FEL 2012 NARA
34th International Free Electron Laser Conference
26-31 August 2012
Nara Prefectural New Public Hall, Nara, Japan

Single-shot reconstruction of beam microbunching by phase-retrieval of coherent optical transition radiation images.

A. Marinelli, M. Dunning, S. Weathersby,
E. Hemsing, D. Xiang, G. Andonian, F. O'Shea,
J. Miao, C. Hast and J. B. Rosenzweig

August 29, 2012

The University of California · UCLA · Let There Be Light
SLAC National Accelerator Laboratory

Outline of the Talk

- Introduction: measuring the transverse dependence of beam microbunching
- Oversampling method for phase-retrieval
- Application to microbunching measurements
- Experimental demonstration
- Possible improvements
- Conclusions

Reconstruction of Microbunched Beams

Microbunching is often described as a one-dimensional entity:

$$b(k) = \frac{1}{N}\sum e^{-ikz_n} = \frac{1}{N}\int \rho(x,y,z)e^{-ikz}dxdydz$$

By integrating over x-y we lose track of any transverse dependence of the density modulation

In many applications it is necessary to keep record of the transverse distribution:

$$b(x,y,k_z) = \frac{1}{N}\int \rho(x,y,z)e^{-ik_z z}dz$$

Microbunching in X-space

$$B(k_x,k_y,k_z) = \frac{1}{N}\int \rho(x,y,z)e^{-ik_x x-ik_y y-ik_z z}dxdydz$$

Microbunching in K-space

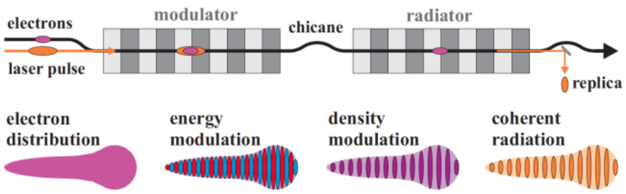
Transverse Optical Replica

Microbunching induced by laser-beam interaction in an undulator.

If $R_{laser} >> R_{beam}$ and $l_{laser} >> l_{beam}$

The microbunching distribution is a replica of the beam's transverse charge distribution.

Diagnostics of compressed beams! (induced microbunching is much larger than MBI, beam image not affected by collective effects…)



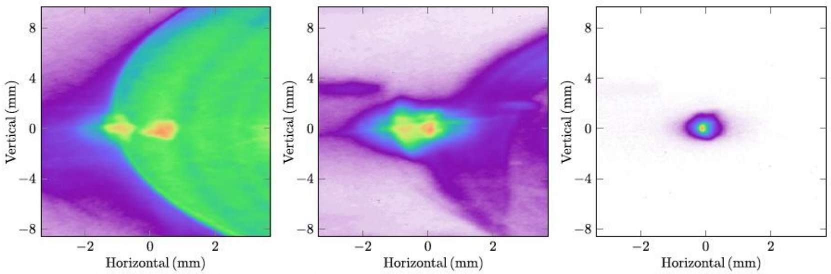
Method for the determination of the three-dimensional structure of ultrashort relativistic electron bunches

Gianluca Geloni, Petr Ilinski, Evgeni Saldin, Evgeni Schneidmiller, Mikhail Yurkov

arXiv:0905.1619v1 [physics.optics]

Transverse Optical Replica

Alternative approach to COTR mitigation for beam imaging



(a) OTR screen, no time delay. (b) LuAG screen, no time delay. (c) LuAG screen, time delay.

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 062801 (2012)

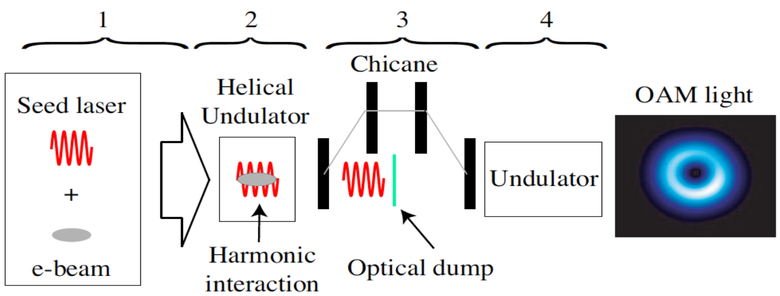
Electron beam profile imaging in the presence of coherent optical radiation effects

Christopher Behrens,[1,*] Christopher Gerth,[1] Gero Kube,[1] Bernhard Schmidt,[1] Stephan Wesch,[1] and Minjie Yan[1,2]

Time resolved measurements by short-pulse seeding

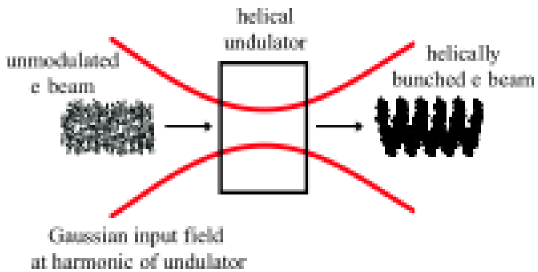
(A. Lumpkin, private communication)

Three-Dimensional Microbunching: Orbital Angular Momentum Modes



Helical charge perturbation from harmonic interaction in a helical undulator:

$$\rho \propto r e^{-\frac{r^2}{2w^2} - i\phi}$$

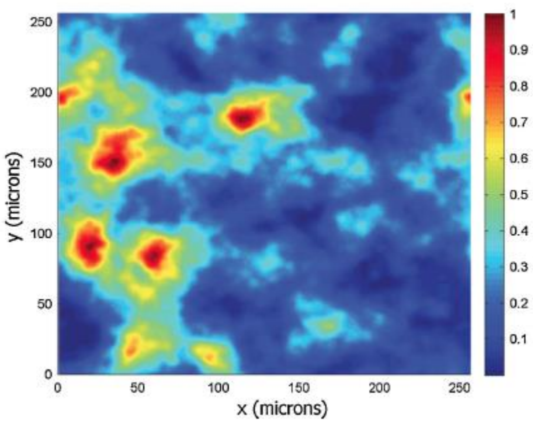


Phys. Rev. Lett., 106, 164803 (2011)

Generation of Optical Orbital Angular Momentum in a High-Gain Free-electron Laser at the First Harmonic

E. Hemsing, A. Marinelli, J. B. Rosenzweig
Particle Beam Physics Laboratory, Department of Physics and Astronomy
University of California Los Angeles, Los Angeles, CA 90095, USA

Three-Dimensional Microbunching: Longitudinal Space-Charge Instability



Transversely incoherent space-charge fields for short wavelengths

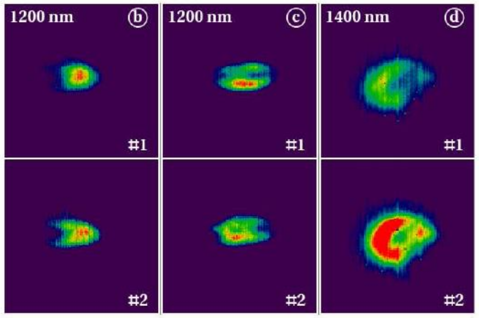
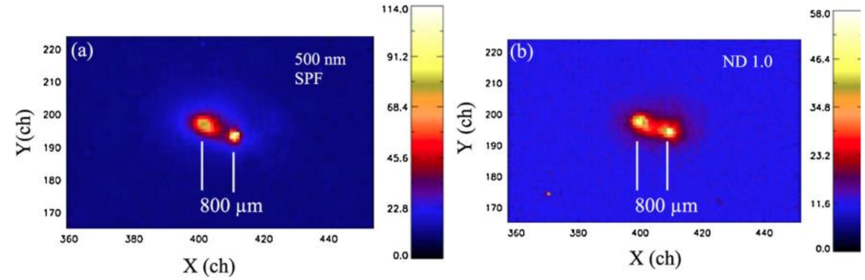


Figure 7: Selection of transverse profiles at different on-crest configurations and various spectral filters. The dimensions of the images are $2 \times 2\,\mathrm{mm}^2$

Schmidt, et al., FEL 2009 (WEPC50)



PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12, 040704 (2009)

Coherent optical transition radiation and self-amplified spontaneous emission generated by chicane-compressed electron beams

