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INVESTIGATION OF SLICE EMITTANCE USING AN ENERGY-CHIRPED ELECTRON BEAM IN A DISPERSIVE SECTION FOR PHOTO INJECTOR CHARACTERIZATION AT PITZ

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Thesis Disputation
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DESY
HELMHOLTZ ASSOCIATION

CONTENT

- Motivation for slice emittance measurements
- Photo Injector Test facility in Zeuthen (PITZ)
- Transverse emittance and measurement techniques
- Slice emittance diagnostics with an energy-chirped beam in a dispersive section
- Slice emittance simulation and measurement results
- Summary and conclusion

Motivation for slice emittance measurements

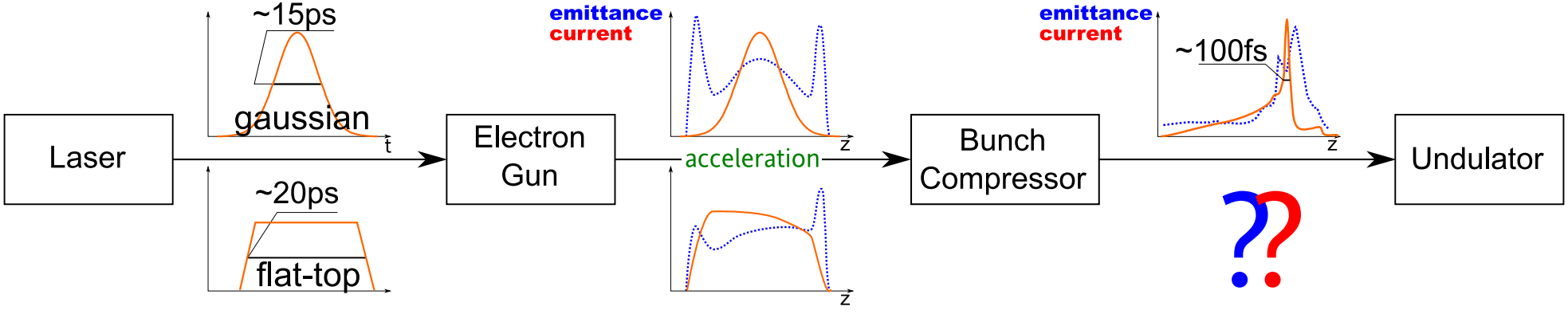
Linac based X-ray FELs require high-brightness electron beams

Electron beam brightness $B \sim \frac{\text{Charge } Q}{\varepsilon_{6D}}$ Charge density in phase space

emittance - beam phase space volume

Longitudinally resolved (slice) transverse emittance diagnostics

- Self Amplified Spontaneous Emission (SASE)



- **Photo injector is one of the best candidates for high-brightness electron beam generation**

  - **Laser pulse properties -> electron bunches:**
    flexible transverse and longitudinal shaping
    bunch charge via laser intensity

to counteract emittance growth, e.g. due to space charge

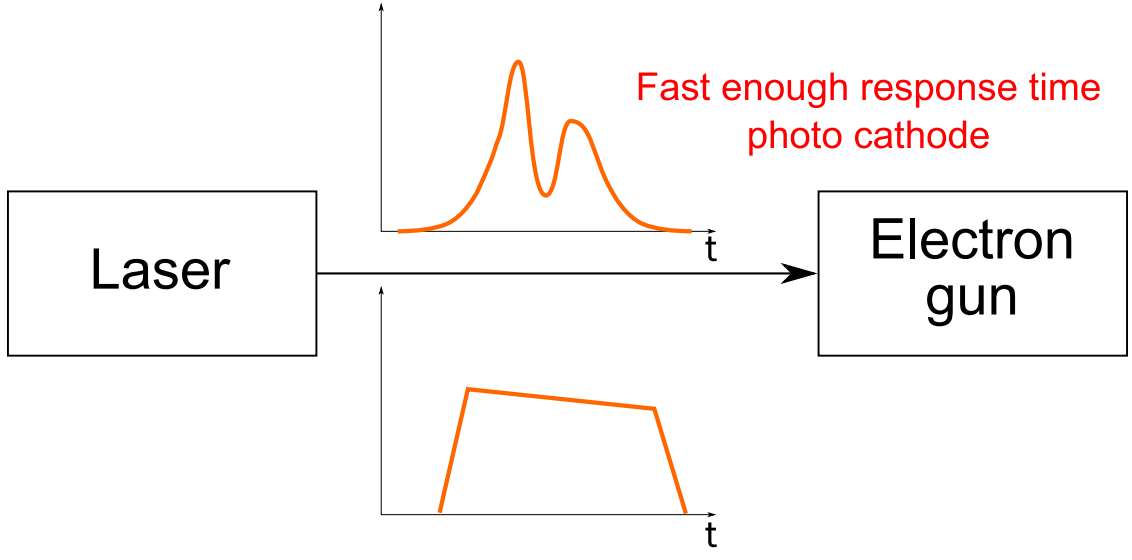
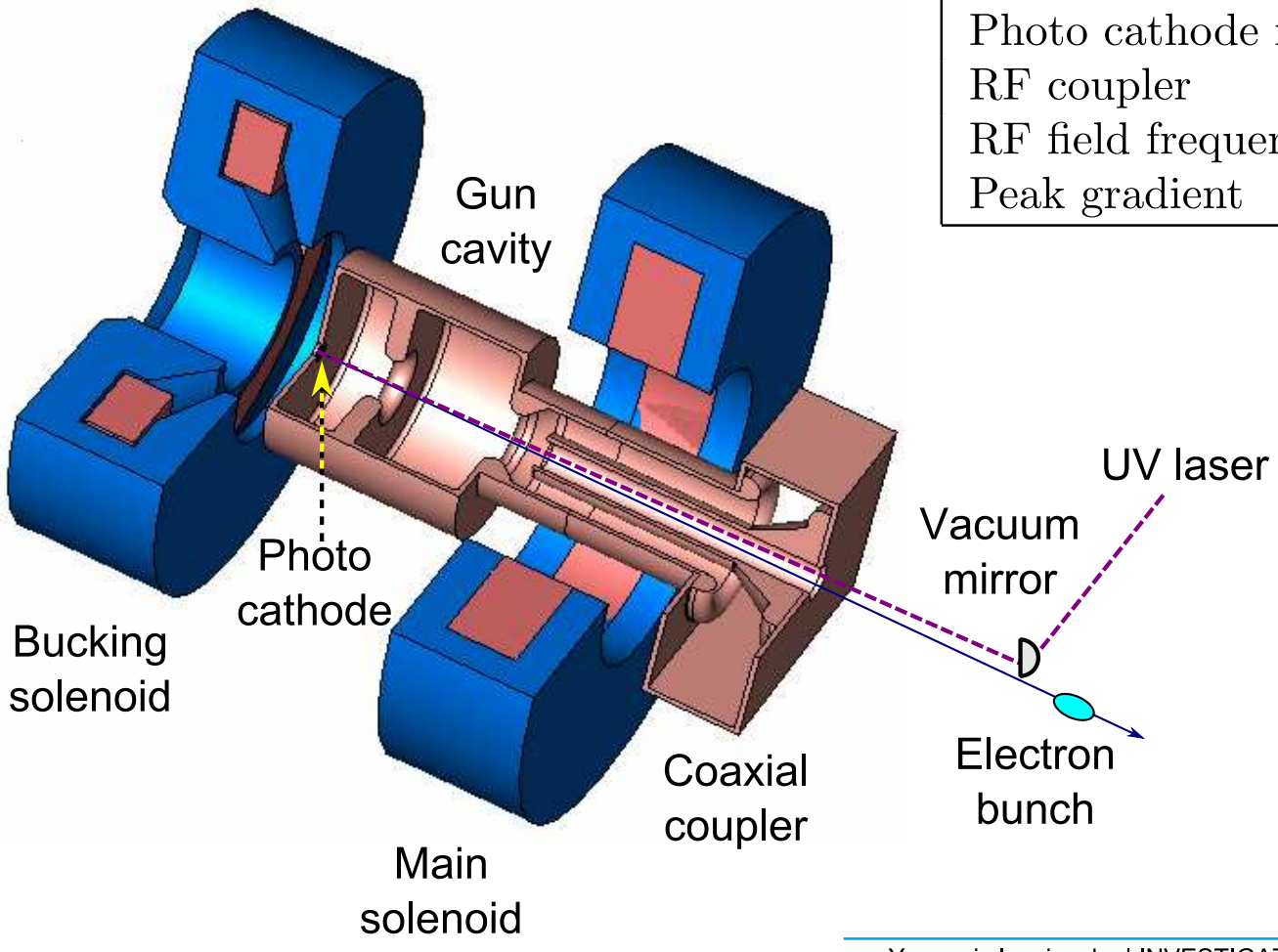


PHOTO INJECTOR TEST FACILITY IN ZEUTHEN

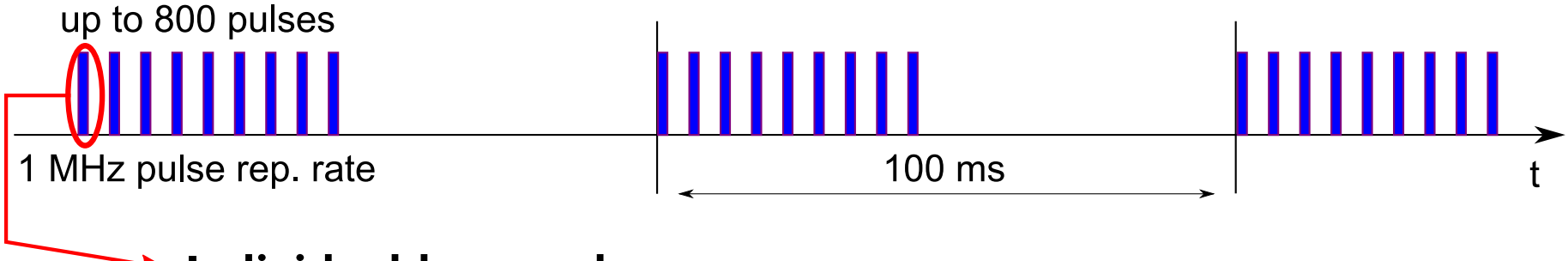
- **Characterization of the high brightness electron beam injectors for FLASH, injector optimization towards the European XFEL requirements**

RF cavity	1.6 cell
Photo cathode material	Cs_2Te
RF coupler	coaxial
RF field frequency	1.3 GHz
Peak gradient	60 MV/m



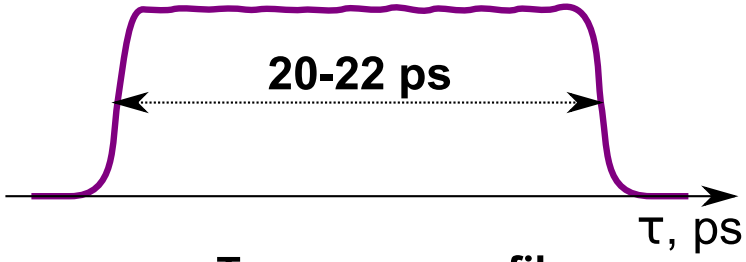
CATHODE LASER SYSTEM AND PULSE STRUCURE

Time structure of macro-pulses

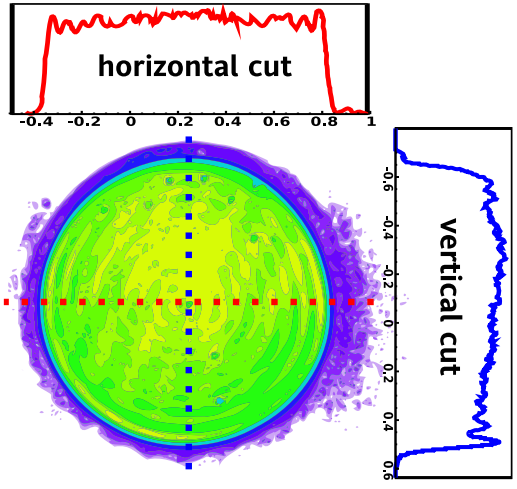


Individual laser pulse

Longitudinal profile



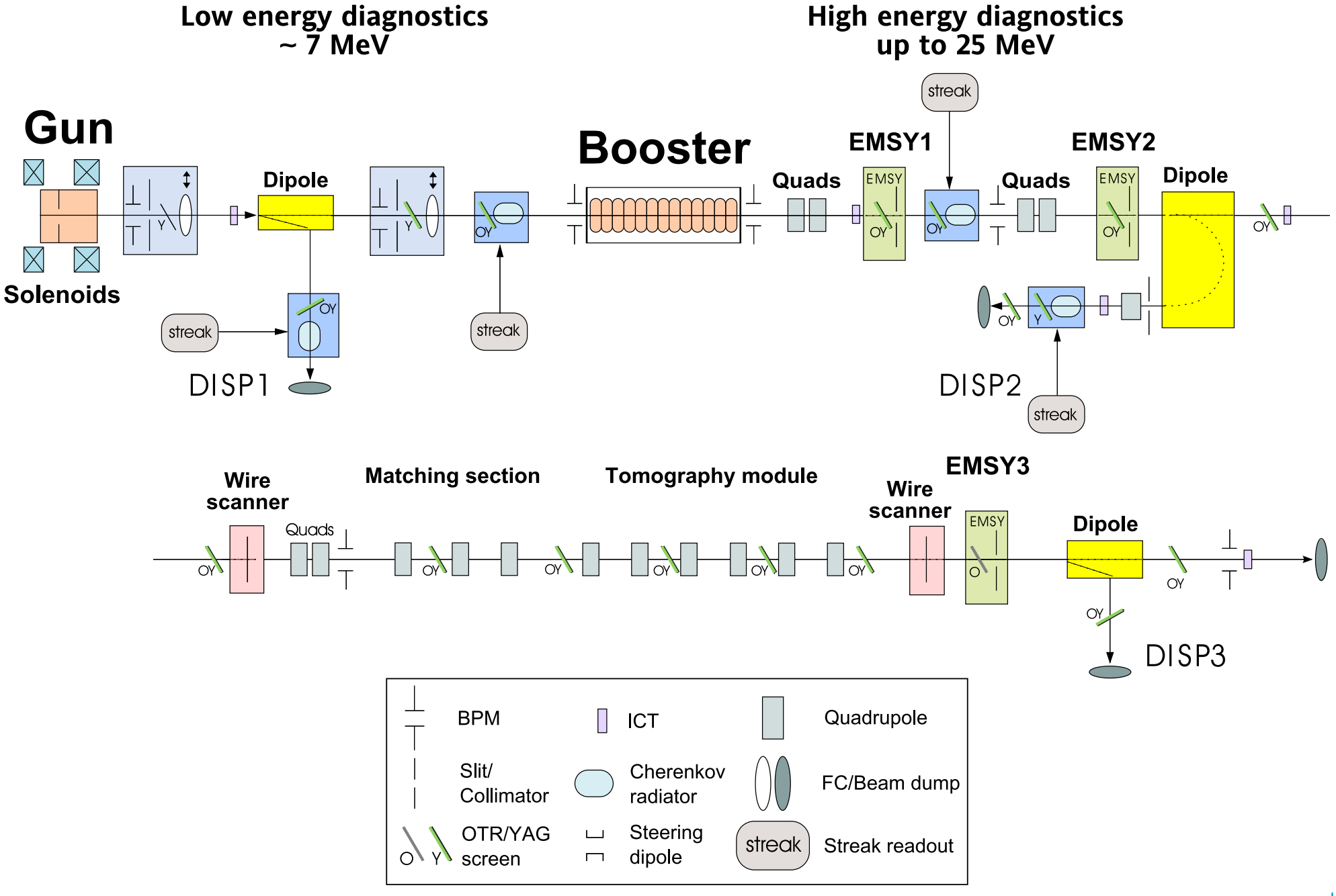
Transverse profile



Nominal parameters

Wavelength	257 nm
Temporal shape	flat-top
FWHM duration	22 ps
rise and fall times	2 ps
Transverse shape	flat-top
Transverse laser RMS spot size	0.0-0.5 mm
Pulse repetition rate	1 MHz
Max number of pulses in a train	800
Pulse energy	$\leq$10 μJ
Train repetition rate	10 Hz

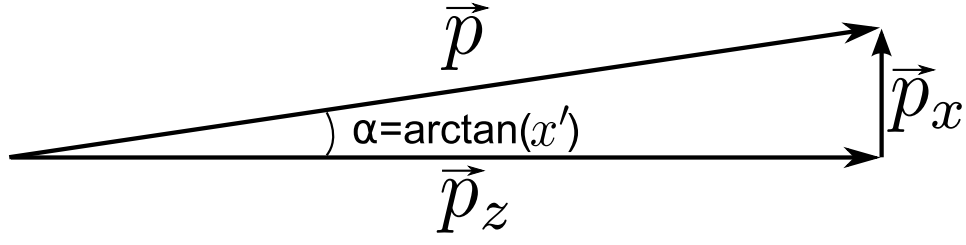
PITZ SETUP DIAGNOSTICS



TRANSVERSE EMITTANCE

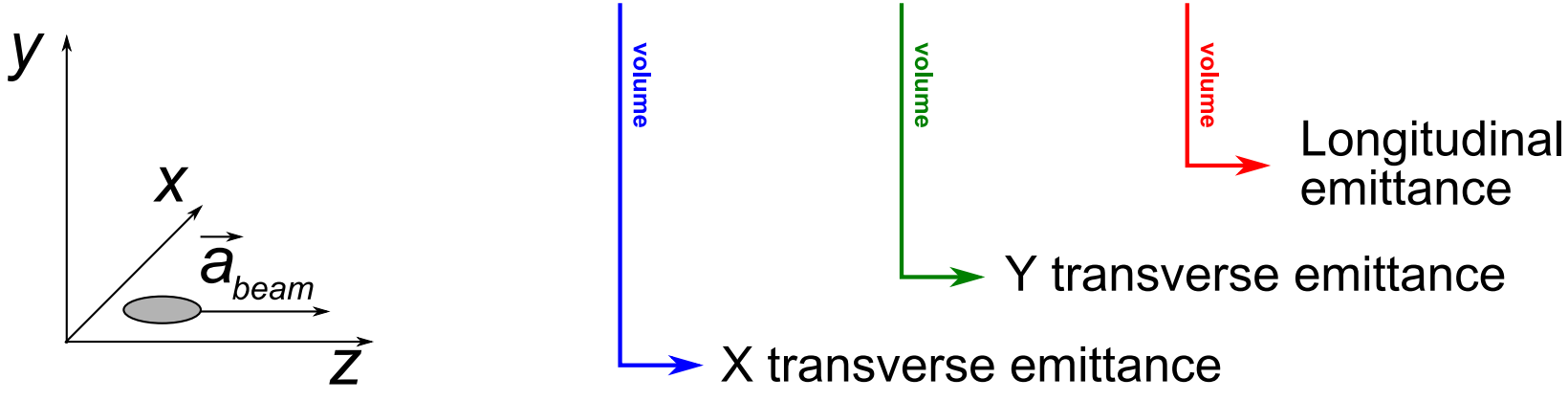
- **6D phase space beam distribution *f(x,y,z,p_x,p_y,p_z)***
- **Emittance is the volume of a phase space distribution**
  - If the momentum spread $\delta p \ll \bar{p}$, and $p_x \ll p_z$

$$p_x = x' \cdot p_z \approx x' \cdot \bar{p}$$



- **If x-y, y-z, z-x correlations are excluded:**

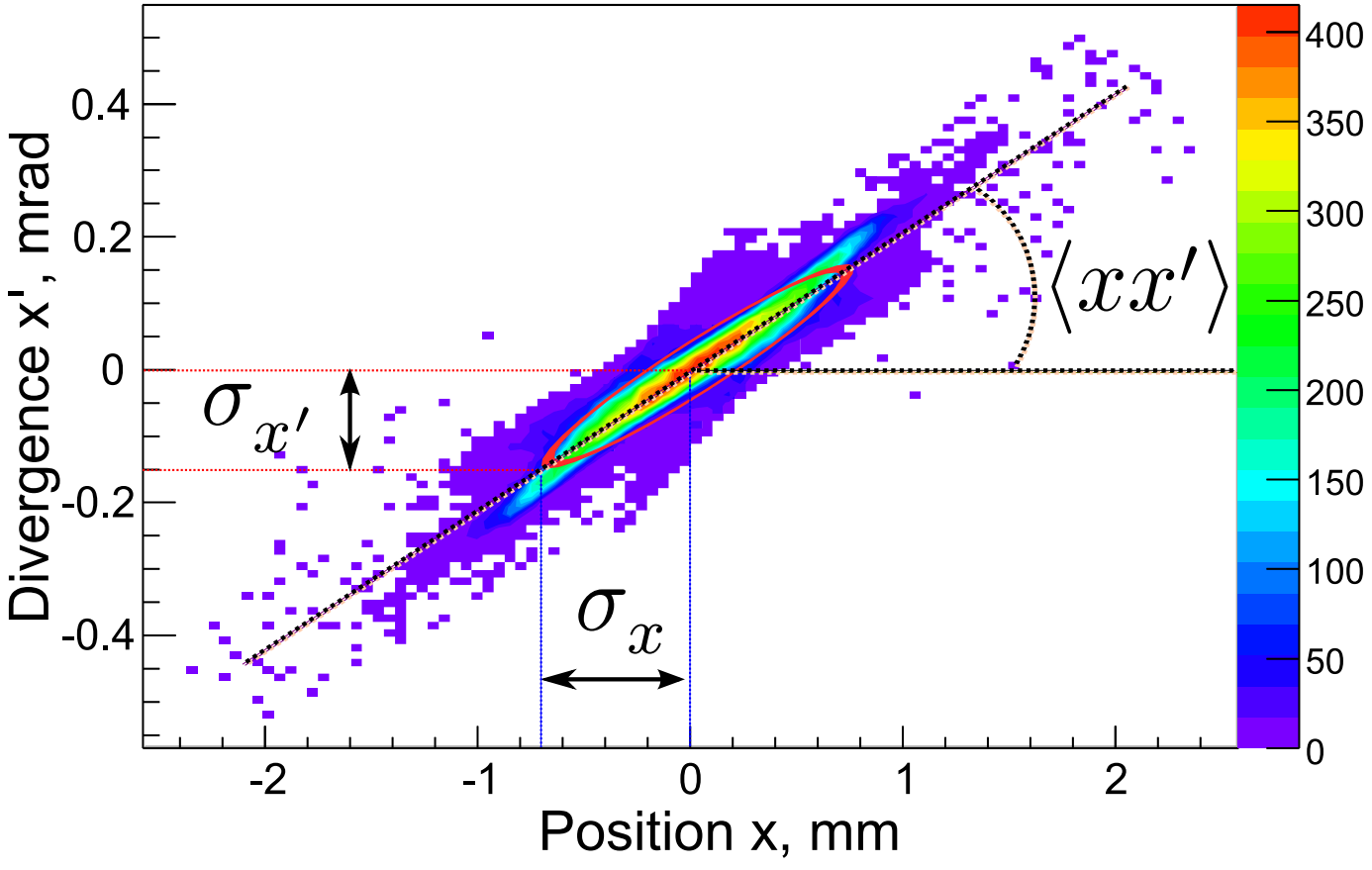
$$f(x, y, z, p_x, p_y, p_z) = X(x, \bar{p}x') \cdot Y(y, \bar{p}y') \cdot Z(z, p_z)$$



