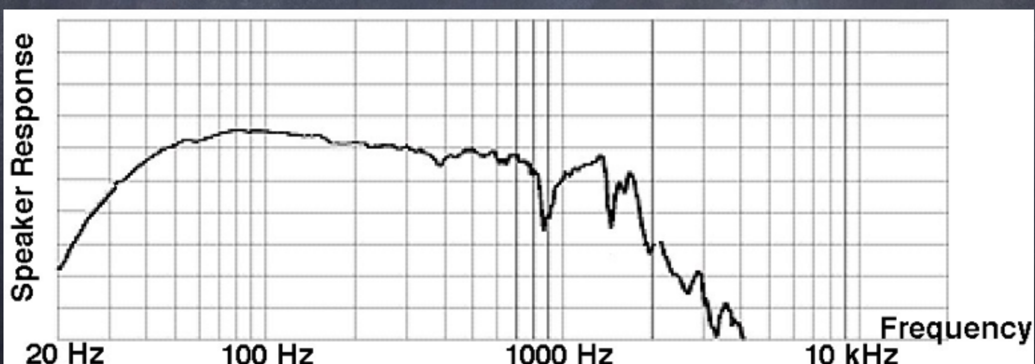
CTF

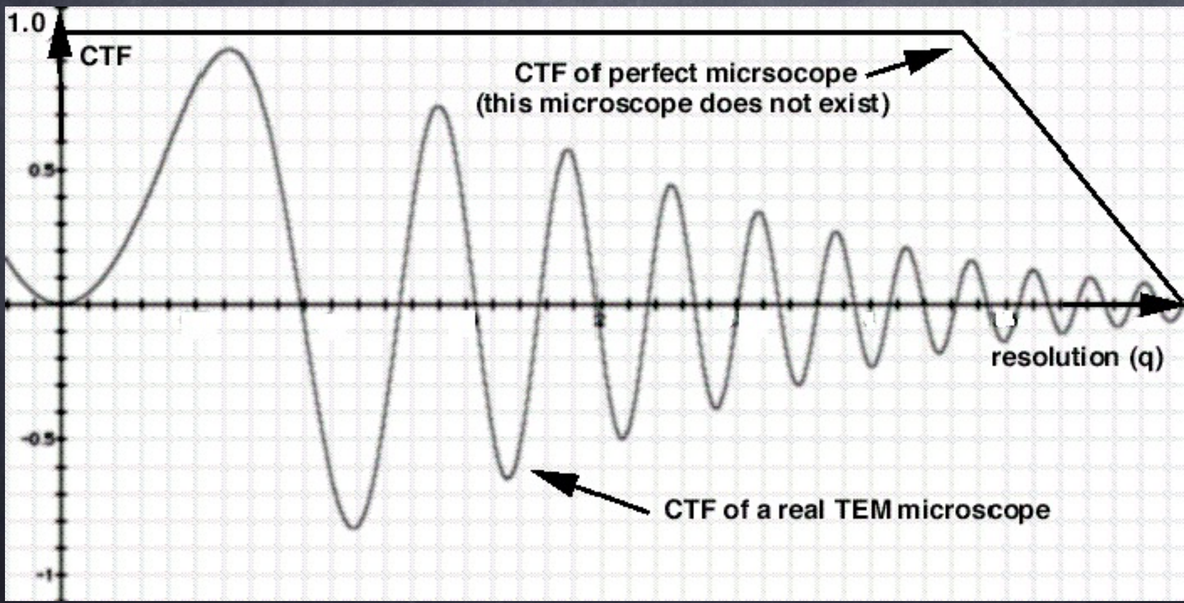
Henning Stahlberg,
Biozentrum, Uni Basel, Switzerland
c-cina.org

2dx Workshop
Basel, August 23, 2016

Transfer Function



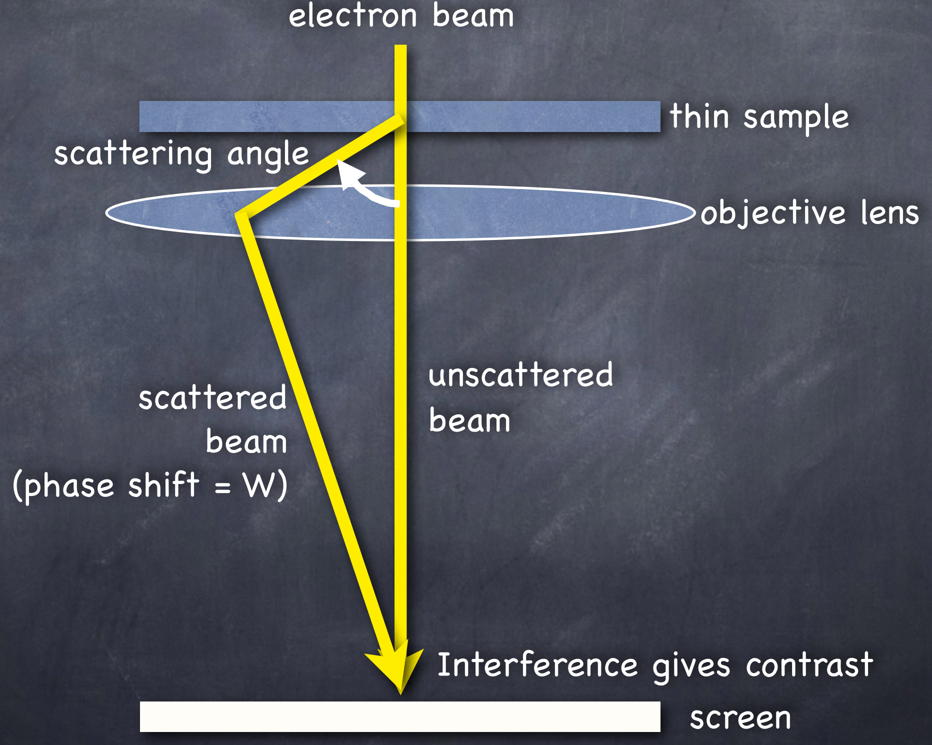
Transfer Function of a TEM



Otto Scherzer

(Mar. 9, 1909 - Nov. 15, 1982)

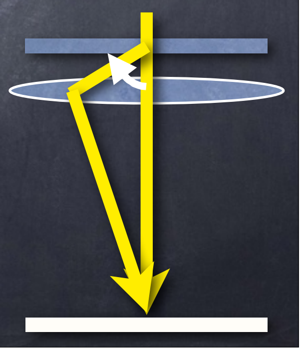
Contrast



Scherzer Formula

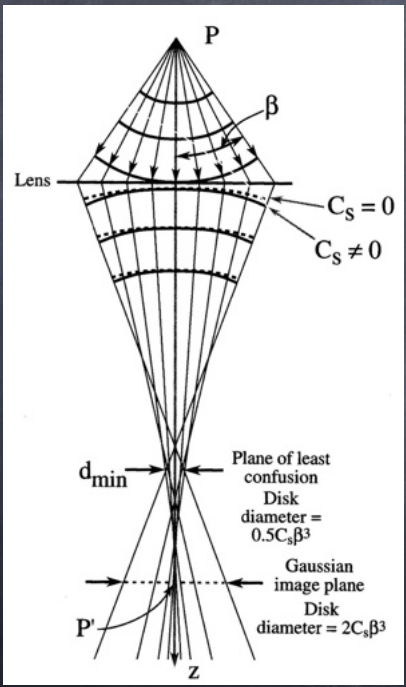
$$\gamma(\mathbf{u}) = \frac{2\pi W}{\lambda} = \frac{\pi}{2}\left[C_s \lambda^3 \mathbf{u}^4 - 2\Delta z \lambda \mathbf{u}^2\right]$$

$\gamma(u)$: Wave aberation function
(phase shift of scattered vs. non-scattered wave)
sin($\gamma(u)$): phase contrast transfer function
cos($\gamma(u)$): amplitude contrast transfer function



u: scattering vector (≈scattering angle)
W: wave aberation
λ: electron wavelength
Δz: defocus
C_s: spherical abberation constant

Spherical Aberation



C_S

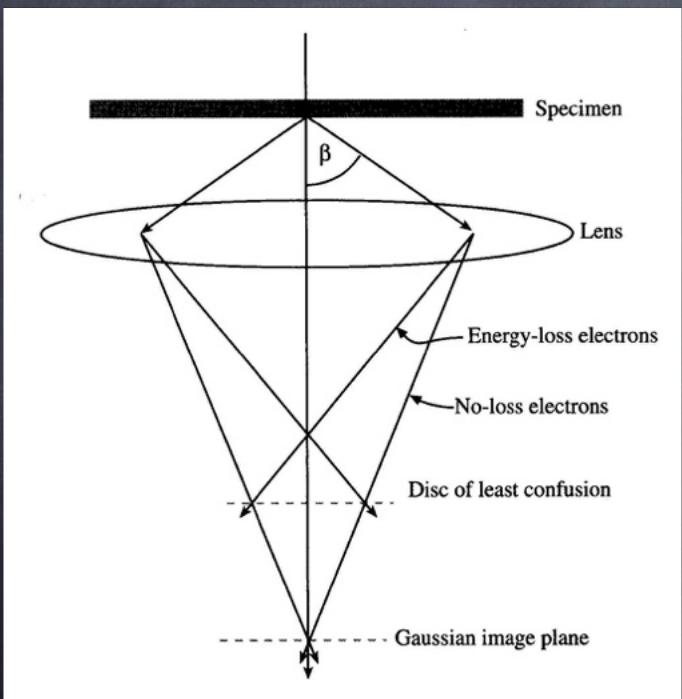
Limits resolution beyond ~ 2 Å

Electrons further from the axis are more strongly bent back towards the axis.

