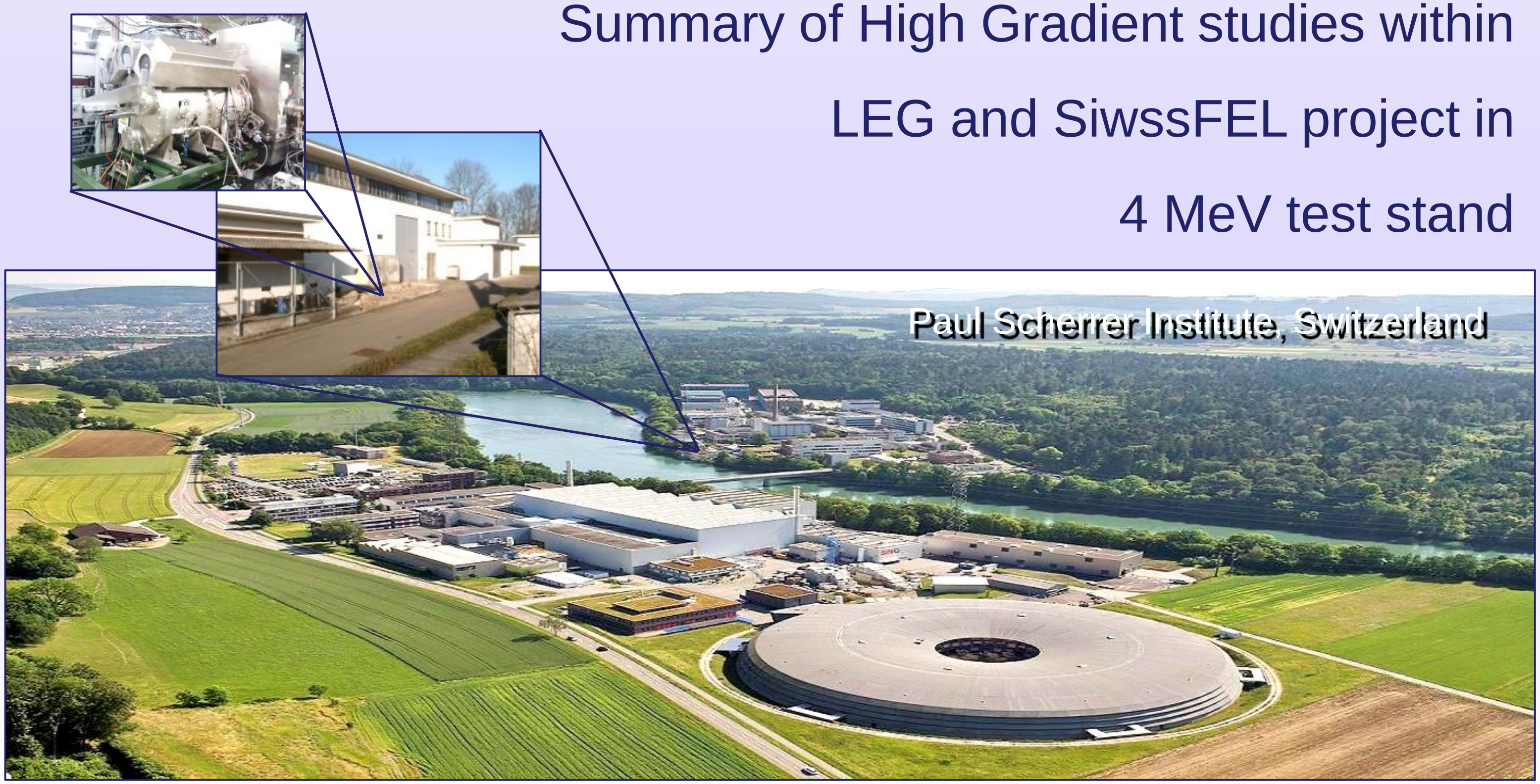
High Gradient Electrodes Studies for Pulsed Electron Gun

