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PAUL SCHERRER INSTITUT

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ELECTROMIGRATION

A Potential Precursor to Explain RF Breakdown in Accelerating Structures

CEA | Claire Antoine, F. Peauger
PSI | F. Le Pimpec

NIM A, 670, p. 79-94, 2012

MEVARC, Albuquerque NM, October 2012

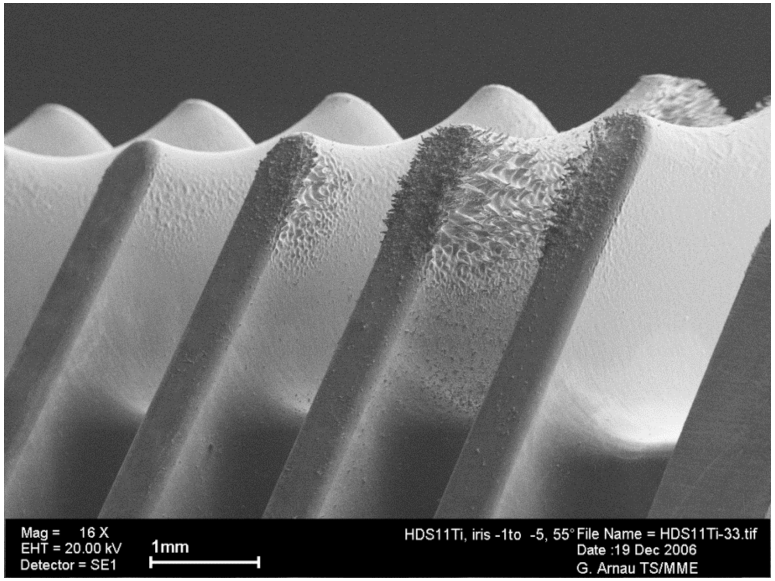
OUTLOOK

Accelerating structures

Toward higher gradients

Breakdown and post mortem cavities examination

Pulse heating, surface currents



Electromigration

Various BD mechanisms

Atomic diffusion; EM

Occurrences of EM

Interconnects/ Liquid Metal Emission Sources

Samples studies

Laser interaction w. surfaces

….

ACCELERATING STRUCTURES

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THE RACE TO COST EFFECTIVE HIGH GRADIENT ACCELERATING STRUCTURES

- Tomorrow's RF acceleration needs
  - Gradient in excess of 100 MV/m
  - Long structures (> 1m – ex: S-band 4m)
  - Higher frequencies (X-band, the K-bands)

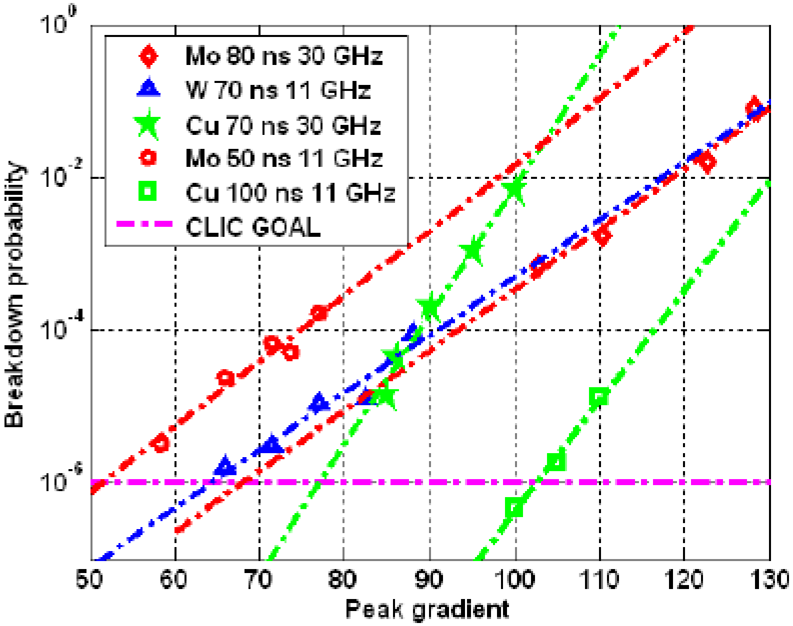
- The limitations
  - High gradient → Breakdown probability increases
  - High frequencies → Tighter machining tolerances

Next generation Lepton Collider (multi TeV range) must be cost effective

- Linear collider (limit losses by SR)
- More efficient conventional acceleration scheme (RF)
- New accelerating techniques (plasma, laser,…)

CLIC – LOWERING THE BREAKDOWN PROBABILITY

S. Döbert, The X-band Accelerating Structure Design and Test-Program Workshop, 19.6.2008

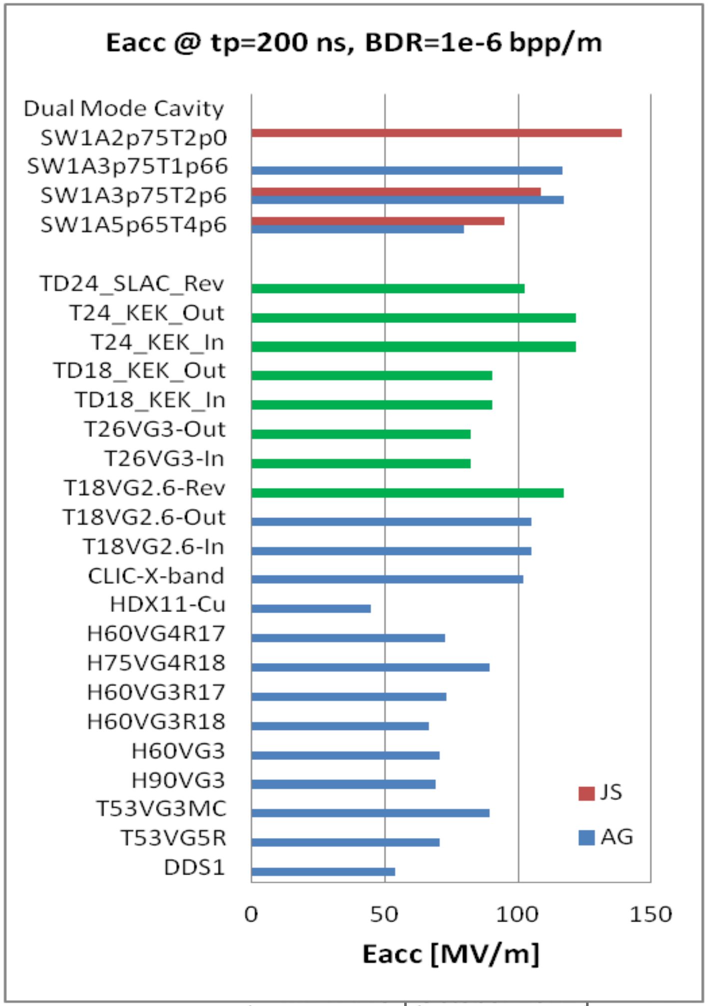


Change of frequencies, pulse length
Change of materials
Change of construction procedures
Change of designs (length, type…)

A lot was done and more has still to be done

Scaled data to 200 ns, 1e-6 bpp/m

A.Grudiev (LCWS11, Granada, September 2011)



~t

JS = Jiaru Shi; AG = Alexej Grudiev

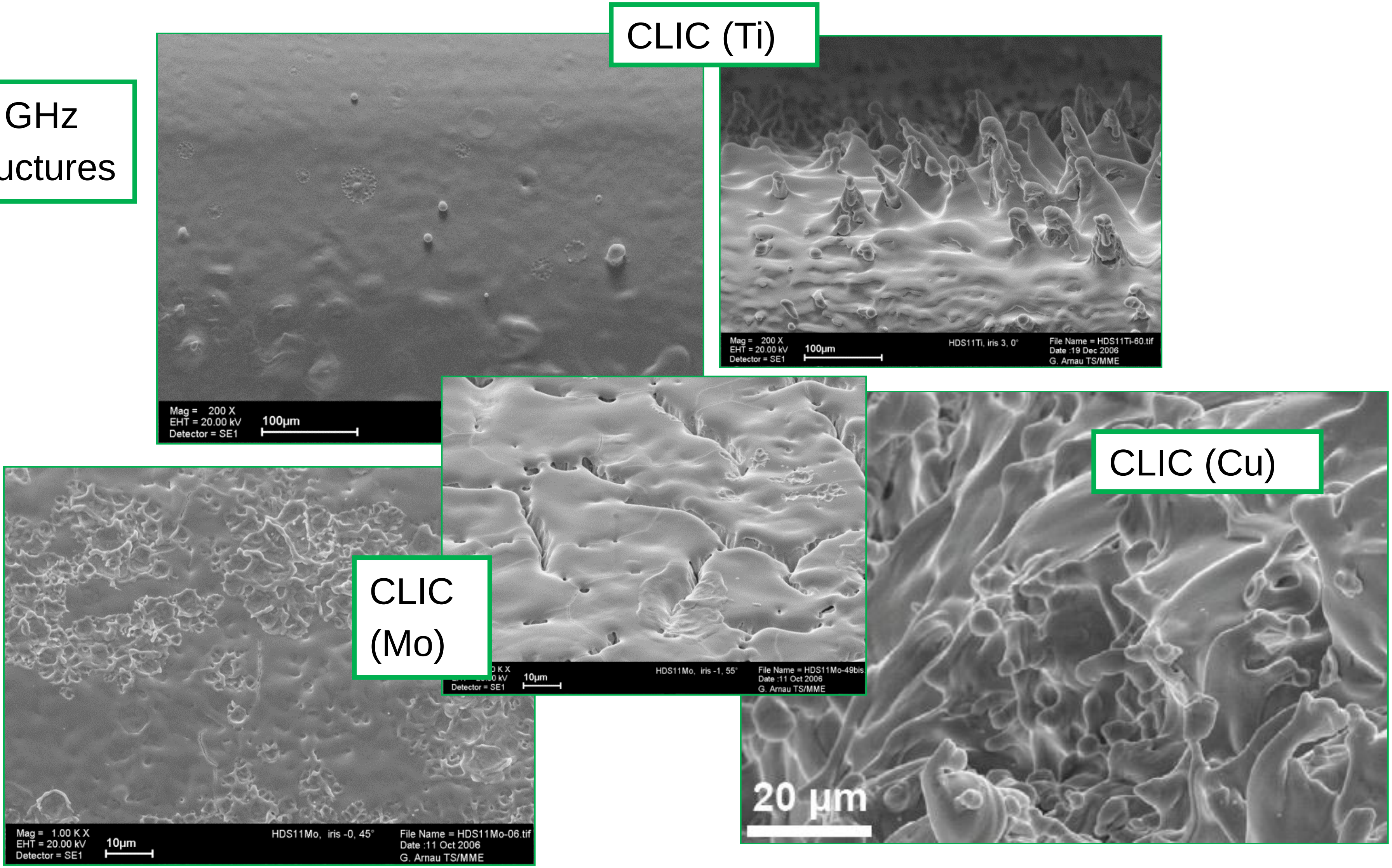
POSTMORTEM OBSERVATION: MELTED SURFACE ?

30 GHz structures

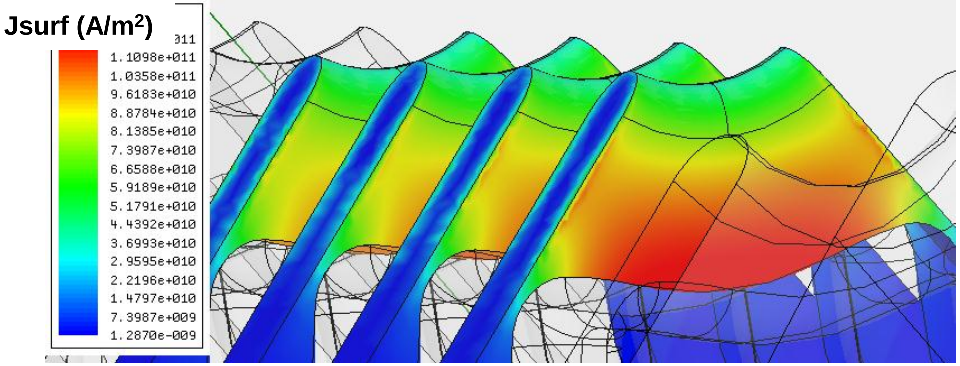
CLIC (Ti)

CLIC (Mo)

CLIC (Cu)



PULSE HEATING AT 30 GHZ (MODELING BY F. PEAUGER)



30 GHz structures, Ti

E_{acc} ~ 90 MV/m 1st cell

(~160 MV/m @ surface)

70 ns pulses every 200 ms

Losses included

Similar current densities :

⇒ J ~ 10^{11}A/m^2, ΔT ~ 700 ° C for Ti

Tm =1668 °C

⇒ J ~ 5.10^{11}A/m^2, ΔT ~ 20 ° C for Mo

Tm =2623°C

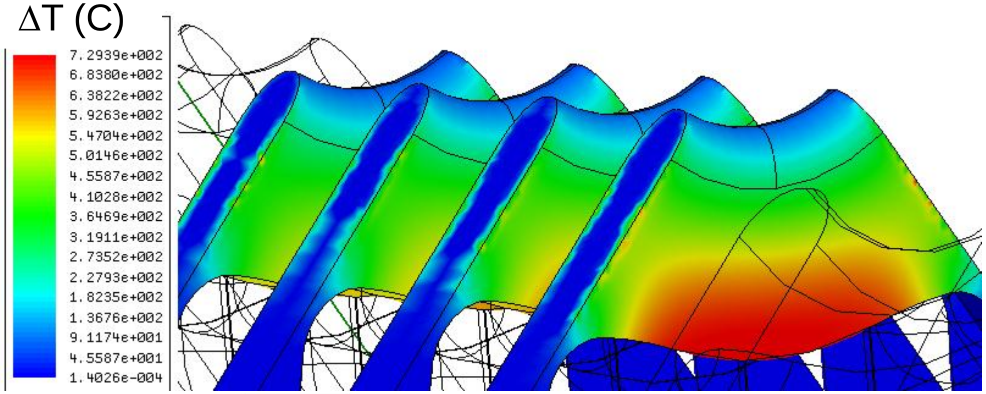
⇒ J ~ 10^{12}A/m^2, ΔT ~ 20 ° C for Cu

Tm =1084°C

RF + thermal : not sufficient to explain observations…

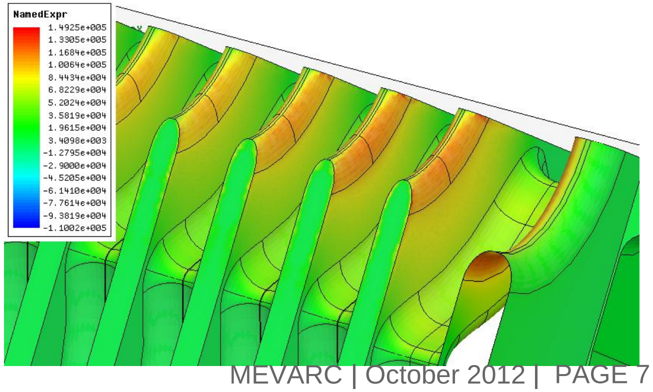
But current densities…. Yes ?

