ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

PAUL SCHERRER INSTITUT

Characterization of Electron Bunches from Field Emitter Array Cathodes for Use in Next-Generation X-Ray Free Electron Lasers

Simon C. Leemann • Public Thesis Defense • January 25, 2007

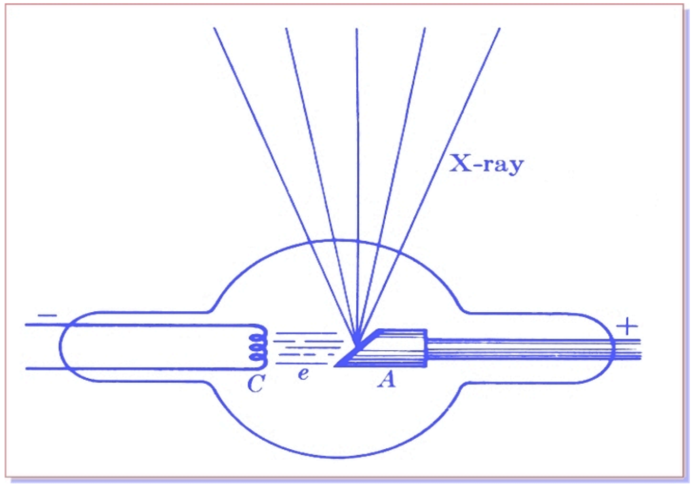
Contents

- Synchrotron Radiation
- X-Ray Free Electron Lasers
- Generating Low Emittance Beams
- 100 keV DC Gun Test Stand
- Experimental Results
- Conclusions & Outlook

Contents

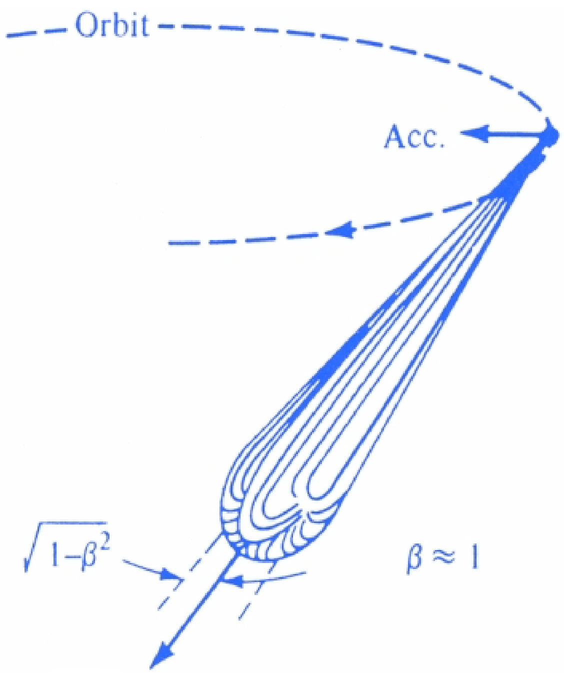
What is Synchrotron Radiation?

When charged particles are accelerated or decelerated they emit electro-magnetic radiation:



Wilhelm Conrad Röntgen, 1895

In a cathode ray tube electrons are accelerated and then stopped → "bremsstrahlung" (a part of the emitted spectrum are X-rays)

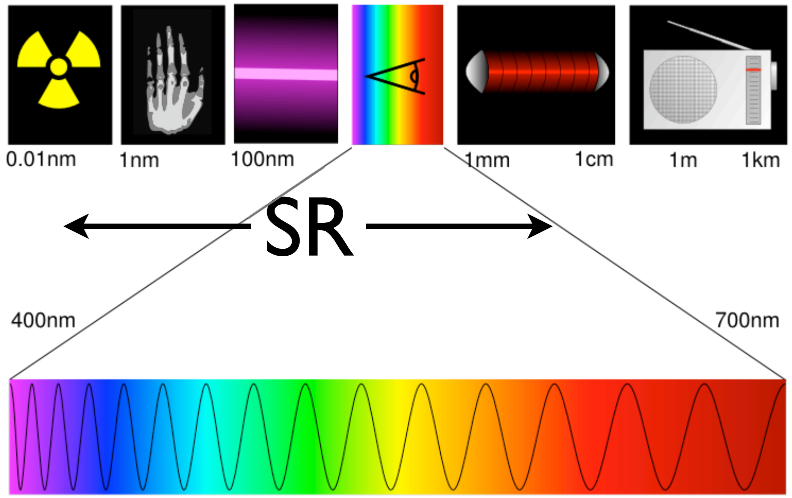


GE Research Lab, Schenectady NY USA, 1947 (70 MeV)

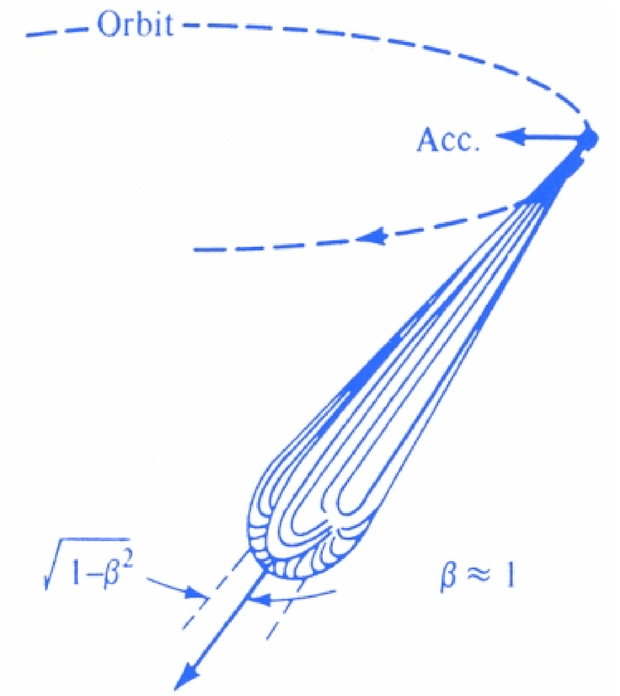
In a synchrotron relativistic electrons are deflected by bending magnets and emit radiation due to the radial acceleration → "synchrotron radiation"

Why Synchrotron Radiation?

- Synchrotron radiation covers the entire spectrum from infrared to hard X-rays



Courtesy of wikipedia.org



- Synchrotron radiation can penetrate matter
- Wavelengths comparable to molecular and atomic dimensions → investigate molecular structures
- Synchrotron radiation is emitted into a narrow cone
- Synchrotron radiation is emitted in short pulses → time-resolved imaging

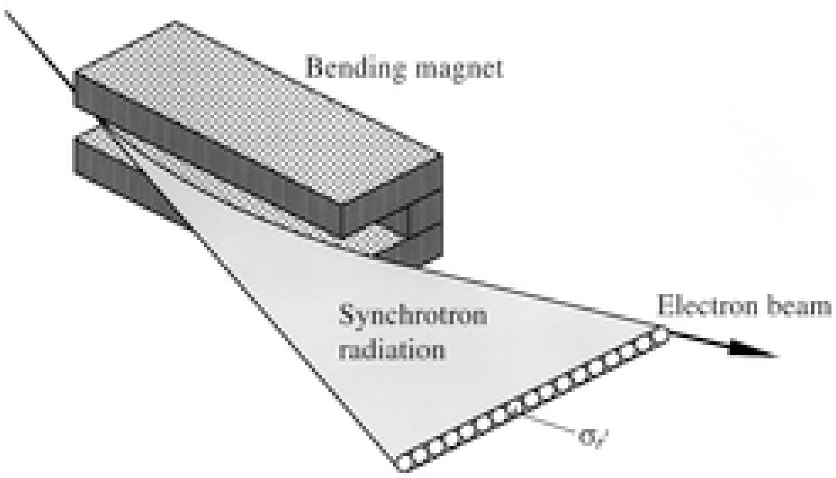
➡ Synchrotron radiation has become an indispensable tool in science, medicine, and engineering

Synchrotron Radiation Source Generations

1st generation sources (up to ~1970)

- Parasitic use of electron storage rings originally built for particle physics experiments (CESR in Ithaca NY, USA or DORIS @ DESY in Hamburg, Germany)

Courtesy of CESR



Courtesy of journals.iucr.org

Synchrotron Radiation Source Generations

2nd generation sources (late 1970s)

- First electron synchrotrons built as dedicated synchrotron radiation facilities (NSLS in Brookhaven NY, USA or SRS in Daresbury, UK)

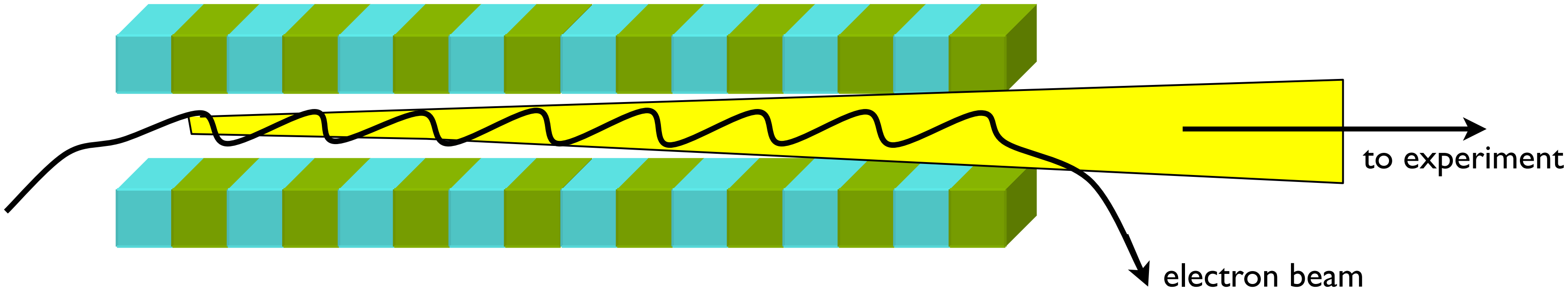
Courtesy of CCLRC

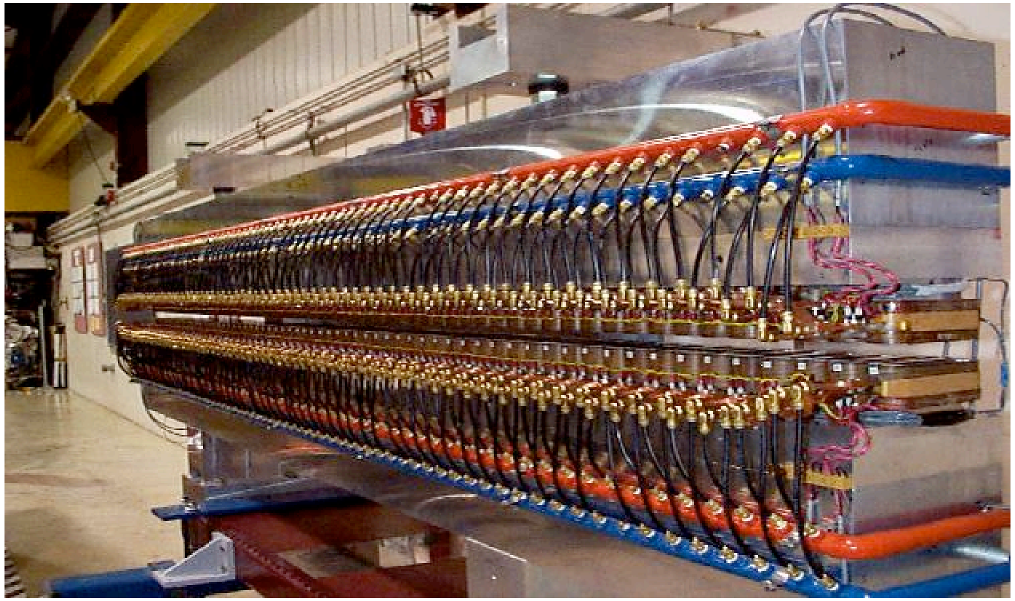
Synchrotron Radiation Source Generations

3rd generation sources (late 1980s)

- Dedicated electron storage rings with undulators and wigglers → hard & intense radiation (ALS in Berkeley CA, USA or SPring-8 in Hyogo, Japan)

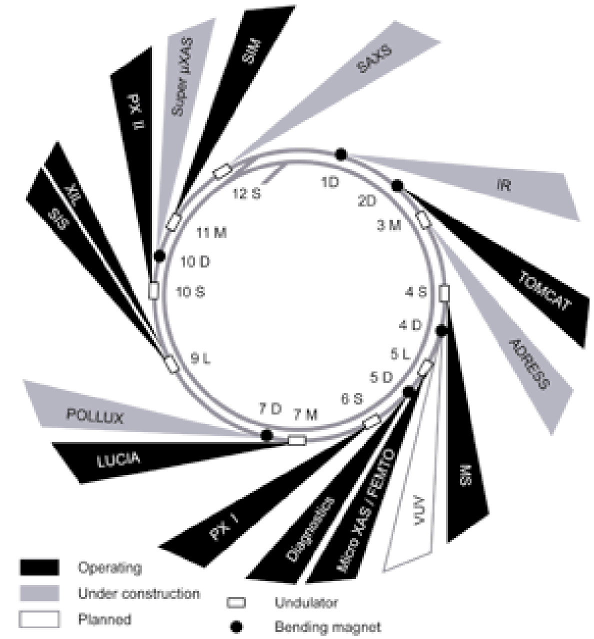
S. Werin: "Tutorial on FEL", CERN Accelerator School, Brunnen, 2003





Courtesy of University of Leicester

The Swiss Light Source SLS at PSI



- SLS is a 2.4 GeV electron storage ring based 3rd generation light source
- In operation since 2001, high availability
- Delivers light to over a dozen beam lines simultaneously
- Undulator, wiggler and bending magnet radiation
- Photon energy: 1 meV - 45 keV (1 mm - 0.03 nm)
- Pulse length > 10 ps

