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

Contents

Motivation Behind the PSI X-FEL

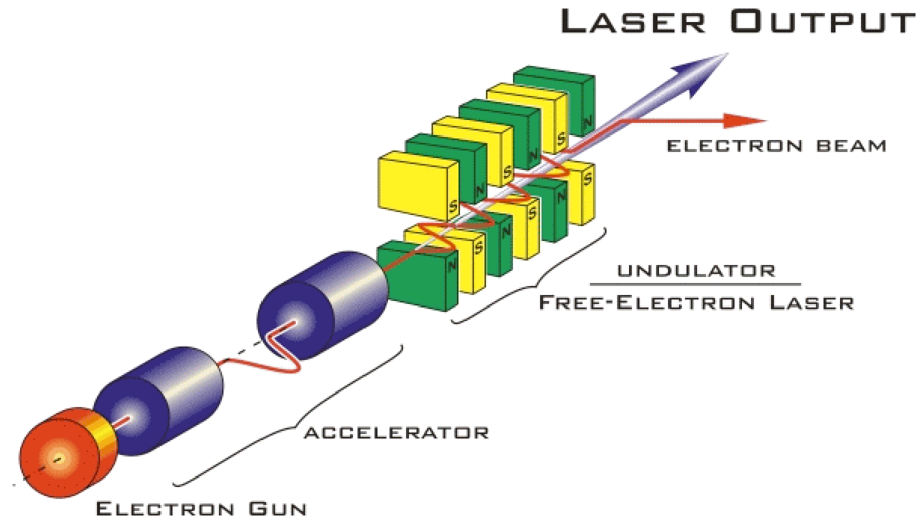
- PSI operates the Swiss Light Source SLS (3rd generation, storage ring based)
- Synchrotron radiation users have increasing demands
  - Even higher peak brightness (the figure of merit of light sources)
  - Hard X-ray radiation
  - Ultra-short pulses → time-resolved imaging of fast processes
  - Fully coherent radiation (spatial and longitudinal coherence)

➡ Need a new "4th generation light source" to fulfill these needs

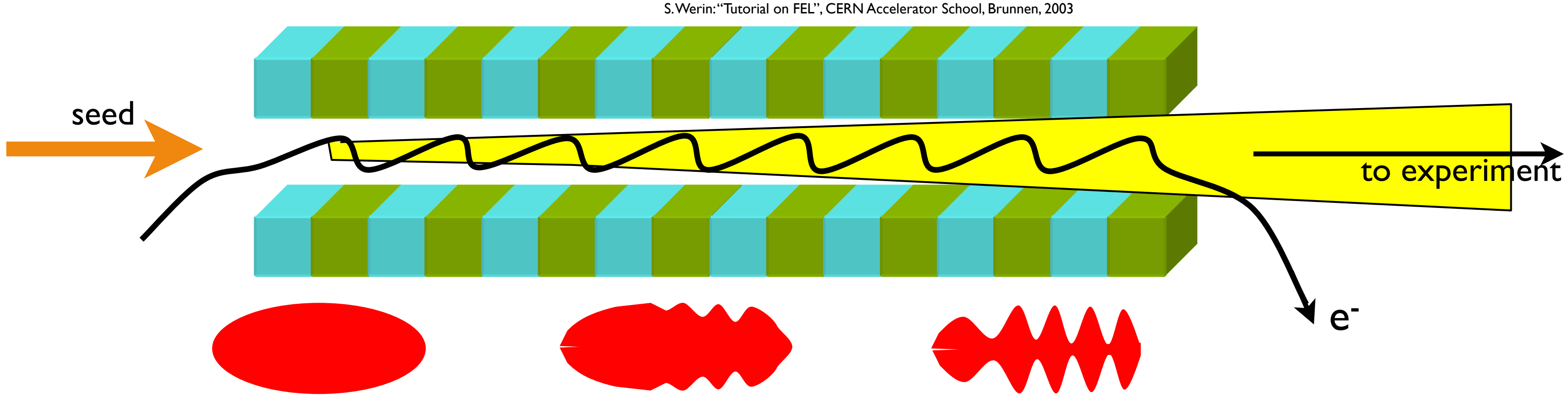
➡ Linac based X-FEL

Layout of the PSI X-FEL

- Single-pass X-FEL consisting of
  - Low emittance electron source
  - Linear accelerator system
  - Bunch compressor system
  - Undulator section
    (single-pass system: seeding)



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



Motivation Behind the LEG Project

- Other 1Å X-FEL projects: LCLS, European X-FEL
  - Electron energies up to 20 GeV
  - Several km long machines

➡ PSI strategy: downscale facility
  - Lower electron beam emittance → less energy required at undulator
  - Lower electron beam energy → linac length reduced
  - Decreased energy and length of machine → lower cost

➡ Low Emittance Gun (LEG) Project
  - Novel type of electron gun with unprecedented emittance ($\epsilon_{x,y}$ = 0.05 mm mrad)
  - High gradient acceleration
  - Conserve low emittance up to relativistic energies
  - Develop diagnostics capable of measuring ultra-low emittance

Brightness & Emittance

- Single-pass X-FEL requires:
  - High electron flux
  - High peak current
  - Small energy spread
  - Small angular spread

  } Brightness is figure of merit: $\mathcal{B} = \frac{Q}{\varepsilon_x \varepsilon_y \varepsilon_z}$

- RMS emittance: measure of the volume occupied by a bunch in phase space

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

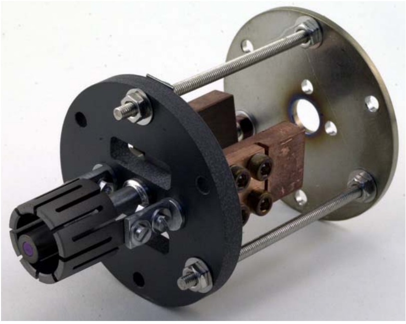
- Liouville's theorem: normalized emittance conserved
  - ➡ Low source emittance
  - ➡ High final electron beam energy

$$\frac{\varepsilon_{x,y}^{(n)}}{\beta\gamma} < \frac{\lambda}{4\pi} \qquad \lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

λ_u : Undulator Period

$K \propto B_u$: Undulator Parameter

Low Emittance Sources



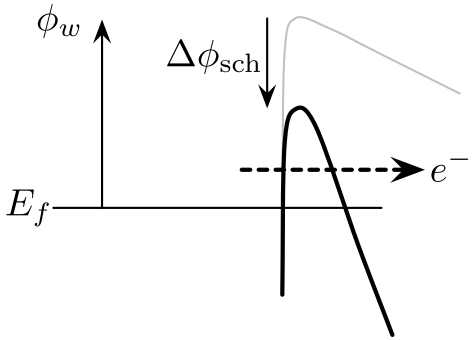
CeB$_6$ thermionic cathode (Shintake et al.)

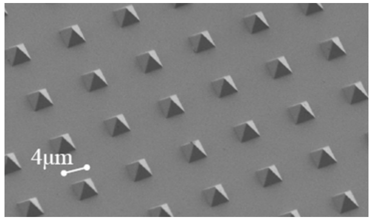
- Thermionic emission
  - Electrons emitted at T > 1000 K
  - Large initial E_{kin} → large initial $p_{x,y}$ → large source $\epsilon_{x,y}$
    - ➡ Prefer cold cathodes

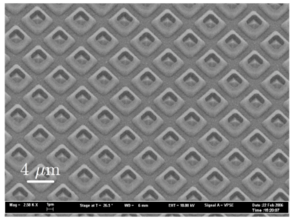
Cs$_2$Te photo-cathode @ PITZ

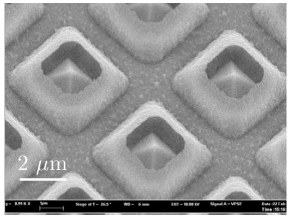
- Photo-electric emission
  - Time structure of electron bunch given by laser pulse
  - For good QE need short laser wavelength λ_γ
    - ➡ $E_\gamma = hc/\lambda_\gamma > \Phi_w$ → large initial energy spread

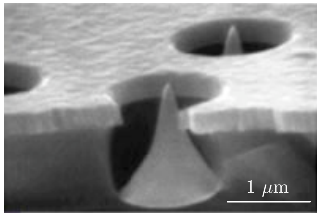
- Field emission
  - Tunneling → emitted electrons have very low E_{kin}
  - Tips in high electric fields → field enhancement
  - Field emitter array (FEA) → increases current
  - Gate layer → trigger pulsed emission
  - Focusing layer → low source $\sigma_{x',y'}$ → low source $\epsilon_{x,y}$