(See electromigration §)



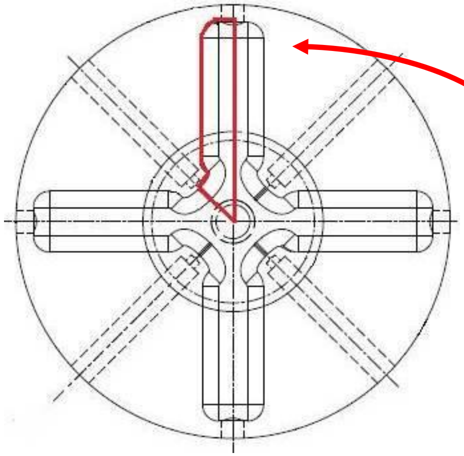
Lorentz forces

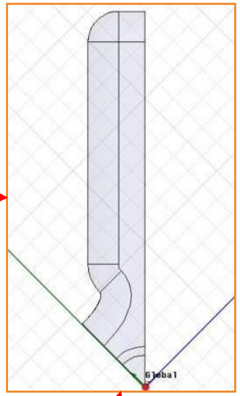
(MPa)



Ti example

PULSE HEATING AT 12 GHZ (MODELING BY F. DEPAYRAS)





12 GHz structures, Cu

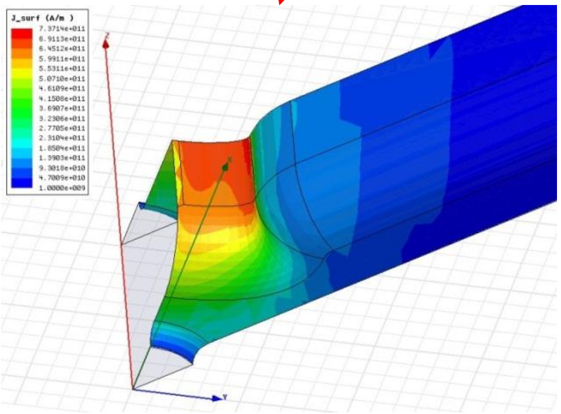
E_{acc} ~ 90 MV/m 1st cell

(~155 MV/m @ surface)

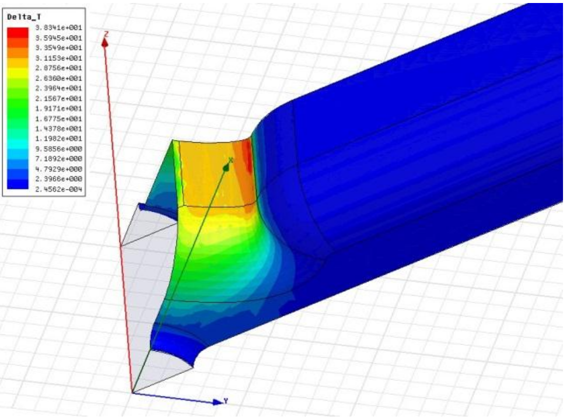
200 ns pulses every 20 ms

Losses included

J_{max} ~ 10^{12}A/m^2



ΔT $_{max}$~ 40 °C for Cu



J : Same order of magnitude as @ 30 GHz….

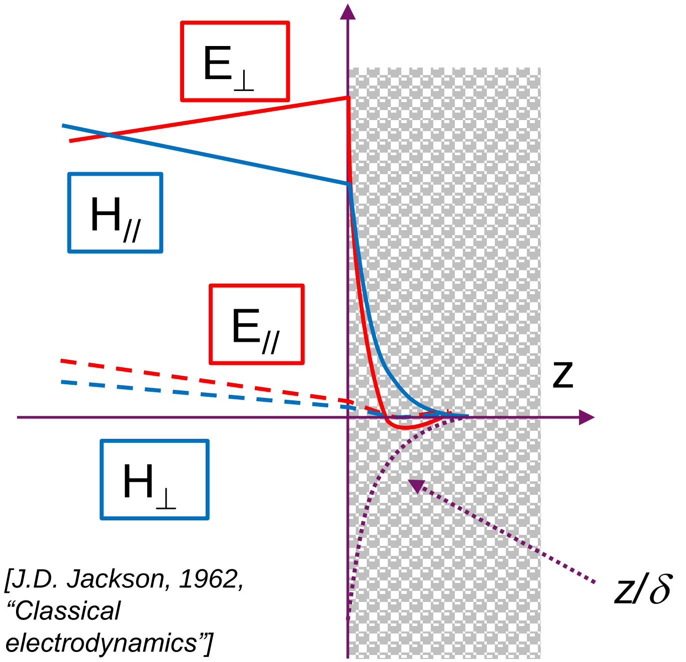
(only B losses !!!!)

EFFECT OF ELECTRICAL FIELD

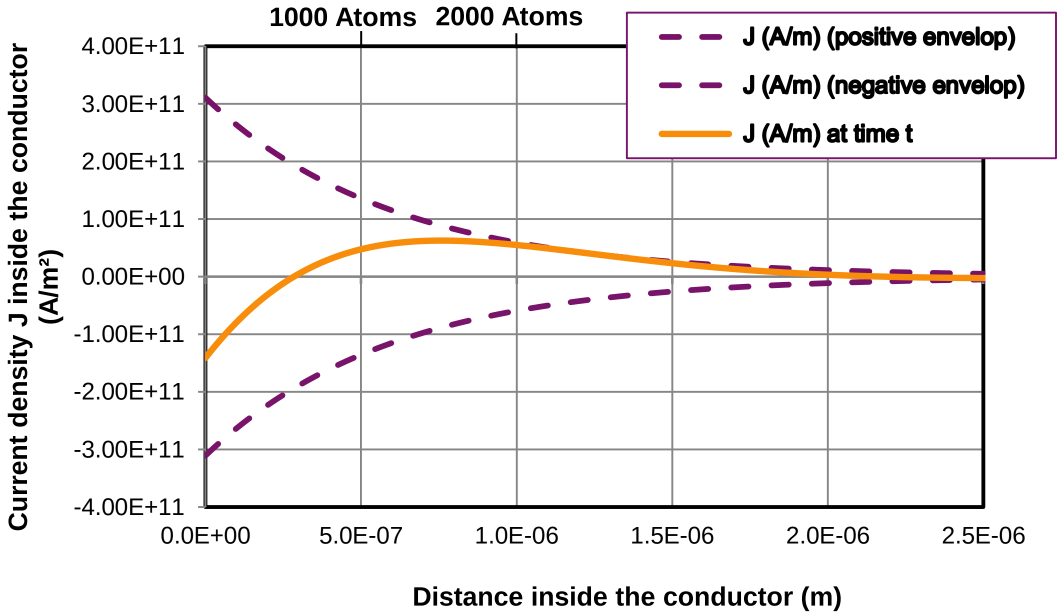
Metallic surface submitted to both electric and magnetic field

Electric field also penetrates non-perfect metals

$$J(z)=\sigma E(z)=\sqrt{\frac{\mu_c\omega\sigma}{8\pi}}(1-i)(n\otimes B_{//})e^{-z(1-i)/\delta}$$



[J.D. Jackson, 1962, "Classical electrodynamics"]



Copper:

- δ ~ 380 nm, σ ~ 58 x 10^6 S/m, ∅ ~ 0.25 nm
- At 373 K mean free path for electrons ~30 nm (120 atoms)
- Time between 2 collisions ~10^{-14} s

Huge current density => high probability of collisions e^--atoms =>high probability of atomic migration

ORIGIN OF SURFACE MELTING ?

- Surface appear to be molten over several mm^2
- In some case arrays of Taylor cones are formed
  - Field emission
  - Dark current
  - Breakdown
- Localized field emitters + overlapping crater cannot explain such uniform melting
- RF pulse heating is not enough to reach melting temperature of metals
- Urgent need to:
  - look at other situations with surface under high field !
  - look closer to surface properties

BD SCENARIOS

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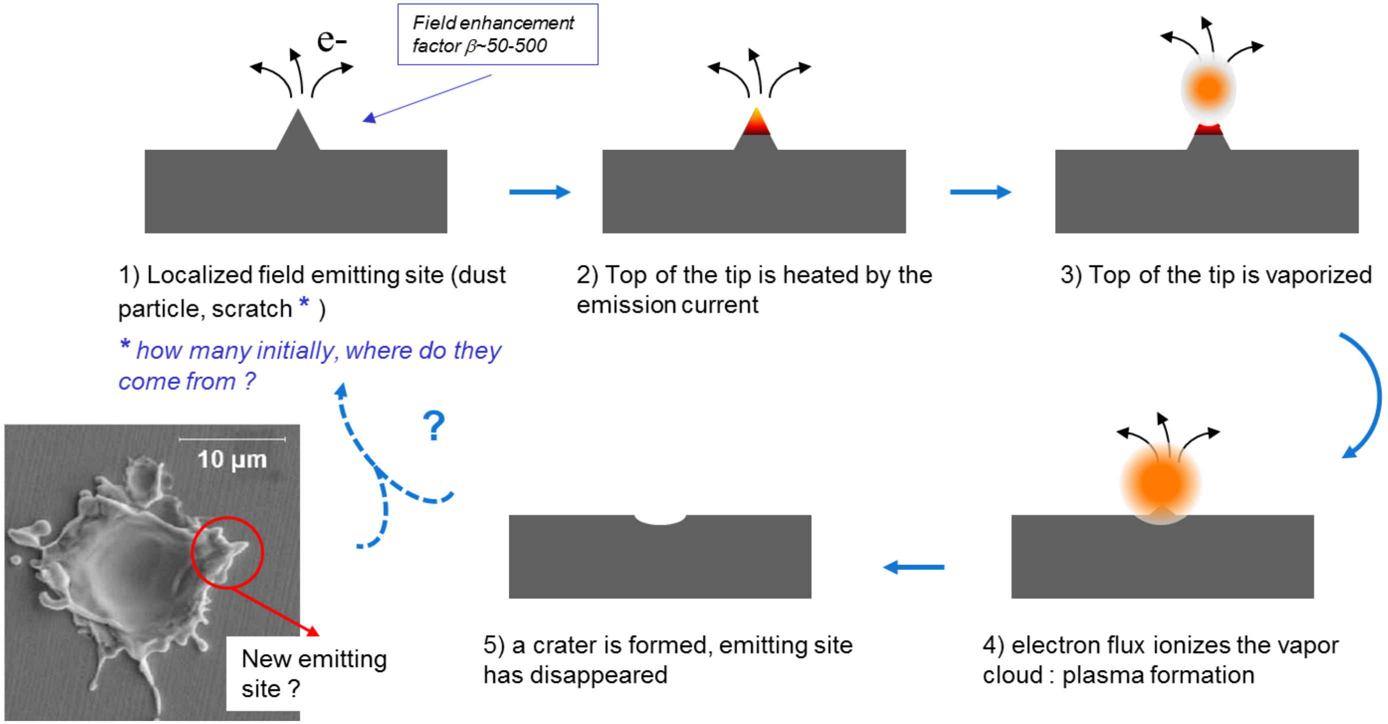
RF BREAKDOWN : A SURFACE PROBLEM
(“ The Standard Model ”)

- Existence of a defect at the surface → FE → Explosive emission



1) Localized field emitting site (dust particle, scratch *)

** how many initially, where do they come from ?*

2) Top of the tip is heated by the emission current

3) Top of the tip is vaporized

4) electron flux ionizes the vapor cloud : plasma formation

5) a crater is formed, emitting site has disappeared

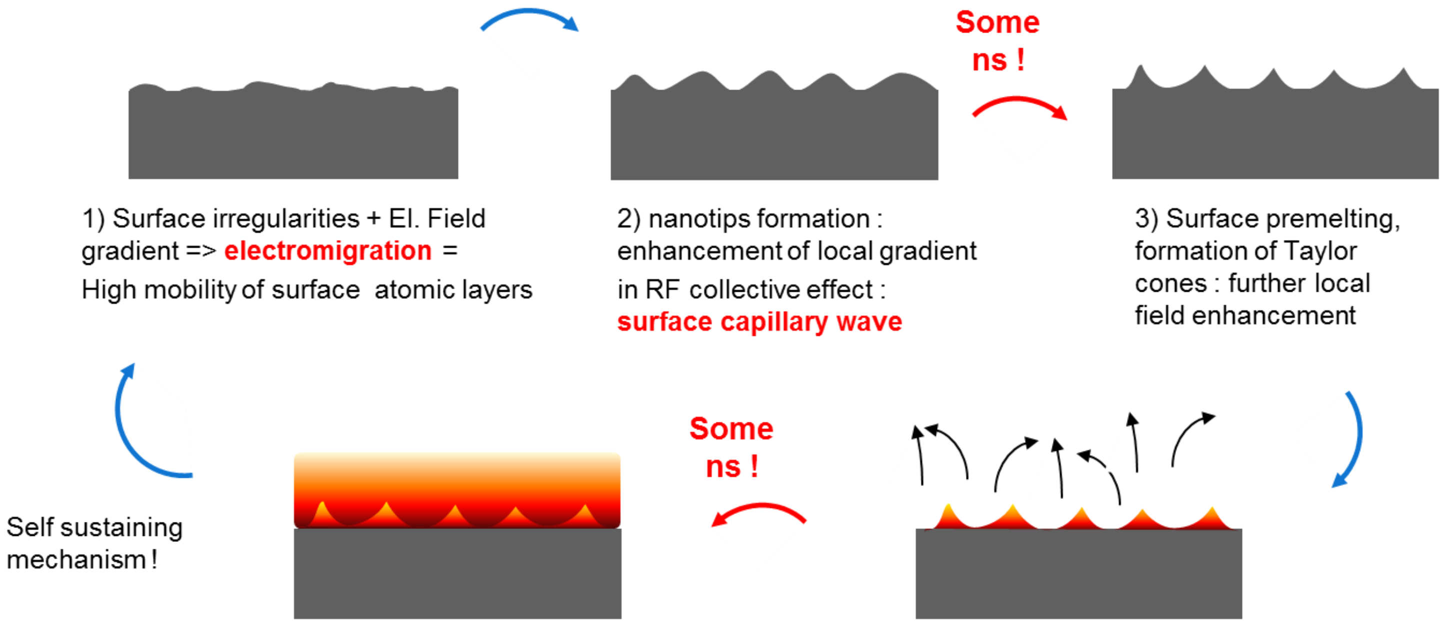
New emitting site ?

- Where do those initial emitters come from ?
- How to explain large melted areas (some 100 µm ∅) without craters?

RF BREAKDOWN : A SURFACE PROBLEM

(An Alternative to the “ Standard Model ”)

Model in use in the LMES/LMIS



1) Surface irregularities + El. Field gradient => **electromigration** = High mobility of surface atomic layers

Some ns !

2) nanotips formation : enhancement of local gradient in RF collective effect : **surface capillary wave**

3) Surface premelting, formation of Taylor cones : further local field enhancement

4) arrays of field emitters

In accelerators => heavy dark current

Some ns !

5) Explosive emission regime :

In accelerators => sustaining dark current and breakdown

Self sustaining mechanism !

- Breakdowns happen on apparently defect free and “clean” surfaces
- On the dimension considered : perfect flat surfaces don’t exist
- Electromigration triggered by high current densities and/or field gradients
- RF: possible contribution via collective effects

ELECTROMIGRATION

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ATOMIC DIFFUSION => ELECTROMIGRATION

- Diffusion and its particular aspect, electromigration, are thermally activated processes :

$$\boxed{D(T) = D_0\, e^{-\frac{Ea}{RT}} = D_0\, e^{-\frac{Qa}{kT}}}$$

where the activation energy E_a is in J.mol^{-1} and Q_a in eV/atom

EM
Definition depends on
Community !!!
Here: any case with E,
and/or I and/or current
induced thermal
gradient

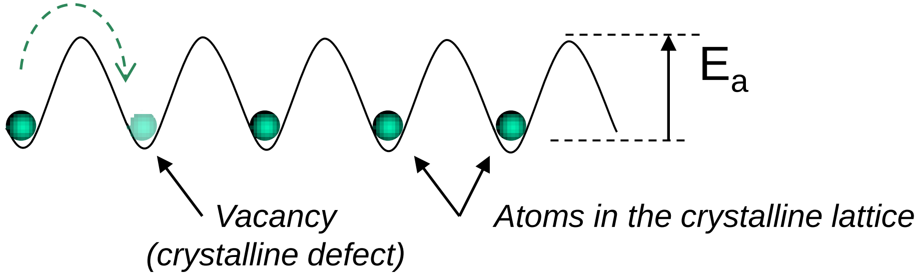
- Self diffusion :

