Progress in high gradient superconducting cavities

Aliaksandr Navitski*

aliaksandr.navitski@desy.de

BERGISCHE UNIVERSITÄT WUPPERTAL

DESY

PHYSICS AT THE TERA SCALE

Helmholtz Alliance

Outline

- Who we are? What is our research topics?
- Motivation for high gradient superconducting cavities
- Why field emission (FE), surface and “Quench” studies
- Parasitic FE studies from Nb:
  - Tasks & strategy
  - Experimental technique & samples
  - Surface defects
  - FE & Heat treatment of Nb
  - What emits?

FE studies: Summary and outlook

Specially prepared Nb samples

- Optical inspection system for 9-cell cavities:
  - OBACHT setup
  - Optical test results
- Quench localization by 2nd sound
  - Basics and strategy
  - 2nd sound detection system @ DESY
  - Correlated 2nd sound, OBACHT and T-map results

Cavity surface & Quench studies: Summary & outlook

9-cell cavities

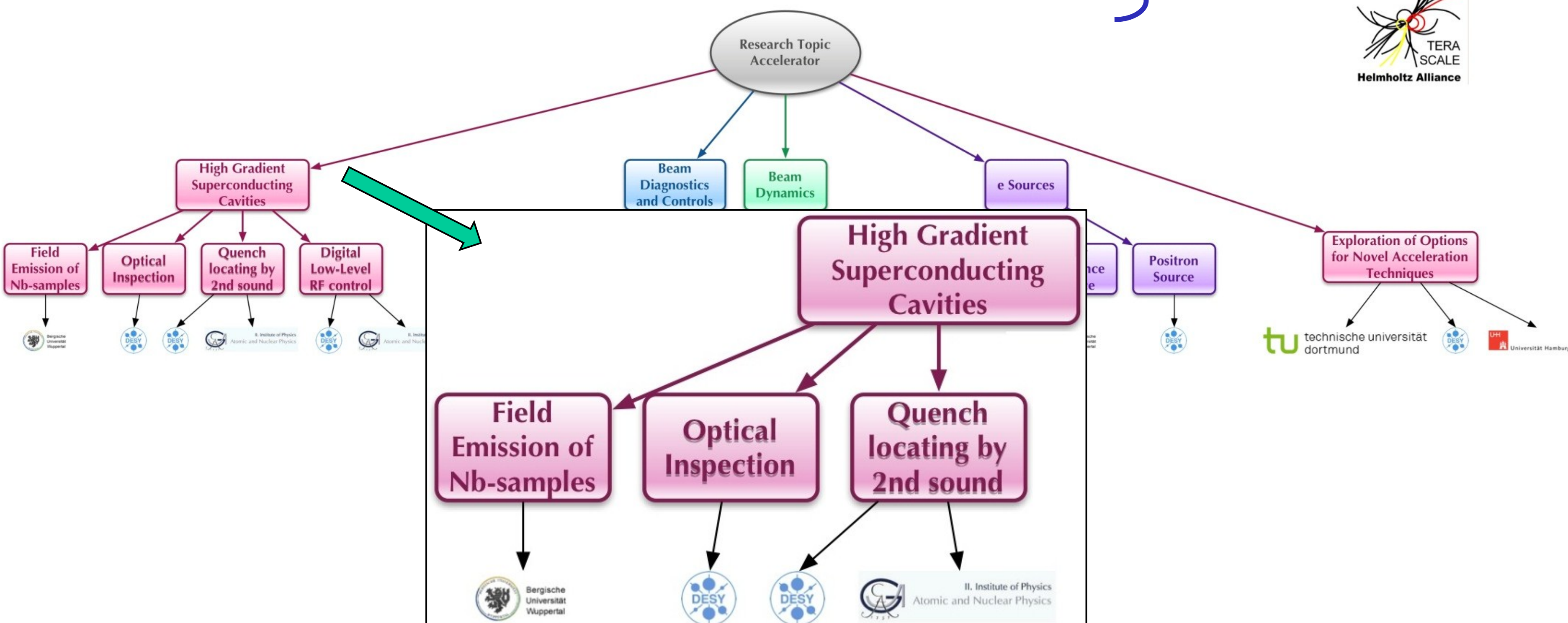
Who we are? What is our topics?

The team:

A. Navitski, G. Müller, S. Lagotzky

A. Navitski, E. Elsen, B. Foster, L. Steder,
F. Schlander, M. Wenskat, S. Aderhold,
J. Schaffran, G. Falley, U. Cornett, T. Külper,
A. Guddat, S. Karstensen, R. Sternberger

D. Reschke, X. Singer



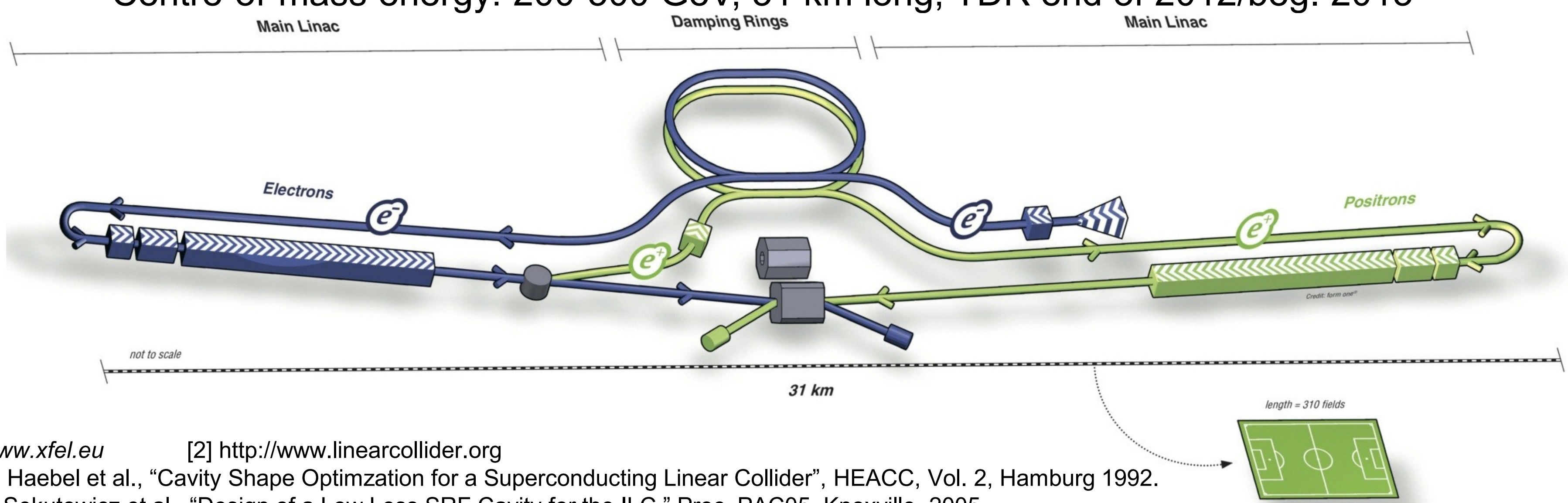
Motivation for high gradient superconducting (SC) cavities:

> European X-ray Free Electron Laser XFEL [1]

- 800 SC 1.3 GHz 9-cell cavities, production **is starting**
- Nominal gradient E_{acc} = 23.6 MV/m @ $Q_0 > 10^{10}$
  E_{peak}/ E_{acc} = 1.98; B_{peak}/ E_{acc} = 4.26 mT/MV/m
- 17.5 GeV beam energy, 3.4 km long

> The International Linear Collider ILC [2]

- 16,000 1.3 GHz 9-cell SC cavities
- Accelerating gradient required: E_{acc} = 31.5 MV/m @ $Q_0 > 10^{10}$
  E_{peak}/ E_{acc}=1.98 (TESLA-shape [3]) or E_{peak}/ E_{acc}=2.36 if Low Loss shape [4] will be chosen
- Centre-of-mass energy: 200-500 GeV, 31 km long, TDR end of 2012/beg. 2013



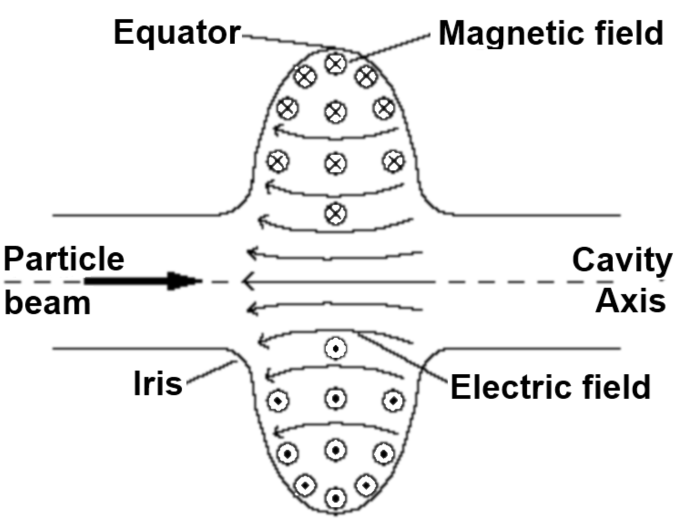
[1] *www.xfel.eu* [2] http://www.linearcollider.org
[3] E. Haebel et al., "Cavity Shape Optimzation for a Superconducting Linear Collider", HEACC, Vol. 2, Hamburg 1992.
[4] J. Sekutowicz et al., "Design of a Low Loss SRF Cavity for the ILC," Proc. PAC05, Knoxville, 2005.

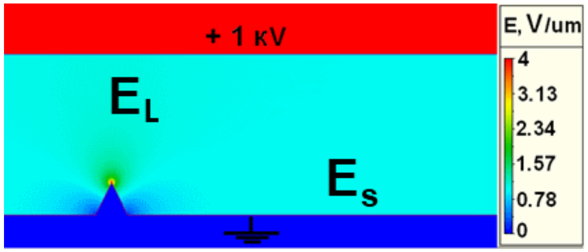
Why **field emission (FE), surface** and “Quench” studies (1)

- FE from particulate contaminations & surface irregularities
  - → electron loading of high gradient SC Nb for XFEL and ILC
    - - degradation of the cavity Q-value
    - - increase of the cavity cryogenic consumption
  - → radiational activation or even mechanical damages

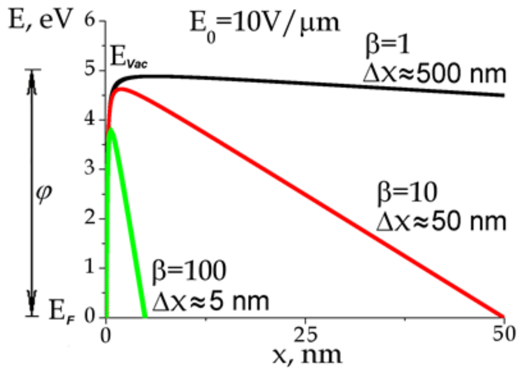
} **Field limitations**

- Surface irregularities might cause high-field Q-drop and quenches [1]





$E_{peak}(E_S) \geq$ 48 MV/m XFEL
75 MV/m ILC



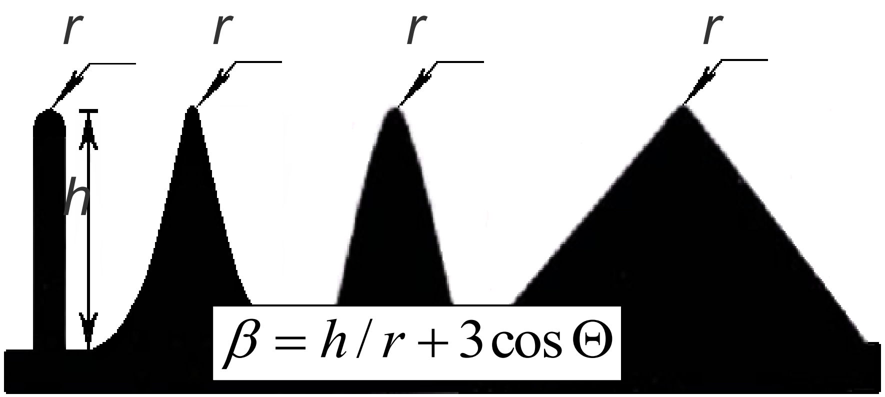
$$\Rightarrow E_L = \beta_E E_S$$

For Nb: 1nA/µm² @ 2000/β MV/m

[1] J.Knobloch et al., Proc. 9th Workshop on SRF (1999), p.77.

Electric field enhancement on defects:

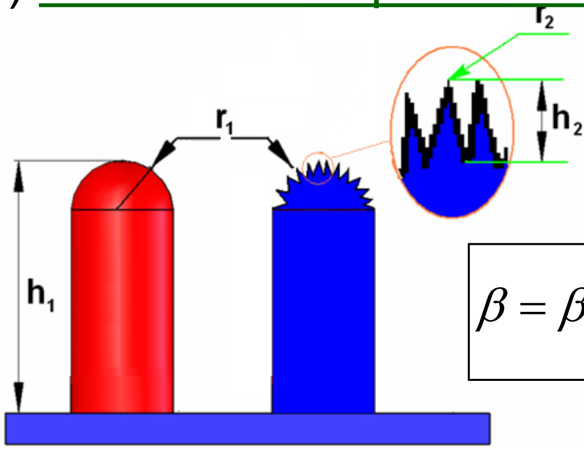
1) Simple field enhancement model:



$$\beta = h / r + 3\cos\Theta$$

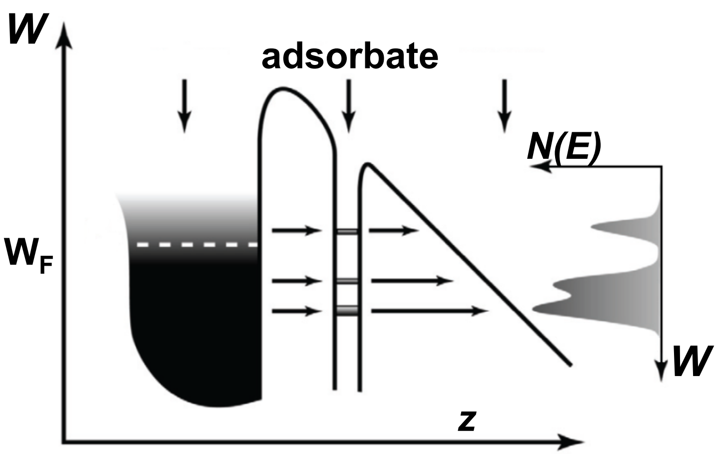
W. J. Orvis et.al. IEEE Trans. on El. Dev. **36**, 2615 (1989).

2) Protrusion on protrusion model:



$$\beta = \beta_1 \beta_2 = \frac{h_2}{r_2}\frac{h_1}{r_1}$$

3) Adsorbates lead to modification of potential distribution and can produce surface states → resonant tunneling



J. D. Jarvis, et al. IFEL 2010, WEPB46 (2010)

4) More complex MIV&MIM models see later

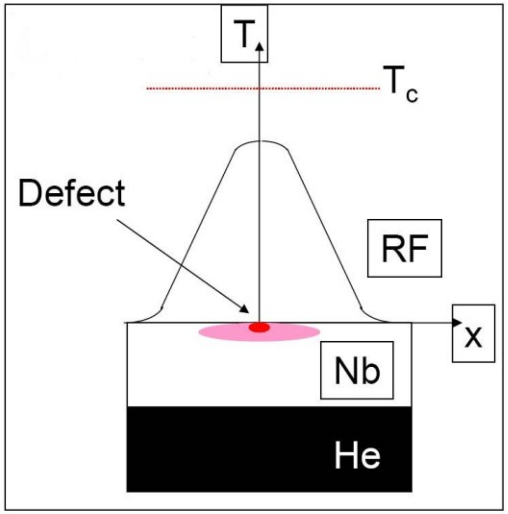
Why field emission (FE), surface and "**Quench**" studies (3)

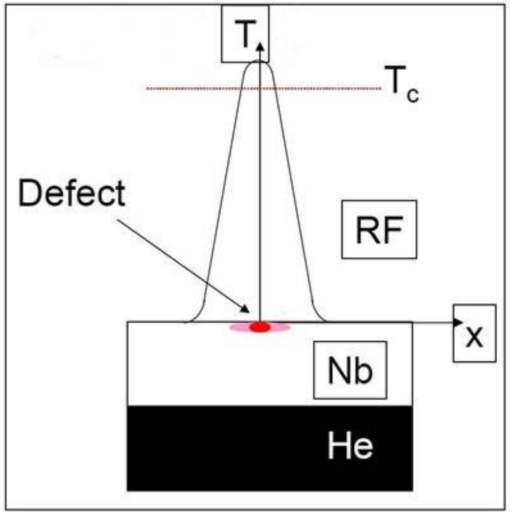
- Dissipation of energy on local defects with higher R_S
  - Inclusion of **impurities**
  - Geometric **defects**
  - Welding seem **imperfections**

- Heating of Nb @ insufficient heat transport to He bath

  → T_C exceeded → Thermal breakdown or **"Quench"**

- Quench localisation can be done using:
  - **Temperature mapping** of the outer surface of the cavity (**very time consuming**, measurements done with temperature dependent resistors)
  - **Second Sound**





H. Padamsee et al.
"RF Superconductivity for Accelerators"

Parasitic FE studies from Nb samples: Tasks & strategy

→ Clear **correlation** between surface defects and FE of the actually EP and HPR Nb
Number density and size of particulates can be much reduced by HPR [1], DIC [2], and clean room assembly, **but** influence of surface defects has been less studied yet

→ Does **grain boundaries** leads to enhance **FE**?

→ **Heat treatments vs. FE**? (e.g. **122 and 800^0C used for cavities fabrication**)

→ How to **eliminate** FE or **shift** to higher fields?

1-st step Systematic measurements of the surface roughness of typical **Nb samples** by means of optical profilometry and AFM:

Aims:
- ⇨ Average surface roughness R_a, R_q
- ⇨ Geometry of defects
- ⇨ Electric field enhancement (and magnetic?)

2-nd step FE study of Nb (after HPR) before/after ***in-situ heat treatment***:

Aims:
- ⇨ Emitter number density
- ⇨ Onset electric surface field of emitters
- ⇨ Electric field enhancement factor β_E of emitters
- ⇨ Activation/ Processing effects

3-d step SEM/EDX identification of emitting defects

Aims:
- ⇨ Correlation between FE and geometry of defects
- ⇨ Understanding of activation/emission mechanisms

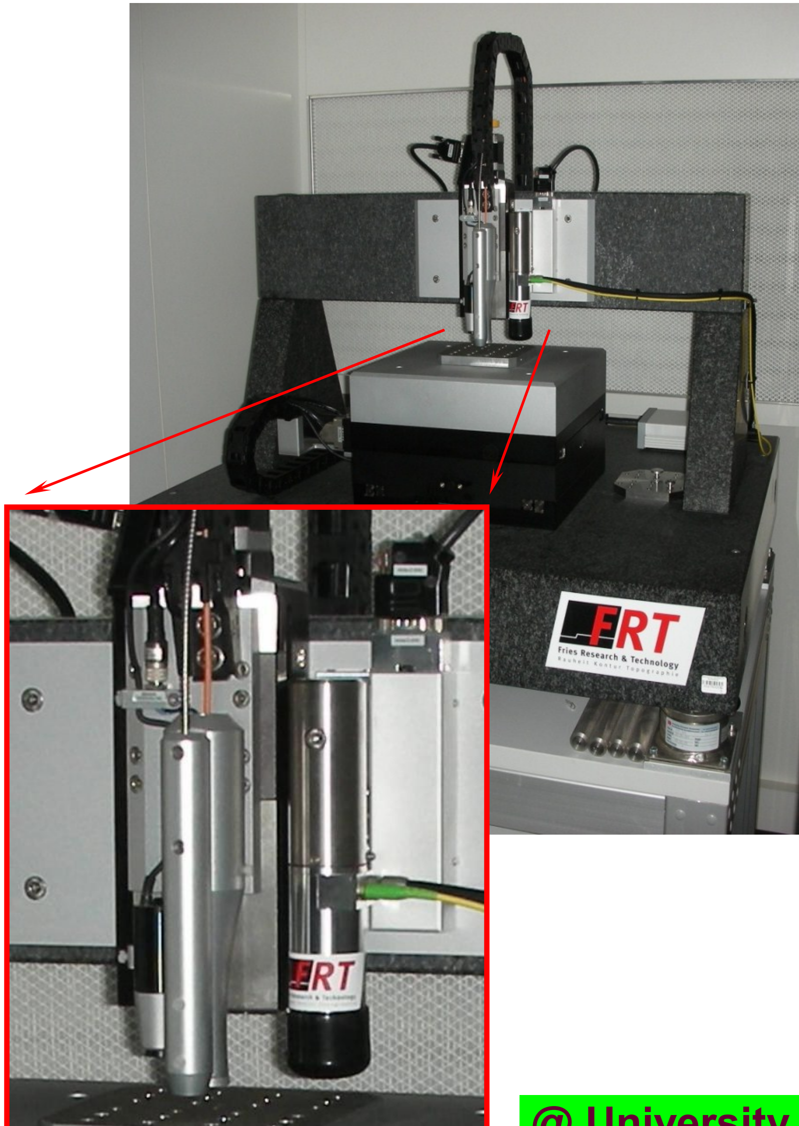
[1] P. Kneisel et al., Proc. 7th Workshop on SRF (1995),p.311. [2] A. Dangwal et al., J. Appl. Phys. **102**, 044903 (2007).