Contents

Today's Synchrotron Radiation User Requests

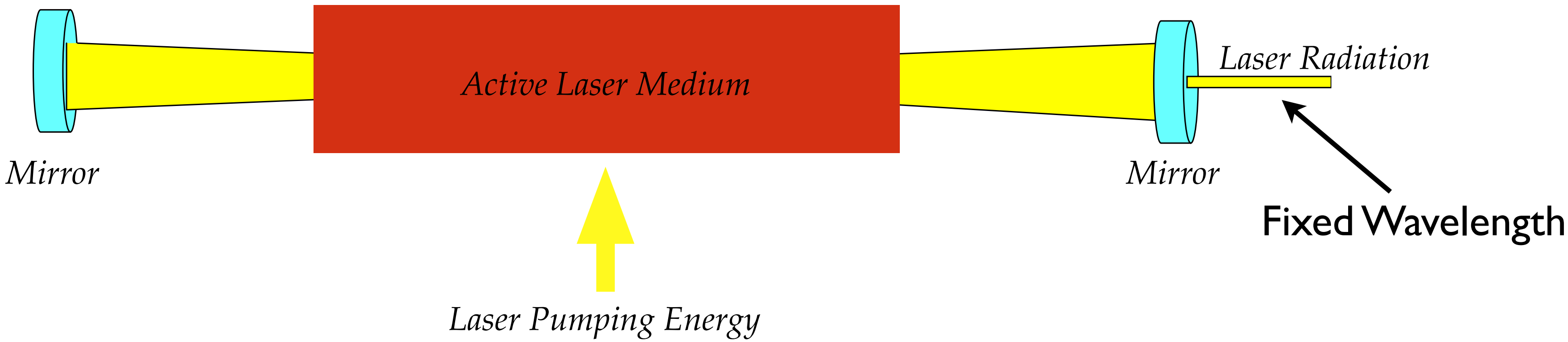
- Beyond what a 3rd generation source can deliver:
  - Even higher peak brightness
    (more photons, smaller beam size, narrower bandwidth)
  - High intensity hard X-ray radiation
    λ = 1Å (~ size of an atom!)
  - Ultra-short pulses
    τ ~ 50 fs
  - Fully coherent radiation
    (laser-like radiation from a point source)

➡ Need a new type of synchrotron radiation source to fulfill these demands, the so called "4th generation source"

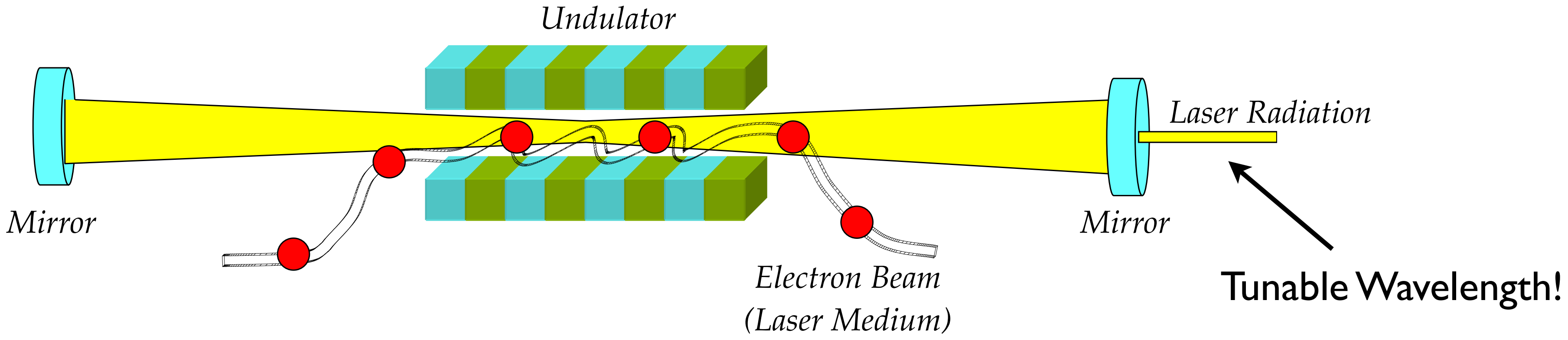
➡ Free Electron Laser (FEL) is such a concept

What is a Free Electron Laser?

- Classical laser system:



- Free Electron Laser:

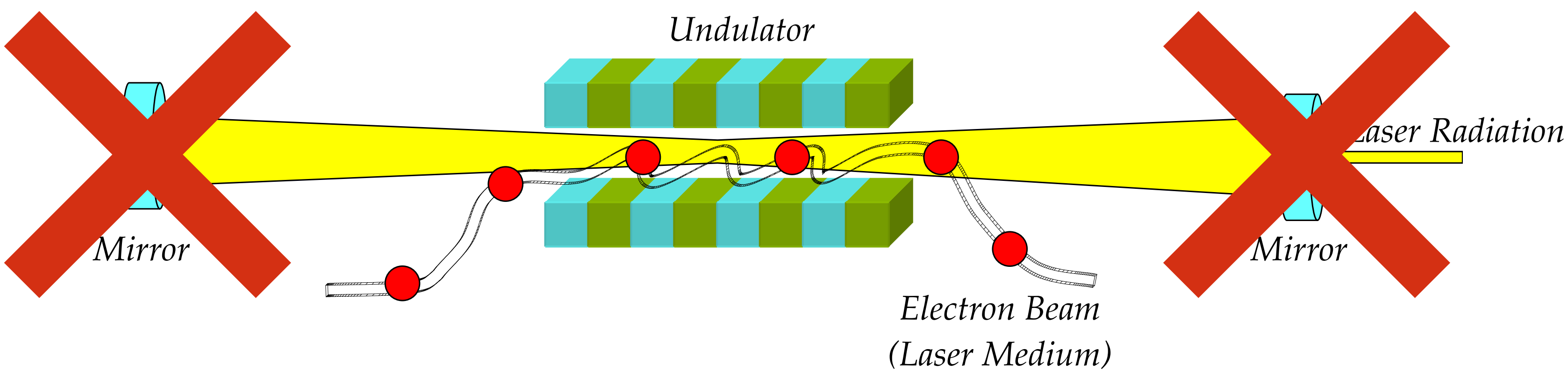


What is an X-FEL?

- X-Ray Free Electron Laser (X-FEL) is an FEL tuned to emit X-ray radiation
  - ➡ Need high electron beam energy (on the order of GeV)

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad \begin{cases} \lambda_u & : \quad \text{Undulator Period} \\ K \propto B_u & : \quad \text{Undulator Parameter} \end{cases}$$

- However, no efficient mirrors exist for X-rays



➡ Single-pass X-FEL required

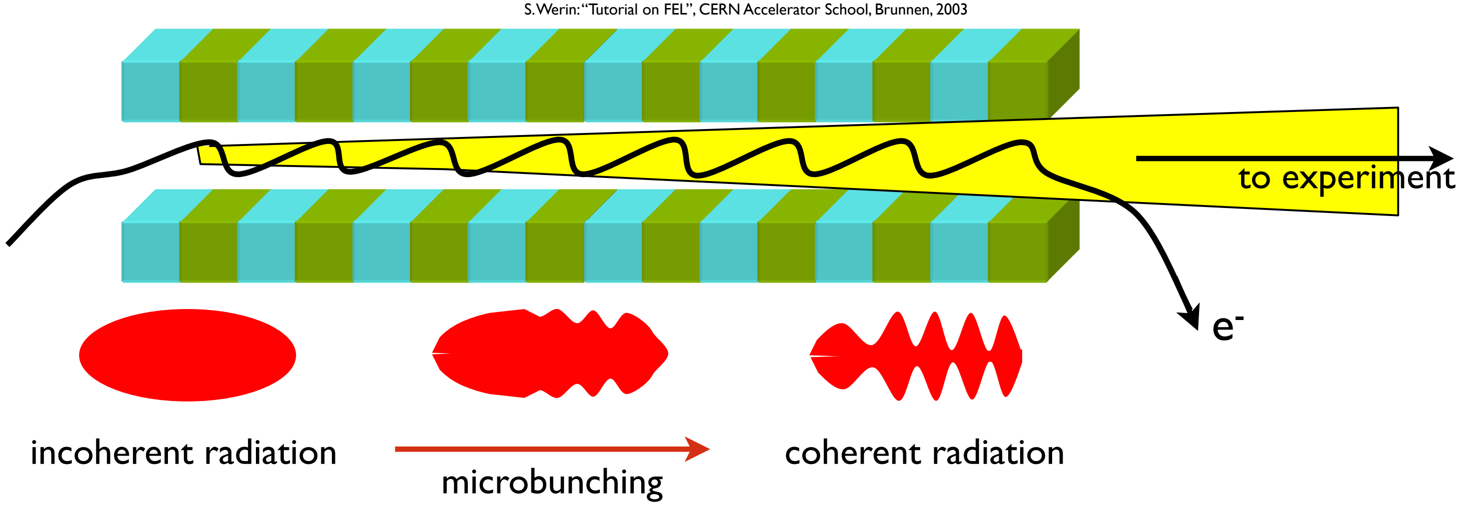
Single-pass X-FEL Systems

For example: SASE X-FEL (self amplified stimulated emission)

- Requires: long undulator, high peak current, overlap between electron beam and photon beam
- Bunch emits incoherent radiation in the undulator
- Radiation acts back on the bunch → energy modulation in the bunch → density modulation of the bunch → “microbunching”
- Microbunches emit coherent radiation

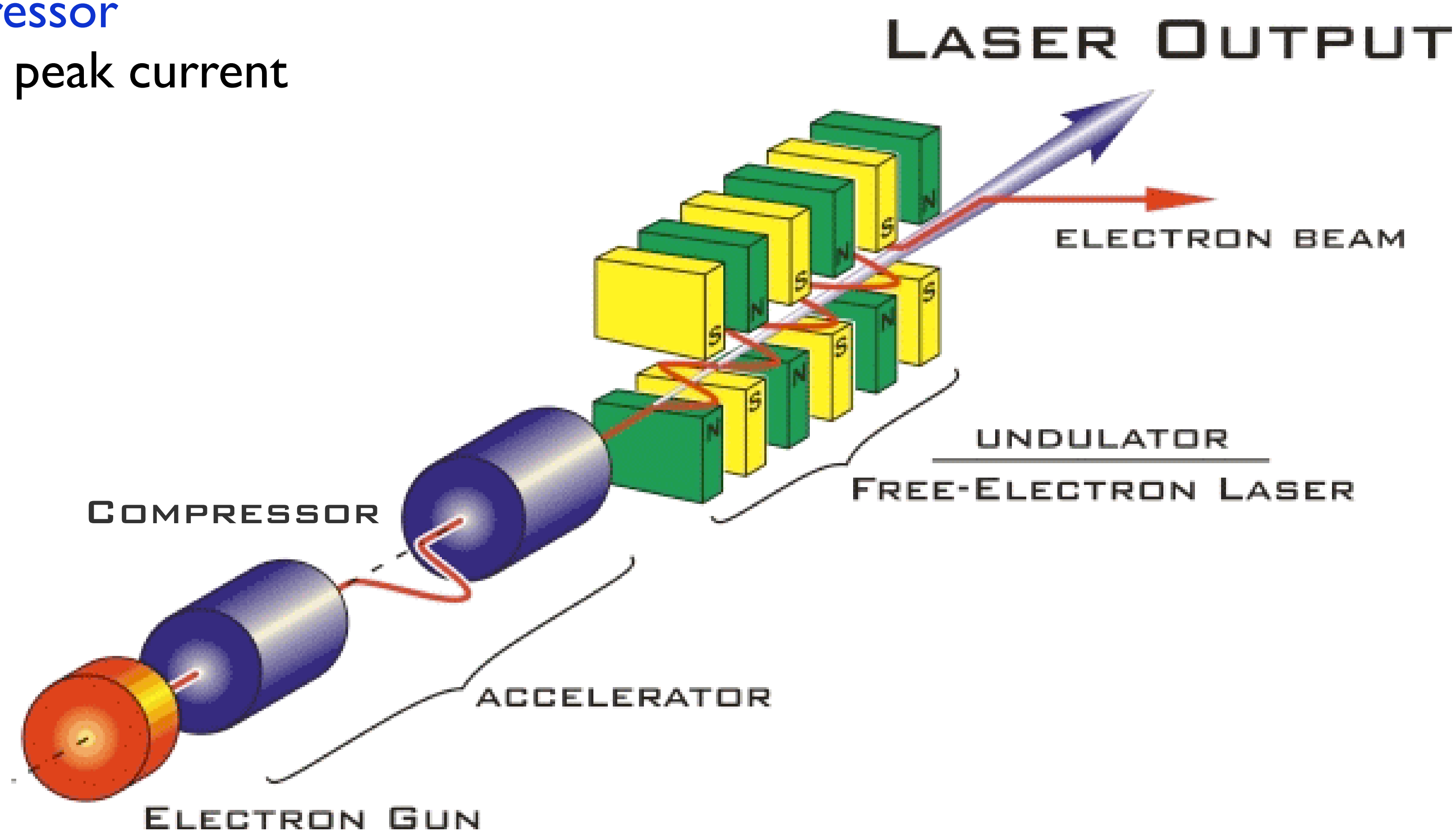
➡ Intense hard X-ray radiation with laser-like properties

S.Werin: “Tutorial on FEL”, CERN Accelerator School, Brunnen, 2003



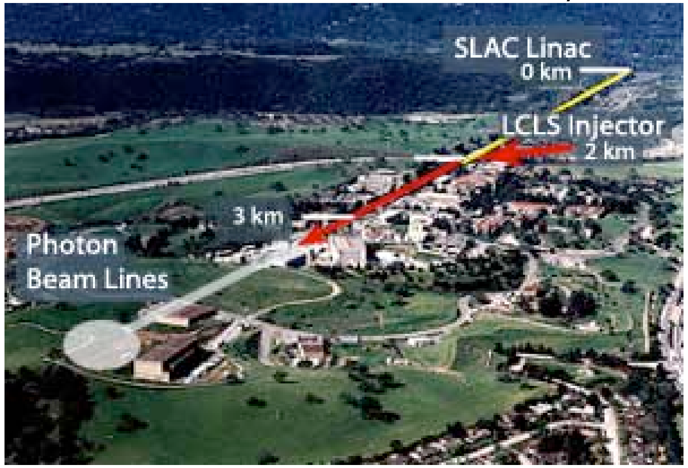
What Kind of Accelerator is Required for an X-FEL?

