PAUL SCHERRER INSTITUT

The PSI X-FEL Project
&
the 100 keV Gun Test Stand

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S. C. Leemann, A. Streun, A. F. Wrulich:
Beam characterization for the field-emitter-array cathode-based low-emittance gun,
Phys. Rev. ST Accel. Beams **10** 071302 (2007)

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- An X-FEL for PSI
- The Low Emittance Gun
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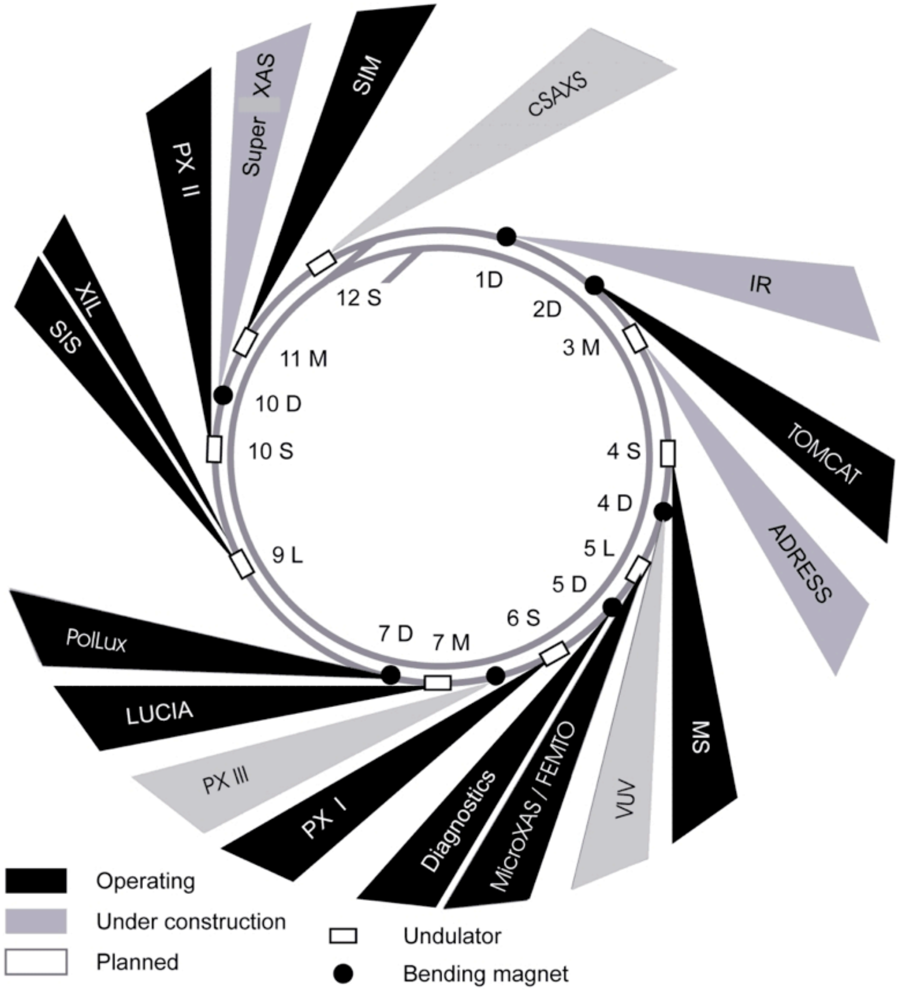
- Experimental Results
- Conclusions & Outlook

The Status Quo at PSI

The X-Ray Free Electron Laser

A Compact X-FEL

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

Synchrotron Radiation Users Have Increasing Demands

- Higher (peak) brightness → single shot imaging
- Intense hard X-ray radiation ($\lambda \sim 1$Å) → imaging of molecular structures
- Ultra-short pulses ($\tau \sim 50$ fs) → time resolved imaging of fast processes
- Longitudinal and spatial coherence ("laser-like radiation from a point source")

However...

- Ultra-short pulses cannot be delivered by storage ring light sources
- Storage ring based light sources do not emit fully coherent radiation

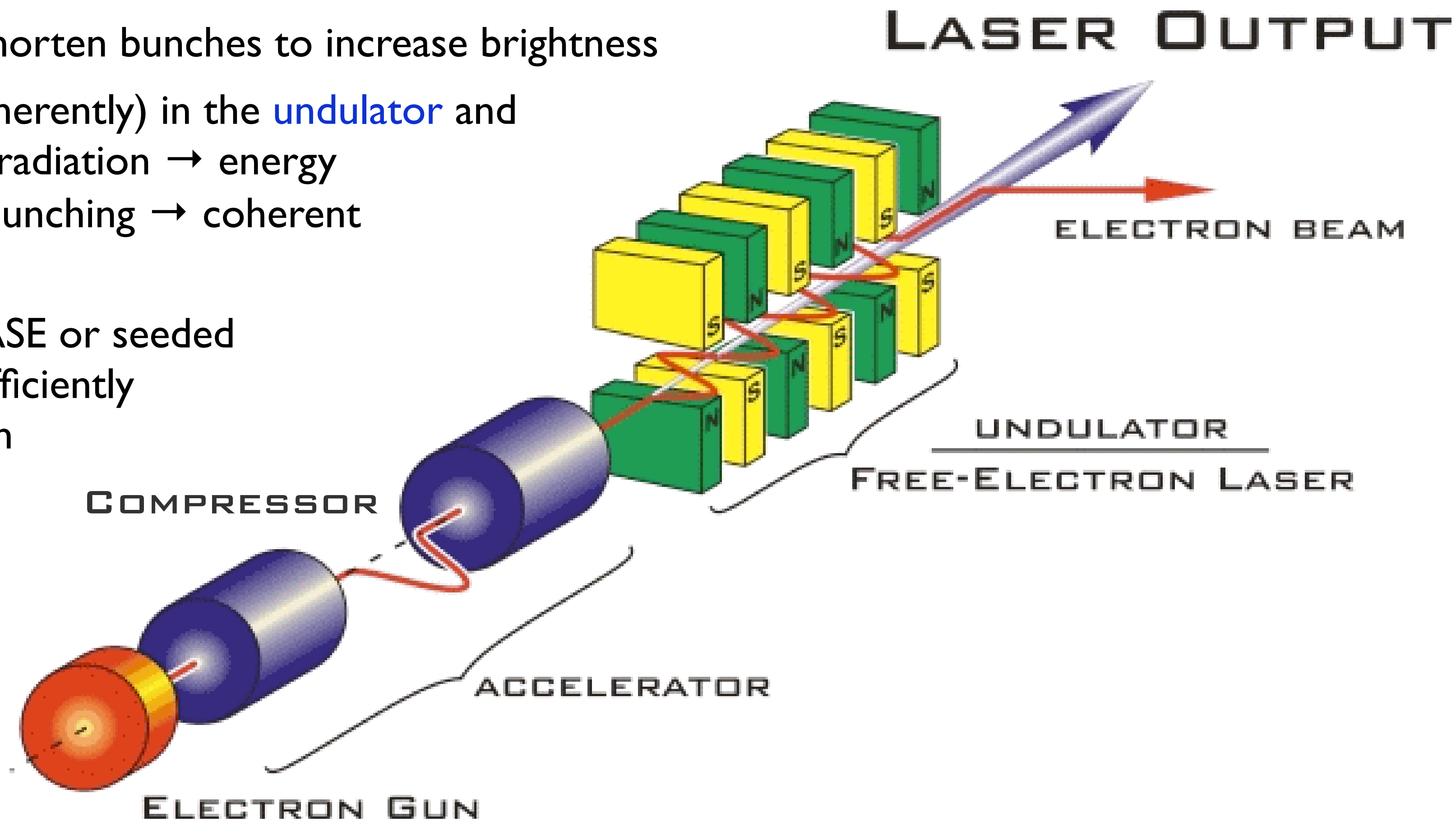
➡ New accelerator concept required

Generic Layout of an X-Ray Free Electron Laser

- High-brightness electron gun (high peak current, low emittance)
- Linac accelerates short bunches to sufficiently high energy

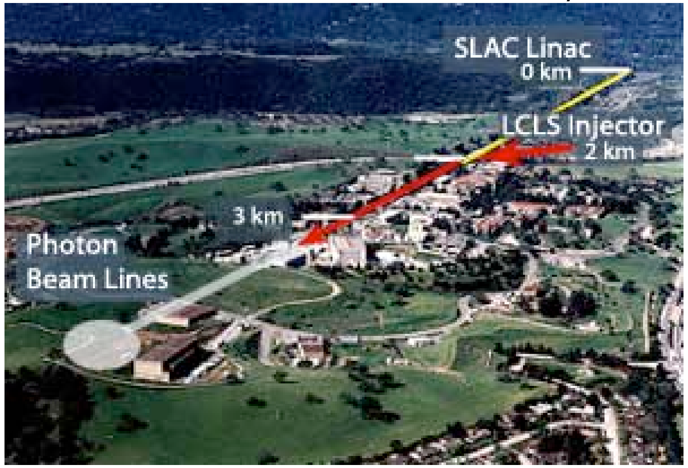
$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \qquad \begin{cases} \lambda_u & : \text{ Undulator Period} \\ K \propto B_u \lambda_u & : \text{ Undulator Parameter} \end{cases}$$

- Bunch compressors shorten bunches to increase brightness
- Bunches radiate (incoherently) in the undulator and interact with emitted radiation → energy modulation → microbunching → coherent radiation ($P_\gamma \propto N_e^2$)
- Single-pass system: SASE or seeded X-FEL → requires sufficiently long undulator section for full saturation



Two 1Å X-FEL Projects

Courtesy of SLAC

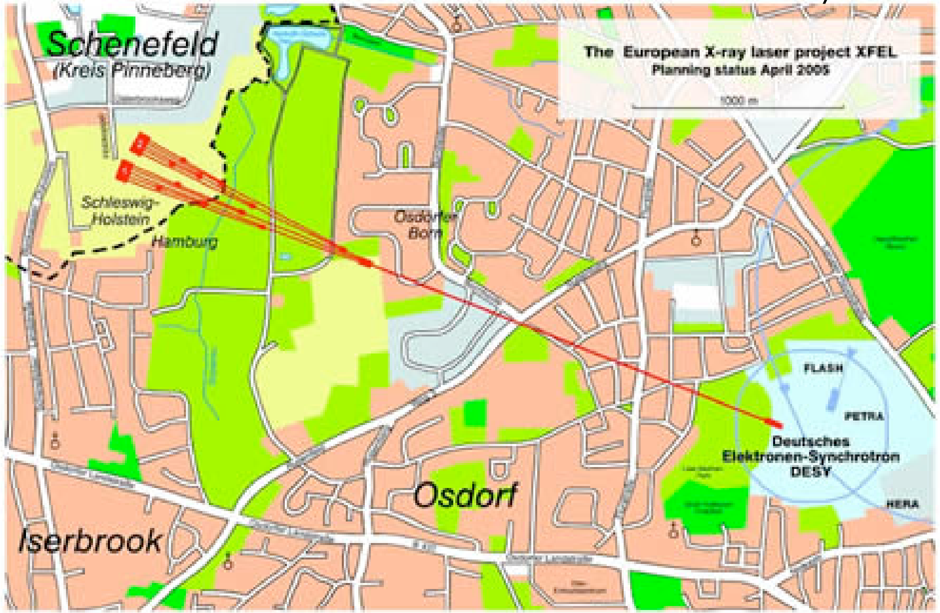


Linac Coherent Light Source (LCLS)

SLAC, Stanford CA, USA

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

Courtesy of DESY



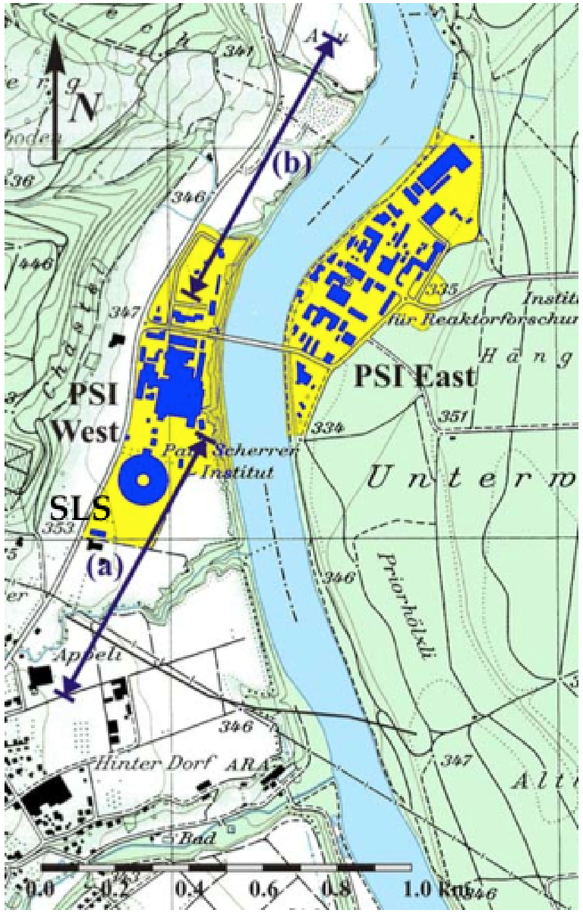
European XFEL

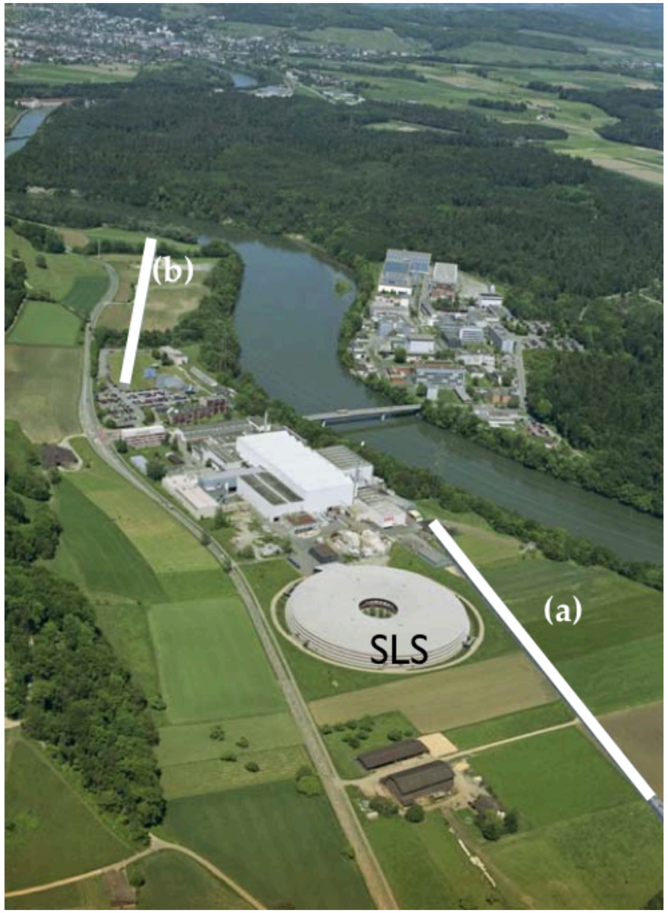
DESY, Hamburg, Germany

- 3.4 km long, 20 GeV, ~1 billion EUR
- Construction starts 2008
- Operational by 2013

PSI is also interested in a 1Å X-FEL, but...

- Budget constraints (~150 million EUR for SLS in 1998)
- In total 800 m length available on the PSI site





➡ Is there an alternative concept for a compact 1Å X-FEL?

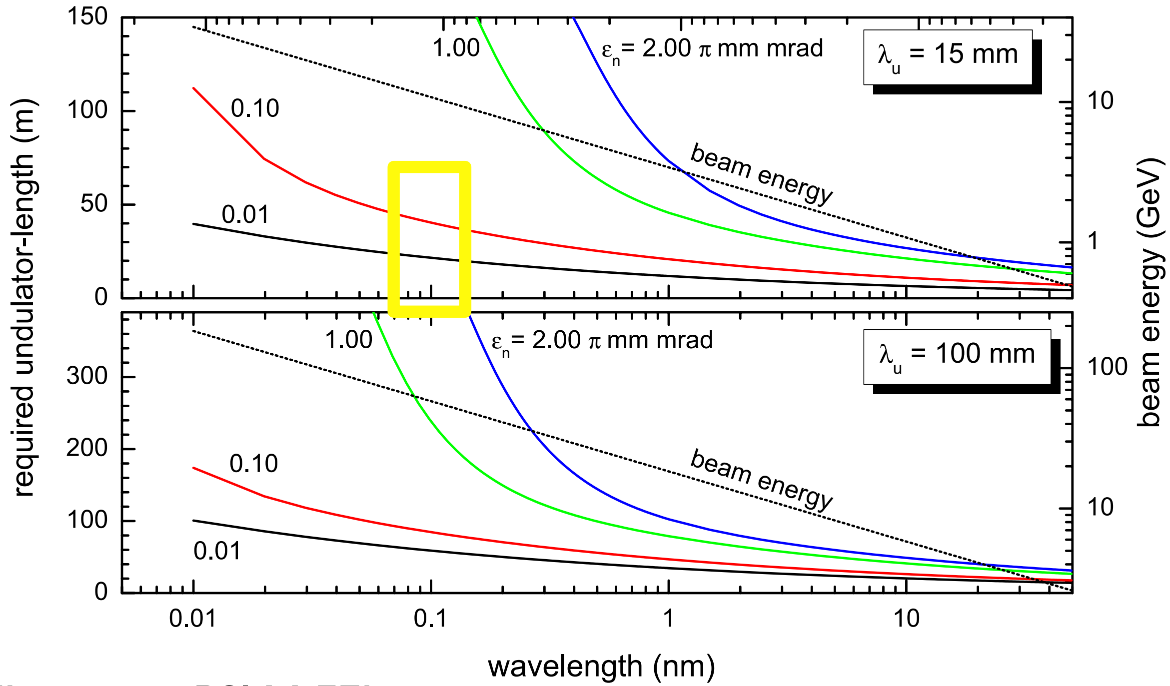
Strategy for a Compact 1Å X-FEL at PSI

- A low emittance electron beam significantly reduces the required beam energy

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

➡ A shorter linac is sufficient

➡ X-FEL becomes shorter and less expensive

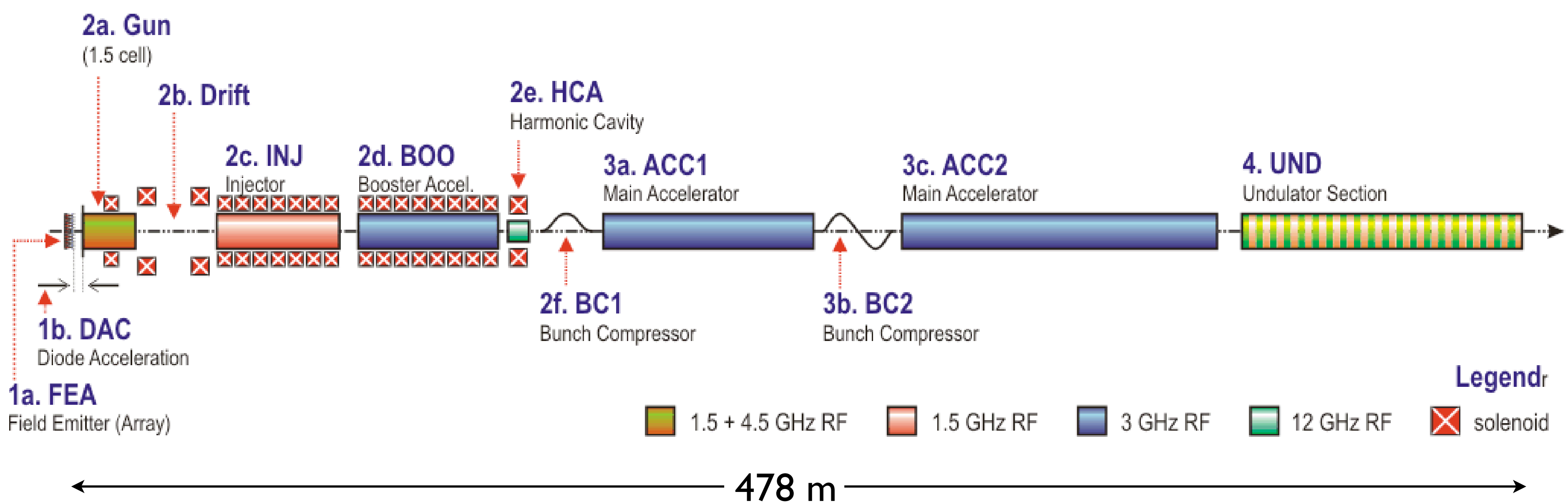


	European XFEL	PSI X-FEL
Beam Energy	20 GeV	6 GeV
Total Length	3400 m	800 m
Cost	1 billion EUR	~ 200 million EUR
Required Emittance	0.9 mm mrad	0.1 mm mrad

9 times lower!