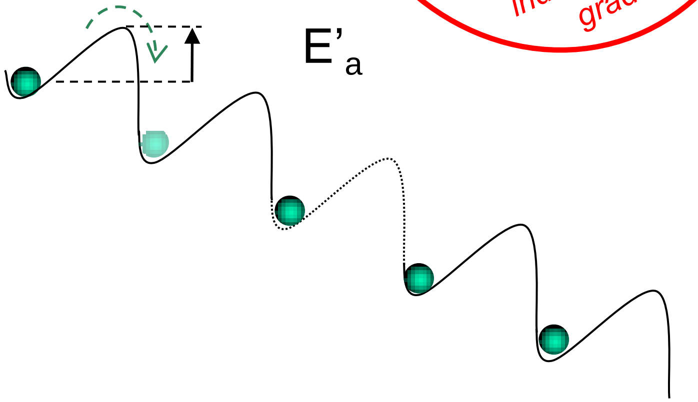
Bulk	Ea (J.mol^{-1}) ~ 146.5 Tm
Surface	Ea (J.mol^{-1}) ~ 55.4 Tm

where Tm is the melting temperature of the metal in K

typical pre-factor D_0 have values around 10^{-2}-10^{-3}cm^2.s^{-1}

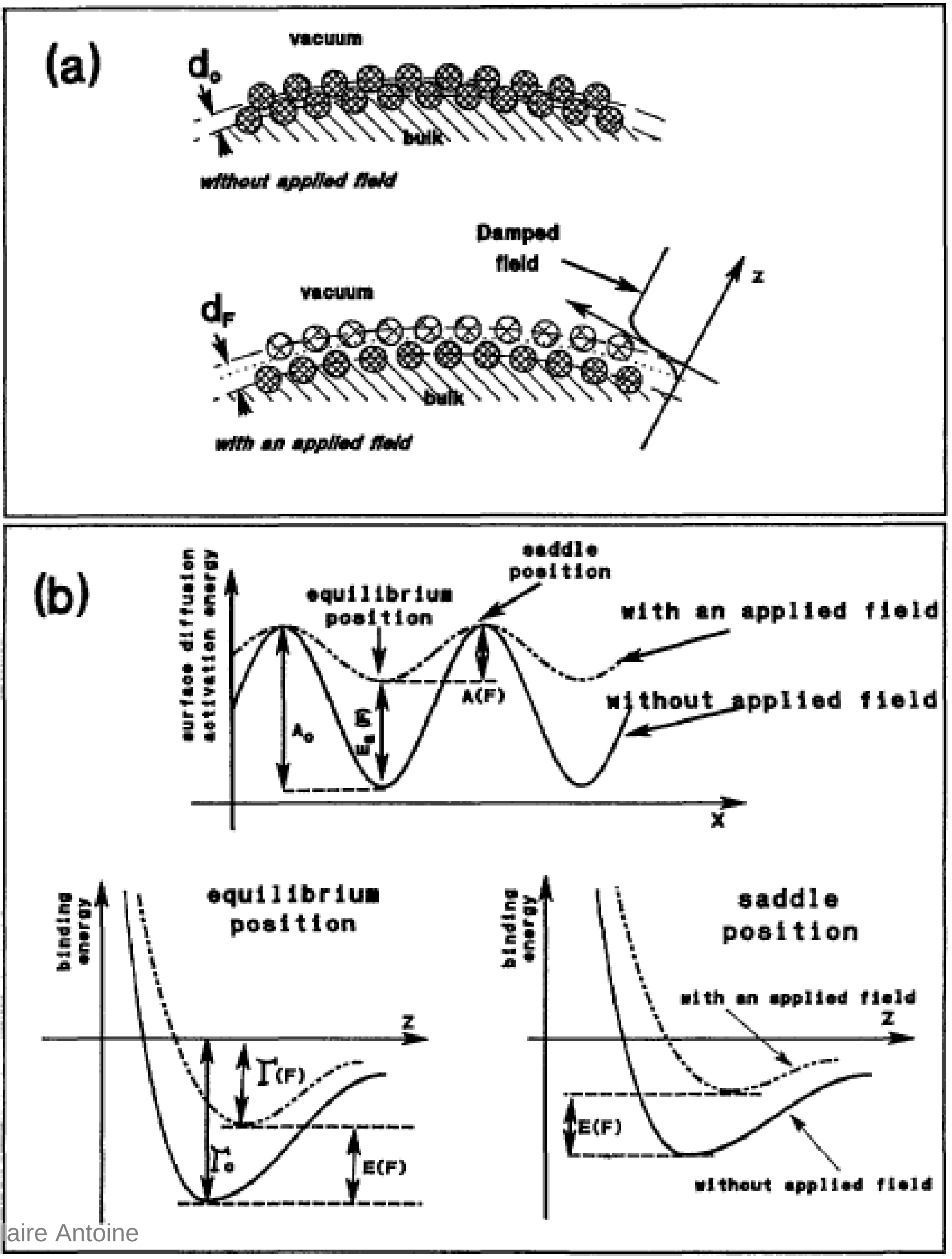
- Effect of el. Field => further decrease of Ea





Field
Current
Thermal

$\}$ *gradients => preferential diffusion direction*



V.T. Binh and N. Garcia, "Atomic metallic ion emission, field surface melting and scanning tunneling microscopy tips".

Journal de Physique I, **1991**. **1**(5): p. 605-612.

W @ 80 K and DC 0.4 V/Å (4GV/m):

- Ea decreased from 3eV to 0.7 eV
- D(80K)~ $2x10^{-5}$ cm^2/s

  => Surface is melted !!!

Tm (W) ~3680 K

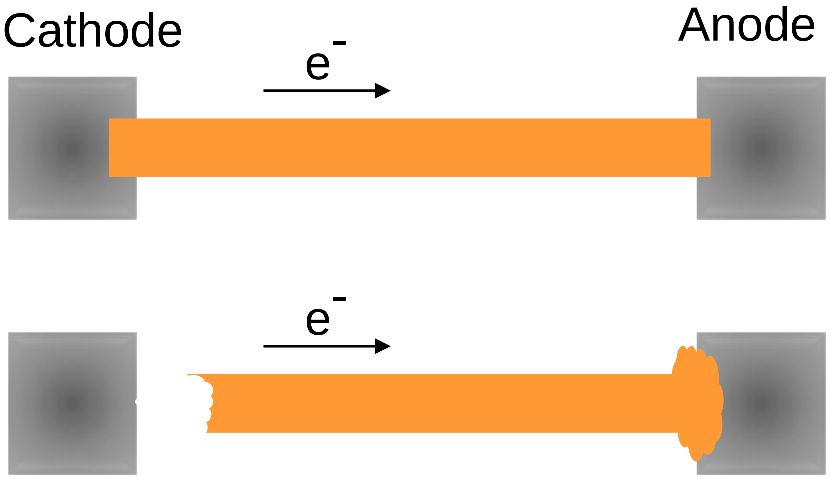
See also J.G. Dash
Surface melting
Contemporary Physics
Volume 30, Issue 2, 1989

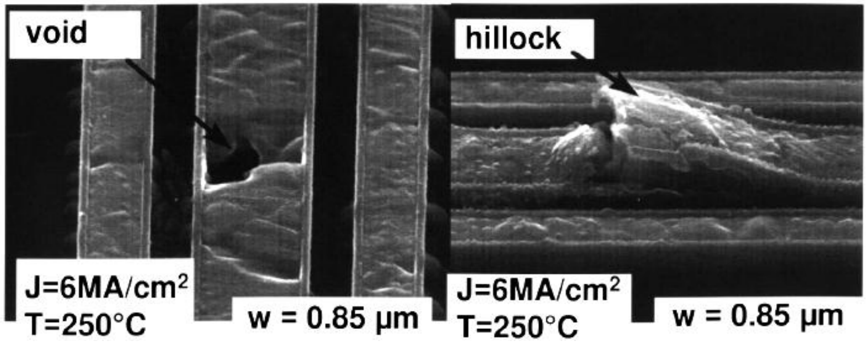
ELECTROMIGRATION OCCURRENCES

Technique	**Field range**	**Current density range**	**Temperature range**	**Comments**
CLIC (RF acceleration)	RF 100MV/m	10^{11}-10^{12} A/m^2	RT to some 100°C	**Heating negligible except in the case of Ti**
FIM/APT	DC 1-10 GV/m **100 MV/m**	~ 10^{-4} A/m^2	20-100K RT	**Electro-evaporation ~30 GV/m**
STM	DC Typical :1 GV/m Starts @ **100 MV/m**	~ 10^{-4} A/m^2	4.5 to RT	**Migration of the less attached atoms (surface, interstitials)**
Vaccum microelectronics, **LMES/LMIS**	DC : 1 GV/m RF : **100 MV/m**	10^{11}-10^{12} A/m^2	Starts at RT, heats up to several 100°C	**Surface melting observed @ 0.5-0.75 T_m**
Electromigration in electronic circuits	DC **<< 100 MV/m** 10-50 V/m	10^{10}-10^{11} A/m^2 Starts @ 10^{8} A/m^2	2-300°C	**In RF once a void is created, it can only increase**
Metallic powder sintering	**<< 100 MV/m** 10 V to MV !	not measurable	Current is used to get surface melting	**RF faster than DC : diffusion increases**

RF makes it worse !?

ELECTROMIGRATION IN µELECTRONICS CONNECTORS





A void and a hillock generated by electromigration.

- Momentum transfer from e-, atoms/ vacancies jumps activation energy lowered /E, …
- Influence of interfaces (enhanced diffusion @ GB, voids @ triple points, interaction w. dielectric defects @ surface …)

Starts @ 10^8 A/m^2 (10^4 A/cm^2)
Typical : 10^{10}-10^{11} A/m^2, 200-300°C, low E. field, DC

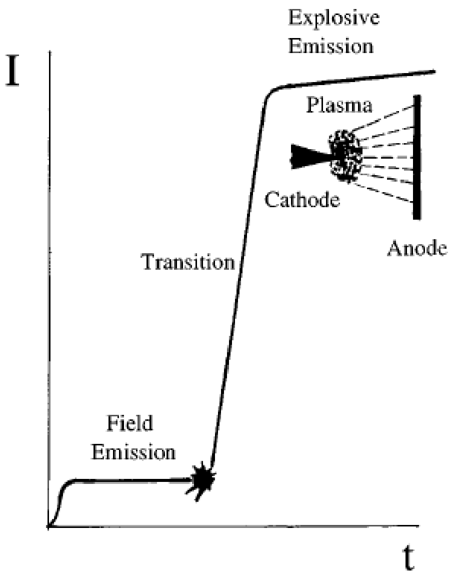
- **RF vs DC : less efficient, but** …
  - breakdown* occurs via thermal gradient, rather than momentum transfer
  - once a hole ∃, it can only ↑↑ ($\text{Mobility}_{\text{vacancies}} \neq \text{Mobility}_{\text{atoms}}$)

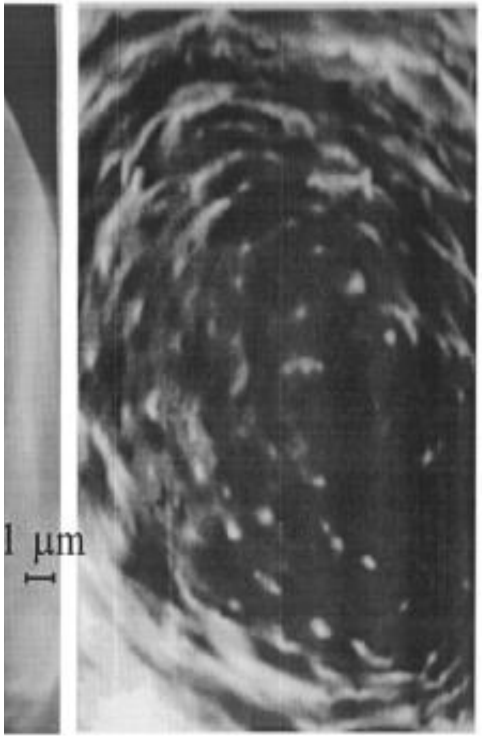
** i.e. breaking of the connection*

LIQUID METAL FIELD EMISSIONS SOURCES

- Needle recovered w. a thin Bi-Sn-Pb (low Tm) in a prismatic resonator (4.7 Ghz) :
- High ν : TMI (Thermocapillary modulation instability) develop.
- In the explosive emission regime, the surface is “liquid”.
- An array of nano-tips is formed (Taylor cones)

G.N. Fursey, "Field emission processes from a liquid-metal surface". Applied Surface Science, 2003. 215(1-4): p. 113-134.





“… explosive emission can be excited on Liq. metal in RF field @ field strength 10 fold less than in pulsed field…” !!!!

LIQUID METAL FIELD EMITTER/IONS SOURCES

Field emission in AC field

Without plasma !!!

Before

After

Stainless Steel

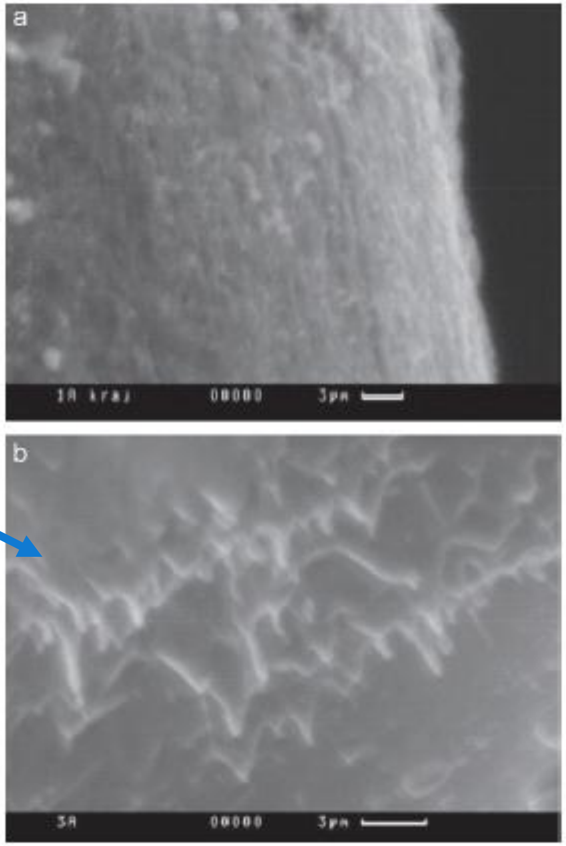


Fig. 3. A surface of the stainless steel before (a) and after (b) field emission experiment.

Evidences of surface melting BEFORE* explosive emission regime :

A.V. Batrakov, D.I. Proskurovsky, and S.A. Popov, "Observation of the field emission from the melting zone occurringjust before explosive electron emission". *IEEE Trans. on Dielectrics and Electrical Insulation, 1999.* ***6(4): p. 410-417.***

G.N. Fursey, et al., "Specific features of field emission from submicron cathode surface areas at high current densities". *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures, 1998.* ***16: p. 232.***

E.O. Popov and A.A. Pashkevich, "The field emission in the alternative electric fields". *Ultramicroscopy, 2007.* ***107(9): p. 838-843.***

Relation between surface melting, microtips formation and Breakdown ?…

LIQUID METAL FIELD EMITTER/IONS SOURCES 2

Even high melting temp metals…

Copper

(T_m~ 933 K)

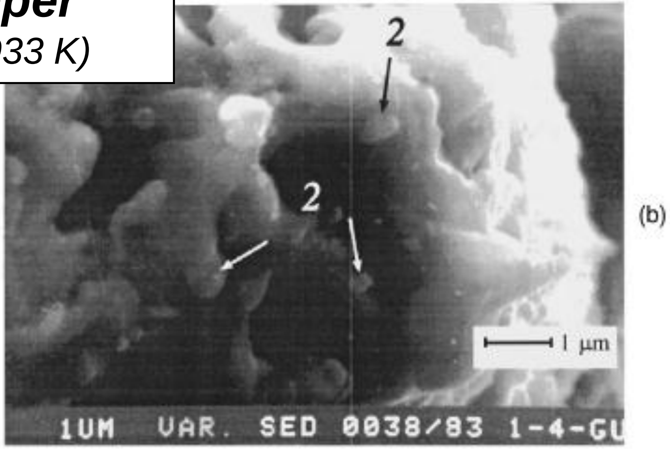


FIG. 13. Nanometer tips on Cu formed during explosive emission at 4.2 Discharge voltage 20 kV, duration 20 ns. (1) Big microprotrusions and nanometer tips.

Graphite

(T_m~ 4000 K)

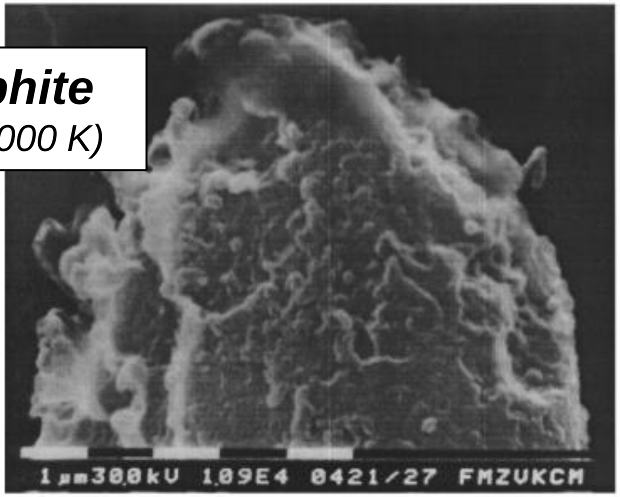


FIG. 14. Generation of the nanometer protrusions on the liquid graphite surface melted by explosive–electron emission.

