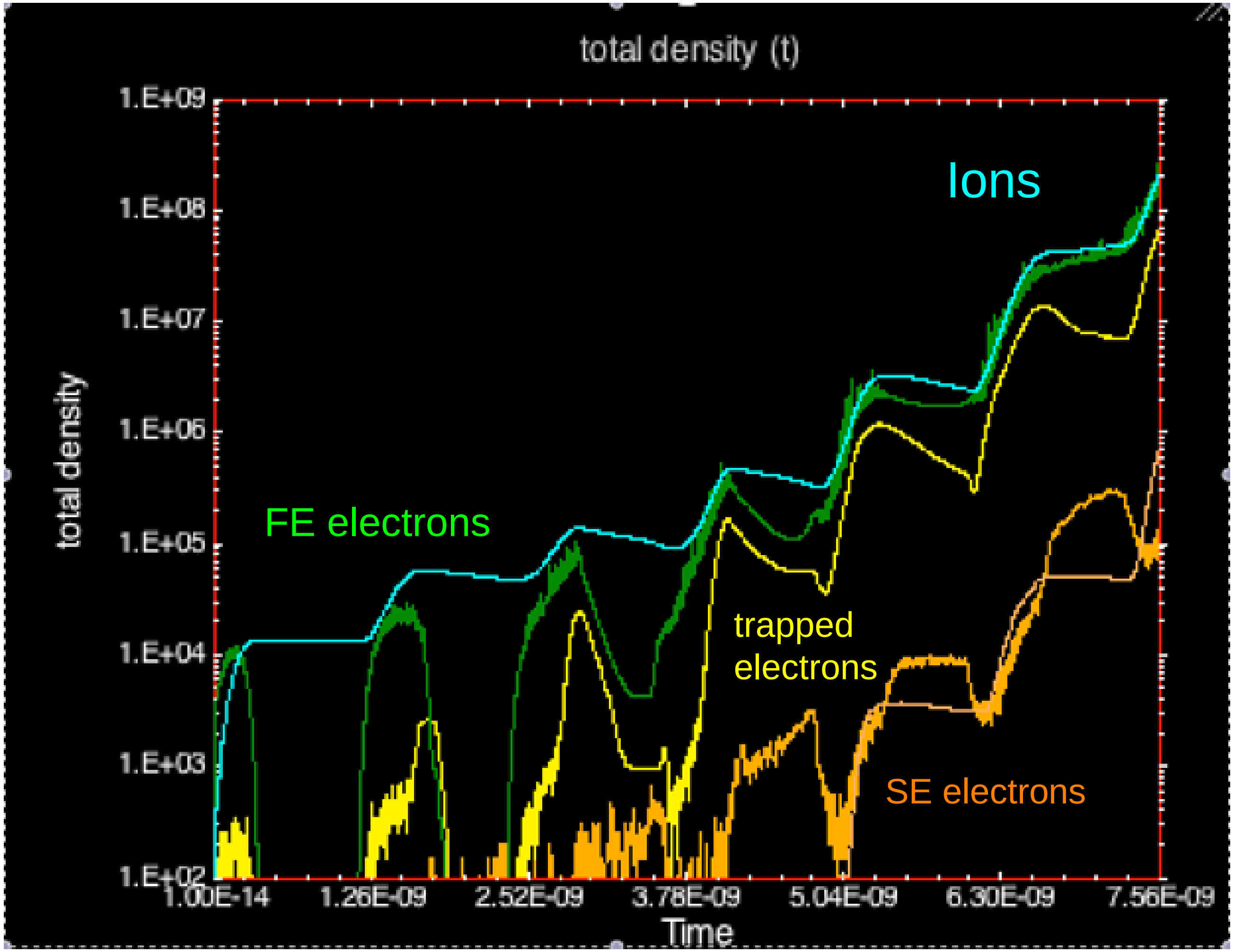
- Evaporation of surface atoms
- Tip explosion by high electric field



[Insepov, Norem (2008)]

OOPIC Pro 2.5D modeling

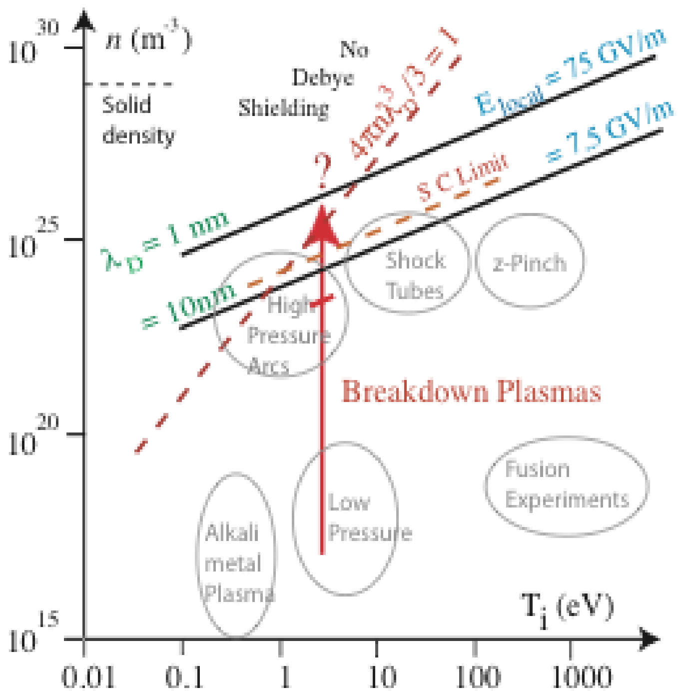
Simulation showing how rf arcs start (805 MHz)

