A review of Arc R&D

J. Norem, ANL/HEP

MAP meeting
Aug 5, 2011

Muon Accelerator Program

Argonne NATIONAL LABORATORY

Breakdown is generally relevant.

- Accelerator
  - Normal Conducting
    - Source of our problems, also CLIC
    - Failure mode for pulsed heating
  - SC pulsed power cleaning, field emission More E => more sensitivity
    - Spontaneous FE
- Fusion
  - Impurities, Stability
  - RF heating limits
- Industrial
  - High power switching
  - coatings
  - Spark plugs
  - . . .
- Satellites
  - . . .
- Intellectual / scientific

But there is still no basic theory.

Should a theory of breakdown explain the breakdown of the scientific method?

Many workarounds.

Who is active?

Historically

- Michelson, Millikan, Lord Kelvin & Alpert
- Juttner / Anders
- Mesyats

Now (this conference)

- CERN / Helsinki / IPP/ Sandia / Other
- SLAC
- High Grad
- Muon
  - ANL

Other conferences

- ISDEIV
- SRF community

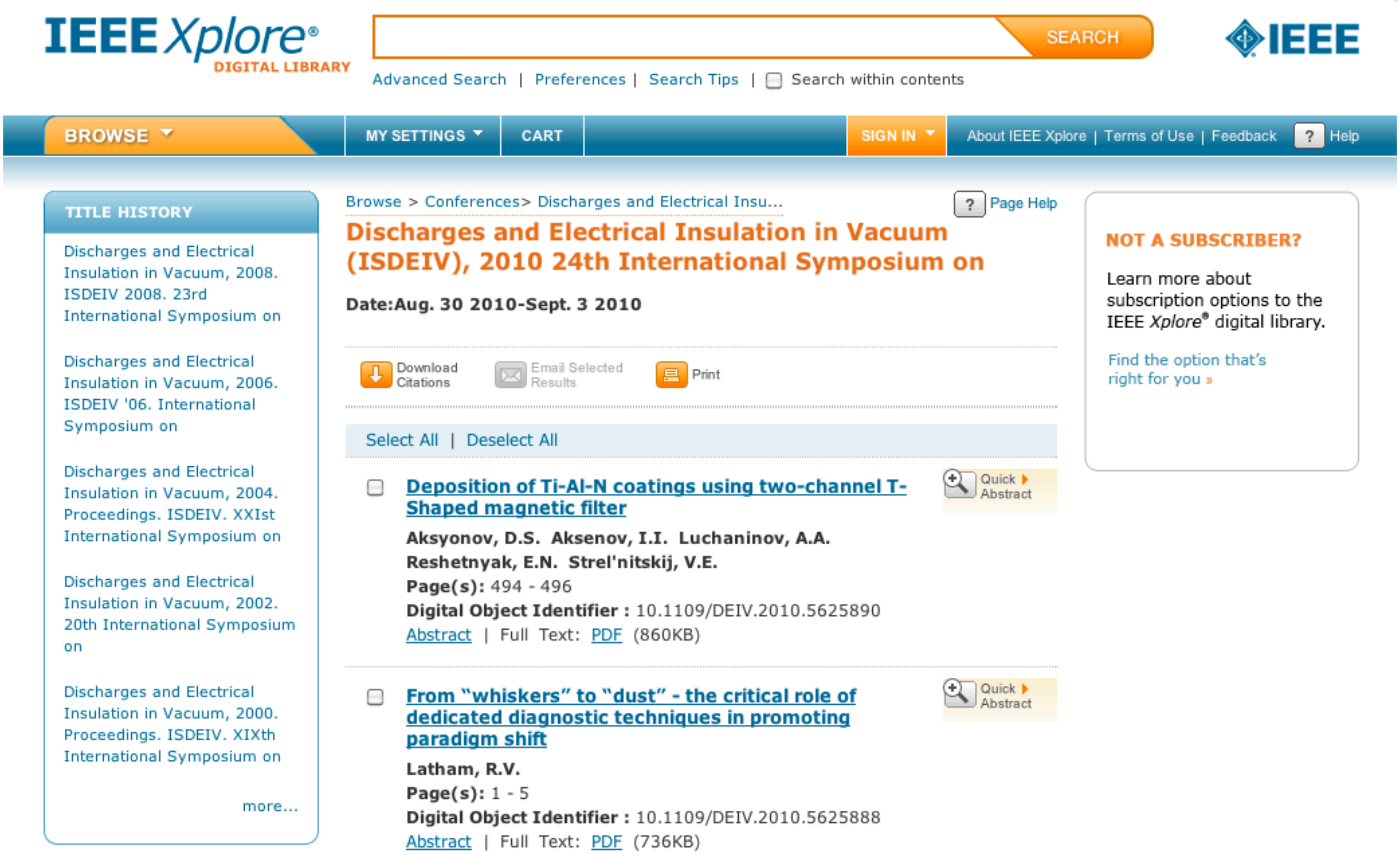
ISDEIV

International Symposia on Discharges and Electrical Insulation in Vacuum

http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=5613127

Large international group that meets every two years

Primarily devoted to coatings and high power switching



SRF2011

Exhibitors Poster Abstract Presentations

- Home
- Conference Venue
- Organizing Committees
- Important Dates
- Registration
- Program
- Tutorial
- Tour Information
- Contact Us
- Visa
- Chicago Attractions

SRF 2011

Dear Colleagues,

We welcome you to attend the 15th International Conference on RF Superconductivity to take place on July 25-29, 2011 in downtown Chicago. Our goal is to continue in the tradition of the 14 previous conferences and provide a lively forum for SRF scientists, engineers, students and industrial partners to present and discuss the latest developments in the science and technology of superconducting rf for particle accelerators.

Pictures taken during the SRF 2011 boat trip and Banquet dinner are available here (picasa link).

http://conferences.fnal.gov/srf2011/

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 (30 talks, 20 on web)

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/CLIC related work was updates.

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.

Many did not put their talks on the web, making it hard to summarize the conf.

Introductory talks

Burkhard Juttner

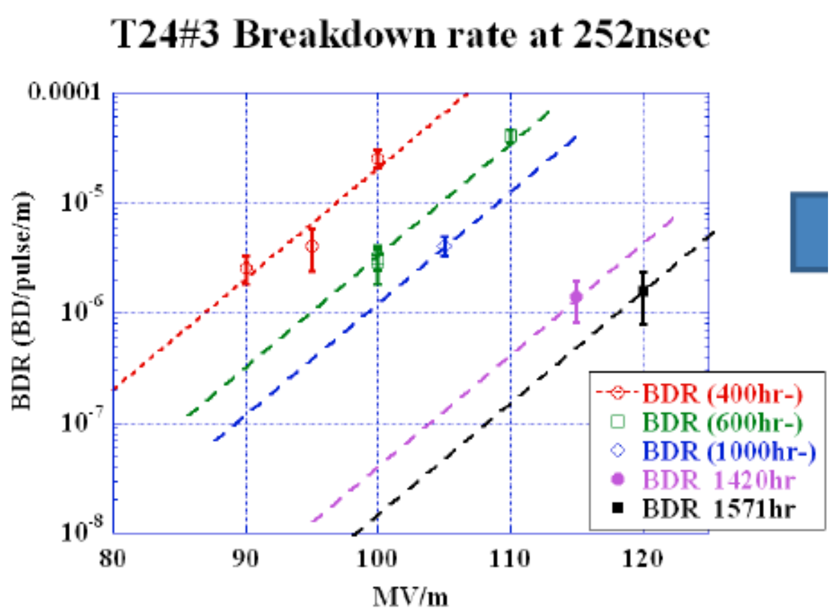
General introduction to the field stressing how small areas cause big problems.