M. Paraliev, C Gough, S. Dordevic

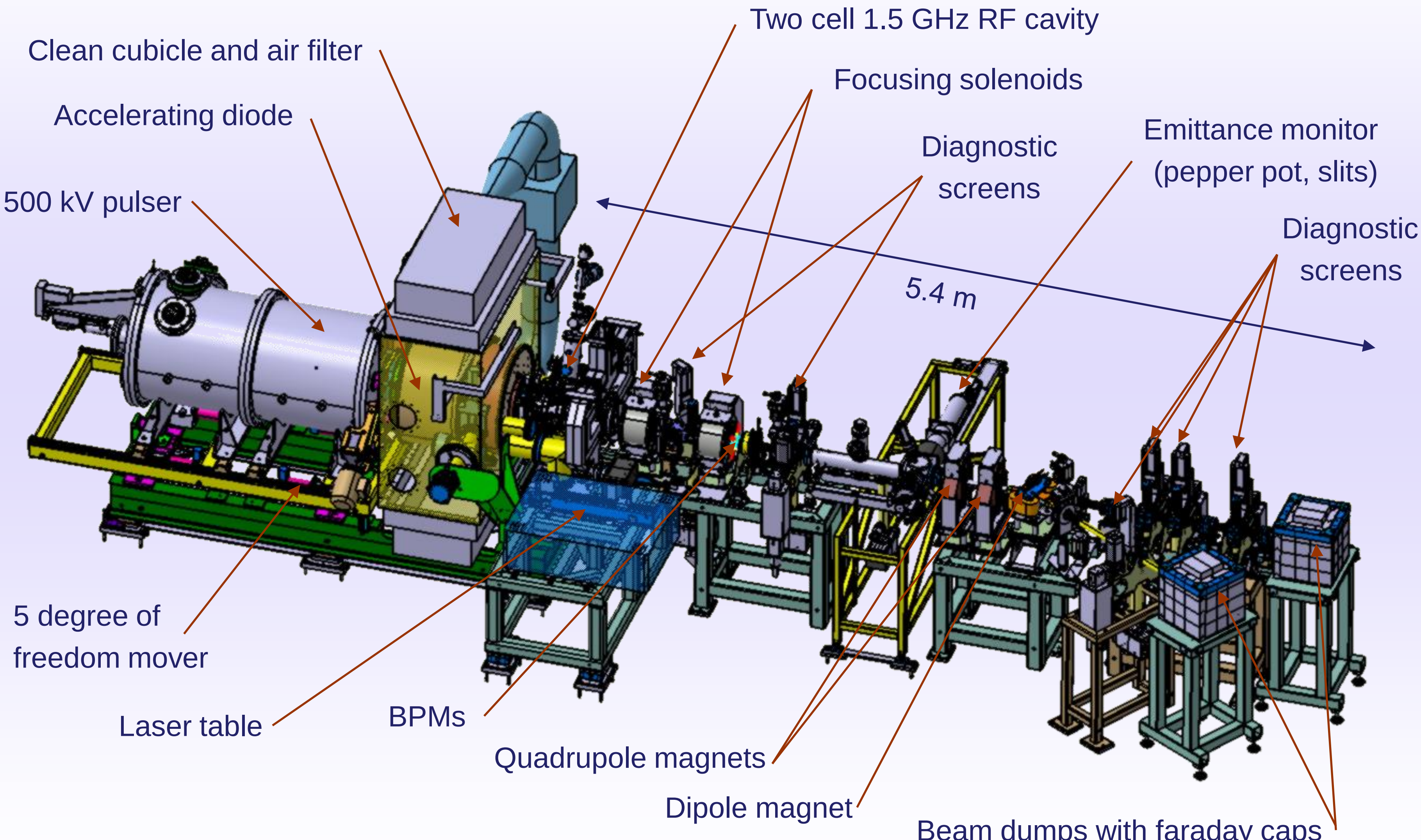
Summary of High Gradient studies within

LEG and SiwssFEL project in

4 MeV test stand

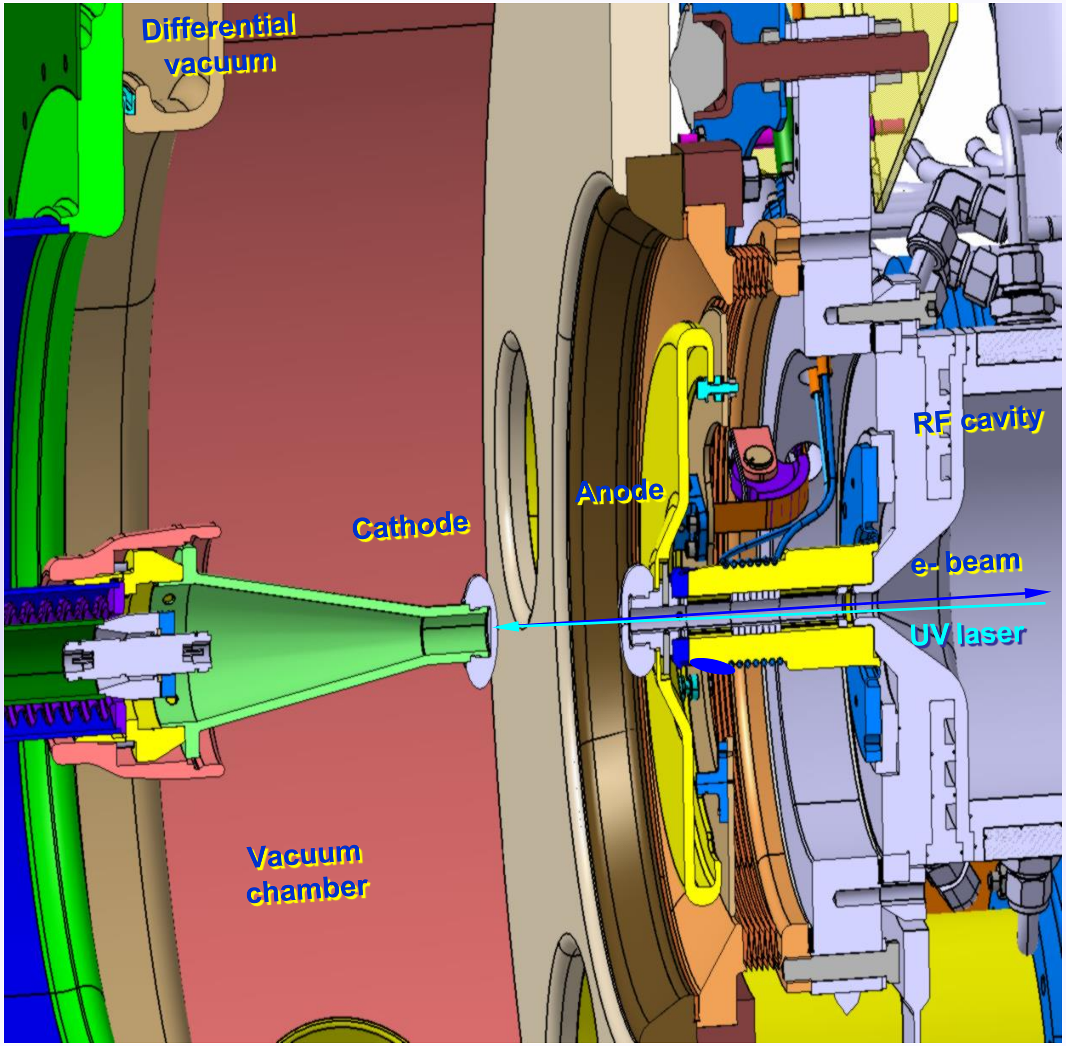


4 MeV Test Stand Overview



3D CAD model of 4 MeV test stand

High Gradient Accelerating Diode



⇑ Accelerating diode cross section

HG Diode parameters

- Max. voltage – 500 kV
- Pulse length FLHM – 250 ns
- Max. rep. rate – 10 Hz
- Laser pulse length – 10 ps
- Laser wave length – 262/266 nm
- Max. laser energy – 250 uJ

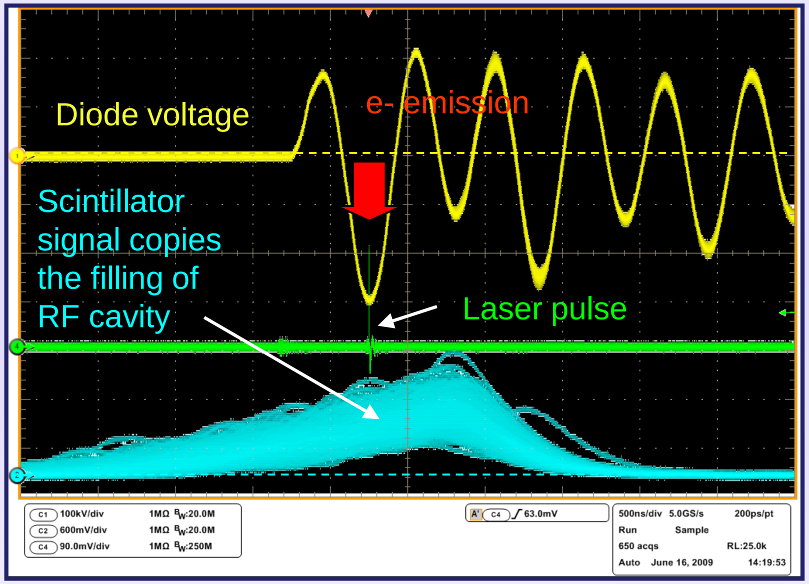
Features

- Variable anode cathode distance
- Adjustable cathode position
- Exchangeable electrodes
- Bolts-free vacuum chamber
- Differential vacuum system
- Scintillator based dark current monitoring system

Diode Accelerating Voltage and HG Test Procedure

Diode acceleration voltage is asymmetric oscillatory pulse produced by Tesla-like transformer.

Laser pulse for photo emission is short (10ps FWHM) with respect to the oscillating accelerating voltage and it arrives at the first negative maximum - quasi DC acceleration.



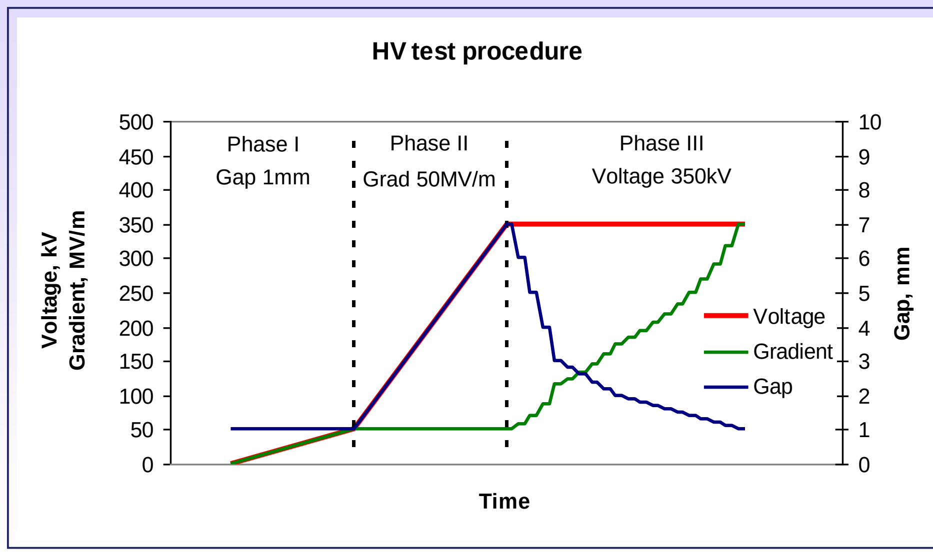
⇑ Accelerating voltage, laser pulse and scintillator signal waveforms

The scintillator registers bremsstrahlung from parasitic e^- emission during RF cavity pulse and HG tests.

HG test procedure:

- Phase I - constant gap
- Phase II - constant gradient
- Phase III - constant voltage

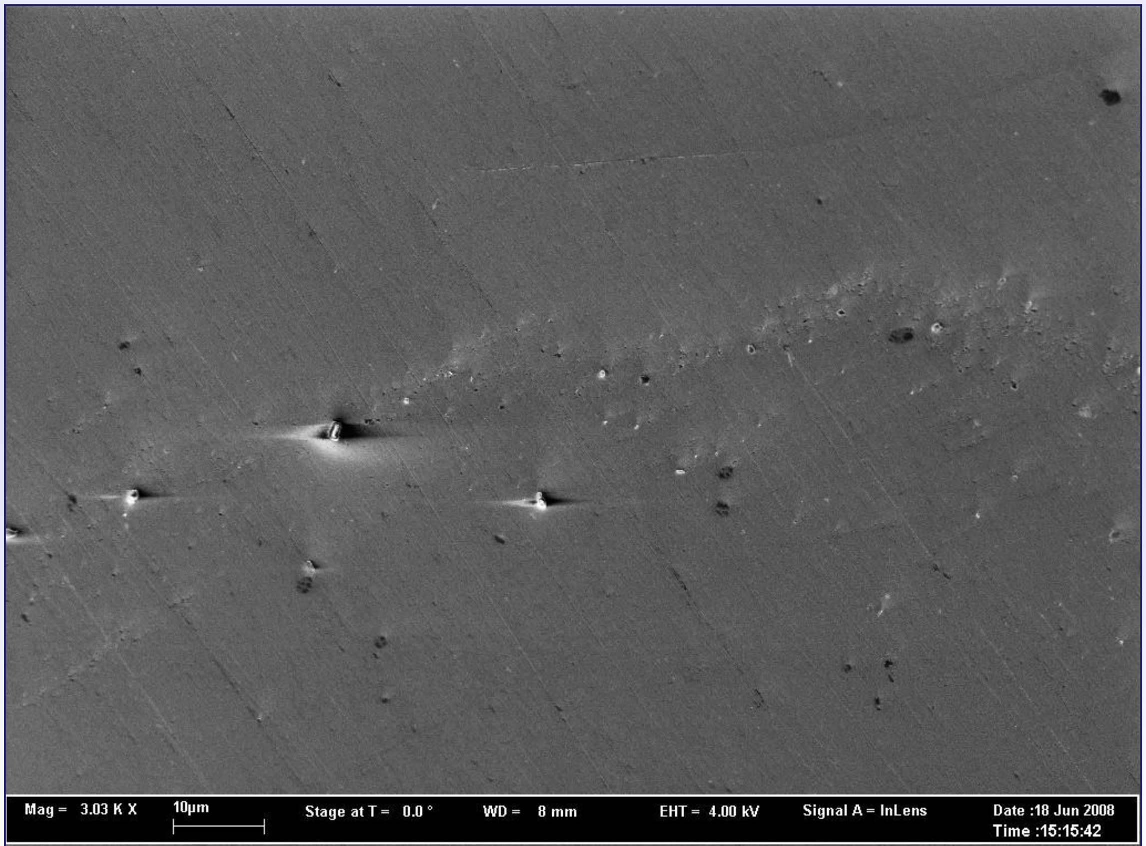
High Gradient test procedure ⇒



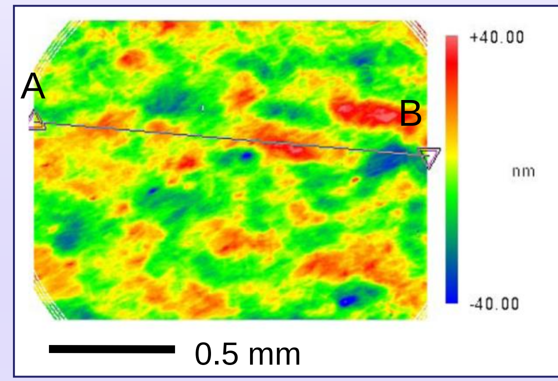
Bare Metal Electrodes

Surface finish appeared to be very important for vacuum breakdown performance of the electrodes.

