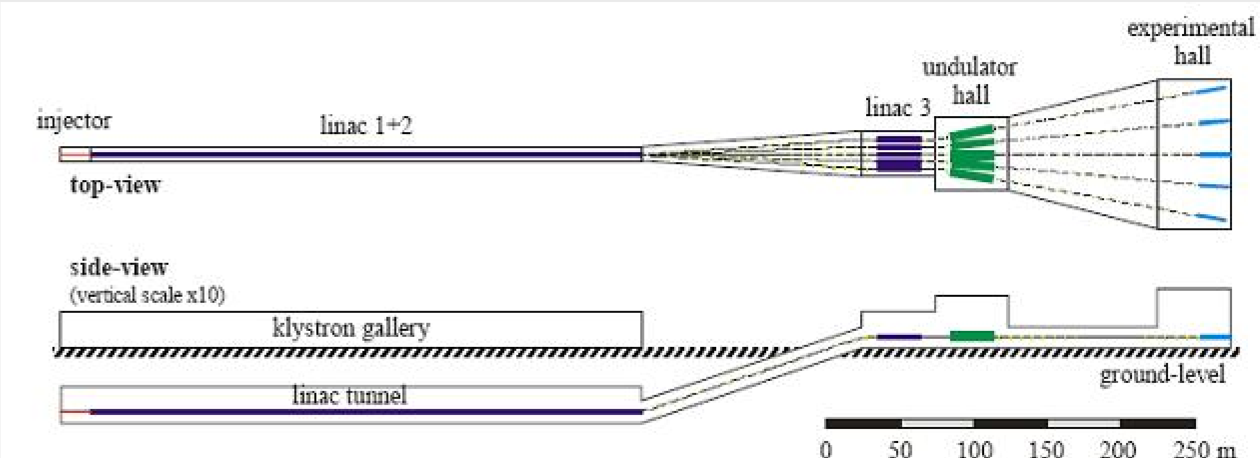
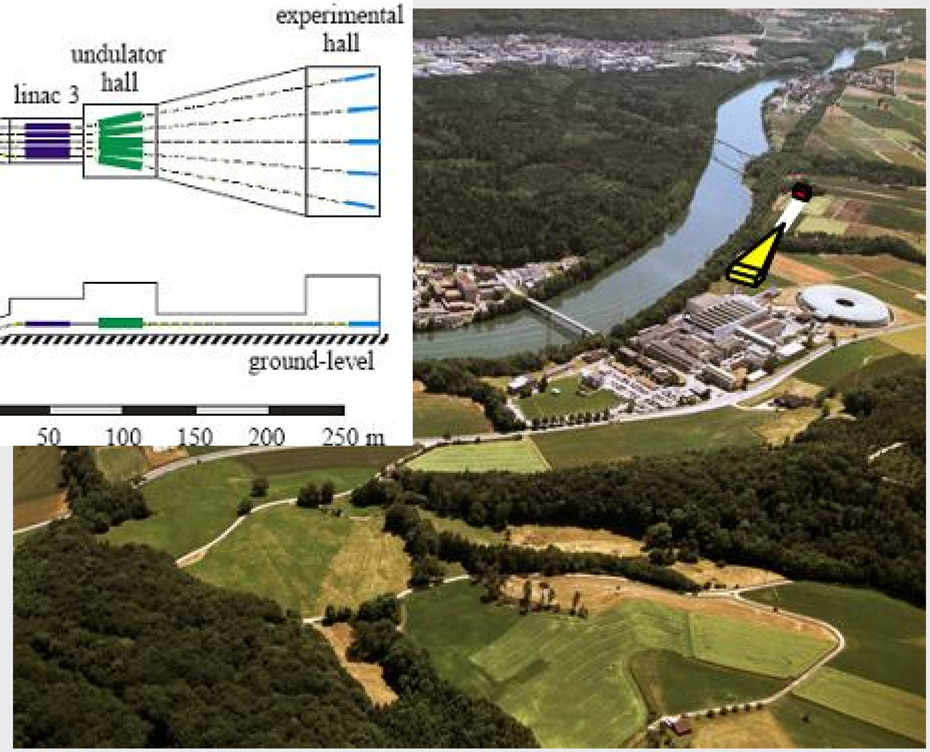
Field Emission

Electron Sources
-
FEL Application

PSI FEL Context



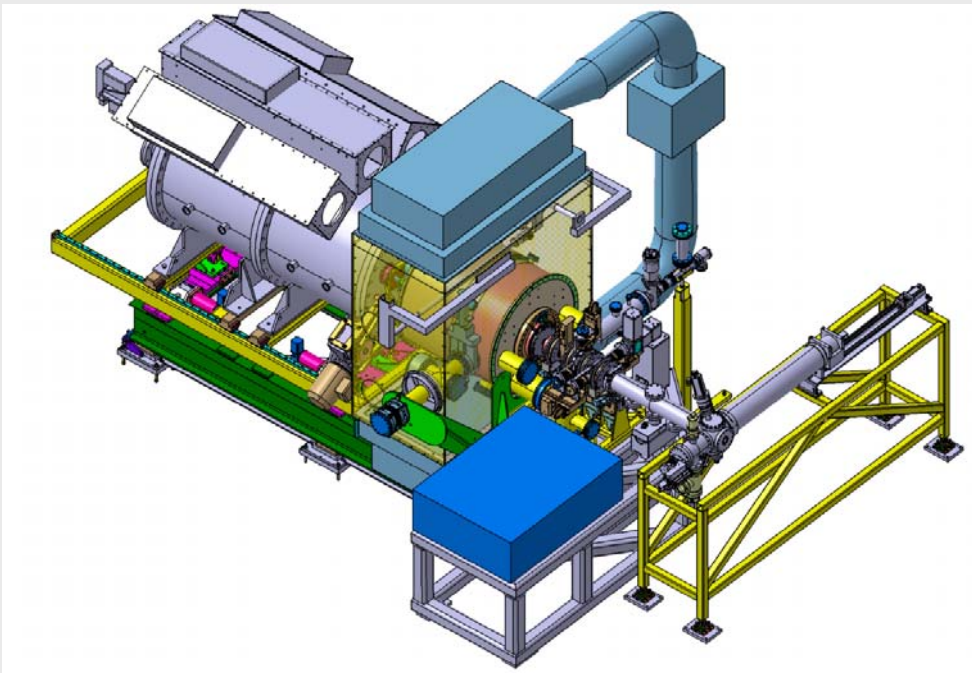


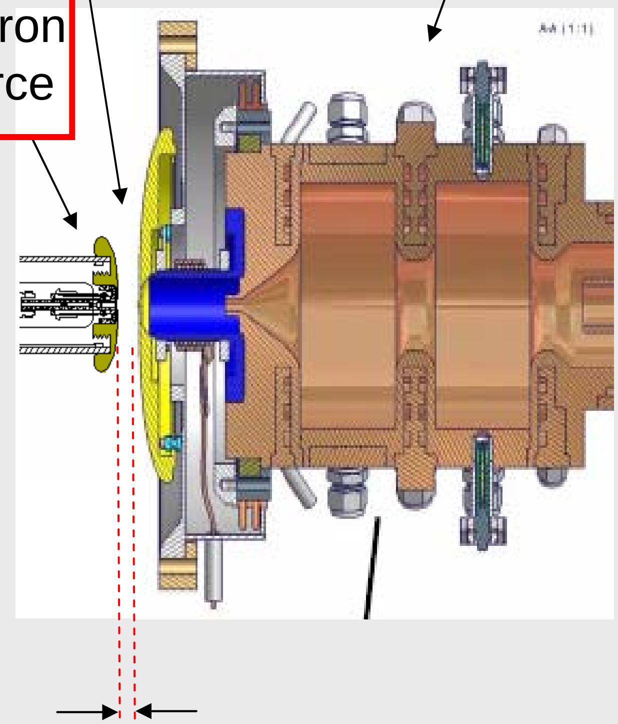
PSI – FEL Project :

0.1nm < λ < 10nm;
10-100fs Pulses
10Hz
Compact Machine < 800 m

Expected Commissioning ~ 2016

Low Emittance Gun





Minimum Peak Current (A)	**5.5**
Normalized Slice Emittance (m.rad)	**5.10^{-8}**
Bunch Length, rms (ps)	**15**
Energy at Gun Exit (MeV)	**4**
Repetition rate (Hz)	**10**

Thermal Emittance

Ultimate limit in Accelerators: Thermal emittance of the Electron Source

$$\varepsilon_{n,rms} = \frac{r}{2}\sqrt{\frac{2E_{kin}}{3mc^2}}$$

Size of the produced Electron Beam

Thermal Agitation of produced electrons

Goal : Emittance < 5.10^{-8} m.rad

Uniform Beam over r
+ Maxwell Distribution

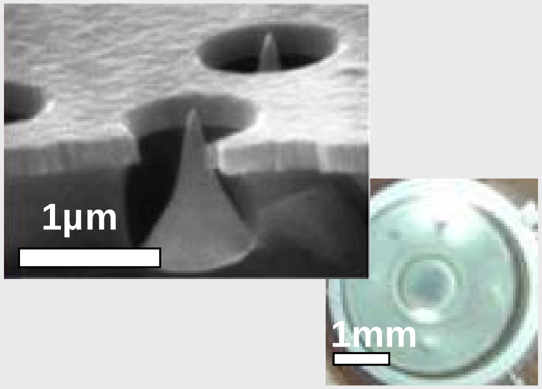
F.E.A. or Single Tip for LEG

Field Emission requires High Field: $F_{Surface} > 3$ GV / m

↓

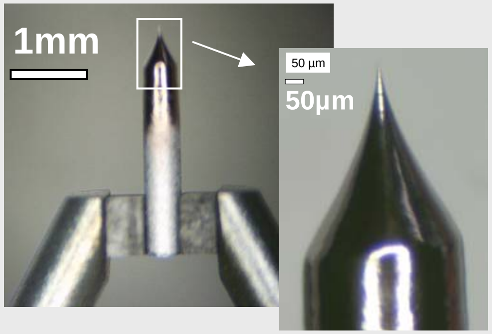
Field Enhancement with **Tip Effect**

Field Emitters Arrays (FEAs)



