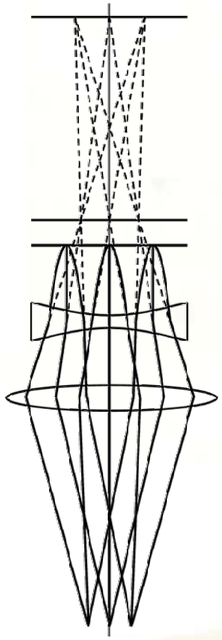
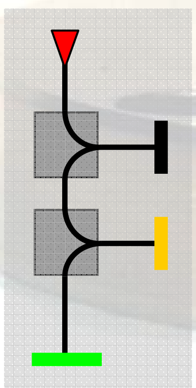
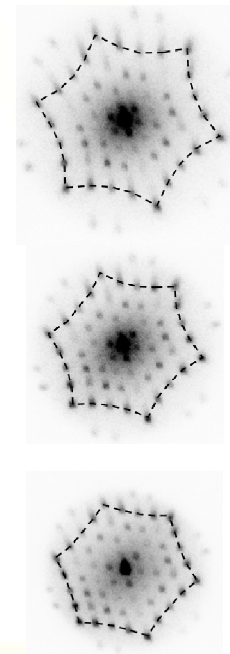
Towards 2λ Resolution

(Limits of Aberration Corrected Electron Microscopy)





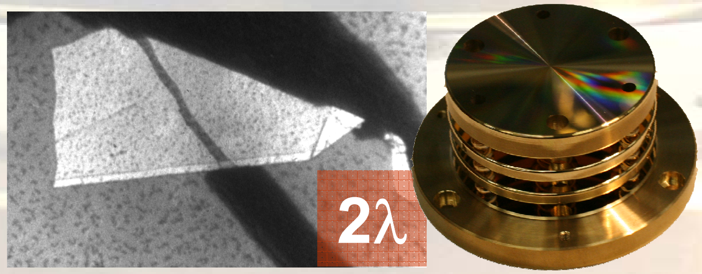


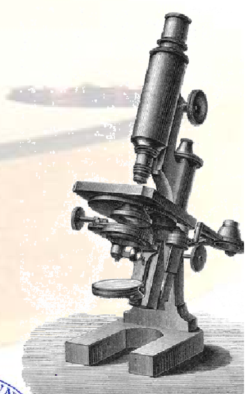
Ruud Tromp

IBM T.J. Watson Research Center

Yorktown Heights, NY

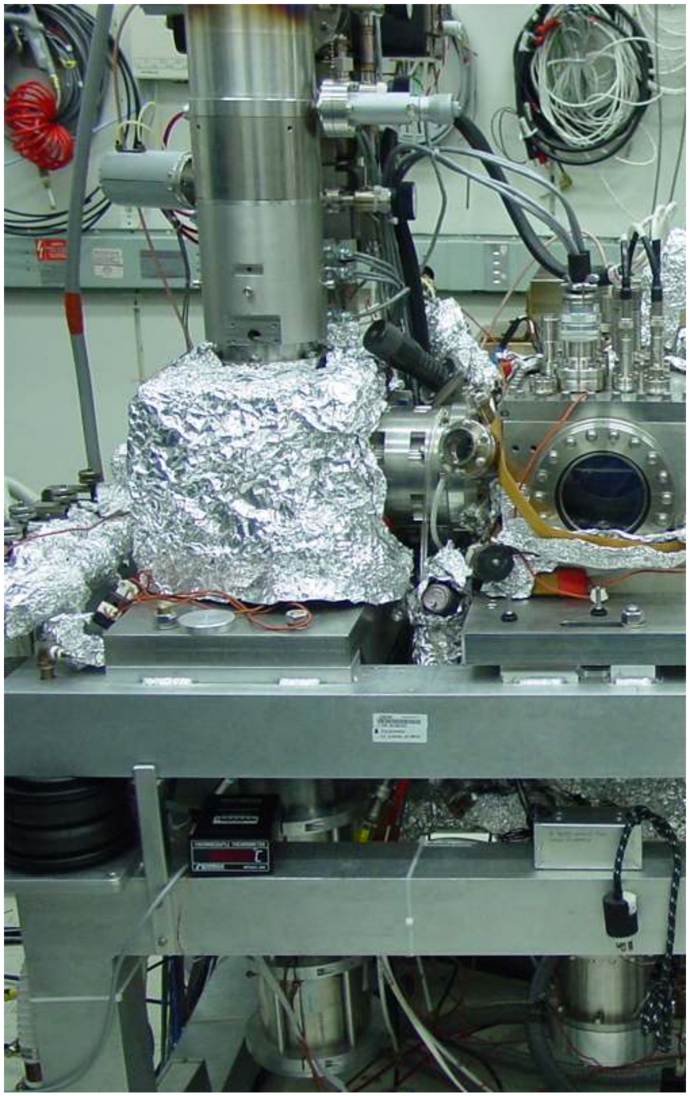
Leiden University

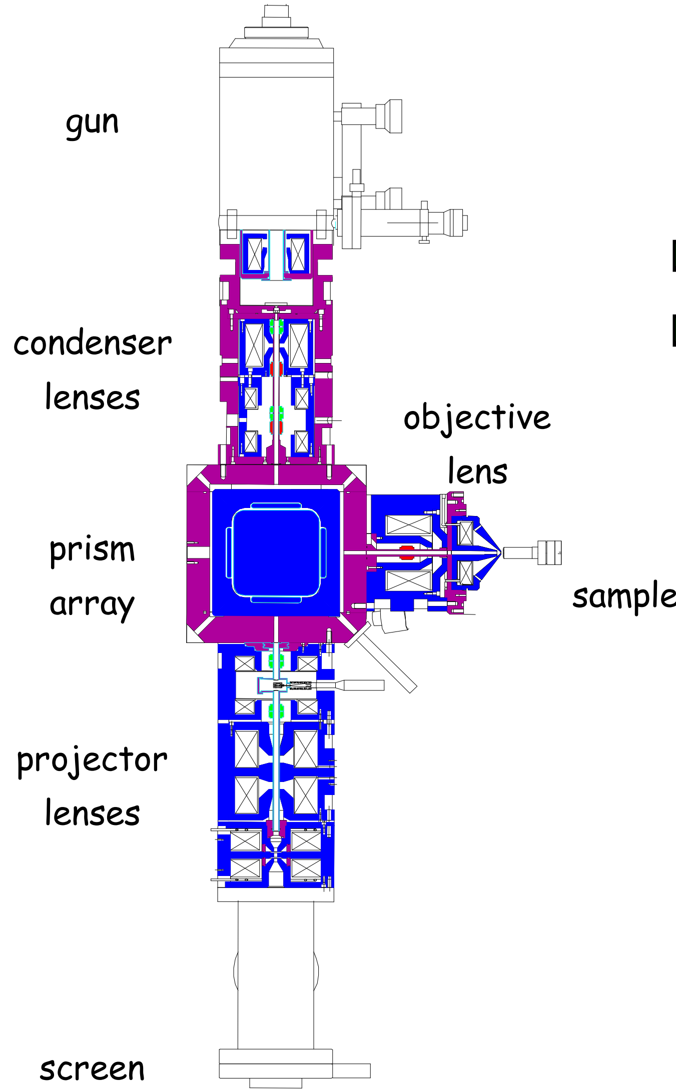


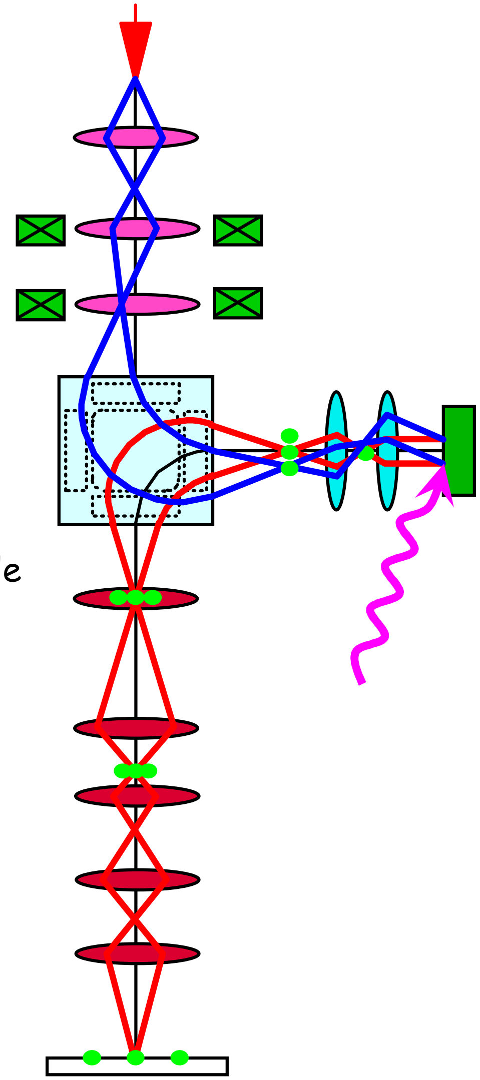


SPECS® IBM® BERKELEY LAB

IBM LEEM/PEEM



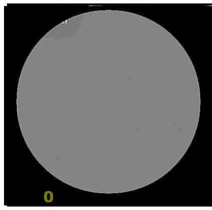
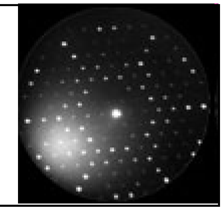
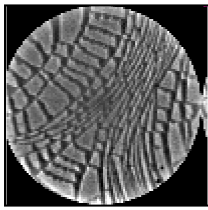
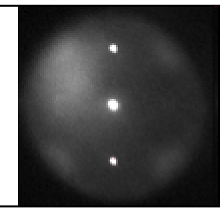
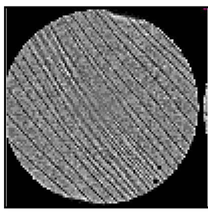
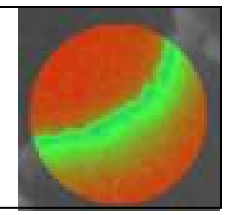
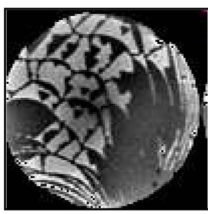
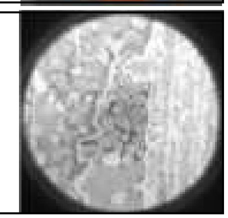
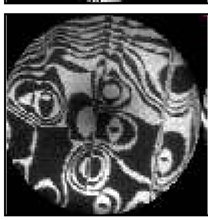
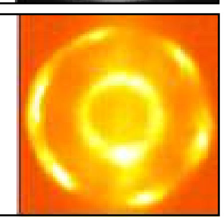




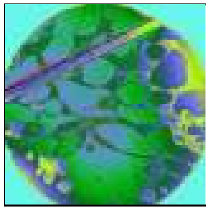
R.M.Tromp, M. Mankos, M.C. Reuter, A.W. Ellis, M. Copel
Surface Review and Letters **5** , 1189 (1998)

SPECS IBM

Lab-based LEEM/PEEM imaging modes

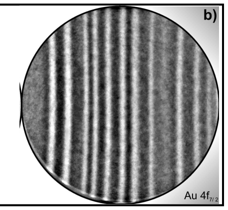
	PEEM imaging Hg light source / laser	(picosecond) LEED Atomic Structure	
	Mirror Microscopy Topography Work Function	Selected Area LEED Local Atomic Structure 200 nm	
	Bright field LEEM Phase contrast	LEEM-IV Imaging Local Atomic Structure 2-5 nm	
	Bright field LEEM Reflectivity Structure factor	LEEM-EELS Local Electronic Structure Spectroscopy + Imaging	
	Dark field LEEM Structure symmetry	PEEM-ARUPS Electronic structure Spectroscopy + Imaging	

Synchrotron-based PEEM imaging modes



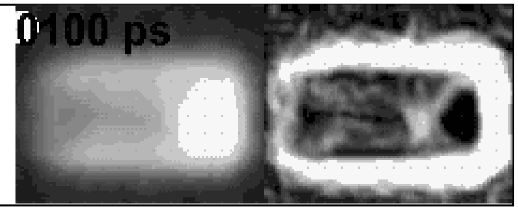
PEEM-IV Imaging
20 nm resolution
Local chemistry

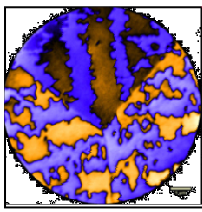
Dynamic Imaging
In-situ processing
Elemental/chemical