A. H. Lumpkin
Fermilab, Batavia, Illinois 60510, USA
R. J. Dejus and N. S. Sereno

Transversely inhomogeneous microbunching

September 2008
SLAC-PUB-13392

THREE-DIMENSIONAL ANALYSIS OF LONGITUDINAL SPACE CHARGE MICROBUNCHING STARTING FROM SHOT NOISE*

D. Ratner, A. Chao, Z. Huang†
Stanford Linear Accelerator Center, Stanford, CA 94309, USA

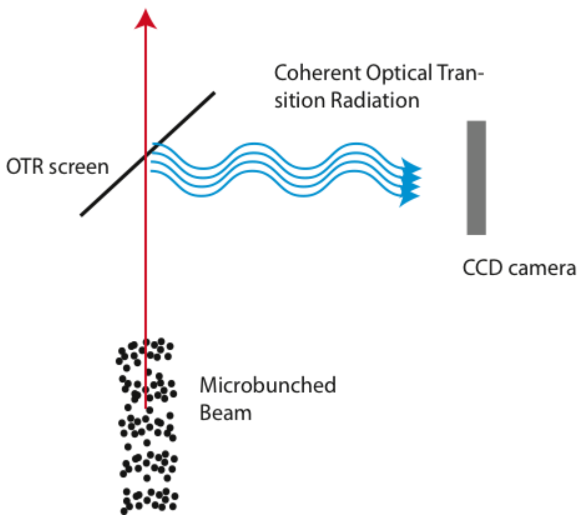
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 13, 110703 (2010)

Microscopic kinetic analysis of space-charge induced optical microbunching in a relativistic electron beam

Agostino Marinelli[1,2] and James B. Rosenzweig[1]
[1]*Particle Beam Physics Laboratory, Department of Physics and Astronomy, University of California Los Angeles, Los Angeles, California 90095, USA*
[2]*Dipartimento SBAI, Università degli Studi di Roma La Sapienza, Via Antonio Scarpa 14, Rome, 00161, Italy*
(Received 18 May 2010; published 29 November 2010)

COTR Diagnostic for Three-Dimensional Microbunching

COTR is a well established diagnostic for microbunched beams



We are interested in reconstructing the transverse dependence of b:

$$b(x,y,k) = \int e^{-ik_z z}\rho(x,y,z)dz$$

Coherent transition radiation diagnosis of electron beam microbunching

J. Rosenzweig *, G. Travish, A. Tremaine
Department of Physics, University of California, Los Angeles, 405 Hilgard Avenue, Los Angeles, CA 90024, USA

Received 10 April 1995

VOLUME 86, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

First Observation of *z*-Dependent Electron-Beam Microbunching Using Coherent Transition Radiation

A. H. Lumpkin, R. Dejus, W. J. Berg, M. Borland, Y. C. Chae, E. Moog, N. S. Sereno, and B. X. Yang
Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439

(Received 21 July 2000)

Ingredients:
-Narrow bandwidth signal is needed (seeding or bandpass filtering)
-Near or far field imaging?
Near field is hard to interpret:

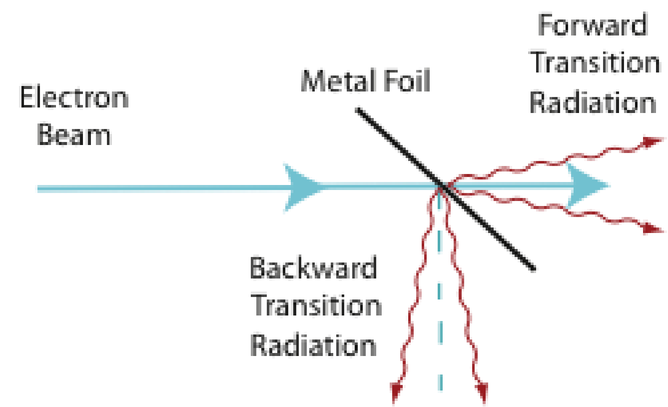
1) Near field COTR is a convolution between b and the OTR Green's function.
2) Intensity pattern mixes two polarizations!

COTR Diagnostic for Three-Dimensional Microbunching: Far Field Imaging

$$\frac{dP}{d\omega d\Omega}|_{1-part} = \frac{e^2}{4\pi^2 c}\frac{sin^2(\theta)}{(1-\beta^2 cos(\theta))^2}$$

$$\frac{dP}{d\omega d\Omega}|_{coh} = \frac{dP}{d\omega d\Omega}|_{1-part}|B(k_x,k_y,k_z)|^2$$

$$B(k_x,k_y,k_z) = \frac{1}{N}\sum_n e^{-ik_x x_n - ik_y y_n - ik_z z_n}$$

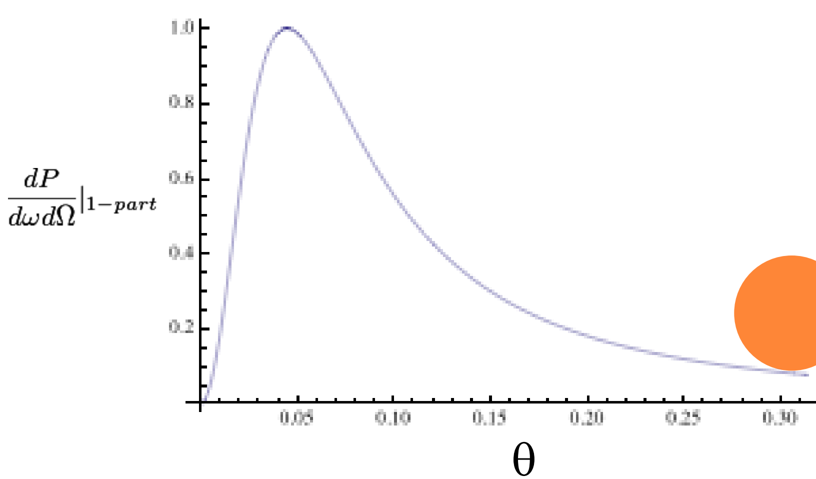


From a single-frequency far-field measurement we can recover $|B^2(k_x,k_y,k)|$

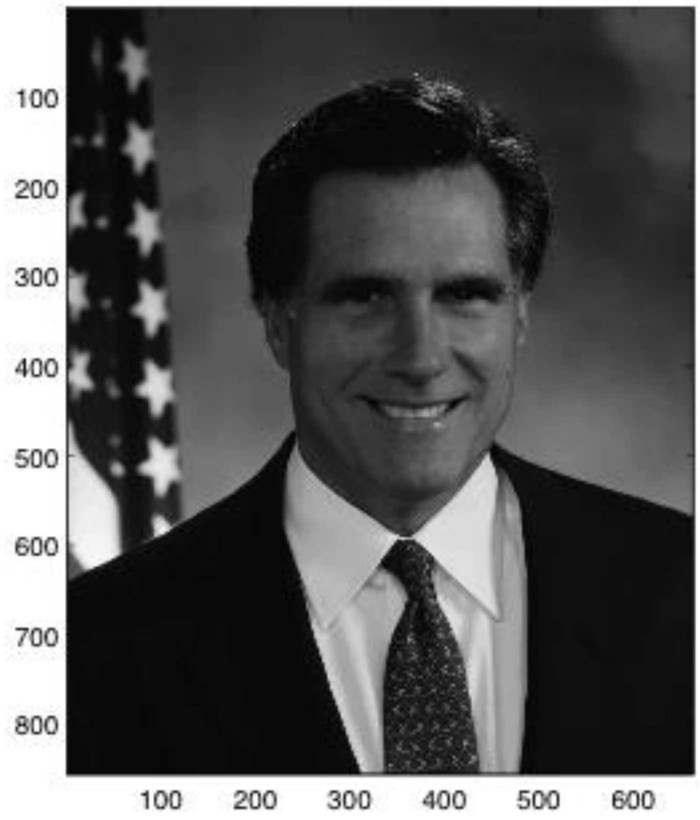
We are interested in

$$b(x,y,k) = \int e^{-ik_x x - ik_y y} B(k_x,k_y,k)\frac{dk_x dk_y}{(2\pi)^2}$$

Phase information on B is needed to recover the signal in x-y space!!