Microelectronic Techniques
Thin Film Deposition

Needle Cathode



Etched Wire

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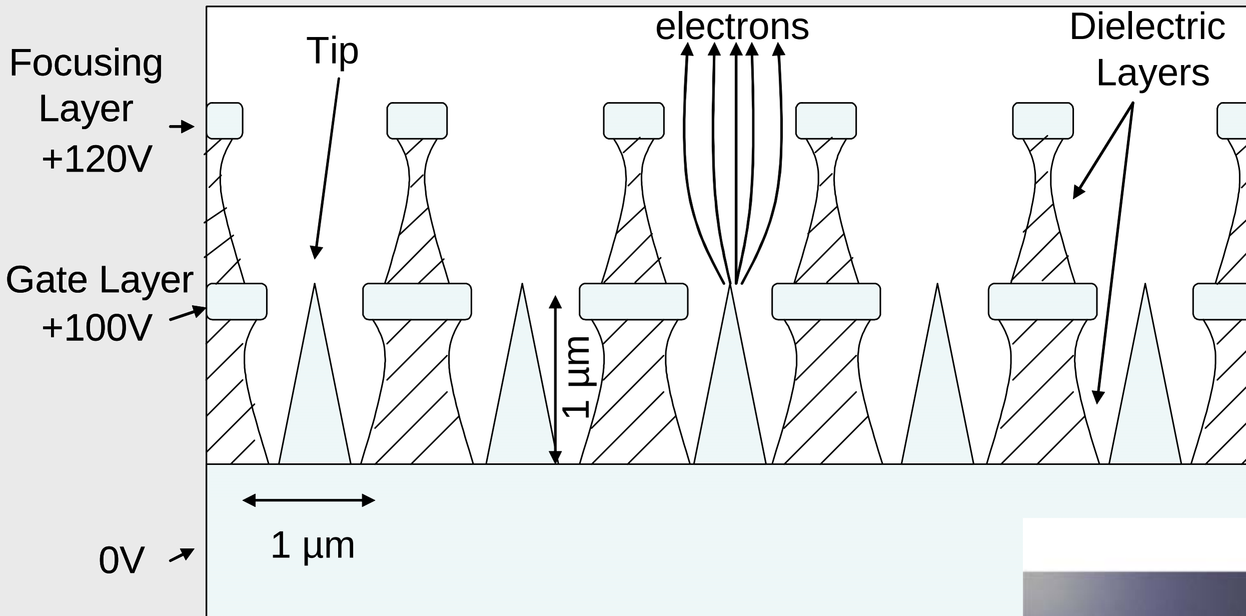
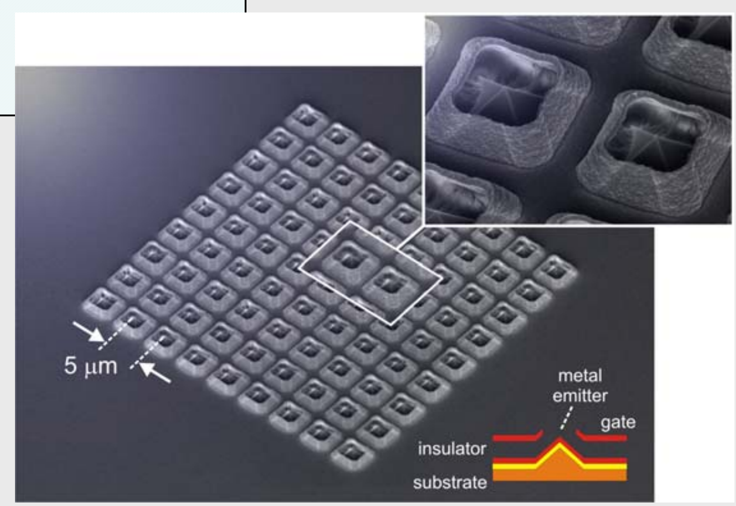
Field Emitters Arrays (FEA)

Electron Sources

Field Emitters Arrays (FEAs)

Principle of FEAs:





FEA's Characteristics:

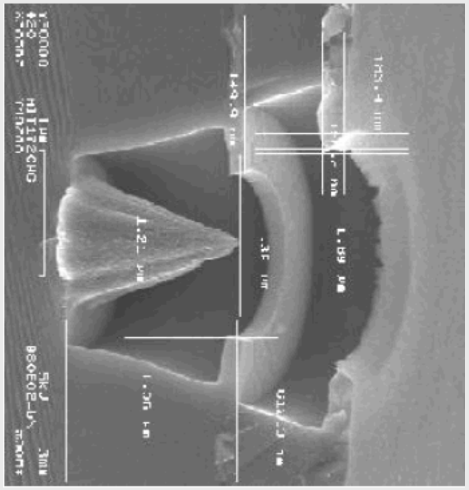
10'000 Tips / FEA

R_{tip}~ 20 – 100nm

$Ø_{FEA}$ < 1mm

Typical I_{FEA} < 1mA

Emittance of FEA Beam

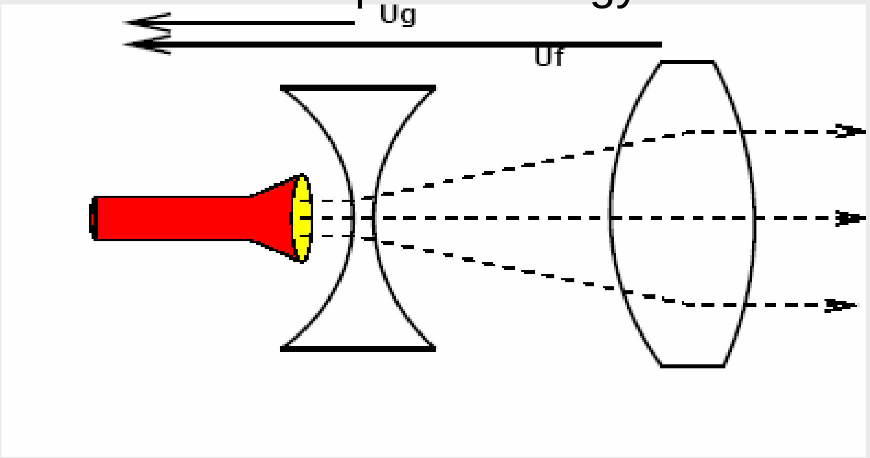


Thermal Emittance / Tip

r~15nm; E_{kin}~300meV

$\varepsilon_{n/Tip} \sim 5.10^{-12}$ m.rad

Optics Analogy

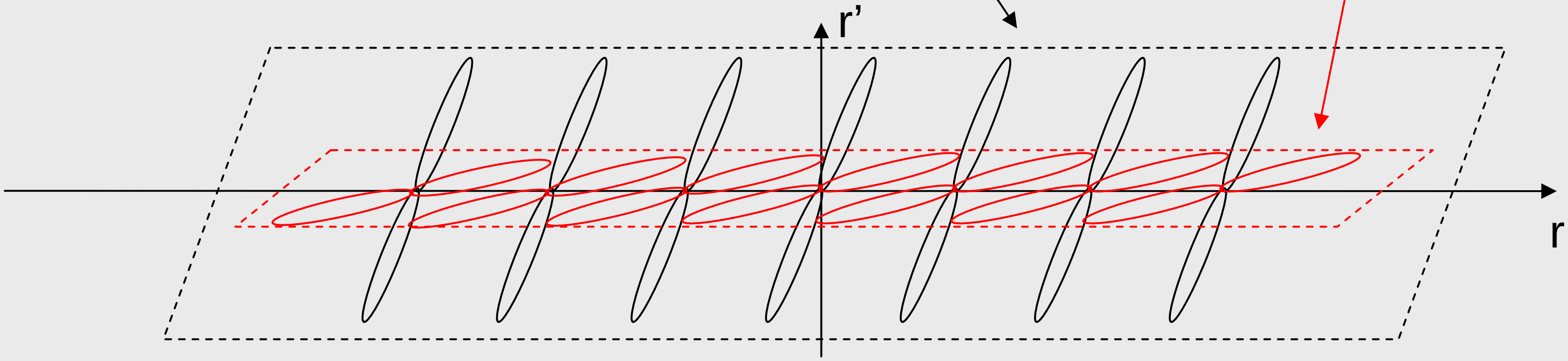


Initially

$\varepsilon_n \sim 2.10^{-6}$ m.rad

After Focusing

$\varepsilon_n < 10^{-7}$ m.rad



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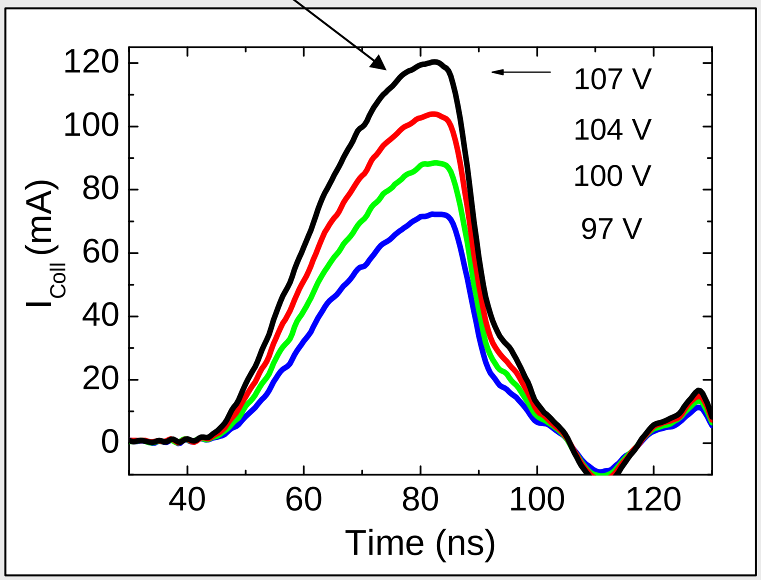
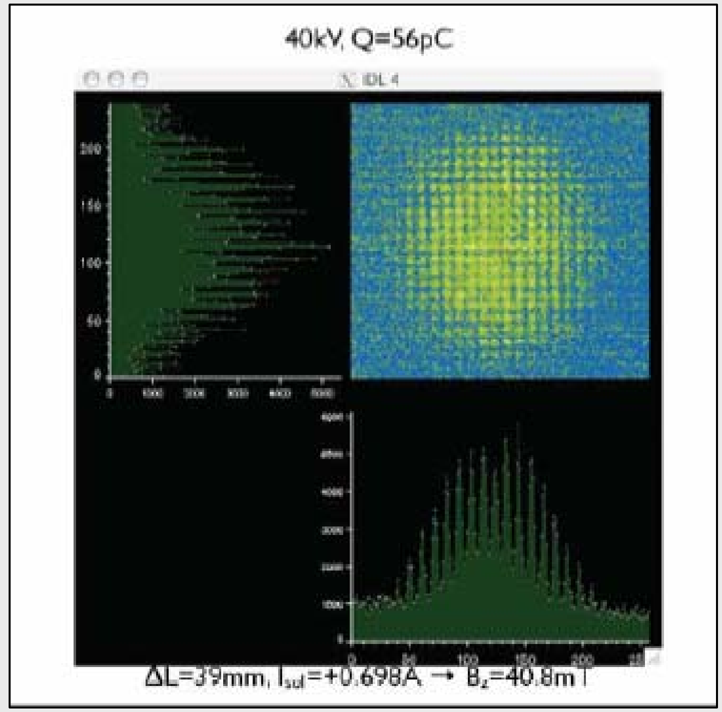
Tests on Commercial Field Emitter Arrays

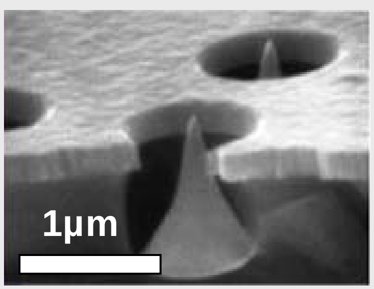
120 mA (Pulses of 30ns at 10HZ)

(Commercial Device)