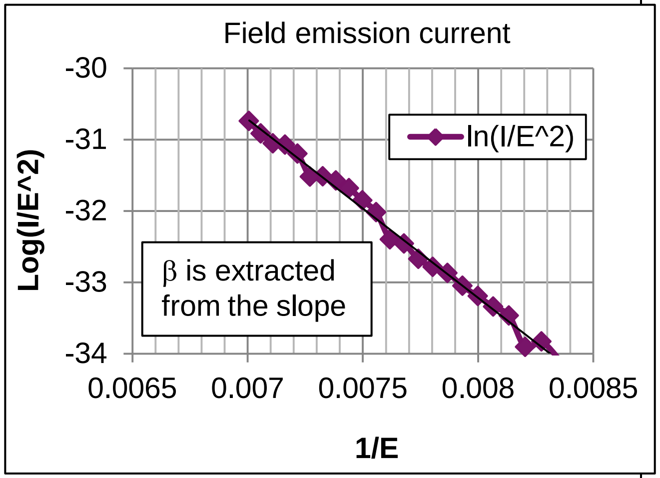
*Nano-protuberance form on **W** @ ~1700 K (Tm =2896 K)…*

*i.e. **>1000° C below melting temperature !***

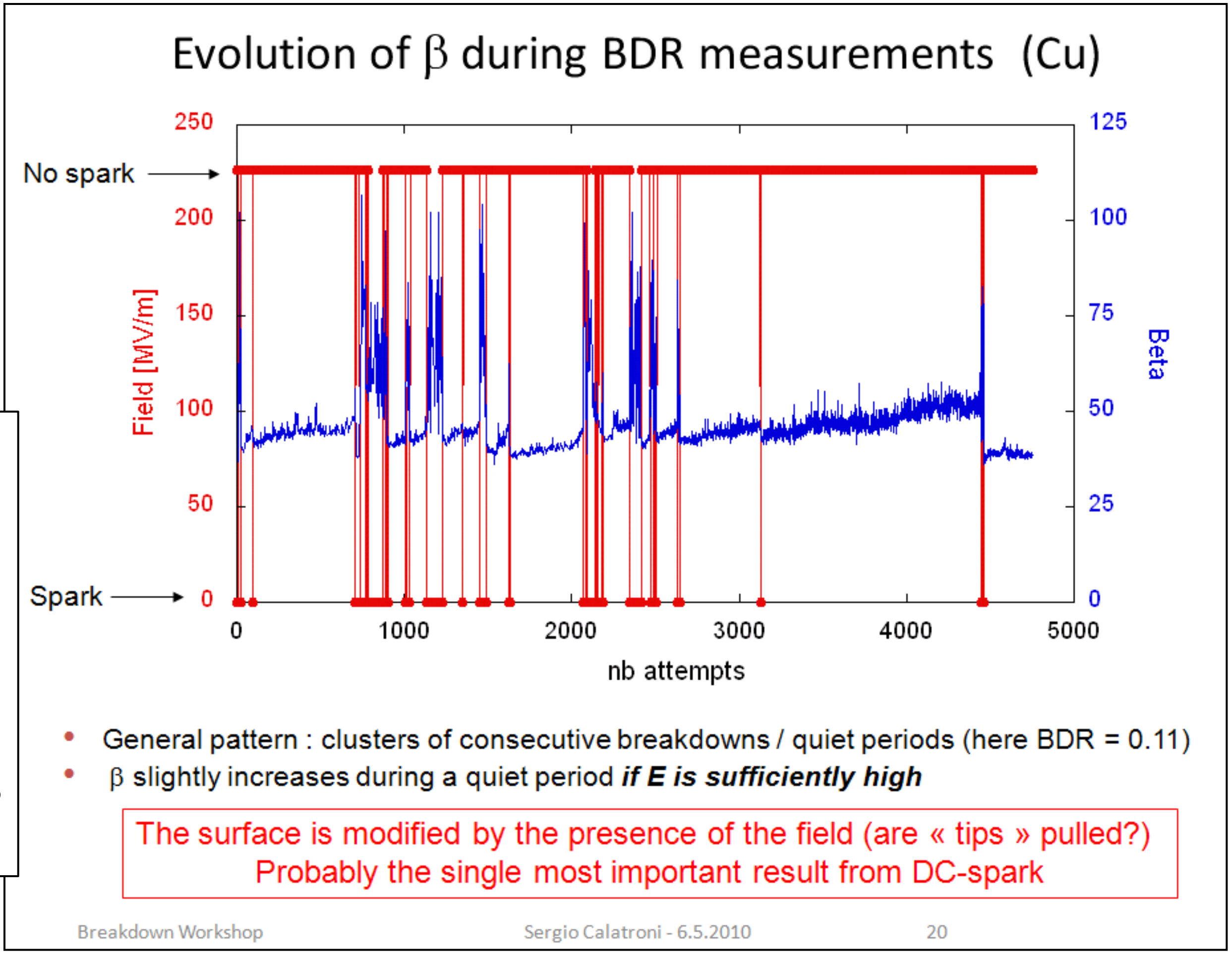
ELECTROMIGRATION AND BREAKDOWN

DC breakdown measurements
Courtesy from S. Calatroni CERN

http://indico.cern.ch/getFile.py/access?contribId=13&sessionId=1&resId=0&materialId=slides&confId=75380



β is extracted from the slope



Evolution of β during BDR measurements (Cu)

- General pattern : clusters of consecutive breakdowns / quiet periods (here BDR = 0.11)
- β slightly increases during a quiet period ***if E is sufficiently high***

The surface is modified by the presence of the field (are « tips » pulled?)
Probably the single most important result from DC-spark

Breakdown Workshop Sergio Calatroni - 6.5.2010 20

Cu:

- Breakdown as soon as $\beta > 48$ $(\leftrightarrow \beta \cdot 225$ MV/m > 10.8 GV/m)
- Consecutive breakdowns as long as $\beta > \beta_{threshold}$

SAMPLES STUDIES WITH HIGH ELECTROMAGNETIC FIELDS

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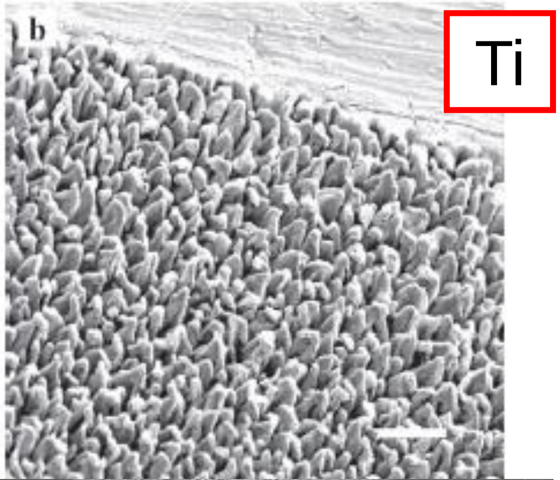
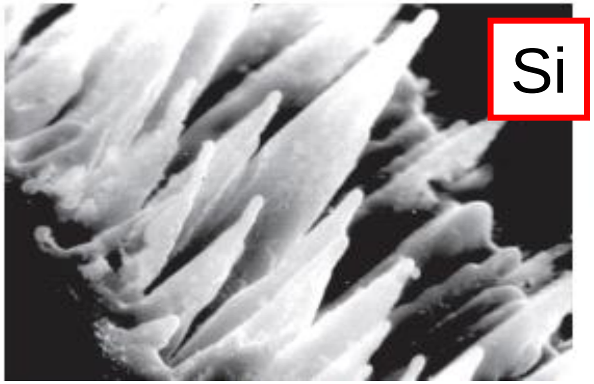
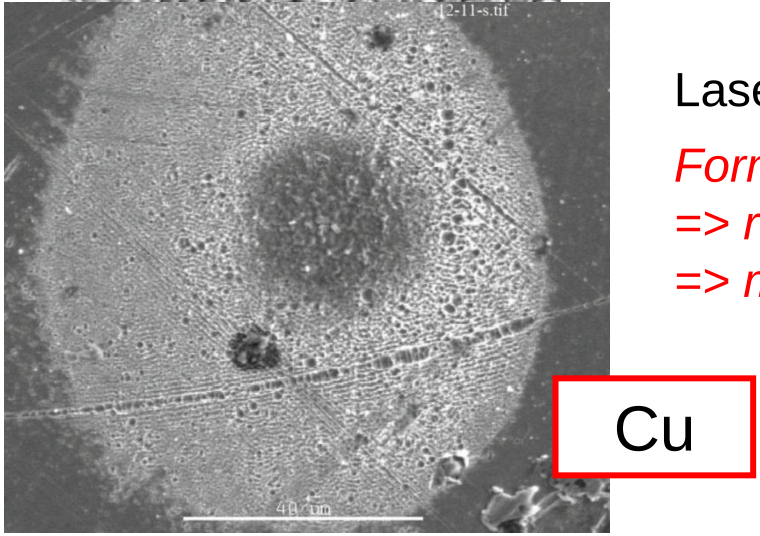
HIGH FLUX LASER IRRADIATION



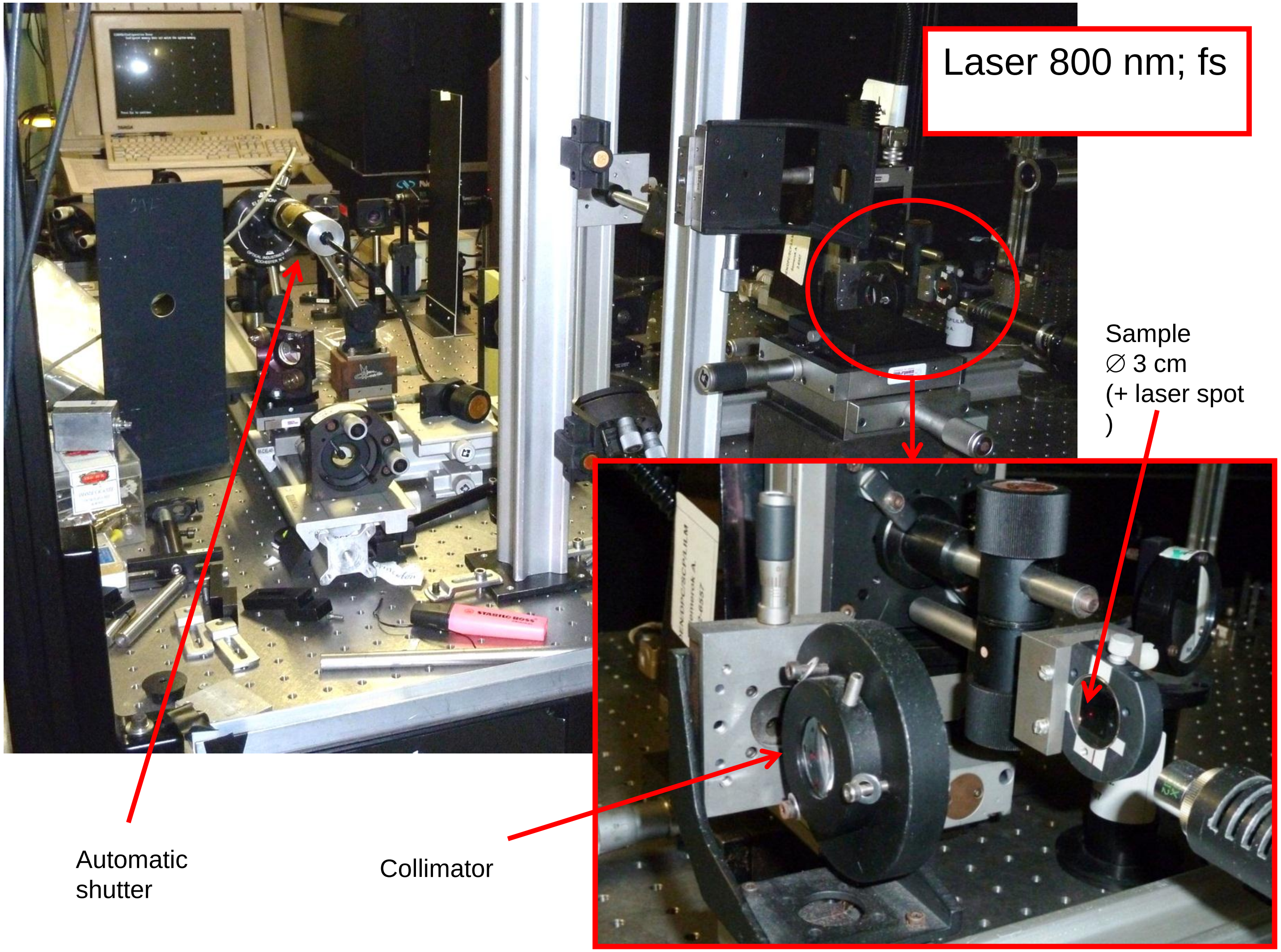




Laser beam : high electric (EM) field

Formation of multiple microtips // beam axis
=> role of Poynting vector ?
=> material testing possibilities?

LASER SET-UP



Laser 800 nm; fs

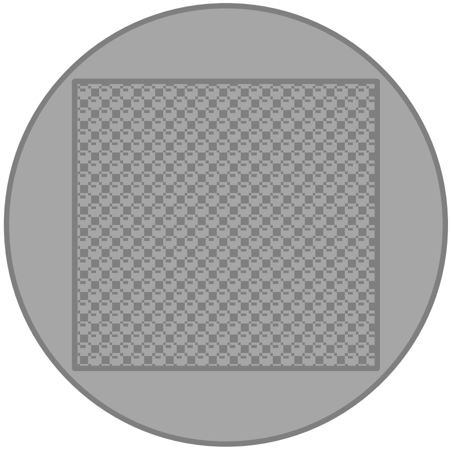
Sample
∅ 3 cm
(+ laser spot
)

Automatic
shutter

Collimator

SIMPLE SAMPLE EXPERIMENT

	Cavités RF »chaudes »	Lasers
frequency	λ ~1cm, ν ~ 10^{10}Hz	λ ~800 nm, ν ~ 10^{14}Hz
Pulse legngth	200 ns	Some fs to some µs
Repetition frequency	20 ms	On demand
Field geometry	E⊥ surface, B // surface NB : progressive wave : reduced Poynting vector ⊥ surface	E, B ⊥ beam axis : with out of plane incidence => E⊥ surface component



- Sample ~ ∅ 3 cm
- ∅ laser spot ~10 µm
- 1 shot every 50-100 µm (automatic displacement)
- => Allows testing numerous conditions : deposited energy, energy density , number of pulses, various polarizations, beam angle…
- Can be done under Argon, vacuum needs specific chamber
- Surface characterization with microscopy and profilometry…

PROPOSED IMPROVEMENTS (MATERIAL POINT OF VIEW)

1. Clean conditions, HPR => reduced field emission
2. Soft surfaces (electropolishing after machining => reduced field enhancement, reduced particle retention, reduced damage on the surface).
3. Alloying => reduced diffusion
4. Monocrystalline materials => reduced diffusion at GB
5. Capping (e.g. Al_2O_3) => reduced secondary emission, reduced diffusion
6. REDUCE FIELD, CURRENT DENSITY OR TEMPERATURE !!!!

* to be balanced w. surface melting

CONCLUSION

Surface properties are different from bulk :

Diffusion, electromigration & melting occur at lower Tp° than bulk

Microwave/RF seem to enhance electromigration.

The observed behavior show that we are very close to the ultimate limits of metals (locally GV/m!)