1-st step

Experimental techniques (1): OP + AFM

Optical profilometer (OP) with atomic force microscope (AFM):

- surface rougness
- emitter geometry
- $\beta_{E,geo}$



- Optical profilometer:
  - white light irradiation and spectral reflection (chromatic aberration)
  - up to 20×20 cm^2 and 5 cm height difference
  - 2 µm (3nm) lateral (height) resolution
- further zooming by AFM:
  - 2 µm precision of positioning with respect to the optical profilometer
  - 34×34 μm^2 scanning range
  - 3 (1) nm lateral (height) resolution
  - contact or non-contact modes
- CCD camera for positioning control
- granite plate with a passive damping system for undisturbed nm measurement
- clean laminar air flow from the back to reduce particulate contamination

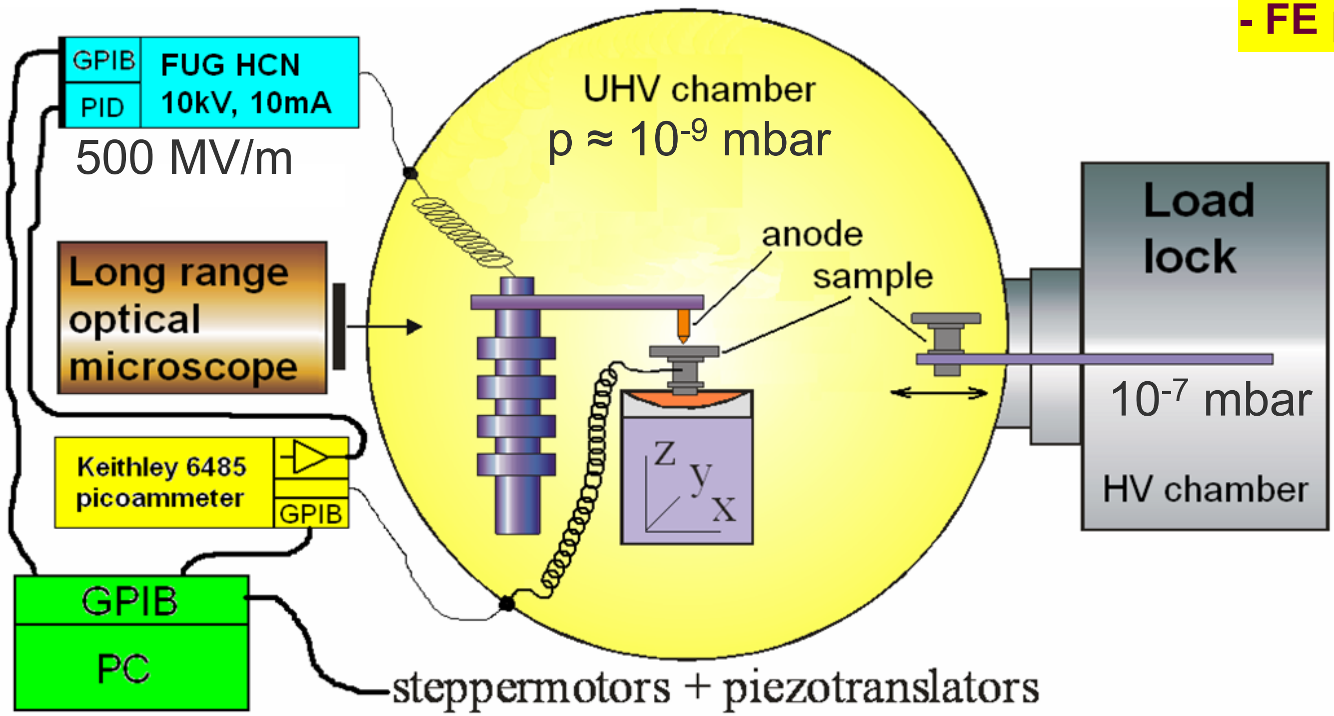
@ University of Wuppertal

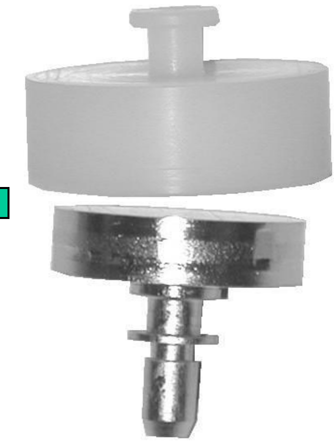
Experimental techniques (2): FESM

Field emission scanning microscope (FESM): →

- localisation of emitters

- FE properties





Dust-free transport
Opening under HV

⇒ Regulated ***V(x,y)*** scans at fixed current ***I*** =1nA and gap Δz ⇒ emitter position
(samples ≤ 25x25 mm², tilt correction ± 1 μm) number density, distribution

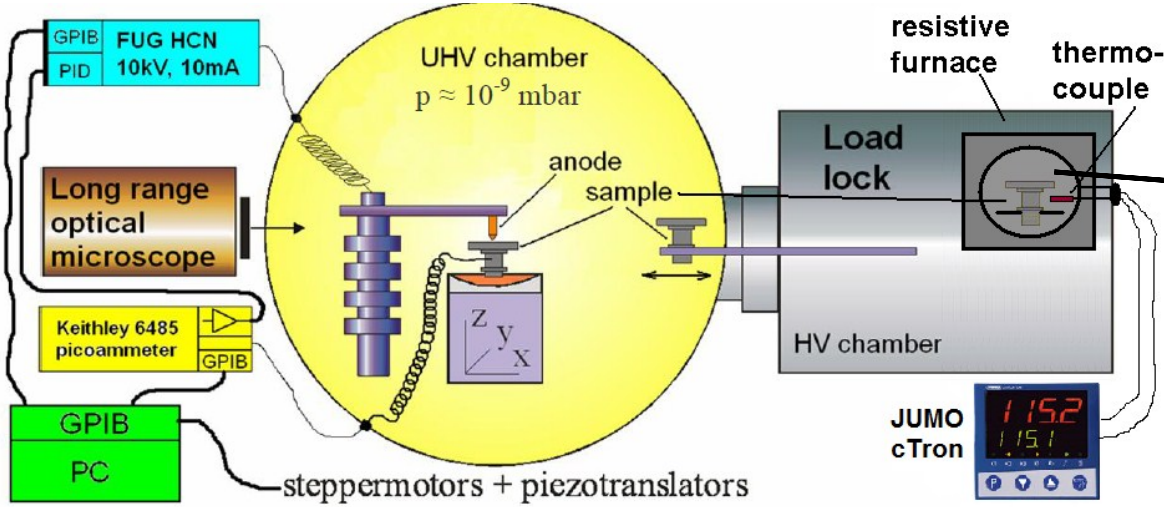
⇒ Spatially resolved ***I(E)*** measurements of single emitters ⇒ E_{on}, $\beta_{E,FN}$, S, I_{max}

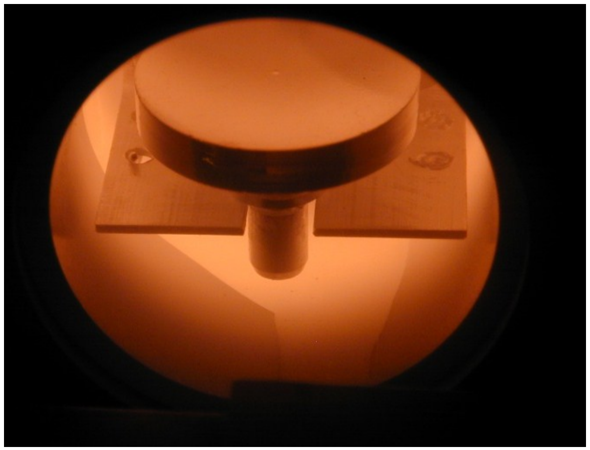
3-d step **Scanning electron microscope (SEM/EDX):** → **Identification of emitting defects**

⇒ Correlation of surface features to FE properties (positioning accuracy ~ 100 μm)

⇒ Determination of foreign material inclusions

Experimental techniques (3): in-situ furnace

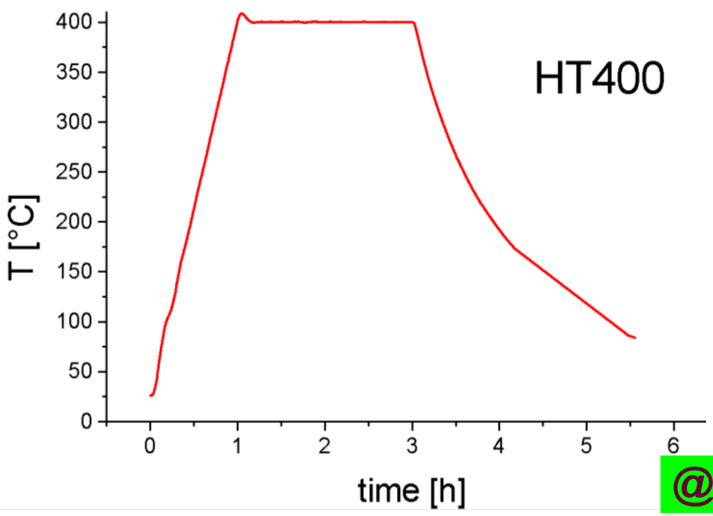




⇒ Heat-treatments of samples <1200 ^{0}C @ $10^{-5} - 10^{-7}$ mbar ⇒ activation effects?

- PID controlled (± 1 ^{0}C, ramps, timers, etc.)

⇒ in-situ experiments in FESM ⇒ FE studies before/after under HV/UHV

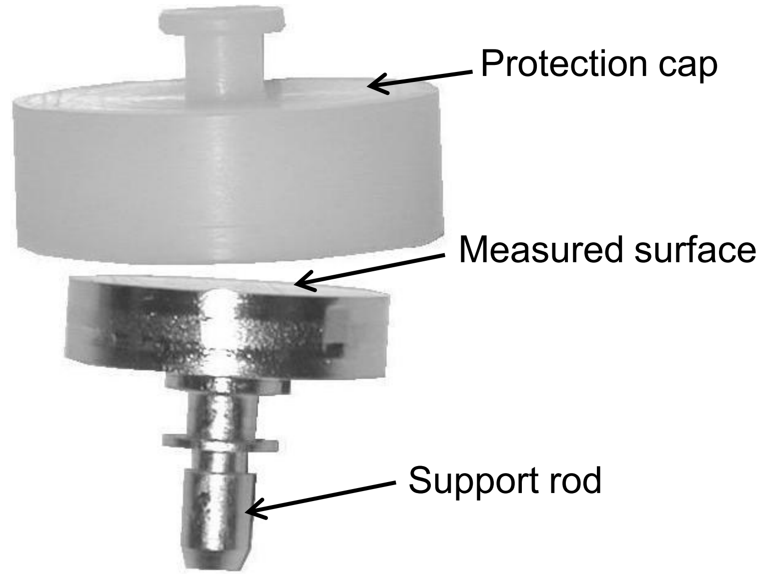


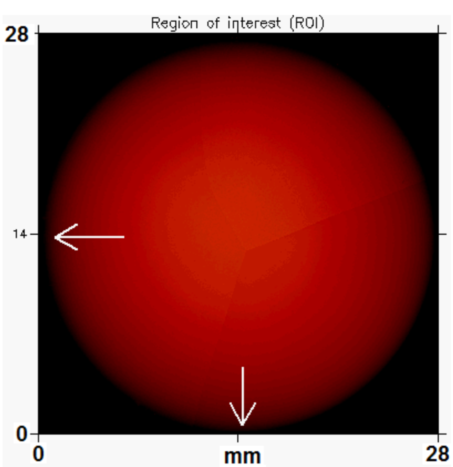
	T, °C	Ramp, h	Heating, h	Samples
HT122	122	3	24	2 LG, 2 SC
HT200	200	1	2	1 SC
HT400	400	1	2	1 LG, 2 SC
HT800	800	1	2	1LG, 2 SC

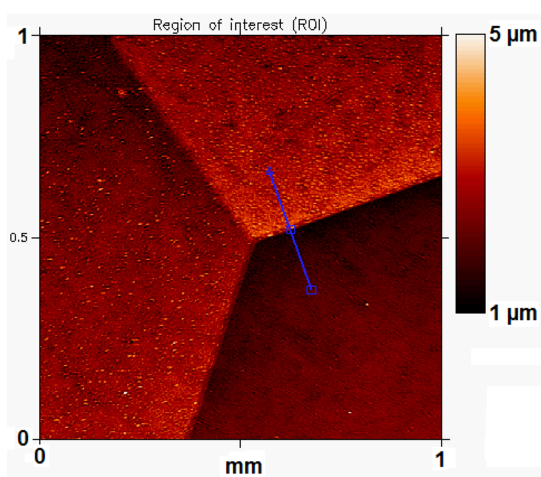
@ University of Wuppertal

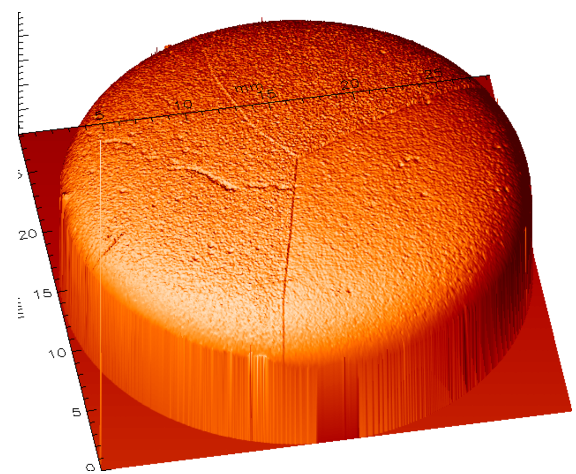
Samples studied:

1) Samples cut from **real Nb cavities**
2) **Specially prepared** [1] flat Nb (RRR>250) samples
   - **Polycrystalline** (PC)
   - **Single crystal** (SC)
   - **Large grain** (LG) → **better correlation** possible, only 3 grains
     - diameter ~28 mm
     - **2 marks** at the edges (90^0) for positioning in different measuring systems
     - got **EP (140 µm)** or **BCP (~40 µm)** @ DESY
     - **HPR** cleaned (cleanroom class 10) @ DESY
     - Transported under **Teflon® protection caps** to avoid contaminations. Caps removed only under UHV (~10^{-7} mbar) or under laminar air flow of the OP

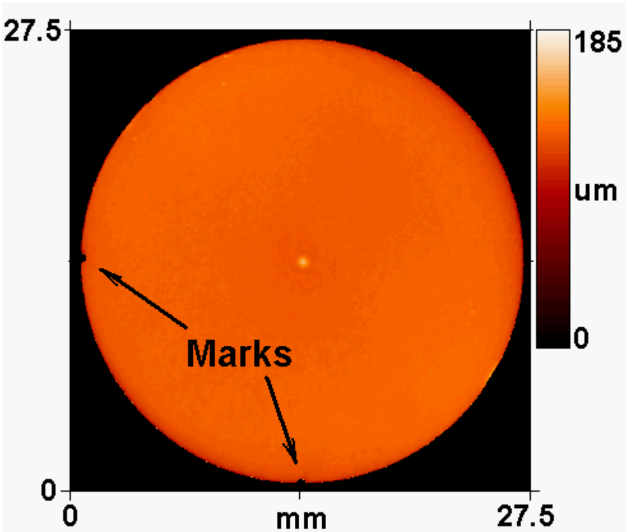








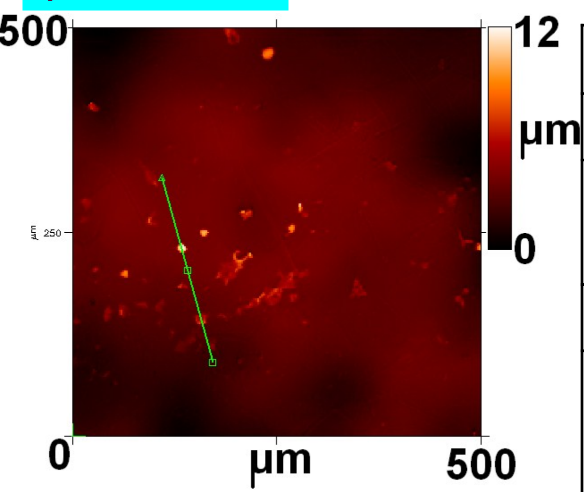
[1] G. Müller et.al., EPAC98, p. 1876 (1998).