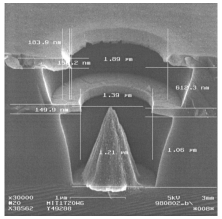






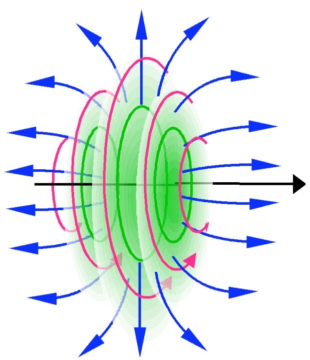


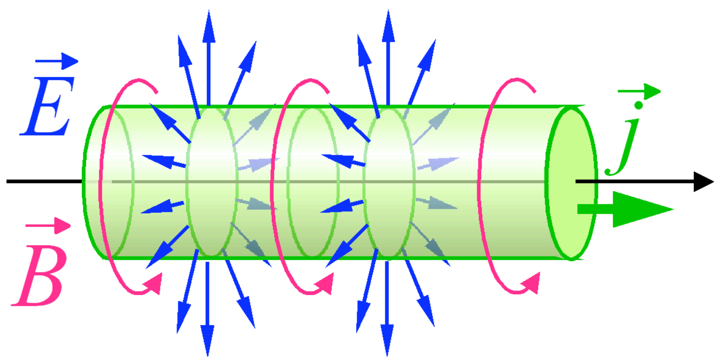


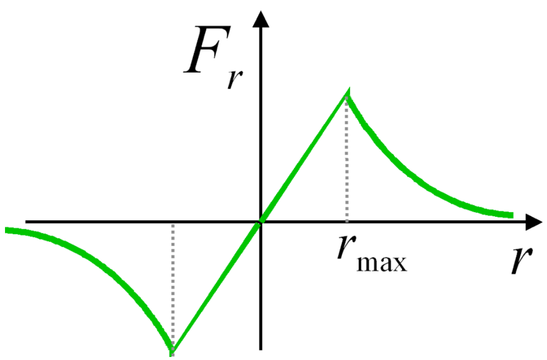


Space Charge Forces

- Space charge forces: direct collective effect where the charge of the entire bunch acts on a single bunch particle







- At high energies electric defocusing (bunch charge) is compensated by magnetic focusing (bunch current)

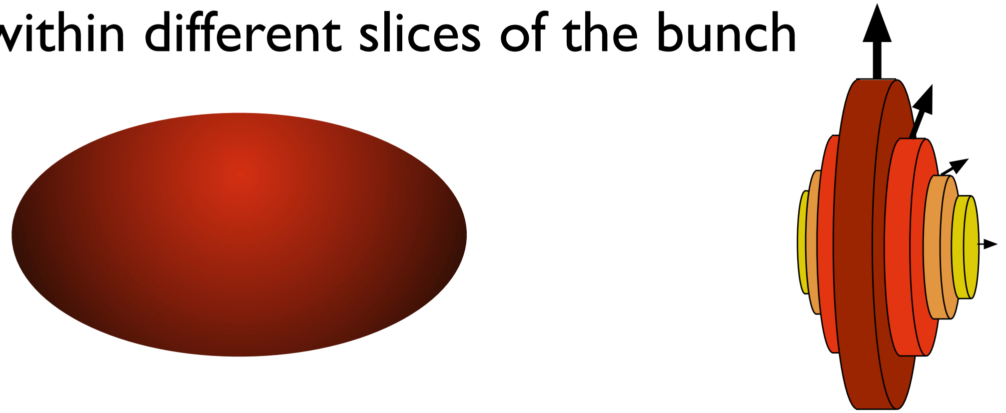
$$F_r = q\,(E_r - \beta c B_\theta) = q(1-\beta^2)E_r = \frac{qE_r}{\gamma^2}$$

- Space charge forces lead to distortions of the bunch's phase space distribution and to coupling between different conjugate coordinates → emittance growth

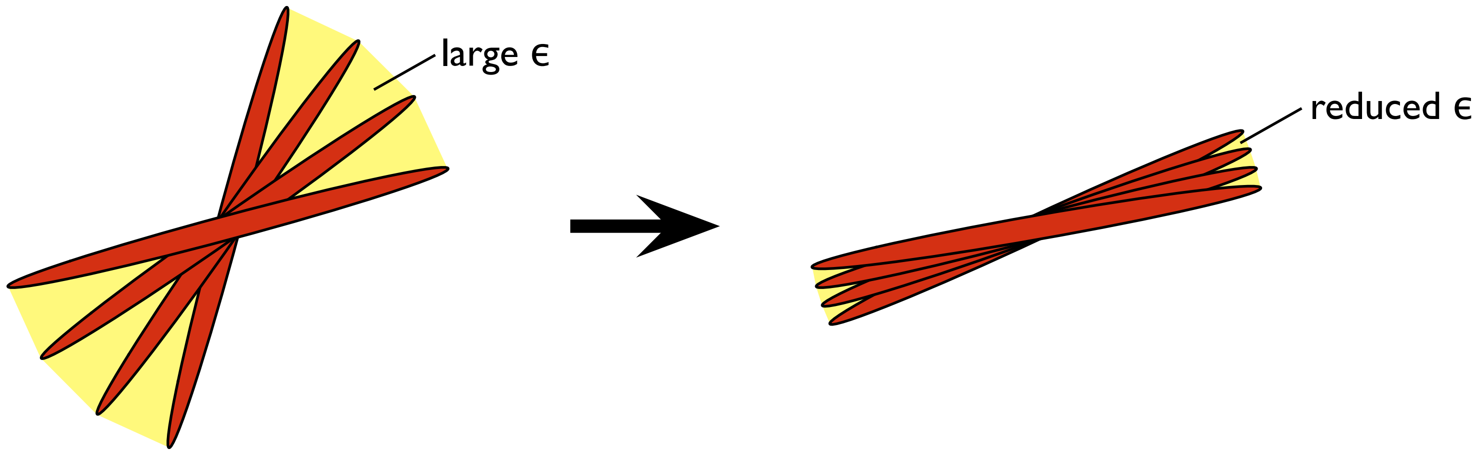
➡ High gradient acceleration → reduce space charge blow-up at low energies
➡ Compensate emittance growth due to space charge blow-up

Emittance Compensation

- Bunch has longitudinal charge modulation → defocusing space charge forces are different within different slices of the bunch



- Carlsten: Use focusing lens (solenoid) and subsequent drift section
- In each slice: superposition of varying defocusing force (space charge) and constant focusing force (lens)
  - ➡ Slices rotate in phase space with different frequencies
  - ➡ At one point along drift slices overlap → emittance minimized