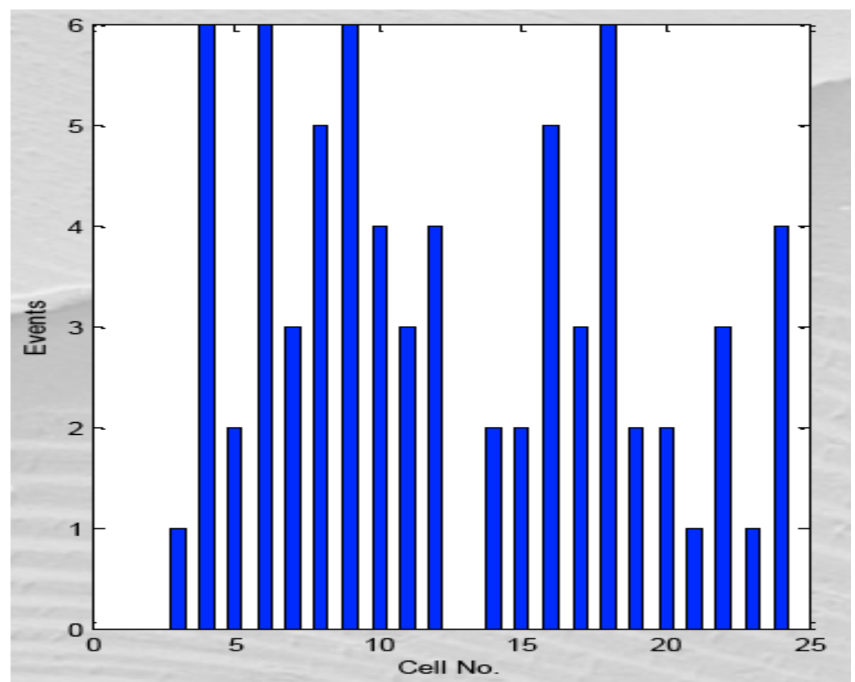
Walter Wuensch

CLIC perspective

High gradient technology has many applications

Test areas: NLCTA, ASTA (SLAC), Nextef (KEK) Klystron and two beam (CERN)

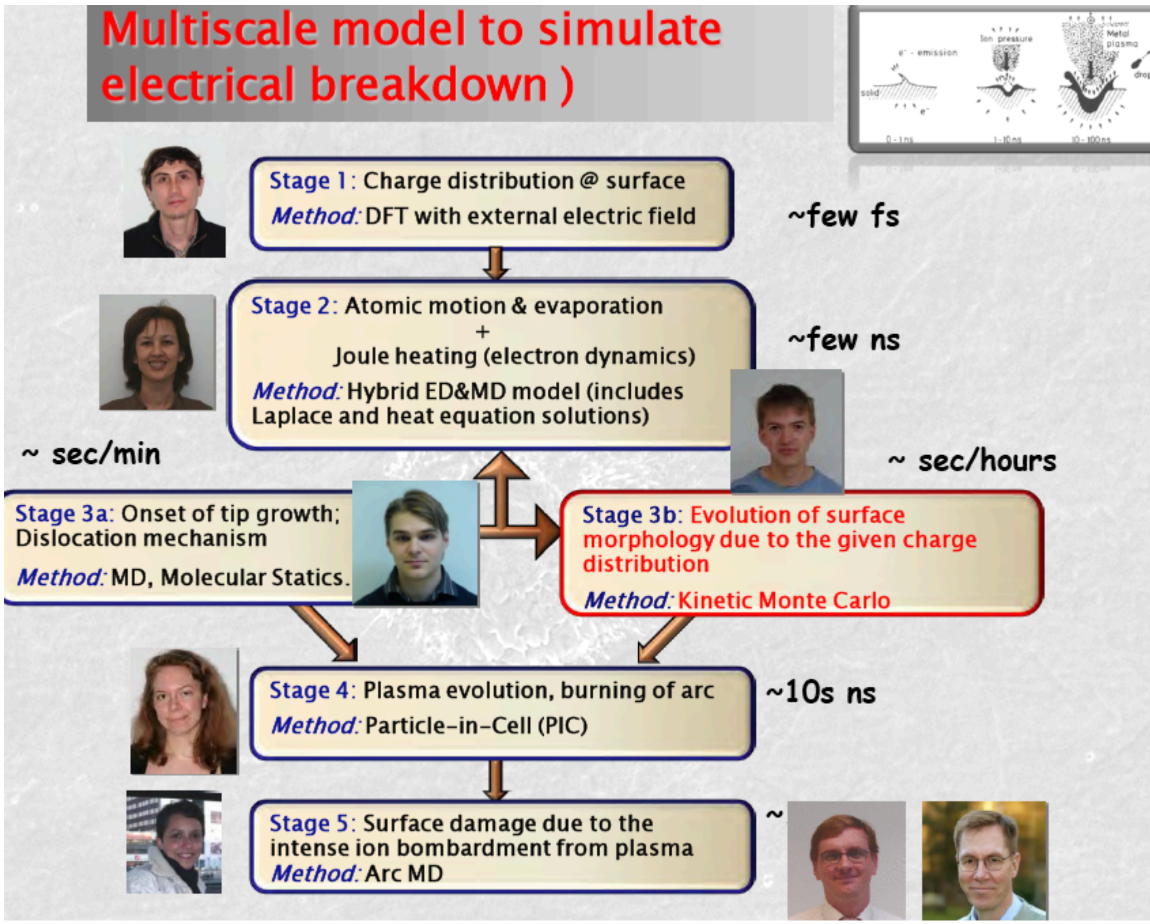




Helsinki

Helsinki in June is great.

They use a number of models



A European Collaboration.

Model triggers

- Arc evolution
- Damage
- Surface deformations
- Metallurgy / morphology

The Helsinki group collaborates with:

CERN

Combined effort to understand small gap experiments
Explanation of arc physics

IPP Garching

Helsinki use IPP model for initial state of BD,
Sheath physics is dominant during BD phase.

Upsala University

Experiments are starting to look at BD in an SEM

Sandia

Sandia has a large effort modeling arcs of various geometries.
Cross checks between Sandia and Helsinki (Hopkins, Crosier,)

And others. . .

Other Helsinki/related efforts:

