Characterization of the transverse profile of the PITZ photocathode laser

- **Motivation**
- **Area of Interest**
- **Laser Beam Characterization**
- **Summary and Outlook**

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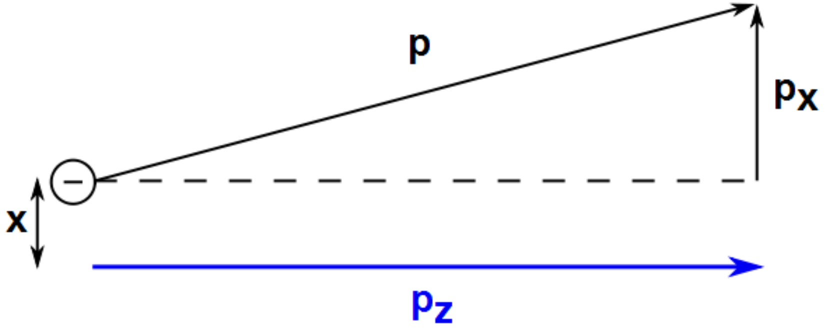
Motivation

- Free electron lasers (FEL) operating in X-ray regime require high brightness electron beams
- Achieved by high peak currents and low transverse emittance
- At Photo injector test facility in Zeuthen (PITZ) injectors for FLASH and XFEL are developed, optimized and characterized, with focus on emittance optimization

Motivation

- Transverse emittance = volume of particle distribution in 4D phase space $[x, y, p_x, p_y]$
- Convenient definition for normalized transverse emittance:

with $x' = \frac{p_x}{p_z}$



$$\epsilon_x = \beta\gamma\sqrt{\sigma_x^2\sigma_{x'}^2 - \mathrm{cov}^2(x, x')}$$

- in a LINAC normalized transverse emittance can only grow

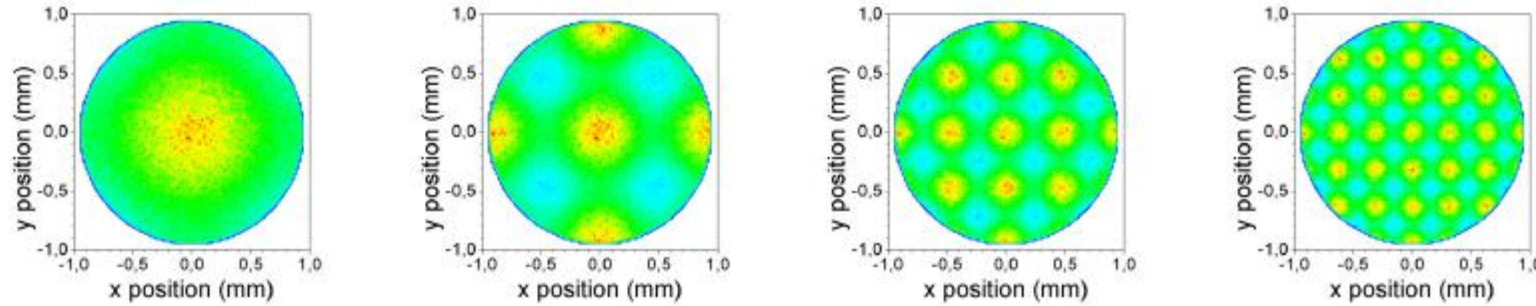
Motivation

- Three main contributor to beam emittance: $\varepsilon \approx \sqrt{\epsilon_{th}^2 + \epsilon_{SC}^2 + \epsilon_{RF}^2}$ (if all are assumed to be independent)
- Thermal emittance ϵ_{th} poses lower limit
- At cathode: $\epsilon_{th,x} = \frac{1}{m_e c} \sigma_x \sigma_{p_x}$
- In a simplified model σ_{p_x} is function of electron affinity, band gap energy and wavelength of cathode drive laser → no degree of freedom in emittance optimization
- → thermal emittance is determined by rms laser spot size σ_x
- σ_x chosen as compromise between ϵ_{th} and ϵ_{SC}
- Optimum: homogeneious intensity distribution (= flat-top distribution)

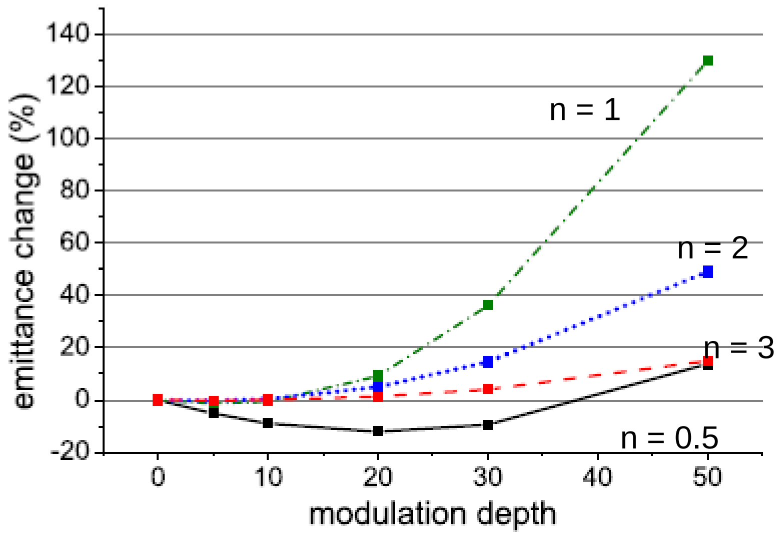
Motivation

> Previous simulation studies on the impact of charge inhomogeneities:

- Modulation of the charge distribution with $q = q_0 \cdot [1 + d\cos(k_n x)] \cdot [1 + d\cos(k_n y)]$



n = 0.5 | n = 1 | n = 2 | n = 3



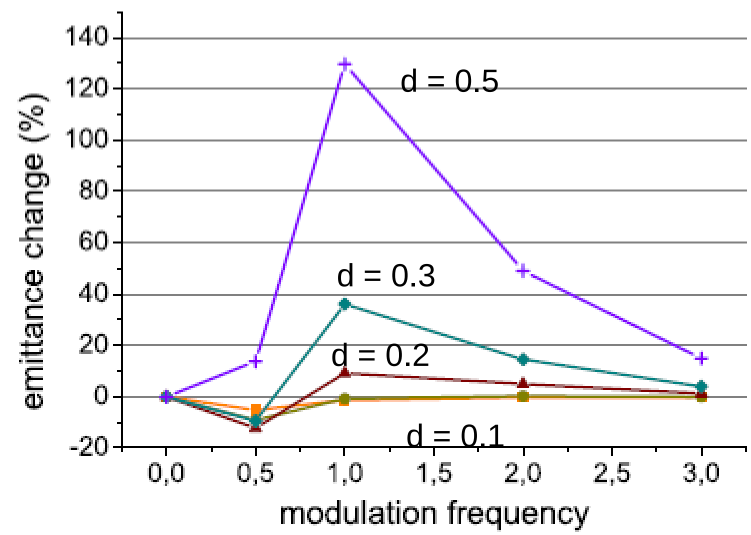
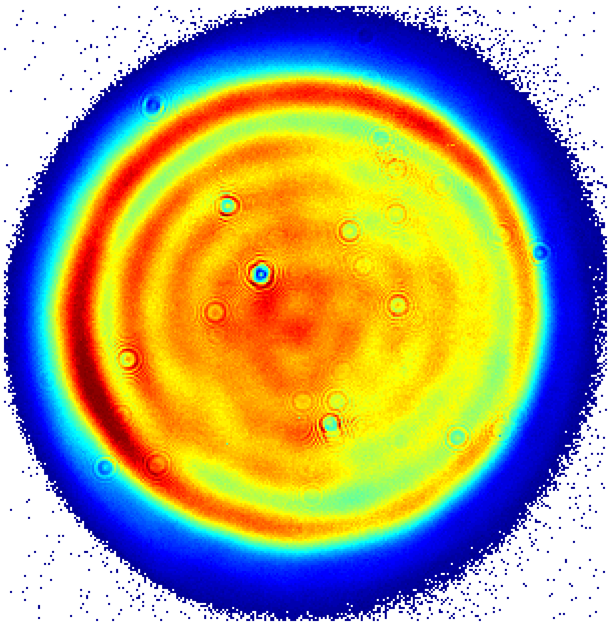


