Recent progress in Understanding Arcs

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MAP meeting
July , 2011

Mechanisms of Vacuum Arcs, Helsinki, June 27 – 30, 2011

Talks:

Burkhard Juettner	Breakdown and arc in ultrahigh vacuum: Large devices affected by microscopic regions
Walter Wuensch (presentation)	Breakdown in high-gradient accelerating structures
Edgar Dullni (presentation)	Pre-breakdown and breakdown phenomena on contacts in vacuum interrupters
Joel Rasch (presentation)	Microwave multipactor and corona breakdown in inhomogeneous fields
Kamel Frigui (presentation)	Microwave breakdown at atmospheric pressure in waveguide filters.
Matt Hopkins (presentation)	Progress Modeling 3D Vacuum Arc Discharge
Jay Hirshfield	Breakdown in a bimodal cavity - status of experiment
Valery Dolgashev	Pulsed surface heating and status of SLAC experiments
Flavio Soldera (presentation)	Local degradation of materials microstructure due to high voltage discharge
Kenneth Österberg (presentation)	Dynamic vacuum measurement
Guenter Mueller (presentation)	Field emission from particulates and surface irregularities as precursor of microplasmas
Rocío Santiago Kern (presentation)	Field Emission Measurements. The mysterious nature of the field enhancement factor
Arno Candel	Parallel Electromagnetic Accelerator Modeling Code Suite ACE3P
John Power (presentation)	Schottky Enabled Photo-electron Emission & Dark Current Experiments
Tomoko Muranaka (presentation)	Scanning Electron Microscope in situ breakdown experiments at Uppsala
Richard Forbes (presentation)	Electrical Thermodynamics and the Formation of Nanoprotrusions
Flyura Djurabekova (presentation)	Multiscale modelling of electrical breakdown
Sergio Calatroni (presentation)	DC spark test system at CERN: main results and future objectives
Yasuo Higashi (presentation)	Development of Scanning Field Emission Microscope
Konstantin Matyash	Particle in Cell simulation of RF and DC break down plasmas
Helga Timko	Modelling plasma build-up in vacuum discharges
Paul Crozier	Vacuum arc simulations using Aleph
Jim Norem (presentation)	Modeling Arcs
Micha Dehler (presentation)	FEA Cathode and Gun Simulations
Marc Fivel	3D Discrete Dislocation Dynamics simulations : principles and applications
Steve Fitzgerald	Dislocations
Aarne Pohjonen (presentation)	Dislocation mechanisms on a near surface void under static electric field induced stress
Stefan Parviainen (presentation)	Atomistic modeling of Atom Probe Tomography
Markus Aicheler (presentation)	B-field Arcs and Wormlike features in CLIC accelerating structures
Walter Wuensch	Summary + Conclusion

http://beam.acclab.helsinki.fi/hip/mevarc11/programme.php

Highlights of the Helsinki meeting

A wide range of modeling techniques was described.

A wide range of experimental applications was discussed.

Plasma and materials properties and mechanisms were covered.

Much of the CERN related work were updates. There is a large group centered at CERN doing work relevant to the linear collider

- CERN: Tests of cavities and small gap arcs
- SLAC: Cavity testing some modeling and measurements of pulse heating damage
- Helsinki: Breakdown modeling, surface dislocations
- Sandia: Arc modeling in support of Helsinki model
- European universities and labs: starting experimental and modeling efforts.

New data on arc damage in spark plugs

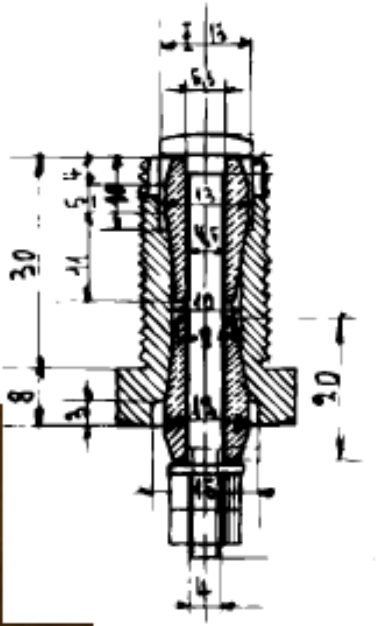
New descriptions of dislocations.

Good talks are not on the web.

Spark plugs

- The mission of the spark plug is to start the combustion of the air/fuel mixture
- Limitation of the lifetime through the increase of the electrode gap due to the erosion of the electrodes
  - Change interval at the beginning:
    1.000 km
  - Change interval today:
    60.000 km (Nickel alloys)

    100.000 km (Platinum)
- The erosion is caused by the interaction between the spark-plasma and the electrode surface

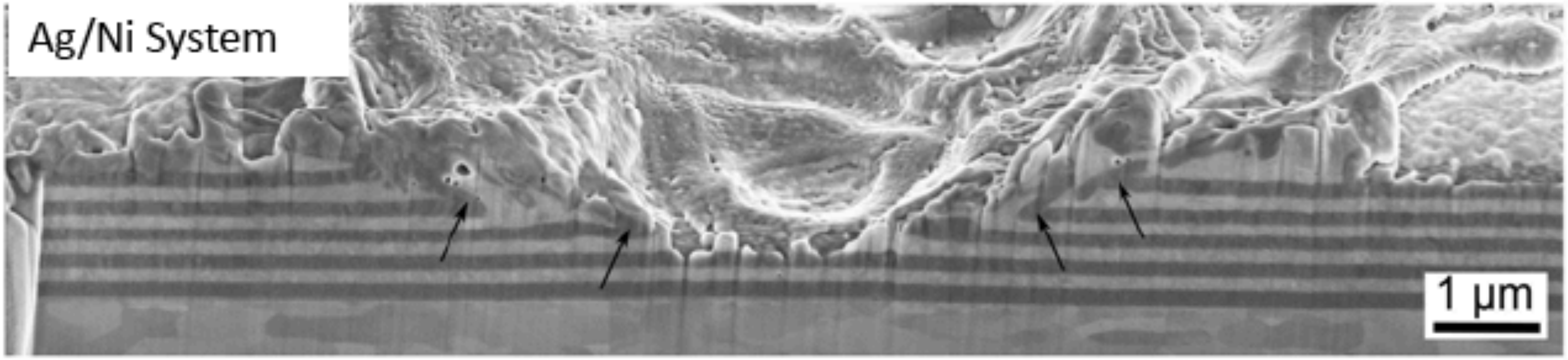


Spark plug from 1902

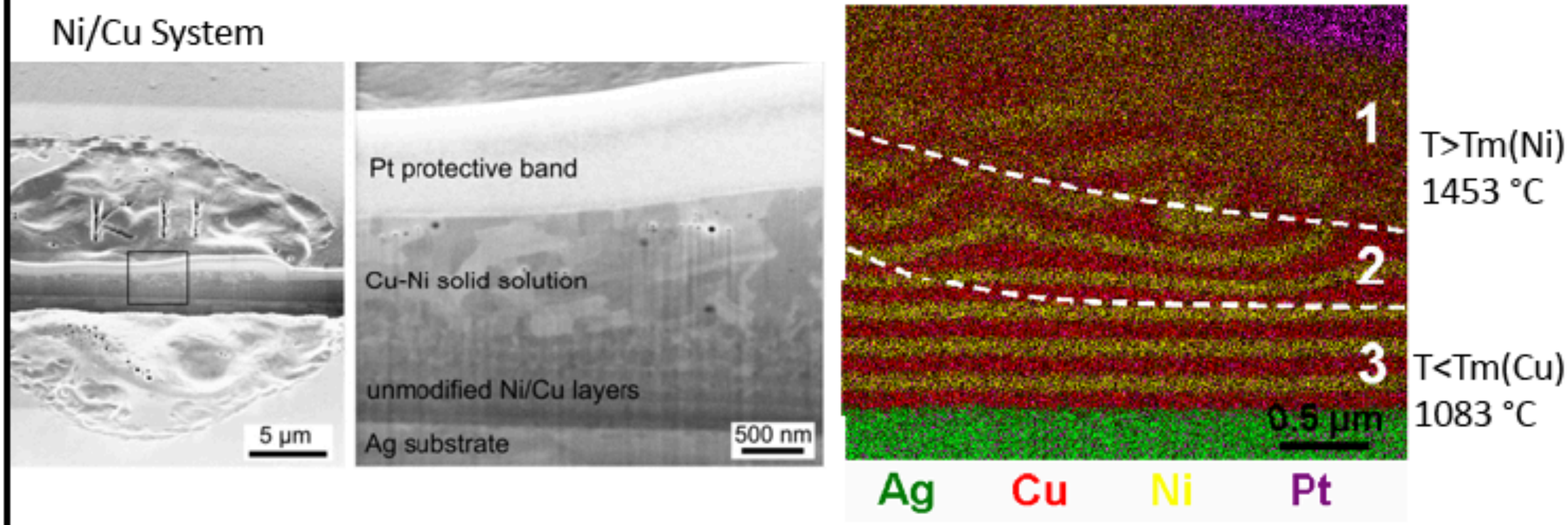
100 Years spark plugs (2002)