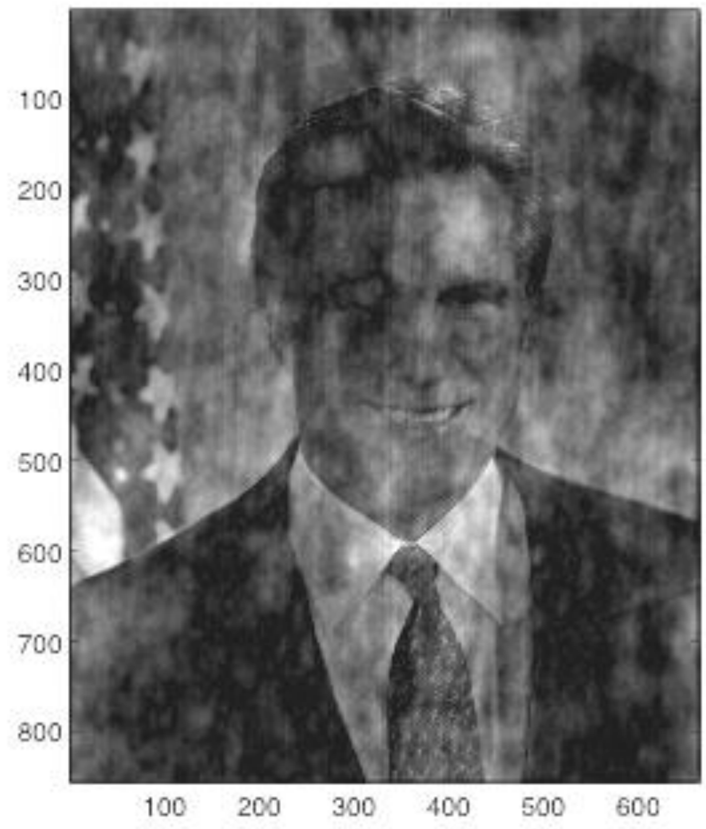
How Important is Knowledge of

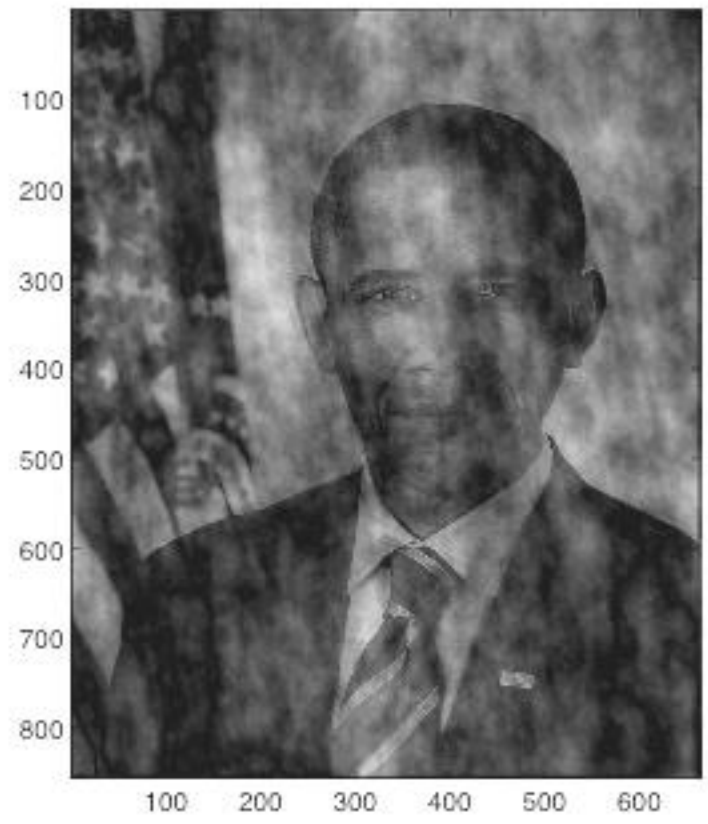


$$IFFT(|Obama_K|e^{iArg(Obama_K)}) = Obama(X,Y)$$

$$IFFT(|Romney_K|e^{iArg(McRomney_K)}) = Romney(X,Y)$$

How Important is Knowledge of

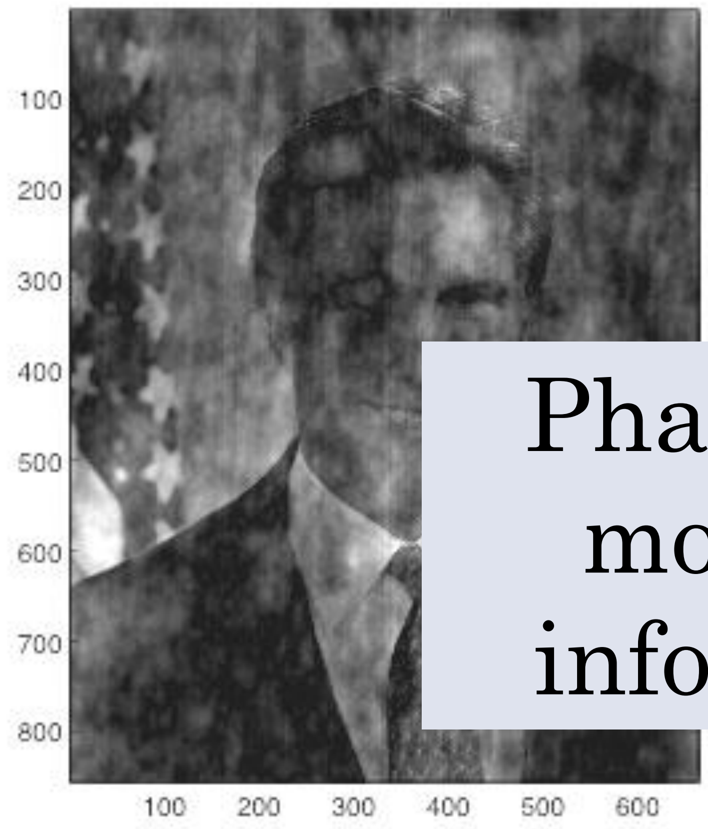


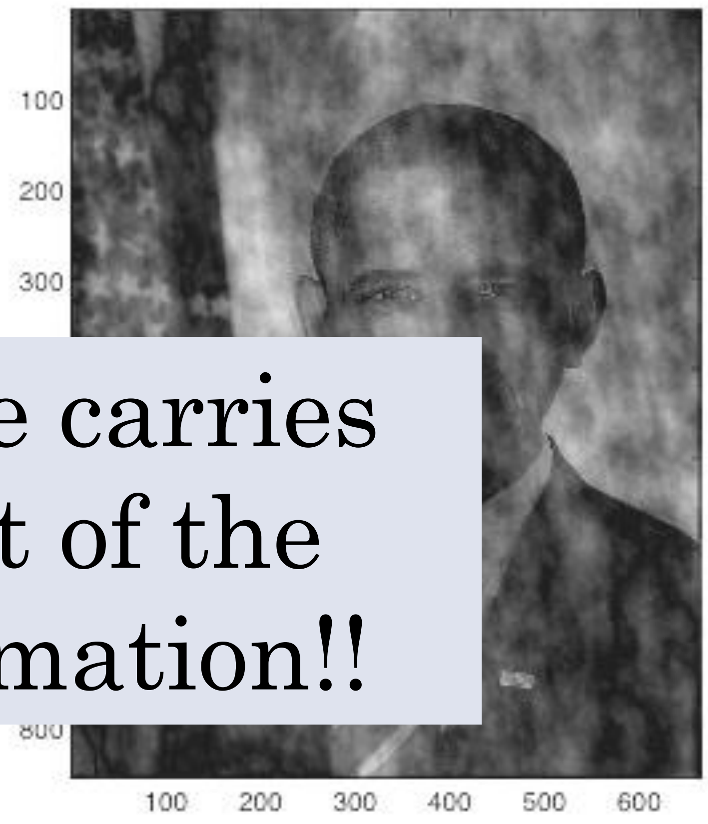


$$IFFT\left(\left|Obama_K\right| e^{iArg(Romney_K)}\right) \approx Romney(X,Y)$$

$$IFFT\left(\left|Romney_K\right| e^{iArg(Obama_K)}\right) \approx Obama(X,Y)$$

How Important is Knowledge of





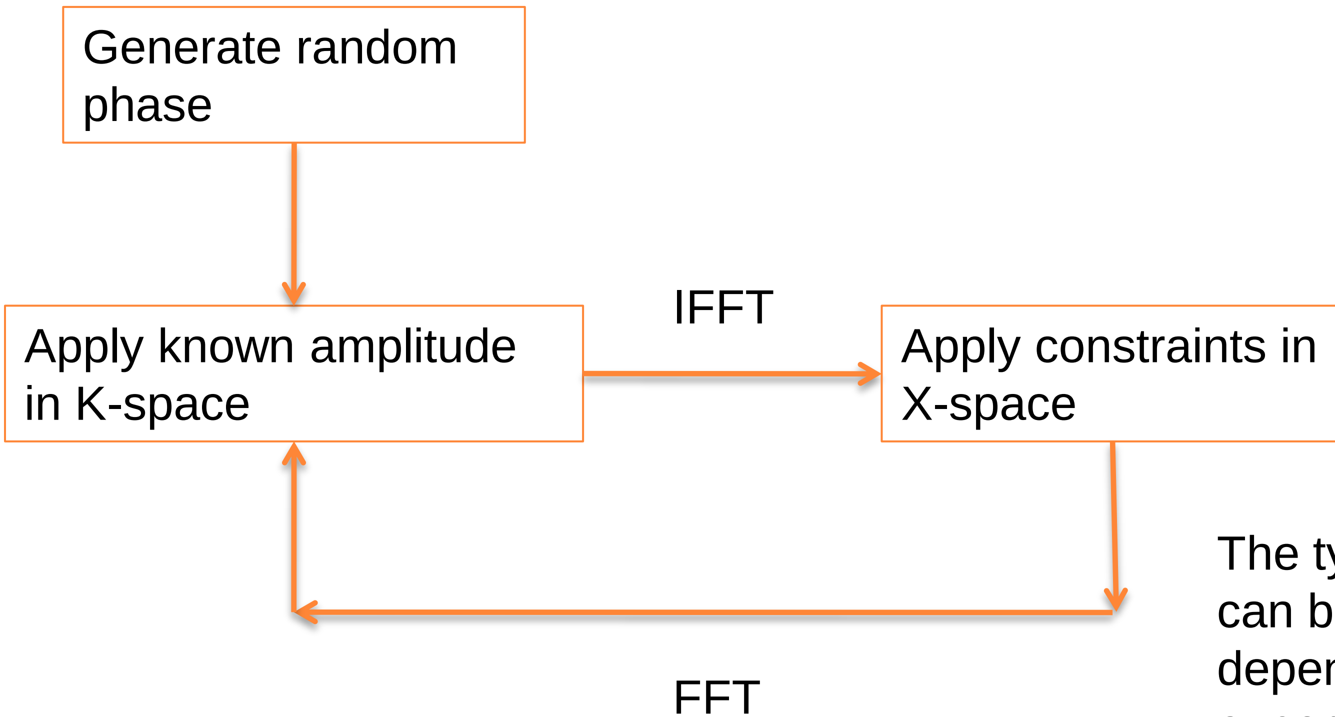
Phase carries most of the information!!

$$IFFT\left(\left|Obama_K\right| e^{iArg(Romney_K)}\right) \approx Romney(X,Y)$$

$$IFFT\left(\left|Romney_K\right| e^{iArg(Obama_K)}\right) \approx Obama(X,Y)$$

Phase Retrieval Algorithms

Phase information can be recovered by means of iterative retrieval algorithms.



The type of constraint that can be applied in X-space depends on the experimental implementation of the method