Or:

Electron waves further from the axis receive more phase shift.

Chromatic Aberation



C_C

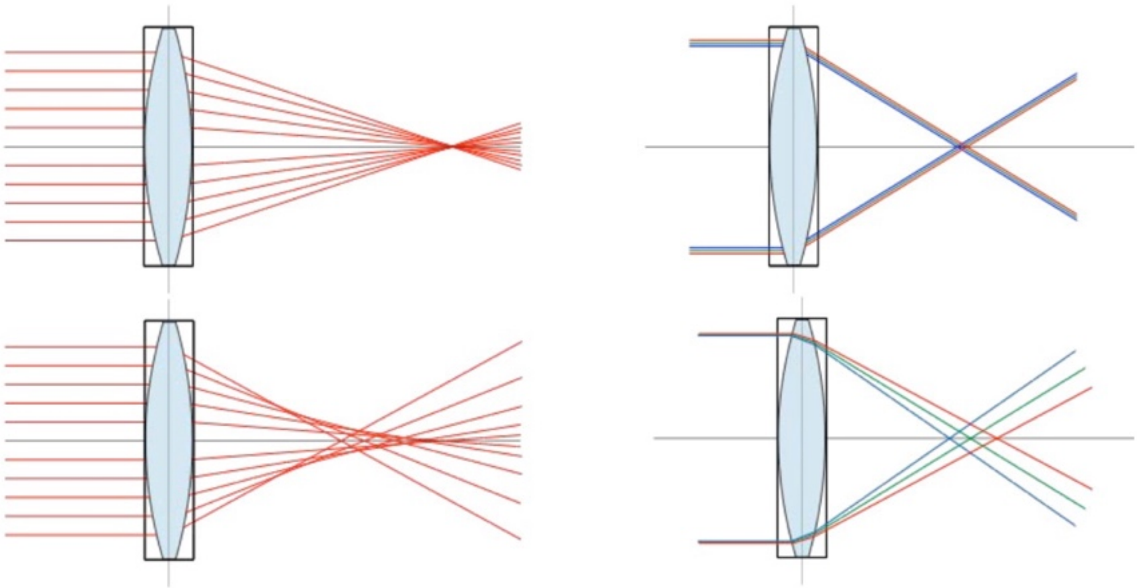
Limits resolution beyond ~ 0.5 Å

Electrons of lower energy are bent more strongly than those of zero-loss energy.

Lens aberrations

C_s-Spherical aberration

C_c-Chromatic aberration



Rays from the outer rim of the lens are focussed more tightly than the inner ones.

Different wavelengths are focussed more tightly than others.

Carsten Sachse, EMBL Talk, 2008

CTF

$$CTF(u) = \{ A * \cos(\gamma(u)) - \mathrm{sqrt}(1 - A^2) * \sin(\gamma(u)) \} * E(u)$$

$$\gamma(\mathbf{u}) = \frac{2\pi W}{\lambda} = \frac{\pi}{2}\left[C_s \lambda^3 \mathbf{u}^4 - 2\Delta z \lambda \mathbf{u}^2 \right]$$

$\sin(\gamma(u))$: phase contrast transfer function

$\cos(\gamma(u))$: amplitude contrast transfer function

u: scattering vector (≈scattering angle)

A: Amplitude contrast fraction. (neg. stain: use 0.07)

Envelope functions

$E(\mathbf{u}) = E_s(\mathbf{u}) \cdot E_c(\mathbf{u}) \cdot E_d(\mathbf{u}) \cdot E_v(\mathbf{u}) \cdot E_D(\mathbf{u})$

with

$E_s(\mathbf{u})$: angular spread of the source

α = opening angle

$$E_s(u) = exp[-(\frac{\pi\alpha}{\lambda})^2(\frac{\delta X(u)}{\delta u})^2] = exp[-(\frac{\pi\alpha}{\lambda})^2(C_s\lambda^3u^3 + \Delta f\lambda u)^2]$$

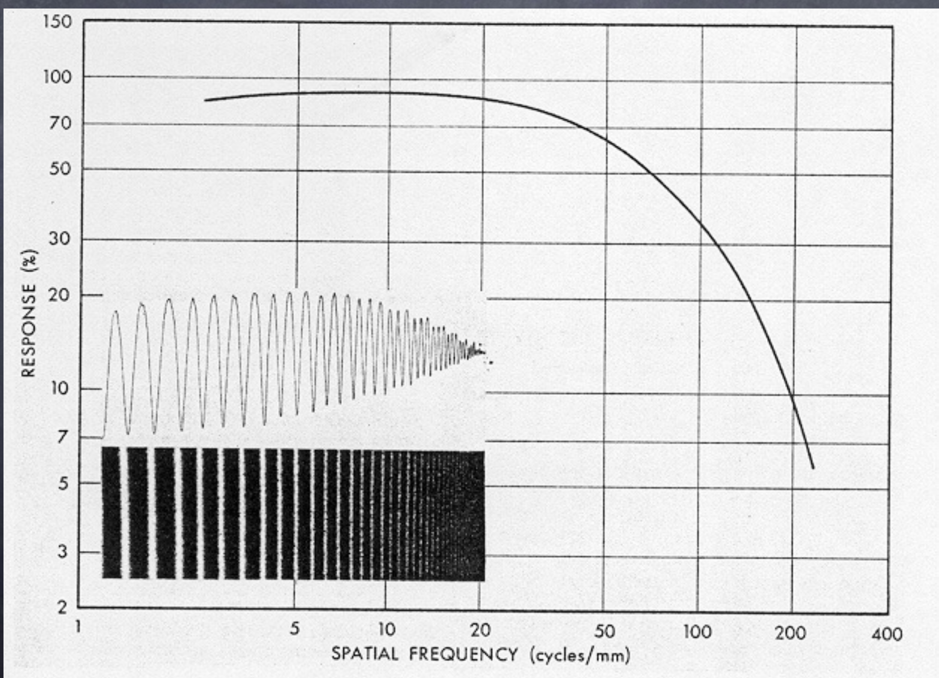
$E_c(\mathbf{u})$: chromatic aberration

$$E_c(u) = exp[\frac{1}{2}(\pi\lambda\delta)^2u^4]$$

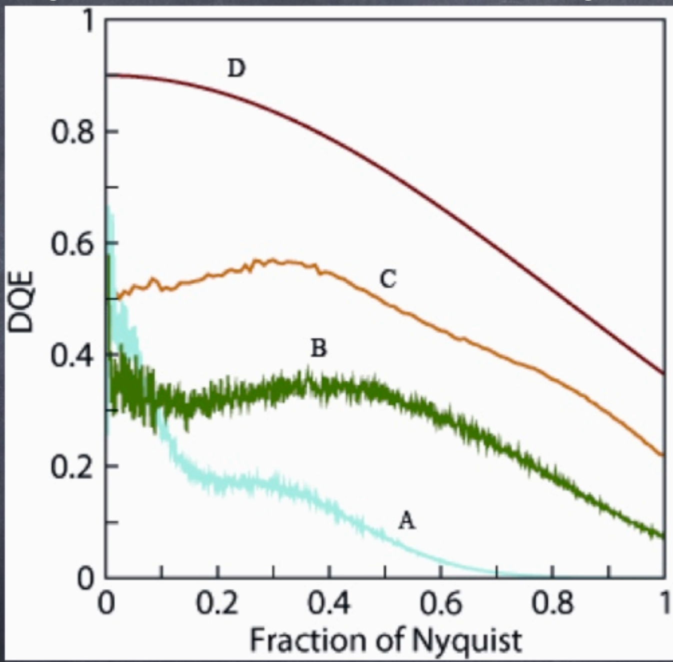
$$\delta = C_c\sqrt{4(\frac{\Delta I_{obj}}{I_{obj}})^2 + (\frac{\Delta E}{V_{acc}})^2 + (\frac{\Delta V_{acc}}{V_{acc}})^2}$$

$E_d(\mathbf{u})$: specimen drift
$E_v(\mathbf{u})$: specimen vibration
$E_D(\mathbf{u}) = MTF_D(u)$: detector