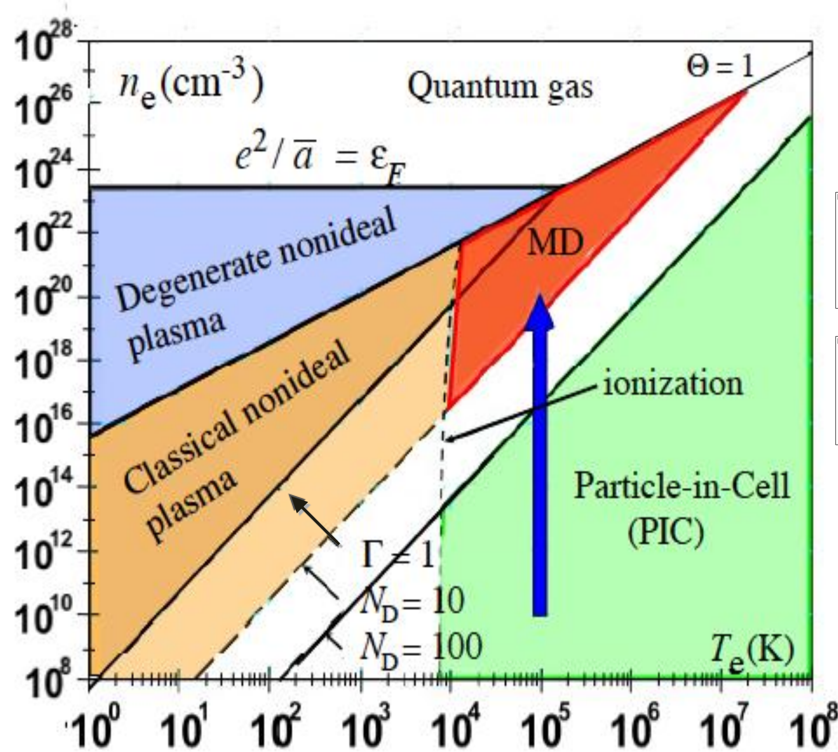


Unipolar Arc model

We have to develop a model that explains unipolar arcs

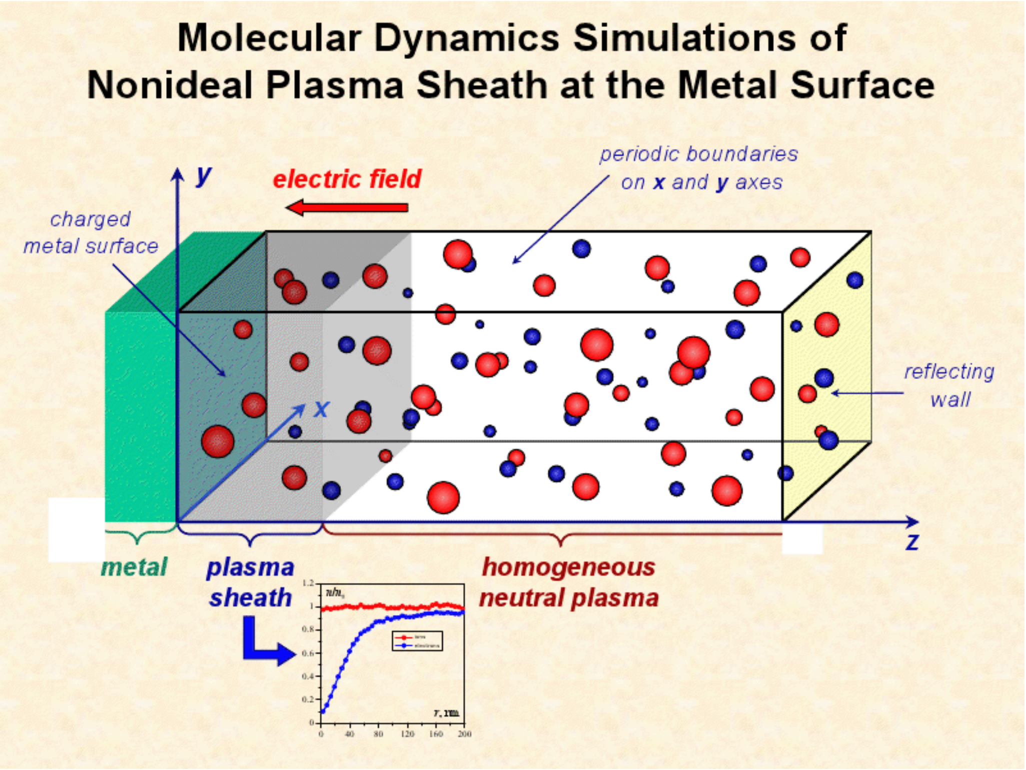
- This seems to be the basic physics that governs gradient limits.
- In rf systems the arcs develop from fracture and ionization of surfaces.
- Lasers, micrometeorites, and other causes can also generate them.
- The arcs are exothermic, develop rapidly and become non-Debye plasmas.