Image source: M. Hänel. *Experimental Investigations on the Influence of the Photocathode Laser Pulse Parameters on the Electron Bunch Quality in an RF – Photoelectron Source*. PhD thesis, Universität Hamburg, 2010.

Area of interest

- Desired: characterization of inhomogeneities of flat-top distribution
- Reality: no sharp edges → bias of characterization (e.g. standard deviation or rms)
- Solution: definition of Area of Interest (AOI)
- AOI finding needs to be automated for reproducibility

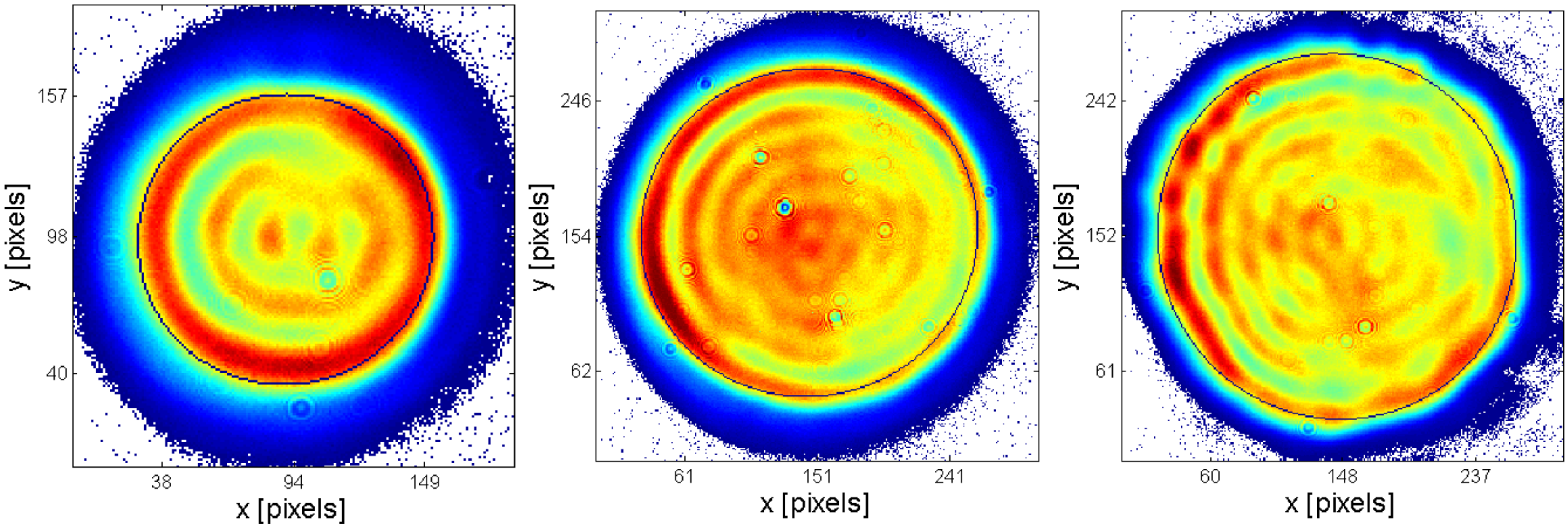


Area of interest

- Attempts with 1D projections did not satisfy
- Final solution: 2D fitting with elliptical Super-Gaussian:
  - Ellipse: $$E(x,y) = \left(\frac{x-x_0}{\sigma_x}\right)^2 + \left(\frac{y-y_0}{\sigma_y}\right)^2 - \frac{2\sigma_{xy}}{\sigma_x^2\sigma_y^2}(x-x_0)(y-y_0)$$
  - Super-Gaussian: $$f_{SG}(x,y) = A \cdot \exp\left(-\frac{1}{2\left(1-\frac{\sigma_{xy}^2}{\sigma_x^2\sigma_y^2}\right)} E^{\frac{G}{2}}(x,y)\right)$$
- This is basically a Gaussian with higher exponent G → steeper flanks (flat-top for G → ∞)
- AOI > 90% of Super-Gaussian

Area of interest

> Examples:



Laser Beam Characterization

- General form of laser spot:
  - Ratio of Semi-axes of ellipse (round ↔ elliptical)
  - Exponent G of Super-Gaussian fit result (↔ steepness/widths of flanks)

- Statistical parameters:
  - Standard deviation: $$\sigma_{a_{ij}} = \sqrt{\frac{1}{T}\sum_{ij}^{T}(a_{ij} - \bar{a})}$$
  - Higher order moments like skew (γ) and kurtosis (k)

$$\gamma = \frac{1}{T}\sum_{ij}^{T}\left(\frac{a_{ij} - \bar{a}}{\sigma_{a_{ij}}}\right)^3 \qquad k = \frac{1}{T}\sum_{ij}^{T}\left(\frac{a_{ij} - \bar{a}}{\sigma_{a_{ij}}}\right)^4 - 3$$

  - Spatial correlation

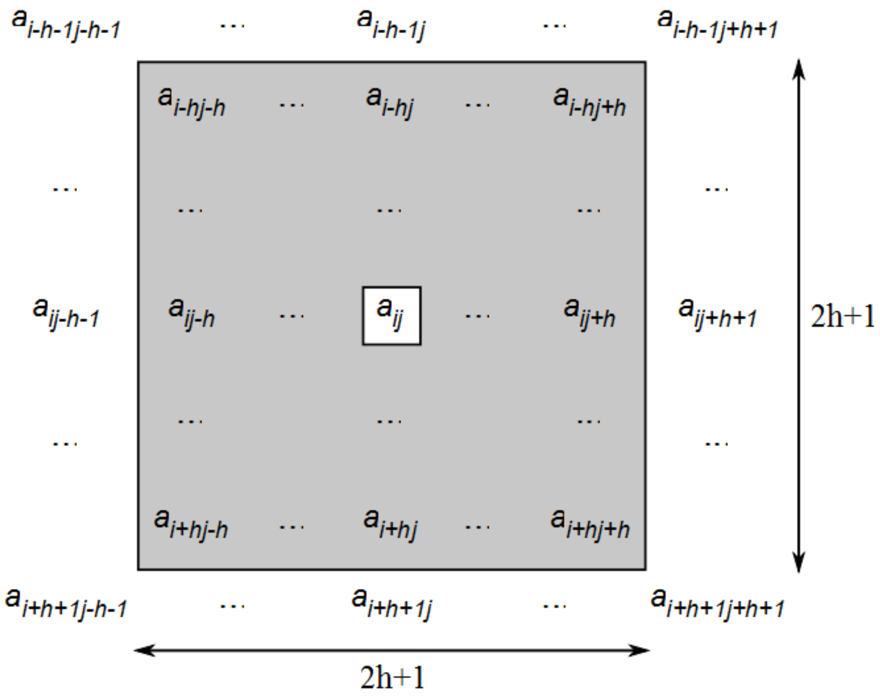
Spatial correlation

- Spatial correlation introduced by Fusco et al. [1]:

$$\mathrm{cov}(a,h) = \frac{1}{T}\sum_{ij}(a_{ij} - \bar{a})(a_{ijh} - \bar{a})$$

with a_{ijh} the local average around a_{ij}:

$$a_{ijh} = \frac{1}{(2h+1)^2 - 1}\sum_{l=-h}^{h}\sum_{k=-h}^{h} a_{i+l\ j+k} - a_{ij}$$



- Spatial correlation:

$$\Lambda = \frac{\mathrm{cov}(a,h)}{\sigma^2_{a_{ij}}}$$

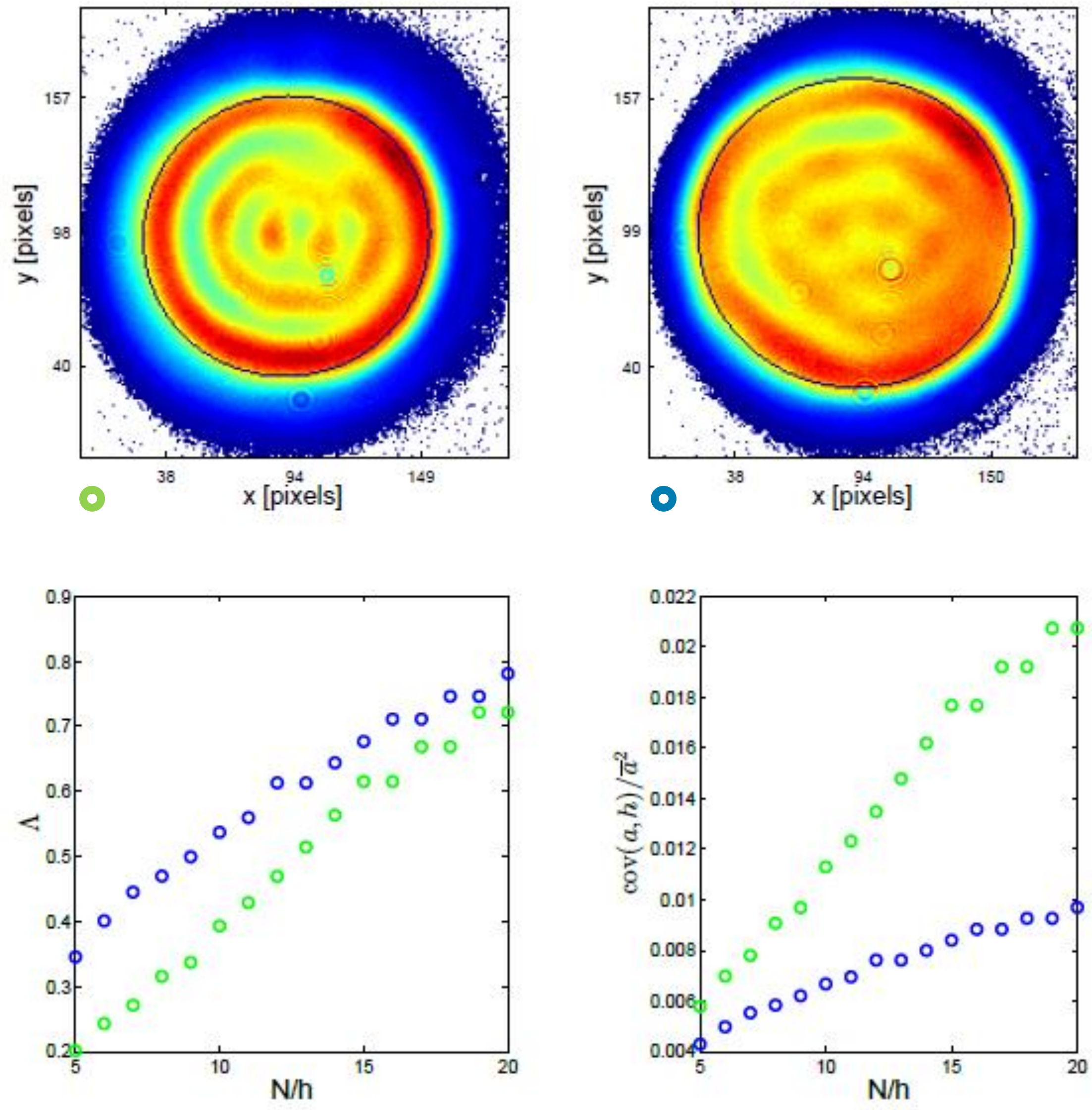
[1] V. Fusco, M. Ferrario, and C. Ronsivalle. Spatial Correlation for Laser Beam Quality Evaluation. Technical Report SPARC-EBD-07/007, INFN/LNF, 2007.

Spatial correlation

- h is the resolution of spatial correlation
- For comparability: choose h relative to spot size $\mathrm{N} \sim \sqrt{T}$
- Λ for different N/h might be interesting: scanning different resolutions can give information on scale of inhomogeneities
- Major disadvantage of Λ : Λ is relative to $\sigma_{a_{ij}} \rightarrow$ direct comparison of different spots is difficult
- Solution: relative covariance ϱ instead of Λ:

$$\varrho = \frac{\operatorname{cov}(a, h)}{\bar{a}^2}$$

Spatial correlation



Expansion in Fourier and Bessel series

- Standard deviation and spatial correlation or relative covariance quantify size and distribution of inhomogeneities statistically but cannot characterize the actual distribution sufficiently
- Spectral transforms can analyze spots in spatial frequencies
- Best candidates: Fourier transform (general, easy to interpret) and Bessel transform due to radial nature of the spots
- Transform in polar coordinates (r, φ) since diffraction pattern is polar

Expansion in Fourier and Bessel series

- 1D Fourier transform for finite, discrete Data:

$$f(t) = \sum_{n=0}^{\infty} c_n \cdot e^{2\pi i \frac{nt}{T}}$$

with
$$c_n = \frac{1}{T} \sum_{t=0}^{T-1} f(t) \cdot e^{-2\pi i \frac{nt}{T}}$$

- 1D Bessel transform in interval (0,b):