- Electron gun
  - ➡ delivers short and intense electron bunches
- Linac (linear accelerator)
  - ➡ accelerates short electron bunches to high energy
- Bunch compressor
  - ➡ increases peak current



Two 1Å X-FEL Projects

Courtesy of SLAC

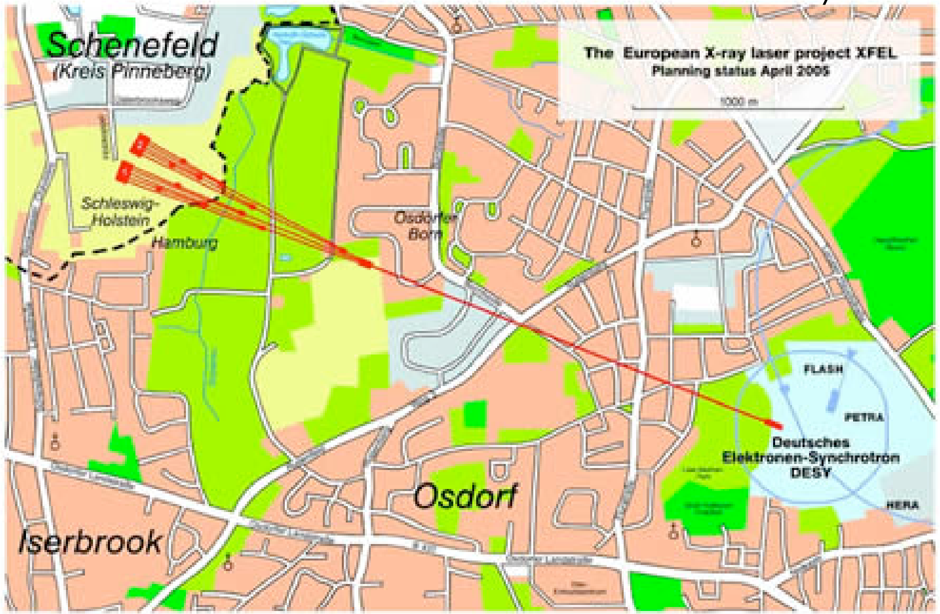


Linac Coherent Light Source (LCLS)

SLAC, Stanford CA, USA

- >3 km long, 14 GeV, ~300 million USD
- Construction started 2006
- Operational by 2009

Courtesy of DESY



European X-FEL

DESY, Hamburg, Germany

- 3.4 km long, 20 GeV, ~1 billion EUR
- Construction starts 2007
- Operational by 2013

A 1Å X-FEL for Switzerland

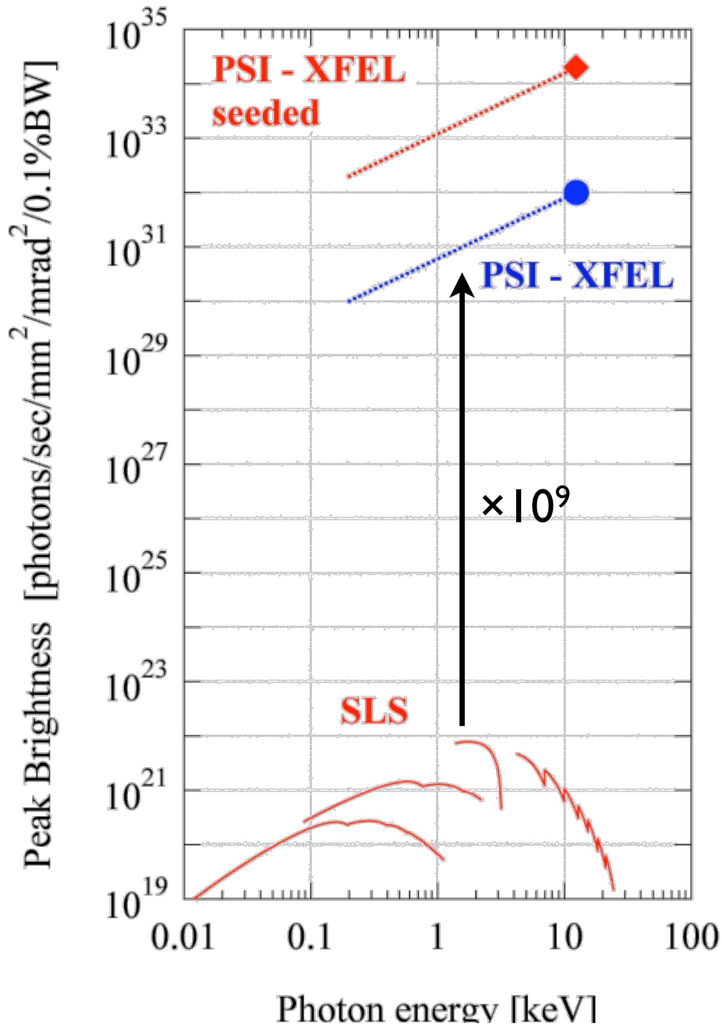
PSI is interested in an X-FEL as a companion synchrotron radiation source to the existing SLS:

SLS

- Large available radiation wavelength range
- Many beamlines simultaneously in operation

PSI X-FEL

- High peak brightness → single-shot imaging
- Ultra-short pulses → time-resolved imaging



➡ However, existing 1Å X-FEL concepts are too large to fit on the PSI site and too expensive for the Swiss synchrotron radiation community

Is There an Alternative 1Å X-FEL Concept?

- Yes! With a high quality electron beam, the required electron beam energy is reduced
  - ➡ A shorter linac is sufficient
  - ➡ X-FEL becomes smaller and less expensive
- High quality electron beam = electron beam with ultra-low emittance

$$\frac{\varepsilon^{(n)}}{\beta\gamma} < \frac{\lambda}{4\pi}$$

	European X-FEL	PSI X-FEL
Beam Energy	20 GeV	6 GeV
Total Length	3400 m	800 m
Cost	1.6 billion CHF	~ 300 million CHF
Required Emittance	0.9 mm mrad	0.05 mm mrad

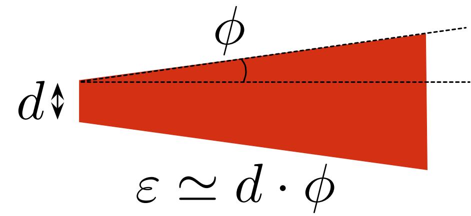
18 times lower!

➡ New challenge: generating ultra-low emittance electron beams

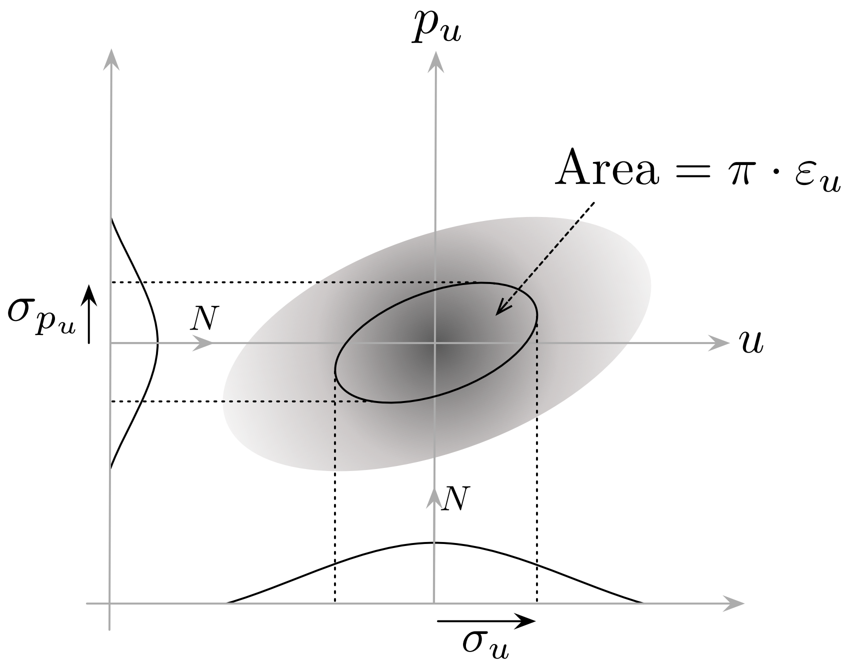
Contents

What is Emittance?

- Simple picture: emittance is a measure of beam quality



- Definition: measure of particle distribution density in phase space



$$\varepsilon_u^{(n)} = \frac{1}{m_e c}\sqrt{\langle u^2\rangle\langle p_u^2\rangle - \langle u p_u\rangle^2}$$

$$\simeq \gamma\beta\sqrt{\langle u^2\rangle\langle u'^2\rangle - \langle u u'\rangle^2}$$

Measure directly

Cannot measure directly → need "trick"

- Liouville's theorem: in Hamiltonian systems, normalized emittance is a conserved quantity → need low emittance source

Survey of Electron Sources

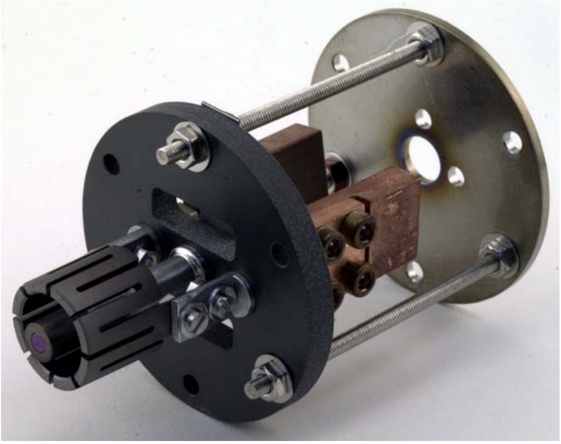
Thermionic emission: the oldest and most well known electron source

- Cathode material is heated to >1000 K upon which electrons have sufficient energy to escape material and enter vacuum
- In order to get high peak current, need higher temperature and/or larger cathode size → blows up source emittance

$$\varepsilon^{(n)} = \frac{\gamma\, r_c}{2}\sqrt{\frac{k_B T}{m_e c^2}}$$

- Emission is DC → need gating grid or chopper (emittance deterioration)

➡ Prefer smaller, pulsed, cold cathodes



CeB_6 thermionic cathode

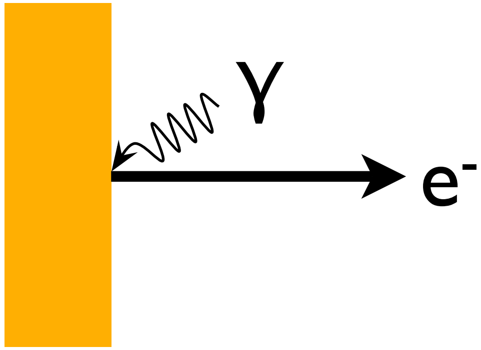
T. Shintake: "Small Emittance Sources/Guns", CERN Accelerator School, Brunnen, 2003

Survey of Electron Sources

Photo-electric emission: cold, short-pulsed emission

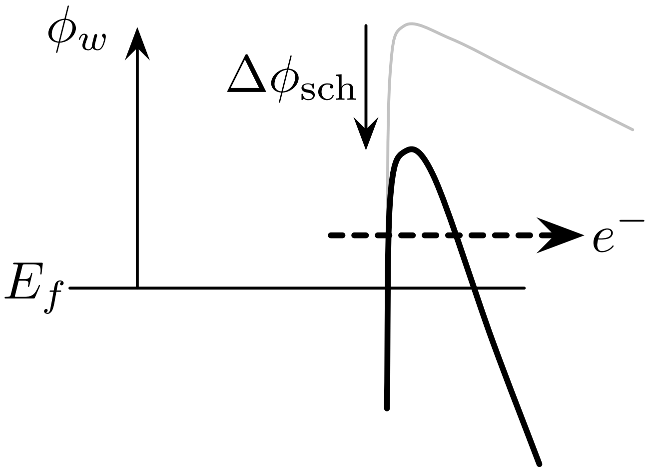
- Cathode material is irradiated with short laser pulses upon which electrons are released to vacuum through the photo-electric effect
- Short-pulse laser systems are available → allow precise control of longitudinal (time structure) and transverse bunch shape
- High peak current through use of short wavelength lasers → photon energy $E_\gamma = hc/\lambda$ is much larger than work function Φ_w → large momentum spread → large source emittance
- Use longer wavelength laser where $E_\gamma = hc/\lambda \sim \Phi_w$ → reduced current → larger cathode area required → increased source emittance

➡ Need an alternative electron emission process!



Cs_2Te photo-cathode @ PITZ

Field Emission



- Bring cathode material into high electric field region
- High external electric fields reduce potential barrier (Schottky effect)
  - ➡ The effective work function $\Phi_{w,e}$ is reduced
  - ➡ The potential barrier thickness is reduced
- Quantum mechanics: there is a finite probability for electrons to tunnel through the potential barrier into vacuum → Fowler-Nordheim law:

$$J_{\mathrm{FN}} \approx 1.54 \cdot 10^{-6} \frac{\beta^2 E^2}{\phi_w} \exp\left(-6.83 \cdot 10^9 \frac{\phi_w^{3/2}}{\beta E}\right)$$

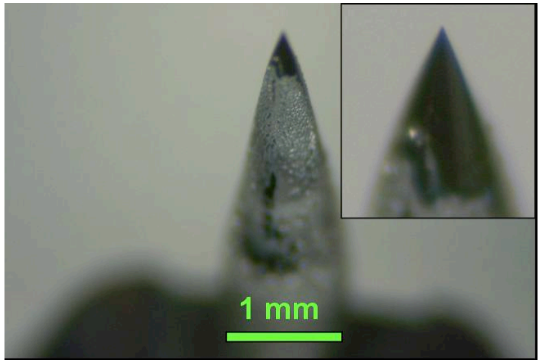
- Since the electrons tunnel through the potential barrier → kinetic energy is lower than the effective work function $E_e < \Phi_{w,e}$
- Providing there is a very high effective electric field (several GV/m) large amounts of current can be drawn from very small areas

➡ Small emission area and low transverse momenta → low source emittance!

