

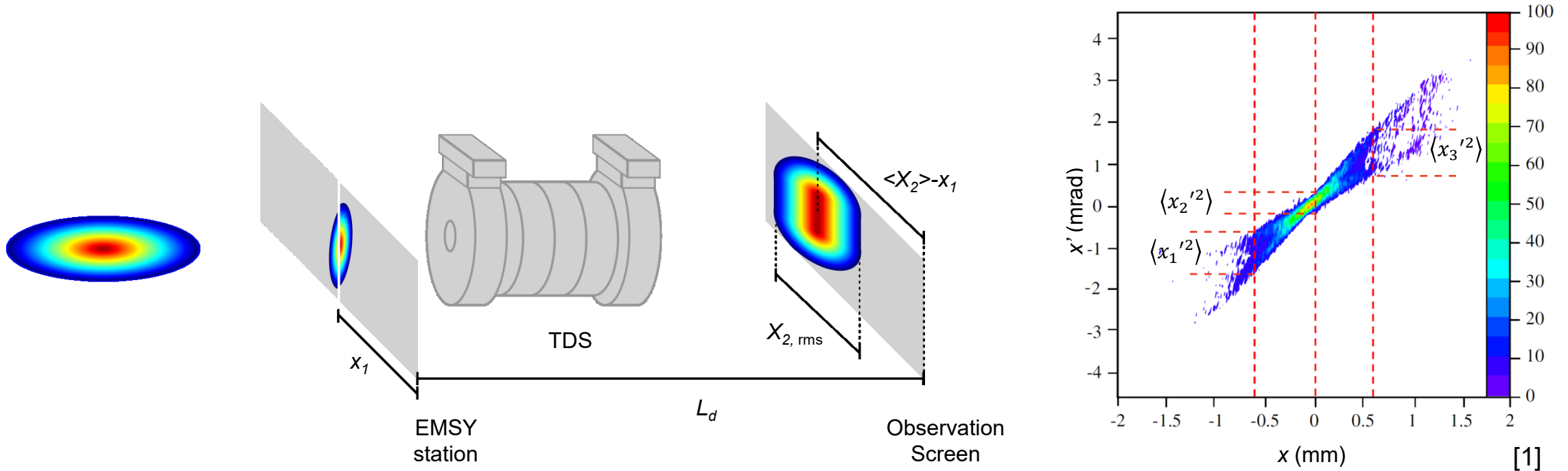
Slice emittance measurement methodology study

Scan of focusing strength (High1.Q09 & Q10, thus R12) to find optimum measurement setting

> Raffael Niemczyk, Zeuthen, January 30th 2020

Recap: Slit Scan Method

Slit-Scan-based slice emittance measurements



> Cut out **emittance-dominated beamlets** from **space charge-dominated beam** with slit

- Measure **size, position** and **intensity** of each beamlet on screen

> Reconstruct phase space at slit position

- Emittance via $\epsilon = \beta\gamma \frac{\sigma_x}{\sqrt{\langle x^2 \rangle}} \sqrt{\langle x_0'^2 \rangle \langle x_0'^2 \rangle - \langle x_0 x_0' \rangle^2}$

[1] S. Rimjaem et al., Nucl. Instr. Meth. Phys. Res. A **671**, 62 – 75 (2012).

Slice emittance with intermediate quadrupoles (Q9/Q10)

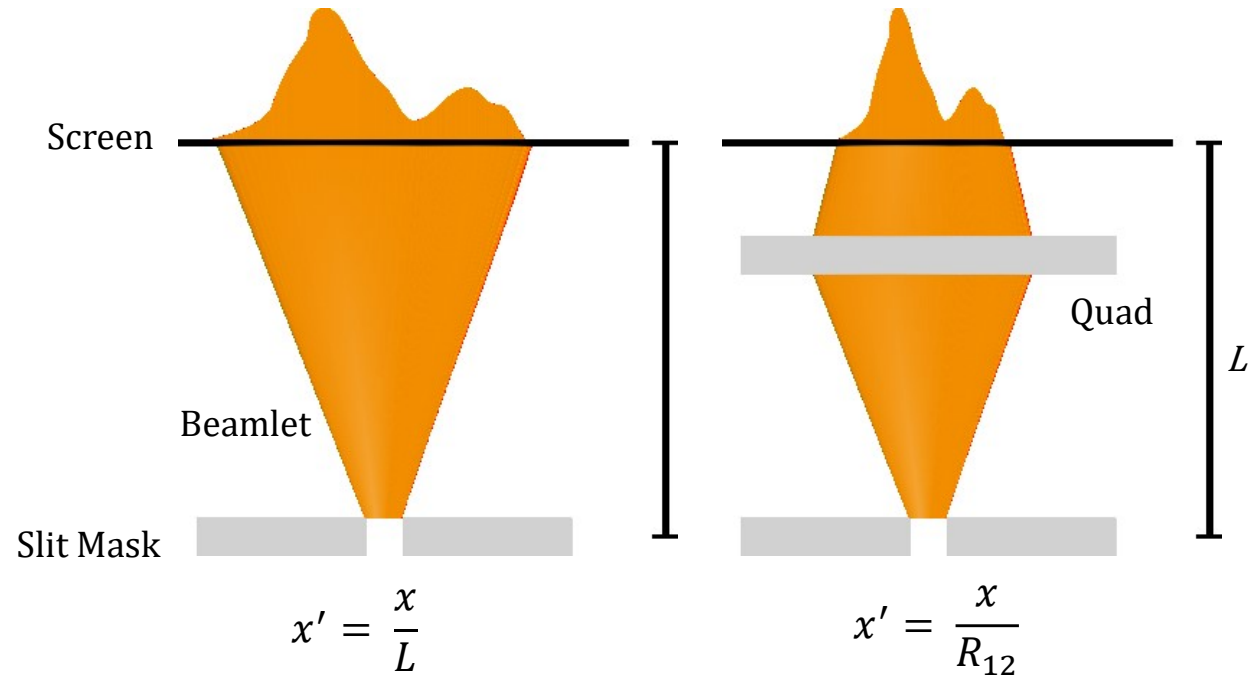
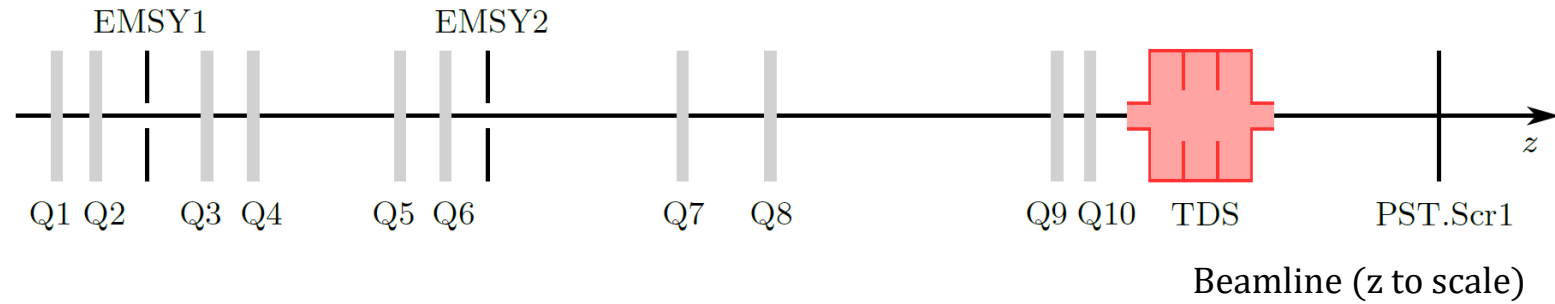
Use of quadrupoles before TDS