Constraints in X-Y Space

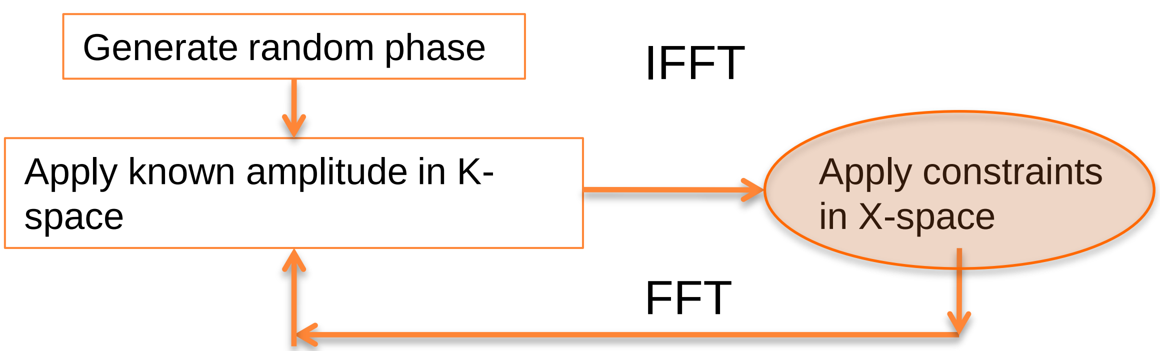
-Support Constraint

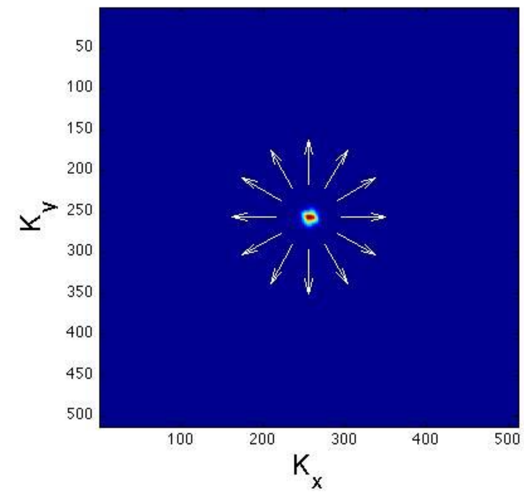
The signal is equal to 0 outside of a finite domain in X. At each iteration this condition is enforced by the algorithm.

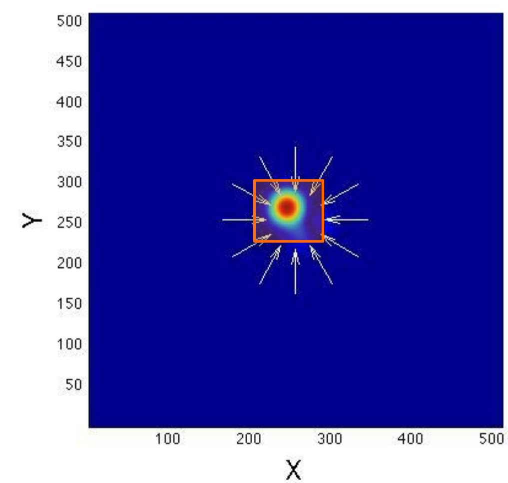
Oversampling condition: $\delta k < \pi / L_{sample}$

Finer sampling in K space gives a stronger constraint in X-space.

-Positivity Constraint
Enforce that signal is real and positive in the domain





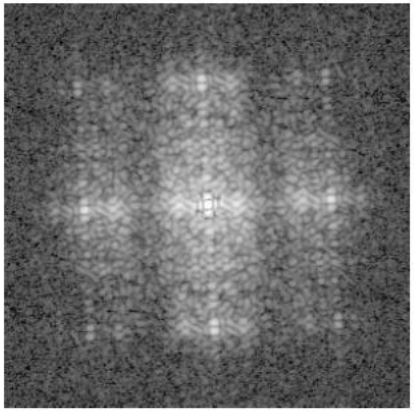


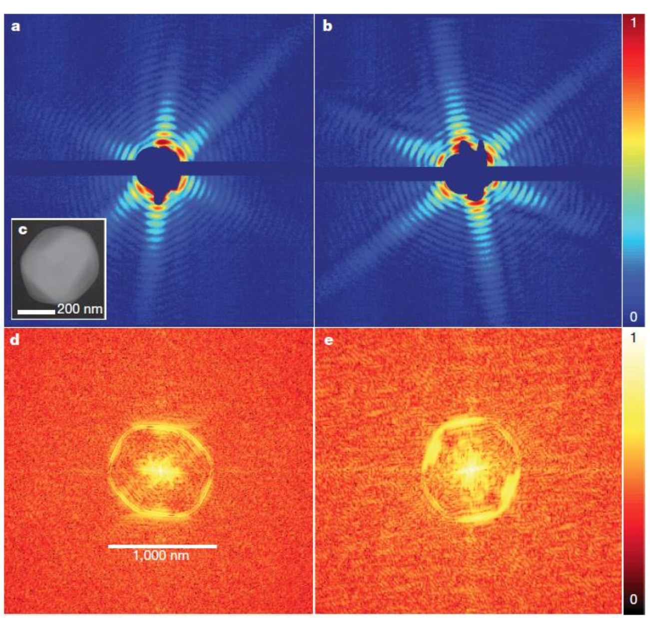
J. R. Fienup, "Phase retrieval algorithms: a comparison," Appl. Opt. 21, 2758-2769 (1982) .
http://www.opticsinfobase.org/abstract.cfm?URI=ao-21-15-2758

Phase Retrieval Algorithms in X-Ray Diffraction Imaging

Frequently used in x-ray microscopy for reconstruction of non-crystalline samples

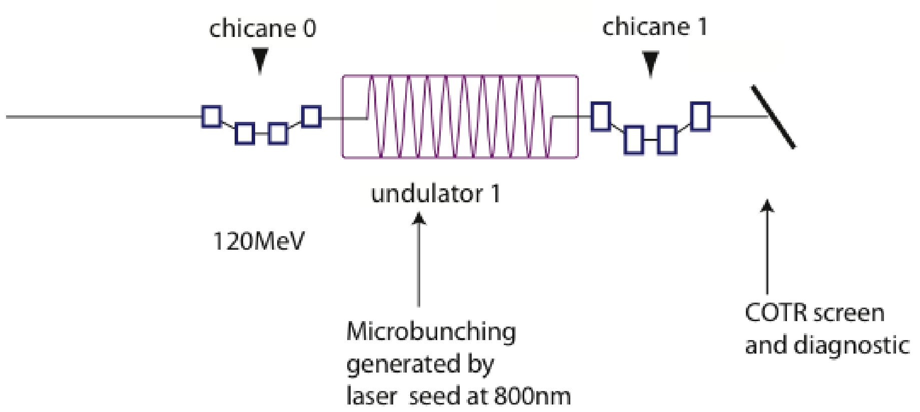
J. Miao et al. Nature **400, 342-344 (22 July 1999)**