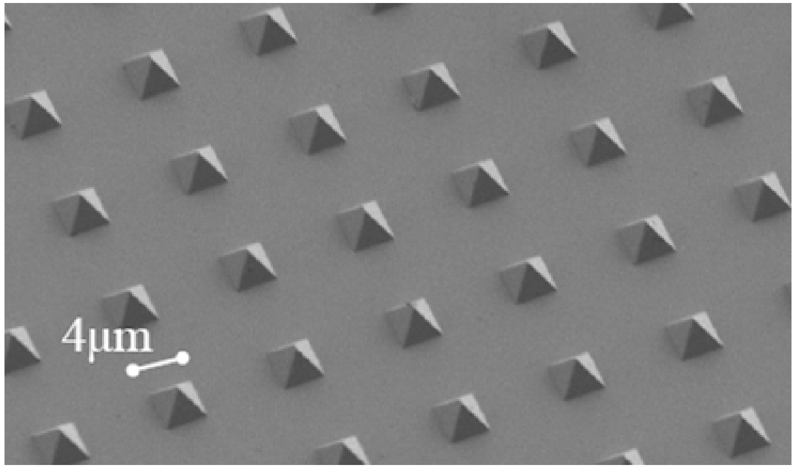
Field Emission Cathodes

High current density requires large effective electric field strength
➡ geometric field enhancement and high external voltage

- Needle-tip emitters → total current insufficient

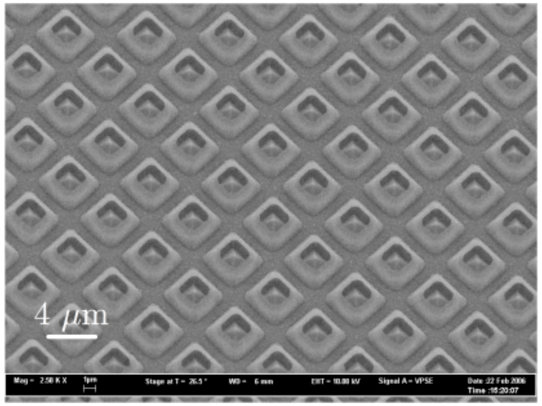


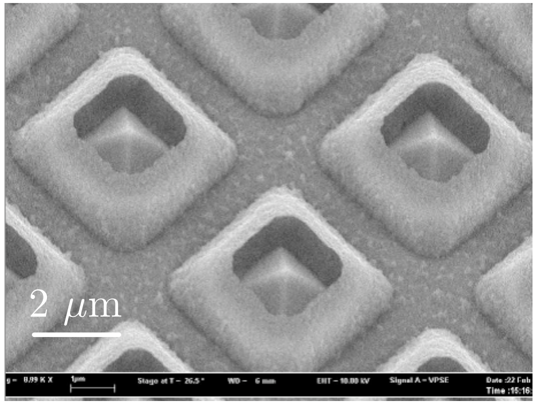
- Field emitter arrays (FEAs) → many nano-tips distributed over cathode surface

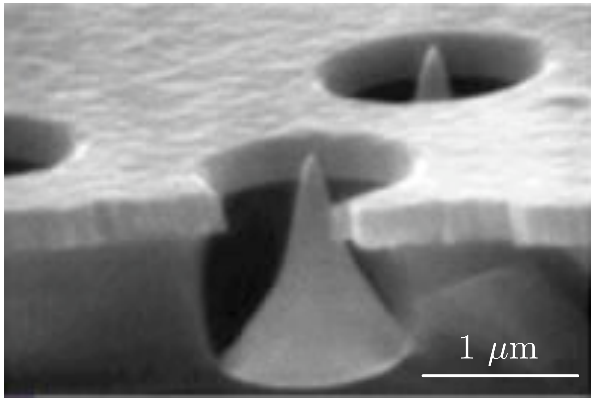


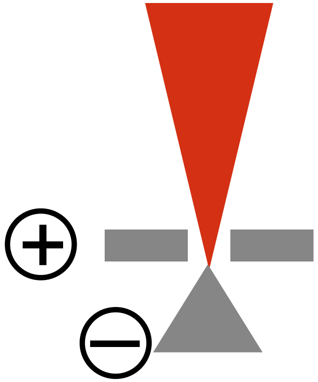
Field Emission Cathodes

- FEAs with gate layer → pulsed emission

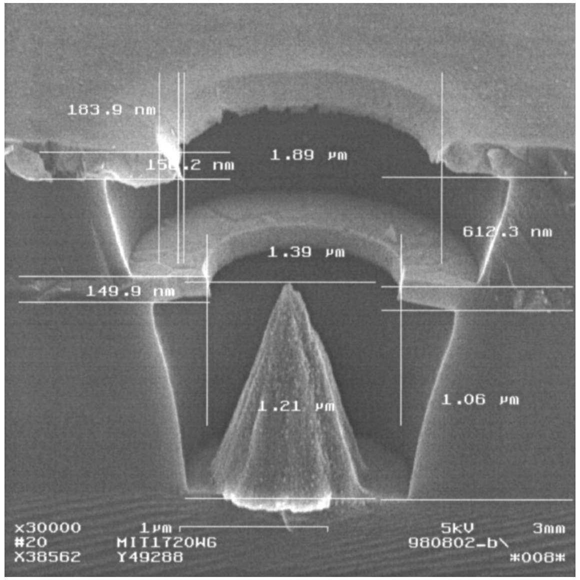


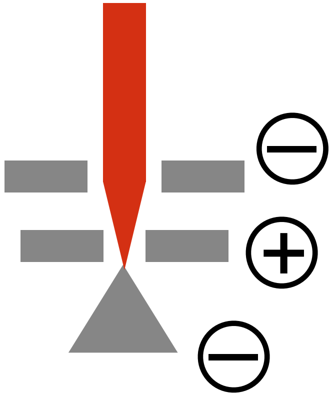






- FEAs with focusing layer → reduce divergence → minimize source emittance





Contents

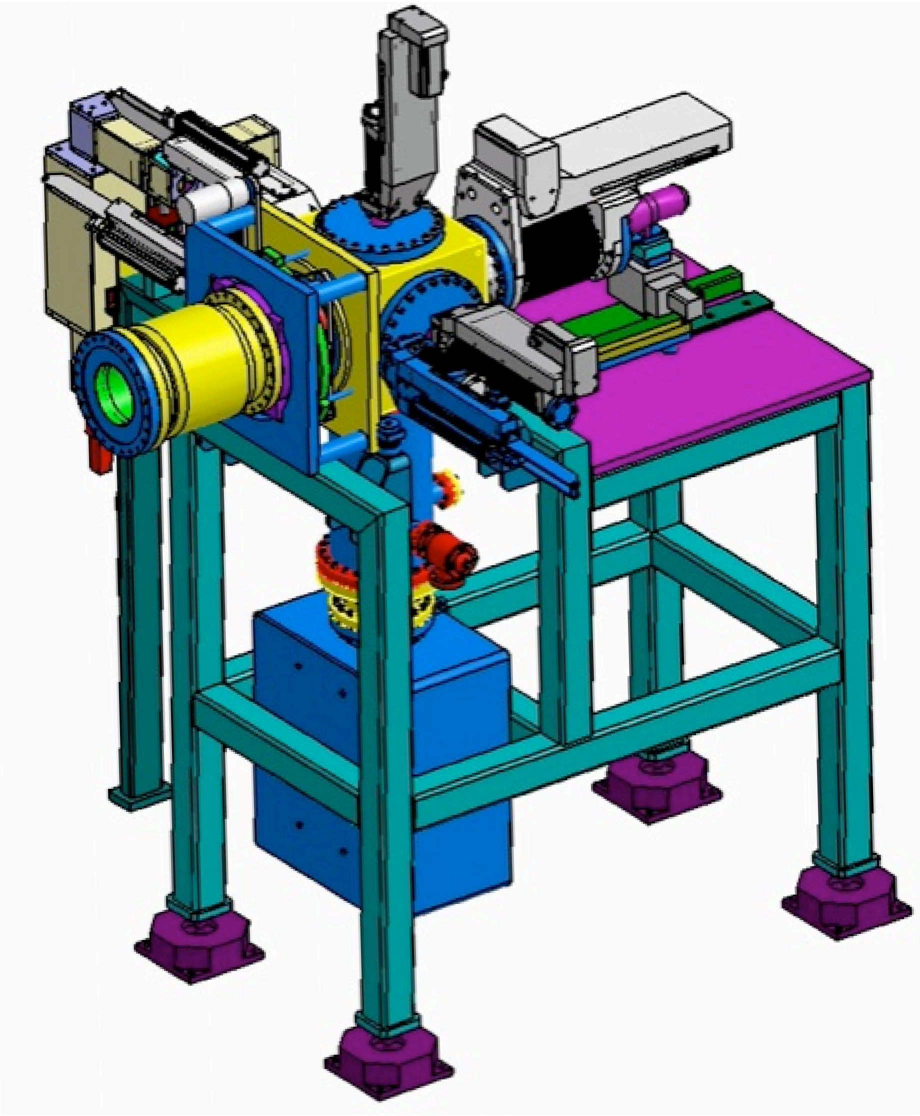
Motivation Behind the 100 keV DC Gun Test Stand

- Gain experience with FEA as cathode in an electron gun
- What are the properties of a bunch emitted by an FEA and accelerated in a HV gap?
- Can the FEA deliver sufficient peak current?
- Do the electron bunches have a low emittance?
- What diagnostic equipment and which diagnostic techniques are required to measure ultra-low emittance?

Overview of the 100 keV DC Gun Test Stand

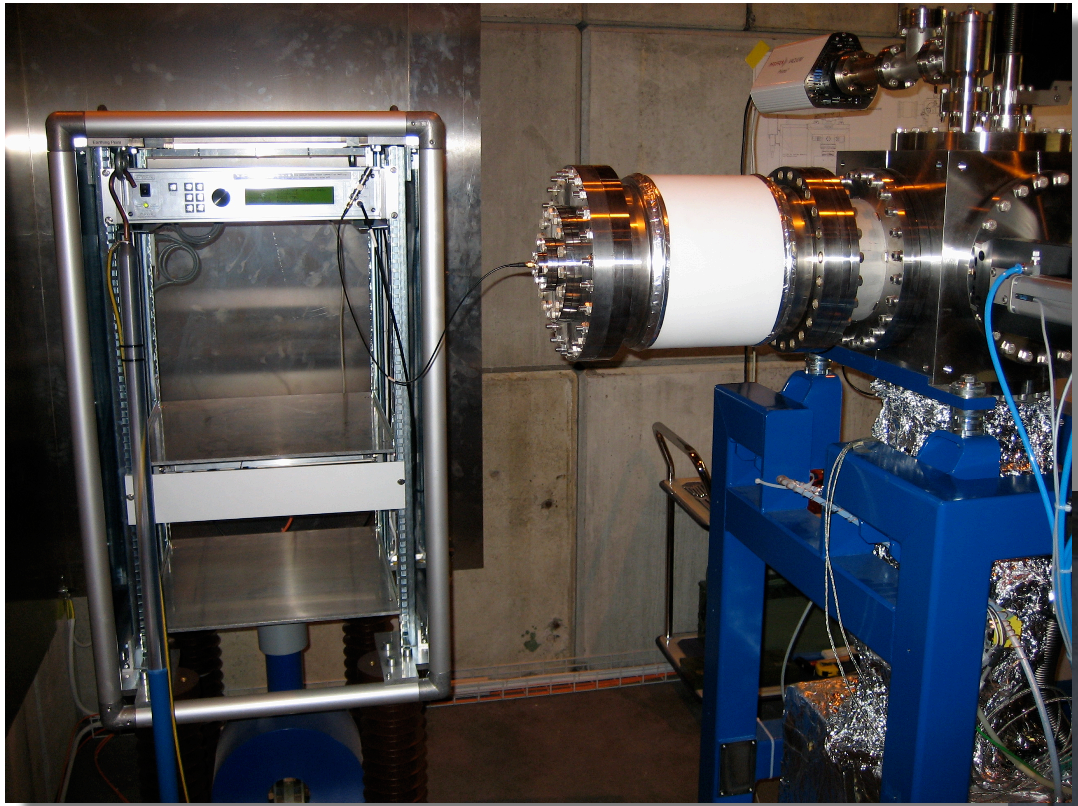
The 100 keV DC Gun Test Stand consists of:

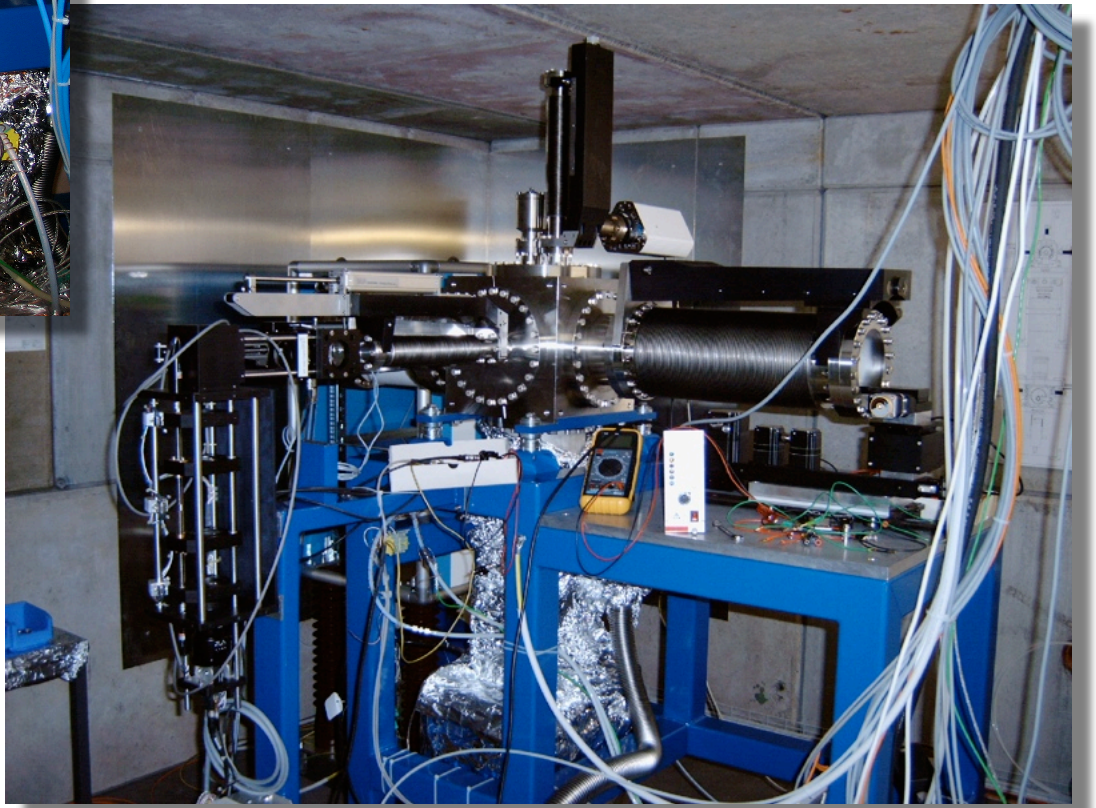
- Electron gun with FEA cathode (exchangeable)
- In-vacuum solenoid magnet → beam focusing, emittance compensation
- Diagnostics module → benchmark FEA performance and investigate beam quality
- Digital control system → experimental control and data acquisition
- Dedicated vacuum system and diagnostics → ensure UHV conditions
- Local access control and safety system → radiation protection and HV safety



Test Stand Bunker and Control System

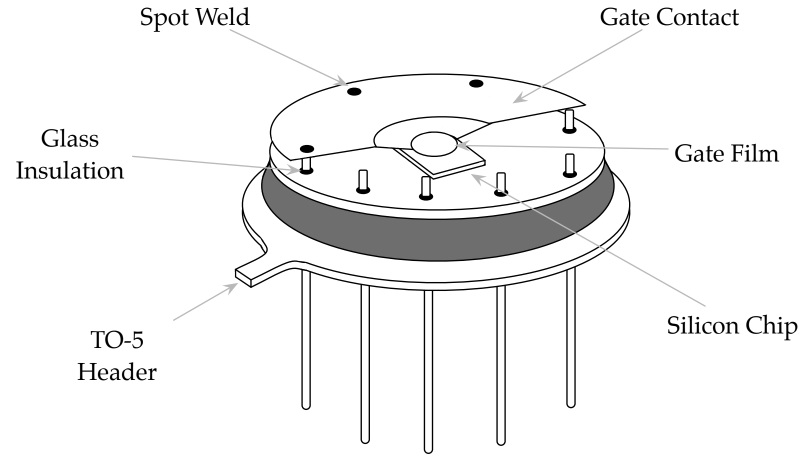
Test Stand Gun, Pulser and Diagnostics Module