The choice of materials/structures/surface preparation… needs to be carefully tailored

Modeling needs to be deepened:

field emission electron flux

diffusion, melting…

Role of surface defect/ surface treatment needs to be studied

Connecting with metallurgy/surface experts might be helpful

THANK YOU FOR YOUR ATTENTION

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DSM
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LIDC2

SPARES

CONCLUSION 2 ☺

- Electromigration is totally negligible at cryogenic temperatures (< 77K)

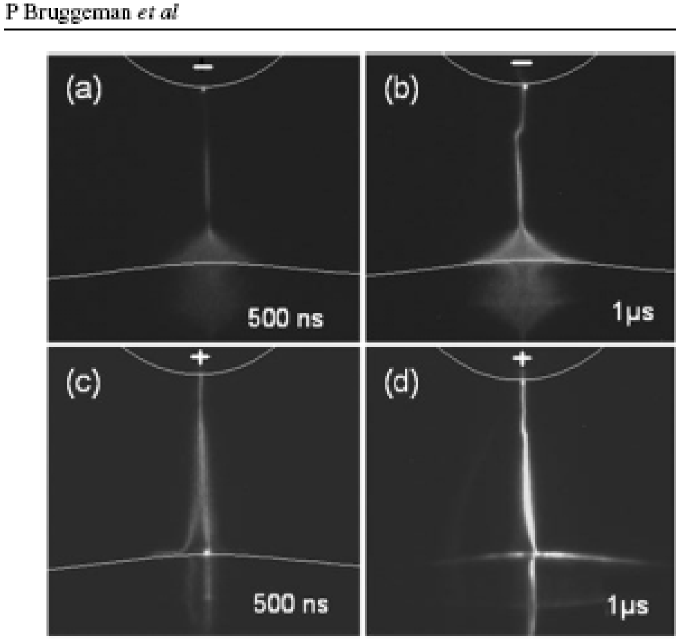
- Superconducting accelerators work without breakdown and (nearly) no field emission…

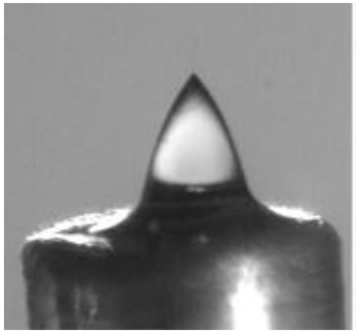
- Should we think to a superconducting CLIC ?

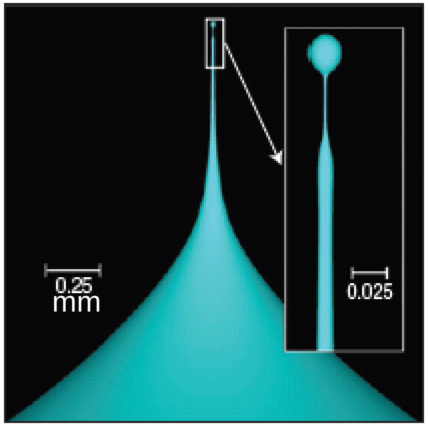
LIQUIDS UNDER HIGH ELECTRICAL FIELD :
e.g. H_2O

Liquids under el. field form **Taylor cones**

Water : Surface instability @ E > ~ 2.4 MV/m

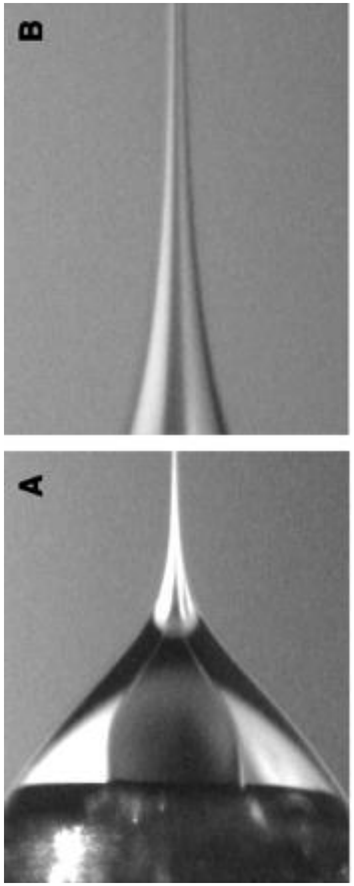




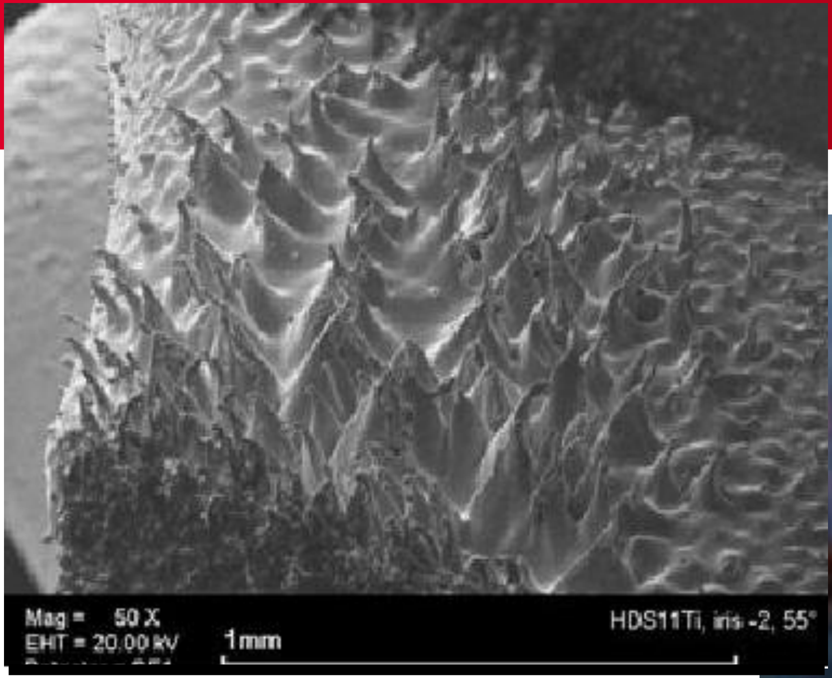


Electrospray nozzles

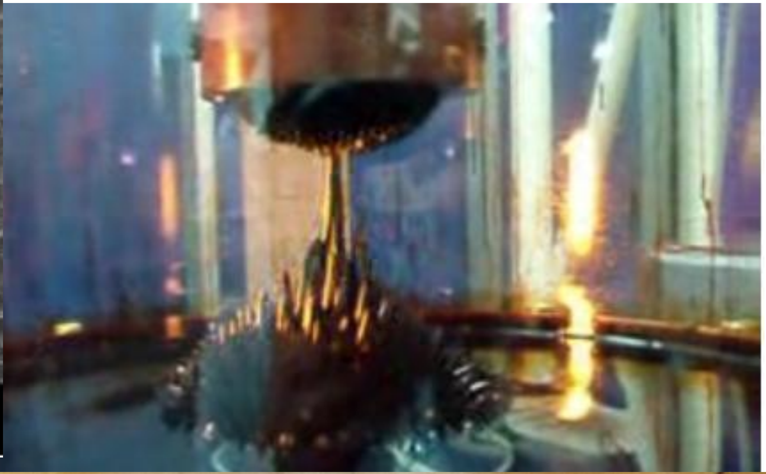
http://www.nature.com/nphys/journal/v4/n2/pdf/nphys807.pdf
http://www.sciencemag.org/cgi/reprint/295/5560/1695.pdf

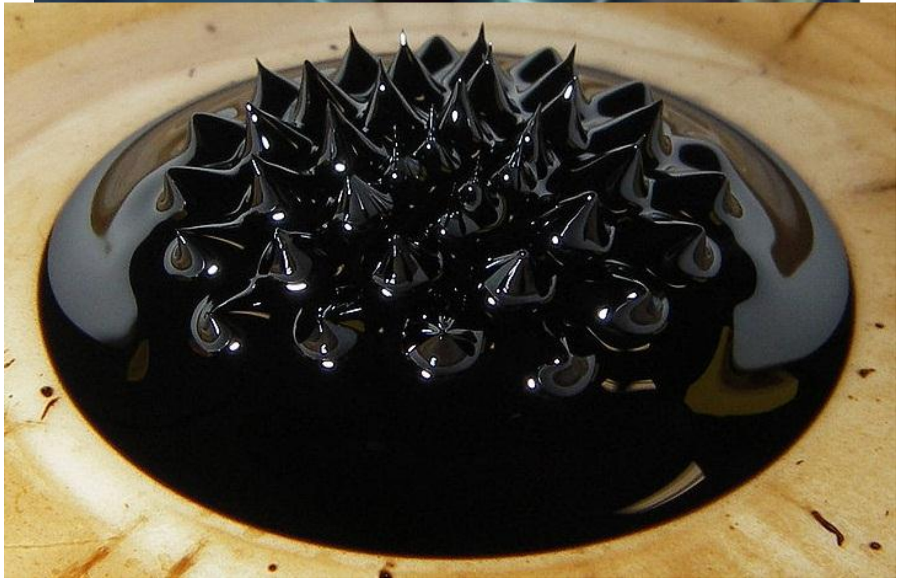


TI SURFACES



http://www.collegehumor.com/video:1788860





Liquid metal in El.field : analogy w. ferrofluids in Magn. field:

=> Ti surface has melted ?!

LIQUIDS UNDER AC ELECTRICAL FIELD :

Conductive metal + AC+ **B** :

http://hal.inria.fr/docs/00/06/89/75/PDF/_these_bachir_4_.pdf

(a) $f = 14$ Hz, $B = 0{,}02$ T

(b) $f = 14$ Hz, $B = 0{,}06$ T

(c) $f = 14$ Hz, $B = 0{,}143$ T

(d) $f = 14$ Hz, $B = 0{,}194$ T

(e) $f = 30$ Hz $B = 0{,}04$ T

(f) $f = 30$ Hz, $B = 0{,}06$ T

(g) $f = 30$ Hz, $B = 0{,}08$ T

(h) $f = 30$ Hz, $B = 0{,}09$ T

(i) $f = 50$ Hz $B = 0{,}03$ T

(j) $f = 50$ Hz, $B = 0{,}06$ T

(k) $f = 50$ Hz, $B = 0{,}08$ T

(l) $f = 50$ Hz, $B = 0{,}11$T

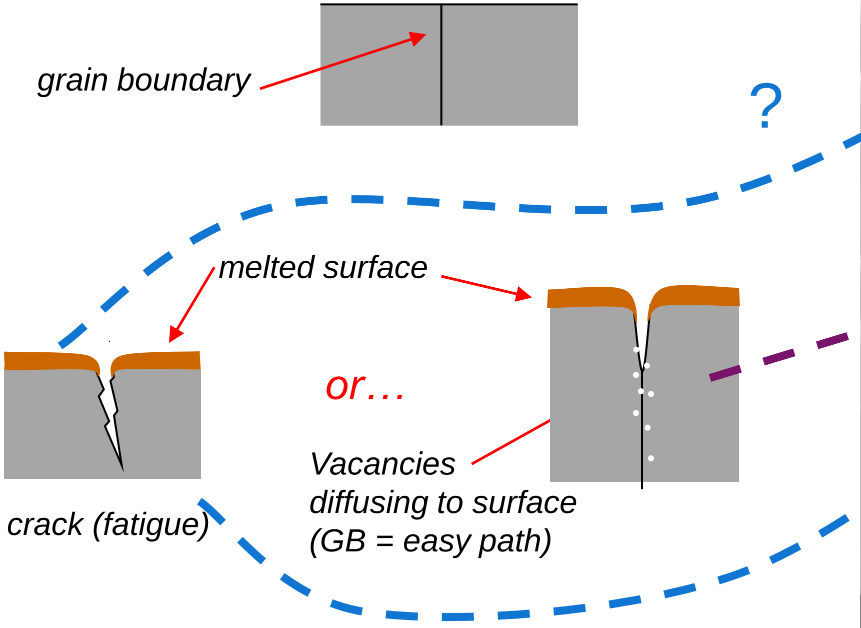
Figure 3.17 : Forme dynamique de l'interface mercure-électrolyte. Vue par-dessus pour différentes valeurs de fréquence et d'intensité de champ magnétique.

ELECTROMIGRATION AND Mo SURFACES

Voids : along Grain Boundaries :

⇒ Diffusion is involved !!!

- is it “electromelting” ?
(≡ electromigration)


grain boundary

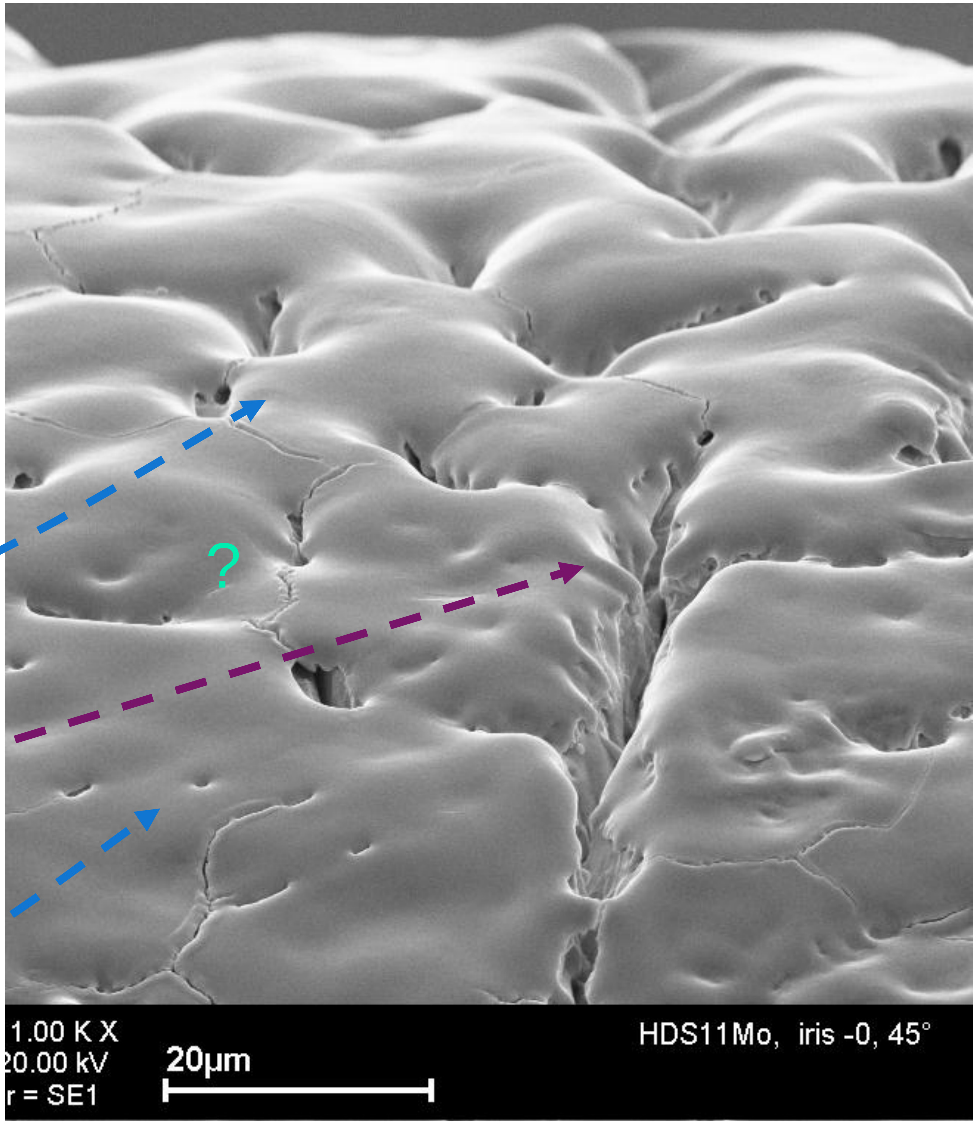
?

melted surface

or…

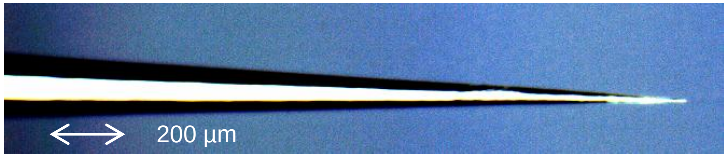
crack (fatigue)

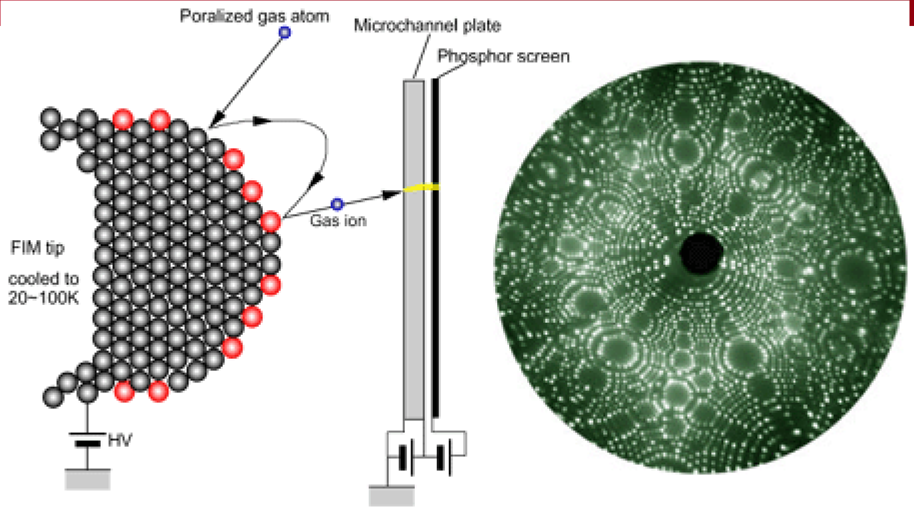
Vacancies diffusing to surface (GB = easy path)



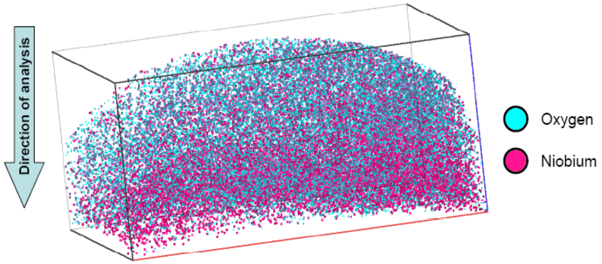
FIM/ATP : electro-evaporation/migration

Electropolished Nb needle





Field Ion Microscopy
Field evaporation of adsorbed atoms



UHV, higher field , TOF detection =>
Atom Probe Microscopy
Field evaporation of tip's atoms

Between 20-100 K

Electro-evaporation @ ~5 -30 GV/m
Electromigration @ ~1 GV/m

Room temperature :
Voltage divided by 5 to 10 !