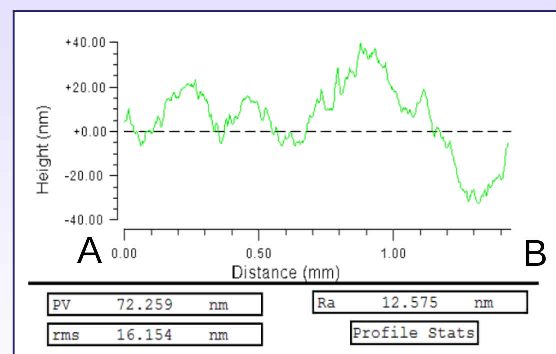
Hand polishing gave the best results.



⇑ Polished st. steel electrode surface under scanning electron microscope



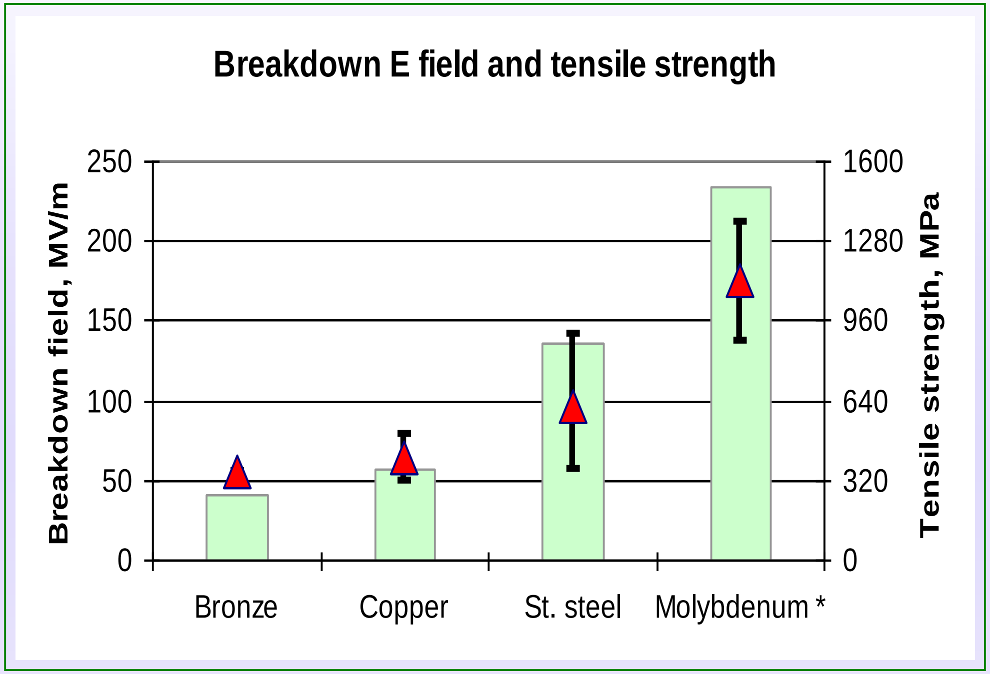
⇑ Typical surface roughness (2D mapping)



⇑ Line height profile

Thanks to E. Kirk and S. Spielmann-Jaggi

Bare Metal Electrodes



⇑ Breakdown field for different metal electrodes (polished).

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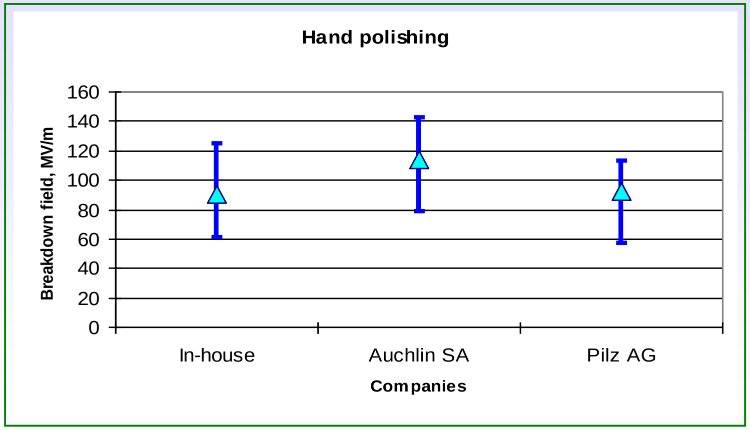
* 2 um molybdenum layer was sputtered on a polished st. steel surface, bulk value of Mo tensile strength is indicated

- Correlation between the material **tensile strength** and vacuum breakdown strength was found
- Different metals **polish differently** and this made breakdown comparison difficult
- Further improvement of polishing did **not increase breakdown** strength.

Breakdown strength limited at 150 MV/m

Hand polishing - companies comparison (st. steel) ⇒

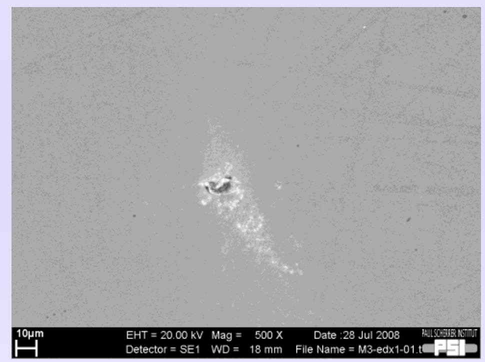


Stainless steel electrodes - Polishing

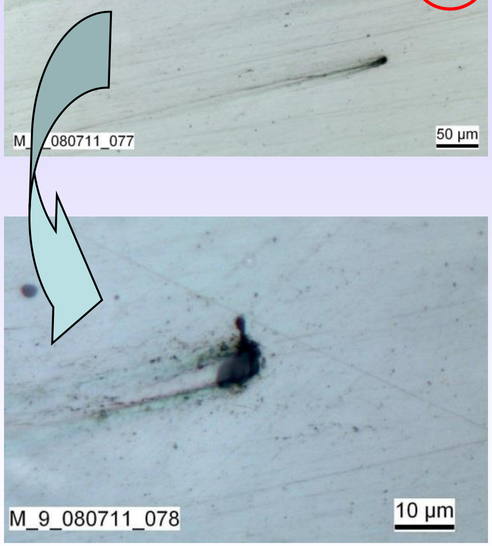
- External companies polishing (Auchlin, Pilz, Buob) – reproducibility, difficult to control the process, expensive
- Developed in-house polishing
- SS electrodes breakdown field ranges from 60 to 128 MV/m

Identifying and avoiding "star bursts"/ "comet" shape defects (embedded particles)

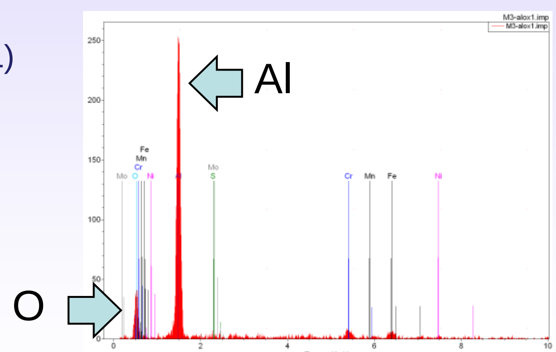
Electrode M9 (SS 316L) Comet shape formed on the polished surface. The tail direction depends on polishing direction. If polished in different directions a star burst shape is formed.



Electrode M3 (SS 316L) scanning electron microscope image of an embedded particle



Electrode M9 (SS 316L) Higher magnification



Electrode M3 (SS 316L) energy-dispersive X-ray spectrum of the embedded particle. Strong presence of Al and O suggested an Al_2O_3 particle from polishing agent.

Thanks to H. Leber

Stainless steel electrodes - Metallurgy

Two different ingots and different raw material form – “rod” and “plate”

- “Rod” – 109 MV/m (av. of 5 pairs)
- “Plate” – 81 MV/m (av. of 7 pairs)

It was not possible to draw a credible conclusion.