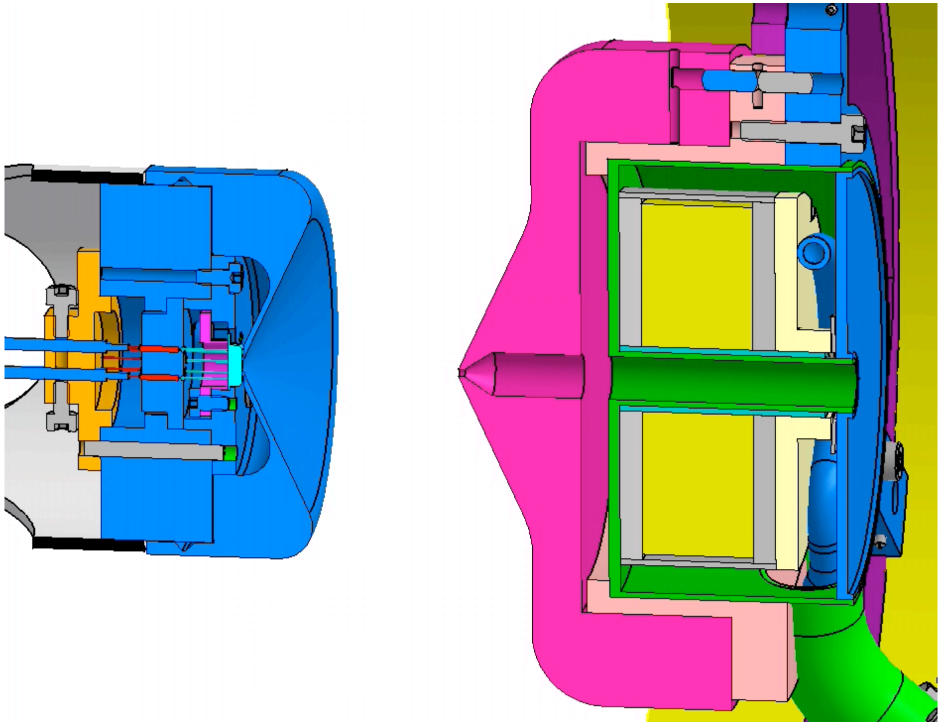




Gun & Solenoid

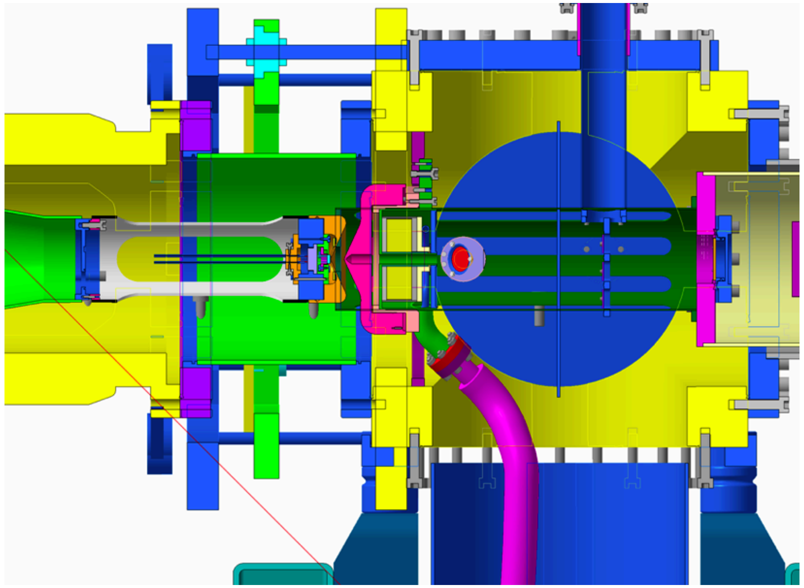
- Used gated FEAs from SRI International (no focusing layer)
- Cathode and anode electrodes (removable) define gun geometry
- Design optimization and particle tracking done with codes MAFIA (2.5D) and GPT (3D)
- Cathode is put on -100 kV DC bias, anode is grounded
- FEA pulser is on cathode potential and applies square pulses to gate layer (0 - 320 V, 5 - 100 ns)
- In-vacuum solenoid with water cooling circuit and high-μ yoke (confines magnetic field, reduces field leak onto cathode) delivers B_z up to 200 mT on axis

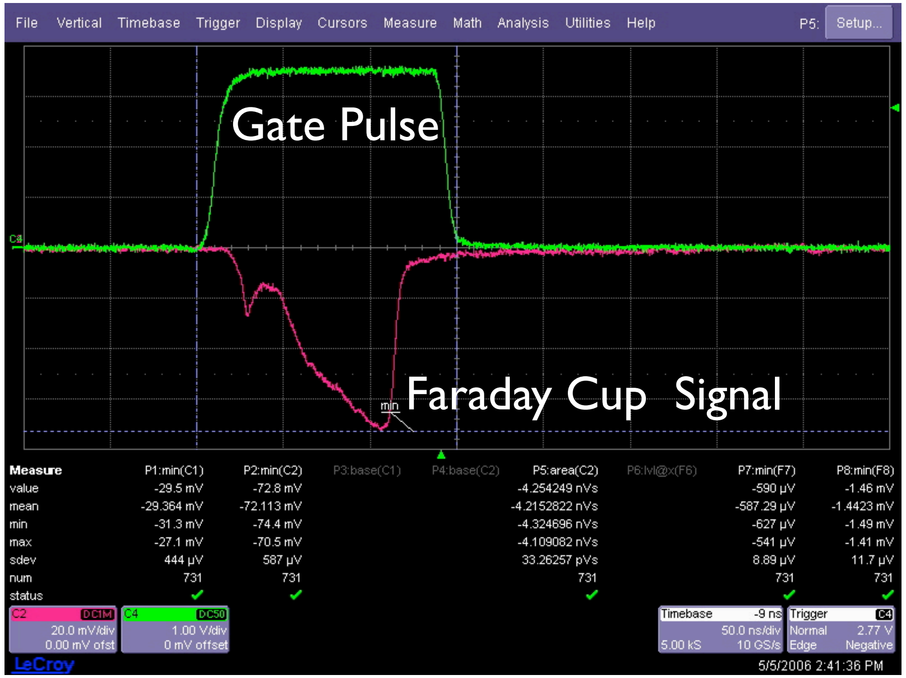


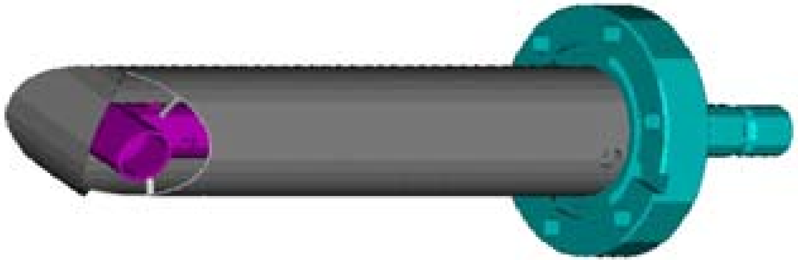


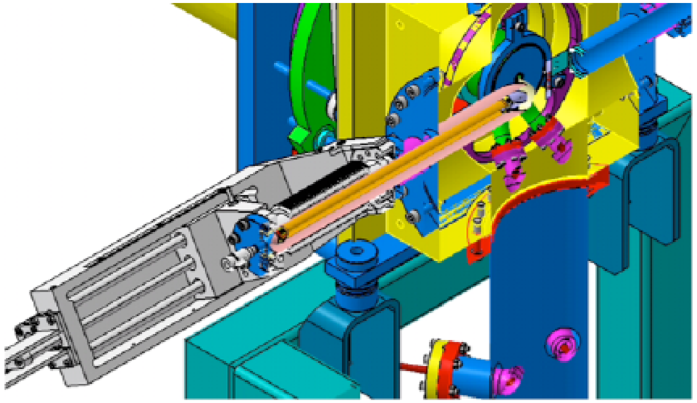
Diagnostics: Measuring Charge-Time Structure

- In order to measure the charge-time structure of the bunch, a Faraday cup can be driven into the beam and read out with a fast oscilloscope (2 GHz, 20 GS/s)
- Measure the voltage over a known resistor → momentary bunch current
- Integration of current signal over pulse length → total bunch charge