Linear Magnetic
Dichroism
Antiferromagnetism

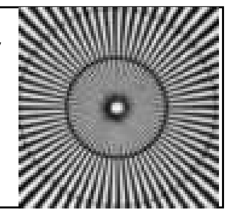
Picosecond
Resolution
Imaging

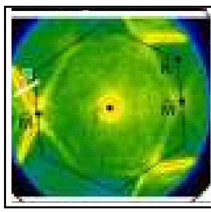




Circular Magnetic
Dichroism
Ferromagnetism

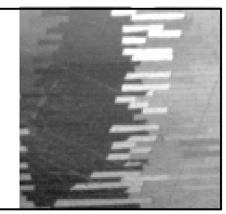
Localized Spectroscopy
Elemental, chemical
Magnetic, Valence

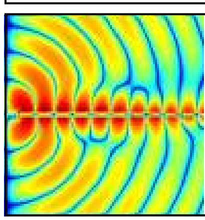




Valence Band Imaging
Surface, bulk
Topological

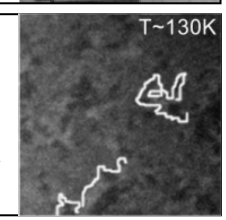
Biological Imaging
Organic, Inorganic
Elemental, chemical





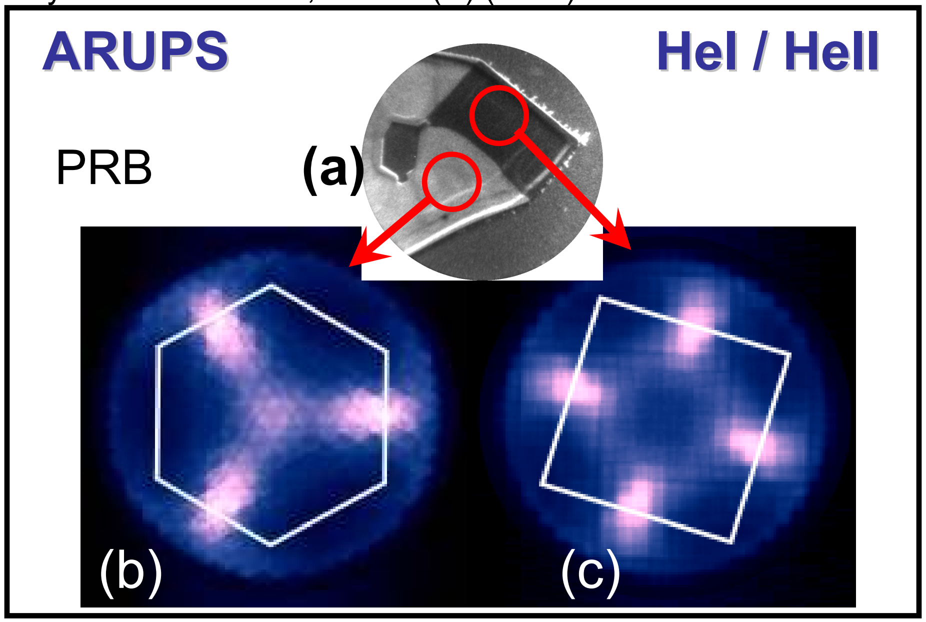
Plasmonics
Dynamics, geometry

Cryo-PEEM
Solid State
Bio, soft matter

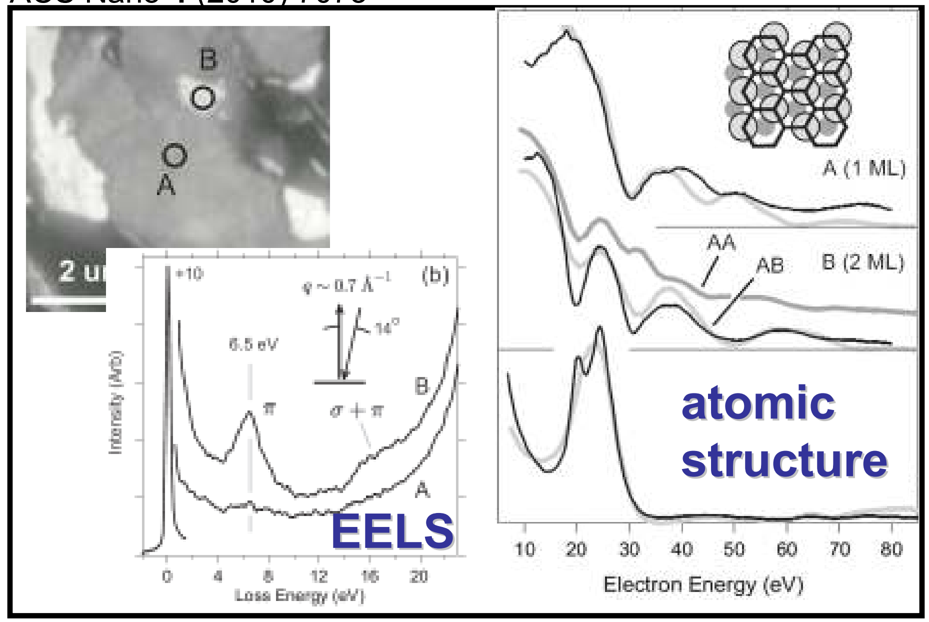


Recent advances in LEEM/PEEM

Physical Review **B79**, 121401(R) (2009)

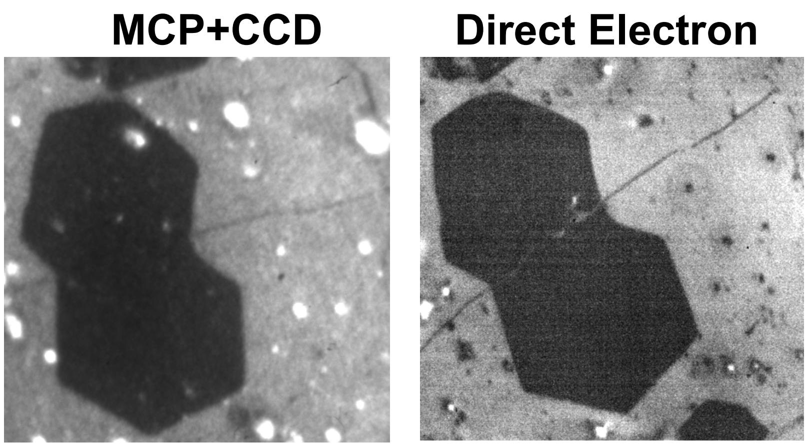


ACS Nano **4** (2010) 7073



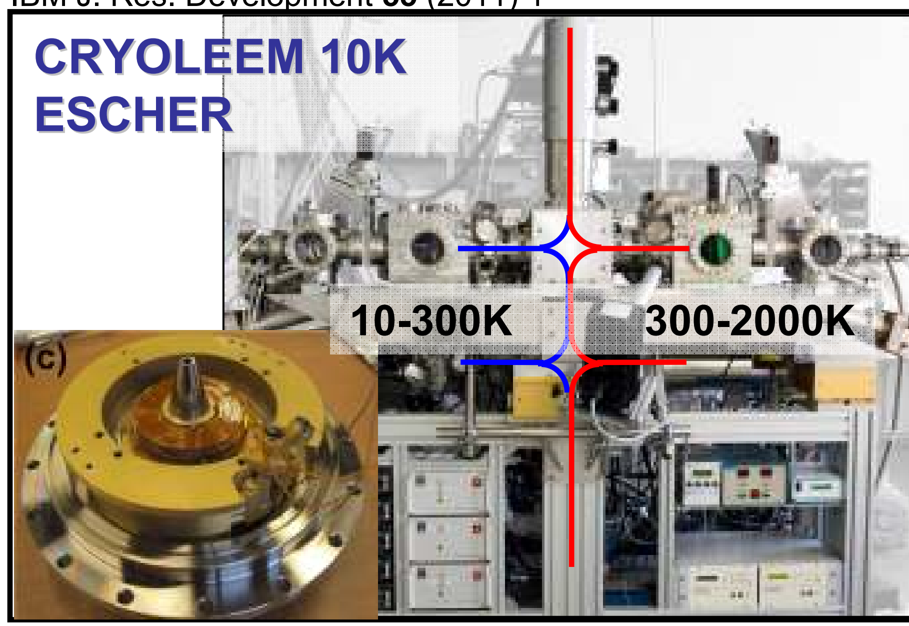
Ultramicroscopy **110** (2009) 33

Improved detector technology



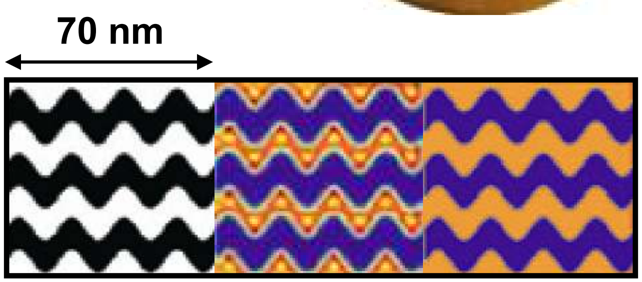
4x resolution improvement, 10x more data

IBM J. Res. Development **55** (2011) 1



Record Resolution in Aberration Corrected Low Energy Electron Microscopy

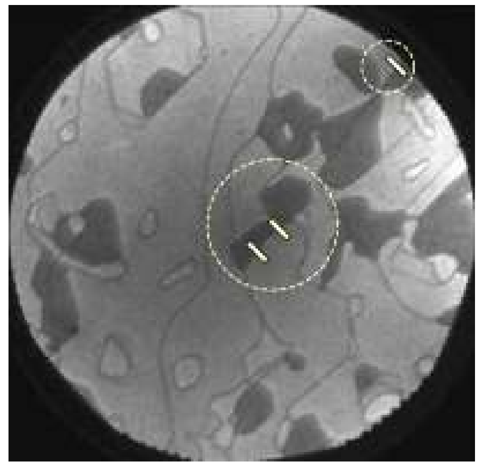
Correct bad objective lens with *equally* bad electron mirror

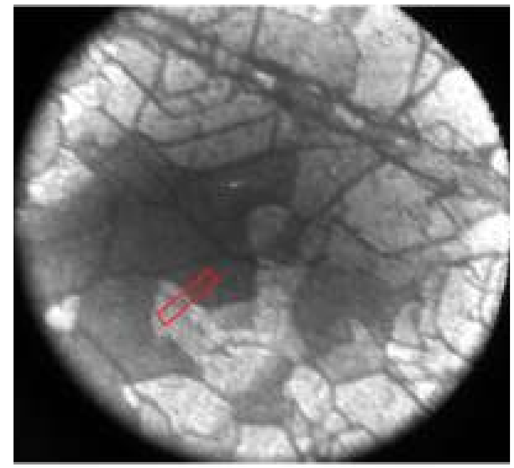


object **uncorrected image** **corrected image**

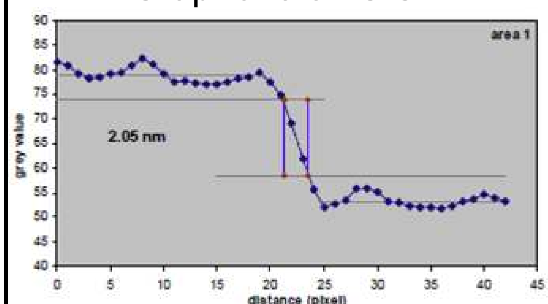
Highest resolution microscope in the world: d = 22λ (300 keV)

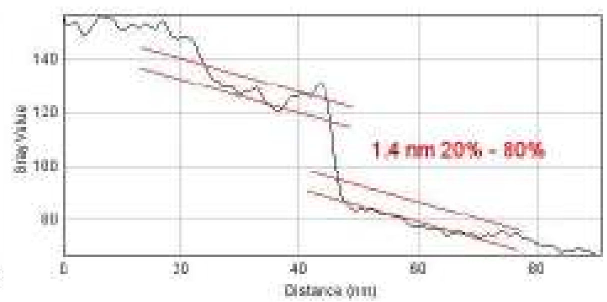
Goal for LEEM: d < 2λ (5 eV)
challenges:
power supplies < 0.1 ppm
vibrations, shielding
image detector





