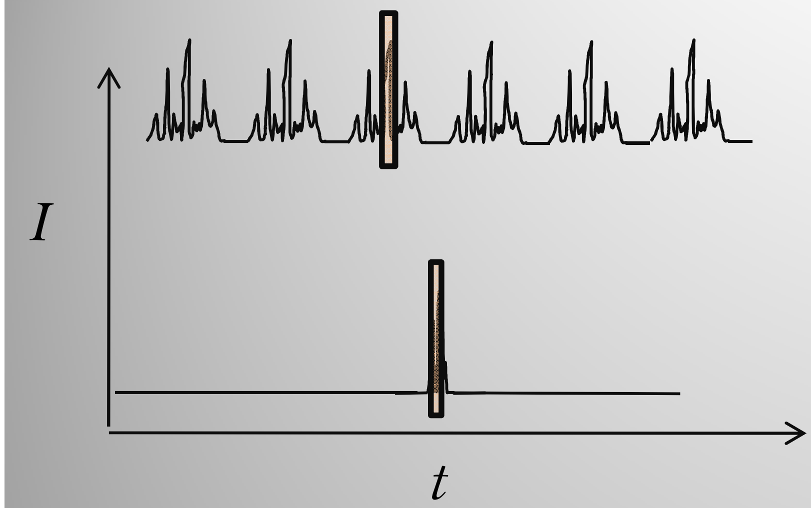
FEL 2012 NARA

Two-dimensional Coherence Measurements of FEL Radiation: The Heterodyne Speckle Approach

Matteo D. Alaimo

University of Milan & INFN

Transverse coherence



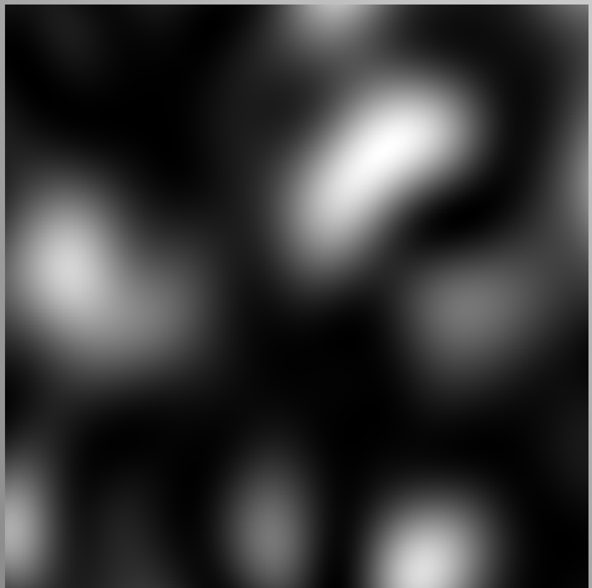
Synchrotron Radiation
pulse duration 30 ps

FEL Radiation
pulse duration 1 ps

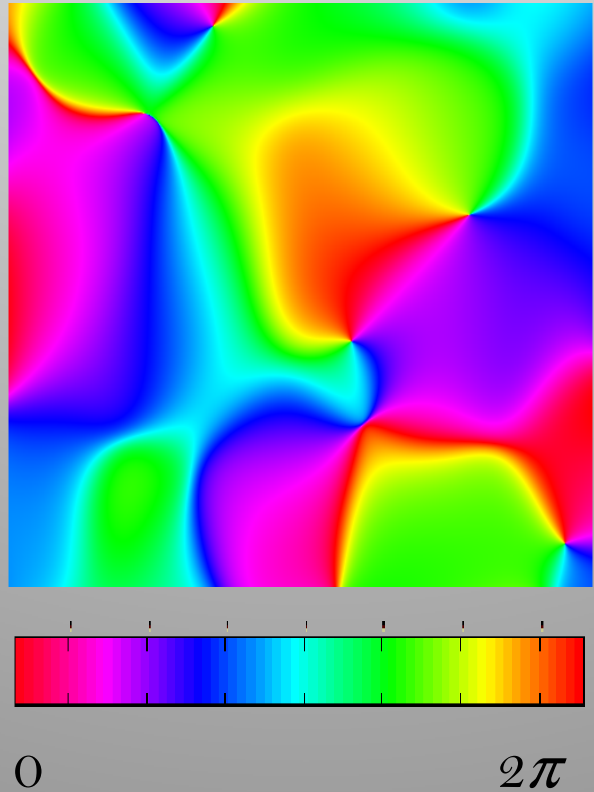
Complex Coherence Factor

$$\mu(P_0, P_1) = \frac{\langle E(P_0) E^*(P_1) \rangle}{\sqrt{\langle I(P_0) \rangle \langle I(P_1) \rangle}}$$

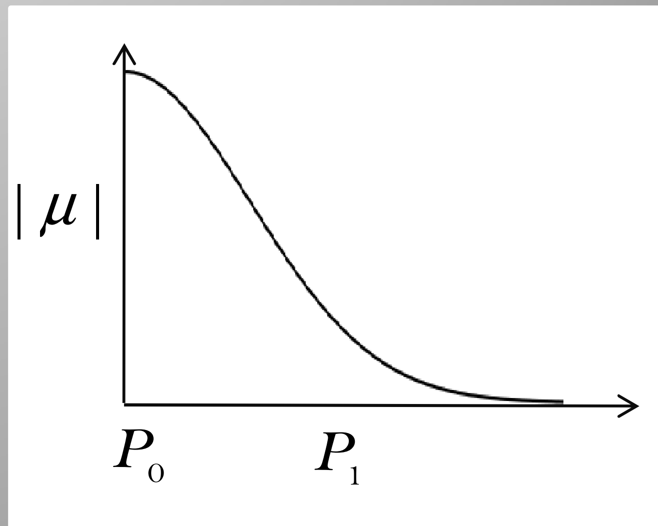
Simulated Amplitude



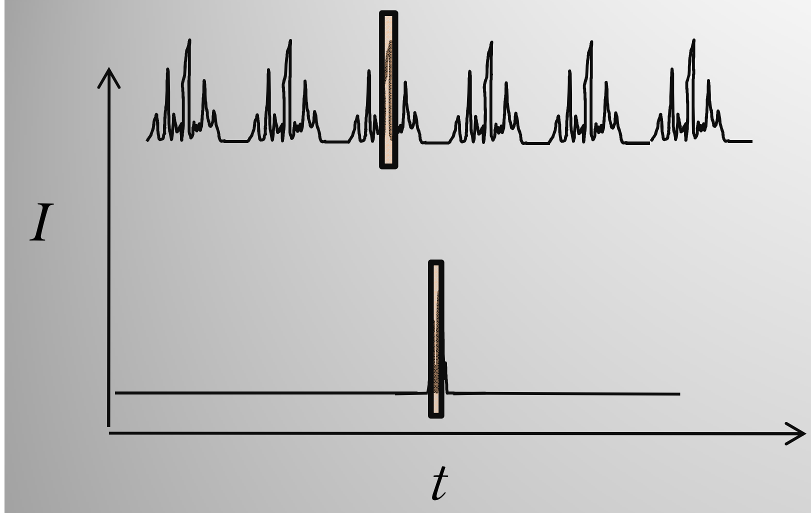
Simulated Phase



Example: gaussian Coherence factor



Transverse coherence



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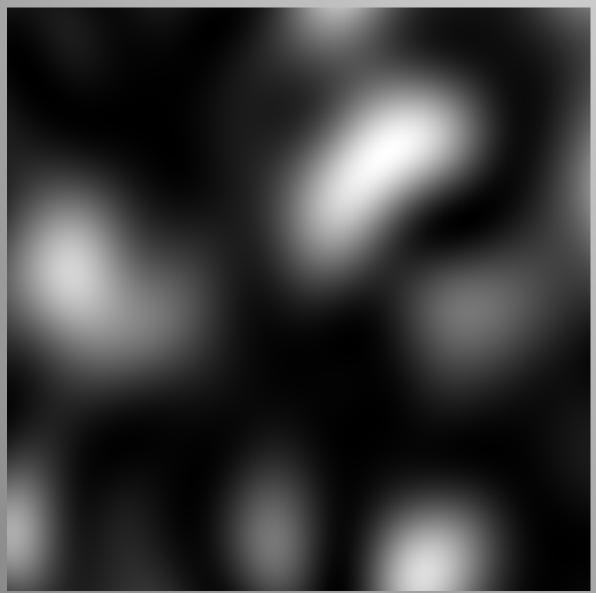

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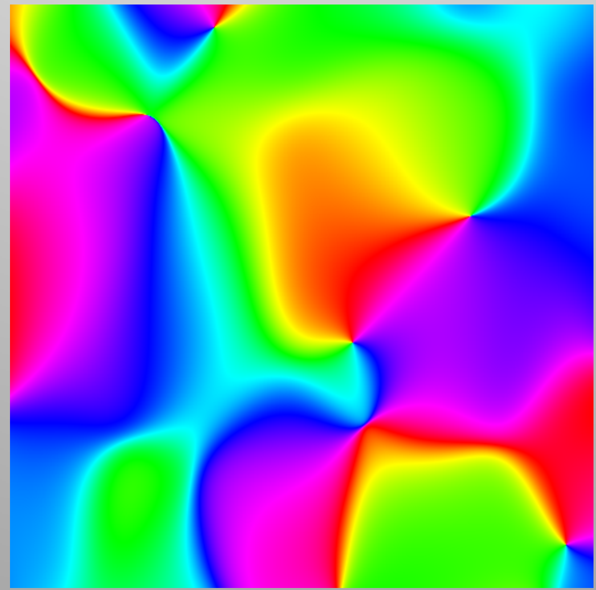
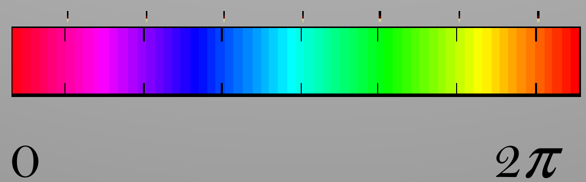
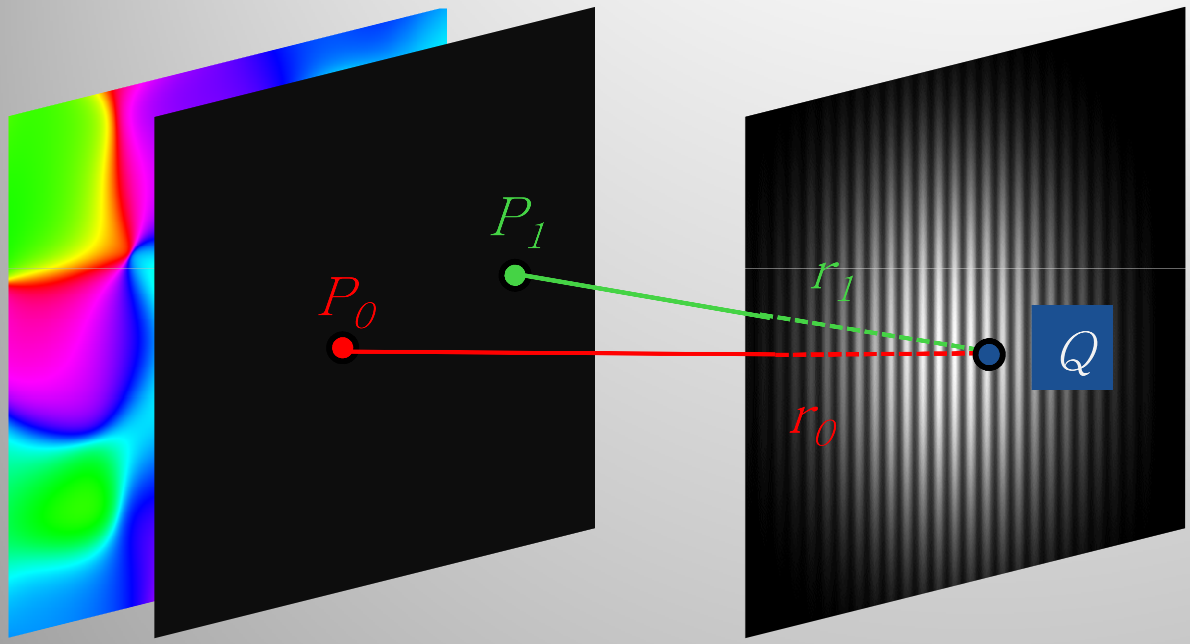
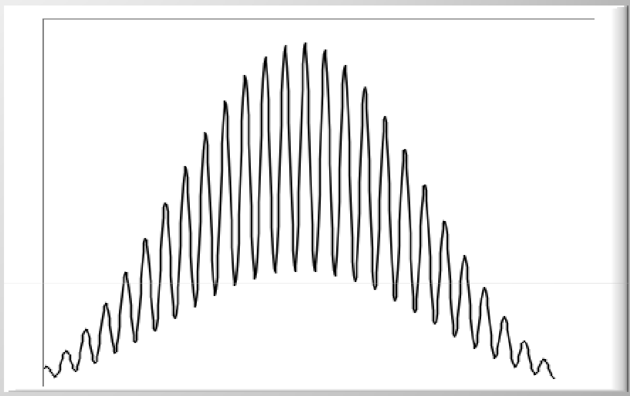




Why coherence is important?