- **Normalized RMS emittance:**

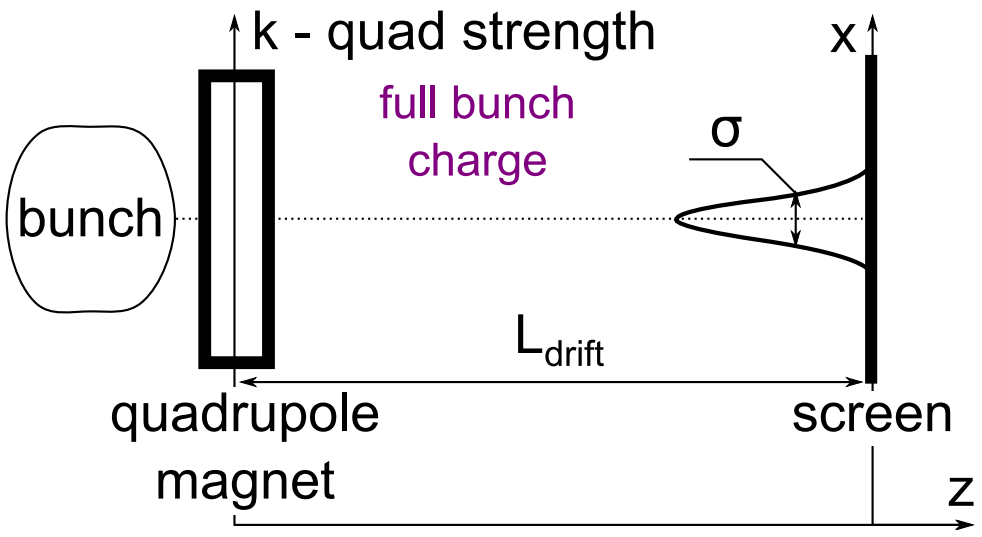
$$\varepsilon_x = \beta\gamma\sqrt{\sigma_x^2\sigma_{x'}^2 - \langle xx' \rangle^2}$$

mean momentum normalization



TECHNIQUES OF EMITTANCE MEASUREMENTS

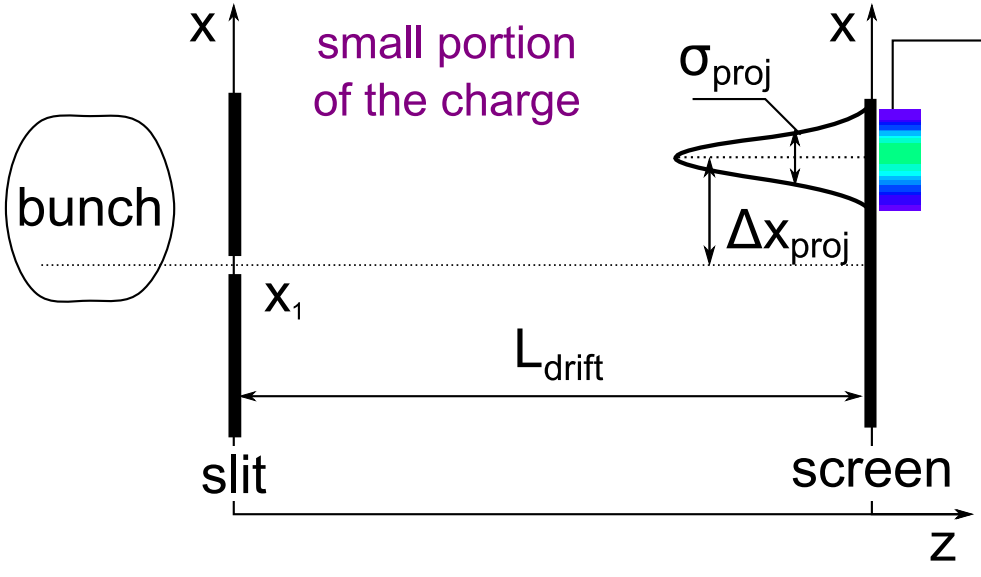
Quadrupole scan

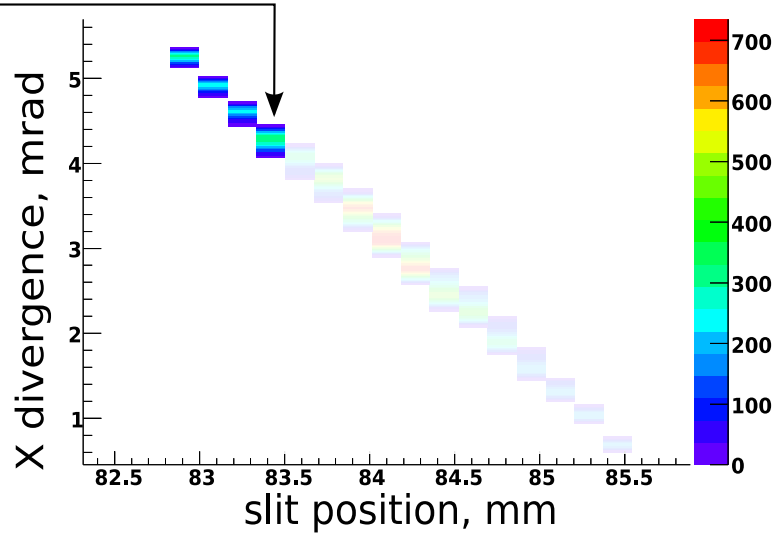


Linear transport model

$$\begin{pmatrix} \sigma^2_{x1} \\ \sigma^2_{x2} \\ \sigma^2_{x3} \end{pmatrix}_{scr} = \begin{pmatrix} M^{11}_{k1} M^{12}_{k1} M^{13}_{k1} \\ M^{11}_{k2} M^{12}_{k2} M^{13}_{k2} \\ M^{11}_{k3} M^{12}_{k3} M^{13}_{k3} \end{pmatrix} \begin{pmatrix} \sigma^2_x \\ \langle xx' \rangle \\ \sigma^2_{x'} \end{pmatrix}_{quad}$$

Slit scan

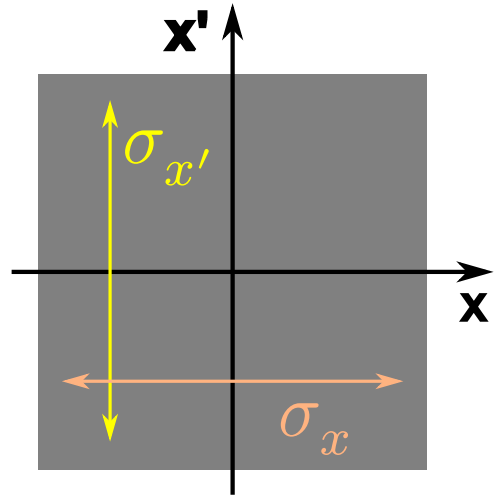


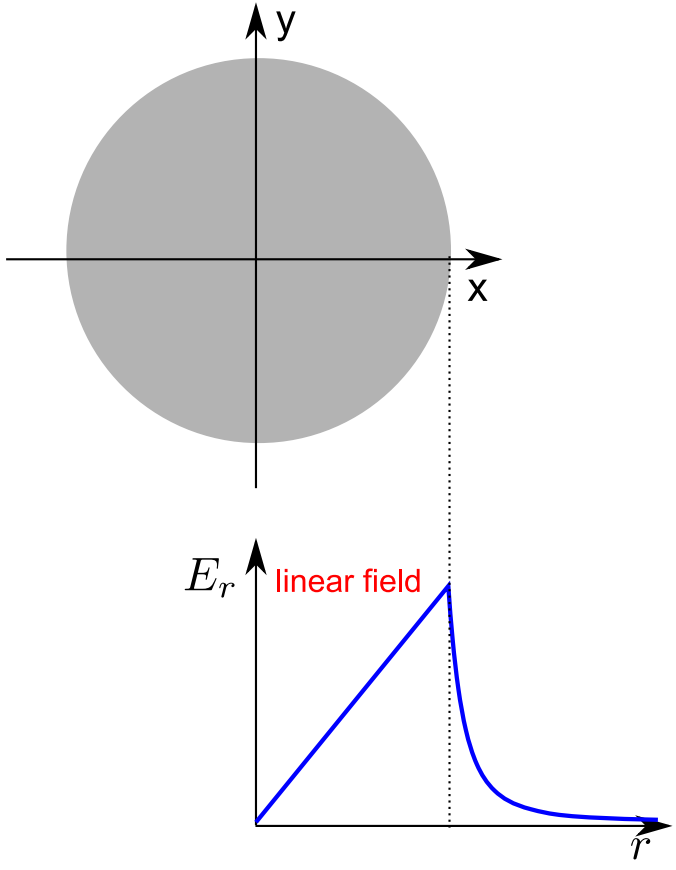


EMITTANCE EVOLUTION IN RF PHOTO INJECTOR

Thermal emittance - initial emittance at the cathode

- Laser transverse profile σ_x
- Laser wavelength and photo cathode material $\sigma_{x'}$





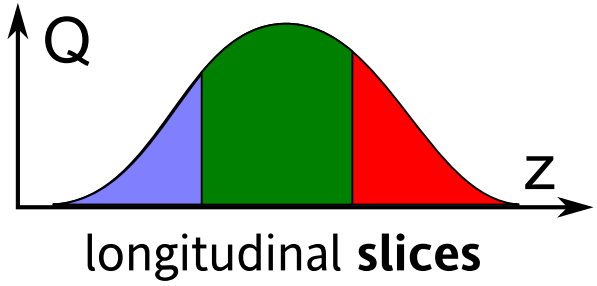
Isotropic particle emission

Homogeneous transverse distribution

Linear defocusing by space charge does not change emittance

But different space charge strength along the bunch introduces correlations in x-z and y-z planes

Longitudinal gaussian profile



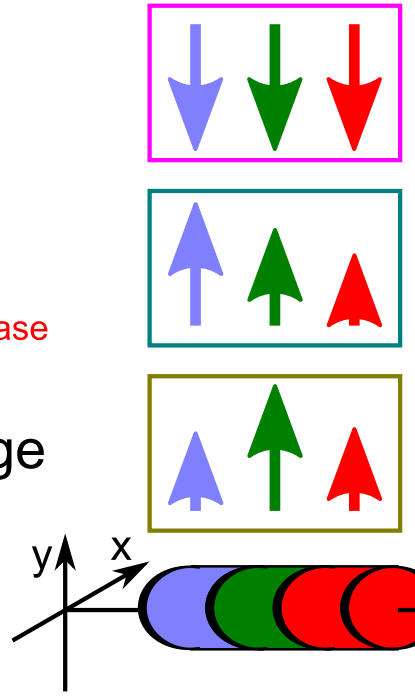
Transverse force

Solenoid

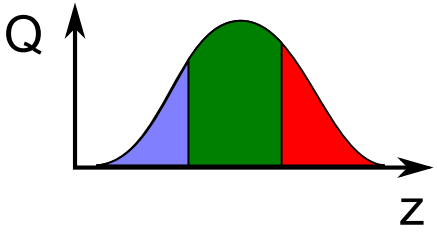
RF

depends on the phase

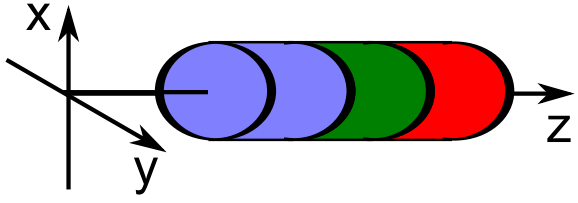
Space charge



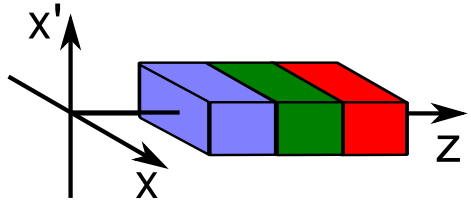
Long. intensity distribution



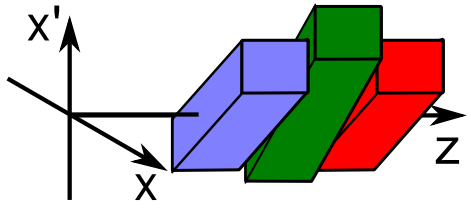
laser shape



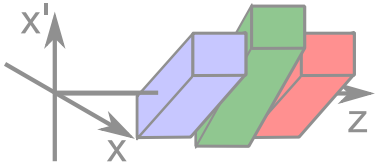
at the cathode

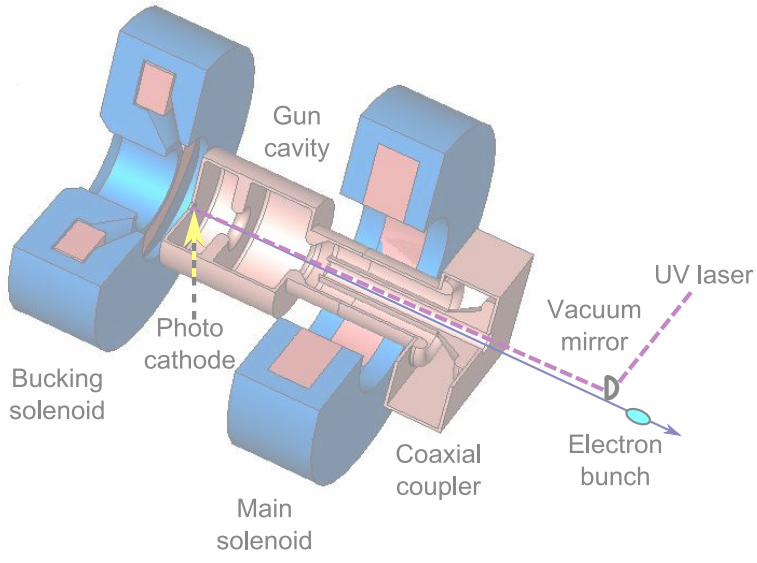


after a drift

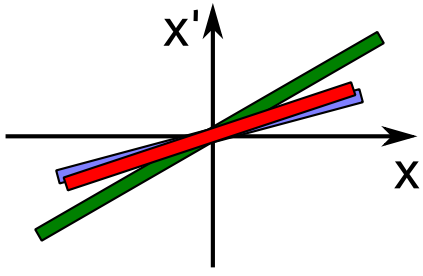


SOLENOID COMPENSATION OF EMITTANCE

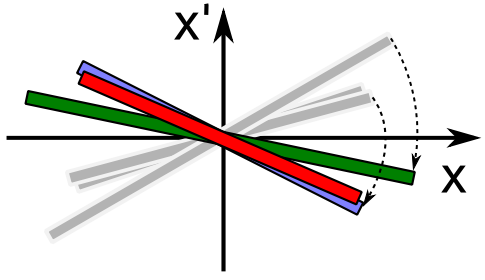




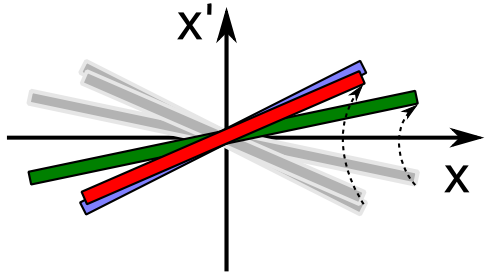
Mismatch due to space charge



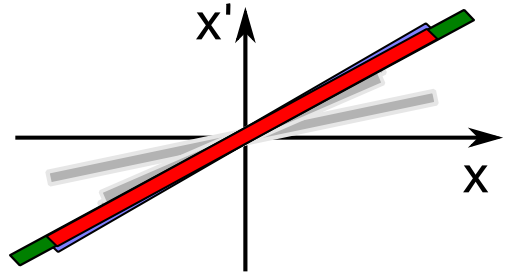
Solenoid focusing kick



Space charge dominated focus



Stronger space charge in the middle leads to rematching



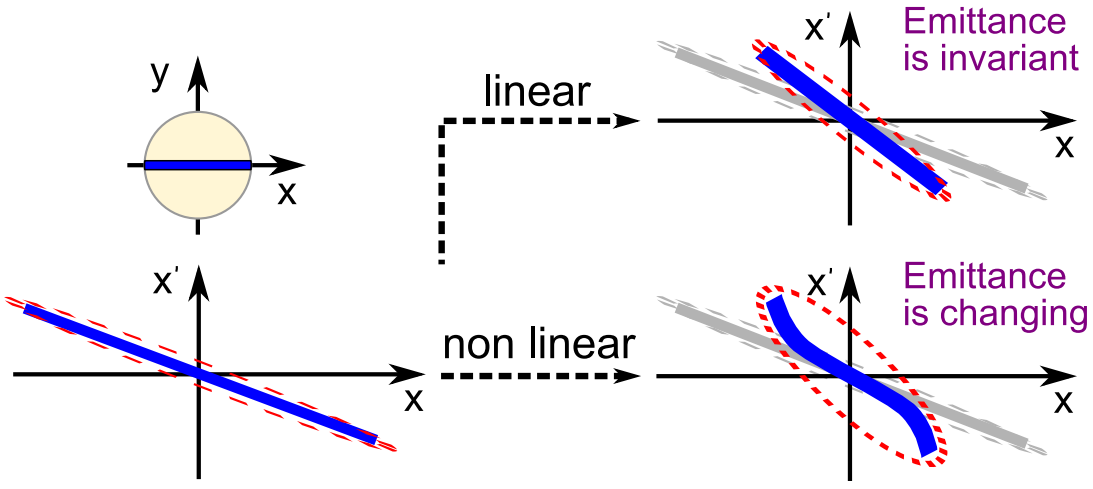
Goals of slice emittance measurements:

Individual emittance of slices

Match of slices in phase space

NON-LINEAR TRANSFORMATION IN PHASE SPACE

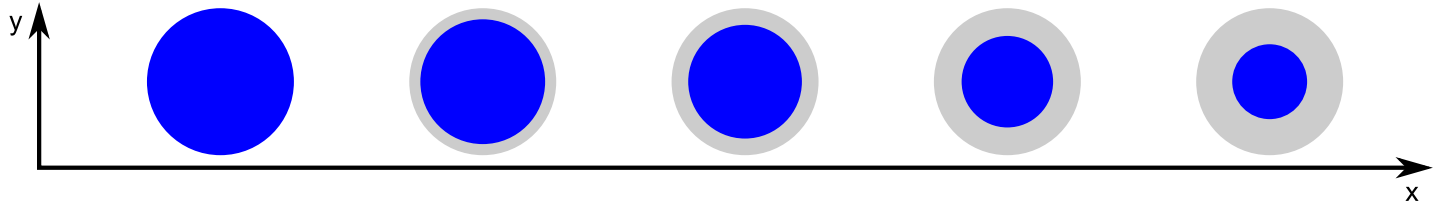
Slice phase space transformations



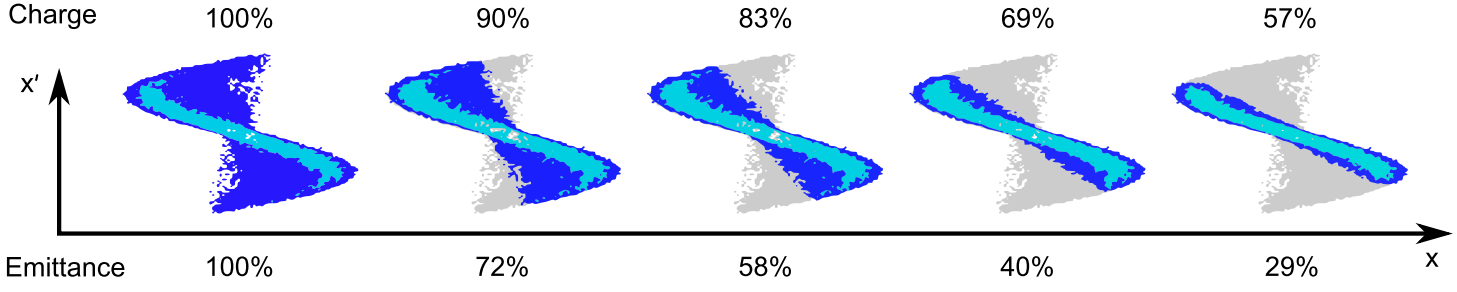
Local transverse RMS emittance can change due to non-linear effects

Simulation results

Transverse distribution at the cathode

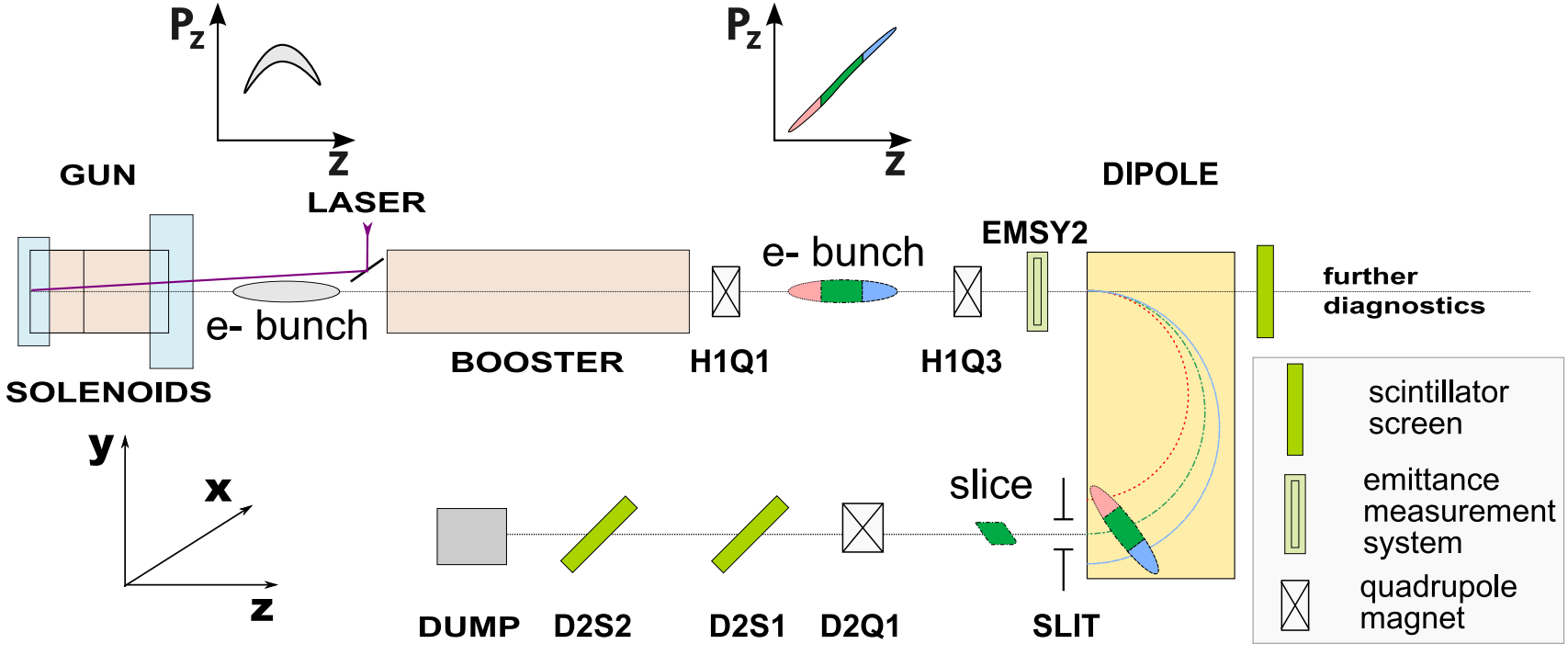


Corresponding phase space of a longitudinal slice at 5m downstream from the cathose

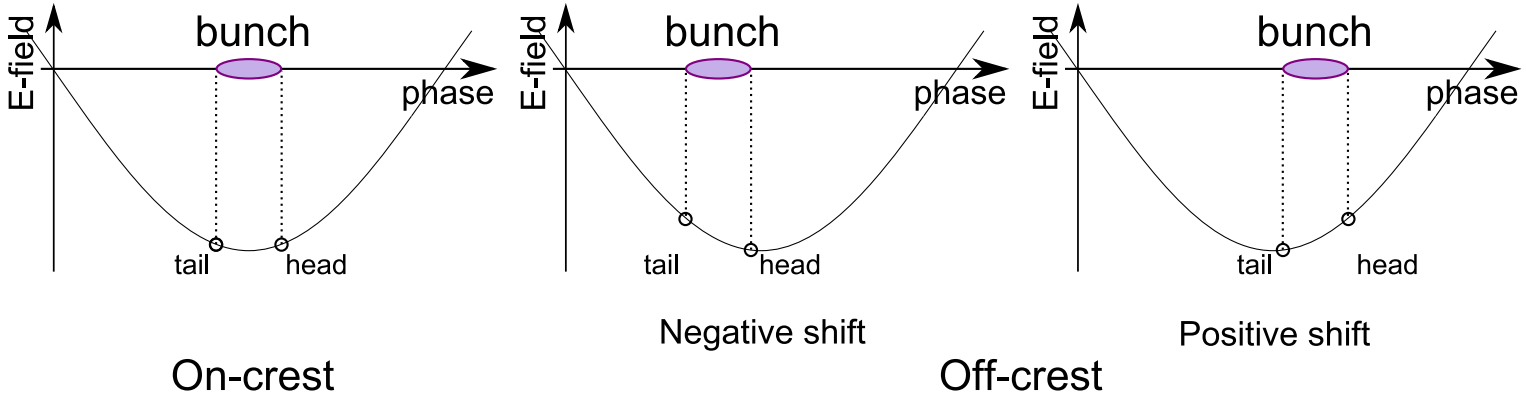


SLICE EMITTANCE MEASUREMENT SETUP

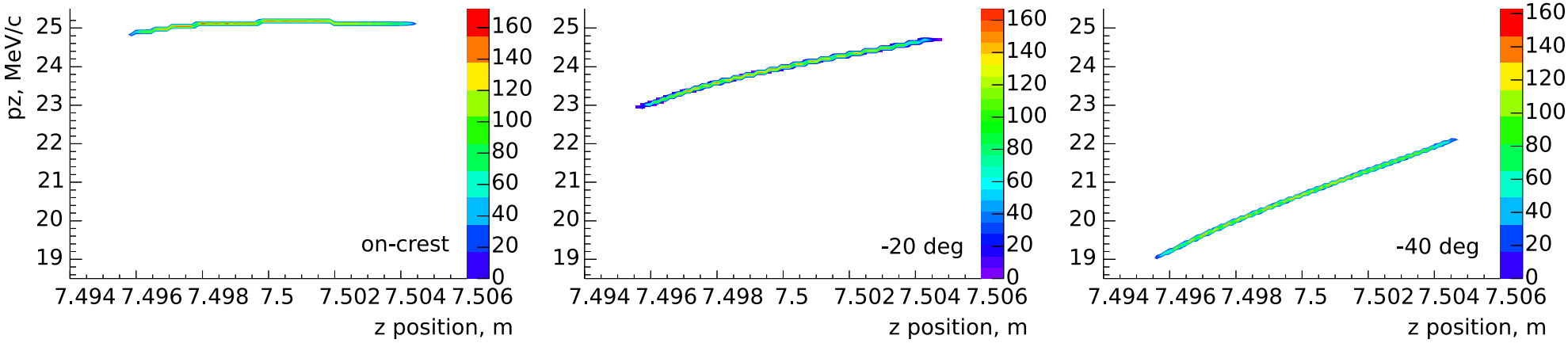
- **Slice emittance measurement:**
  - A beam is first accelerated off-crest in the booster
  - The beam longitudinal distribution is rotated into transverse one (vertical) in a dipole
  - A part of the beam is cut out by a slit at the dipole exit and its emittance is measured



The phase choice for acceleration in the booster



Simulated longitudinal phase space distributions



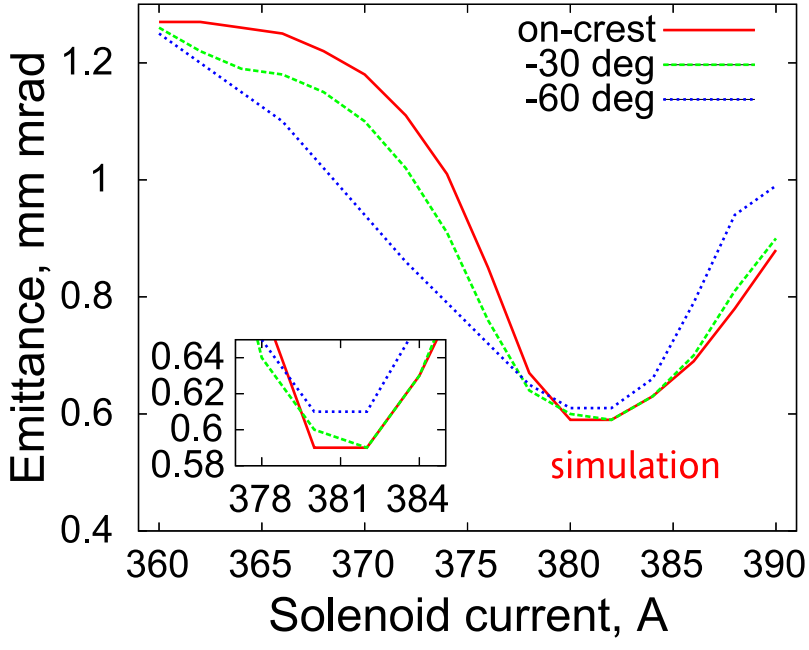
BEAM EMITTANCE AT OFF-CREST PHASES

Average slice emittance: $\varepsilon_{av} = \sum_{i=1}^{n} w_i \cdot \varepsilon_i$

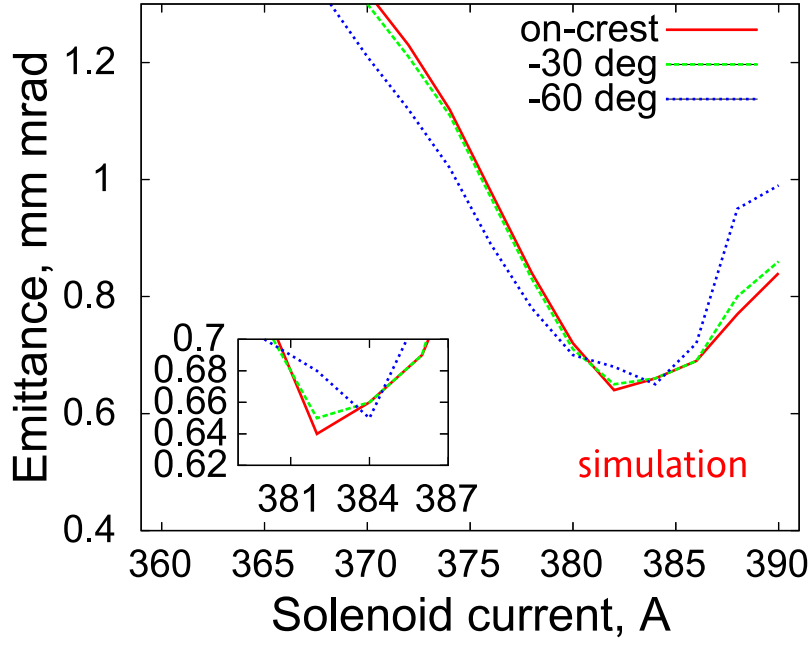
Peak current slice emittance: $\varepsilon_{pk} = \varepsilon_k,\ where\ I_k = max(I_1, I_2, \cdots, I_n)$

Slice emittance at the position of H1Q3 for different phases off-crest

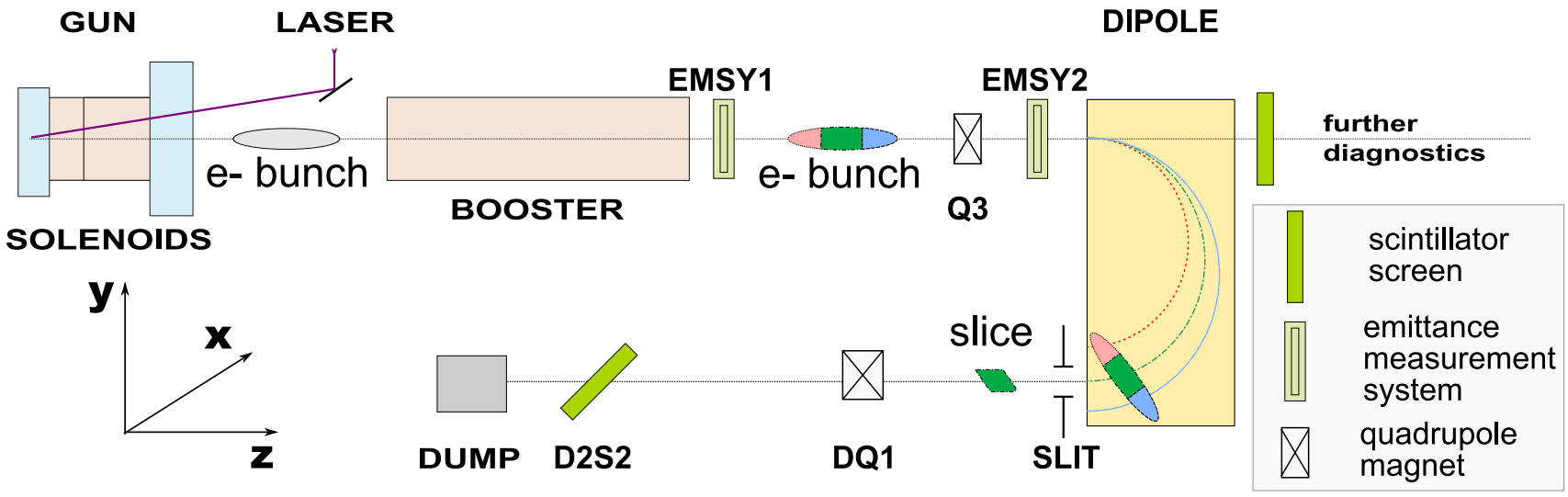
Average slice emittance



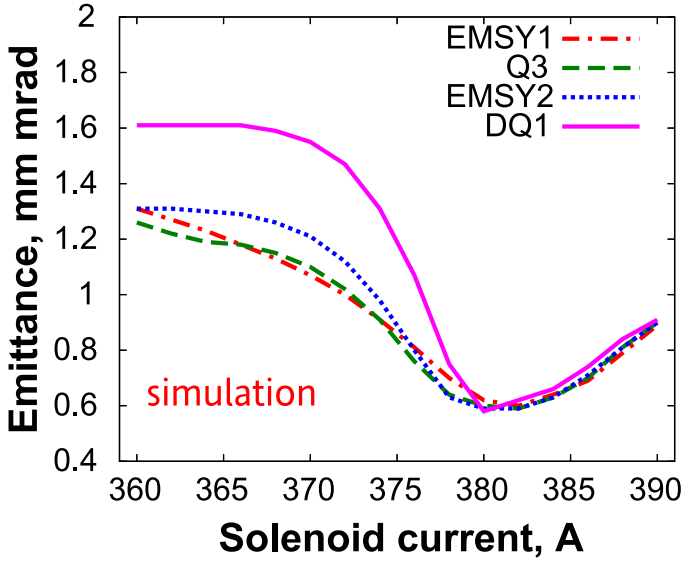
Peak current slice emittance



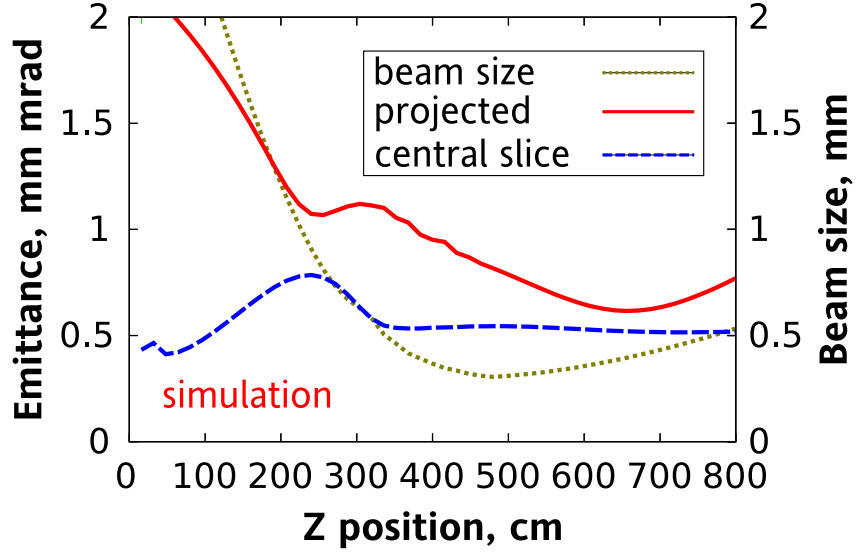
SCHEMES OF EMITTANCE MEASUREMENTS



Slice emittance -30 deg off-crest

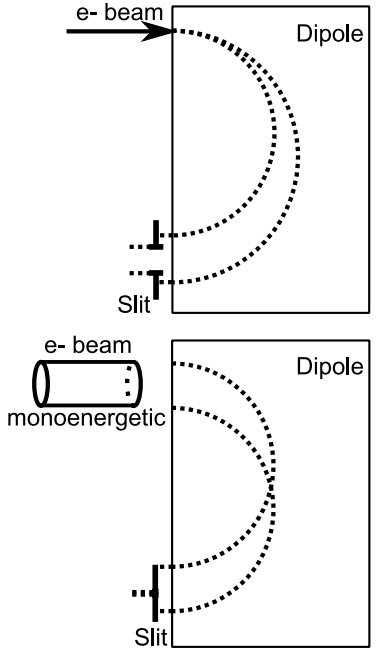


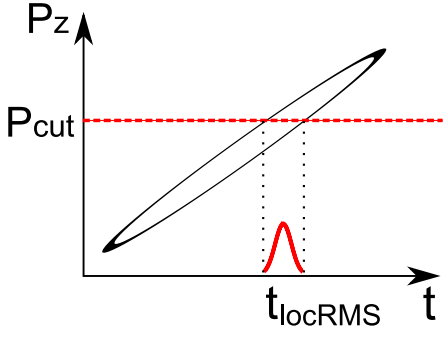
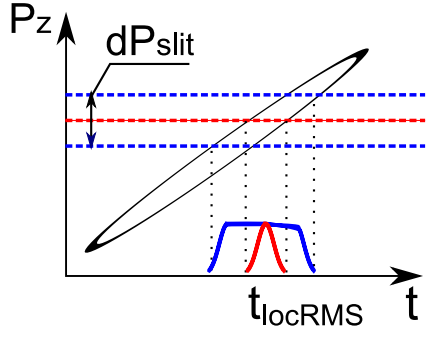
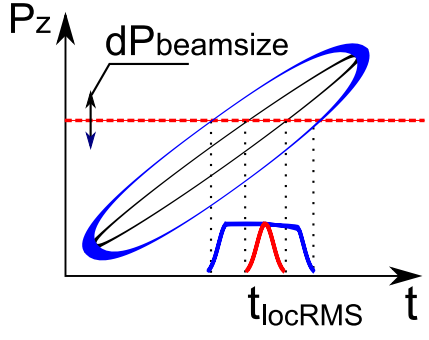
Beam size, projected and slice emittance along the setup