5 types of surface defects:

- **particles**
- **scratches**
- **grain boundaries**
- **round hills and holes**
- **crater-like pits**

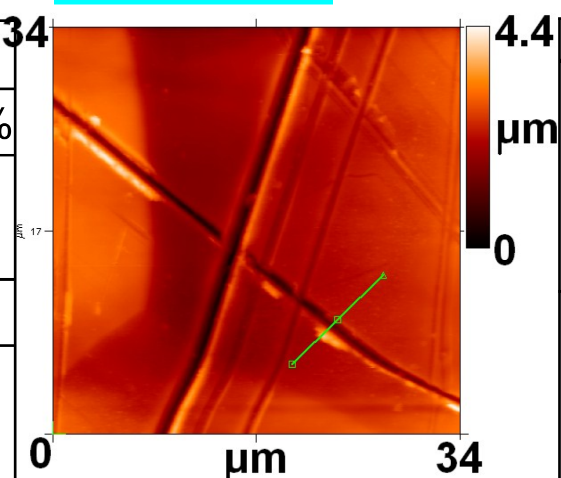
1) Particles:



< 5 μm	43 %
5 - 15 μm	48.4 %
15 - 25 μm	6.1 %
> 25 μm	2.5 %

R_a = 0.276 μm
R_q = 0.548 μm
$\beta_{E,max} \geq 15$

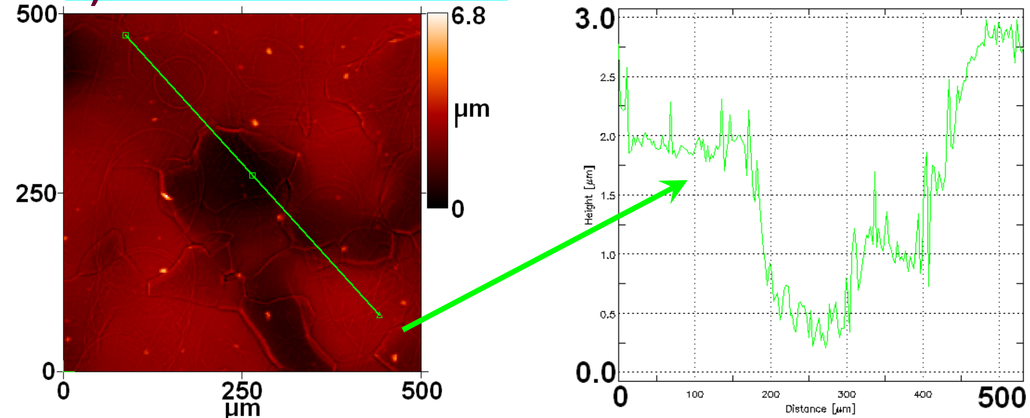
2) Scratches:

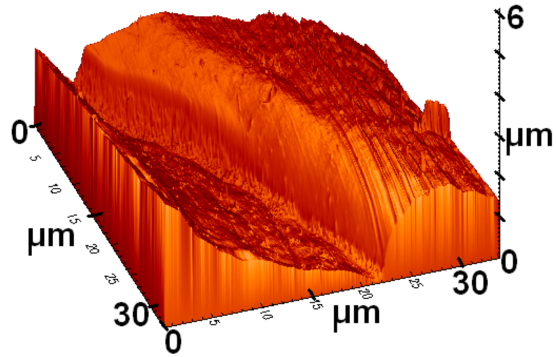


4 - 100 μm width
11 μm - 2.7 mm length
ridge height < 10 μm

R_a = 0.466 μm
R_q = 0.646 μm
$\beta_{E,max} \geq 13$

3) Grain boundaries:

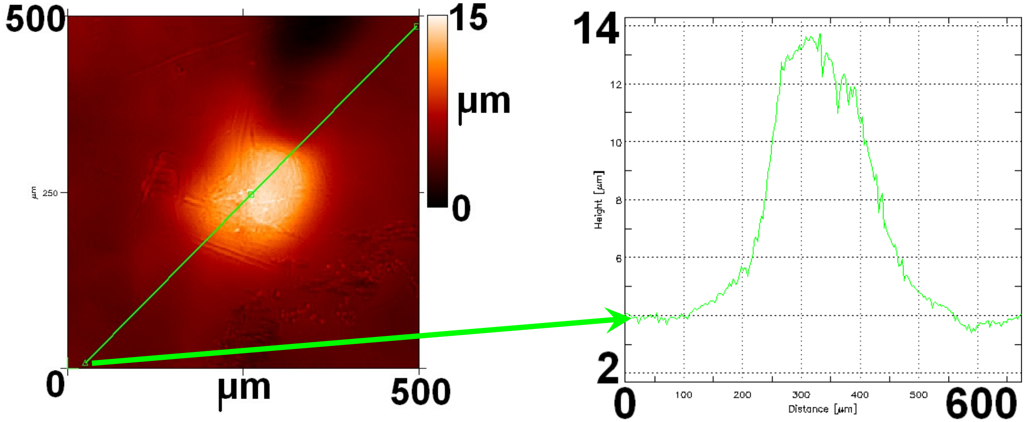




step height < 1.55 µm
edge radius < 0.78 µm

$\beta_{E,max} < 4$

4) Round hills and holes:



height < 17 µm
size 10 - 440 µm

$R_a = 0.295$ µm
$R_q = 0.489$ µm
$\beta_{E,max} < 4$

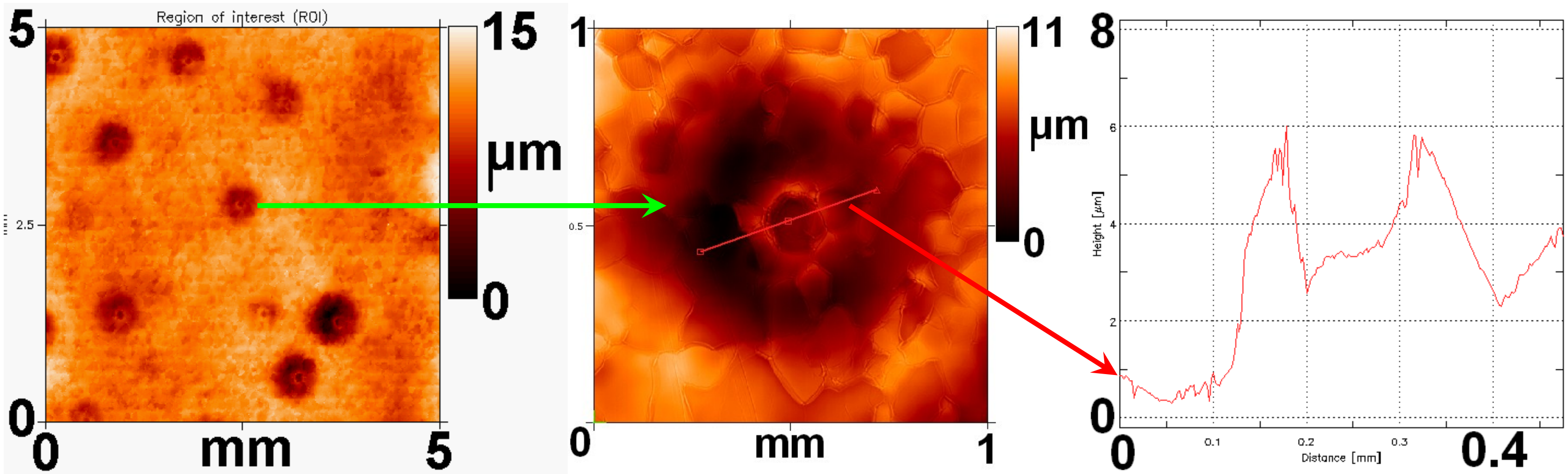
⇒ foreign material inclusions → modified chemical reactions during EP

⇒ small β_E → only weak EFE expected

⇒ but **magnetic** field enhancement β_M should be considered

Cuts from nine-cell Nb cavities

5) Pits on a half-cell surface of tested Nb cavity (E_{acc} < 16 MV/m, Z111):



⇒ ≤ Ø 800 µm with crater-like centers (~Ø 100µm) and sharp rims (5-10 µm height)

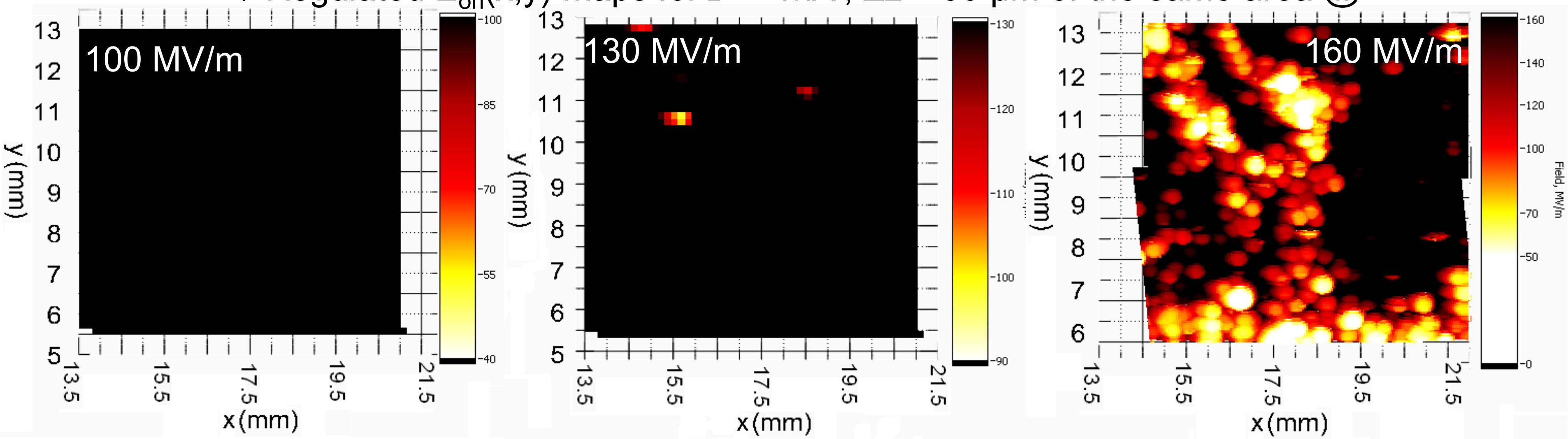
⇒ R_a = 0.418 µm, R_q = 0.557 µm, $\beta_{E,max}$ > 10

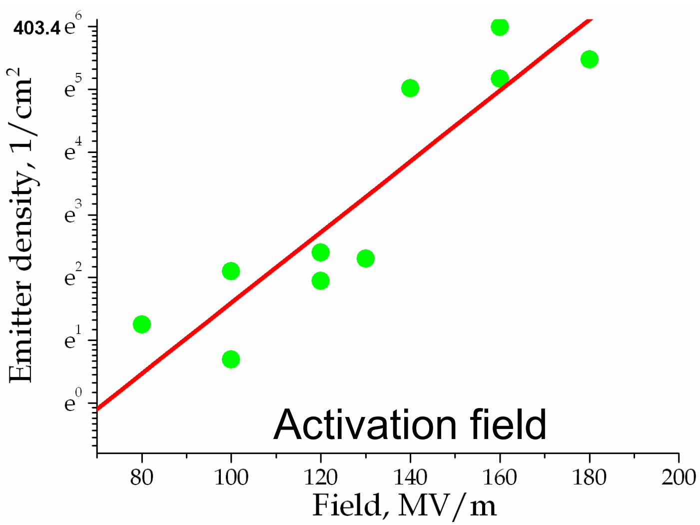
⇒ Appear more densely distributed on the lower than on the upper half-cell of vertically treated cavities.

⇒ Hints for problems with washing off the acid solution after electropolishing

FE results (1): EP poly-Nb samples

⇒ Regulated $E_{on}(x,y)$ maps for I = 1nA , $\Delta z \approx$ 50 µm of the same area @

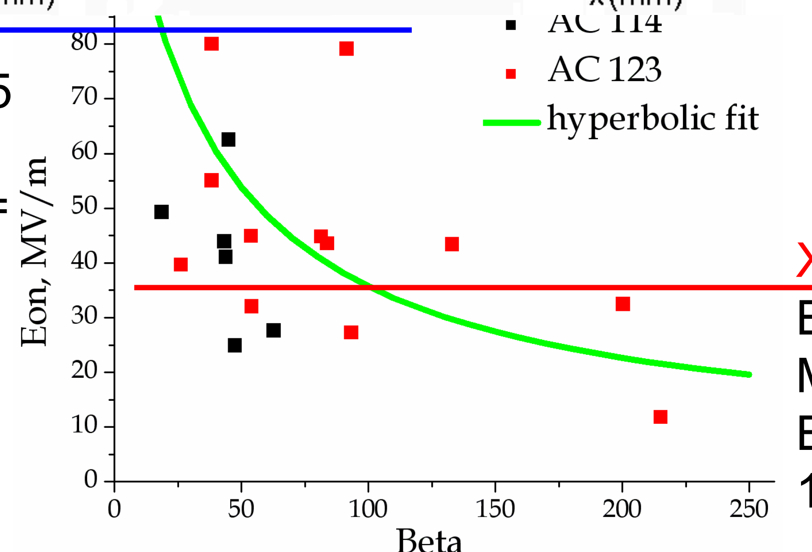




ILC

E_{acc}= 35 MV/m

E_p/E_{acc}= 2.4



XFEL

E_{acc}=25 MV/m

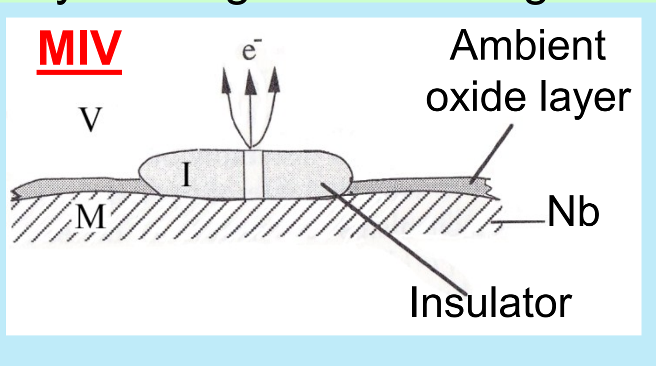
E_p/E_{acc}= 1.98

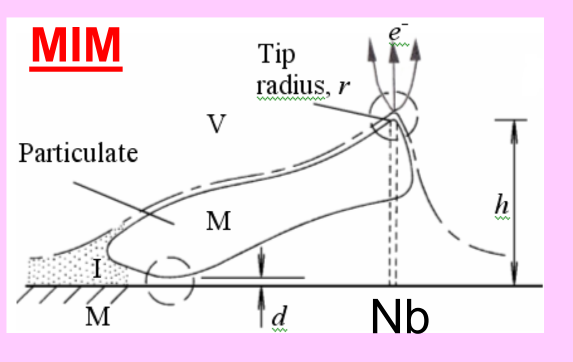
- ⇨ Emitter density increases exponentially
- ⇨ Activation of emitters is observed at E_{act} = (2-4) E_{on}
- ⇨ Scratches with **nm sharp edges** →high EFE
- ⇨ Defects with **β > 50** for XFEL and **β > 20** for ILC should be avoided

FE results (2): Explanations of the E activation effect

(1) Nb surface oxide:

→ activation by burning of conducting channels:

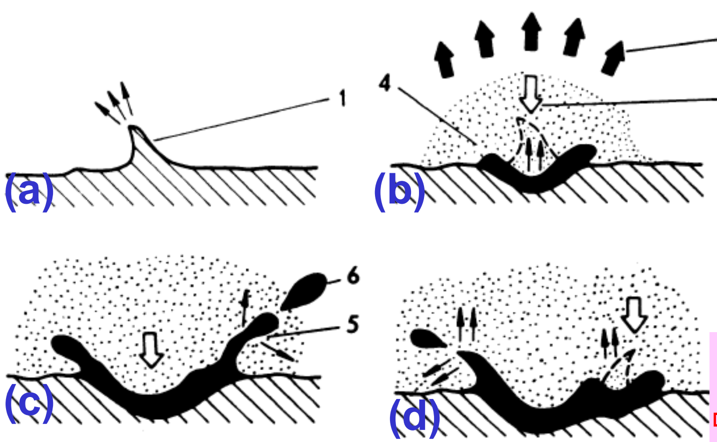


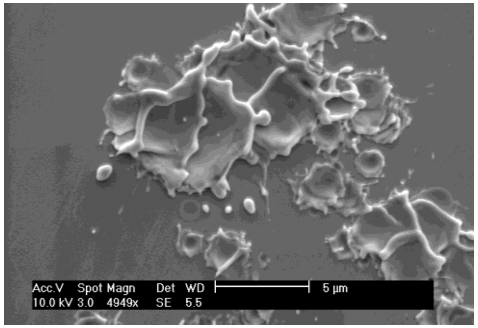


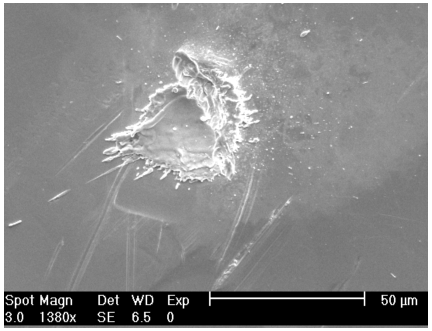
Switch-on state persists! for a long period without E under UHV at RT → permanent formation of conducting channels [1]

(2) Micro-discharge or explosive-emission-induced erosion of Nb [2]

- ►Micro-discharge → molten craters on a bigger area with sharper features as the initial ones
- ►The primary FE sites can be one of the above mentioned
- ►Process is irreversible







Impact for cavities:

⇨ **heating** [3] or **rf power** [2] might activate emitters too

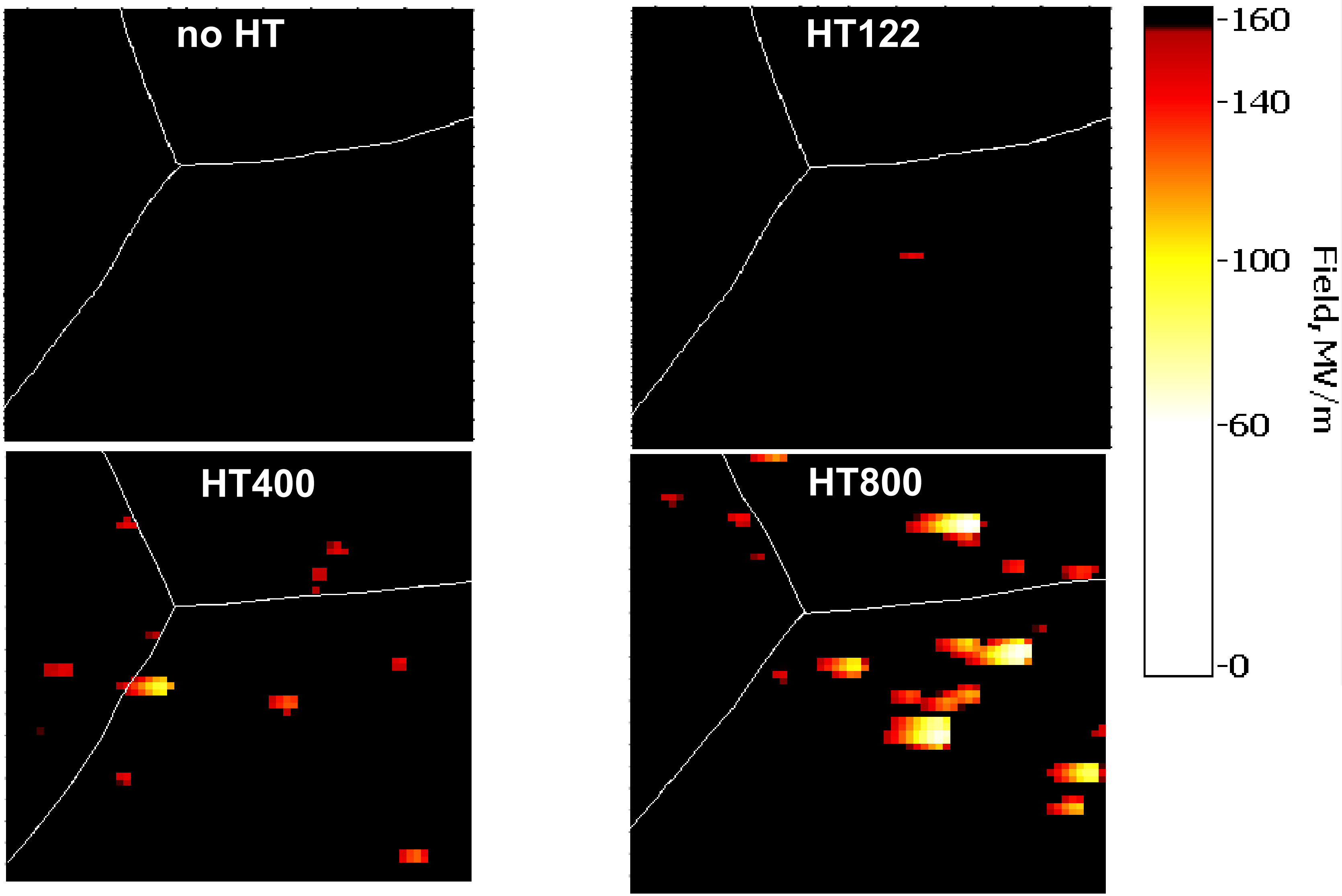
[1] R. V. Latham, "High vacuum insulation," (1995)
[2] J. W. Wang, et al. SLAC-PUB-7684 (1997)
[3] E. Mahner, Part. Acc. 46, pp.67-82 (1994)