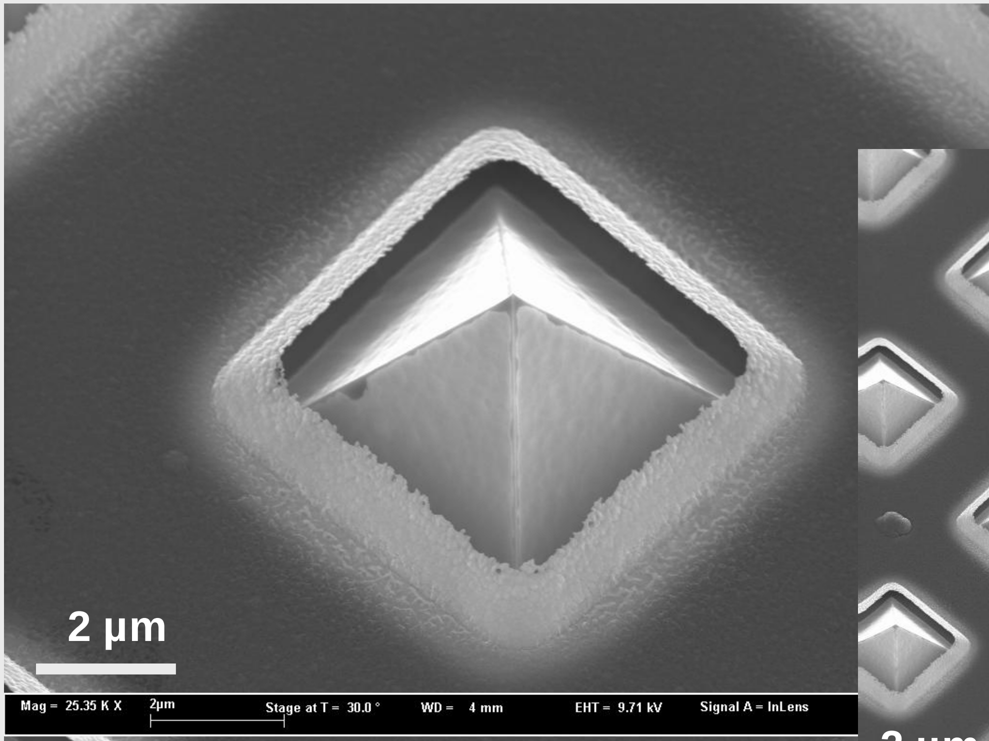
50000 Tips
Ø = 1 mm

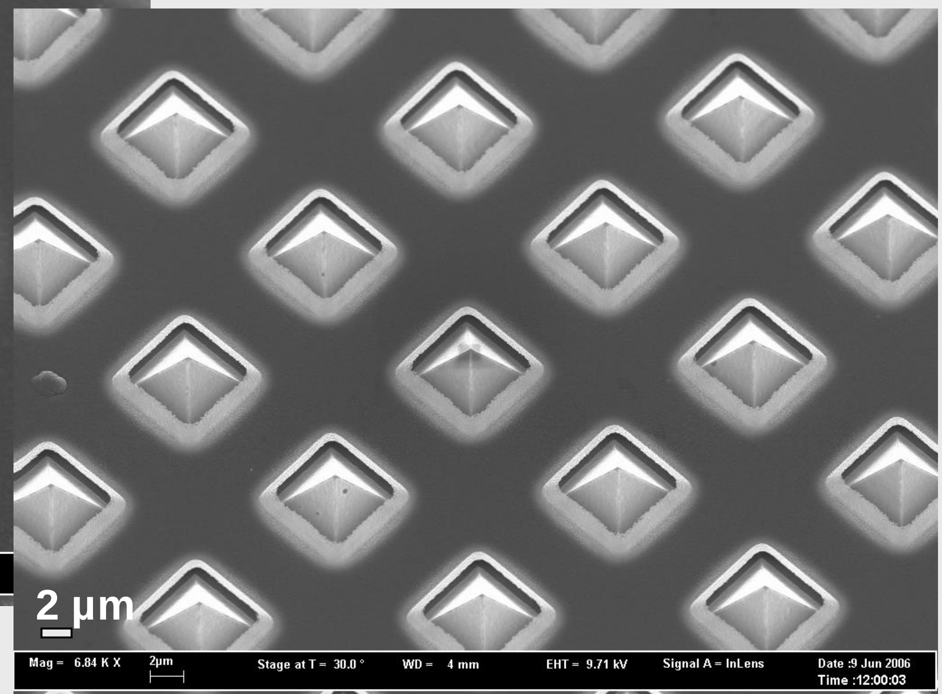


Projected Emittance Single Gated FEA:
ε_n~ 2.10^{-6} m.rad at 40 keV
Source: S.C. Leemann

Field Emitter Arrays Fabrication at PSI

Pyramid Shape – PSI FEA





Source: E. Kirk

- Mo Tips (Field Enhancement Factor: <β> ~ 90)
- Metallic wafer

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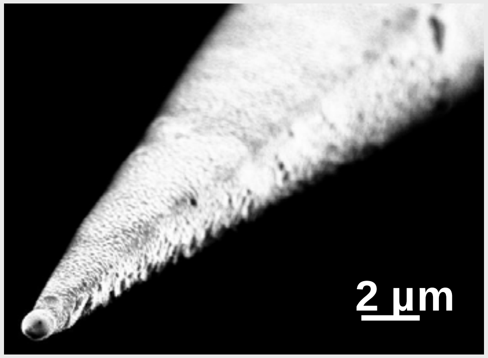
Needle Cathode

Electron Source

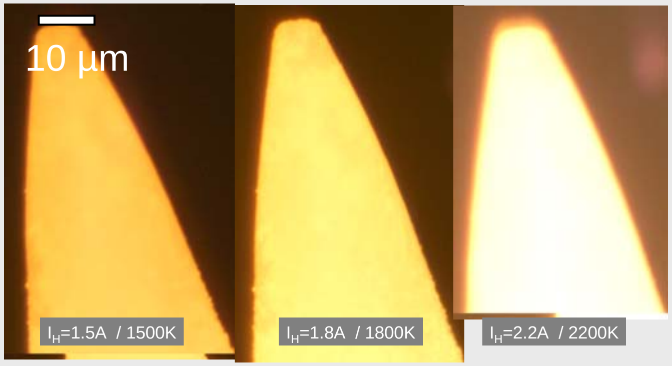
Single Tip Electron Source



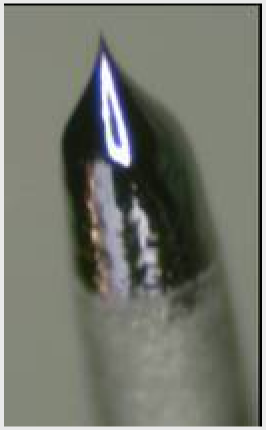
ZrC robust, Φ_{ZrC} ~ 4 eV

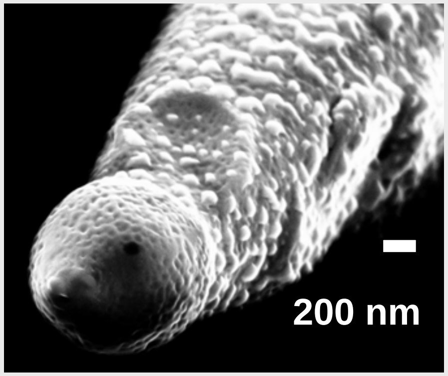
Possibility of Faceting the Tip

r_{apex} ~ 1 to 5 µm



1 mm





Required Operating Voltage
V_{Tip} > 10 kV

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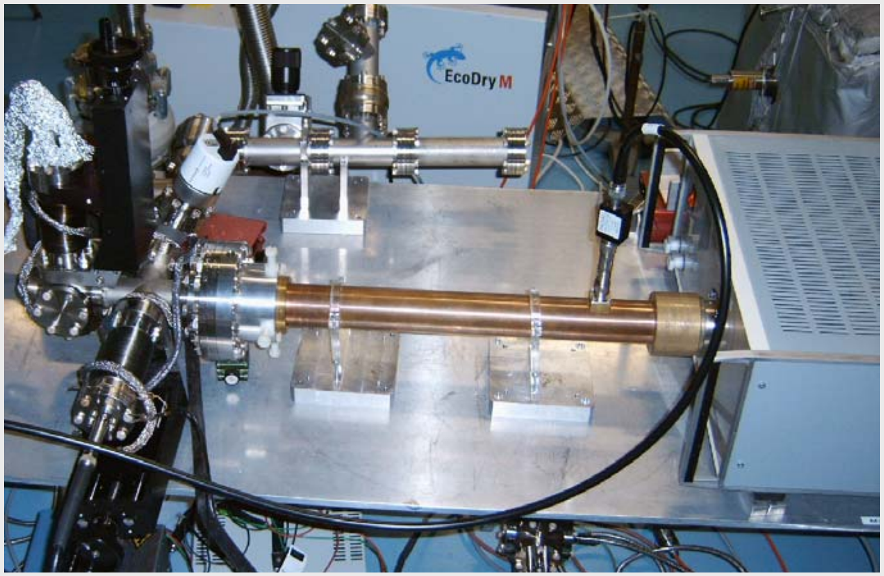
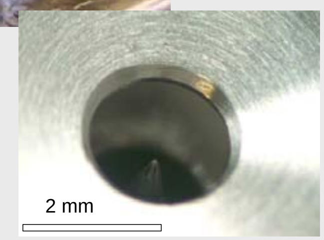
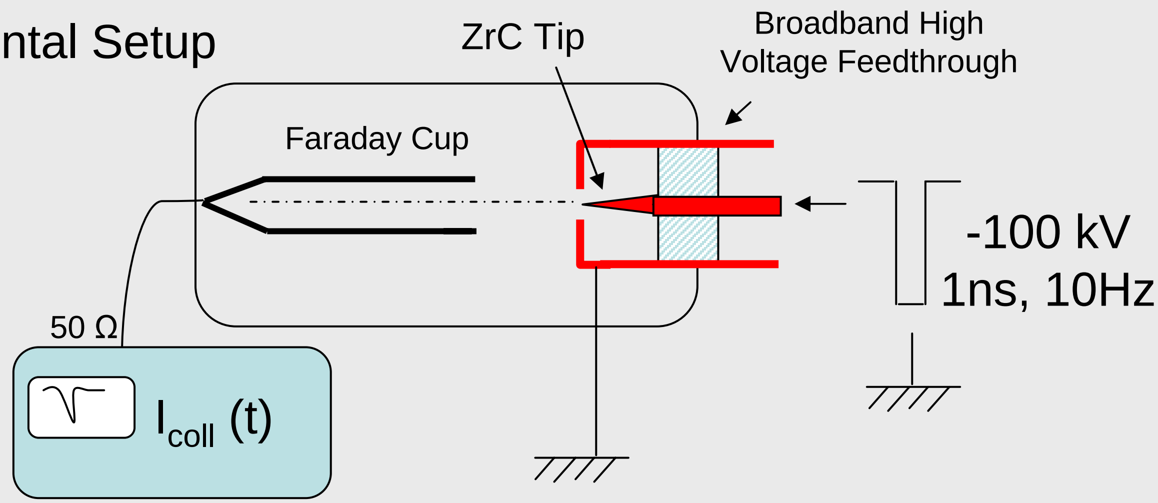
Single Tip ZrC performances