Main contributions to the resolution

- Correlated momentum spread (booster phase)
- The longitudinal phase space "thickness"
- The slit at the dipole exit
- The beam size at the dipole entrance



transv. size	infinitely small	infinitely small	finite
slit opening	infinitely small	finite	infinitely small
mom. spread	finite	finite	finite
Longitudinal phase space			

TIME RESOLUTION

$$\zeta = \frac{\tau}{t_{RMS}} = \sqrt{\left(\frac{z_{locRMS}}{z_{RMS}}\right)^2 + \frac{(w_{slit}/(2\sqrt{3}))^2 + \sigma_y^2}{(2R\frac{p_{RMS}}{\overline{p}})^2}}$$

Time resolution to bunch length ratio

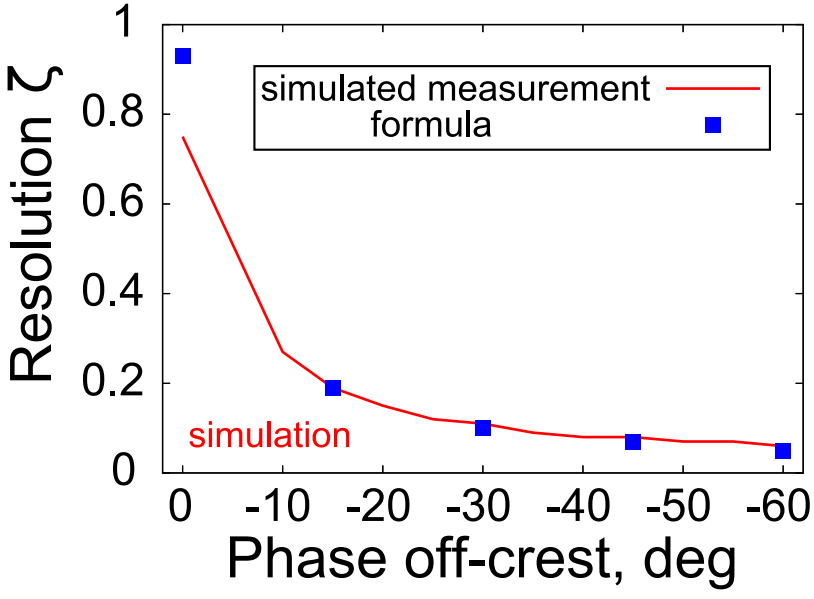
long. ph. sp. "thickness"

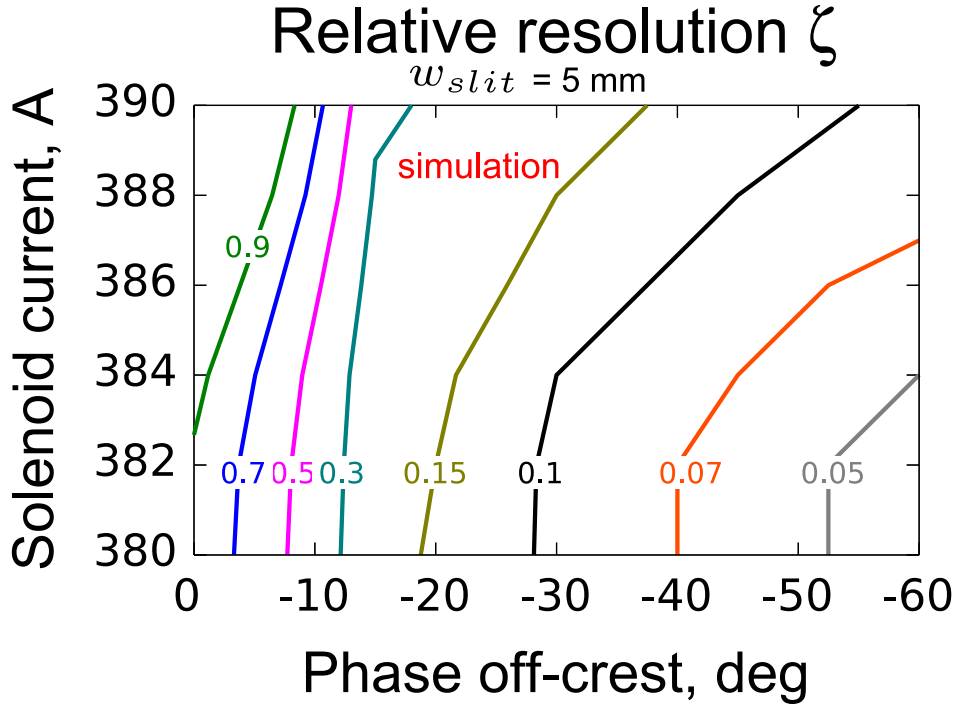
negligible for phases < -10 deg

slit width

mom. spread

beam size





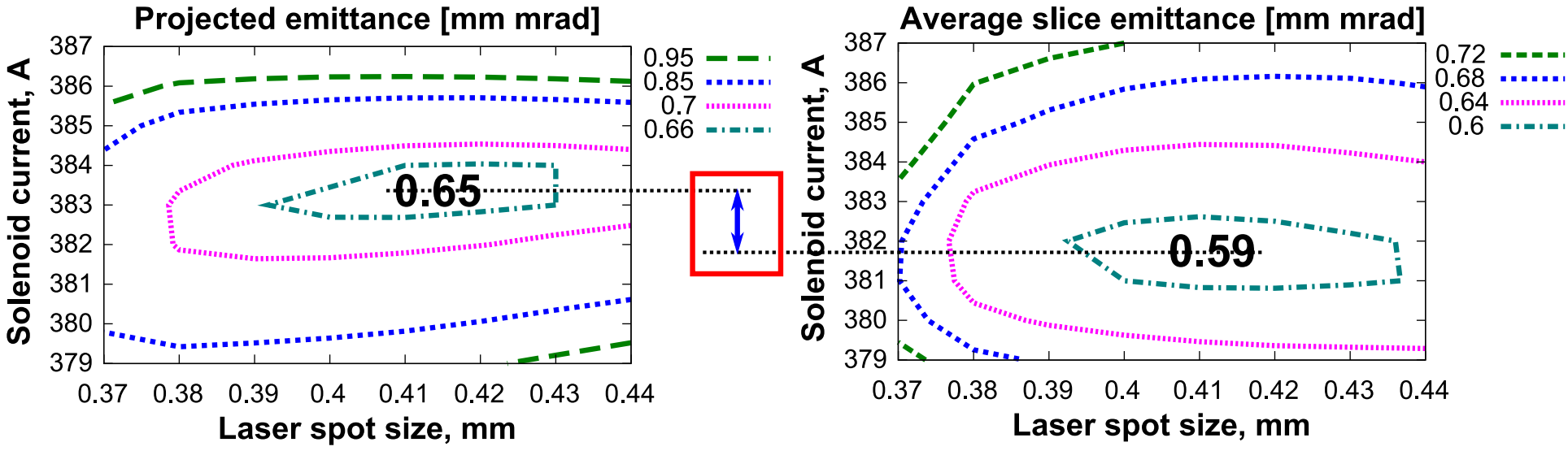
for the nominal settings the RMS resolution:
~2.0 ps with -30 degrees
~1.5 ps with -50 degrees

SLICE EMITTANCE MEASUREMENT PROGRAM

- **Feasibilty of measurements with different charges**

  0.11 nC, 0.23 nC, 0.5 nC and 1 nC

- **Comparison to projected emittance results**

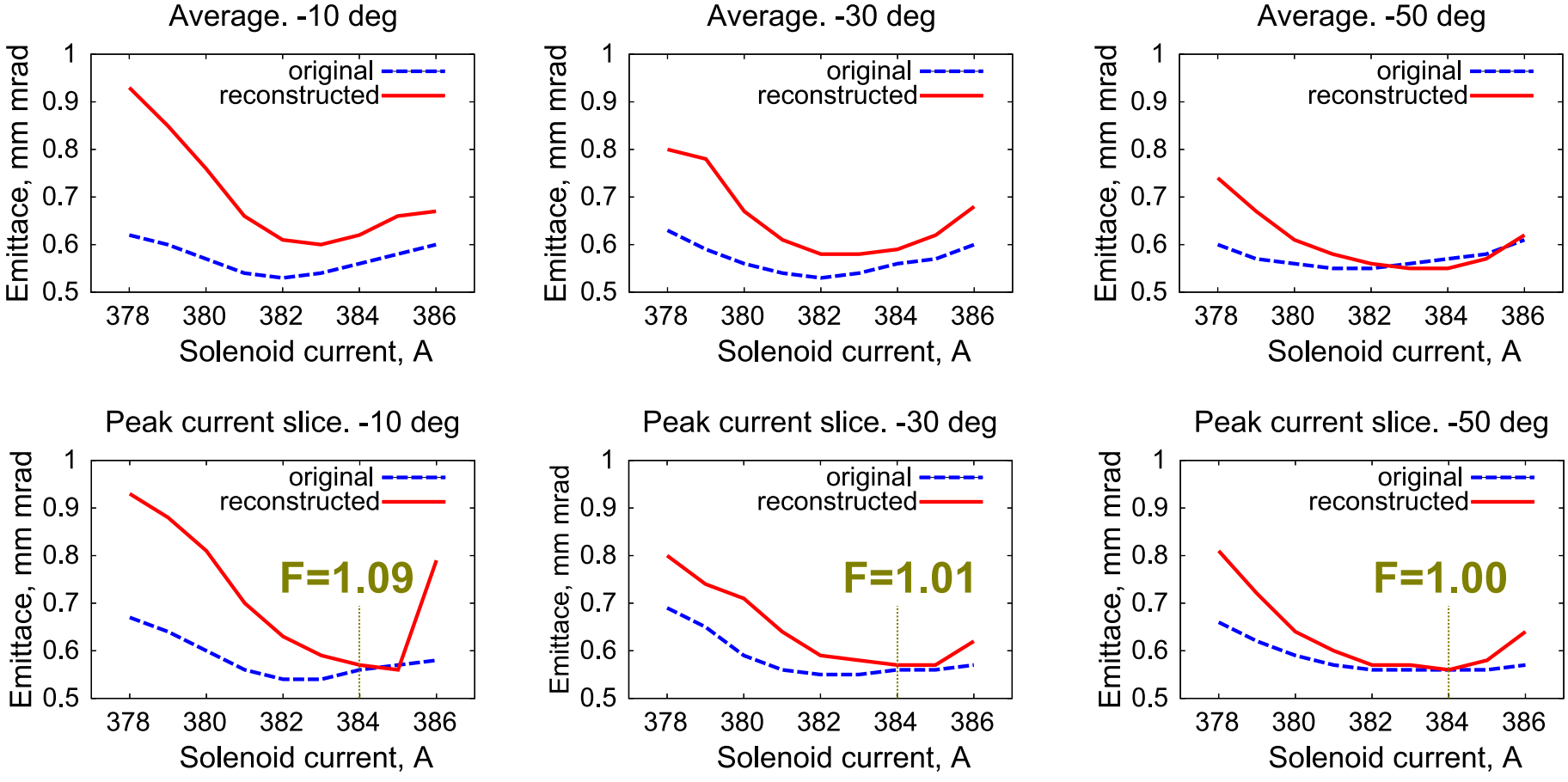


- **Comparison quad VS slit scan**

SIMULATION OF A QUAD SCAN MEASUREMENT

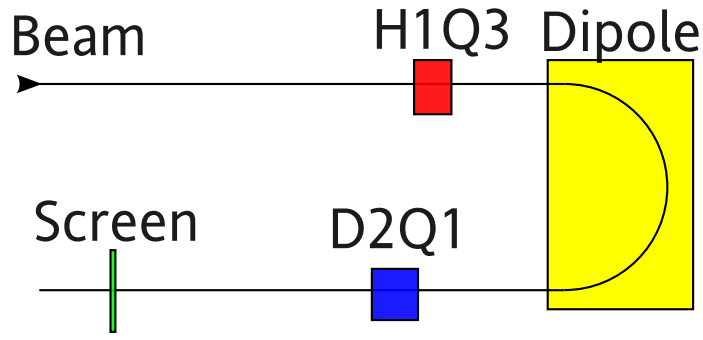
Orignal - slice emittance calculated at the quadrupole magnet position
Reconstructed - simulated measurement with space charge included

~384 A is a focus at the dipole entrance



Good matching confirms that the linear model for emittance reconstruction is sufficient

RESOLUTION LIMIT



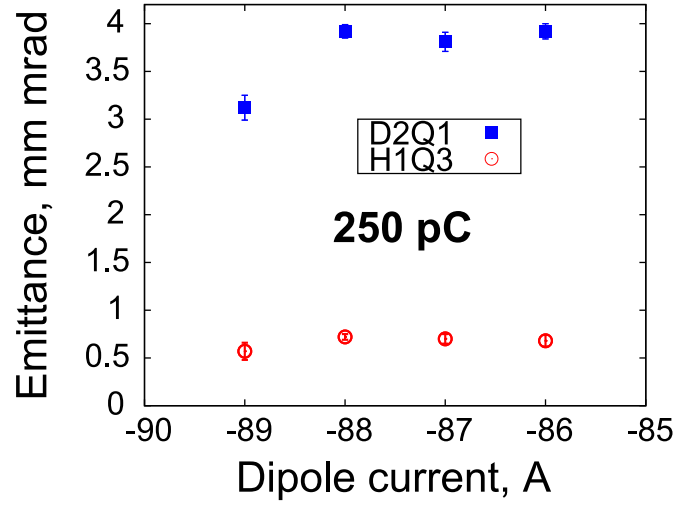
- **Measurement results using both quadrupole magnets**

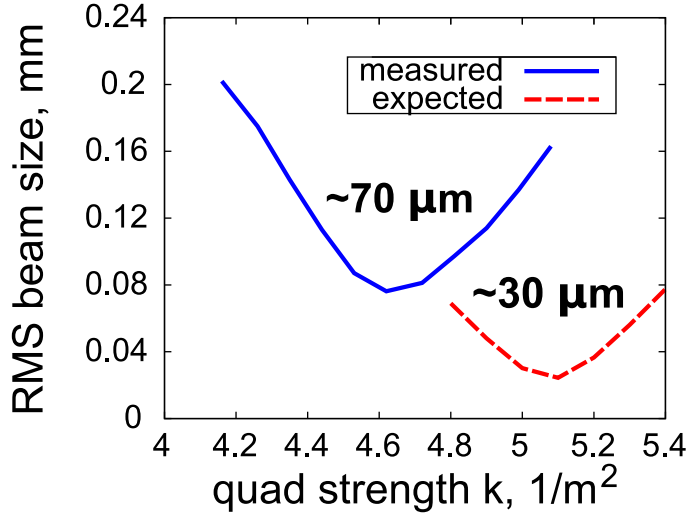
- **Results obtained with H1Q3 were used to evaluate the expected beam size in scans with D2Q1**

  poor optics alignment down to 30 µm confirmed with a calibration grid

  space charge reducing the bunch charge and changing the off-crest phase does not affect the minimum size

  screen YAG. In general can be cross checked with the OTR screen, but the intensity is ~ 20 times lower compared to YAG





Only H1Q3 was used for the measurements

110 pC - A QUAD SCAN MEASUREMENT

Setup:

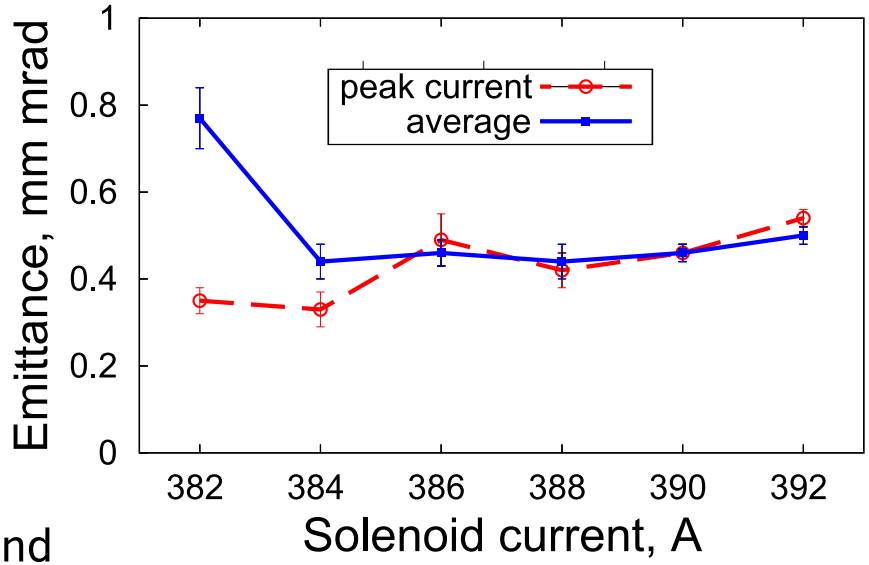
Laser spot RMS 0.18 mm

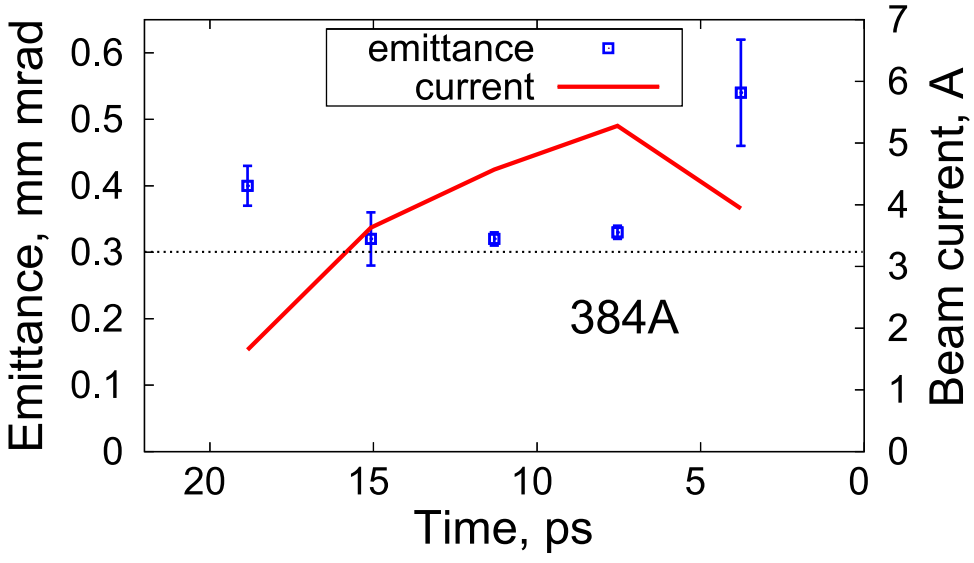
-20 degrees off-crest

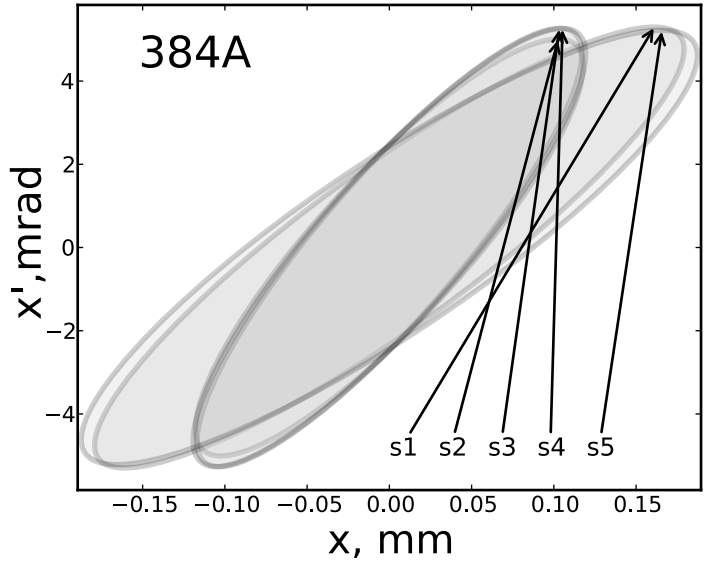
Results:

Peak current slice emittance at 384 A:
0.33∓0.01 mm mrad

Minimum slice emittance does not correspond to the best slice matching

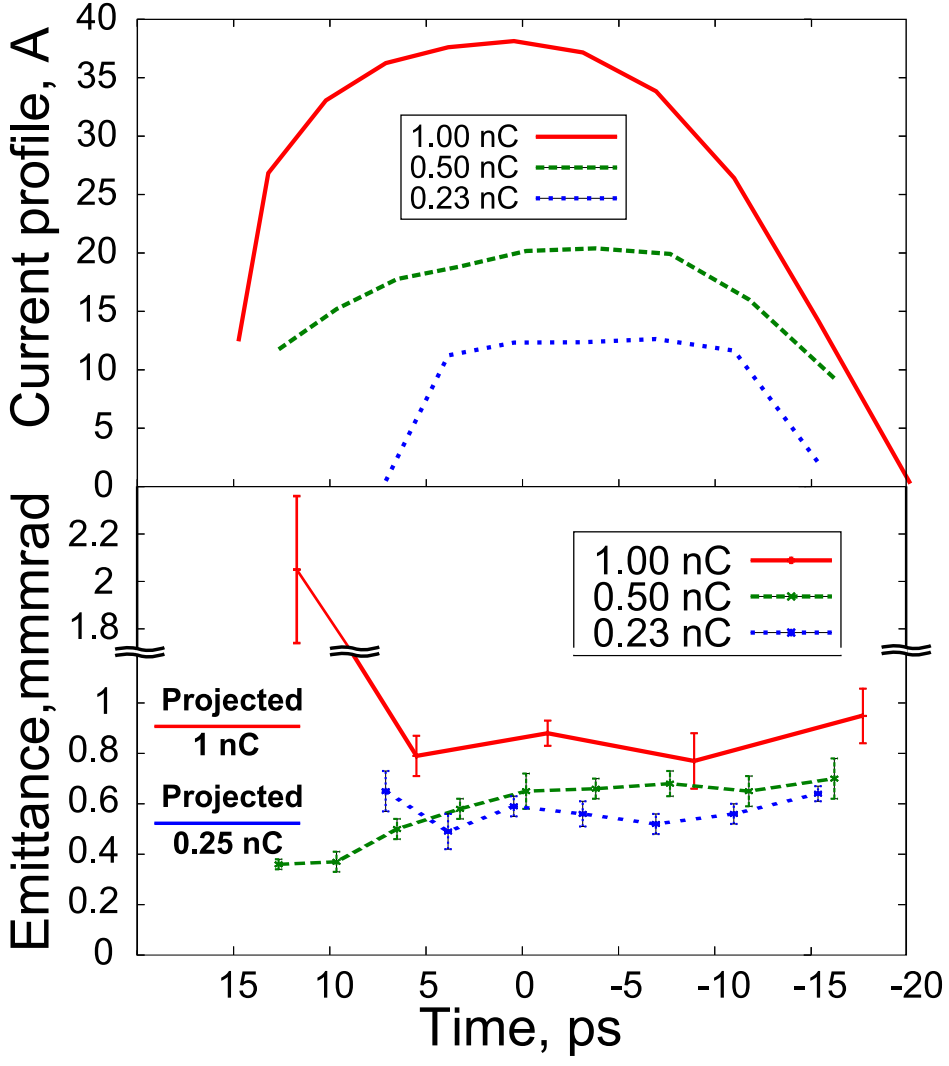




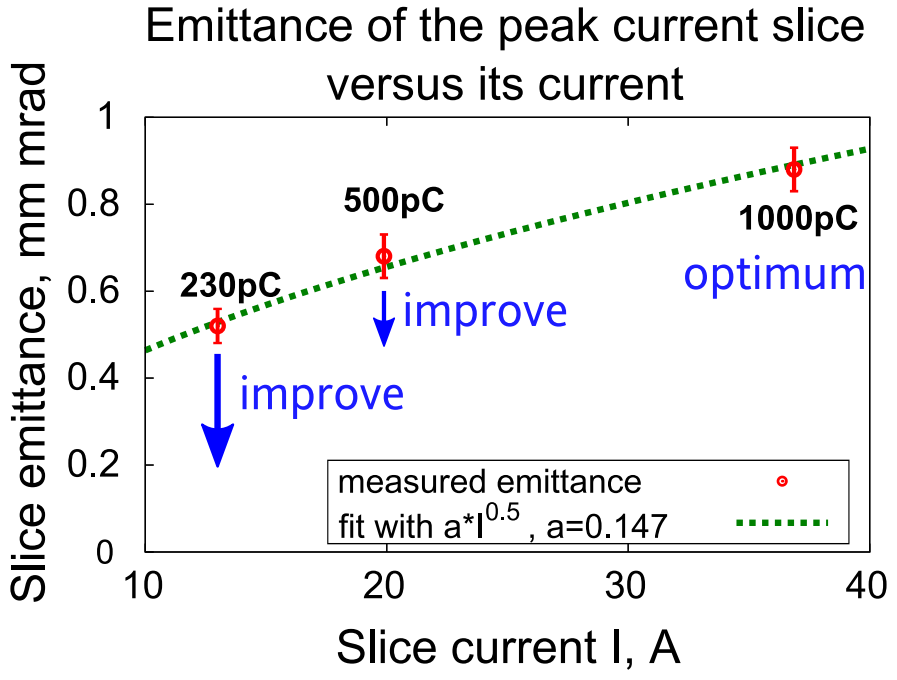


SUMMARY: DIFFERENT BUNCH CHARGES

- **0.23 nC, 0.5 nC and 1 nC were measured with the same setup.**



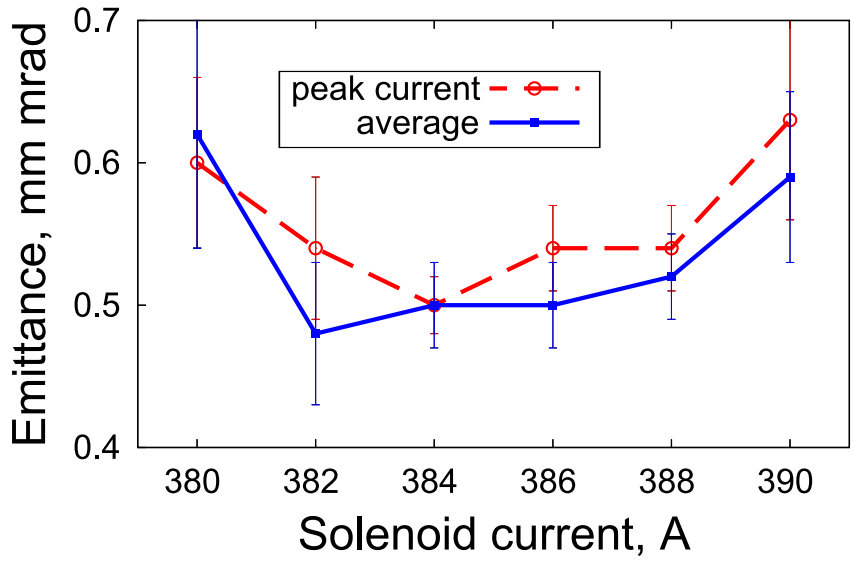
Same measurement conditions for all bunch charge values

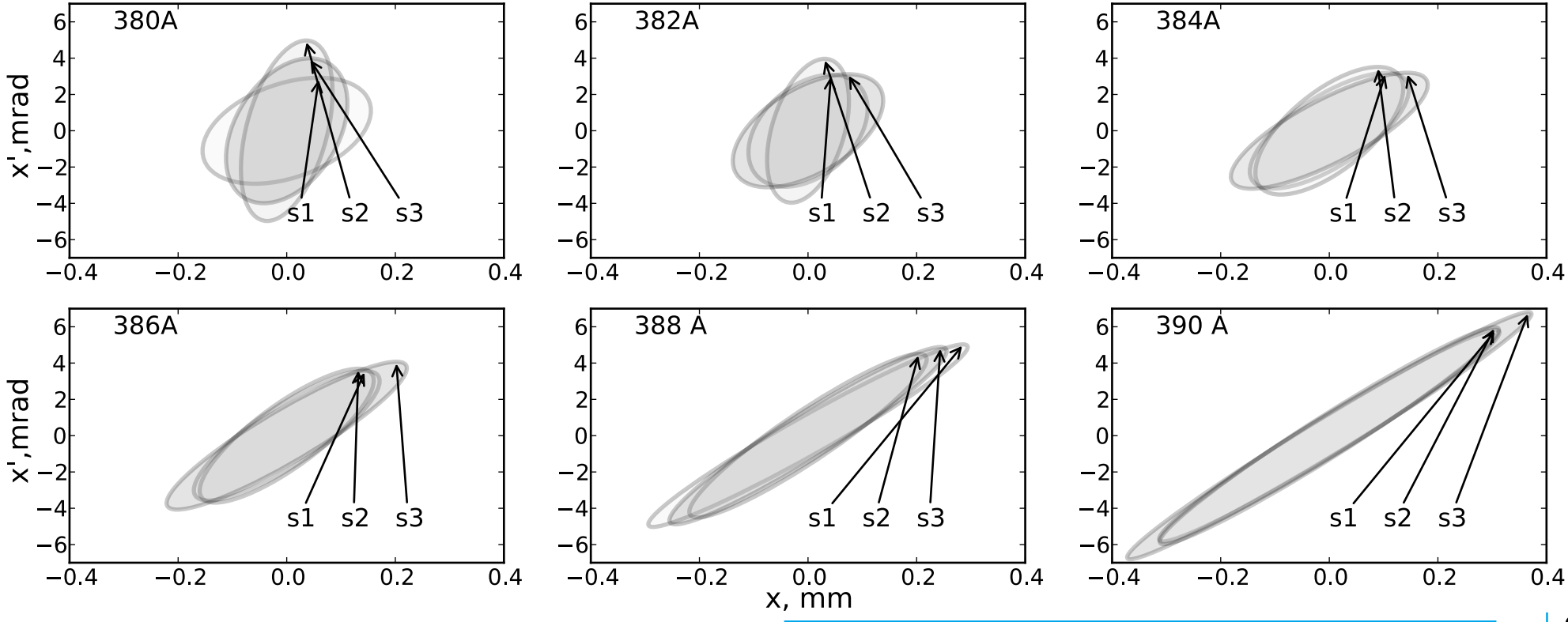


SLICE EMITTANCE SOLENOID SCAN

Setup:

Laser spot RMS 0.3 mm
-30 degrees off-crest
230 pC

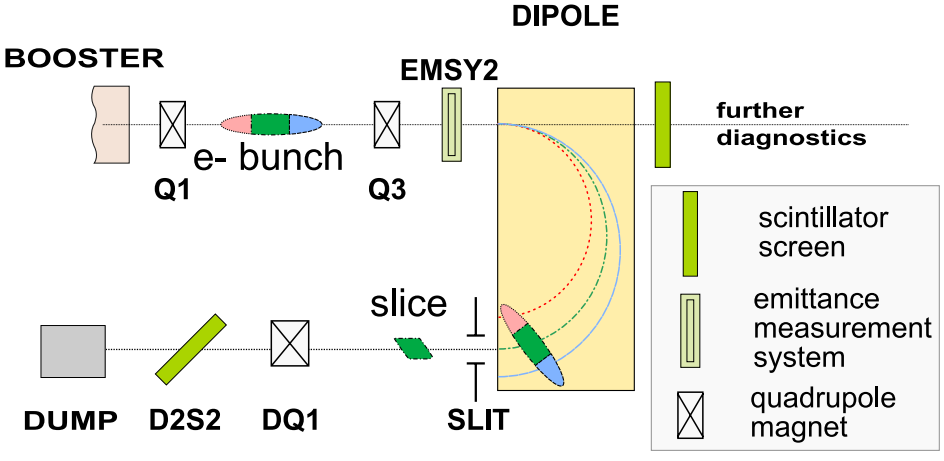


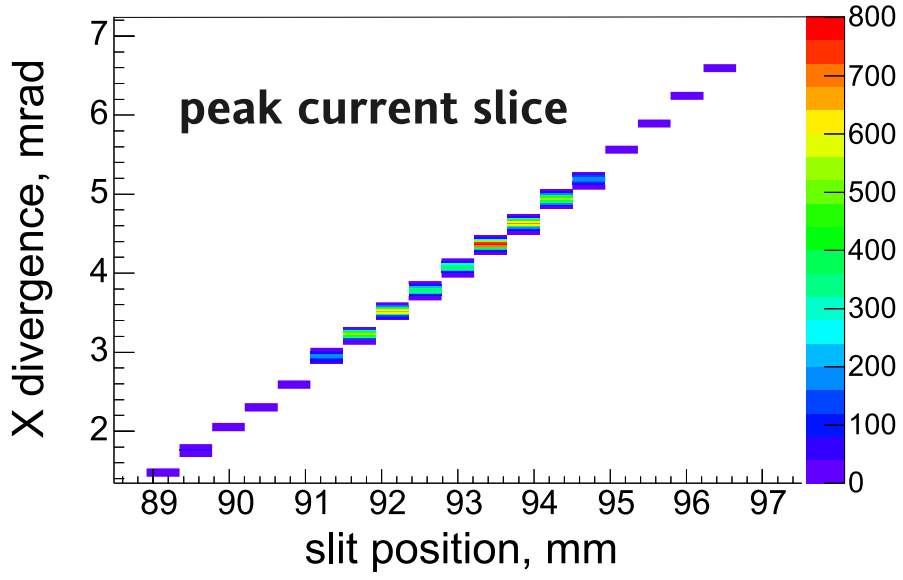


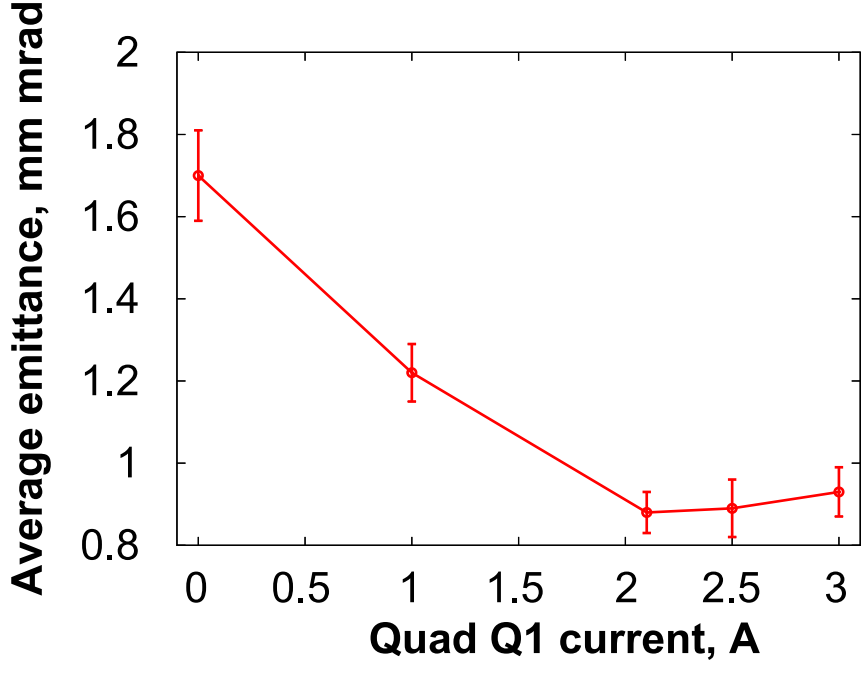
1 nC - A SLIT SCAN MEASUREMENT

- **First measurement**
  ε=1.7 mm mrad
- **Small beamlets due to strongly correlated beam**
  - **resolution ≈ 100 µm**
    and the beamlet size 120-150 µm

Focus the beam to increse uncorrelated divergence !

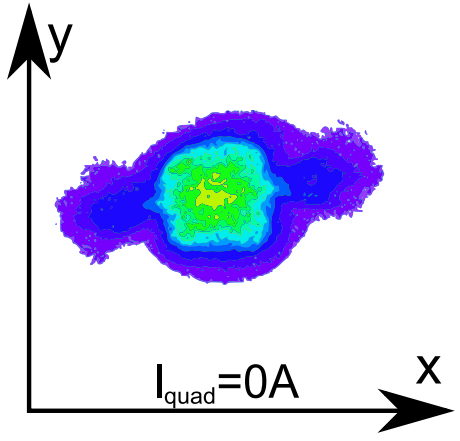




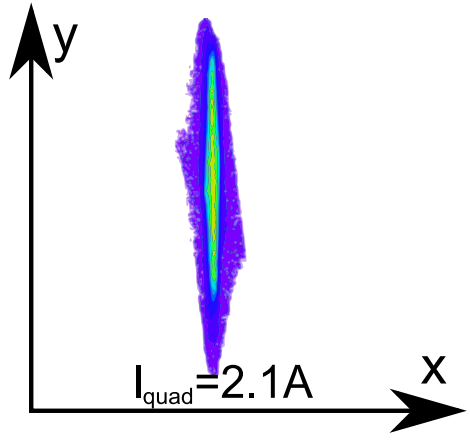


1 nC - A SLIT SCAN MEASUREMENT

Transverse beam profiles at EMSY2

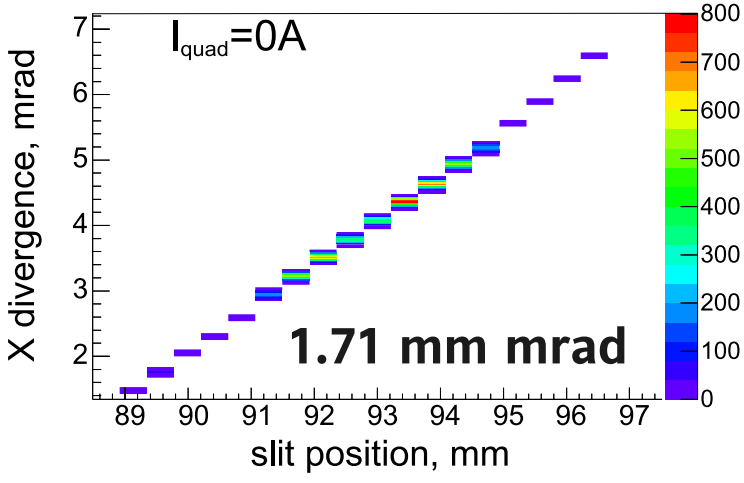


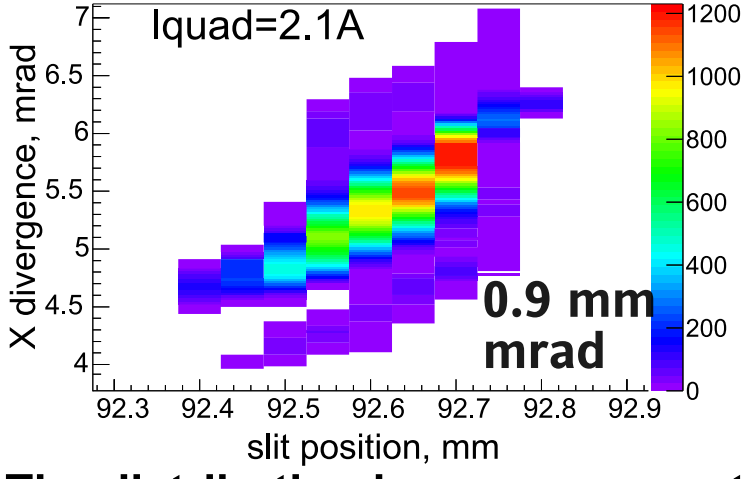
Low intensity halo
is separated in space



The halo is separated in divergence
(in space it is hidden in the core)

