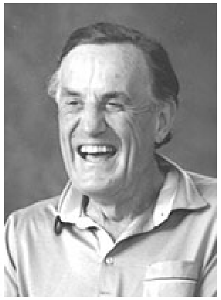
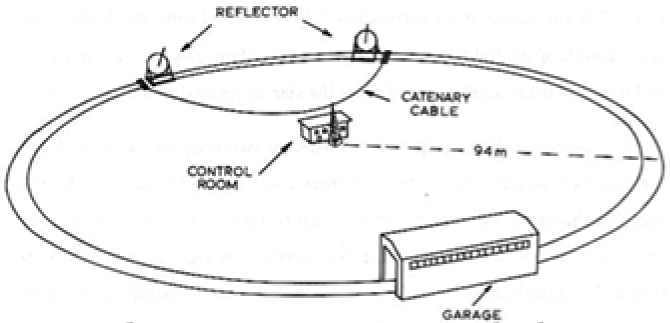
Hanbury Brown and Twiss Interferometry at XFEL Sources

Ivan Vartaniants

Photon Science, DESY, Hamburg, Germany
NRNU, 'MEPhI', Moscow, Russia

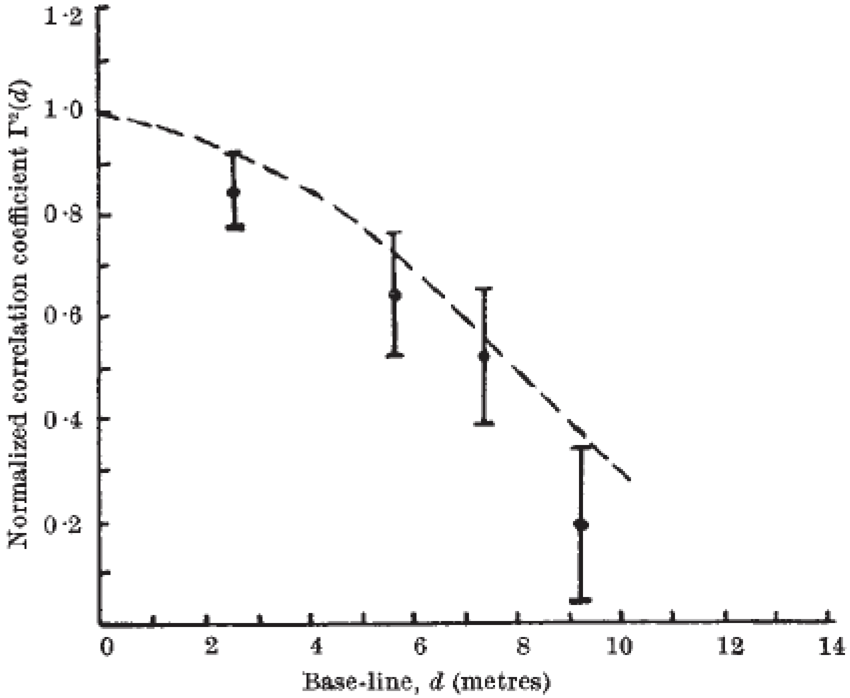
Hanbury Brown and Twiss interferometry





HBT telescopes measuring light intensity I from Sirius

Image from G. Goldhaber, Proc. Int. Workshop on Correlations and Multiparticle production (CAMP - LESIP IV), World Scientific (1991).

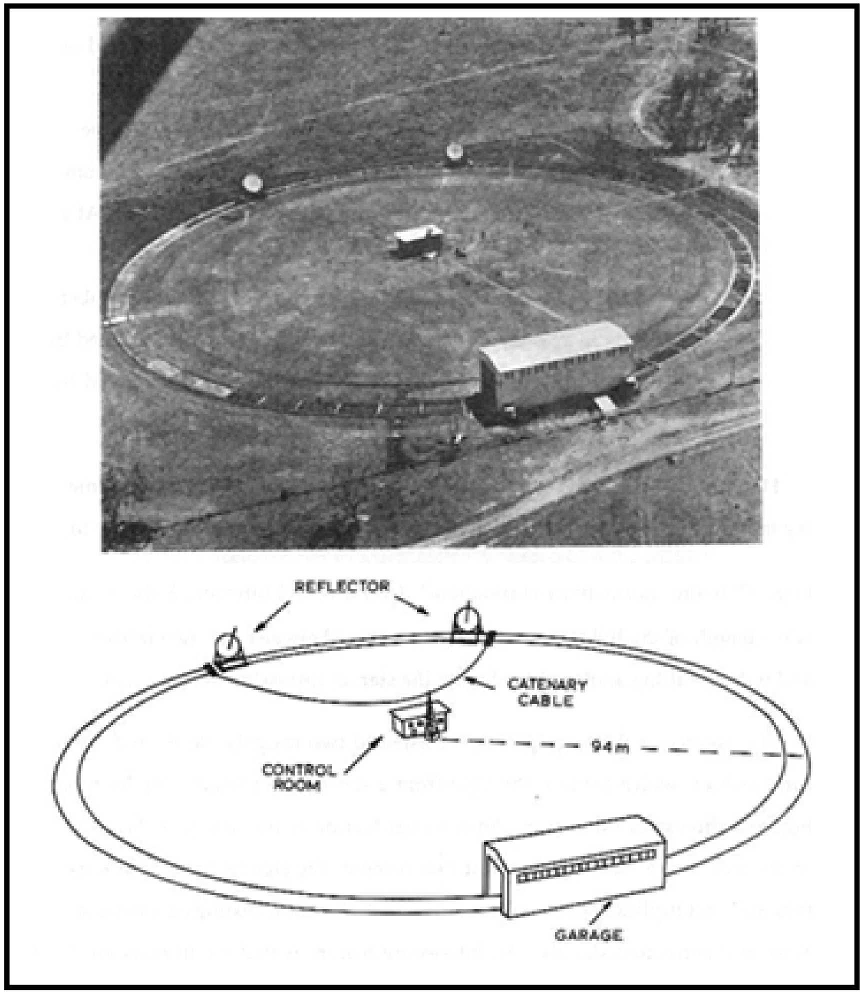


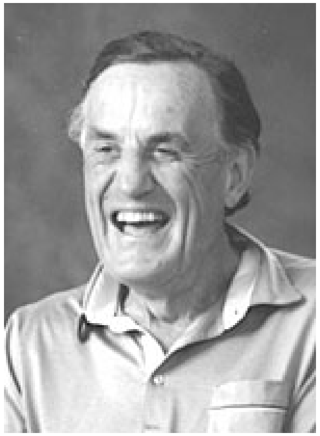
Experimental contrast ζ_2 compared with theoretical for 0.0063 sec. angular star size

Figure from Hanbury Brown, R. , and Twiss, R. Q. , *Nature*, 178, 1046 (1956)

$$g^{(2)} = \frac{\langle I_1 I_2 \rangle}{\langle I_1 \rangle \langle I_2 \rangle} = 1 + \zeta_2(d)$$

Hanbury Brown and Twiss interferometry





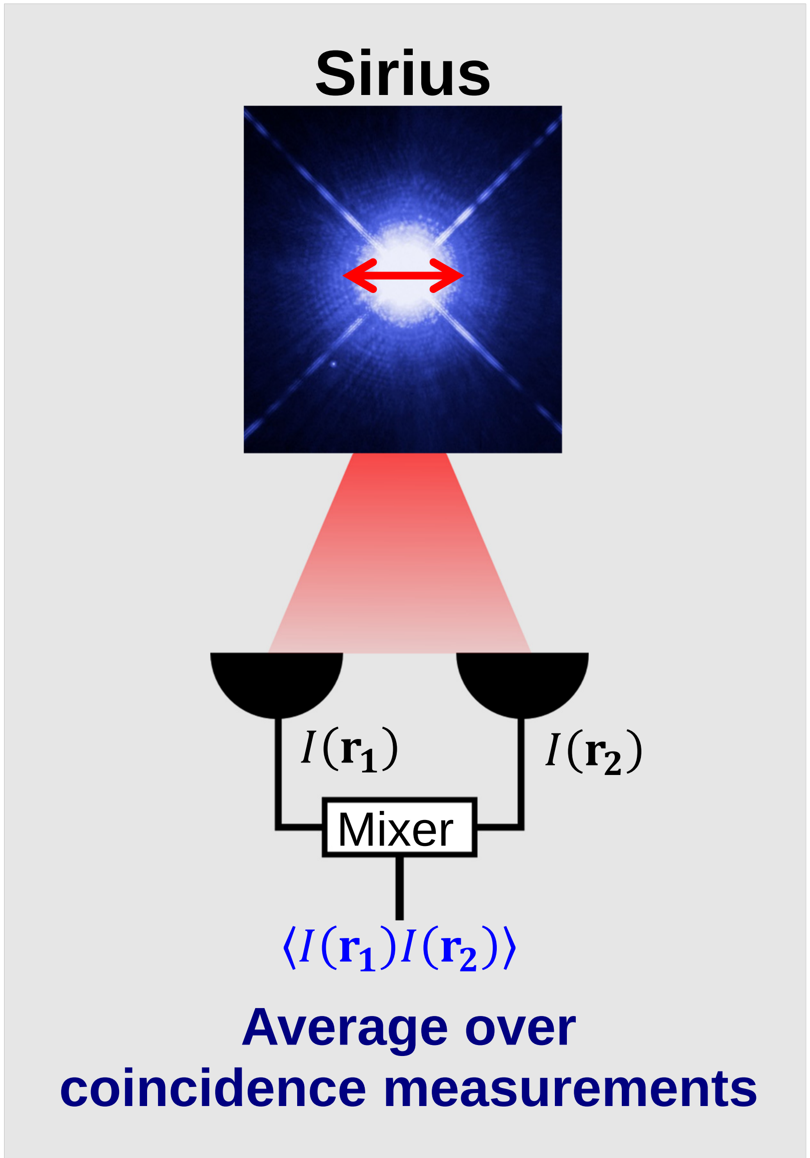
Robert Hanbury Brown

Richard Q. Twiss

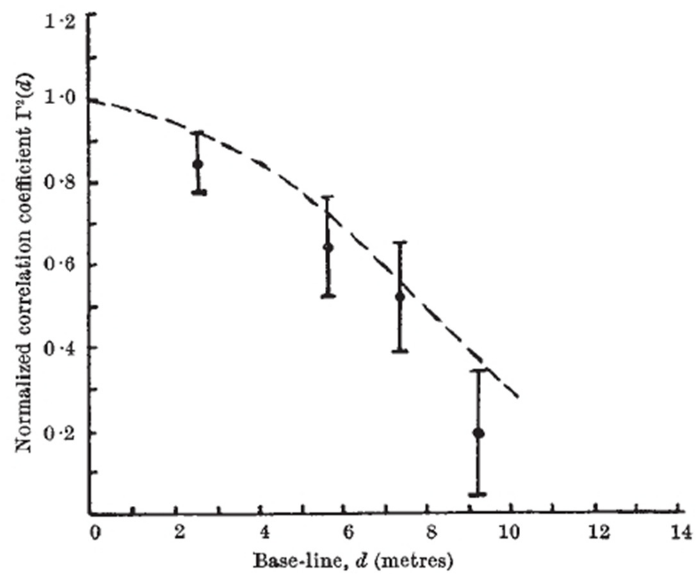
Telescopes measuring correlations of light from Sirius

From G. Goldhaber, Proc. Int. Workshop on Correlations and Multiparticle production (CAMP - LESIP IV), World Scientific (1991)

Hanbury Brown and Twiss experiment



$$g^{(2)}(\mathbf{r}_1,\mathbf{r}_2) = \frac{\langle I(\mathbf{r}_1) I(\mathbf{r}_2)\rangle}{\langle I(\mathbf{r}_1)\rangle\langle I(\mathbf{r}_2)\rangle}$$



Sirius angular size: **0.0063”**

Hanbury Brown and Twiss, Nature 1956
Hanbury Brown and Twiss, Nature 1957

Quantum optics

- Thermal (chaotic) sources
- Lasers
- Bose-Einstein Condensates
- Microcavities
- Synchrotron sources
- **XFELs**