Graphene on SiC

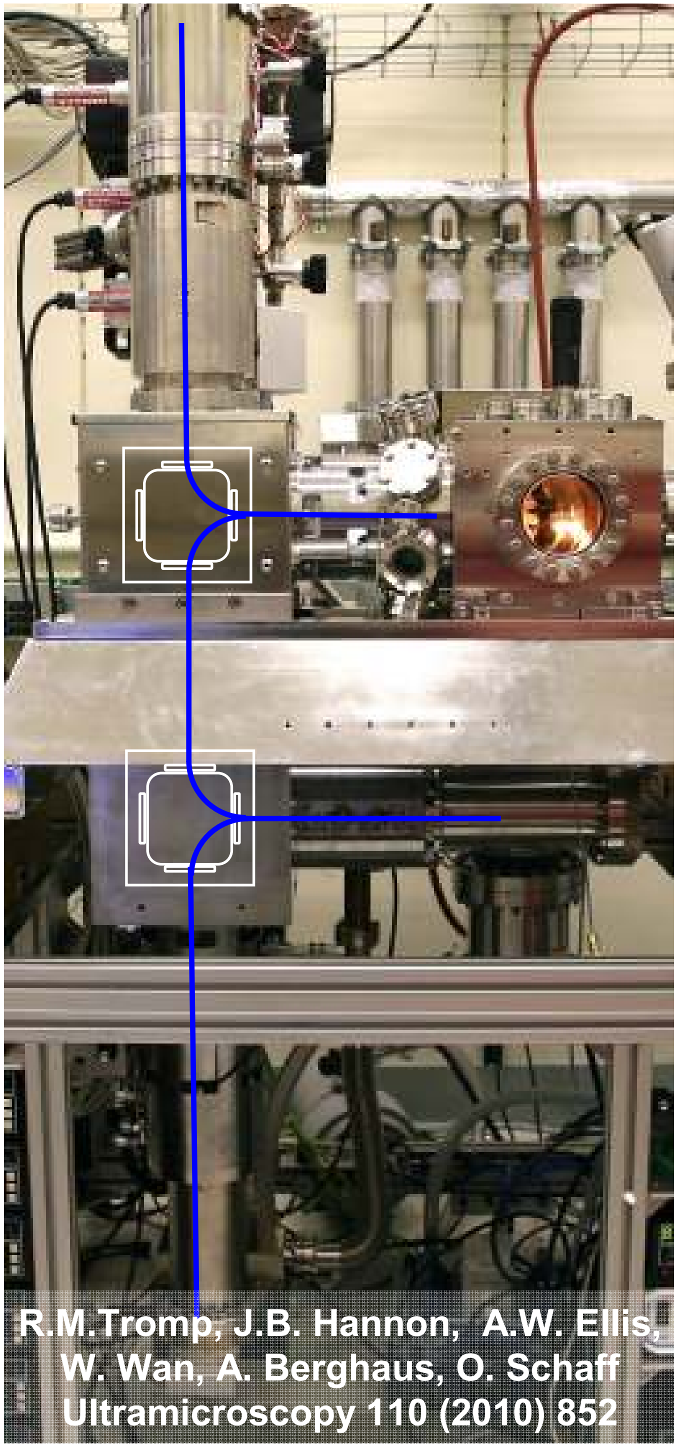




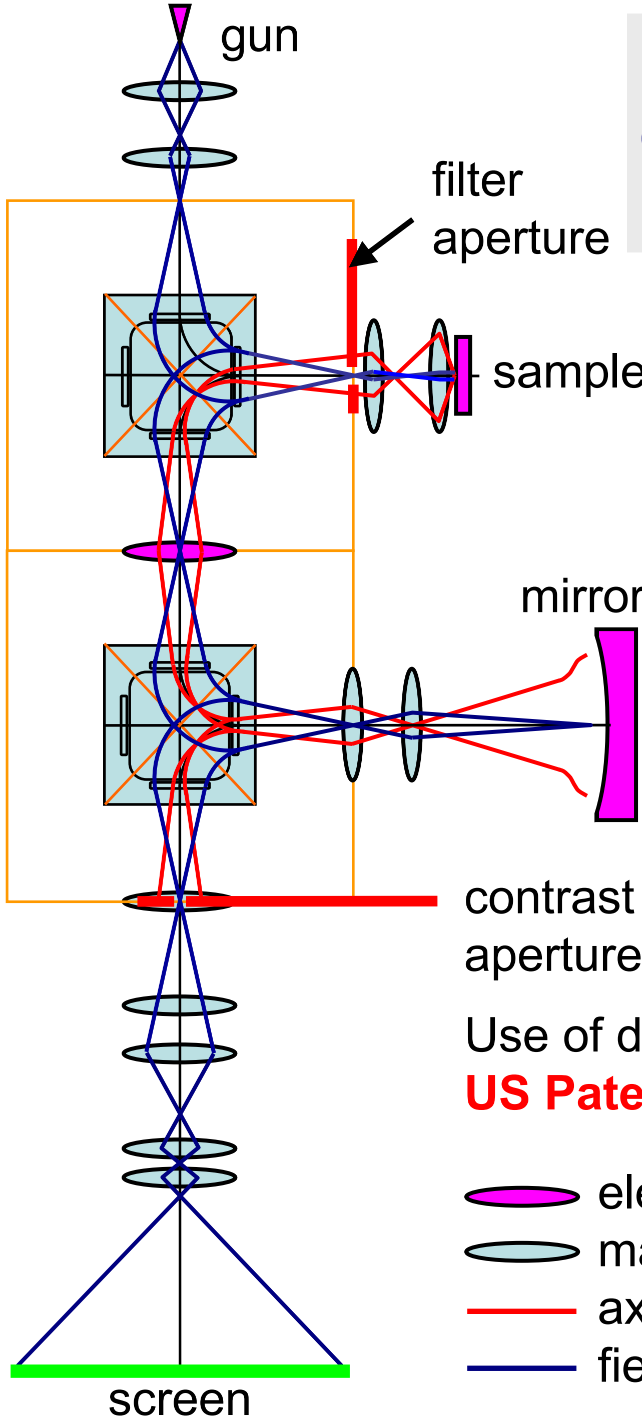
2009: 4 nm
2010: 2 nm
2011: 1.4 nm = 2.3λ
2013 goal: 1.0 nm

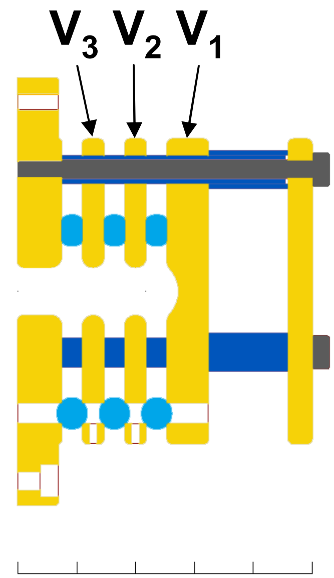
Ruud Tromp
Jim Hannon
Arthur Ellis
Oliver Schaff -SPECS
Weishi Wan -LBNL

aberration correction ray diagram



R.M.Tromp, J.B. Hannon, A.W. Ellis, W. Wan, A. Berghaus, O. Schaff
Ultramicroscopy 110 (2010) 852

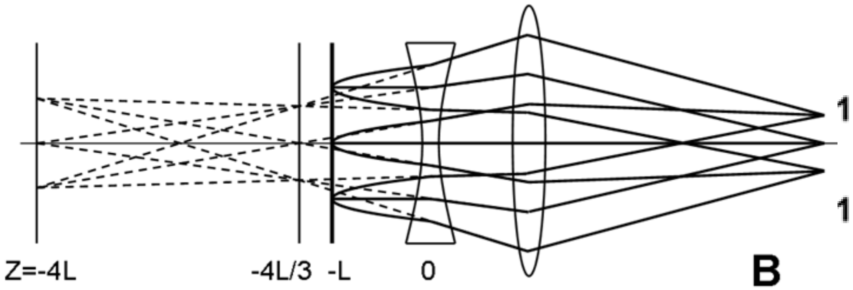




Use of double prism array:
US Patent 7348566

- electrostatic lens
- magnetic lens
- axial ray
- field ray

Aberrations of the cathode objective lens up to 5th order



Uniform field:

$$C_c = -C_3 = -L(E/E_0)^{1/2}$$

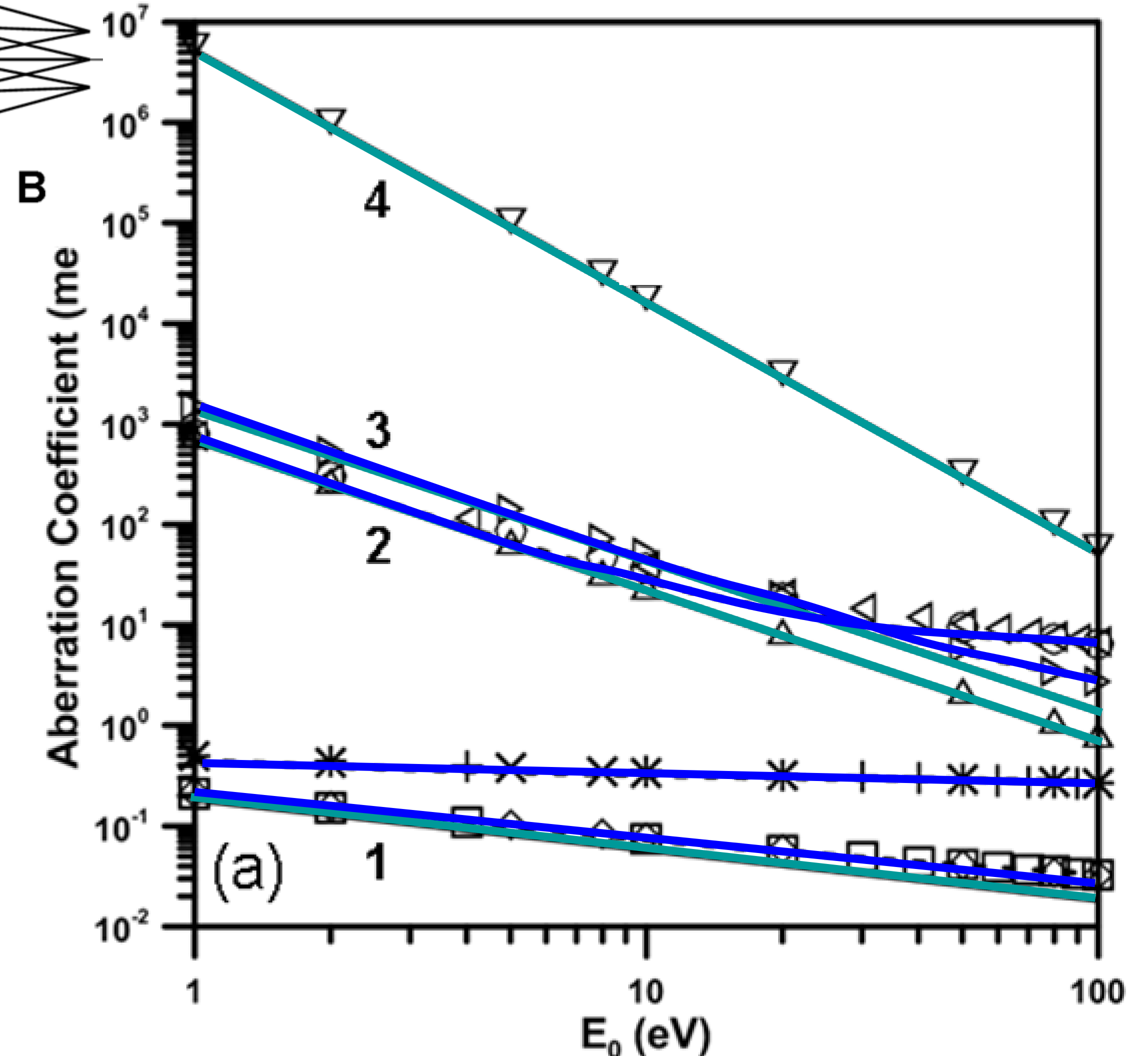
$$C_{cc} = C_5 = \frac{1}{4}L(E/E_0)^{3/2}$$

$$C_{3c} = -\frac{1}{2}L(E/E_0)^{3/2}$$

$$C_{c3} = -\frac{1}{8}L(E/E_0)^{5/2}$$

$$C_{3cc} = \frac{3}{8}L(E/E_0)^{5/2}$$

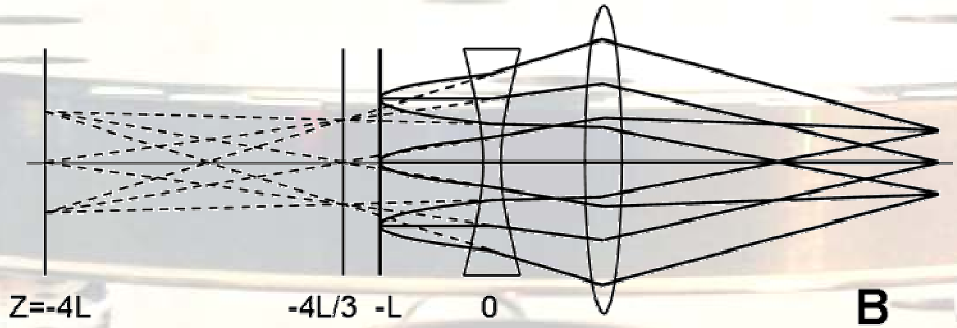
$$C_{c4} = \frac{5}{64}L(E/E_0)^{7/2}$$



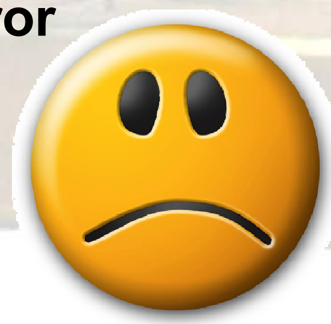
E.Bauer, Ultramicroscopy **17** (1985) 51
R.M. Tromp, W. Wan, S.M. Schramm, Ultram. **119** (2011) 33

IBM

How to measure and correct aberrations?