- Phase contrast imaging
- Coherent Diffraction Imaging and Topography
- X-Ray Photon Correlation Spectroscopy



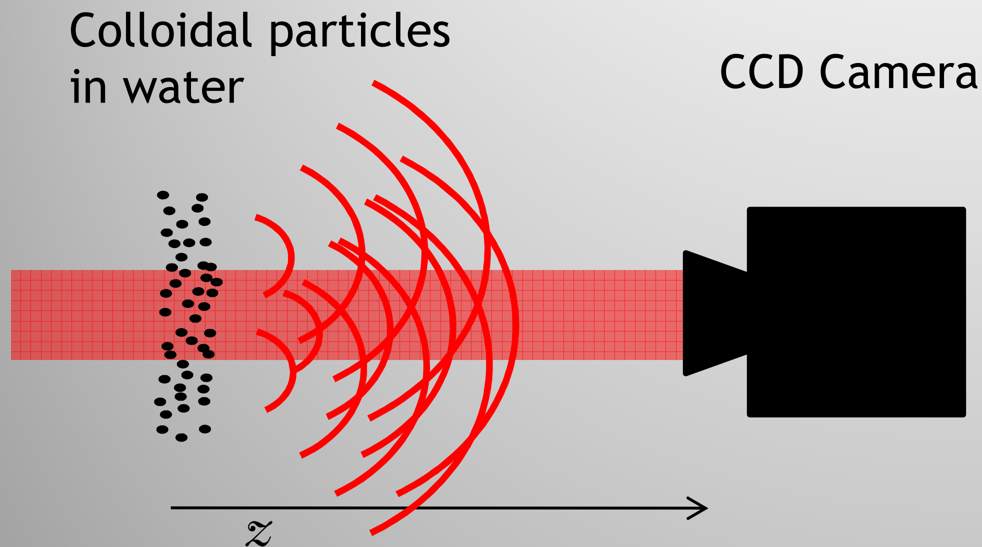


Visibility:

$$V = \left(\frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \right)$$

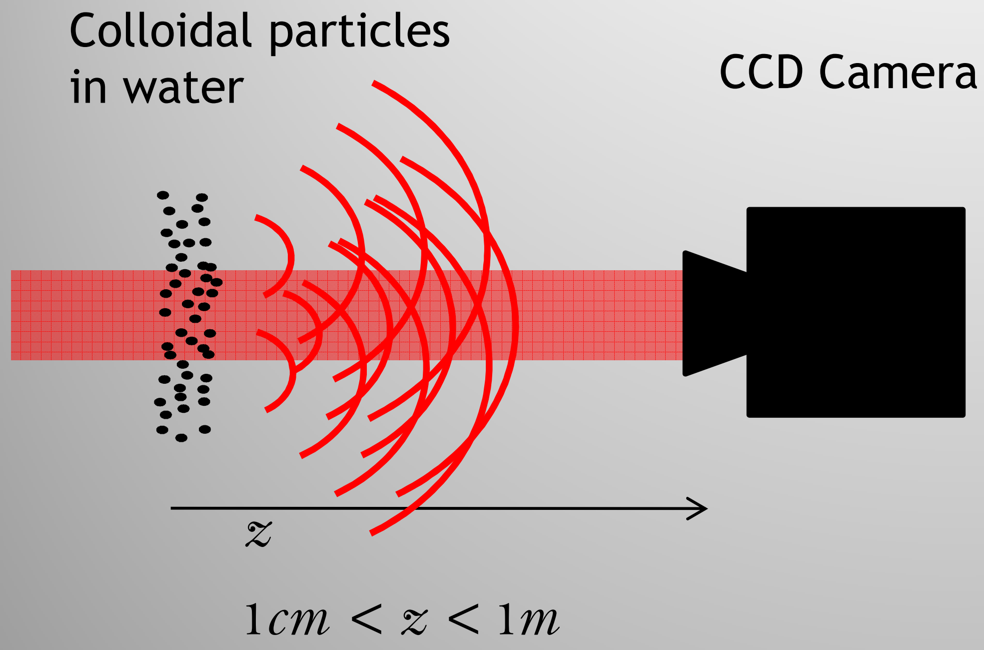
$$V \propto \left| \mu(P_0, P_1) \right|$$

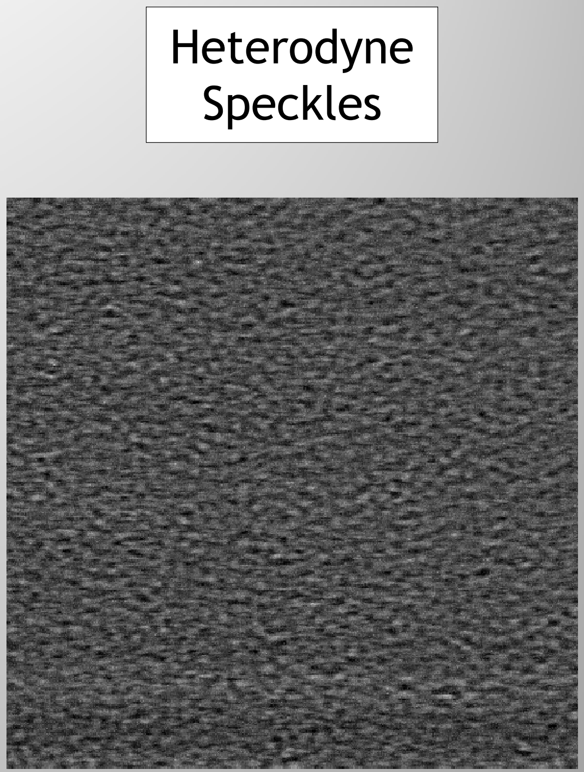
Heterodyne Speckle Approach



$$1cm < z < 1m$$

Heterodyne Speckle Approach



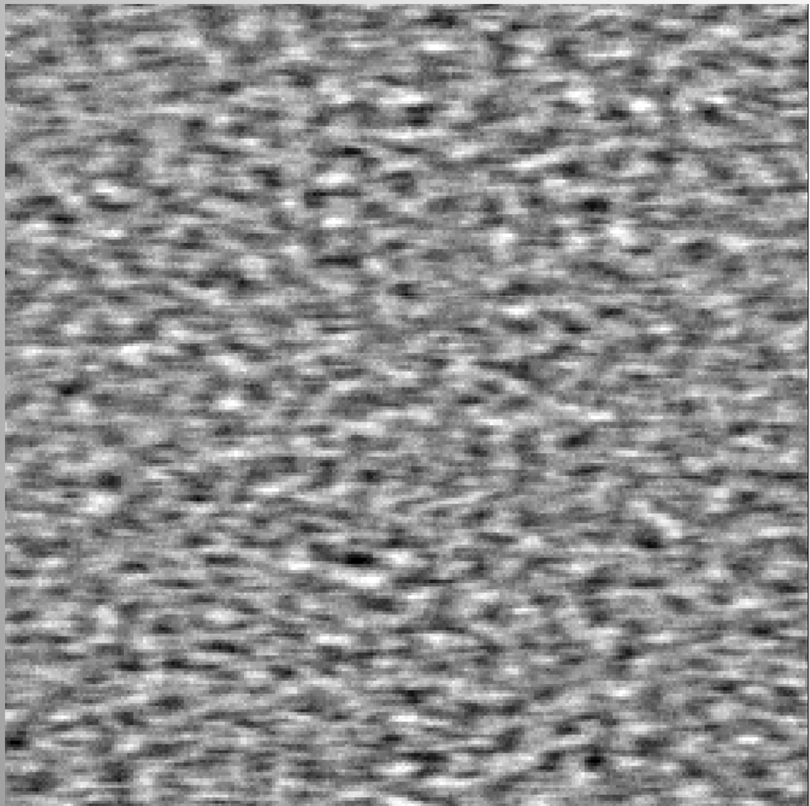


Probing the transverse coherence of an undulator X-ray beam using brownian particles, PRL, M.D. Alaimo & al.

Heterodyne speckle approach for two-dimensional map of SR coherence, JSR (in submission), M.Manfredda & al.

Heterodyne Speckles

Speckles (ID06 – ESRF - λ=0.1 nm)



E_T : transmitted field

E_S : scattered field

$$I = \left\langle \left| E_T + \sum_{s}^{N} E_s \right|^2 \right\rangle = \left\langle \left| E_T \right|^2 \right\rangle + \left\langle 2 \sum_{S}^{N} \Re E_T^* E_S \right\rangle + \left\langle 2 \sum_{S,S'}^{N} \Re E_S^* E_{S'} \right\rangle$$

Heterodyne Term

$$\sum_{S}^{N} E_S << E_0$$

Heterodyne Speckles

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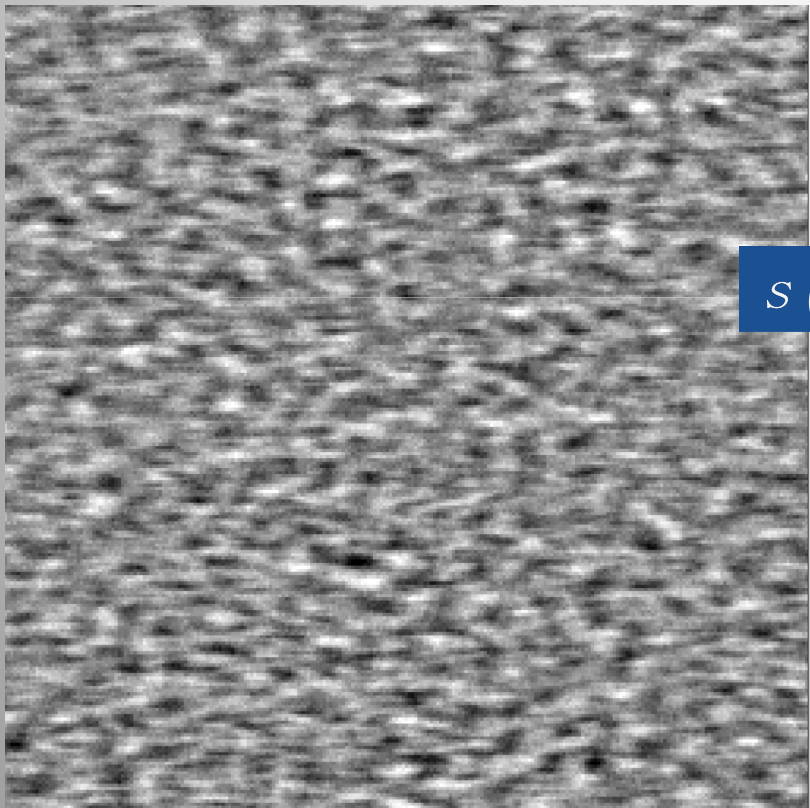
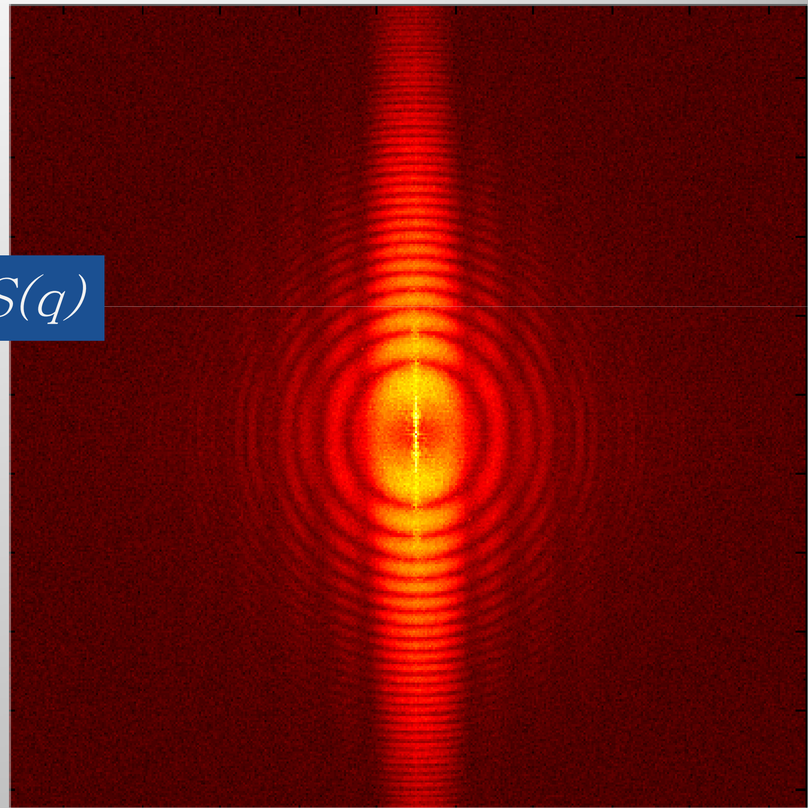


$\mathscr{F}$

s *(r)* → $S(q)$

Spatial power spectrum



S(q) = I(q) T(q) H(q) C(q)

I (q): particle form factor (flat)

T(q): Talbot trasfer function [$\sin^2(q^2 z/2\ k)$]

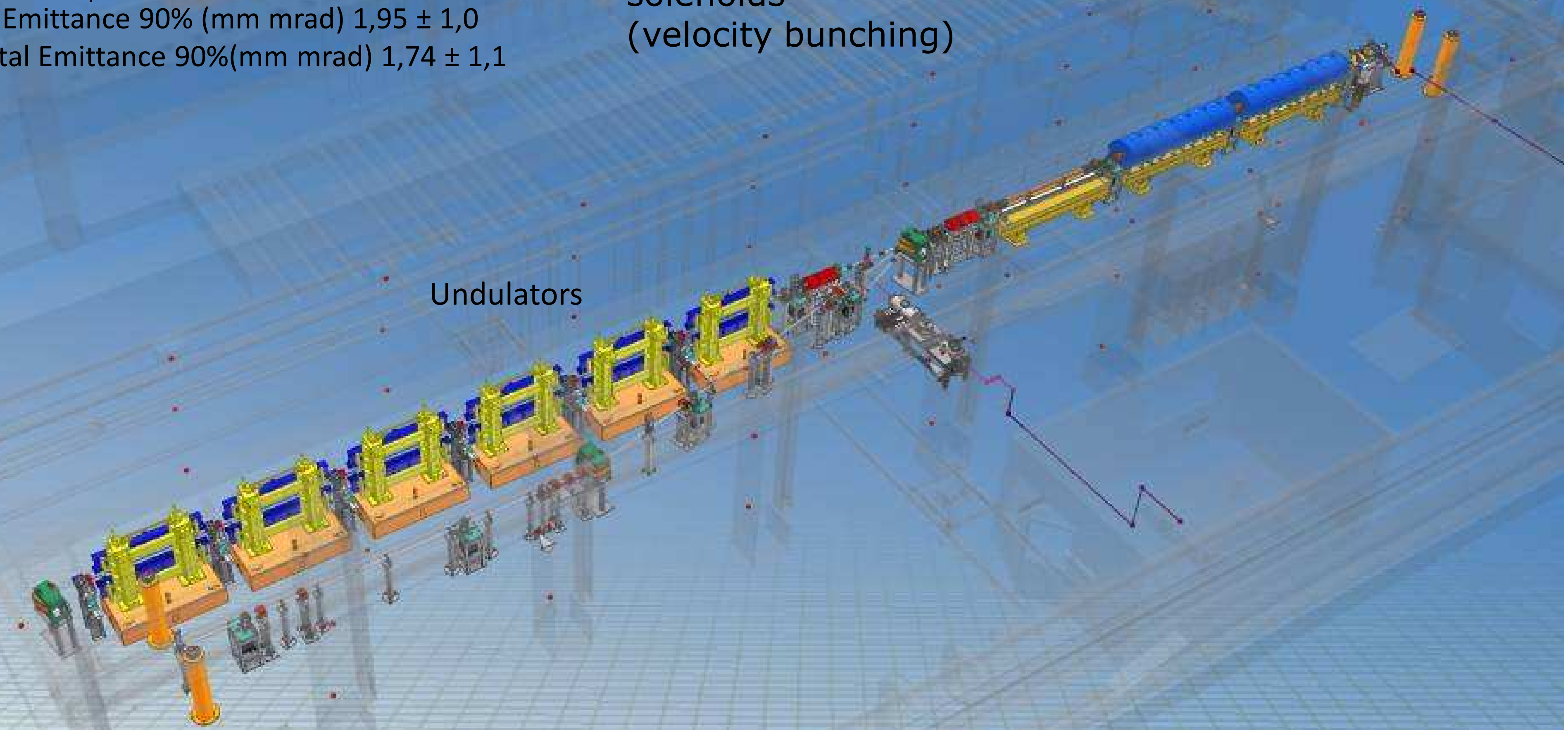
H(q) = Sensor transfer function

$$r = \frac{q}{k} z$$

C(r(q)) = $|\mu|^2$ (µ: Complex Coherence Factor)