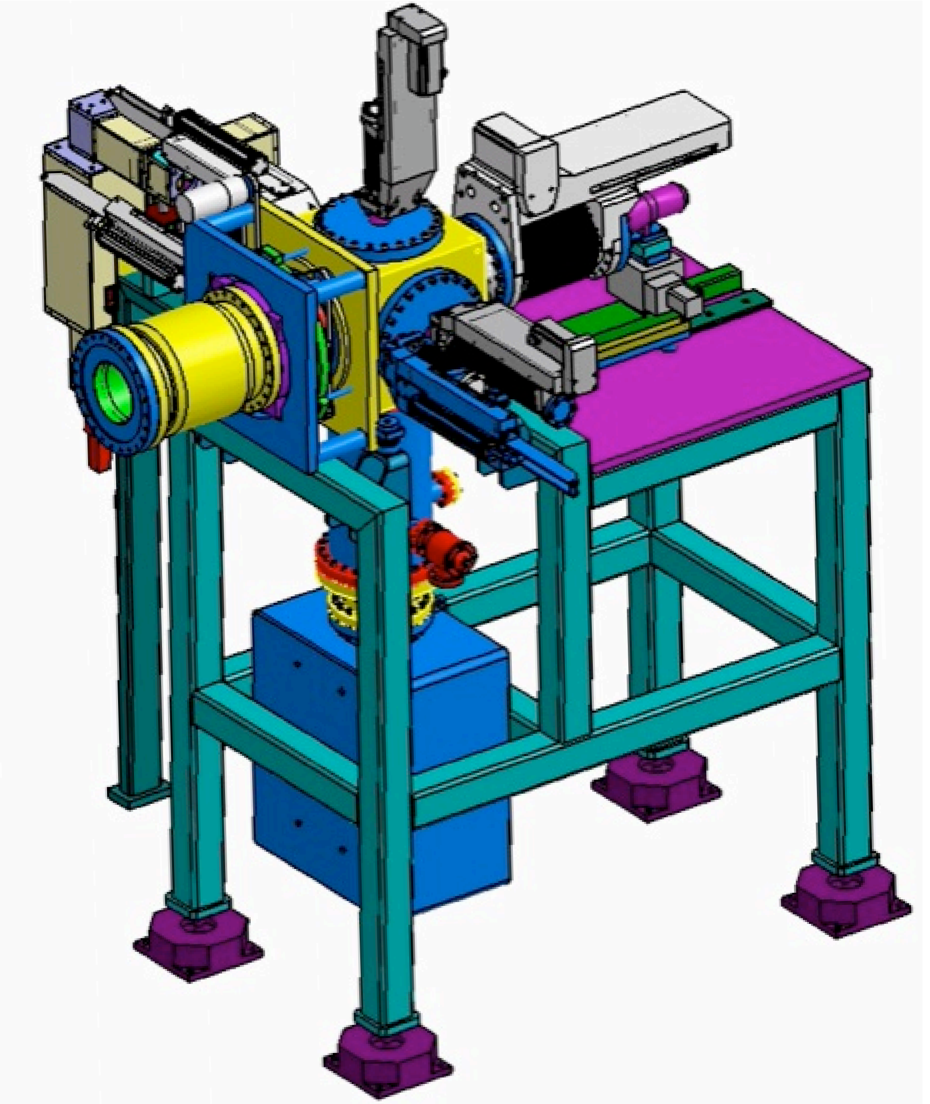


Motivation Behind the 100 keV Gun Test Stand

- Investigate bunches emitted from pulsed FEAs
- Demonstrate emittance compensation
- Develop diagnostic procedures to measure ultra-low emittance and reconstruct full transverse phase space

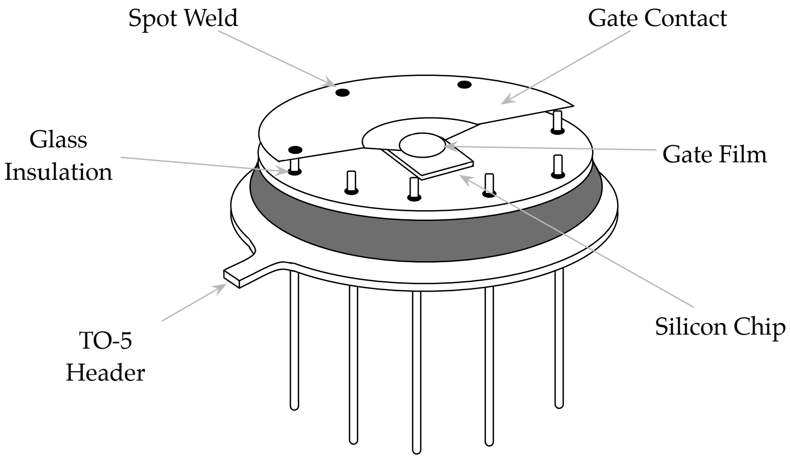
➡ 100 keV Gun Test Stand designed, assembled and commissioned:

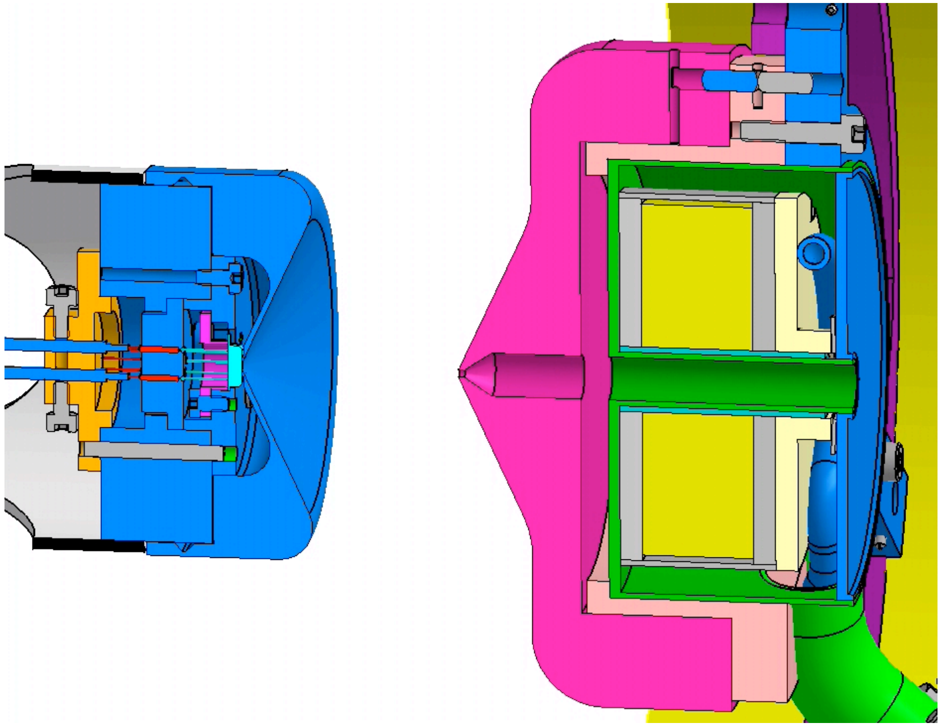
- DC HV diode, FEA pulser on HV potential
- Pulsed emission of space charge dominated bunches from FEAs
- In-vacuum solenoid magnet:
    - Focusing
    - Emittance compensation
- Diagnostic module:
    - Measure charge-time structure of bunches
    - Measure emittance & Courant-Snyder parameters (several methods → compare results)
    - Reconstruct full transverse phase space distribution



Gun & Solenoid

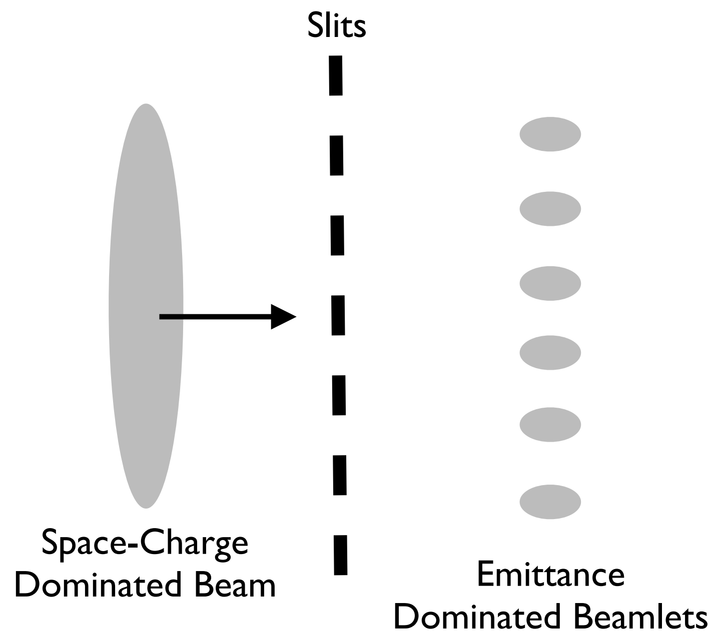
- FEA (r = 0.5 mm) on TO-5 mount installed in transistor holder, coaxial connection to cathode-side SMA feedthrough
- 100 kV, 11 mm gap, $\hat{I}$ = 100 mA, τ = 5 ns
- Extensive parameter studies:
  - ES/MS solver: MAFIA 2.5D
    - ➡ cathode and anode electrode size/shape optimized for lowest emittance at gun exit
    - ➡ solenoid specifications optimized for emittance compensation (I_{max} = 3 A, B_z = 200 mT on axis)
  - Particle tracking: GPT 3D
    - ➡ alignment tolerances