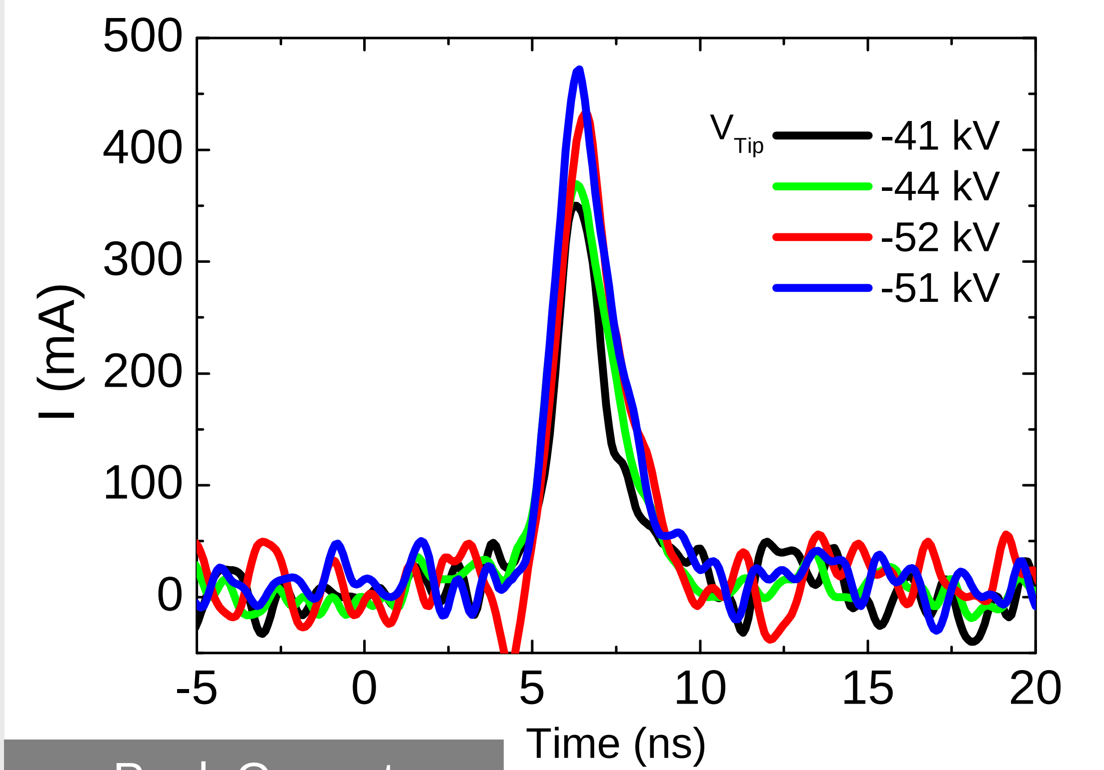
Experimental Setup



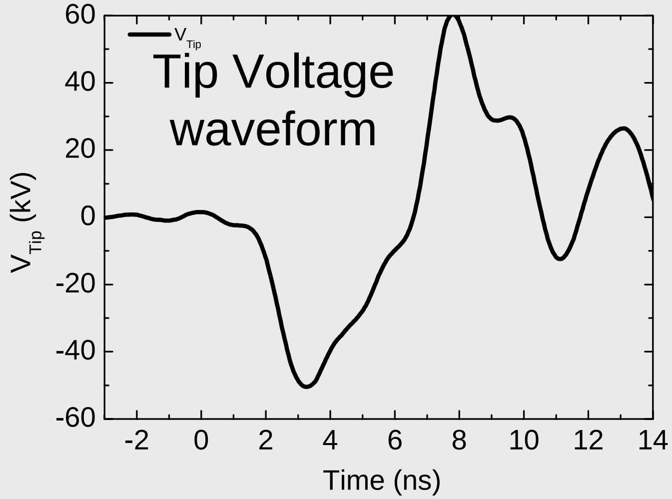


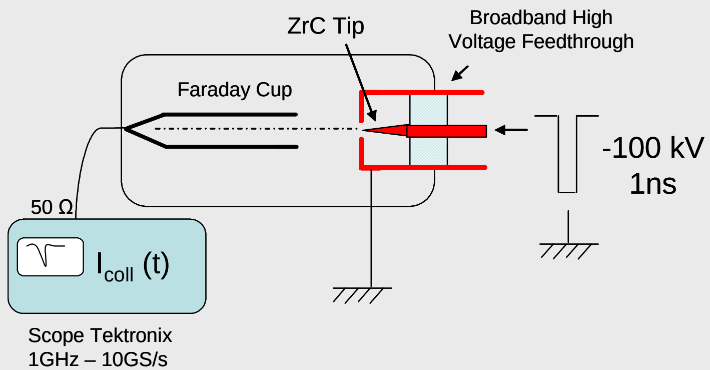
Scope Tektronix
1GHz – 10GS/s

High Current Pulses from a ZrC Tip

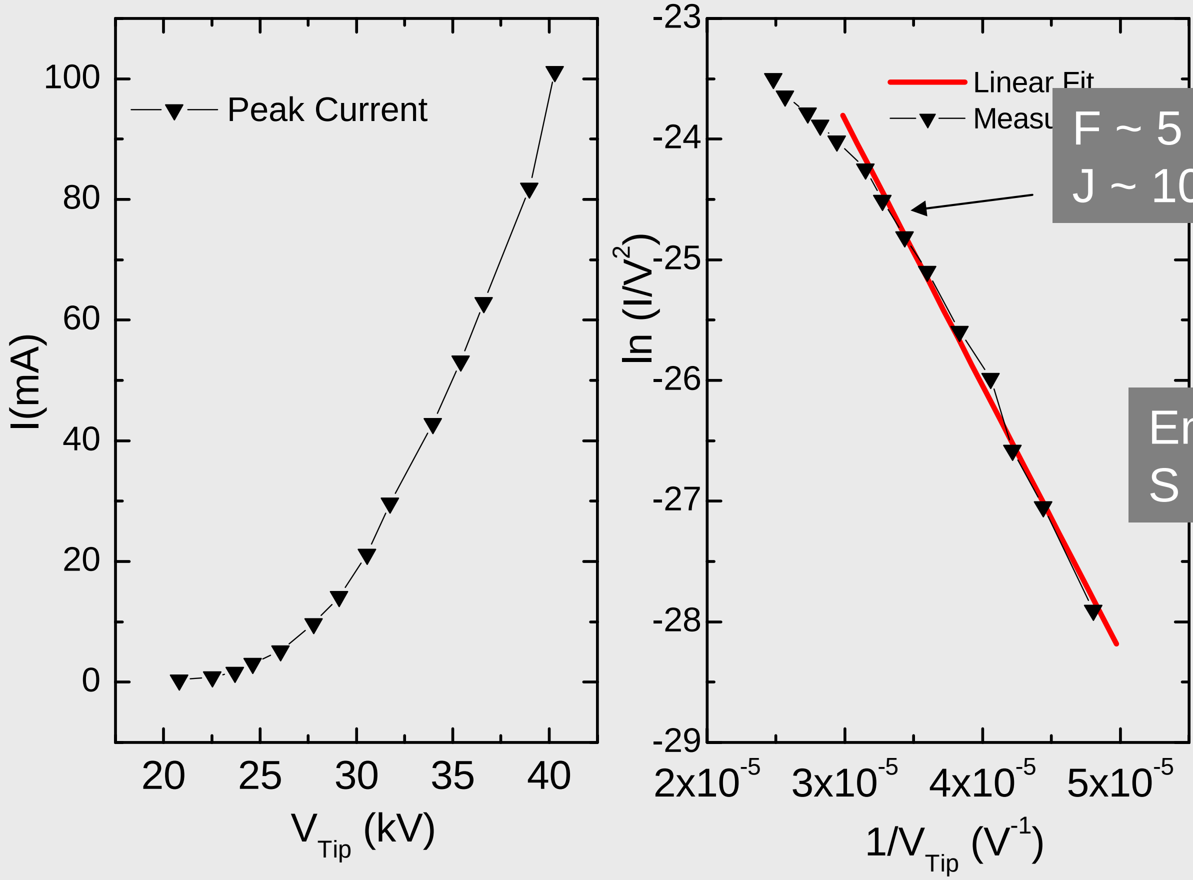


Peak Current
By Field Emission
~ 500 mA





Fowler – Nordheim Analysis



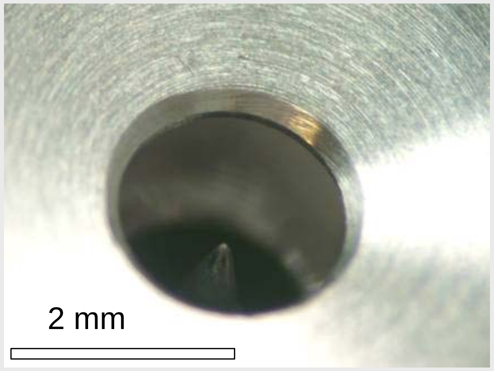
F ~ 5 GV/m
J ~ 10^{12} A/m^2

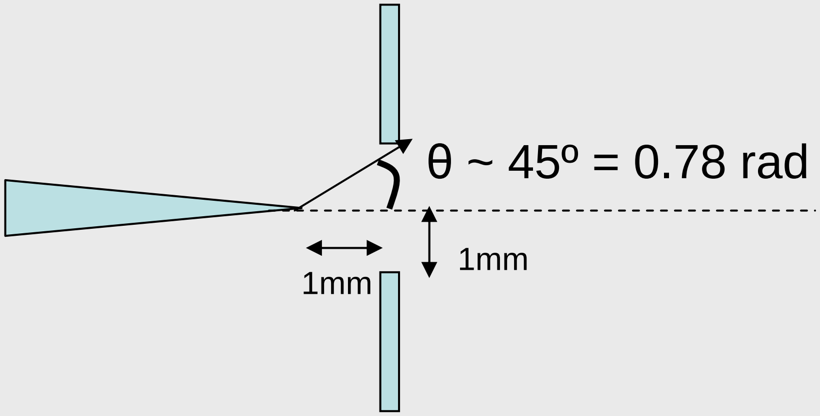
Emitting Area:
S ~ 12000nm^2 (Ø ~ 120nm)

$$\ln\left(\frac{I}{V^2}\right) = -p\left(\frac{1}{V}\right) + m$$

ZrC Tip, Gate 2mm
Voltage Pulses: 1ns at 10Hz
Φ_{ZrC} ~ 3.5eV, 10^{-9} Torr

Rough estimation of the Emittance from a ZrC Tip





Measure 1

$S \sim 12000 nm^2$

$Ø_{Beam} \sim 125nm$

$\beta = 192000\ m^{-1}$

$r_{apex} \sim 1/(5\beta) \sim 1\mu m$

$\varepsilon_n \sim r_{beam}.\theta \sim 62\ nm*0.78\ rad \sim$ **5.10^{-8} m.rad**

$$B_{Max} = \frac{I_{Max}}{\varepsilon_n^2}$$

$\sim 10^{14}\ A.m^{-2}.rad^{-2}$

Needle Cathode Beam: Attractive but too long bunches (ns)

How to modulate the emission in the ps range ?