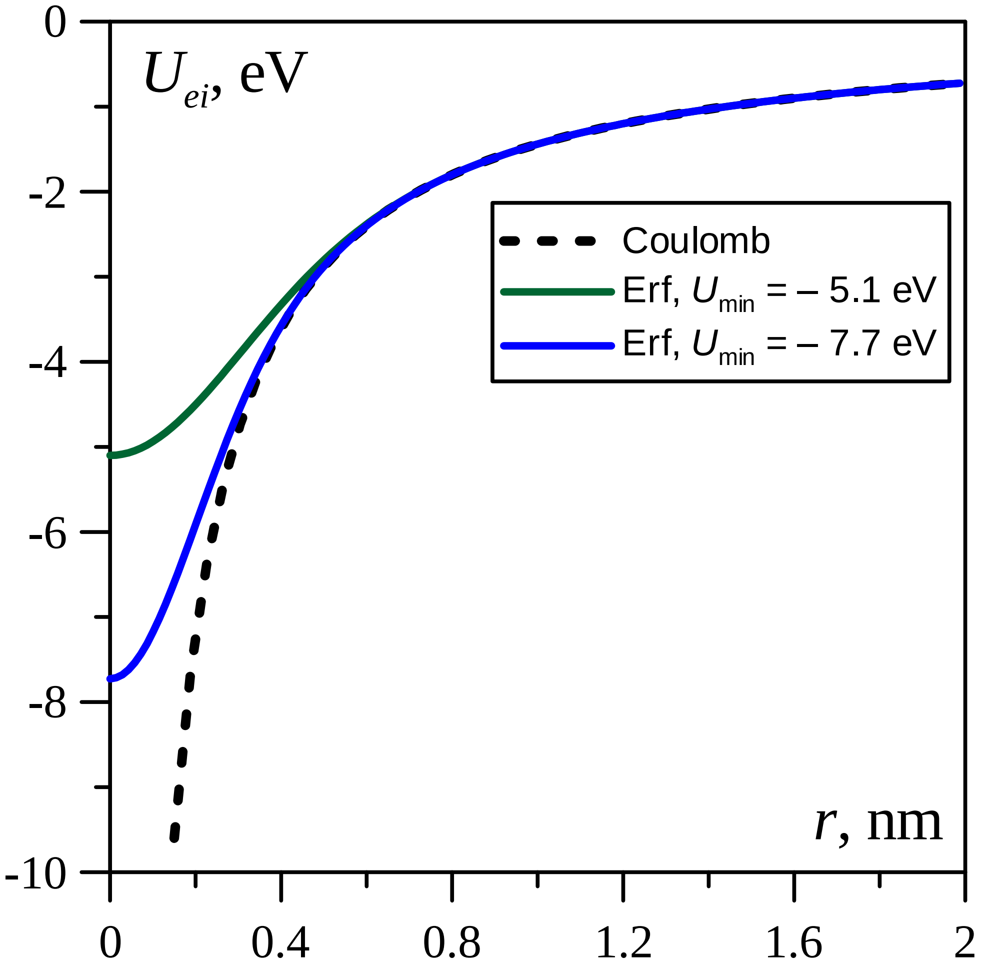
Simulation Features

- Classical molecular dynamics (MD) simulations with a *e-i* pseudo-potential to account for quantum effects
- Two component plasma of electrons and copper ions
- Long range Coulomb interactions (*N*-body problem)
- Periodical boundary conditions for transversal dimensions
- Ideal absorption of electrons to the surface with generation of the surface electrostatic field
- Simulation of the relaxation process
- Averaging over an ensemble of initial states



[Accepted for publication in PR STAB, 2012]

Interaction Potentials



Electron-ion interaction potential

Ionization potential for Copper

$\boldsymbol{U_{min} = U_{ei}(0) = -7.73}$ **eV**

(σ = 0.21nm)