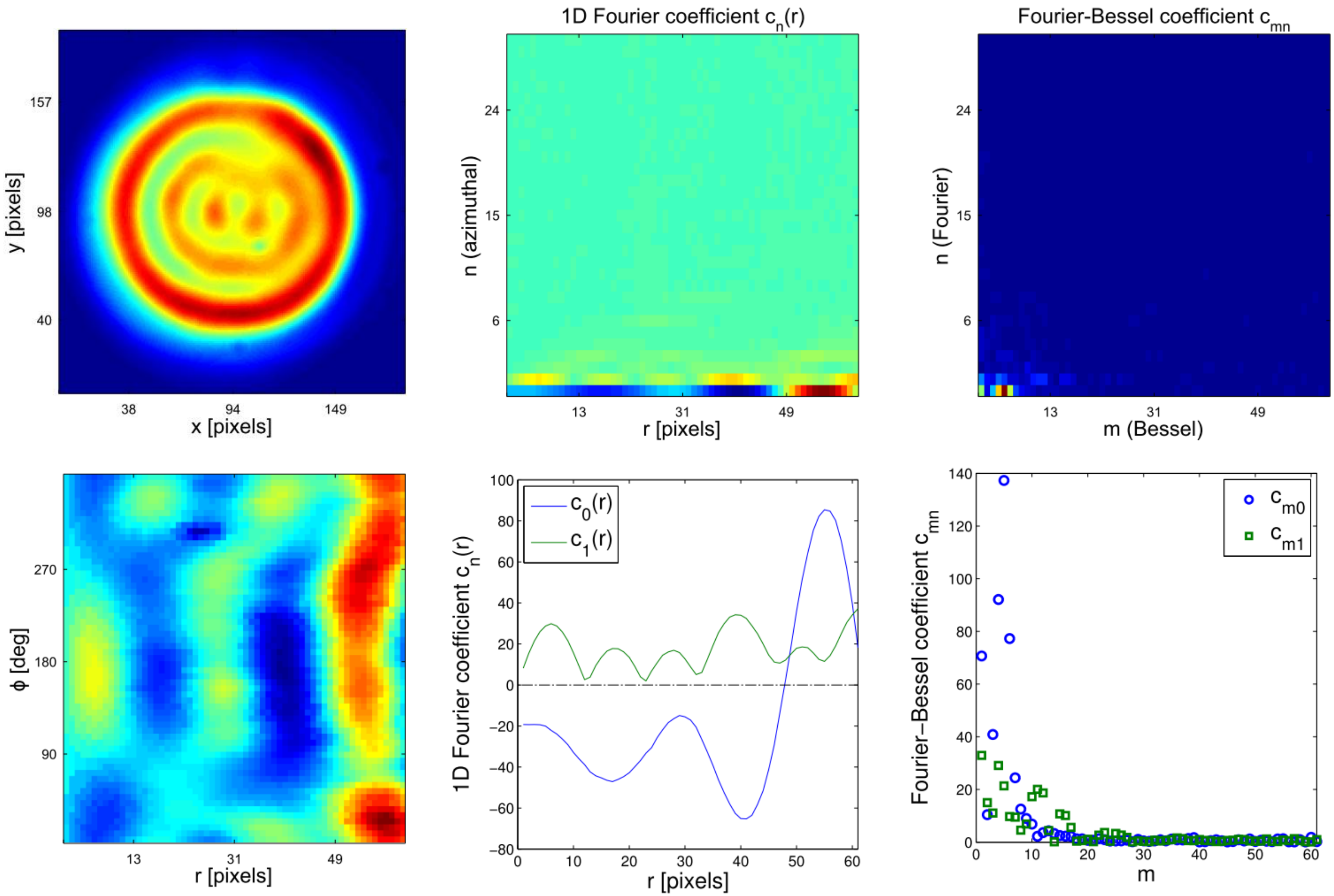
$$f(r) = \sum_{m=1}^{\infty} c_{\nu m} J_\nu\left(\alpha_{\nu m} \frac{r}{b}\right)$$

with
$$c_{\nu m} = \frac{2}{b^2 [J_{\nu+1}(\alpha_{\nu m})]} \int_0^b f(r) J_\nu\left(\alpha_{\nu m} \frac{r}{b}\right) r dr$$

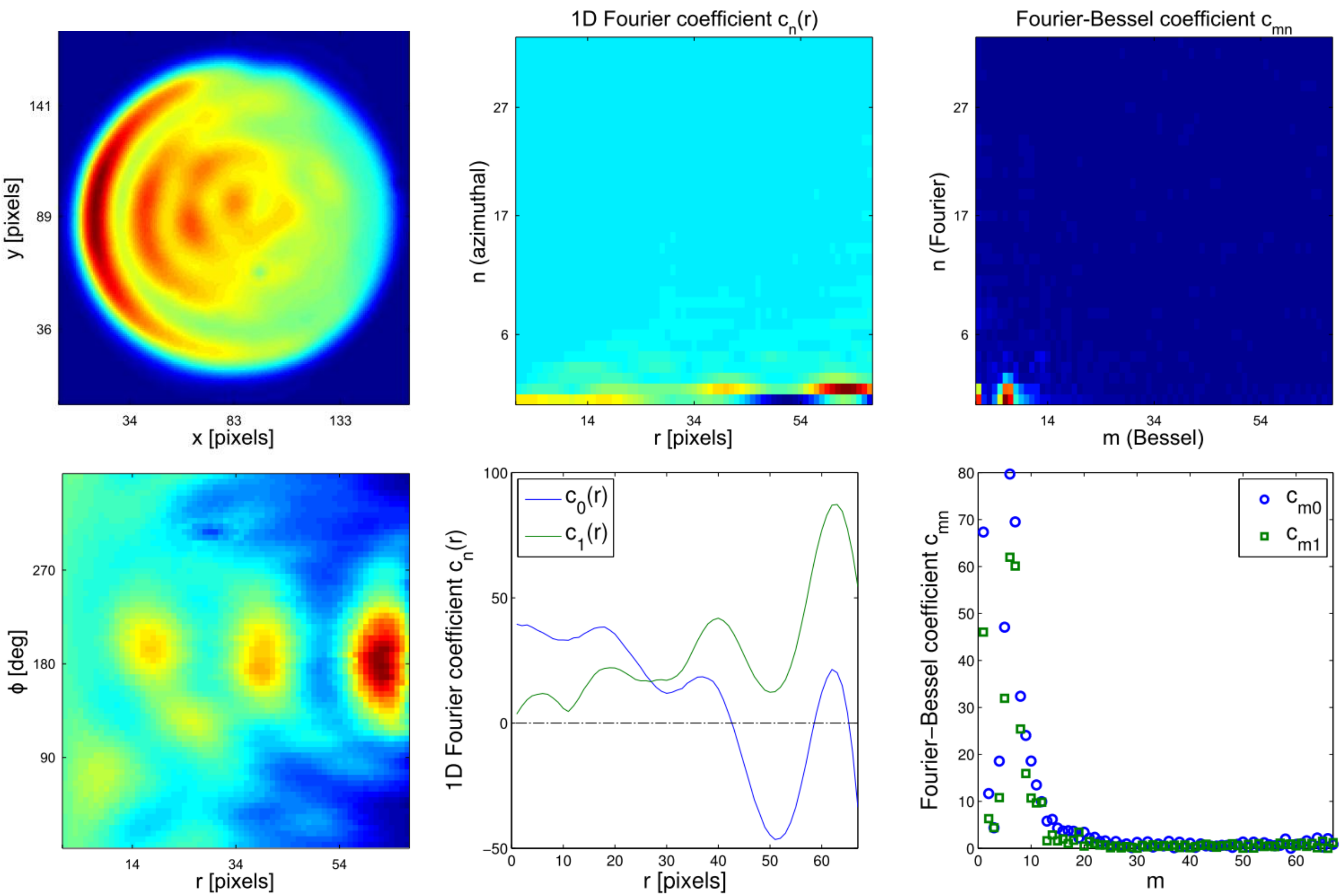
Expansion in Fourier and Bessel series

- 2D transform = subsequent 1D transforms in each dimension
- Data is periodic in φ so Fourier transform is the obvious choice in this dimension $\rightarrow$ either 2D Fourier or Fourier-Bessel transform
- Bessel proved to be less numerically accurate, so Fourier transform was applied first
- Since Bessel transform only works for real values, only the absolute values were transformed further