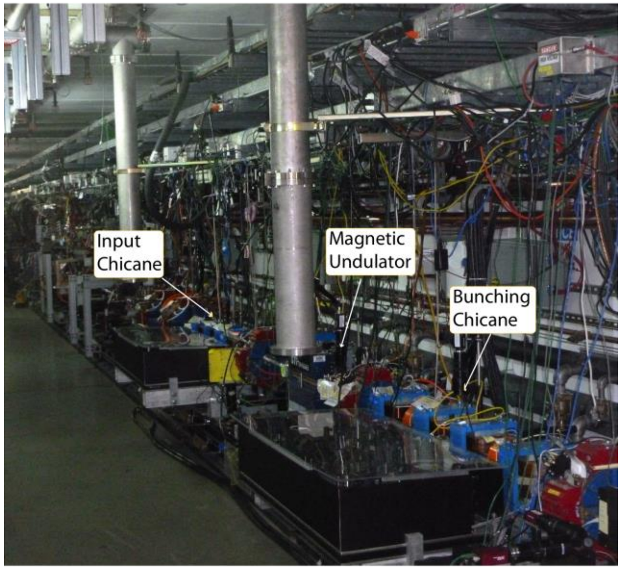




M. Marvin Seibert et al.
Nature ***470, 78–81 (03 February 2011)***
doi:10.1038/nature09748

Experimental Demonstration at NLCTA

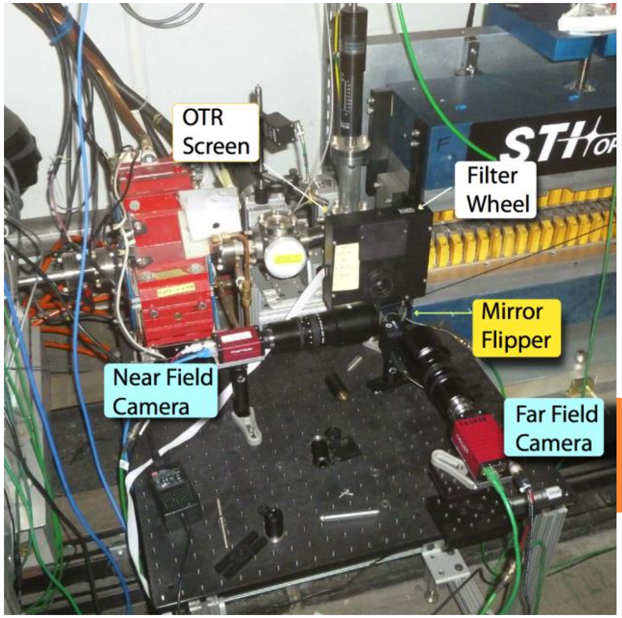




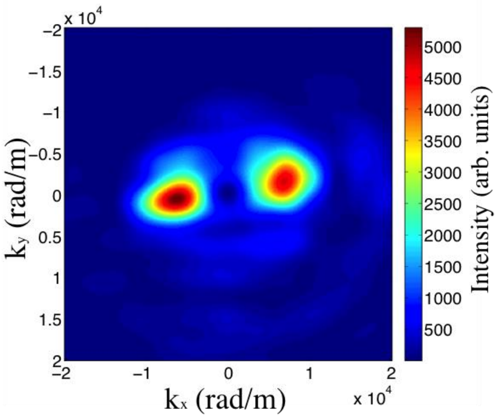
-COTR experiment performed with the ECHO beamline setup.

-Proof of principle: transverse optical replica of uncompressed beam. Reconstruction benchmarked with incoherent OTR!

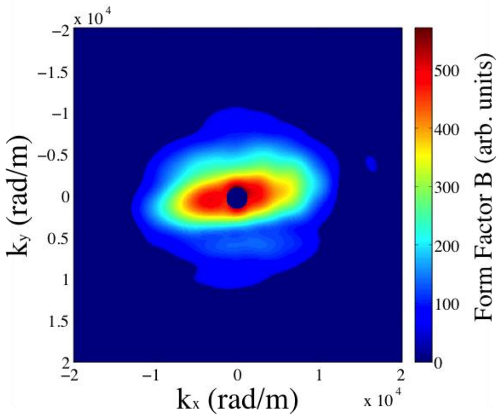
-Seeded microbunching: positivity constraint in x-y