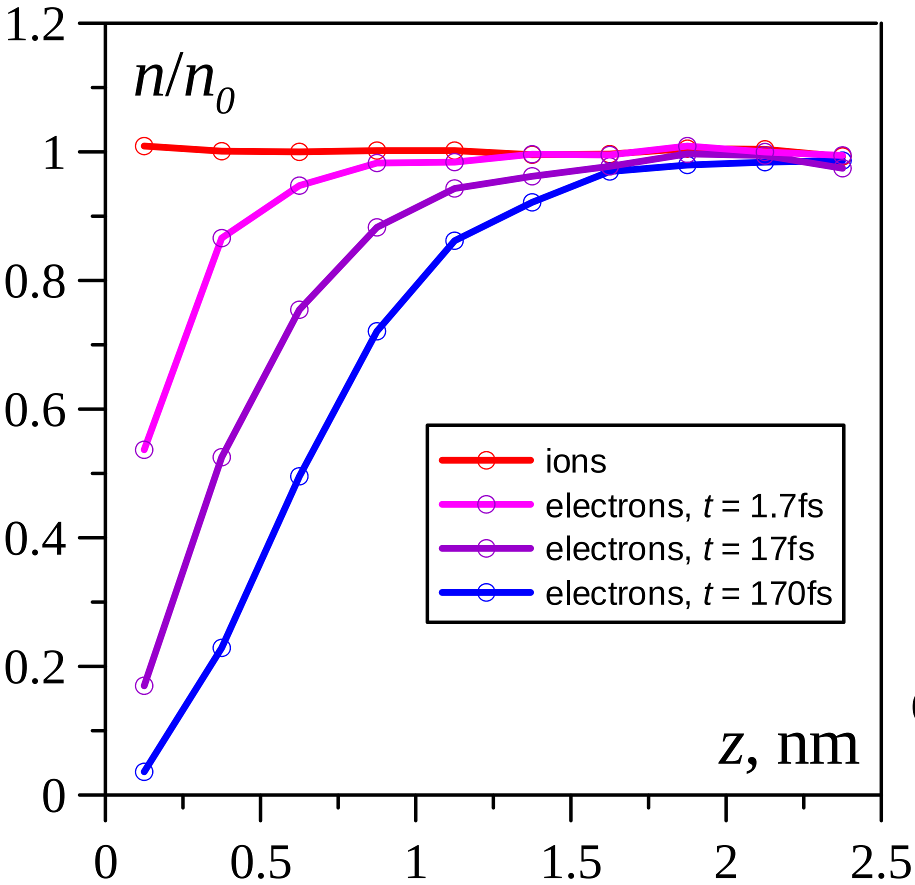
Test potential

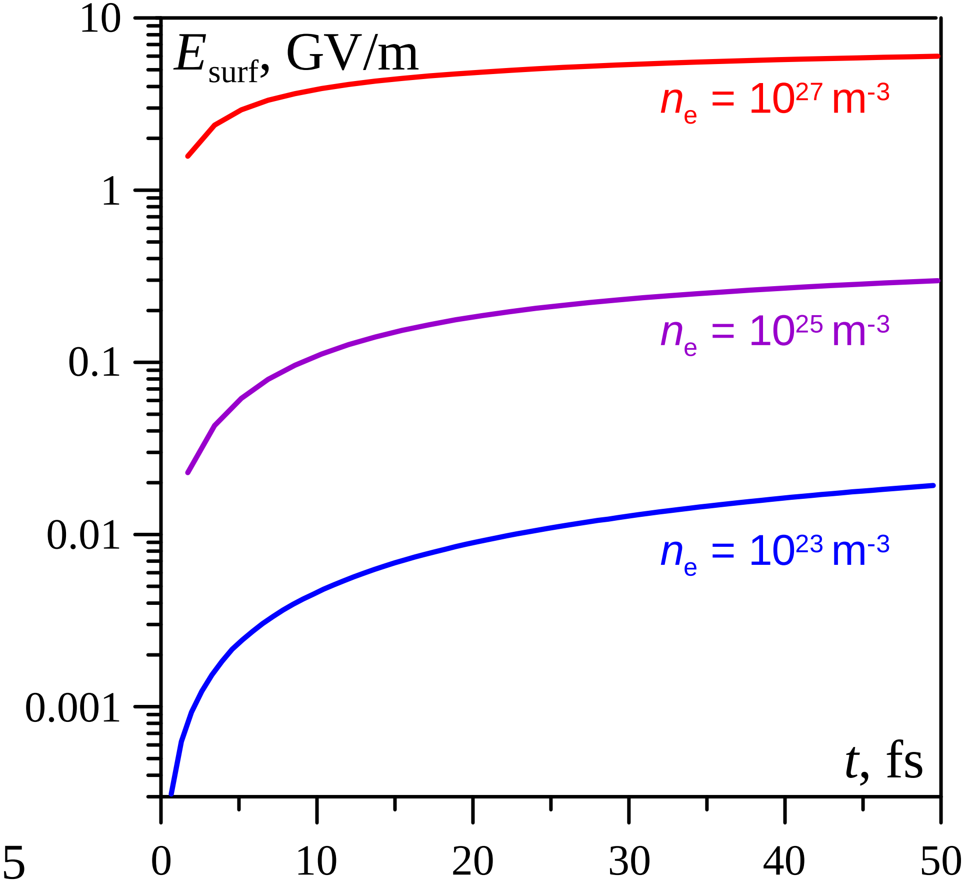
$U_{min} = U_{ei}(0) = -5.1$ eV

(σ = 0.32nm)

Electron-electron and ion-ion potentials are pure Coulomb. The erf-like electron-ion interaction potential given above was used e.g. for simulations of sodium clusters in Raitza et al, Contrib. Plasma Phys (2009).