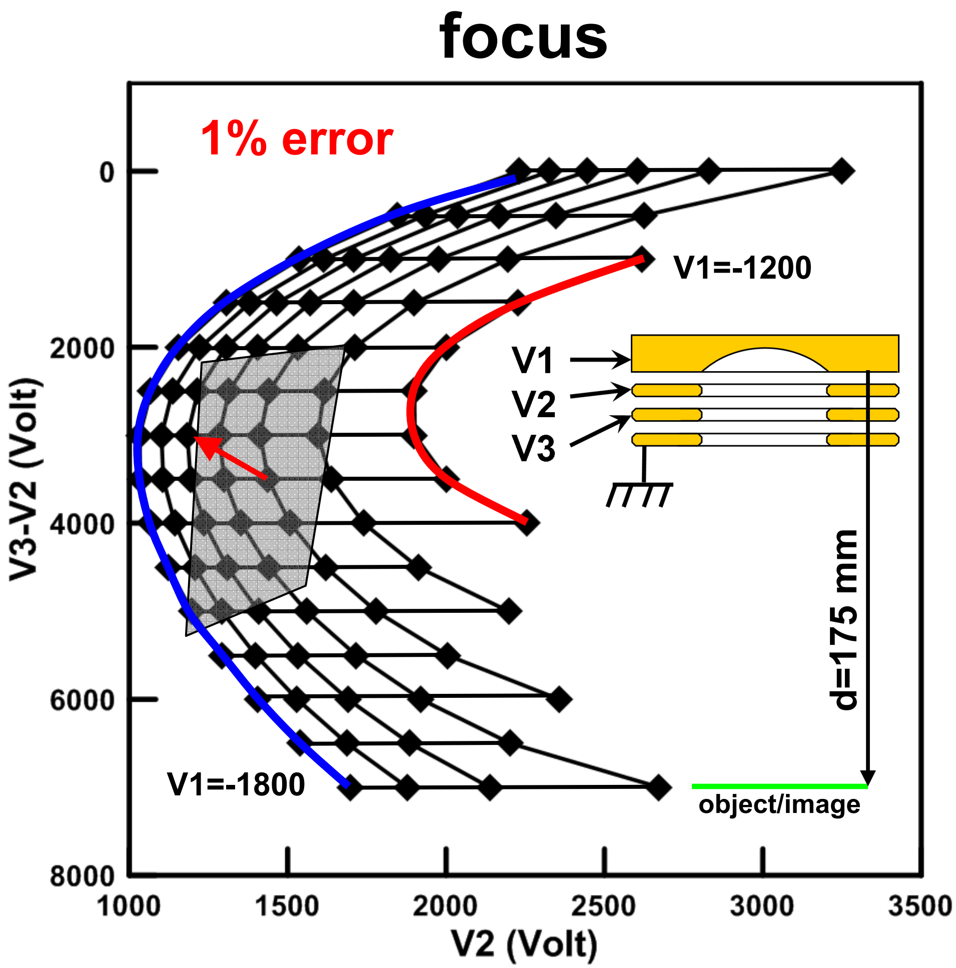
- **Aberrations of the cathode lens are energy dependent; measurement/correction at one energy is not good enough…**
- **C_c and C_3 have different energy dependence**
- **Aberrations contain contributions from the uniform field and from the magnetic part of the objective lens; how do we measure?**
- **C_c scales with M^2, C_3 with M^4: must control magnification**
- **Would like to automatically track the energy dependence with the electron mirror**

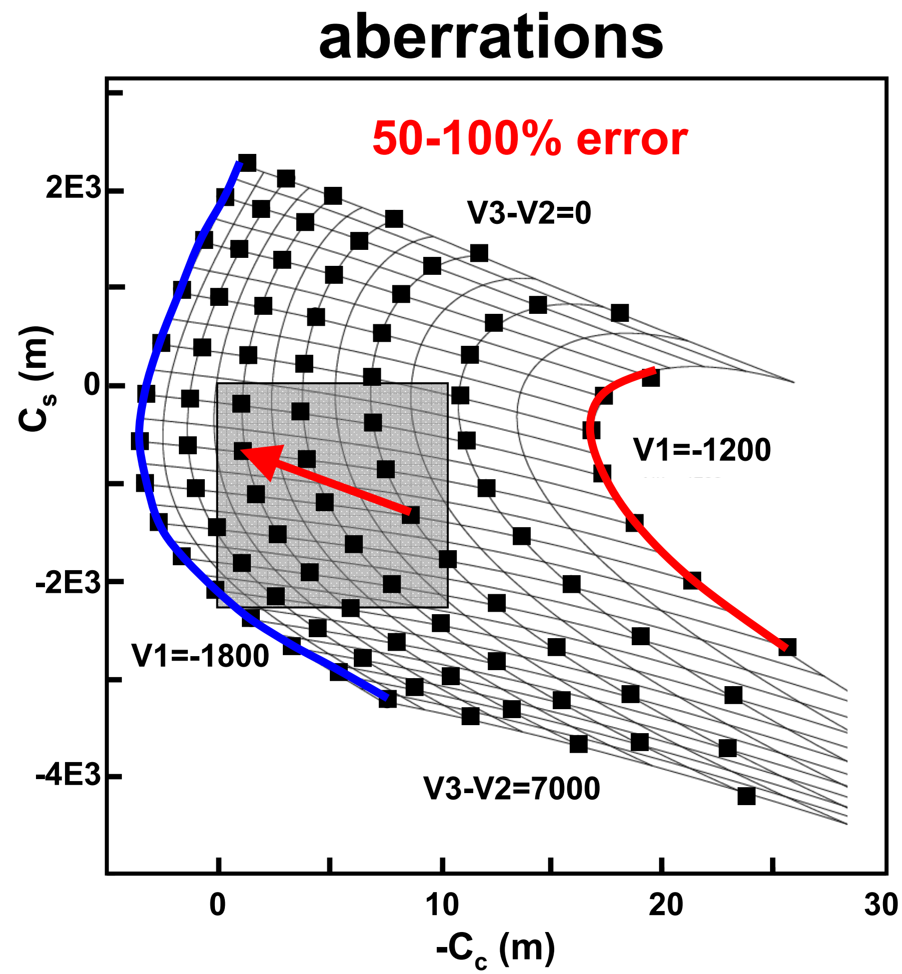


Not so easy…

R M Tromp. *Ultramicroscopy* **111** (2011) 273-81

Correlation of first and higher order properties

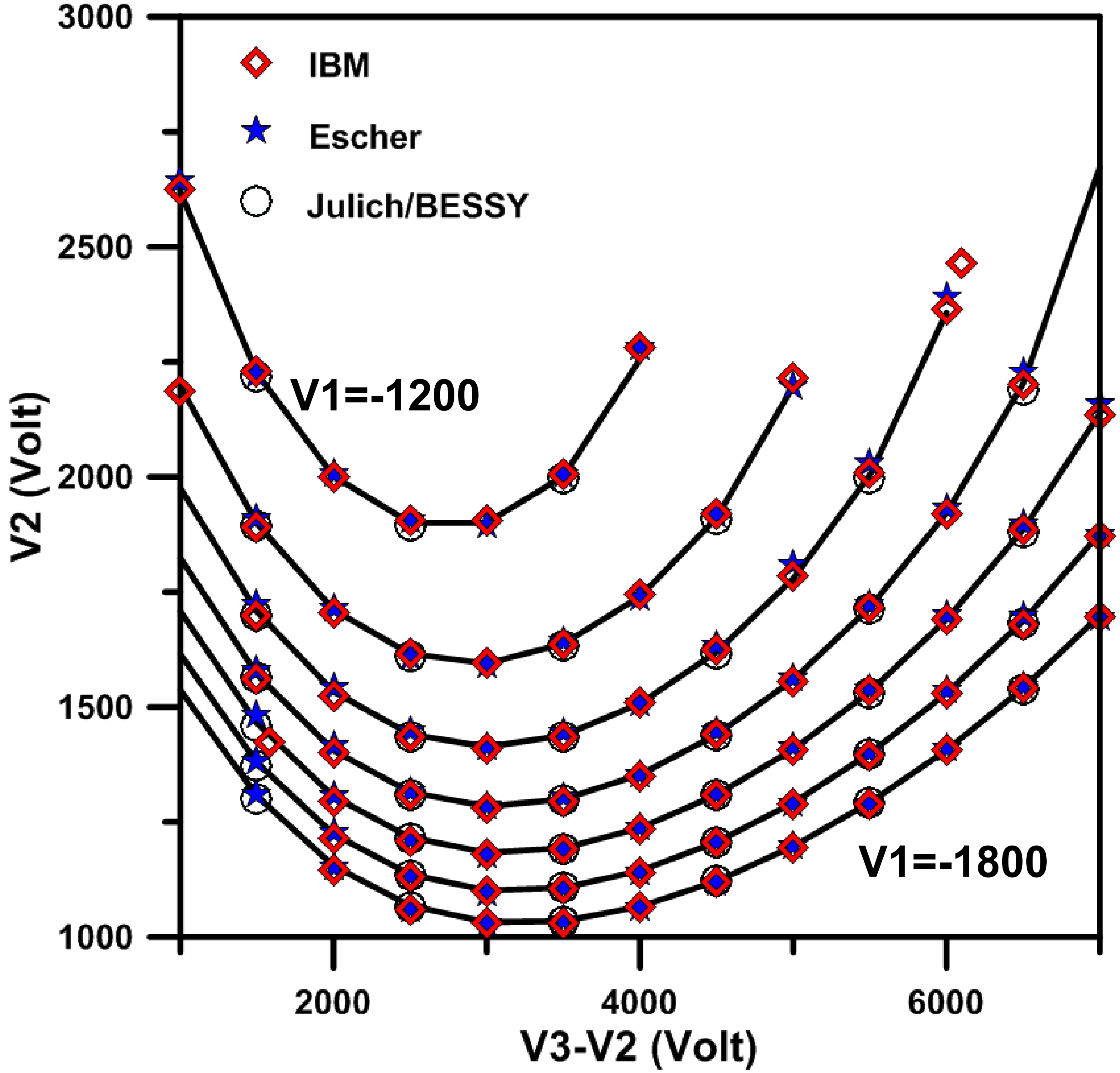


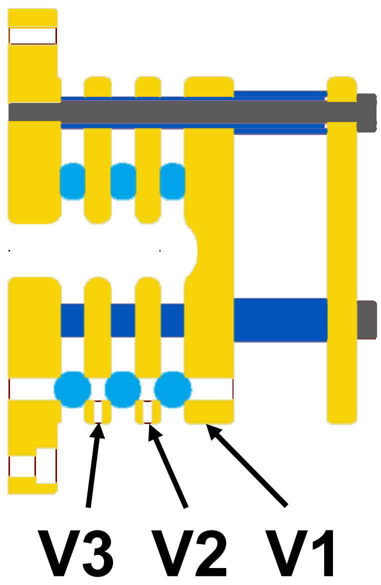


Aberration map (right) directly correlated to focus map (left)
Small error in focus setting gives large error in aberration constants

R.M. Tromp, J.B. Hannon, A.W. Ellis, W. Wan, A. Berghaus, O. Schaff, Ultram. **110** (2010) 852