➡ New challenge: generating ultra-low emittance electron beams

Accelerator Requirements



- Low emittance electron source (5.5 A peak current, 0.05 mm mrad normalized projected emittance)
- Pulsed DC acceleration (250 MV/m acceleration to 1 MeV, 15 ps RMS bunch length)
- 2-frequency RF cavity (1.5 & 4.5 GHz SW cavity, acceleration to 3.8 MeV, ballistic compression)
- Emittance compensation (solenoid magnets)
- Injector linac (velocity bunching) & booster linac (acceleration to 250 MeV, TRW structures)
- Main linac sections (acceleration to 1080 MeV & 6 GeV in TRW structures)
- Magnetic bunch compressors (at 250 MeV & 1080 MeV → 50 fs RMS bunch length, 1.5 kA peak current)

Gun Requirements

- Realization of the PSI X-FEL depends on a novel type of electron gun

➡ "Low Emittance Gun (LEG) Project"

- Electron gun with unprecedented emittance ($\epsilon_{x,y}$ = 0.05 mm mrad)
- High gradient acceleration (250 MV/m pulsed)
- Conserve low emittance up to relativistic energies
- Implement diagnostics capable of measuring ultra-low emittance

Contents

Thermionic Electron Sources

- Oldest and most well known electron source → lots of experience
- Good cathode materials have low ϕ_w → very sensitive to vacuum conditions and contamination
- In order to get high peak current, need very high temperature and/or large cathode size → blows up source emittance

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

- A priori DC source → need pulsed grid or chopper

➡ Prefer smaller, pulsed, cold cathodes

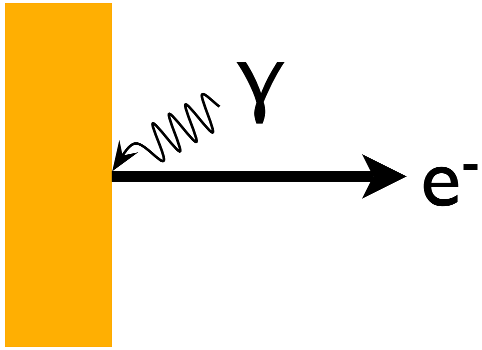
CeB_6 thermionic cathode

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

Photo-Electric Electron Sources

- Irradiate cathode material with short laser pulses → electrons are released into vacuum
- Big advantage: time structure of electron bunch given by laser pulse; short-pulse laser systems are available
- High accelerating gradient → avoid materials with low work function Φ_w (dark current!)
- High peak current through use of short wavelength lasers → $E_\gamma = hc/\lambda$ 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

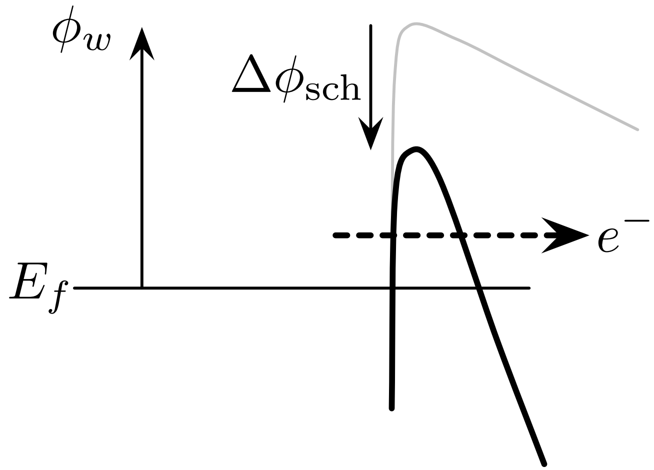
➡ Need an alternative electron emission process (ideally: pulsed, cold, small emission area, low transverse momentum spread)



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:



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

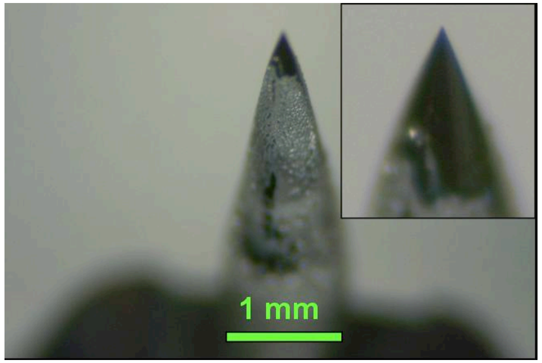
- Since the electrons tunnel through the potential barrier → kinetic energy is lower than the effective work function $E_e < \Phi_{w,e}$
- Provided there is a very high effective electric field (several GV/m) large amounts of current can be drawn from very small areas

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

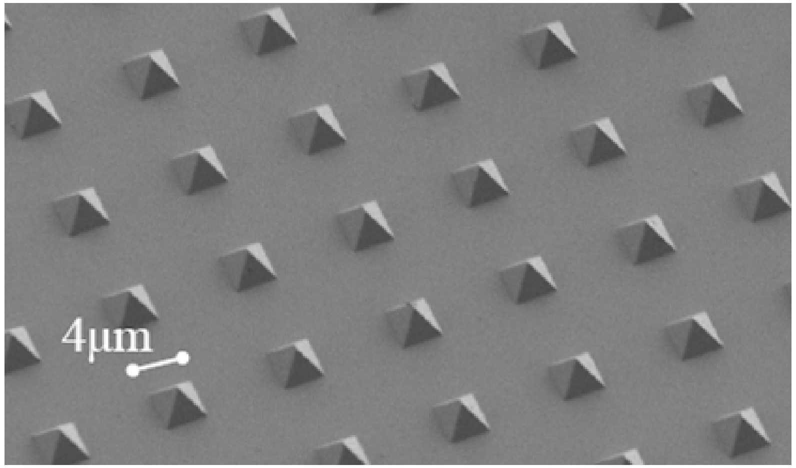
Field Emission Cathodes (I)

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

- Needle-tip emitters → total current insufficient

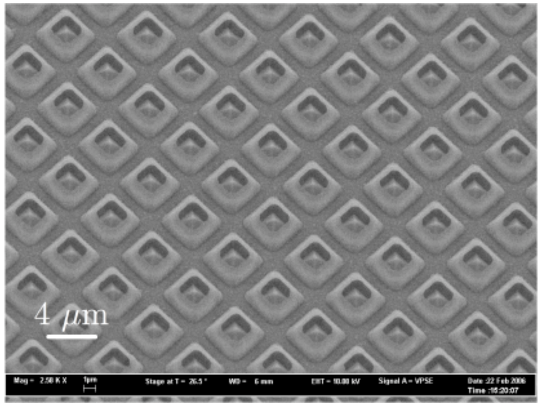


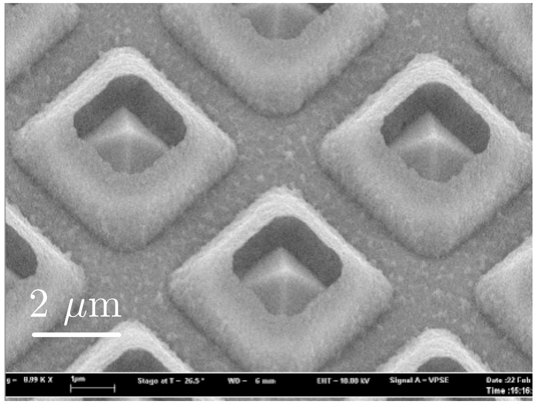
- Field emitter arrays (FEAs) → many nano-tips distributed over cathode surface

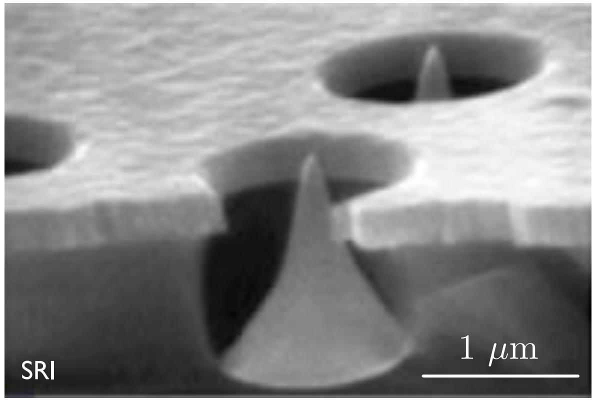


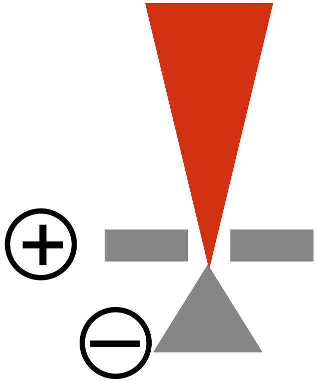
Field Emission Cathodes (II)

- FEAs with gate layer → pulsed emission

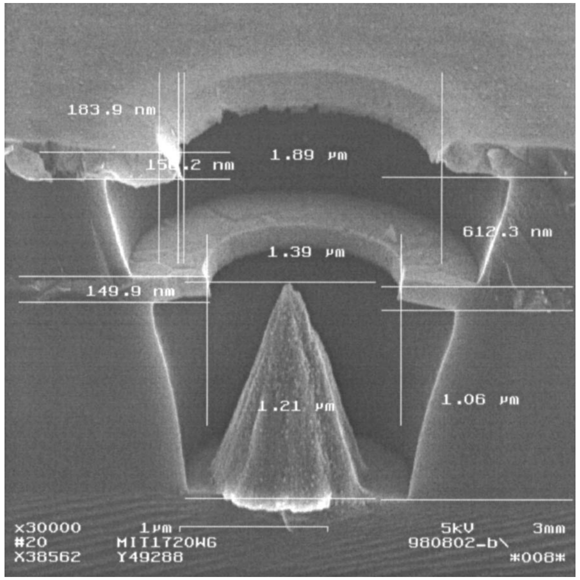


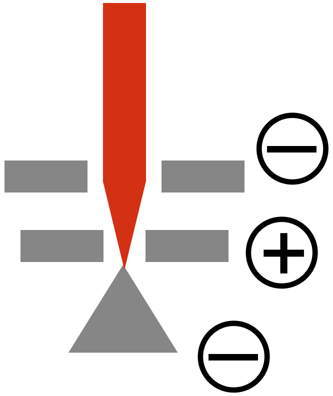






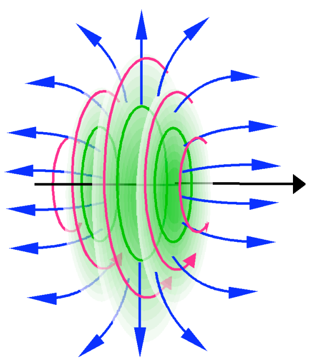
- FEAs with focusing layer → reduce divergence → minimize source emittance

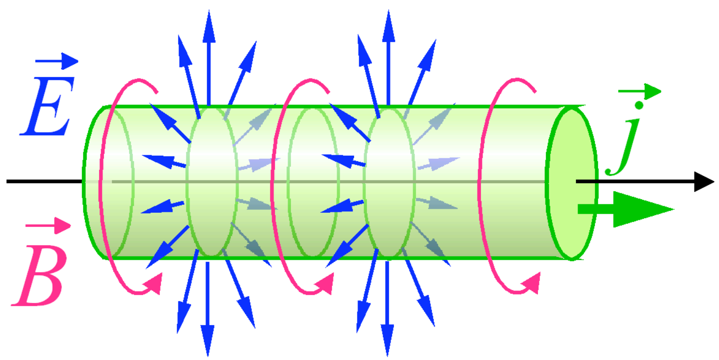


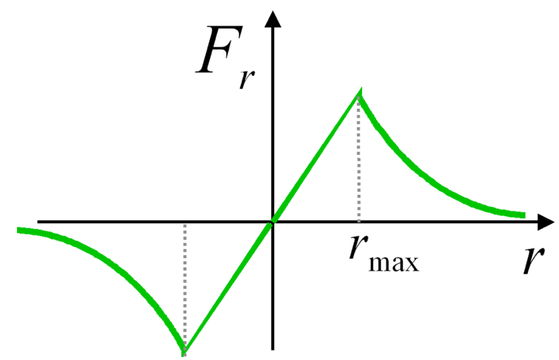


Space Charge Forces (I)

- Once a low emittance electron bunch has been emitted by the cathode, can its emittance deteriorate?
- Space charge forces: In high charge bunches there is a direct collective effect where the charge of the entire bunch acts on a single bunch particle







$$\iint \vec{E}\, d\vec{\sigma} = \frac{1}{\varepsilon_0} \iiint \rho\, dV \quad \longrightarrow \quad E_r = \frac{\rho r}{2\varepsilon_0} = \frac{Ir}{2\varepsilon_0 \pi r_0^2 \beta c}$$

$$\oint \vec{B}\, dl = \mu_0 \iint J\, d\vec{\sigma} \quad \longrightarrow \quad B_\theta = \frac{\mu_0 J r}{2} = \mu_0 \frac{Ir}{2\pi r_0^2} = \mu_0 \varepsilon_0 \beta c E_r$$

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

Space Charge Forces (II)

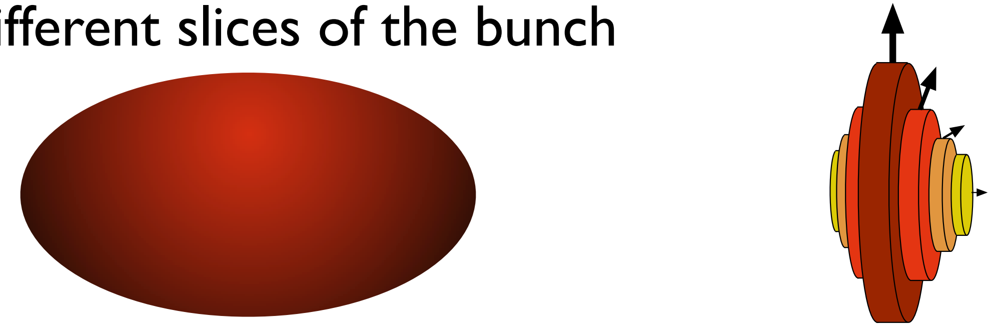
- Space charge forces are repulsive and act a defocusing lens with a strength that depends on the local charge density
- Space charge forces lead to distortions of the bunch's phase space distribution and to coupling between different conjugate coordinates → emittance growth

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

- However, at very high energies the focusing magnetic force cancels the defocussing electric force → the resulting space charge force vanishes and the phase space distribution of the bunch is "frozen"
- Thus, emittance blow-up due to space charge forces is a concern at low energy
- Strategy: Generate low emittance electron bunch and accelerate as quickly as possible to high energy in order to conserve low emittance ($\gamma > 10$ requires $E_{kin} > 5$ MeV)
- However, no matter how quickly the bunch is accelerated, there will always be a finite amount of emittance growth due to space charge forces at low energy → compensation mechanism?