Electro-etched, top view

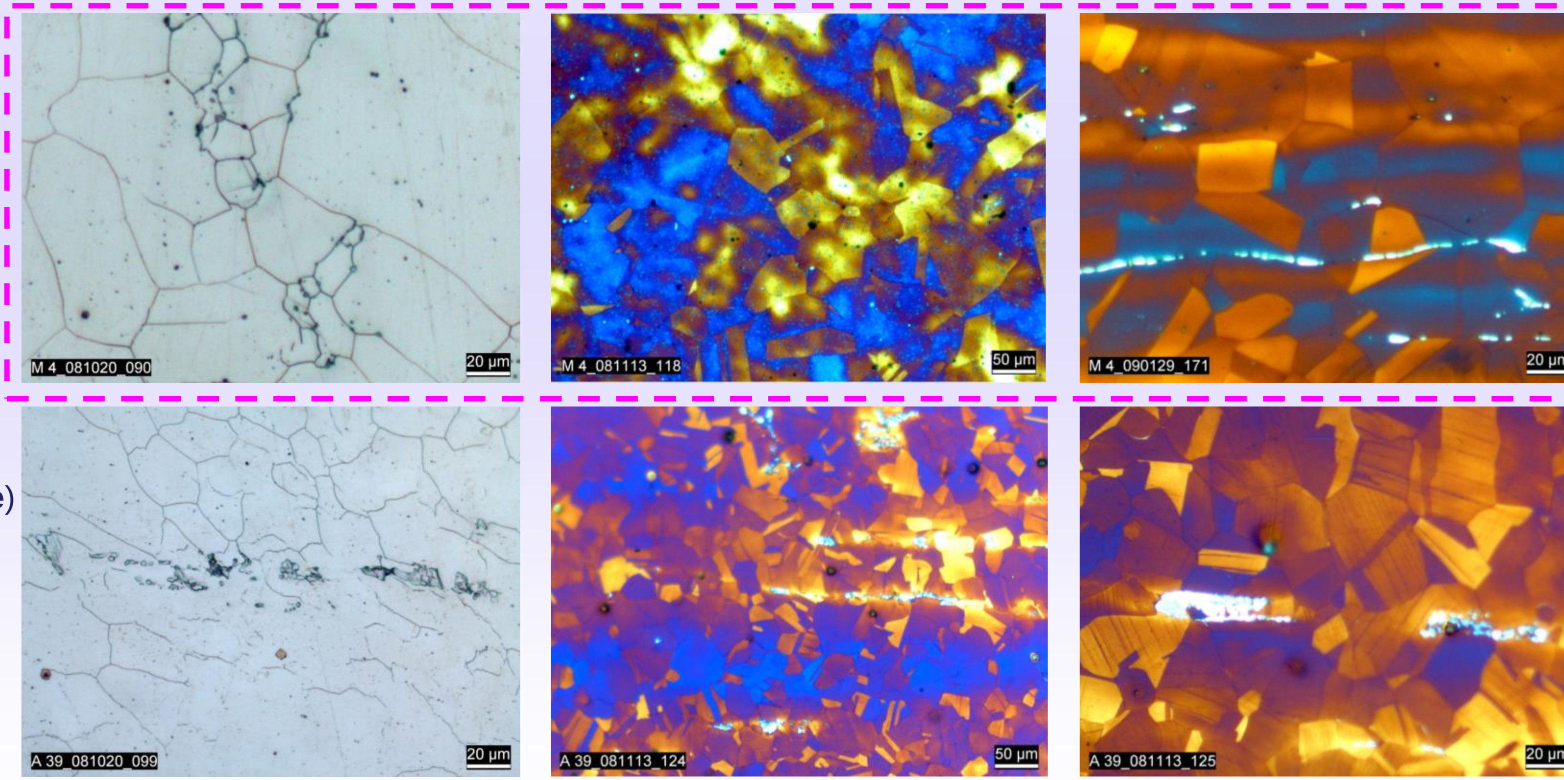
Electro-polished and Beraha tint etched by immersion

Electro-polished and tint etched by immersion in Beraha solution (M4 - Longitudinal, A39 - Top)

Electrode M4 (SS 316L **rod**)

Better?!

Electrode A39 (SS 316L **plate**)

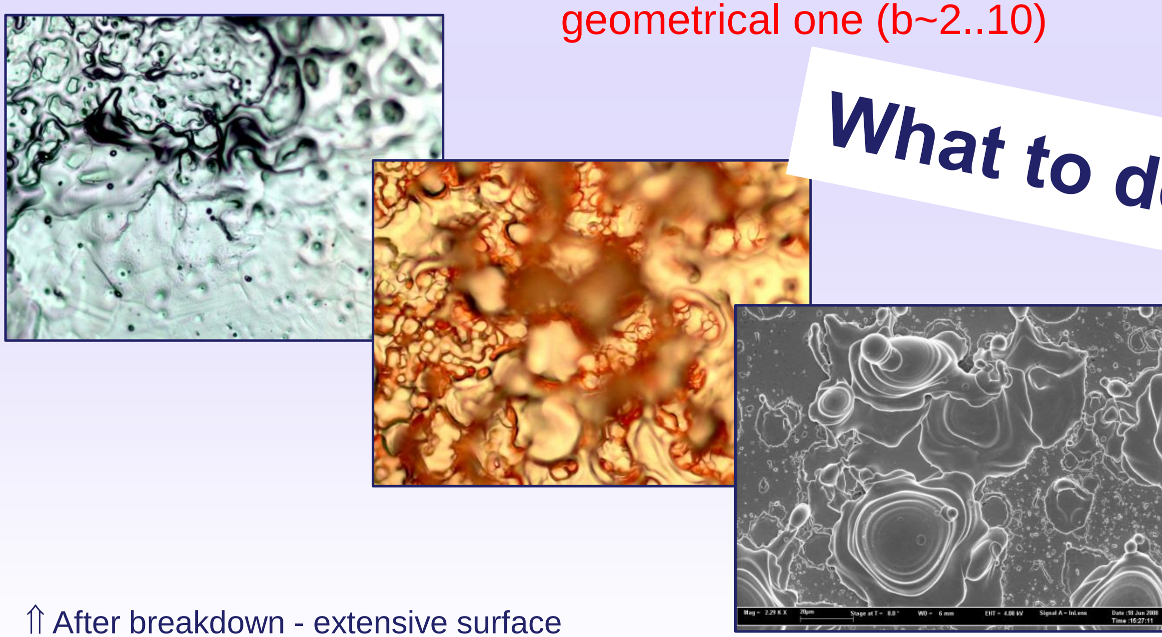


Thanks to H. Leber

Bare Metal Electrodes

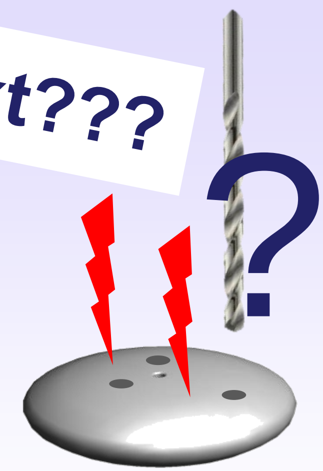
- **Large electrode** area makes difficult to map micro-defects
- Extensive breakdown **surface damage** hinders identification of possible surface defects
- **Unable to correlate defects** to breakdown sites
- Improvement of polishing **did not improve** breakdown strength further

The breakdown **does not** necessarily occur where the highest electric field is expected (sharp edge)! Suggests the surface condition results in higher “field enhancement” than the geometrical one (b~2..10)



⇑ After breakdown - extensive surface damage at macro- and micro-scale

What to do next???



Diamond Like Carbon (DLC) Coating

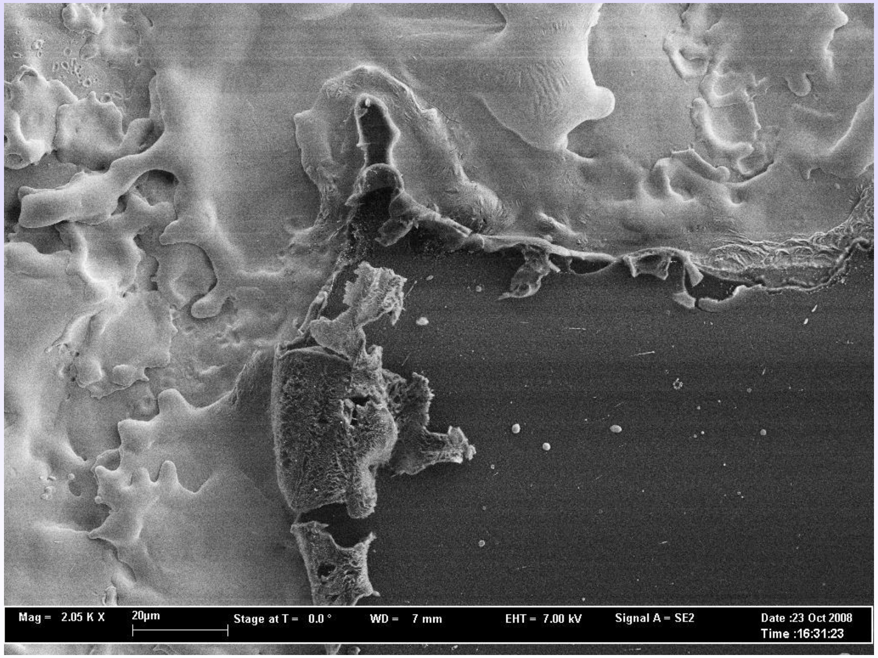
Using PACVD (Plasma Assisted Chemical Vapor Deposition) process to deposit hydrogenated amorphous DLC (a-C:H) with tailored properties.

Features:

- **Smooth surface (amorphous)**
- **Mechanical properties comparable to these of diamond (high hardness)**
- **Unique electrical properties**

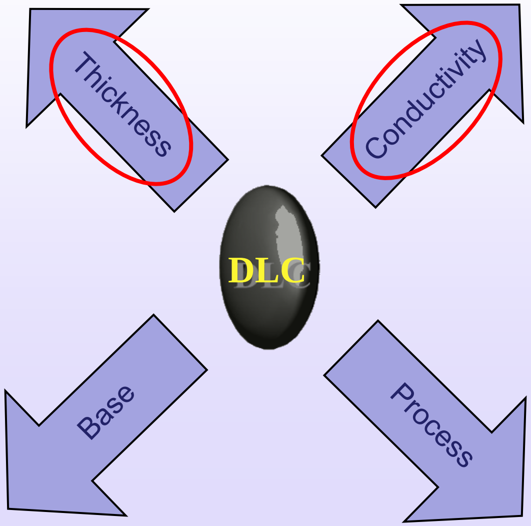
⇓ Intact DLC surface type PSI 080815-UF (Bekaert)

⇓ Destroyed DLC surface (same type).