SPARC

- **6 sections undulator; 77 periods per section**
- Magnetic Length 215 cm
- K factor: from 0.5 and 3
- Beam energy E_B(MeV) 162,5±0,27
- Beam charge(pC) 312 ±16
- Energy Spread (proj: %) 0,2 ± 0,015
- Energy Spread (slice %) 0,050 ±0,005
- Length r.m.s. (ps) 1,65 ± 0,05
- Beam current I_{peak}(A) 75,63 ±3,5
- Vertical Emittance 90% (mm mrad) 1,95 ± 1,0
- Horizontal Emittance 90%(mm mrad) 1,74 ± 1,1



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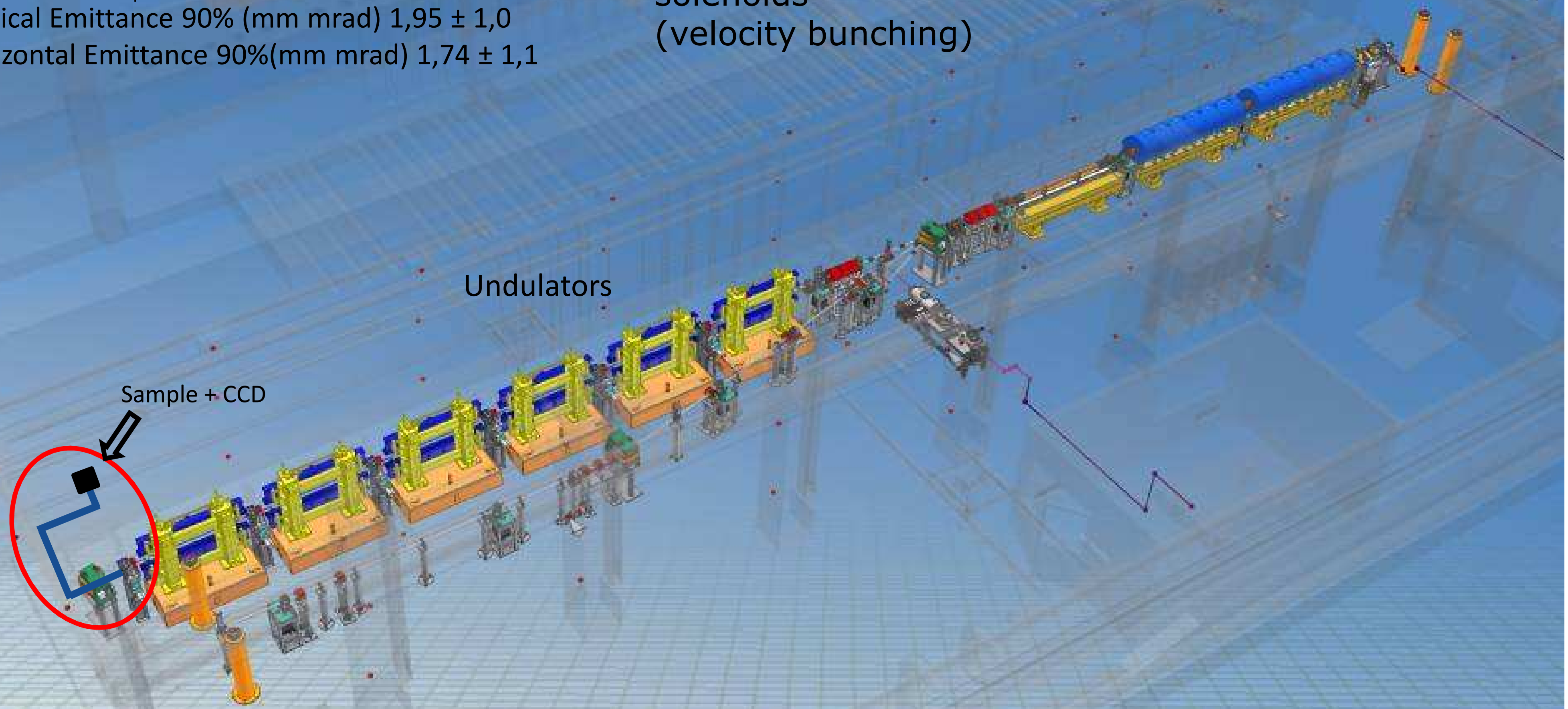
1.6 cells RF injector
UCLA/BNL/SLAC design
120 MV/m

3 SLAC type Focalization
solenoids
(velocity bunching)



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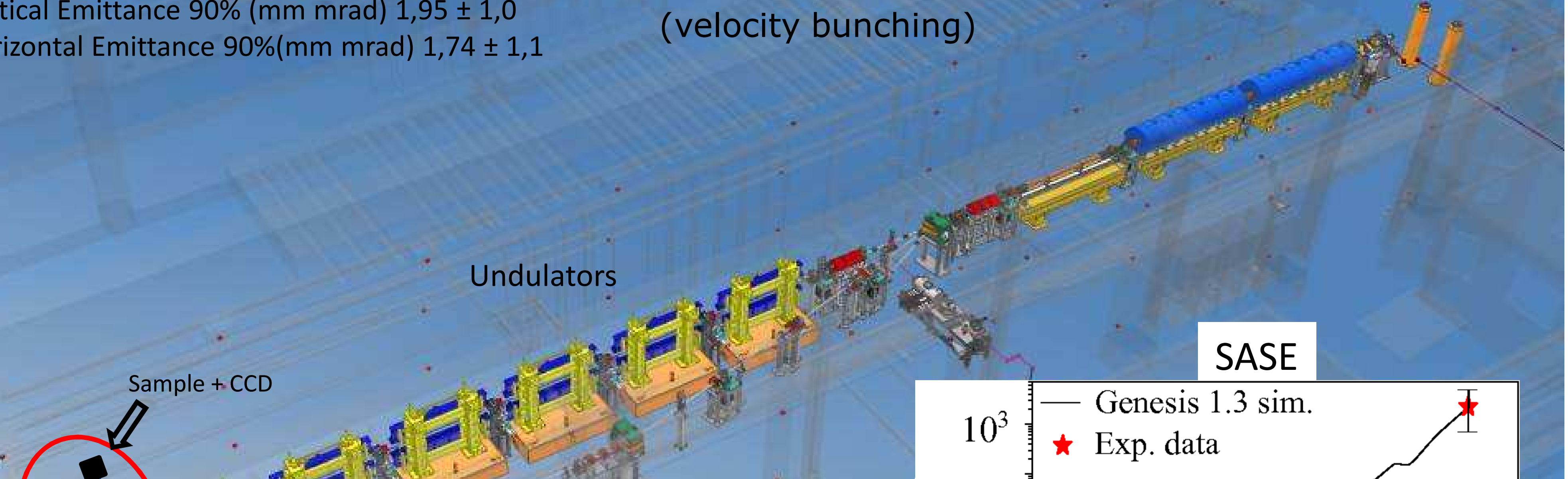
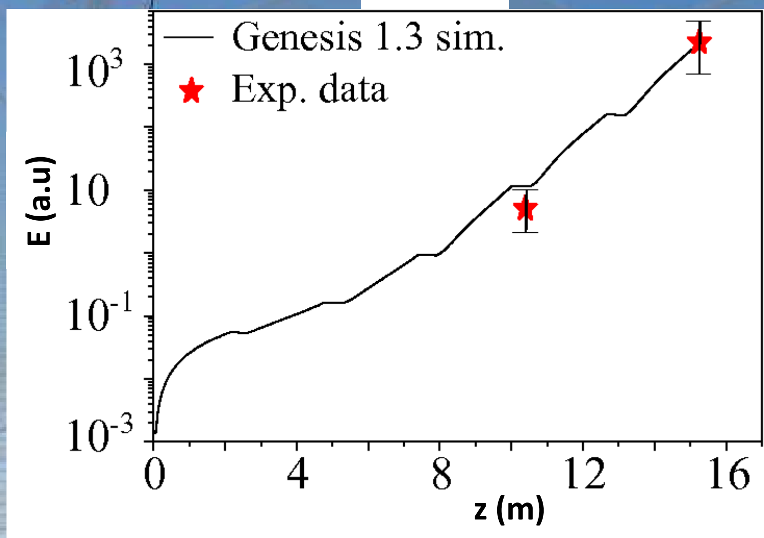


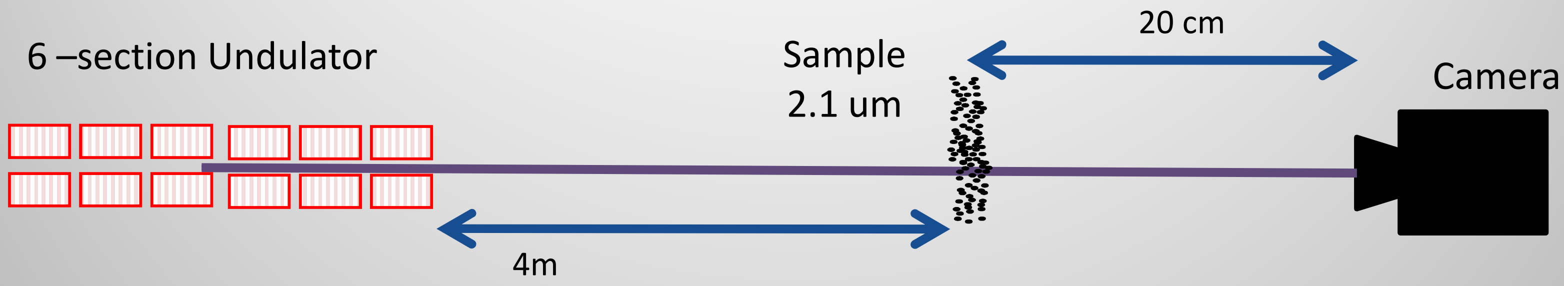
SASE



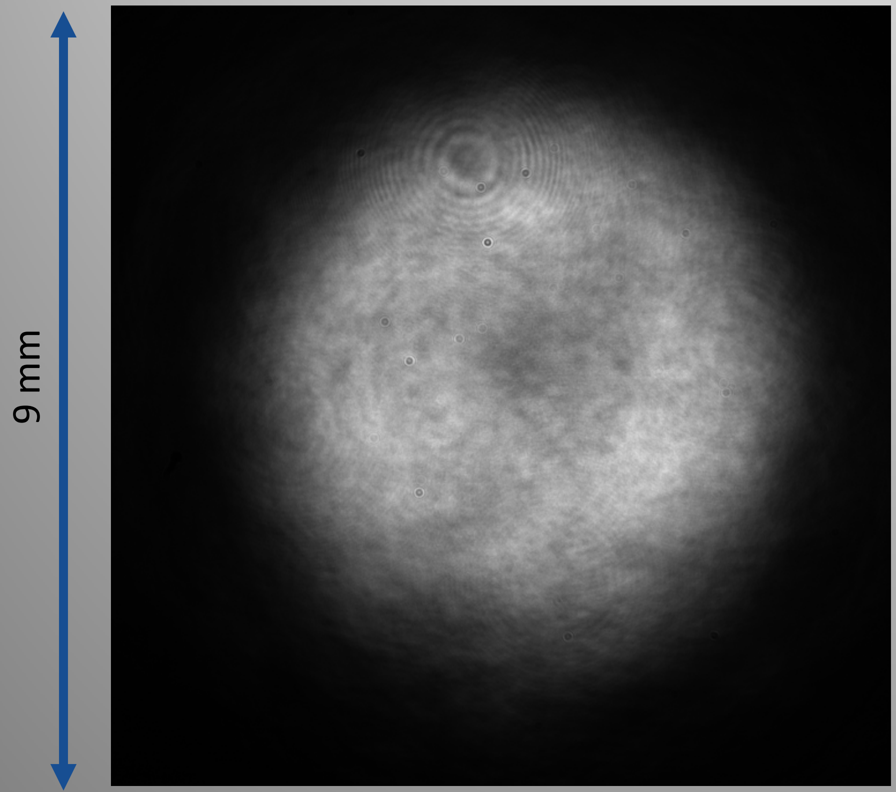
Degree of transverse coherence expected ~ 0.95 (Genesis 1.3)

SPARC Setup (LNF – Frascati)

$\lambda = 400nm$



I(t) : image



$$= \left\langle \left| E_T \right|^2 \right\rangle + \left\langle 2\sum_S^N \Re E_T^* E_S \right\rangle$$

SPARC Setup (LNF – Frascati)

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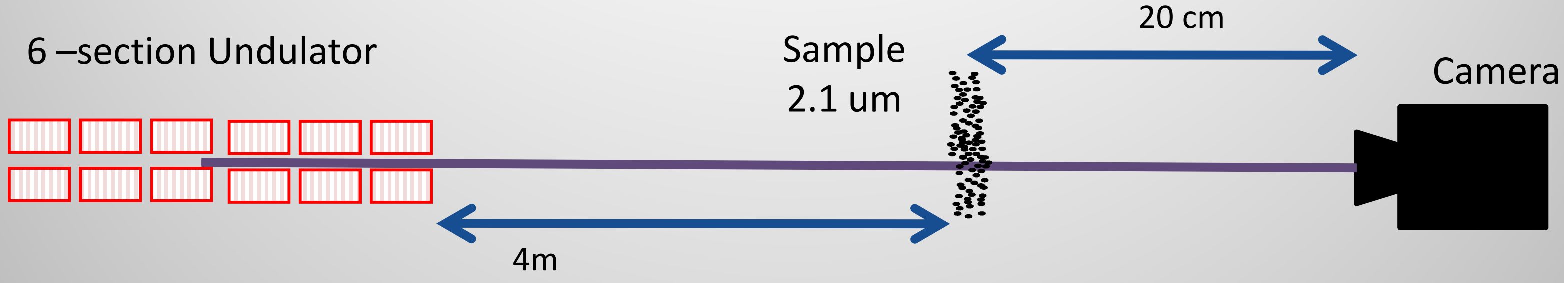