Quantum optics

Nobel prize: 2005

Glauber has formulated:

The source to be coherent, has to be coherent in all orders of correlation function

N-th order correlation function:

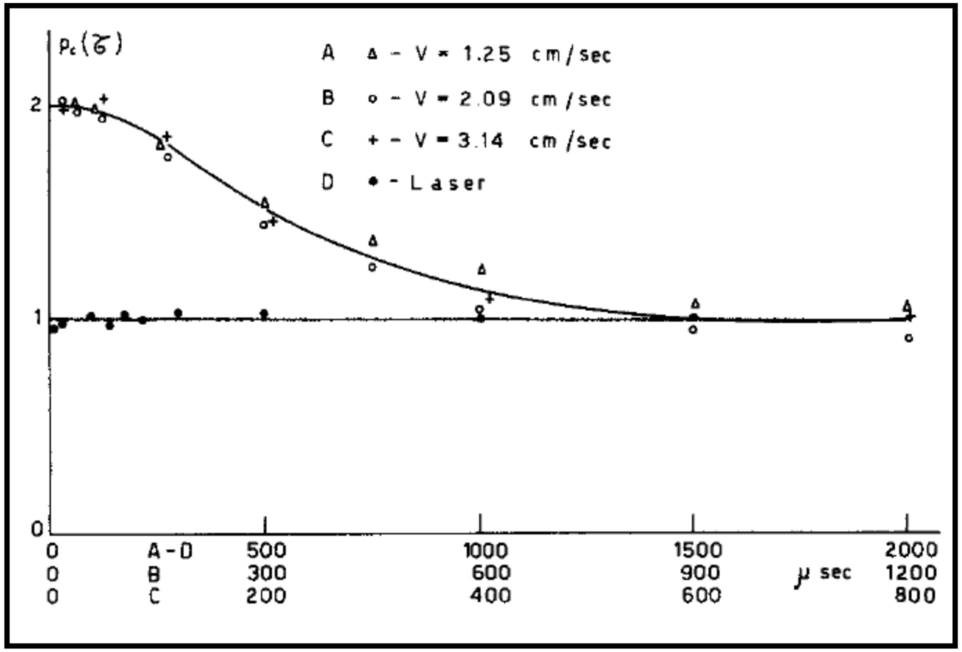
$$g^{(n)}(x_1,\dots,x_n)=\frac{\langle I(x_1)\dots I(x_n)\rangle}{\langle I(x_1)\rangle\dots\langle I(x_n)\rangle}=1$$

Special case, **1-st order** correlation function:

$$g^{(1)}(x_1,x_2)=\frac{\langle E(x_1)E(x_2)\rangle}{\left\langle\sqrt{I(x_1)}\right\rangle\left\langle\sqrt{I(x_2)}\right\rangle}$$

R. Glauber, Phys. Rev., **131**, 2766

Laser sources and chaotic sources



Chaotic sources (Gaussian Statistics)

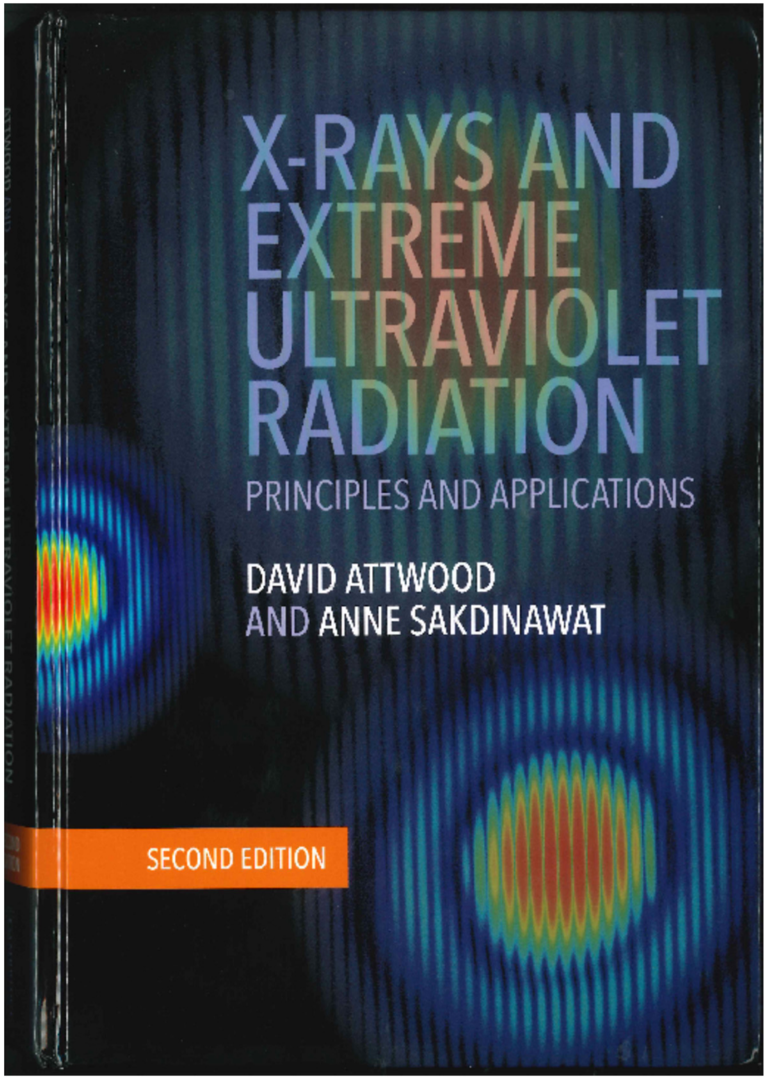
$$g^{(2)}(\mathbf{r_1},\mathbf{r_2}) = 1 + \frac{\tau_c}{T} \mid \gamma_{12} \mid^2$$

τ_c : coherence time
T: pulse duration
τ_c/T high at FELs

F.T. Arecchi et al., *Phys. Lett.* (1966)

E. Ikonen, *Phys. Rev. Lett.* (1992)

1-st order coherence LCLS

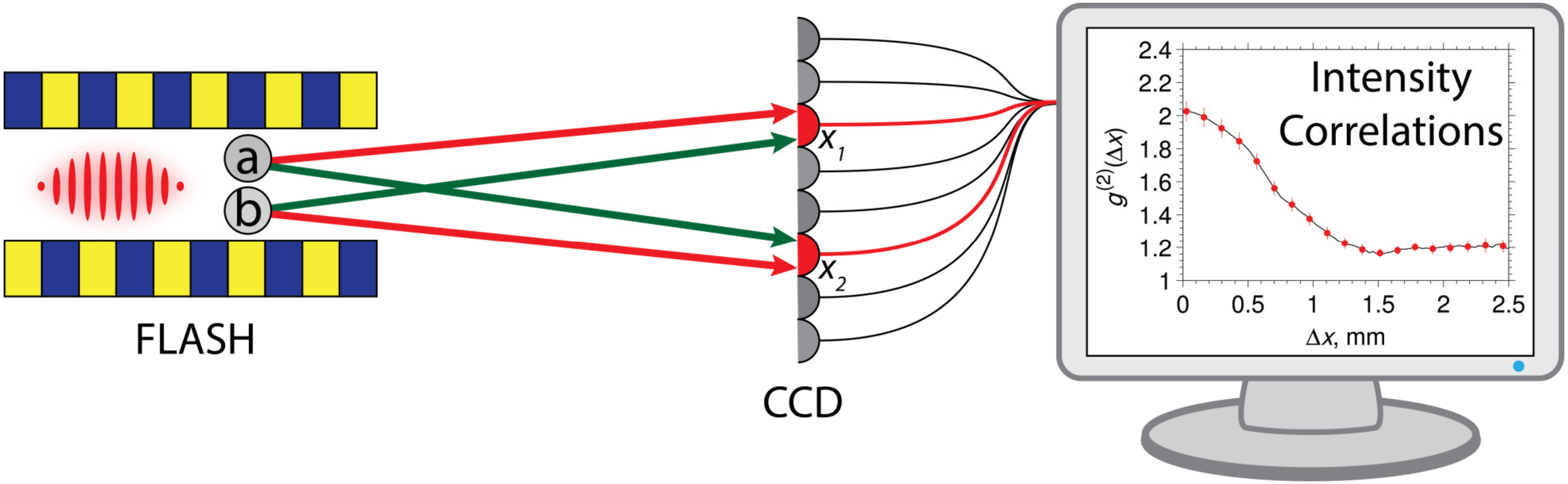


I. Vartaniants, *et al.*, Phys. Rev. Lett. **107,** 144801 (2011).

Basic question:

Whether XFEL's are really laser-like sources according to Glauber's definition?

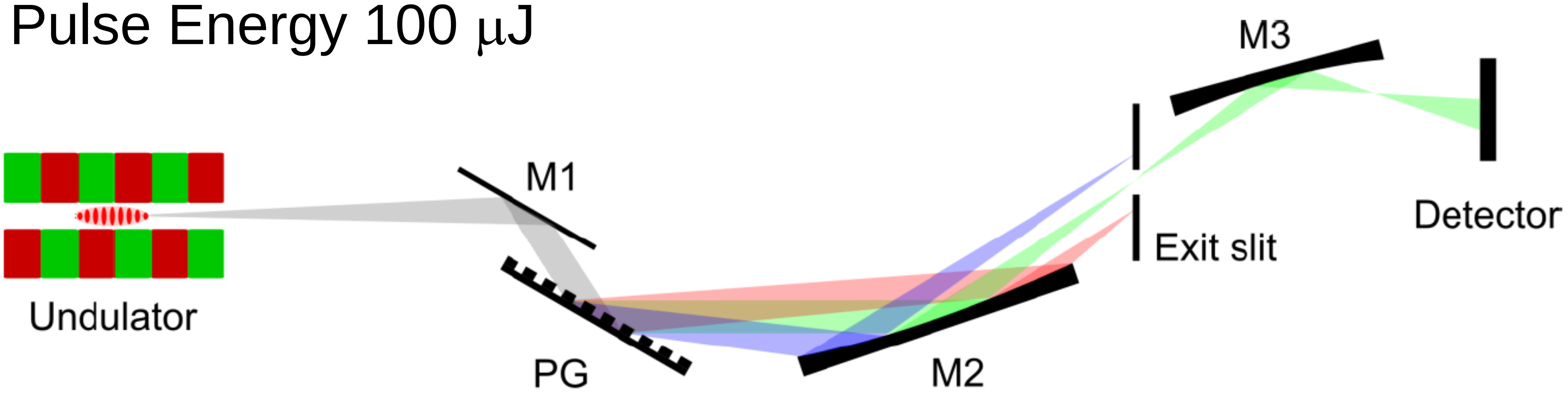
Hanbury Brown - Twiss Interferometry at FELs



A. Singer *et al., Phys. Rev. Lett.* **111**, 034802 (2013)
O. Gorobtsov *et al., Phys. Rev. A* **95**, 023843 (2017)
O. Gorobtsov *et al.,Sci. Rep.* **8**, 2219 (2018)
O. Gorobtsov *et al., Nat. Commun.* 9, 4498 (2018)

Intensity-Intensity Correlation Measurements at FLASH

λ=5.5 nm
Bunch charge 0.6 nC
Pulse Energy 100 μJ



$\tau_c \sim 1/\Delta\nu$

$$g^{(2)}(\mathbf{r_1},\mathbf{r_2}) = 1 + \frac{\tau_c}{T} \mid \gamma_{12} \mid^2$$

FLASH, PG2 beamline, (March,2012)