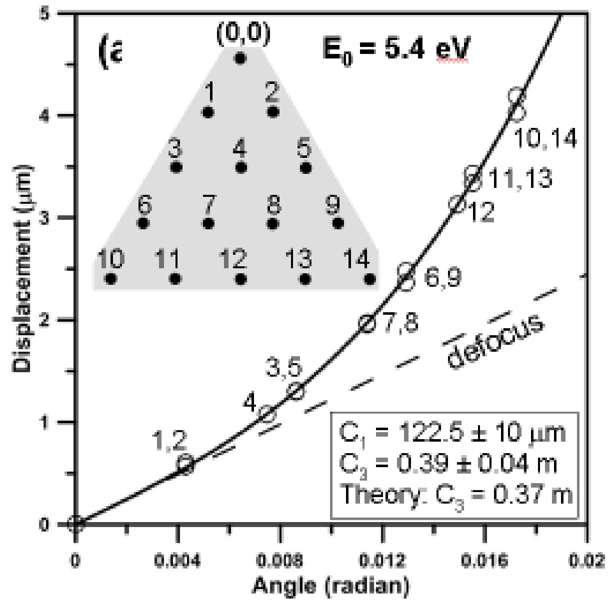
Mirror focusing: theory vs experiment

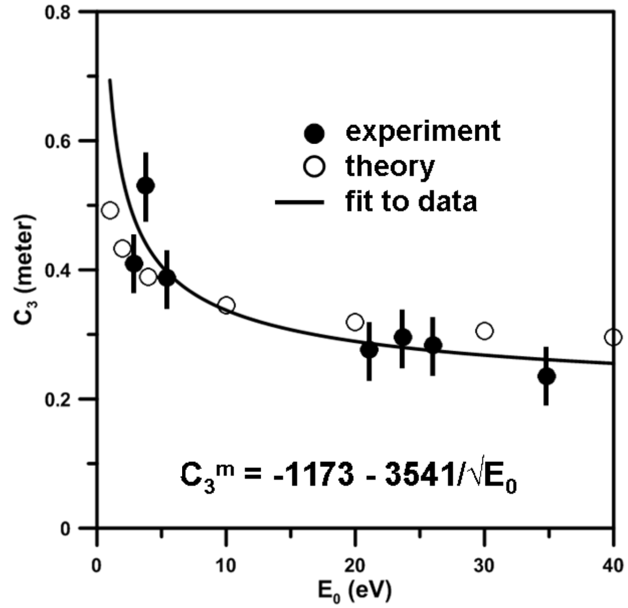


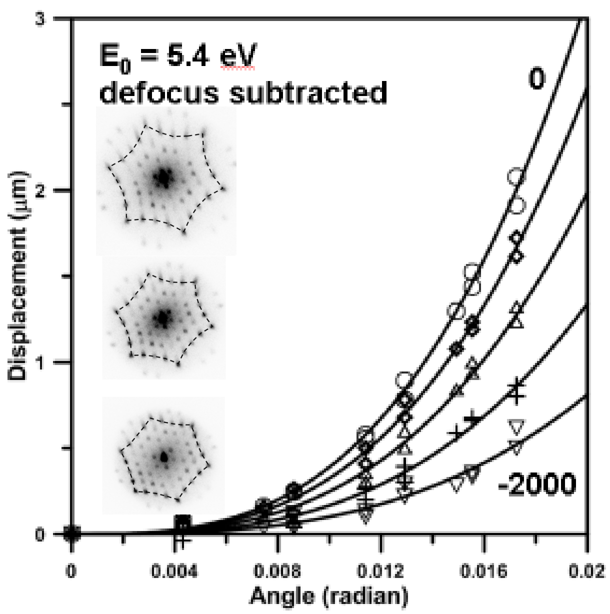


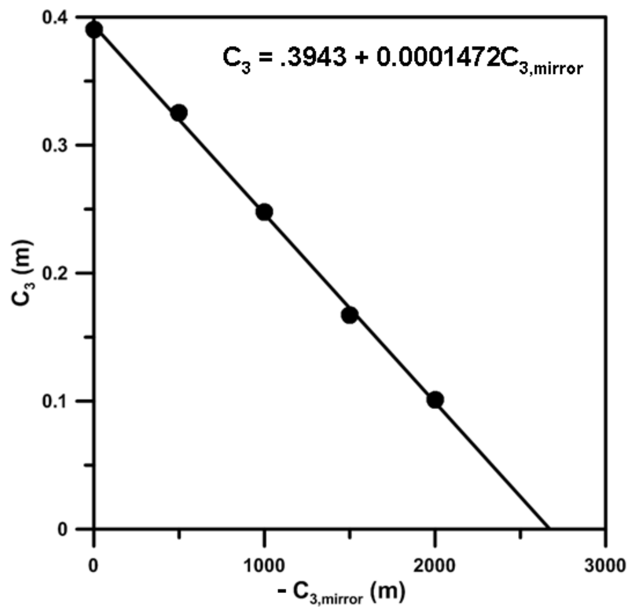
Adjustable parameter:
V1 offset of **10 V**
(out of 16500, i.e. **0.06%**)

Measurement and Correction of C_3 : $\delta = c_1\alpha + c_3\alpha^3$









Electron Mirror:

$C_3 = 0.3943 + 0.0001472 C_3^m$

$C_3 = C_3^o + C_3^m/M^4$

$1/M^4 = (0.0001472)^{1/4}$

$M = 9.07$ (8.5, +7%)

Objective lens:

$C_3^o = a + b/\sqrt{E_0}$

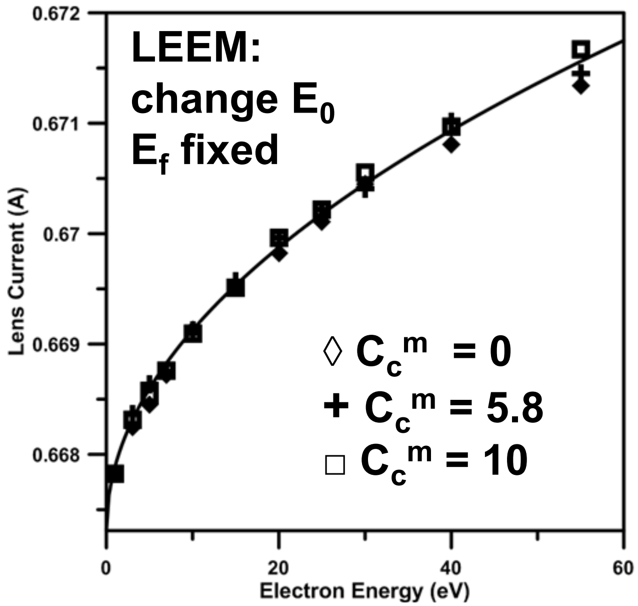
Track spherical aberration:

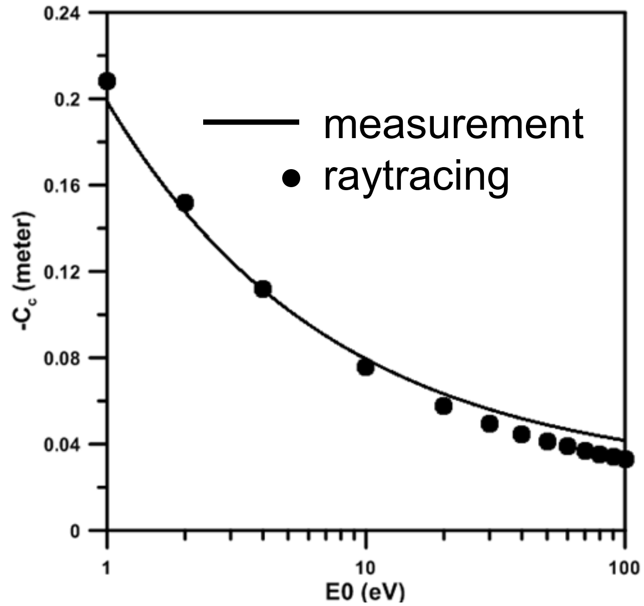
$a + b/\sqrt{E_0} + C_3^m/M^4 = 0$

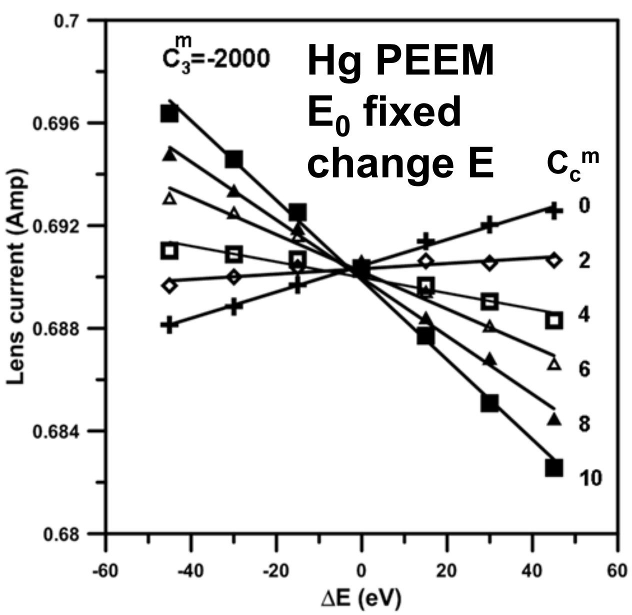
R.M. Tromp, J.B. Hannon, W. Wan, Berghaus, O. Schaff, Ultramicroscopy
http://dx.doi.org/10.1016/j.ultramic.2012.07.016

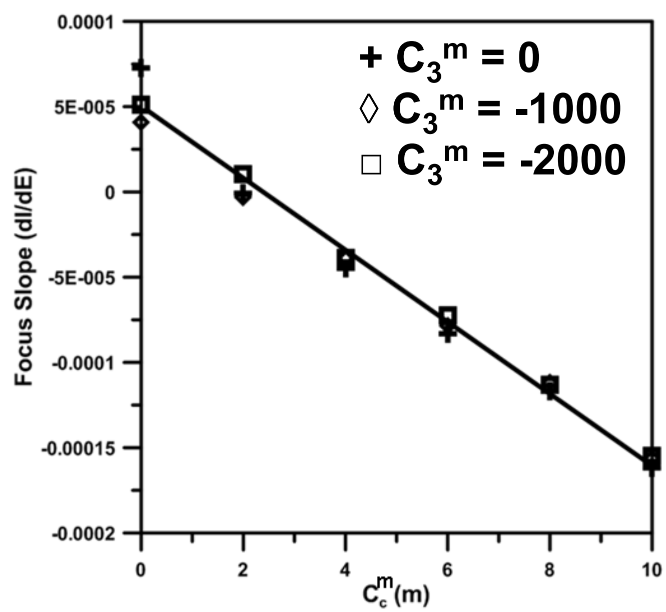
IBM

Measurement and Correction of C_c : $E_f = E_0 + E$









Uniform field (LEEM):

$I = I_0 + a\sqrt{E_0}$

$dI/dE_0 = a/(2\sqrt{E_0})$

Magnetic field + mirror (Hg PEEM):

$dI/dE = c - s.C_c^m$

Correction:

$dI/dE_0 + dI/dE = 0$

Track chromatic aberration:

$C_c^m = (c + a/(2\sqrt{E_0}))/s$

R.M. Tromp, J.B. Hannon, W. Wan, Berghaus, O. Schaff, Ultramicroscopy
http://dx.doi.org/10.1016/j.ultramic.2012.07.016

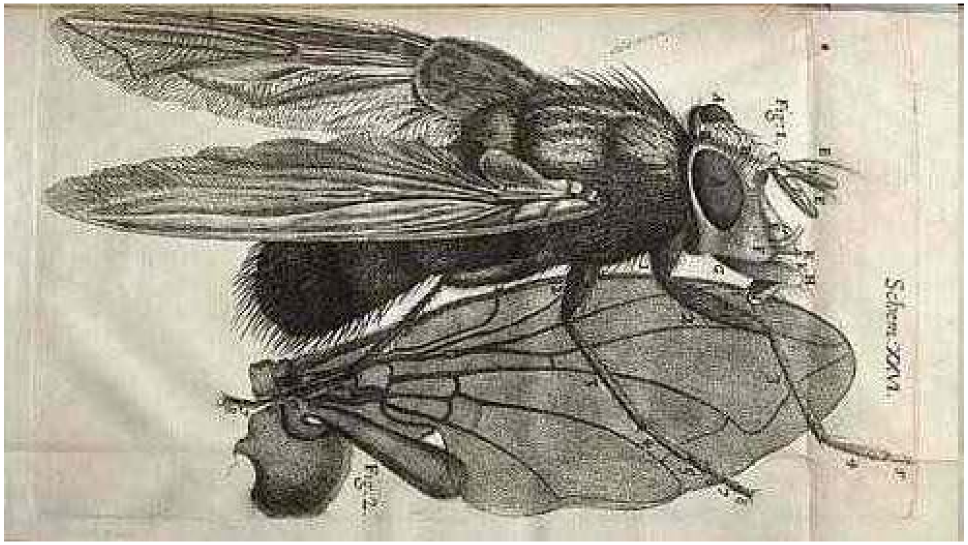
IBM

Experiments conform very closely to theory

- **Excellent agreement focusing properties <0.1%**
- **C_c and C_3 of the electron mirror can be set *quantitatively*, independent of each other, and at fixed mirror focal length**
- **C_c and C_3 of the objective lens are in good agreement with theory, and can be measured routinely with simple experimental procedures**
- **Electron mirror can seamlessly track C_c and C_3 aberrations of objective lens as E_0 is changed:**

