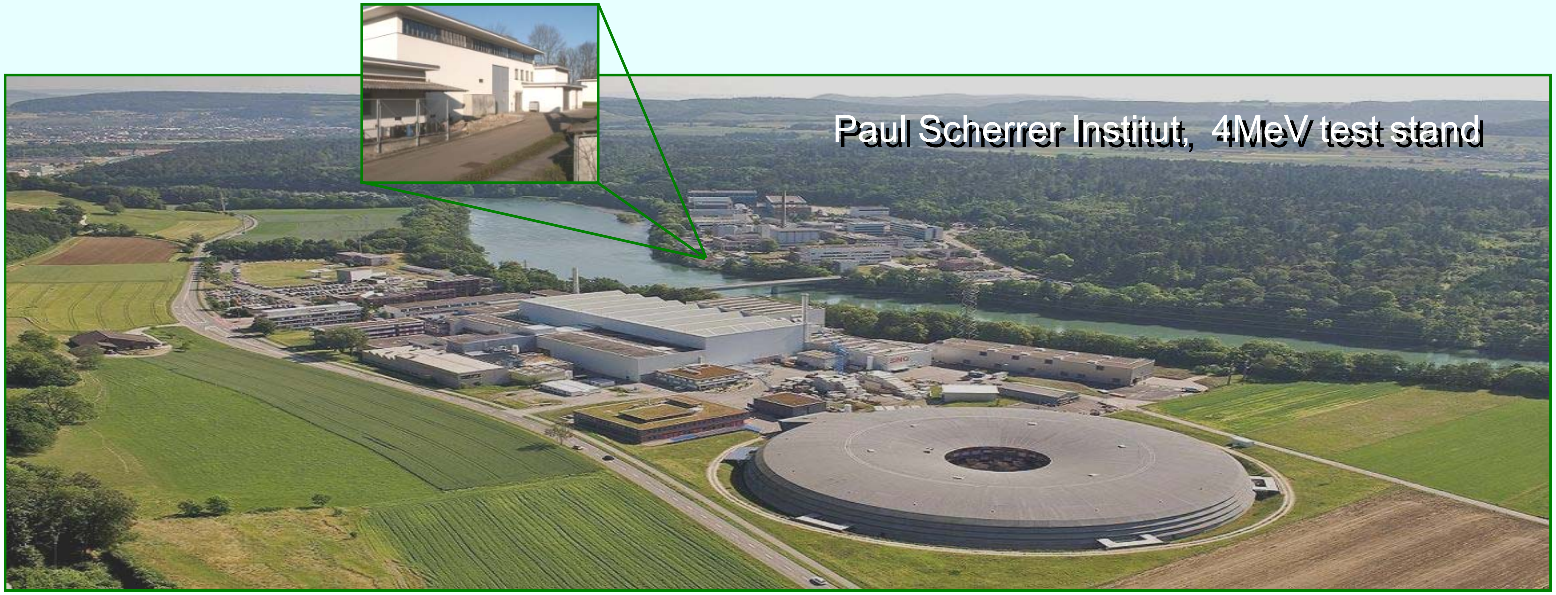
Development of Pulsed High Gradient Photoelectron Gun

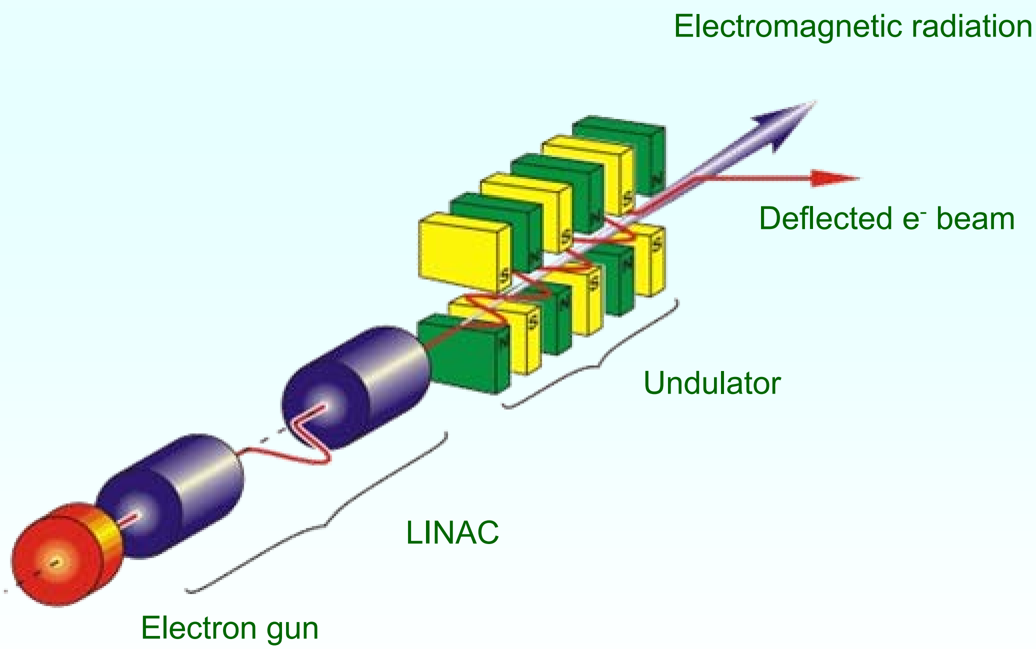
SwissFEL project



Presented by Martin Paraliev

Motivation

- X-ray Free Electron Lasers (XFEL) are important for future experimental physics
- Cost and size of the XFEL facilities reduce availability for science.
- Low emittance electron beam relaxes beam requirements (peak current and energy) and reduces undulator saturation length.



Concept and key elements of FEL

Critical wavelength λ_{cr} [1]

$$\lambda_{cr} \cong 18\pi \enclose{circle}{\varepsilon_n} \frac{\sigma_E}{\gamma} \sqrt{\frac{1}{\gamma} \frac{I_A}{I}}$$

Gain length L_g and FEL Pierce parameter ρ [2]

$$L_g \approx \frac{\lambda_u}{4\pi\rho}$$

$$\rho = \frac{1}{\gamma} \sqrt[3]{\frac{I}{I_A} \frac{\enclose{circle}{\varepsilon_n}\beta}{\gamma} \left(\frac{K\lambda_u f(\xi)}{8\pi} \right)^2}$$

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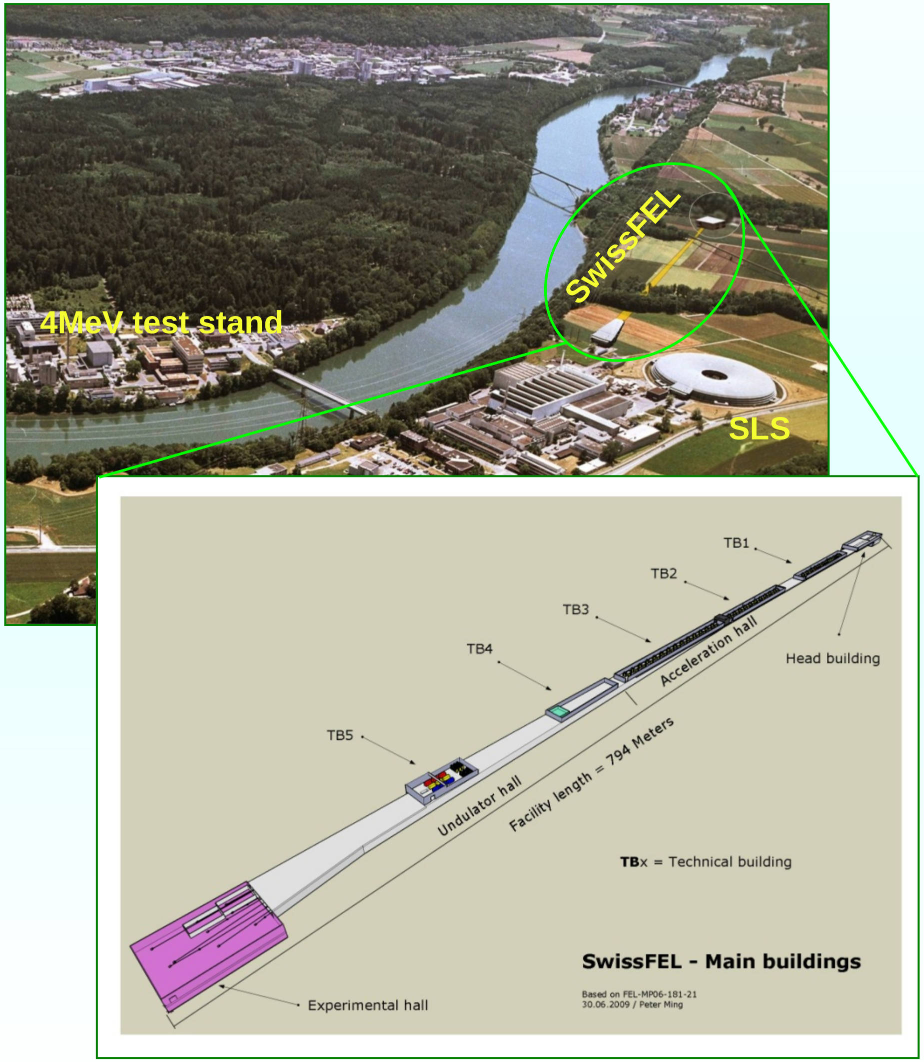
[1] R.J. Bakker *at al*, “Ultra High Brightness Accelerator Design” Proc. of FEL 2006, BESSY, Berlin, Germany

[2] The Technical Design Report of the European XFEL, DESY, Germany

SwissFEL project - Compact X-ray Free Electron Laser



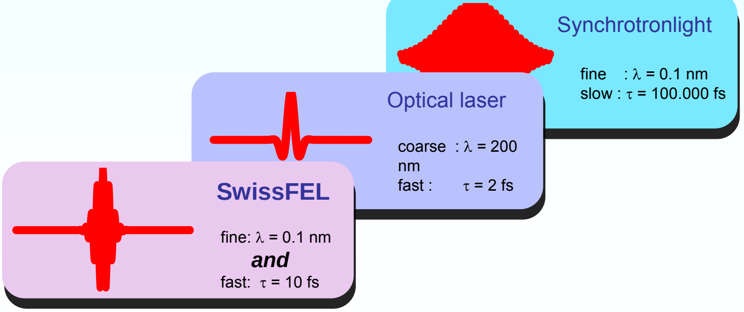
Location and layout of the future XFEL machine at PSI

SwissFEL

Wavelength tunable from	1 - 100 Å
Pulse duration	1 - 20 fs
Repetition rate	100 - 400 Hz
Construction period	2012 - 2015
Estimated investment cost	250 MCHF

Novel experiments in:

- Nanoscale Magnetization Dynamics
- Solution Chemistry and Surface Catalysis
- Coherent Diffraction by Nanostructures
- Ultrafast Biochemistry
- Time-Resolved Spectroscopy of Correlated Electron Materials