Thanks to E. Kirk

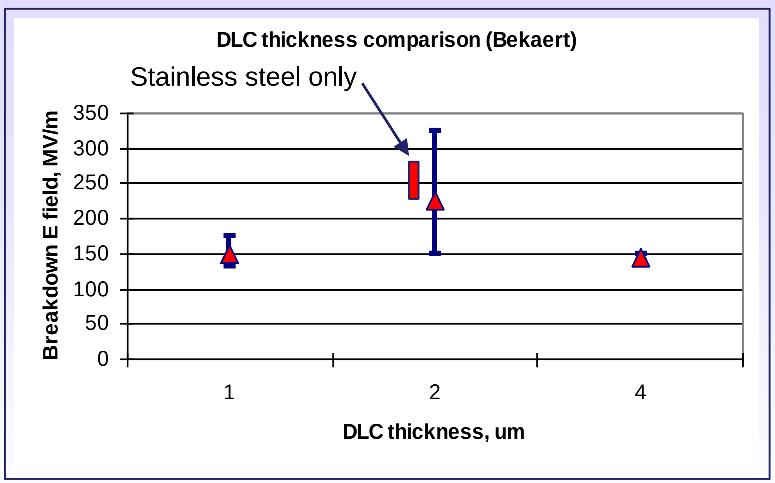
DLC – parametric study



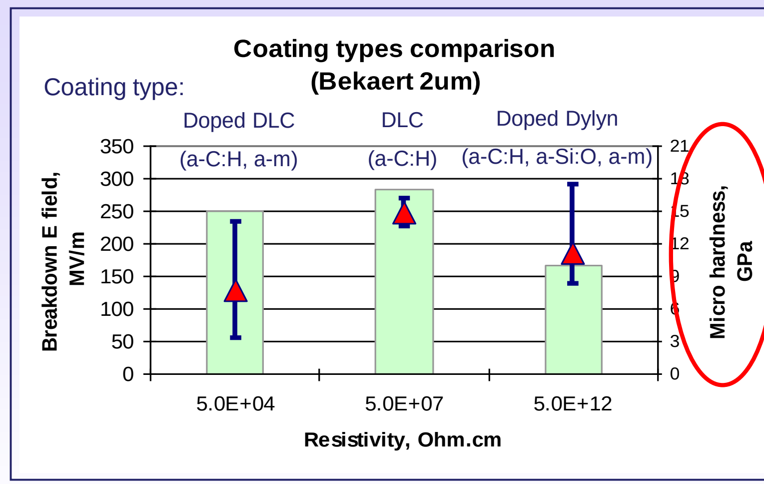
- Coating thickness
- Coating electrical conductivity (DLC type)
- Base metal type (internal stress, adhesion, roughness)
- Process (& companies)

2 um DLC coating with **“standard”** (undoped) conductivity gave the best performance – possibly due to the coating process optimization (mechanical properties)

Note the correlation with hardness!

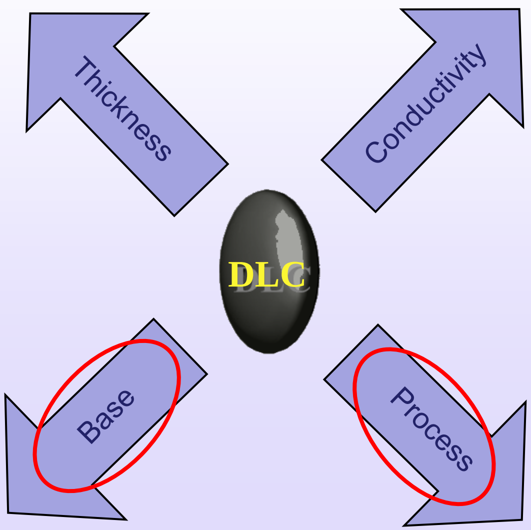


⥣ Breakdown strength vs DLC thickness - st. steel, Cu, bronze (Bekaert)



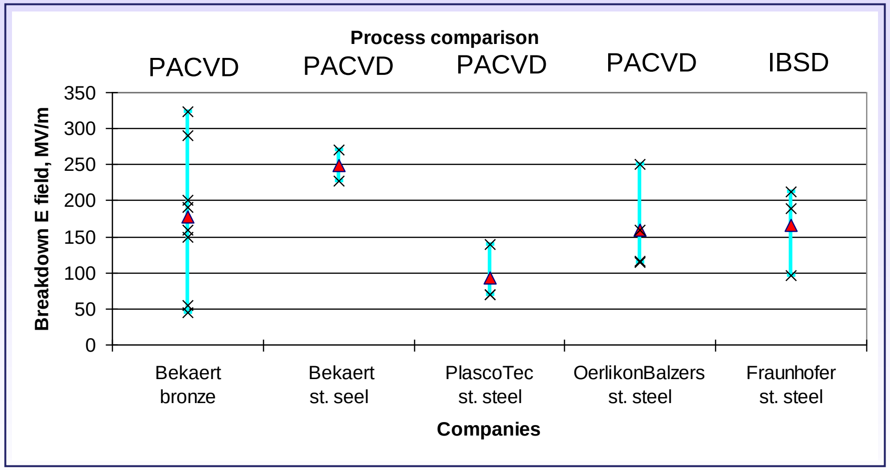
⥣ Breakdown strength vs DLC type (resistivity) - st. steel, 2um (Bekaert)

DLC – parametric study

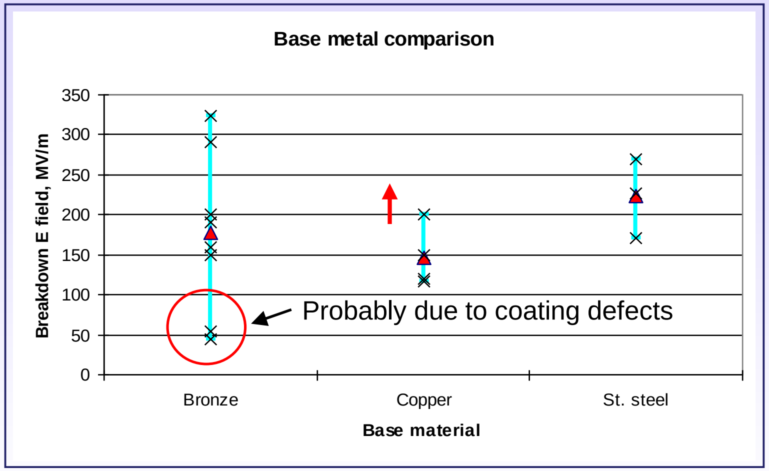


- Bekaert coatings gave better results
- The general impression is that **softer base** material give better results (not conclusive - different adhesion, different metals polish differently and so on)
- Number of tested electrodes is small. "Sudden dead" effect, attributed to coating defects "contaminates" the results.
- Larger base **surface roughness** gave lower breakdown strength

Copper results are actually higher because some of the samples were not tested until breakdown (saved for e^- beam experiments)



⇑ Breakdown strength (2 um DLC) vs process (companies)



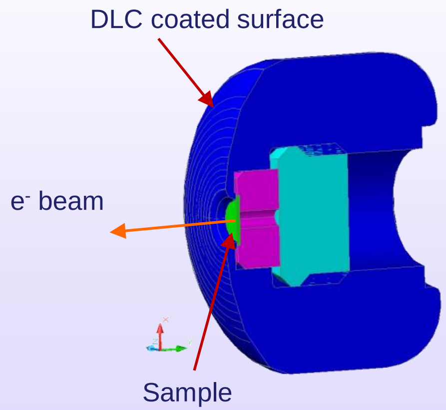
⇑ Breakdown strength vs base metal (2 um, Bekaert)

"Hollow" cathode geometry

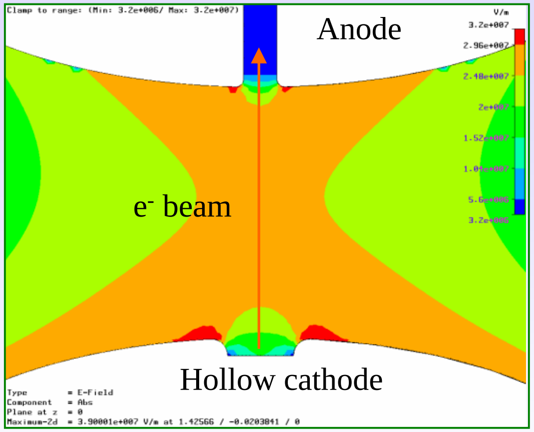
DLC coated electrodes for HG tests

- New cathode materials
- Field emitting arrays

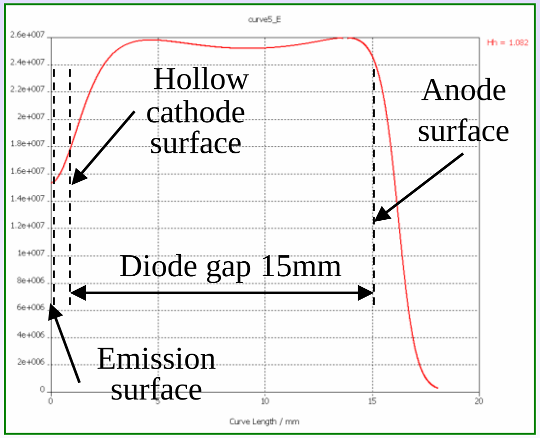
Electric field at the sample's surface is about 50% of the max acceleration field due to cathode recess screening effect.