Electromigration @ ~100 MV/m

(neutral) atoms in electrical field : 1) STM

Scanning Tunneling Microscope

=>

Atom displacement :

typically 100 MV/m to 5000 MV/m

Change in hopping activation energy

=> Increased diffusion

Not enough but very low J !

Atoms displaced by voltage pulse in an STM tip

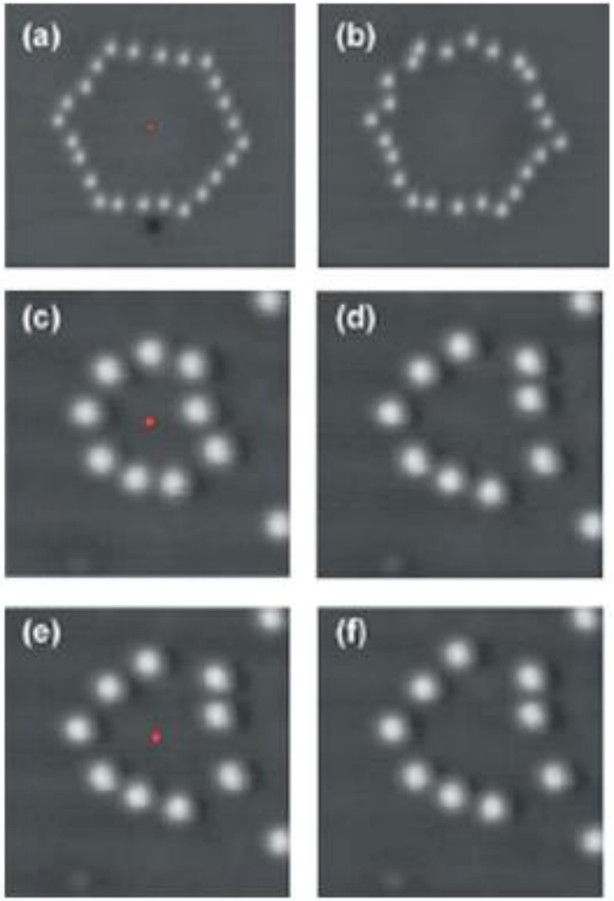
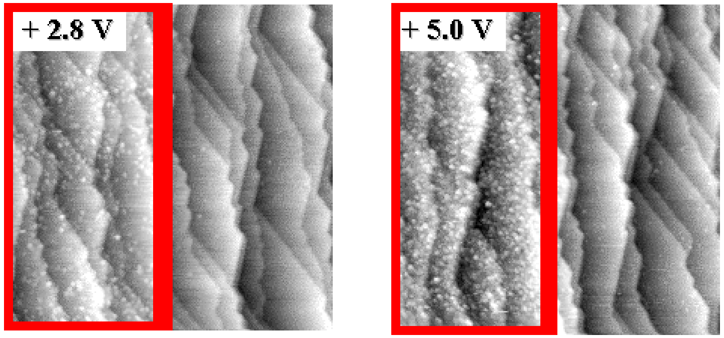


FIG. 3. (a) Image (20 × 20 nm²) of 24 Au atoms arranged in a hexagon shift to new adsorption sites if a voltage pulse of −600 meV is applied in the center. (b) The atoms jump outwards although they are 6 nm away from the tip. (c)–(f) The same effect can be observed with Ag atoms (8 × 8 nm²) here the maximal range is 3 nm.



Niobium surface after expositions to high field in a STM

Surface pre-melting

Pre-melting = general phenomena* (but not universal)

- Depends on crystalline orientation (loose packed)
- Starts @ T~ 0.75 Tm
- Highly influenced by strain

[22]

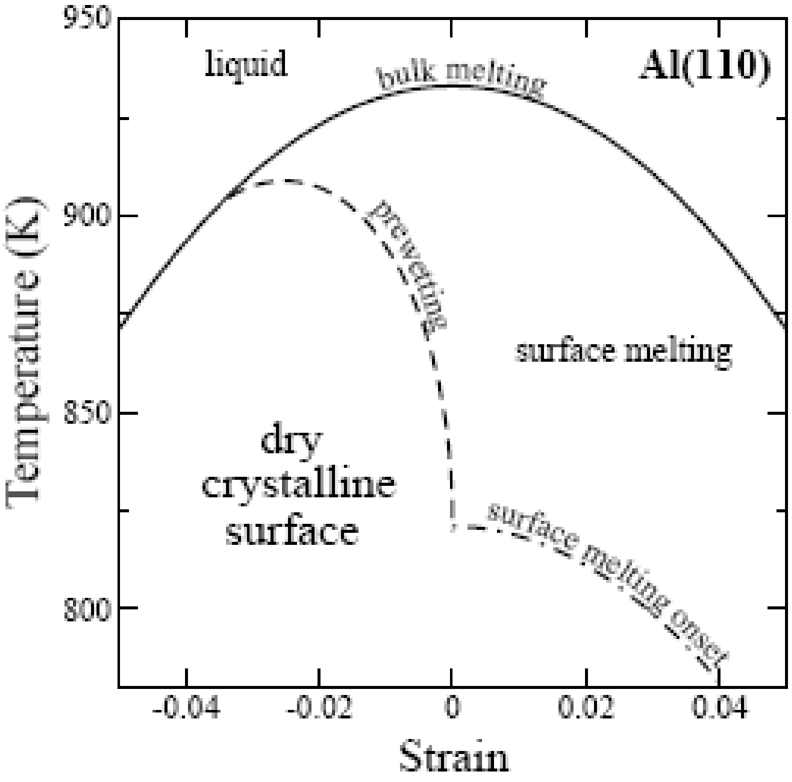
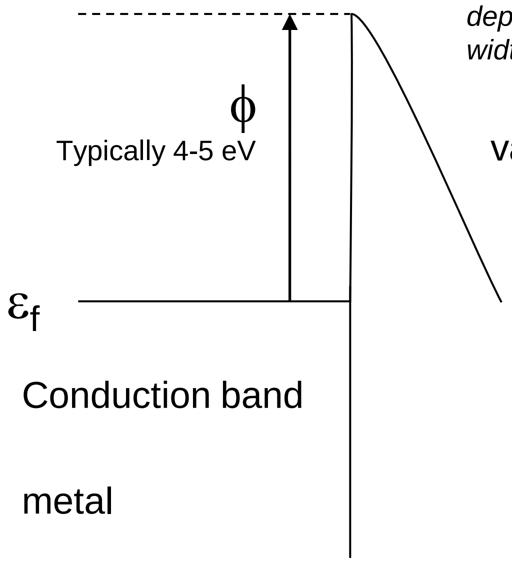


Fig. 19. Phase diagram of a metal surface in presence of in-plane strain. Note that the negative (compressive) strain can give rise to a prewetting transition. From Ref. [62].

** melting only displays half of the usual hysteresis for 1rst order phase transformation : super cooled melts can exist whereas overheated solids don't*

EFFECT OF SURFACE LAYERS (OXIDES)…1

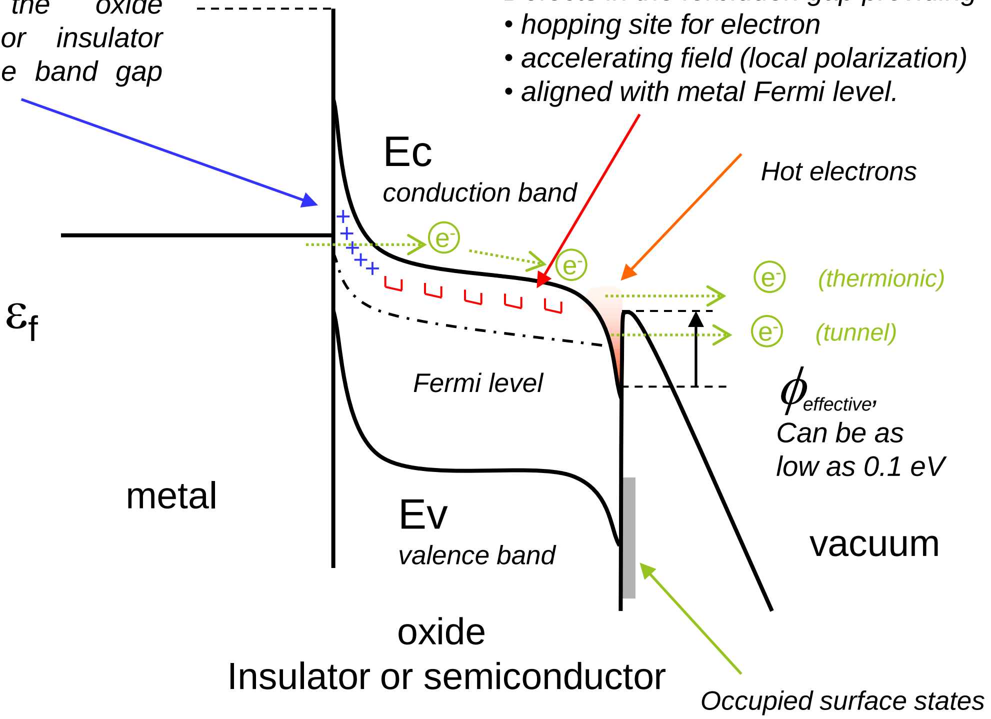
Bare metal :



Curvature at the interface: in this example we consider p-type space charge at the metal oxide interface: holes are injected into the oxide (semiconductor or insulator depending on the band gap width)

Metal with surface oxide:

Defects in the forbidden gap providing
- *hopping site for electron*
- *accelerating field (local polarization)*
- *aligned with metal Fermi level.*



- localized states inside gap = pending chem. bond, foreign atoms, vacancies, dislocations…

•Very likely to happen inside oxides, very irreproducible !

=> may be the source of variability from sample to sample

EFFECT OF SURFACE LAYERS (OXIDES)…2

PHd's : M. Jimenez in 1994, J. Tan in 95, S. Maissa in 96

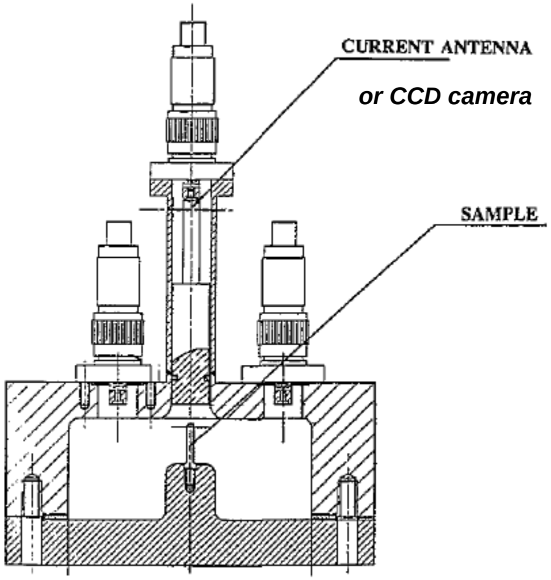


Figure 2. General sketch of the cavity.

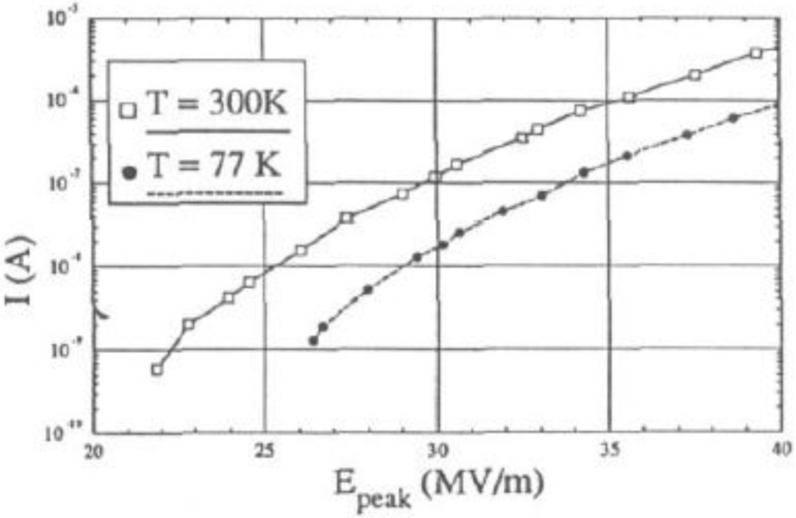
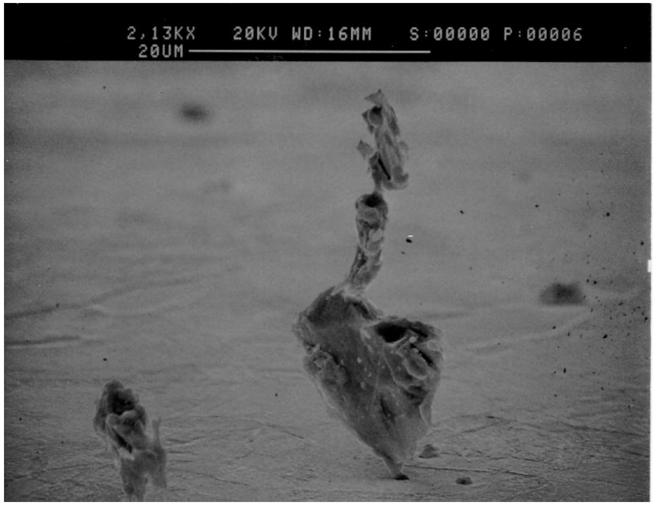
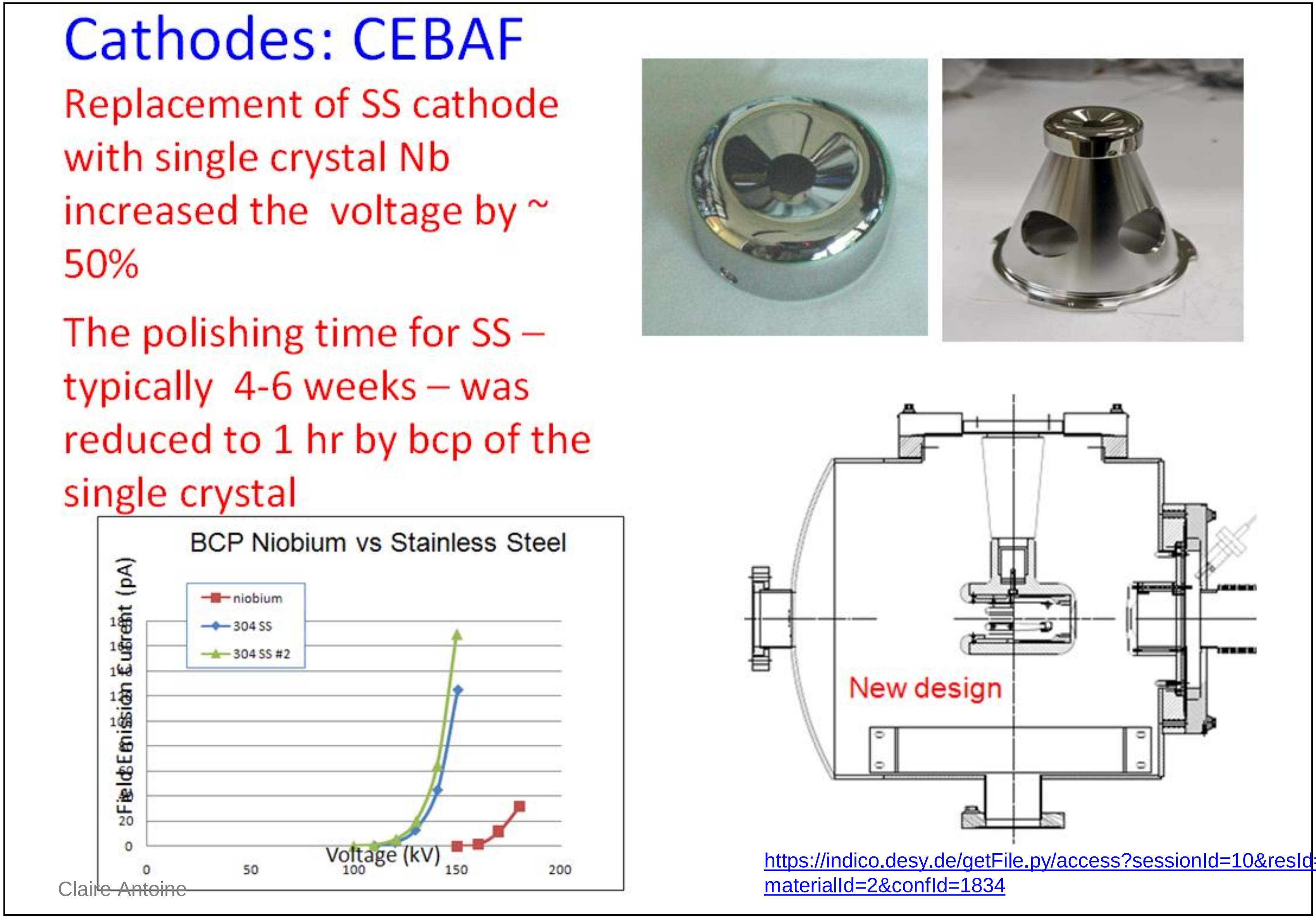