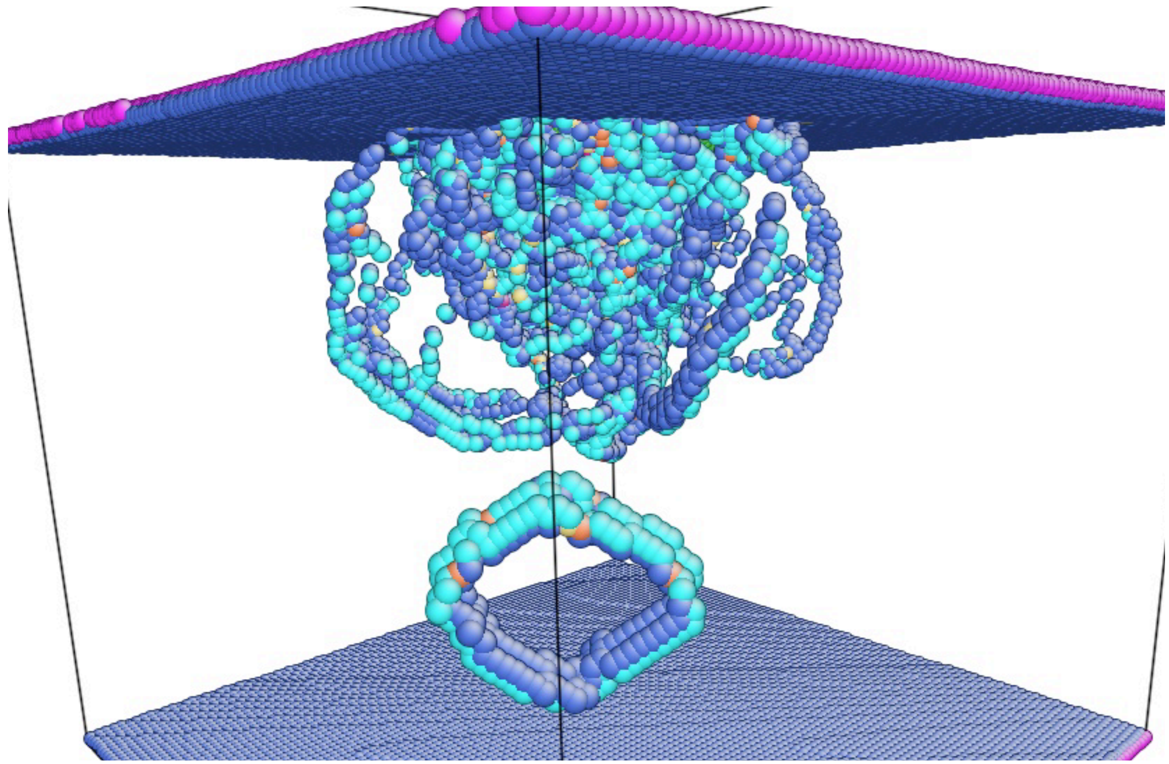
Stefan Parviainen

Studies of Atom Probe Tomography theory
Atomic motion and ion optics

Steve Fitzgerald, Aarne Pohjonen and Marc Fivel

Study of dislocation and dislocation dynamics
Movies of dislocation loops flying through materials

Insepov's loops



Industrial interest

Edgar Dullni, (ABB group)

Studies of commercial vacuum interuptors

Joel Rasch (Chalmers-CNES_IAP Collab.)

Breakdown in aerospace

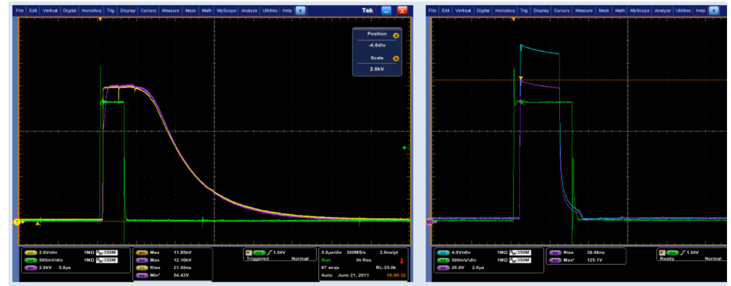
Kamel Frigui (Limoges/CRS Thales)

Breakdown in waveguide filters at atmospheric pressure (tuning stubs)

CERN (Calatroni)

Modifying their arc gap to look at high frequencies, high rep rates.

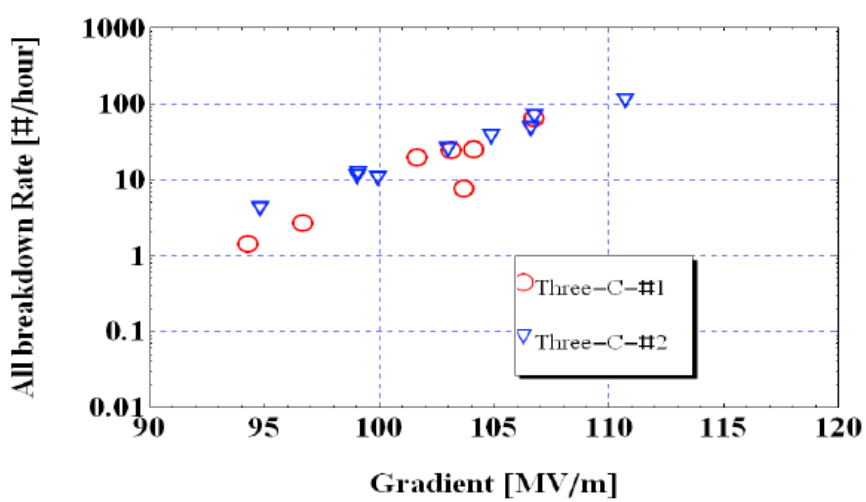
- Coaxial contacts
- Large temperature range
- Faster solid state electronics

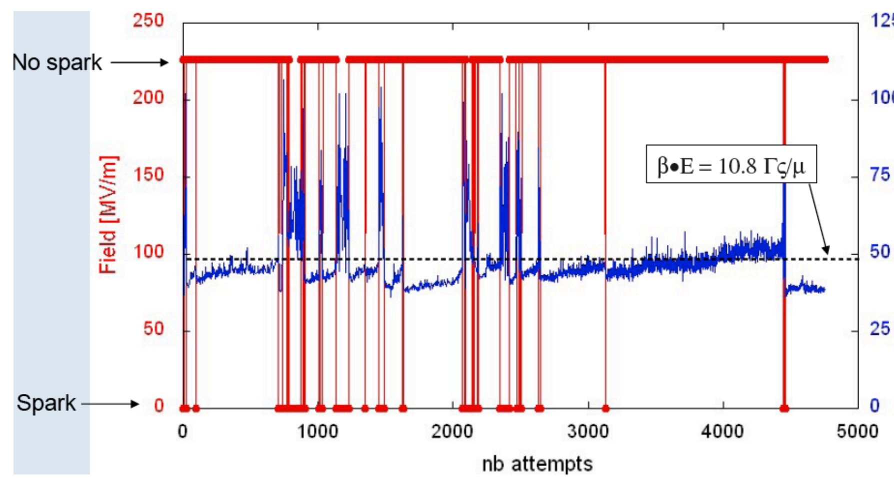


12 kV pulses, no load
Green: trigger (3 μs width)
Pink & yellow: voltage output

12 kV pulses, short circuit
Green: trigger (3 μs width)
Pink & blue: current output

New results on cleanliness and surface modification (surface changes)