Corresponding phase space distributions

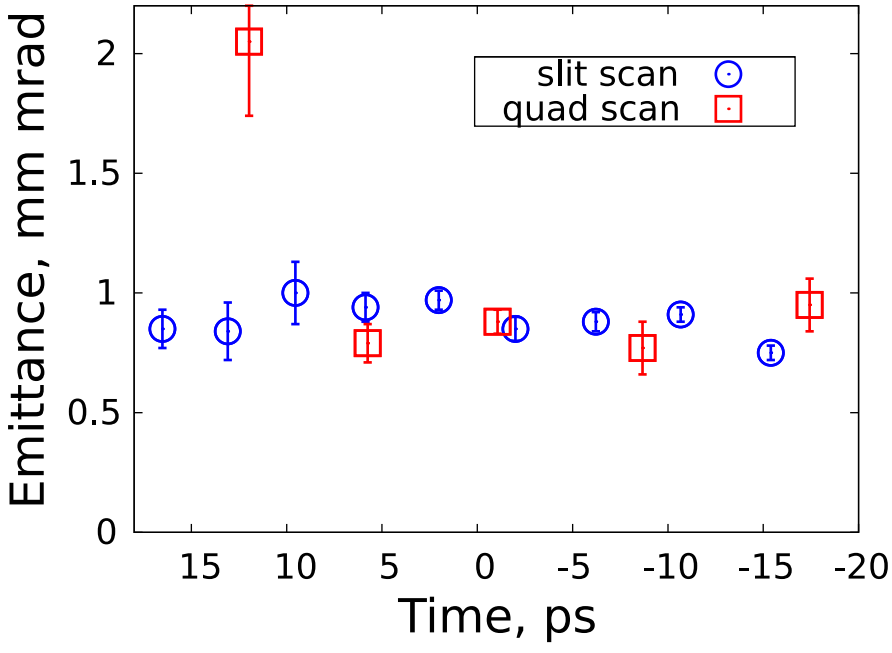


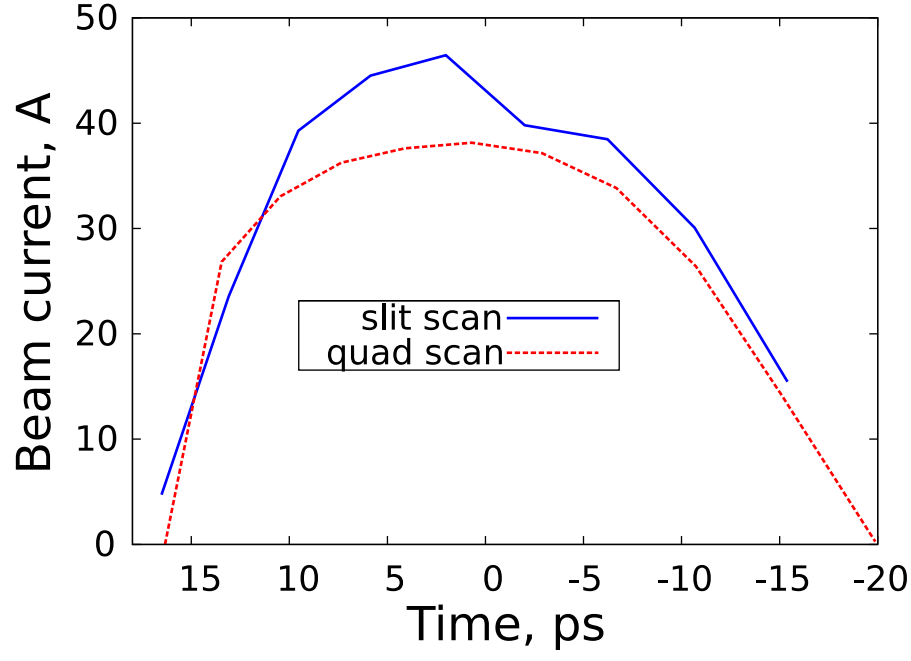


The distribution is more compact

SUMMARY: 1 nC MEASUREMENTS

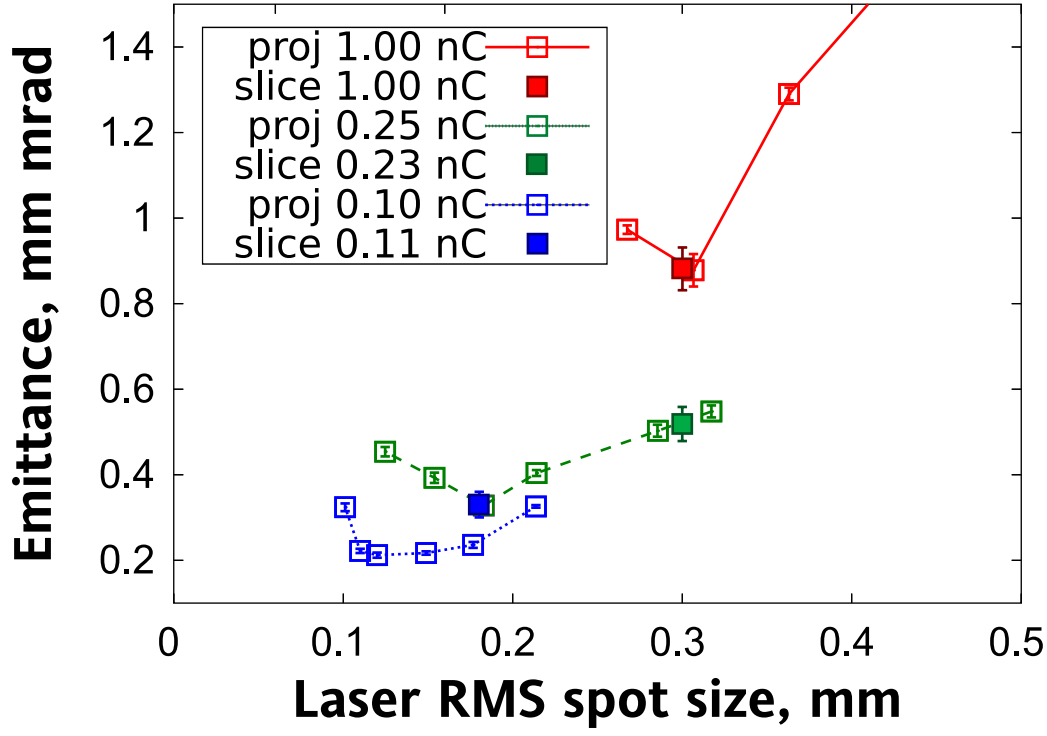
- 1 nC was measured using two techniques, slit scan and quad scan
- Slit scan results are represented for the case of a focus on EMSY2 using an additional quadrupole





SLICE VERSUS PROJECTED EMITTANCE

- **Slice** is measured using the **quadrupole scan** whereas **projected** is obtained using the **slit scan**
- **Slice emittance** is a subject to systematic error due to **non-linear phase space distribution distortion**
- **Projected emittance** is a subject to systematic error due to **insensitivity to low intensity tails**



SUMMARY AND CONCLUSIONS

- Horizontal slice emittance measurement setup is implemented and commissioned
- RMS time resolution of the setup reaches 1.5 ps at -50 degrees off-crest
- Slice emittance was measured with bunch charges down to 110 pC
- Minimum peak current slice emittance occurs at a different solenoid current compared to the best slice matching
- Quad scan is affected by non-linear dynamics, slit scan with 10 um slit mask is insensitive to low intensity tails
- Comparison to similar experiments in other labs:

Lab	Technique		Charge	Emittance	Reference
PITZ	off-crest	quad slit	1 nC	0.8-2 mm mrad	IPAC11 THPC113
SLAC GTF		quad	0.3 nC	1-3 mm mrad	PAC03 WPAB027
SPARC	RFD			1.3 mm mrad	EPAC08 TUPC105

FUTURE OF SLICE EMITTANCE DIAGNOSTICS WITH AN ENERGY CHIRPED BEAM

- Crosscheck with RFD
- Less transport influence when compared to RFD
- YAG versus OTR can be studied after improving the read-out optics
- Thermal emittance with long flat-top beams using the quad scan
- Full beam optimization can be done based on slice emittance

A new dispersive section contains vertical slice emittance setup

ACKNOLEDGEMENT

Sincere gratitude is addressed to

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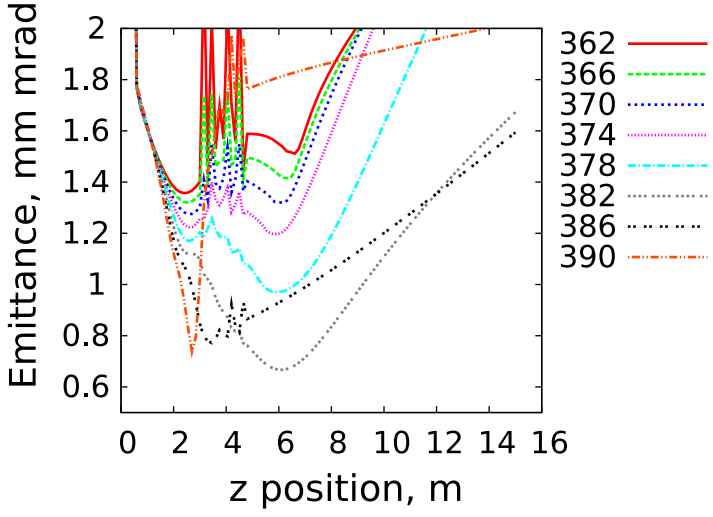
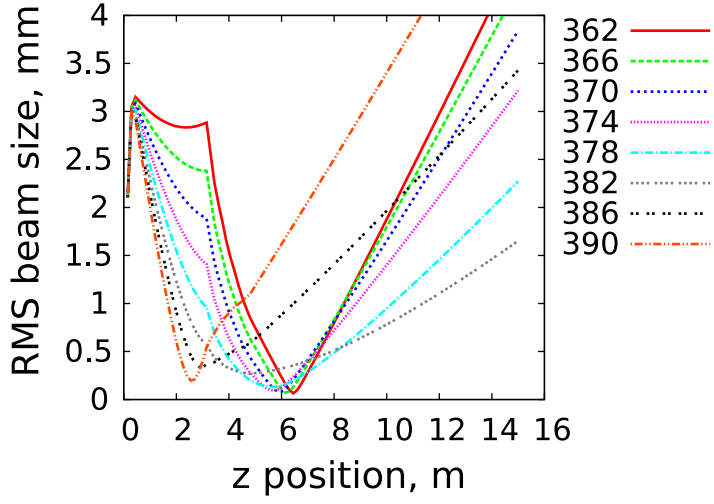
Thank you for your attention!

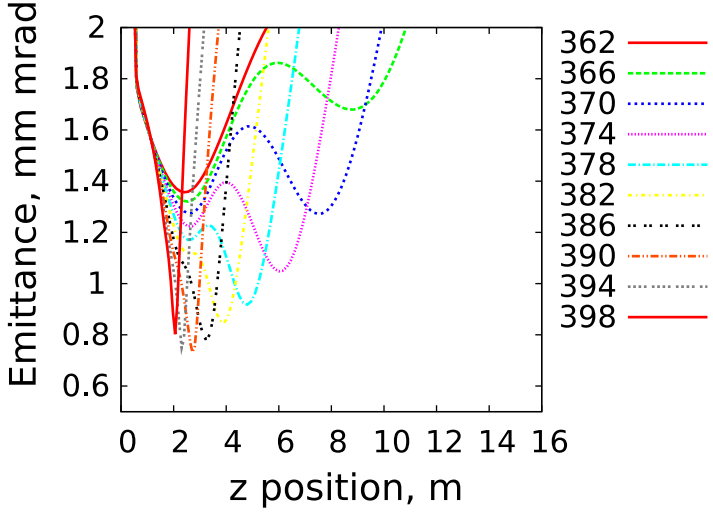
ROLE OF ADDITIONAL ACCELERATION IN BOOSTER

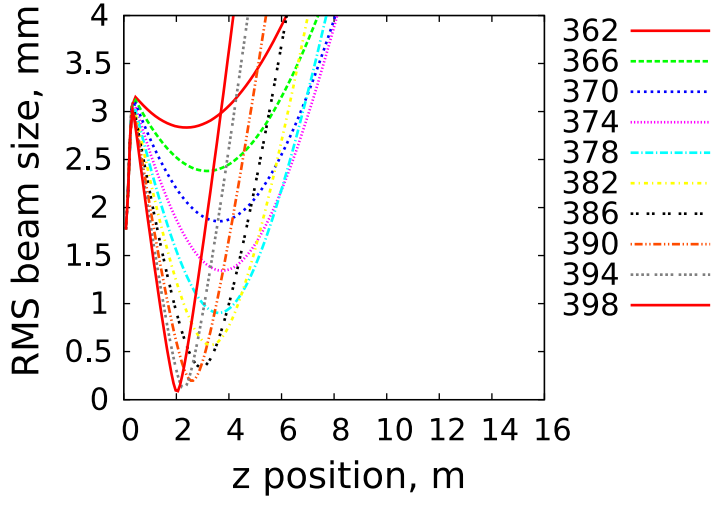
Emittance and beam size in the setup with the booster cavity



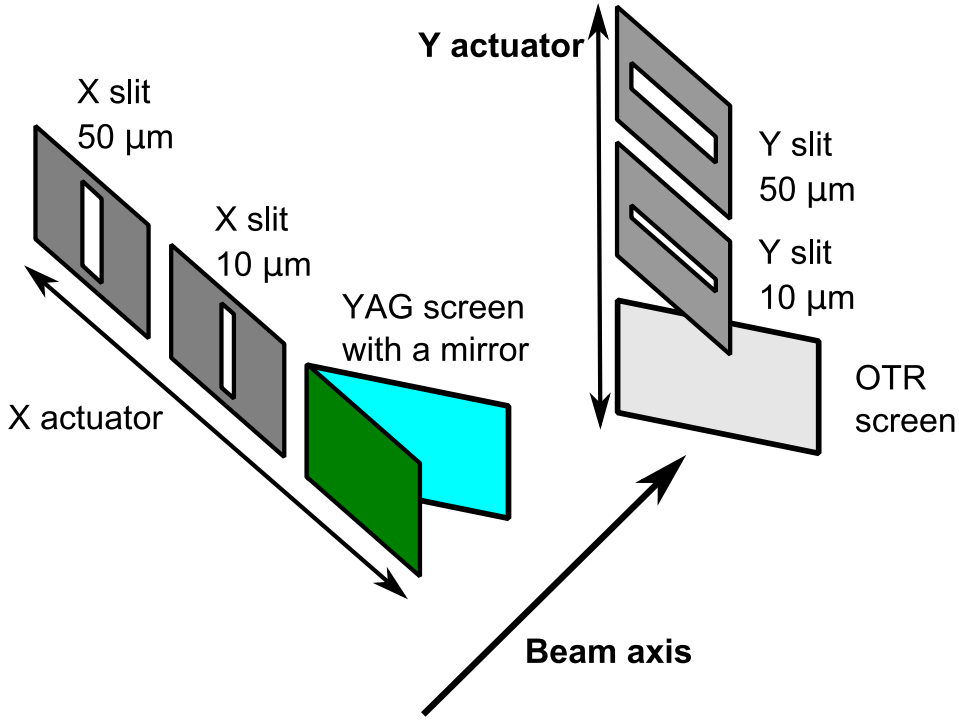


Emittance and beam size in the setup without the booster cavity





EMITTANCE MEASUREMENT SYSTEM (EMSY)



THE MINIMUM BEAM SIZE IN QUAD SCAN

- **A thin lens model in a paraxial approximation with a monoenergetic beam**

The drift length from the quadrupole magnet to the screen

Emittance

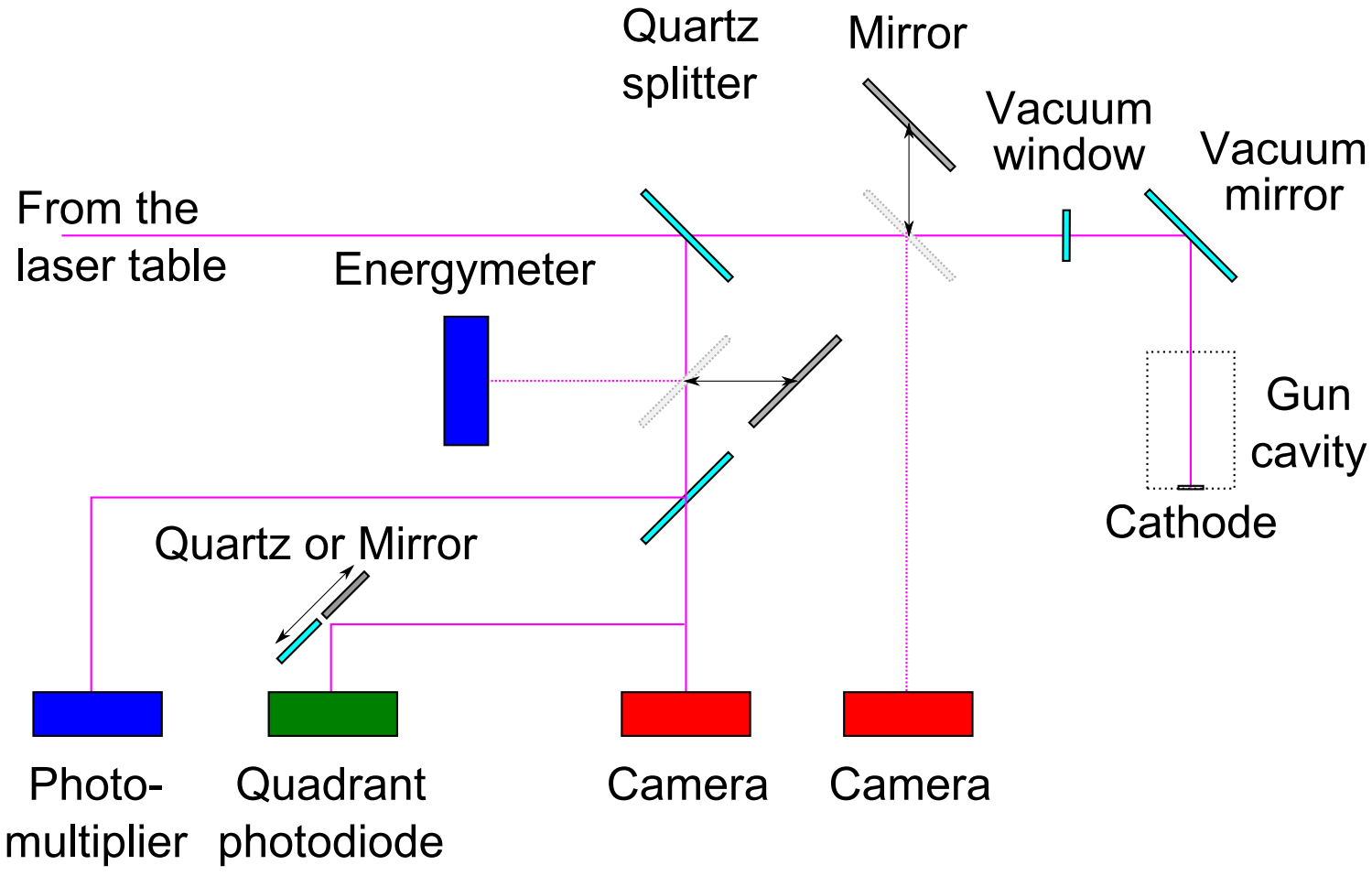
$$\sigma_{scr}^{min} = \frac{L_d \varepsilon}{\gamma \beta \sigma_x}$$