Figure 3. Field-emitted current from the same sample at liquid nitrogen (*T* = 77 K) temperature and room temperature (*T* = 300 K).



- metallic particles in rf tend to reassemble along el. field lines => antennas with high β
- insulating particles : explosive in RF (polarization)
- both melt during processing => localized plasma
- but : influence of temperature => some thermionic emission => Influence of an oxide layer ?
- not much influence of the substrate material

P. KNEISEL PRESENTATION
@ TTC MEETING JUNE 16-19TH 2009



Cathodes: CEBAF

Replacement of SS cathode with single crystal Nb increased the voltage by ~ 50%

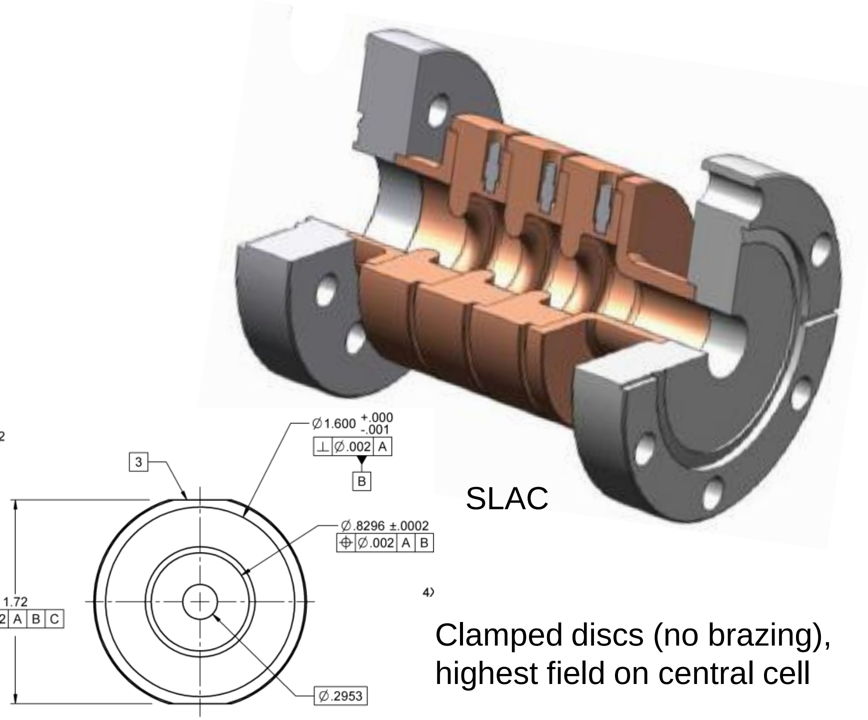
The polishing time for SS – typically 4-6 weeks – was reduced to 1 hr by bcp of the single crystal

BCP Niobium vs Stainless Steel

https://indico.desy.de/getFile.py/access?sessionId=10&resId=3&materialId=2&confId=1834

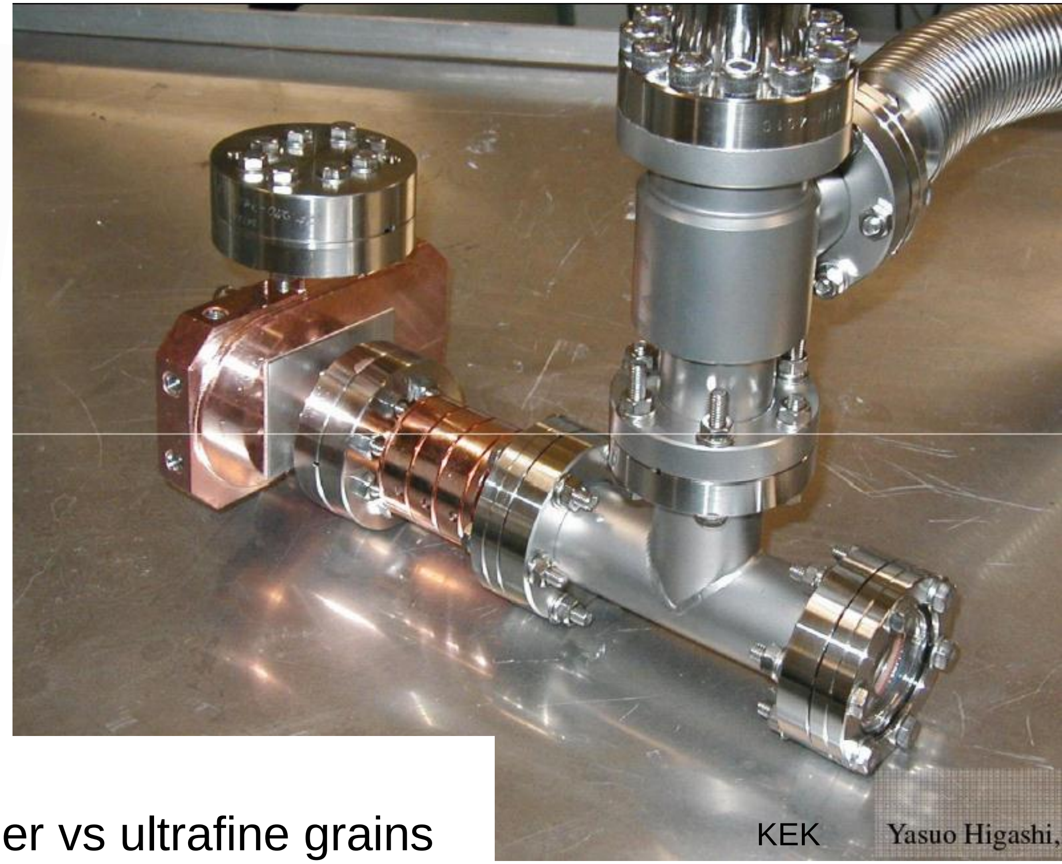
PROPOSED PROGRAM (material point of view)

Collaboration w. SLAC or KeK ? Local bench test ?



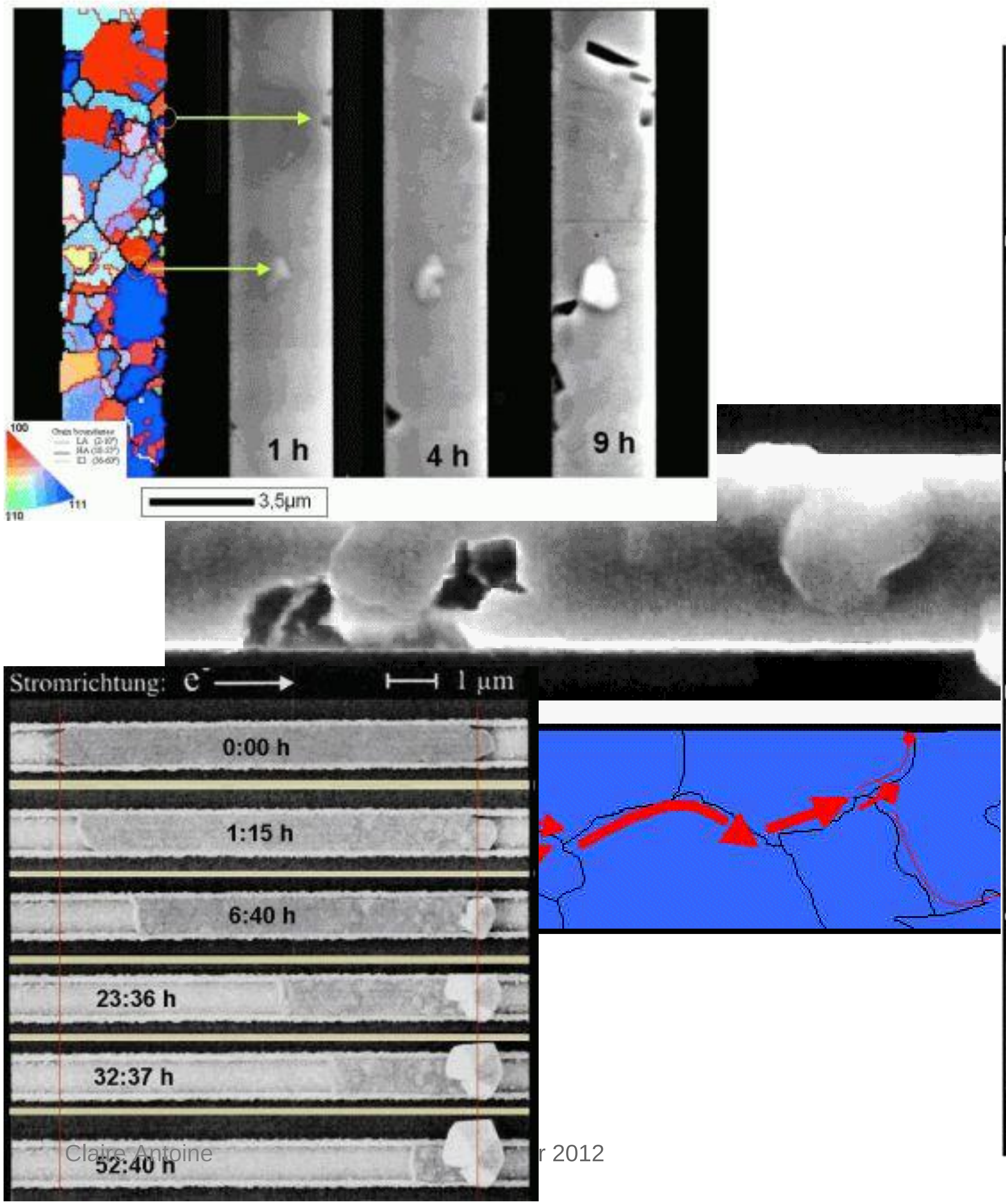
SLAC

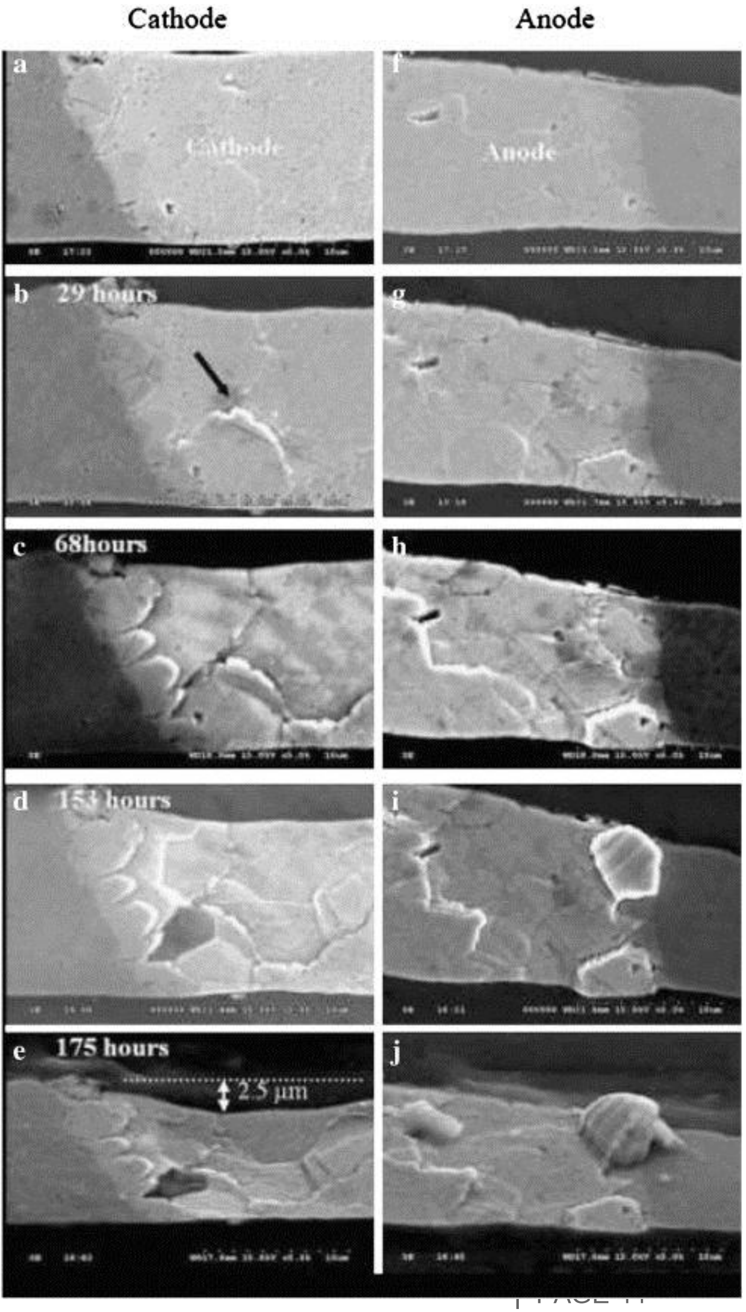
Clamped discs (no brazing), highest field on central cell


KEK

Yasuo Higashi,

Possible tests :
1. monocrystalline copper vs ultrafine grains
2. surface treatments (EP)
3. annealing
4. HPR


100
110
111
1 h
4 h
9 h
3,5µm
Stromrichtung: e⁻ →
1 µm
0:00 h
1:15 h
6:40 h
23:36 h
32:37 h
52:40 h


Cathode
Anode
a
Cathode
f
Anode
b 29 hours
g
c 68hours
h
d 153 hours
i
e 175 hours
2.5 µm
j