> Conventional setup:

- > No quads before slit used
- > Measurement EMSY1->PST.Scr1
- > High1.Q9/Q10 used
 - > Higher S2N ratio
 - > Better time resolution

> Phase space reconstruction changes

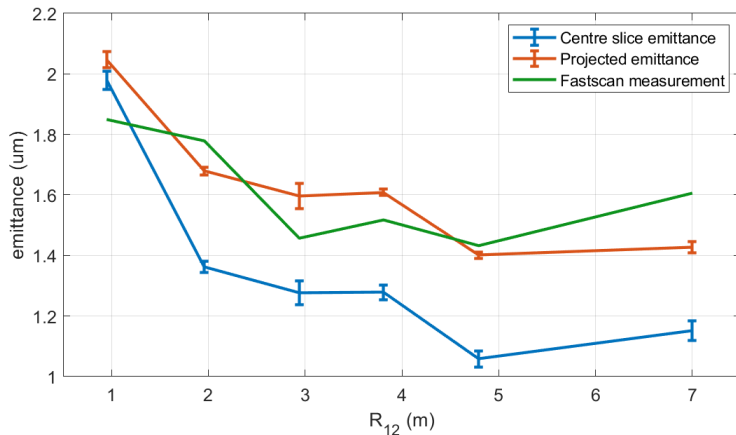
$$\begin{aligned} \begin{pmatrix} x \\ x' \end{pmatrix}_{s_2} &= \begin{pmatrix} R_{11} & R_{12} \\ R_{21} & R_{22} \end{pmatrix}_{s_1 \rightarrow s_2} \cdot \begin{pmatrix} x \\ x' \end{pmatrix}_{s_1} \\ \Rightarrow x_2 &= R_{11} \cdot x_1 + R_{12} \cdot x'_1 \\ \Rightarrow x'_1 &= \frac{x_2 - R_{11}x_1}{R_{12}} \end{aligned}$$



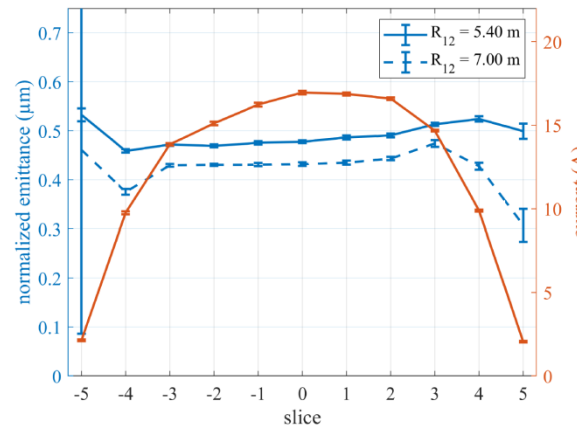
Slice emittance with intermediate quadrupoles (Q9/Q10)

Tried first in May 2019

- Use of High1.Q09/Q10 published in IBIC'19 Proc.
- Increase of measured emittance observed
- Measurement with different focusing done, to find optimum focusing (August'19)
- Redone with better injector/more sample points



Measurement from 2019-08-16



Measurement from 2019-05-12

SLIT-BASED SLICE EMITTANCE MEASUREMENTS OPTIMIZATION AT PITZ

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W. Hillert, University of Hamburg, 22761 Hamburg, Germany

Abstract

At the Photo Injector Test Facility at DESY in Zeuthen (PITZ) high-brightness electron sources are optimized for use at the X-ray free-electron lasers FLASH and European XFEL. Transverse projected emittance measurements are carried out by a single-slit scan technique in order to suppress space charge effects at an energy of ~20 MeV. Previous slice emittance measurements, which employed the emittance measurement in conjunction with a transverse deflecting structure, suffer from limited time resolution and low signal-to-noise ratio (SNR) due to a long drift space from the mask to the observation screen. Recent experimental studies at PITZ show improvement of the temporal resolution and SNR by utilizing quadrupole magnets between the mask and the screen. The measurement setup is described and first results are shown.

is negligible, the transverse emittance is usually measured with a quadrupole scan, where the emittance is reconstructed from beam images measured after propagation through different beam optics [5]. For a correct reconstruction the beam transport matrix has to be well-known.