⥣ Hollow cathode cross-section



⥣ Electrostatic simulation of the field in the accelerating diode

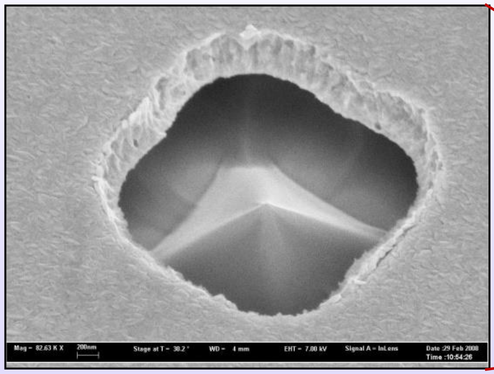


⥣ Electric field profile along the acceleration path

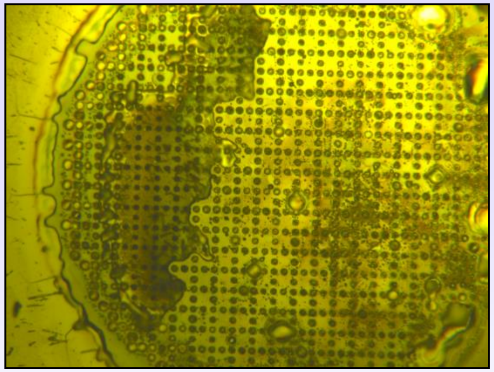
Features:

- ✓ Reusable
- ✓ Easy to exchange the sample
- ✓ Protects sample's edges
- ✓ No conditioning needed
- ✓ Matched 50 Ohm electrical connection

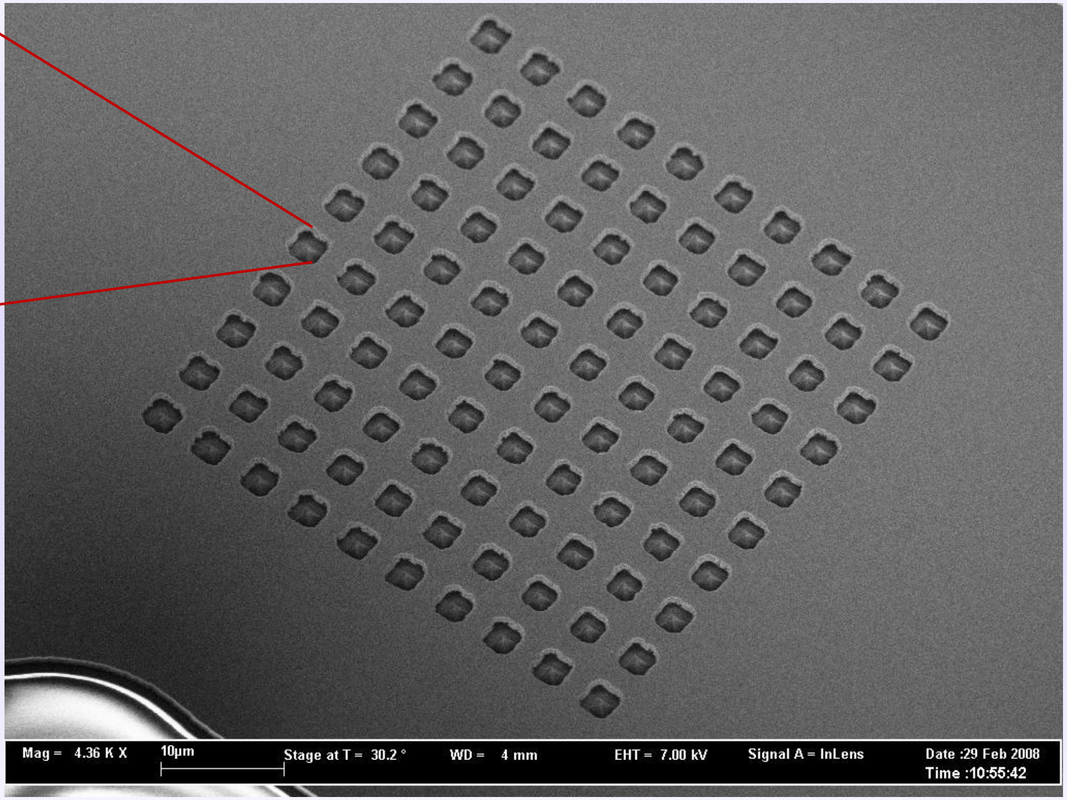
Pyramid (single gate) FEAs



⇑ Individual FEA emitter



⇑ FEA exposed to High Gradient. Part of the gate destroyed (removed) after the breakdown



⇑ FEA array

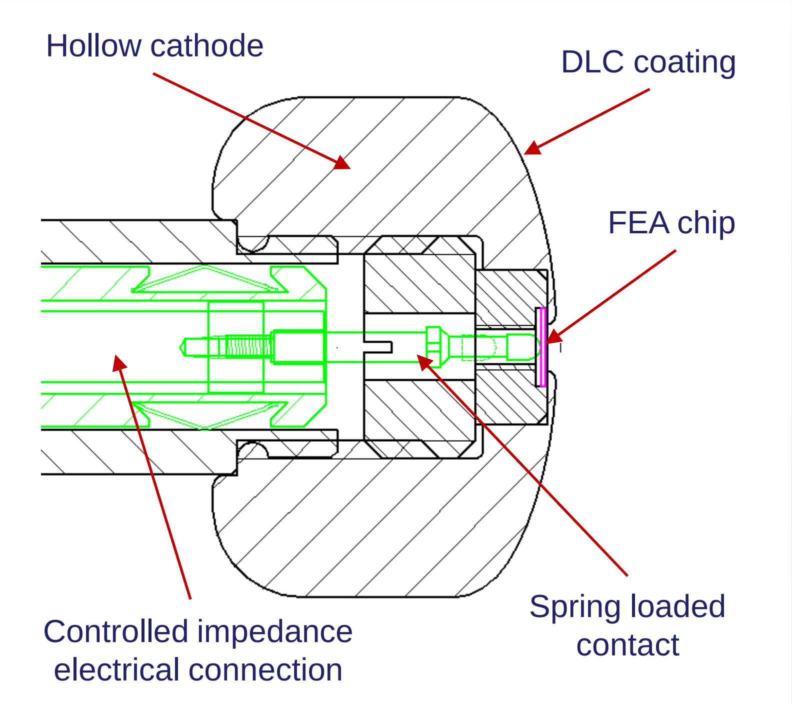
Example: HG FEA emission tests

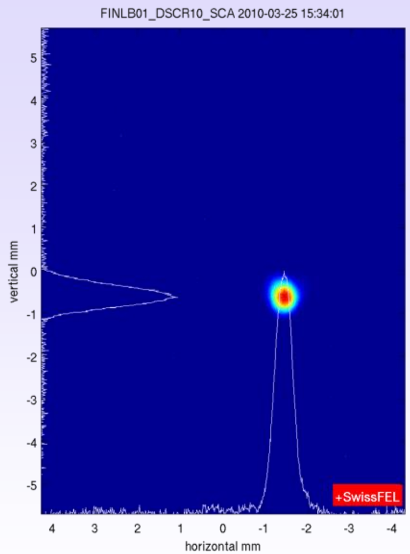
FEA Highlights:

Max gradient*	**30 MV/m**	(230 kV, 1 pC)
Max beam energy*	**300 keV**	(11 MV/m, 1.5 pC)
Max emitted charge	**>10 pC**	(9 MV/m, 250 keV)

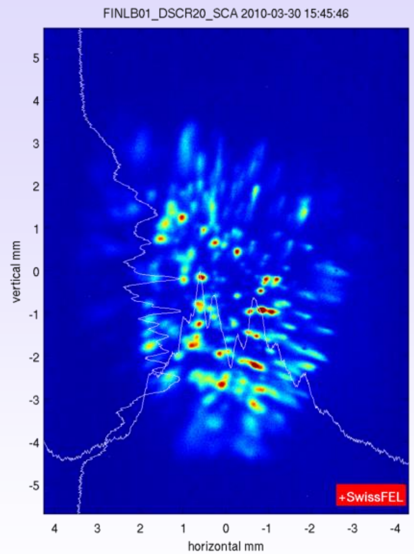
*Not limiting values – Destruction value not tested due to limited time and number of samples

➢ **Up to our knowledge - record values**





⇑ Focused FEA veam

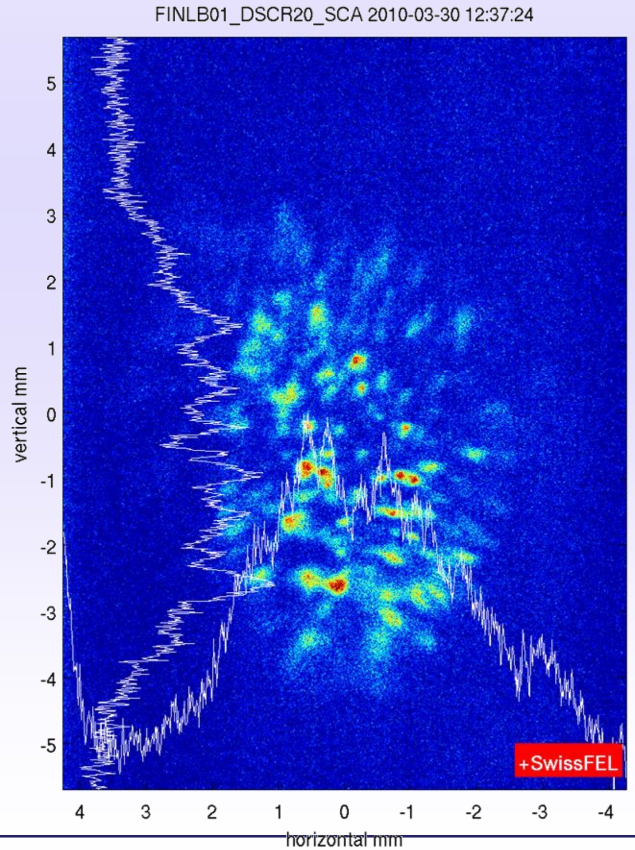


⇑ Cathode imaging

FEAs can be used in High Gradient environment

Extracted FEA charge vs background pressure (Ar)

Pressure, mbar	7.6e-9	1.3e-6	2.6e-6	5.5e-6	9.9e-6	2.2e-5
Charge, pC	1.4	1.3	1.3	1.3	1.3	1.4



Emitted charge and emission pattern did not change within more than 3 order of magnitude change of gas pressure (Ar injection).