Laser assisted field emission (Photo-Field Emission)

(ref. M. Boussoukaya et. al. , NIM A 264, 131-134, 1988)

Combination of Field Emission and Photoemission

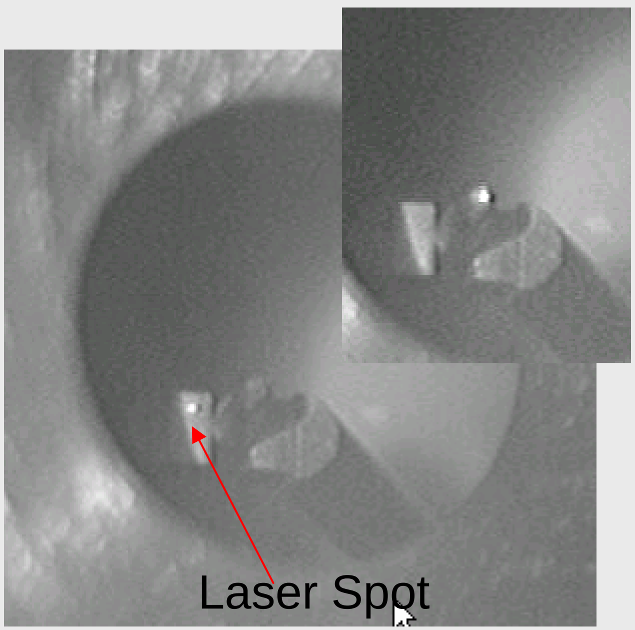
Photo-Field Emission Single Tip

<u>Nd:VAN Laser</u>:
11µJ, 16ps (rms)
266nm, 30Hz
Spot Radius σ_r ~100 µm (rms)

Tip Radius < 100µm

electrons

Ø~4mm



Laser Spot
(off axis): ø ~100µm

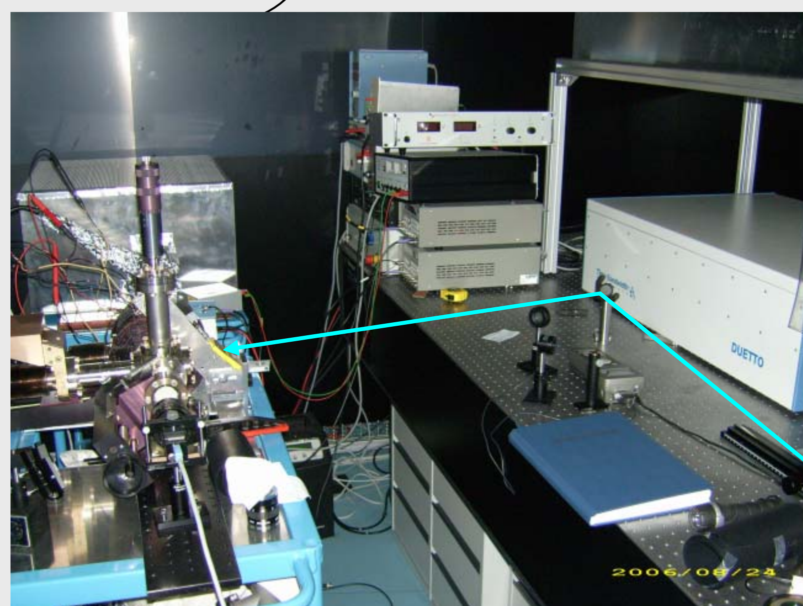
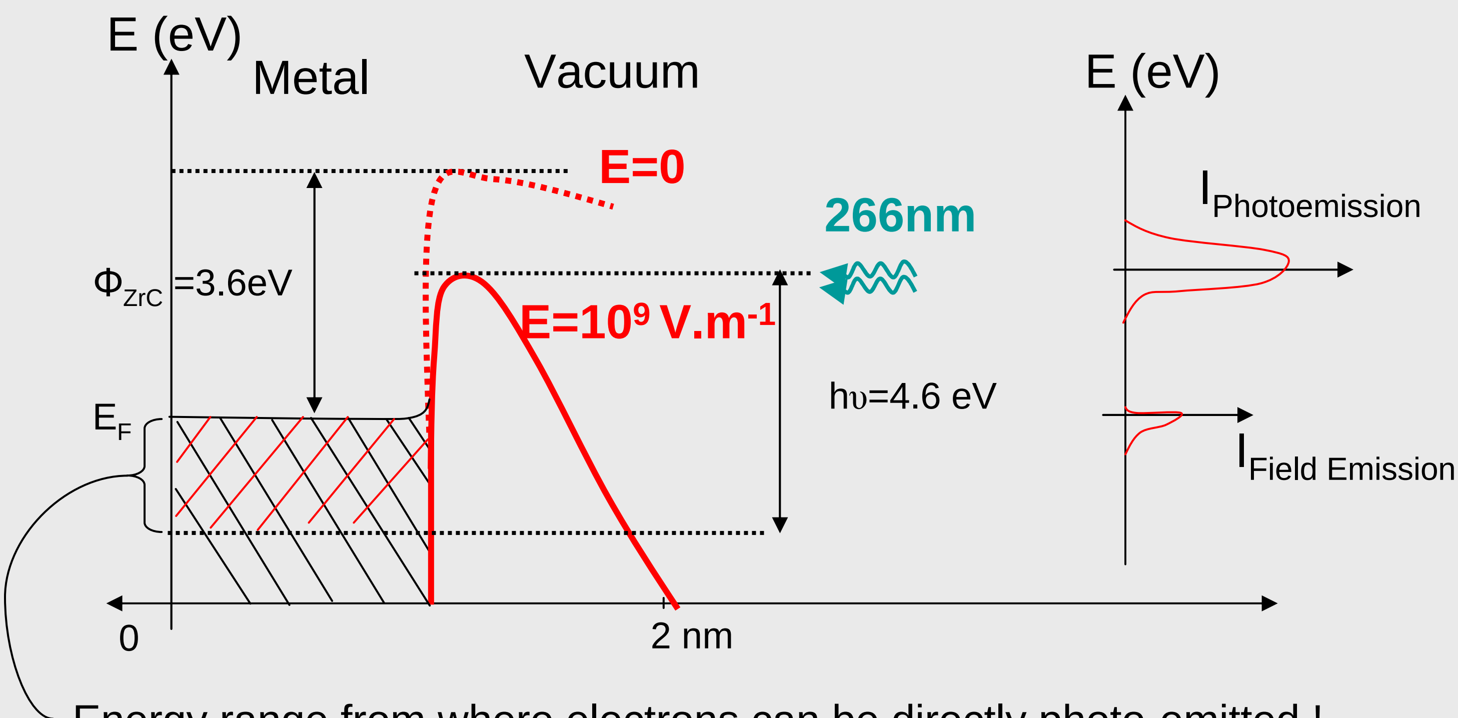


Photo-Field Emission Principle

Schottky Effect ⇨ Larger Electron Reservoir for Photoemission ⇨ Higher Quantum Efficiency



Energy range from where electrons can be directly photo-emitted !

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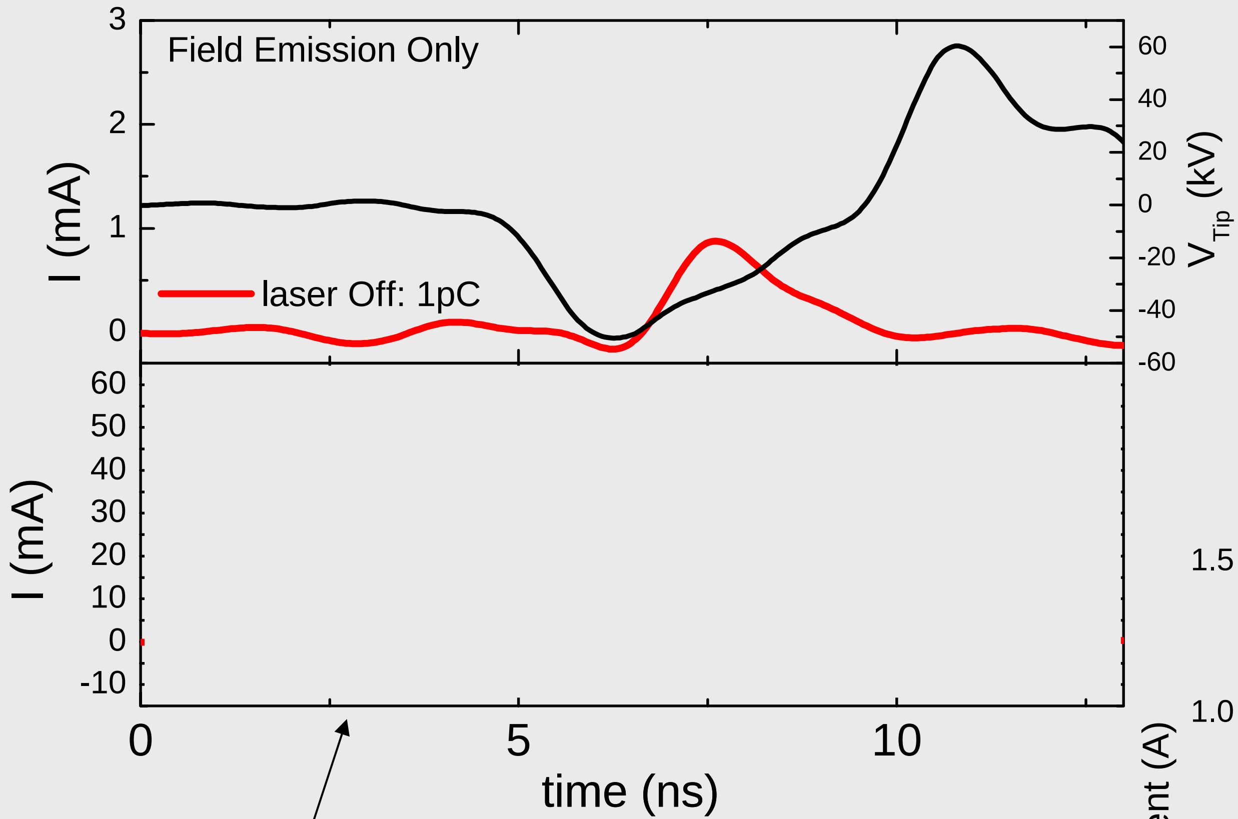
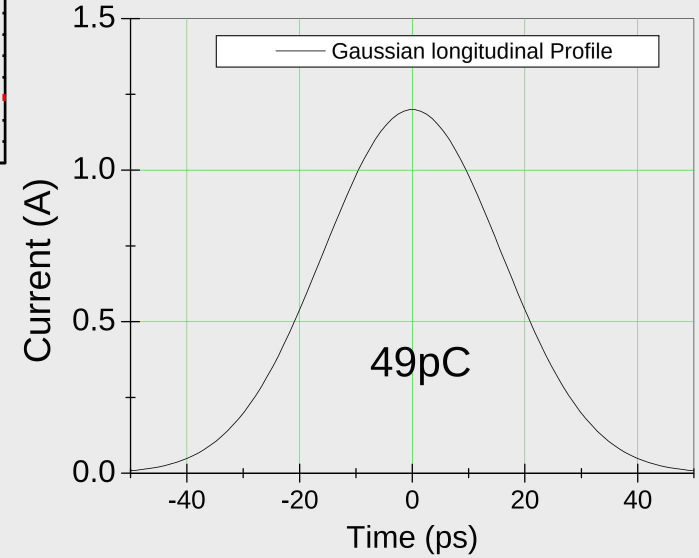
Photo-Field Emission Current