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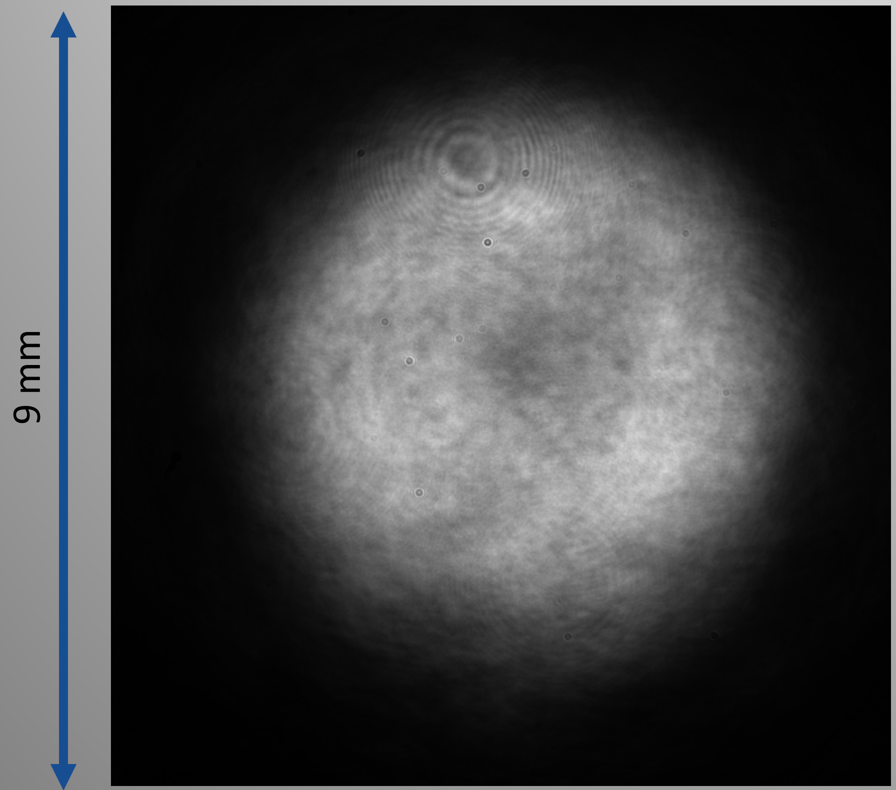
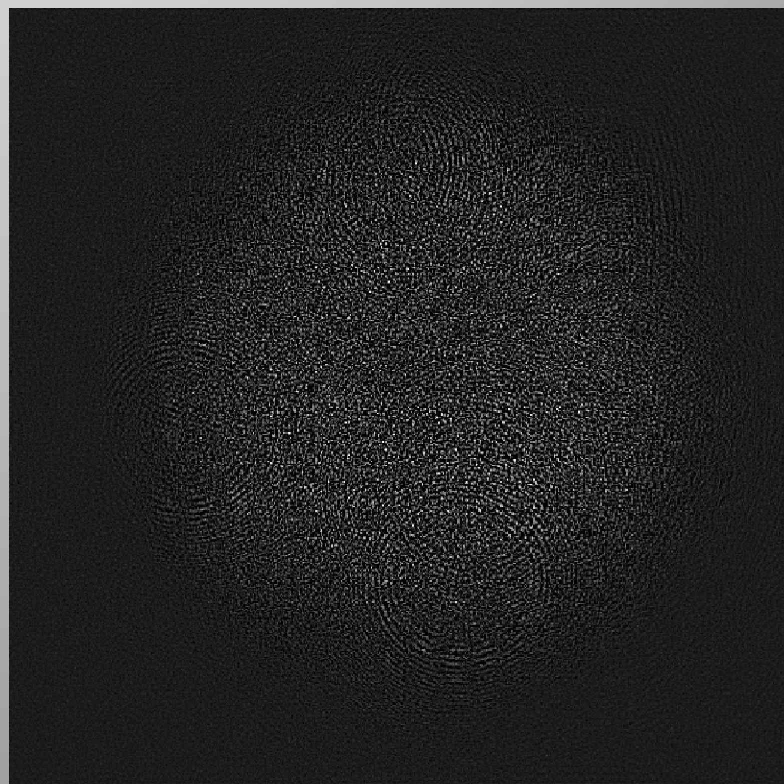


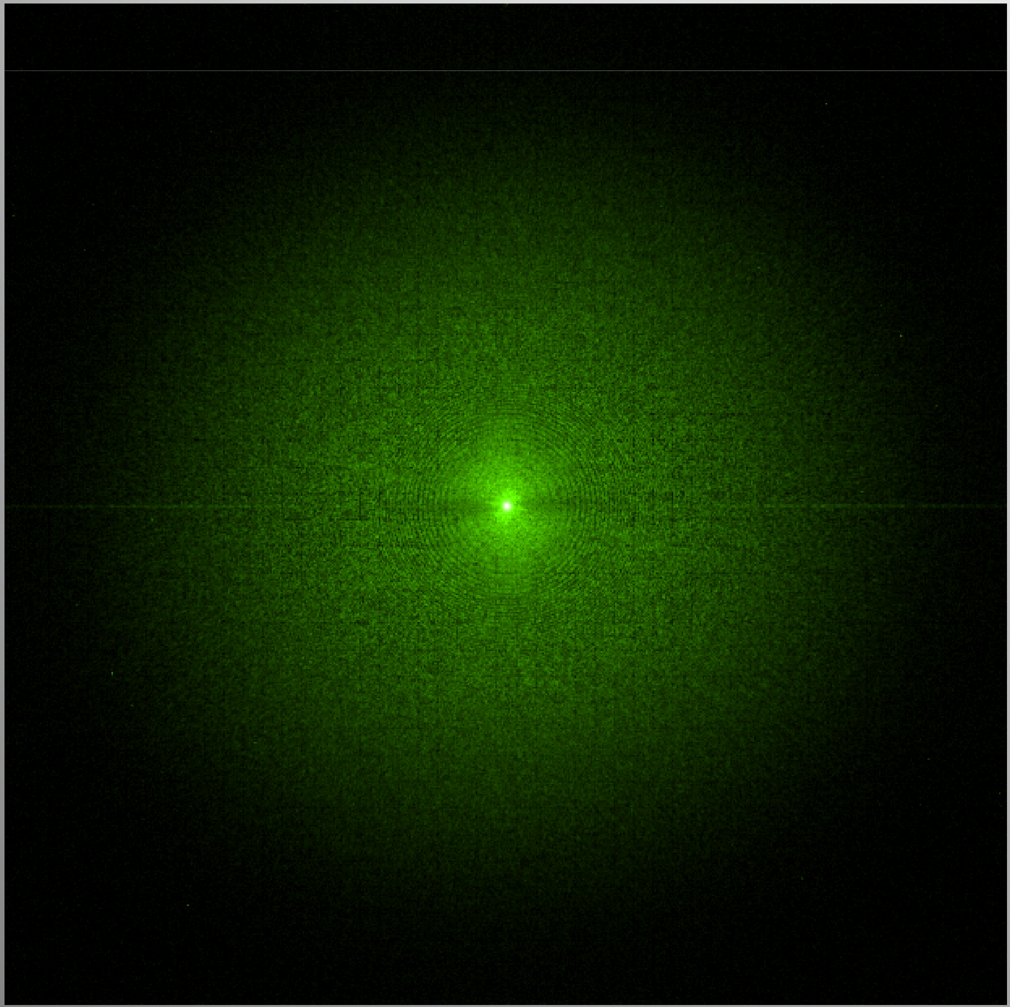
I(t)-I(t+τ): image difference



SPARC Transverse Coherence

Full Coherence Factor

Typical 2D Power Spectrum



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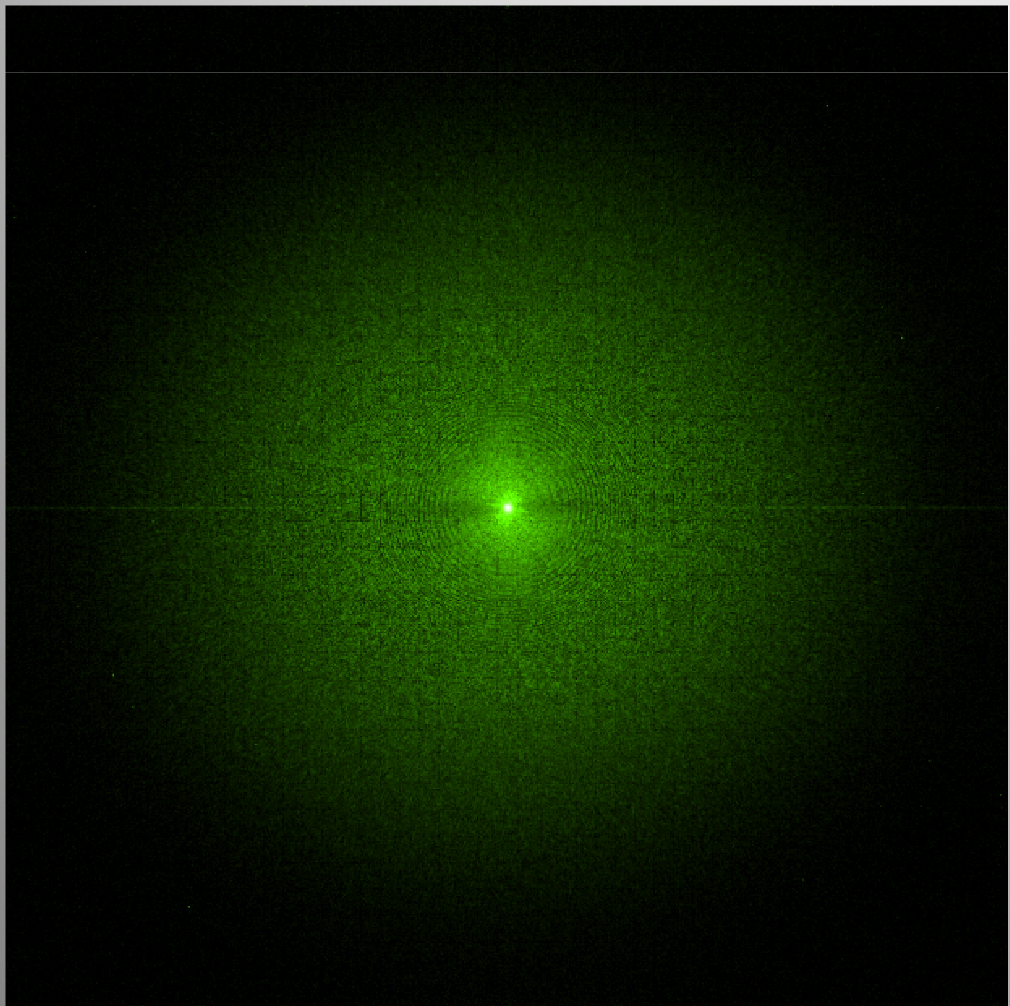