At PITZ low beam energies of ~20 MeV and high bunch charges on the order of 1 nC complicate the beam transport due to strong space charge effects [6]. Therefore a single-slit mask is moved through the electron beam, allowing reconstruction of the phase space from the beamlet images on a screen downstream [7–9]. From the phase space the normalized transverse emittance

$$\epsilon_{n,x} = \beta \gamma \sqrt{\langle x^2 \rangle \langle x'^2 \rangle - \langle x x' \rangle^2}, \quad (1)$$

is calculated, where β is the mean electron velocity normalized to the speed of light, γ the average Lorentz factor and $\langle x^2 \rangle$, $\langle x'^2 \rangle$ and $\langle x x' \rangle$ the second-order beam moments [3].

Placing a transverse deflecting structure (TDS) downstream the slit mask, or operating an accelerating cavity off-crest while observing the beam image in a dispersive section allows for slice emittance measurements. Time-resolved emittance measurements with the booster are limited to ~2 ps [10], while slice emittance measurements with the TDS have already reached a resolution of down to ~1 ps [11].

However, the signal strength on the screen is low due to the small number of electrons passing the slit and the long drift length. Moreover, the TDS expands the beamlet in the vertical plane, leading to a low signal-to-noise ratio (SNR) which will underestimate the slice emittance due to signal removal during image noise subtraction. The use of quadrupole magnets between the slit mask and the observation screen reduces both the horizontal and vertical beta function at the measurement screen, which not only improves the time resolution, but also enhances the SNR for slice emittance measurements.

INTRODUCTION

Low transverse emittance is crucial for high-gain x-ray free-electron lasers (FEL) [1]. During the lasing process, the radiation is amplified by the electron beam within the cooperation length, which is often much smaller than the total bunch length. The transverse emittance inside this short longitudinal slice of the electron beam, i.e., the slice emittance, is more relevant for the FEL process than the projected emittance, thus of great interest for the FEL tuning [2].

At the Photo Injector Test Facility at DESY in Zeuthen (PITZ), see Fig. 1, RF electron guns are optimized and conditioned for use at the free-electron lasers FLASH and European XFEL in Hamburg [3]. Until now, the PITZ injector was experimentally optimized based on transverse projected emittance, as a reliable slice emittance diagnostics is still not established. Since the projected emittance optimization may not coincide with slice emittance optimization [4], the slice emittance diagnostics is in preparation.

For high-energy beams, where the space charge effect

MEASUREMENT SET-UP

The RF electron gun operating at 1.3 GHz accelerates the electrons to an energy of ~6.3 MeV. A photocathode UV

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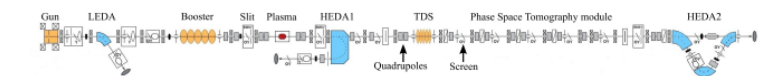


Figure 1: Schematic of the PITZ beamline.

Scan of quadrupoles strength (R12 scan)

Different focusing strength (should) yield different SNR's

- > Measured on 2019-12-20_A
 - > ~ 2.5h measurement time, without preparation
- > Gun: 6.3 MeV/c, Booster 19.4 MeV/c
- > Charge ~ 250 pC
- > Imain = 370 A
- > Laser: 90%-truncated Gaussian
- > RF5 lifetime was issue
- > Charge fluctuation (laser power fluctuation)

20.12.2019 19:57 O. Lishilin, R. Niemczyk Quadrupole calibration for slice emittance measurements

```
Setting High1.Q09 High1.Q10 R12
1 -4.6A +4.8A 0.67m
2 -4.3A +4.5A 1.50m
3 -4.0A +4.3A 2.75m
4 -3.7A +4.0A 3.60m
5 -3.4A +3.7A 4.10m
6 -3.0A +3.4A 5.50m
7 -3.2A +3.5A 4.60m
8 -2.7A +3.1A 5.98m
9 0.00A 0.00A Drift
```

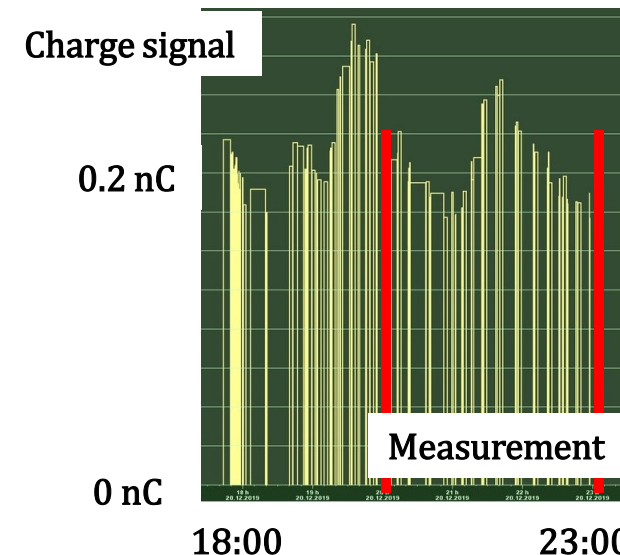
Set the quadrupoles via the following routine: Degauss, go from zero directly to the current value