Synchrotronlight

fine : λ = 0.1 nm
slow : τ = 100.000 fs

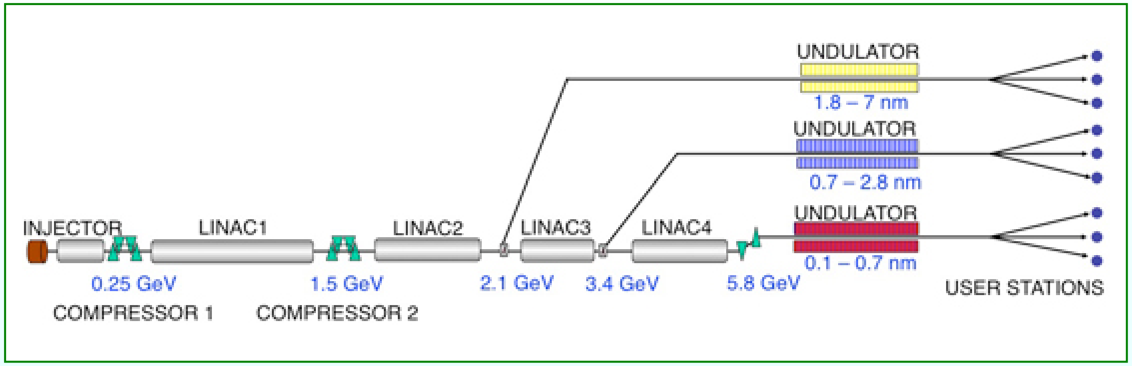
Optical laser

coarse : λ = 200 nm
fast : τ = 2 fs

SwissFEL

fine: λ = 0.1 nm
and
fast: τ = 10 fs

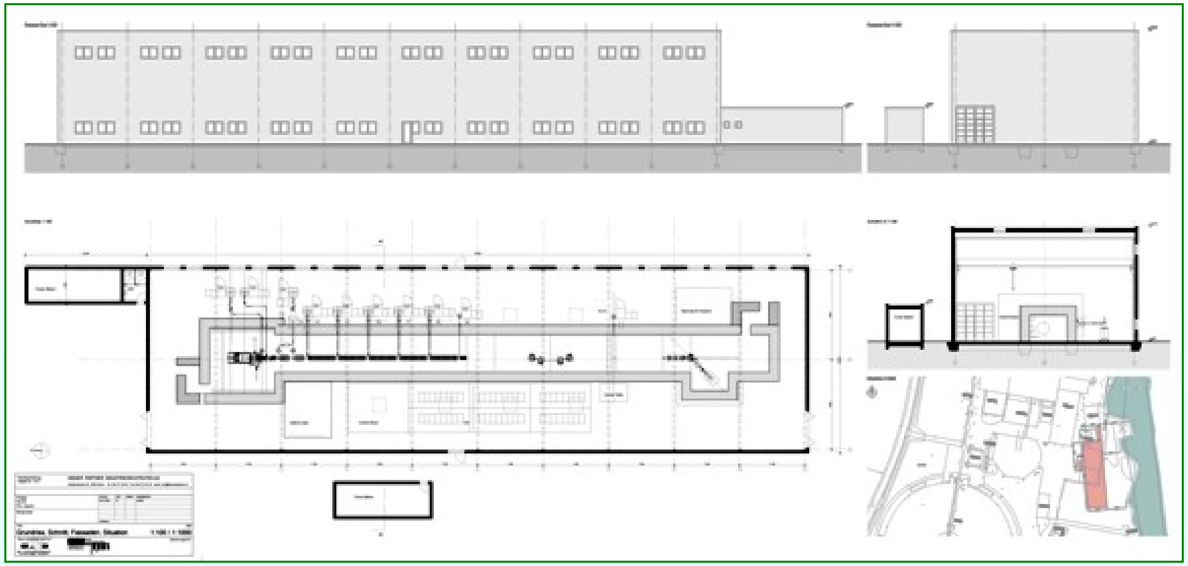
SwissFEL conseptual layout and target parameters



- ➢ Modular approach – adding experimental stations.
- ➢ Final layout - Three split experimental lines.

Branch	1	2	3	Units
Wavelength range	0.1 - 0.7	0.7 - 2.8	1.8 - 7.0	nm
Photon energy range	12 - 1.7	1.7 - 0.43	0.67 - 0.17	keV
Polarization	planar	variable	variable	
Peak power	2	6	6	GW
Peak brilliance	10^{31} - 10^{33}	10^{30} - 10^{32}	10^{29} - 10^{31}	ph/s/mm^2/mrad^2/0.1 % bw
Flux	5.10^{10}	5.10^{11}	1.10^{12}	ph/pulse/0.1 % bw
Pulse Energy	0.1	0.4	0.4	mJ
Spectral width (rms)	0.04 - 0.08	0.1 - 0.3	0.2 - 0.4	%
Beam-size (rms)	25	50	70	µm
Pulse duration (rms)	25	25	25	fs
Repetition rate	10 - 100	10 - 100	10 - 100	Hz

250MeV test stand

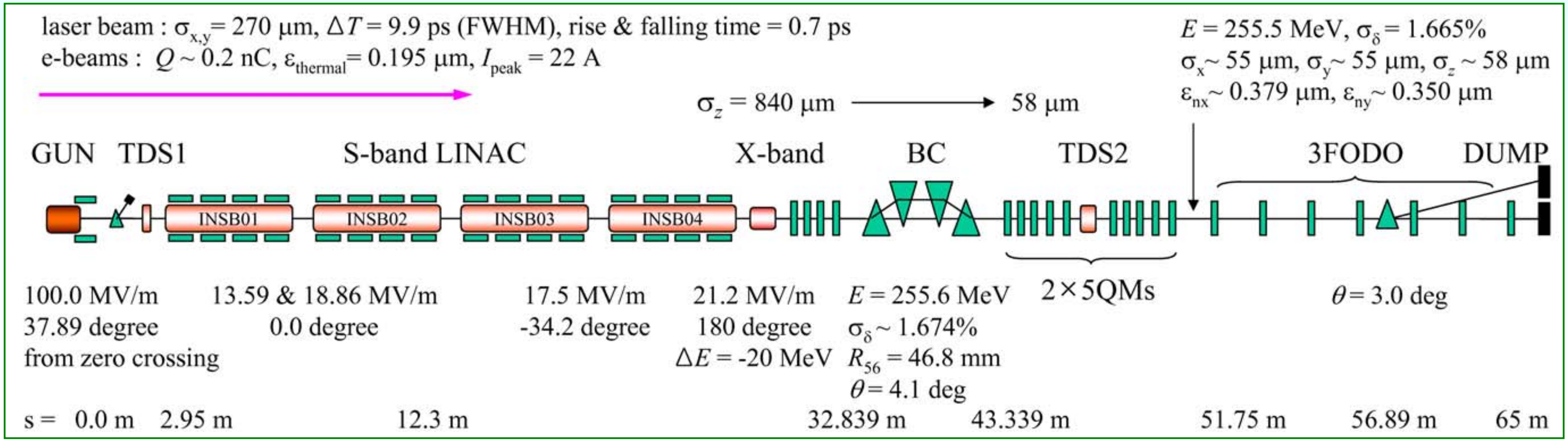


Multi functional building

250MeV test stand layout

Total length ~70m

Emittance <0.4 mm mrad



laser beam : $\sigma_{x,y}$= 270 μm, ΔT = 9.9 ps (FWHM), rise & falling time = 0.7 ps

e-beams : $Q \sim 0.2$ nC, $\varepsilon_{\mathrm{thermal}} = 0.195$ μm, $I_{\mathrm{peak}} = 22$ A

$E = 255.5$ MeV, $\sigma_\delta = 1.665\%$

$\sigma_x \sim 55$ μm, $\sigma_y \sim 55$ μm, $\sigma_z \sim 58$ μm

$\varepsilon_{nx} \sim 0.379$ μm, $\varepsilon_{ny} \sim 0.350$ μm

$\sigma_z = 840$ μm → 58 μm

GUN TDS1 S-band LINAC X-band BC TDS2 3FODO DUMP

100.0 MV/m
37.89 degree
from zero crossing

13.59 & 18.86 MV/m
0.0 degree

17.5 MV/m
-34.2 degree

21.2 MV/m
180 degree
ΔE = -20 MeV

$E = 255.6$ MeV
$\sigma_\delta \sim 1.674\%$
$R_{56} = 46.8$ mm
$\theta = 4.1$ deg

2×5QMs

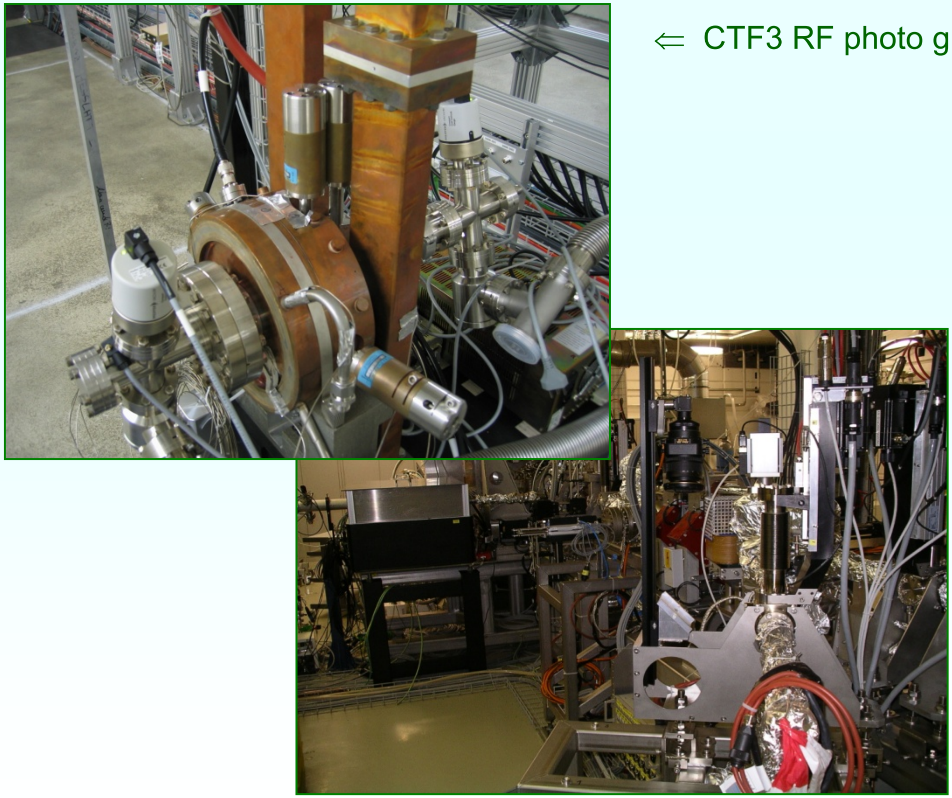
$\theta = 3.0$ deg

s = 0.0 m 2.95 m 12.3 m 32.839 m 43.339 m 51.75 m 56.89 m 65 m

4MeV Low Emittance Gun Test Stand

Two photo injector technologies considered:

- RF - base line (CTF RF photo gun – 3GHz, 2.5 cell)
- High gradient pulsed - more innovative and risky - based on field and photo-assisted field emission (including Field Emitting Arrays).