Modulation Transfer Function (MTF) of photographic film

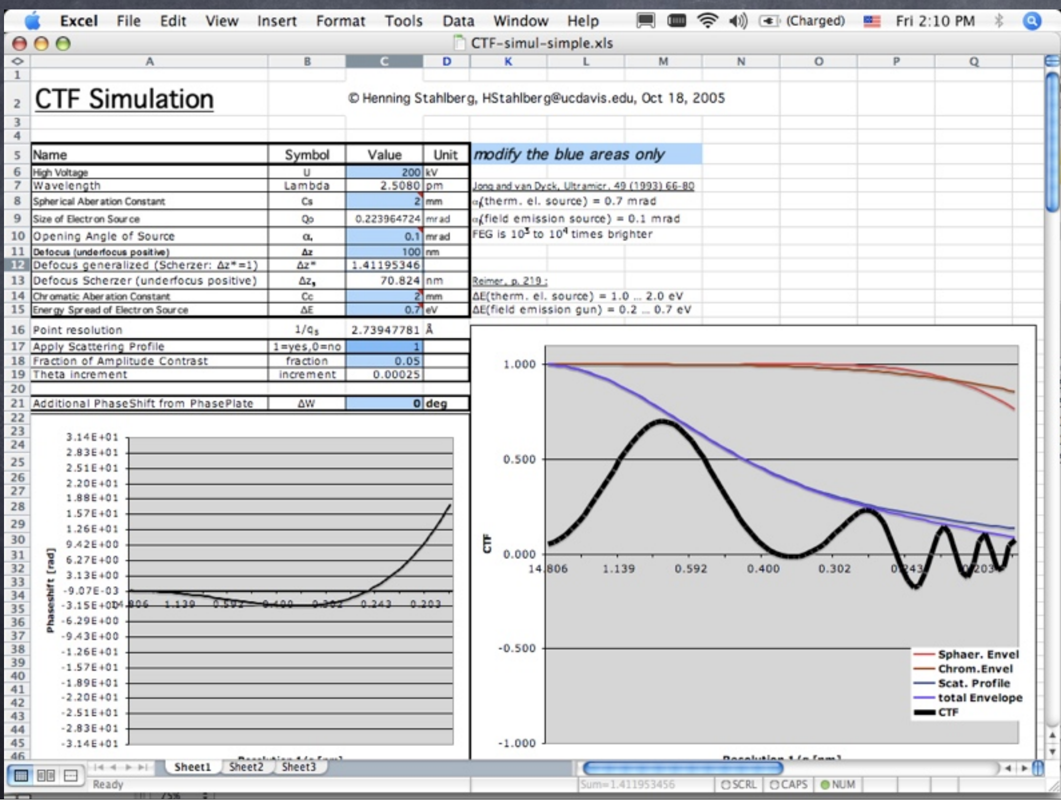


Detector Quantum Efficiency (DQE) of different detectors

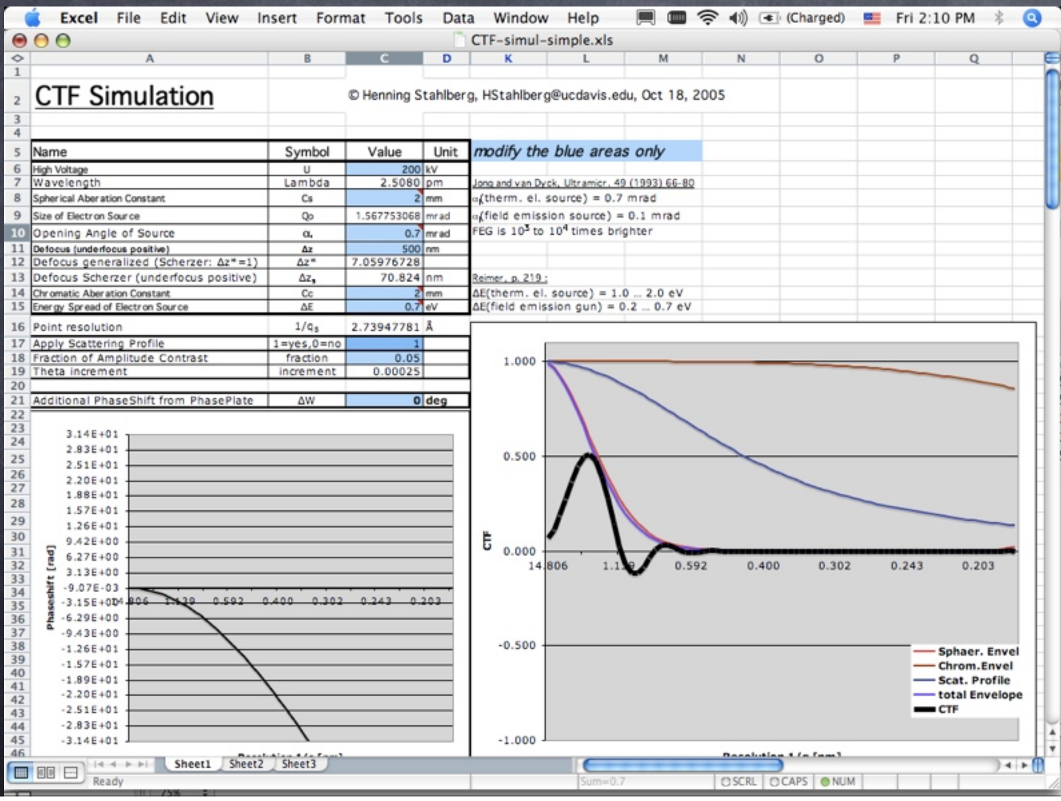


Spatial frequency dependence of the DQE for four different electron detectors in a 300 keV electron microscope: (A) current generation CCD detector, (B) Kodak SO-163 film, (C) backthinned CMOS detector, (D) a proposed detector. (R. Henderson, 2012)

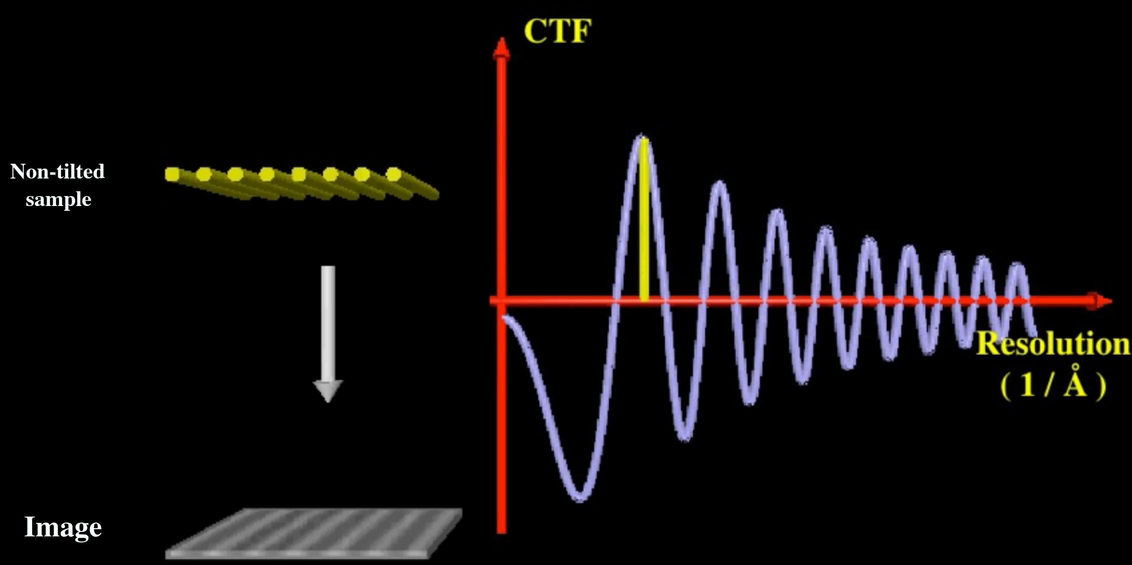
CTF simulation



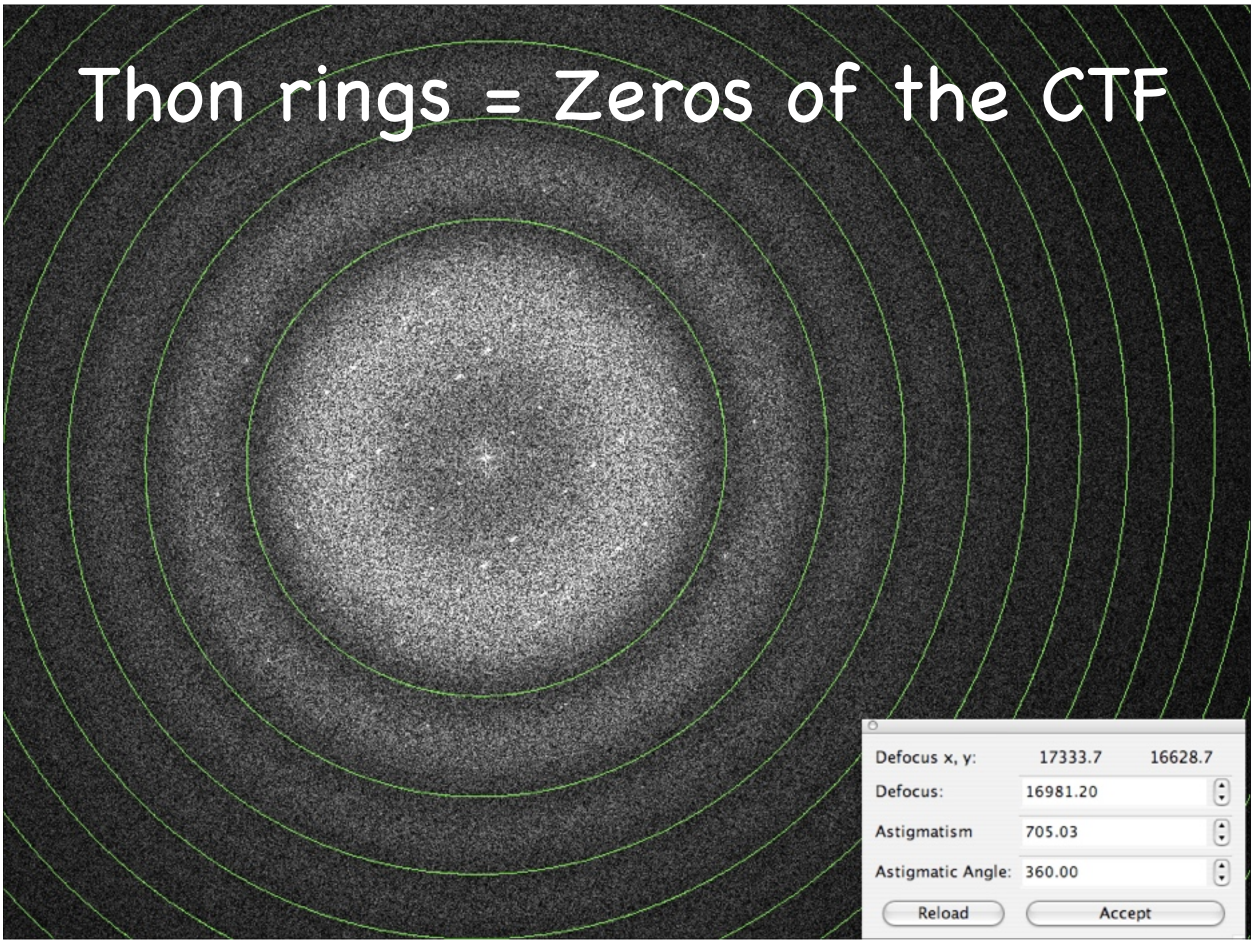
Excel sheet available on http://c-cina.org