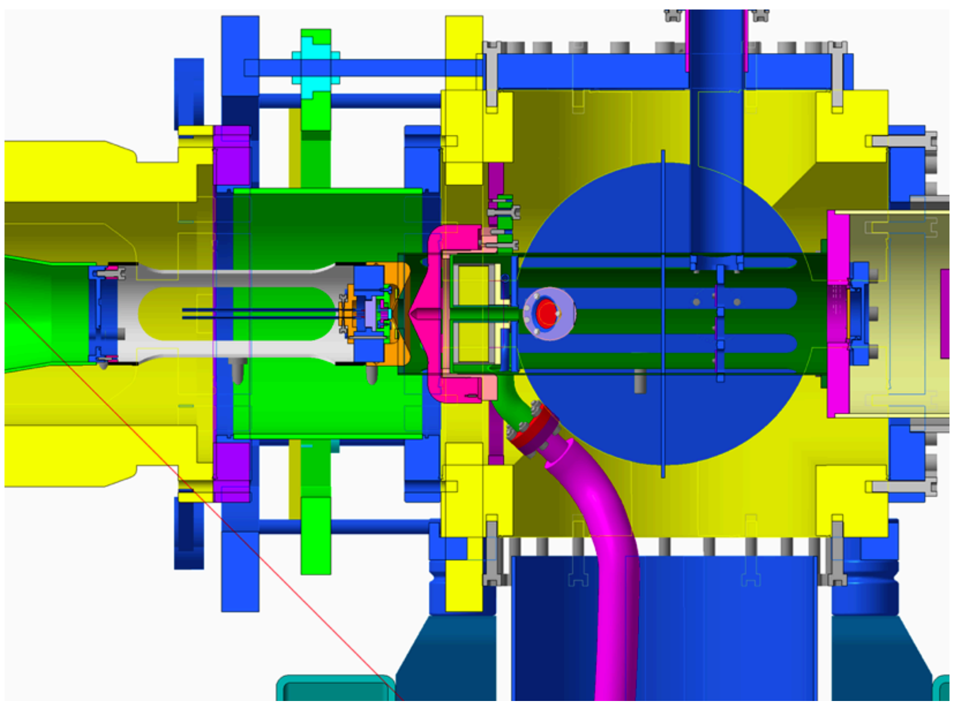


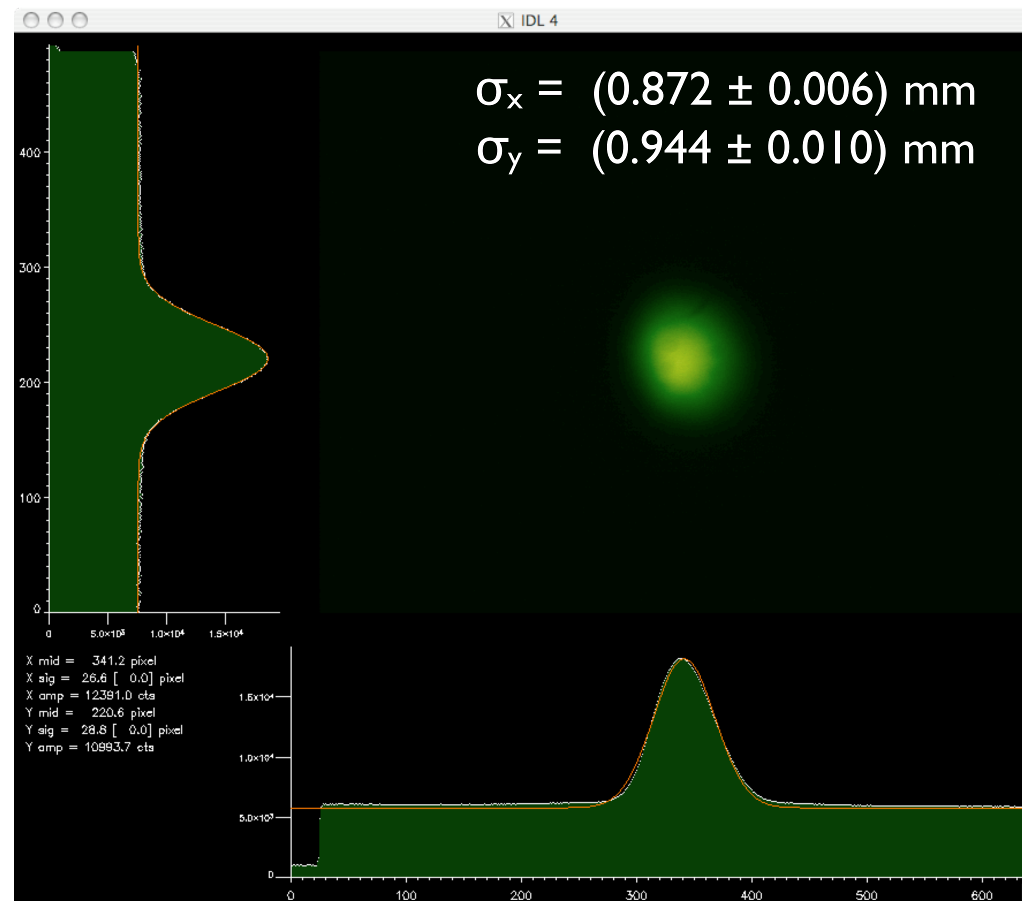


Diagnostics: Measuring Beam Size & Imaging the Bunches

Two screen monitor systems with dedicated zoom optics and CCD camera

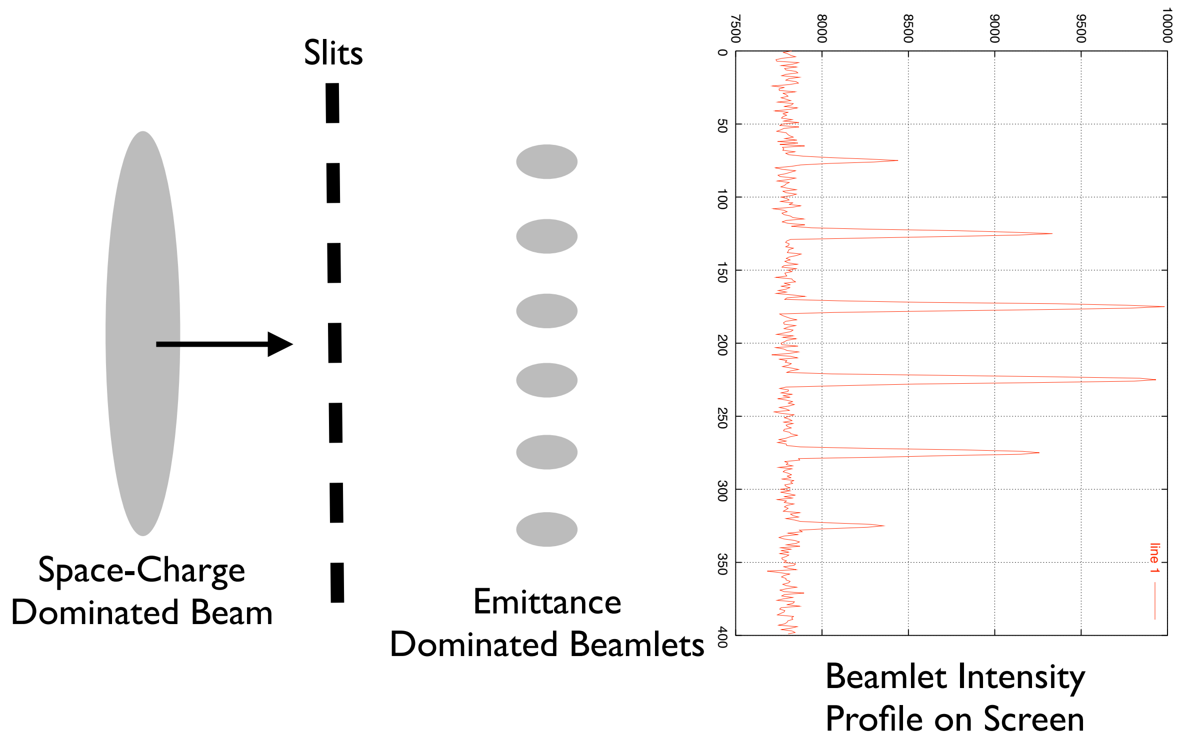
- YAG: crystal at 45° angle driven into beam laterally → measure beam size/profile at location of minimum emittance
- P43 phosphor: Coating on vacuum window at the end of the diagnostics module (movable) → measure beam size/profile and beam image at various positions along beam path





Diagnostics: Measuring the Transverse Bunch Emittance

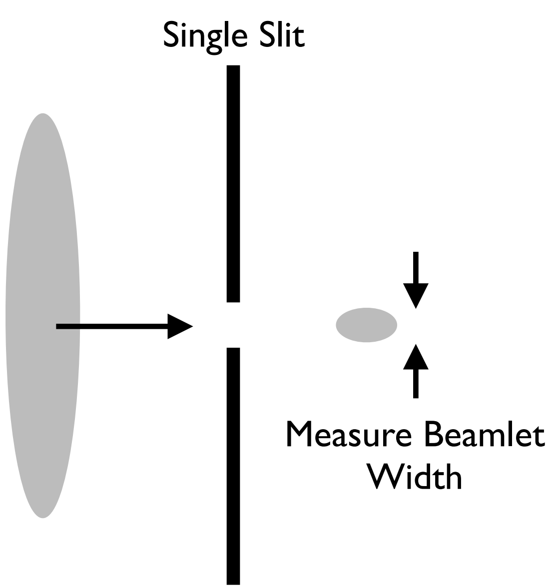
- Various measurements → compare methods, benchmark accuracy
- Measure transverse bunch properties: Insert obstruction, image emerging beamlet(s) downstream → calculate bunch properties at location of obstruction

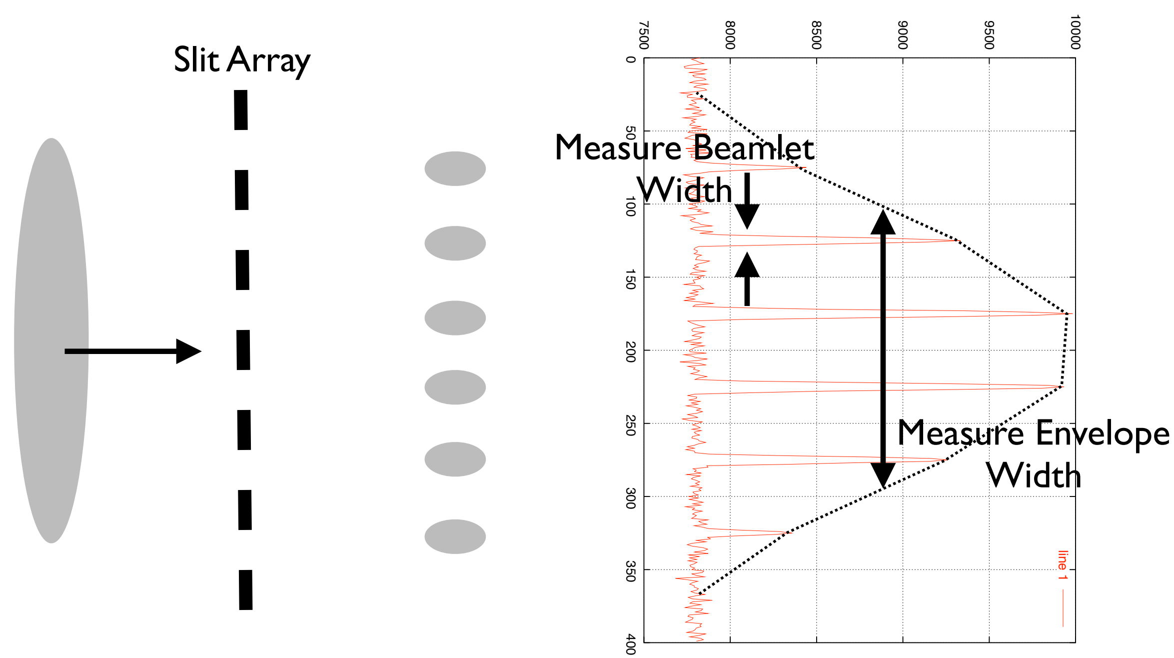


- Inserts have to fully stop beam outside hole/slit → 100 µm tungsten masks

Diagnostics: Measuring the Transverse Bunch Emittance

- Single slit mask (20 μm): together with beam size at location of the slit this gives emittance
- Slit array mask (20 μm, 170 μm pitch): measure divergence within different beamlets and beam envelope → emittance, phase space ellipse
- Pinhole array mask (50 μm, 320 μm pitch): corresponds to using a horizontal and vertical slit array in one single shot
- Mask dimensions optimized according to simulation results (MAFIA)



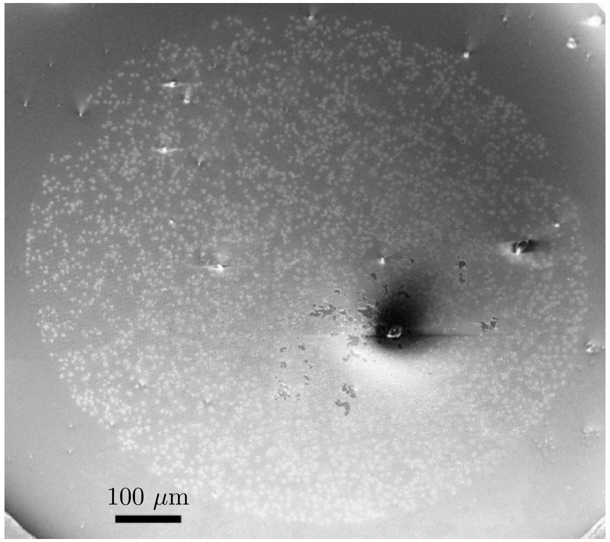


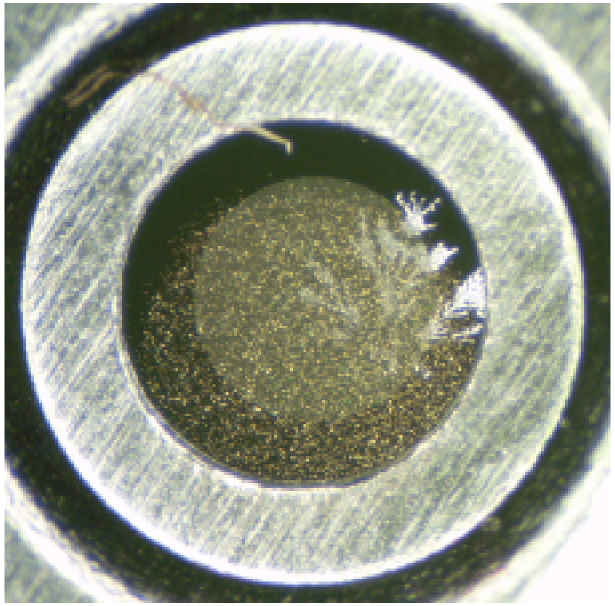
Contents

FEA Performance

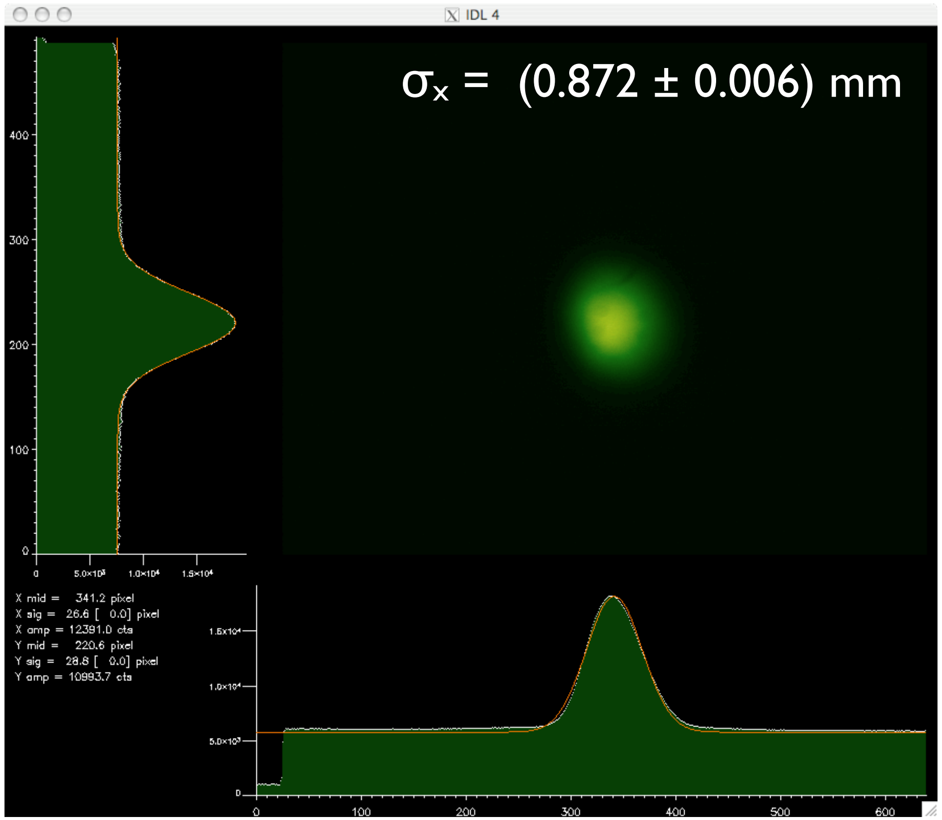
- Gun sustains stable DC HV of 100 kV
- Lifetime issue: FEAs are extremely sensitive to HV breakdown (after HV arc FEA is usually destroyed due to bridge between tips and gate layer)
- SRI FEAs operated at 40 kV
  - ➡ At higher accelerating voltage more severe damage to FEA (ion back-bombardment, HV arcs)
- SRI FEAs gate voltage limited to < 200 V
  - ➡ At high gate voltages instabilities in emission are observed (tip to gate emission → local vacuum degradation → can induce HV breakdown)

➡ Maximum emission from SRI FEAs:
$\hat{I} = 2$ mA, $Q = 100$ pC (in 100 ns)





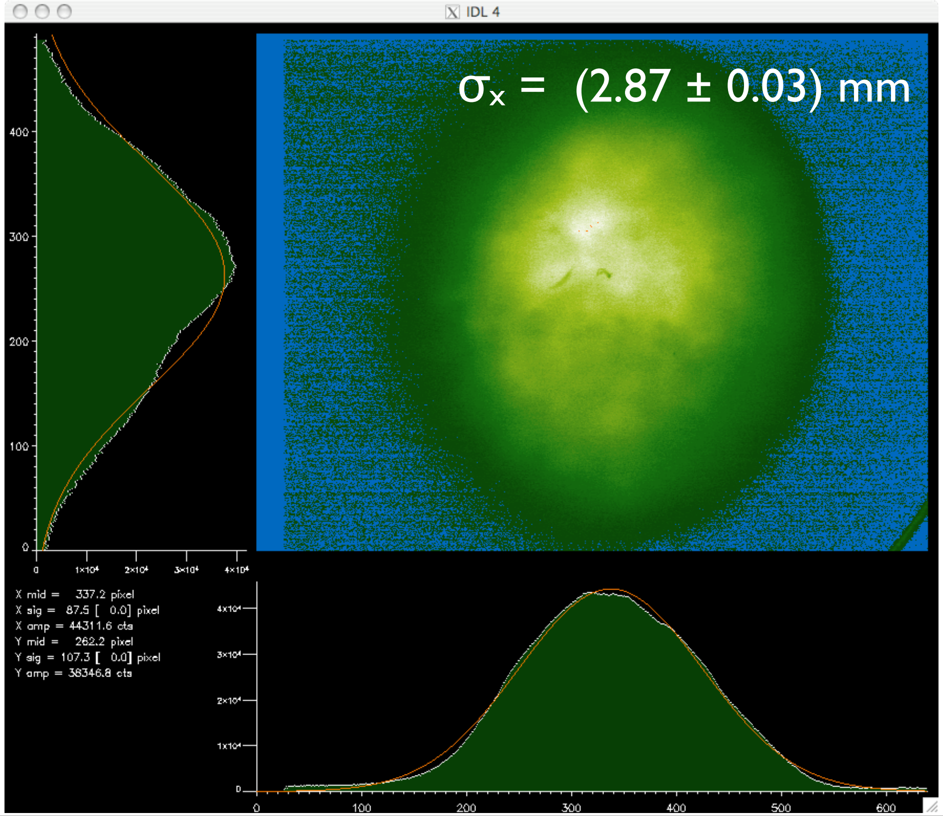
Transverse Beam Images and Profile Measurements



Focused beam

- At 40 kV and with low bunch current needed to average over several images to get sufficient SNR