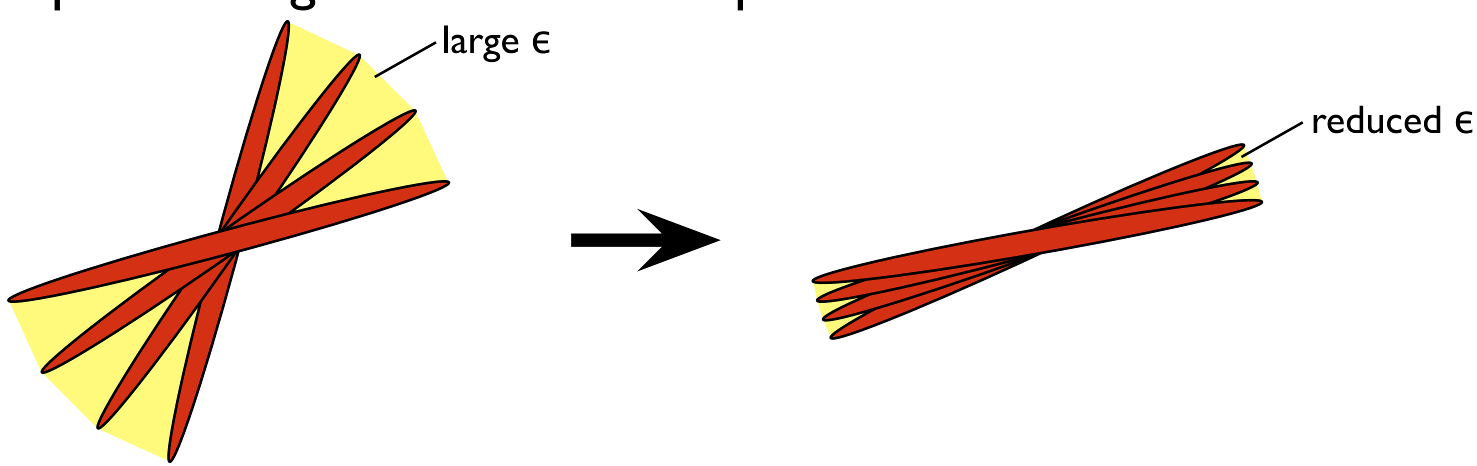
Emittance Compensation

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



- B. E. Carlsten, LANL, 1989: make use of focusing lens (solenoid) and subsequent drift section to compensate emittance blow-up due to space charge forces
- 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



Contents

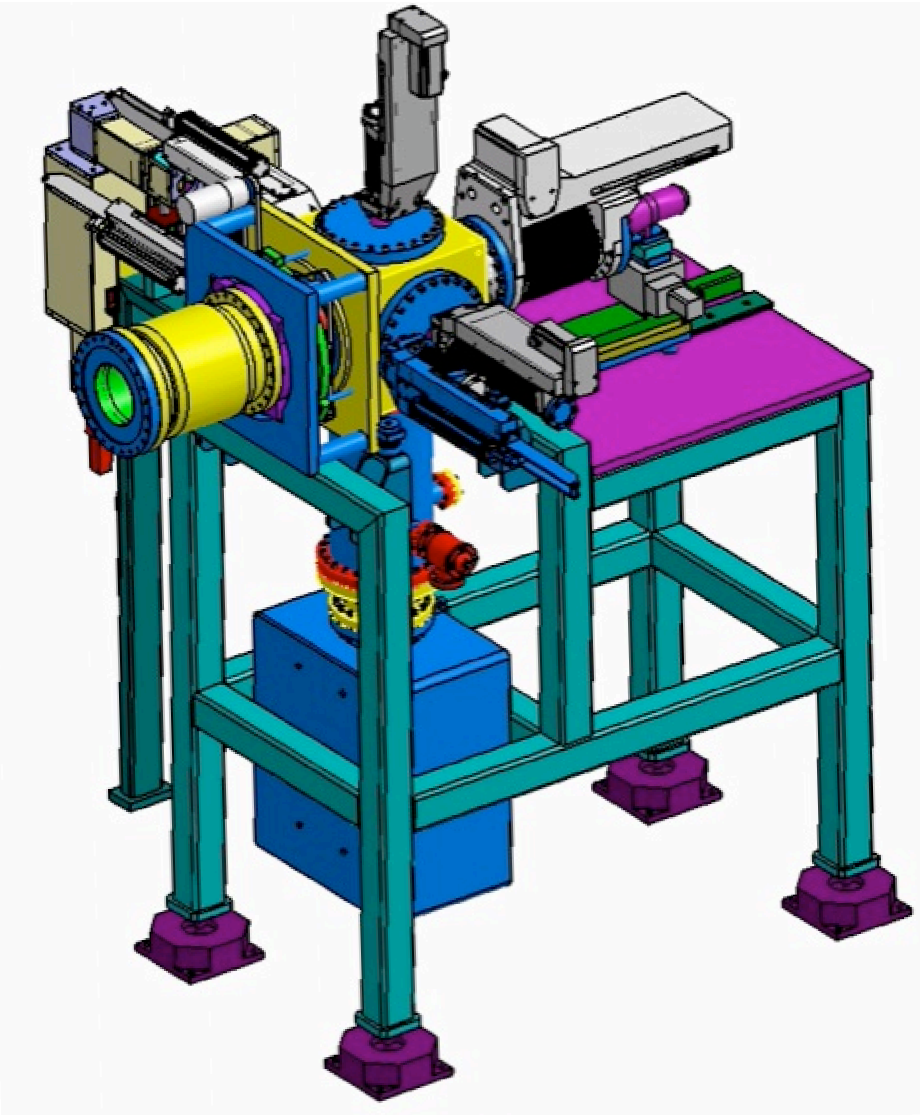
Motivation Behind the 100 keV Gun Test Stand

- 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?
- Investigate emittance compensation

Overview of the 100 keV Gun Test Stand

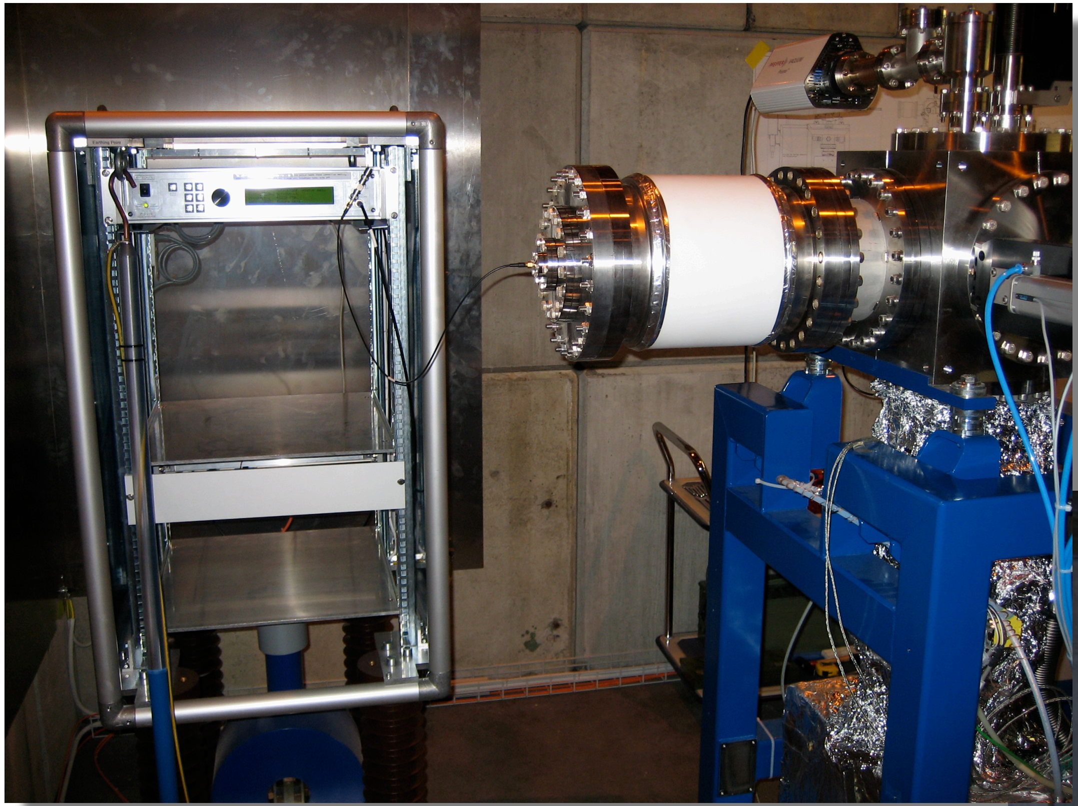
The 100 keV Gun Test Stand consists of:

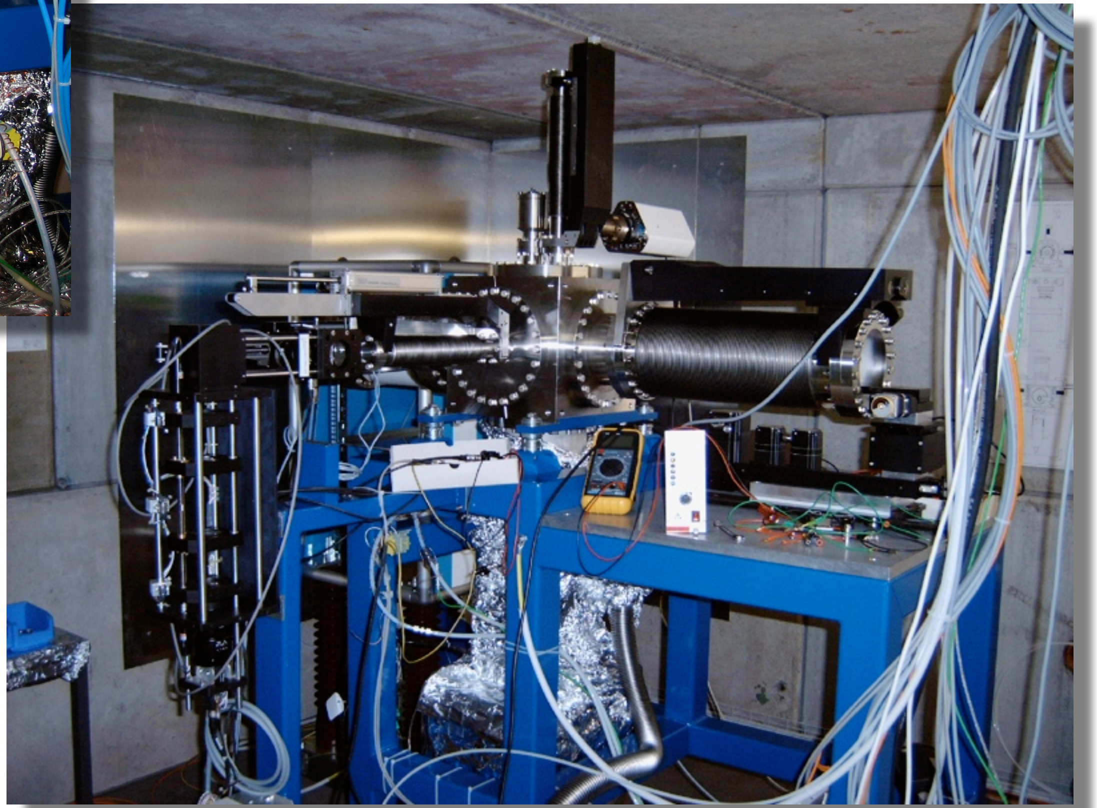
- Electron gun (DC accelerating voltage) with pulsed FEA cathode (exchangeable)
- In-vacuum solenoid magnet → beam focusing, emittance compensation
- Diagnostics module → benchmark FEA performance and investigate beam quality (exchangeable inserts)
- EPICS as digital control system → experimental control and data acquisition
- Dedicated vacuum system and diagnostics to ensure UHV conditions
- Local access control and safety system for radiation protection and HV safety



Test Stand Bunker and Control System

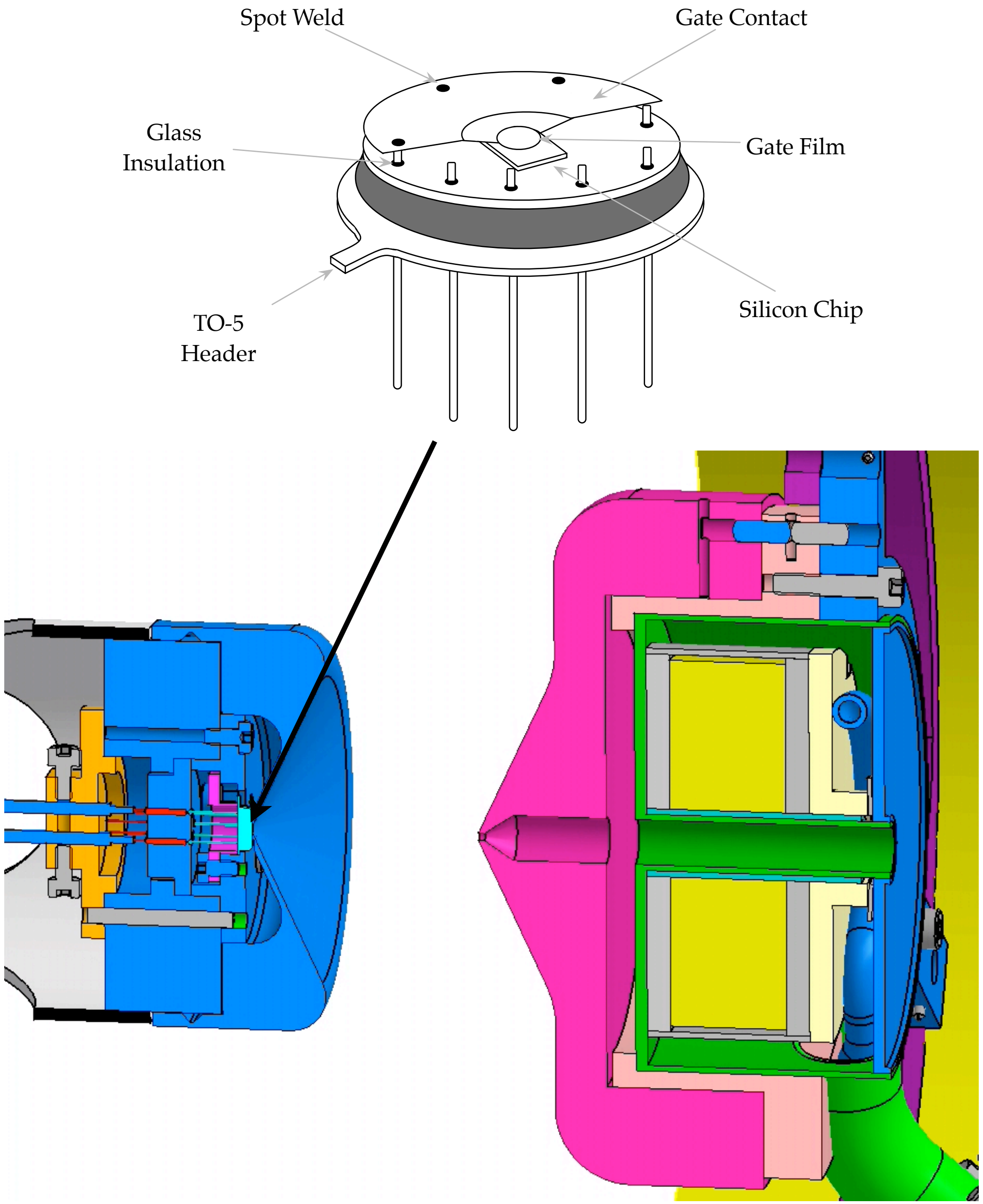
Test Stand Gun, Pulser and Diagnostics Module





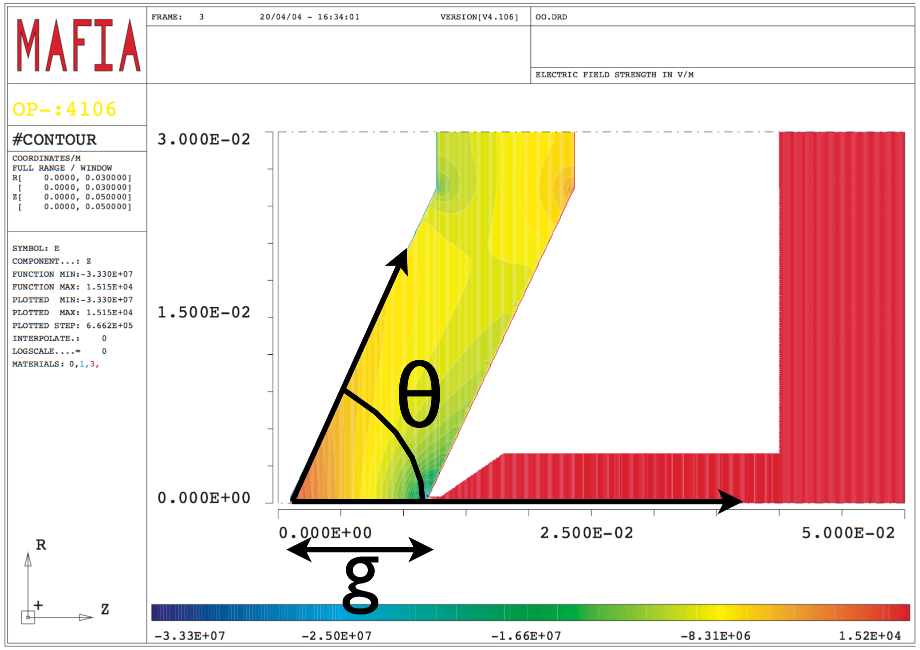
Gun & Solenoid

- Used gated Spindt-type FEAs (Mo) from SRI International (unfocused)
- Cathode and anode electrodes (removable) define gun geometry
- 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



Simulation & Design Optimization

- Simulations performed in 2.5D with MAFIA (ES/MS solver, particle tracking) and in 3D with GPT (tolerance studies)
- Design of cathode and anode electrodes optimized:
    - Gap reduced to increase accelerating gradient while keeping peak surface electric field strength manageable
    - Size of anode iris minimized while preventing beam scraping
    - Shape of cathode and anode optimized for minimum emittance at gun exit
- Solenoid settings for minimum emittance at gun exit



Macro-particles: 20,000

Active emitter radius: 100 µm

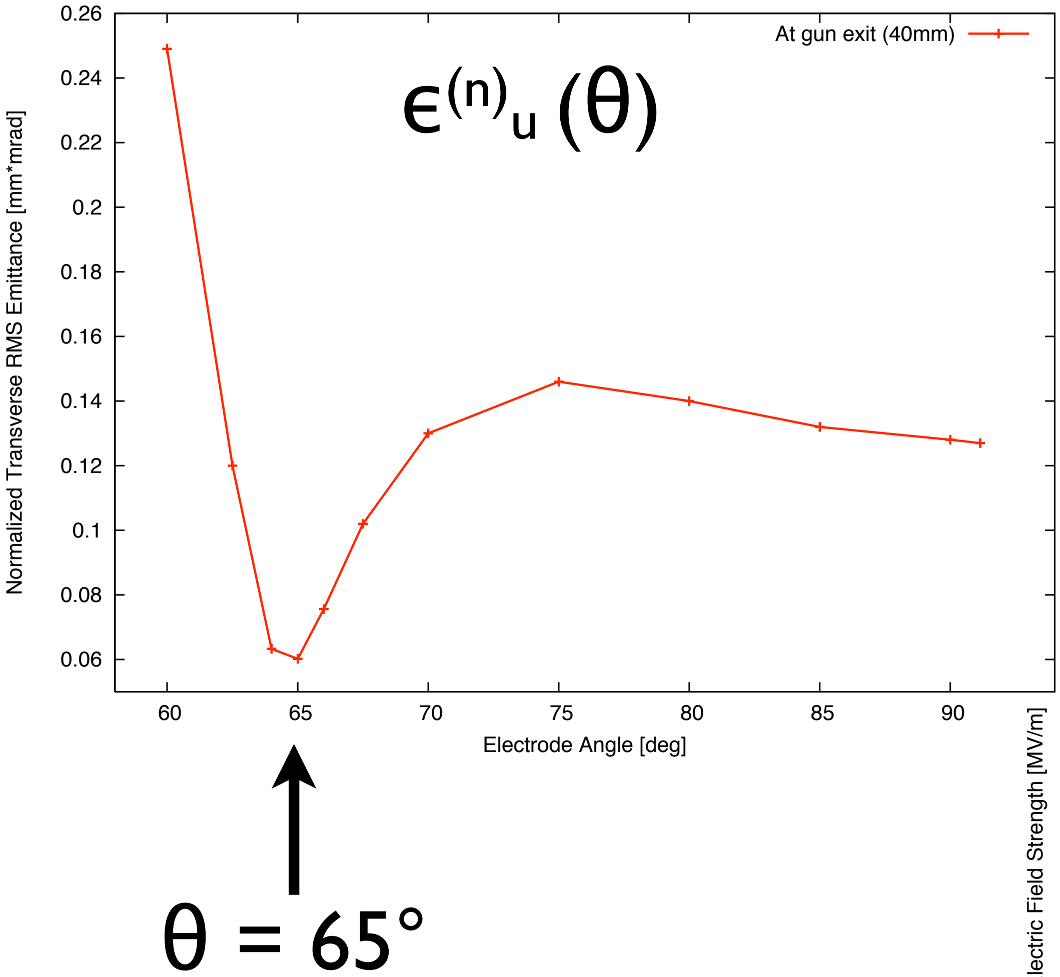
Pulse from: Gaussian, cut-off at ± 3 σ_t