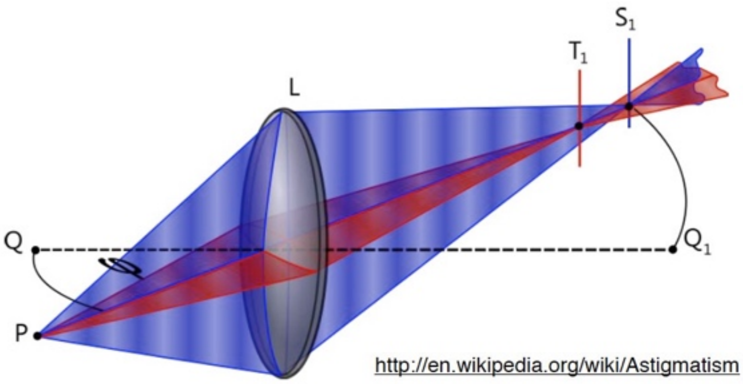
Contrast Transfer Function



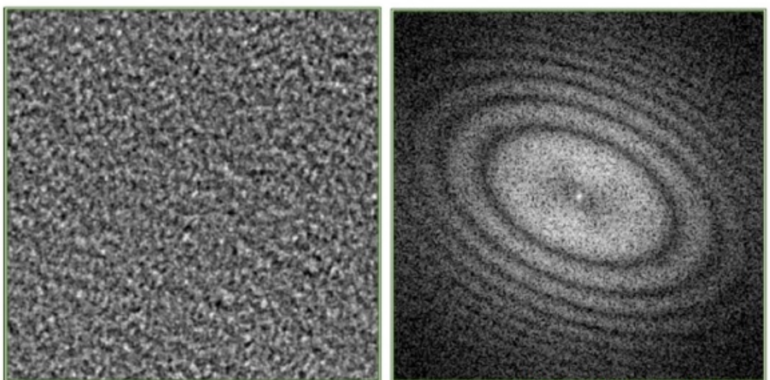
Continuously changing defocus



Thon rings can reveal astigmatism



http://en.wikipedia.org/wiki/Astigmatism



Orlova, CTF talk 2004

CTFFIND3 determines Defocus and Astigmatism

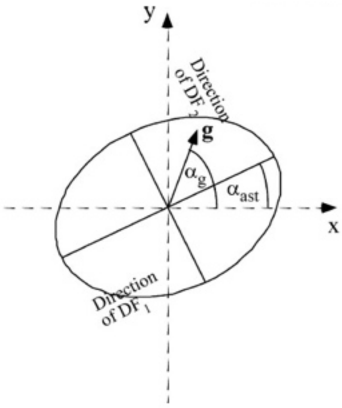
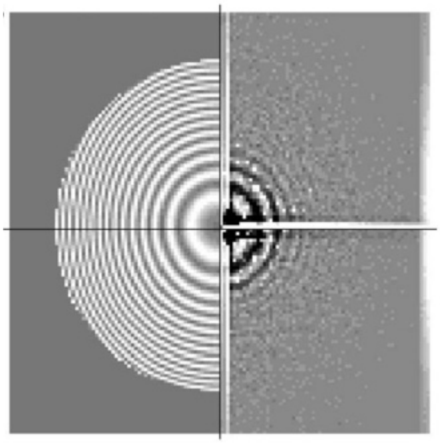


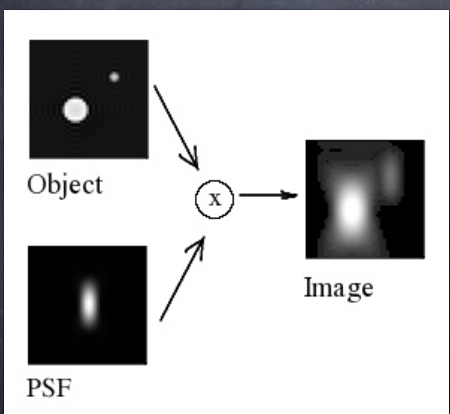
Fig. 3. Definitions for the CTF parameters DF_1, DF_2, and α_{ast}. The angle α_g of the scattering vector $g = k' - k$ (k, wave vector of the incident wave; k', wave vector of the scattered wave) is used in Eq. (6), indicating the point where the CTF is evaluated.



Mindell & Grigorieff, JSB 2003

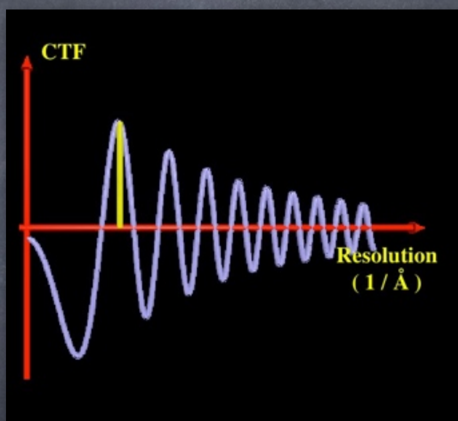
Real Space:
Point Spread Function

Object ⊗ PSF = Image



Fourier Space:
Contrast Transfer Function

FT(Object) • CTF = FT(Image)

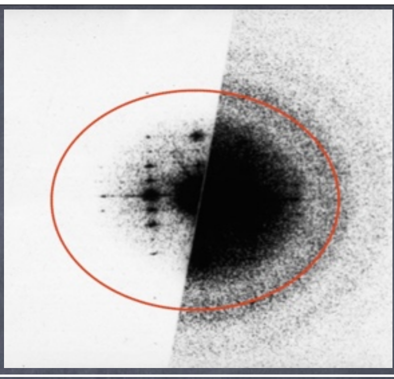


FT(PSF) ≈ CTF

PSF ≈ FT(CTF)