Crates in multilayer systems

Ag/Ni System

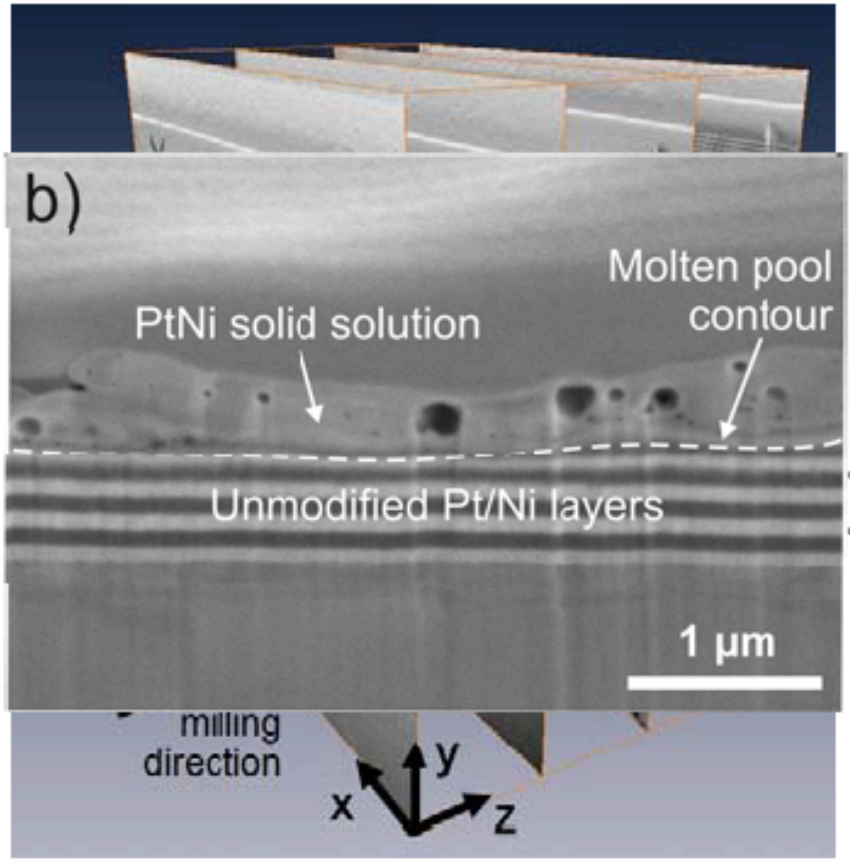


Ni/Cu System

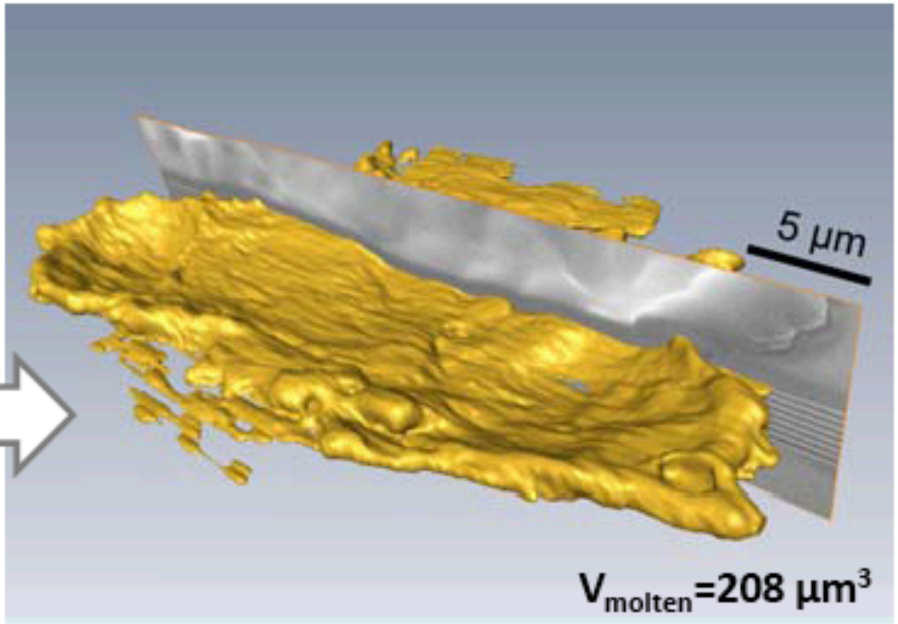


N. Jeanvoine et. Al. Pract. Metallogr. **43** (2006) 479

FIB-Tomography of craters



Serial cross sectioning of crater
200 slices



3D reconstruction of the molten pool
resolution ~100 nm

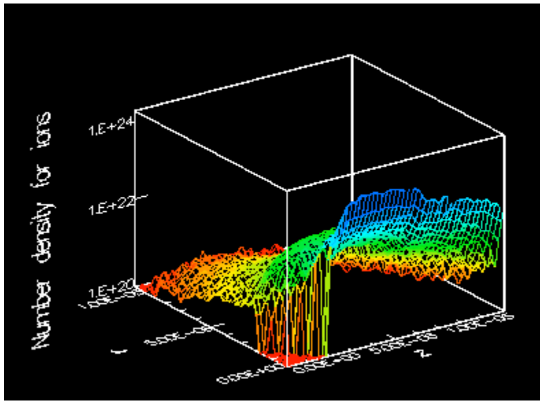
N. Jeanvoine *et al*, Adv. Eng. Mat. 10 (2008)

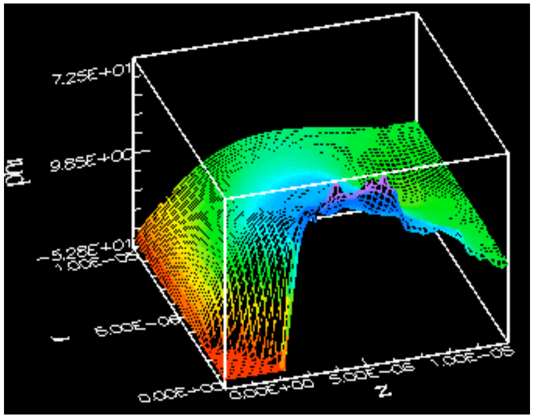
Getting back to our OOPIC Pro results.

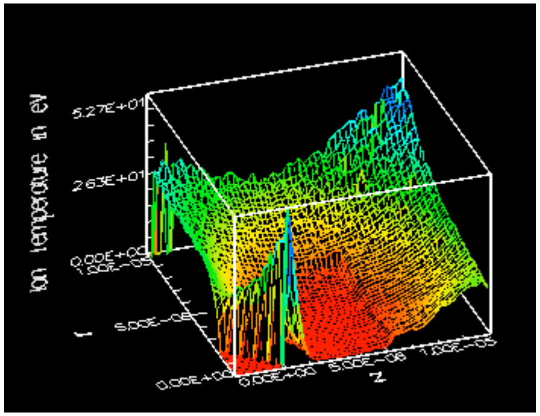
Dimensions and parameters of arc

OOPIC Simulations (at ~ 6 ns), $r_{max} = Z_{max}$ = 10 microns

Ion Density, Phi, T_I







Arc dimensions a few microns.