E-field and density vs time





$T_e = 1\text{eV}, \quad n_0 = 10^{27}\text{m}^{-3}, \quad \Gamma = 2.32$

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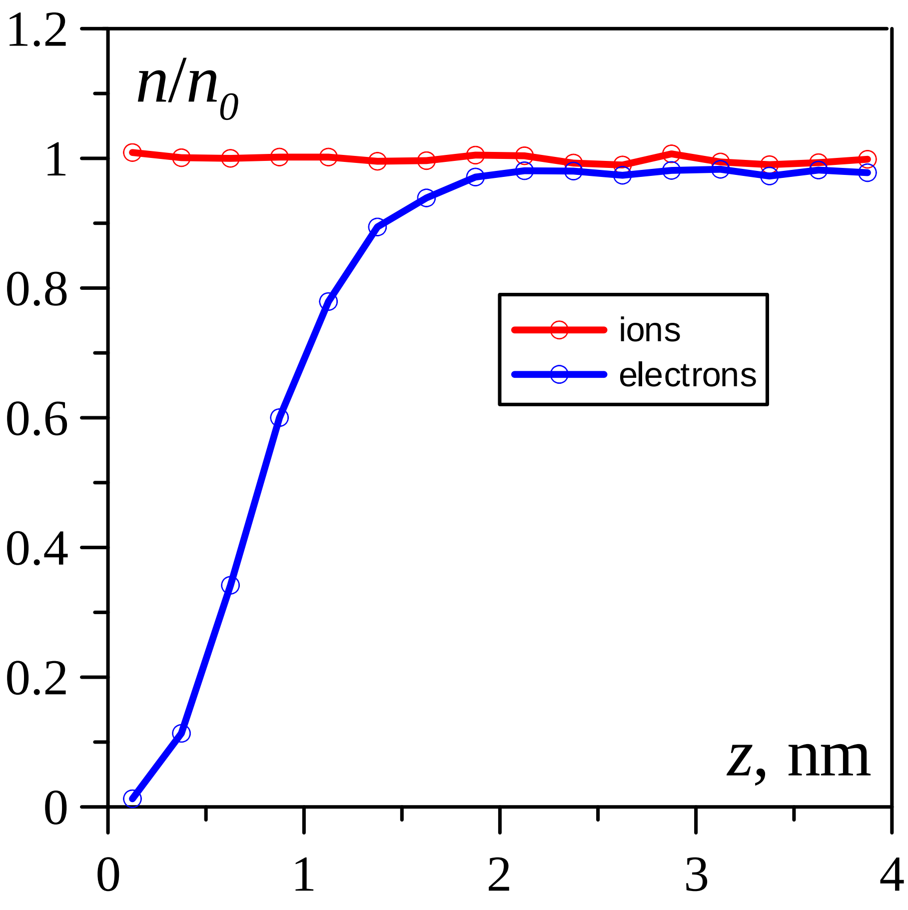
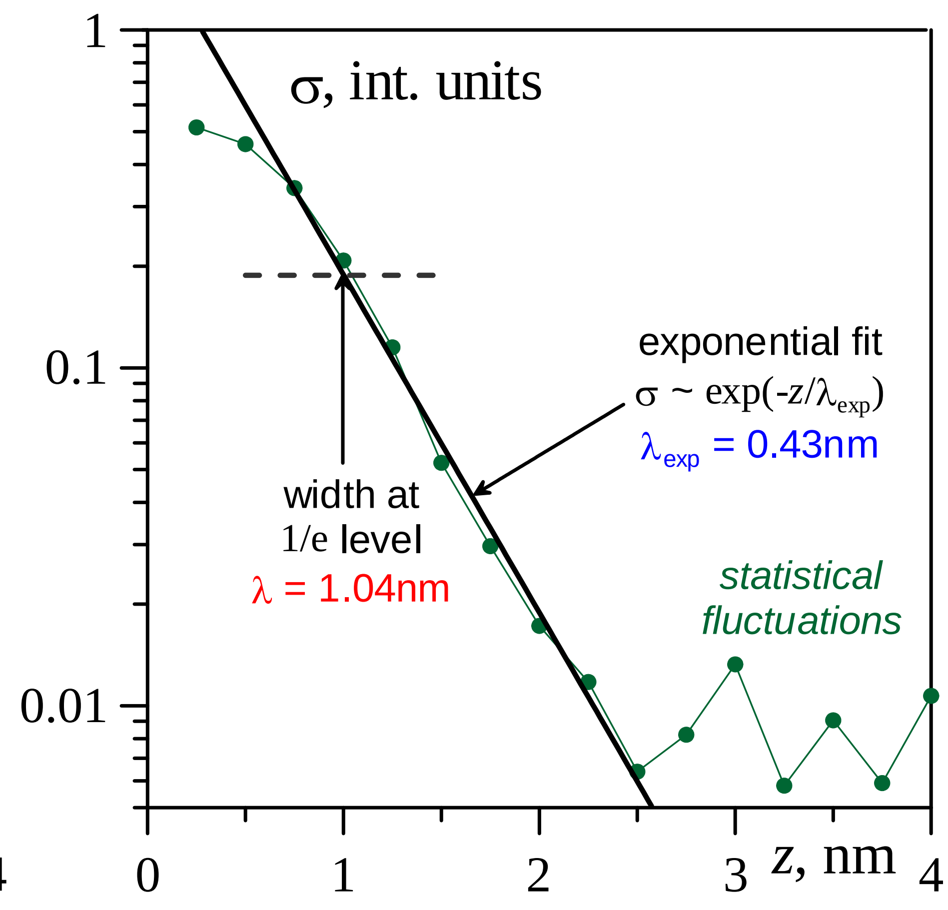
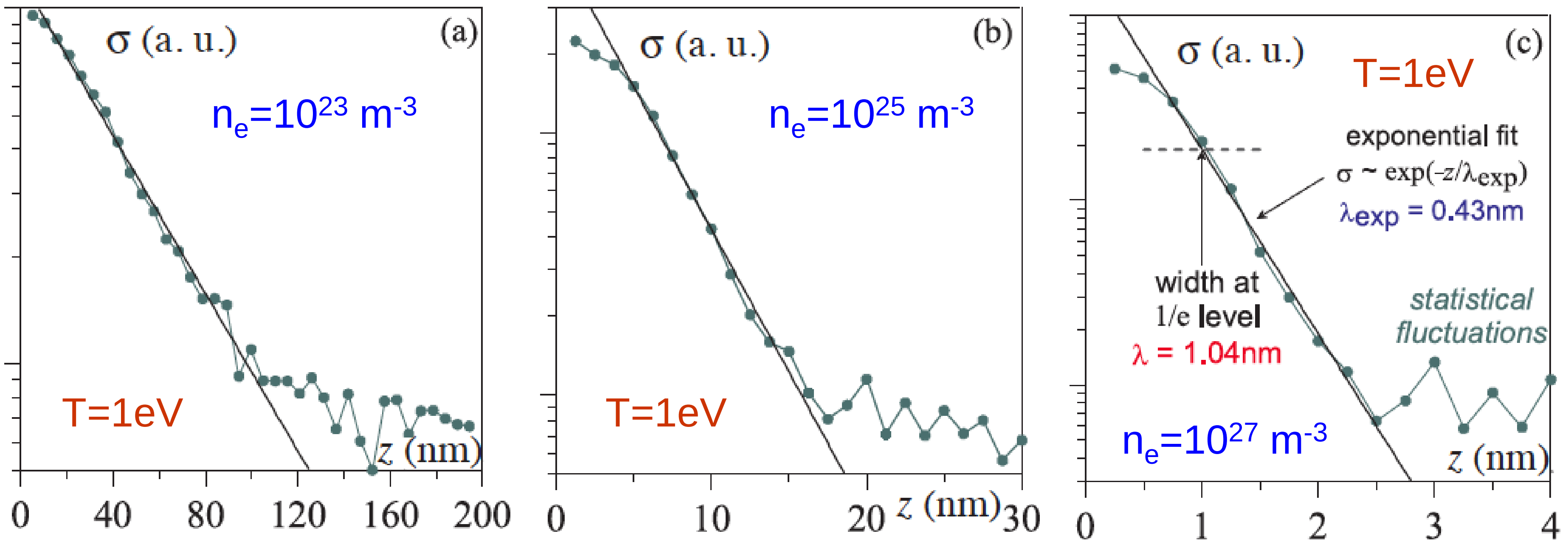
Stationary plasma sheath