FE & Heat treatment (1): Results on LG Nb samples

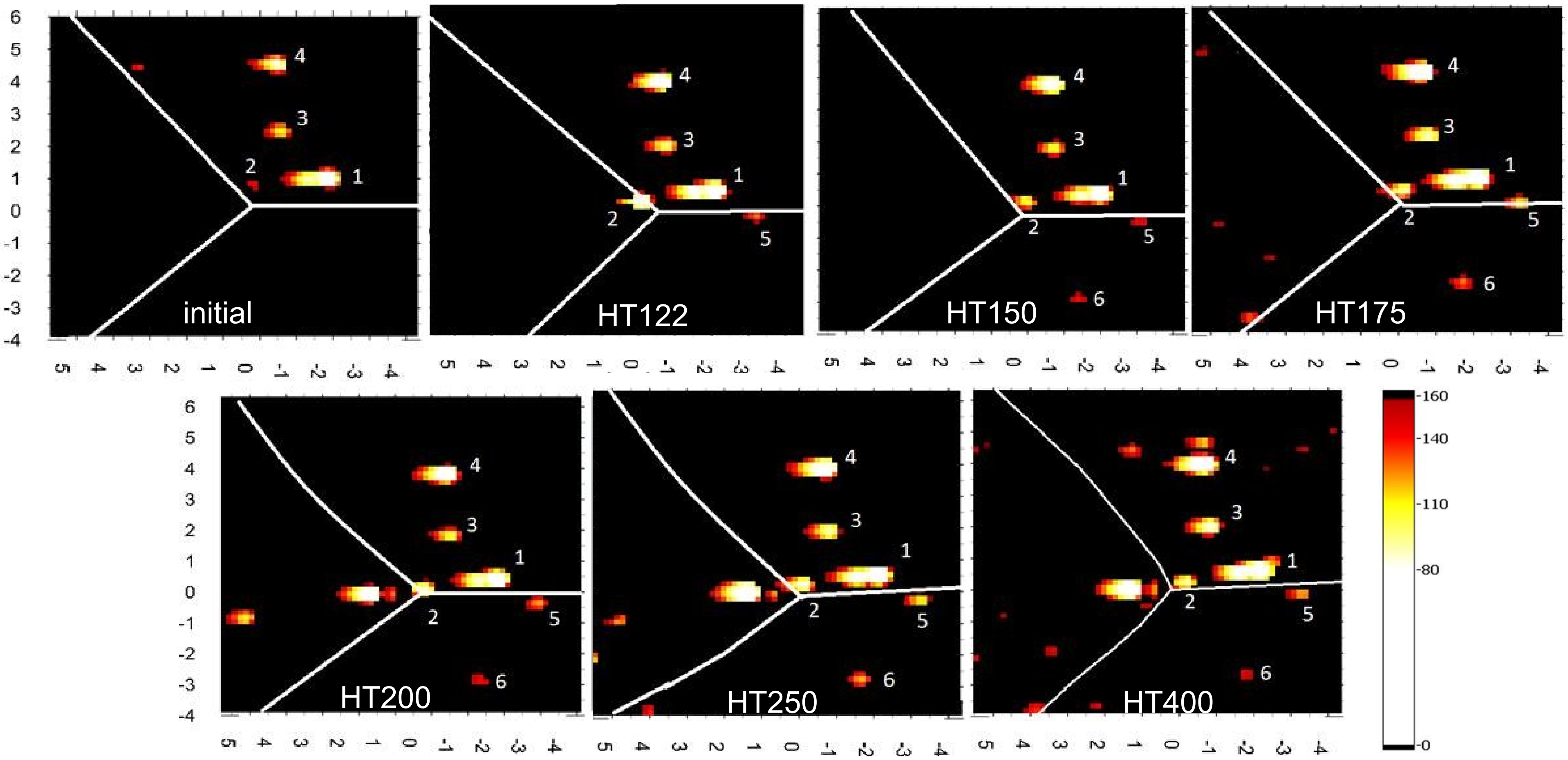
Field maps @ 1 nA fixed FE current: same 1cm² area, $Ø_a$ = 300µm

⇒ **No FE** on grain boundaries**!**

⇒ Does **grain orientation** plays a role**?**



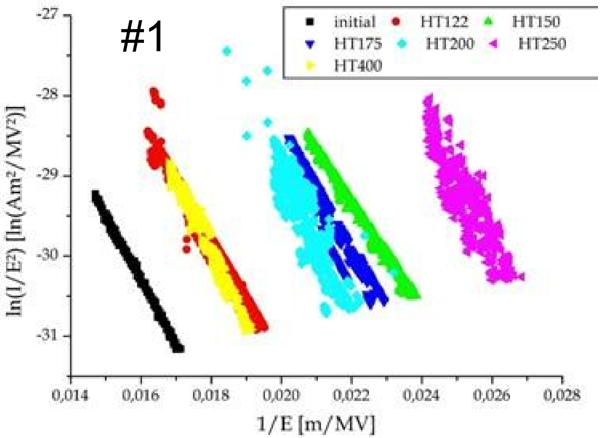
FE & Heat treatment (2): Results on LG Nb samples

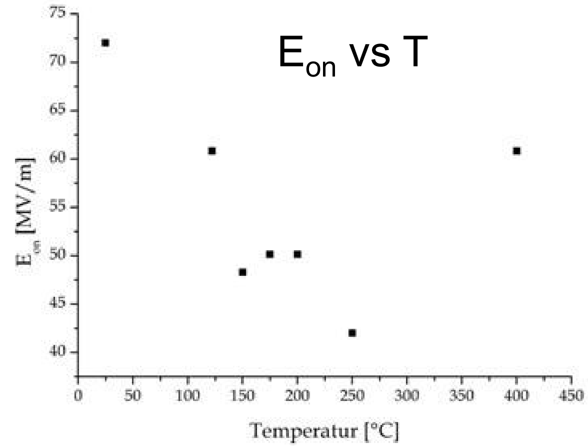


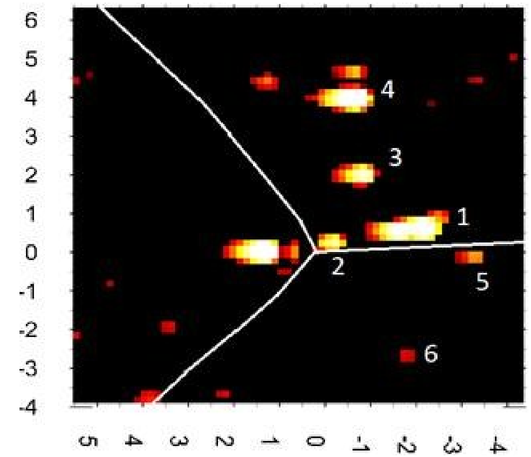
→ A clear **rise of the emitter density** (N/cm²) with increasing temperature

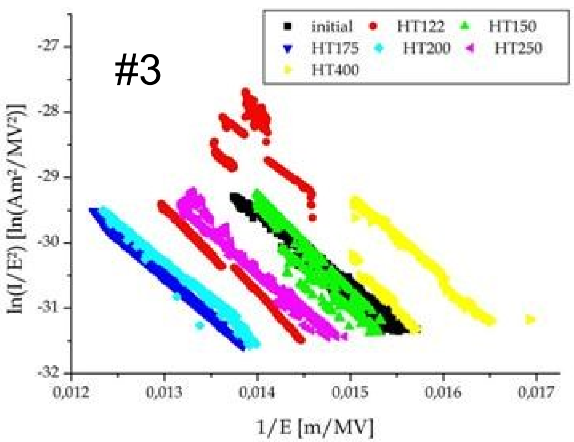
FE & Heat treatment (3): Conditioning of single emitters by HT

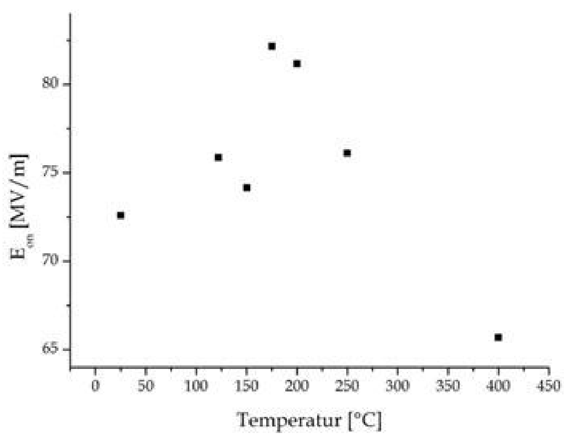
FN-Plots (log(I/E²) vs 1/E)







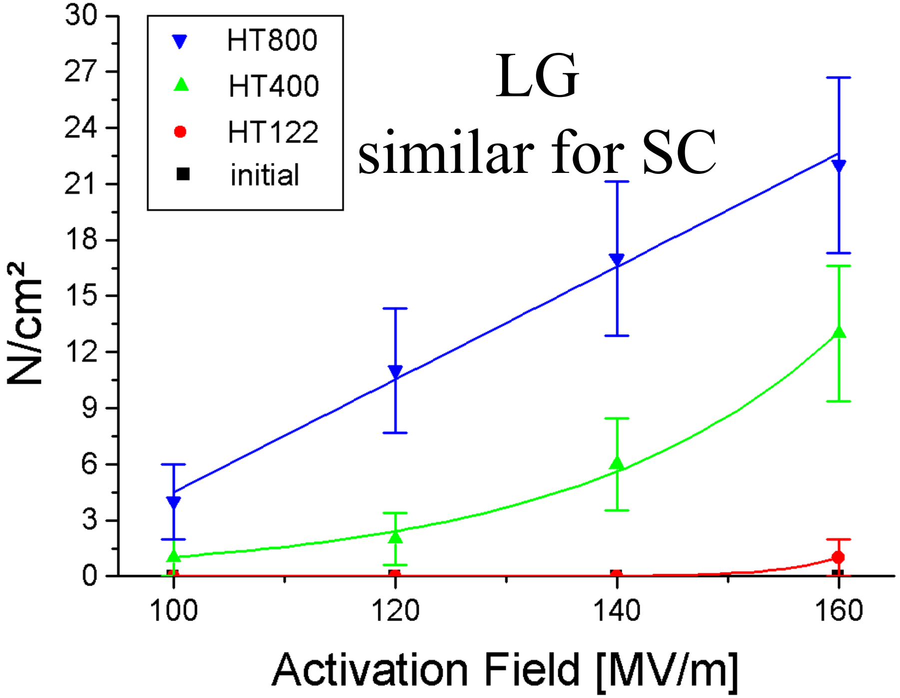


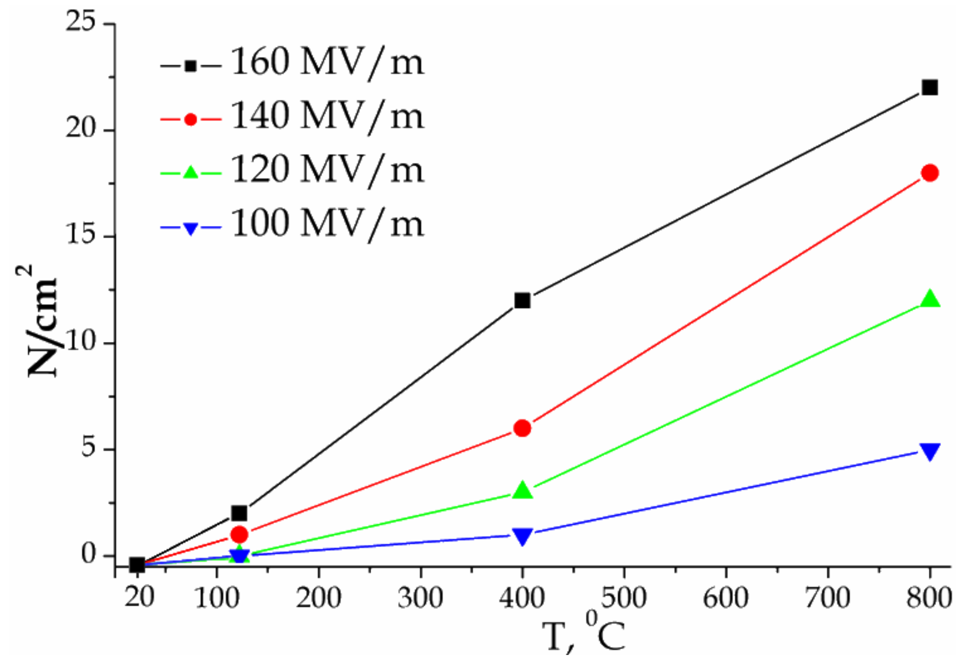


- Conditioning of emitter 1 and emitter 3 by HT
- Stability as well as E_{on} is affected by the HTs
- Two different emitters react in two completely different ways

→ HTs can make emitters either **stronger** (lower E_{on}) or **weaker** (higher E_{on})
→ No clear trend can be observed, yet
→ Is there a HT where most emitters become weak/strong?

FE & Heat treatment (4): Statistics





⇒ Emitter number density **increases** with T ^{0}C

⇒ Some **deactivation** is observed, but $N(E_{akt})$ still **increase** on average

⇒ $N(E_{akt})$ is **exponential** for (HT122, HT400)

but more **linear** for (HT800)

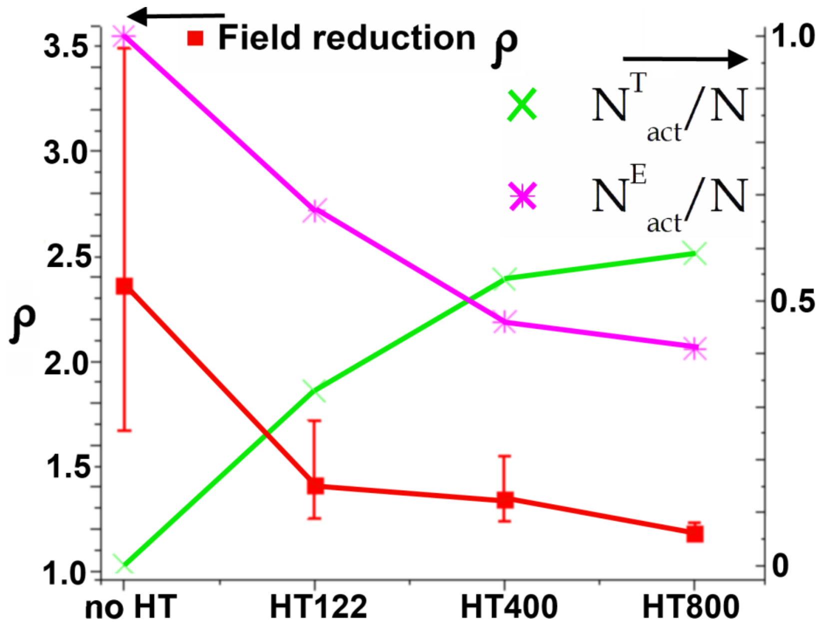
⇒ N(T) is **linear**

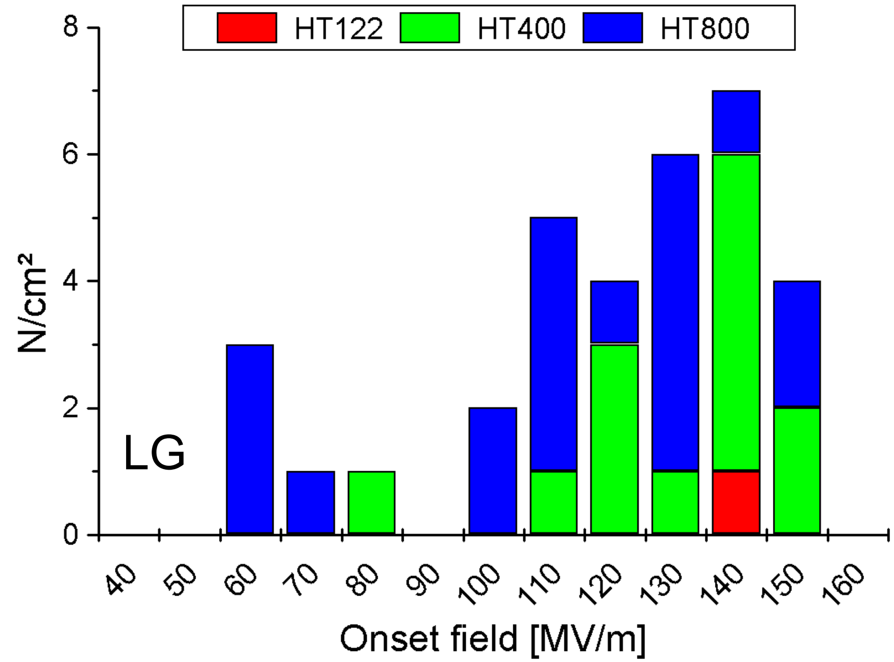
Reason?: Competing mechanisms

FE & Heat treatment (5): Activation effect & onset field

There is a number of **potential emitters** which might be activated by:

- electric field (N_{act}^{E}) → **exponential increase with E [1]**
- heating (N_{act}^{T}) → **linear increase with T⁰C**
- rf power → ???





⇒ Number of **T⁰C** activated emitters N_{act}^{T} **increases** with T⁰C

⇒ Number of **E** activated emitters N_{act}^{E} **decreases** with T⁰C

⇒ Final onset field E_{on} become smaller with T⁰C (→ ~50 MV/m)

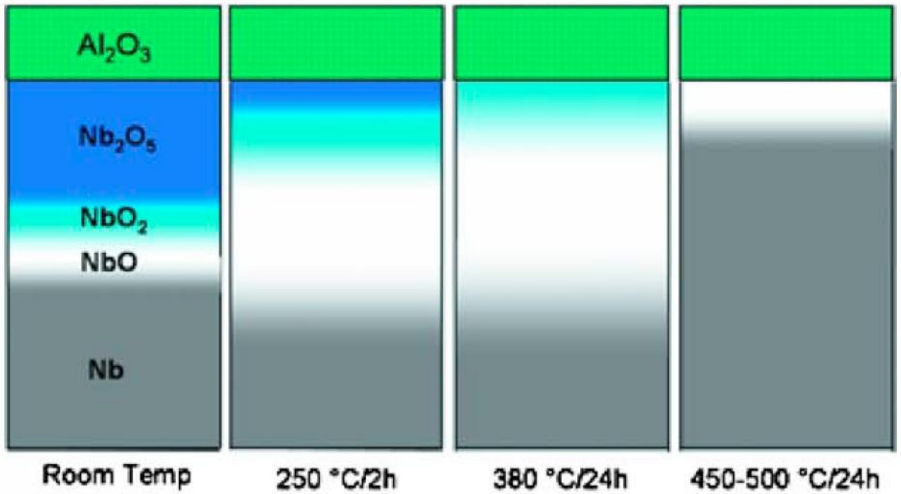
→ emitters **become stronger!!!** @ fields **relevant for acc.**

Reduction factor ρ:
- Smaller that for EP Nb
- Decrease with T⁰C

[1] A. Navitski PhD thesis BUW (2010)

FE & Heat treatment (6): Explanation of T°C activation?