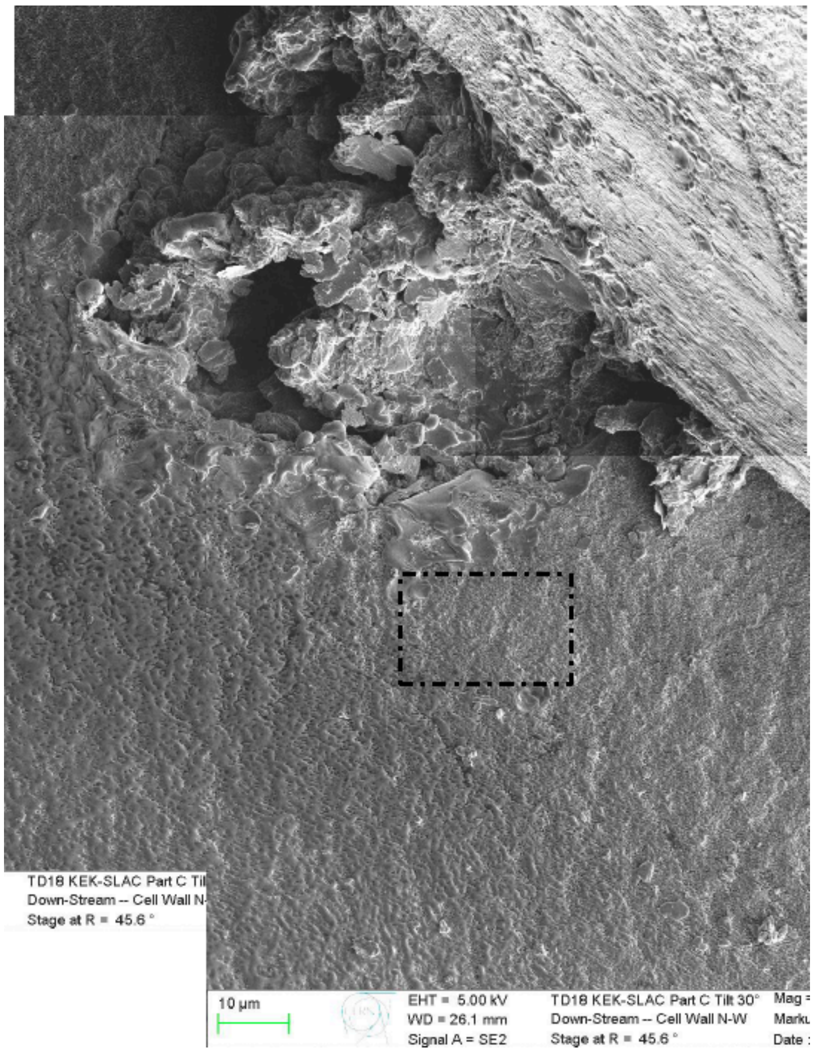


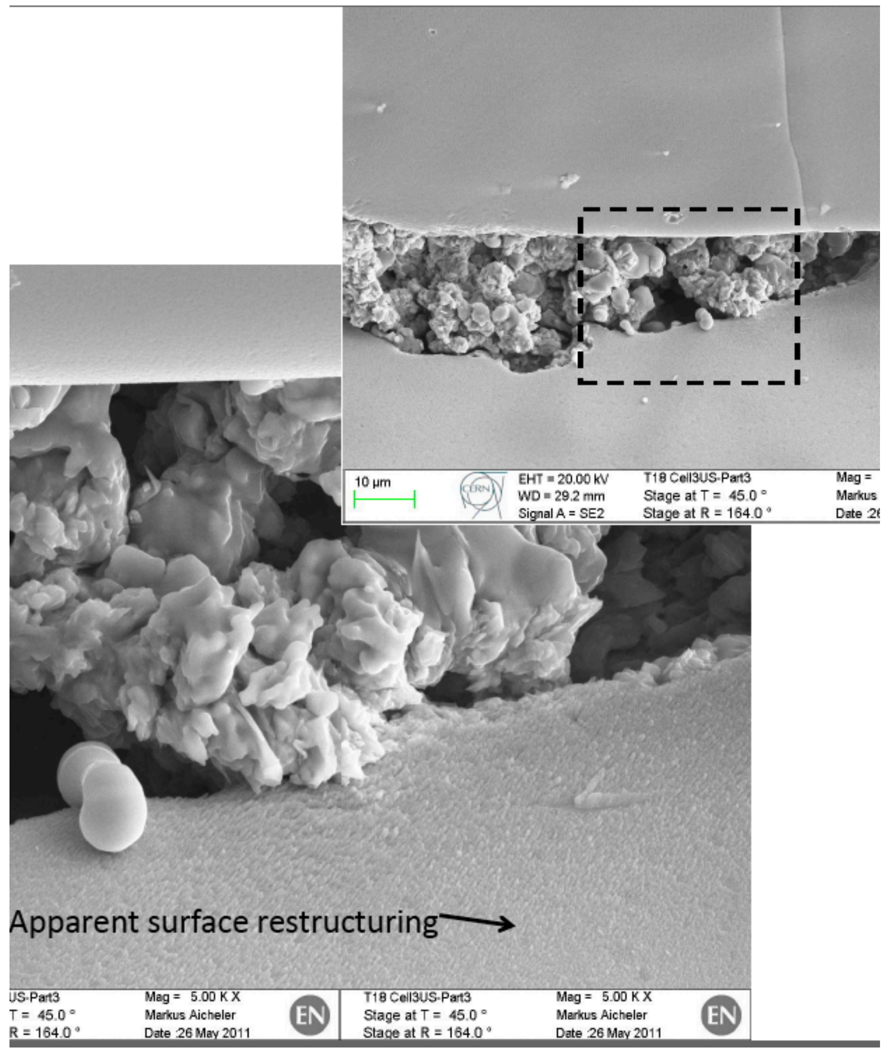
The near perfect surface processing affected only the processing time. The second structure processed to maximum gradient in a few minutes vs few hours for the normally processed structure.

CERN (Aicheler)

SEM images of arcs in cavities and small gap system

They see arcs at the braze joint, far from the iris.