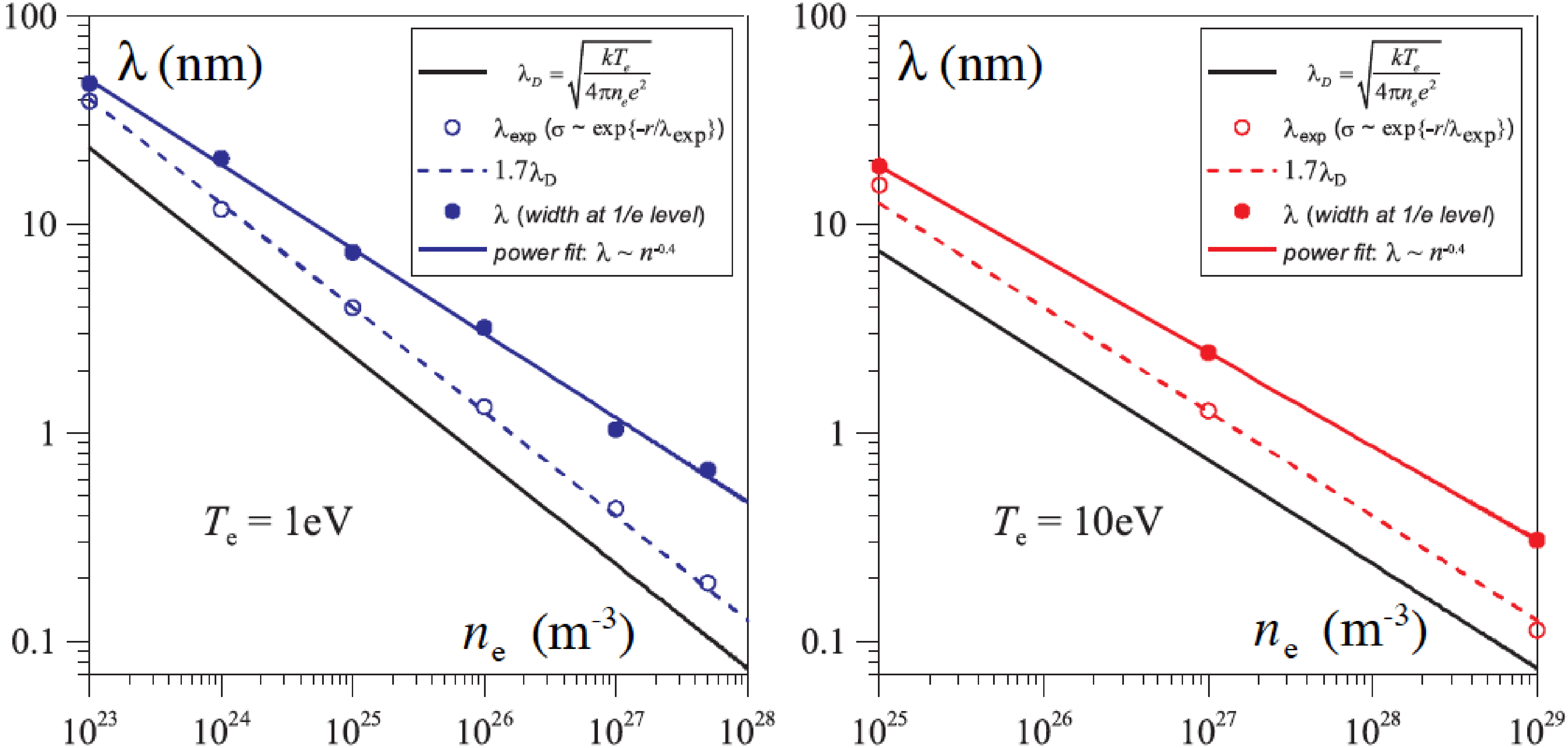
T_e = 1eV, $n_0 = 10^{27}$ m^{-3}, Γ = 2.32

Stationary plasma charge



The solid line is an exponential fit – the classical Debye law at 1eV.