Second Order Correlation Measurements

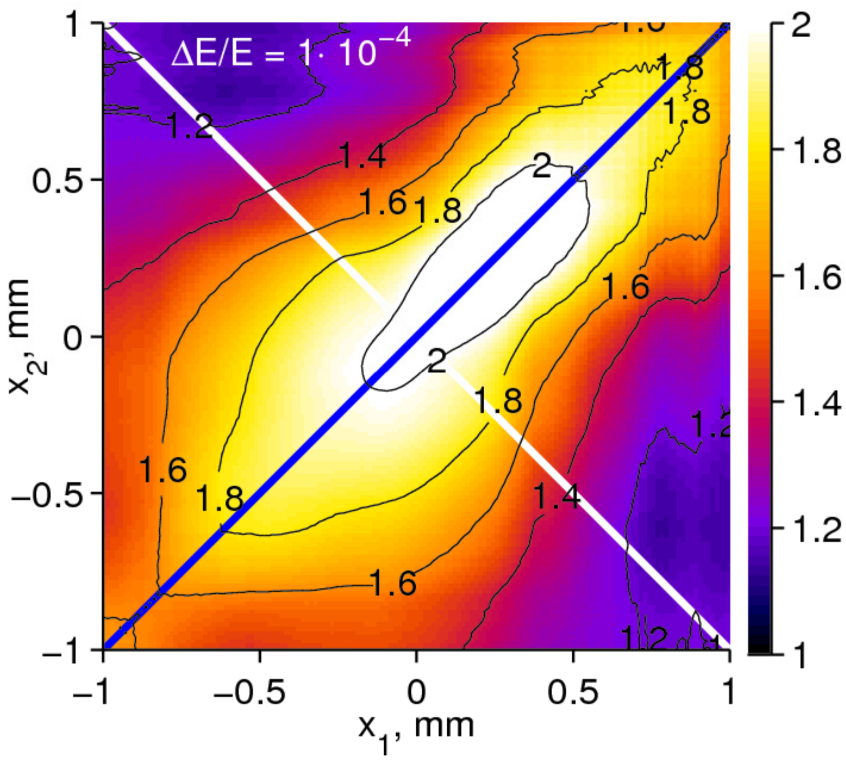
30 μm

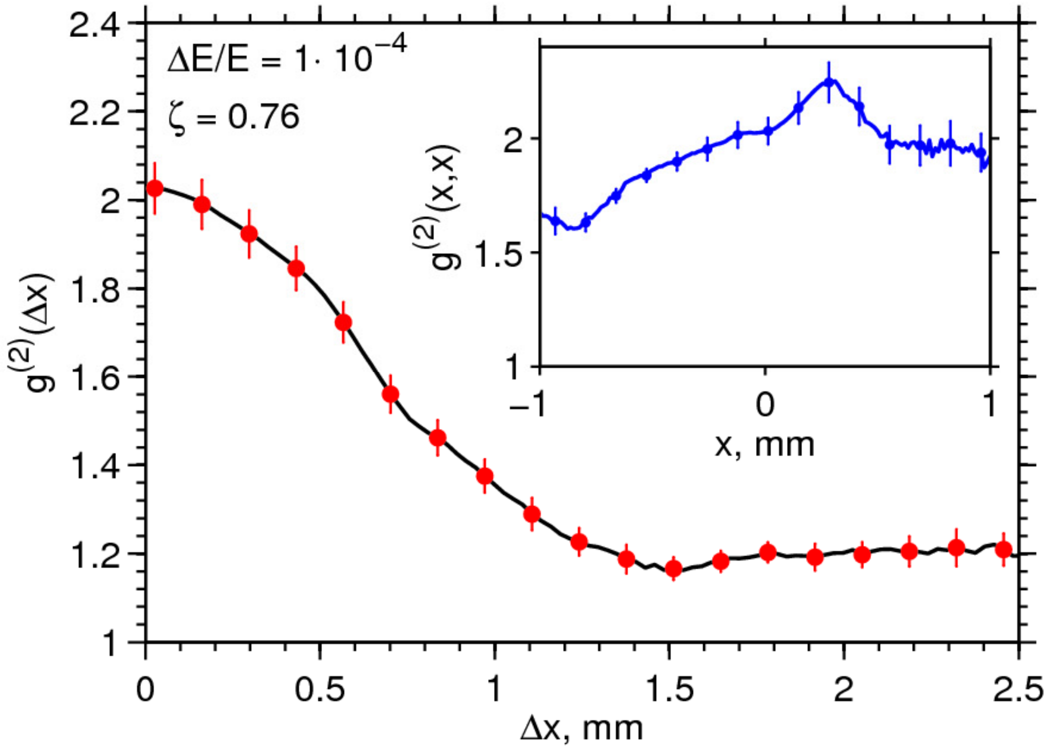
ΔE/E=0.8·10^{-4}

$$g^{(2)}(x_1, x_2) = \frac{\langle I(x_1) I(x_2) \rangle}{\langle I(x_1) \rangle \langle I(x_2) \rangle}$$

Second Order Correlation Measurements

Exit slit: 30 μm



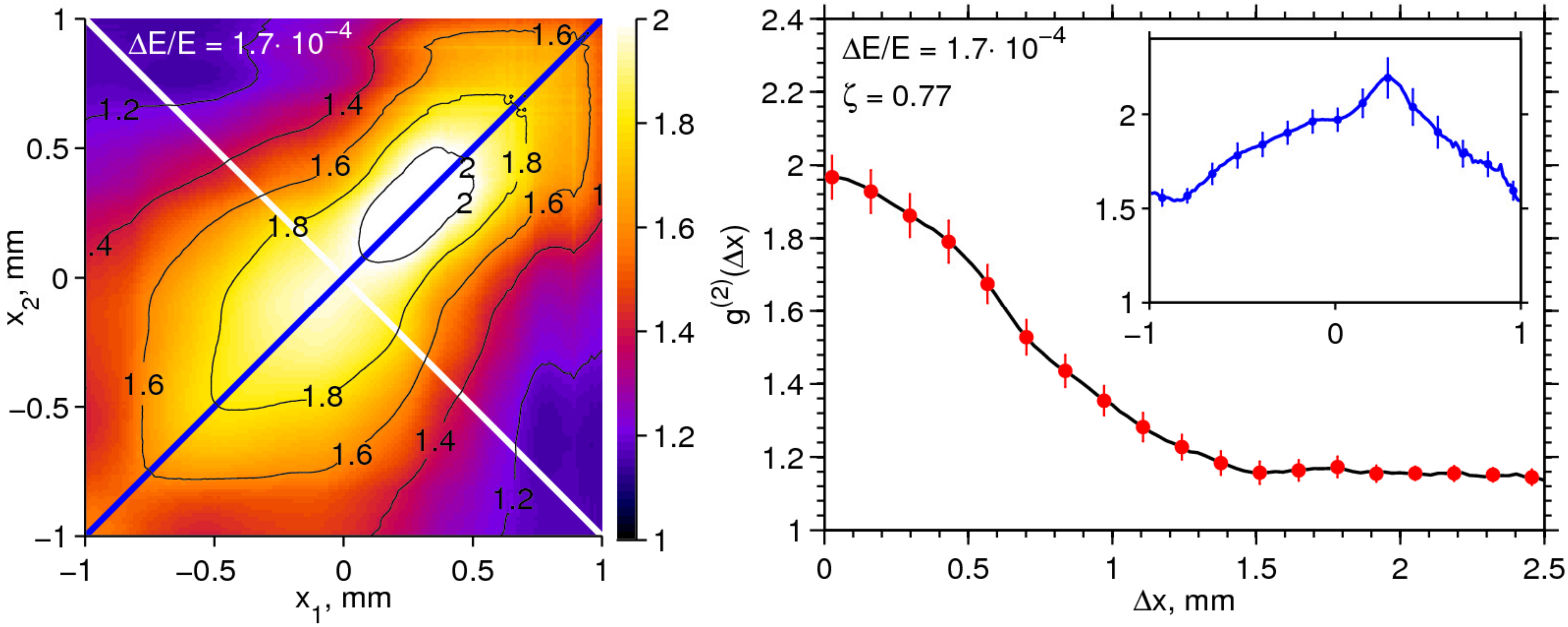


Single longitudinal mode!