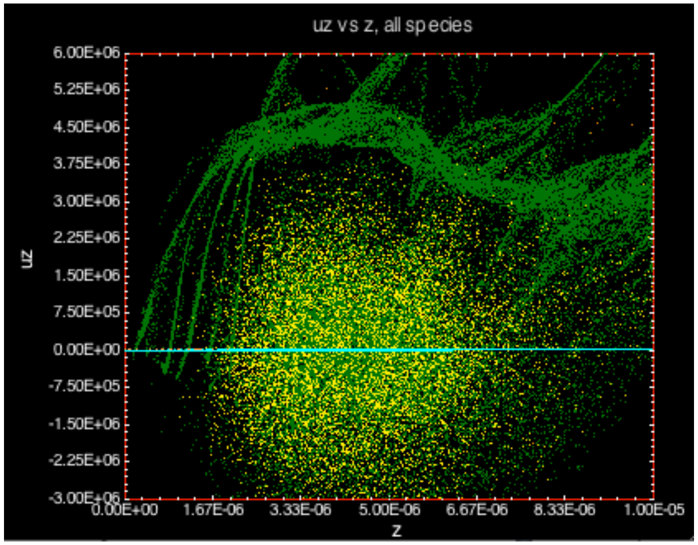
The arc is at the cathode.

Primary electron current

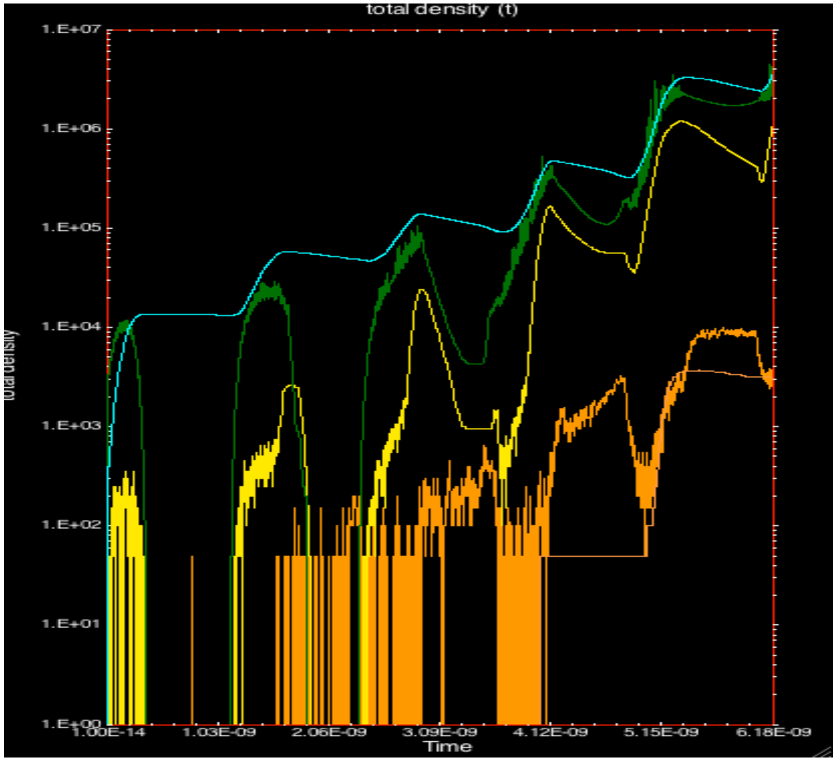
Space charge limit can be seen in v_z vs z

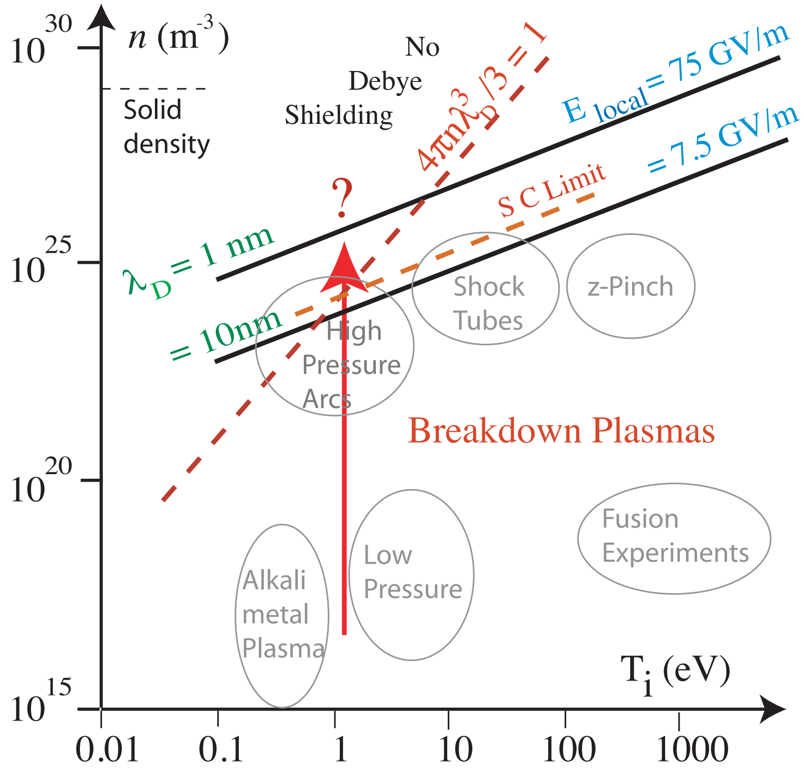
Plasma functions as a virtual cathode

Collision length remains constant ~ 10 μ



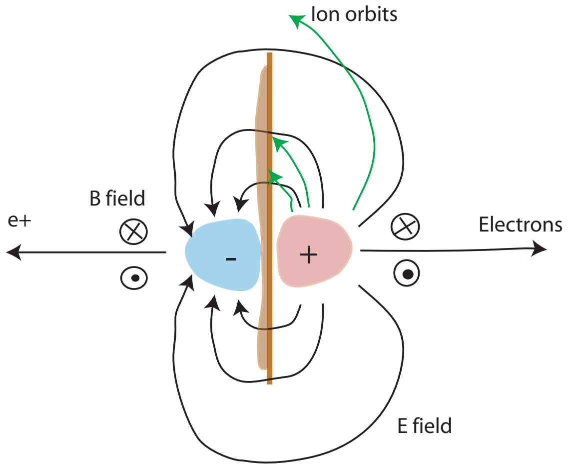
The 805 MHz arc becomes non-Debye.





Increasing Plasma density

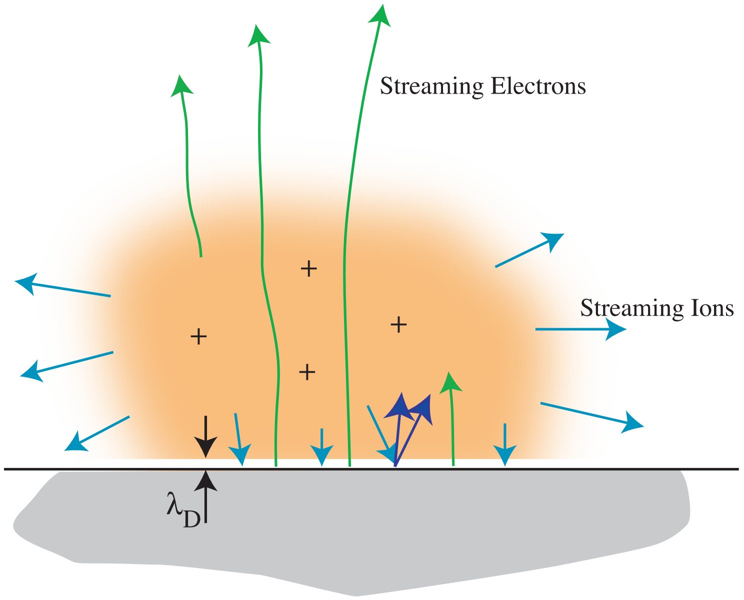
Increasing surface fields



The electric field distribution can be calculated.
giving plasma pressure.