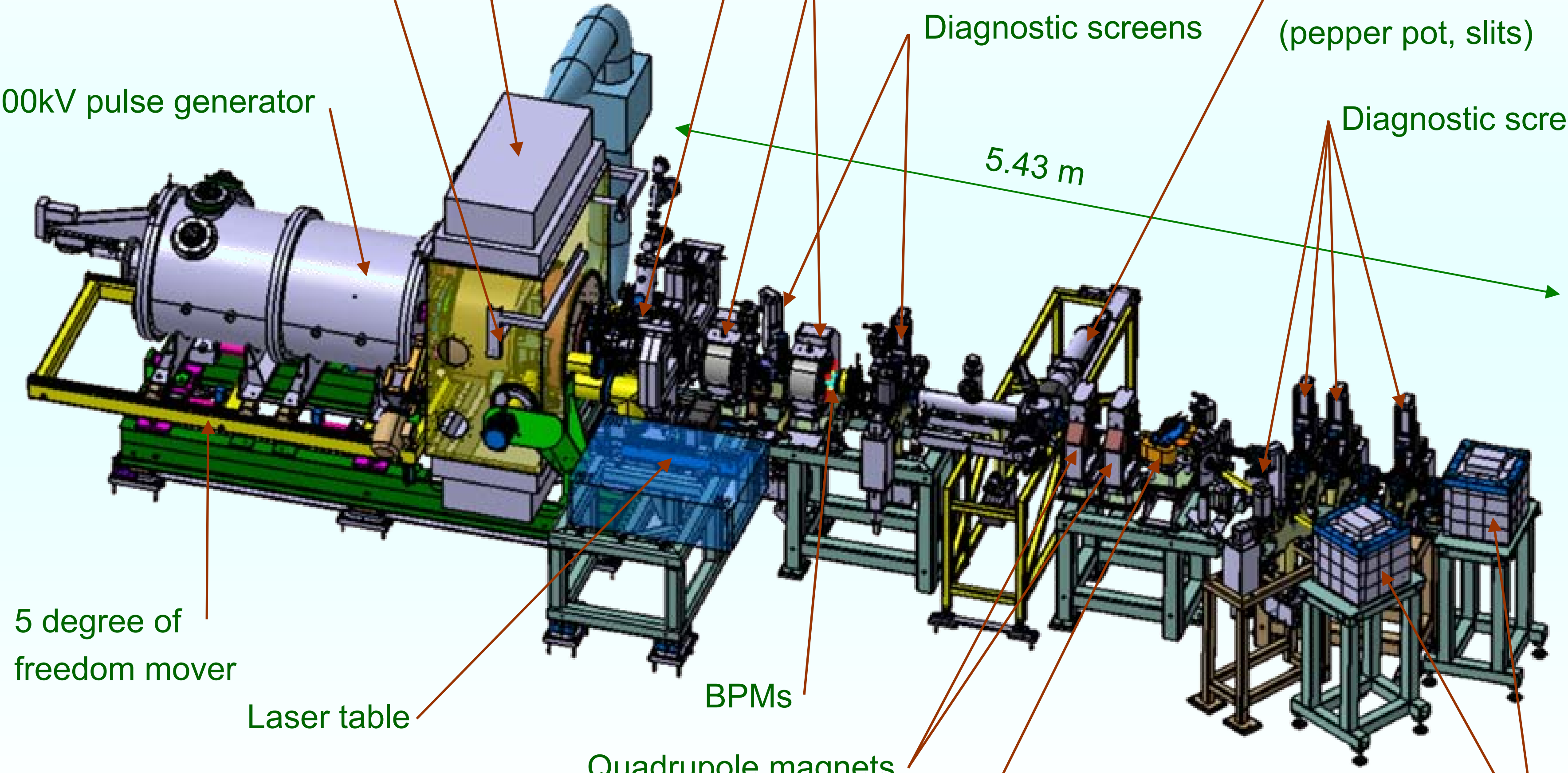
⇐ CTF3 RF photo gun (CERN)

⇐ 4MeV LEG test stand (PSI)

Main topics

- Test stand overview
- High Gradient tests
- Beam characterization
- Field emitter arrays development

Test stand overview



Clean cubicle and air filter

Vacuum chamber with
pulsed accelerating diode

500kV pulse generator

Two cell 1.5GHz RF cavity

Focusing solenoids

Diagnostic screens

Emittance monitor
(pepper pot, slits)

Diagnostic screens

5 degree of
freedom mover

Laser table

BPMs

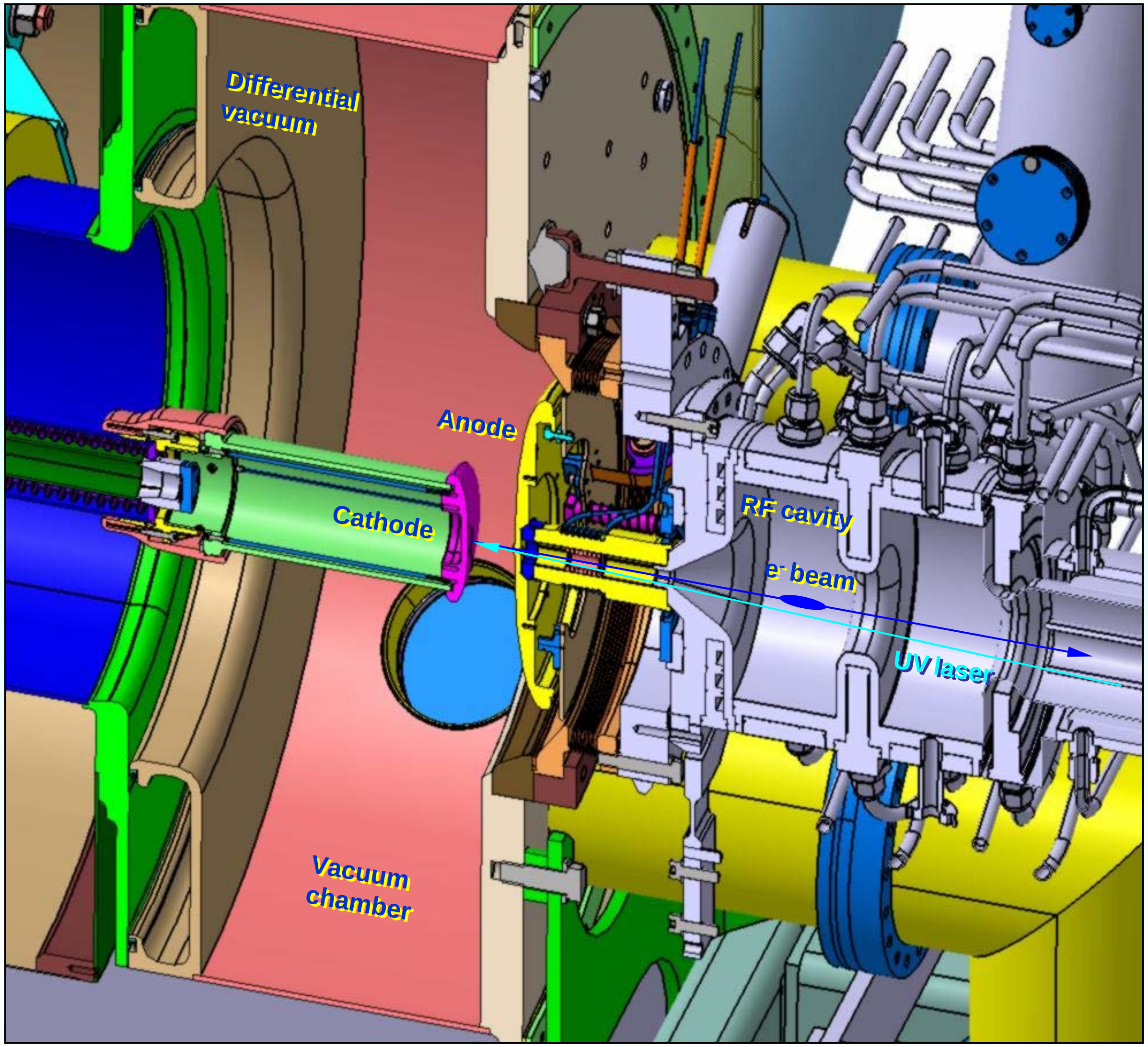
Quadrupole magnets

Dipole magnet

Beam dumps with faraday caps

3D CAD model of 4MeV test stand

Vacuum chamber and cavity



System parameters

- Max accel. diode voltage - 500kV
- Diode pulse length FLHM – 250ns
- Two sell RF cavity 1.5GHz
- Max RF power - 5MW
- RF pulse length – 5us
- Beam energy - 4MeV
- Rep. rate - 10Hz
- Laser pulse length – 10ps
- Laser wave length – 262nm
- Max laser pulse energy – 250uJ

Features

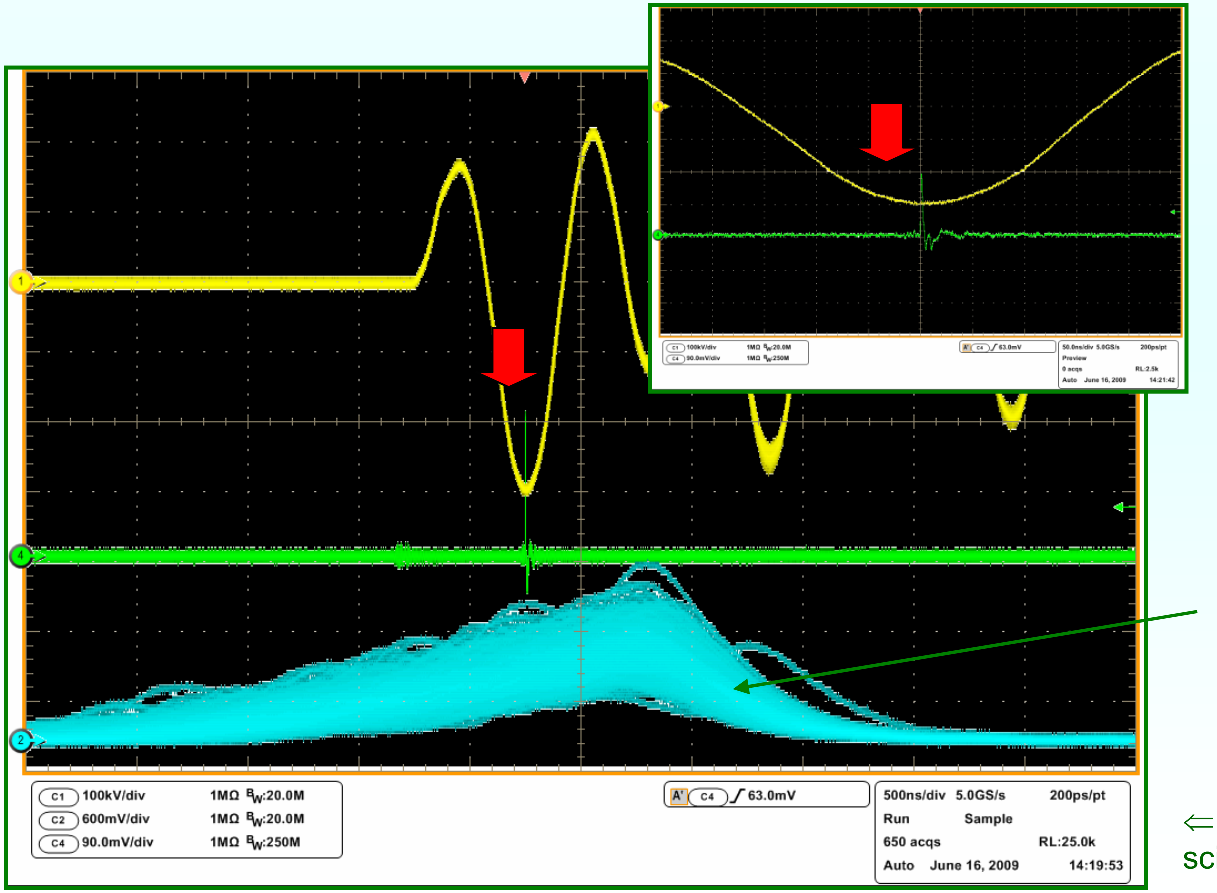
- Variable anode cathode distance
- Adjustable cathode position
- Exchangeable electrodes
- Differential vacuum system
- Bolts-free vacuum chamber
- Scintillator based dark current monitoring system