Coherence length: l_c=0.93 mm
Beam size: 0.45 mm
Degree of coherence: 76%

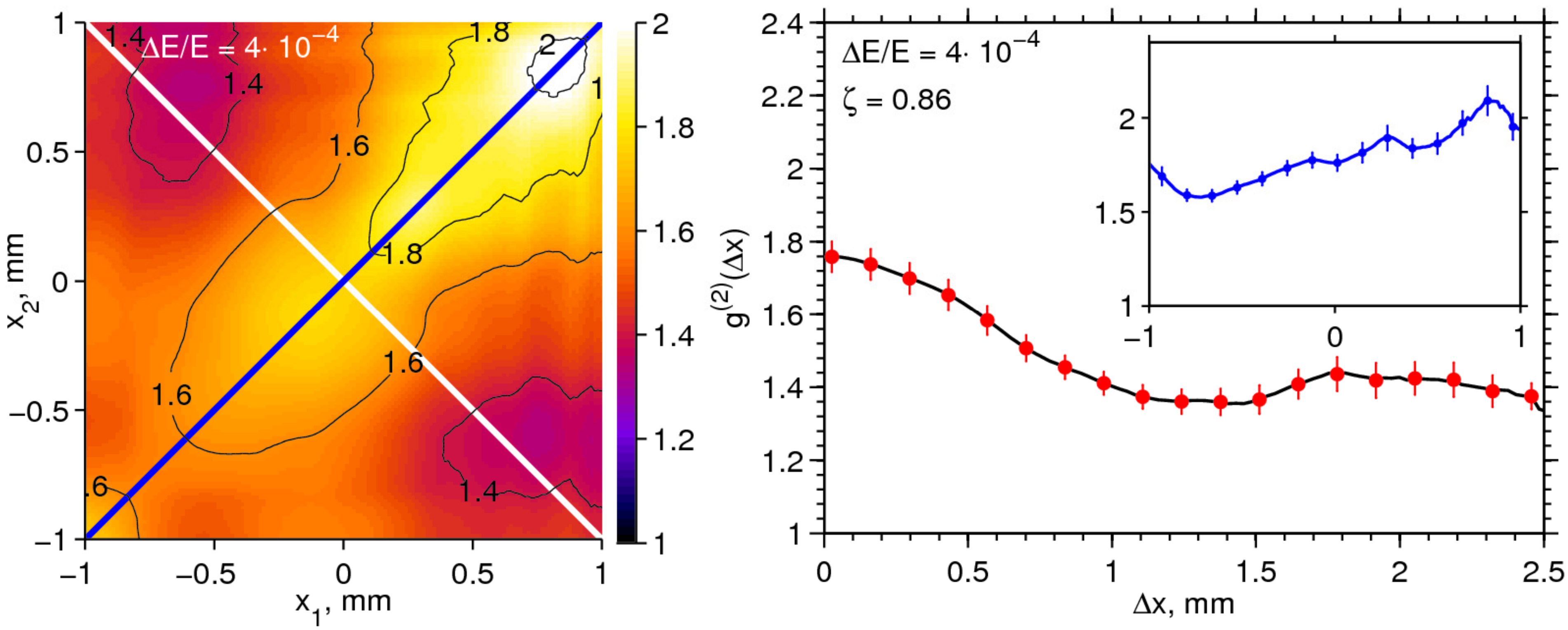
Second Order Correlation Measurements

Exit slit: 60 μm



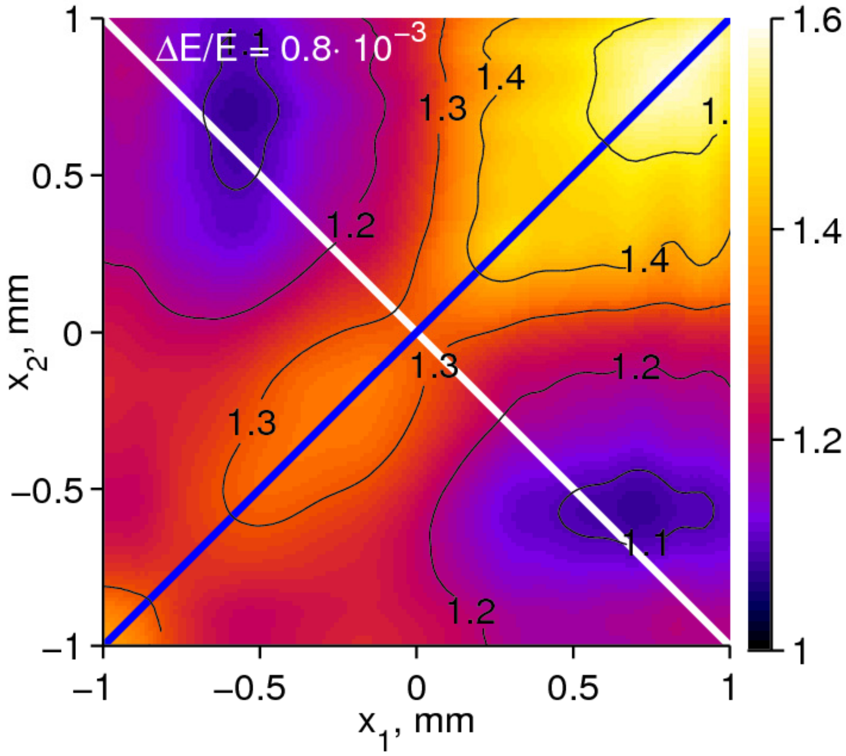
Second Order Correlation Measurements

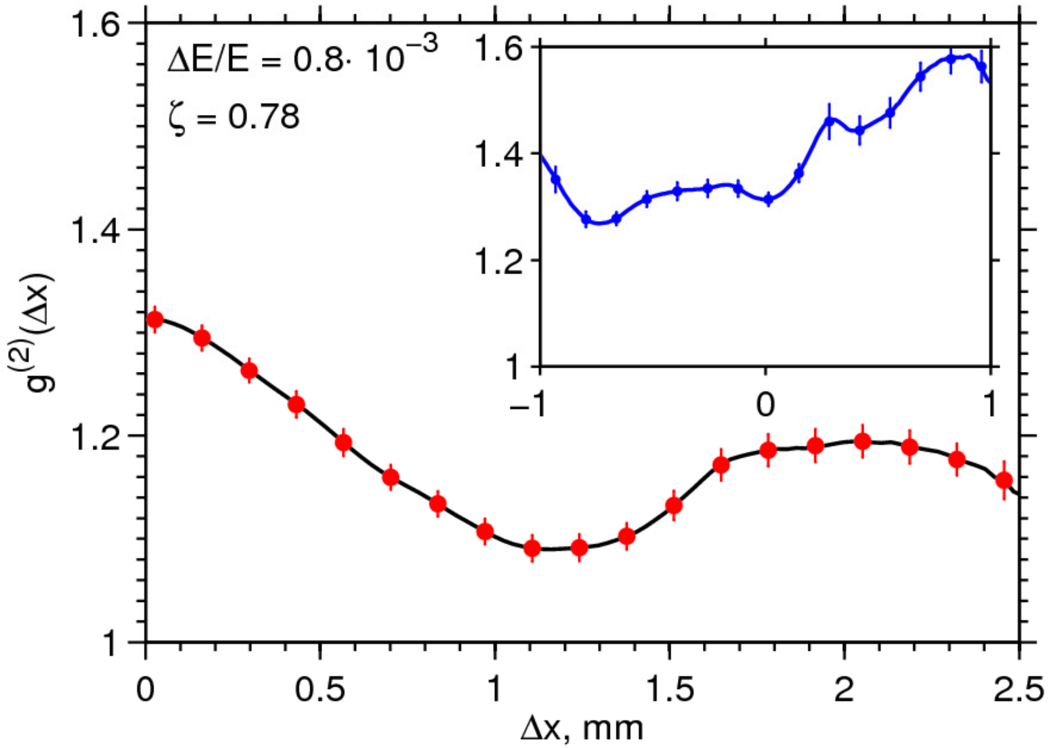
Exit slit: 150 μm



Second Order Correlation Measurements

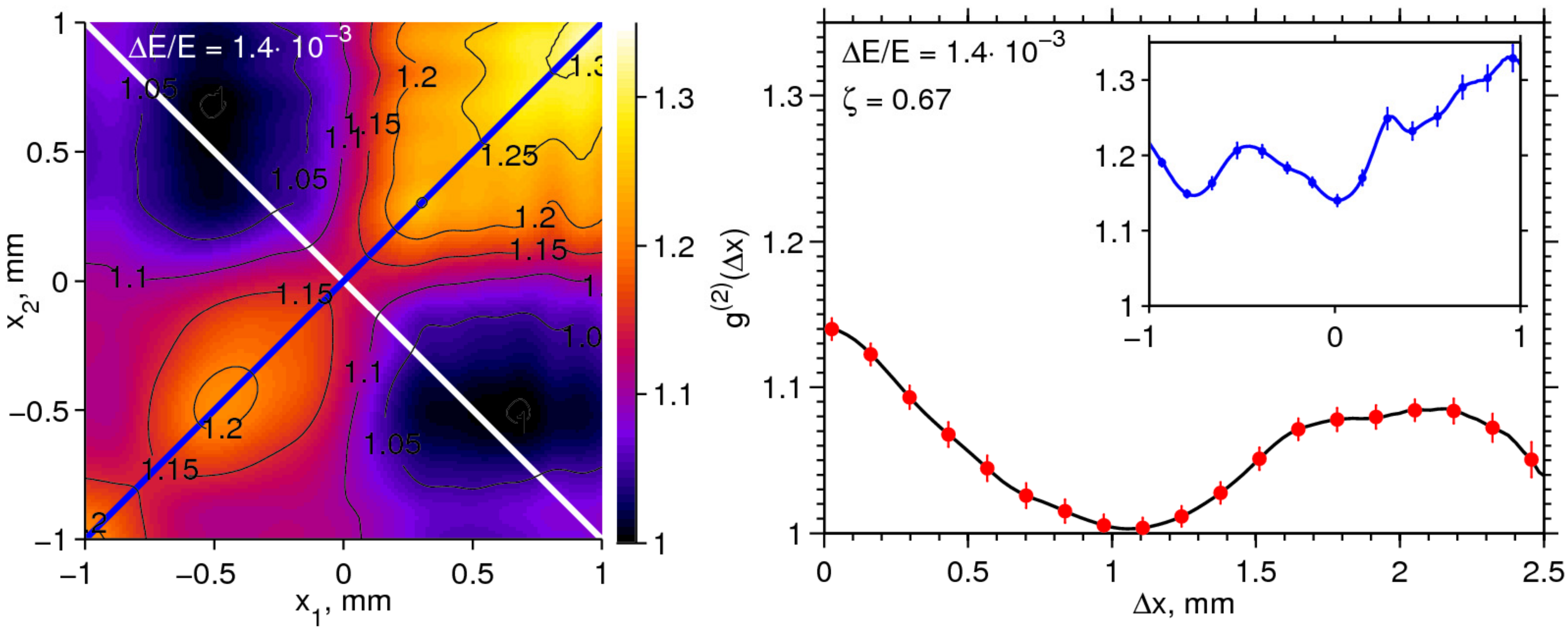
Exit slit: 300 μm





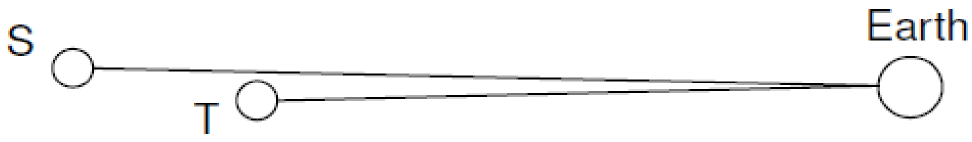
Second Order Correlation Measurements

Exit slit: 500 μm

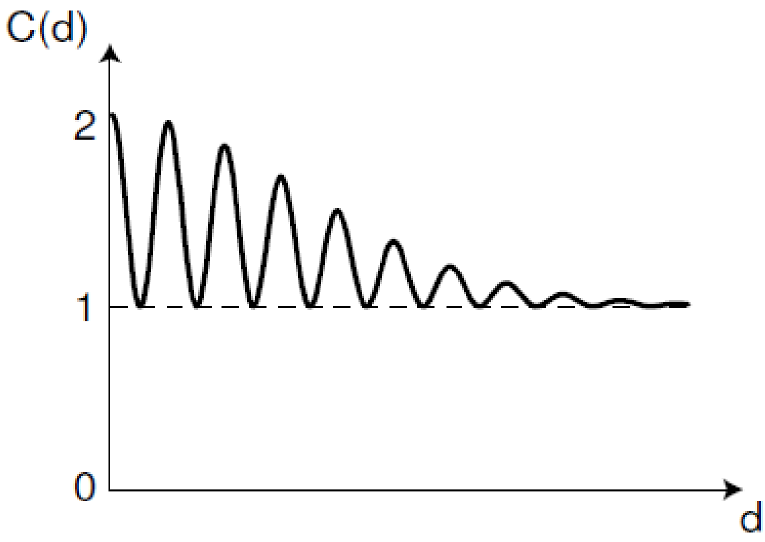


What is the origin of the 2-nd maximum?

Second order correlation measurements



(a)

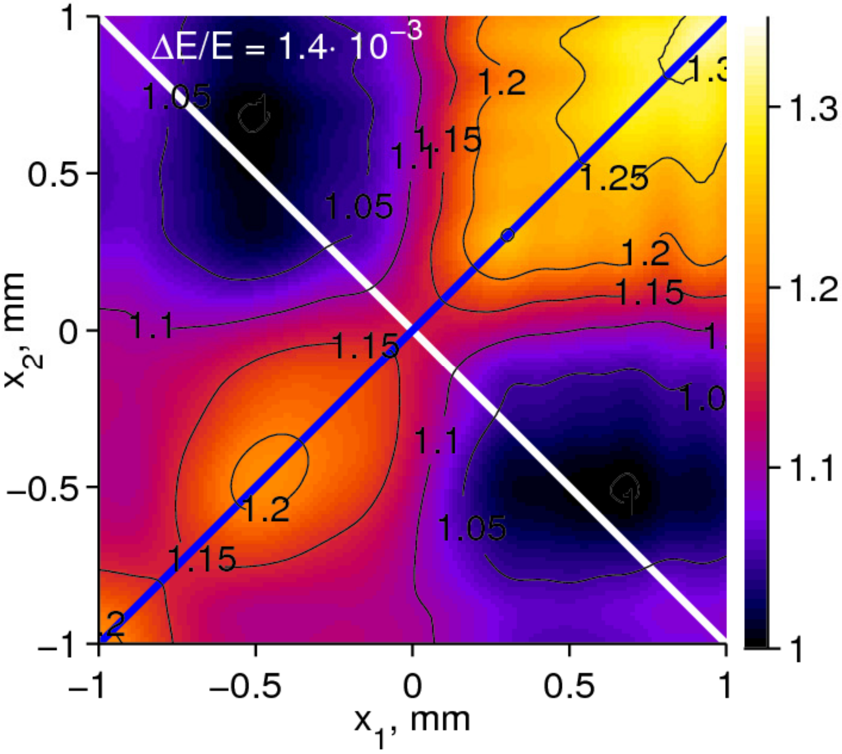


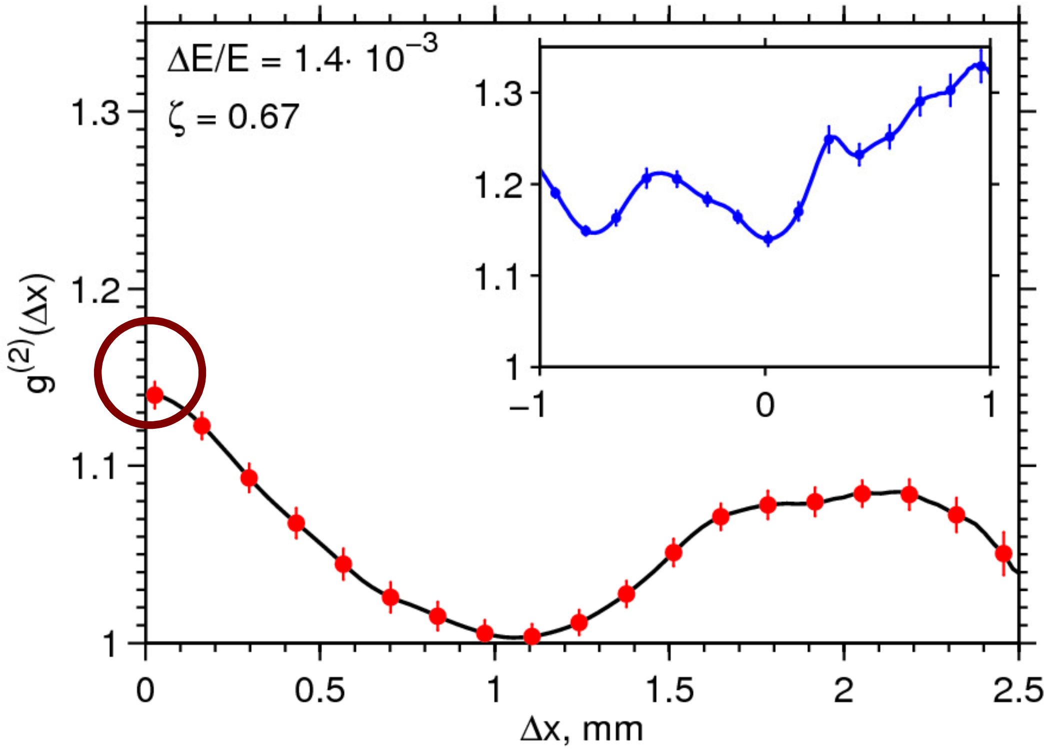
(b)