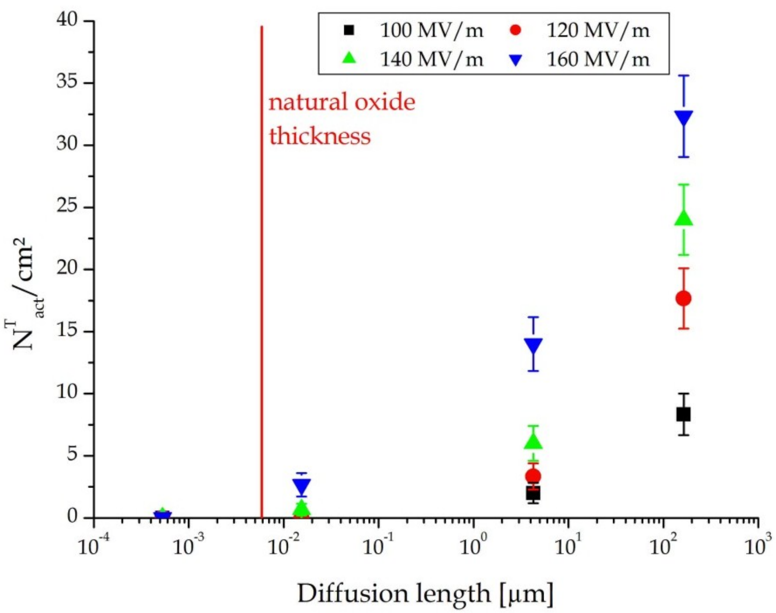
Reduction of isolating Nb_2O_5 layer by heat treatment [1]:



⇒ Enhance **MIM-activation** of particles

⇒ Enhance **MIV-activation** or surface defects

Nb_2O_5 natural (~5nm) isolating
NbO_2 semiconducting
NbO metalic



→ First emission **appears @ D(T)> natural Nb_2O_5**

→ **Increase** of *D(T)* lead to **decrease** of d_{Ox} and **increase** of N even for low electric fields

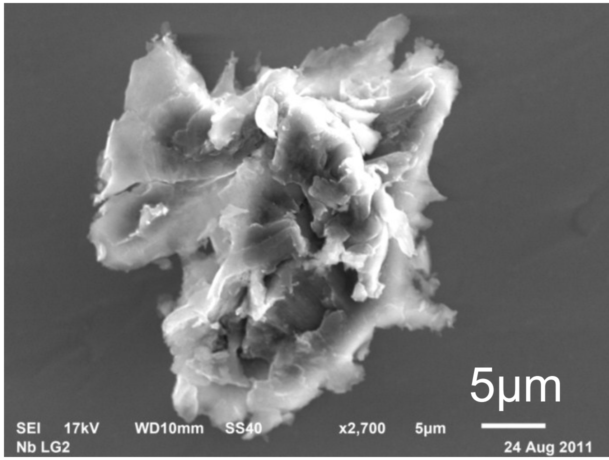
→ Slightly **different** *D(T)* for **different** crystal orientation **might contribute** to the varying emitter activation

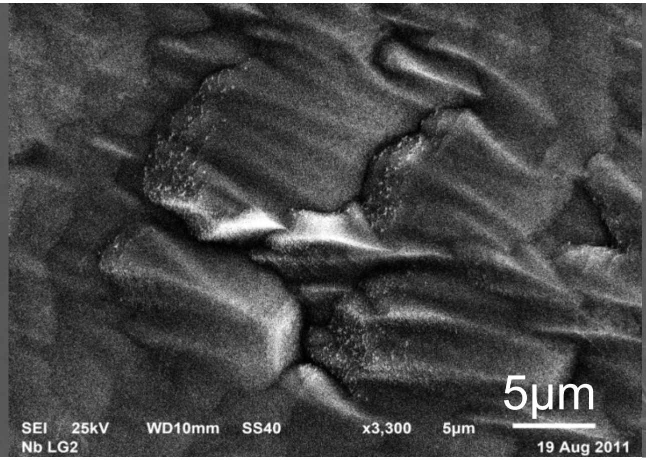
$$D(T) = \sqrt{t \cdot k(T)}$$

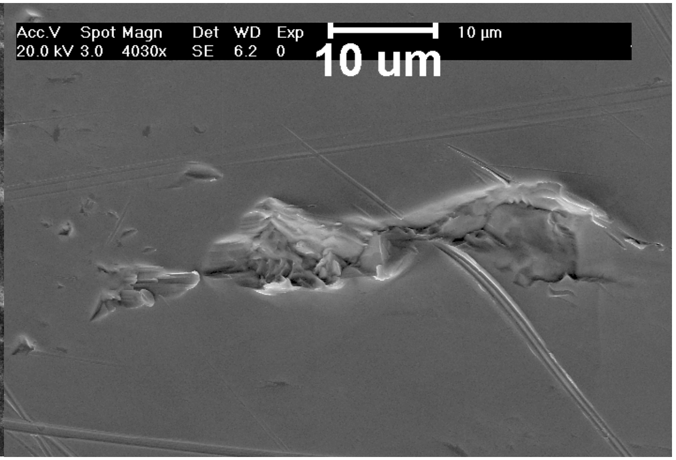
Impact on cavities:
⇨ **Heating** activate emitters, **rf power, too?**

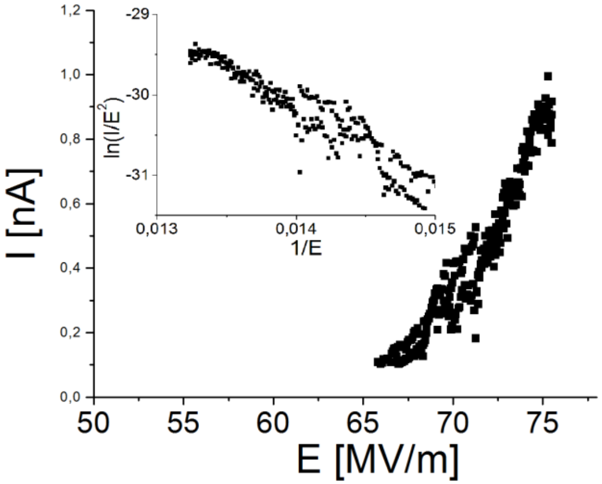
[1] T. Proslier et.al. Appl. Phys. Let., 93, 192504 (2008)
[2] G. Ciovati, Appl. Phys. Letters **89**, 022507 (2006).

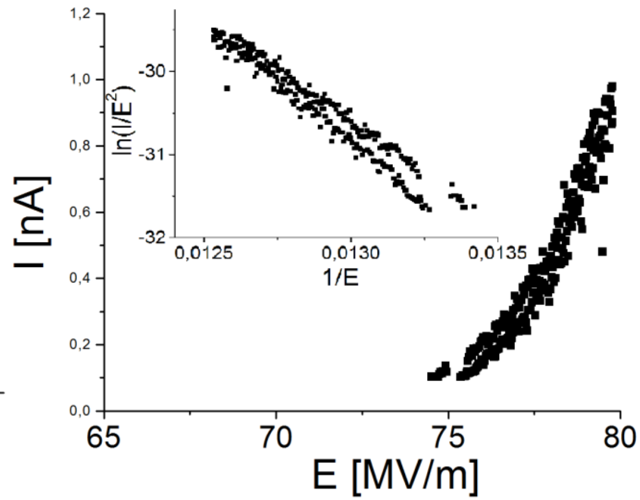
What emits (1): SEM-FESM correlated study

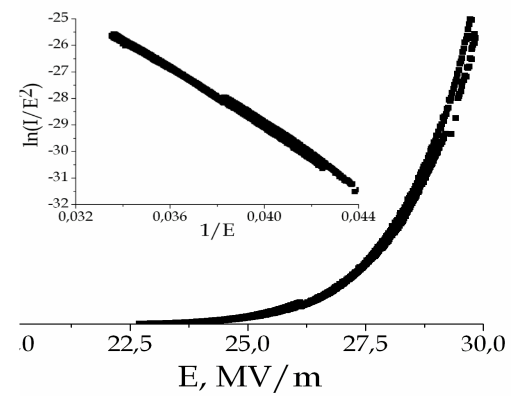












Al-Partikel

β=37-86

S_{FN}=0.2-143nm²

E_{on}=78 MV/m

Material defect:

β=19-22

S_{FN}=27µm²

E_{on}=80 MV/m

Scratch:

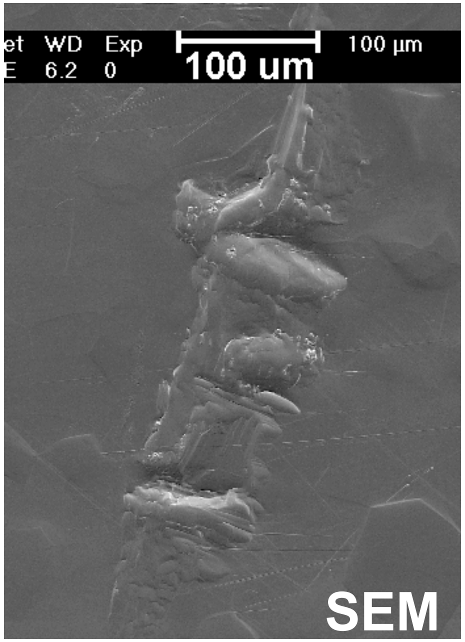
β=93

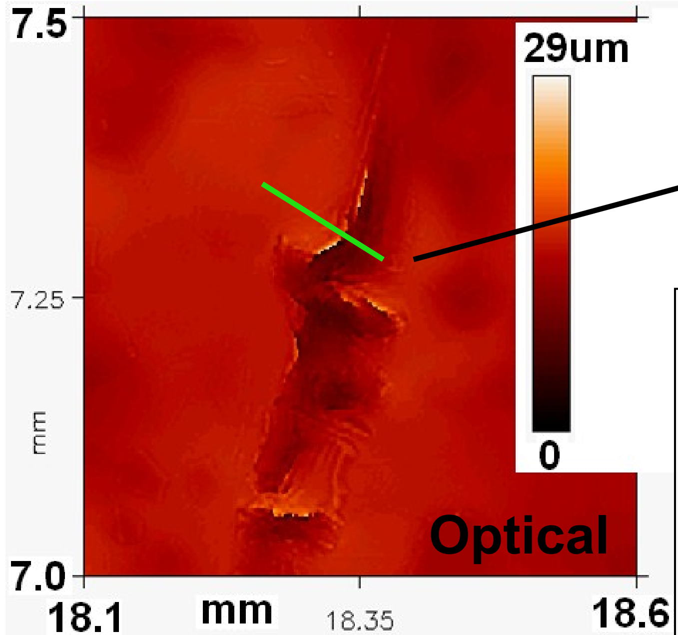
S_{FN}=96 nm²

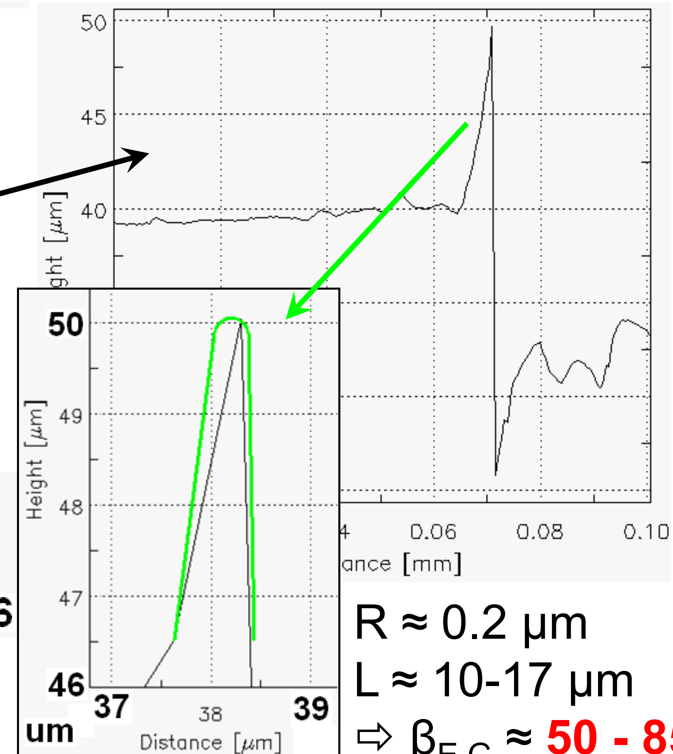
E_{on}=27 MV/m

E_{act} ≈ 160 MV/m

What emits (2): Example of a scratch-emitter



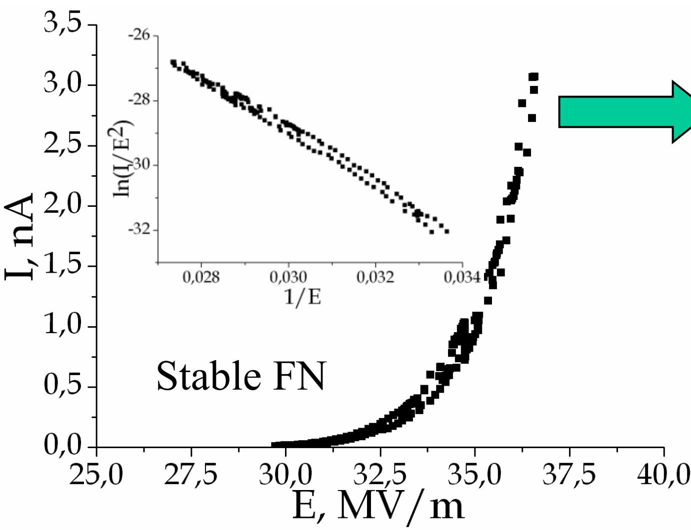




R ≈ 0.2 µm

L ≈ 10-17 µm

⇨ $\beta_{E,G}$ ≈ **50 - 85**



E_{act} ≈160 MV/m

E_{on} = 35 MV/m

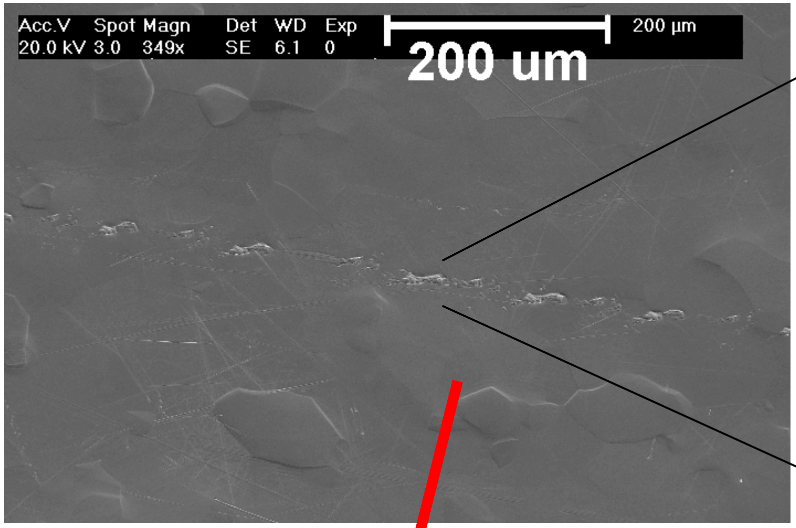
S ≈ 70 nm^2

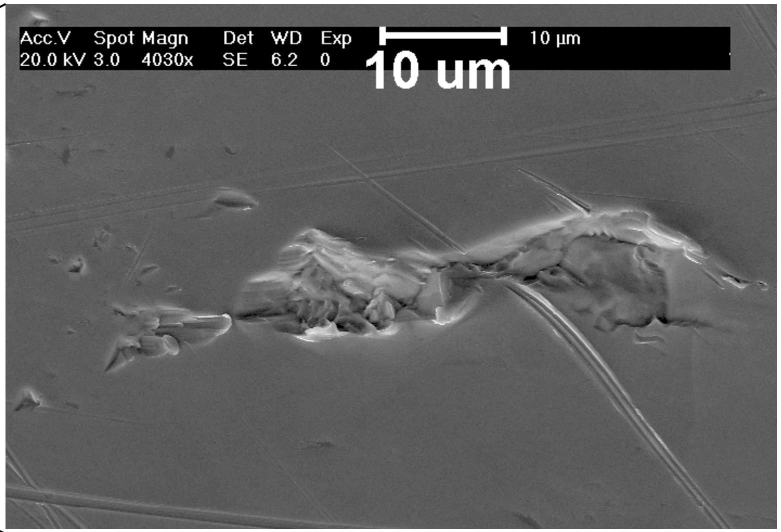
$\beta_{E,FN}$ ≈ **60**

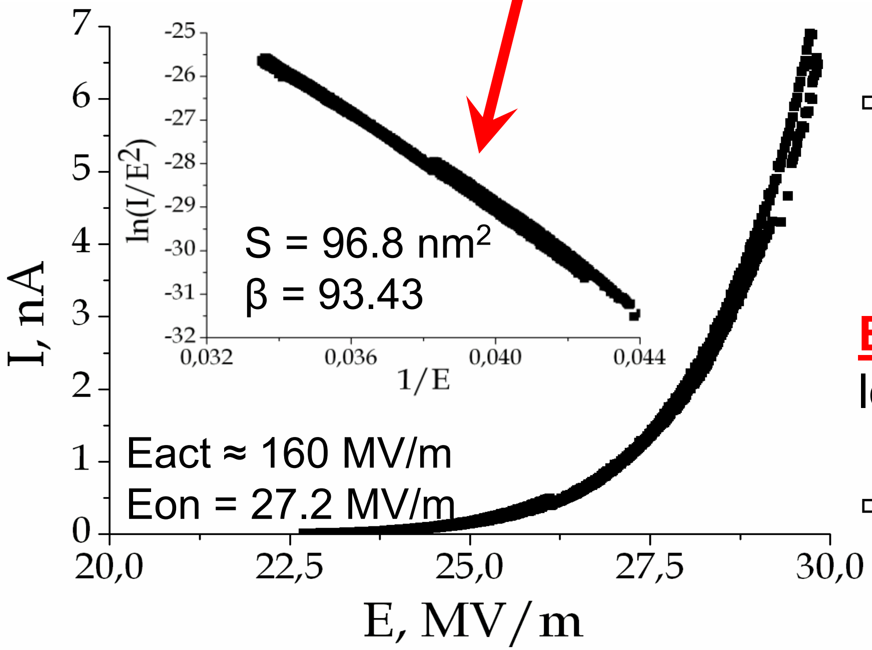
⇨ Large scratches → good correlation

$\beta_{E,FN} \approx \beta_{E,G}$

What emits (3): Example of a scratch-emitter 2







⇨ Stable I-V → good electrical contact → emission from surface irregularities (no influence of adsorbates)

But: Mostly it is **difficult** to identify emitter location due to **complex geometry** of defects

⇨ AFM can be helpful in case of small clear structures and enough positioning accuracy

What emits (4): Statistics

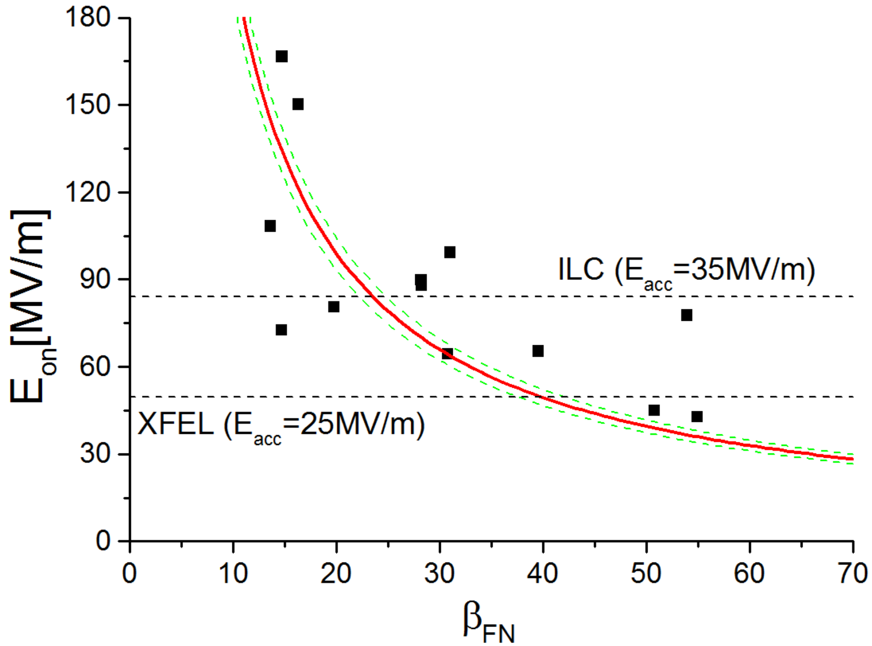
Three types of HT-activated emitters:

a. 56% particulates (e.g. **Nb**, **Si**, **Al**)
b. 30% scratches
c. 14% other surface features

Deactivation or weakening of FE after exposure to air:

Reason?: - Oxidation of Nb?
- Adsorbates?