20.12.2019 20:39 O. Lishilin, R. Niemczyk TDS Klystron died during slit scan

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Shutter was open, at slit position 36/41
TDS Klystron lifetime: ~3 min 30 sec
```

20.12.2019 23:13 O. Lishilin, R. Niemczyk Charge after slice emittance measurement

The charge dropped from 250 pC to 220 pC, i.e. by 30 pC, more than 10%

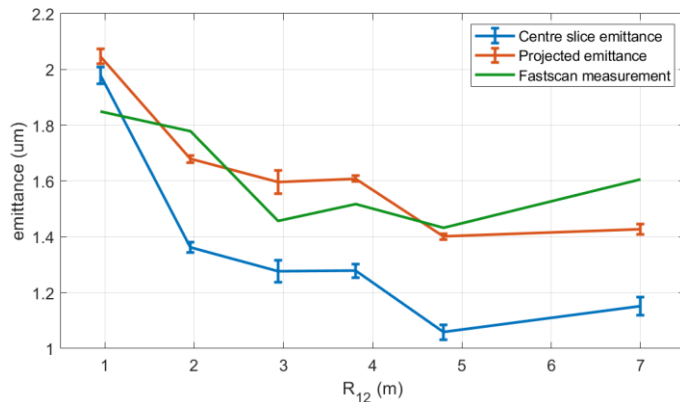


Signal =
Low.ICT1/ONE_CH:
Absolute values off –
relative change
interesting

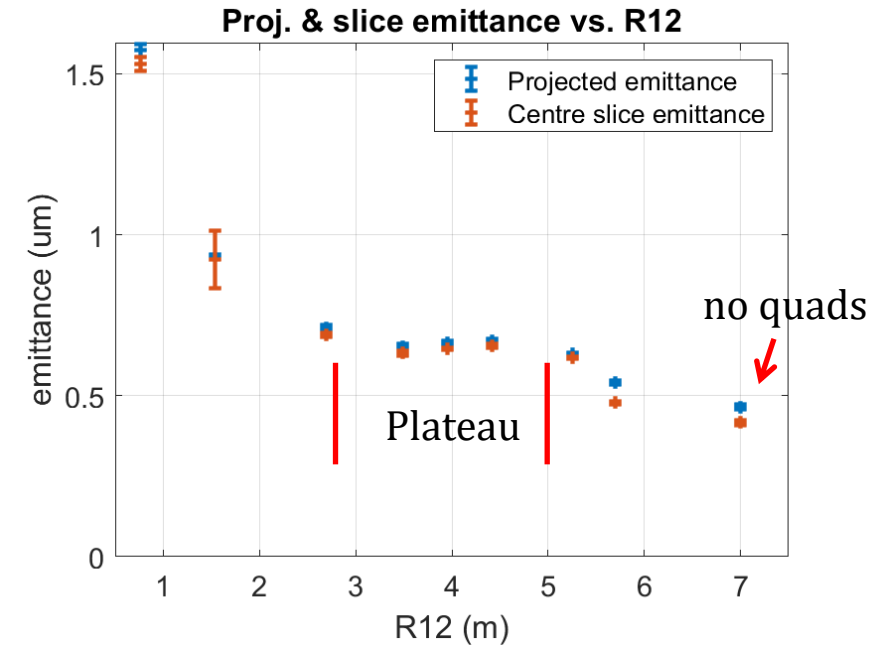
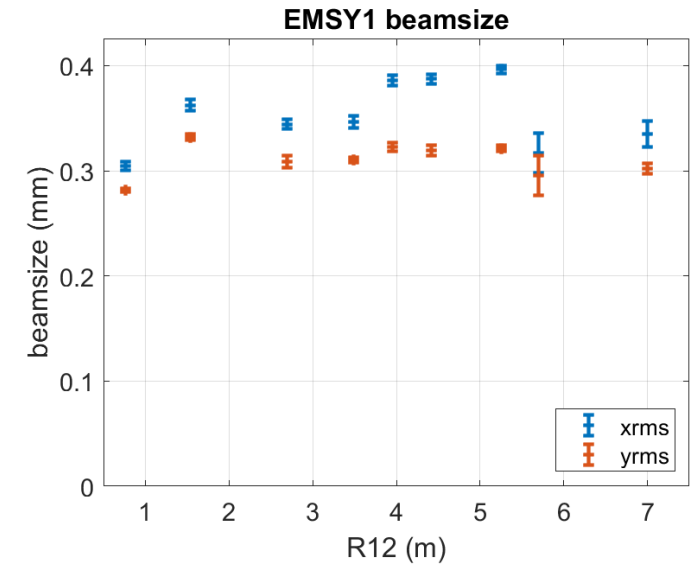
Scan of quadrupoles strength (R12 scan)

Different focusing strength (should) yield different SNR's

- > EMSY1 beamsize fluctuation
 - > Settings before EMSY1 constant (no change expected)
 - > Charge drifts likely case
- > Projected & slice emittance
 - > Earlier measurement confirmed (experiment repeatable)
 - > R12 [2.8m to 5m]: Increase of measured emit due higher SNR
 - > Emittance independent of R12 on plateau → Proper setting for slice emittance measurement