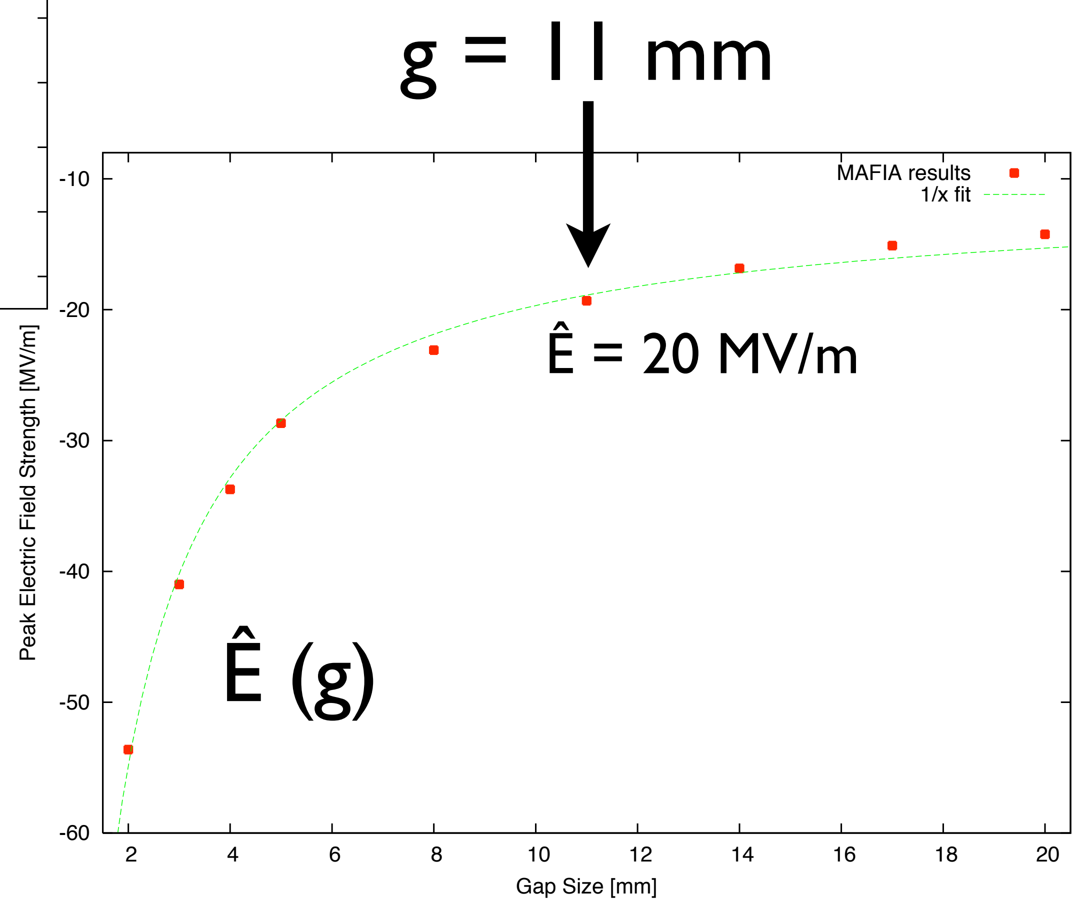
Pulse length σ_t: 20 ps

Total bunch charge: 5 pC
(peak current $\hat{I}$ = 100 mA)

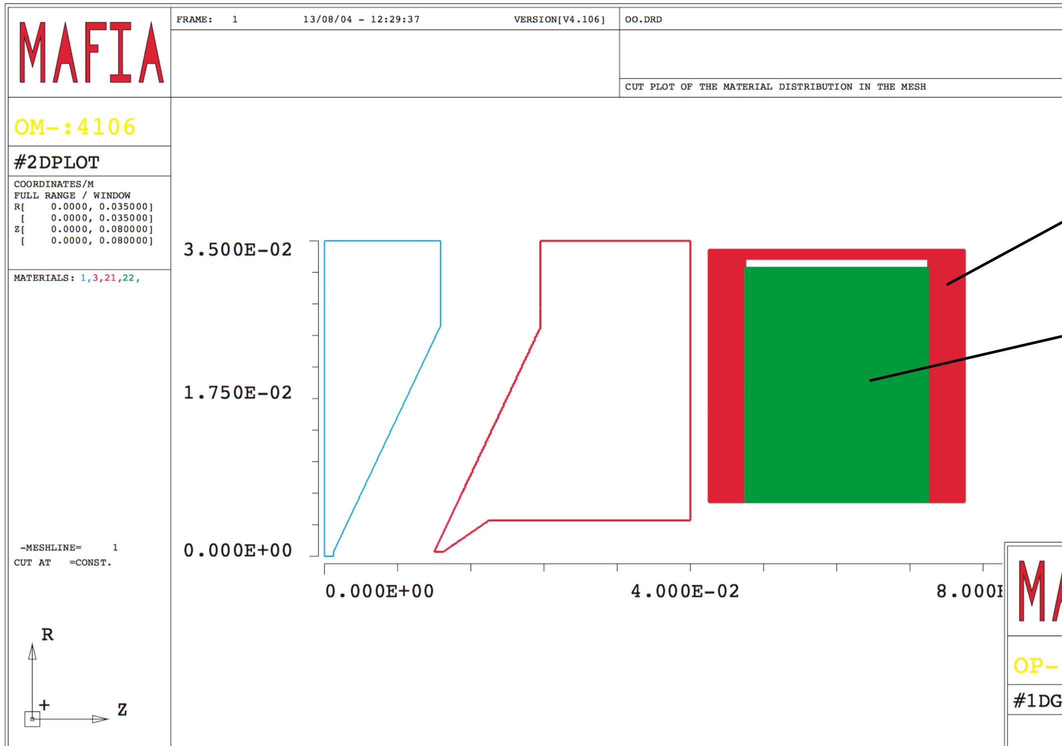
Initial energy: γ_0 = 1.0001
(corresponds to 50 V gate voltage)

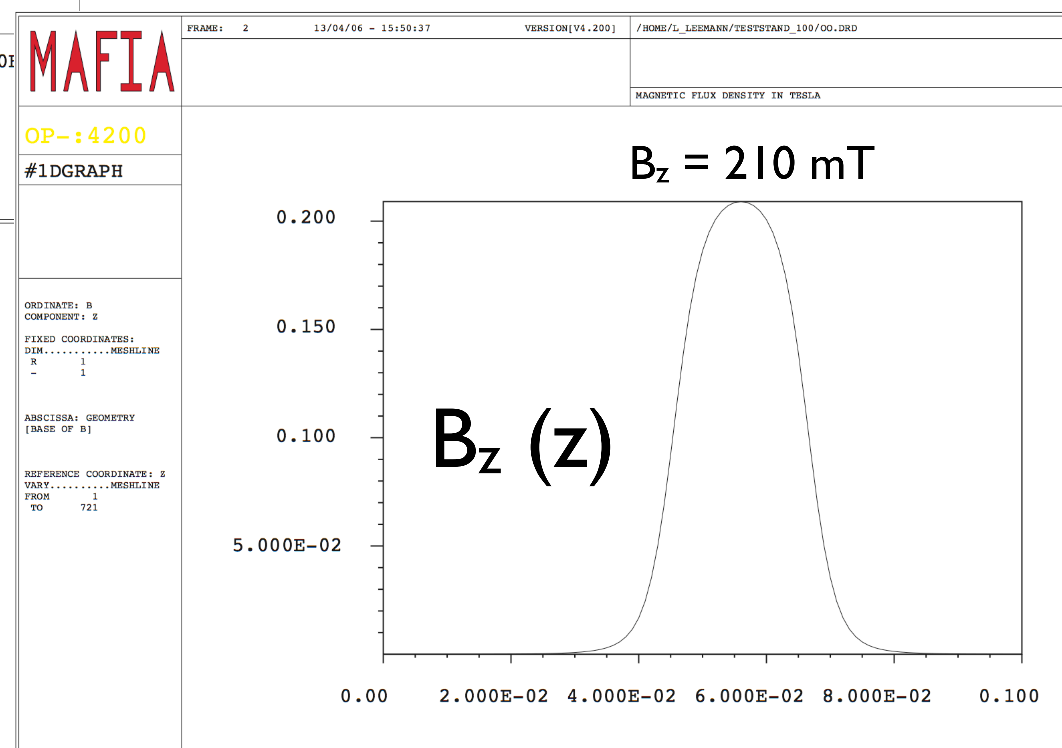
Gun Optimization Results





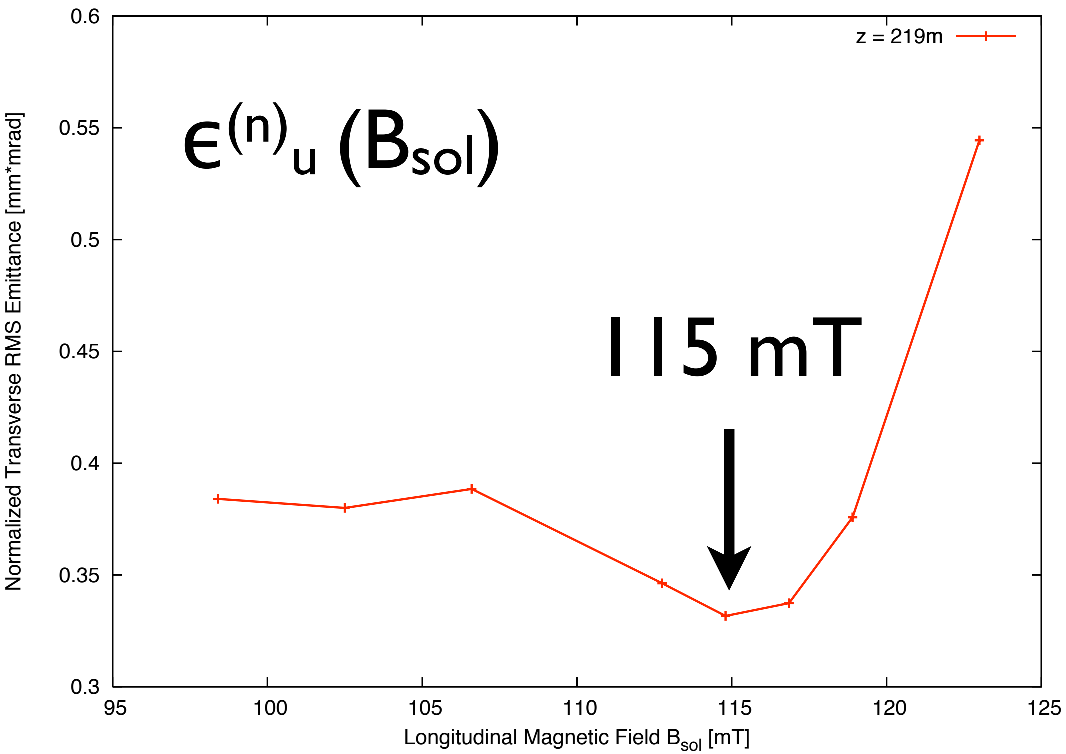
Solenoid Design Results



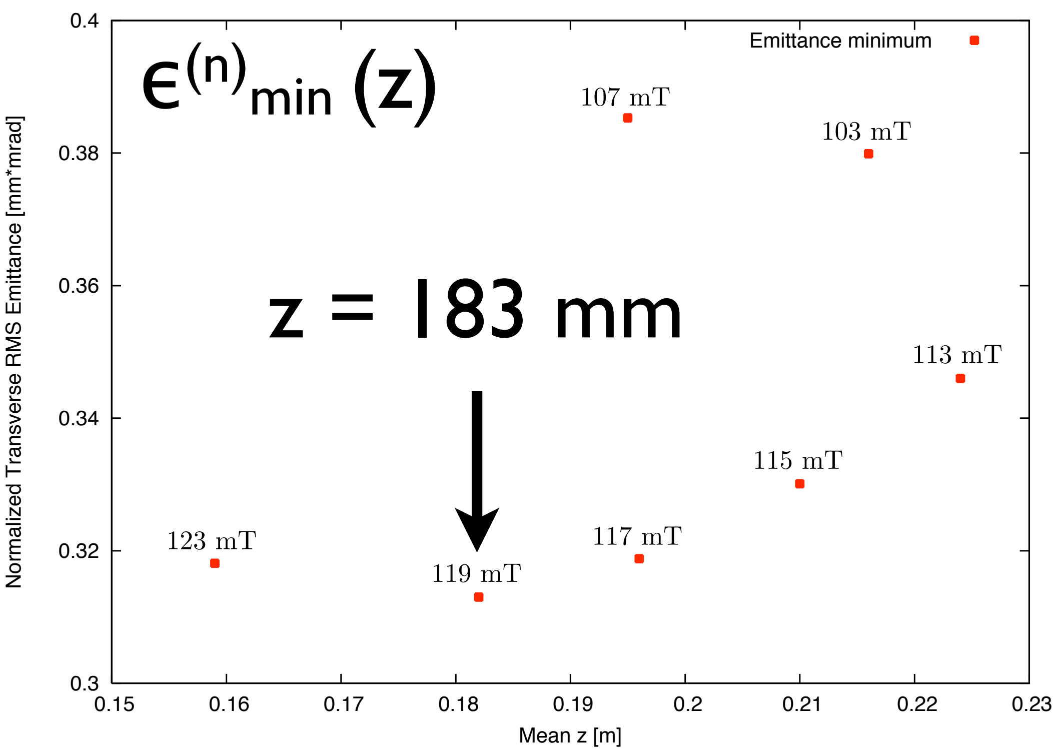


- Magnet iron yoke confines field → no bucking coil required at cathode
- Beam sufficiently focused throughout diagnostics section

Solenoid: Emittance Compensation



- Tuning range sufficient for emittance compensation
- Global emittance minimum at location of YAG screen and inserts



Tolerances

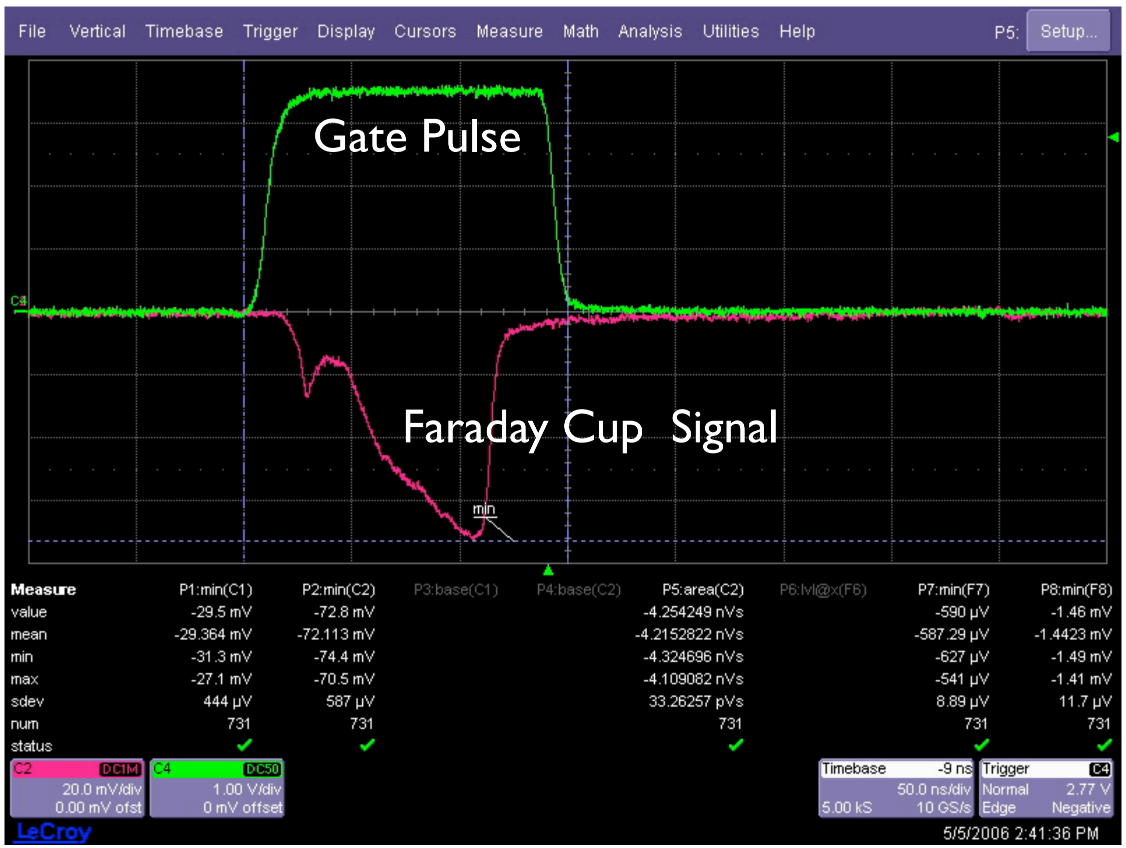
- Import fields generated by MAFIA ES and MS solvers into GPT
- Apply transverse displacement or rotation around vertical axis to simulate misalignment
- Observe resulting emittance increase → determine alignment tolerance