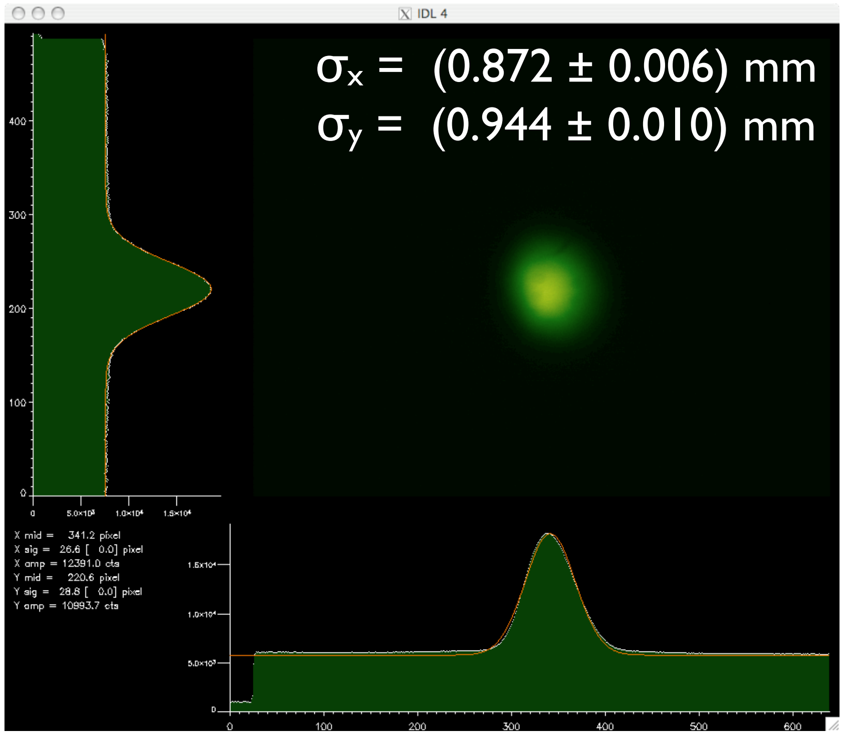
Defocused beam

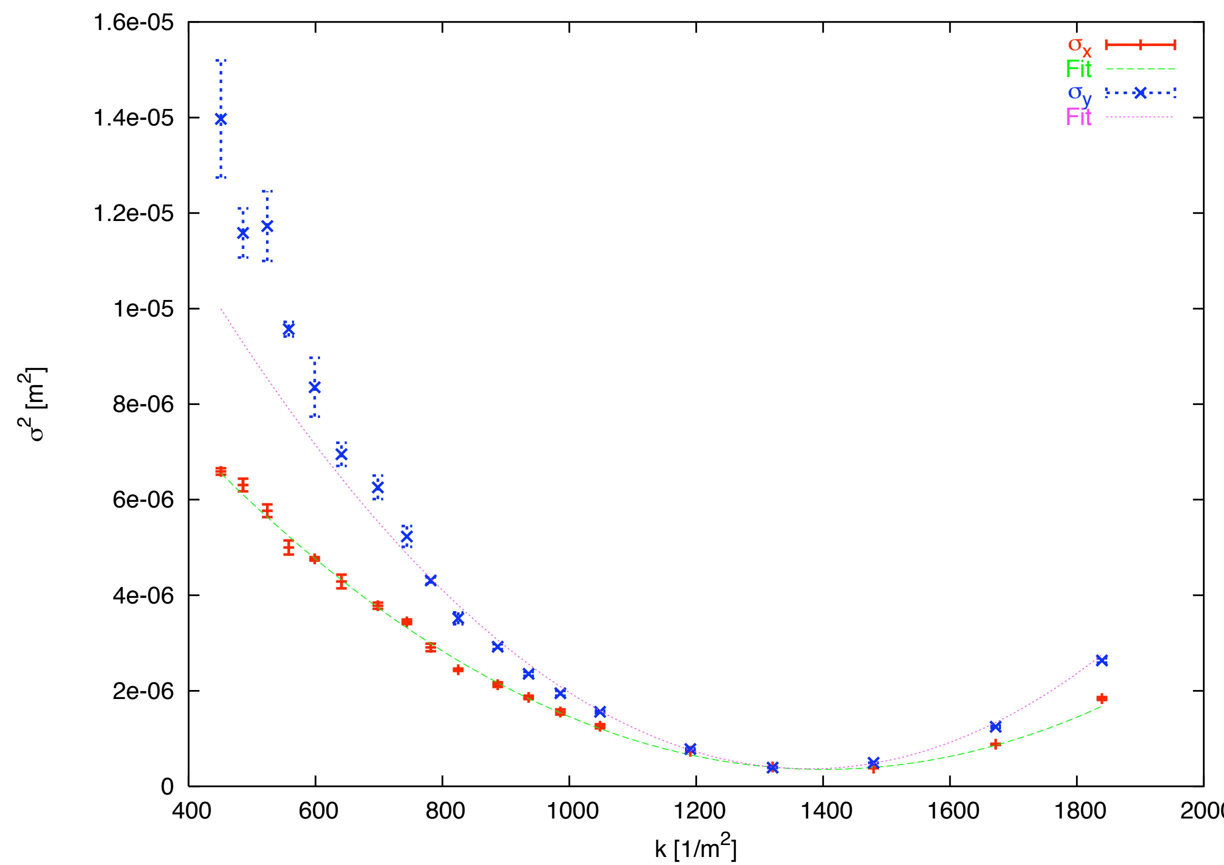


- Hot spots and non-uniformities discovered in the transverse beam image (HV breakdown causes damage to emitting surface, cathode contamination)

Solenoid Scan (Emittance Measurement)

- Measure downstream beam size (P43) as a function of solenoid current





Solenoid Scan (Emittance Measurement)

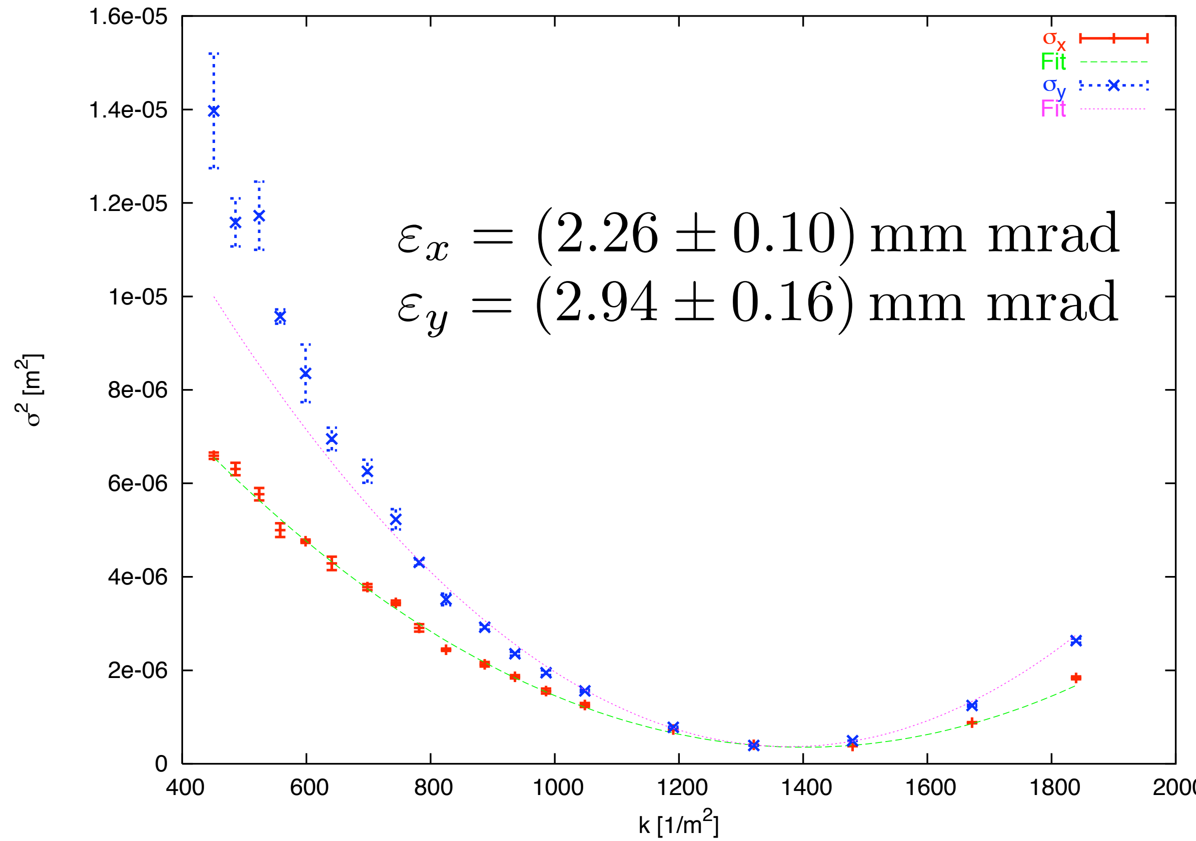
- Model solenoid lens and express beam size as a function of solenoid current

$$\mathcal{M} = \mathcal{M}_{\mathrm{d}}\,\mathcal{M}_{\mathrm{sol}} = \begin{pmatrix} \cos\phi - L\sqrt{k}\sin\phi & \frac{1}{\sqrt{k}}\sin\phi + L\cos\phi \\ -\sqrt{k}\sin\phi & \cos\phi \end{pmatrix} \quad \text{where} \quad \begin{array}{rcl} \phi & = & \sqrt{k}\cdot l \\ k & = & (\frac{B_{\mathrm{sol}}}{2p/e})^2 \end{array}$$

$$\sigma = \sqrt{\varepsilon\left(\beta_s^2\mathcal{M}_{11}^2 - 2\alpha_s\mathcal{M}_{11}\mathcal{M}_{12} + \frac{1+\alpha_s^2}{\beta_s}\mathcal{M}_{12}^2\right)}$$

- Fit for σ as a function of I_{sol} returns emittance and Courant-Snyder parameters at the location of the solenoid

- Codes *SOLSCAN* & *EML* developed to perform fitting and return results with errors



Alternative Emittance Measurement: Single Slit Method

- Measure beam size at location of the single slit insert (YAG)

$$\langle u^2 \rangle$$

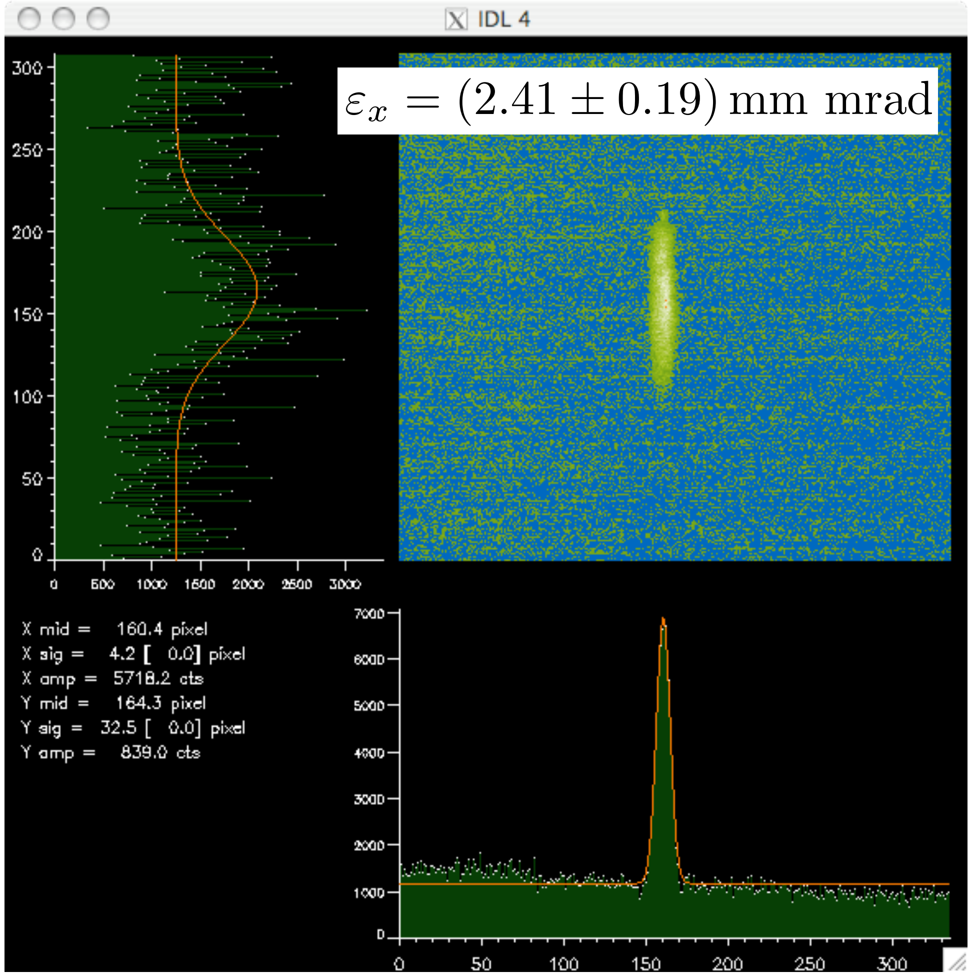
- Measure beamlet width σ_u downstream of a horizontal or vertical slit (P43)

$$\langle \tilde{u}'^2 \rangle = \frac{\sigma_u^2}{L^2}$$

- If linear correlation between divergence and location is removed, emittance becomes a simple product of beam size and uncorrelated divergence