 - > R'12 around 3.5m were used so far



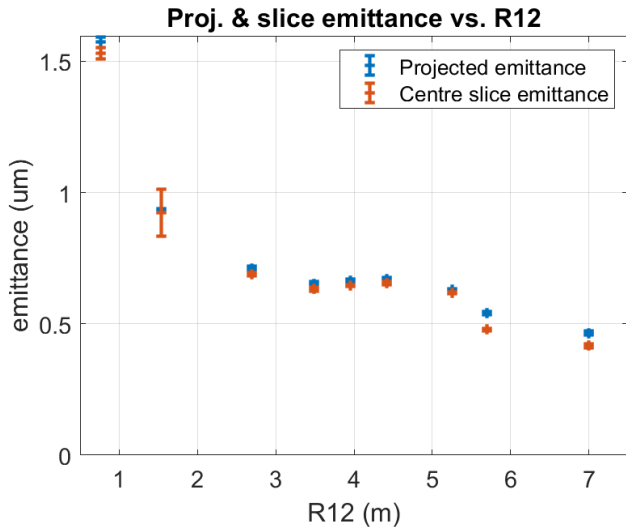
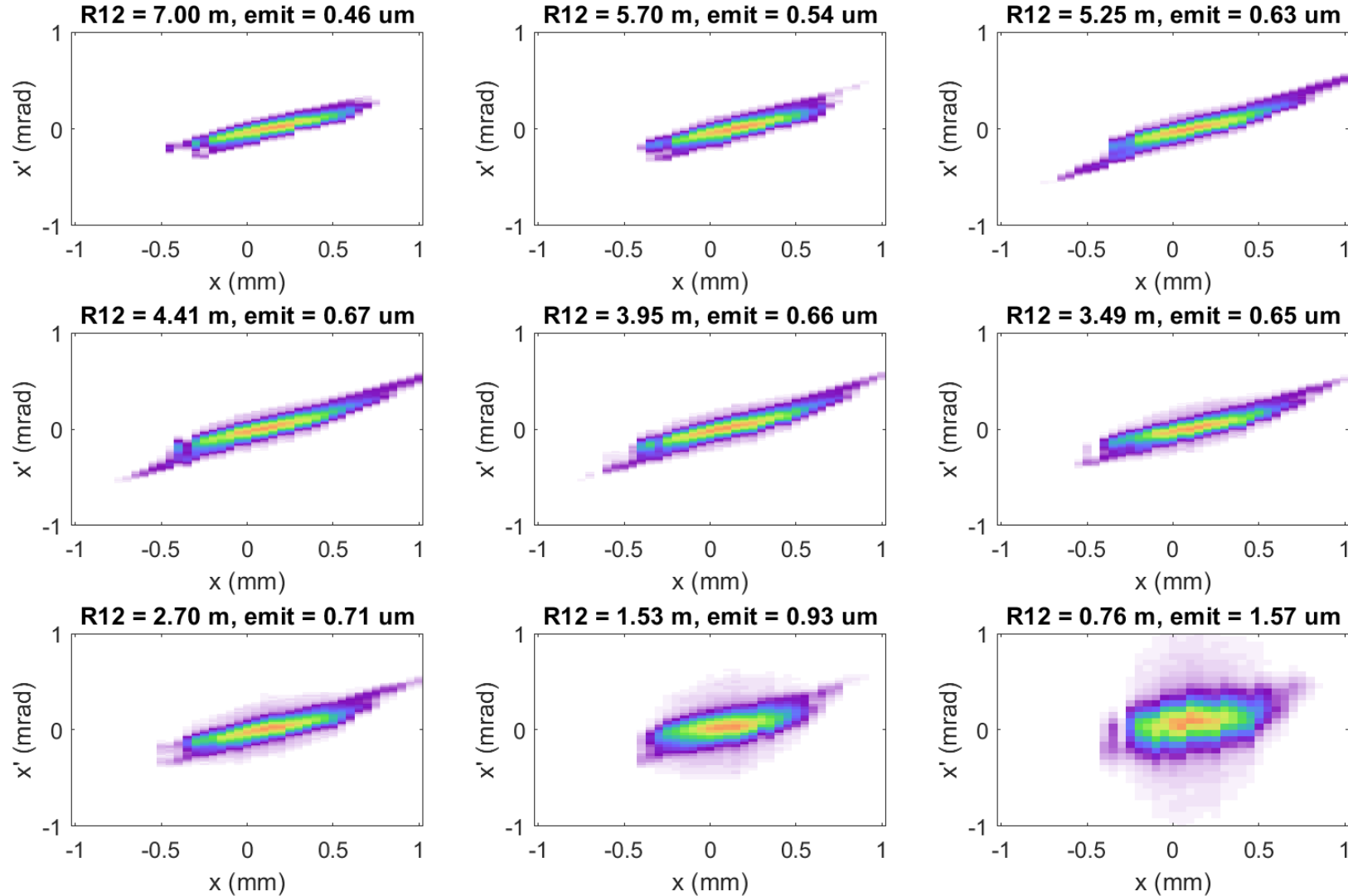
Measurement from 2019-08-16
→ Reproducible result



Scan of quadrupoles strength (R12 scan)

Centre slice phase space for different focusing

- For $R12 < 2.7\text{m}$ tails (in x) vanish → contradicts higher SNR interpretation
- For decreasing $R12$ tails visible → explains emittance increase
- For $R12 < 2.7\text{m}$ angular halo (in x') visible → Emittance increase
- Stronger focus (smaller $R12$) → bigger halo

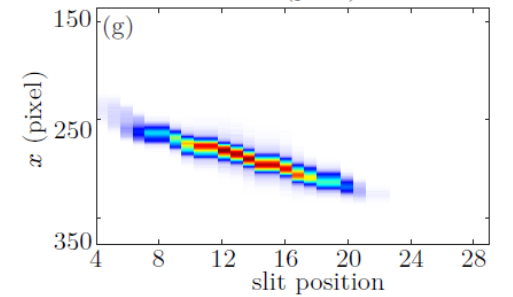
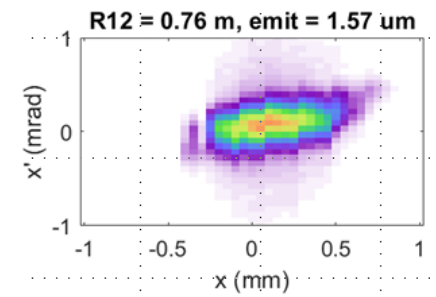
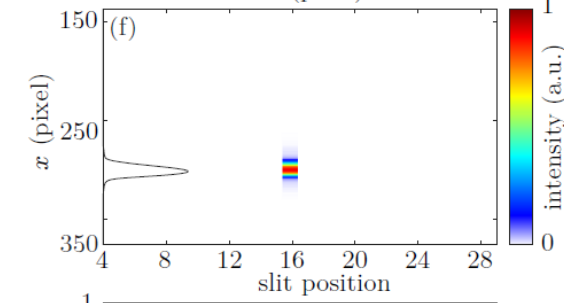
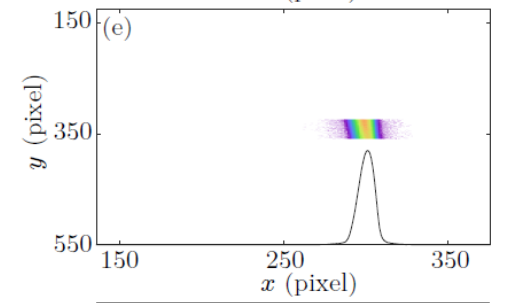
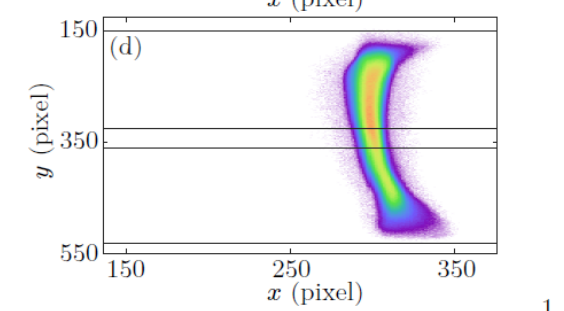
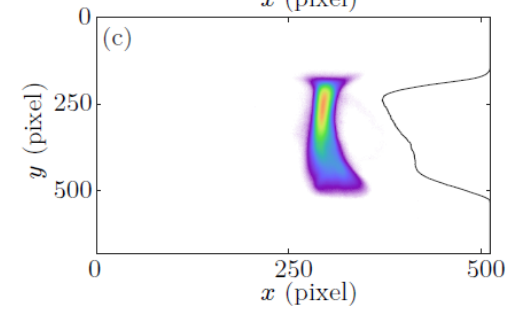
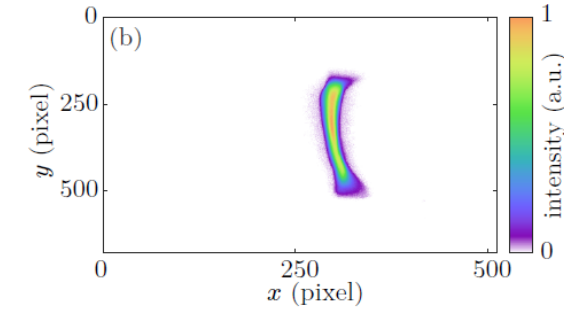
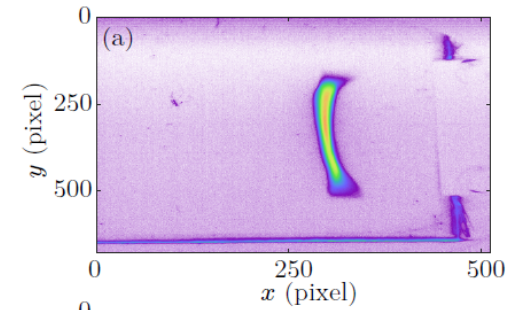


Phase space reconstruction

Assembly of (slice) phase space from raw beamlet images