Automatic Tracking Aberration Correction (ATrAC)

But… every ointment has its fly…

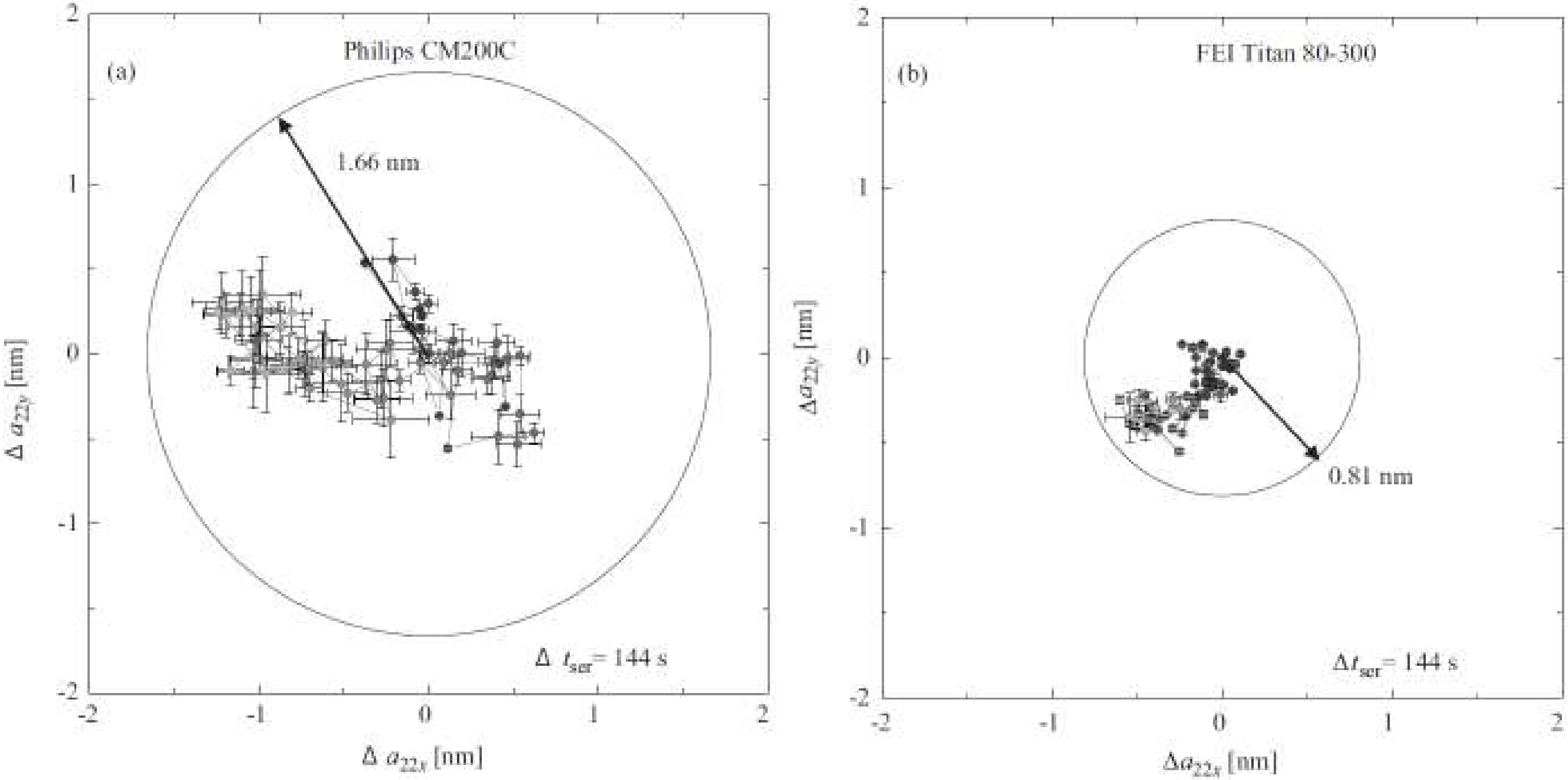


R. Hooke, Micrographia, 1665

How does the resolution depend on the degree to which we correct?
Does it make a big difference if we are a few percent off?
How stable is the corrected state?

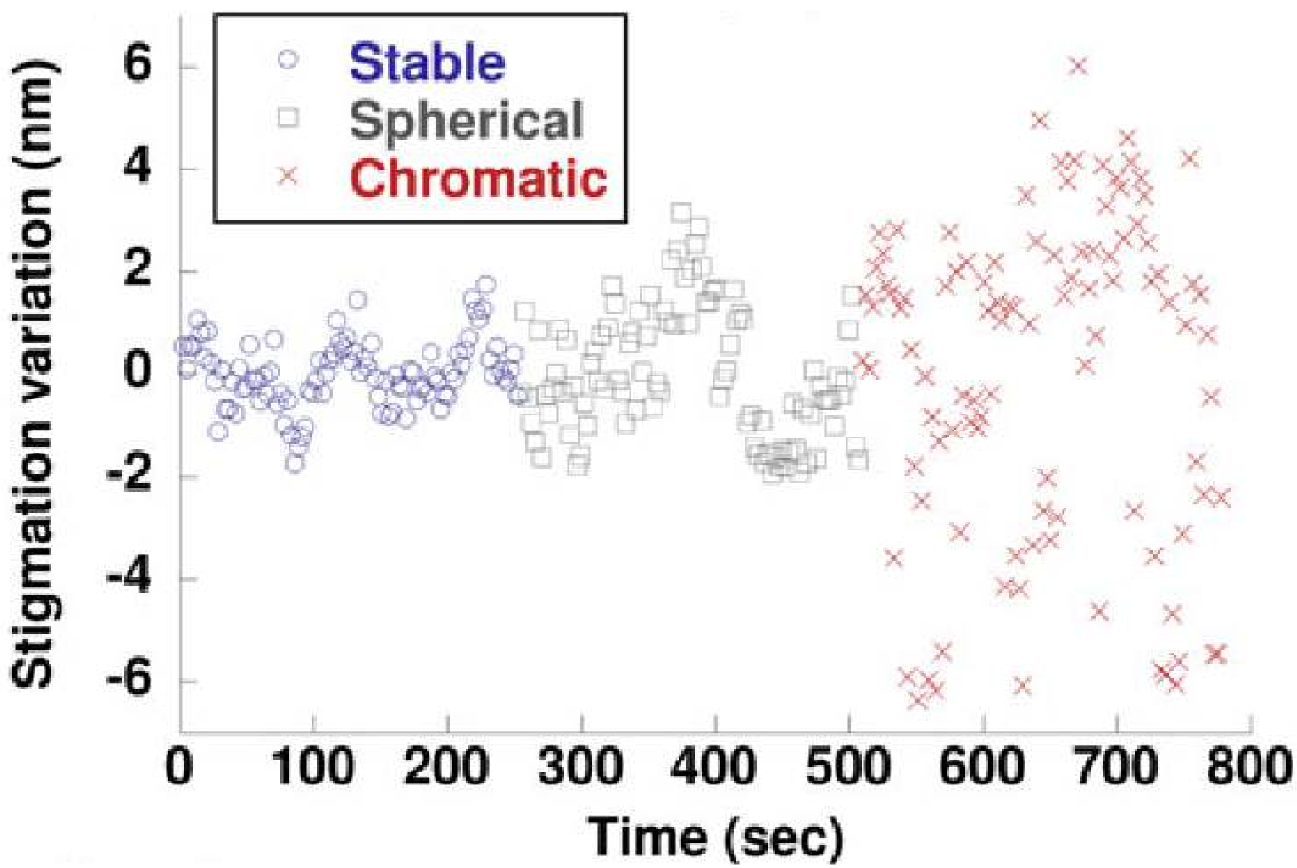
TEM Stability I

Lifetime of the corrected state is just a few minutes.
Enough for a focus series, but problematic for longer experiments.



J. Barthel, A. Thust, Ultramicroscopy **11** (2010) 27

TEM Stability II – TEAM I



P. Ercius, M. Boese, Th. Duden and U. Dahmen (2012).
Operation of TEAM I in a User Environment at NCEM.
Microscopy and Microanalysis,**18** (2012) pp 676-683

Intrinsic Instability of Corrected Electron Optics

Image = FT^{-1} (FT(object) x Contrast Transfer Function x MTF)

Object **Objective lens aberrations** **Detector**

$$W = e^{i2\pi\chi} = \cos(2\pi\chi) + i\sin(2\pi\chi)$$

$$\chi = -\frac{1}{2}\lambda q^2 \Delta z + \frac{1}{4} C_3 \lambda^3 q^4 + \frac{1}{6} C_5 \lambda^5 q^6$$

$$E_c(q) = \exp\left(-\frac{(\pi C_c \lambda q^2)^2}{16\ln 2}\varepsilon^2\right)$$

$$\delta = 1/q_r \propto C_3^{1/4}$$

$$\delta = 1/q_r \propto C_5^{1/6}$$

$$\delta = 1/q_i \propto C_c^{1/2}$$

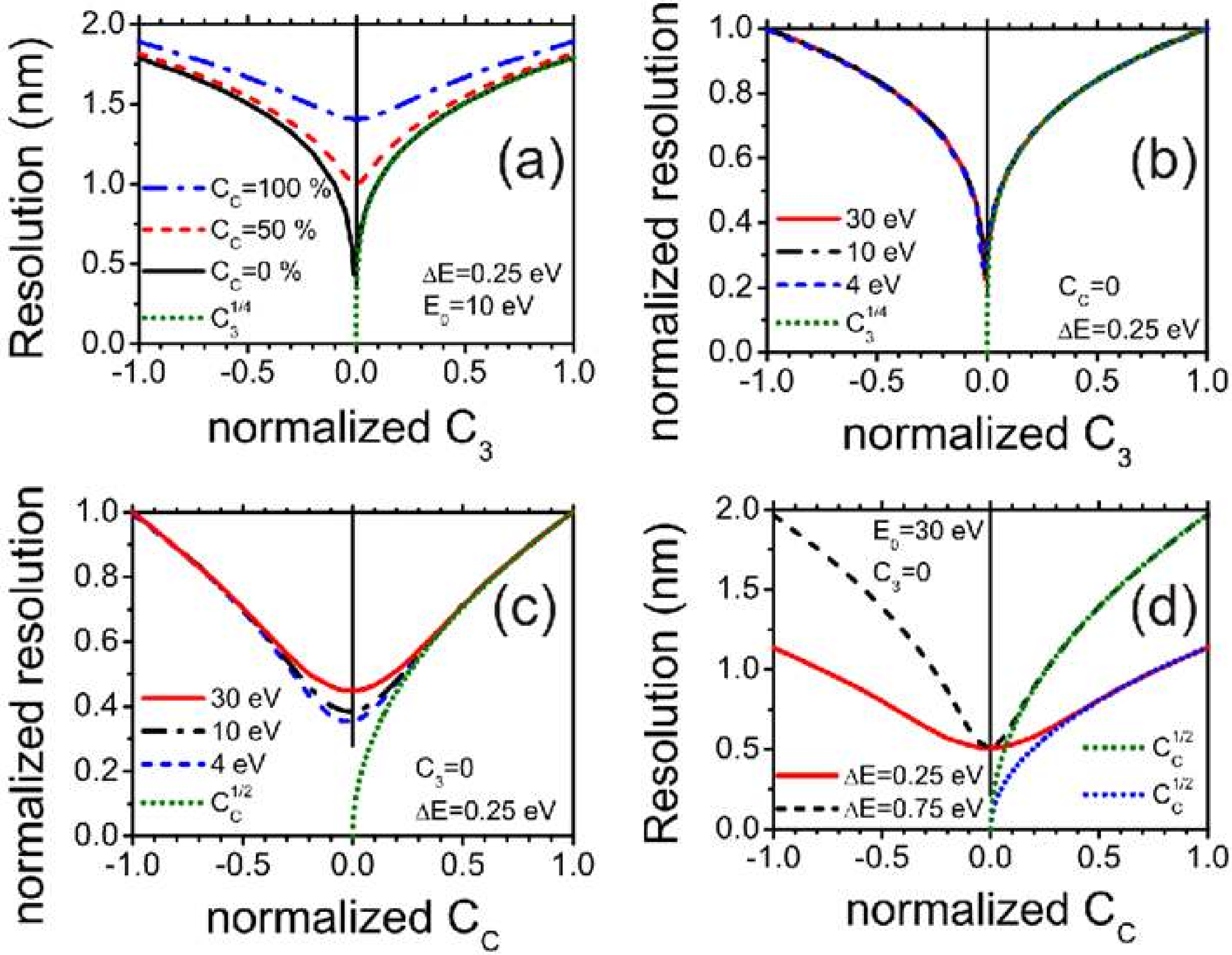
$\partial\delta/\partial C = 1/C^{n/(n+1)}$ diverges to ∞ as C → 0

intrinsically unstable….