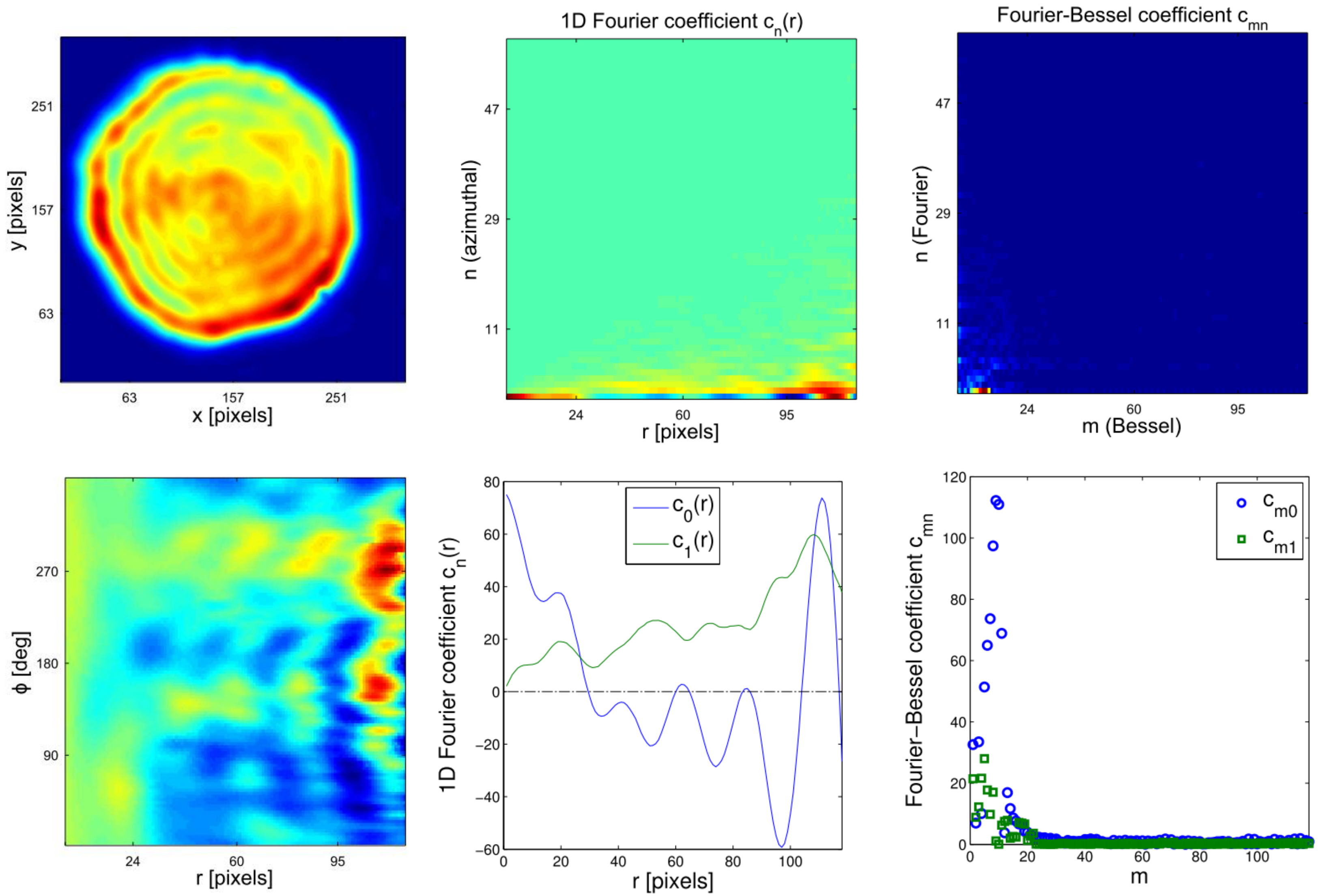
Expansion in Fourier and Bessel series



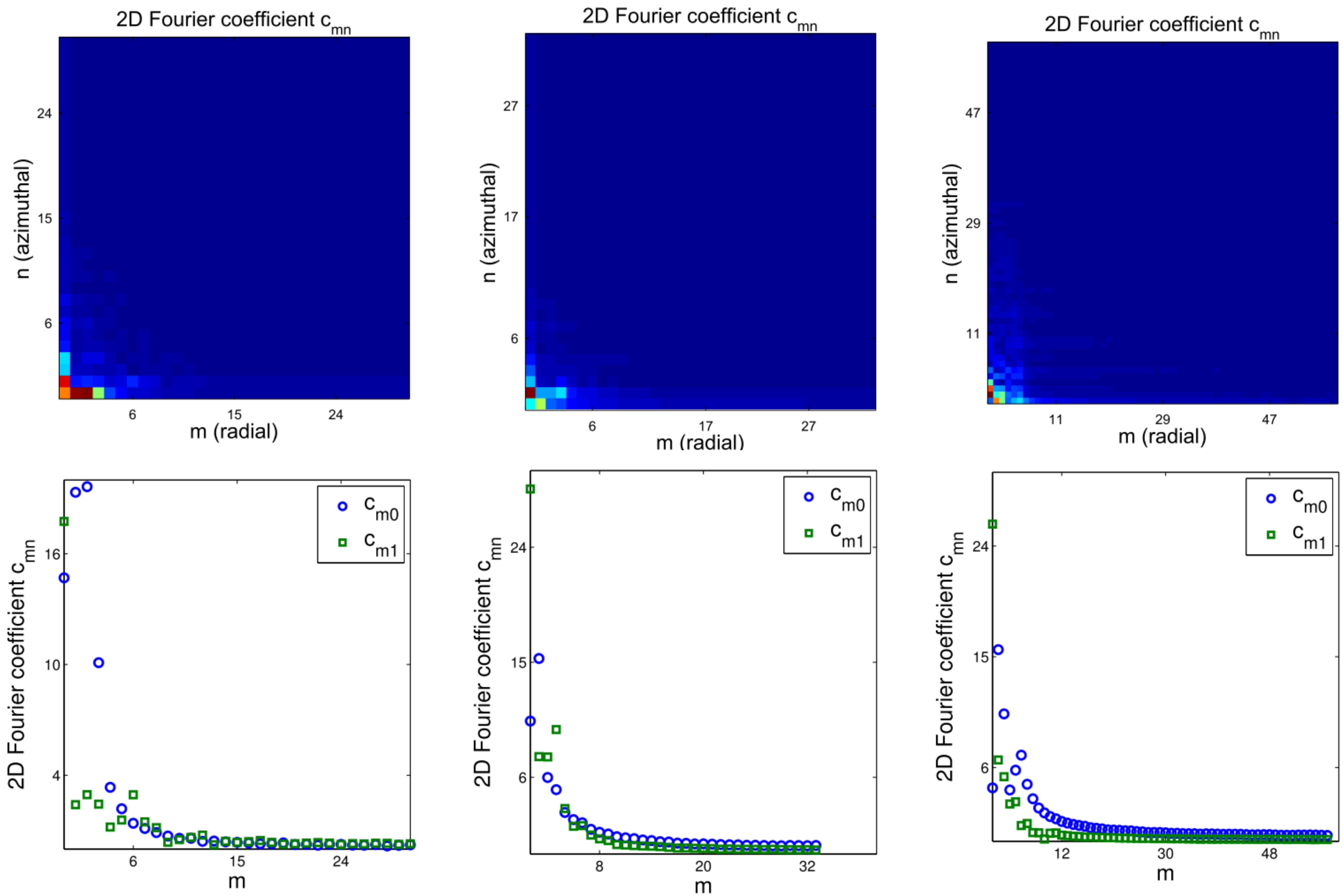
Expansion in Fourier and Bessel series



Expansion in Fourier and Bessel series

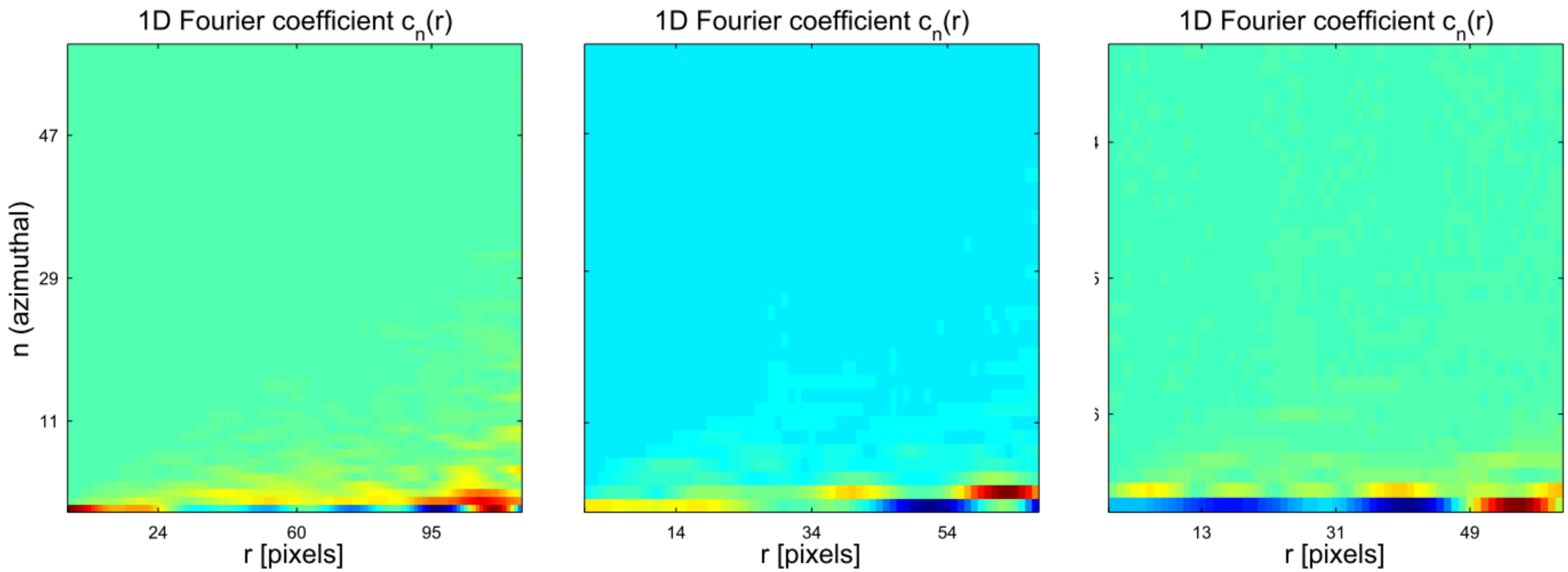


Expansion in Fourier and Bessel series



Expansion in Fourier and Bessel series

- 2D spectra disqualified: too much, complex data that is hard to interpret and give little information (aim is, to provide operation