- Filter of raw images
- Determine where to slice beamlets
- Do projection of sliced beamlets
- Reconstruct phase space from all (sliced) beamlets
 - Consider R11 and R12
- Calculate angle from pixel and size from slit position
- Calculate area → (Slice) emittance

- Angular phase space halo from spatial beamlet halo

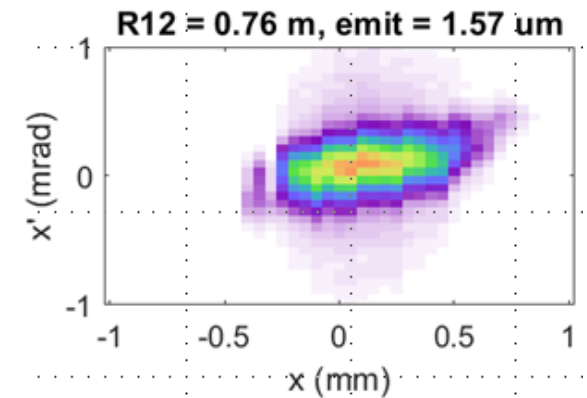


Angular phase space halo

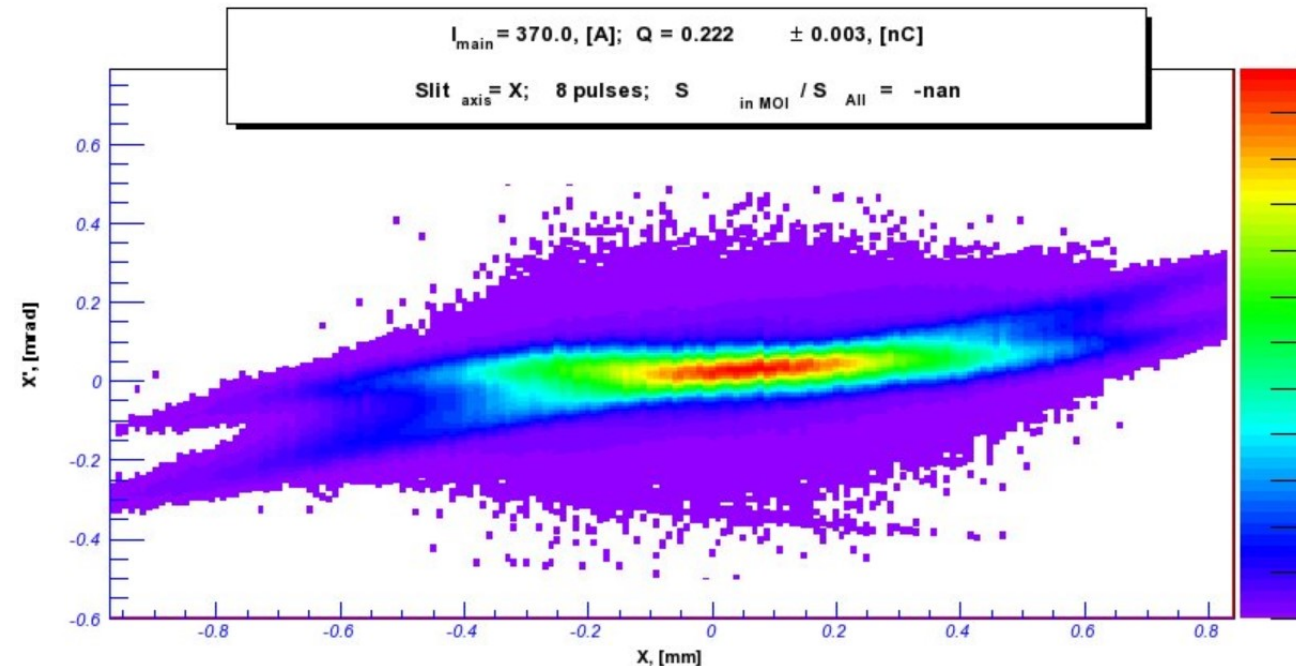
Fastscan measurement on PST.Scr1 btm

- > Earlier observation in May 2019
- > Very pronounced in fastscan on PST.Scr1 btm
 - > Despite lack of focusing
 - > But also: no TDS → Higher charge density
- > Fastscans with different number of pulses on both YAG and LYSO might help understand issue

Centre slice phase space, strongest focusing, 2019-12-20



Fastscan measurement, projected phase space, EMSY1 → PST.Scr1 LYSO, no TDS, no quads



Scan of quadrupoles strength (R12 scan)

Signal-to-Noise ratio for different focusing strength

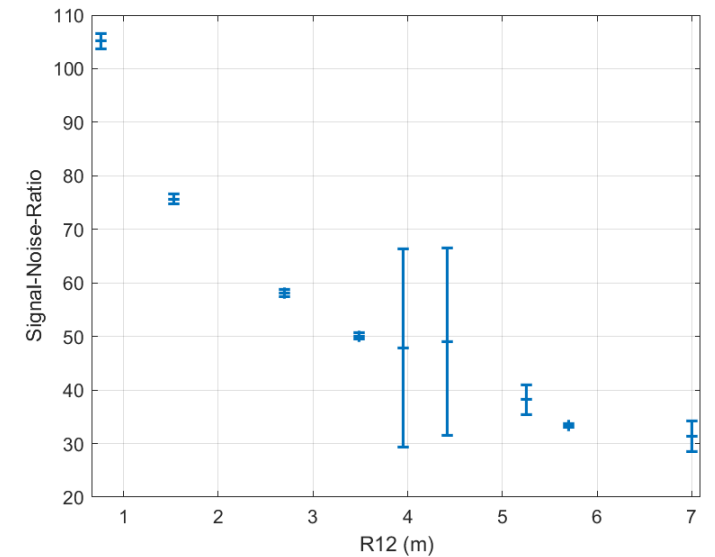