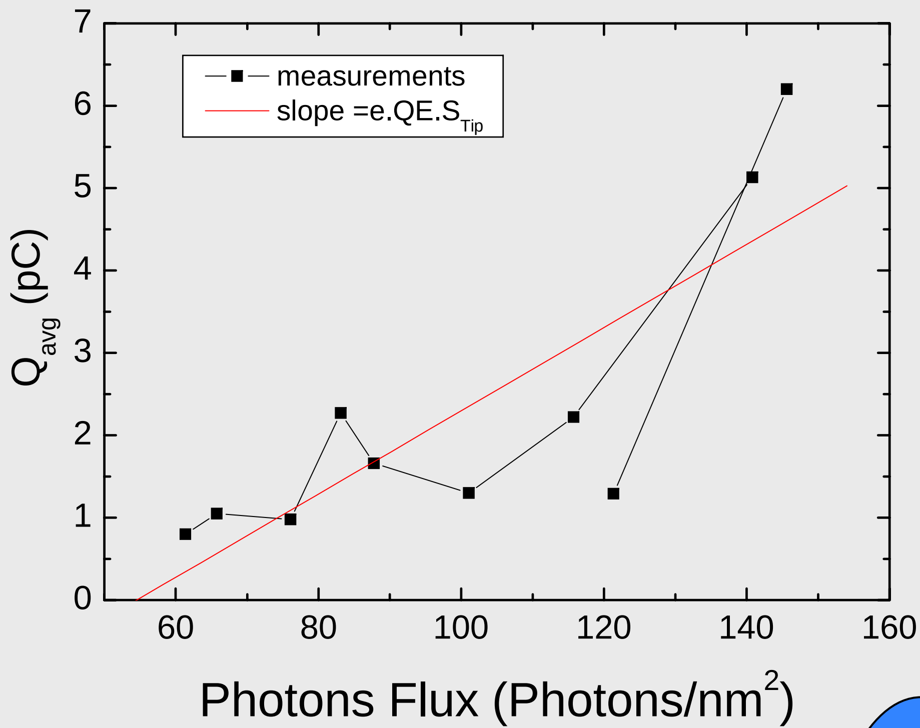
2µJ at 266nm
49pC
Q.E. > 10^{-4}



Limited by Scope Bandwidth (<1GHz)

Laser: 2µJ / σ_z=16ps / σ_r=75µm / 30Hz / 266nm
ZrC tip / V_{Tip}=-51kV

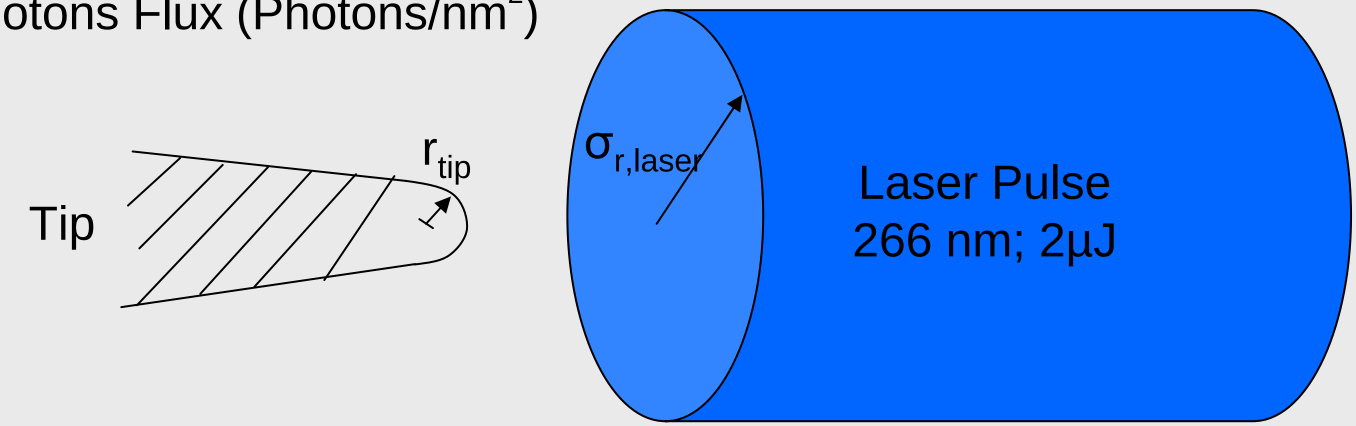
Emitting Area (Photo-Field Emission)



How many photons intercepted by Tip ?

r_{tip} ~30 µm ; QE=10^{-4}

r_{tip} ~10 µm ; QE=10^{-3}



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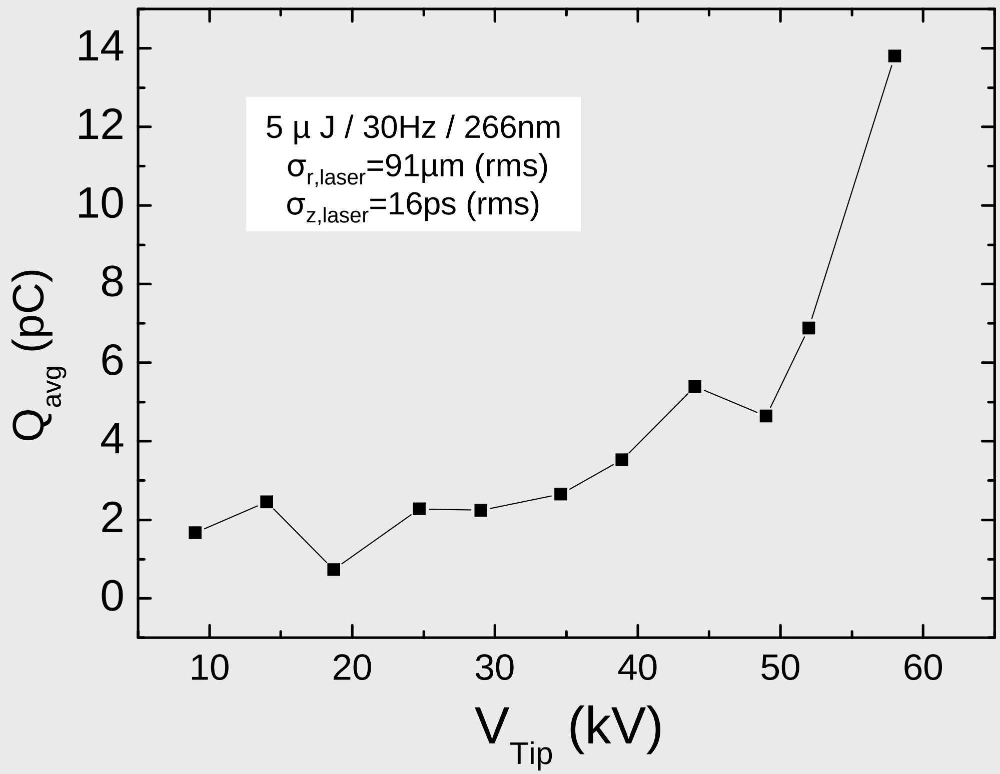
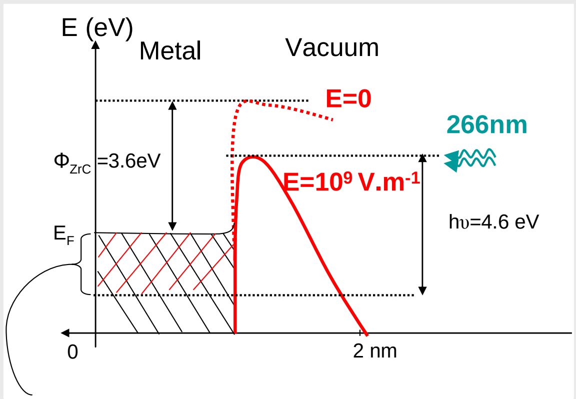
Exponential Increase of the Emitted Charge



Combination of Fowler-Nordheim and Schottky Dependence



$$Q(V_{Tip}) = e.N_{Photons}\cdot\left(\frac{1}{E_F}\right)^{3/2}\left[E_F^{\ 3/2} - \left(E_F+\phi-h\upsilon-\sqrt{\frac{q^3\beta V_{tip}}{4\pi\varepsilon_0}}\right)^{3/2}\right]$$

→ Photo-emission term

$$+1{,}4.10^{-6}.S.\exp\left(\frac{10.4}{\sqrt{\phi}}\right).\beta^2.V_{tip}^{\ 2}\exp\left(\frac{-6{,}44.10^7.\phi^{3/2}}{\beta V_{tip}}\right)$$