⇐ Vacuum chamber and cavity cross section

Diode Accelerating Voltage

Emission is triggered by laser pulse (green waveform) at maximum negative peak of the accelerating voltage (yellow waveform) - Infinite persistence mode

Laser pulse is short (10ps FWHM) with respect to accelerating voltage change - quasi DC acceleration.`



C1 100kV/div 1MΩ BW:20.0M
C4 90.0mV/div 1MΩ BW:250M
A' C4 63.0mV
50.0ns/div 5.0GS/s 200ps/pt
Preview
0 acqs RL:2.5k
Auto June 16, 2009 14:21:42

C1 100kV/div 1MΩ BW:20.0M
C2 600mV/div 1MΩ BW:20.0M
C4 90.0mV/div 1MΩ BW:250M
A' C4 63.0mV
500ns/div 5.0GS/s 200ps/pt
Run Sample
650 acqs RL:25.0k
Auto June 16, 2009 14:19:53

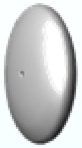
The scintillator (blue waveform) registers some parasitic X-ray activity form the RF cavity.

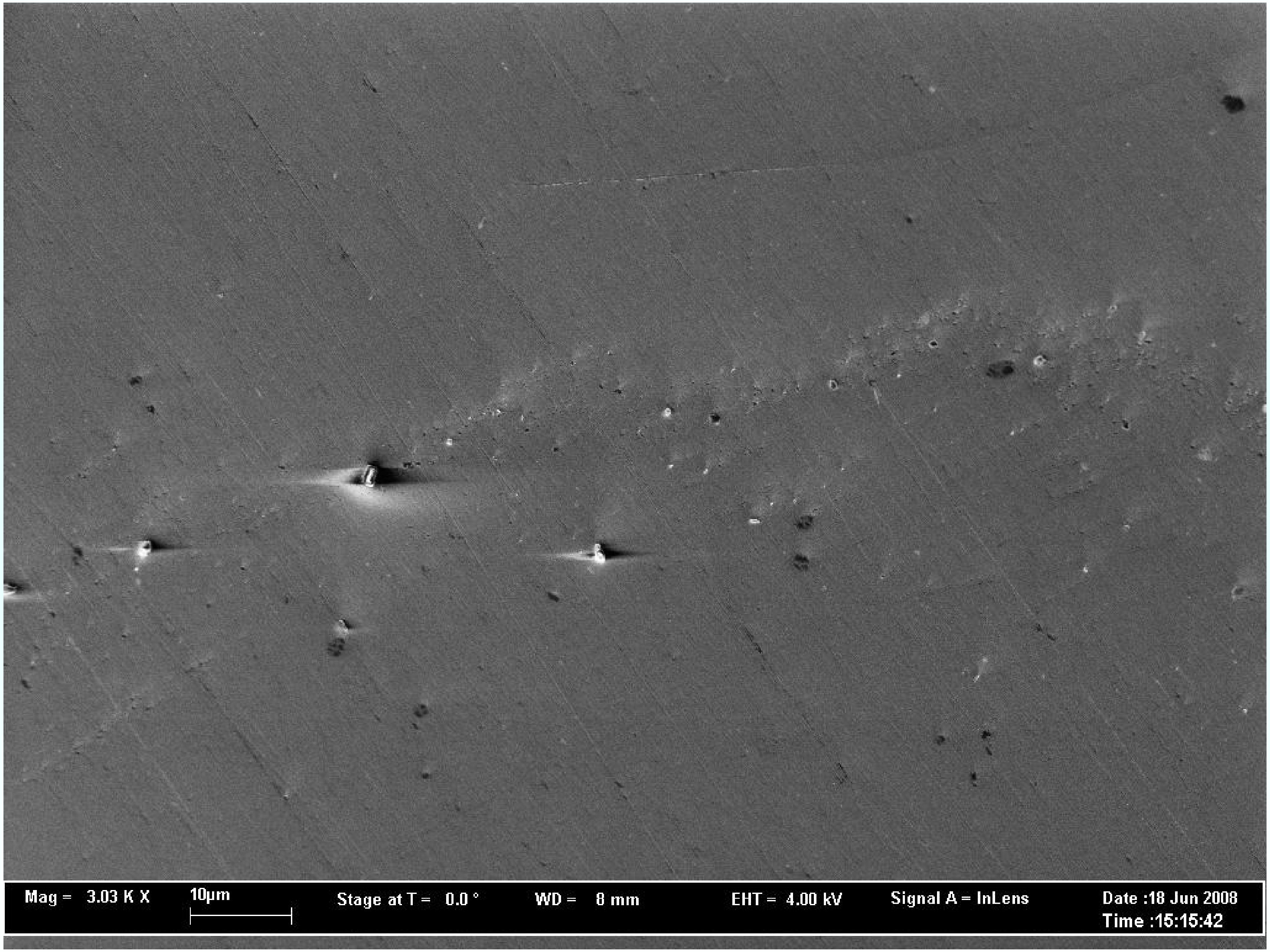
In case of break down or extended dark current, some distinctive pulses appear, synchronized with the high voltage waveform.

The scintillator signal copies the filling of RF cavity

⇐ Accelerating voltage, laser pulse and scintillator signal waveforms

Stainless steel electrodes – surface quality





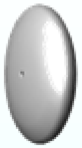
Typical SEM picture of polished electrode surface

There are clearly defects on the surface (embedded particles, inclusions, voids) but it is hard to correlate them with a breakdown location.

⇑ Polished electrode surface under scanning electron microscope

Thanks to E. Kirk

Stainless steel electrodes - roughness



Hand polishing reproducibility is an issue!

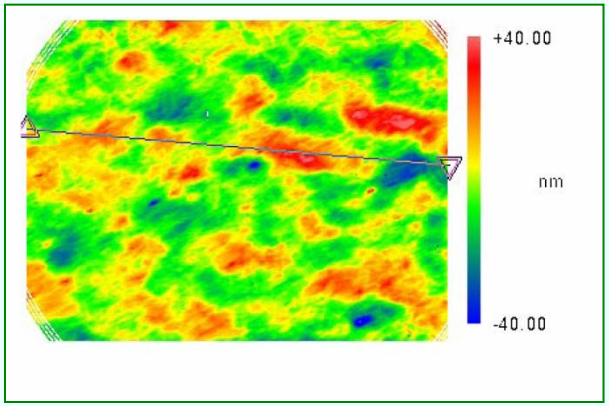
The gross geometric surface features (like iris edge radius) are not necessarily the location of a breakdown.

Surface roughness

Surface roughness evaluation was performed “on fly”. There are not enough samples measured to get a correlation between vacuum breakdown voltage and surface roughness on a micro scale. There are some systematic issues as well. (measurement area, “post mortem” measurement…)

A more systematic study is required to evaluate the possible correlation between roughness (type of suitable roughness measurement) and breakdown voltage.

Further attempt to improve the polishing did not give significant improvement in breakdown voltage (limited ~ 120MV/m)

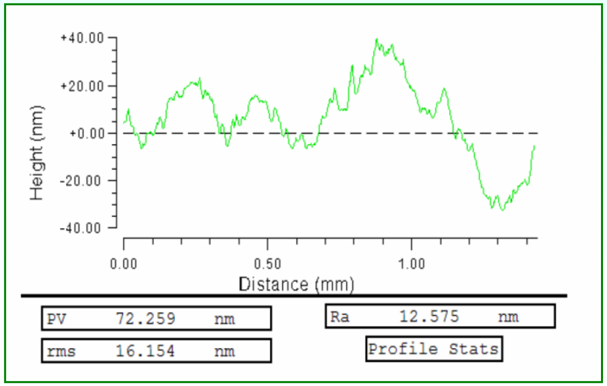


⇐ Cathode M5 (SS 316L) height map (09.09.2008).

∆Hpp =72nm

Hrms = 16nm

Ra = 13nm



PV 72.259 nm

rms 16.154 nm

Ra 12.575 nm

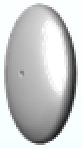
Profile Stats

⇐ Cathode M5 (SS 316L) Line height profile:

- 1.5 mm long
- Ra = 12.6 nm
- Rp-p = 72.3 nm
- Rrms = 16.2 nm

Thanks to S. Spielmann-Jaggi

Stainless steel electrodes - metallurgy



Breakdown performance vs. metallurgical characteristics of the SS.

Two samples of SS 316L from different ingots (different base form as well – rod and plate) were sent for analysis. The “rod” electrodes gave 109 MV/m (average of 5 pairs), “plate” electrodes 81 MV/m (average of 7 pairs)

It was not possible to draw a credible conclusion.

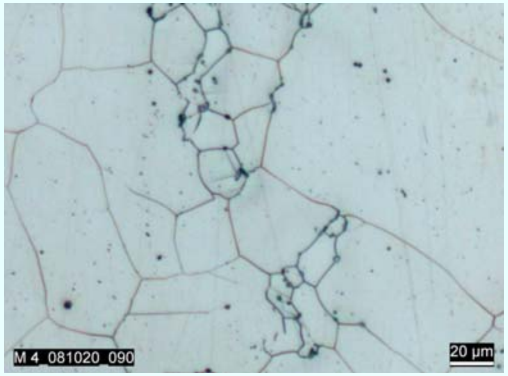
Electro-etched, top view

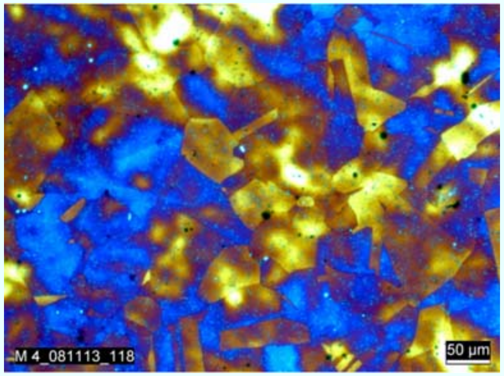
Electro-polished and Beraha tint etched by immersion

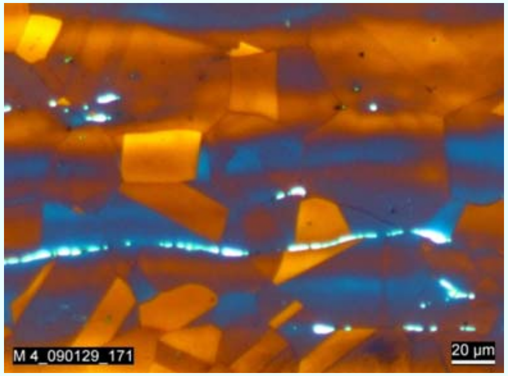
Electro-polished and tint etched by immersion in Beraha solution (M4 - Longitudinal, A39 - Top)

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

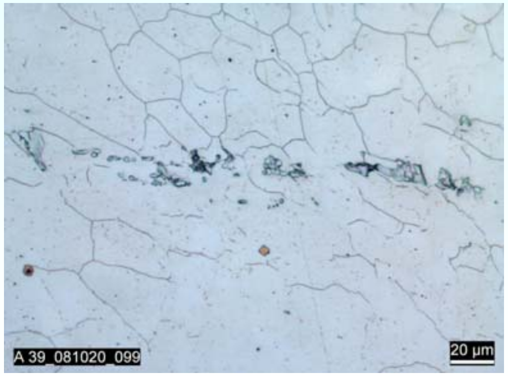
Better?!