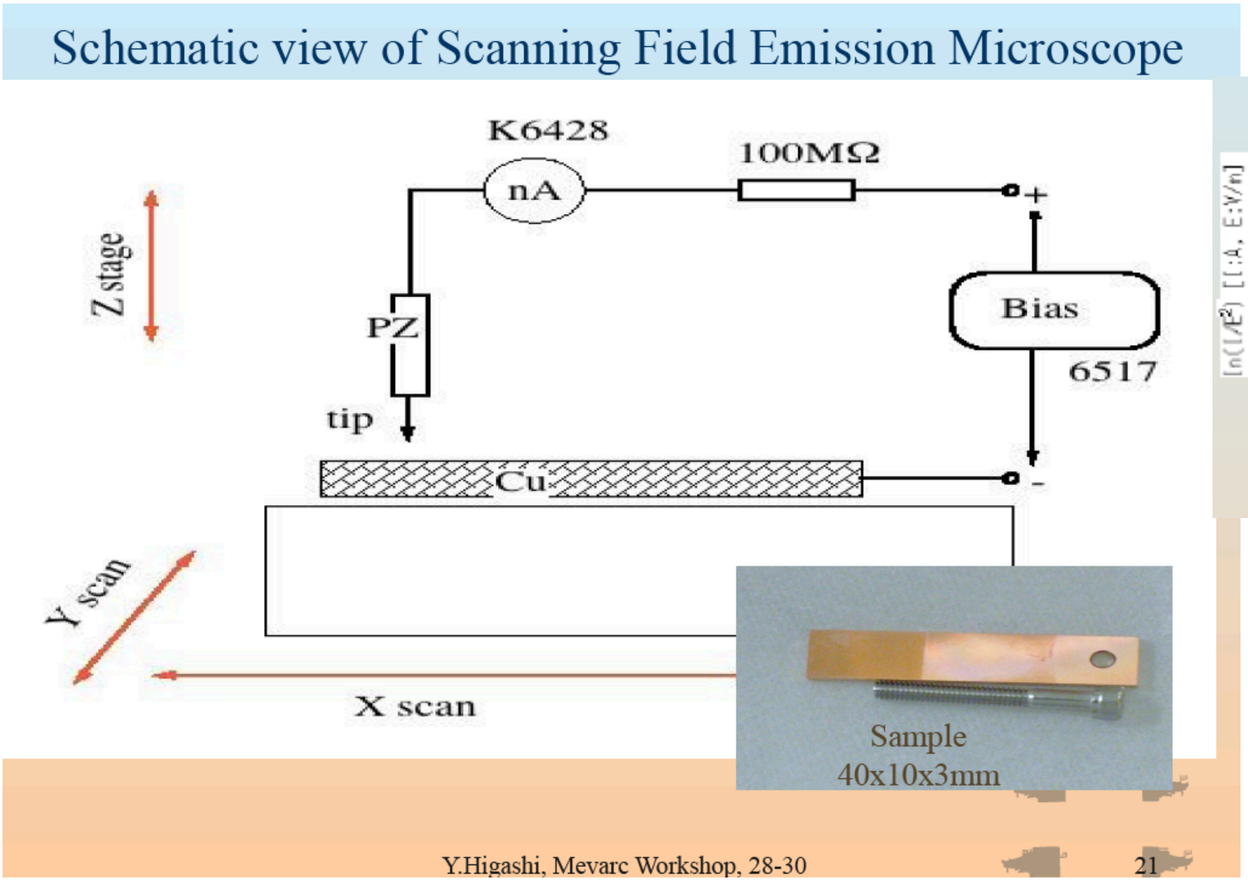


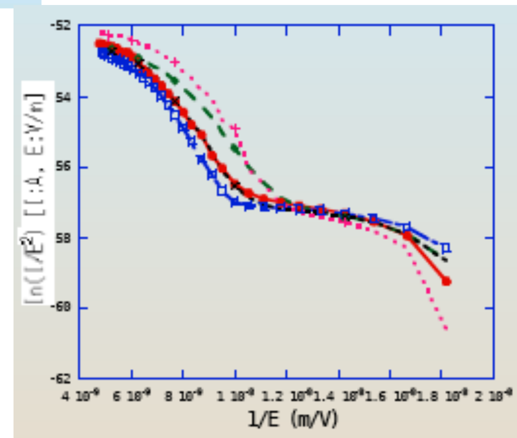


KEK

Yasuo Higashi

Building a scanning Field Emission Microscope



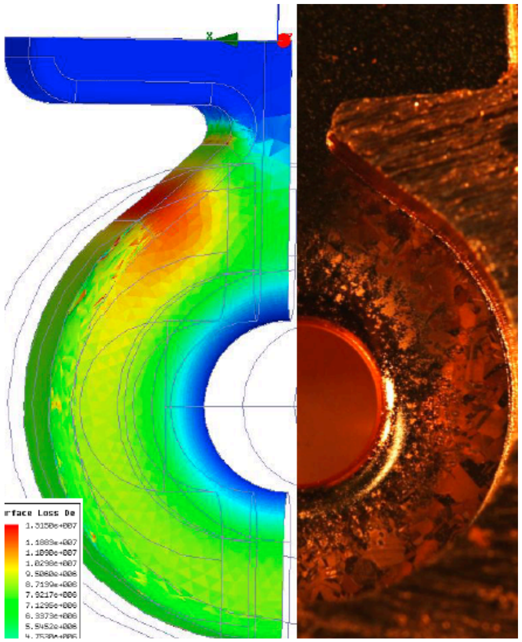


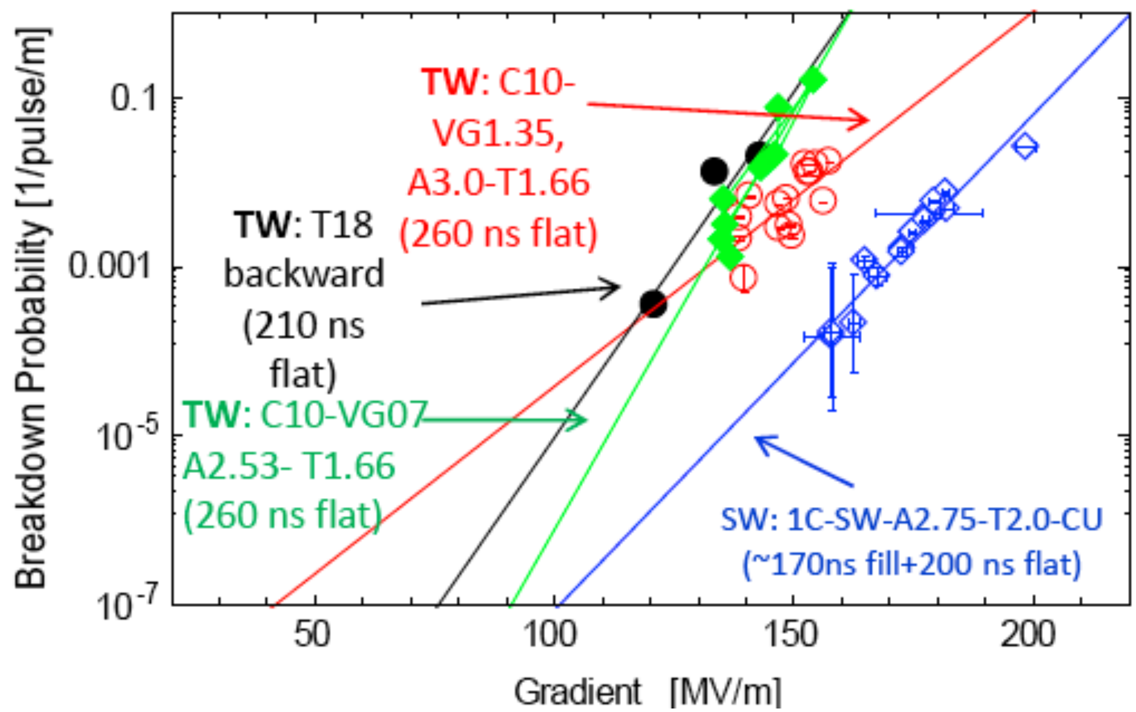
Lisa Laurant at SLAC is buying/building one of these.

SLAC

Valery Dolgashev

Summary of recent SLAC results, frequently reported by others.





Arno Candel

Summaries of Parallel Electromagnetic Accelerator Modeling results

ACE3P simulations of Waveguide operation

Field emission with space charge limit

Pulsed heating - evidence from changing cavity shapes, rf profiles & B_{rf} fields

Richard Forbes

Cold field electron emission (CFE) can be part of the formation of vacuum arcs.

With accelerators, this process is often modelled by using (a) the Fowler-Nordheim type (FN-type) equation developed by Murphy & Good [1,2] in 1956 and (b) a specific aproximation developed by Charbonnier & Martin [3] in 1962 for a correction factor "*v*" in this equation. This remains satisfactory for many modelling purposes, but there have been subsequent developments.

Overall, it is now recognized that FN-type equations are the CFE equations that apply to *"bulk"* (i.e., large) *metal* point-like emitters (and to arrays of such emitters).

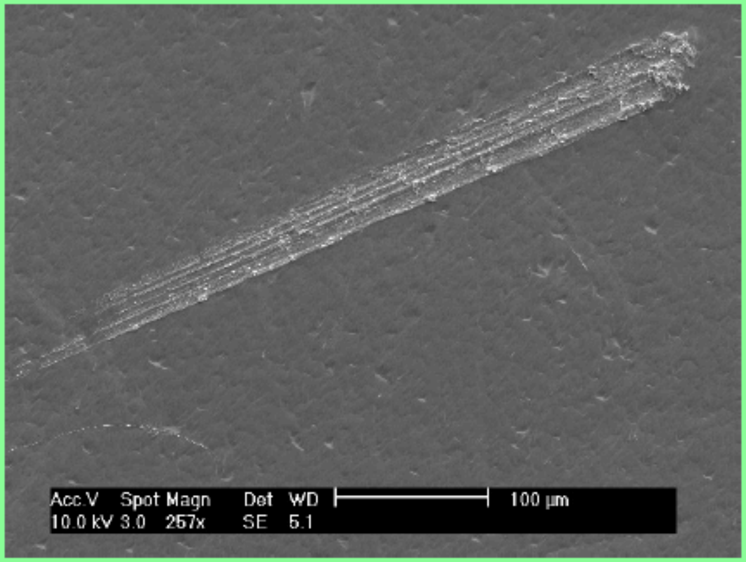
Theoretical developments over the last 15 years can be classified into:

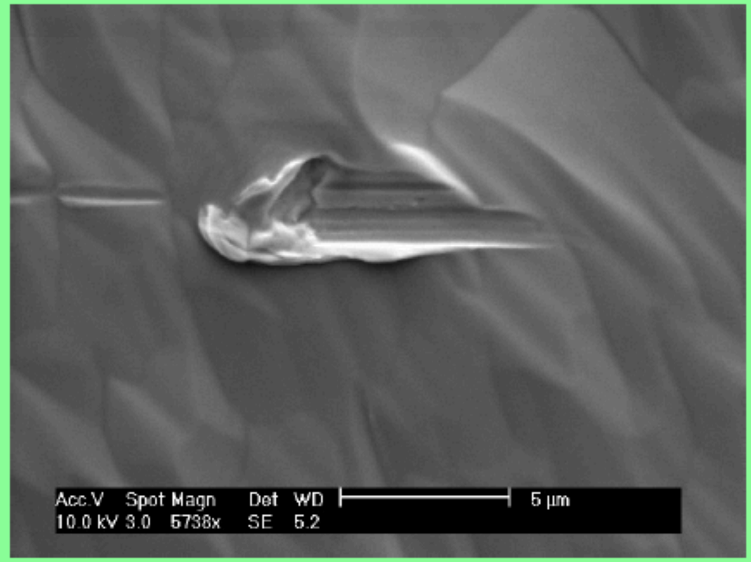
- Improvements in underlying theory, and/or in applying it (charged surface theory, electrostatics, tunnelling theory, statistical mechanics).
- Improvements (of various kinds) to FN-type equations.
- Development of theory for *small* emitters.
- Development of theory for *non-metallic* emitters.
- Improved theory for analysing current-voltage characteristics.

All except (probably) Heading 4 are relvant to accelerator breakdown. Various progress items are listed below, with an emphasis on the author's contributions.

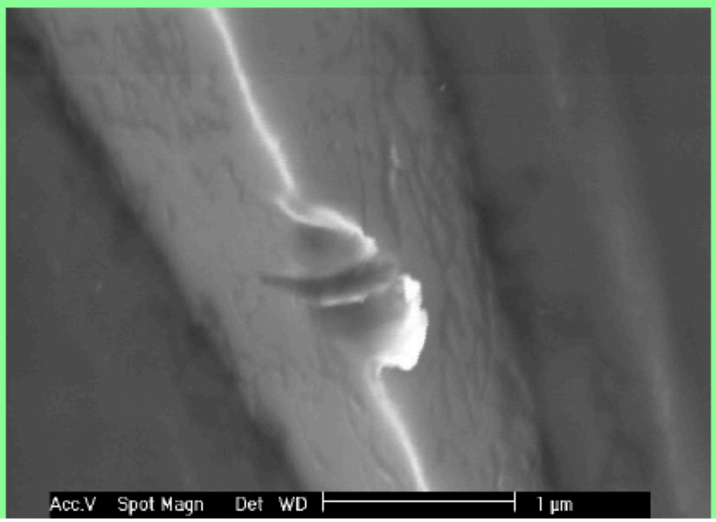
Guenter Mueller

Uses Scanning Field Emission Microscope and SEM to find emitters in Nb.





E_{on}(2nA) < 60 MV/m
~500 µm long scratch
(mishandling of sample)

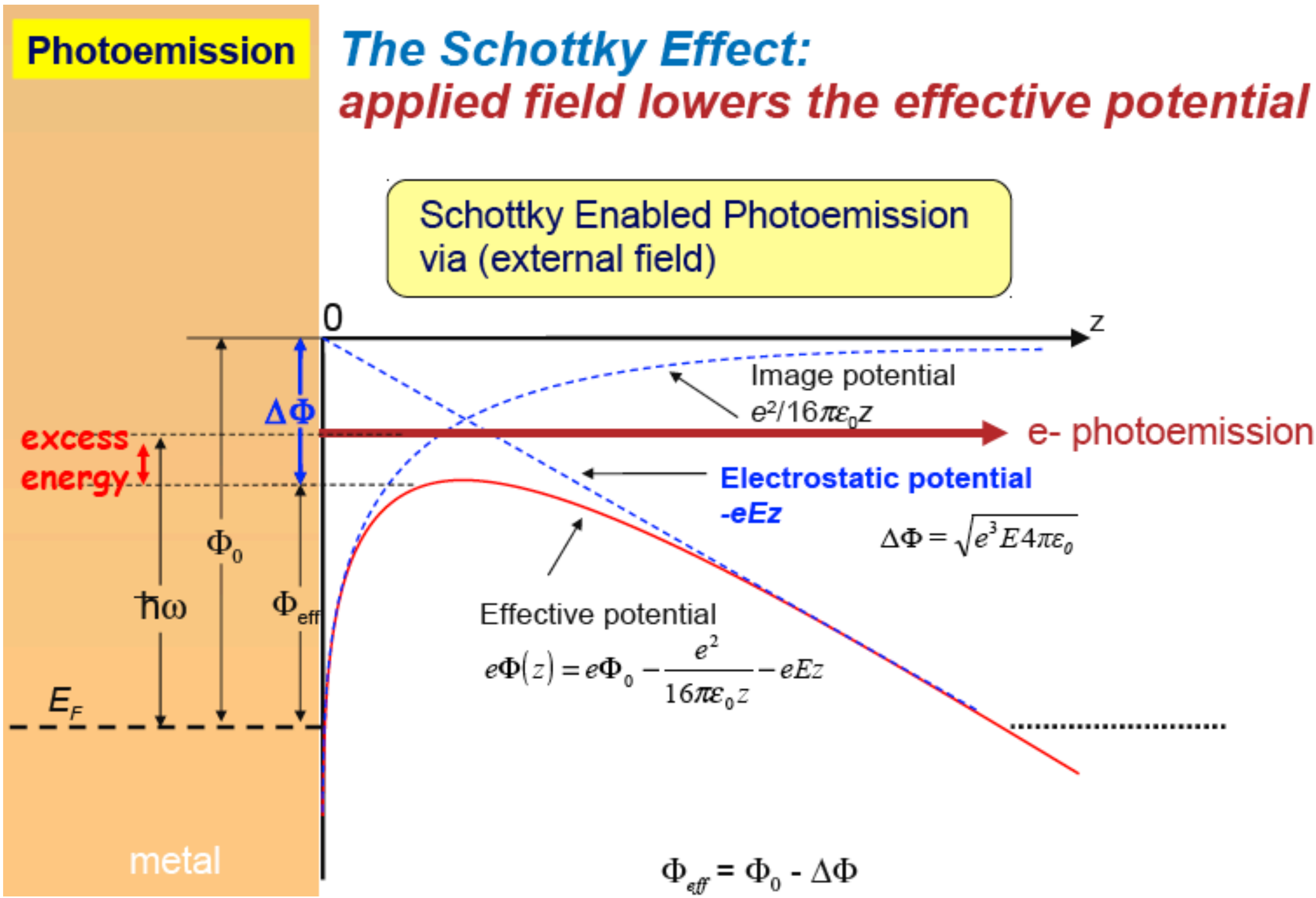


E_{on}(2nA) = 90 MV/m
~5 µm long groove
$\beta = 71$, $S = 2.3 \cdot 10^{-6}$ µm^2

E_{on}(2nA) > 140 MV/m
~1 µm small defect

John Power

Study of how photoemission and field emission interact.



Flavio Soldera ! !