→ Field Emission term

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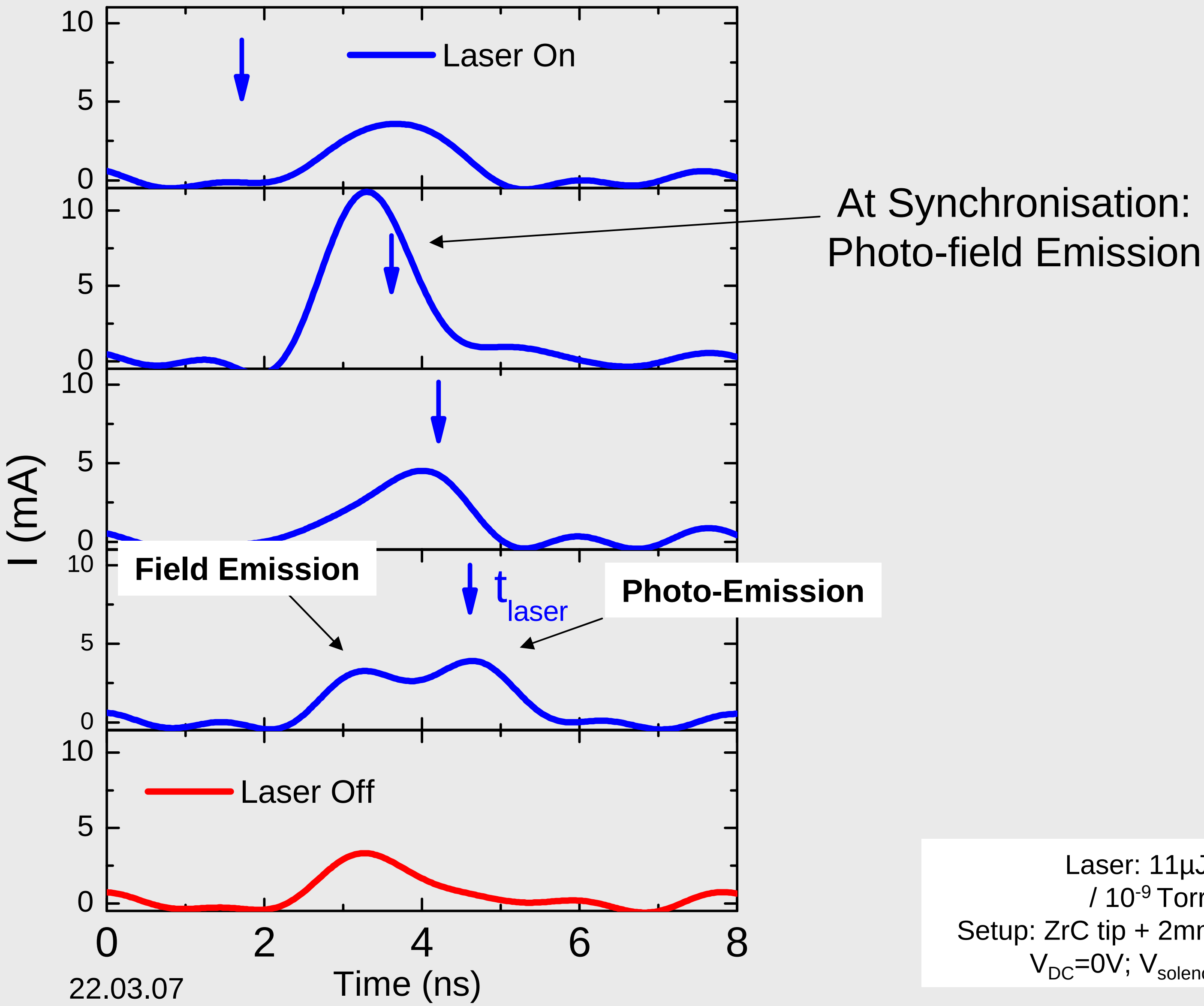
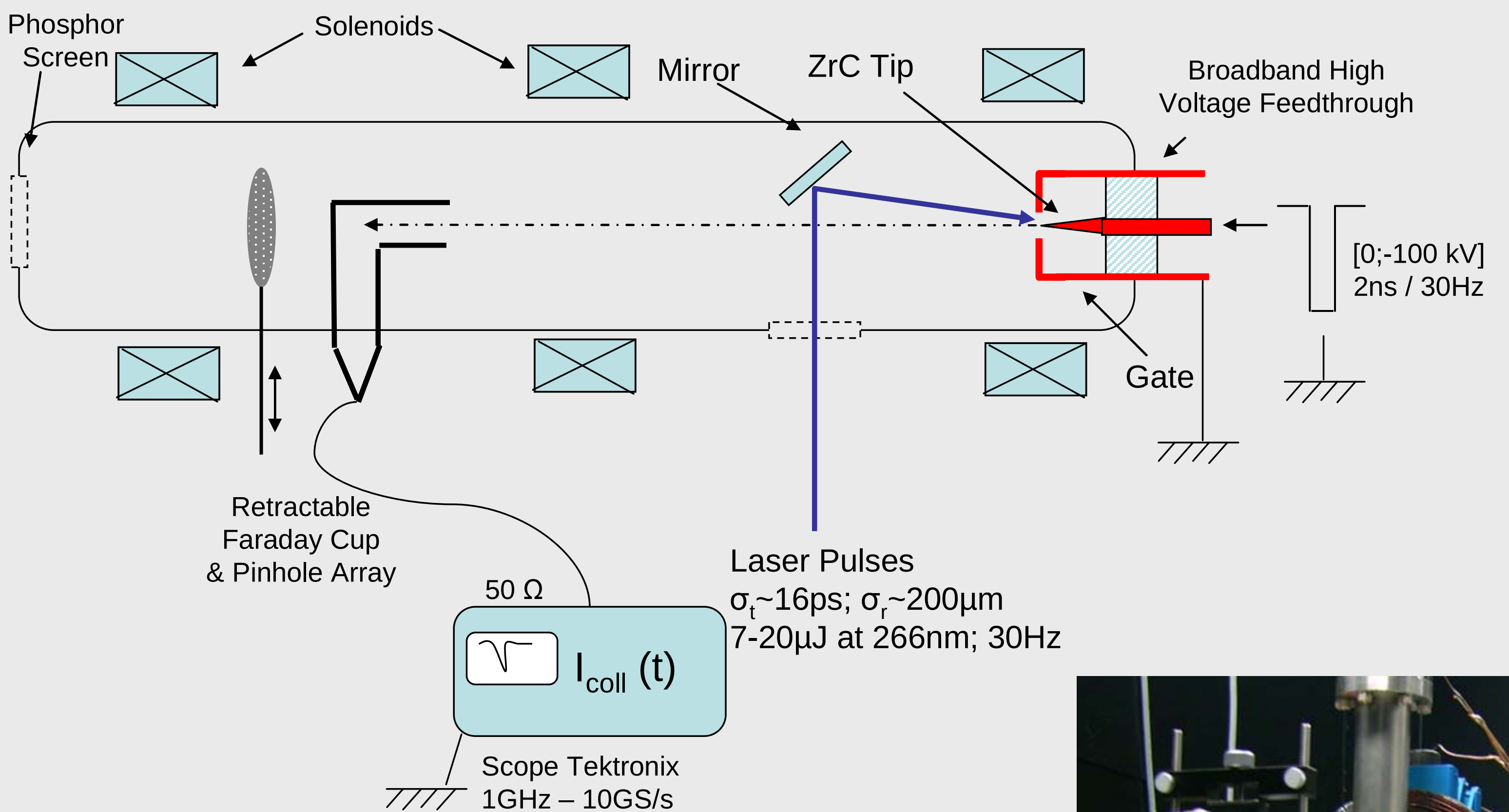
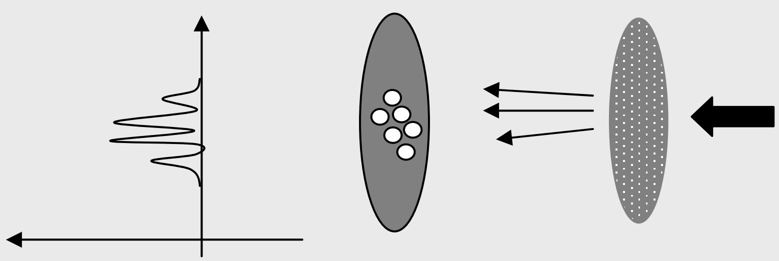
Delay Voltage Pulse / Laser Pulse



Laser: 11µJ / 30Hz / 266nm
/ 10^{-9} Torr; Scope 1GHz
Setup: ZrC tip + 2mm aperture + Focus Elect;
V_{DC}=0V; $V_{solenoid}$=14V; V_{Tip}=-40kV

Electron Beam Transverse Properties





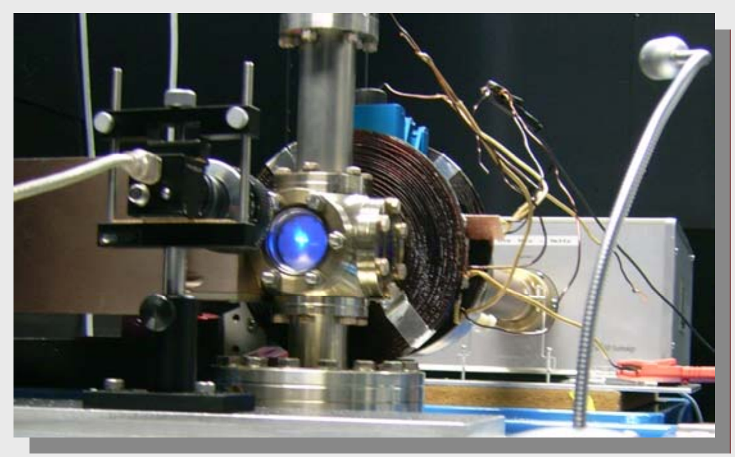


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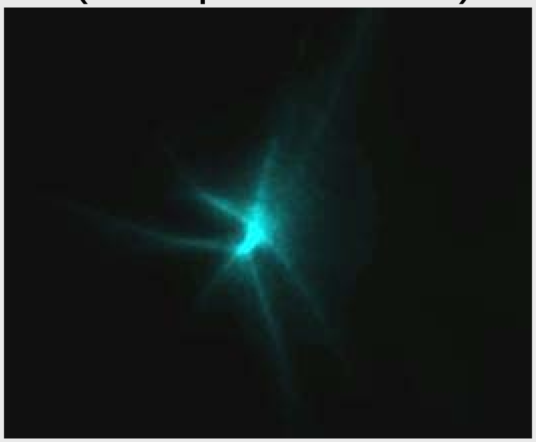
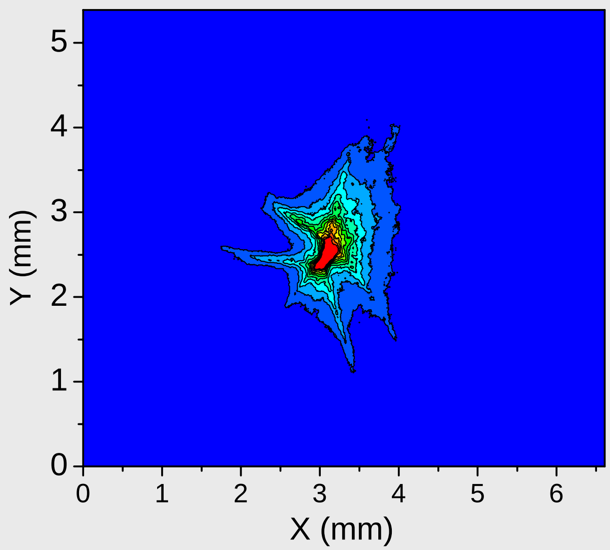
Photo-Field Emission Beam Spot size

Electron Beam Spot (Phosphor Screen)





Laser: 11µJ / 30Hz / 266nm / 10^{-9} Torr; Scope 1GHz
Setup: ZrC tip + 2mm aperture + Focus Elect;
V_{DC}=0V; $V_{solenoid}$=14V; V_{Tip}=-40kV