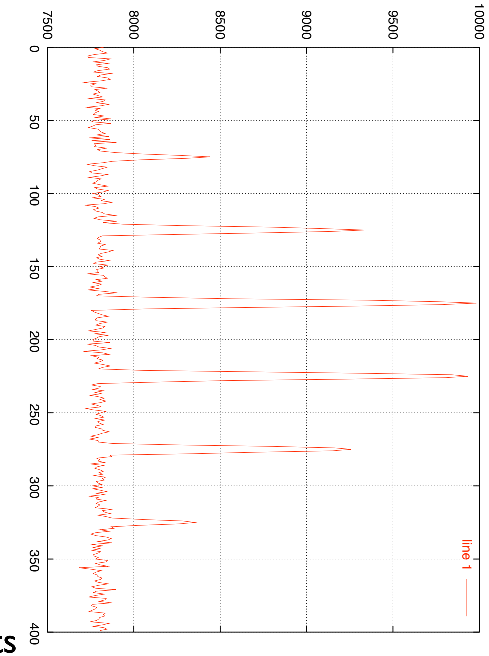




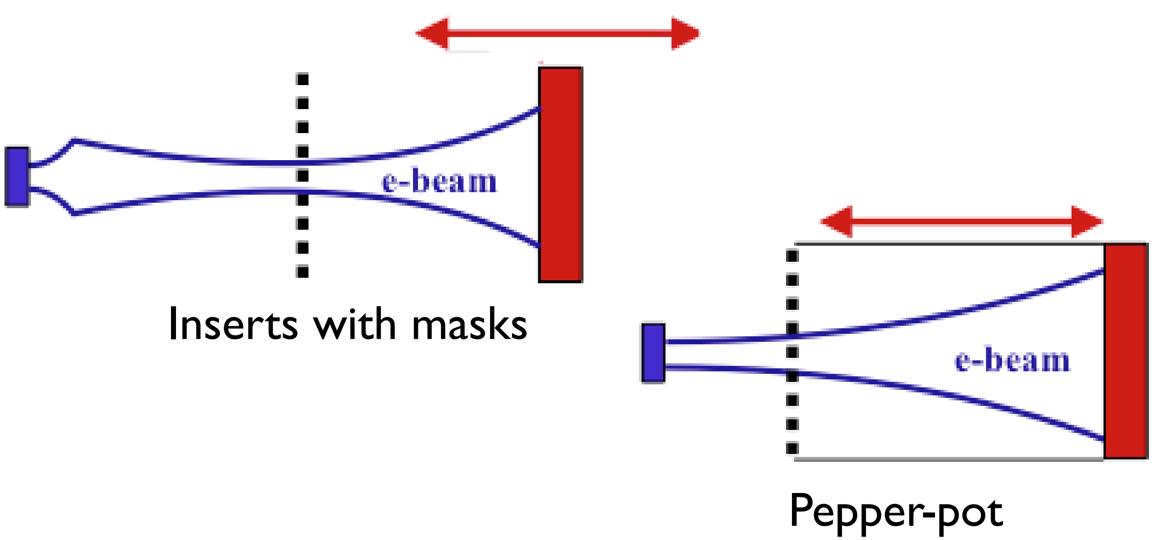
Diagnostics: Slit & Pinhole Inserts

- Emittance measurement: requires single slit beamlet image and beam size at slit location
- Courant-Snyder parameter measurement: requires image of beamlets from slit array (two shots) or pinhole array (single shot)
- Phase space distribution: use relative beamlet intensity information to reconstruct phase space density
- Longitudinal beam sampling: Pepper-pot (pinhole array attached to movable screen monitor)



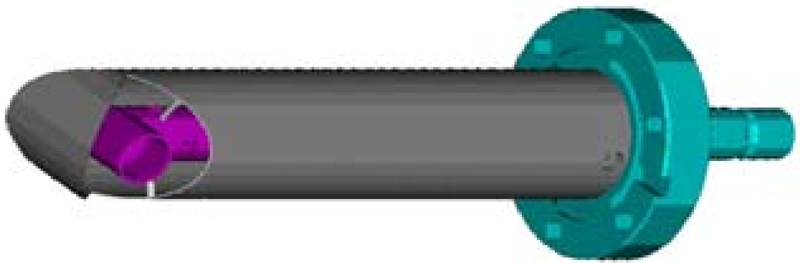


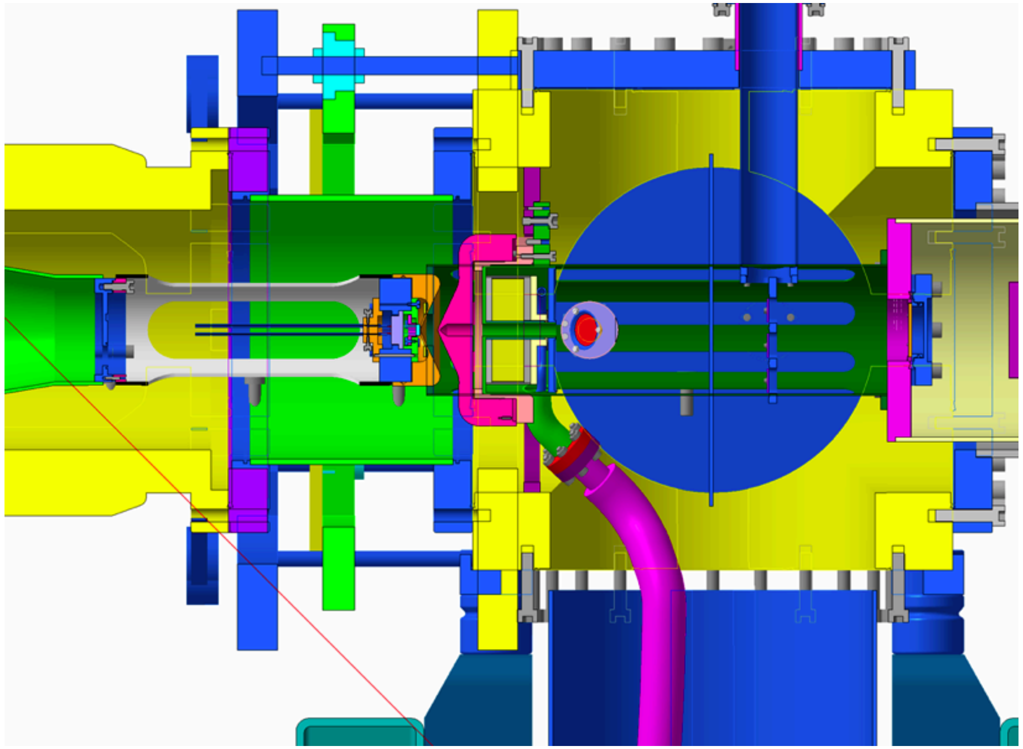
Beamlet Intensity Profile on Screen



Diagnostics: Faraday Cup & Screen Monitors

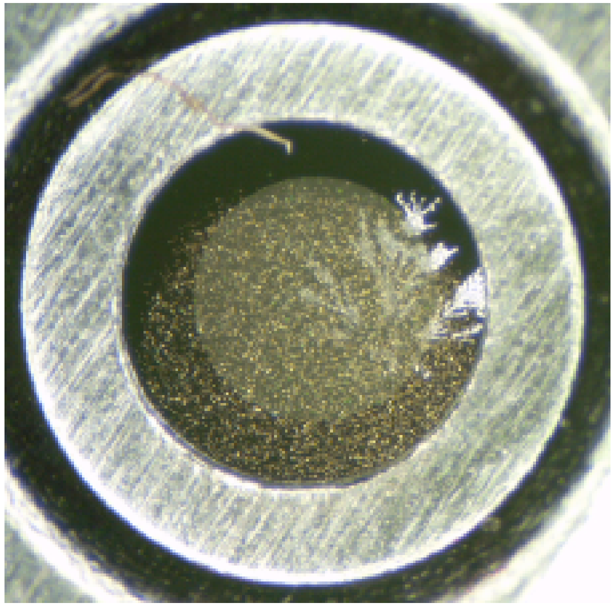
- Vertical and horizontal inserts for obstructive measurements:
  - Each insert carries three tungsten masks (100 μm): single slit, slit array and pinhole array
- Screen monitors systems (with CCD cameras & zoom optics):
  - YAG: insert at fixed longitudinal position → beam size/profile measurement
  - P43 phosphor: ultimate beam stop, can be moved to desired longitudinal position → beam size/profile measurement, image beamlets
- Coaxial Faraday cup & fast oscillo-cope (2 GHz, 20 GS/s)
  ➡ Measure charge-time structure of 5-100 ns bunches