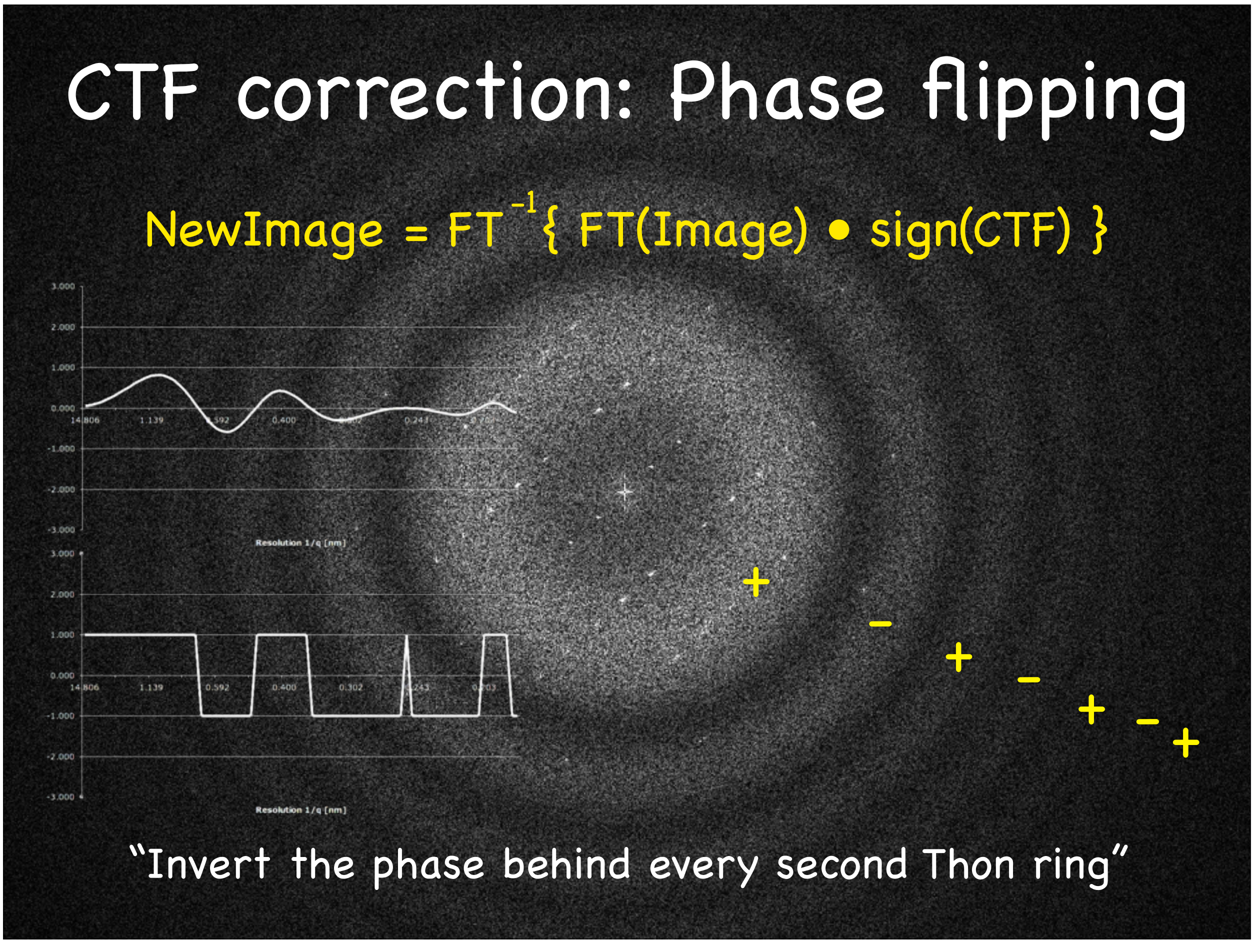
What the FFT can tell us

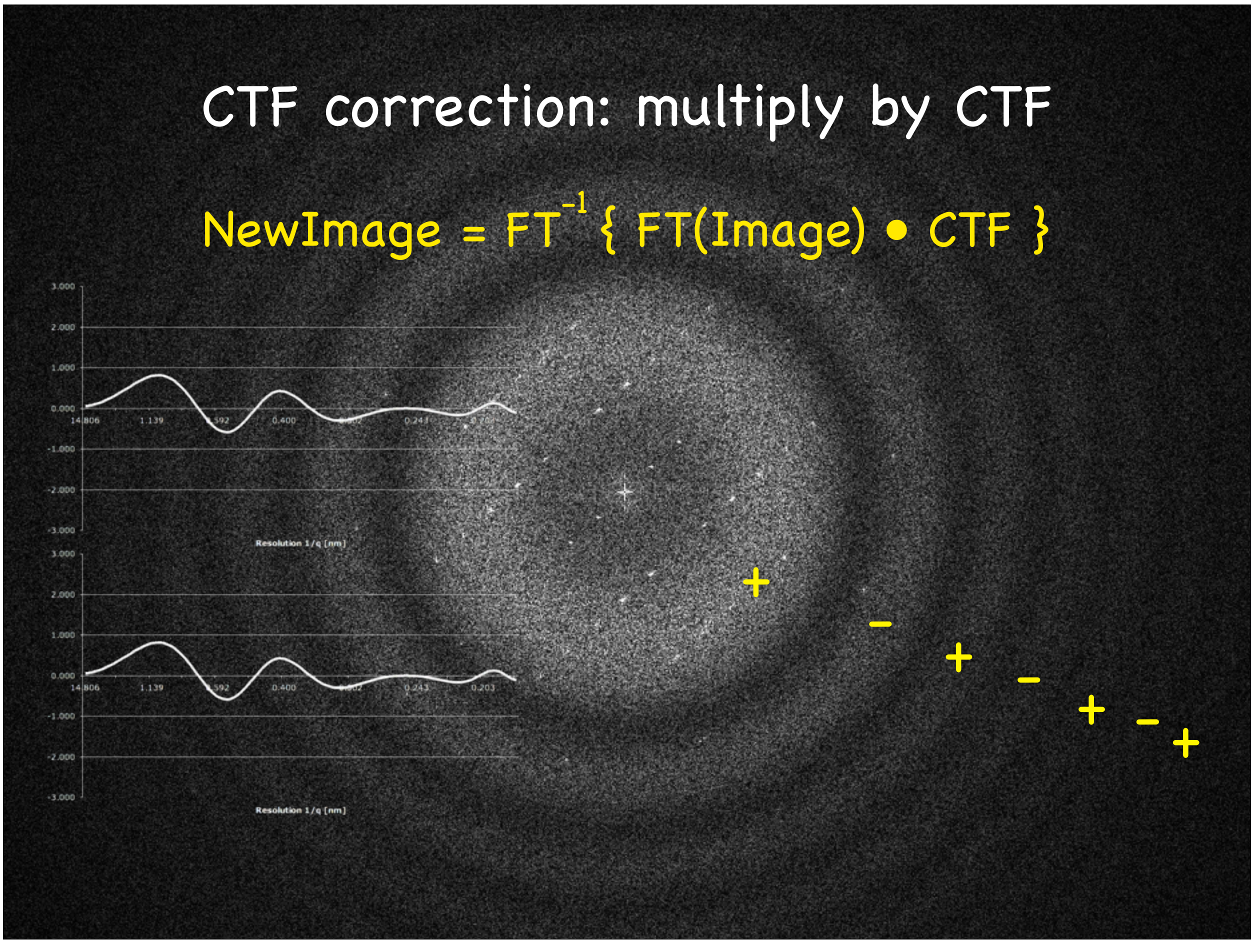
(After David deRosier, 2006)

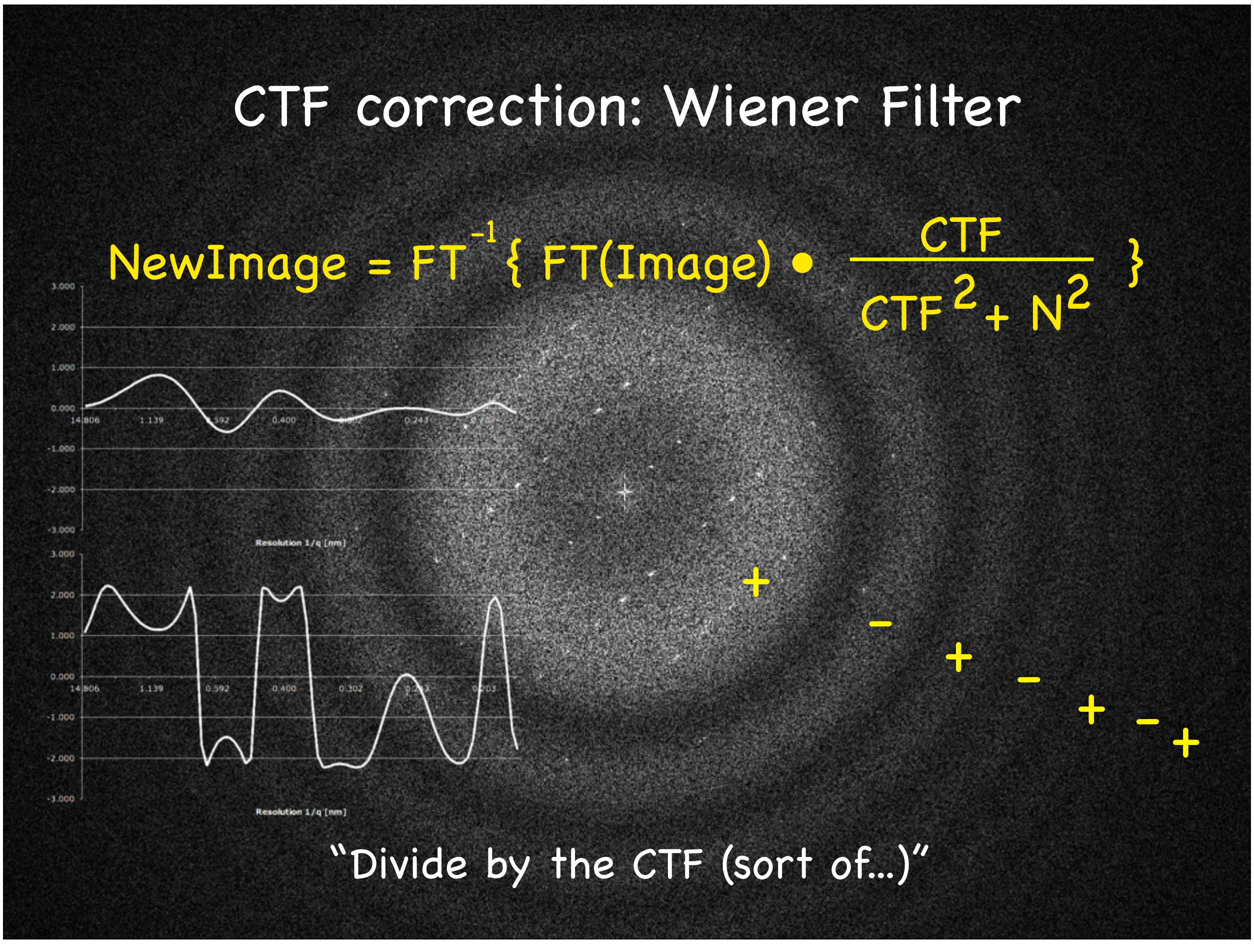


Spot positions	Unit cell size and shape
Spot size	Size of coherent domains
Intensity relative to background	Signal to noise ratio
Distance to farthest spot	Resolution
Amplitude and Phase of spots	Structure of molecules
Radius of Thon rings	Amount of defocus
Ellipticity of Thon rings	Amount of astigmatism
Assymetric intensity of Thon rings	Amount of instability
Direction of assymetry	Direction of instability

Can we correct the CTF ?