We are finding that the arc is complex.

Ions heat the near surface
electrons heat the far surface
internal B field < 100 T
rf growth time ~ 1 ns
radius 3 - 100 μ



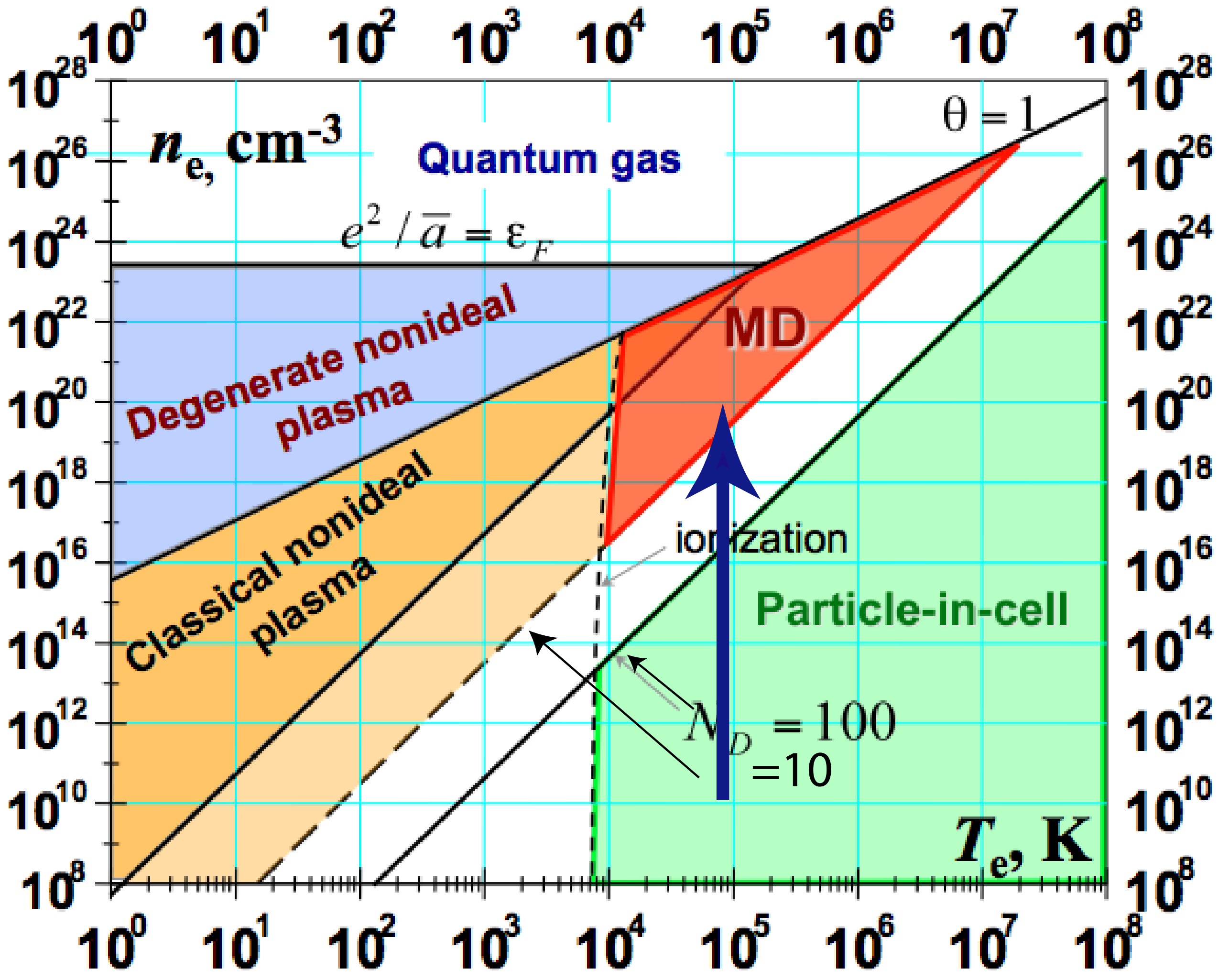
Defining parameters
- Surface electric field
- Self-sputtering yield

Typical parameters	Initiation	Burning
Plasma density	1E13 /m^3	1E24 - 1E26 /m^3
Sheath potential	50 V	75 V
Average surface field	20 MV/m	10 GV/m
plasma pressure	0	100 MPa
Debye length	~1 μ	~1 nm

How do we understand the dense plasma / surface interaction?

PIC codes are not designed for this environment.

Molecular Dynamics (MD) becomes more useful at high densities.



Nonideality parameter for electrons

$$\Gamma = \left(\frac{4\pi n_e}{3}\right)^{1/3}\frac{e^2}{kT}$$

Number of electrons in the Debye sphere

$$N_D = \frac{4\pi r_D^3}{3} n_e$$

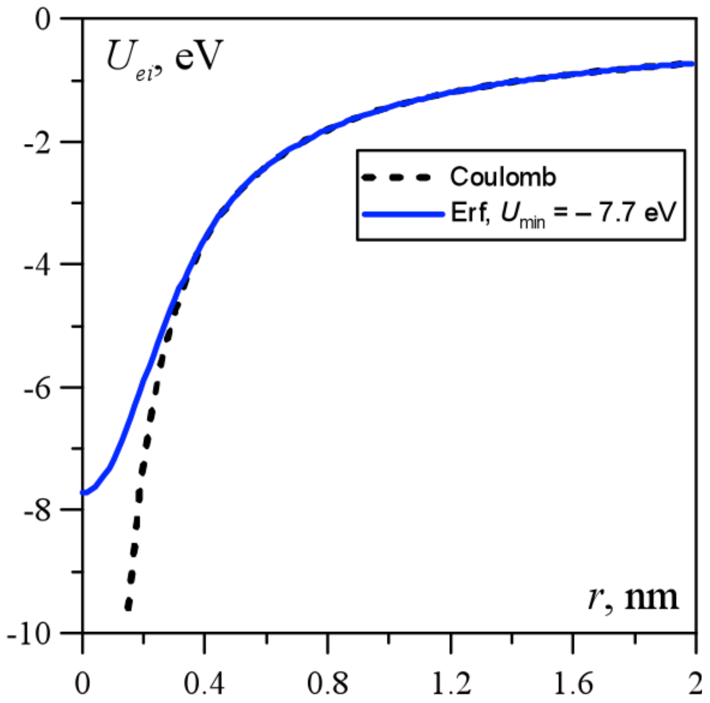
Degeneracy parameter

$$\theta = \varepsilon_F / kT$$

We can calculate the non-Debye sheath with MD.