G. Baym, *Acta Physica Polonica* ***29***, *1839 (1998)*

Second Order Correlation Measurements

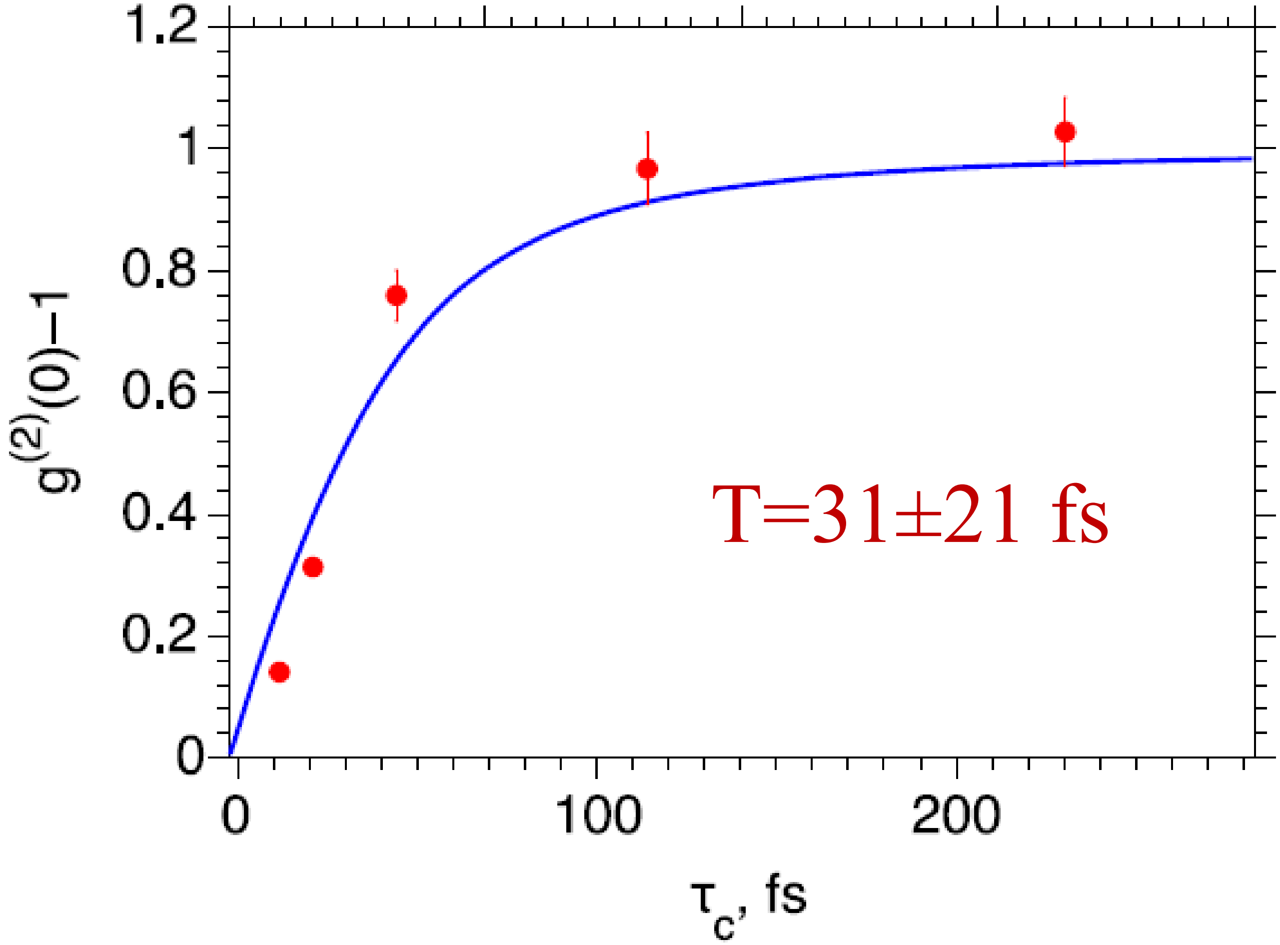
500 μm





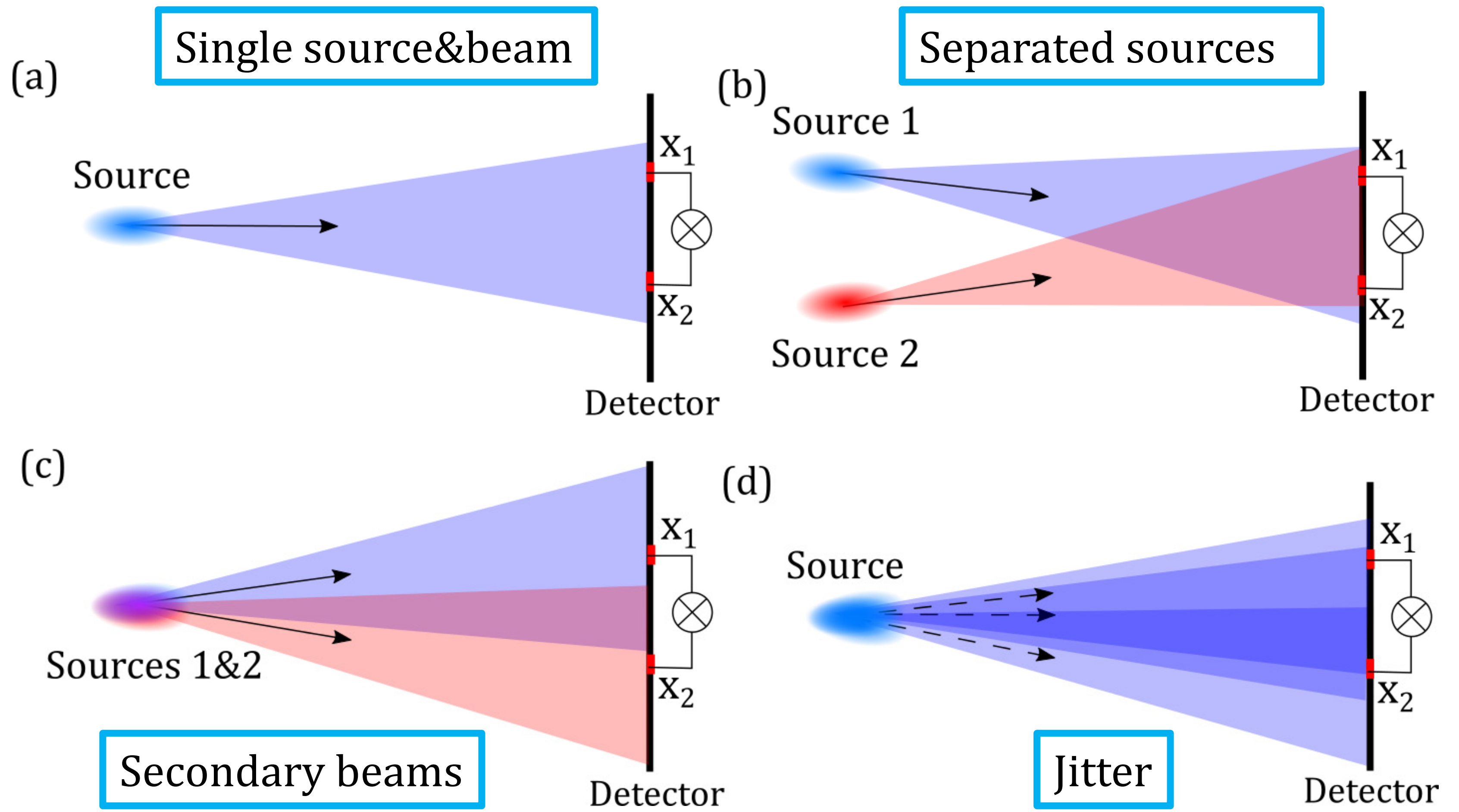
$$g^{(2)}(\mathbf{r_1},\mathbf{r_2}) = 1 + \frac{\tau_c}{T} \mid \gamma_{12} \mid^2$$

Pulse duration



A. Singer et al., Erratum PRL 117, 239903 (2016)

Different configurations



O. Gorobtsov, *et al.*, Phys. Rev. A **95,** 023843 (2017)

Hanbury Brown and Twiss interferometry in diffraction mode at LCLS

HELMHOLTZ
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O. Gorobtsov *et al.*, *Sci. Rep.* 8, 2219 (2018)

SCIENTIFIC REPORTS

OPEN

Diffraction based Hanbury Brown and Twiss interferometry at a hard x-ray free-electron laser

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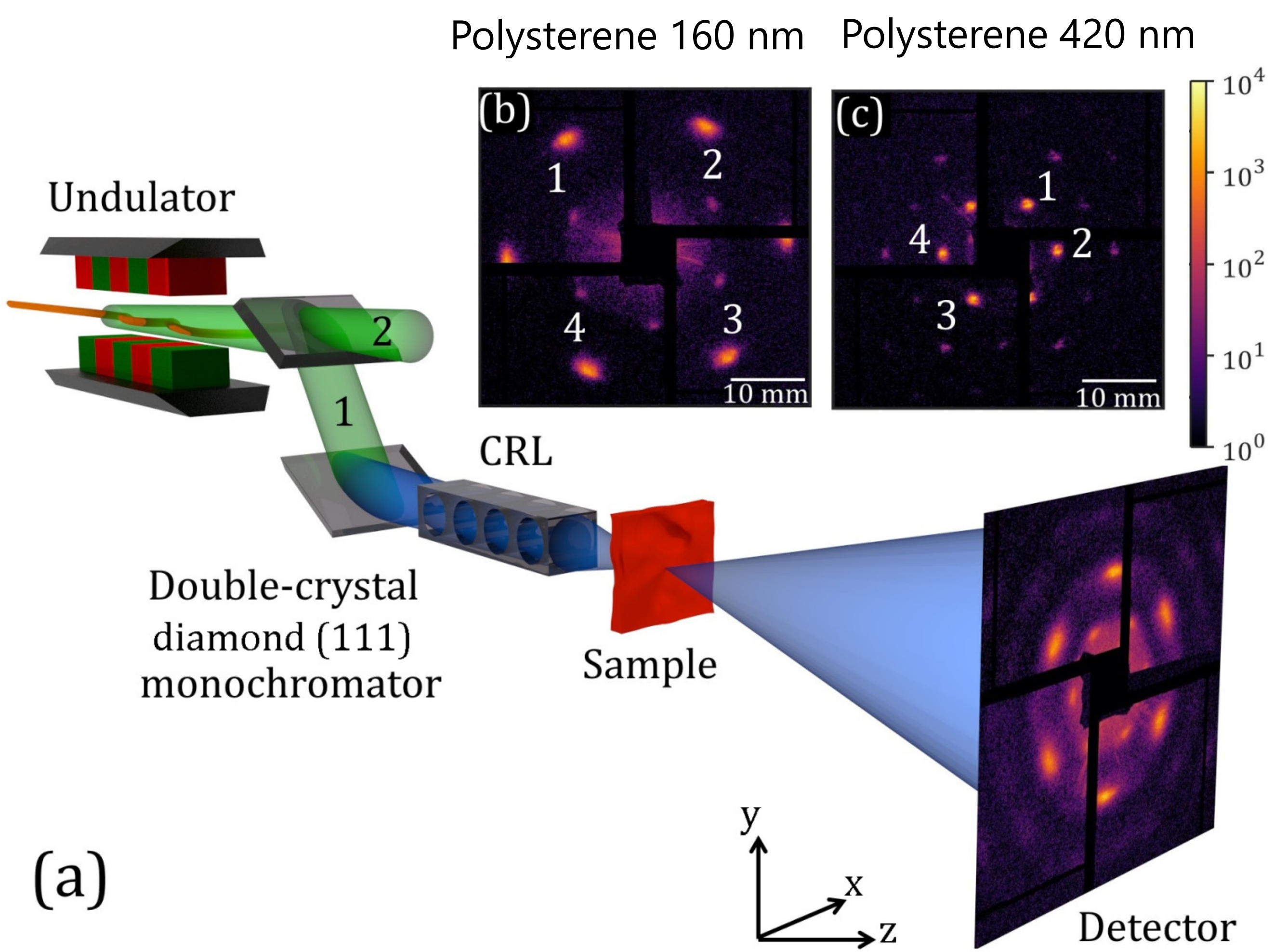
O. Yu. Gorobtsov[1], N. Mukharamova[1], S. Lazarev[1,2], M. Chollet[3], D. Zhu[3], Y. Feng[3], R. P. Kurta[1,9], J.-M. Meijer[4,10], G. Williams[3,11], M. Sikorski[3,9], S. Song[3], D. Dzhigaev[1], S. Serkez[5], A. Singer[6,12], A. V. Petukhov[4,7] & I. A. Vartanyants[1,8]