GRAIN BOUNDARIES ENHANCED DIFFUSION…

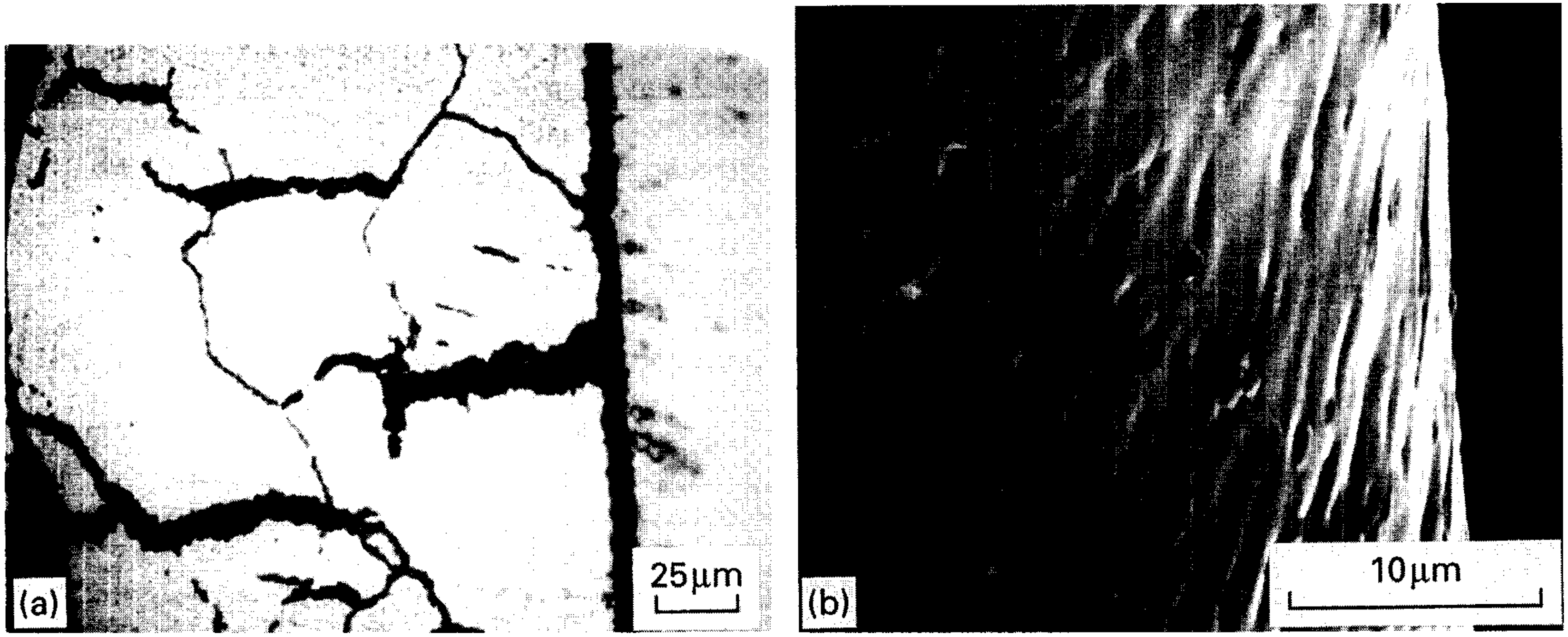
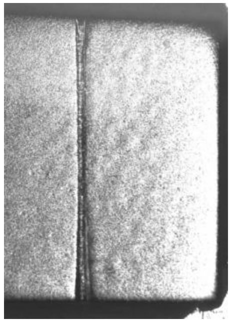


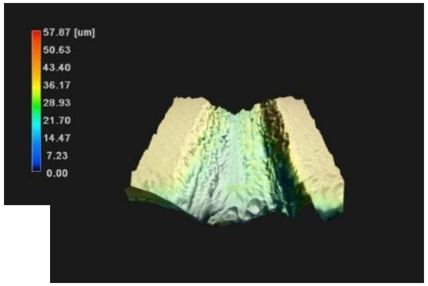
Figure 2 (a) Liquid metal diffusion into the grain boundaries and (b) formation of solid precipitates along the shank of the emitter tip.

FIELD ENHANCEMENT DUE TO MORPHOLOGY

Single Nb crystal with notch on the surface :

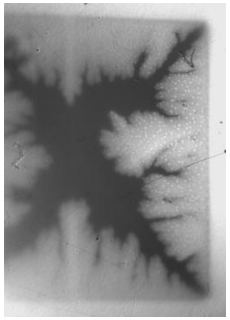
0.5 mm ⇔





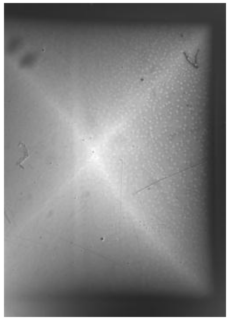
[A. Polyanskii et al, FNAL/FSU]

H=40 mT
T=7K



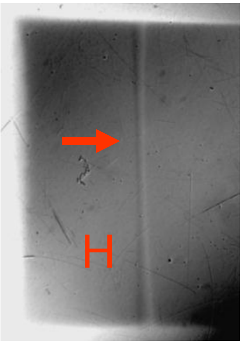
⊗
H

H=80 mT
T=7K

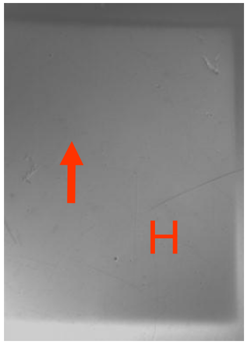


H ⊥ surface

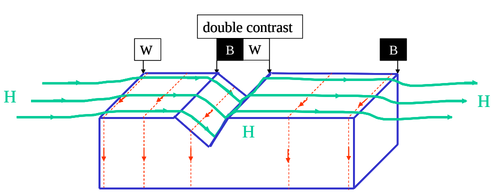
H ⊥ surface: notch has small impact on flux distribution even at higher T



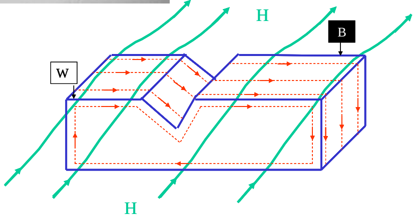
T=5.6K



H // surface

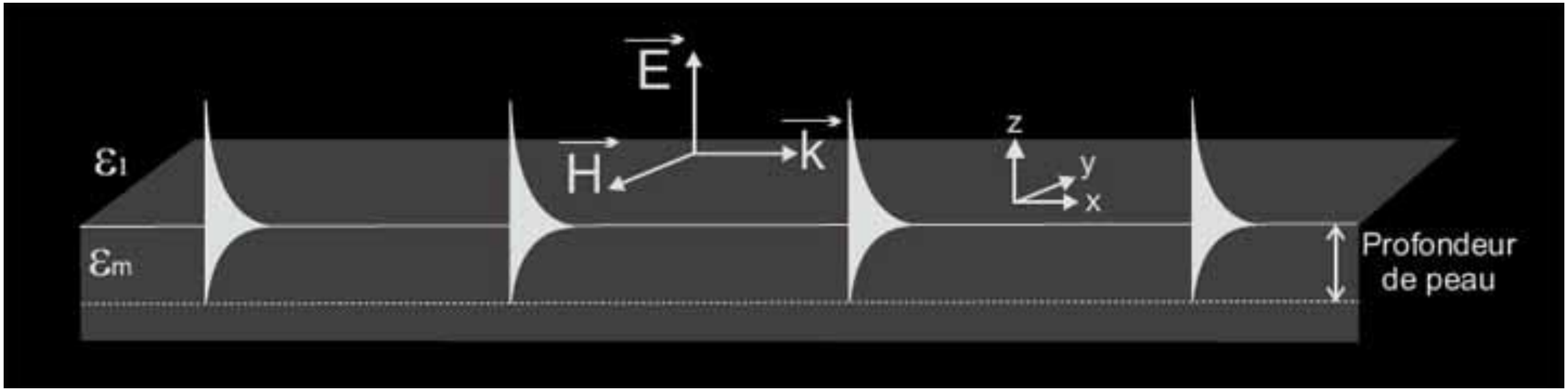


MO contrast is double at the groove, when in-plane field perpendicular to groove



No MO contrast at the groove, when in-plane field parallel to groove

PLASMONS

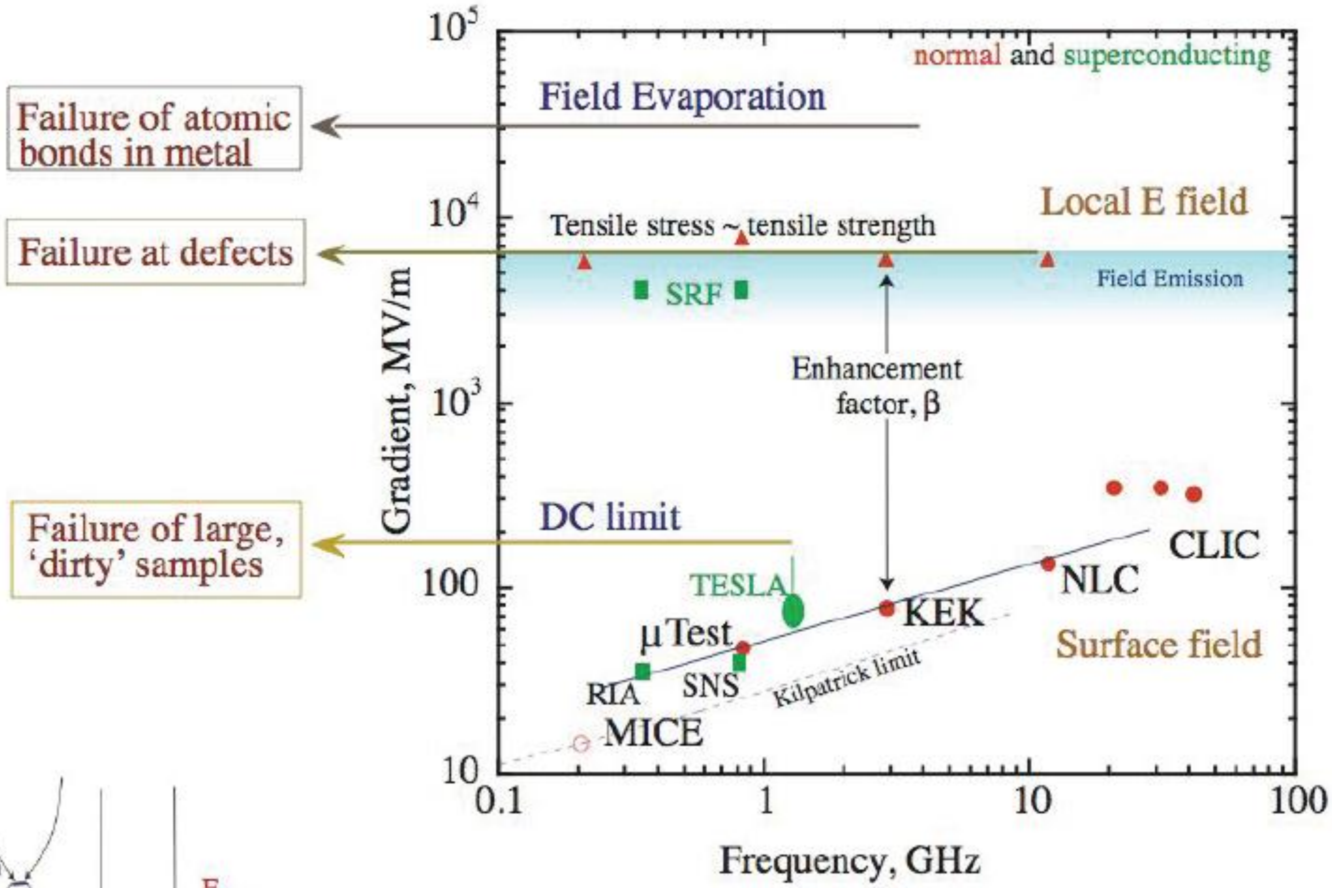


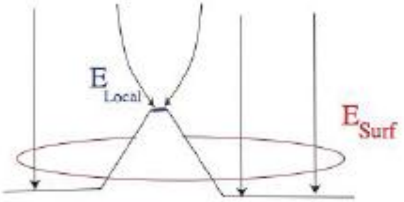
http://optoelectronics.eecs.berkeley.edu/ThesisDan.pdf

Surface Waves
Surface waves can be illustrated in several different ways. In optics, they are called surface plasmons. They also exist at radio frequencies, where they are simply called surface currents
. If the conductor is smooth and flat, the surface waves will not couple to external plane waves. However, they will radiate if scattered by bends, discontinuities, or surface texture.

J. NOREM. "PULSED POWER PROCESSIG AND RF GRADIENT LIMITS". IN SUPERCONDUCTING MATERIAL WORKSHOP. 2006. ARGONNE, USA.

The high gradient universe.





$E_{Local} = \beta\, E_{Surf}$

SURFACE MODIFICATIONS UNDER HIGH EM FIELD

Where is electromigration observed ?

Clic Cavities

Field Ion Microscopy /Atom Probe Tomography

(FIM/ATP) => electro-evaporation @ E~30 000 MV/m, electromigration @ E~1 000 MV/m, low J, low T°

Tunneling microscopes => typically E~3-5 000 MV/m, low J, RT

Electronic devices => typically J ~10^4-10^9A/cm^2, low E, 200-400°C

Microwave/field sintering* : RF much faster than DC => ∃ ? “*non heating microwave effect* ” ?

Metal purification => *e.g. H in metal matrix : force is not only momentum transfer, => electronegativity, polarizability, crystalline structure…*

Field Emission Sources

Liquid metal ions sources => liquid metal in E-field => many Taylor cones => local field enhancement => runaway => breakdown.

Electrosprays (ionic or polarizable liquids)

High flux laser irradiation

* *Powder metallurgy*

CONCLUSION

- Surface properties are different from bulk :
  - Diffusion, electromigration & melting occur earlier
- Microwave/RF seem to enhance electromigration.
- The observed behavior show that we are very close to the ultimate limits of metals (locally GV/m!)
- The choice of materials/structures/surface preparation… needs to be carefully tailored

•RF pulse heating calculation have been applied to 12 GHz structures => same range of J and surface field : electromigration is also expected !

- Modeling of the material aspect should be undertaken:
  - field emission electron flux
  - diffusion, melting…
- Connection with metallurgy experts might be helpful
- Role of surface defect/ surface treatment must be studied

OTHER EFFECTS TO BE ACCOUNTED

Parameters affecting melting => local Tm

Composition : a factor 2 to 3 : $T_{m\ Cu} = 1358$ K, $T_{m\ Ti} = 11941$ K, $T_{m\ Cu} = 2896$ K,

Skin depth + Joule effect + Thermal properties **~x 20 variations** !!!

=> see F. P. calculation

Diffusion

Stress diffusion >> bulk diffusion

Surface diffusion >> bulk diffusion

=>

Interfacial (Surface, Grain Boundaries) premelting => local T^S_m typically 20-30 % lower than T_m bulk

Electron bombardment (field emission)

Already studied : fatigue, breakdown on emitting site

Parameters affecting local E => βE

Dust particles => typically β~100-500, but very localized.

Surface roughness => typically β ~1.5-2

30 GHZ RF TEST RESULTS

Goal:

- E_{acc} ~150 MV/m
- E_{surf} ~ 270 MV/m
- 150 ns pulses / 200ms
- breakdown rate (BDR) $<10^{-7}$

Actual RF tests results

- 70 ns pulse length, BDR 10^{-3}
  - Ti structures E_{acc} ~ 63 MV/m, E_{surf} ~ 113 MV/m
  - Mo structures E_{acc} ~ 51 MV/m, E_{surf} ~ 92 MV/m
  - Cu structures E_{acc} ~ 61 MV/m, E_{surf} ~ 110 MV/m
- 70 ns pulse length, BDR 10^{-6}
  - Ti structures E_{acc} ~ 36 MV/m
  - Mo structures E_{acc} ~ 42 MV/m
  - Cu structures E_{acc} ~ 42 MV/m

Limitation : Breakdown Rate

Change 30 GHz to 12 GHz: E_{acc} ~100 MV/m / E_{surf} ~ 200 MV/m
200 ns pulses / 20 ms, BDR $<10^{-6}$

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