staff with crucial information for emittance optimization, those 2D spectra will not help)
- Better approach: focus on 1D spectra:



- We can see: main part of inhomogeneities is made up of frequencies $n \leq 10$

Expansion in Fourier and Bessel series

- Further reduction: relative, weighted Fourier projection

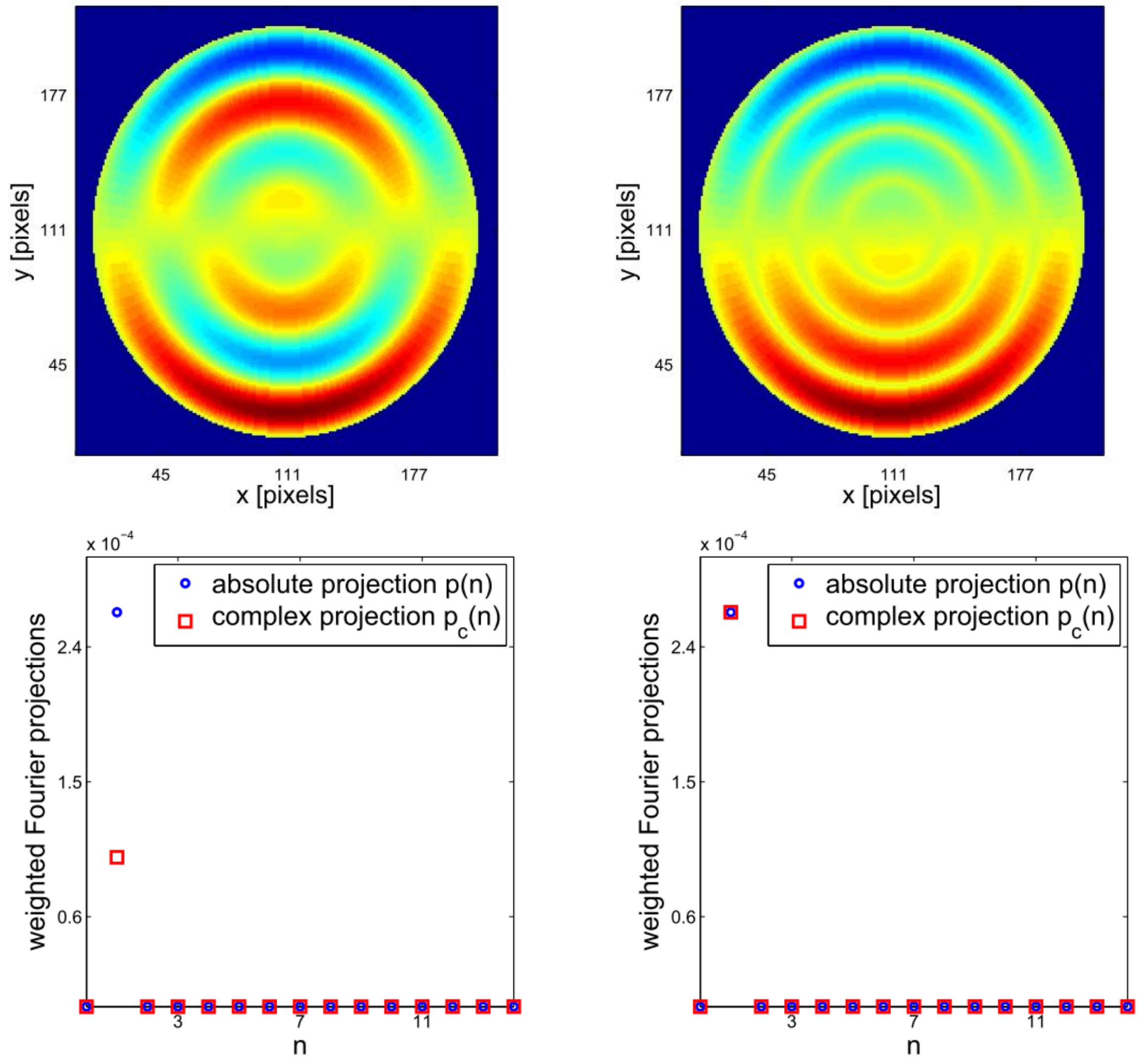
$$p(n) = \frac{1}{\bar{a}} \cdot \sum_r |c_n(r)| \cdot \frac{\pi\,[r^2 - (r - \Delta r)^2]}{A_{AOI}}$$