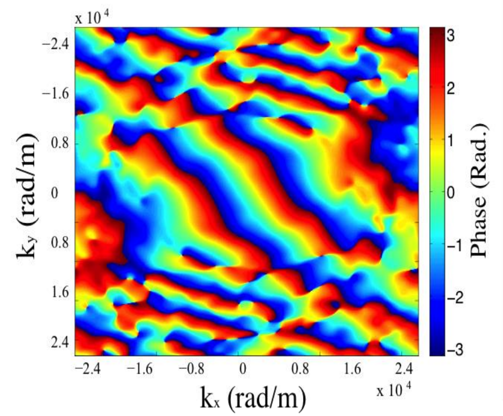
Experiment at 800nm



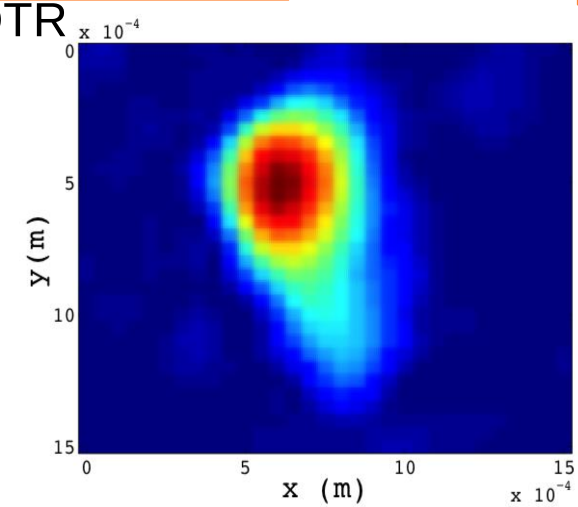
Far Field COTR



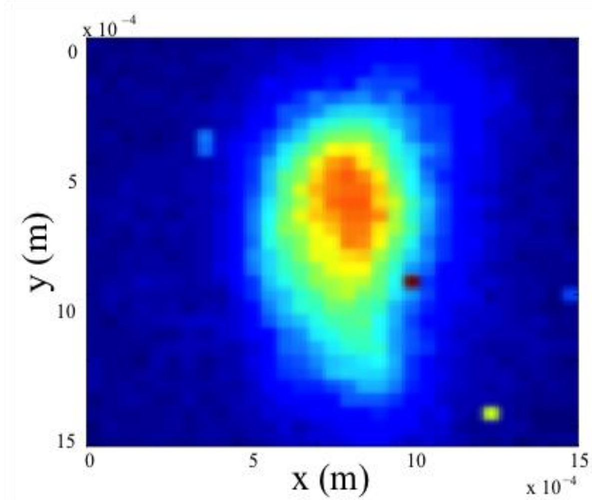
$|B (k_x,k_y)|$



Phase{$B (k_x,k_y)$ }



Reconstructed Microbunching

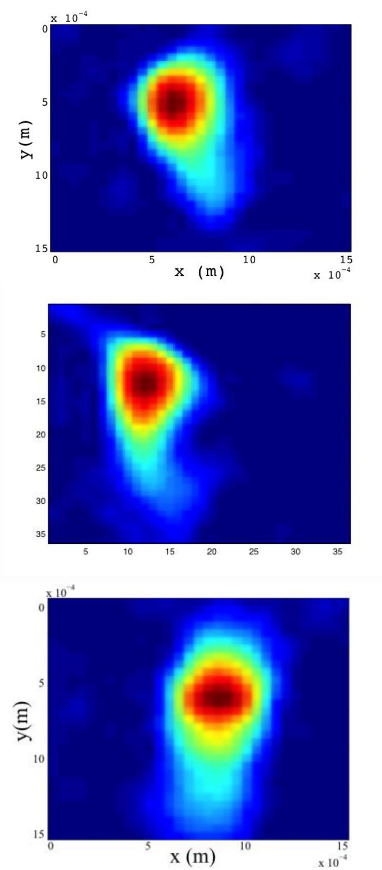


Near Field Incoherent OTR

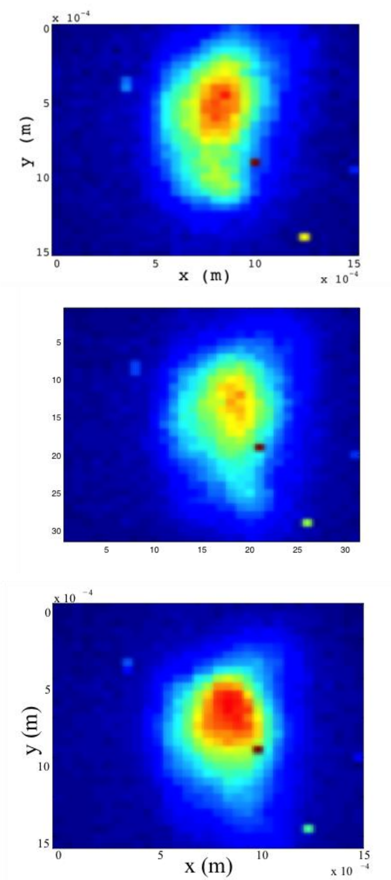
EXPERIMENT AT 800NM

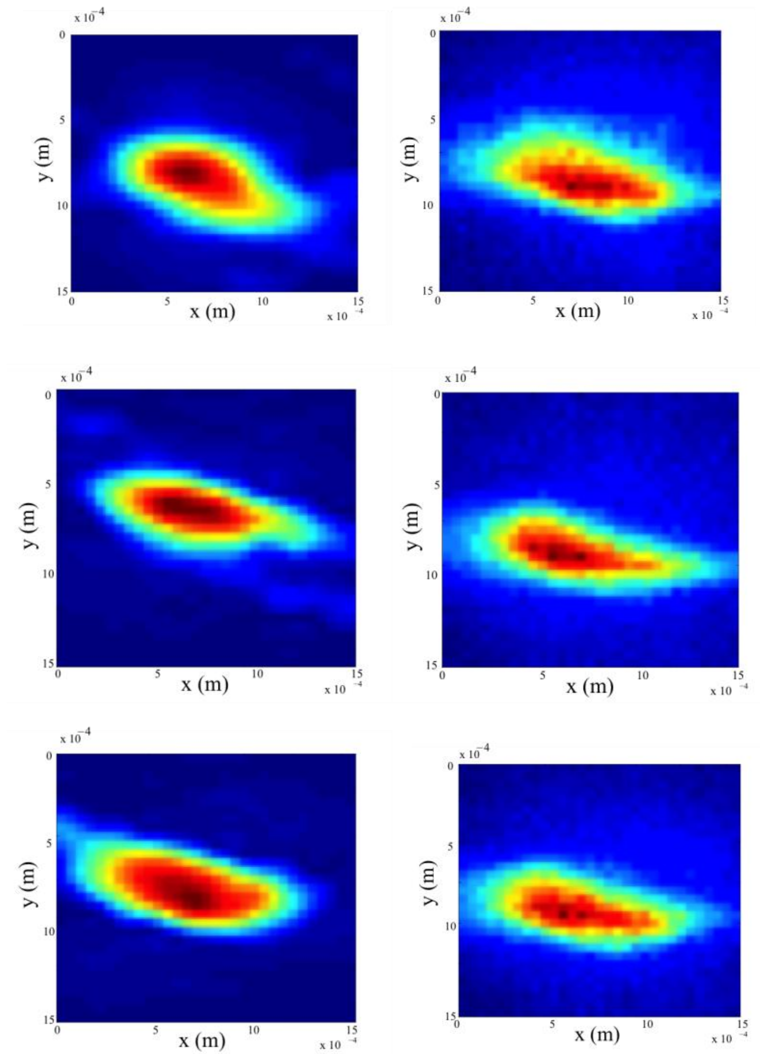
Beam fluctuates from shot-to-shot.

Reconstruction

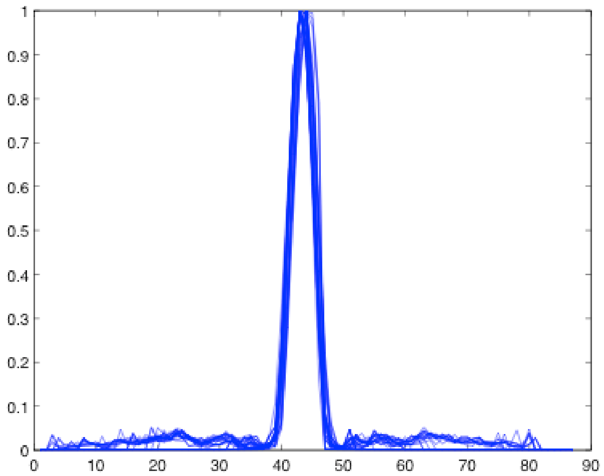


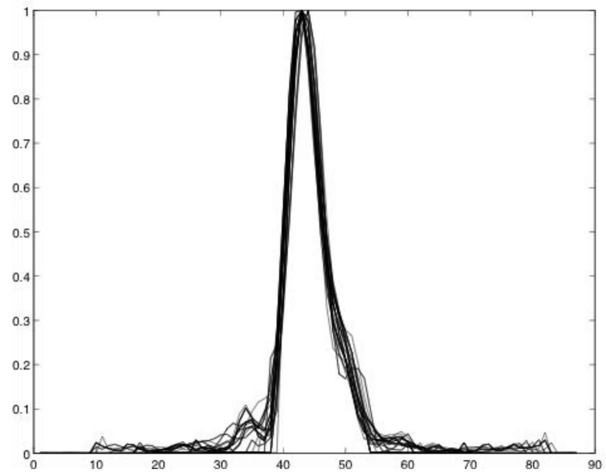
Near Field Incoherent OTR



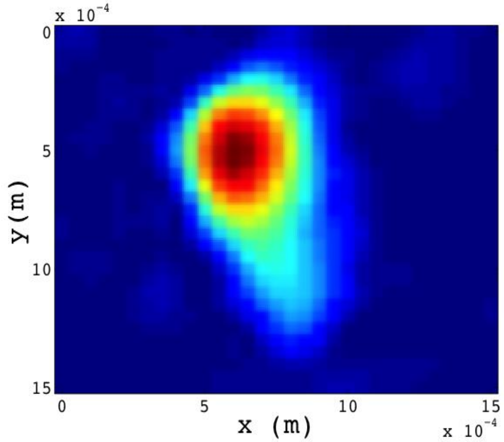


Consistency of the Reconstruction



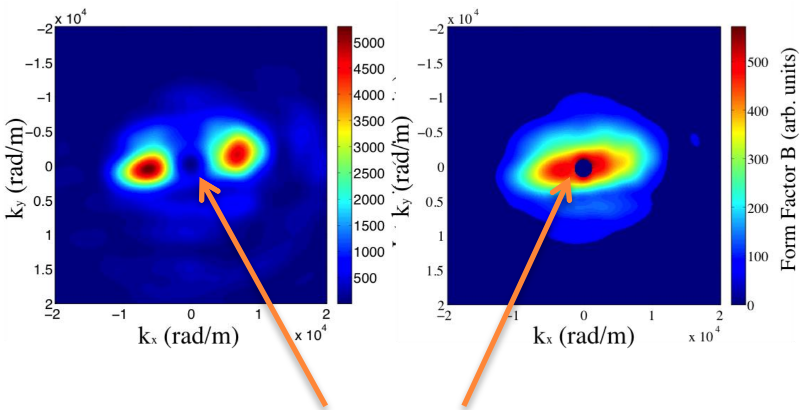


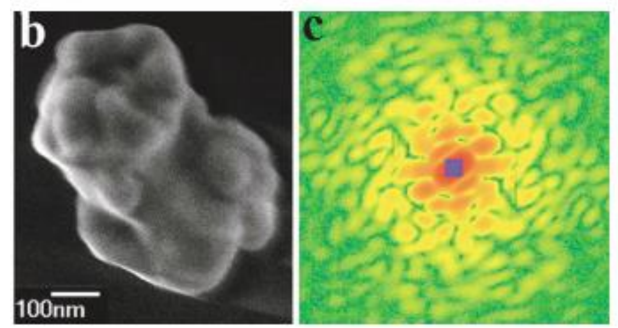
X-Y projections for 50 independent reconstructions



Theory predicts unique solution for the reconstruction:
profile is consistent for independent reconstructions

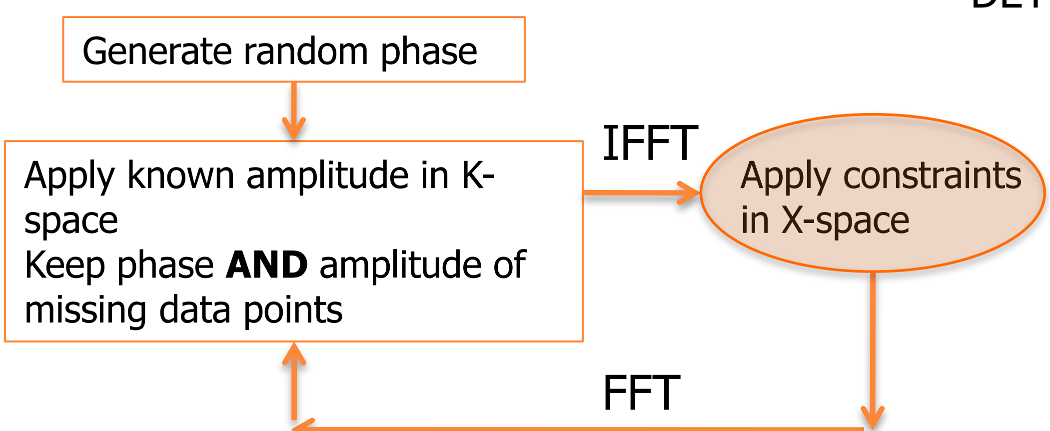
The Missing Center Problem…





COTR has a null on axis:
MISSING DATA POINTS NEAR AXIS FROM FAR-FIELD COTR

In X-ray diffraction imaging, same problem but for the opposite reason: DIRECT BEAM BLINDS THE DETECTOR.