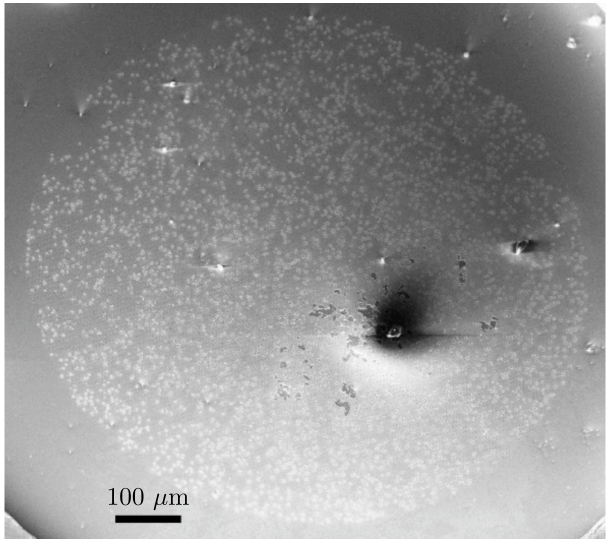




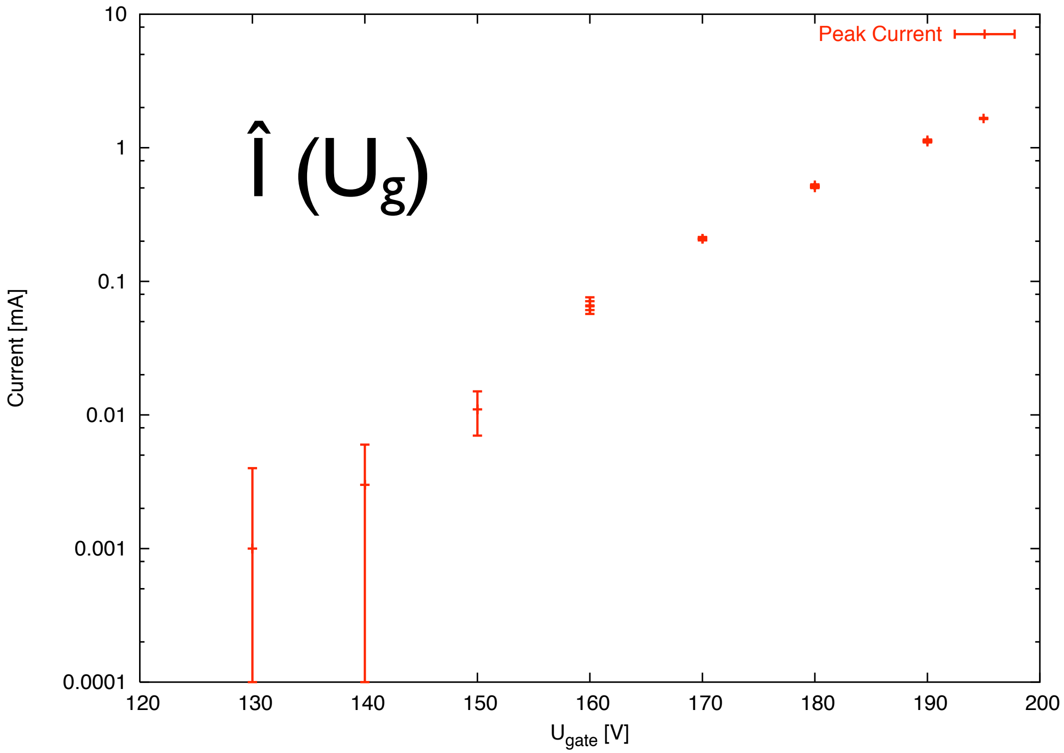
Performance: Operation Boundaries

- Gun sustains stable DC HV of 100 kV
- Slight misalignment of cathode with respect to anode increases surface peak electric field (> 20 MV/m on anode iris) → reduce DC HV
- 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)





Performance: Peak Current & Bunch Charge

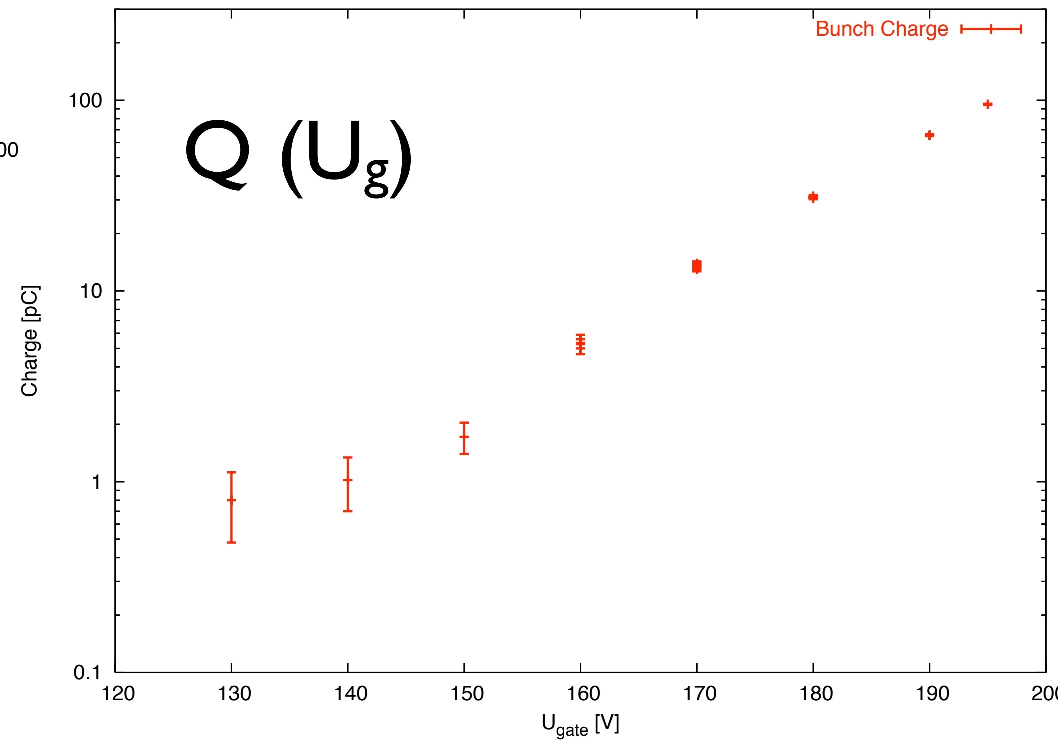


- Exponential increase of field emitted current with gate voltage as predicted by Fowler-Nordheim law

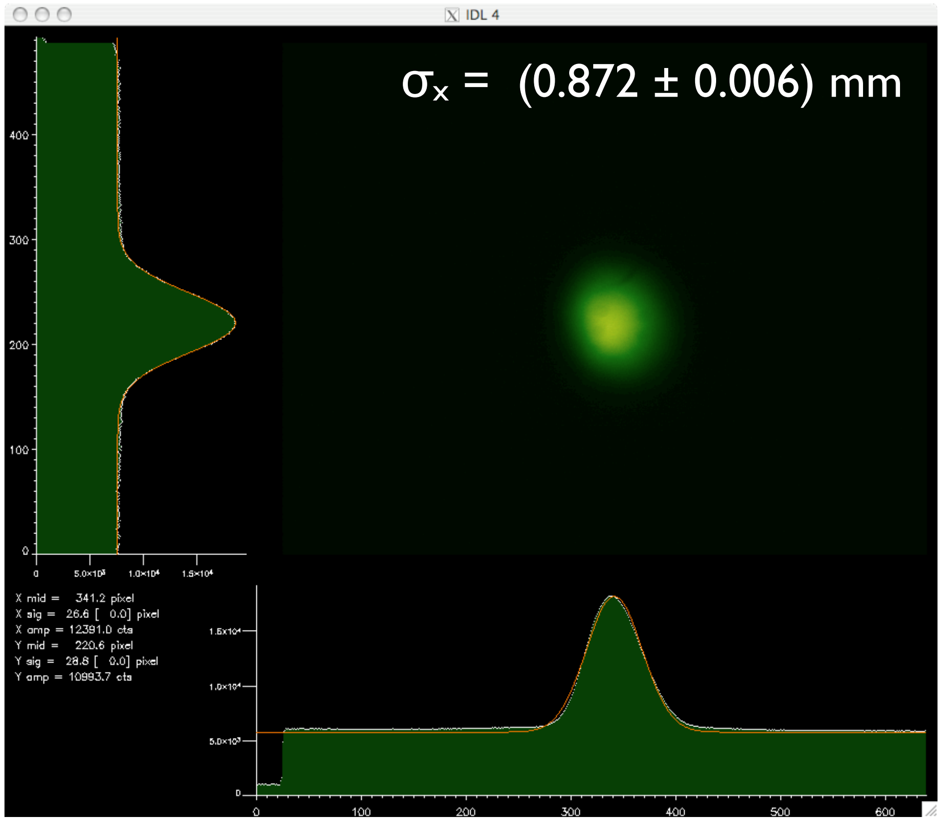
➡ Emission current very sensitive to gate voltage