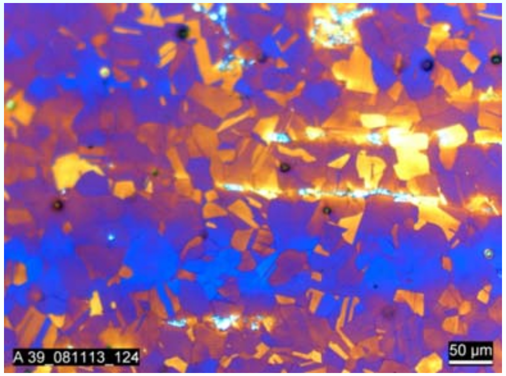


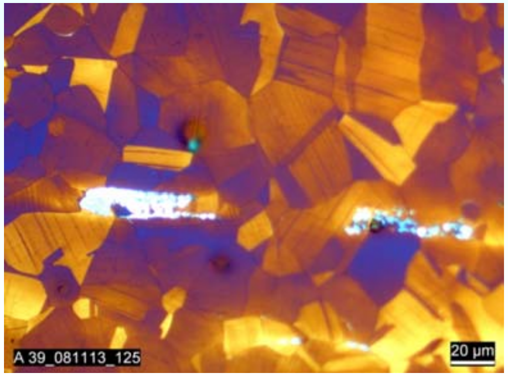




Electrode A39
(SS 316L **plate**)

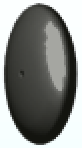






Thanks to H. Leber

Diamond Like Carbon (DLC)



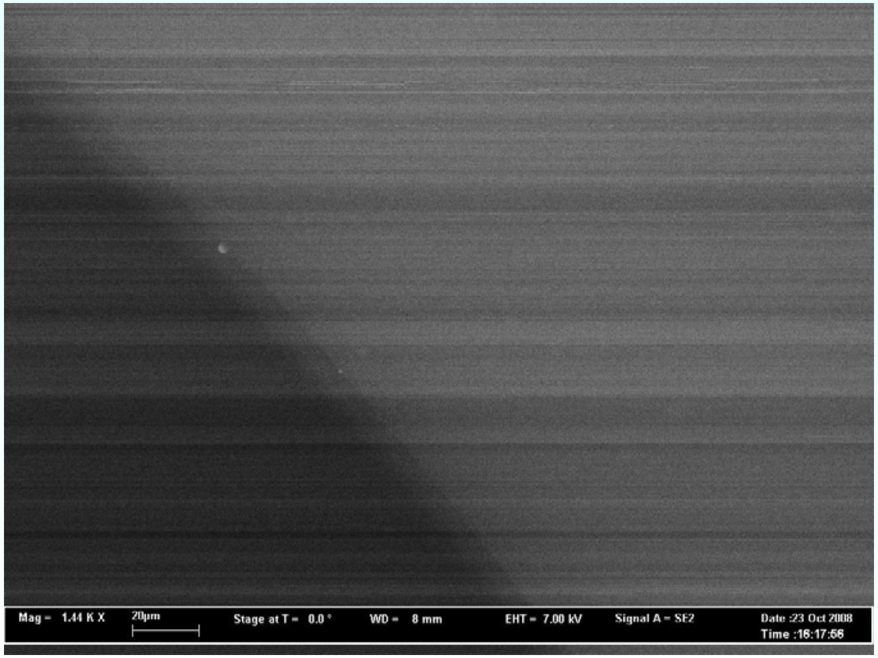
There is a broad spectrum of opinions about breakdown and emission properties of DLC.

The technology is able to deposit DLC with tailored properties (thickness and conductivity) on virtually any type of metal surface (www.bekaert.com).

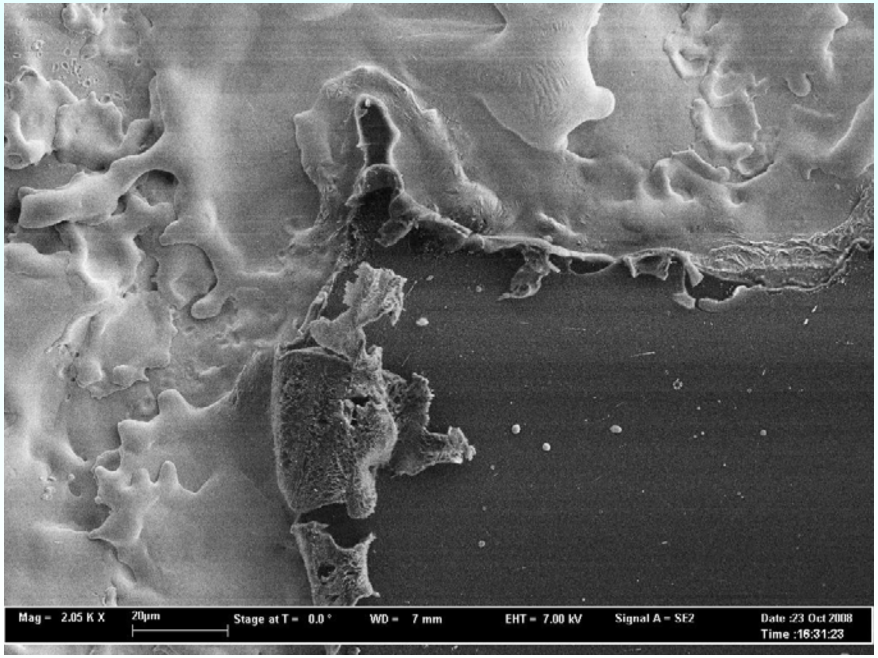
Features:

- **Smooth and stable surface**
- **Mechanical properties comparable to these of diamond**
- **Unique electrical properties**

⇓ Intact DLC surface type PSI 080815-UF

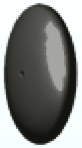


⇓ Destroyed DLC surface (same type).



Thanks to E. Kirk

DLC – photo emission



- DLC coating structure is complex – hard to determine the exact emission process [1].
- DLC and Diamond Like Nanocomposite (DLN) properties are not well defined since they depend on the sp2/sp3 bonding ratio (graphite/diamond) and doping levels [2].

Two possible electron photoemission mechanisms – simplified energy band diagrams

[1] J. Robertson, “Field emission from carbon systems”, Mat. Res. Soc. Symp. Proc. Vol. 62, 2000

[2] A. Wisitsorat, “Micropatterned diamond vacuum field emission devices”, PhD thesis, Nashville, TN, 2002

Simplified energy band diagram data:

Copper work function $W_{Cu} = 4.7$ eV

Titanium work function $W_{Ti} = 4.33$ eV

DLC (DNL) assumptions:

DLC relative dielectric constant $\varepsilon_r = 4$

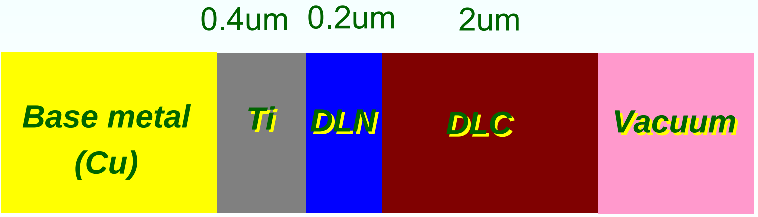
DLC band gap energy $E_G = 5.54$eV (intrinsic)

DLC electron affinity $-0.5 < \chi < 0.5$ eV

External field E = 100 MV/m

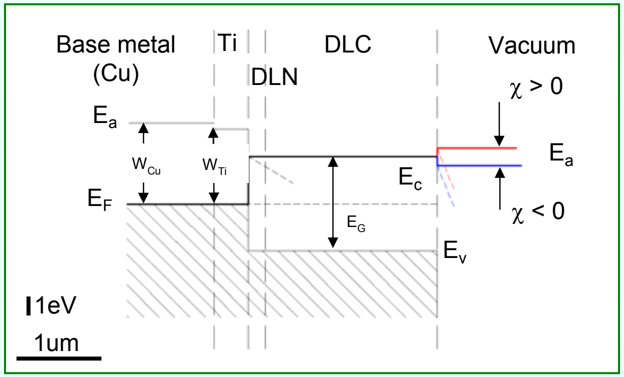
DNL conductivity is not taken in account

Photon energy $h\nu$ 4.7 eV (262 nm)



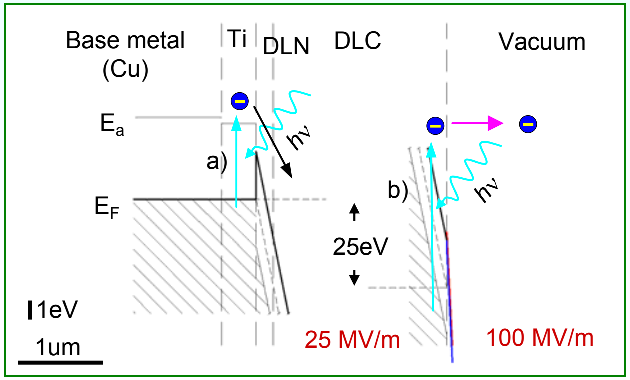
⇑ Typical DLC layer structure (PSI 080815-UF)

0 MV/m

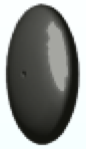


a) Emission from DLC conduction band b) photoemission from DLC valence band

100 MV/m



DLC – First results



Results for DLC type PSI 080815-UF (2μm thick , Resistivity $10^6..10^7\ \Omega$.cm)

- Electrode pair A4/A3 – **227MV/m@1.76mm**
- Electrode pair A6/A5 – **270MV/m@1.5mm**
- Electrode pair A8/A7 – **100MV/m@4mm (with laser)**

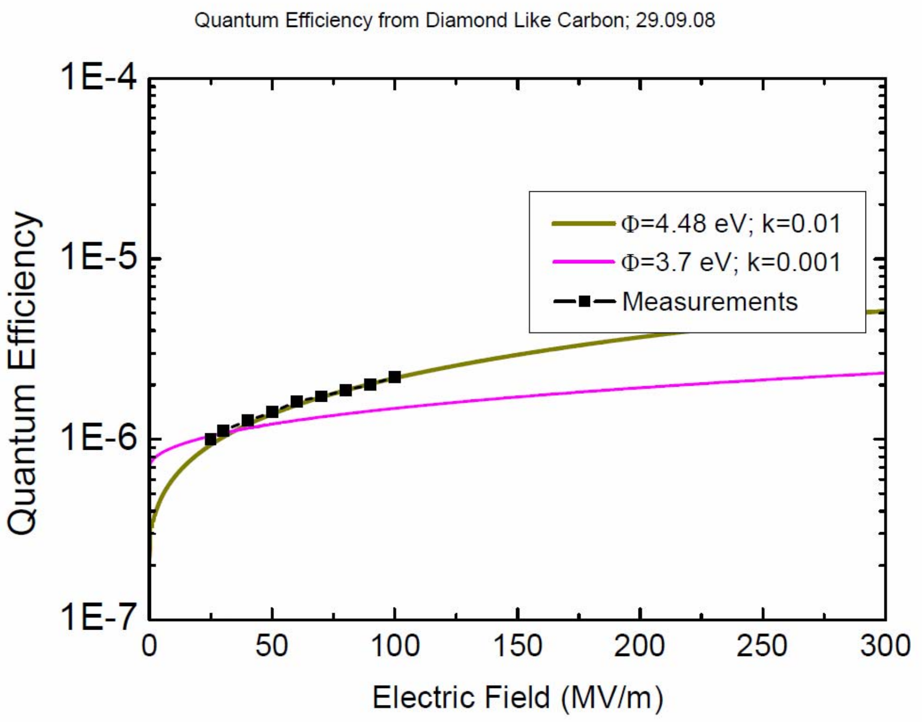
The results were unexpectedly good!