Overall impact on Nb cavities performance



FE studies: Summary & outlook

- **OP** & **AFM** → fast quality control of Nb surfaces (roughness/defects)
- **FESM** is very useful tool for FE studies

  but: -only for small samples; -dust-free operation requires cleanroom

  → concentrate on emitter processing, study of FE-preventing coatings/treatment
- Highest field enhancement given by nm sharp 1) scratch-protrusions & 2) particles

  - to be prevented by:1) more careful handling and 2) better cleanliness or ???.
- Grain boundaries: **no FE** but might reduce the magnetic field limit?
- Heat treatment ($T \geq 120^0C$) leads to activation of field emitters:

  → No. of emitters increase exponentially with E field and linearly with T, °C

  → Activation by E field at E_{act}/E_{on}= 3 for polycryst. & 1.7 for SC, LG Nb

  → There is a number of **potential emitters** which might be activated

  → **E** and **T** are competing driving forces of activation

  → **Avoid** any HTs of non-cleaned and rough Nb

  → activation by **rf power**!!! in a cavity should be considered and studied
- Nb surface oxide seems to be **responsible** for the activation

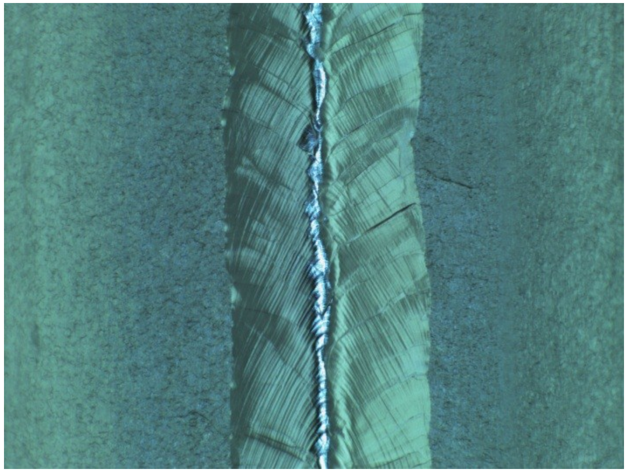
  → **Will intentional oxidation prevent low field FE?**

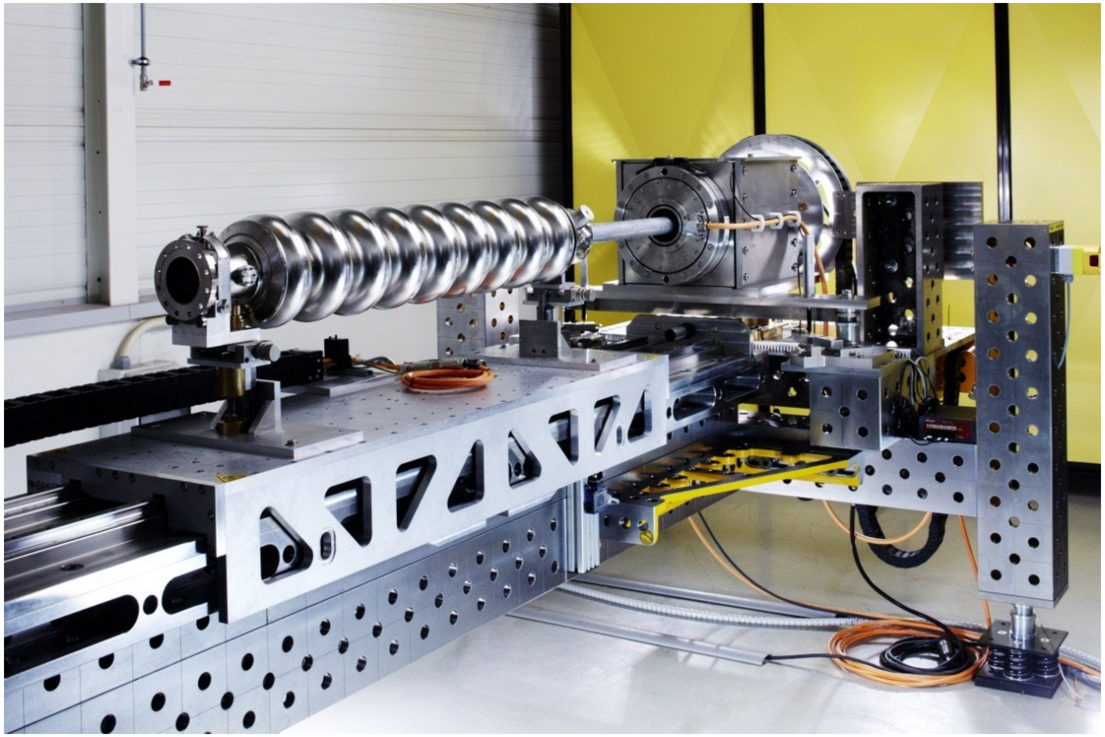
  → does grain orientation play a role?

→ Defects with **β > 50** for FXEL and **β > 20** for ILC should be **avoided**

OBACHT – Optical Bench for Automated Cavity Inspection with High Resolution on Short Time Scales

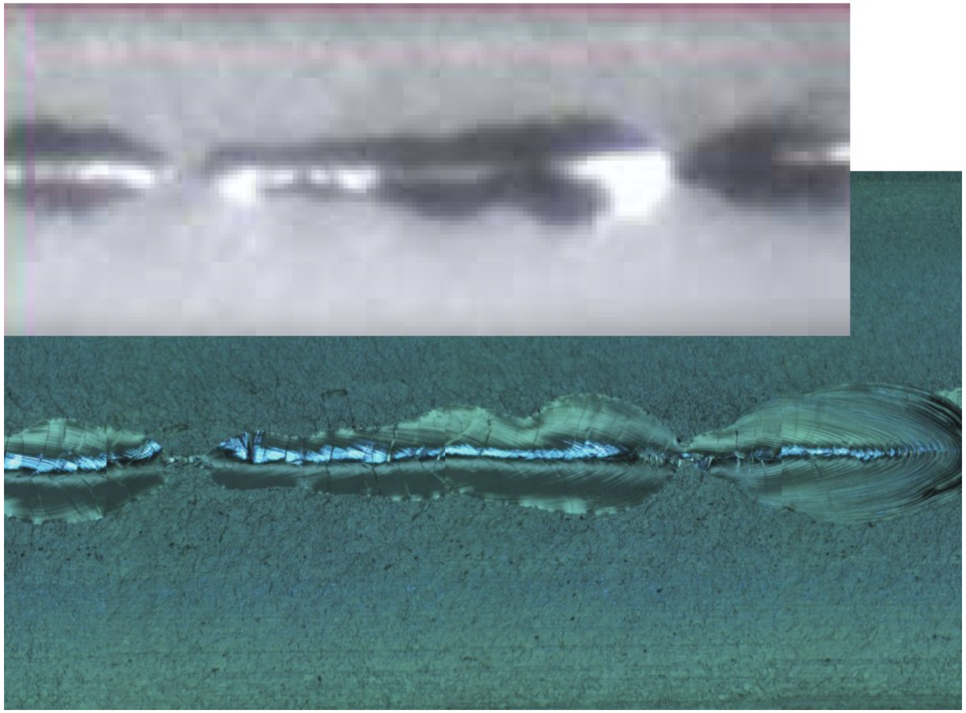
- **Large amount** of cavities (also dressed) can be **inspected**: ILC-HiGrade, (European XFEL)
- **Fully automated** (LabView) cavity inspection with Kyoto Camera System yields
  - 2790 pictures in ~8 hours: welding seems of equator (iris) every 4°(10°) + equator left/right
  - ~12 x 9 mm pictures (2488 x 2616 pixels, ~10 µm/pixel) in *.bmp, *.png and/or *.jpg
- Movable sled with cavity (axial posit. ~10 µm) and Kyoto camera (angular posit. ~0.01°),
- Collision free movements assured by optical tests (**to be upgraded now**)
- Fully **automatic** cavity **positioning**, **illumination**, and image **recording**
- **Automatic** image **processing** and possibly defect **recognition** (for details contact M. Wenskat)
-





Examples of the OBACHT tests (1)

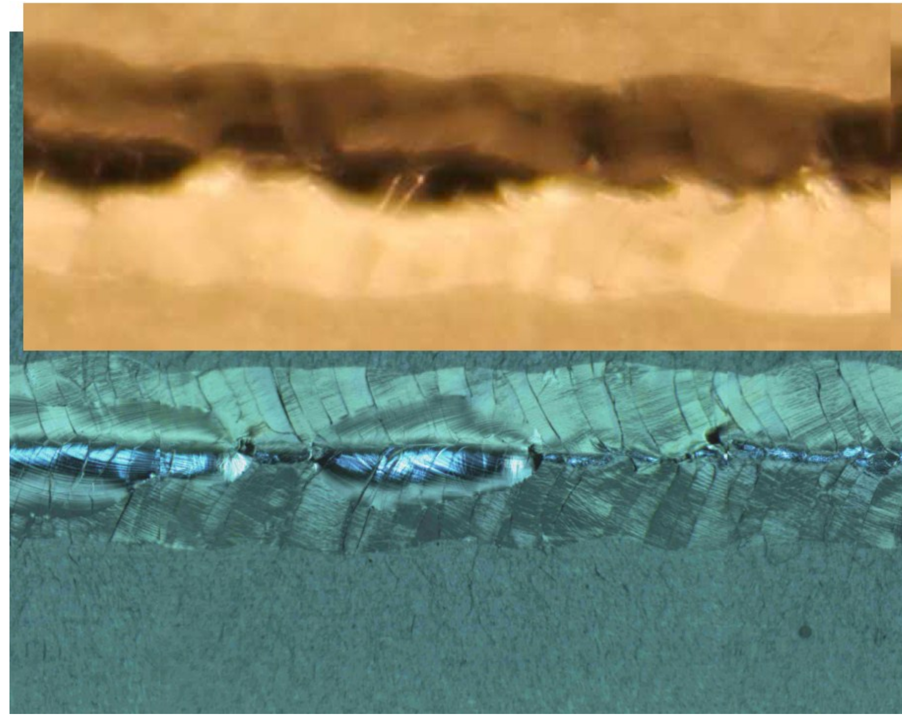
> **Optimization** of equator welding parameters:



Initial, **not optimized**

→ **e^{-} -beam not penetrated everywhere**

→ **strong variation of the seem- width**



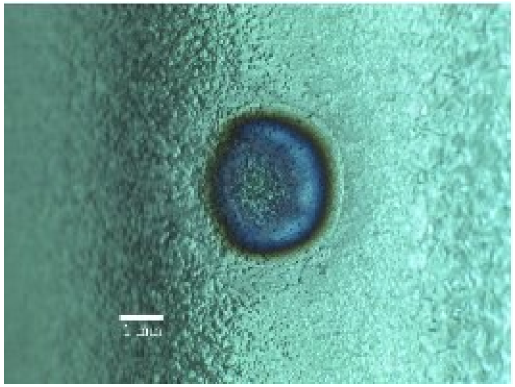
Final, **optimized**

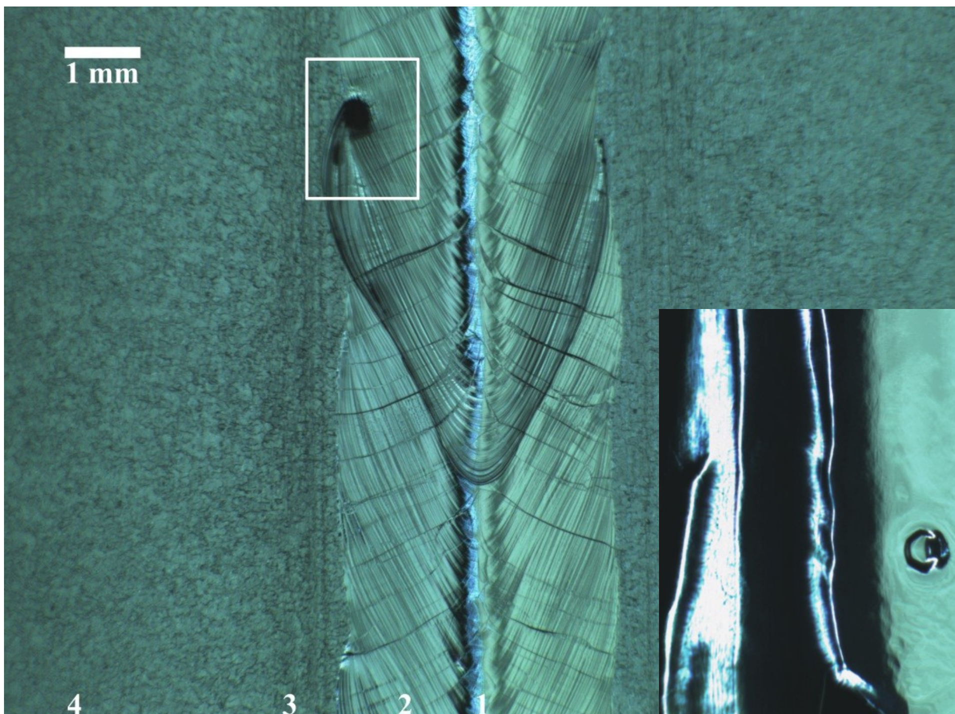
→ **e^{-} -beam fully penetrated**

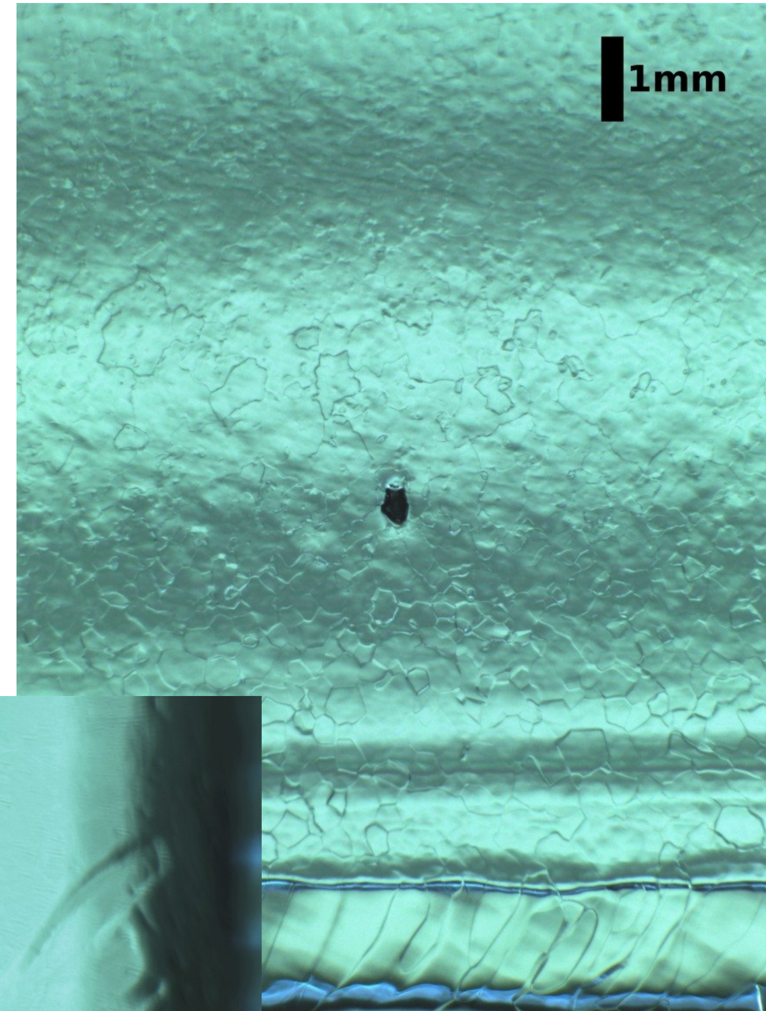
→ **homogeneous welding seem**

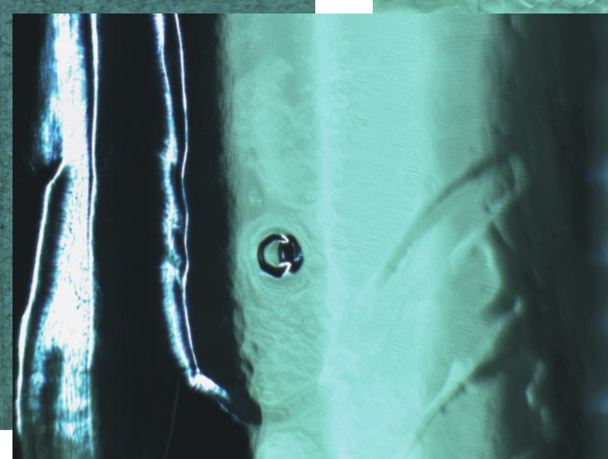
> **OBACHT** provides much **better resolution and image quality** as compared to the conventional **endoscopes** (see upper images)

Examples of the OBACHT tests (2)

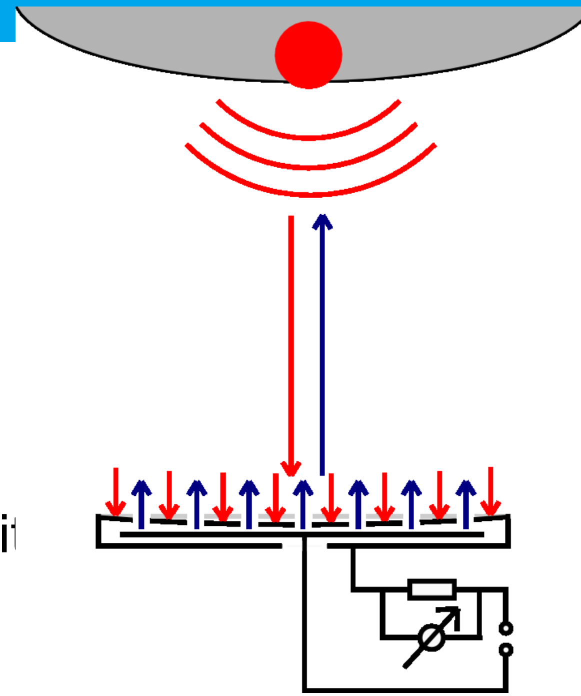








Quench localization by Second sound (1)

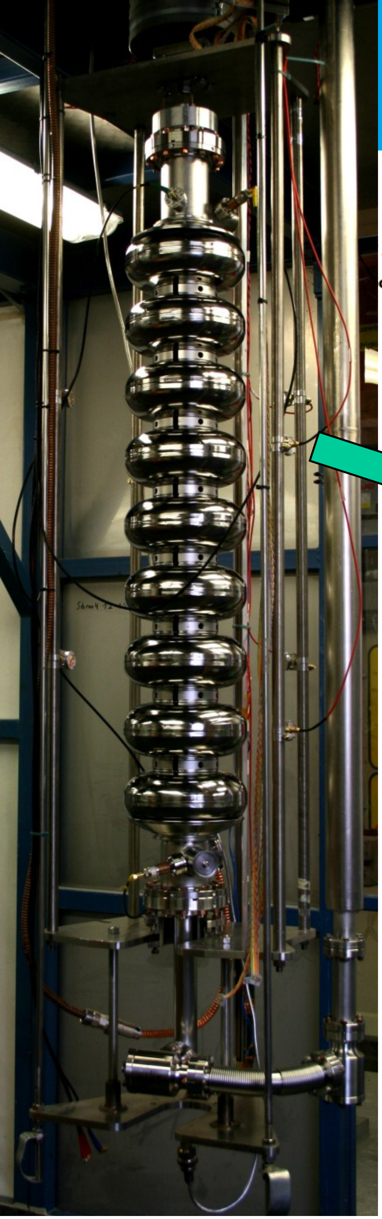


A quenching spot provides a heat pulse leading to
→ temperature wave or 2nd Sound
→ **disequilibrium**: 'superfluid' helium (Bose-Einstein condensate) breaks to 'normal' liquid helium
→ **equalization** induces He flow which can be measured