- Maximum performance given by stable emission of FEA and not by space charge limit of cathode
- Î = 2 mA, Q = 100 pC (in 100 ns)

➡ Emittance dominated beam



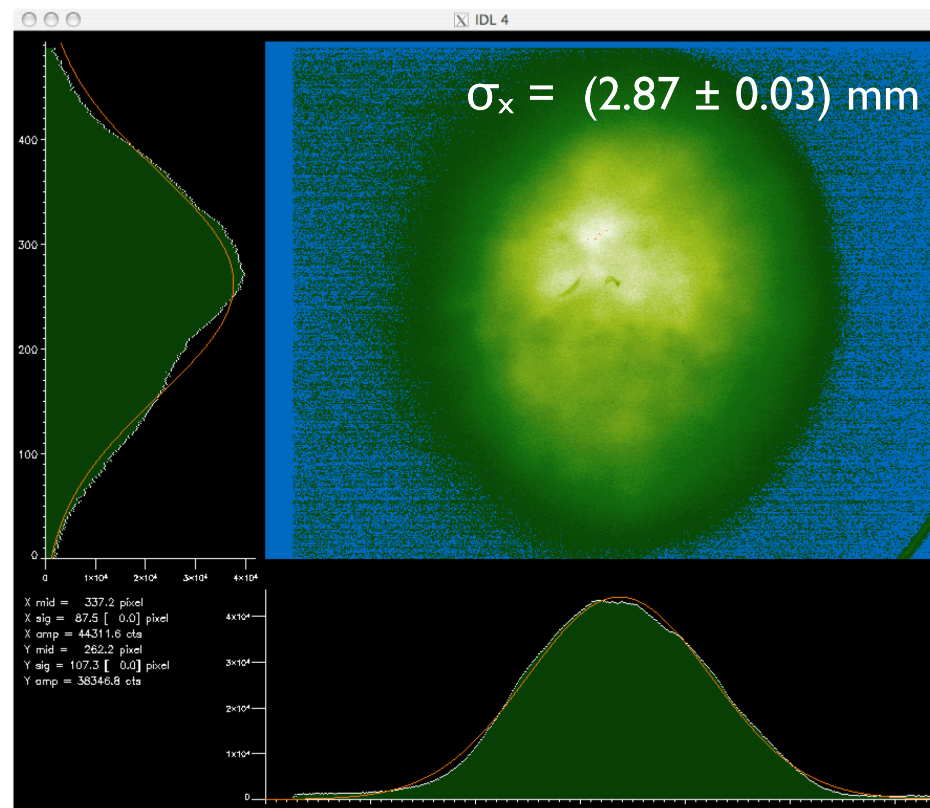
Beam Profile Measurements



Focused beam

- At 40 kV and with low bunch current needed to average over several images to get sufficient SNR
- Hot spots and non-uniformities discovered in the transverse beam image

Defocused beam



- Beam size independent of bunch charge (emittance dominated beam)
  ➡ Emittance compensation cannot be investigated with this FEA type
- Beam size evolution in agreement with theoretical model

Emittance Measurements: Solenoid Scan

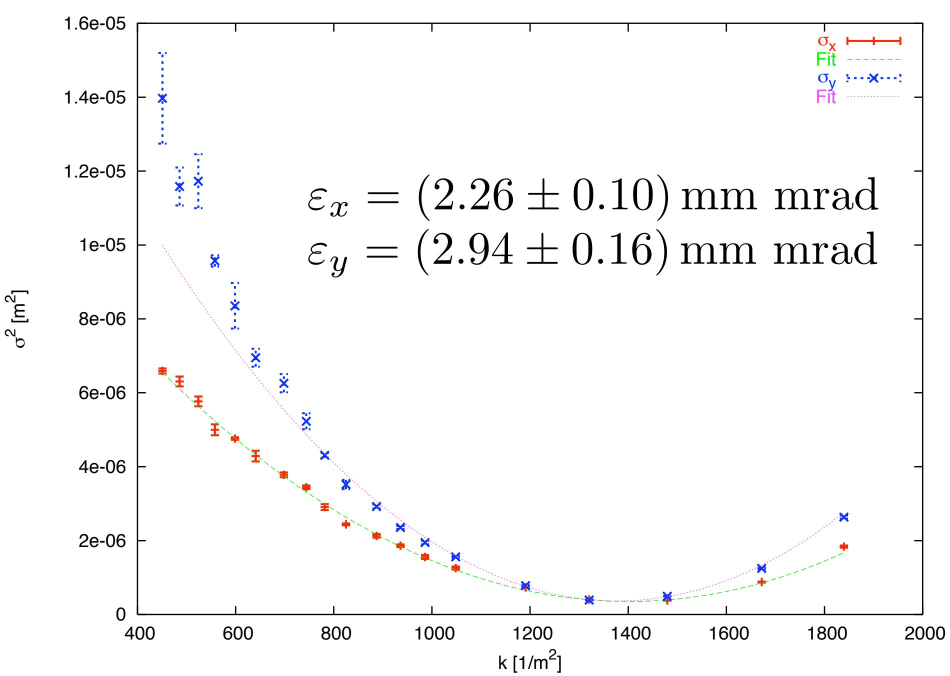
- Measure downstream beam size (P43) as a function of solenoid current
- Model solenoid as thin/thick lens with hard/smooth (as calibrated) edges

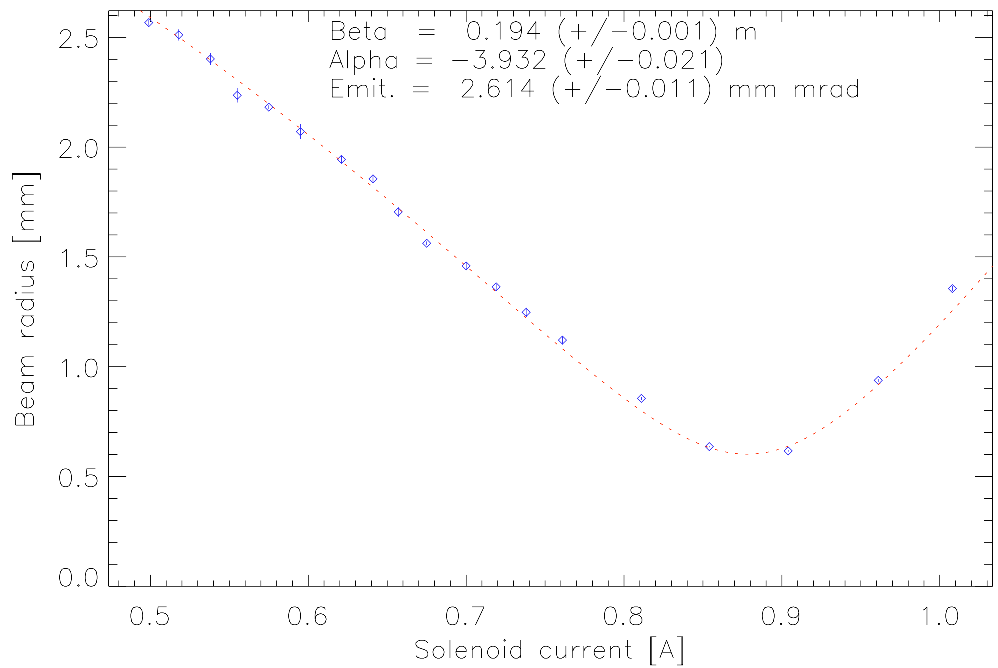
$$\mathcal{M} = \mathcal{M}_{\rm d}\,\mathcal{M}_{\rm sol} = \begin{pmatrix} \cos\phi - L\sqrt{k}\sin\phi & \frac{1}{\sqrt{k}}\sin\phi + L\cos\phi \\ -\sqrt{k}\sin\phi & \cos\phi \end{pmatrix} \quad \text{where} \quad \begin{array}{rcl} \phi & = & \sqrt{k}\cdot l \\ k & = & (\frac{B_{\rm sol}}{2p/e})^2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