No dark current was detected using the scintillator. (Solid angle factor ~2×10^{-4})

The photo emitted charge was **10..15pC**.

Quantum efficiency (relative) was measured **over large electric field strength range – 25..100MV/m**

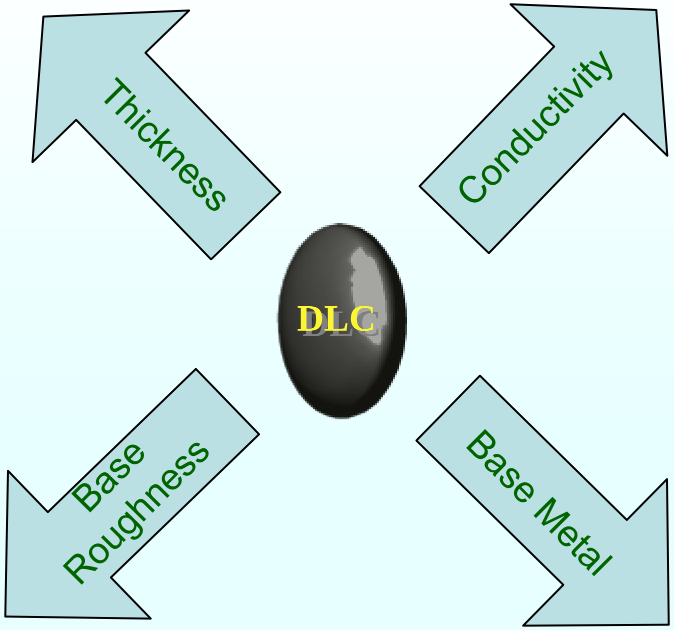
A breakdown occurred after an attempt to increase the laser power on the cathode surface, at 50MV/m.

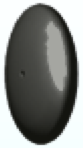


⇐ Measured quantum efficiency and analytical fit using single Schottky barrier photo-field emission assumption.

Thanks to R. Ganter

DLC – parametric study



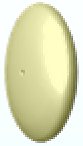


DLC types tested to study the influence of coating layer parameters.

- **First configuration** – 2μm thick DLC on polished stainless steel, ρ ~ $5x10^6$ Ω.cm (PSI 080815-UF) – 3 pairs
- **Thicker coating layer -** 4μm thick DLC , ρ ~ $5x10^6$ Ω.cm (PSI 080815-UF) – 4 pairs
- **Higher conductivity** - 2μm thick DLC , ρ ~ $5x10^4$ Ω.cm (PSI 080815-RG) – 4 pairs
- **Low conductivity -** 2μm thick DLC , Resistivity ~ $5x10^{11}$ Ω.cm (PSI-080815-HR) – 4 pairs
- **Base metal -** 2μm thick DLC , ρ ~ $5x10^6$ Ω.cm (PSI 080815-UF) – bronze 8 pairs, copper 5 pairs
- **Base metal roughness** 2μm thick DLC , ρ ~ $5x10^6$ Ω.cm (PSI 080815-UF) rougher stainless steel – 1pair

Configuration	Thickness	Resistivity	Base	Av. Gradient	Samples	Note
First configuration	2 μm DLC	5.10^6 Ω.cm	Polished st. steel	**248 MV/m**	2 (+1[1])	Range 227..270 MV/m [1] Used for photo emission
Thicker layer	4 μm DLC	5.10^6 Ω.cm	Polished st. steel	145 MV/m	4	Range 140..150 MV/m
Higher conductivity	2 μm DLC	5.10^4 Ω.cm	Polished st. steel	200 MV/m	2 (+2[2])	Range 167..233 MV/m [2] 2 samples died at ~55MV/m
Low conductivity	2 μm DLC	5.10^{11} Ω.cm	Polished st. steel	185 MV/m	4	Range 137..291 MV/m
Copper base	2 μm DLC	5.10^6 Ω.cm	Polished copper	**>200 MV/m[3]**	2 (+3[4])	[3] Used for emission [4] Used in other configurations
Bronze base	2 μm DLC	5.10^6 Ω.cm	Polished bronze	**232 MV/m**	5 (+2[5])	Range 150..324 MV/m [5] 2 samples died at ~50MV/m
Rough surface	2 μm DLC	5.10^6 Ω.cm	Rough st. steel	122 MV/m	1	

Other materials

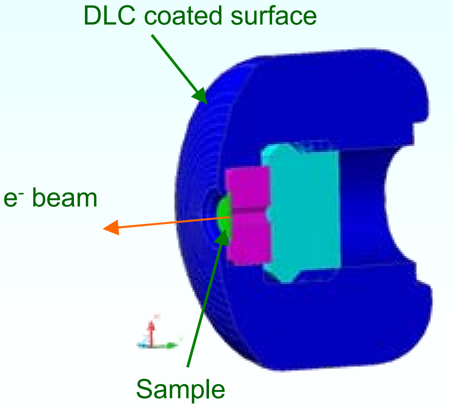


Even the detailed vacuum breakdown mechanism is not yet well understood there is some evidence that following mechanical properties affect the vacuum breakdown strength.

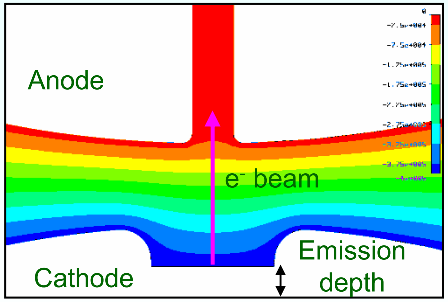
- **Melting temperature**
- **Hardness**

Preliminary results for other materials

Configuration	AISI	DIN	Surface	Deposition	Av. Gradient	Samples	Note
St. Steel (ref.)	~316L	1.443	polished	No	87 MV/m	7	Range 61..128 MV/m
SS (Decolletage)	~316L	1.4404+S+Cu	polished	No	**119MV/m**	4	Range 90..142 MV/m
SS (Implant)	~316LVM	1.4441	polished	No	99 MV/m	7	Range 57..137 MV/m
Mo coating	~316L	1.443	polished	Mo 2μm	138 MV/m	1	Without plasma cleaning
Mo coating	~316L	1.443	polished	Mo 2μm	**212 MV/m**	1	Plasma cleaning before deposition
ZrN coating	~316L	1.443	polished	ZrN 0.5μm	38 MV/m	1	Bad adhesion



Hollow cathode cross-section

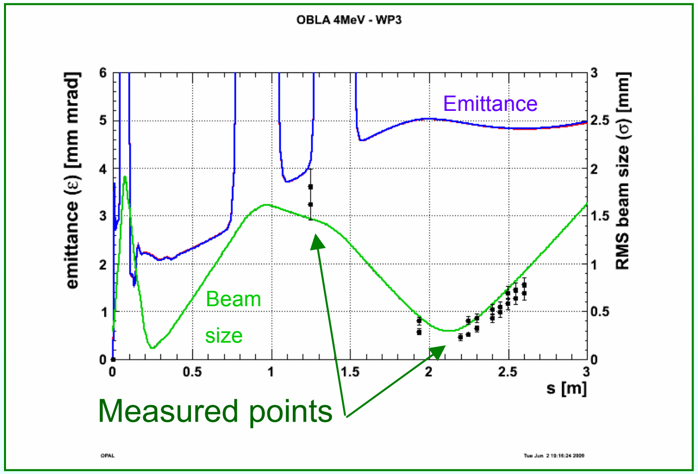


Electrostatic simulation of the field in the accelerating diode.

"Hollow" cathode geometry:

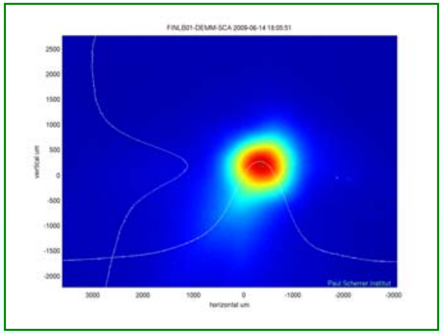
- Emission from other materials
  - small sample
  - reduced surface field
- Emission from FEA chips
- Explore the effect of electrostatic focusing

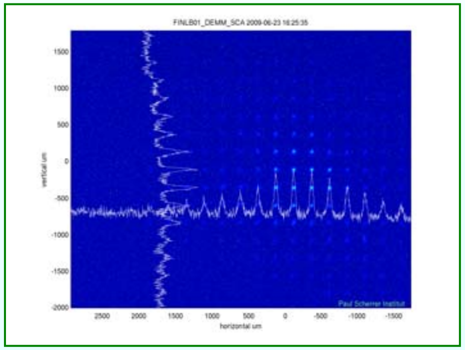
Electron beam characterization



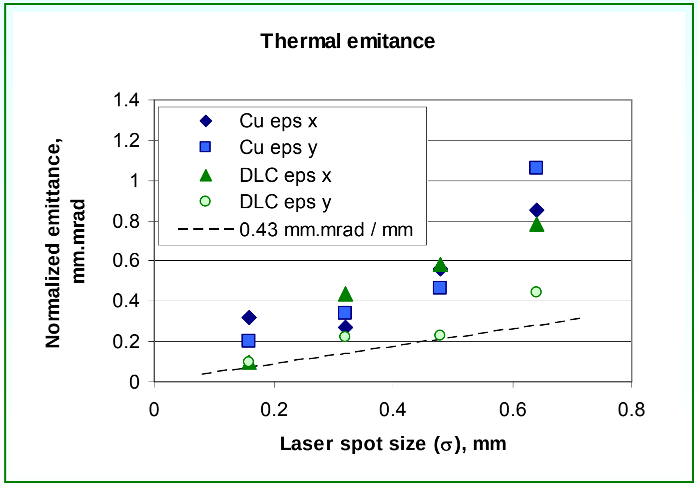
OPAL simulation of beam emittance and beam envelope, compared with measurements

Beam on emittance ⇒ monitor screen.