We use classical molecular dynamics (MD) simulations with a pseudopotential to account for quantum effects

- Two component plasma of electrons and copper ions
- Long range Coulomb interactions (*N*-body problem)
- Nearest image method (periodical boundary cond.) for the transversal dim.
- Absorption of electrons to the surface with generation of $E_{surface}$.
- Simulation of the relaxation process
- Averaging over an ensemble of initial states
- Image charges

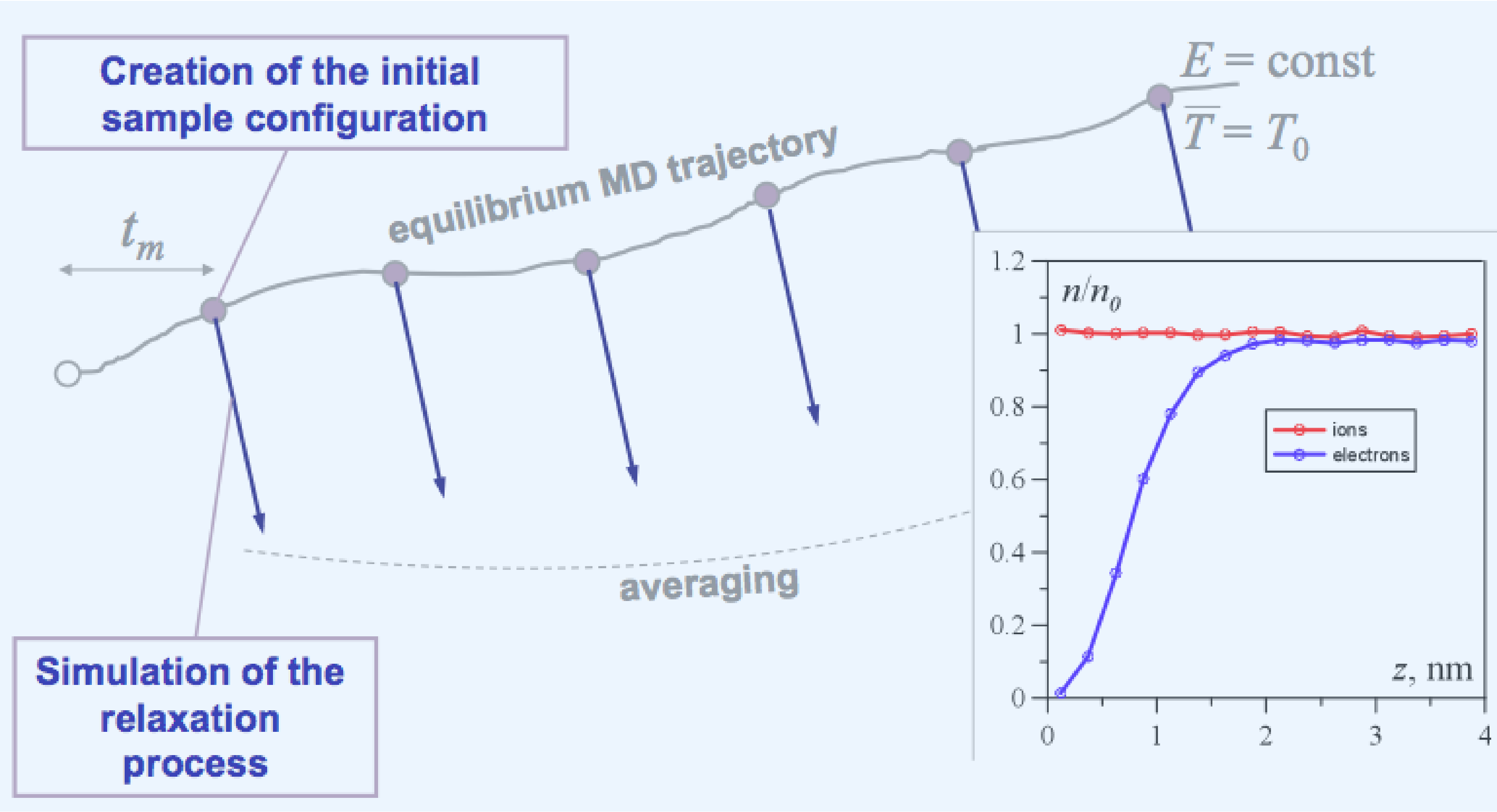


Electron-electron and ion-ion potentials are pure Coulomb. The erf-like electron-ion interaction potential used cuts off at small radii, with