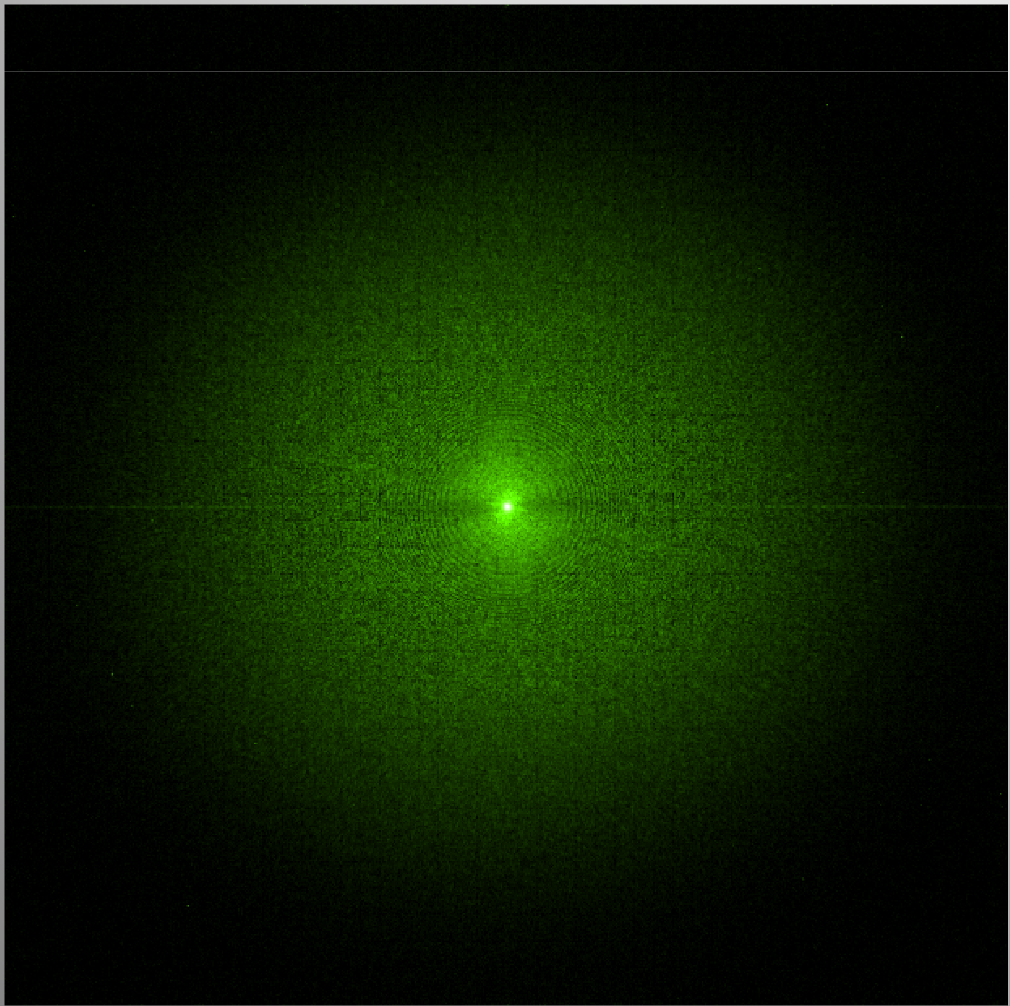
1200 px

600 px

SPARC Transverse Coherence

Full Coherence Factor

Typical 2D Power Spectrum



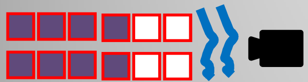
1200 px

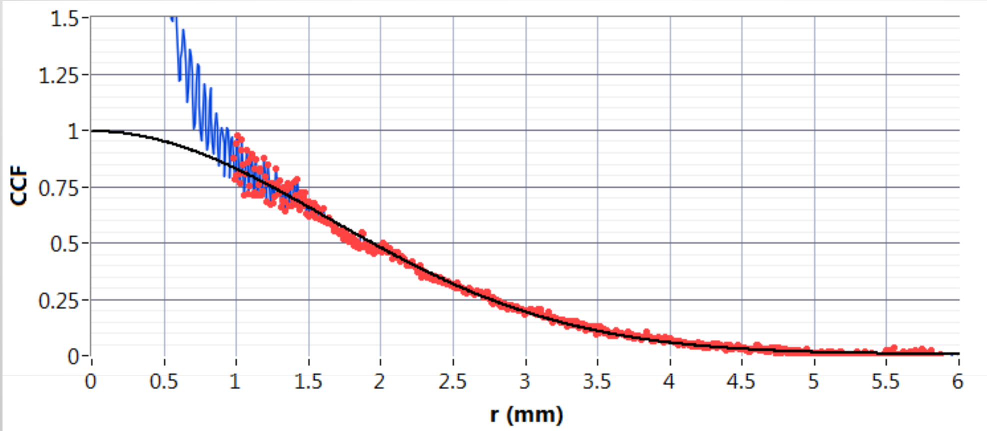
600 px

720 000
Young's double slit experiments

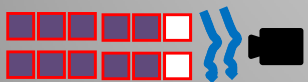
SPARC Transverse Coherence

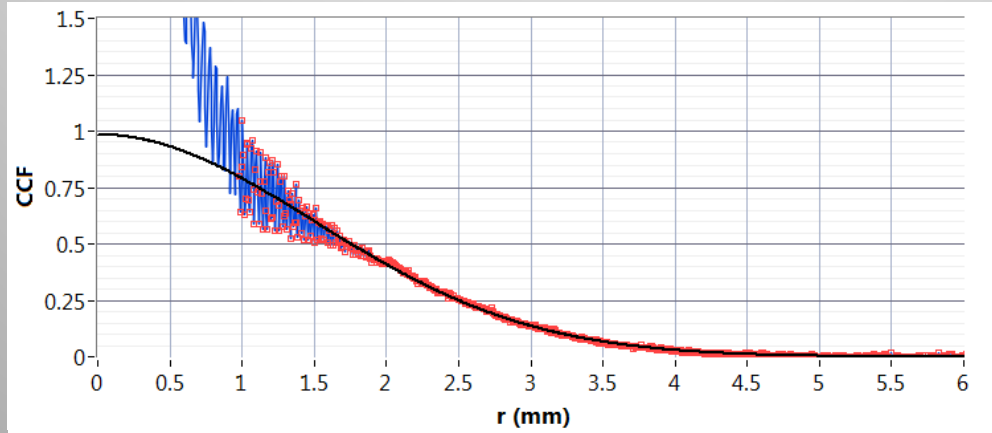
4 UD Sections



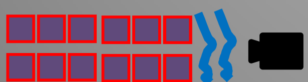


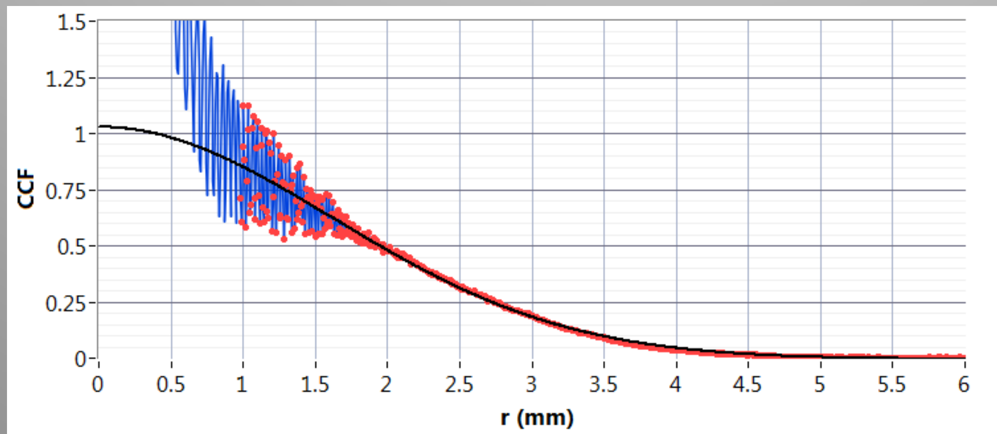
5 UD Sections





6 UD Sections





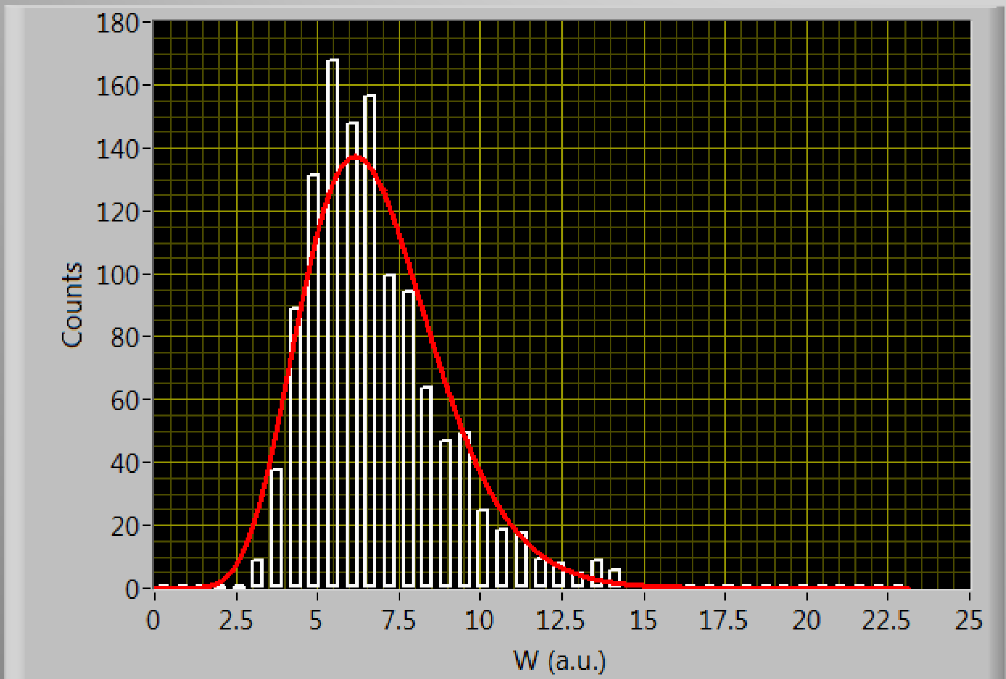
	σ_{COH}	σ_{COH}/σ
4U	1.64 mm	0.7
5U	1.50 mm	0.8
6U	1.62 mm	0.82

Number of modes

Gamma function

$$M = M_T \cdot M_L = \frac{1}{\sigma_W^2} \qquad \sigma_W^2 = \frac{\sqrt{\left\langle \left(W - \langle W \rangle\right)^2 \right\rangle}}{\langle W \rangle}$$

4 undulators



4U	M=10.5
5U	M=6.5
6U	M=3.2

Statistical analysis on the same images used for coherence measurements

Conclusions and perspectives

Heterodyne speckle approach

Simple and direct interferometric setup

Two -Dimensional map

Valid for different wavelength

Time resolved

Poster **THPD066**
Michele Manfredda

Conclusions and perspectives

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Poster **THPD066**
Michele Manfredda

Outlooks

Improvements in samples for different wavelength

Improving background subtraction

High order Correlations (asymmetric CCF)

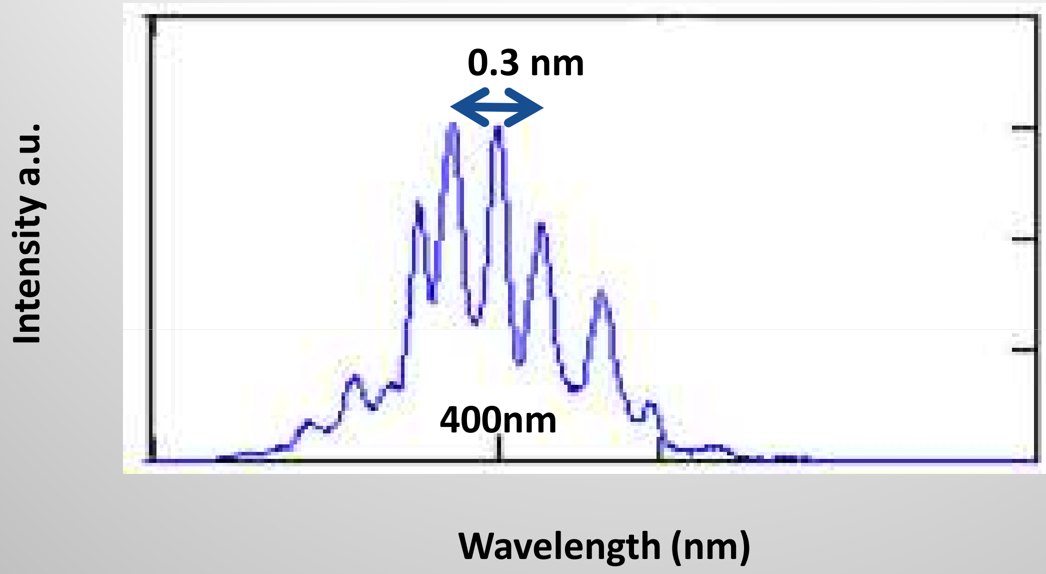
Thank you for your attention

Special Thanks
M. Manfredda, M. A. C. Potenza, M. Giglio and **G. Geloni**
for the strict cohoperation

I thank all **ID02, ID06** and **ESRF** Staff for providing
technical support and useful hints.

Thanks to **L. Serafini**, **V. Petrillo**
for the cohoperation within INFN and SPARC.
Thanks to all the SPARC (LNF) and INFN staff who
cohoperated at this work.

Temporal Coherence



Coherence Length

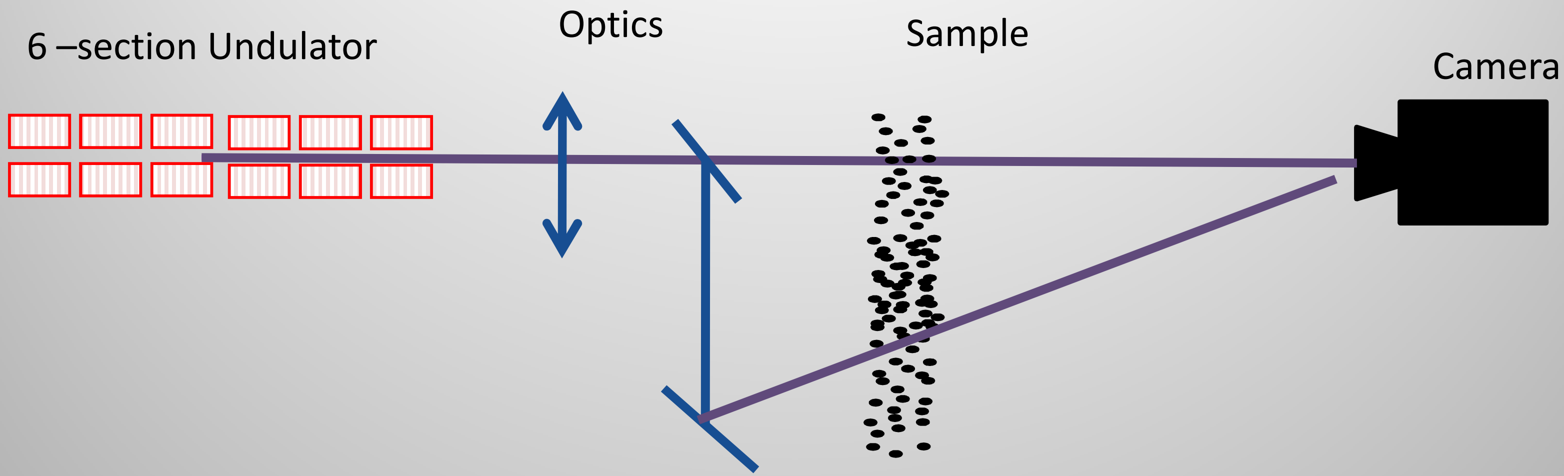
$$\ell_C = \frac{\lambda^2}{2\Delta\lambda} \approx 270\,\mu m \quad \Rightarrow \quad \ell_c >> \delta l$$

Maximum experimental transverse displacement

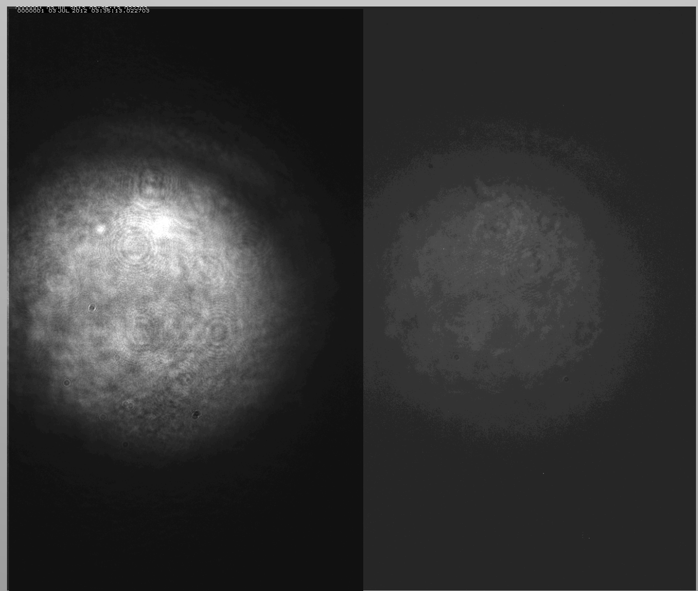
$$\delta l \approx 90\,\mu m$$

SPARC Setup (LNF – Frascati)