Emission pattern

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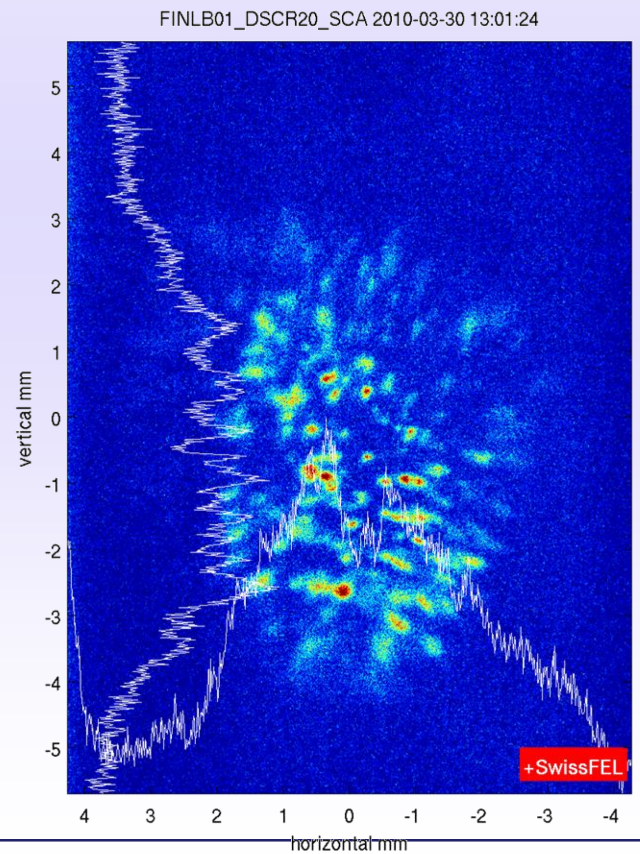

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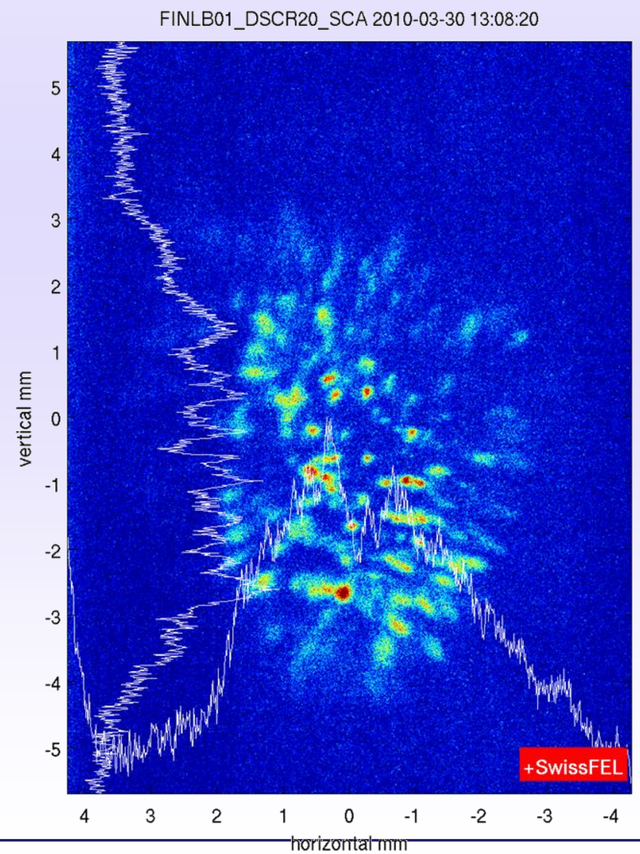

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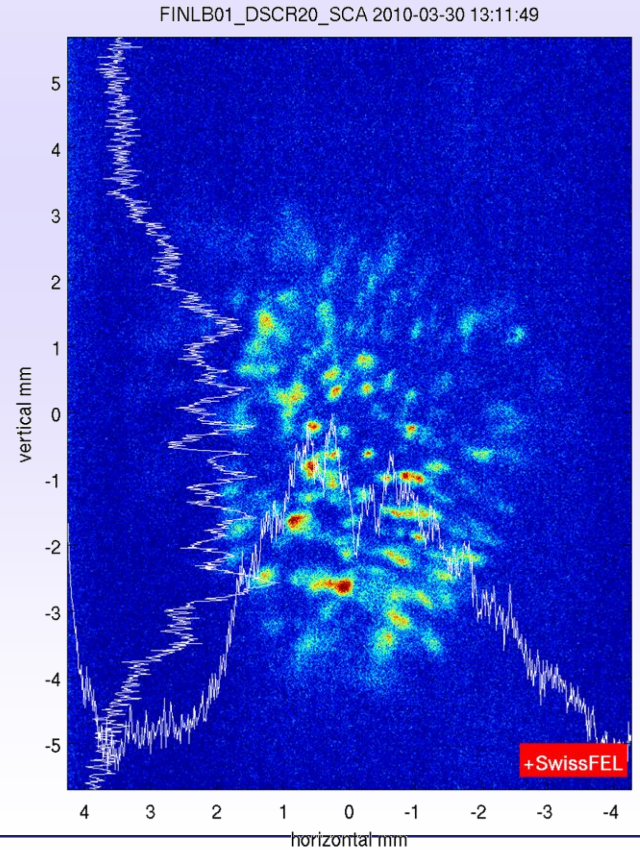

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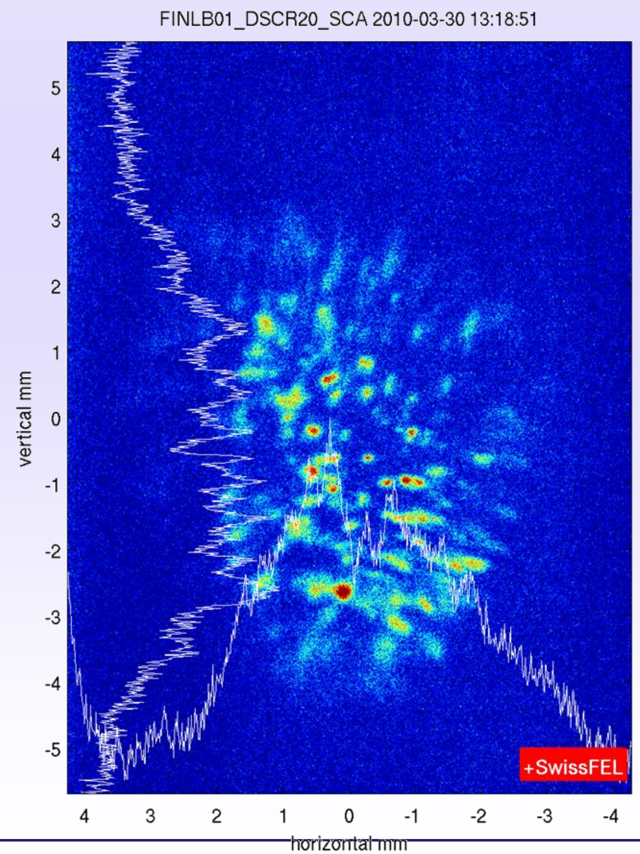

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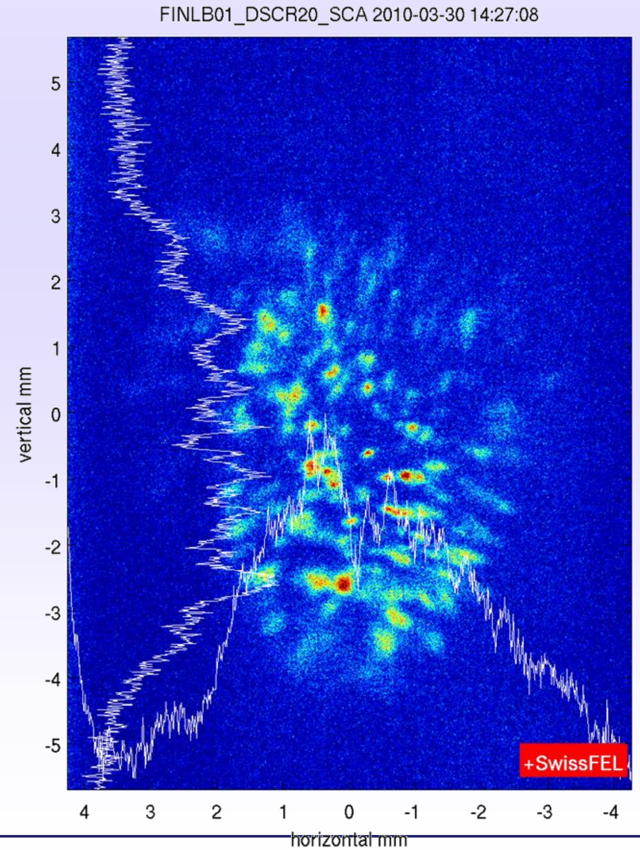