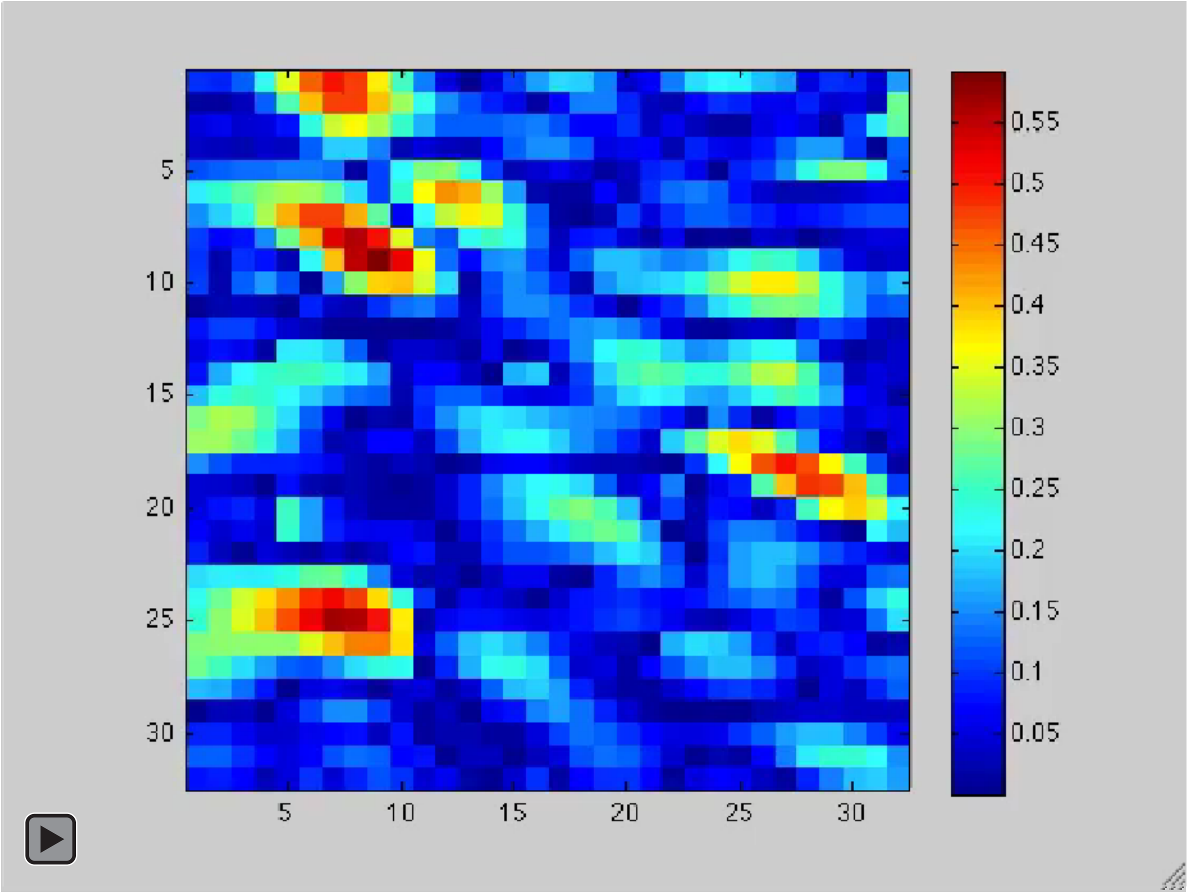
Rigorous way of dealing with possible inconsistencies:

Reconstruction of a yeast cell from X-ray diffraction data

Pierre Thibault,[a] Veit Elser,[a*] Chris Jacobsen,[b,c] David Shapiro[b] and David Sayre[b]

Not necessary in this case due to strong oversampling

Iterative Algorithm: Demonstration



Possible Improvements

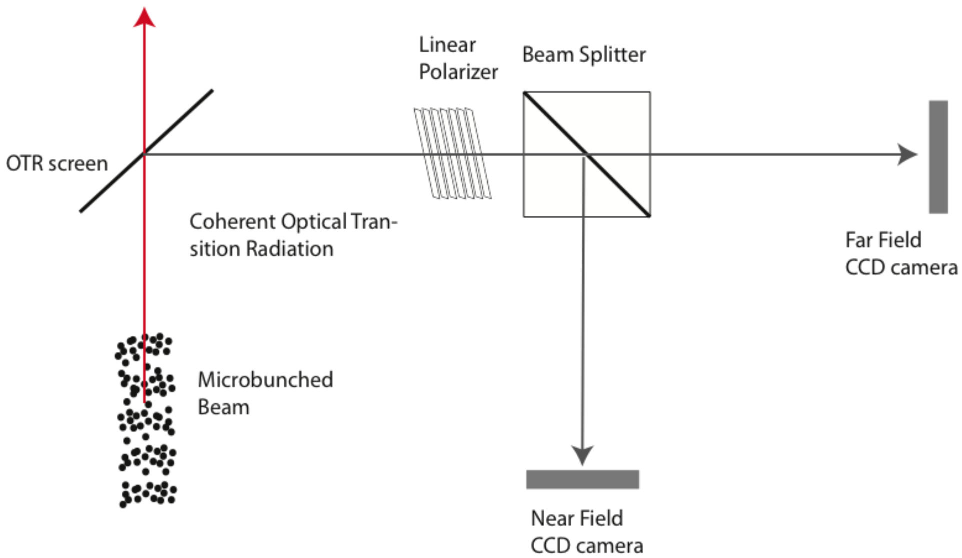
-Use of undulator radiation

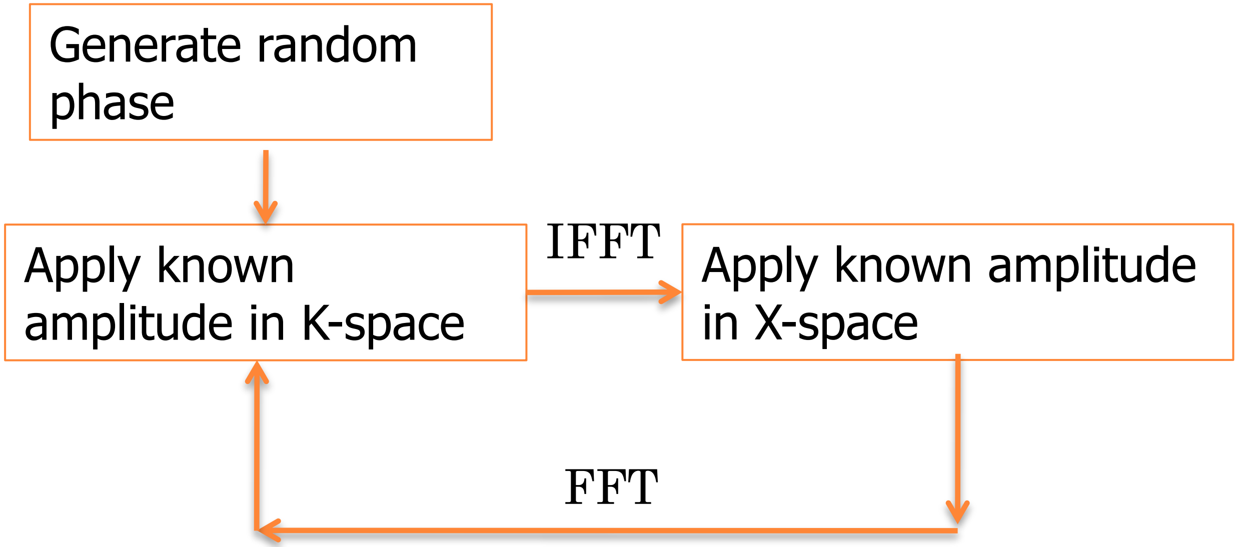
(no null on axis, collect more information on the beam's Fourier transform)

-Simultaneous near/far field COTR imaging for non-positive microbunching (OAM or space-charge)

-Using MBI as the seed.