IBM

S.M. Schramm, S.J. van der Molen, R.M. Tromp Phys. Rev. Lett. **109** (2012) 163901

Aberration correction in LEEM



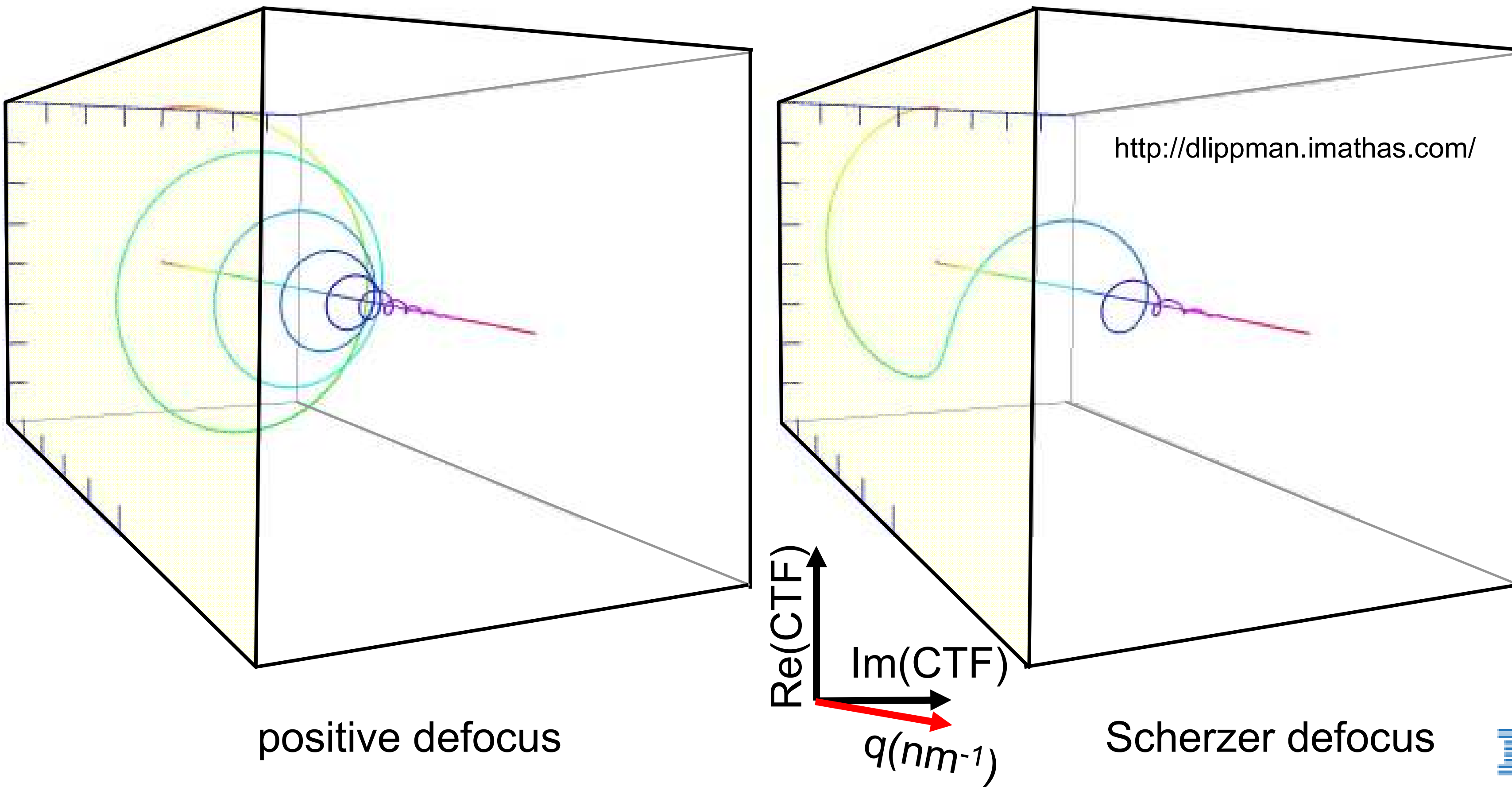
$\partial\delta/\partial C_{c,3}$ diverges near corrected state

S.M. Schramm, S.J. van der Molen, R.M. Tromp Phys. Rev. Lett. **109** (2012) 163901

3D contrast transfer function

Contrast transfer function is given by $e^{i2\pi\chi}$ where χ is the aberration function.

$$\chi(q)=C_1\lambda q^2/2+C_3\lambda^3 q^4/4+C_5\lambda^5 q^6/6+\ldots$$

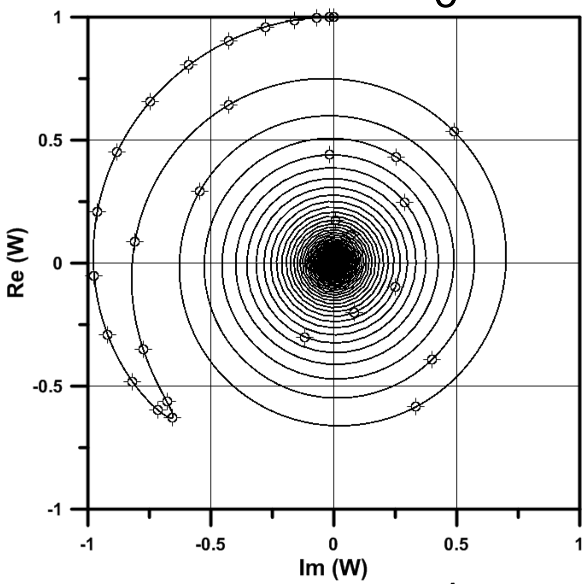


positive defocus

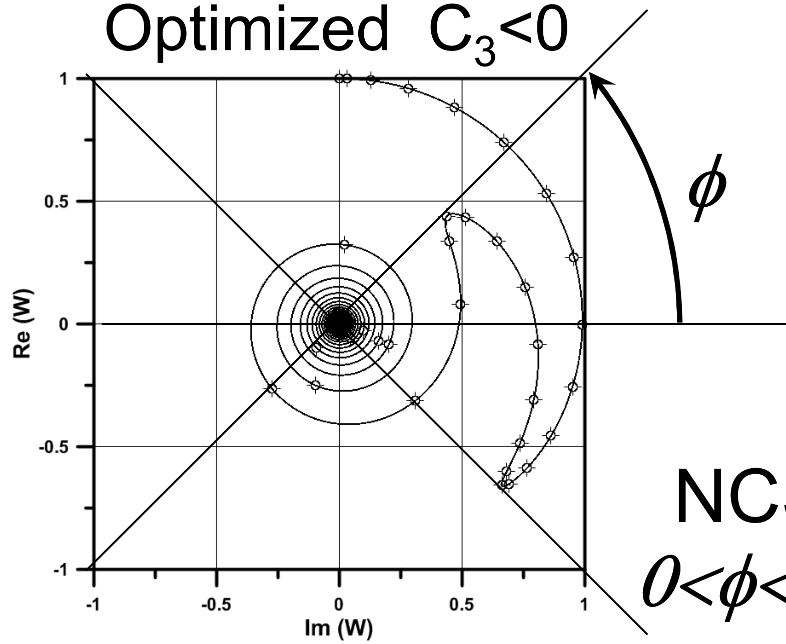
Scherzer defocus

Optimization of χ

Scherzer $C_3=0$

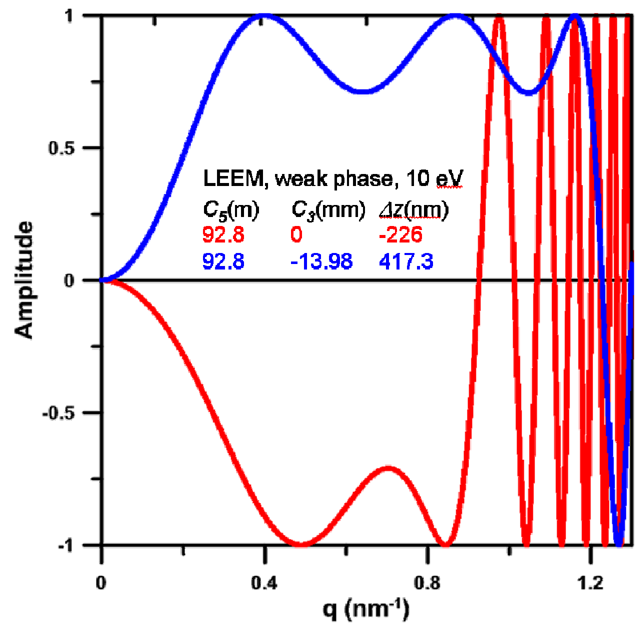


Optimized $C_3<0$



NCSI

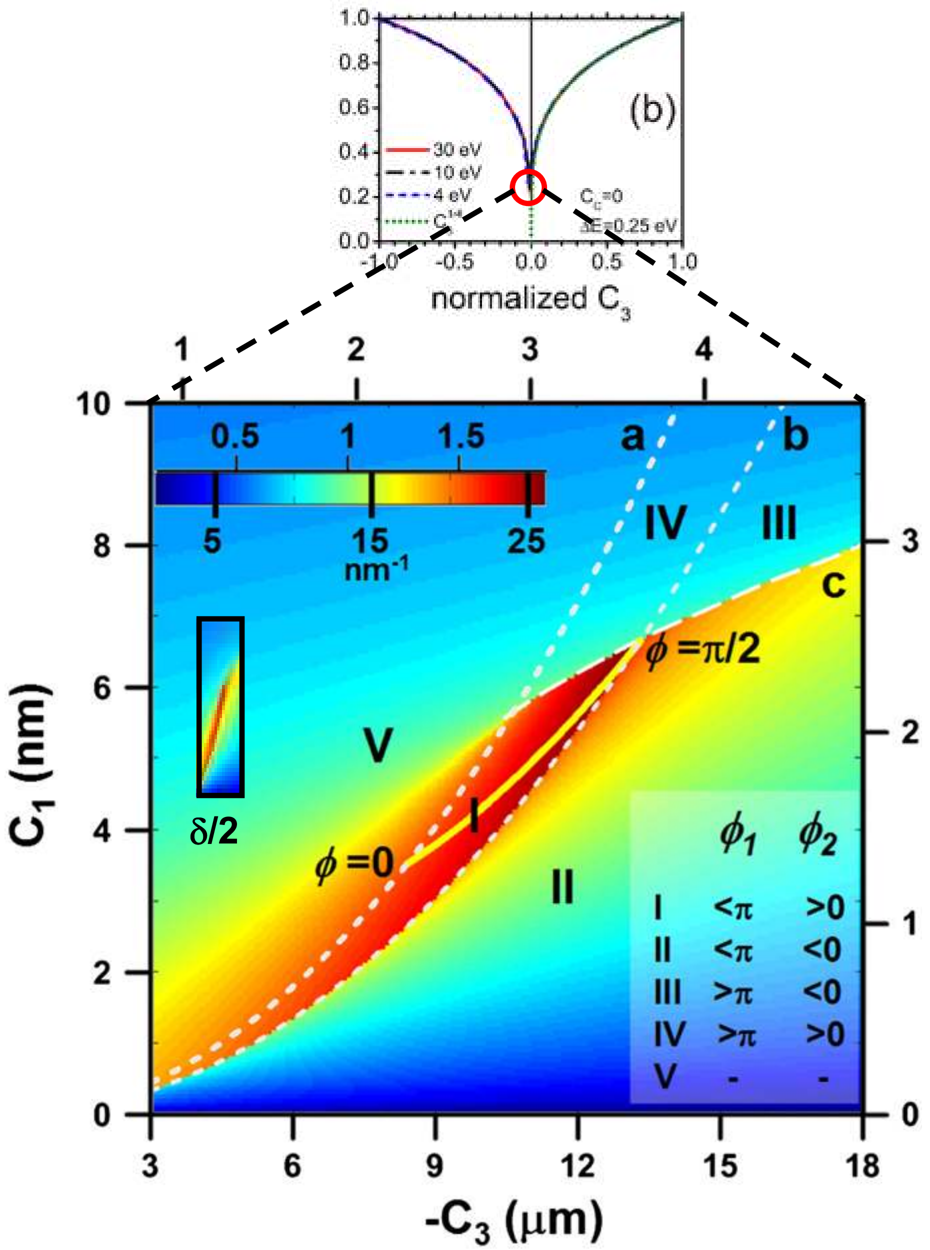
$0<\phi<\pi/2$



S.M. Schramm, S.J. van der Molen, R.M. Tromp Phys. Rev. Lett. **109** (2012) 163901; R.M. Tromp, S.M. Schramm, Ultramicroscopy ***125*** *(2013) 72-80*