$$U_{ei}(r) = -\frac{Ze^2}{r}\, erf\left(\frac{r}{\sigma_{ei}}\right)$$

Many initial states are averaged

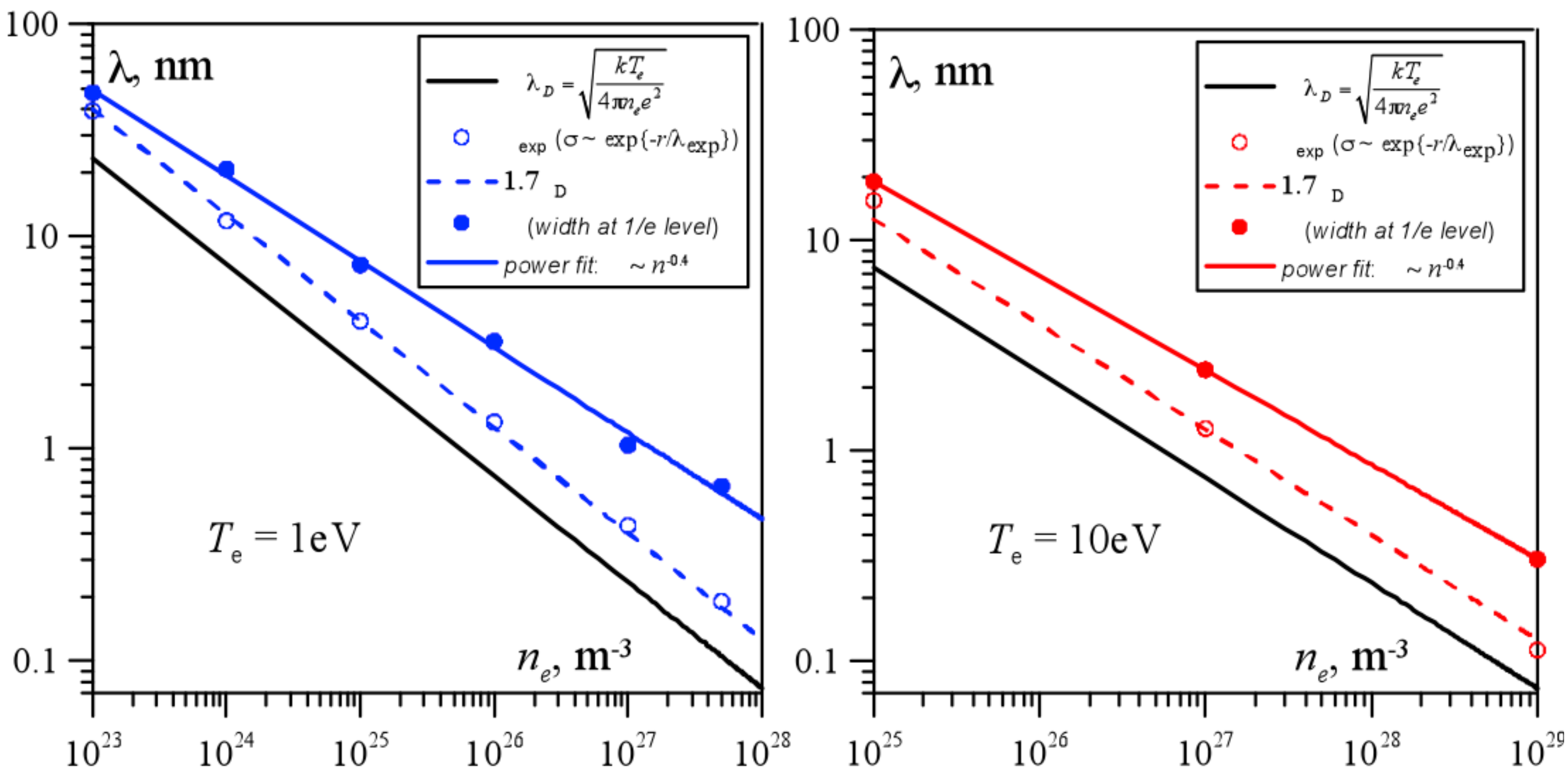
MD of a dense plasma



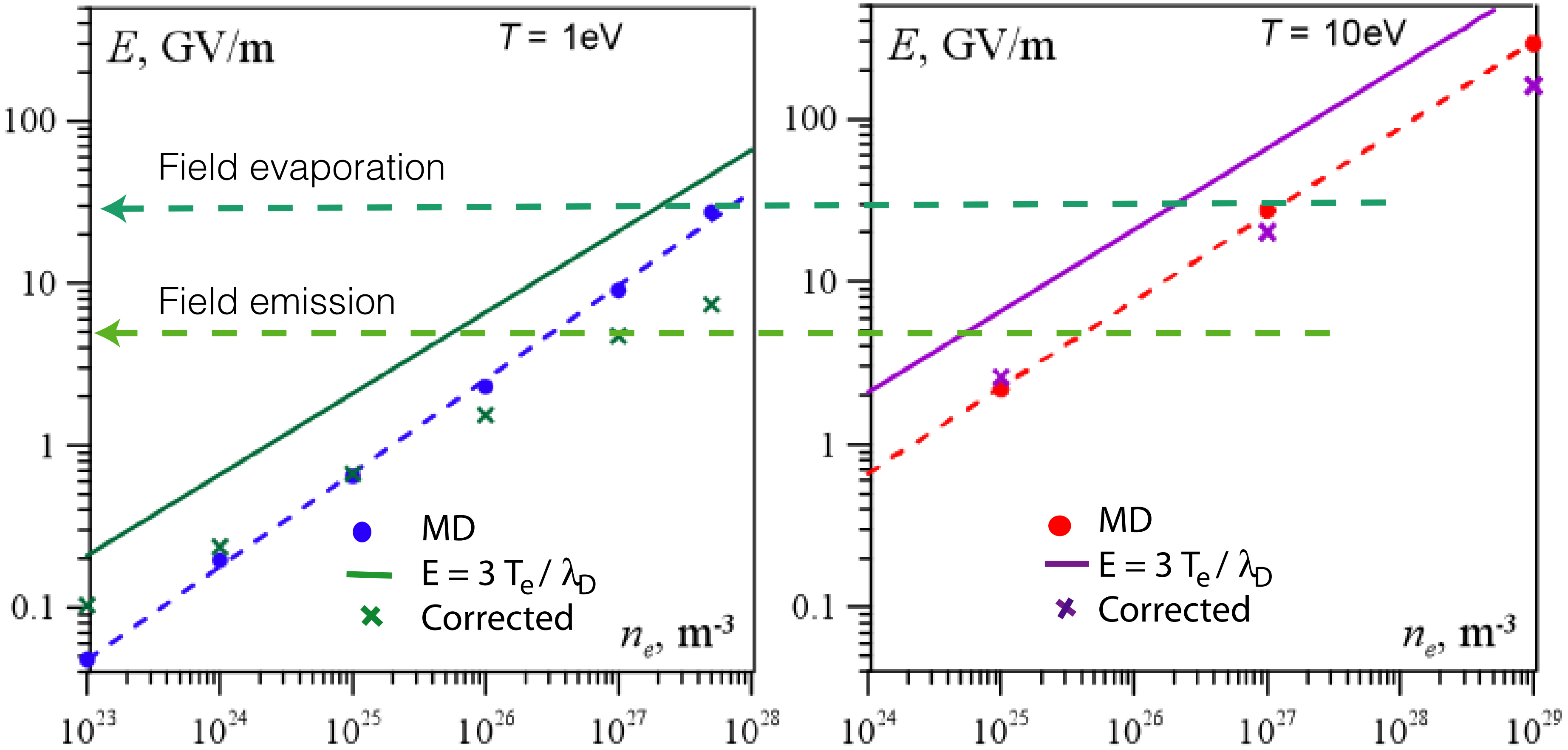
Creation of the initial sample configuration

Simulation of the relaxation process

MD shows that sheaths are modified at high density.



The surface field can also be calculated.



Modeling gives a consistent picture of the surface environment.

OOPIC says the plasma potential is 70 V, and the density, n > 1E25 m^{-3}.

Molecular Dynamics show this is compatible with a surface field of ~ 1E9 V/m.

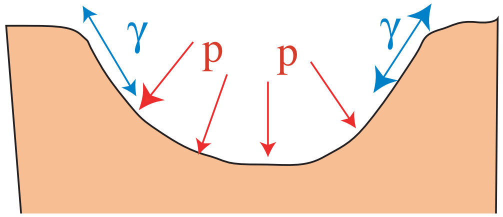
The surface pressure in the arc is given by

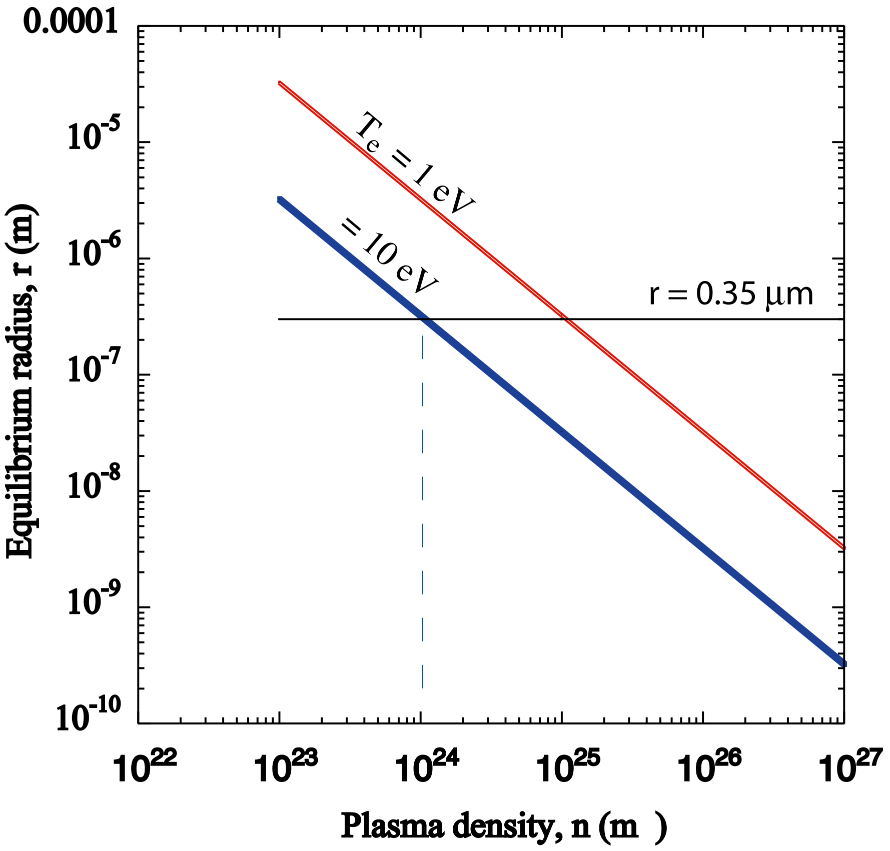
$$p = nK(T_i + \phi) - \varepsilon_0 E_{surf}^2/2 \sim nk\phi \sim 90 \text{ MPa}.$$

The scale of damage measures the density.

$$\text{Damage dimensions} \rightarrow p = 2\,\gamma/r$$
$$\sim 2\,(1 \text{ n/m})_{[Cu]} / (0.1\,\mu) \sim 20 \text{ MPa}$$