CTF correction: Phase flipping
NewImage = FT-1{ FT(Image) • sign(CTF) }
Resolution 1/q [nm]
Resolution 1/q [nm]
+
–
+
–
+
–
+
"Invert the phase behind every second Thon ring"

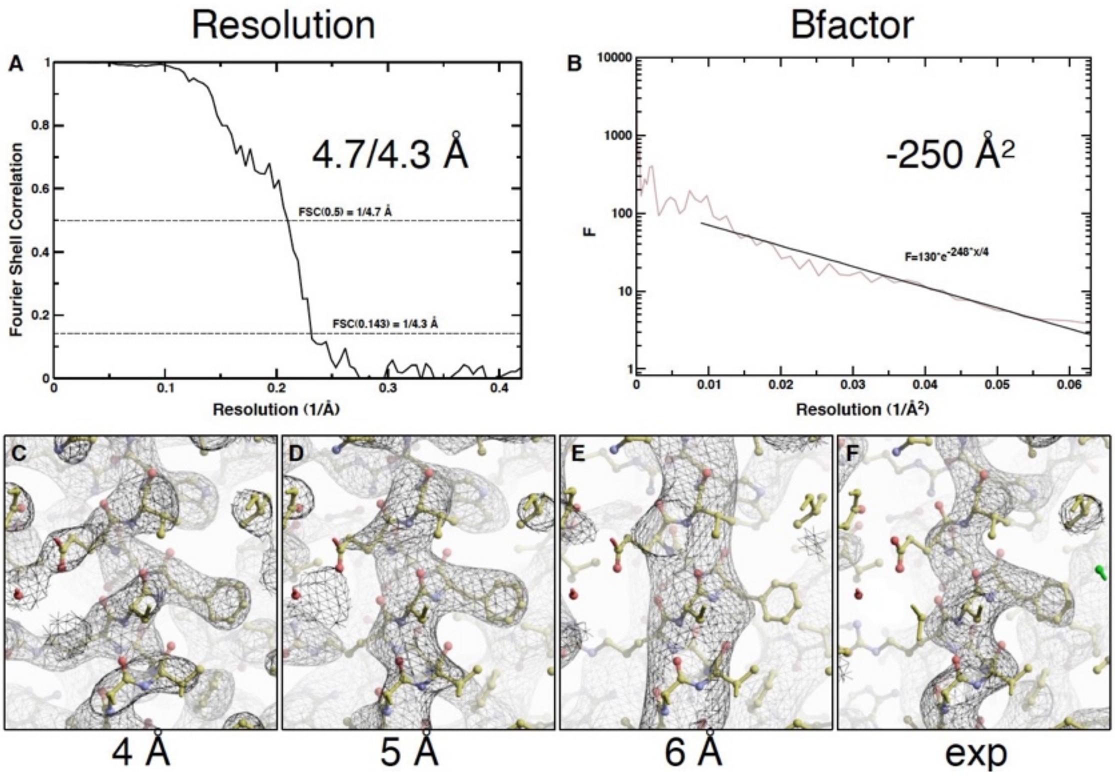

CTF correction: multiply by CTF
NewImage = FT-1{ FT(Image) • CTF }
Resolution 1/q [nm]
Resolution 1/q [nm]
+
–
+
–
+
–
+



Methods of CTF Correction

- Phase flipping
- CTF multiplication
- Wiener filtering
  (Böttcher et al. 1997, Penczek et al., 1997)
- CTF multiplication of 2D image, and Wiener filtration of 3D volume
  (Grigorieff 1998, Sachse et al. 2007)
- In 2dx currently most successful:
  Phase flipping before unbending.
  Amplitude correction is taken over by PCO.

B-factor correction at high resolution



Carsten Sachse, EMBL Talk, 2008

Defocus varies on an image of a tilted sample

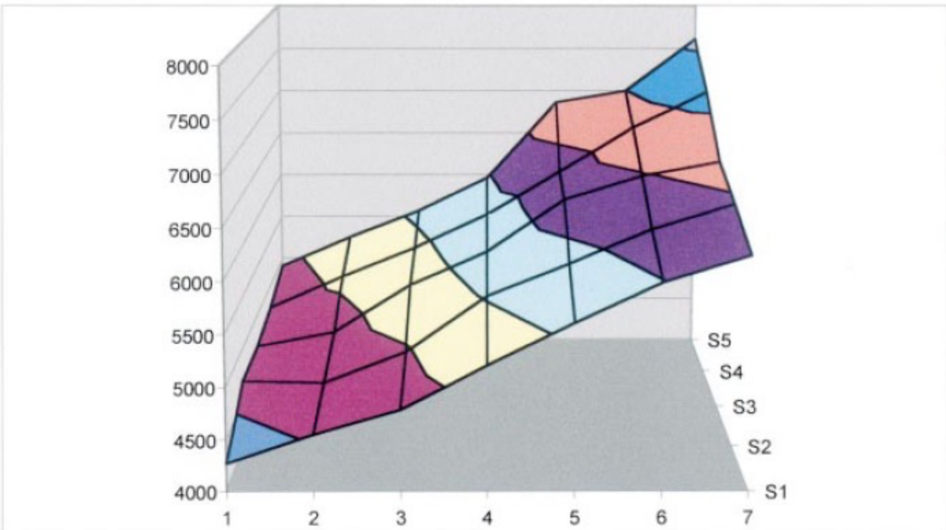
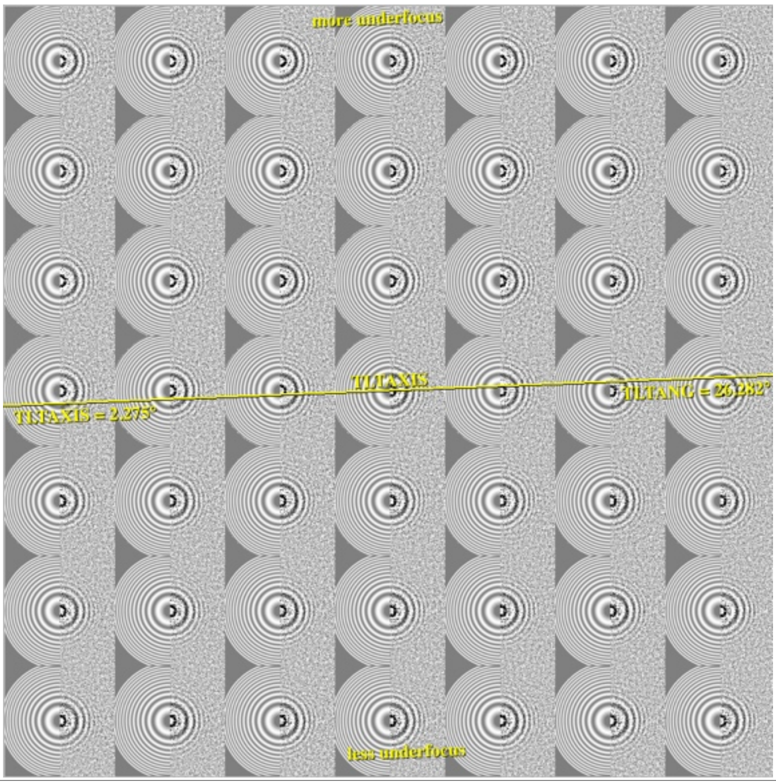