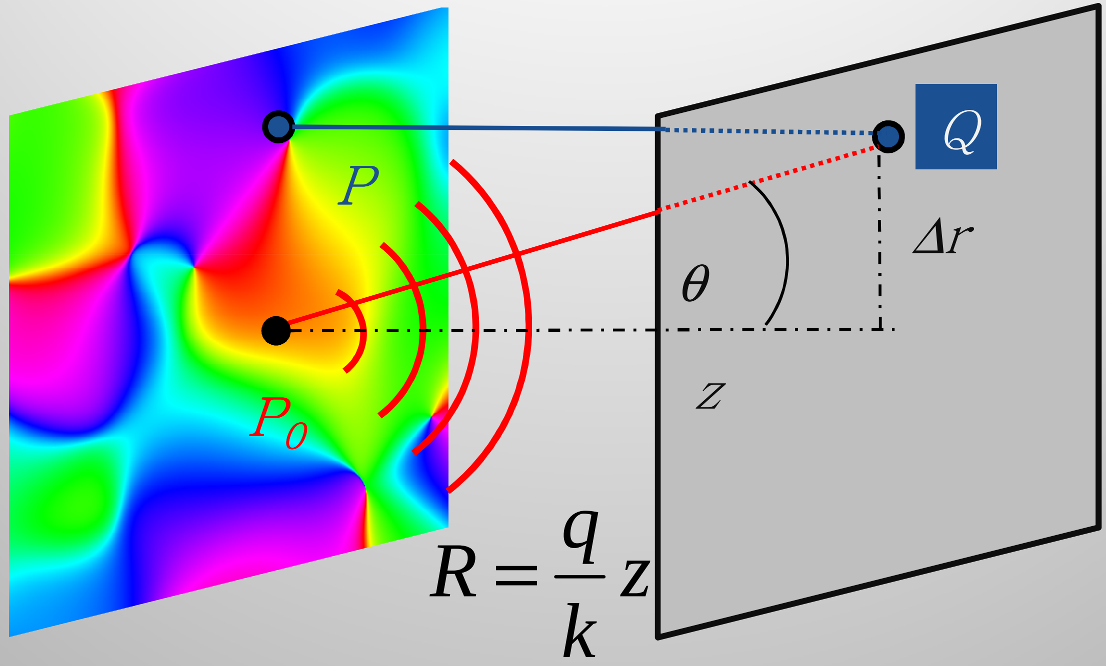
$\lambda = 400nm$



Possibile with visible wavelength only



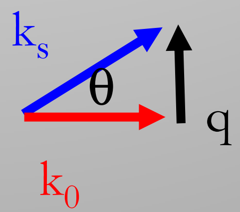
In-Line Holography



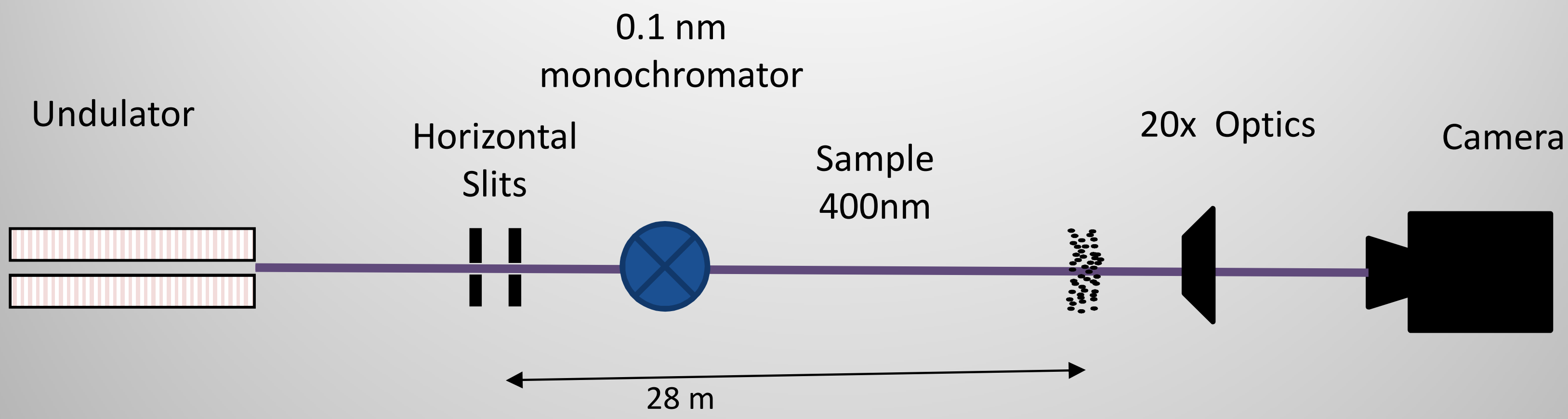
$$R = \frac{q}{k} z$$

$$\Delta r = \vartheta z$$

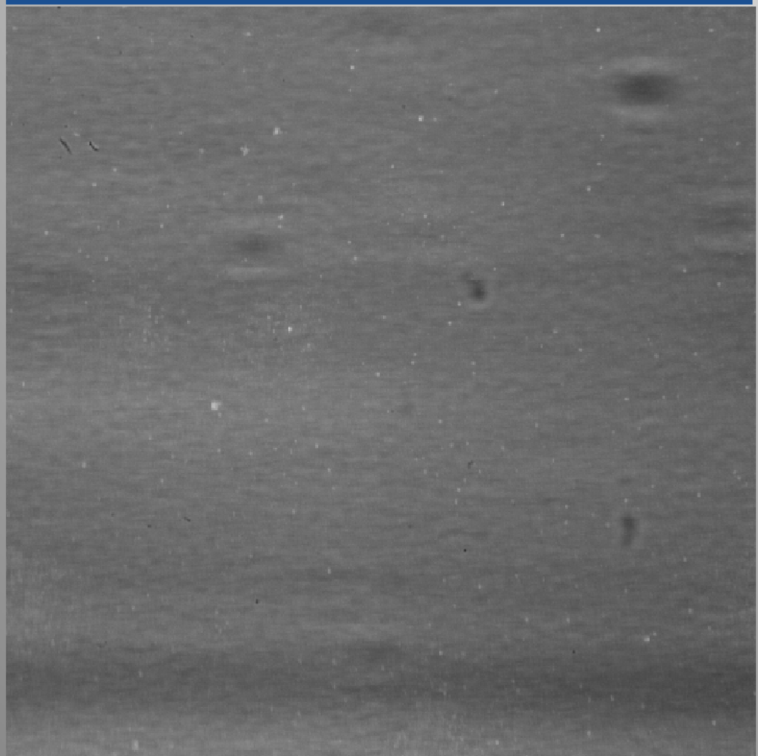
$$\vartheta = \frac{q}{k}$$



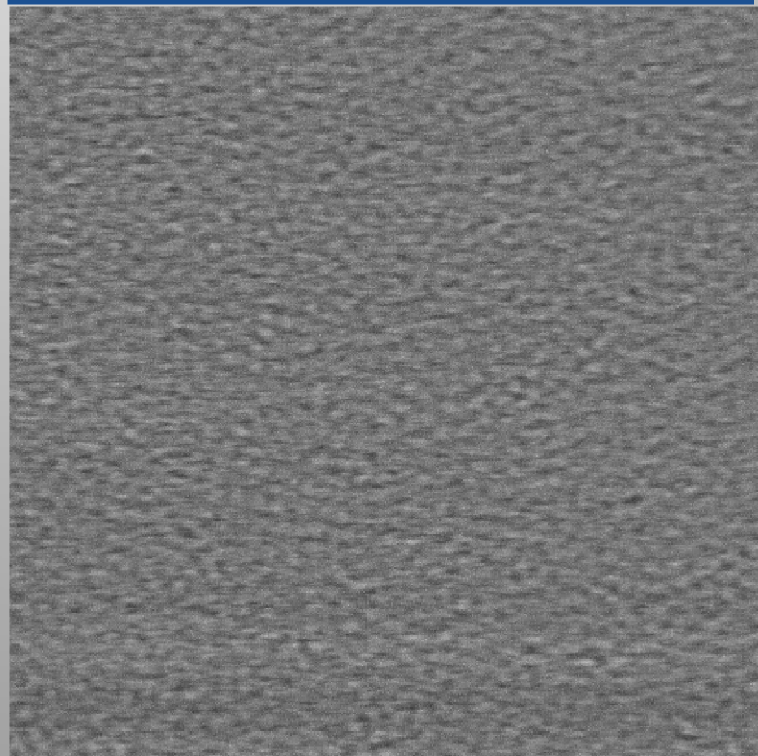
Synchrotron - ID 06 Setup



Raw Image



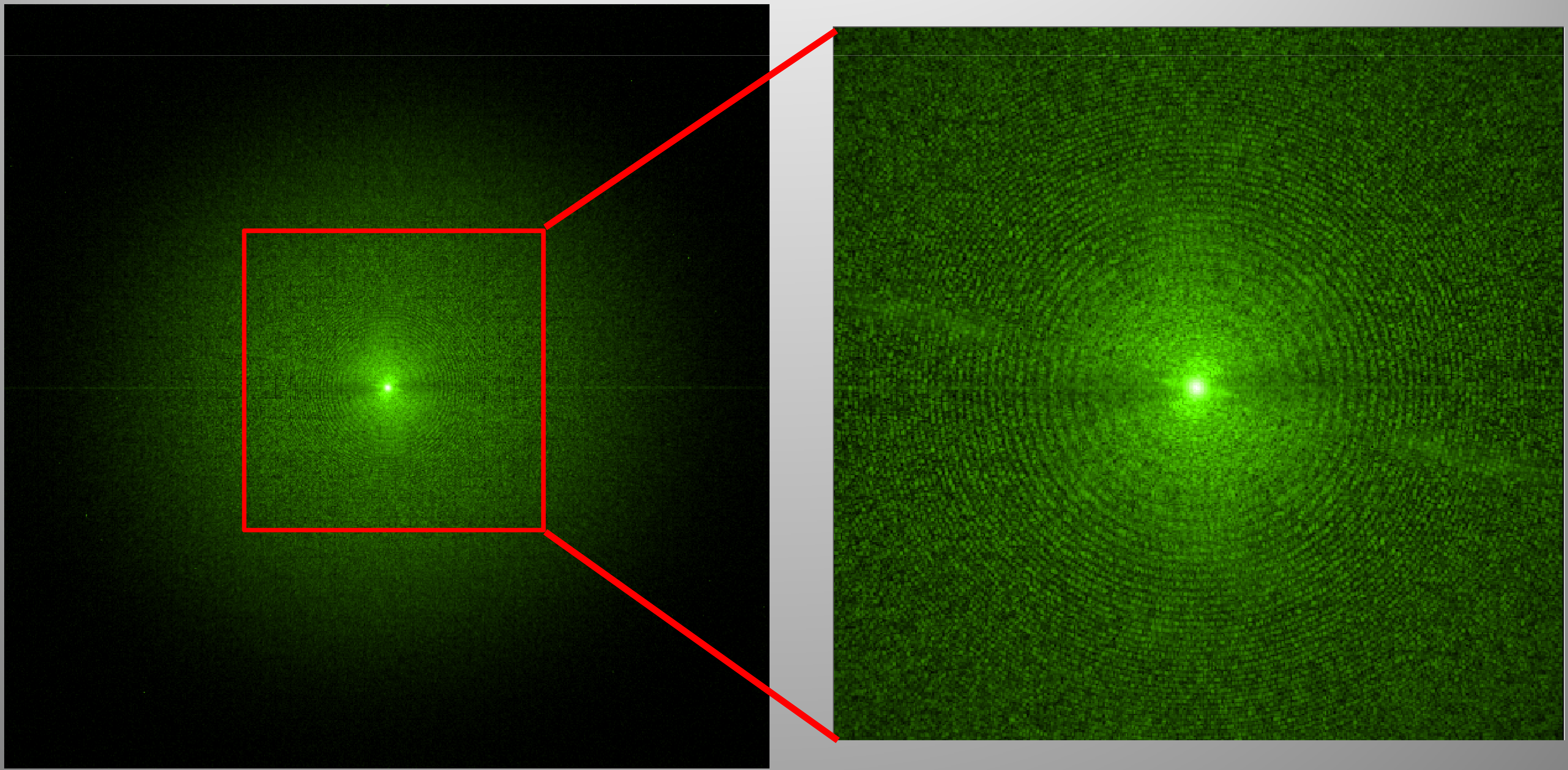
Difference Image



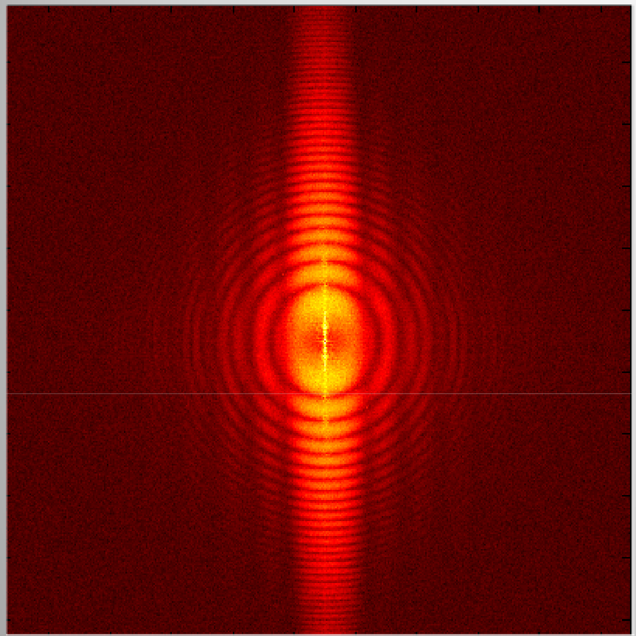
SPARC Transverse Coherence

Full Coherence Factor

Typical 2D Power Spectrum

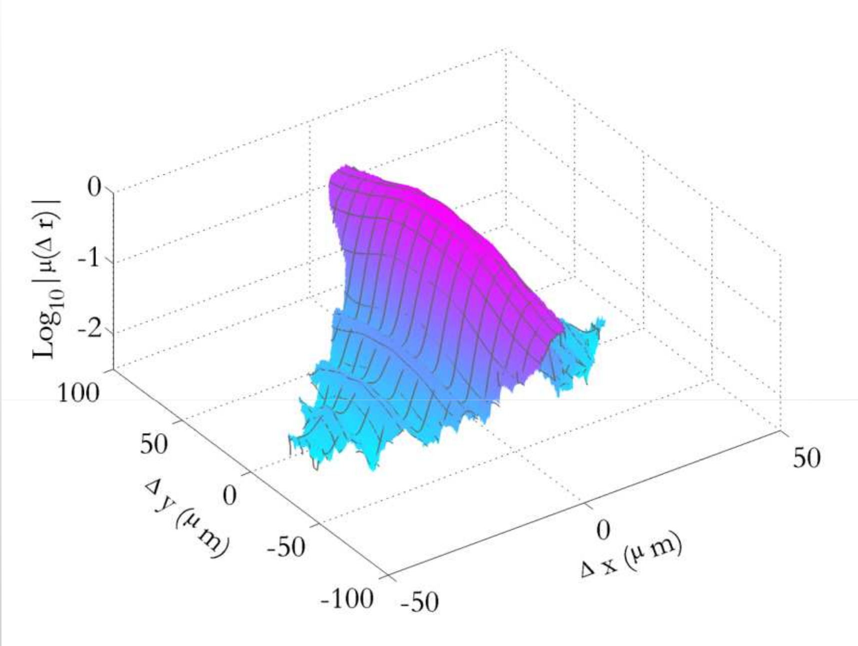


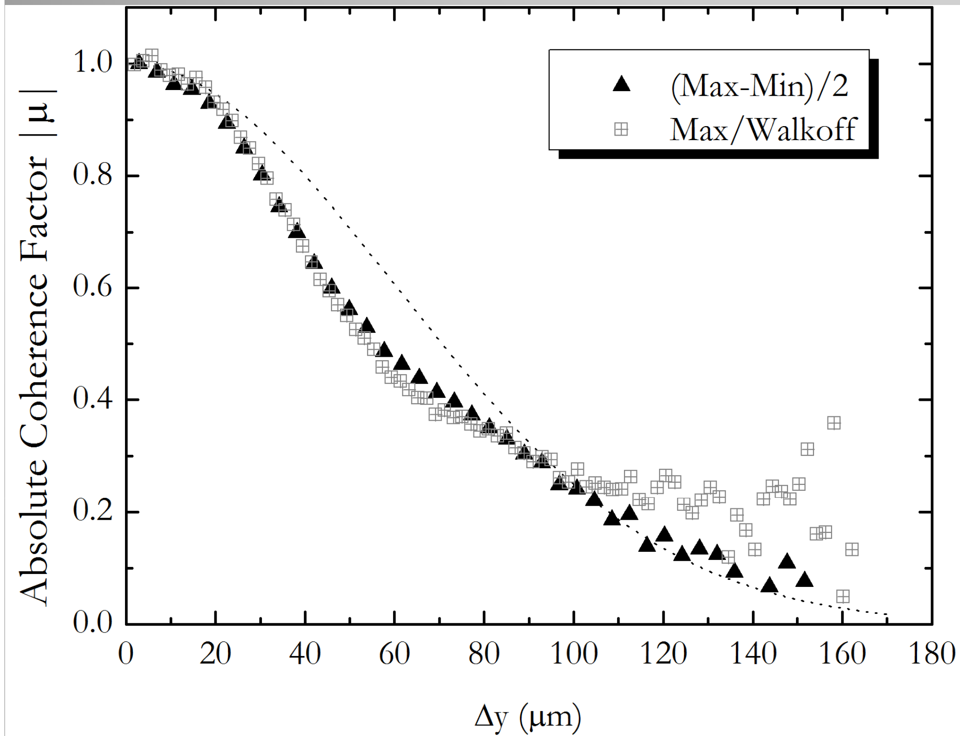
ESRF ID06 - Coherence Factor