DESY

Collaboration with LCLS

Diffraction experiment at LCLS



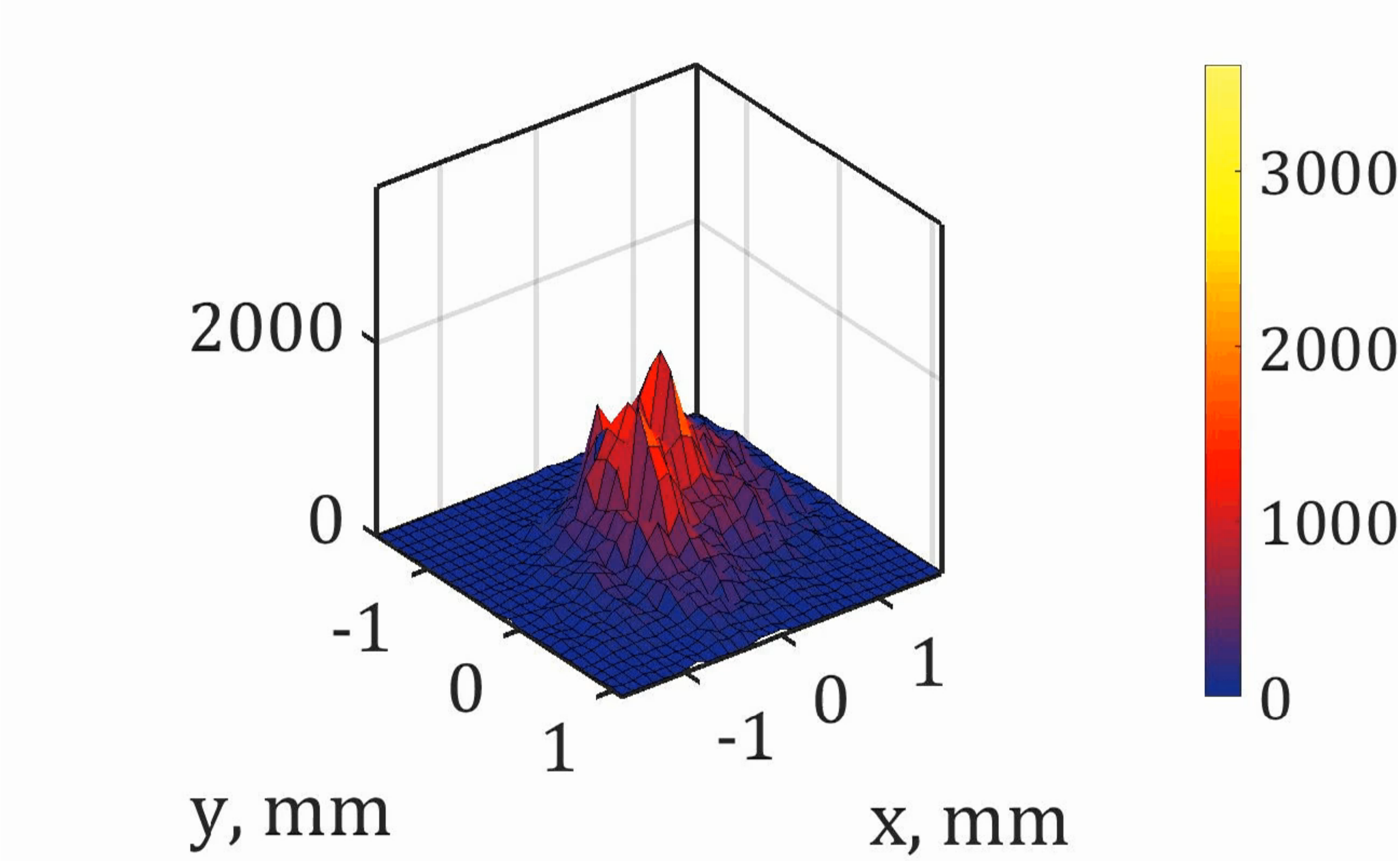
Measurements of response of colloidal crystals to IR laser irradiation

Beamline: XPP
Wavelength: 1.5498 A
Bandwidth: 10^{-4}
Repetition rate: 120 Hz
Pulse duration: 42 fs (?)
Focus size: 50 um
Distance: 10 m
Pixel size: 110 um
Intensity: 10^9 ph/pulse

N. Mukharamova *et al.*, *Appl. Sci.*, *7*, *519 (2017)*

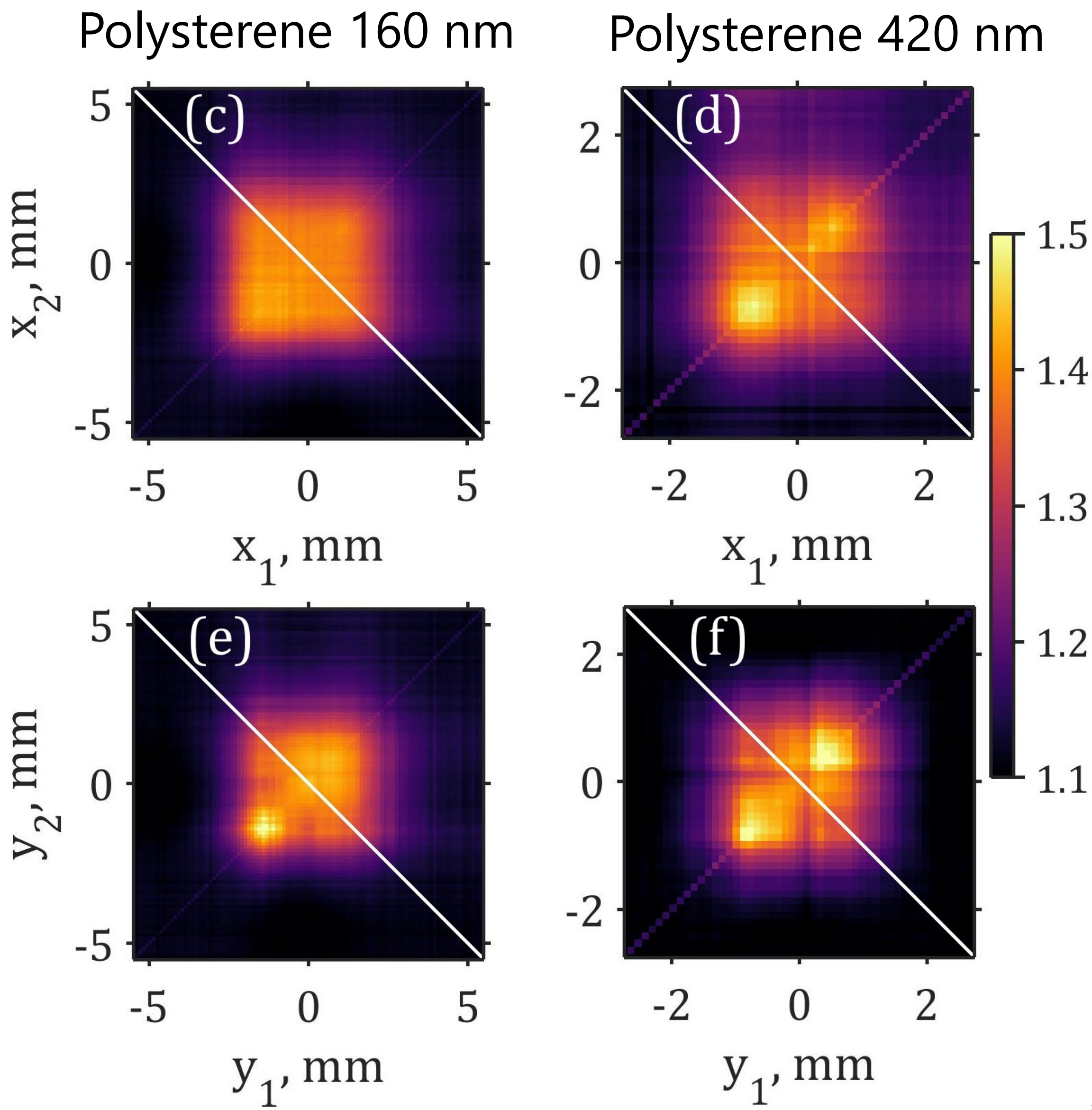
Bragg dance

Shot-to-shot changes in the Bragg peak intensity



Intensity-intensity correlation function

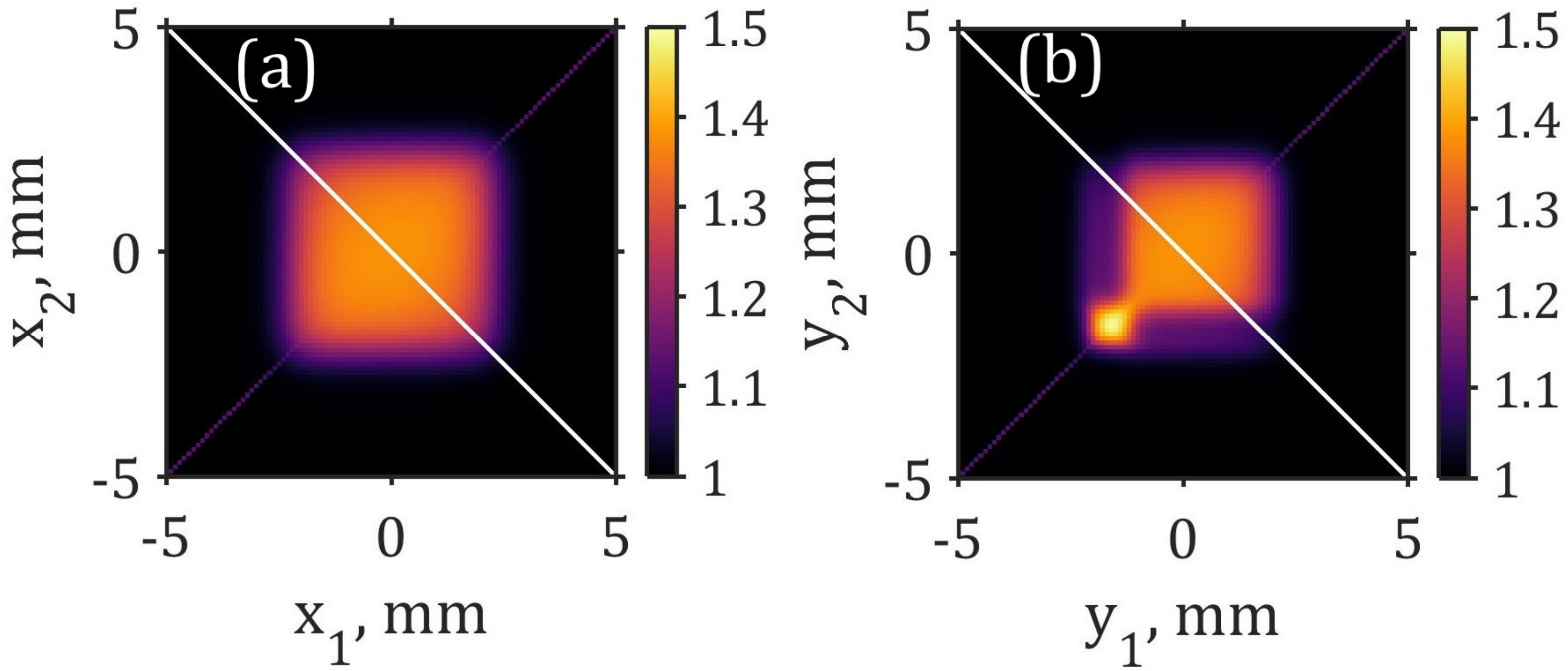
$$g^{(2)}(x_1, x_2) = \frac{\langle I(x_1) I(x_2) \rangle}{\langle I(x_1) \rangle \langle I(x_2) \rangle}$$