Spark plugs

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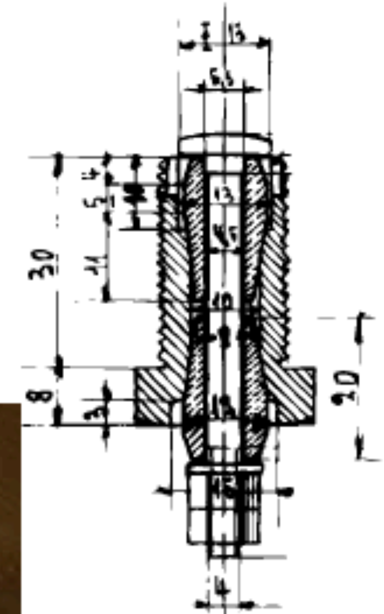
Lehrstuhl Funktionswerkstoffe

- 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)

Material Engineering Center Saarland (MECS)

Crates in multilayer systems

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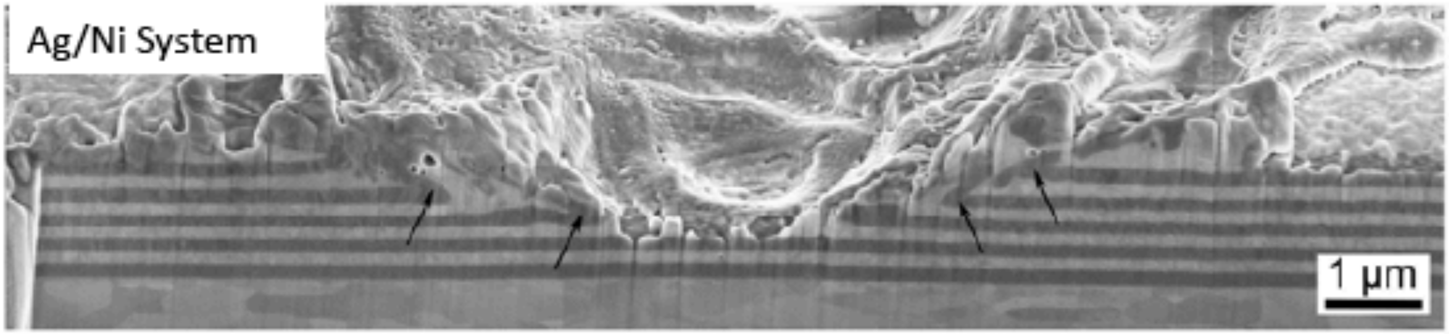
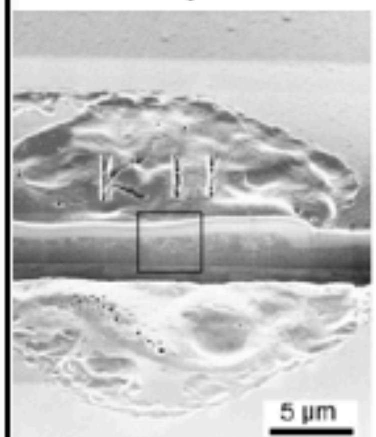
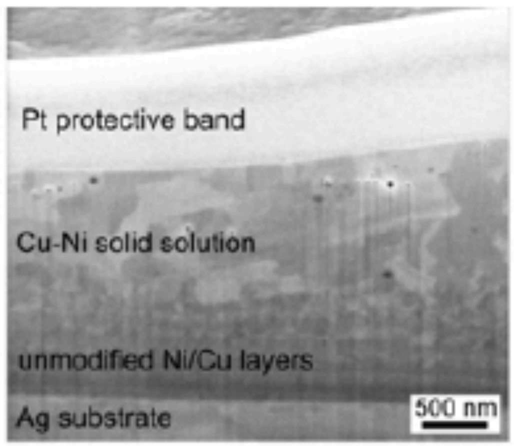
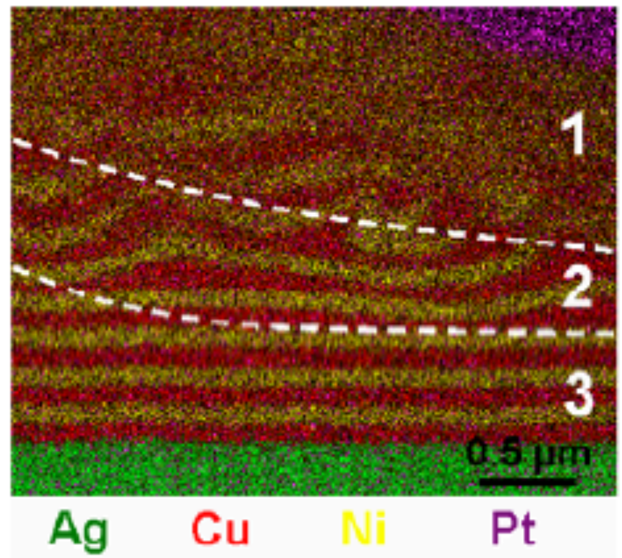
Ag/Ni System



Ni/Cu System







T>Tm(Ni)
1453 °C

T<Tm(Cu)
1083 °C

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

FIB-Tomography of craters

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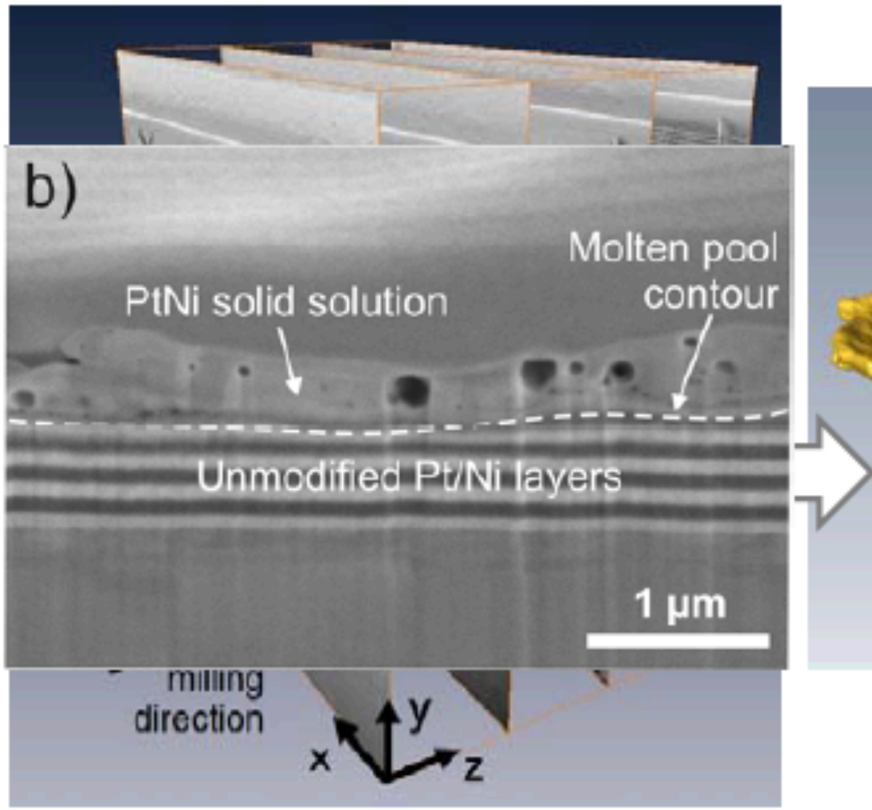
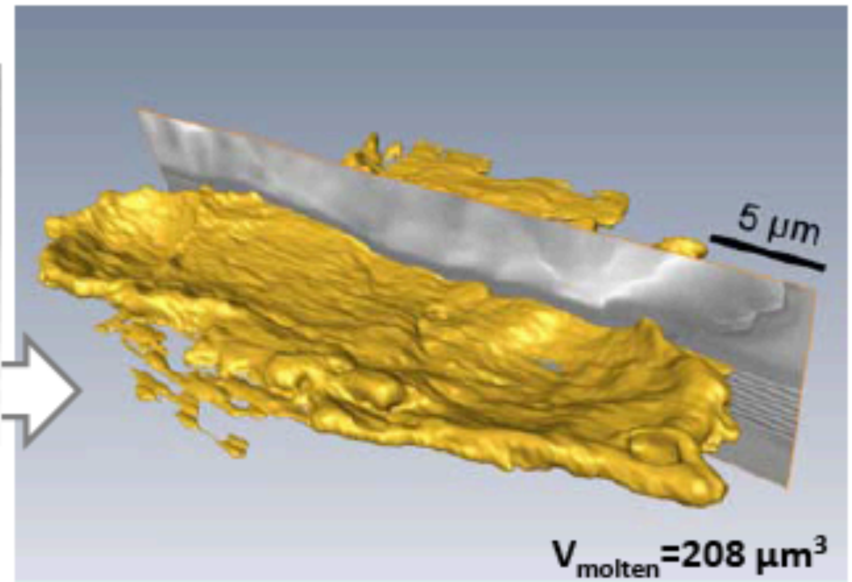