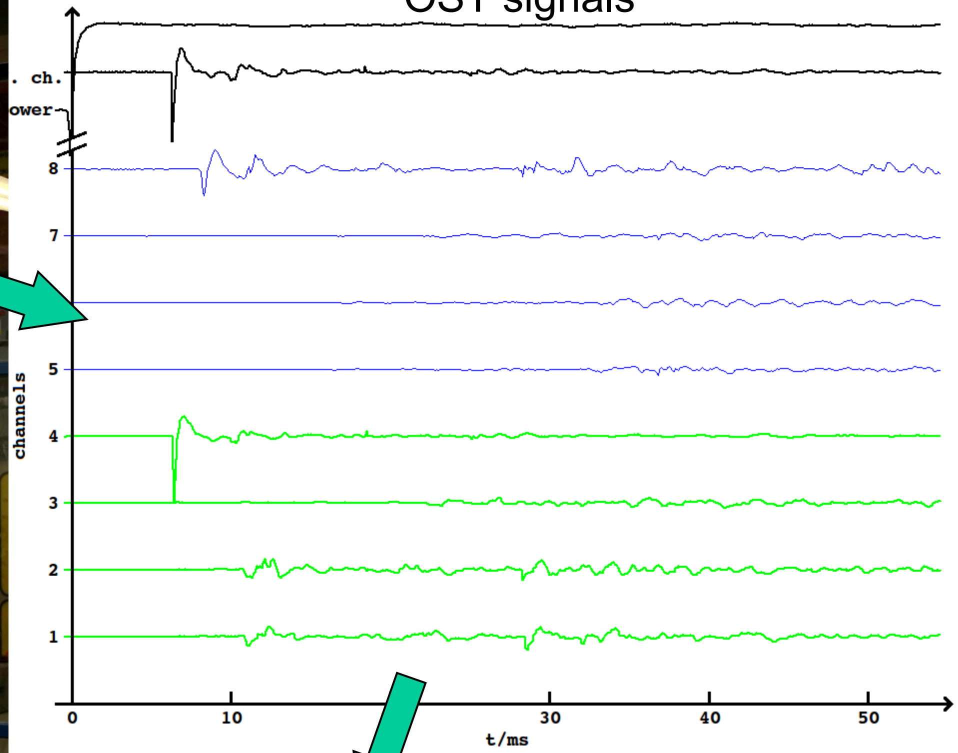
- Transducer consists of a metal plate and a porous diaphragm with a thin Au-layer connected as capacit
- 2nd sound wave will make the membrane oscillate
- Voltage changes can be measured
- Determination of quench location via triangulation
- A first setup and first measurements have been realized at Cornell University, USA since 2008 [1]

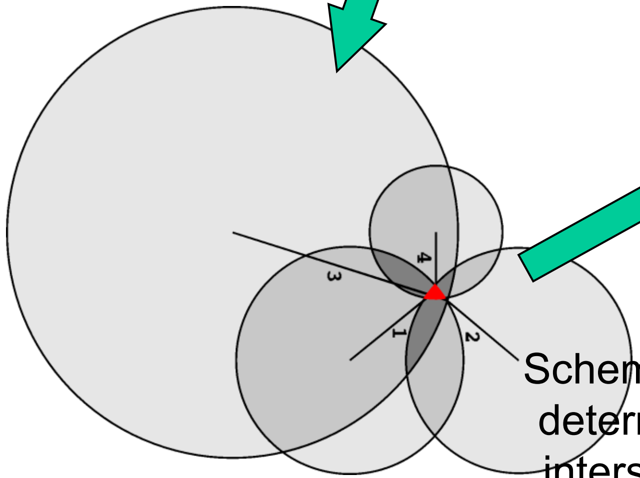
[1] Z.A. Conway et al., Oscillating Superleak Transducers for quench detection in superconducting ILC cavities cooled with He-II, Proceedings of LINAC08, Victoria, BC, Canada THP036

Quench localization by Second sound (2)

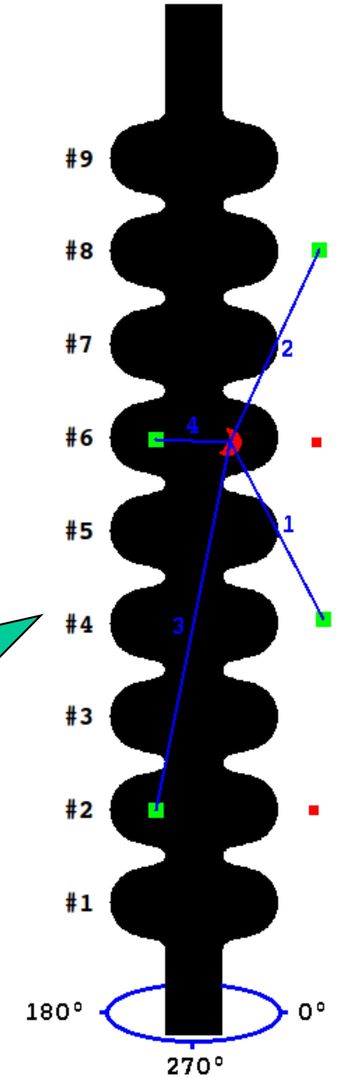


OST signals





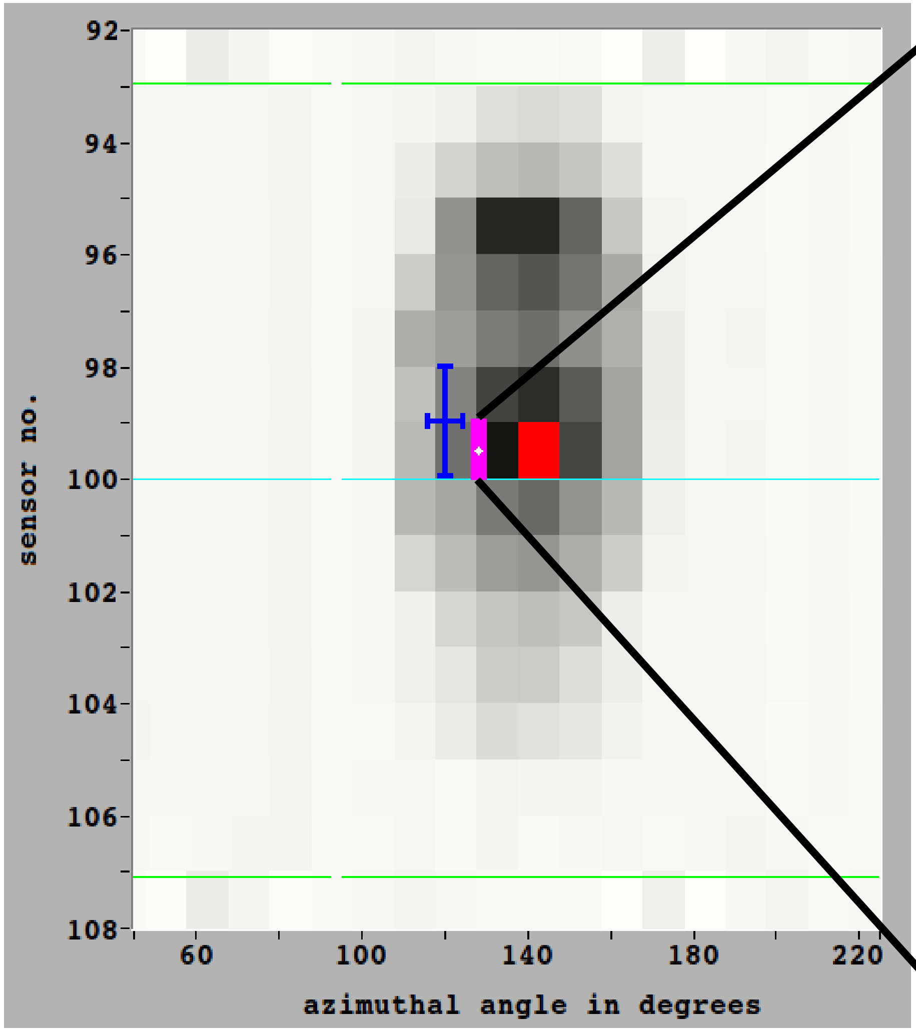
Schematic drawing of determination of the intersecting volume

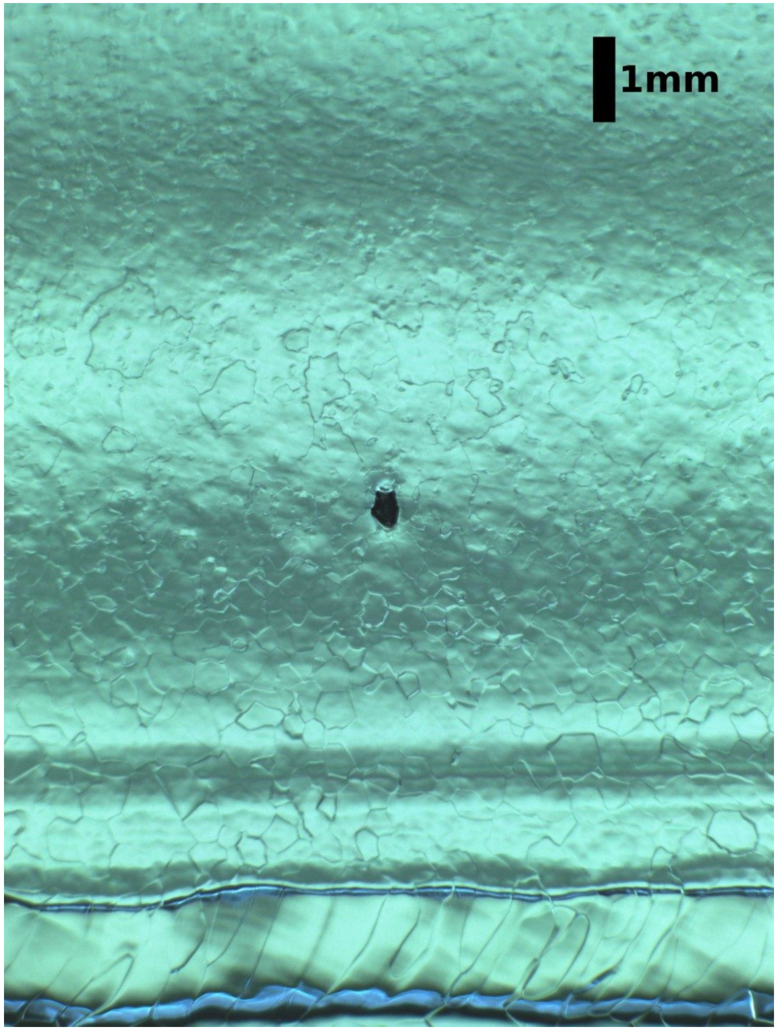


Calculation result

Quench localization example

- Z161, cell #2 in pi-mode: Second sound (blue) vs. OBACHT (pink) and T-map (red)





Cavity surface & Quench studies: Summary & outlook

- Real 9-cell cavity can be inspected and analyzed also during mass production
- OBACHT optical inspection & 2^{nd} Sound quench localization used @DESY routinely
- 2^{nd} Sound setup is reliable and is able to locate the quench position with the same precision like the temperature mapping (~10 mm)
  → **Upgrade** to 16 OSTs per insert for better accuracy and additional R&D planned
- Automatic image processing and defect recognition is still to be optimized/developed to analyze thousands of pictures taken
- Unfortunately, still not clear correlation of all diagnostic methods (~10)
  - Quench localization and optical inspection do not fit
  - Often huge "objects" seen with optical inspection – no effect for performance
  - Additional surface mapping technique required?

Future plans:

- Clear identification of the gradient limiting factors

  → 24 cavities ordered within the EU ILC-HiGrade program for further analysis/diagnostics
- Solid understanding/control of the industrial mass-production process (XFEL)
- Elaboration of cavity treatment technique providing

  at least E_{acc} > 35 MV/m at production yield of >90% in one pass

Thank you for your attention !

BERGISCHE UNIVERSITÄT WUPPERTAL

DESY

PHYSICS AT THE TERA SCALE
Helmholtz Alliance

Acknowledgments

- Dr. R. Heiderhoff from BUW, J. Ziegler, A. Matheisen, N. Steinhau-Kuehl from DESY
- Financial sup.: Helmholtz Alliance “Physics at the Terascale,” BMBF “Verb. projekt” 05H09PX5

HELMHOLTZ ASSOCIATION · ilc higrade · SEVENTH FRAMEWORK PROGRAMME · CRISP · Bundesministerium für Bildung und Forschung

Back slides

Back slides

Former Heat-experiments + field emission:

*E. Mahner, 1994 (*low-purity Nb samples [3]*):*

- increase of emitter density @ T < 800 ^{0}C
- decrease @ T < 1000 ^{0}C
- disappearing of emitters @ T > 1200 ^{0}C
- no clear correlation to surface defects
- speculation about segregation of impurities @ grain boundaries

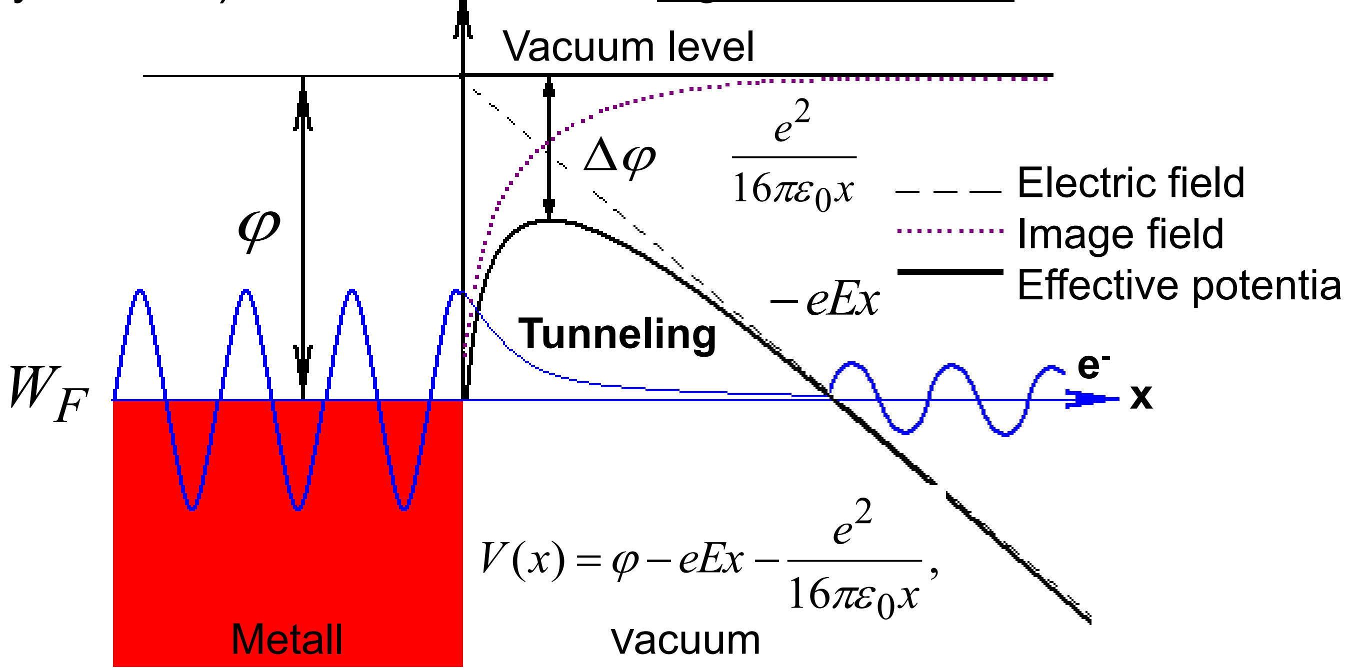
• *A. Dangwal, 2009* (LG samples [4]):
evidence for grain boundary assisted FE @ 250 MV/m after 150 ^{0}C for 14 h

➡ **Clear answers and detailed studies are required!!!**

[3] E. Mahner , Part. Accel. **45**, 67 (1994).
[4] A. Dangwal et al., PRST Accel. Beams **12**, 023501 (2009).

Theoretical background of electron FE (1)

FE → emission of electrons from the surface of a condensed phase into another phase (usually vacuum) under the action of <u>high electric field</u>



FE → quantum mechanical tunneling of electrons through a deformed potential barrier of suitable hight and thickness

<u>Fowler and Nordheim</u> → first correct mathematical explanation (for metall) by solving Schrödinger equation with WKB approxim. → transmition coeff. through triang. barier:

→ <u>FN equation</u>:

$$I_{FN} = A\frac{SE^2}{\varphi\ t^2(y)}\exp\left(-B\frac{\varphi^{3/2}\upsilon(y)}{E}\right)$$

const. A = 154 and B = 6830
S – effect. emission area in m^2
E – field, V/μm
t(y), v(y) tabulated Nordheim functions
y=Δφ/φ

Theoretical background of electron FE (2)

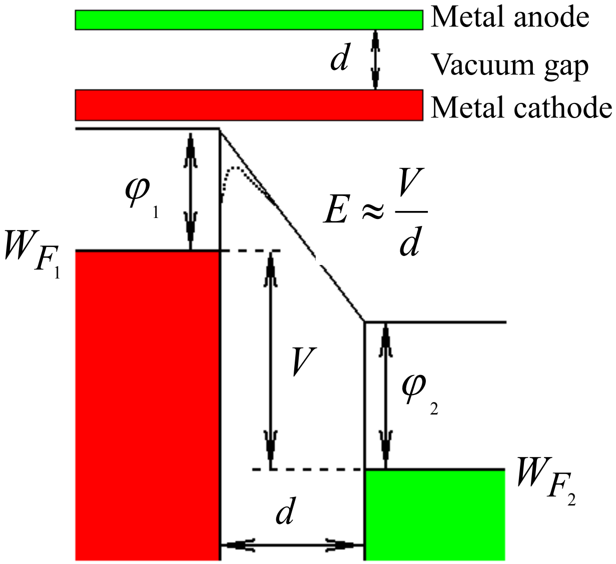
1) Strong dependence on φ → choose of material is important

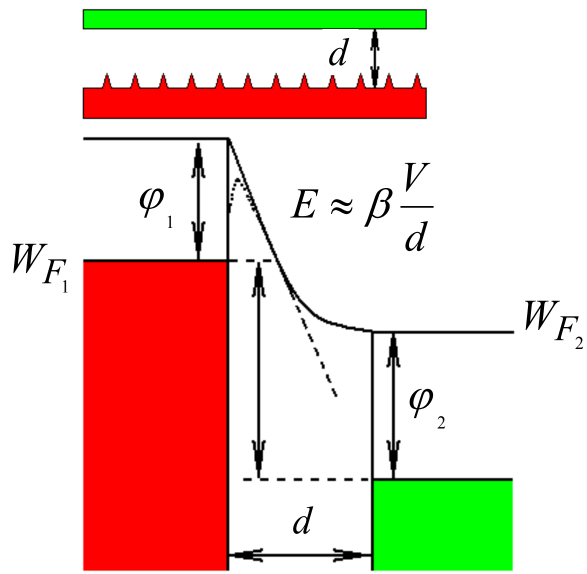
→ slight change in work function (adsorbates) → large fluctuations

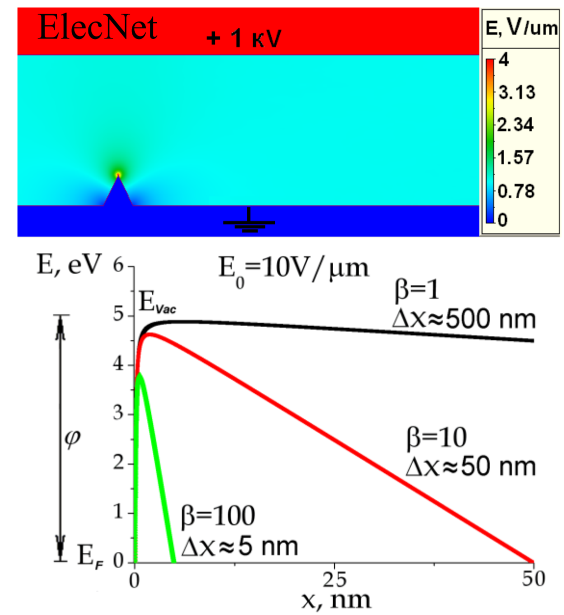
2) For metalls φ ≈ 4-6 eV → E > 1 GV/m ! is required to get measurable current from a planar metal

But! experimentally: FE appear at E ~ 10 MV/m

⇨ rougness of a real surface is an important issue!