Screening length vs density



The non-Debye sheath can be extrapolated from Debye with small corrections

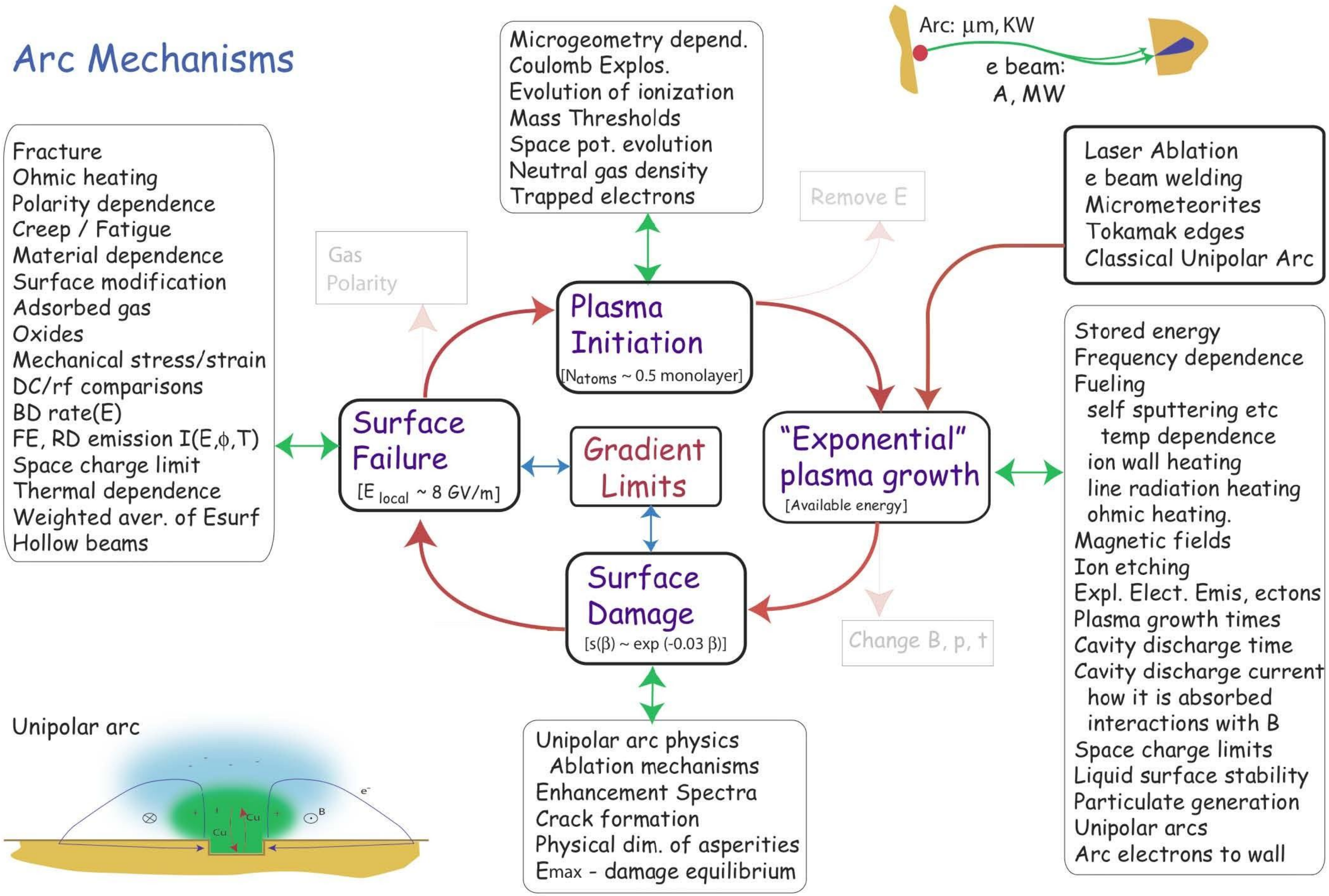
Direct simulation of plasma sheath formation

We simulated the development of the arc and its density limits

- **Non-ideal (non-Debye) plasma were simulated in a wide range of Γ, θ, T, n.**
- **The electric field and charge build up is determined**
- **The electrical field close to Debye predicted in most part of the sheath space**
- **The non-classical deviation is at very close proximity of the surface**
- **Ions were takes into account in specific approximation**

T, eV	n_e,1e27, m-3	Γ	θ	λ_D, nm
1	1e-4	0.11	0.001	23.5
1	1e-3	0.23	0.004	7.43
1	1e-2	0.5	0.017	2.35
1	0.1	1.08	0.079	0.74
1	1.0	2.32	0.36	0.24
10	0.01	0.05	0.002	7.43
10	1.0	0.23	0.036	0.74
10	100	1.08	0.79	0.07

Summary of the Arc model



Other applications of arcing

- We are beginning to develop parameter sets for these cases:
- Tokamak edge plasmas
- Large surface area and long DC pulses.

  This model predicts breakdown will occur at E_{local} >5 – 6 GV/m.
- $(\phi/\lambda_D)\beta$ ~ 6 GV/m
- With a 100 eV sheath potential, and λ_D ~ 6 μm gives,
- β ~ (6 GV/m)(6E-6m)/(100 eV) ~ 400,
- Laser Ablation, micrometeorite impacts
- Tiny areas and very short DC pulses.
- Dense plasmas can appear and arcs must trigger more quickly.

  With $\lambda_D \sim 0.1$ μm,
- $(\phi/\lambda_D)\beta$ ~ 11 GV/m,
- ϕ ~ (11 GV/m)(1E-7m)/30 ~ 40 eV
- These arcs would have similar parameters and would develop as described above

Future Plans for unipolar arc studies

In rf systems, the arcs occur randomly, and therefore cannot be studied. Triggered unipolar arc can be studied in specifically designed experiment.