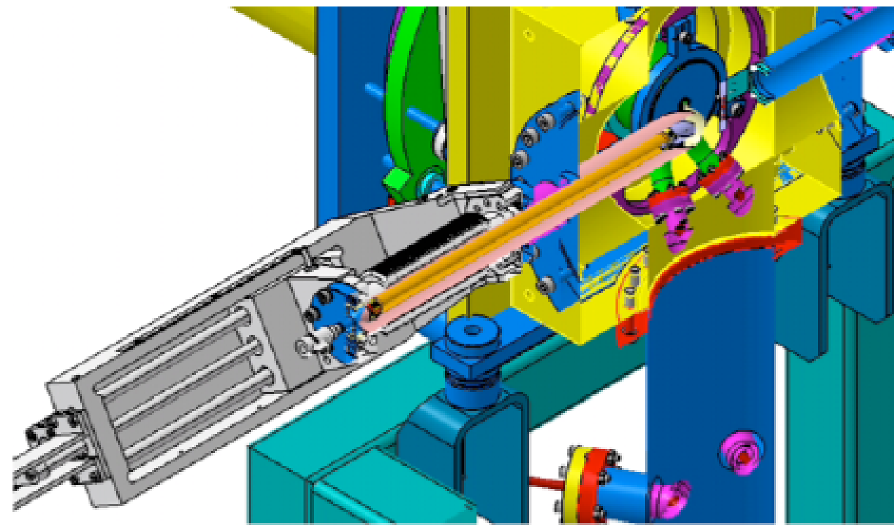
- In order for emittance growth to remain < 5 % require:
  - transverse displacement "shift" < 0.6 mm
  - rotation around vertical axis "tilt" < 25 mrad tilt

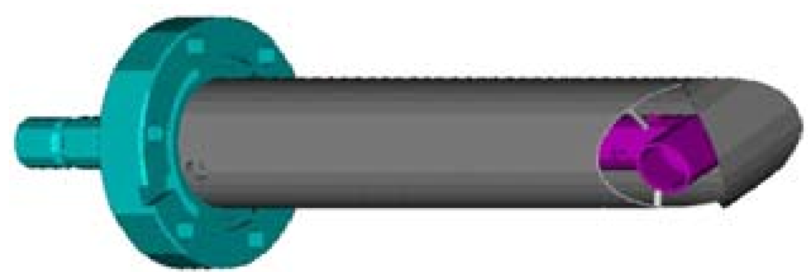
➡ Started design of 3D mover motor system to correct for misalignment of cathode with respect to anode/solenoid

Diagnostics: Measuring Charge-Time Structure

- A coaxial Faraday cup (> 4 GHz BW) can be driven into the beam
- Fast oscilloscope (2 GHz, 20 GS/s) measures collected current
- Integration of current signal over pulse length gives total bunch charge

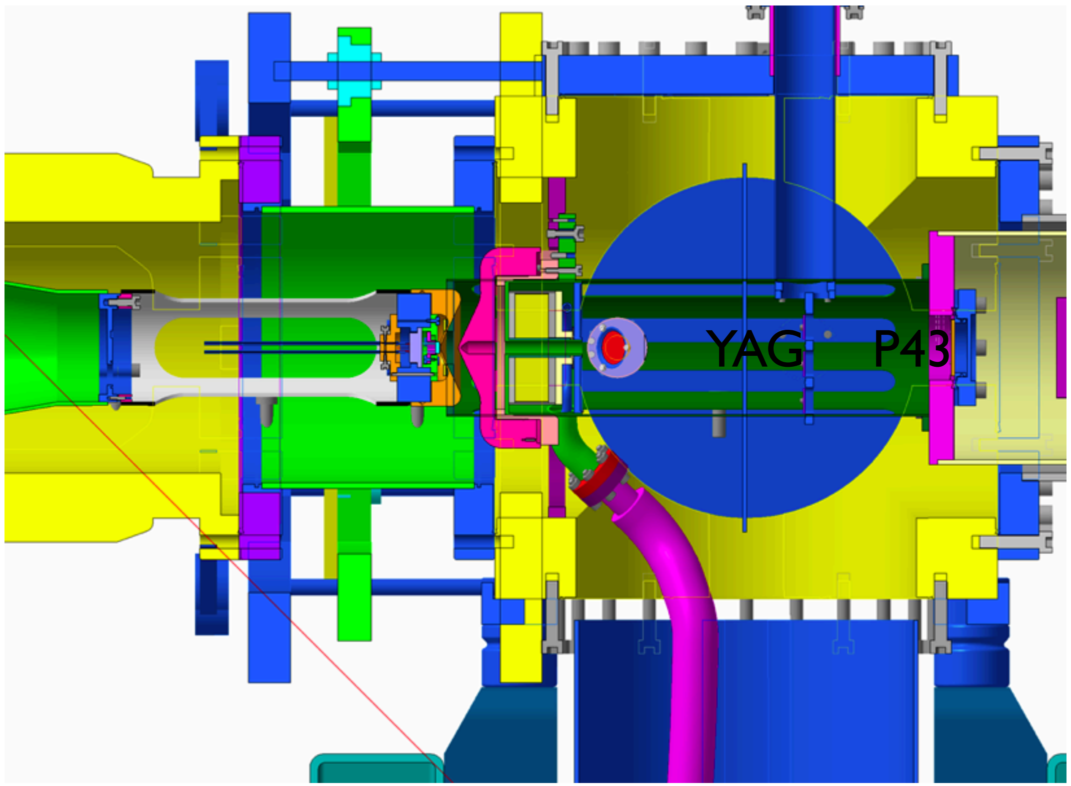


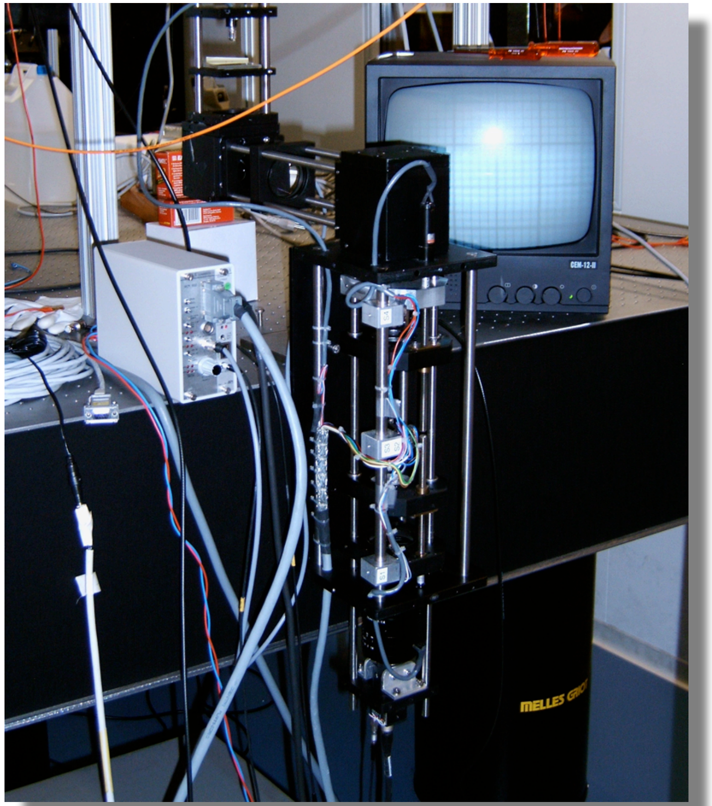




Diagnostics: Imaging the Bunches

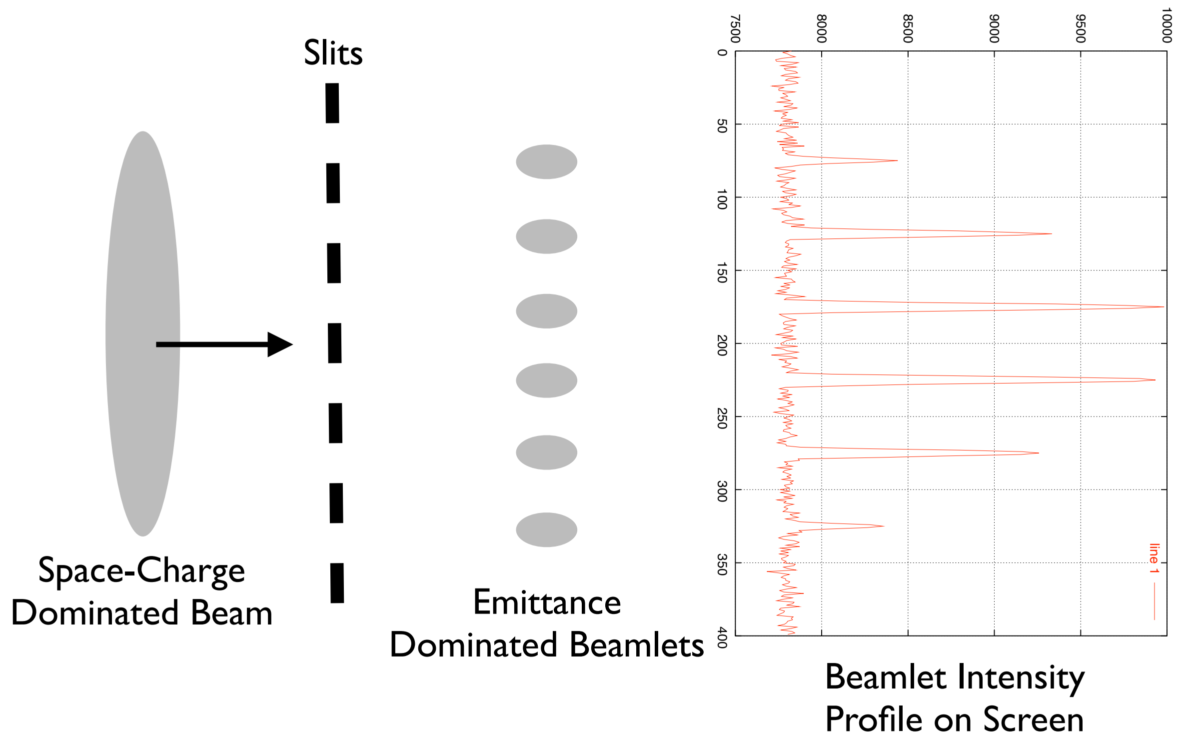
- Two screen monitor systems with dedicated zoom optics and CCD camera
- YAG: crystal (0.3 mm) at 45° angle driven into beam laterally → measure beam size at location of inserts
- P43 phosphor: Coating on vacuum window at the end of the diagnostics module (movable) → measure beam size and image beam image at various longitudinal positions





Diagnostics: Measuring Transverse Properties (I)

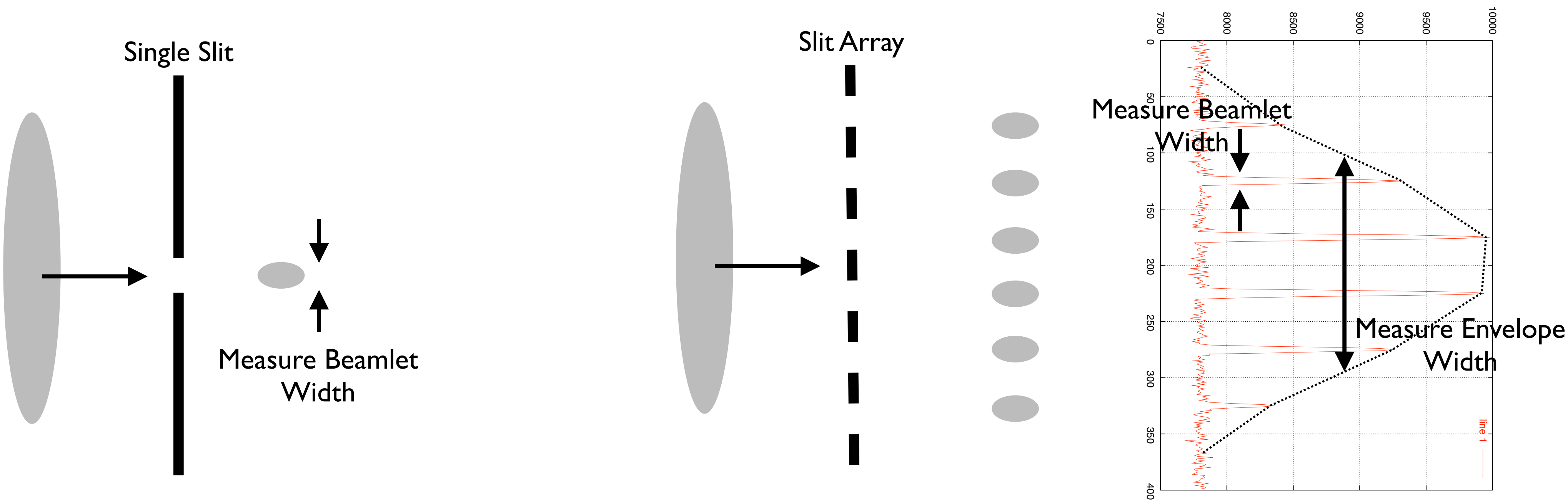
- Various measurements methods → compare methods, benchmark accuracy
- Measure transverse bunch properties: Insert obstruction, image emerging beamlet(s) downstream → calculate bunch properties at location of obstruction



- Inserts have to fully stop beam outside hole/slit → 100 μm tungsten masks
- 2 lateral inserts (hor/ver) with mask holders; each holds three different masks

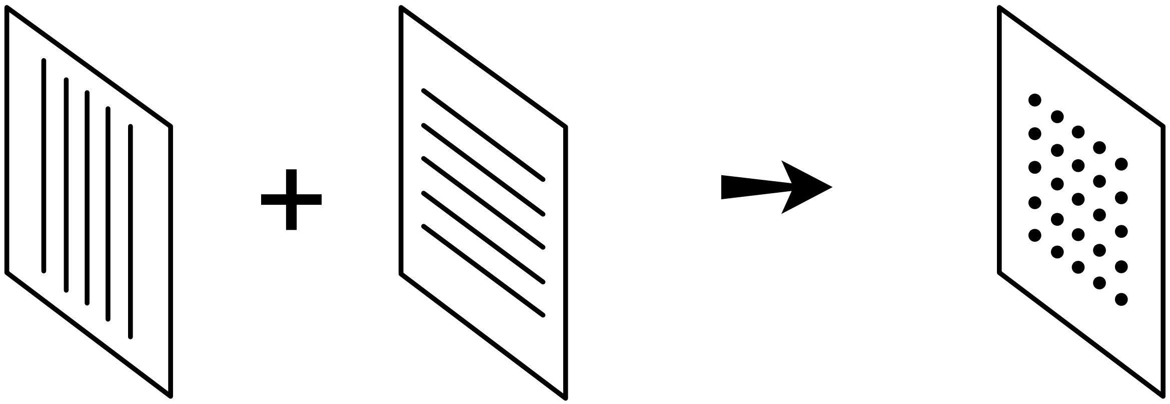
Diagnostics: Measuring Transverse Properties (II)

- 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

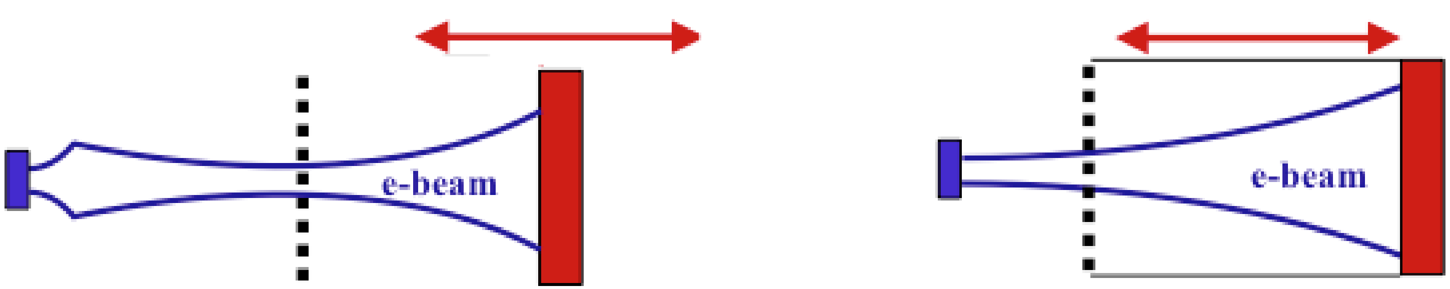


Diagnostics: Measuring Transverse Properties (III)

- Pinhole array mask (50 μm, 320 μm pitch): corresponds to using a horizontal and vertical slit array in one single shot

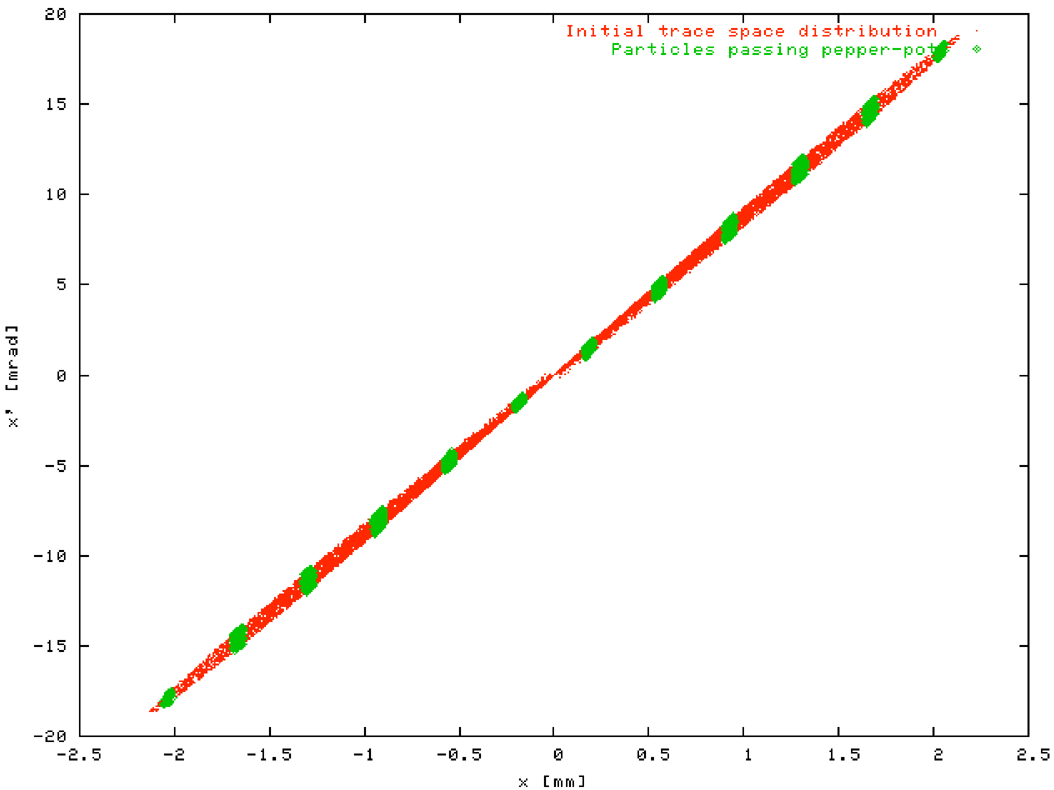


- Pepper-pot (50 μm, 320 μm pitch): like pinhole, but allows longitudinal sampling