→ assumption of uniform electric field in the vacuum gap cannot be applied

Sommerfeld and Bethe included a **field enhancement factor β !** due to sharp features

⇨ of utmost importance in FE theory

Modified FN

$$I_{FN} = A\frac{S(\beta E_0)^2}{\varphi\ t^2(y)}\exp\left(-B\frac{\varphi^{3/2}\upsilon(y)}{\beta E_0}\right)$$

$$E = \beta E_0 = \beta\frac{V}{d}$$

European ILC-HiGrade programme

XFEL order includes 24 cavities as a part of the ILC-HiGrade program:

> Initially, serve as **quality control (QC)** sample for the ***XFEL*** cavity production
- extracted on a regular basis, roughly **one cavity/month**
- after the **normal acceptance test** will be **taken out** of the production flow

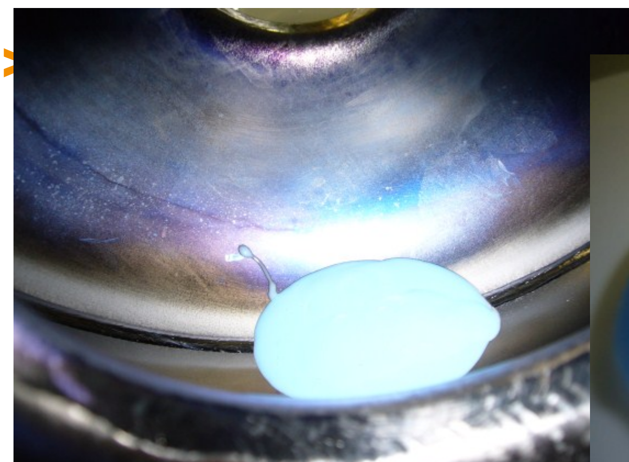
> Will be delivered with **full treatment** of the inner surface but **without helium tank** to **maximize** the data from the QC cavities

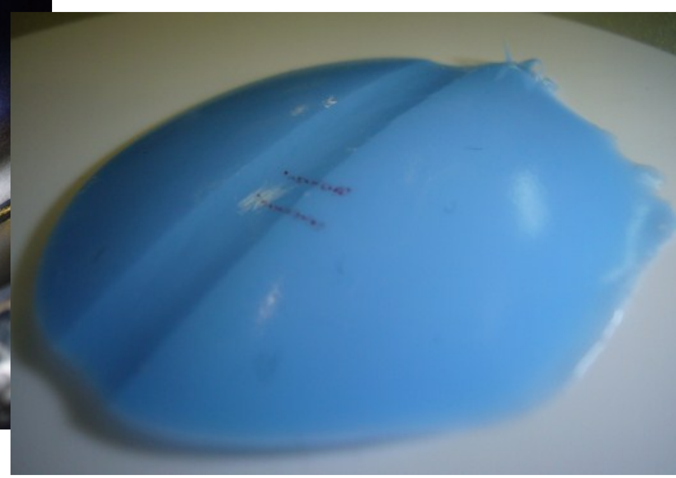
> Further handling done within the frame of the ILC-HiGrade program **as feasibility study** for meeting the **ILC performance goal**:
- surface mapping technique will be applied starting from the second cold RF test
- high resolution optical inspection with OBACHT to improve understanding of defects
- serial tests of the Centrifugal Barrel Polishing procedure
- tests of the repair procedure by means of Local Grinding
- use of replica as additional surface study technique

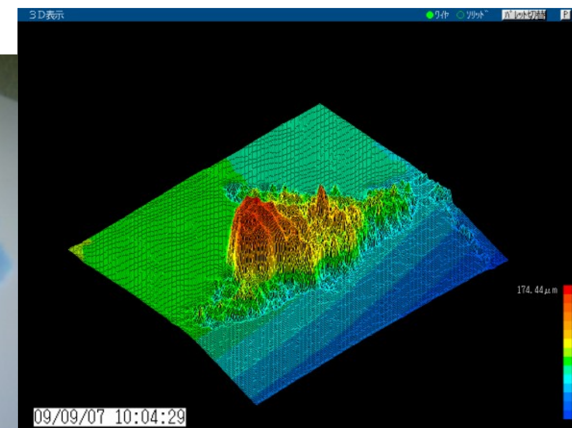
Gain of **experience** with industrial **mass-production** of **800 XFEL cavities**:
- monitoring of the process
- analysis of cavity database
- experience/knowledge gain with inspection/repair of gradient limited cavities of XFEL

Replica as additional surface study technique for cavities

- **Replica** is non-destructive testing tool of inner cavity surface
  - helps analyse 3D geometry of defects
  - deliver resolution down to 1 μm
  - do not leave residues on the surface if done correctly (at least after HPR)
  - no cavity performance degradation
- **Replica** in use at KEK (shown below [1]), Fermilab [2], CEA/DSM/DAPNIA [3] etc.
- Similar technique ***has been/is to be used at*** **DESY** for:
  - **tests** of the surface defect geometry
  - **correlation** between 3D topography and 2D images from OBACHT







[1] K. Watanabe, et. al, TTC2010.
[2] M. Ge et. al, SRF2009, TUPPO064.
[3] S. Berry et. al, EPAC04, TUPKF018

Centrifugal Barrel Polishing (CBP) of Nb cavities

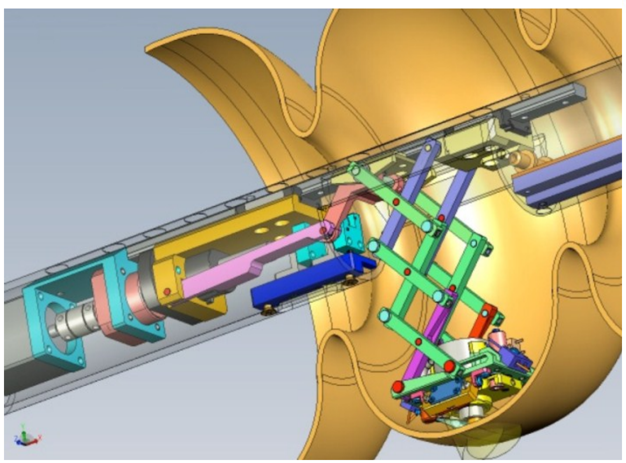
- CBP is an ***acid-free*** surface polishing technique using abrasive media
  - **reduce chemistry** amount, only light EP (~10 µm) finally required [1]
  - **~10x smaller** surface **roughness** compare to chemistry alone [2] with mirror-like surface
  - **better *Q_0*** and ***E_{acc}*** might be achieved
- CBP machines in use at FNAL (shown below, [2]), Cornell and JLab
- Identical machine ***has been ordered*** **by Uni Hamburg** and made available at DESY HiGrade Lab for:
  - **serial tests** of the polishing procedure (partially with **ILC-HiGrade cavities**) as feasibility study for meeting the ILC performance goal
  - **further optimizations/understand.** of the process (H-free polishing, time, etc.)
  - Study of CBP as **cavity repair** and possibly **preparation technique**

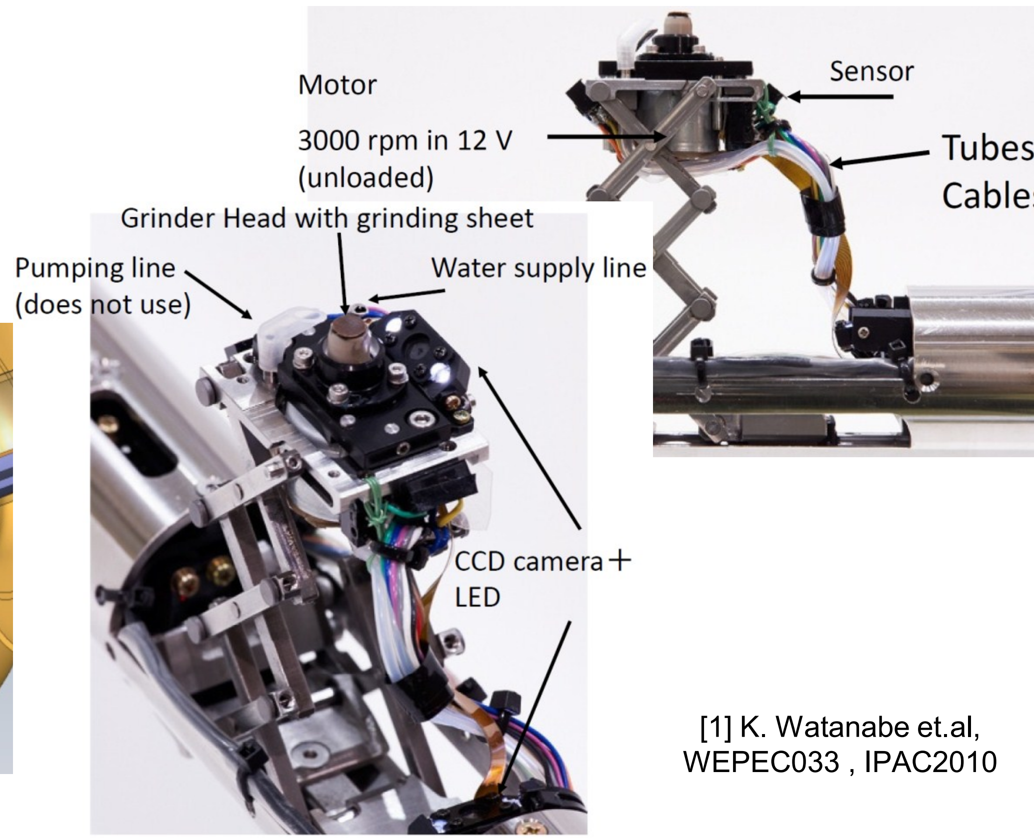
Individual Barrels rotate 115 RPM in opposite direction to main shaft

[1] A. D. Palczewski et.al, WEPPC094 , IPAC2012
[2] C. A. Cooper et.al http://lss.fnal.gov/archive/2011/pub/fermilab-pub-11-032-td.pdf

Local grinding as repair technique for cavities

- **Local grinder** is a mechanical polishing technique used for **local** defects removal
- Defects unaffected by standard chemical polishing can be eliminated [1]
- Local grinder in use at KEK (shown below [1]) and deliver very promising results
- Similar machine ***is planned to been ordered*** **by Uni Hamburg** and made available at DESY HiGrade Lab for:
  - **serial tests** of the repair procedure (partially with **ILC-HiGrade cavities**) as feasibility study for meeting the ILC performance goal
  - **further optimizations** of the process

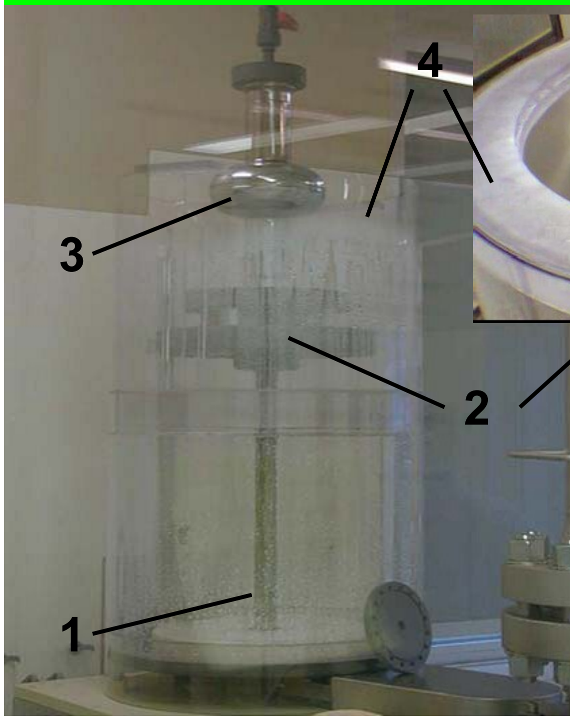


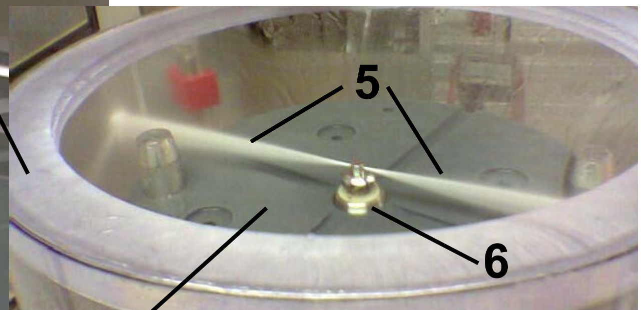


[1] K. Watanabe et.al, WEPEC033 , IPAC2010

Experimental techniques (4): HPR + DIC

High pressure ultra pure water rinsing (HPR) [1]:



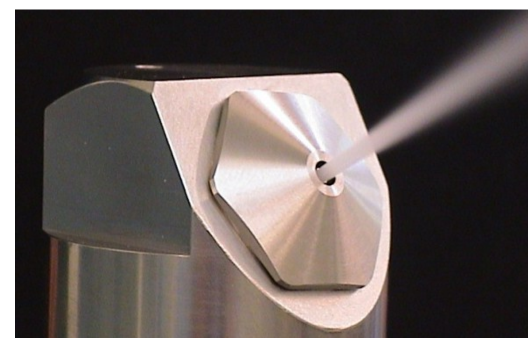


The HPR system for 9-cell cavities at DESY: rotating high pressure water pipe (1), vertically moving support plate (2), 1-cell cavity under rinse (3), protection envelope (4); (b) high-pressure water jet streams (5) emerging from the nozzle(6)

- class 10-class 100 clean room
- 100 bar of high-purity water jets

→ Scrub the chemical residues and particulate contaminants to avoid field emission and quenches

Dry ice (CO_2) cleaning (DIC) [2]:



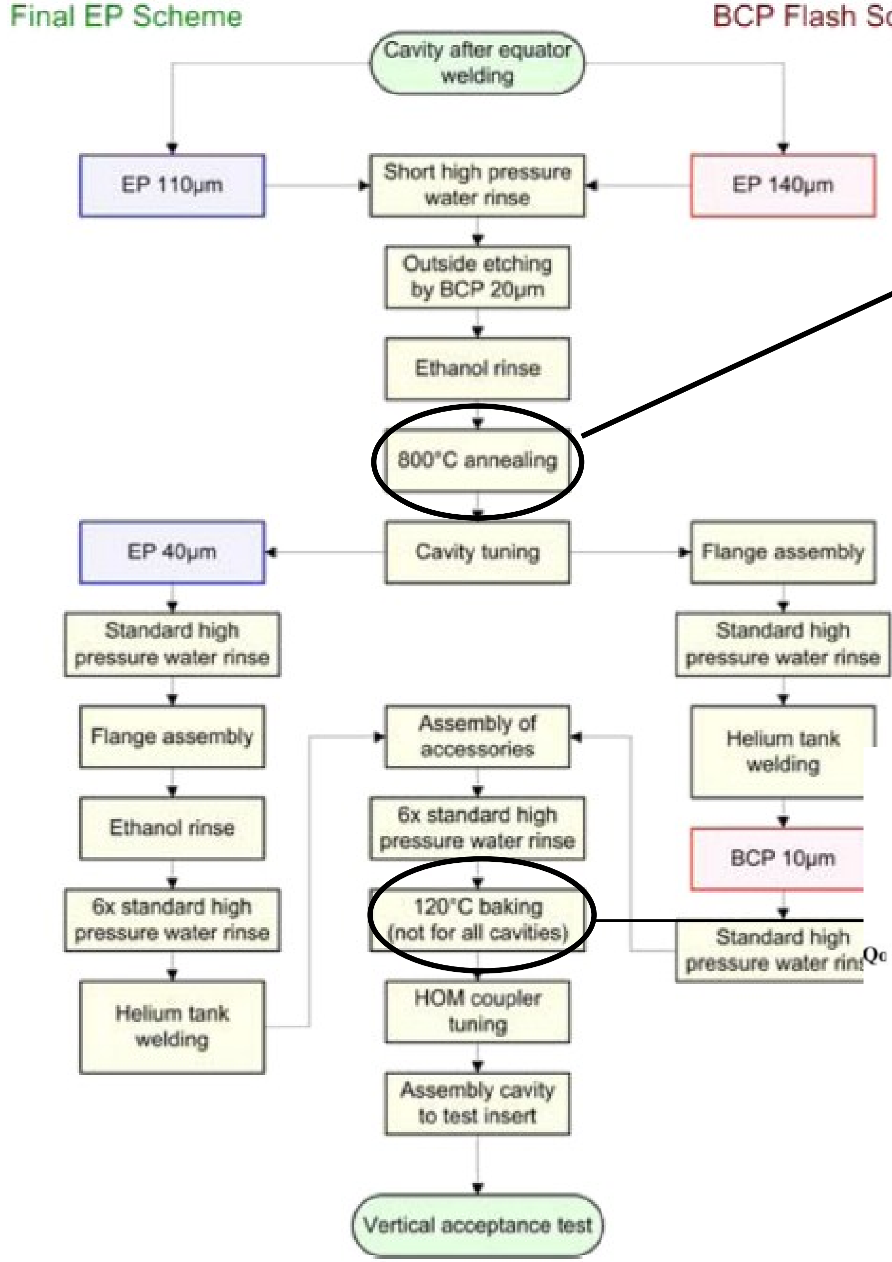
High-pressure dry-ice jet emerging from DIC nozzle

- class 10 clean room
- 50 bar CO_2, 12 bar N_2 (particle filtered to < 0.05 μm)
- CO_2 snow jet (45%) is surrounded by supersonic nitrogen
- -18 / -10°C temperature of liquid CO_2
- developed @ Fraunhofer Institut Produktionstechnik

und Automatisierung Stuttgart, Germany for DESY

[1] H. Padamsee, “RF superconductivity,” Wiley, ISBN 978-3-527-40572-5.A (2009)
[2] D. Werner and C. Zorn, in Proceedings of Precision Cleaning, Clean Tech, Frankfurt 2000.

Cavity treatment



- <u>Removal of hydrogen</u> after polishing
- Reduction of mechanical stress
- <u>Option</u>: Backe at 1400°C for removal of other O-,N- and H-atoms

<u>Midtemperture heting</u>:
Removl of High-Field Q-drops by improving SC properties

<u>High temperture heating:</u>
removal of insulting oxide layer