Simulated intensity-intensity correlation function

One beam
Intensity (rms): 1.6 mm
Coherence length: 10 mm
Background noise: 2%

Two beams
Secondary beam:10% of intensity
Position difference: 1.5 mm

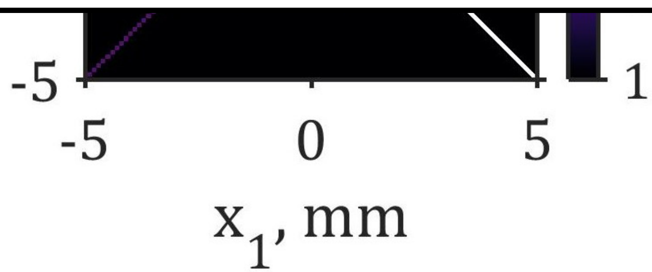


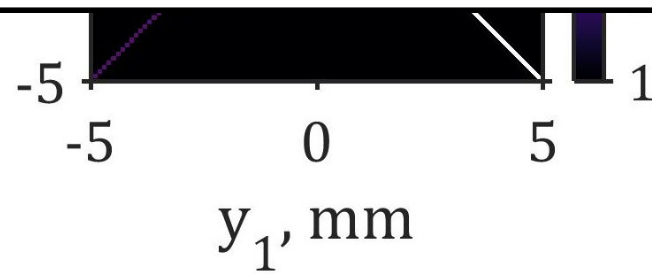
Simulated intensity-intensity correlation function

One beam
Intensity (rms): 1.6 mm
Coherence length: 10 mm
Background noise: 2%

Two beams
Secondary beam:10% of intensity
Position difference: 1.5 mm

Our analysis has shown that pulse duration is about 11-12 fs instead of expected 40 fs provided by XT CAV measurements





HBT experiments at SASE FELs

Our results demonstrate definitely that SASE XFELs statistically behave as chaotic sources and not as a fully coherent sources!

What about seeded FELs?

Hanbury Brown and Twiss interferometry at the externally seeded FERMI source

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O. Gorobtsov *et al., Nat. Commun.* *9*, *4498 (2018)*

nature COMMUNICATIONS

ARTICLE

DOI: 10.1038/s41467-018-06743-8 OPEN

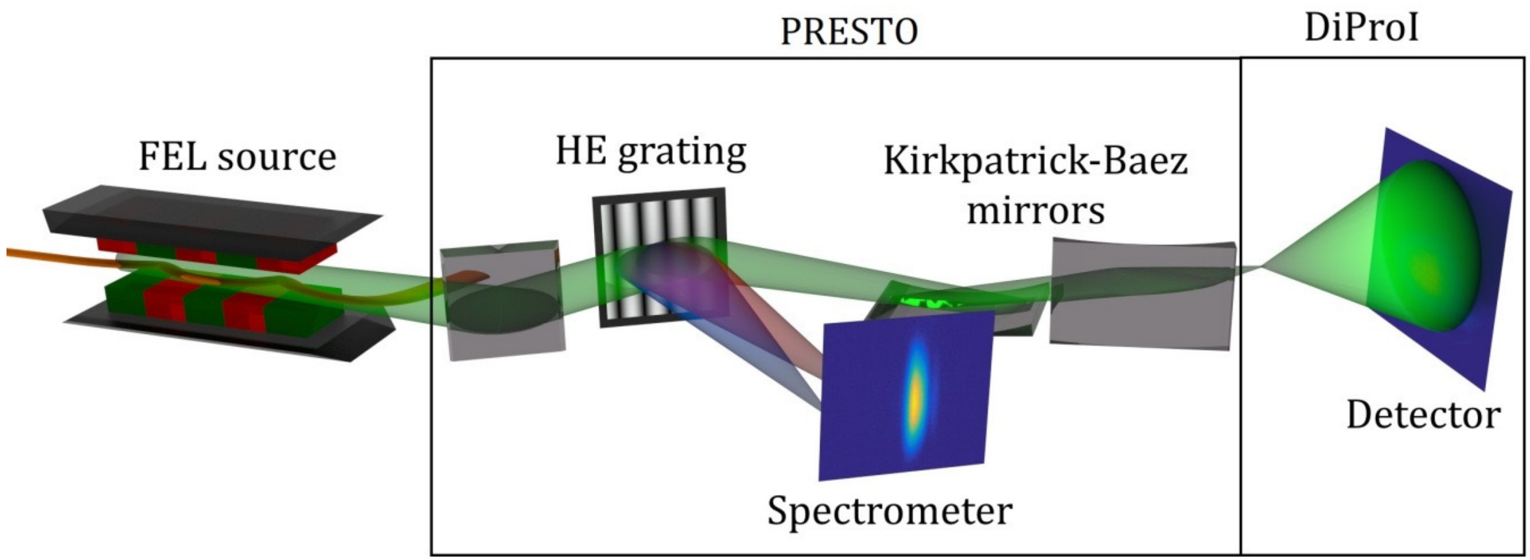
Seeded X-ray free-electron laser generating radiation with laser statistical properties

Oleg Yu. Gorobtsov[1,9], Giuseppe Mercurio[2,10], Flavio Capotondi[3], Petr Skopintsev[1,11], Sergey Lazarev[1,4], Ivan A. Zaluzhnyy[1,5,12], Miltcho B. Danailov[3], Martina Dell'Angela[6], Michele Manfredda[3], Emanuele Pedersoli[3], Luca Giannessi[3,7], Maya Kiskinova[3], Kevin C. Prince[3,8], Wilfried Wurth[1,2] & Ivan A. Vartanyants[1,5]