- Fit for σ as a function of I_{sol} returns ε, β, α at the location of the solenoid

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

- Wrote codes *SOLSCAN* & *EML* to perform fitting and return results with errors





Emittance Measurements: Single Slit Measurement

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

$$\langle u^2 \rangle$$

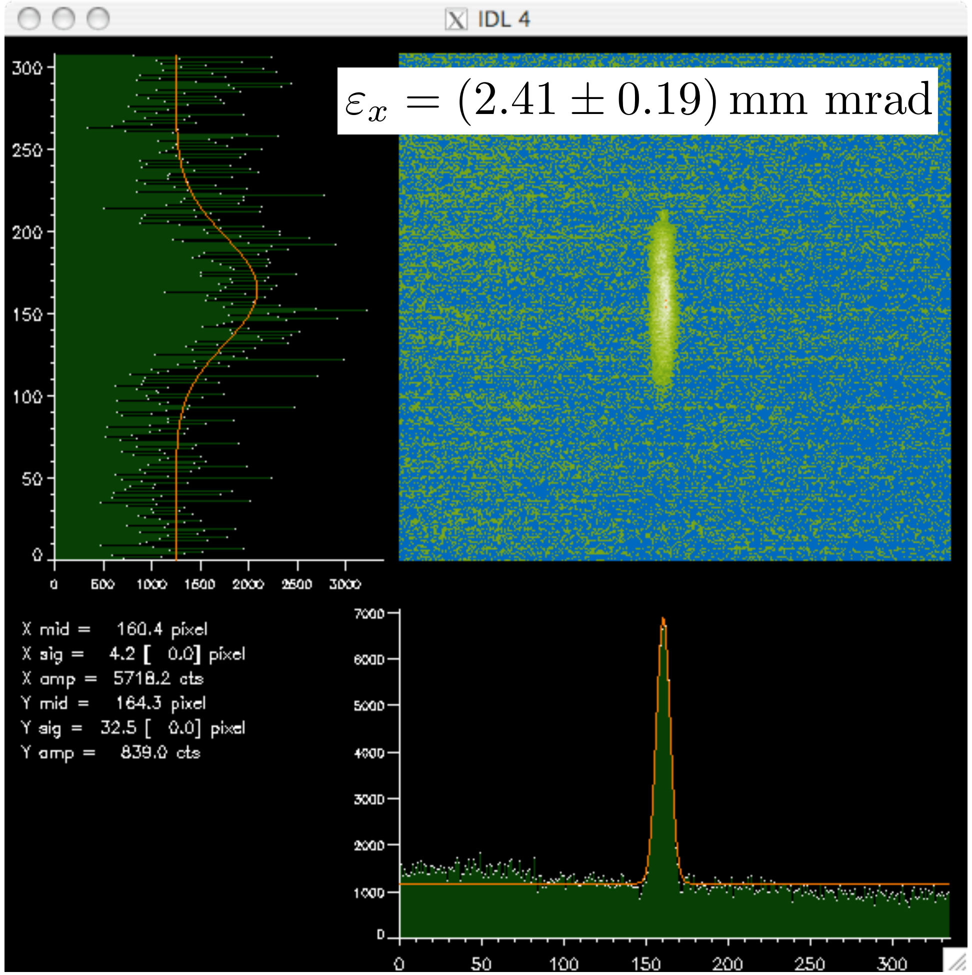
- Measure beamlet width σ_u downstream of a horizontal or vertical slit (P43)

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

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

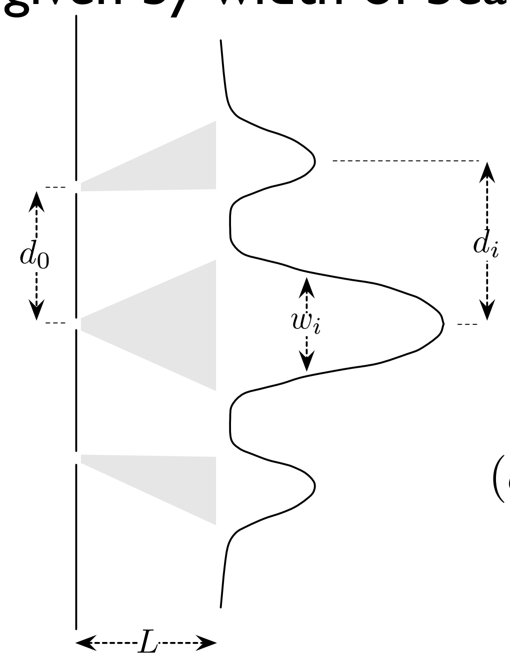
$$u' \quad \longmapsto \quad \tilde{u}' = u' - m\,u$$

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

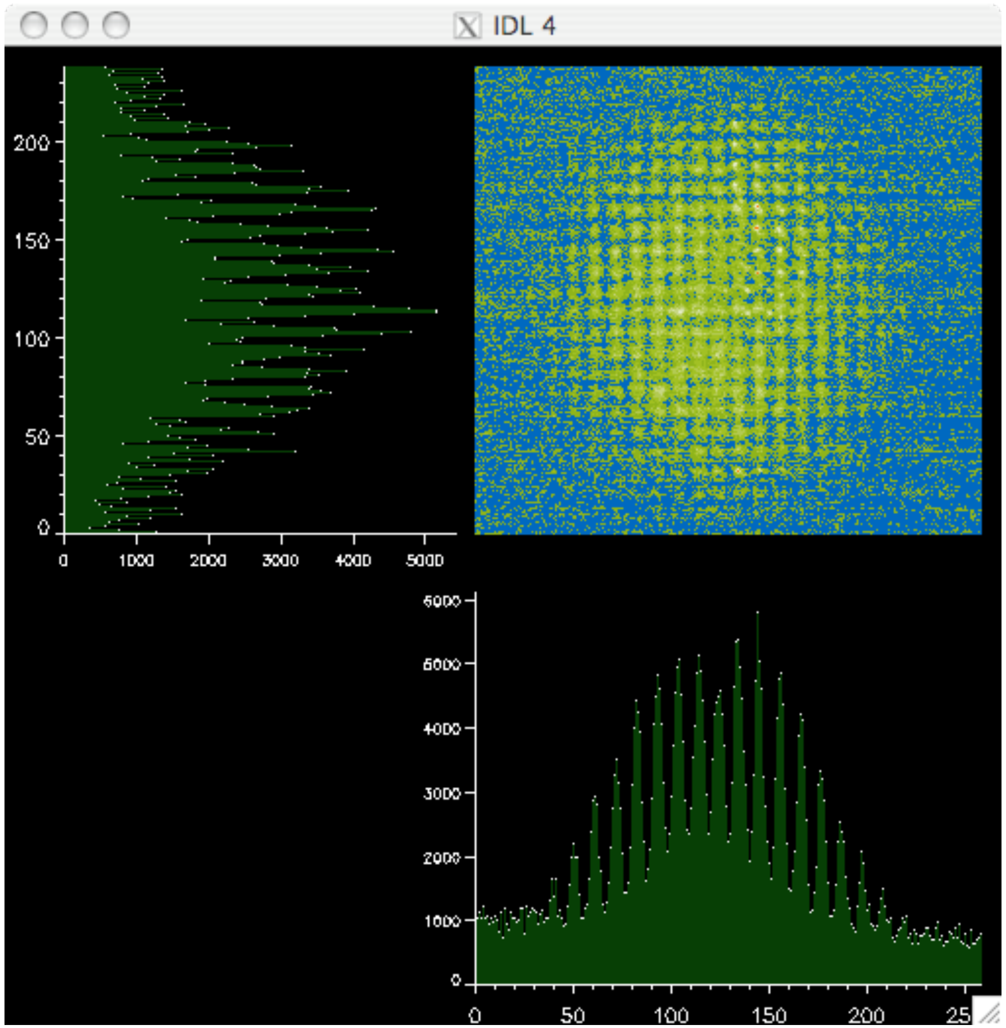


Emittance Measurements: Pinhole Array Measurement (1)

- 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



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



Emittance Measurements: Pinhole Array Measurement (2)