We are interested in:

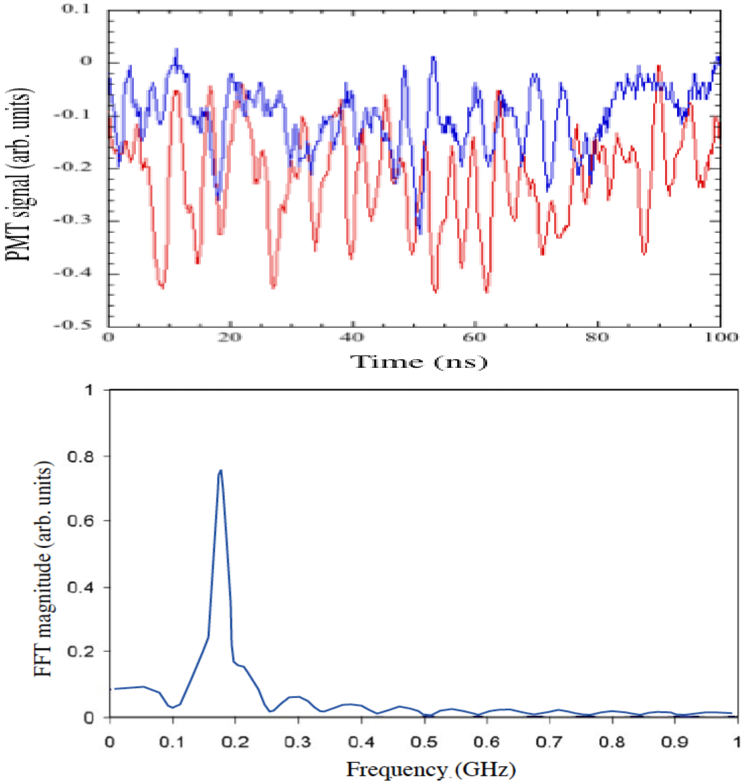
- **Oscillations**
  - How do they depend on material, B field, size and other variables?
  - Does the ecton model or FE model look more realistic?
- **What parameters determine unipolar arc behavior**
  - Cohesive energy (sublimation energy) Tmelt , hardness, ionization potential.
  - Can the maximum density, (maximum E field etc.) be measured?
- **What determines the surface damage?**
  - What causes pits, cracks, "chicken track" formation? EEE?
- **How do magnetic fields interact with unipolar arcs**
  - Both formation & stability of the arc
- **What threshold determines unipolar arc formation?**
  - Can "subcritical", "unlit" arcs make tracks (CERN "worms")

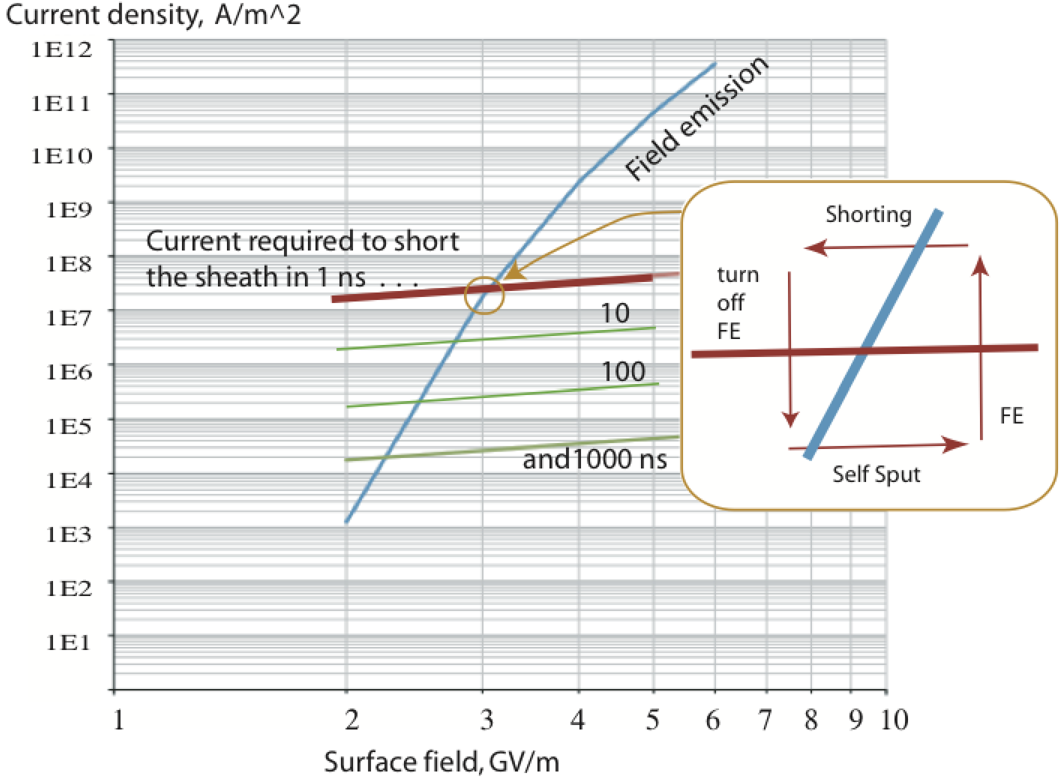
Summary

- Sheath potential formation was simulated for the 1st time.
- Picture of arcs becomes simpler and more general (Tokamaks, laser ablation, micrometeorites).
- We find electrostatic fields can both trigger and drive arcs.
- Materials properties are the clue for understanding of unipolar arc formation and rf breakdown.
- We are exploring new applications and constraints on our model, with a number of papers underway.

Feasible model of oscillations at rf breakdown

- **805 MHz PMT signal** **Field emission shorting plasma sheath**





We can explain the oscillations we see in rf breakdown

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Tonks-Frenkel instability

Capillary waves can measure surface fields

- Dimensions of structures imply $E_{surface}$ ~ 1 GV/m, if $P_{surface\ tension} = P_{Electrostatic}$.