- Unfortunately, this neglects the phase, different spots with the same $p_n(r)$ are possible
- $\rightarrow$ complex Fourier projection

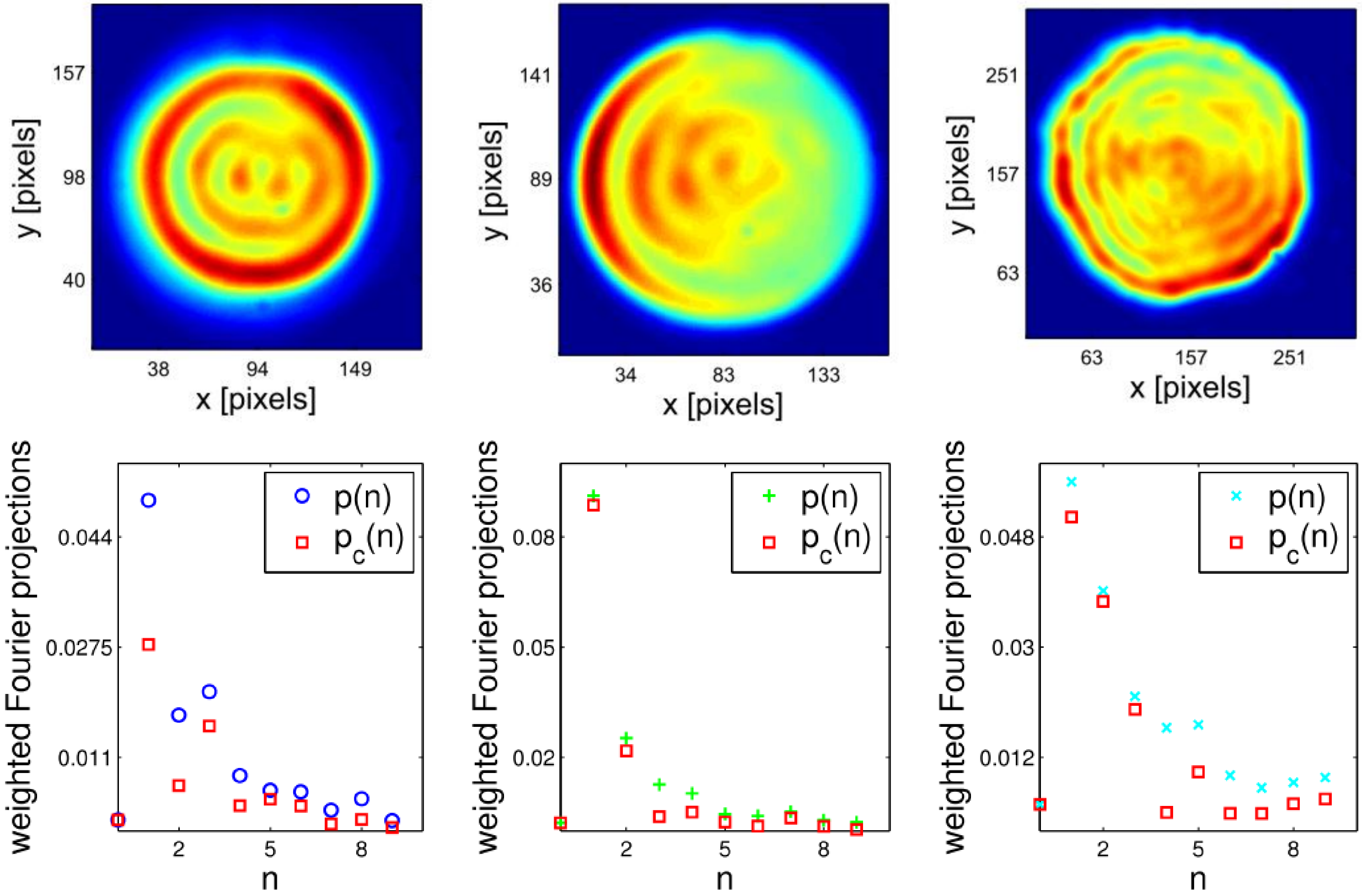
$$p_c(n) = \frac{1}{\bar{a}} \cdot \left| \sum_r c_n(r) \cdot \frac{\pi\,[r^2 - (r - \Delta r)^2]}{A_{AOI}} \right|$$

- $\rightarrow p(n)$ characterizes angular frequencies, $p_c(n)$ the global impact