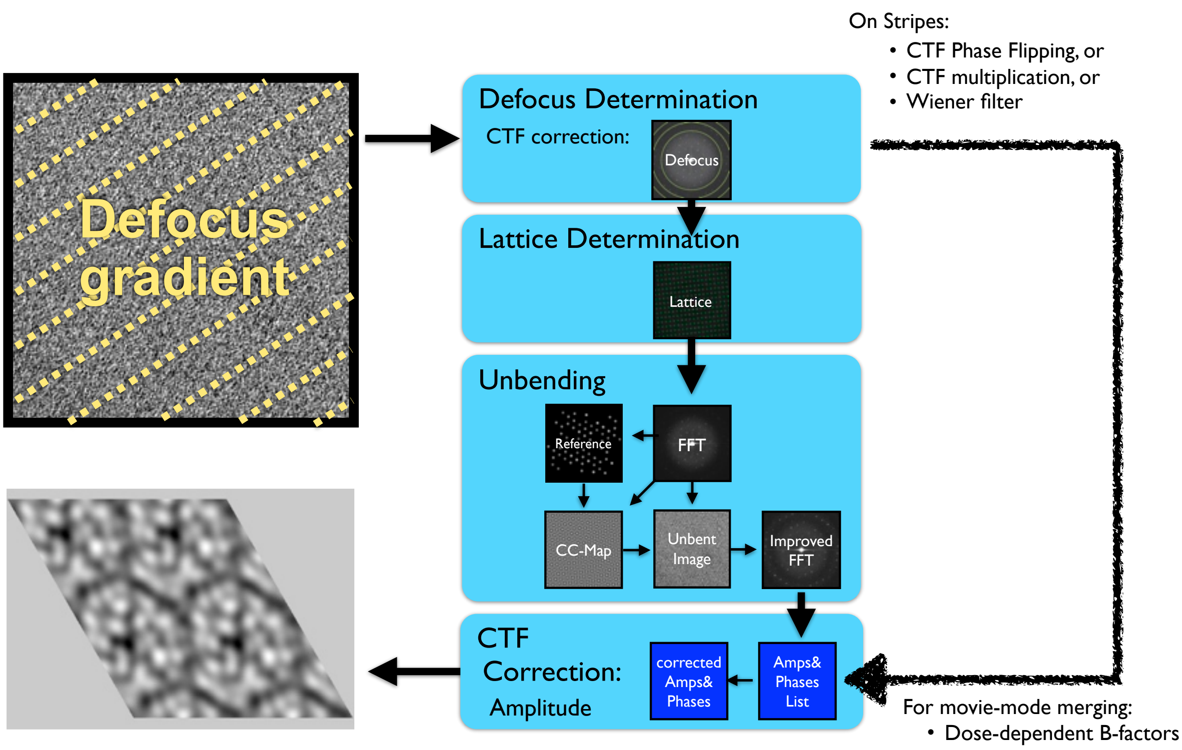
Fig. 6. Position dependent PhCTF determination. This graph illustrates a typical nominal '0' tilt on our CM200 cryo-EM/Gatan cryo-holder system. The system exhibits a systematic 6° tilt with respect to the nominal tilt angles that, if not corrected for, causes a defocus spread of almost 3000 Å. After our diagnostic analysis, the holder is now systematically used at a nominal −6° tilt to compensate for this effect. However, the defocus difference between front and back of the plot of ~ 600 Å – perpendicular to the tilt axis of the goniometer – is not correctable with the current set up. Moreover, due to a recent repair of this particular holder, the nominal '0°' tilt position requires recalibration.

van Heel et al., Quart. Rev. Biophys. 2000

In 2dx, we apply CTFFIND3 in 7x7 locations to measure the tilt geometry



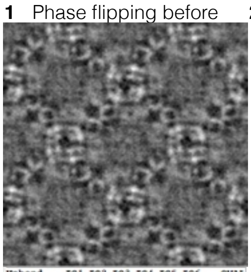
In 2dx, we correct the CTF before any further image processing by Phase flipping in stripes



(Almost) Non-Tilted 2D Crystal

Image: 2014-05-26_14-33-45_0020025100
Tilt axis: 29.2°
Tilt angle: -3.8°
Defocus: 9462.4, 10.179.7, 81.92°

1 Phase flipping before

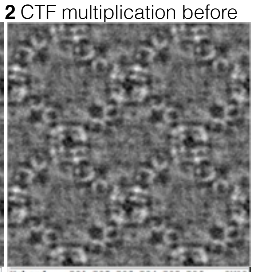


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	95	101	119	181	239	255.8
Unb.II	26	100	90	147	188	236	269.2
MovieA	50	125	147	245	222	212	338.5
MovieB	53	134	174	266	269	200	375.0

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	180	34	93	27	9	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8
Sym.PhaRes=	---		Num.Spots= .	

2 CTF multiplication before

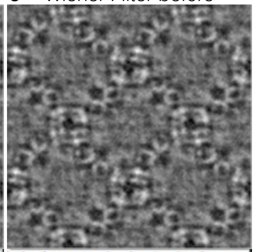


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	25	96	84	115	182	209	298.8
Unb.II	25	103	89	140	174	250	251.6

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	174	37	99	28	9	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8
Sym.PhaRes=	---		Num.Spots= .	

3 Wiener Filter before

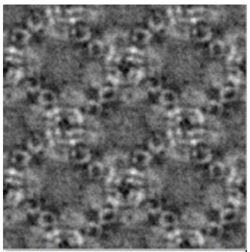


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	23	98	91	115	199	218	278.6
Unb.II	25	102	91	136	189	224	292.8

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	178	44	108	30	9	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8
Sym.PhaRes=	---		Num.Spots= .	

0 CTF correction after

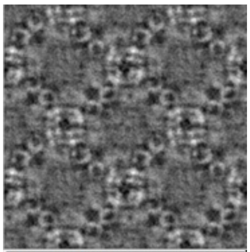


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	98	97	123	200	215	259.2
Unb.II	25	98	99	151	211	271	283.4

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	180	35	94	27	9	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8

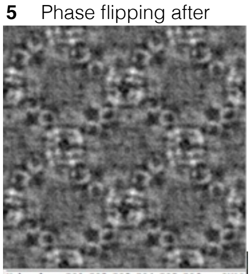
4 TTF correction after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	98	97	123	200	215	259.2
Unb.II	60	123	159	223	270	246	448.9

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8

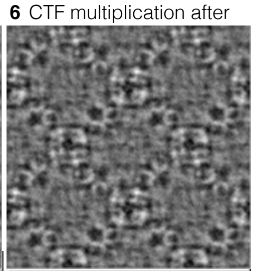
5 Phase flipping after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	98	97	123	200	215	259.2
Unb.II	25	99	94	140	200	224	276.2

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8

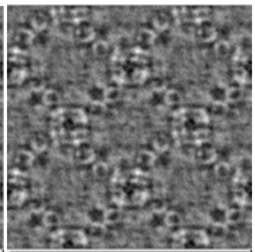
6 CTF multiplication after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	98	97	123	200	215	259.2
Unb.II	26	99	97	136	163	206	335.2

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8

7 Wiener Filter after



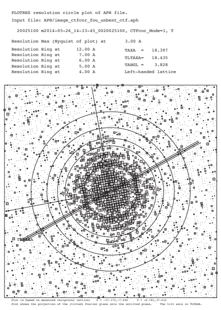
Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	24	98	97	123	200	215	259.2
Unb.II	26	99	97	149	174	228	312.8

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	26.3	39.8	---	29.2
Grid TAngle	-3.6	-7.8	---	-3.8
Xst. TAxis	15.6	28.8	---	18.4
Xst. TAngle	3.6	7.8	---	3.8

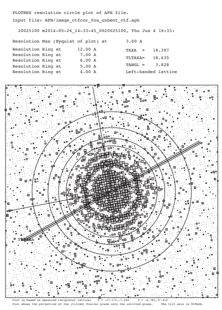
(Almost) Non-Tilted 2D Crystal

Image: 2014-05-26_14-33-45_0020025100
Tilt axis: 29.2°
Tilt angle: -3.8°
Defocus: 9462.4, 10.179.7, 81.92°

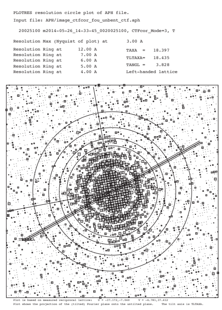
1 Phase flipping before



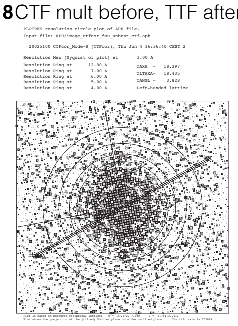
2 CTF multiplication before



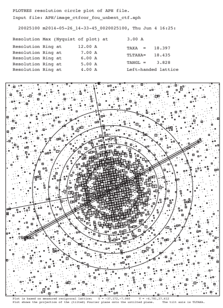
3 Wiener Filter before



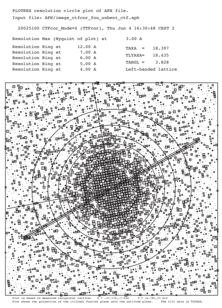
8 CTF mult before, TTF after



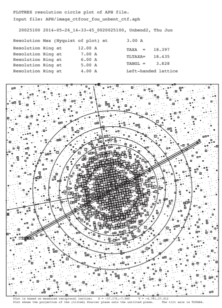
0 CTF correction after



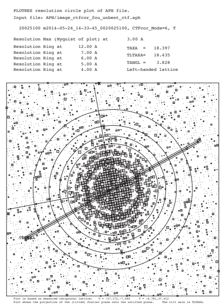
4 TTF correction after



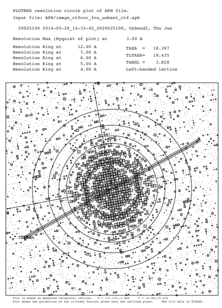
5 Phase flipping after



6 CTF multiplication after

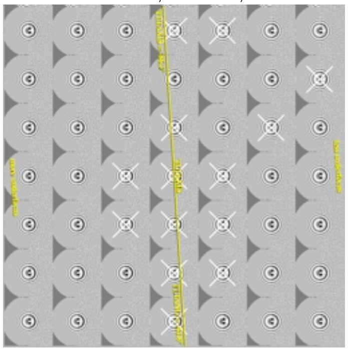


7 Wiener Filter after

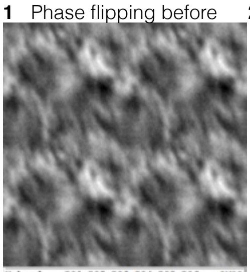


Tilted 2D Crystal

Image: 2014-07-29_14-27-19_0020012900
Tilt axis: 86.3°
Tilt angle: -44.8°
Defocus: 19022.2, 19231.7, 80.0°