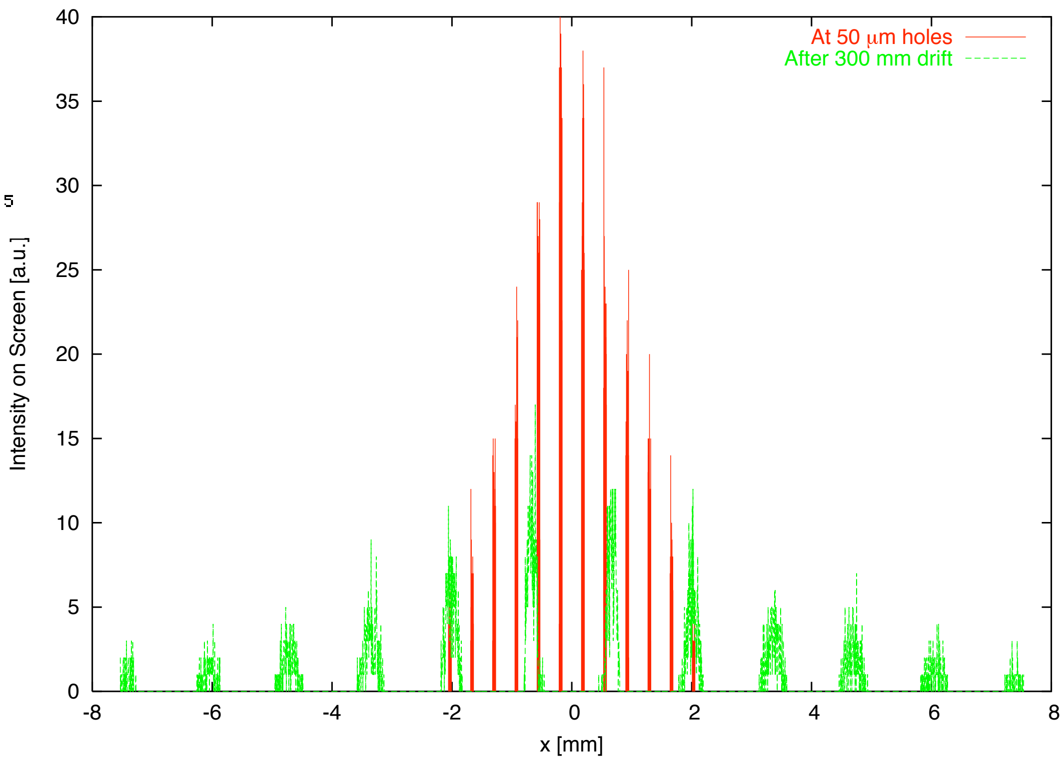
Inserts with masks   Pepper-pot

Simulations for Diagnostics



- Track particles through slit/pinhole arrays (MAFIA)
- Simulate screen monitor image and phase space reconstruction

➡ Optimized insert dimensions



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Lifetime & Performance

Beam Images & Profile Measurements

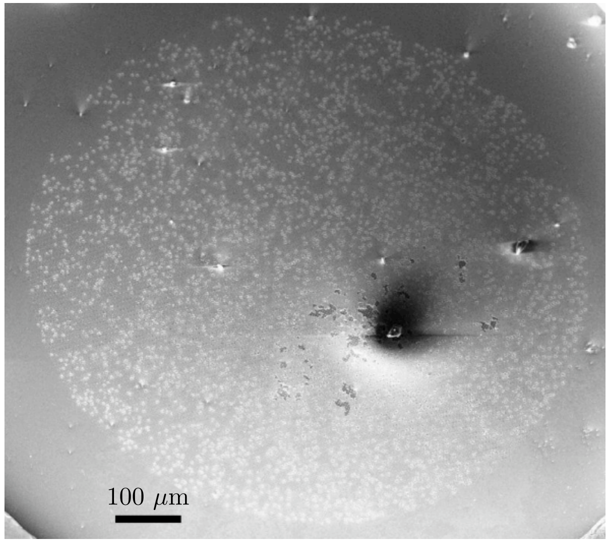
Emittance Measurements

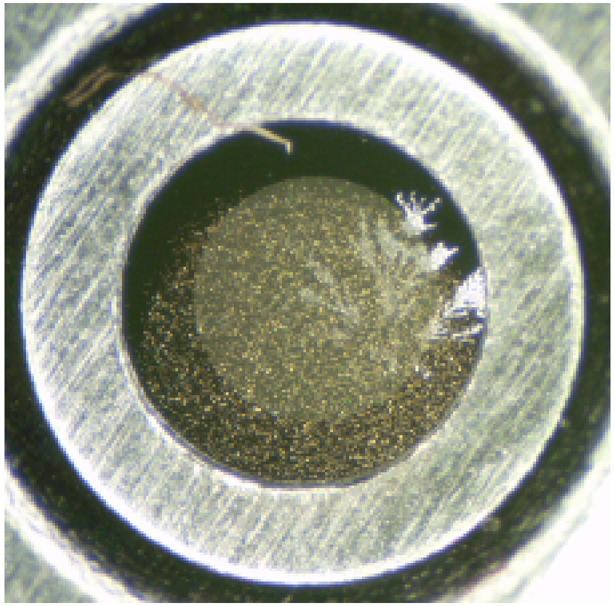
Phase Space Reconstruction

Emittance Studies

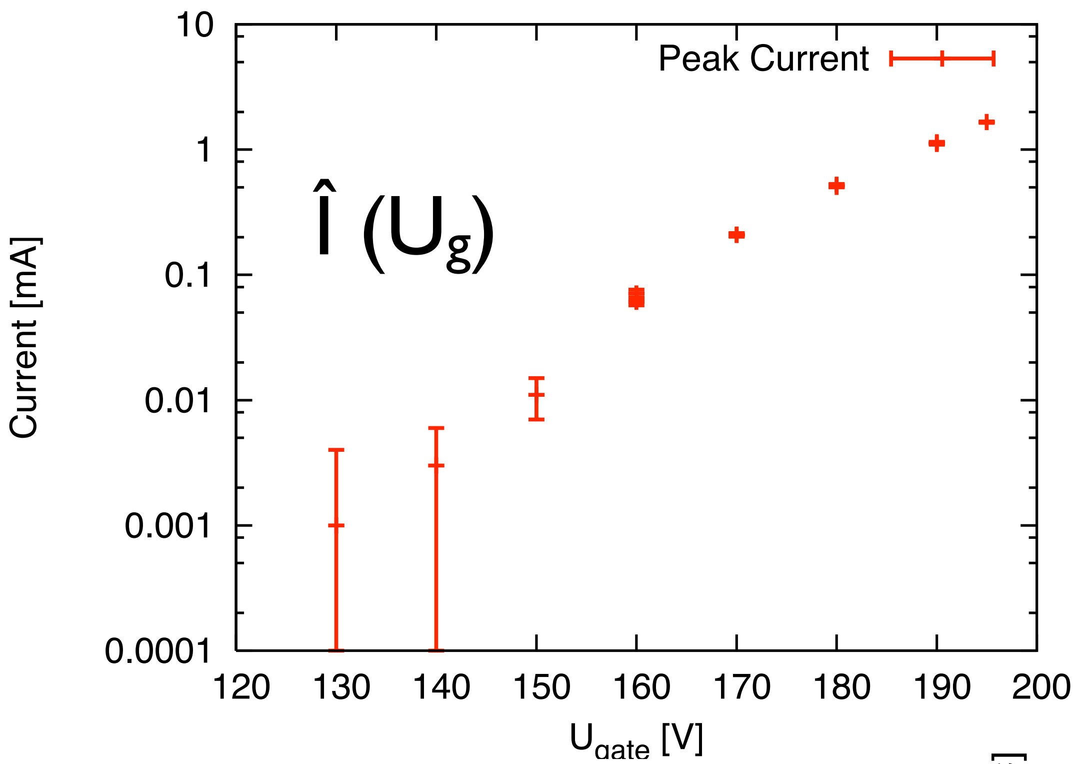
FEA Lifetime

- 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)





FEA Performance: Peak Current & Bunch Charge

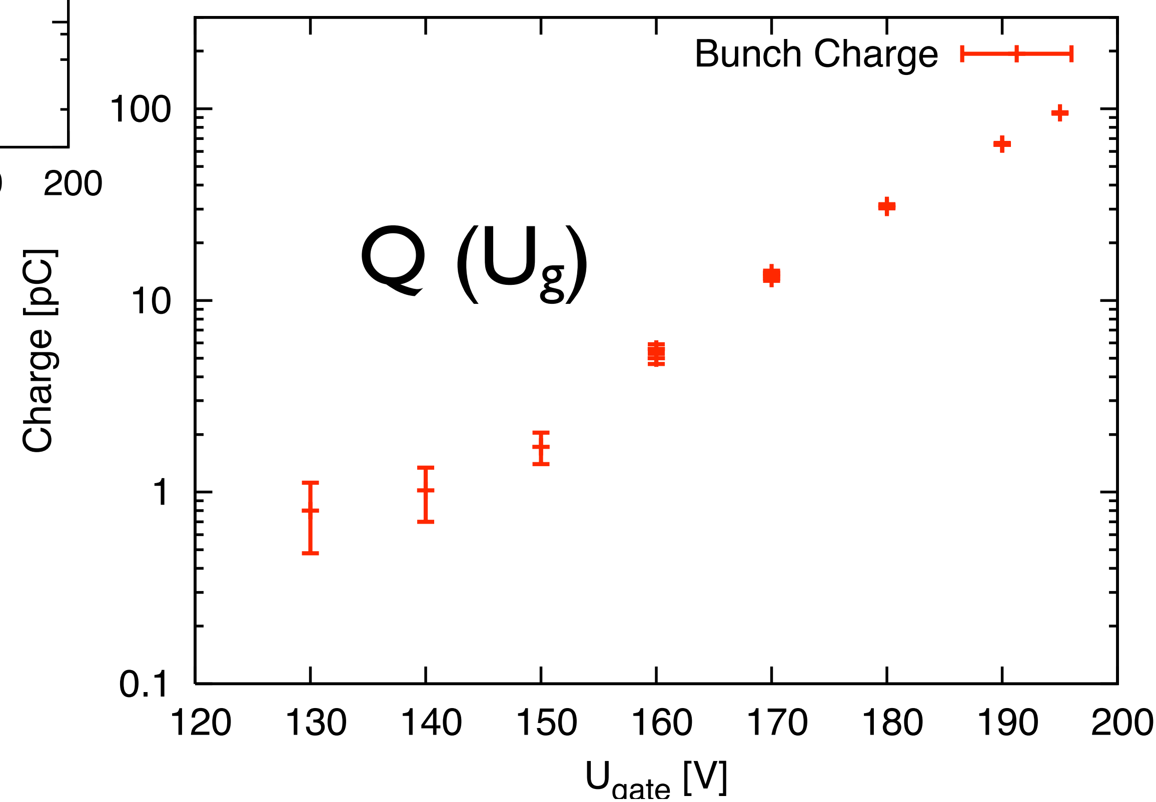


- Exponential increase of field emitted current with gate voltage as predicted by Fowler-Nordheim law

➡ Emission current very sensitive to gate voltage

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

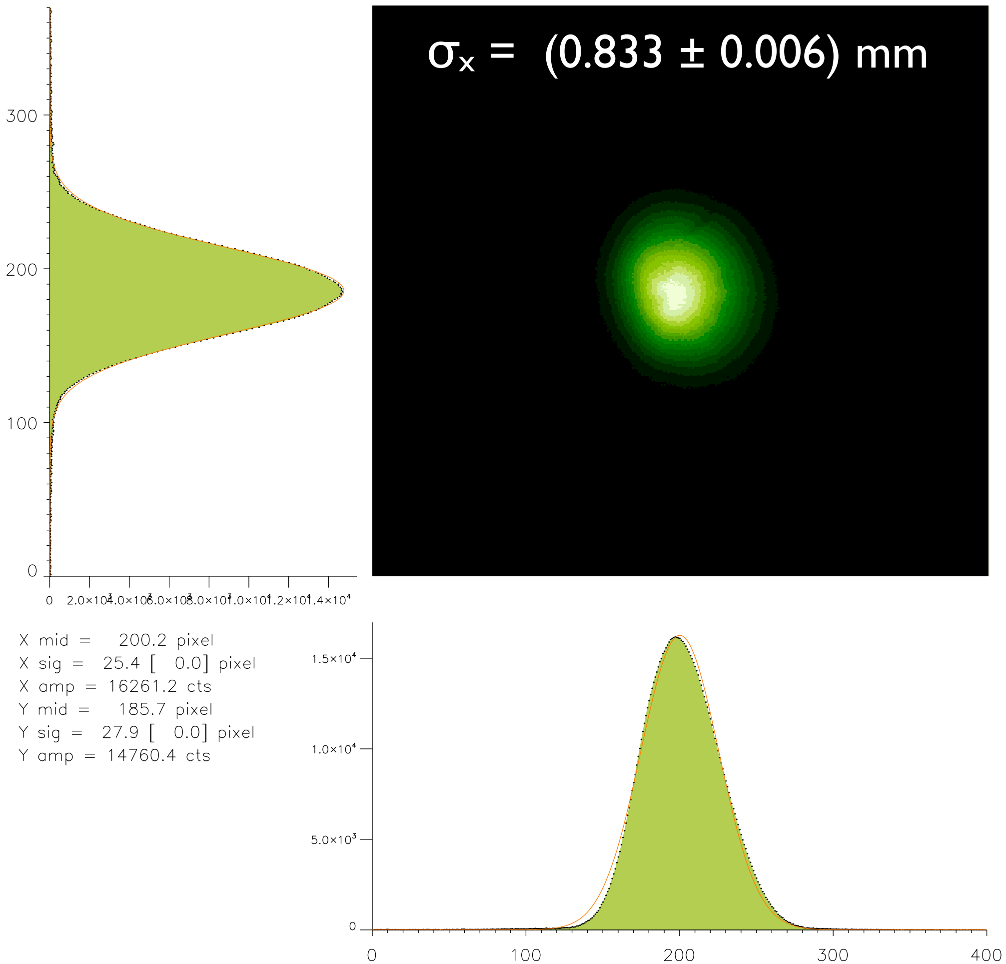
➡ Emittance dominated beam?



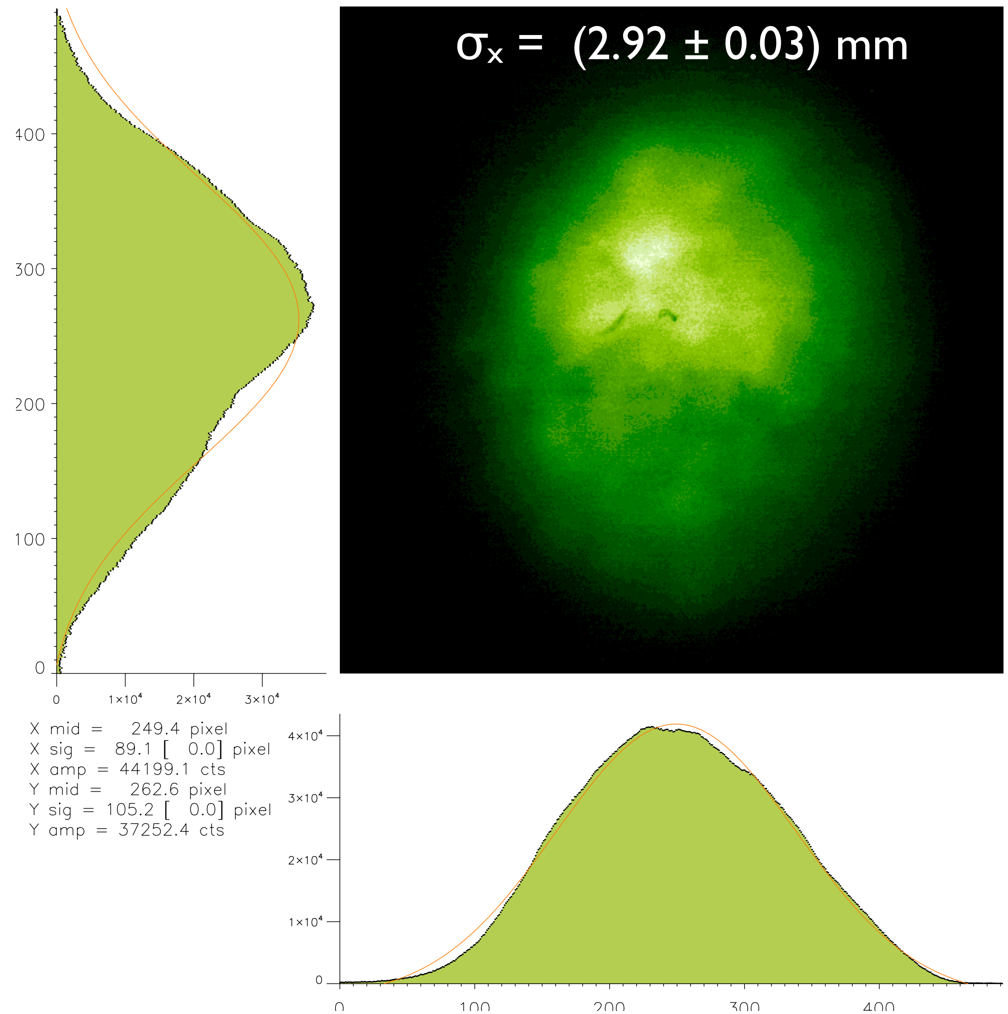
Beam Images & Profile Measurements

- Hot spots and non-uniformities discovered in the transverse beam image
- Verified beam size independent of bunch charge → emittance dominated beam