Minimum beam size at the screen obtained in the quadrupole scan

Relative momentum

Beam size at the quad location

Monitoring of intensity, transverse profile and pointing

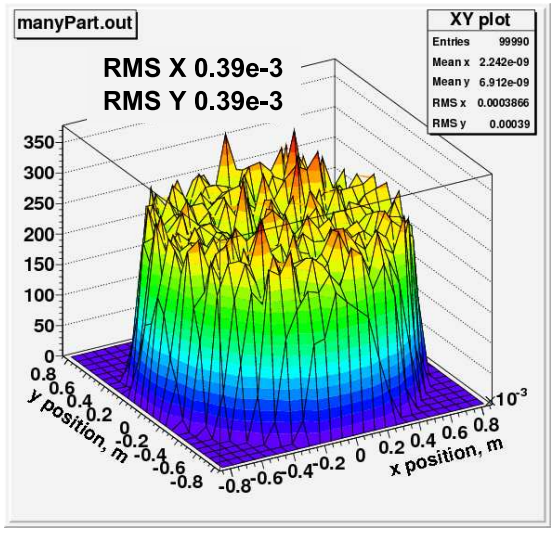


TRANSVERSE PROFILE EVOLUTION

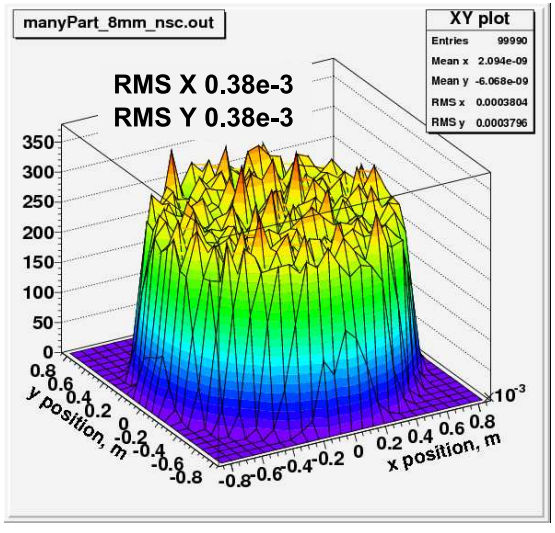
RF Solenoid

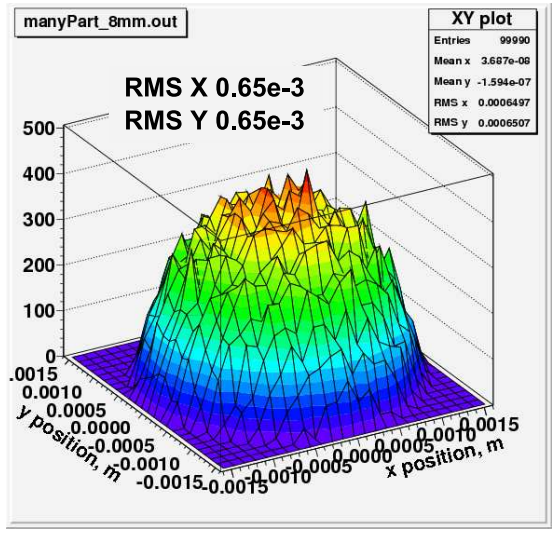
RF Solenoid Space Charge

At the cathode

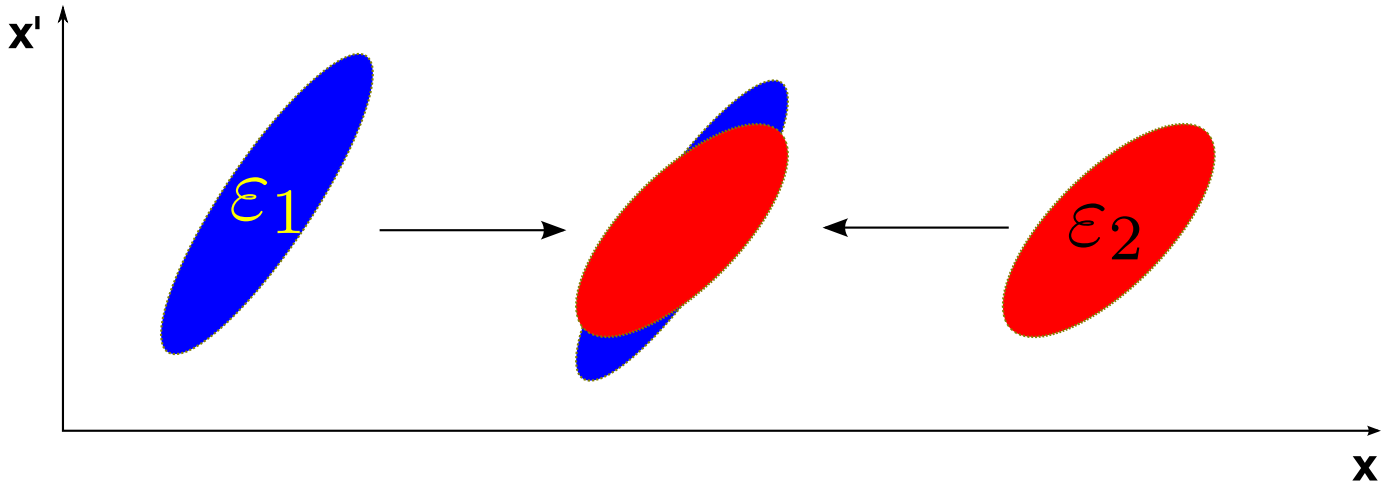


8 mm downstream





MISMATCH PARAMETER



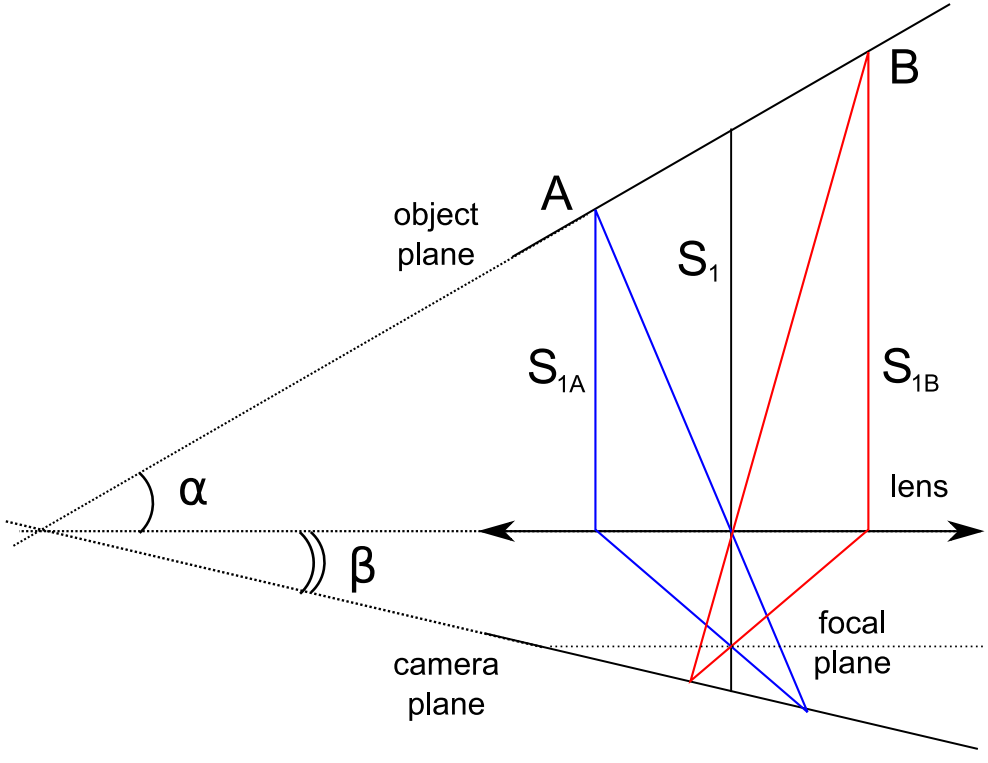
$$F = \frac{\left(\sigma_{x_1}^2 \sigma_{x'_2}^2 + \sigma_{x_2}^2 \sigma_{x'_1}^2 - 2\left\langle xx' \right\rangle_1 \left\langle xx' \right\rangle_2\right)}{2\varepsilon_1 \varepsilon_2}$$

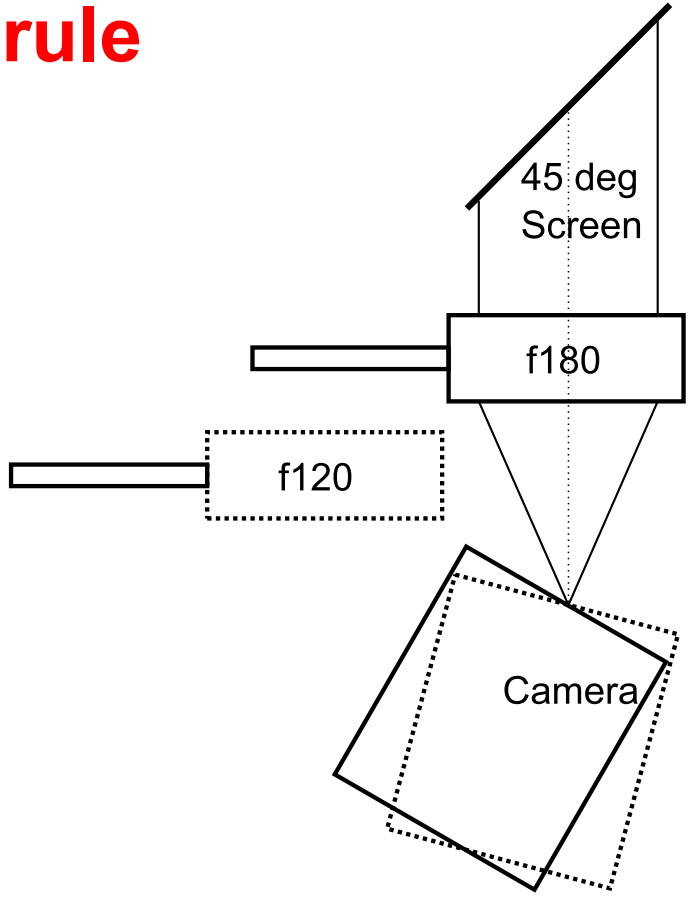
$$1 \leq F < \infty$$

Exact matching $F = 1$

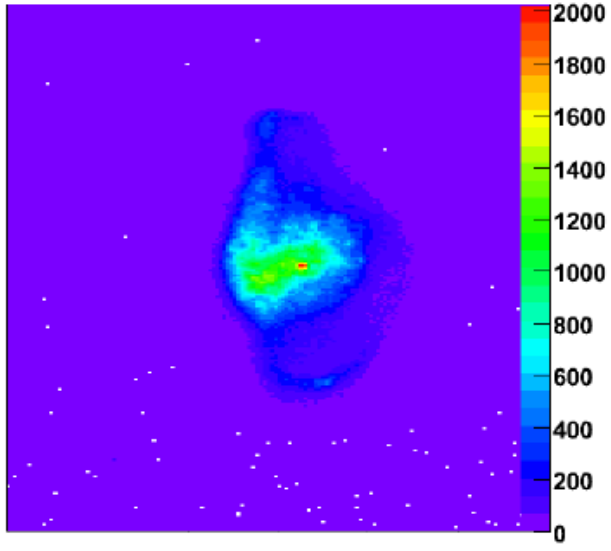
- **Depth of focus is a problem for slit scan measurements with a 45 degree screen**

Scheimpflug's rule

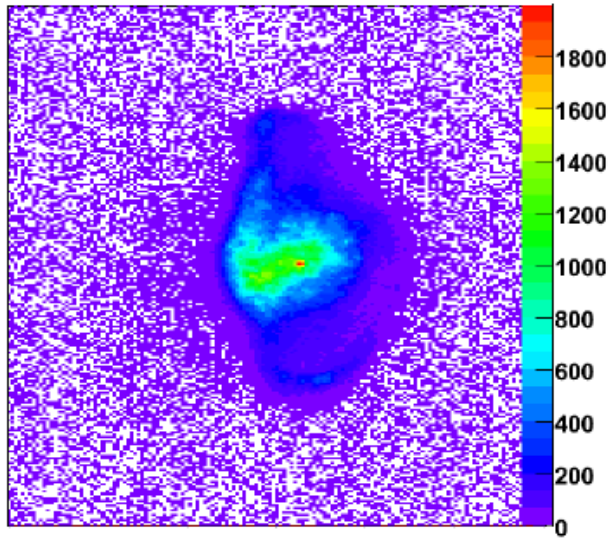




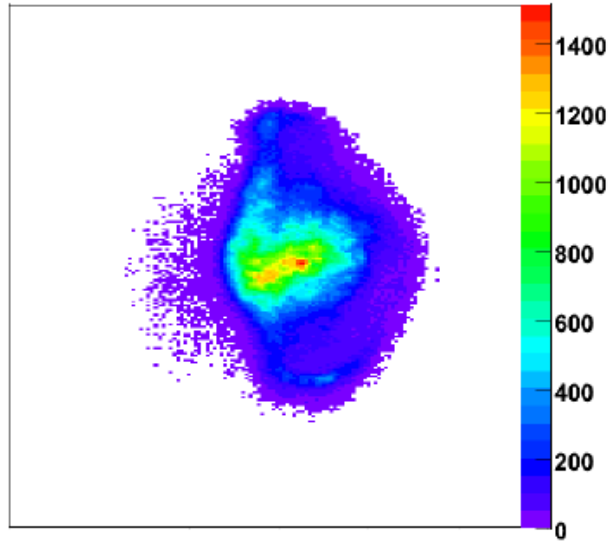
Raw



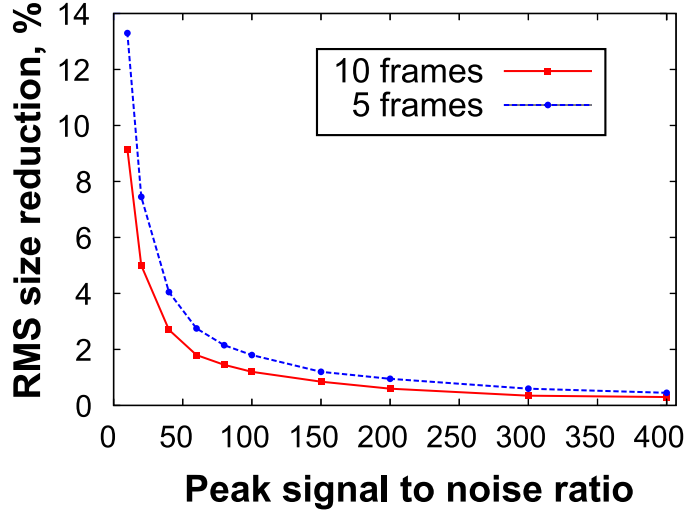
Raw - Background



Processed



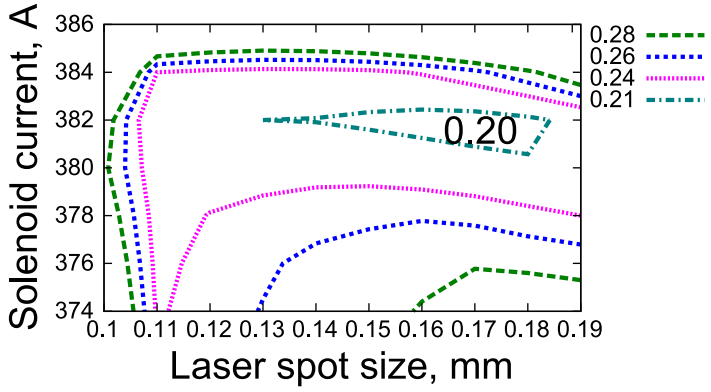
- **Systematical error due to processing**
  - A Gaussian shape is assumed for the benchmarking
  - Real camera noise model is used for the studies
  - Typical peak signal to noise for a periphery beamlet is in the range 20-30

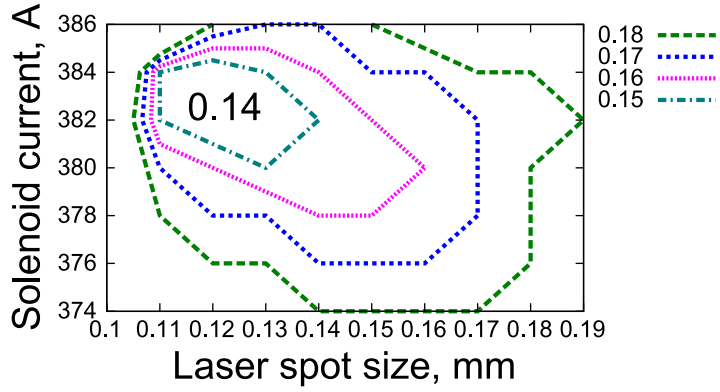


SIMULATION STUDIES OF SLICE EMITTANCE

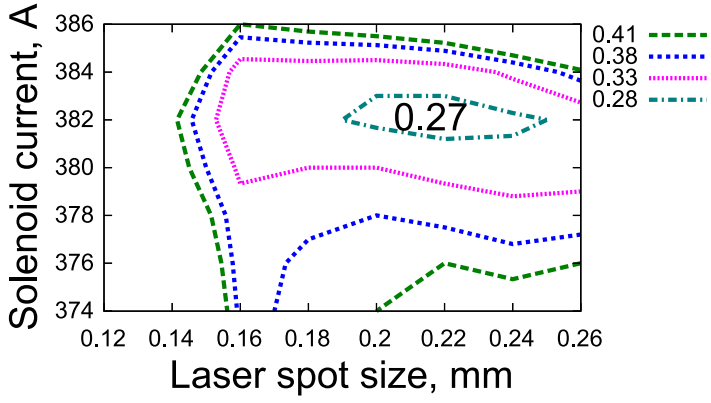
Projected emittance [mm mrad] | **Average slice emittance [mm mrad]**

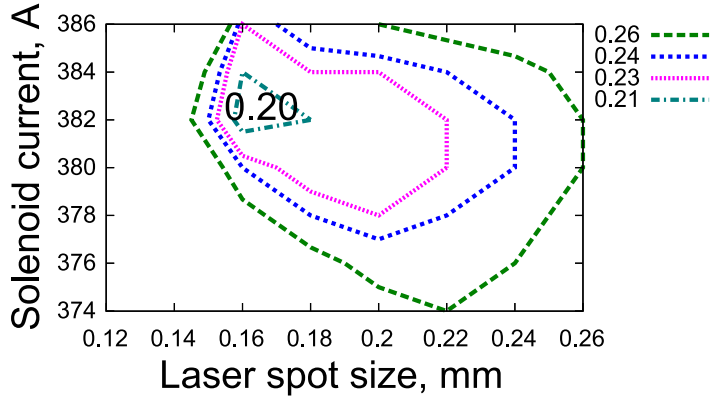
100 pC



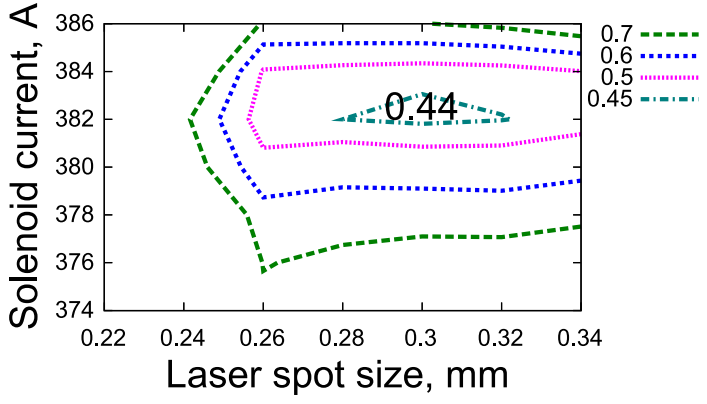


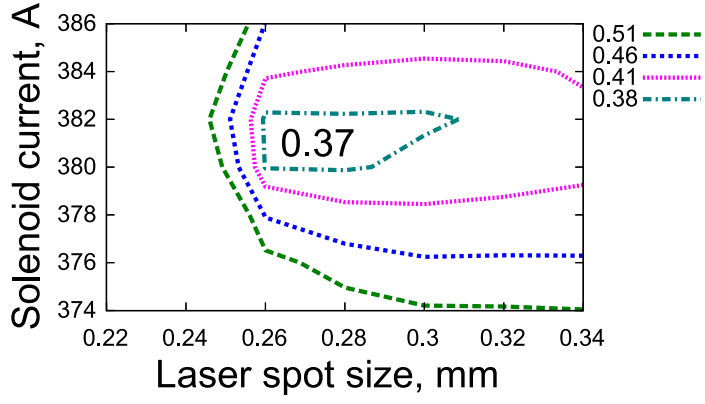
230 pC





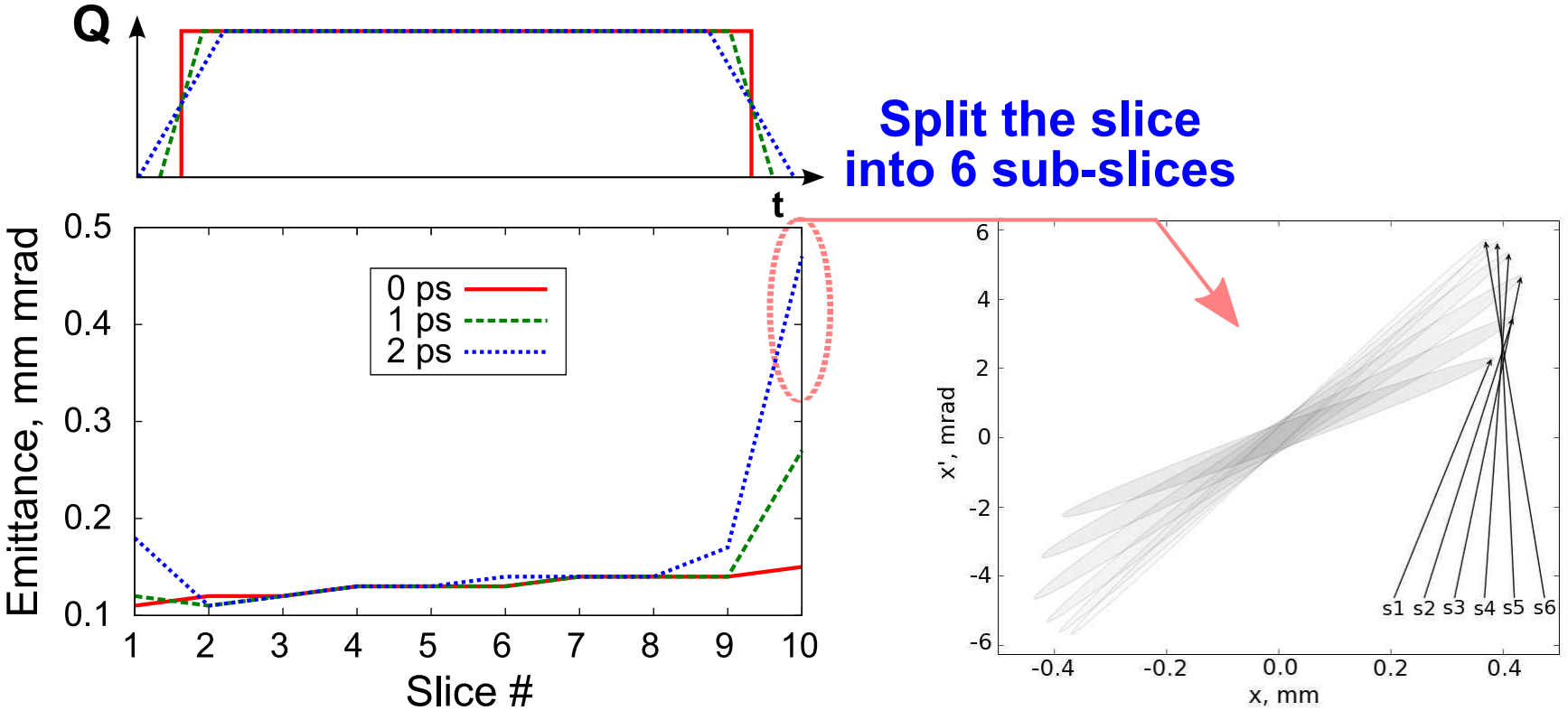
500 pC





SLICE EMITTANCE AT BUNCH EDGES

- **Longer laser rise and fall time result in more particles within the changing space charge field region**
- **Changing charge profile leads to an internal slice mismatch**