$$u' \quad \longmapsto \quad \tilde{u}' = u' - m\,u$$

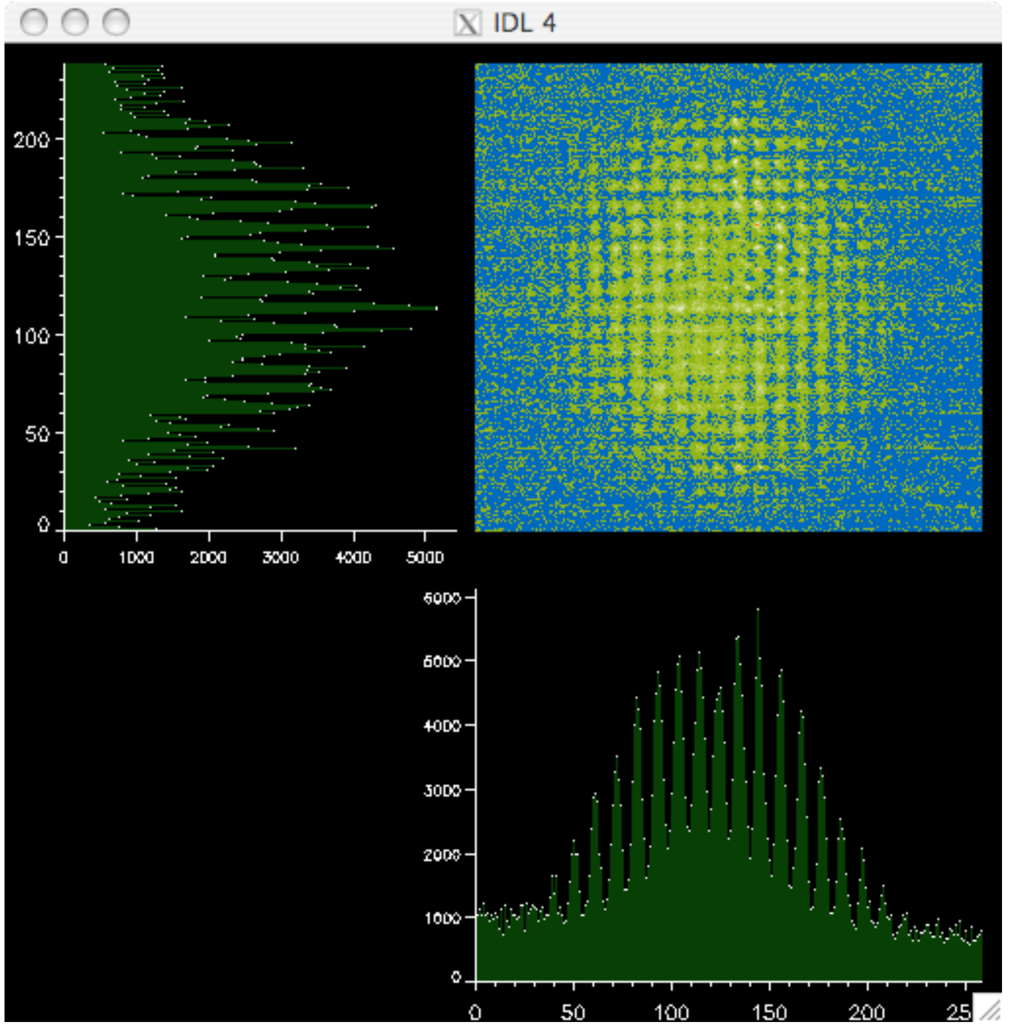
$$\varepsilon_u = \sqrt{\langle u^2 \rangle \langle u'^2 \rangle - \langle uu' \rangle^2} \quad \longmapsto \quad \sqrt{\langle u^2 \rangle \langle \tilde{u}'^2 \rangle}$$

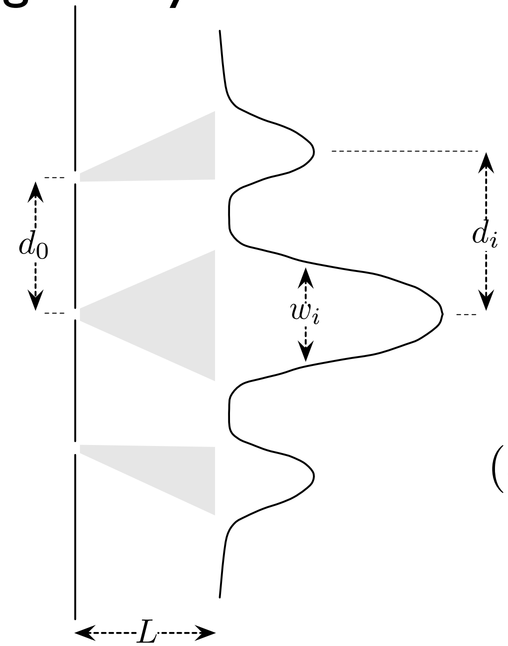


➡ Good agreement with solenoid scan results

Pinhole Array Measurements

- Measure beamlet images downstream of a pinhole array (P43)
- Calculate histogram of beamlet images and subtract background
- Divergence centroid for each bunch slice given by shift of beamlet image with respect to pinhole
- Divergence spread of each bunch slice given by width of beamlet image





$$(d_i - d_0)/L \longrightarrow x'_i$$

$$w_i/L \longrightarrow \sigma'_i$$

Pinhole Array Measurements

- Divergence centroid and spread for each slice gives phase space distribution

$$\bar{u}'_m = \frac{\langle u_m - m\,w \rangle}{L} \qquad m \in \mathbb{N}_0$$

$$\sigma'_m = \sqrt{\langle (u_m - m\,w)^2 \rangle / L^2 - (\bar{u}'_m)^2}$$

- Using weighted averages, calculate second order moments → ϵ, β, α

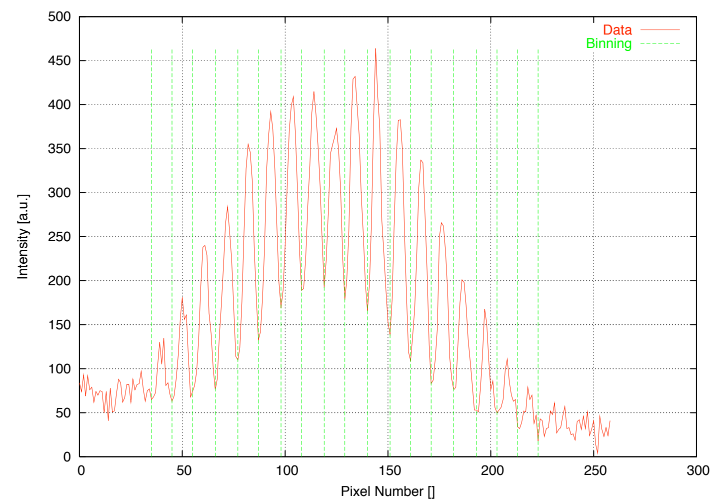
$$\langle u^2 \rangle = \frac{\sum_{m=1}^{N} I_m\, \bar{u}_m^2}{\sum_{m=1}^{N} I_m}$$

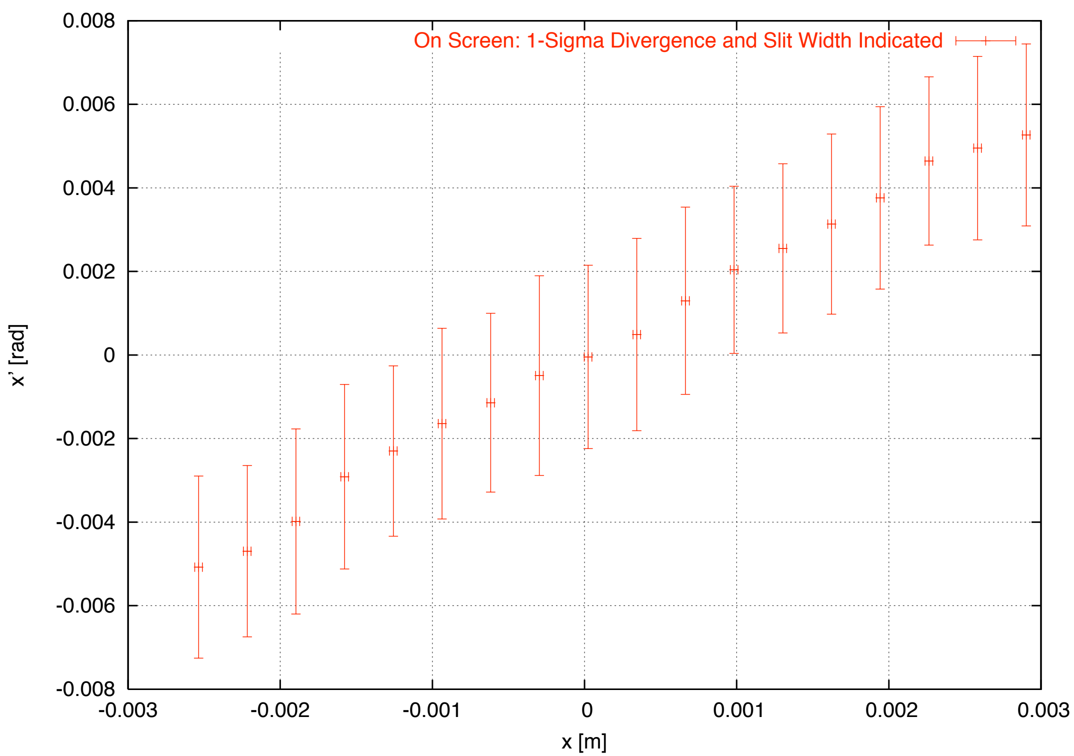
- Code *RECONSTRUCTION* developed to do entire post-processing and return results with errors

$$\varepsilon_x = (2.846 \pm 0.262)\ \mathrm{mm\ mrad}$$

$$\beta_x = (0.592 \pm 0.027)\ \mathrm{m}$$

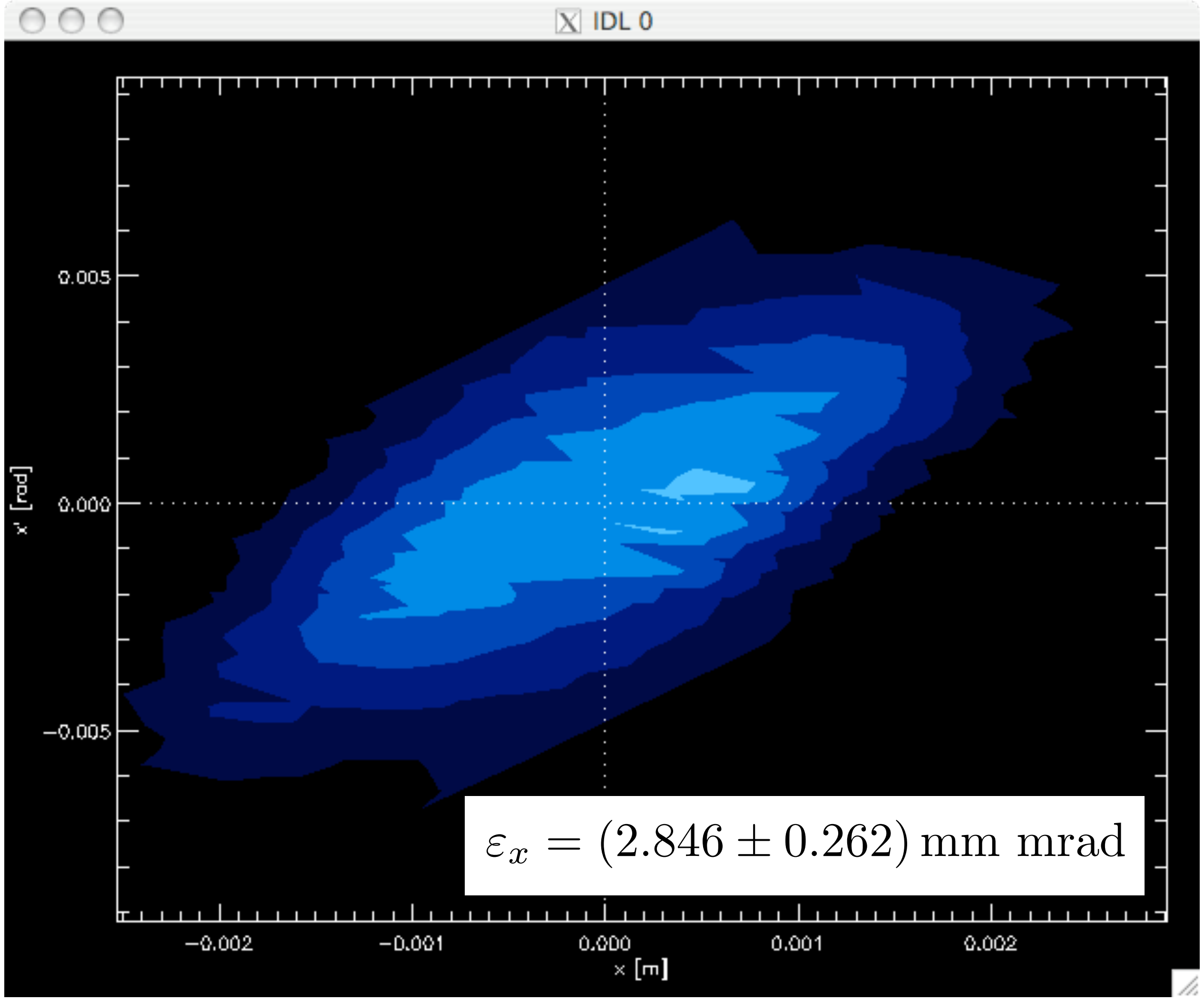
$$\alpha_x = (-1.17 \pm 0.061)$$





Transverse Phase Space Reconstruction

- Relative intensity of beamlet images → reconstruct phase space density
- Developed code *PHSPDENS* to map each pixel on CCD to an area in phase space and calculate distribution density



Contents

- Synchrotron Radiation
- X-Ray Free Electron Lasers
- Generating Low Emittance Beams
- 100 keV DC Gun Test Stand
- Experimental Results
- Conclusions & Outlook

Conclusions & Outlook

- Test stand has been successfully commissioned and is fully operational
- Different measurement techniques deliver compatible results
- FEA cathodes can be benchmarked in terms of performance and transverse beam properties
  - SRI FEAs do not deliver sufficient amounts of current
  - Experimental evidence for increased source divergence (and hence increased source emittance) due to lack of focusing layer

➡ PSI has started in-house development of new FEAs optimized for use in an electron gun

  - Focusing layer → reduce source emittance
  - Metallic substrate → reduce bulk resistance → increase emission

- Test stand will be used to benchmark PSI FEAs → optimize FEA design

Thank You

As always in an experimental effort, there are many contributors without whom the final results would have not been achievable. I offer my sincere gratitude to:

Rafael Abela, Andreas Adelmann, Åke Andersson, Ernst Baumann, Robin Betemps, Theo Bieri, Michael Böge, Sigi Bohr, Marlen Bugmann, Mirek Dach, Micha Dehler, Andreas Duffner, Reno Gaiffi, Romain Ganter, Dave George, Benjamin Gross, Peter Häberli, Max Heimgartner, Martin Heiniger, Colin Higgs, Matt Horvat, Peter Huber, Bruno Jakob, Babak Kalantari, Albert Kammerer, Eugenie Kirk, Christof Kraus, Juraj Krempasky, Markus Kropf, Andreas Jaggi, Andreas Lüdeke, Matthias Moser, Marco Negrazus, Hansjörg Oehler, Benedikt Oswald, Martin Paraliev, Marco Pedrozzi, Fréderic Le Pimpec, Thomas Schietinger, Volker Schlott, Lothar Schulz, Martin Steinacher, Andreas Streun, Detlef Vermeulen, Christian Vollenweider, Albin Wrulich, Elmar Zehnder, Charlie Zumbach.