1 Phase flipping before

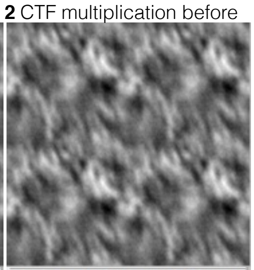


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	42	74	41	77	137	184	809.5
Unb.II	44	86	52	76	143	182	909.4

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	668	69	56	13	8	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

2 CTF multiplication before

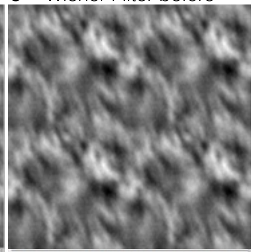


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	69	48	68	141	174	756.4
Unb.II	44	85	53	78	158	187	776.4

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	578	83	66	15	8	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

3 Wiener Filter before

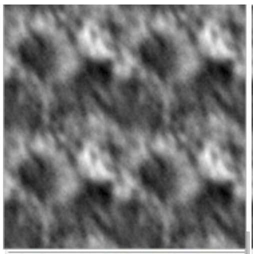


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	43	68	52	62	142	167	762.0
Unb.II	43	90	51	87	148	175	914.8

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	613	79	63	14	7	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

0 CTF correction after

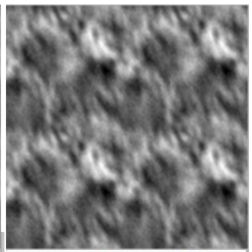


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	45	73	37	84	147	164	829.2

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	670	67	49	9	7	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

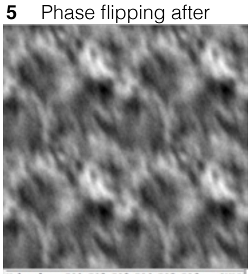
4 TTF correction after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	47	84	57	69	119	121	871.5

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

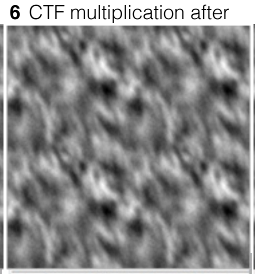
5 Phase flipping after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	43	83	52	74	160	169	910.0

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

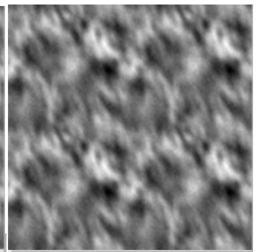
6 CTF multiplication after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	42	87	59	65	160	179	925.9

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

7 Wiener Filter after



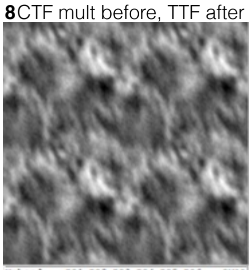
Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	44	88	58	72	157	168	932.1

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

Tilted 2D Crystal

Image: 2014-07-29_14-27-19_0020012900
Tilt axis: 86.3°
Tilt angle: -44.8°
Defocus: 19022.2, 19231.7, 80.0°

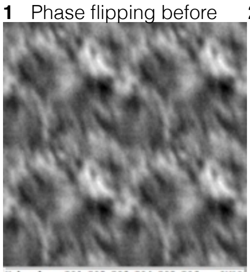
8 CTF mult before, TTF after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	69	48	68	141	174	756.4
Unb.II	47	86	50	80	100	118	862.7

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	669	67	49	9	7	7

1 Phase flipping before

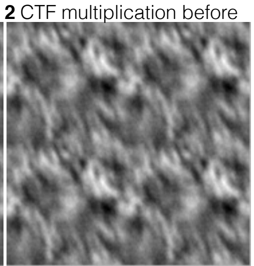


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	42	74	41	77	137	184	809.5
Unb.II	44	86	52	76	143	182	909.4

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	668	69	56	13	8	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

2 CTF multiplication before

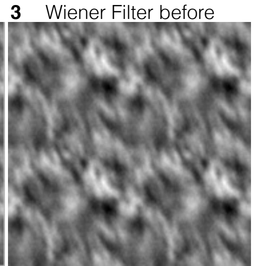


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	69	48	68	141	174	756.4
Unb.II	44	85	53	78	158	187	776.4

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	578	83	66	15	8	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

3 Wiener Filter before

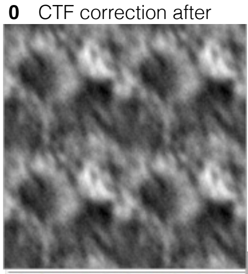


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	43	68	52	62	142	167	762.0
Unb.II	43	90	51	87	148	175	914.8

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	613	79	63	14	7	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8
Sym.PhaRes=	---		Num.Spots= .	

0 CTF correction after

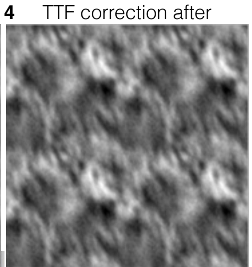


Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	45	73	37	84	147	164	829.2

PowerBins	[A]	15	12	9	7	5	3
(noise=7)	#	670	67	49	9	7	7

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

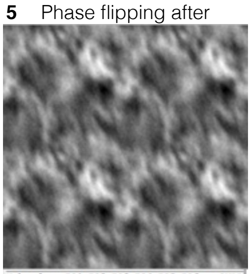
4 TTF correction after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	47	84	57	69	119	121	871.5

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

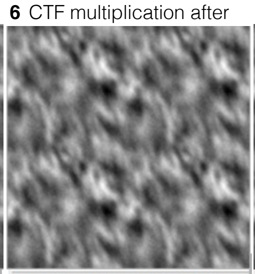
5 Phase flipping after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	43	83	52	74	160	169	910.0

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

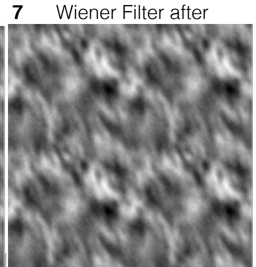
6 CTF multiplication after



Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	42	87	59	65	160	179	925.9

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

7 Wiener Filter after



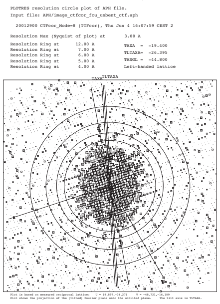
Unbend	IQ1	IQ2	IQ3	IQ4	IQ5	IQ6	QVAL
Unb.I	40	64	35	67	152	178	733.3
Unb.II	44	88	58	72	157	168	932.1

Tilt Info	Defoc.	Latt.	SpSplit	Merge
Grid TAxis	86.4	-85.6	---	-86.3
Grid TAngle	38.9	-44.2	---	-44.8
Xst. TAxis	-27.4	-19.1	---	-19.4
Xst. TAngle	-38.9	-44.2	---	-44.8

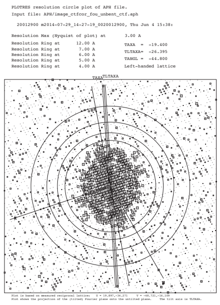
Tilted 2D Crystal

Image: 2014-07-29_14-27-19_0020012900
Tilt axis: 86.3°
Tilt angle: -44.8°
Defocus: 19022.2, 19231.7, 80.0°

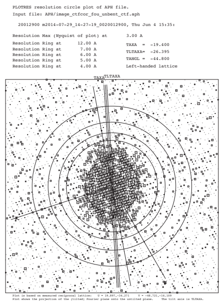
8 CTF mult before, TTF after



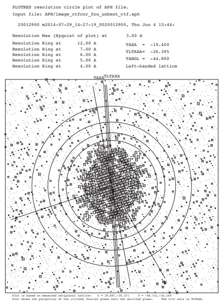
1 Phase flipping before



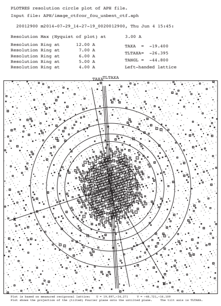
2 CTF multiplication before



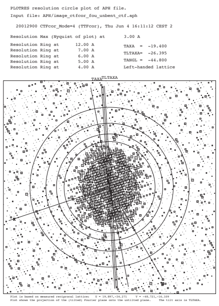
3 Wiener Filter before



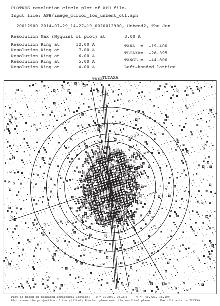
0 CTF correction after



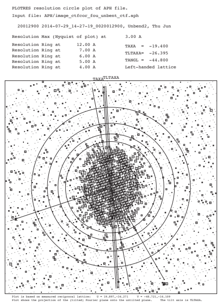
4 TTF correction after



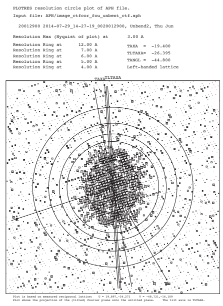
5 Phase flipping after



6 CTF multiplication after



7 Wiener Filter after



Conclusions CTF

- The CTF defines the transfer of contrast from the sample onto the image.
- The PSF defines the impact on the image from a point in the sample. PSF = FFT(CTF).
- CTF needs to be fitted and corrected.
- CTF for tilted samples can be done in various ways. In 2dx, recommendation is Phase Flipping before unbending.