Double Intensity Measurement





In the double intensity measurement the phase retrieval is performed on ONE polarization of the COTR field

The constraint in X space is the measured amplitude in the near field zone

The microbunching distribution is recovered by deconvolving the final signal with the OTR Green's function.

USING MBI AS THE SEED

$$\left\langle |b(\boldsymbol{k})|^2 \right\rangle_{(\delta z^2)} \approx \frac{4}{3}\left[\frac{I}{I_A\gamma}\frac{R_{56}L}{\sigma^2}\right]^2 \frac{e^{\left[-\sigma'^2 k^2\left(R_2^2+\theta_y^2 R_{34}^2\right)-k^2 R_{56}^2\sigma_p^2\right]}}{\left[\gamma^2 R_q^2+1\right]^2}$$

D. Ratner
Ph.D. Thesis

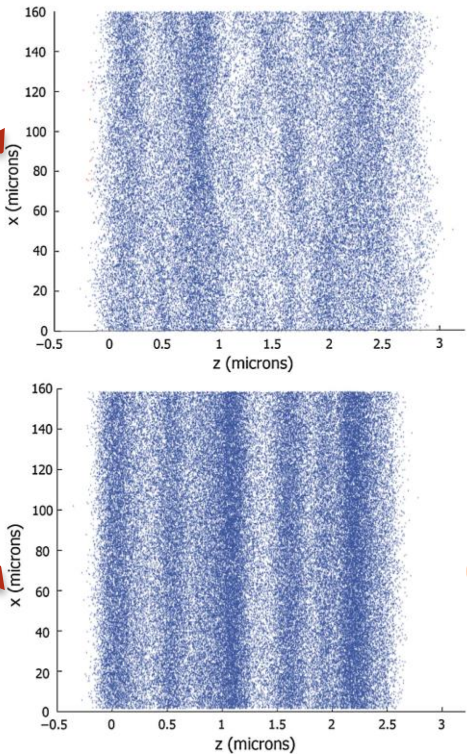
$$R_2 \equiv R_{52} + \theta_x R_{12}$$

Ideally, at ¼ betatron period + n/2 periods, microbunching is a replica of the beam

Optical replica is an expensive device…
Can we use MBI as the seed?

Transverse motion during the LSC interaction and in subsequent transport flattens the microbunching distribution…

Without/with emittance



A. Marinelli
PRSTAB 13, 110703 (2010)
1098-4402

Using MBI as the Seed

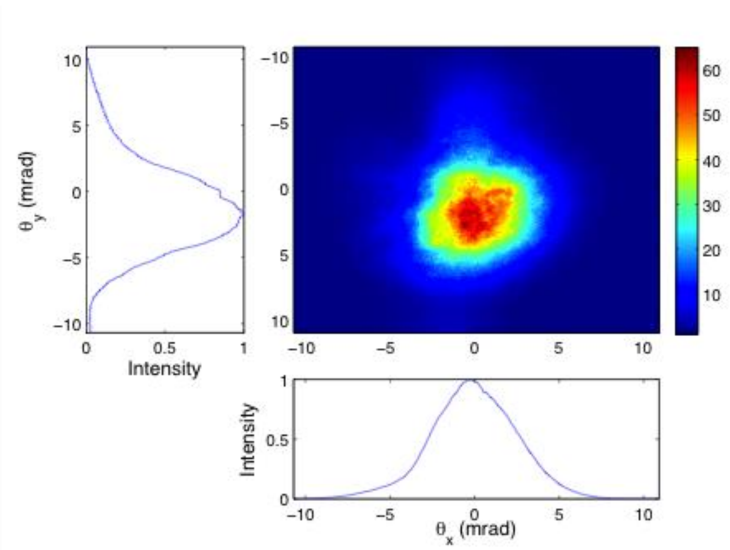
Long wavelength space-charge interaction is transversely coherent

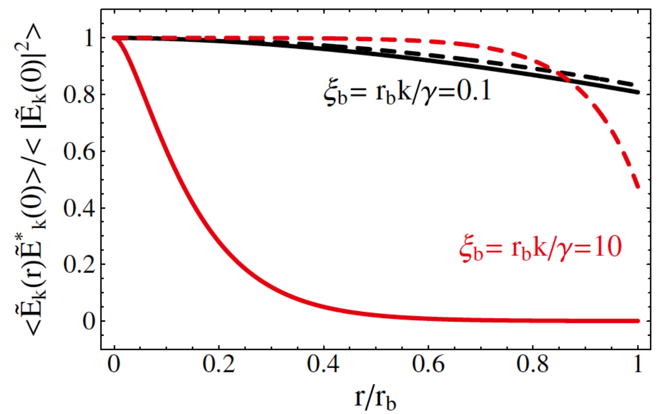
Strong compression can transfer transverse coherence to short wavelengths

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 034401 (2008)

Models of longitudinal space-charge impedance for microbunching instability

Marco Venturini*
Lawrence Berkeley National Laboratory, University of California, Berkeley, California 94720, USA
(Received 20 August 2007; published 25 March 2008)



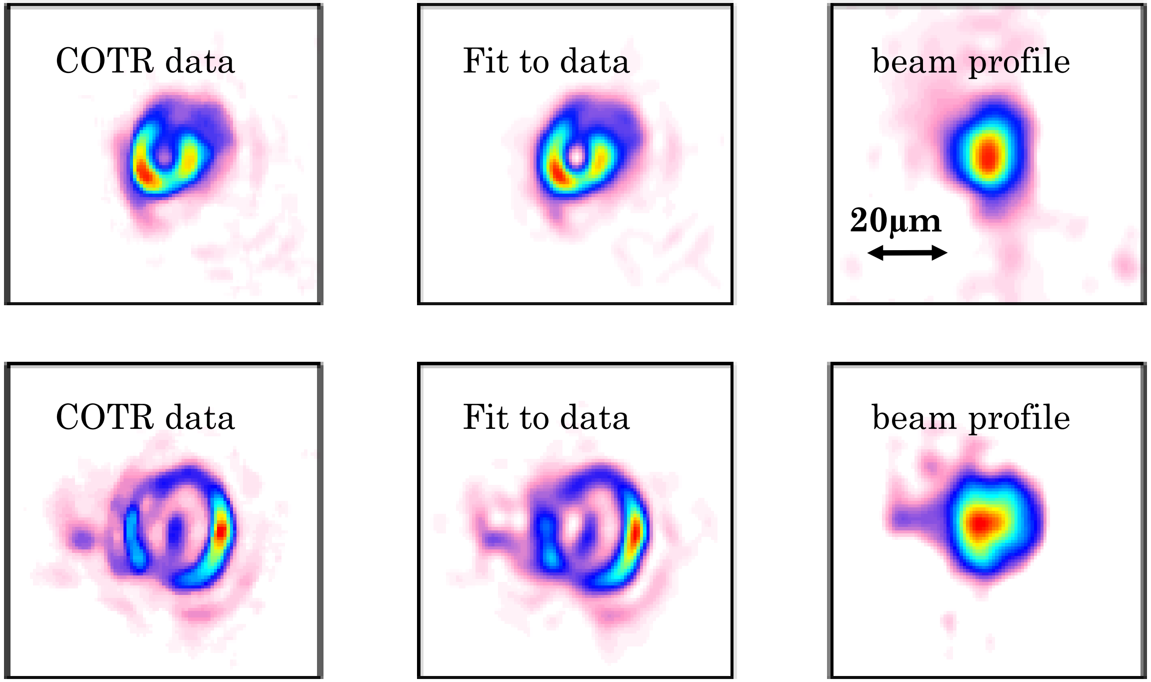


Single mode far-field coherent undulator radiation from LSCA experiment…

Alternative Approach:

N. Bourgeois
AAC 2012

Least square minimization algorithm on near-field image.



Courtesy of N. Bourgeois (Oxford University)

Summary and Conclusions

1) Oversampling phase retrieval techniques can be used for the reconstruction of beam microbunching
2) A microbunching reconstruction experiment, based on phase-retrieval techniques, has been designed and performed at the NLCTA test facility at SLAC.
3) This technique has applications in compressed/time resolved beam diagnostics and represents an alternative for COTR mitigation.
4) Extension to general microbunching by double intensity measurement can give insight in many beam physics and advanced FEL experiments.

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