IBM

Working parameters AC-TEM, AC-LEEM



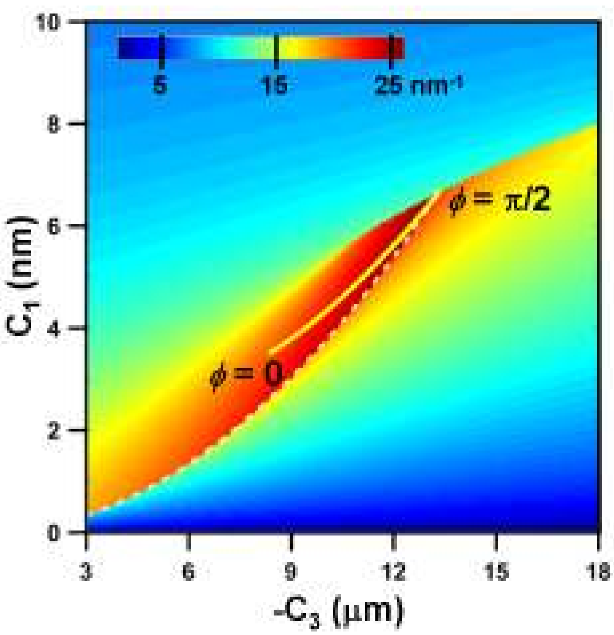
Operating margins are razor-thin.
$\phi = \pi/4$:
Range of defocus < 0.3 nm
$\Delta C_3 < 0.25\ \mu m$

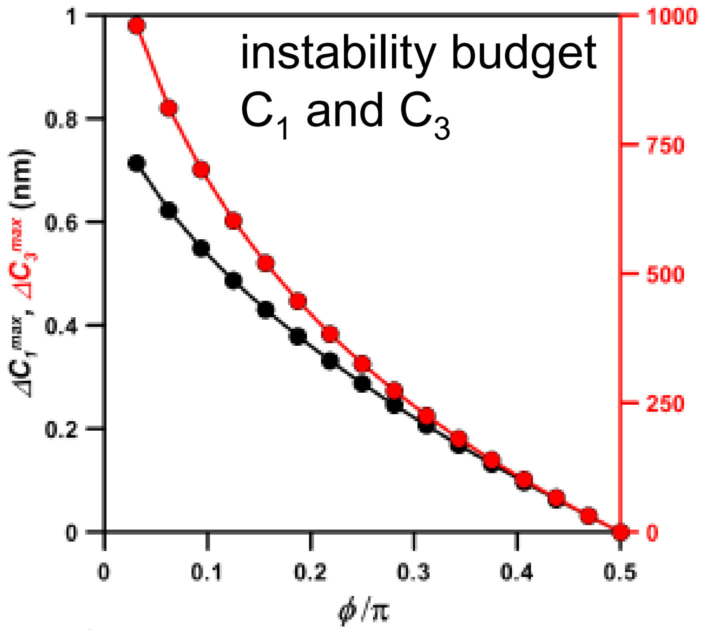
Further 2x resolution improvement is probably impossible.
Situation for LEEM will be the same below 1 nm.

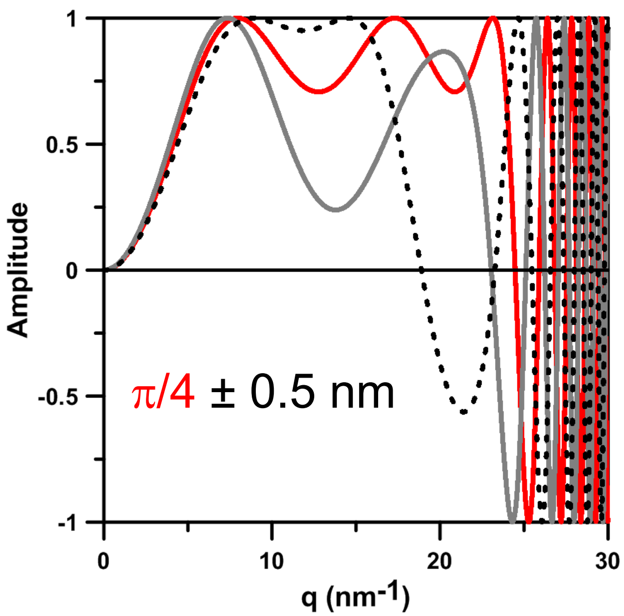
S.M. Schramm, S.J. van der Molen, R.M. Tromp Phys. Rev. Lett. **109** (2012) 163901; R.M. Tromp, S.M. Schramm, Ultramicroscopy ***125*** *(2013) 72-80*

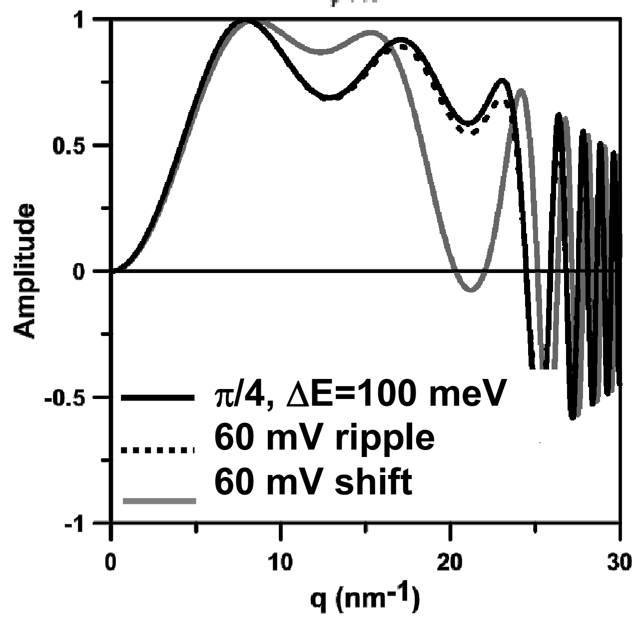
IBM

What does this mean in practice?



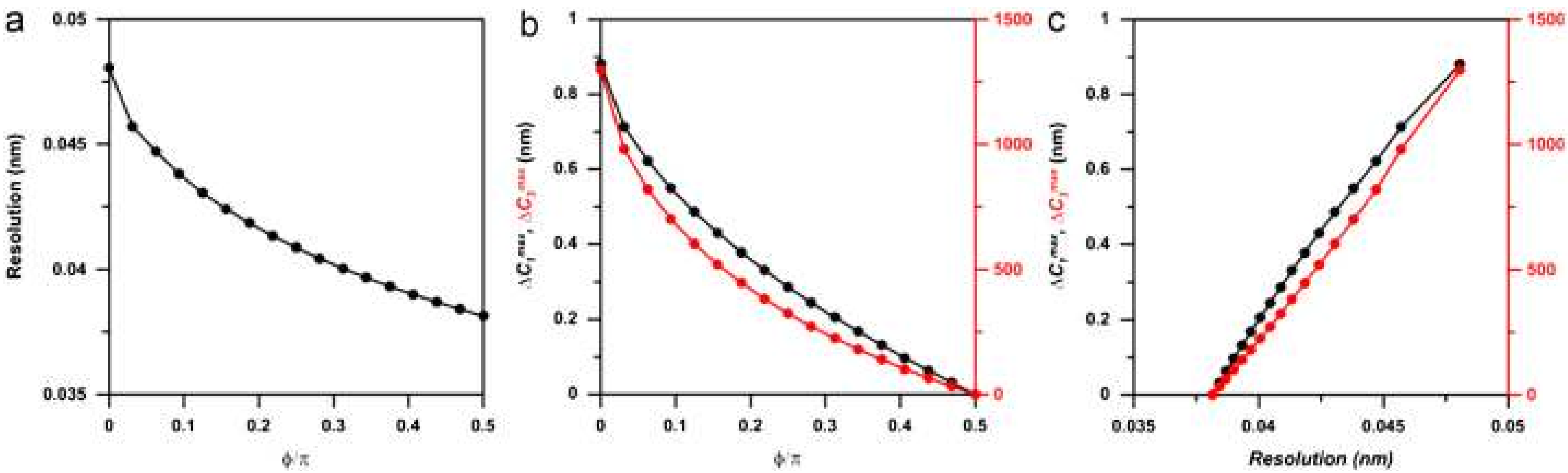






Highly sensitive to:
Defocus
Z-drift
Astigmatism
Voltage fluctuations
T-variations
etc

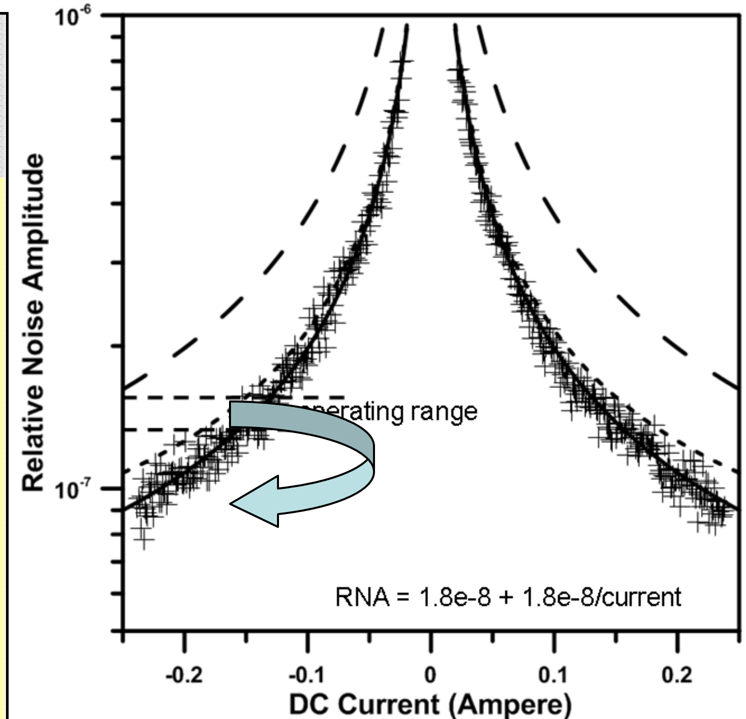
Trade resolution vs stability…

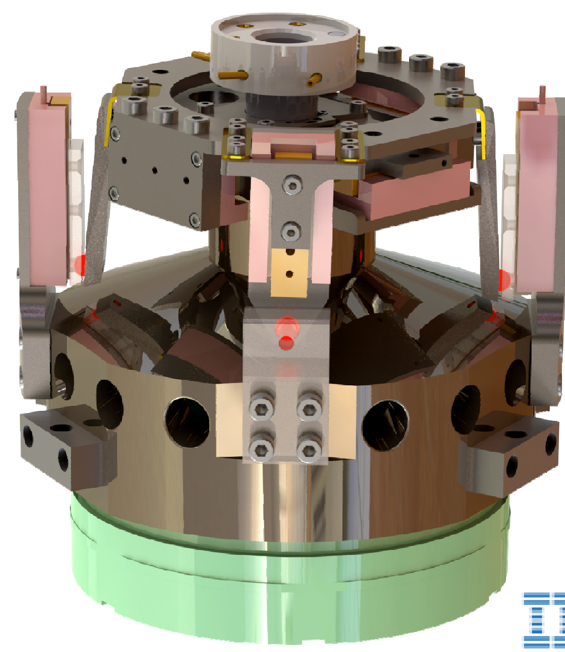


At 0.1 nm resolution system is very stable
At < 0.05 nm resolution life becomes difficult,
and lifetime of the corrected state becomes very short.
Pick where you want to be.

The hunt for 1 nm in AC-LEEM

- **Improve power supplies (< 0.1 ppm)**
  - *reduction of AC ripple*
- **New sample stage**
  - *improved stability and shielding*
- **Improve acoustic/vibration isolation**
  - *improvements to pump isolation*
  - *active damping installed*
- **Improve electromagnetic shielding**
  - *integrated shielding in new stage*
  - *more μ-metal*
- **Improve MTF of detector**
  - *Medipix detector tested (2x)*
  - *Direct Electron detector (4x)*
- **Don't lose patience**





IBM

Jim Hannon
Art Ellis
Oliver Schaff
Andreas Berghaus
Weishi Wan
Sebastian Schramm
Sense Jan van der Molen
Robert Bilhorn
Liang Jin