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Emission pattern

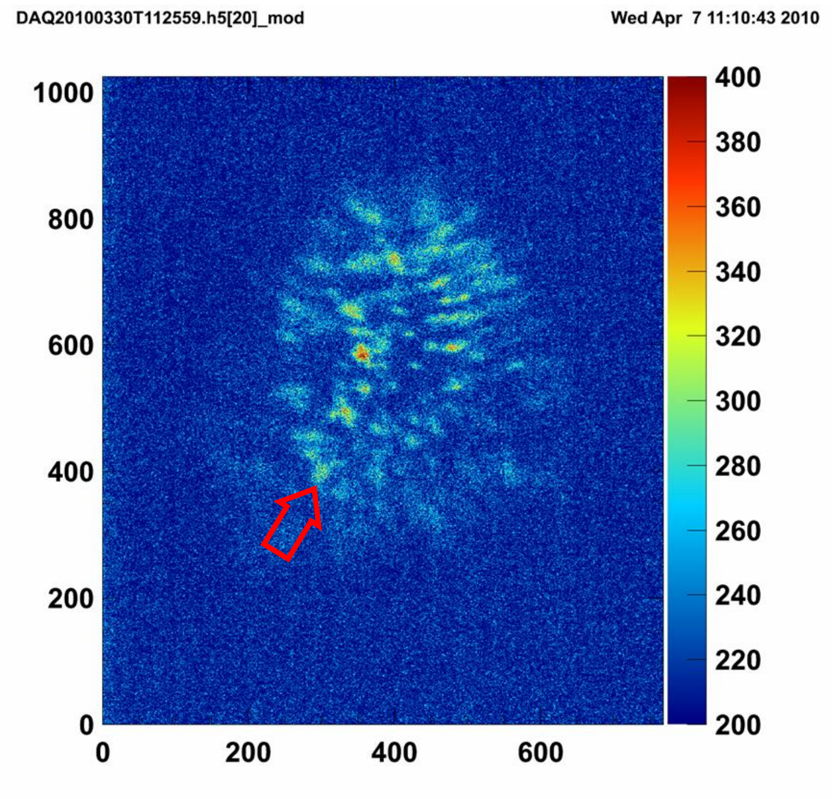
FEA Emission Stability

Shot-to-shot fluctuations of the emission pattern – 20 consequent images.

Machine settings:

Pulser: 250kV@15mm

Charge: ~2pC (Uch 115V)



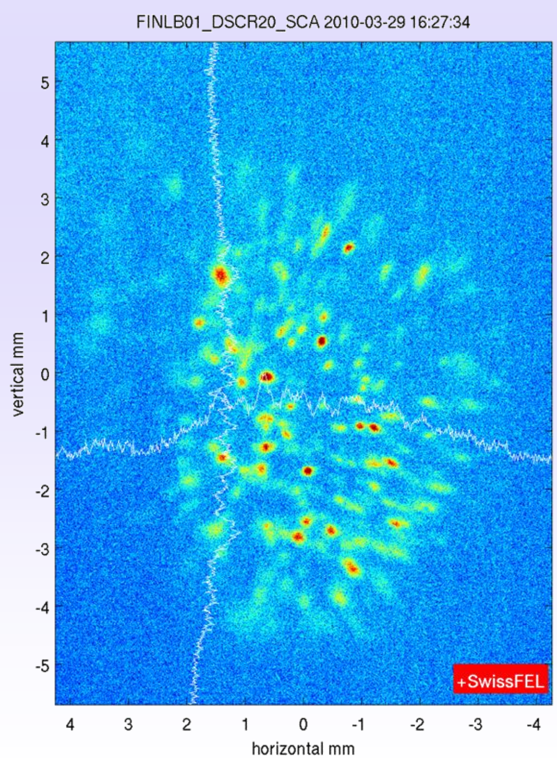
- Emission pattern is very stable.
- Single spots get more active but overall emitted charge does not change significantly.
- Activated emitters do not seem to be destroyed and reappear after a while.
- 150..300 distinguishable emitting points. This particular array has ~40k emitters.
- No spark like events were observed at this emitted charge level (<2pC).

Photo-assisted emission

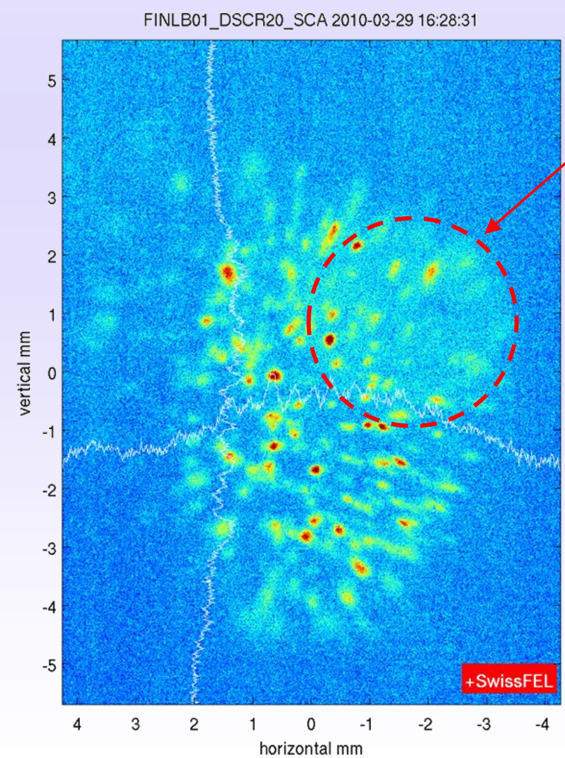
What to expect?

FEA Gate area	3e-6 m^2 (2mm diameter)
Tip area with high grad	1e-16 m^2 (assuming 10nm x 10nm)
All tips	4e-12 m^2 (100k tips)
QE gate	1e-6 (poor photo emitter)
QE tips	1 (assumed)
Laser pulse E	3uJ (266nm)
Charge from tips	**0.8pC**
Charge from gate	**0.6pC**

Photo-assisted emission did not give much hope for homogenizing the emission pattern.



⇐ Without laser



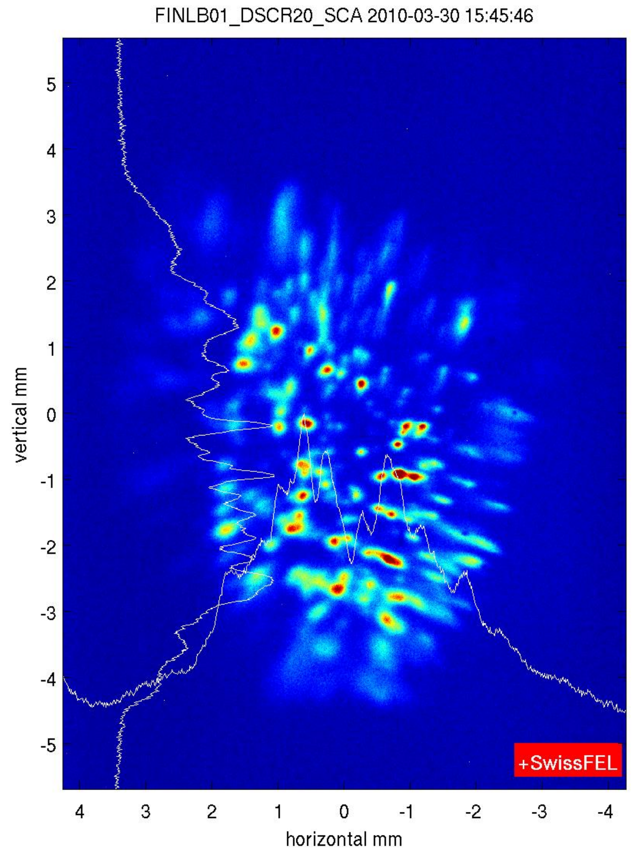
Laser beam

⇐ With laser

Pattern evolution with increasing gate voltage

Machine settings: 250kV @ 15mm, 1Hz
Gate voltage (Uch) increased from 116 to 130V
Charge changed from 2.2 to 7.9pC

Uch = 130V



- Emission pattern changes with increasing gate voltage.
- During increasing U gate there were several spark like events without pulse energy loss.
- FEA was destroyed at Uch = 130V. Most likely the destructive arc was triggered by one of the spark-like events.
- For homogenizing the FEA emission the individual tips' voltage (drop) should differ with more than 20V

Summary

500 kV pulser (4 MeV test stand) made possible to study HG breakdown in macroscopic electrode spacing – realistic accelerator geometries

Bare metal electrodes breakdown strength depends strongly on surface quality and mechanical properties of the metal (?) but is limited to 150 MV/m (macroscopic gaps, x100 us pulses)

Hydrogenated amorphous DLC (a-C:H) coating has exceptionally good vacuum breakdown performance for short damped oscillatory pulses. Surface breakdown field surplus, due to DLC coating, makes possible to do additional field shaping.

- Max surface gradient >300 MV/m @ 1mm
- Photo-emission at >150 MV/m @ 2mm
- No detectable dark current
- Stable operation (no conditioning needed)

Testing of variety of photocathode materials and FEAs was possible due to DLC coated electrodes.

- Different material QE evaluation
- FEA integration in high gradient environment

Thank you for your attention

Project team in 4 MeV test stand bunker - some time ago...

Other Coating Materials

- Mo, 1 um on steel – 80 MV/m
- Mo, 2 um on steel – 138 MV/m, 212 MV/m, 50 MV/m
- TiN, 2 um on steel – 73 MV/m, 70 MV/m, 90 MV/m

- Very limited number of tests