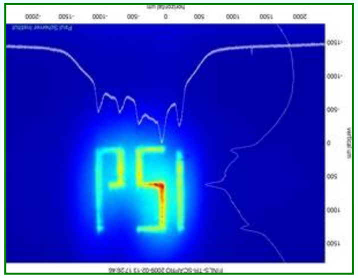


⇐ Pepper-pot image

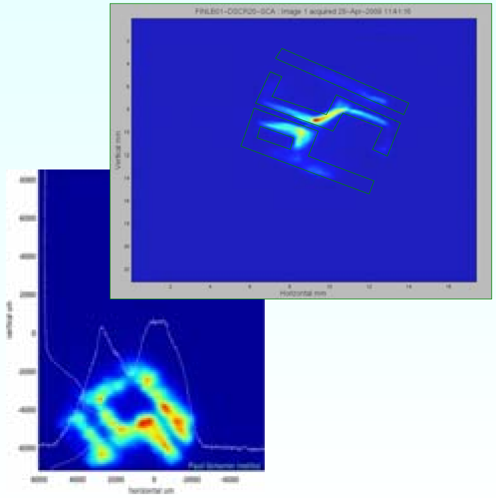


Measured thermal emittance vs laser spot size (extraction field 50MV/m, λ_{laser} = 262)

Cathode imaging helps to study the beam propagation and laminarity

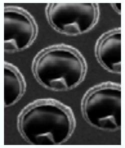


PSI logo projected on the cathode

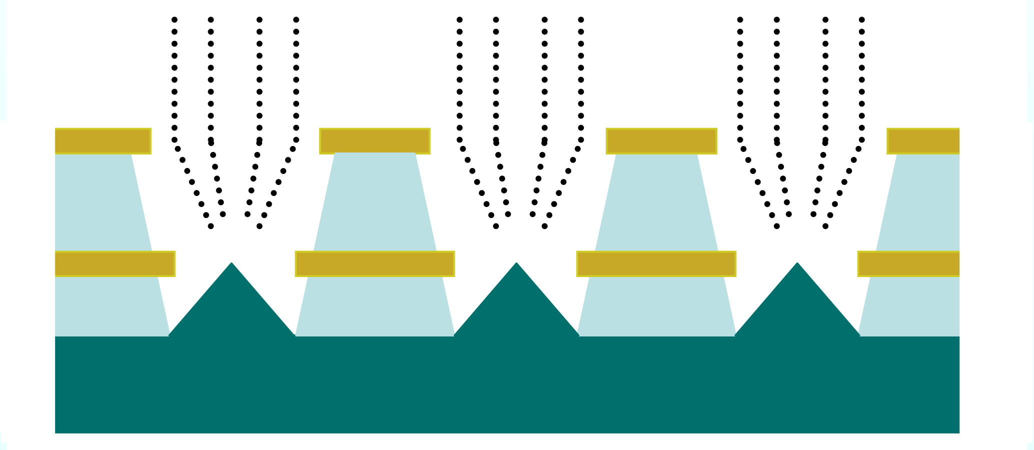


Electron beam images on YAG screen two

Field Emitter Arrays (FEA) as a low emittance electron beam source

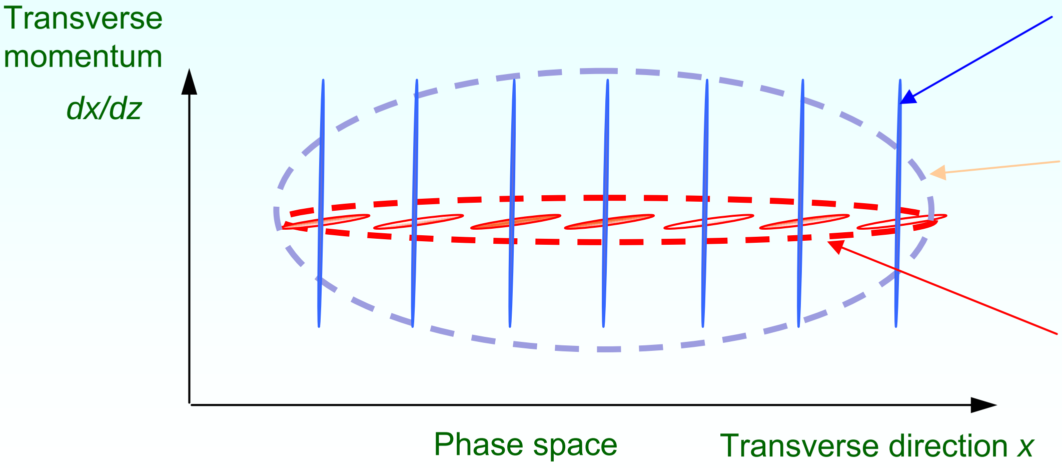


Double-gated emitter array



Field emitter array cross section

- **First emitter gate controls the emission**
- **Second emitter gate focuses individual beamlets (reduces overall emittance)**
- **High gradient acceleration**

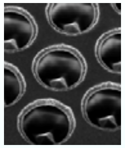


Individual emitter ε_n ~ 5x10-3 mm mrad
(σ_x~1 μm, $\delta\theta$ ~ 15°, Ue~100 V)

Envelope of whole array (single gate) ε_n ~ 2.5 mm mrad
(σ_x~0.5 mm, $\delta\theta$ ~ 15°, Ue~100 V)

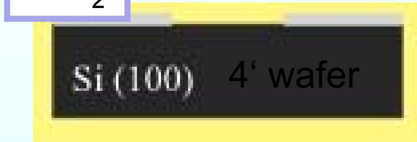
Envelope (double gate) ε_n < 0.1 mm mrad
(σ_x~0.5 mm, $\delta\theta$ ~ 0.5°, Ue~100 V)

FEA fabrication



1. Etching mask patterning

SiO_2

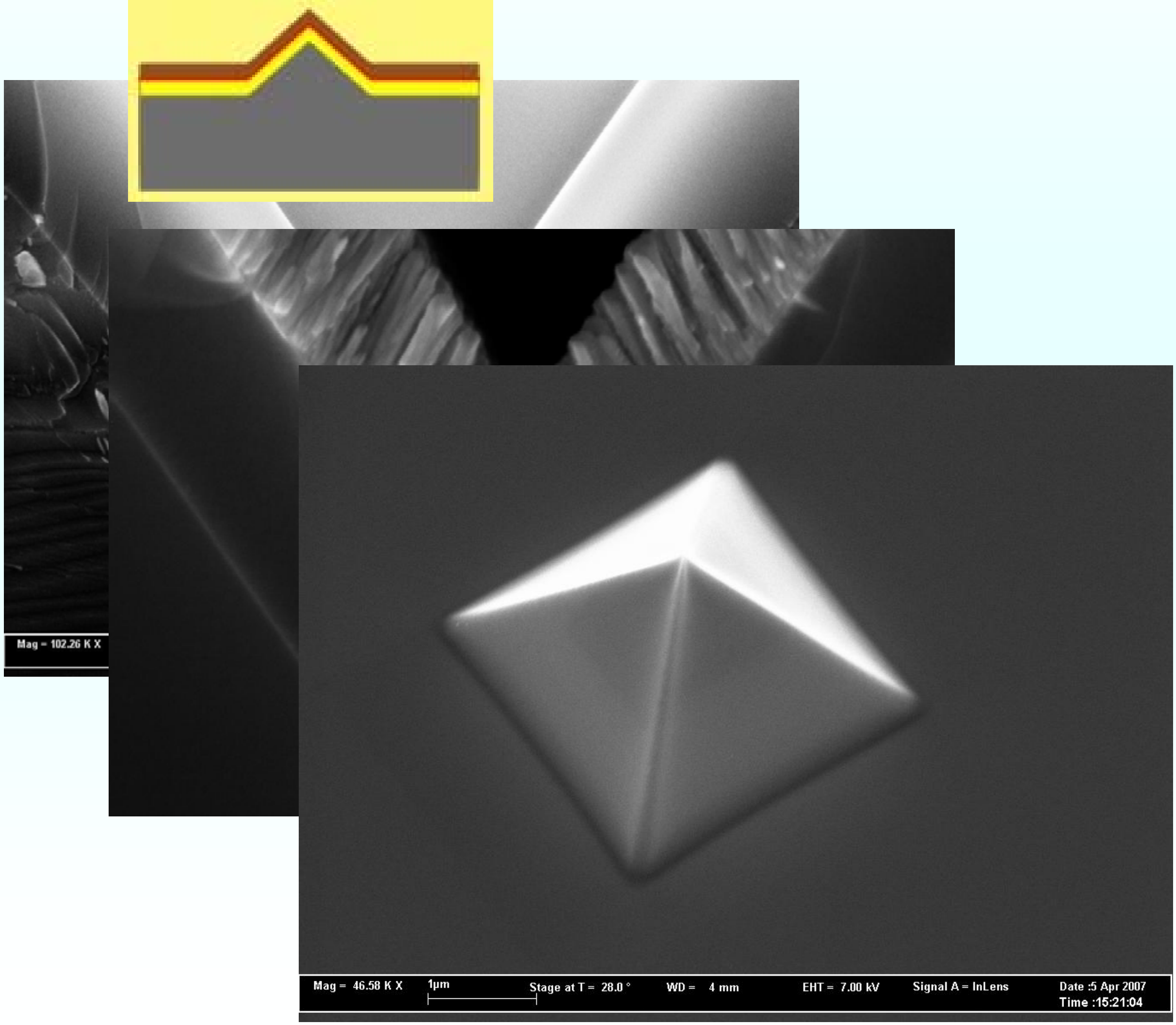


2. Mold (anisotropic) etching
and oxidization

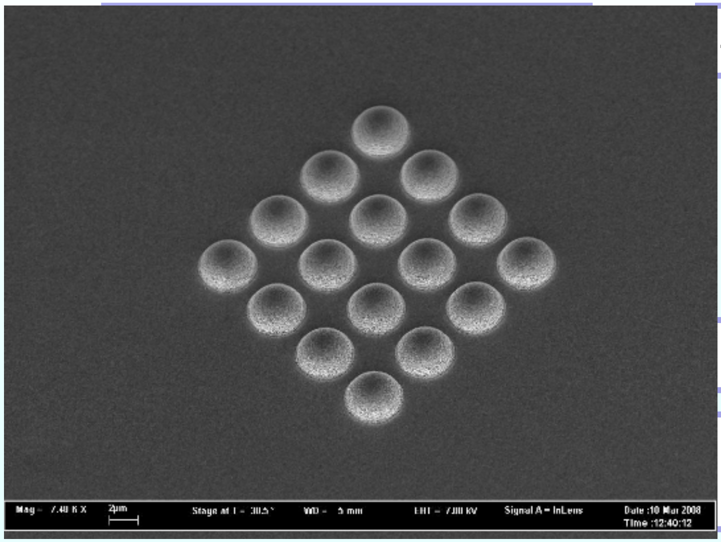
3. Multi-layer deposition
and electro-plating