Focused beam

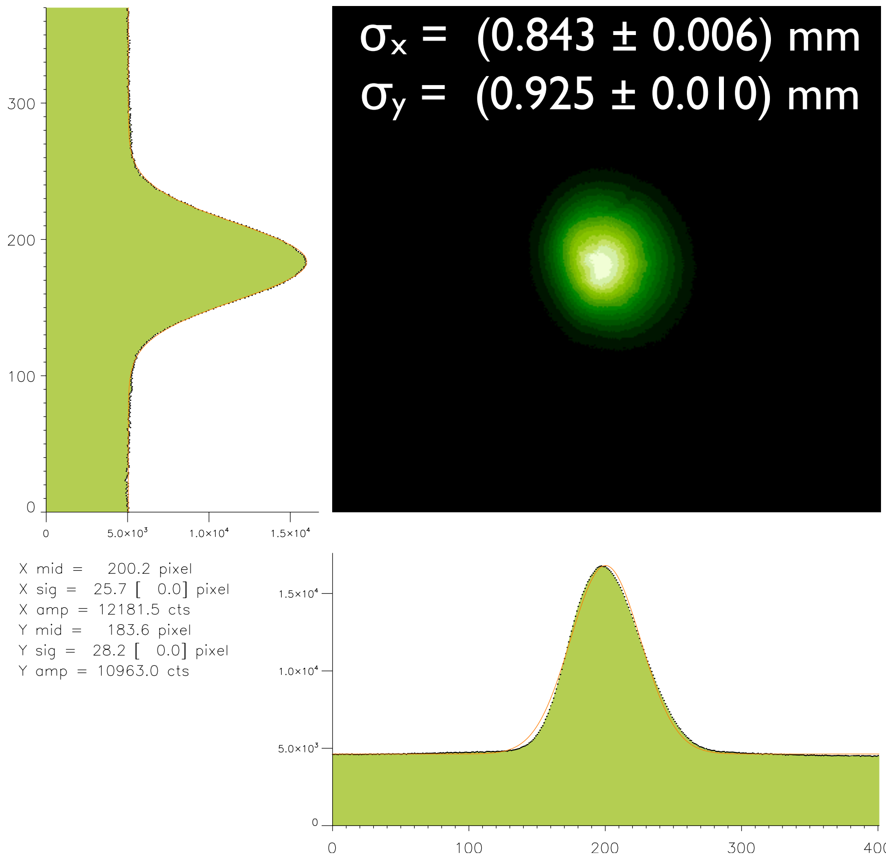


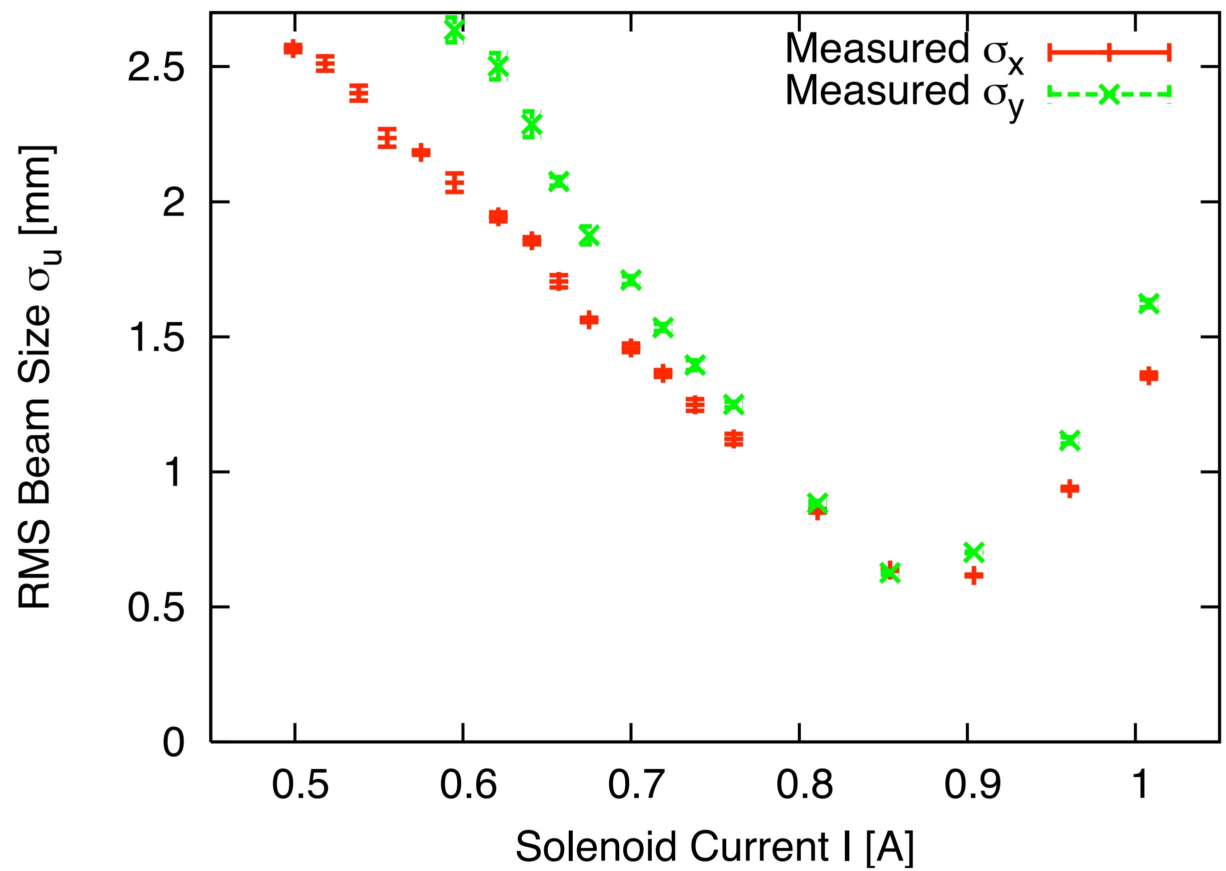
Defocused beam



Solenoid Scan (I)

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





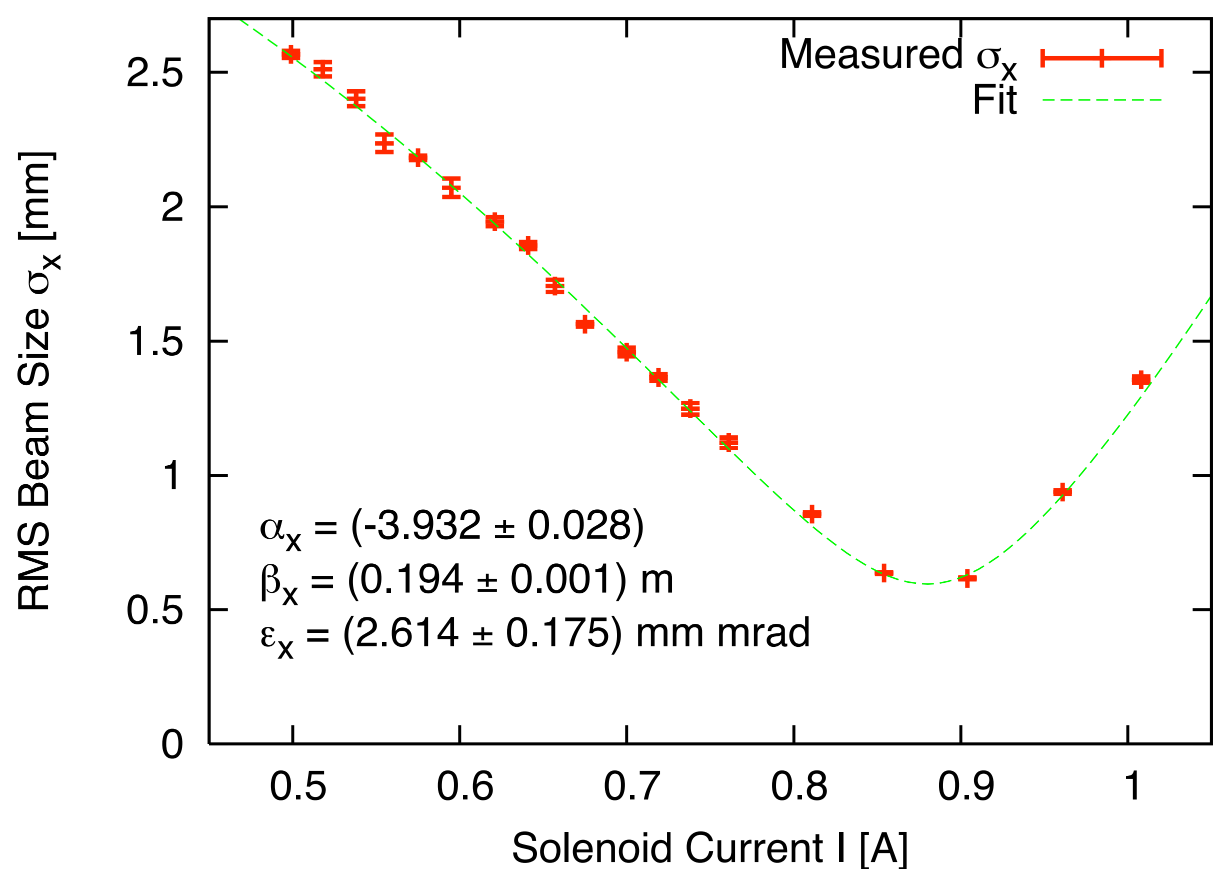
Solenoid Scan (II)

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

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

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

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

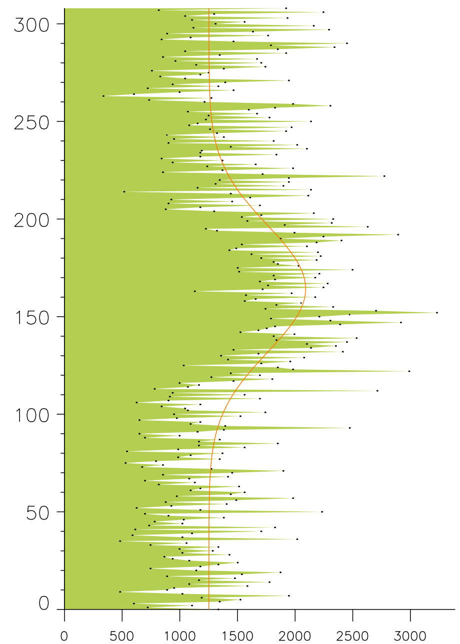


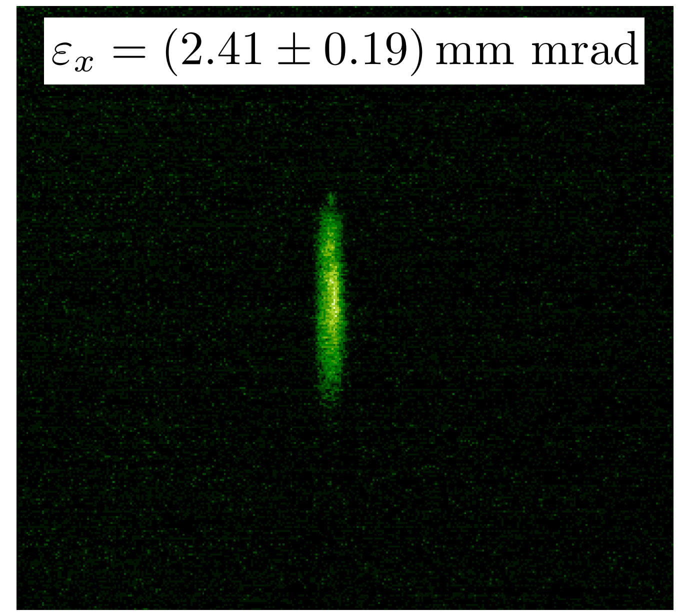
Alternative Emittance Measurement: Single Slit Method

- Measure beam size at location of the single slit insert (YAG screen)
  $\langle u^2 \rangle$

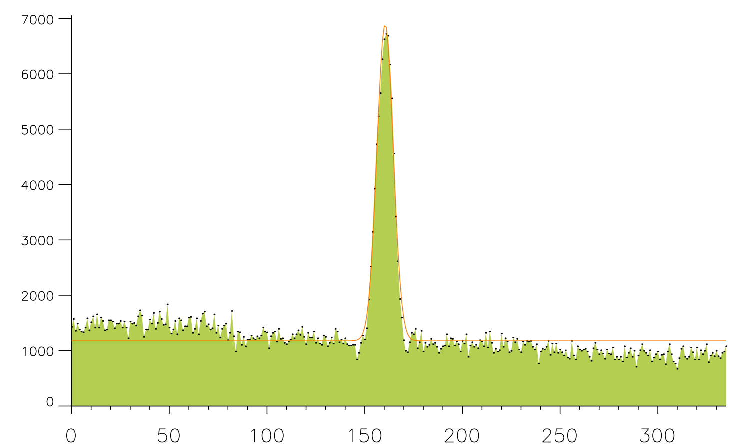
- Measure beamlet width σ_u downstream of a horizontal or vertical slit (P43)
  $$\langle \tilde{u}'^2 \rangle = \frac{\sigma_u^2}{L^2}$$

- If the linear correlation between divergence and position is removed emittance becomes a simple product of beam size and uncorrelated divergence spread
  $$u' \quad \longmapsto \quad \tilde{u}' = u' - m\,u$$
  $$\varepsilon_u = \sqrt{\langle u^2 \rangle \langle u'^2 \rangle - \langle uu' \rangle^2} \quad \longmapsto \quad \sqrt{\langle u^2 \rangle \langle \tilde{u}'^2 \rangle}$$





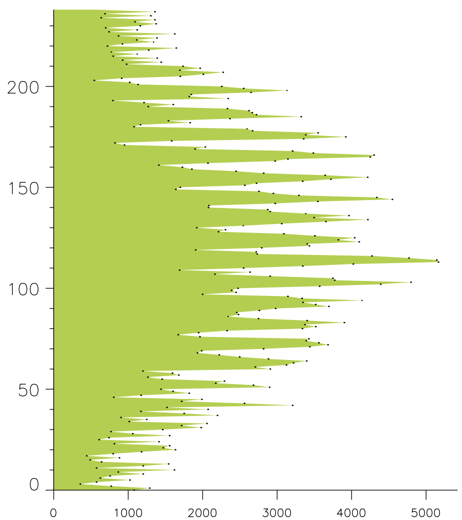
X mid = 160.4 pixel
X sig = 4.2 [0.0] pixel
X amp = 5718.2 cts
Y mid = 164.3 pixel
Y sig = 32.5 [0.0] pixel
Y amp = 839.0 cts

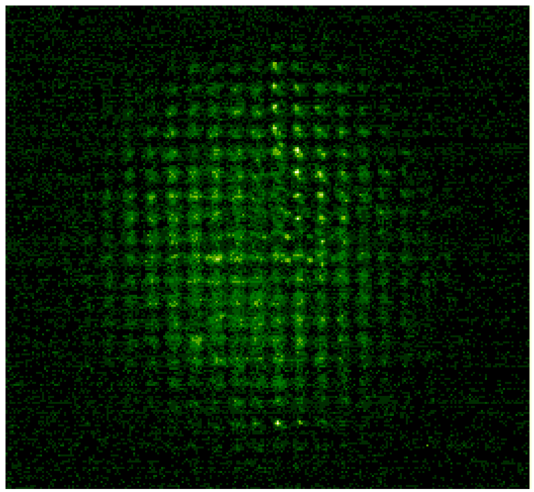


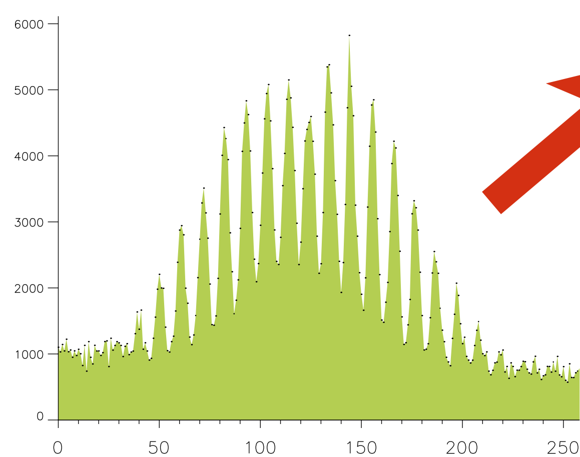
➡ Good agreement with solenoid scan results

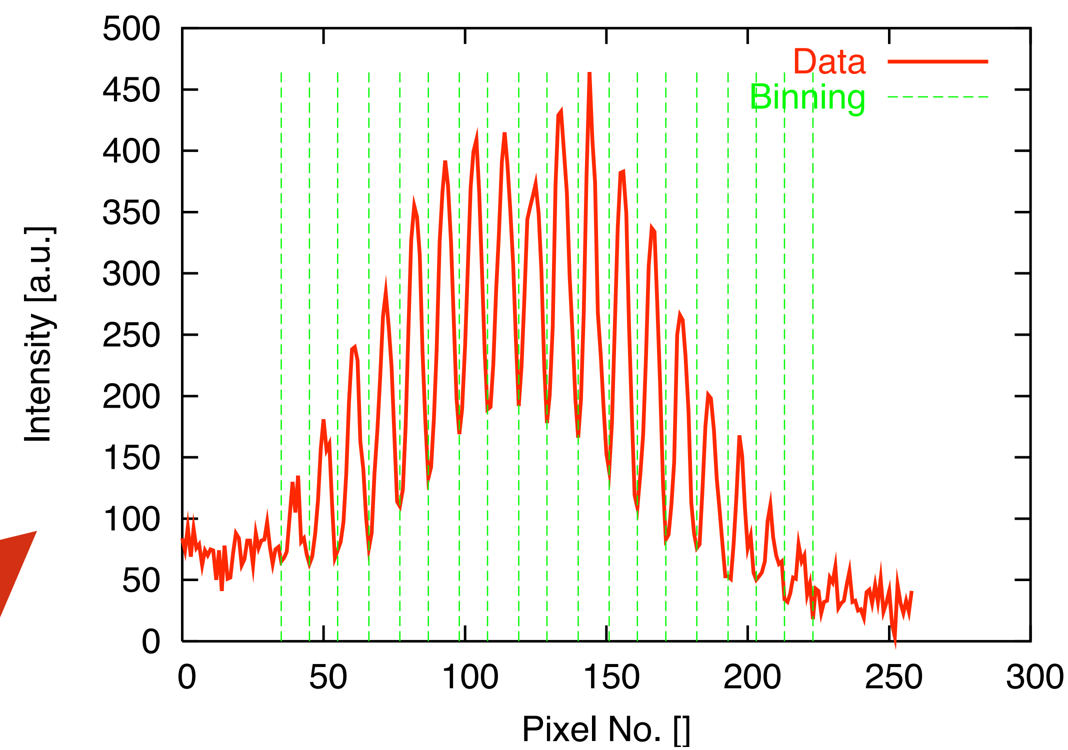
Emittance Measurements with a Pinhole Array (1)

- Measure beamlet images downstream of the pinhole array (P43 monitor)
- Calculate histogram of beamlet images and subtract background