- 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

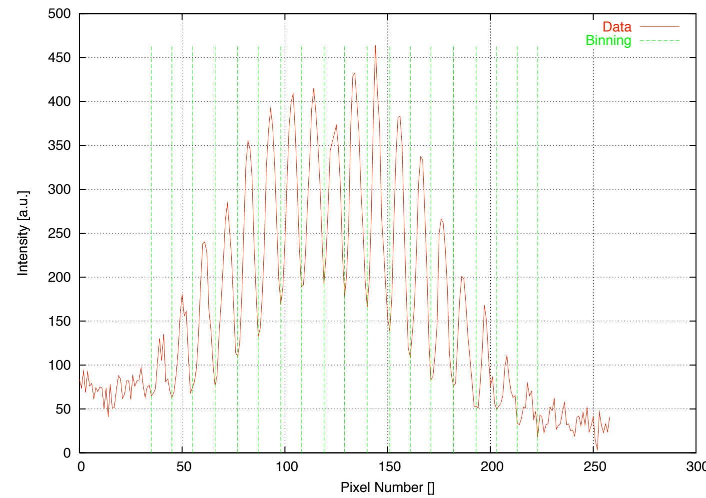
$$\langle u^2 \rangle = \frac{\sum_{m=1}^{N} I_m\,\bar{u}_m^2}{\sum_{m=1}^{N} I_m}$$

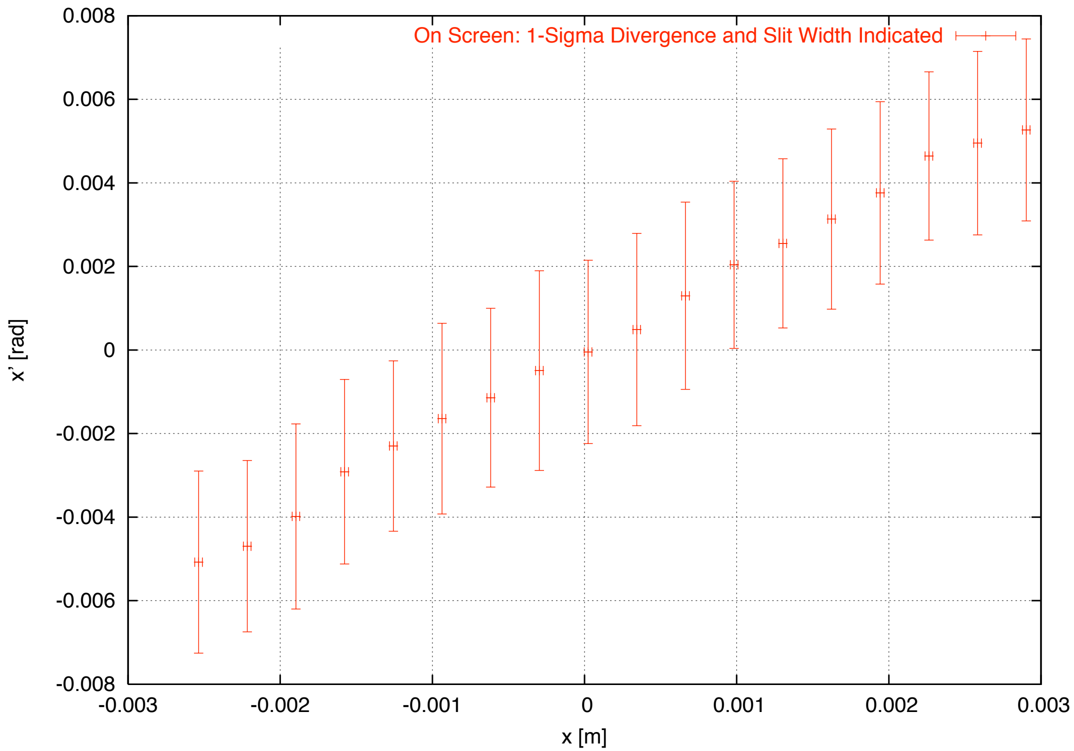
- Wrote code *RECONSTRUCTION* to do entire post-processing and return results with errors

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

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

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

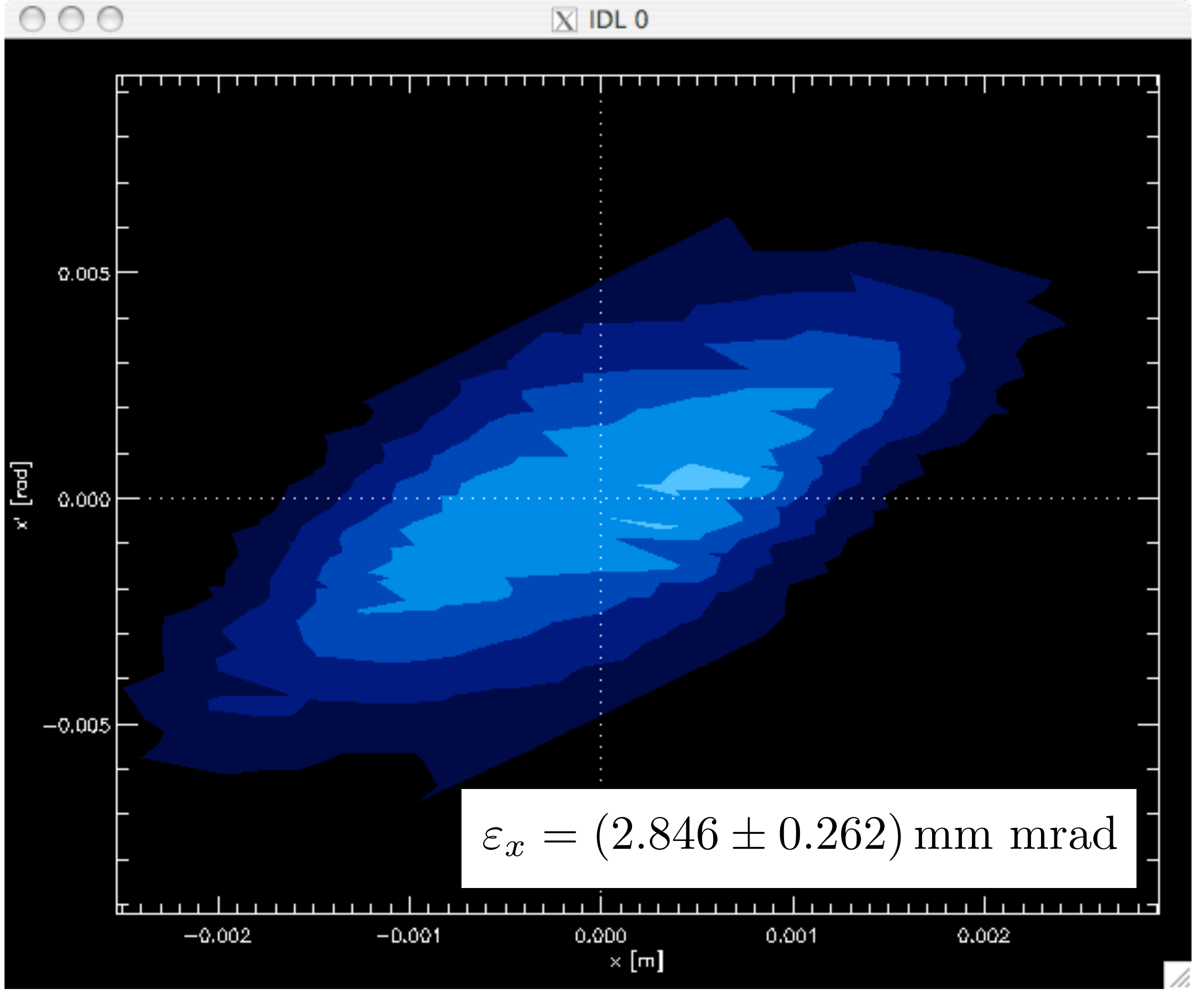




Emittance Measurements: Pinhole Array Measurement (3)

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

➡ Emittance results show large source divergence due to lack of focusing layer



Conclusions & Outlook

- Full transverse phase space reconstruction of emitted bunches possible
- Different measurement techniques in agreement
- Test stand is fully operational and ready to measure new cathode types

- LEG Project needs new FEAs with
  - More current → reach 5.5 A goal
  - Focusing layer → lower source divergence → lower emittance
  - ➡ PSI has started in-house development of new FEA cathodes

- Future tasks
  - Benchmark new PSI cathodes
  - Install and commission 3D mover motor system → correct misalignment
  - Use pepper-pot (for space-charge dominated beams) → long. sampling
  - Gun modification for laser-assisted FE from single tip field emitter