11µJ at 266nm
Q=12pC; 40 keV
FWHM =740 µm

Electron Beam Profile

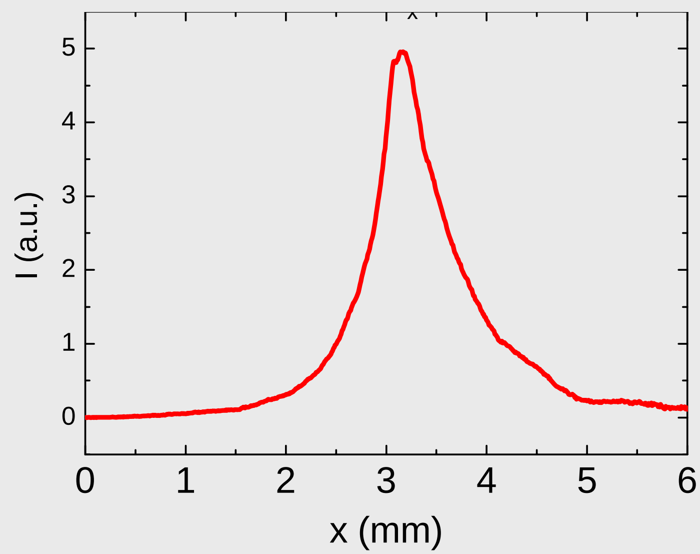
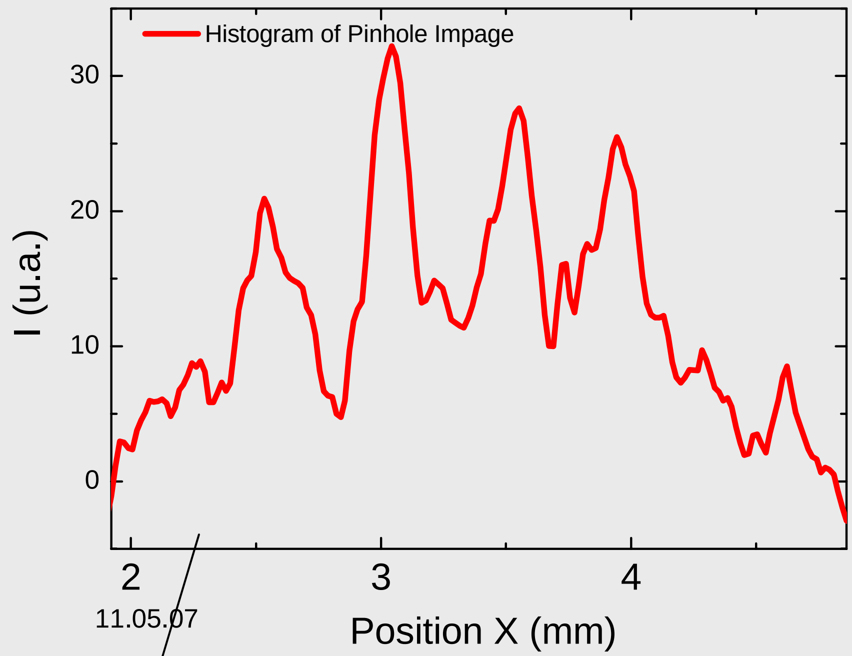
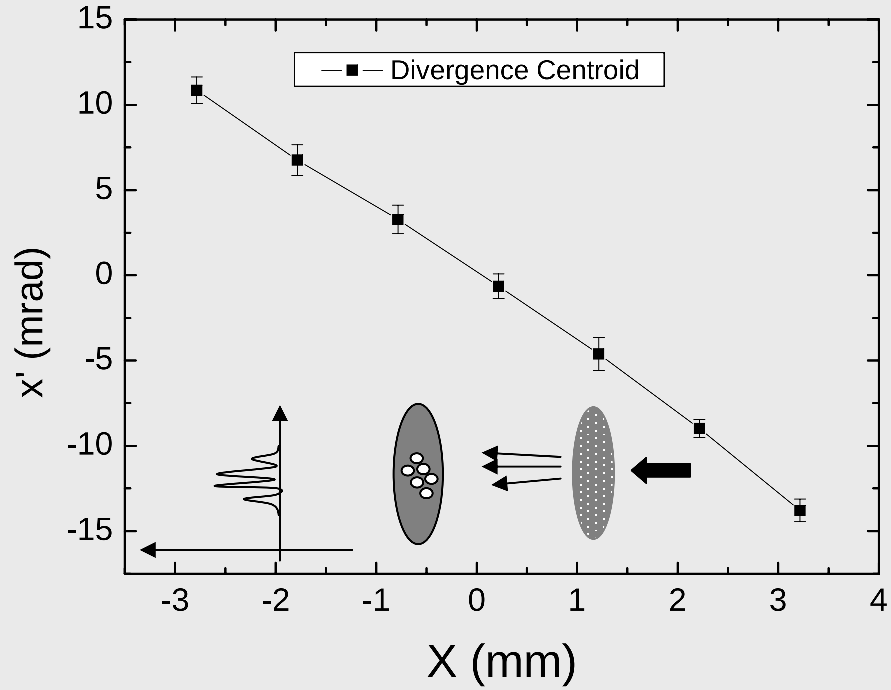


Photo-Field Emission Emittance





Weak Signal after Pinhole Array

ε (mm.mrad) = 1.3 (+/- 0.2)

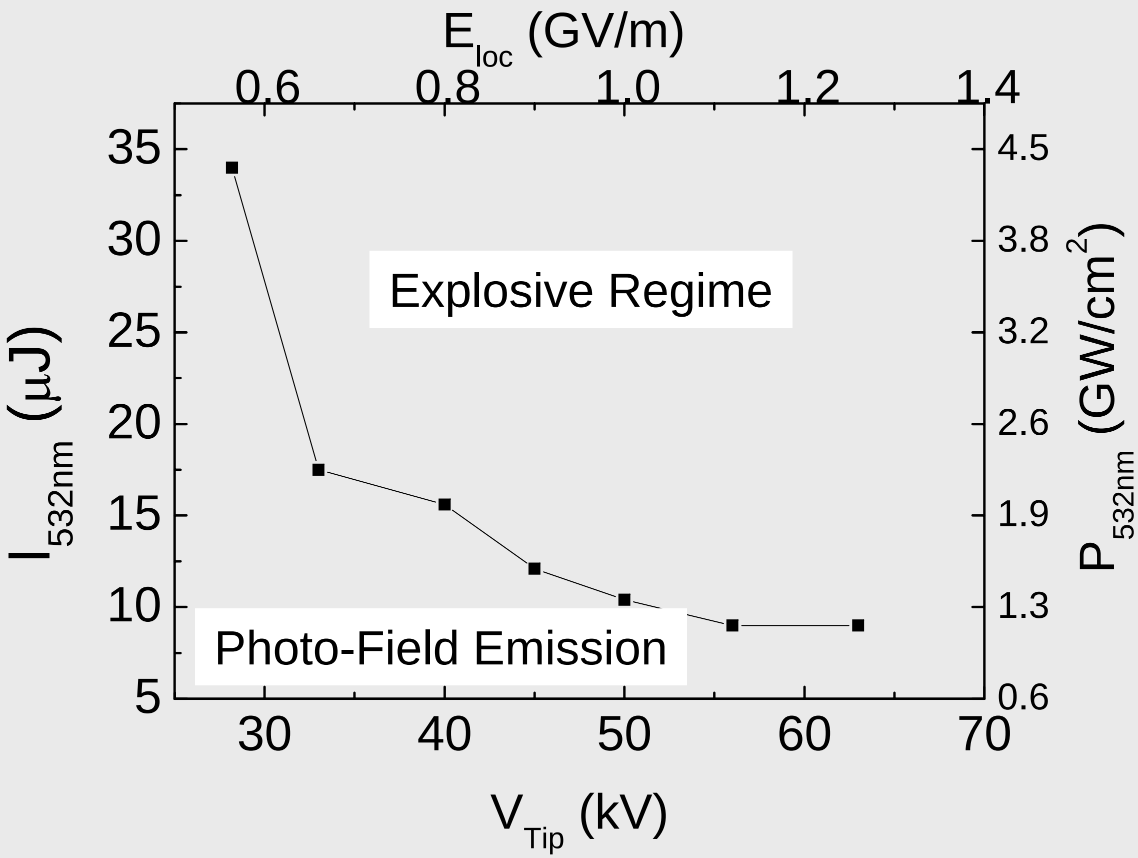
Normalized Emittance (27 keV; 20pC)

$\varepsilon_n = \beta\gamma\varepsilon$

$\varepsilon_n = 0.5 \pm 0.1$ mm.mrad

Laser: 2.3µJ / σ_z=16ps / σ_r=75µm / 30Hz / 266nm
ZrC tip: V_{Tip}=-27kV

Threshold for Plasma initiation



High E_{Field}

easier to trigger Plasma

EEE numbers:

$J \sim 10^8$ A/cm^2

Losses: 10^{-8} g/C

$E_{EEE} > 10^4$ J/g

$P \sim 10^9$ Pa

Litterature: $I_{Ablation} \sim 20 GW/cm^2$ for Copper when No Gradient

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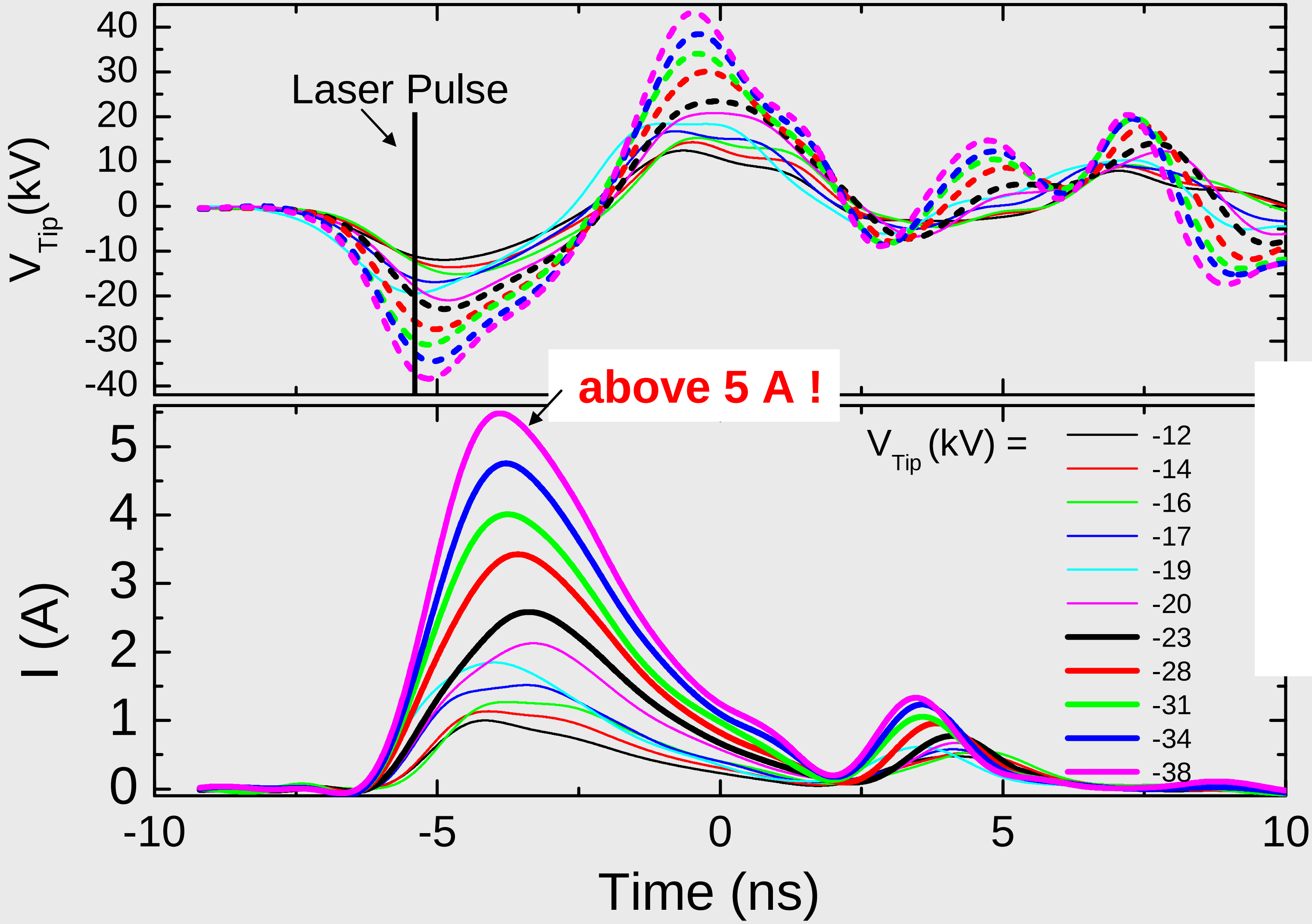
Laser Induced Plasma Emission



Explosive Electron Emission = Stationary Process

Laser Pulse: 532nm; 20µJ; 16ps; 10Hz; P_{Laser} >1 G W/cm2

PSI FEL - R. Ganter

Conclusion :

FEA Technology: Great Potential: No laser needed
PSI Status: All metal single gated FEA
Issues: Double gate fabrication; Uniformity

Needle Cathode + Laser: Approaching PSI FEL requirements (1A; 0.5mm.mrad)
Issues: Synchronization and Pointing stability

Laser induced Plasma Emission: Very Intense; Stable
Issue: Control of bunch length