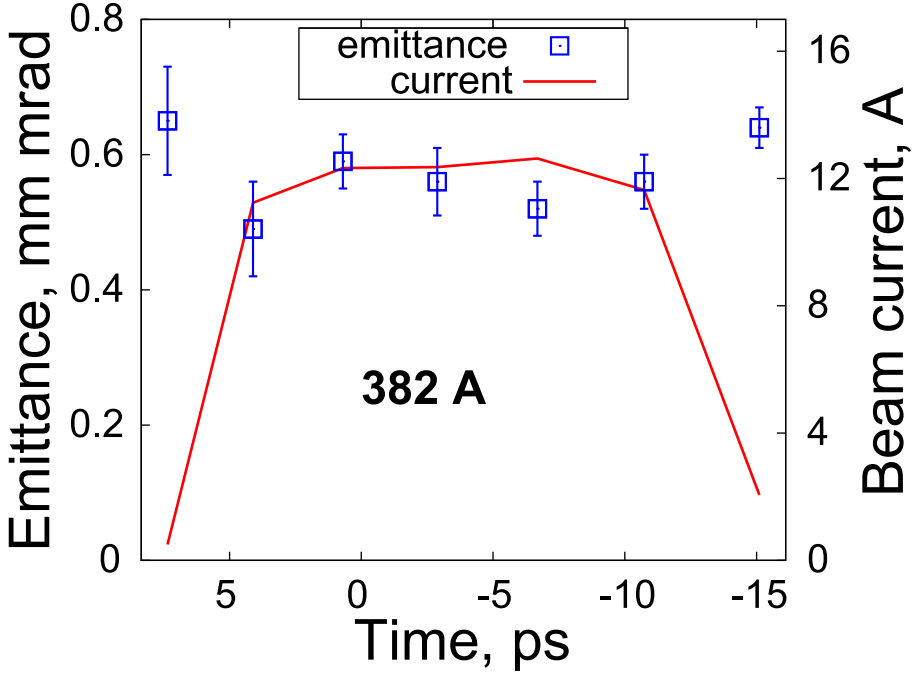


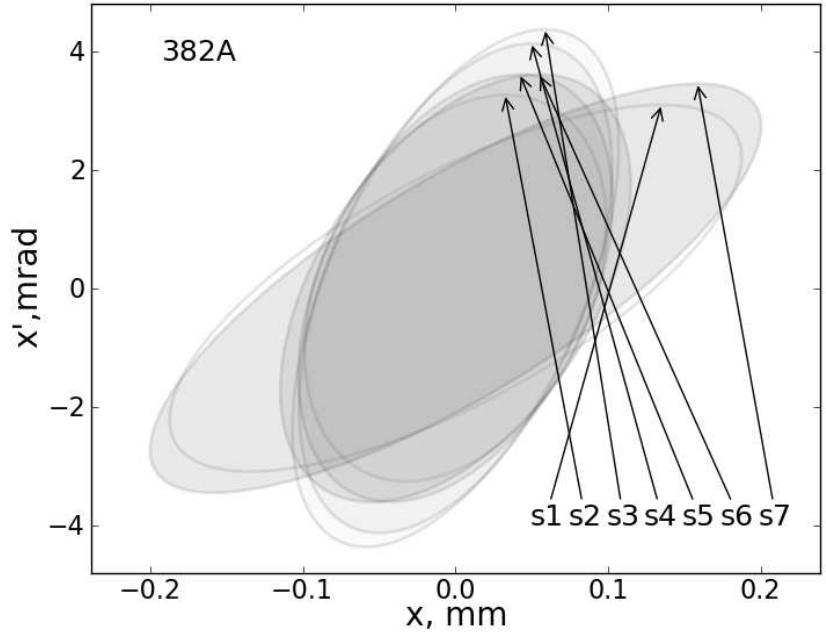
230 pC - A QUAD SCAN MEASUREMENT

Results:

Peak current slice emittance at 382 A 0.52∓0.04 mm mrad

Minimum slice emittance occurs at a solenoid current lower solenoid current then the best slice matching



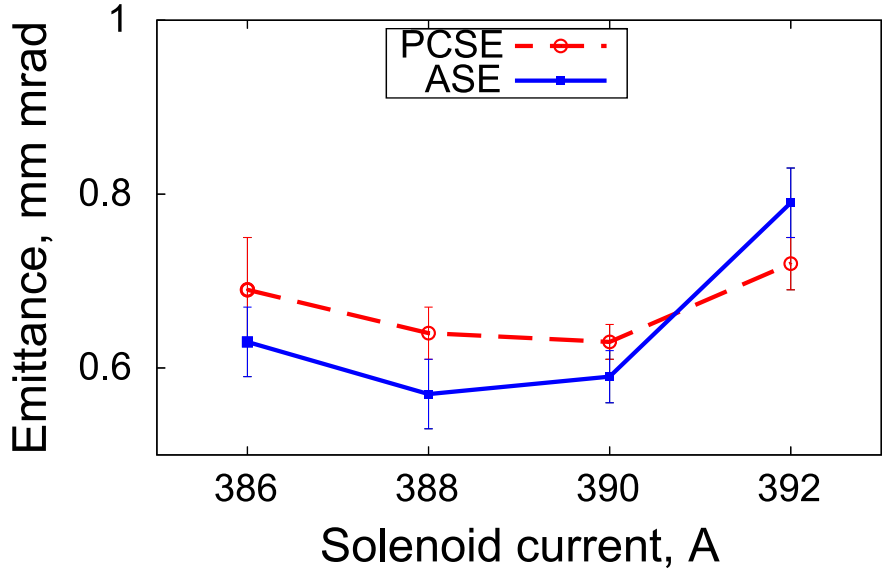


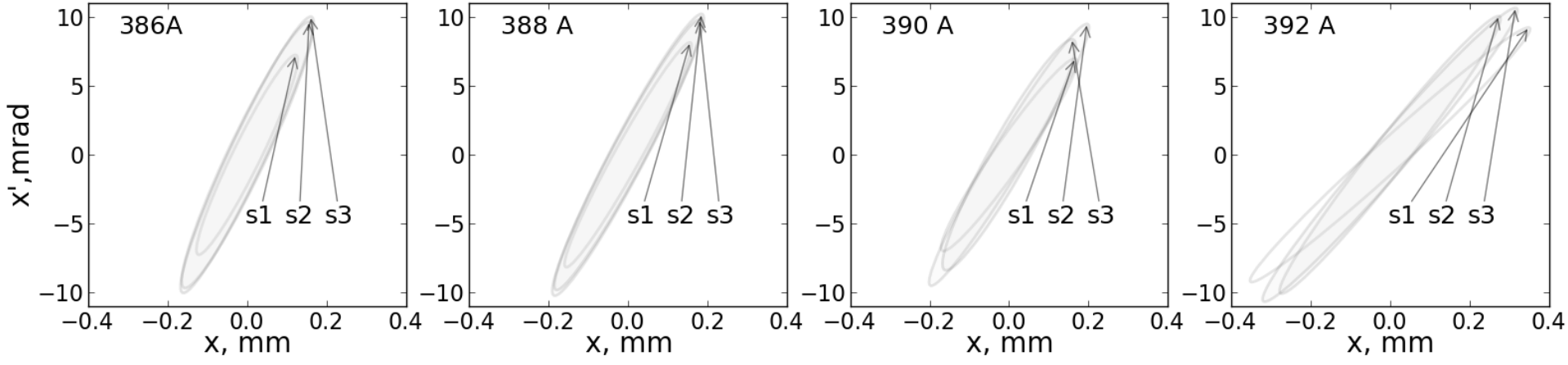
500 pC - A QUAD SCAN MEASUREMENT

Setup:

Laser spot RMS 0.3 mm

-30 degrees off-crest



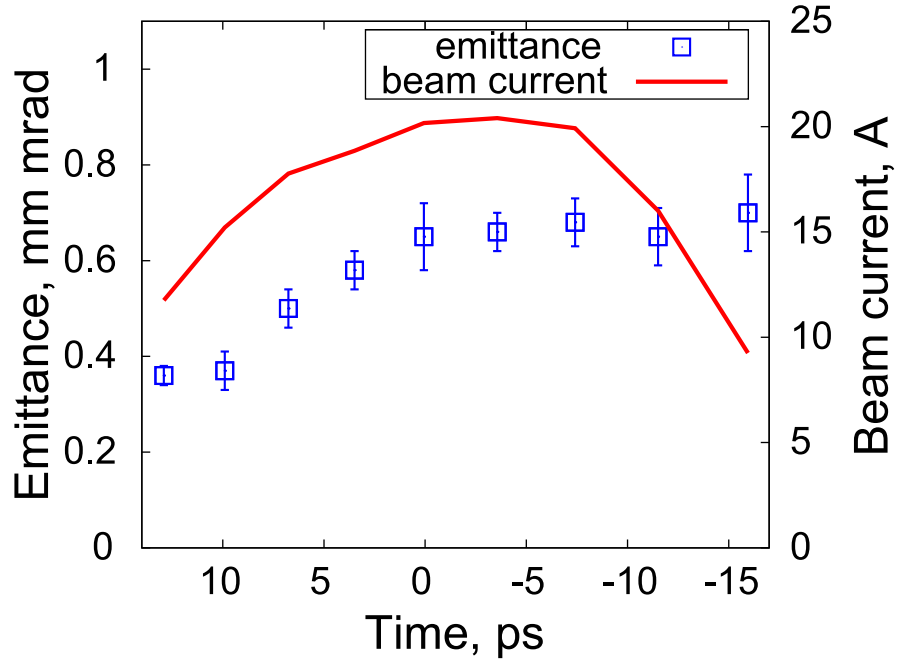


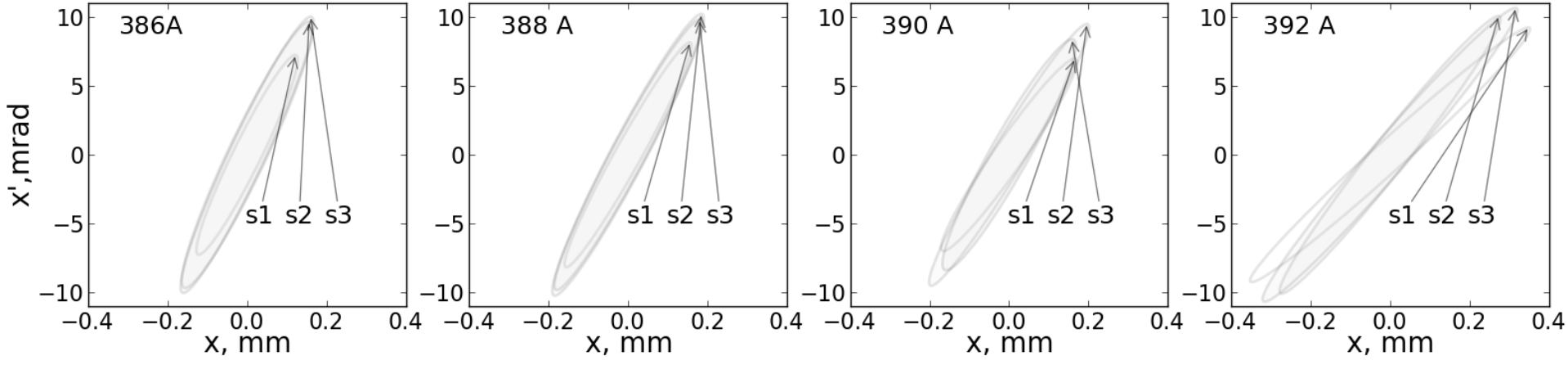
500 pC - A QUAD SCAN MEASUREMENT

Results:

Peak current slice emittance at 390 A 0.66 ∓ 0.04 mm mrad

Minimum slice emittance occurs at higher solenoid then the best slice matching





1 nC - A QUAD SCAN MEASUREMENT

Setup:

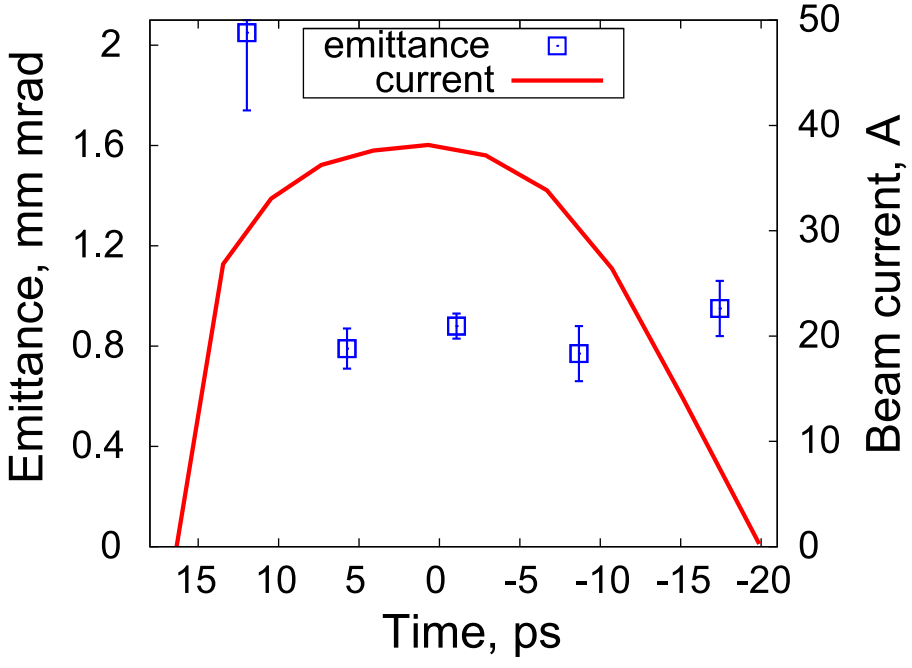
Laser spot RMS 0.3 mm

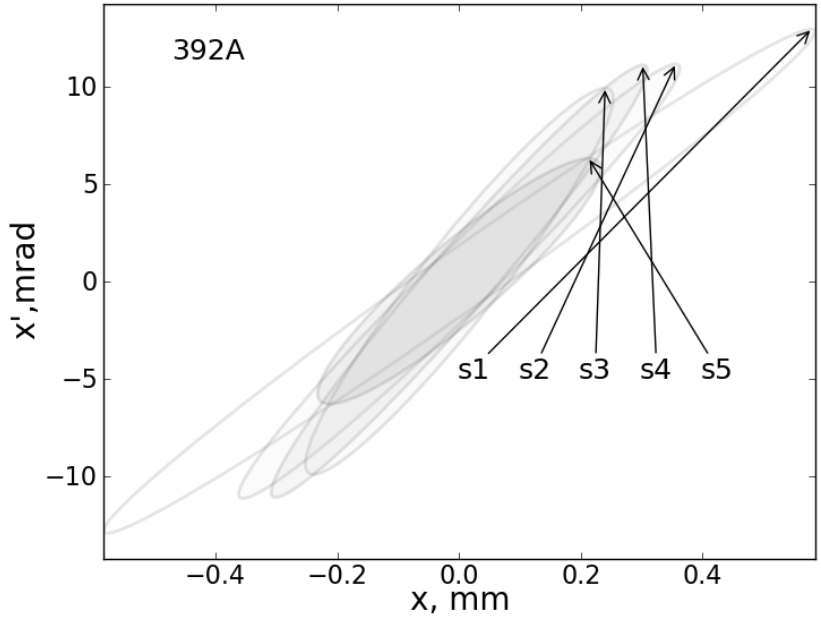
-30 degrees off-crest

only one solenoid current - the best point of projectyed emittance

Results:

Peak current slice emittance at 392 A 0.88∓0.05 mm mrad



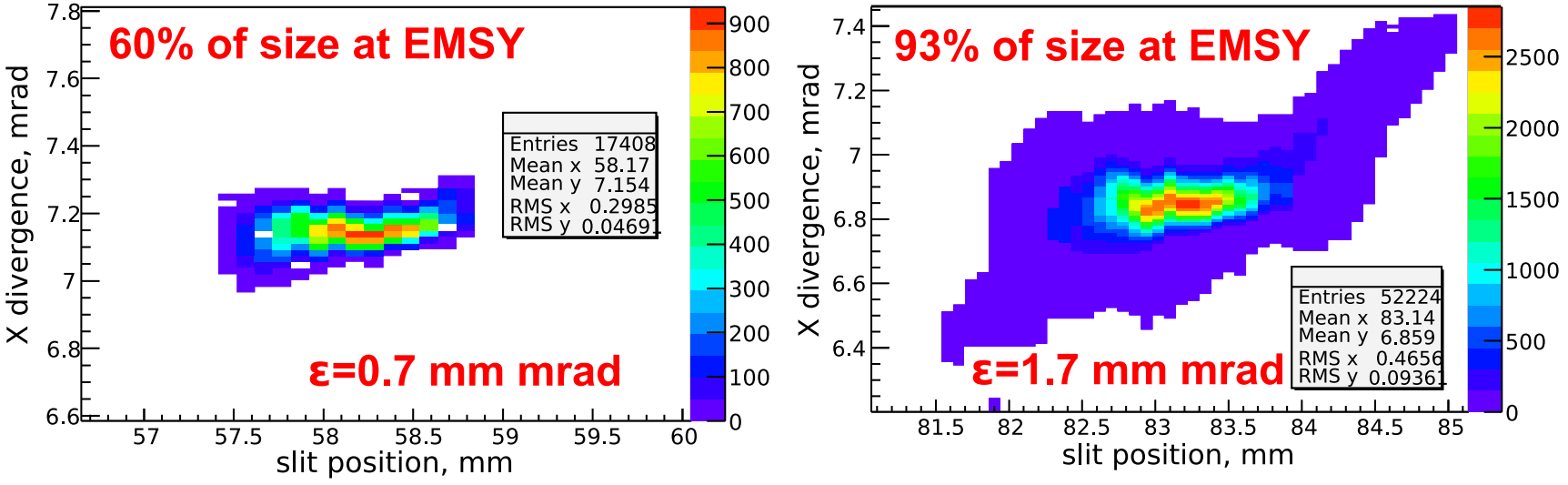


COMPARING SLICE AND PROJECTED EMITTANCE

- **A systematical difference in slice and projected emittance is in slit mask of different width**

Slit scan at EMSY2 in the straight section

10 µm slit **50 µm slit**



A low intensity halo is observed with 50 µm

Halo: 30% of charge, increases emittance 2.5 times

Quad scan non-linearity mainly affects the halo that is not visible in projected emittance measurements meaning a comparison is possible