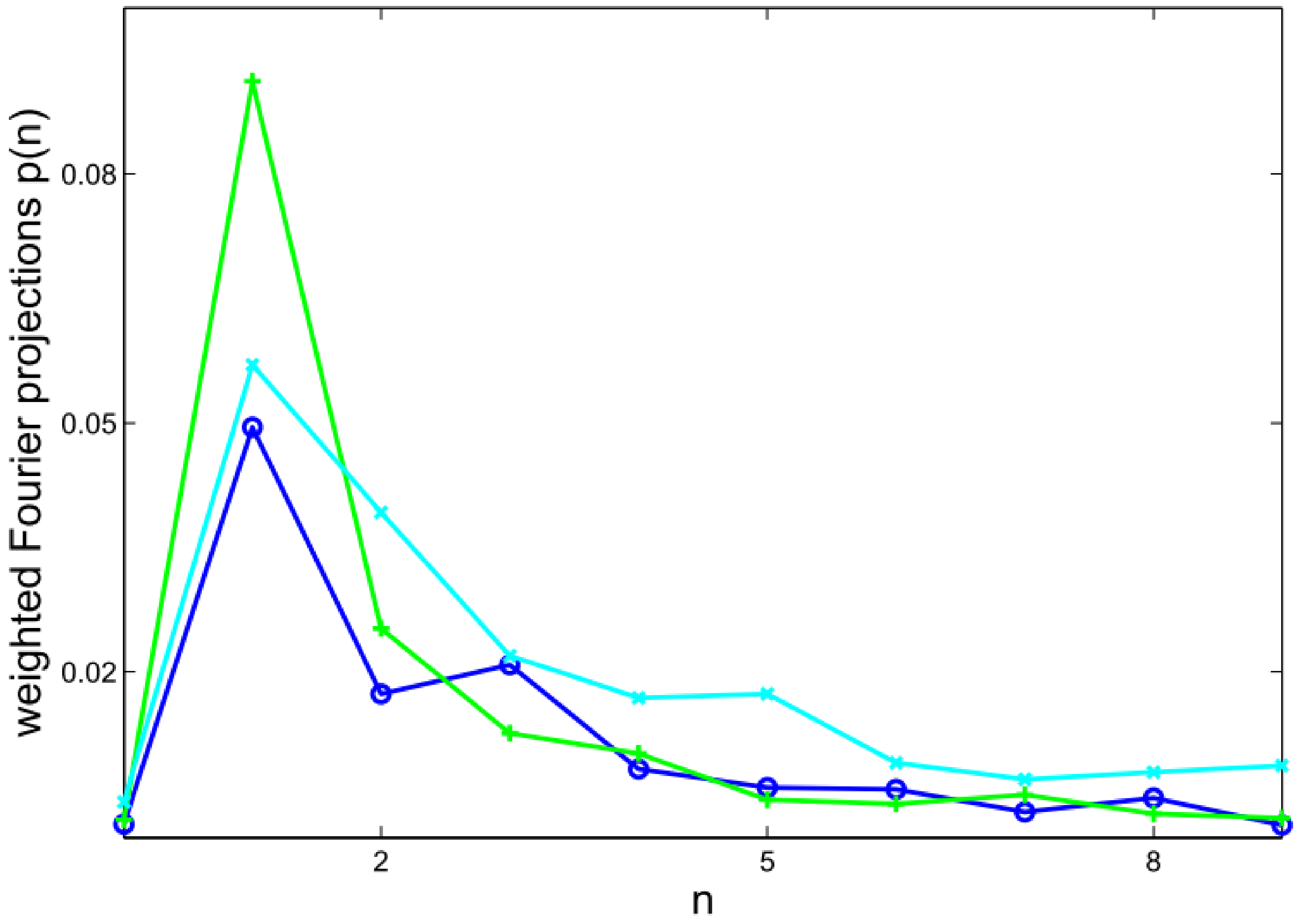
Expansion in Fourier and Bessel series



Expansion in Fourier and Bessel series



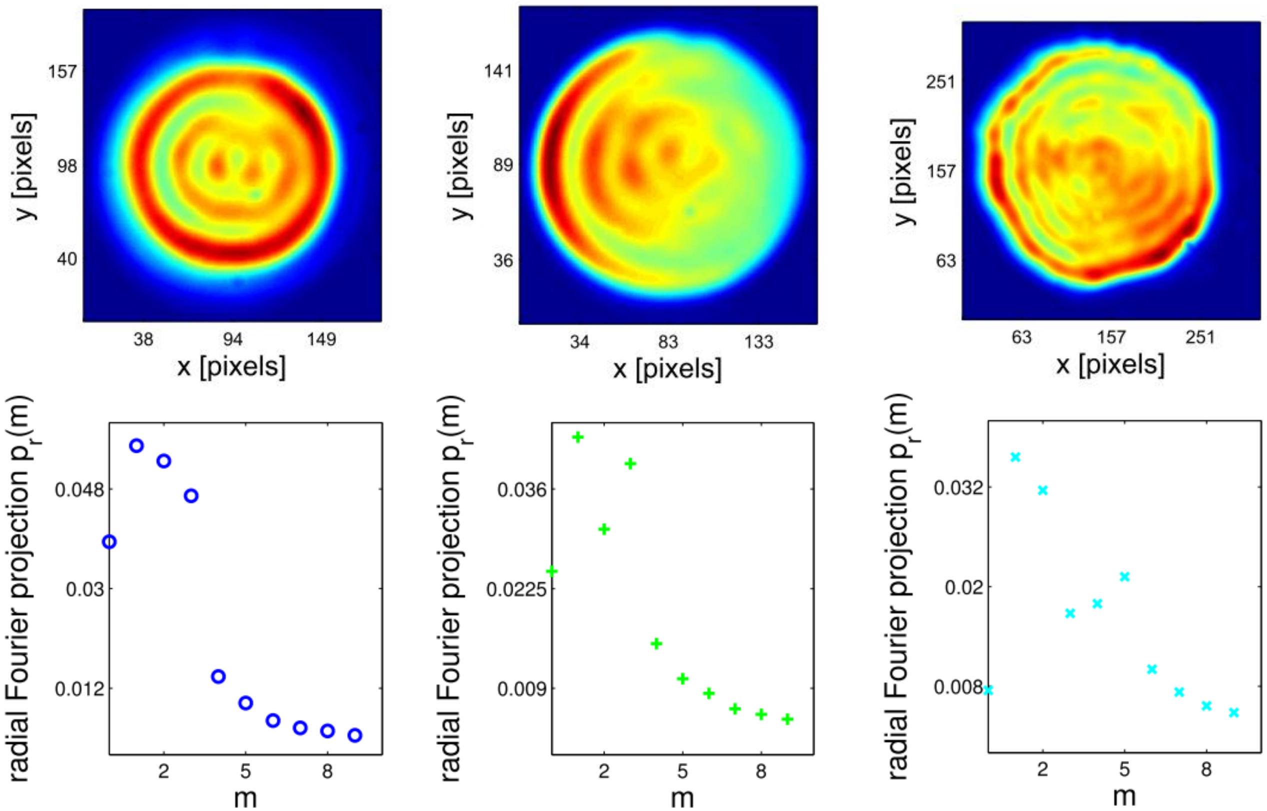
Expansion in Fourier and Bessel series



Expansion in Fourier and Bessel series

- Comparing $p(n)$ and $p_c(n)$ can show radial impact but not actual frequencies
- → radial projection

$$p_r(m) = \frac{1}{\bar{a}} \cdot \frac{\Delta\varphi}{2\,\pi} \sum |c_m(\varphi)|$$



Summary

> Algorithm for automatic AOI definition was developed

> Characterization parameters:

- General form of laser spot:
  - Ratio of semi-axes
  - Exponent of Super-Gaussian
- Statistical distribution of inhomogeneities:
  - Relative standard deviation $\sigma_{a_{ij}/\bar{a}}$
  - Relative covariance ϱ or spatial correlation
- Spatial distribution of inhomogeneities:
  - azimuthal: weighted Fourier projection $p(n)$ and $p_c(n)$
  - Radial Fourier projection $p_r(m)$ (or Bessel projection)

Outlook

- Next steps: impact of suggested parameters on emittance needs to be studied
- Either experimental or by simulation
  - Experiment: high need for accelerator run time, spatial distribution of laser intensity cannot be modified arbitrarily, variation is very limited
  - Simulation: restrictions in the simulation software ASTRA limits investigation to rotationally symmetric distributions (still good estimates or reasonable as first step?)
- Quantum efficiency must be implemented in analysis
- High resolution measurements of the quantum efficiency distribution of the photocathode are needed

Thank you for your attention.