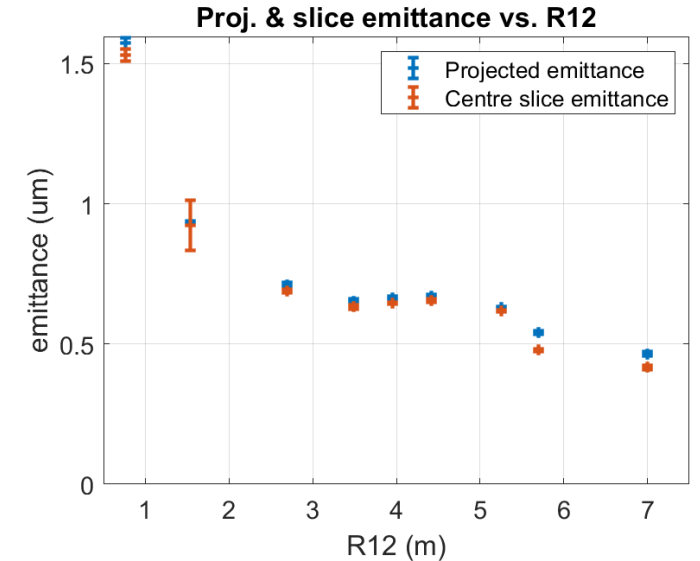
- > Noise level = rms of pixel value of all pixel in MOI in all background images (typically ~6.8)
- > Signal level
 - > Take filtered images
 - > Smooth with Gaussian (sig = 0.5 pixel) → Remove hot spots
 - > Divide signal (for each focusing strength (R12), each slit position, each of ten images at each slit position) by noise level
 - > Average SNR 'along' statistics for each slit position
 - > Take max SNR 'along' slit position (-> centre beamlet)
- > SNR higher with stronger focusing

Max. pixel filling observed*: 770

Bkg pixel filling: ~77 -> 10% of max

→ Effectively 700-criterion (also important for fastscan)

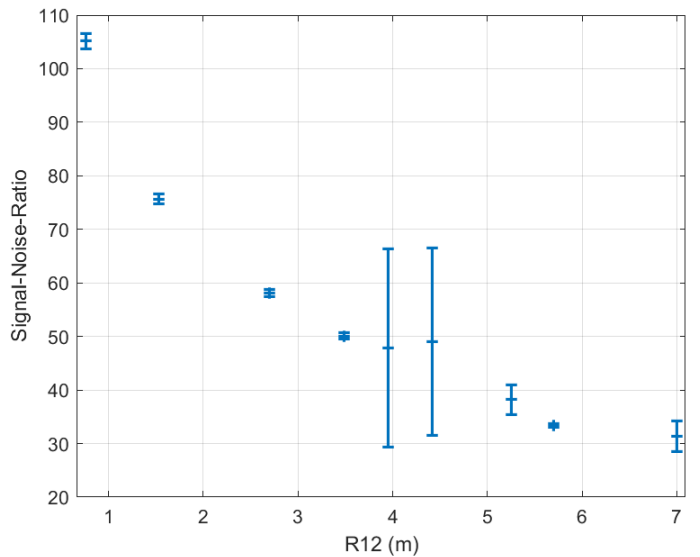
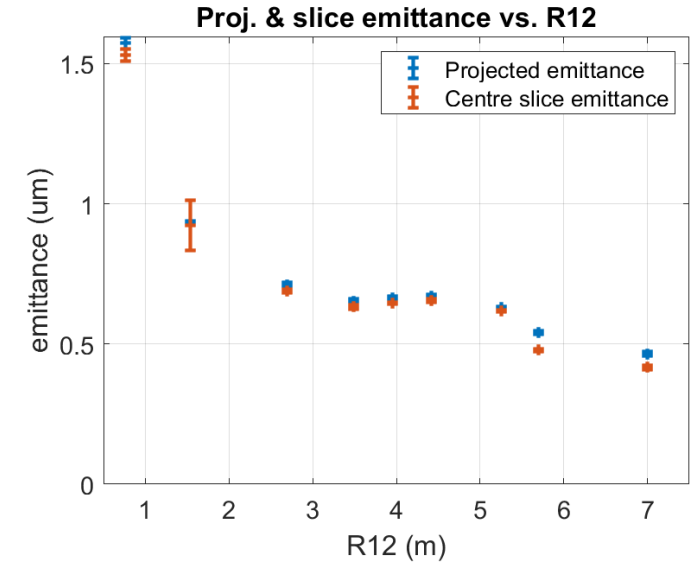
* ten-times averaged raw images, strongest focusing



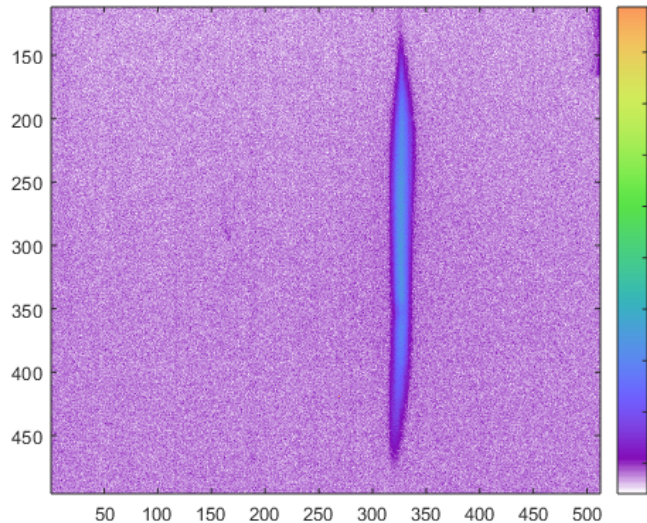
Scan of quadrupoles strength (R12 scan)

High uncertainty for two settings

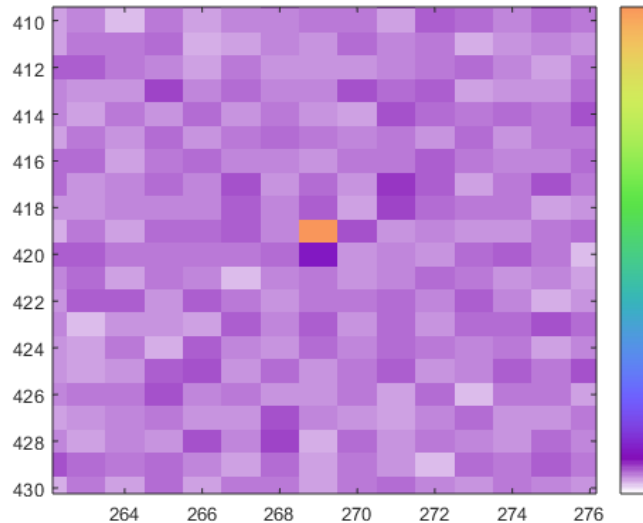
- > Few times salt'n'pepper noise observed
 - > Single pixel with very high filling -> not real, from camera
- > Example below
- > Might make smoothing necessary
- > Gives high uncertainty bars



Raw beamlet image, central slit position



Zoom of left image



Outlook

Summary

- > Focusing scan (R12 scan) result reproducible
- > Plateau for intermediate focusing (R12 = 2.8m to 5m) → Proper measurement setting
- > Higher SNR for stronger focus explains higher measured emittance
- > For strongest focusing angular halo observed → Strong slice emittance increase
 - > Angular halo from spatial beamlet halo
 - > Issue of screen/screen station?
 - > Beam halo also observed in thermal emittance measurement
 - > Also LYSO, also telescope, same screen orientation
 - > There: Scattering in screen material blamed (observed earlier at REGAE) [1]
- > Analysis of slice emittance/SNR for different TDS voltages pending
- > Verification of correct calculation of R11 and R12 in process

[1] M. Hachmann, PhD thesis, Uni. Hamburg (2017)