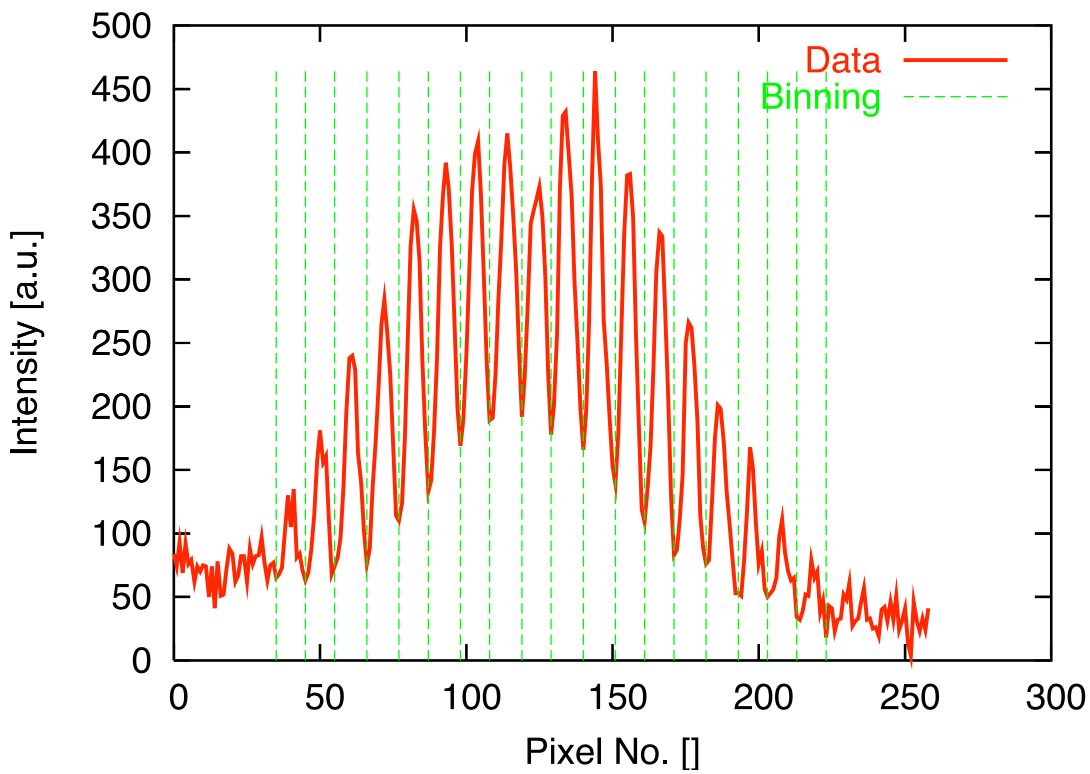


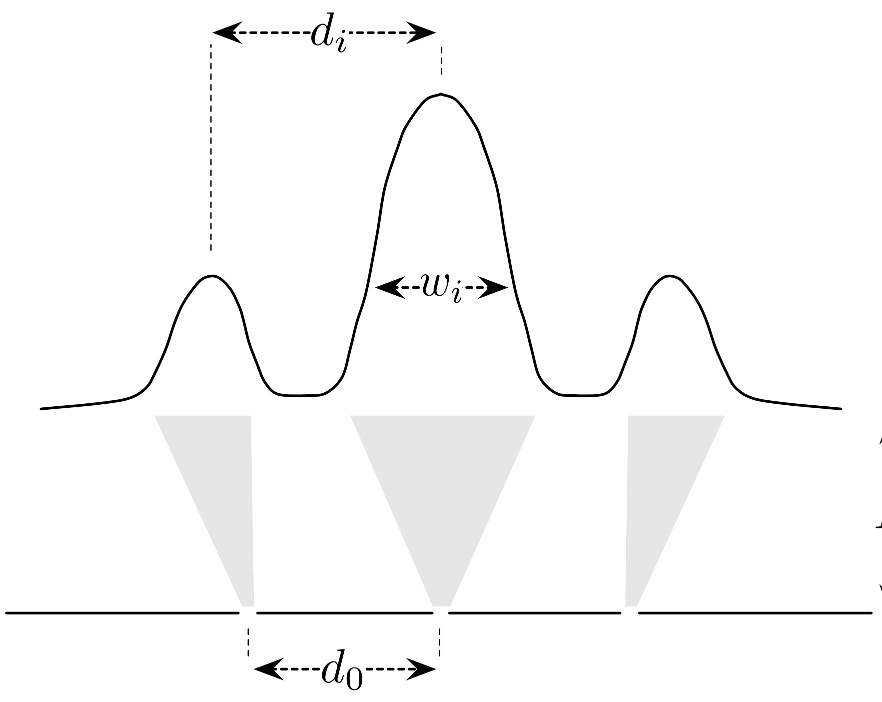




Emittance Measurements with a Pinhole Array (II)

- Divergence centroid for each bunch slice is given by shift of beamlet image centroid with respect to pinhole position
- Divergence spread of each bunch slice is given by width of beamlet image





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

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

Emittance Measurements with a Pinhole Array (III)

- 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 intensity weighted averages, calculate second order moments of distribution

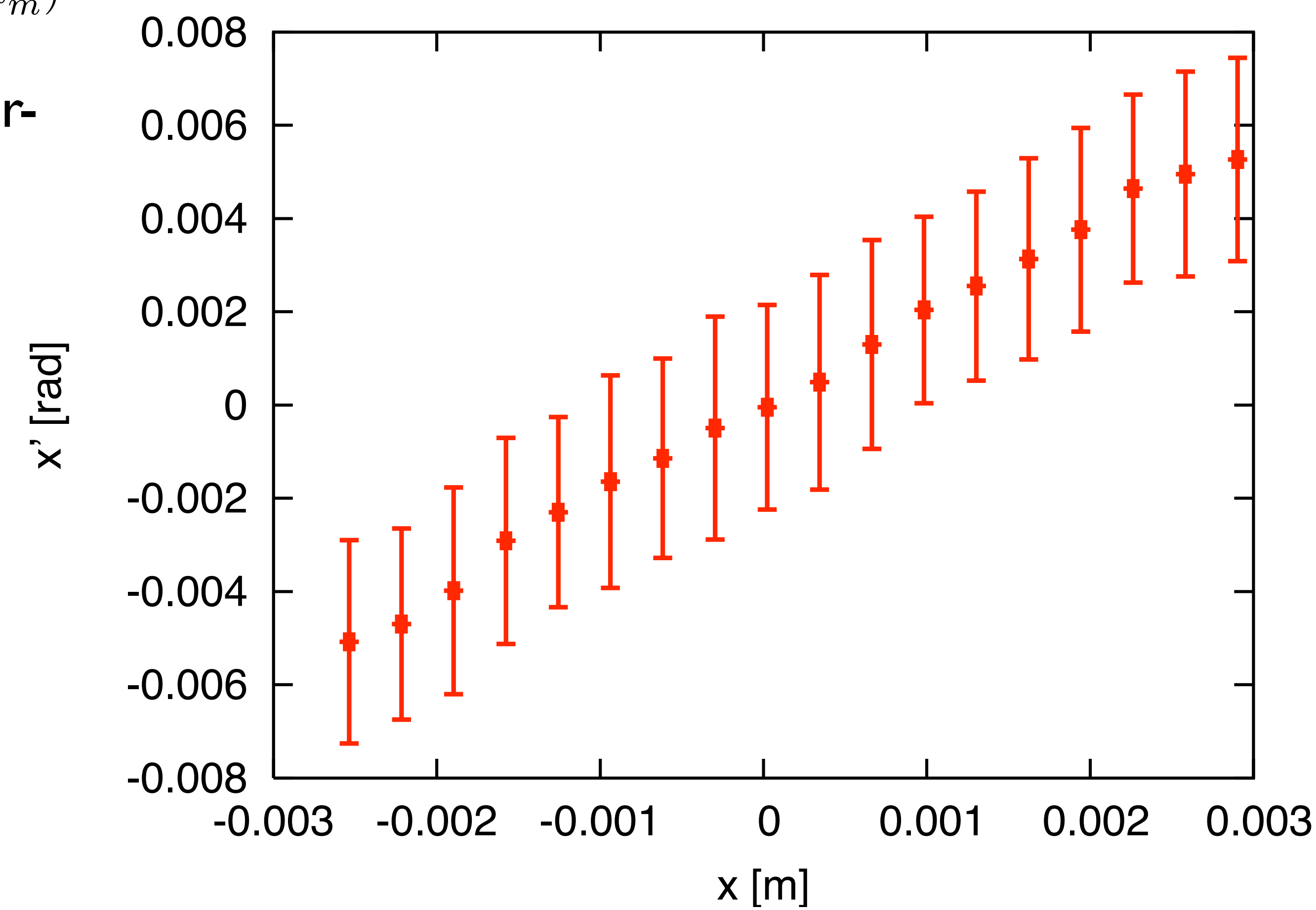
$$\langle u^2 \rangle = \frac{\sum_{m=1}^{N} I_m\, \bar{u}_m^2}{\sum_{m=1}^{N} I_m}$$

- Second order moments of distribution → ϵ, β, α

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

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

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



➡ Good agreement with other emittance measurement results

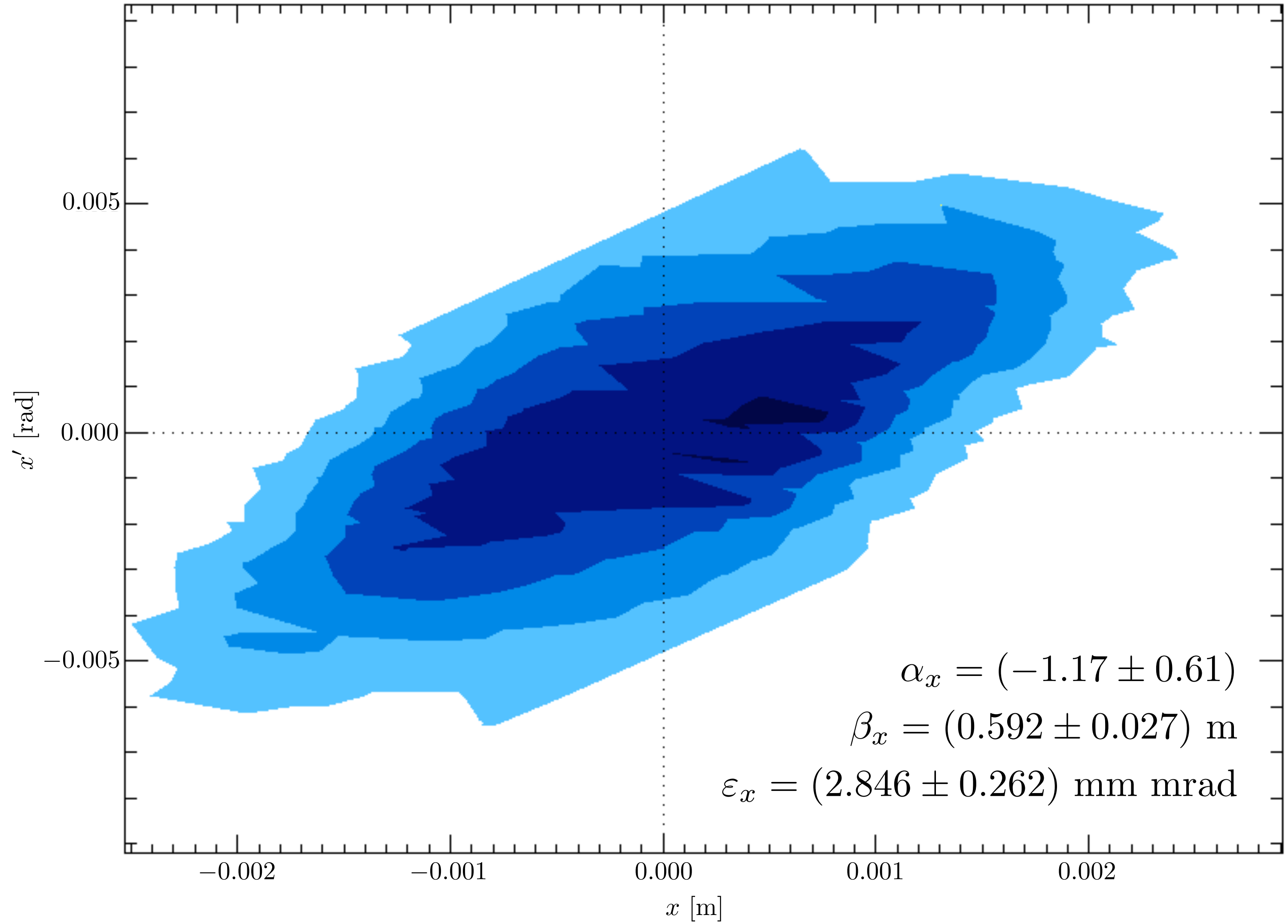
Reconstruction of Transverse Phase Space Density

- Drift between pinhole and screen is given by a simple mapping

$$\begin{pmatrix} u_0 \\ u_0' \end{pmatrix} \longmapsto \begin{pmatrix} u_0 + L\,u_0' \\ u_0' \end{pmatrix}$$

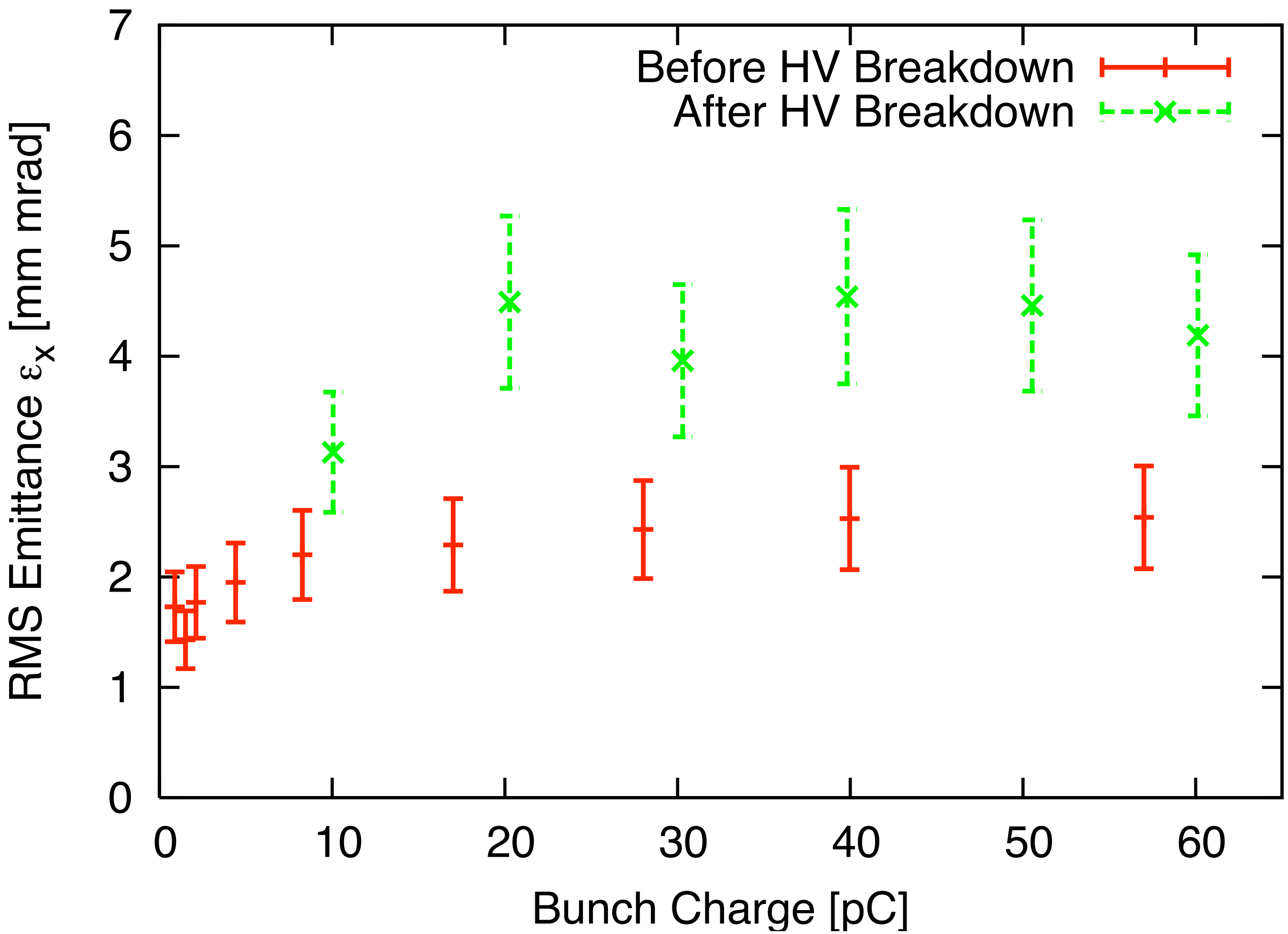
- Invert this function to map every pixel in the CCD image to an area in phase space

- Relative beamlet intensity → phase space distribution density



Emittance Studies I

- Emittance independent of bunch charge → emittance dominated beam (transition to space charge dominated beam expected at ~190 pC)
- HV breakdown causes FEA surface damage → non-uniform emission → emittance increase



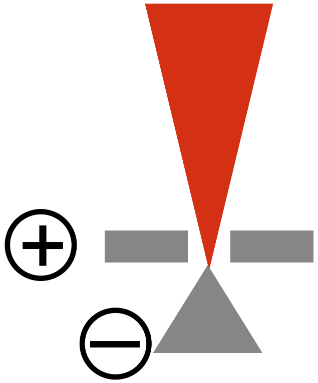
Emittance Studies II

Emittance dominated beam → source emittance conserved → estimate source divergence:

- Measured normalized transverse emittance: ϵ_x = 1 mm mrad
- E_{acc} = 40 keV
- U_g = 173 V
- σ_x = 0.3 mm (Gaussian beam emerging from FEA with r = 0.5 mm)

$$\sigma_{x'} = \frac{\sigma_{\gamma\beta_x}}{\beta} = \sigma_{\gamma\beta_x}\sqrt{\frac{m_e c^2}{2eU_g}} \approx \frac{\varepsilon_x^{(n)}}{\sigma_x}\sqrt{\frac{m_e c^2}{2eU_g}}$$

➡ $\sigma_{x'}$ = 130 mrad



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Conclusions & Outlook

- Test stand has been successfully commissioned and is fully operational
- Different measurement techniques deliver compatible results
- Test stand allows benchmarking of FEA cathodes 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 divergence → minimize source emittance
  - High tip density → increase bunch charge
  - Metallic substrate → reduce bulk resistance → increase peak current

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

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