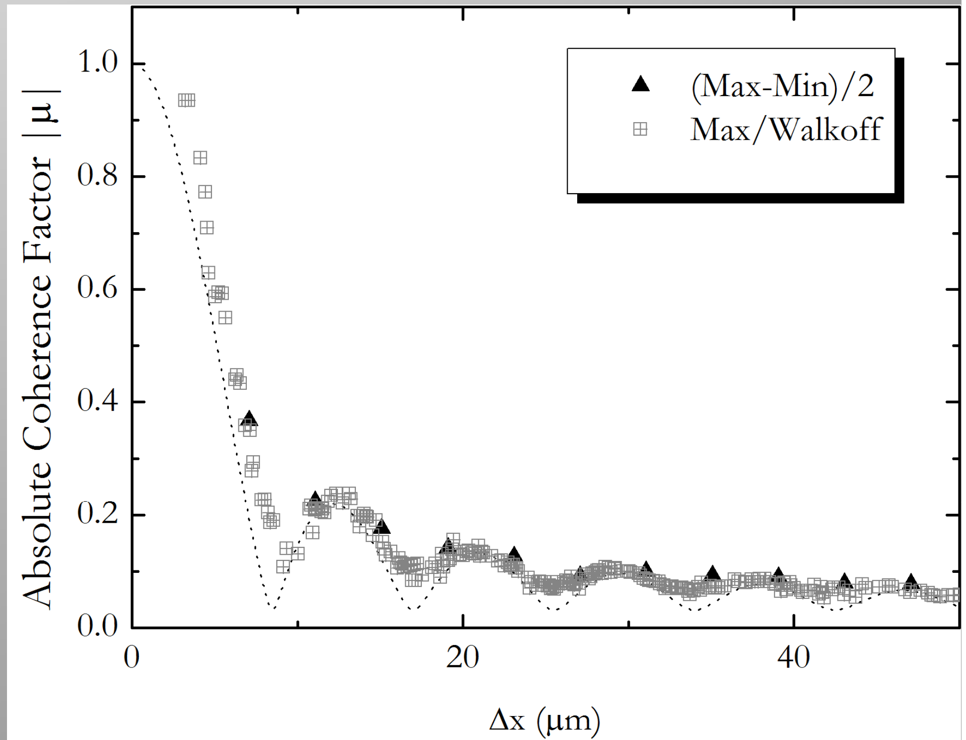


Average of 10 Power Spectra

Z = 800mm



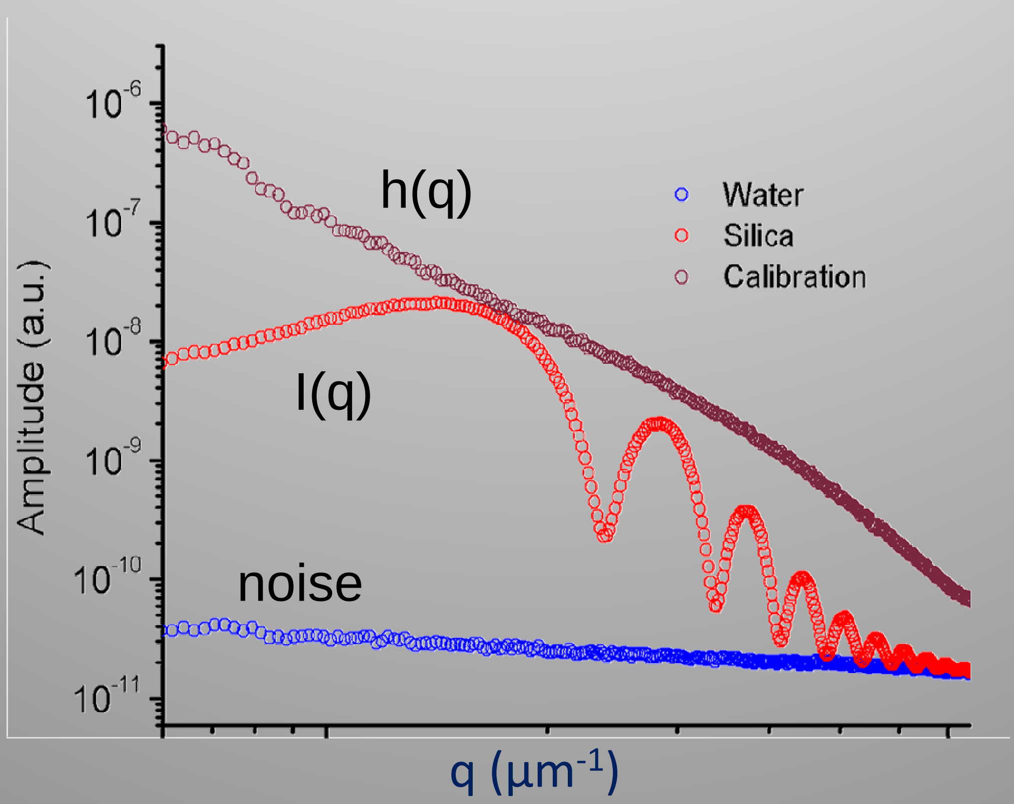




The Signal

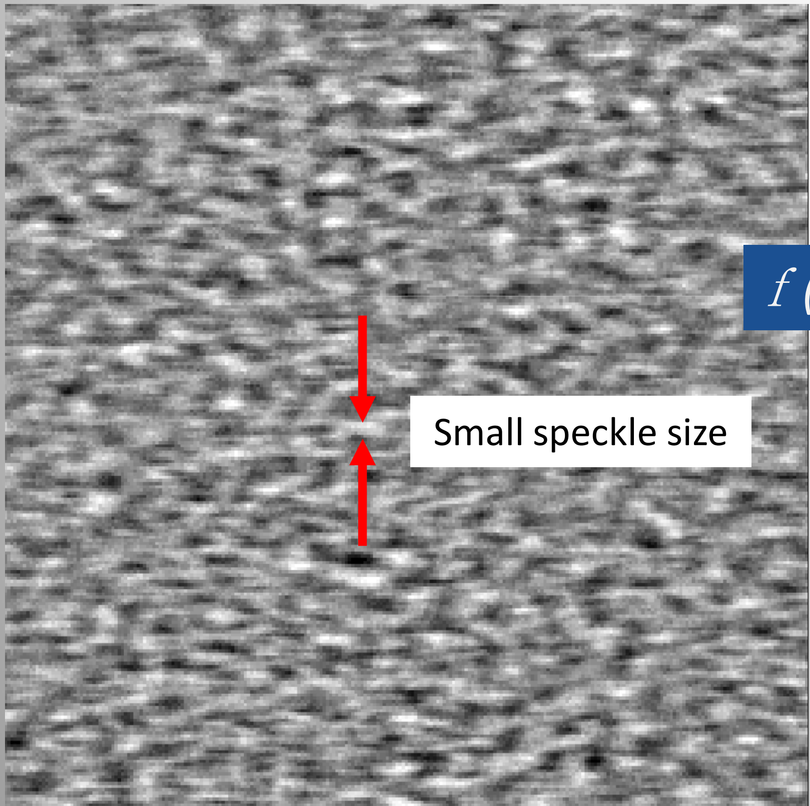
$$I(q) = C(q,z)\, T(q,z)\, F(q) H(q) + noise(q)$$

- T(q) : Talbot Transfer Function
- C(q): Coherence Factor
- F(q): Particle form factor (const)
- H(q): Instrumental Transfer Function (scintillator)
- Shot noise



Heterodyne Speckles

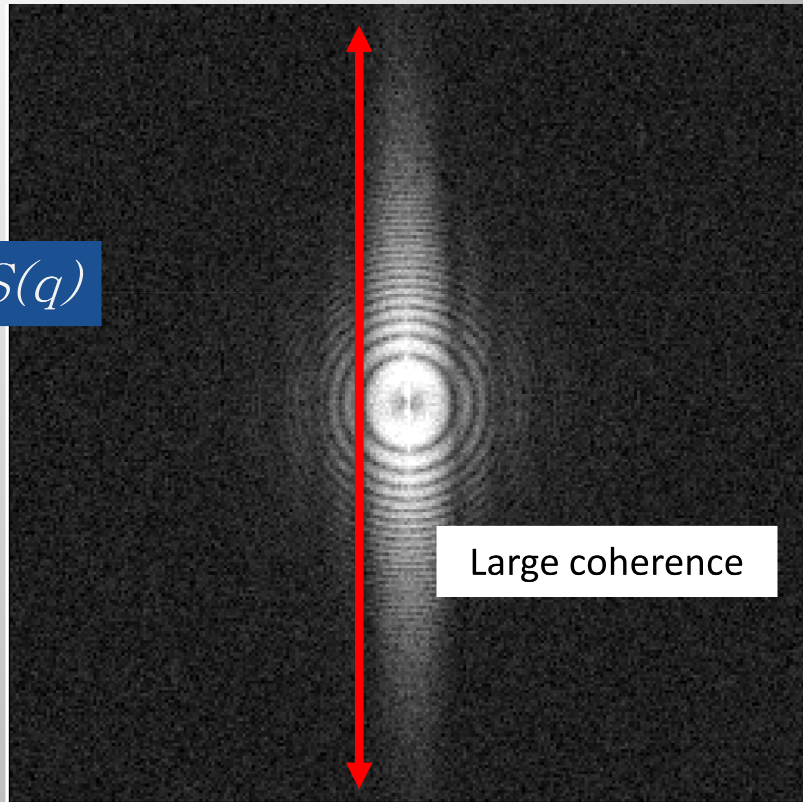
Speckles (ID06 - ESRF)



$\mathscr{F}$

$f\,(r)$ → $S(q)$

Spatial power spectrum



$$\boldsymbol{S(q) = I(q)\ T(q)\ H(q)\ C(q)}$$

I (q): particle form factor (flat)

T(q): Talbot trasfer function [$\sin^2(q^2 z/2\ k)$]