Plasma pressure pushes
Suface tension flattens

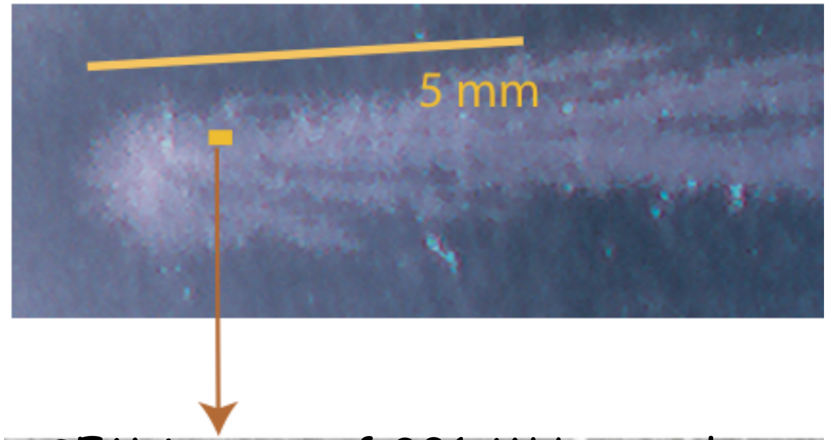




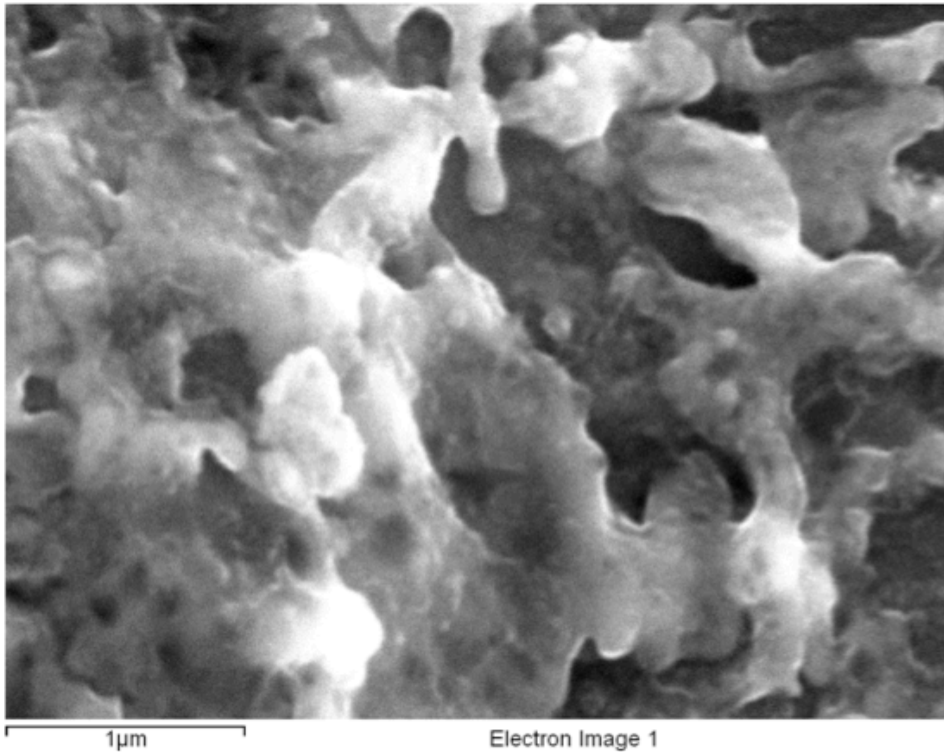
Small structures come from high density, high pressure plasmas

We can calculate the pressure from our SEM images.

- Schwirzke ('91) has shown cylindrical damage craters with $r \sim 0.35\ \mu$ in laser expts.
- Sub-micron structure in cavities.



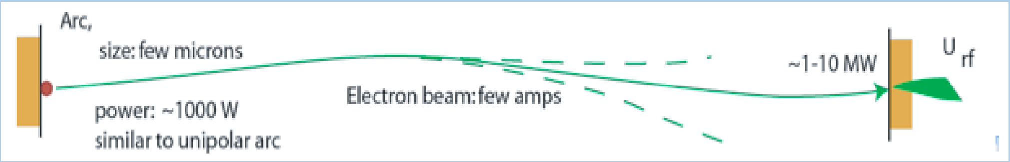
SEM images of 201 MHz coupler.

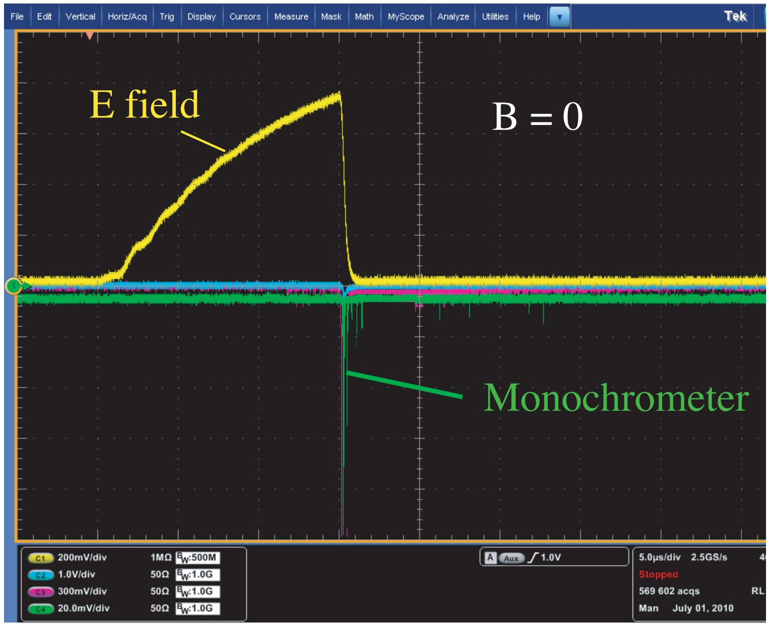


We see two extreme forms of arcs in our cavities

Killer arcs:

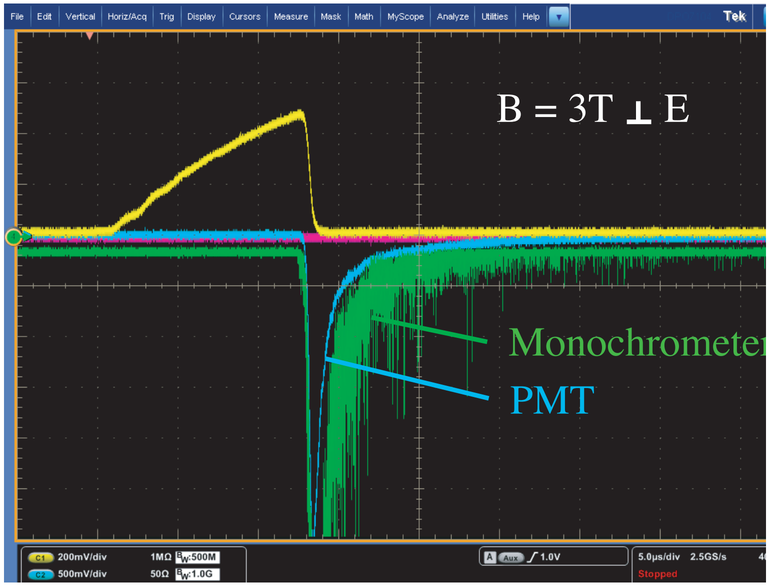
arcs short cavity
remove driving fields
arcs die quickly
small (~5μ ?) arc pits





Parasitic arcs:

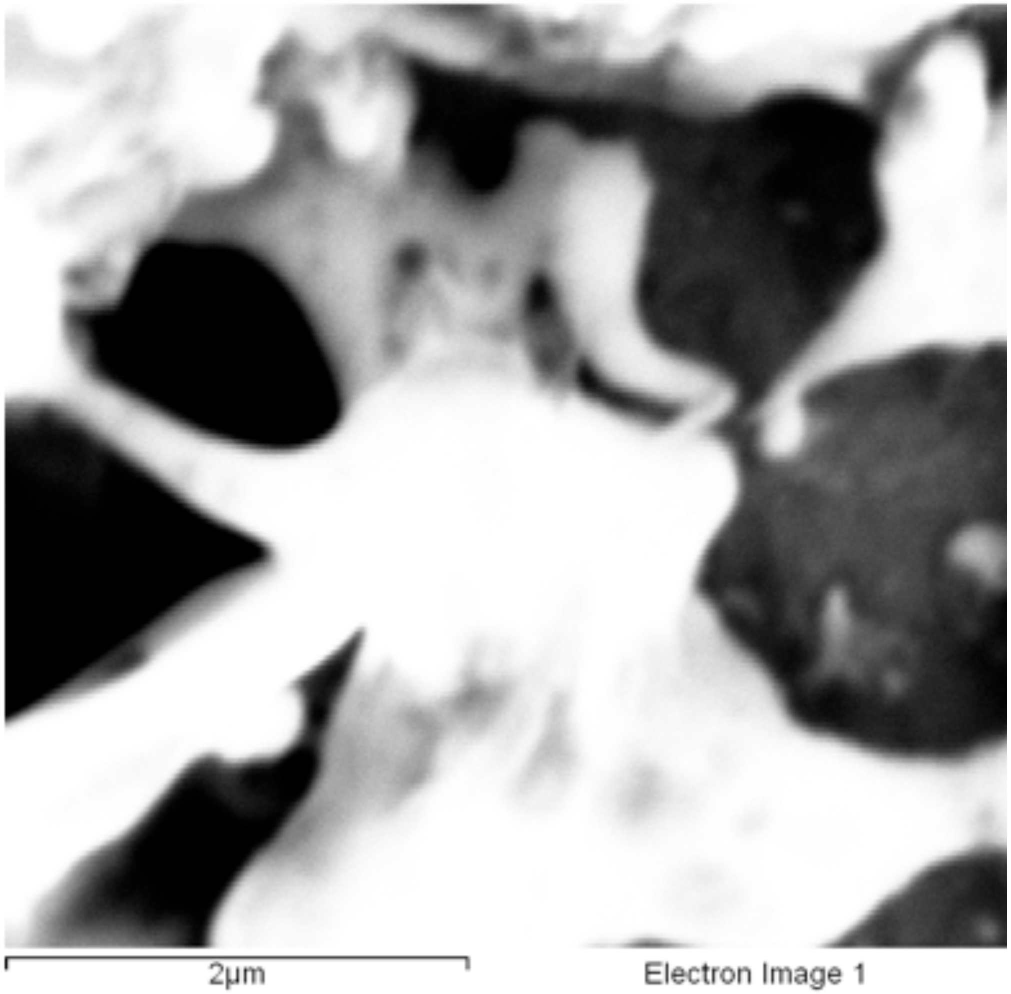
arcs cannot short cavity
driving fields persist longer
radiation losses?
arcs get bigger (~cm) and hotter
can last even after the field is gone
larger region of arc damage



Different arcs produce different damage

Killer arcs

Parasitic arcs



Field enhancements, β, are a source of confusion.

Fitting historical field emission data seems to give a wide range for β and A.

$2 < \beta < 1000$

$1\ \mathrm{nm}^2 < A <$ many μ^2 (emitting areas are very hard to measure)

(This wide range is not seen in cavities however.)

These values are not compatible with a whisker model of enhancement factors.

The validity of the Fowler-Nordheim field emission model (and quantum mechanics) has been questioned.

We look at very small structures:

Emitters are small, ($A \sim 1\ (\mathrm{nm})^2$) with natural βs around 100.

They are formed at crack junctions and spattered particulates.

If they sit on other structures, their βs can be much larger.

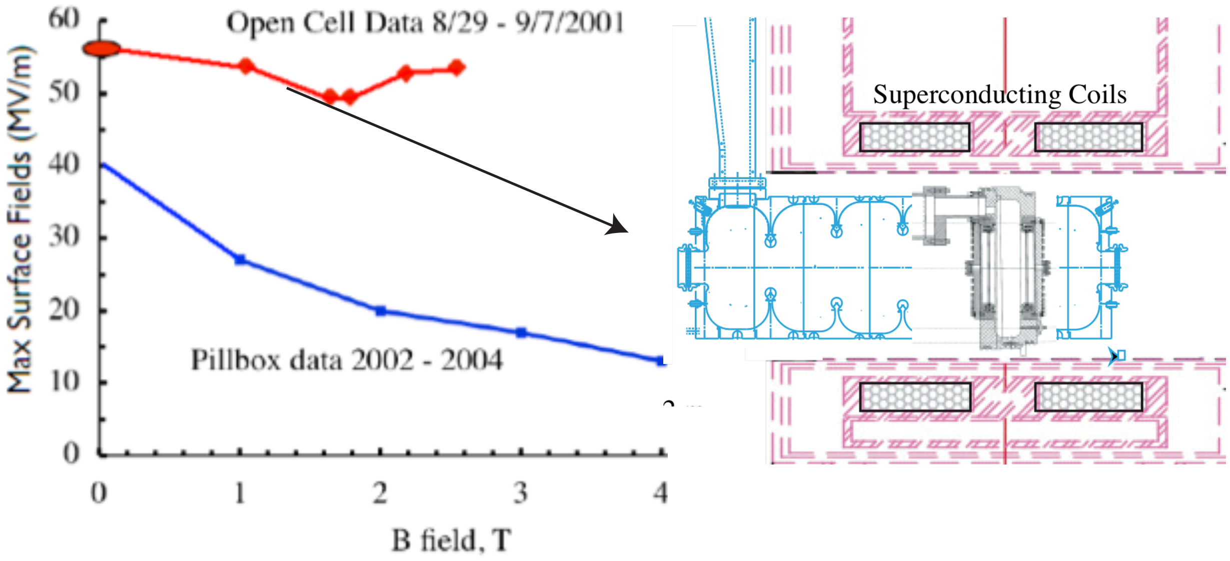
If there are lots of them, the combined A will be much larger.

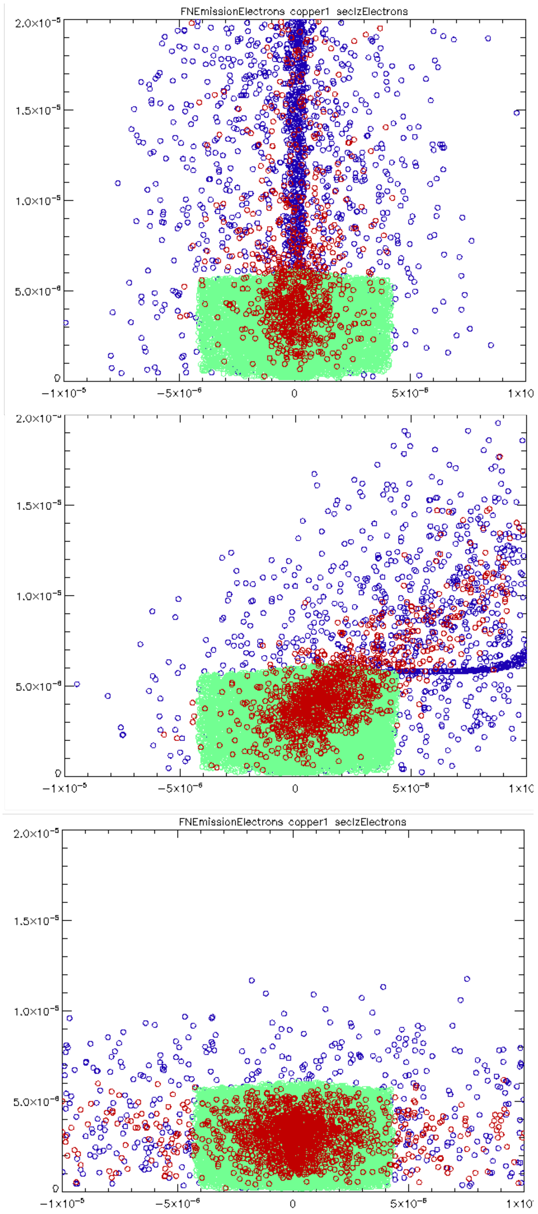
Surfaces are rough, so lots of structures to sit on and lots of spatters/cracks.

Magnetic field effects are complex.

- Experimental data is ambiguous: two cavity shapes

Simulations difficult





- VORPAL results will show ExB effects

- Larmor focusing of electrons, $r_L = 0.3\ [\mu]\ W_{eV}^{1/2}$

  If ***E*** || ***B***, arc is more compact and damaging,

  If ***E*** ⊥ ***B***, or ***B*** = 0, arc is more spread out

Conclusions

It seems that the arcs that discharge cavities may heat the metal deeply and not leave the sort of fine structure that can be used to determine the arc parameters.

There is considerable worldwide effort in this field and it is increasing.