Serial cross sectioning of crater
200 slices

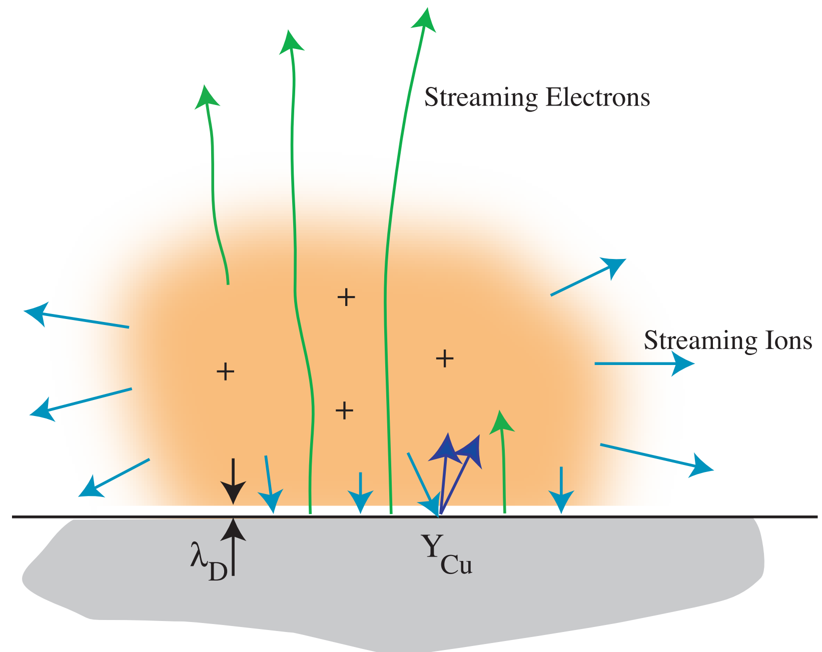


3D reconstruction of the molten pool
resolution ~100 nm

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

Zeke and I .

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

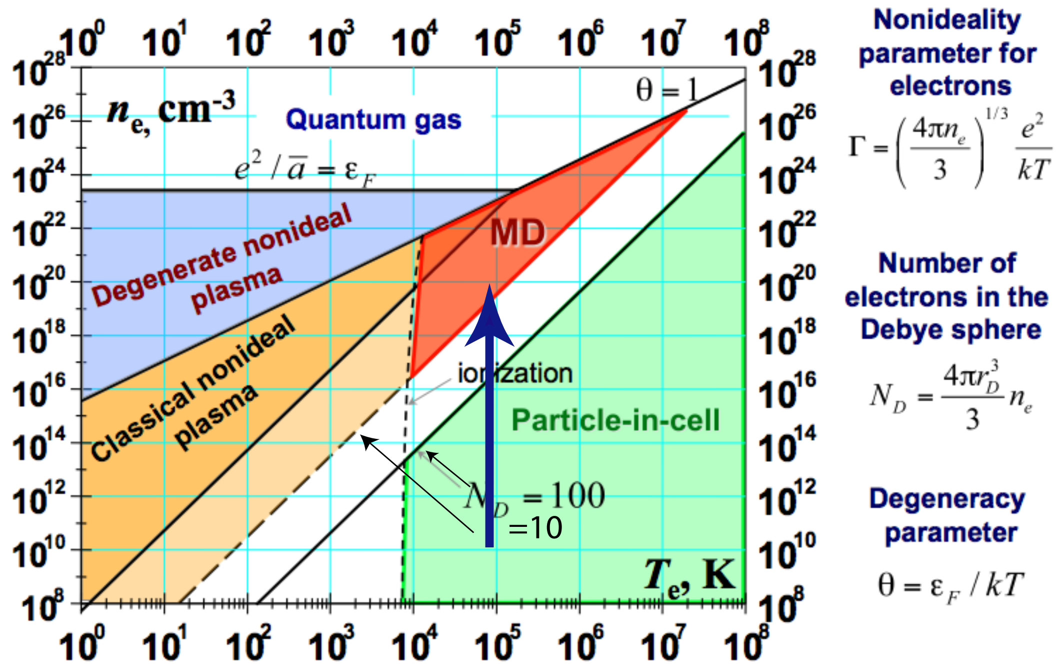


Defining parameters:
- Surface electric field
- Self-sputtering yield

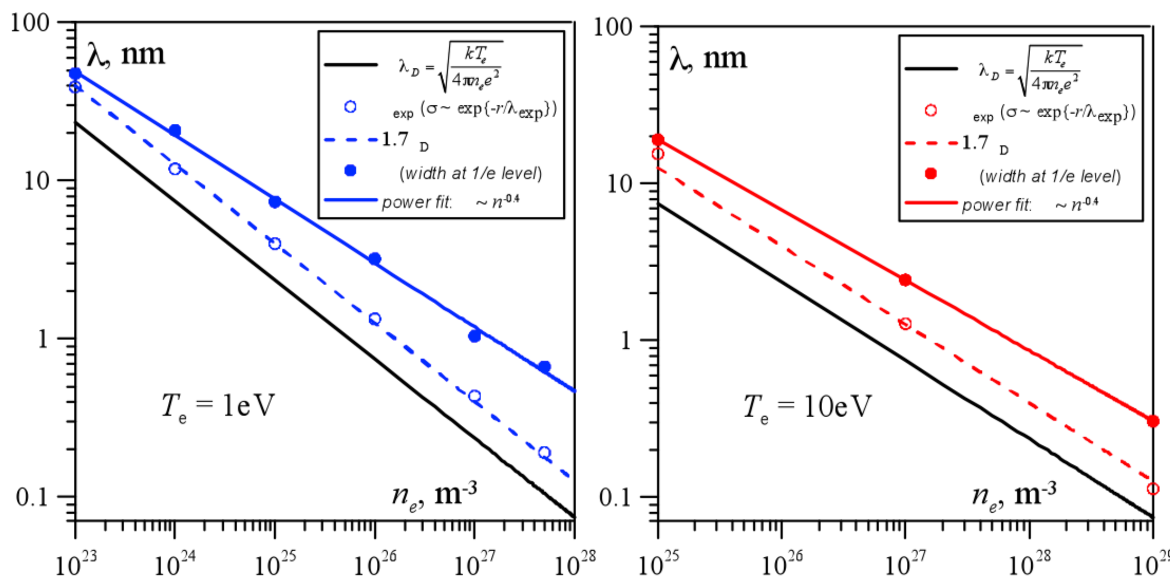
Typical parameters	Initiation	Burning
Plasma density	1E13 /m^3	1E24 - 1E26 /m^3
Sheath potential	50 V	75 V
Average surface field	20 MV/m	10 GV/m
plasma pressure	0	100 MPa
Debye length, λ_D	~1 μ	~1 nm
Surface temperature	~30°C	>1300 $^\circ$C
Self-sputtering yield	<1	~10
Arc power to surface	0	~1E12 W/m^2

We can understand the dense plasma / surface interaction.

We are using Molecular Dynamics to study the dense sheath.



The results are reasonable, and show how arc surfaces behave at high densities.



Summary

The effort is becoming more interesting.

More people, more approaches, more data.