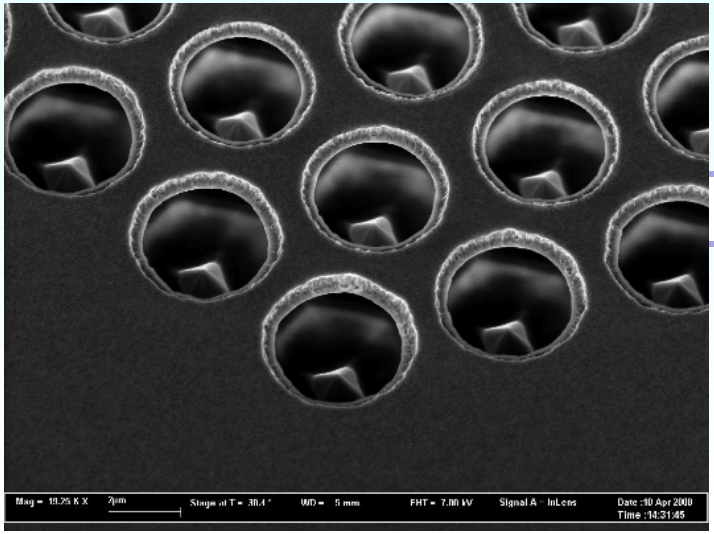
Ti/Pd
Mo

4. De-molding



FEA fabrication





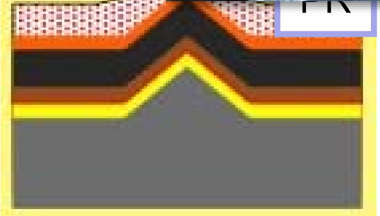
4. De-molding

5. Dicing (sa

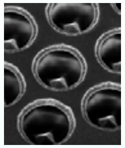
6. Depositio
and

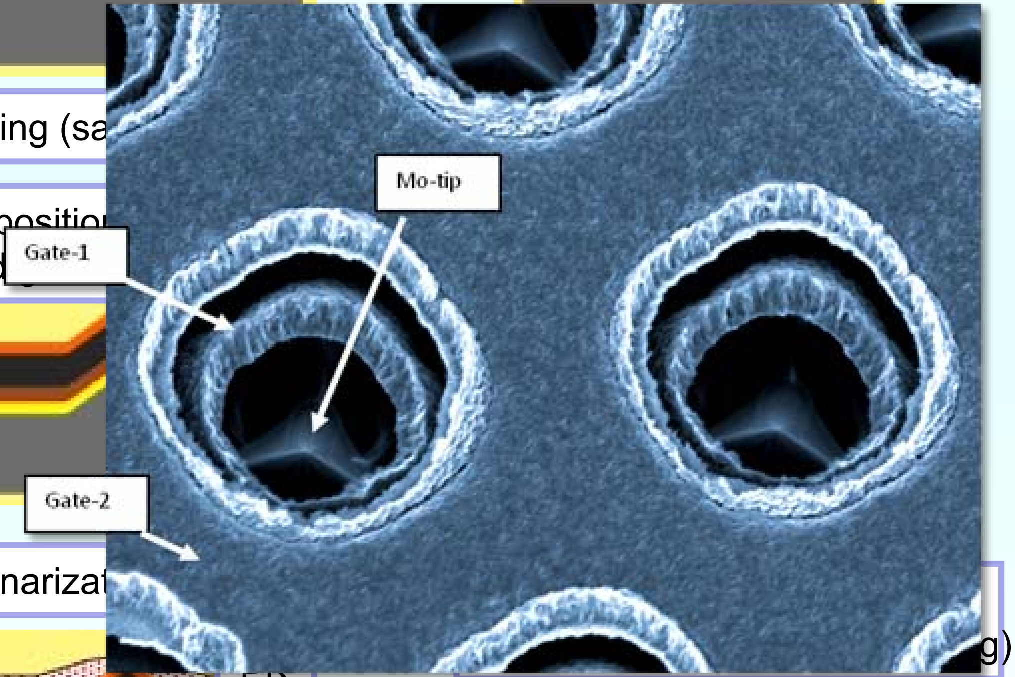
7. Planarizat

PR



8. Etch-back



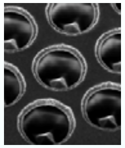


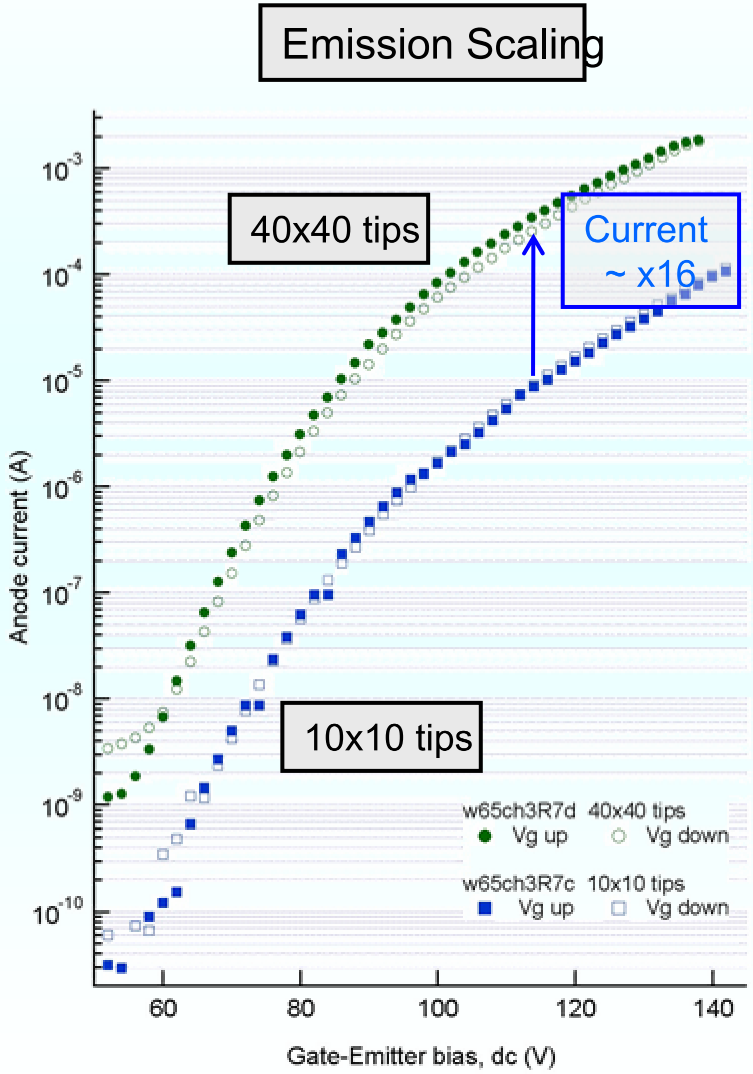
g)

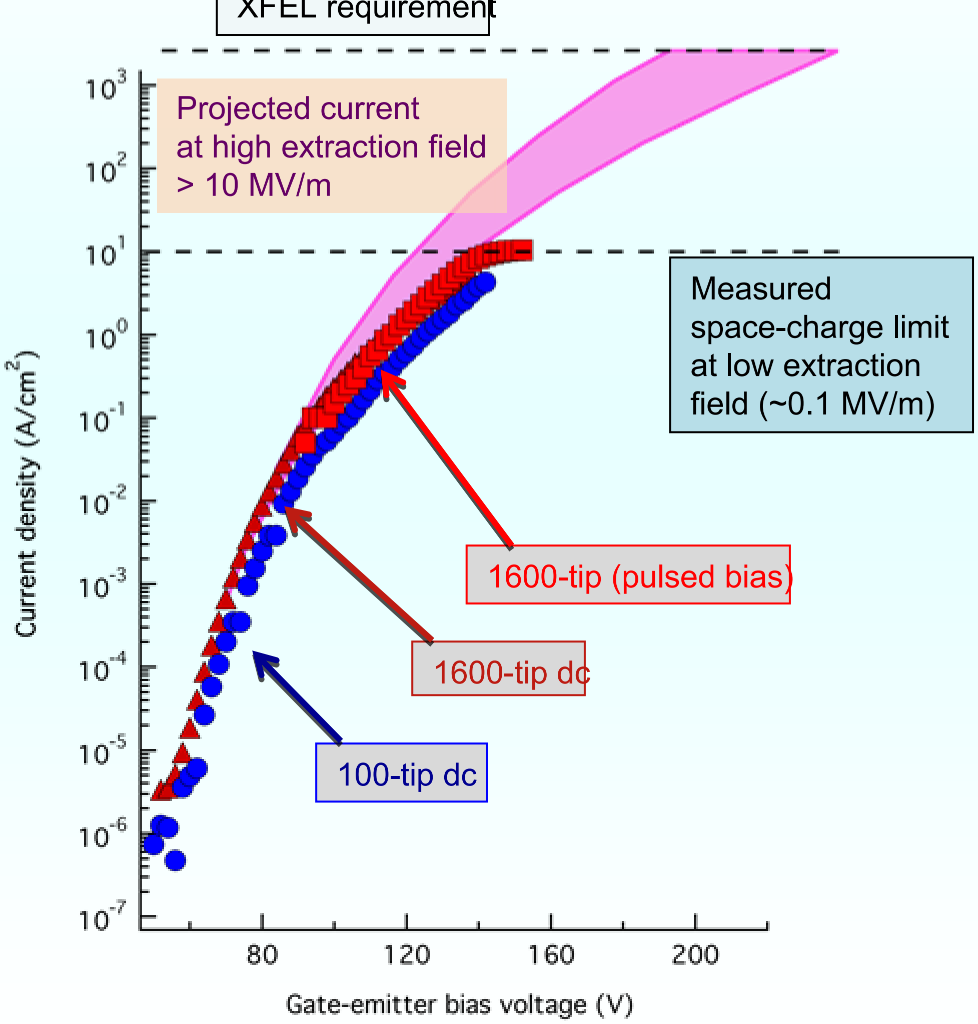
[11. Dicing (sawing)]

12. For second-gate, repeat 6-9

FEA evaluation

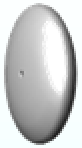






Thanks to S. Tsujino

Summary



- **Very encouraging results with DLC coated electrodes (present limits):**
  - **Breakdown field up to 300 MV/m**
  - **Photo emission at up to 170 MV/m**
  - **Stable emission at 100 MV/m (~40 pC)**
  - **Charge up to 80pC (~10 ps laser)**
  - **Quantum efficiency ~10^{-6}**

- **200 MV/m breakdown with 2 um Mo on stainless steel**
  - **The emission properties are to be explored further**

- **Beam parameters evaluation**
  - **Low energy beams emittance preservation**
  - **Improvement of low emittance measurement techniques**
  - **Comparison of different emitting materials**

- **Progress with single and double gated FEA devices**
  - **Demonstrated working double gated device**
  - **Control apex radius in 10 nm scale (single gate FEA – current homogeneity)**
  - **Single tip current capability – 3 – 20 uA per tip for small arrays**

Outlook

- **In parallel with the RF photo injector base line design we continue to investigate alternatives for high brightness electron sources.**

- **4 MeV pulsed high gradient photo gun test stand is used to study new cathode materials and techniques for generation and handling of low emittance electron beams.**

- **An extensive R&D work is continuing on field emitter arrays based, room temperature cathode.**

Thank you for your attention!

Discussion