H(q) = Sensor transfer function

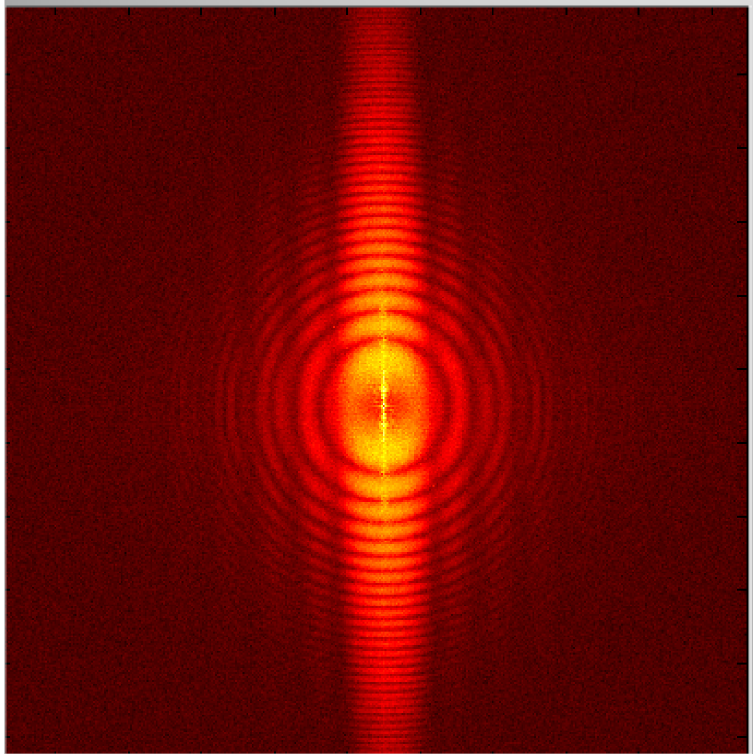
$$r = \frac{q}{k} z$$

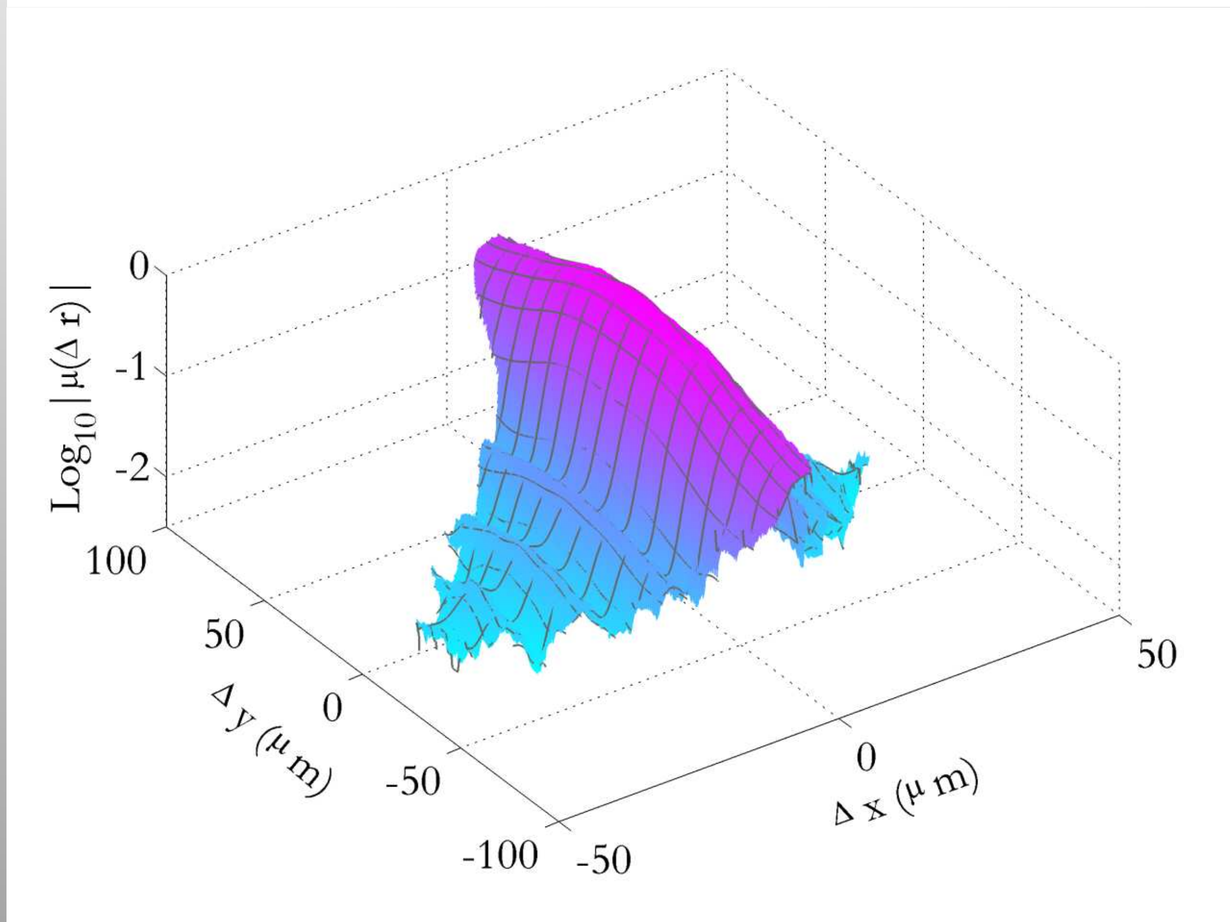
$C(r(q)) = |\mu|^2$ (μ: Complex Coherence Factor)

2D MAP

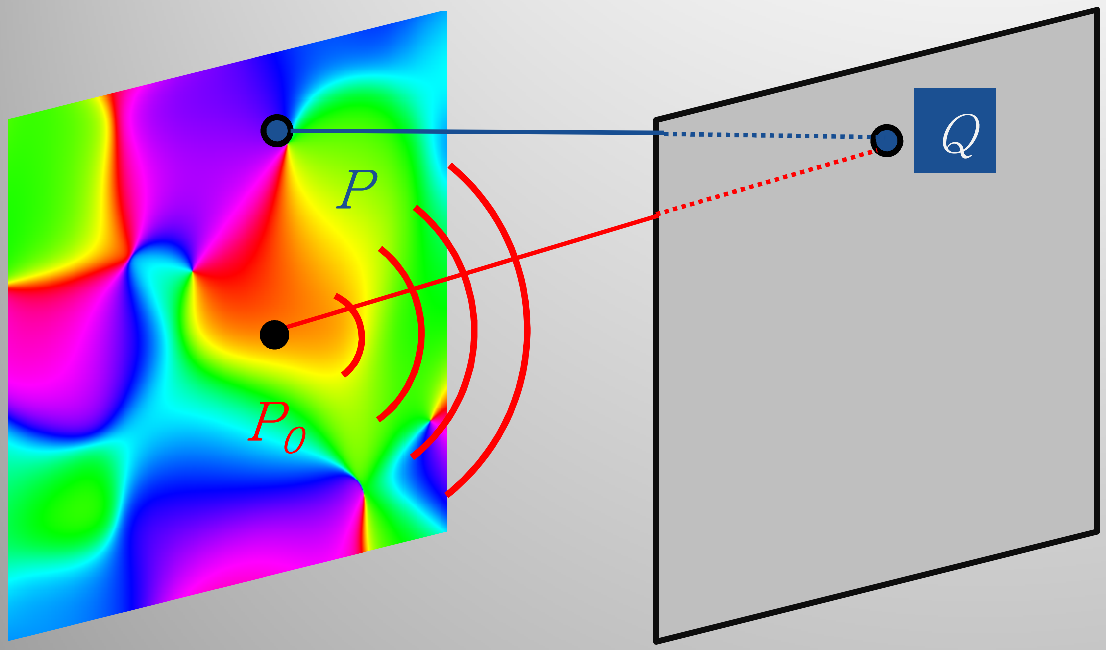
Z = 838mm
10 images acquired

H(q) known





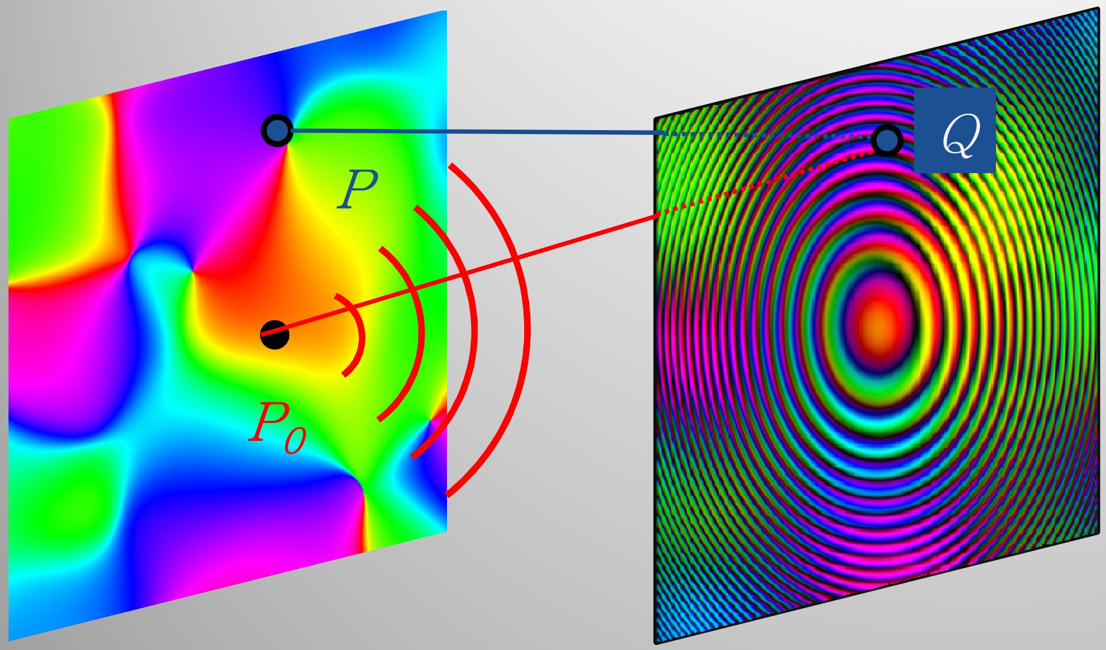
In-Line Holography



Resulting Intensity

$$I(Q) = const + \frac{e^{ikr_0}}{r_0} e^{ikz} E(P_0)^* E(P)$$

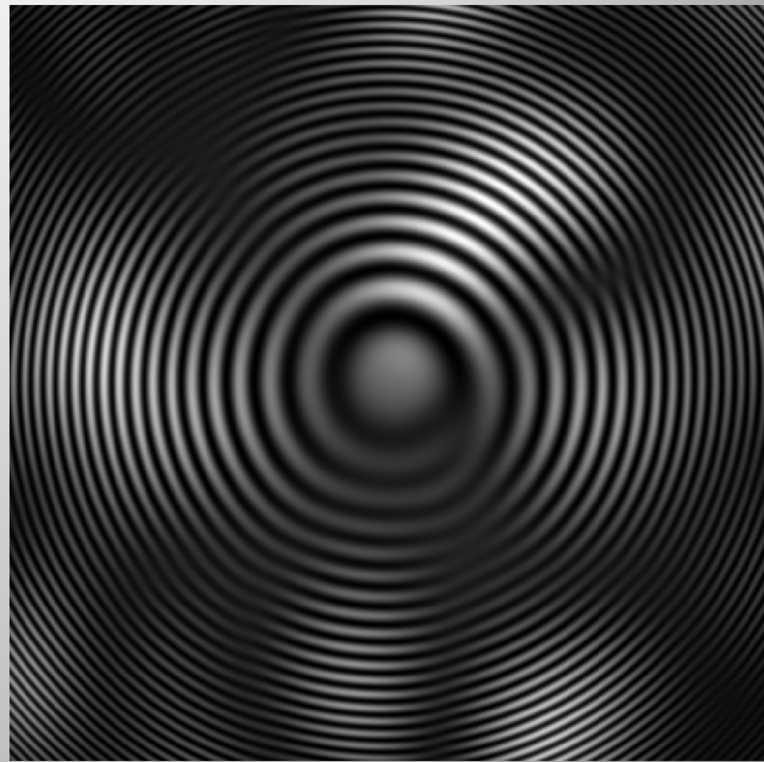
In-Line Holography



Resulting Intensity

$$I(Q) = const + \frac{e^{ikr_0}}{r_0} e^{ikz} E(P_0)^* E(P)$$

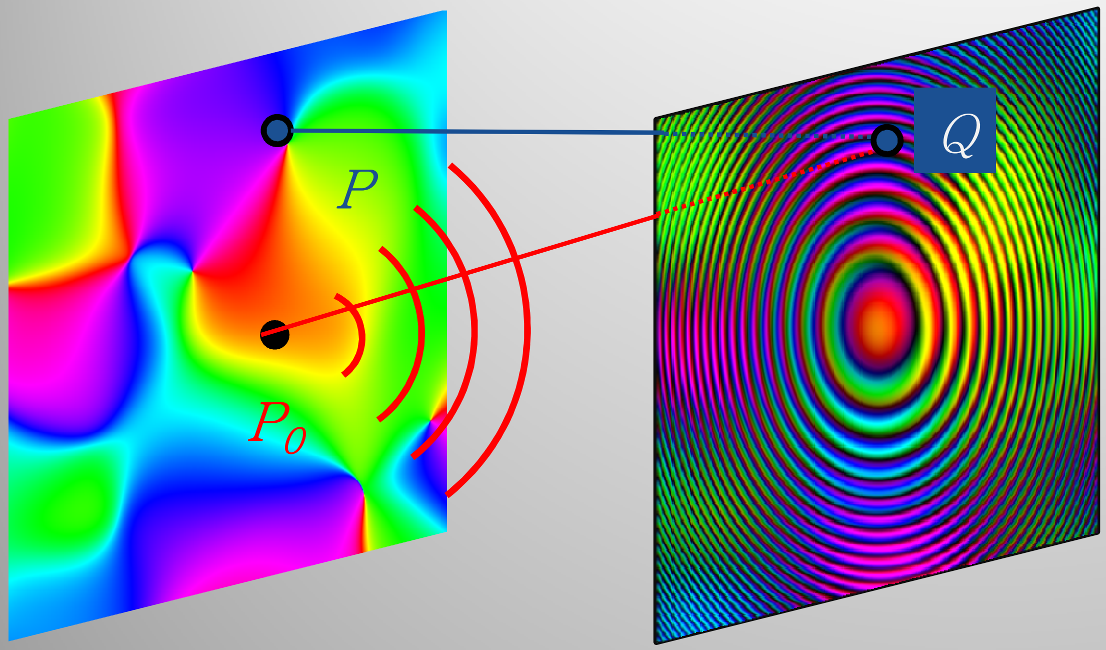
Simulated Istantaneous intensity



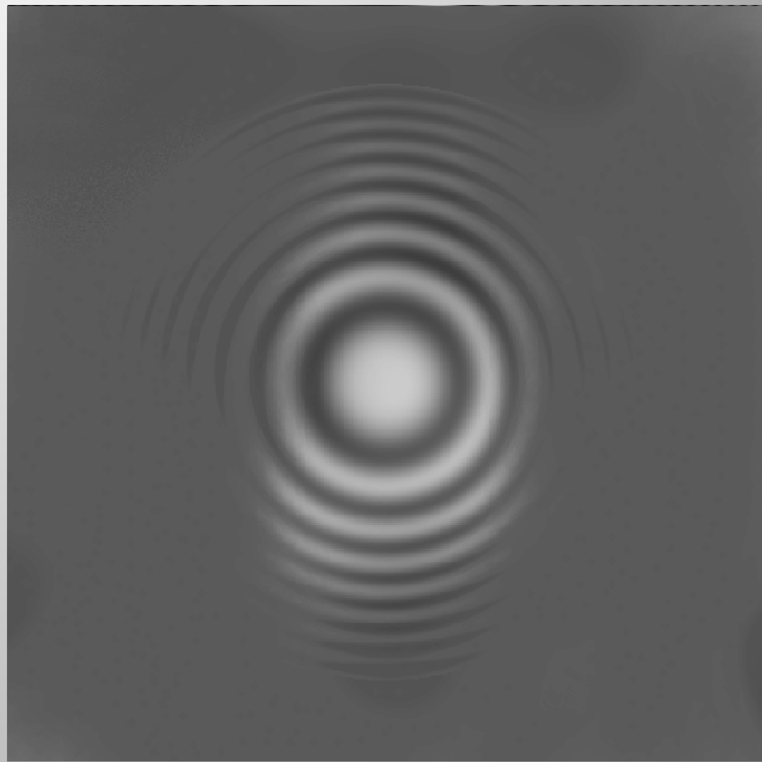
Intensity

$$I \sim E_S(P_0)^* E_T(P)$$

In-Line Holography



Simulated Summation of many shots



Resulting Intensity

$$I(Q) = const + \frac{e^{ikr_0}}{r_0} e^{ikz} E(P_0)^* E(P)$$

FEL: all the spikes in the pulse

Synchrotron: in 1 ms -> 10^{14} longitudinal modes

Intensity

$$I \sim \langle E_S(P_0)^* E_T(P) \rangle$$

Visibility:

$$V(d) = \left(\frac{I_{max} - I_{min}}{I_{max} + I_{min}} \right)(d)$$