DESY

Collaboration with W. Wurth group and FERMI

HBT experiment at FERMI

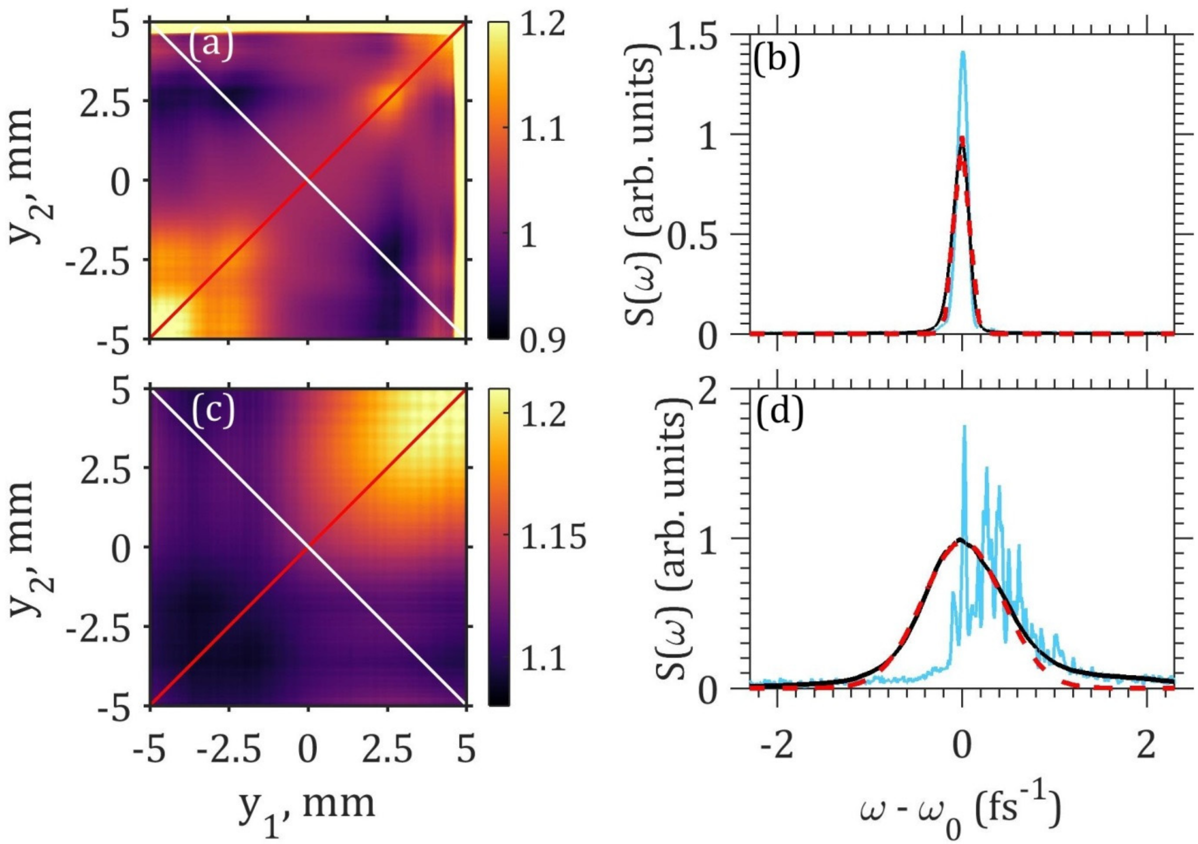


Layout of experiment at the seeded FEL FERMI

HBT experiment at FERMI

Seeded

SASE



$g^{(2)}-1 = 0.03$

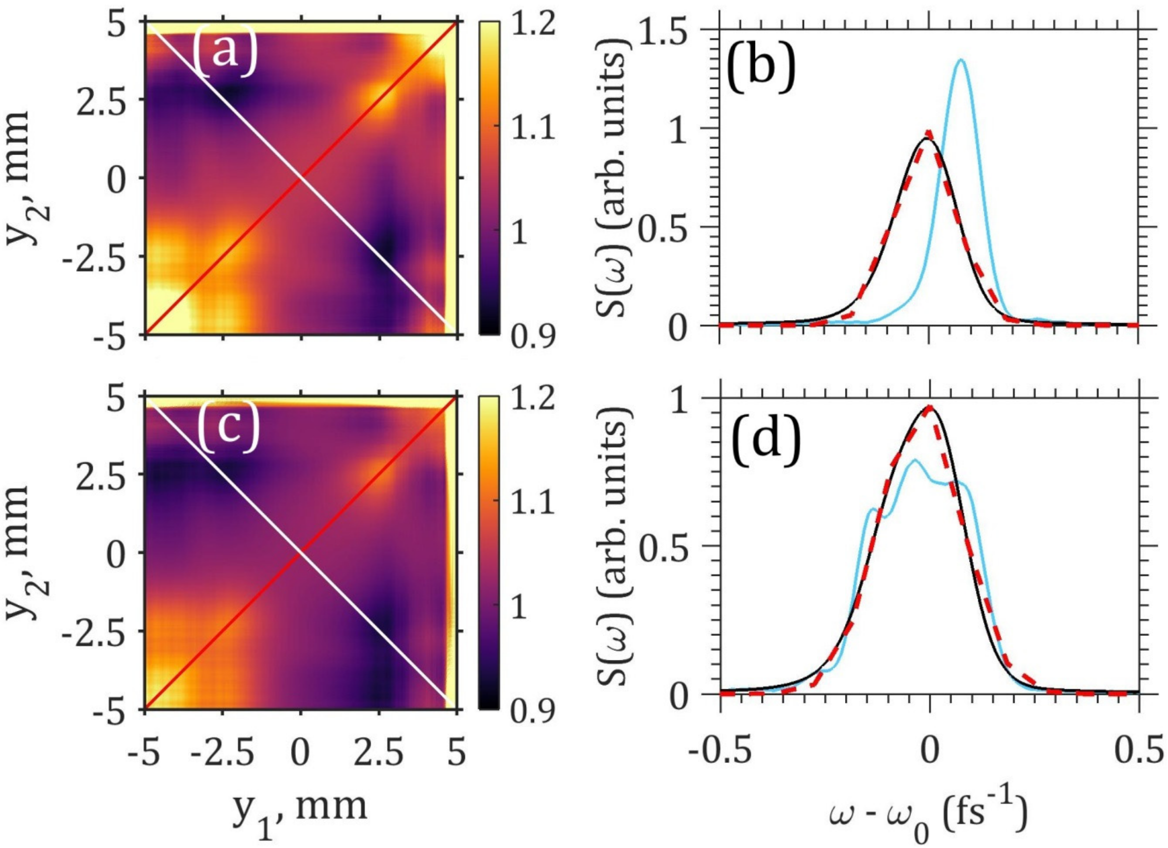
$g^{(2)}-1 = 0.1$

Seeded and SASE mode correlation functions and spectra

HBT experiment at FERMI

Single pulse

Multiple pulses



$g^{(2)}-1 = 0.02$

$g^{(2)}-1 = 0.07$

Seeded mode single and multiple pulses analysis

Summary

Seeded FEL source FERMI statistically behaves as a real laser-like source according to Glauber's definition

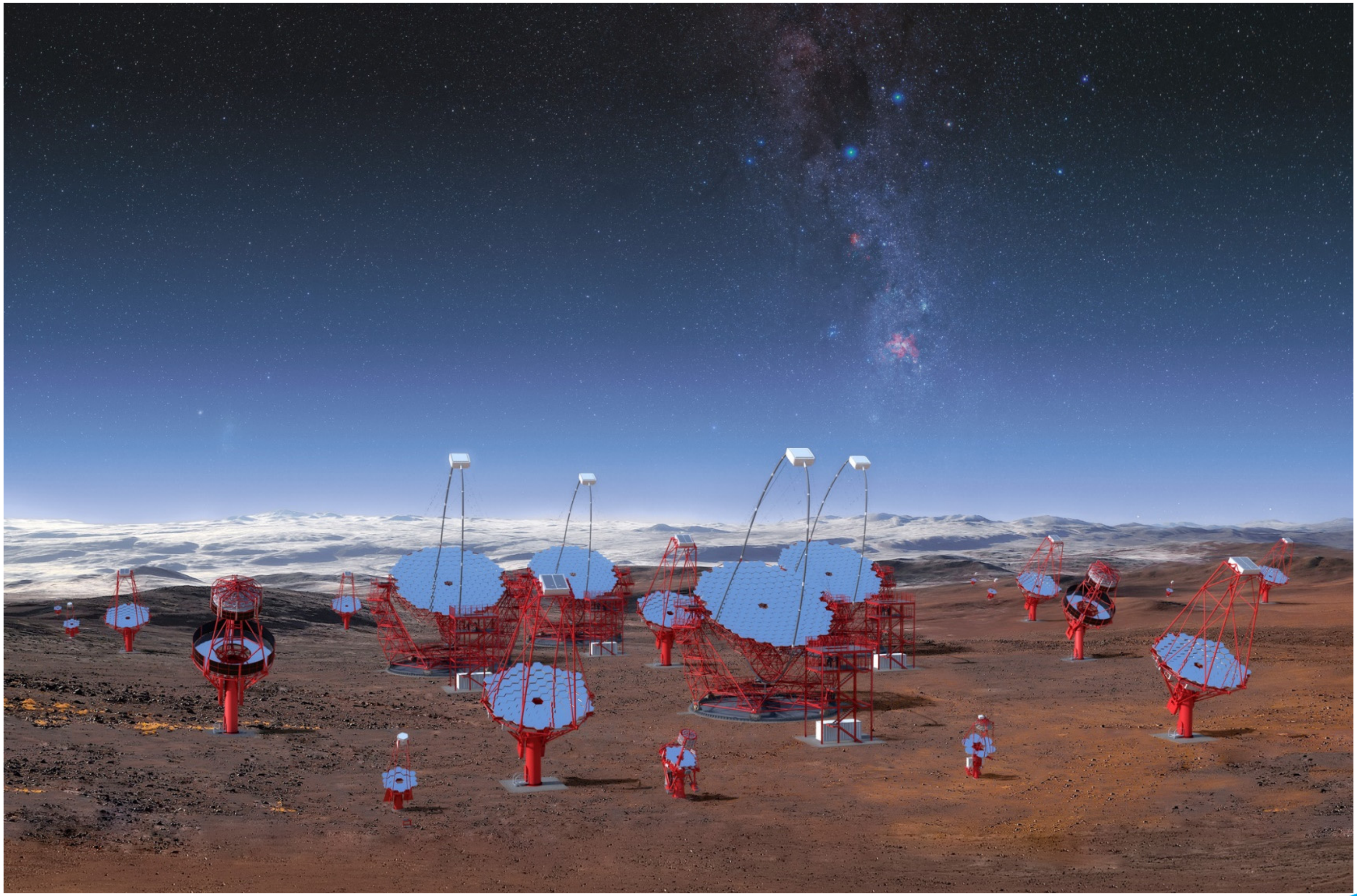
Still open question!

What is the statistical behavior of self-seeded XFEL pulses?

We hope to clarify this question at European XFEL!

Future of HBT interferometry

Cherenkov Telescope Array



CTA Telescopes in Southern Hemisphere

Cherenkov Telescope Array

nature COMMUNICATIONS

ARTICLE

Received 30 Oct 2014 | Accepted 4 Mar 2015 | Published 16 Apr 2015

DOI: 10.1038/ncomms7852

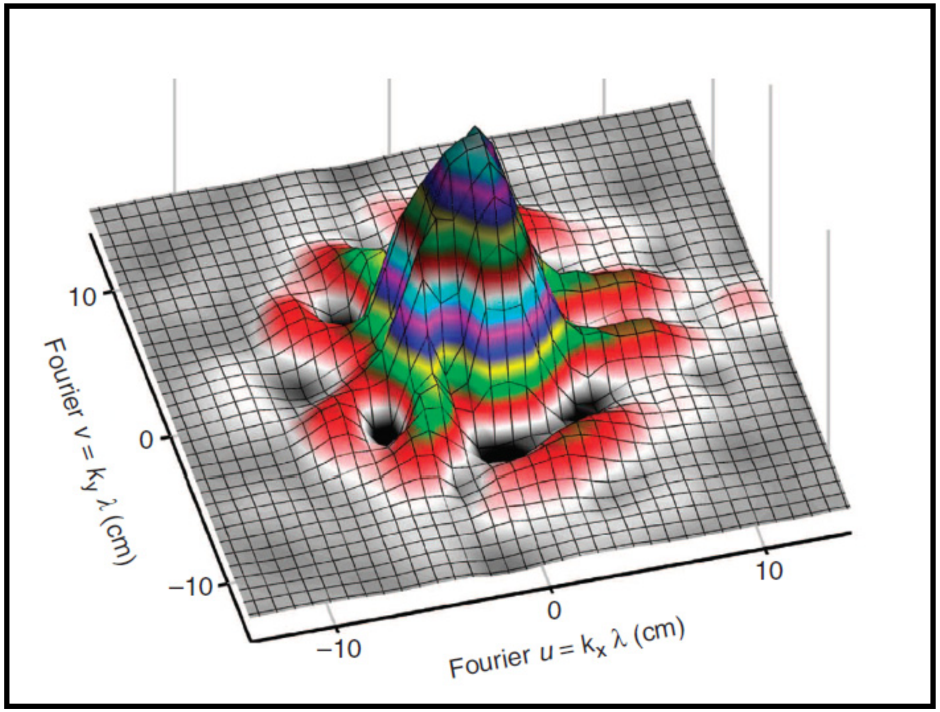
OPEN

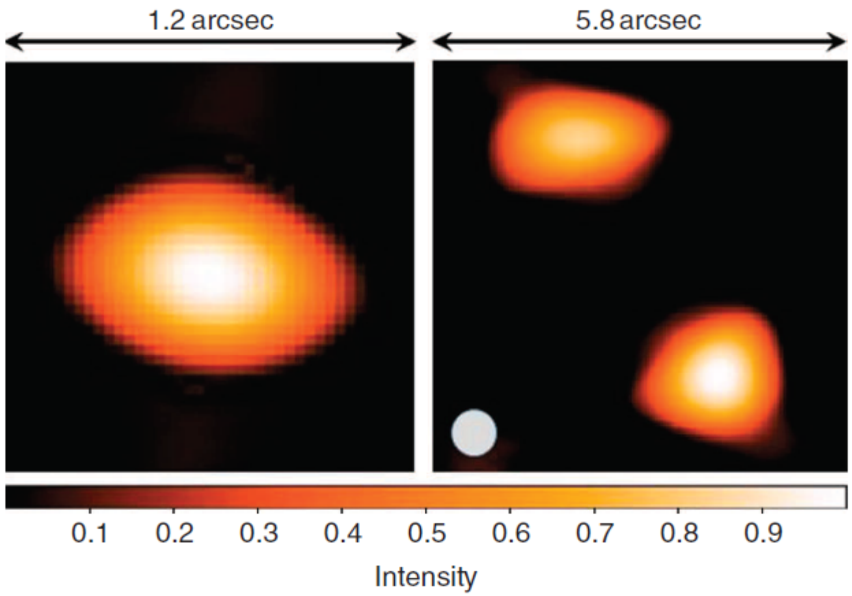
Optical aperture synthesis with electronically connected telescopes

Dainis Dravins[1], Tiphaine Lagadec[1,†] & Paul D. Nuñez[2,3,†]

DESY

Cherenkov Telescope Array





Second-order optical coherence surface measurements

Optical images of the "stars" reconstructed from intensity interferometry

Laboratory experiments

D. Dravins *et al.*, *Nature Comm.* (2015)

Coherent X-ray Scattering and Imaging Group at DESY

Present members:

- S. Lazarev
- Y-Y. Kim
- D. Lapkin
- D. Assalauova
- N. Mukharamova
- R. Khubbutdinov
- L. Gelisio

Former members:

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- A. Mancuso (now@XFEL)
- O. Yefanov (now@CFEL)
- R. Dronyak
- J. Gulden (now@FH-Stralsund)
- U. Lorenz (now@Uni. Potsdam)
- A. Singer (now@Cornell Uni.)
- R. Kurta (now@XFEL)
- I. Besedin (now@MISR)
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- D. Dzhigaev (now@PETRA III)
- O. Gorobtsov (now@Cornell Uni.)
- I. Zaluzhnyy (now@UCSD)
- M. Rose

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Former members of the group:

- A. Singer
- U. Lorenz
- O. Gorobtsov

Group of W. Wurth:

- G. Mercurio
- F. Sorgenfrei

Present members of the group:

- Young Yong Kim
- L. Gelicio

FERMI:

- K. Prince
- L. Gianessi
- M. Kiskinova
- F. Capotondi

FLASH, LCLS, FERMI teams

We are looking for motivated PostDocs to join our group!

Thank you for your attention!