Aberration Correction in Microscopes

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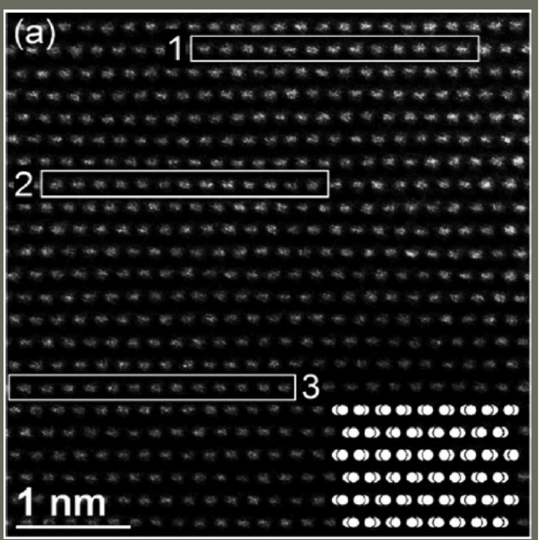
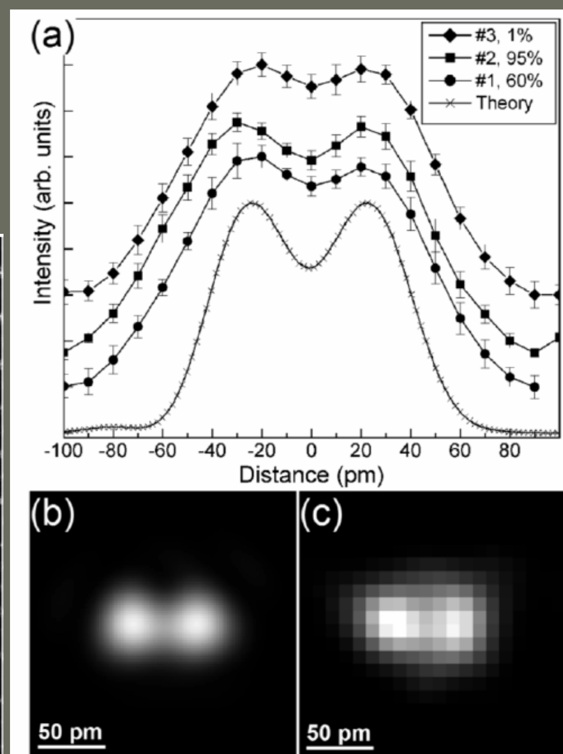
TEAM 0.5 Results

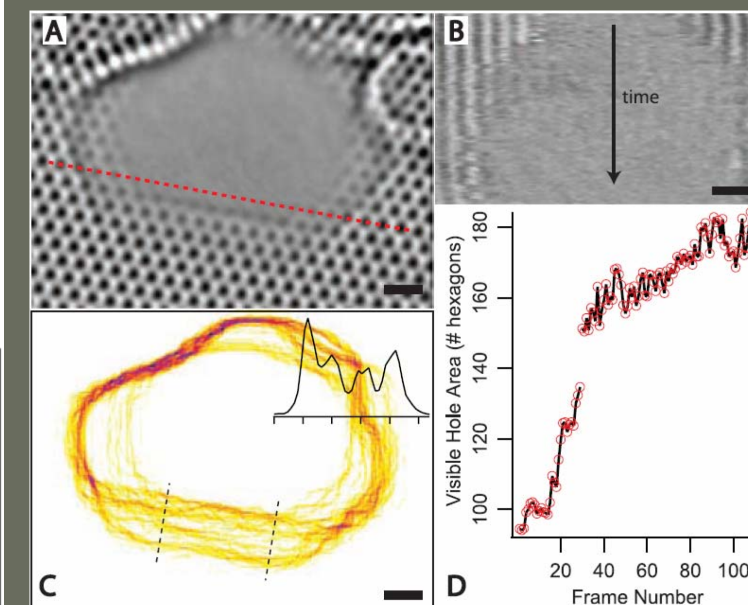
Atomic Resolution Imaging with a Sub-50-pm Electron Probe





Erni et al, PRL **102**, 096101 (2009)

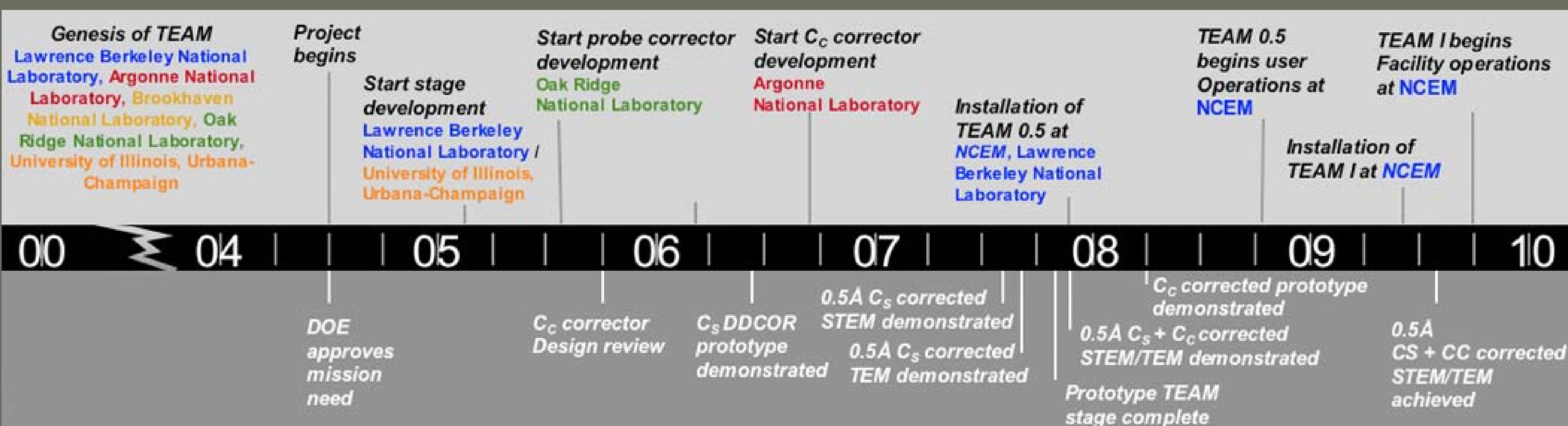
Graphene at the Edge: Stability and Dynamics



Girit et al, Science **323**, 1705 (2009)

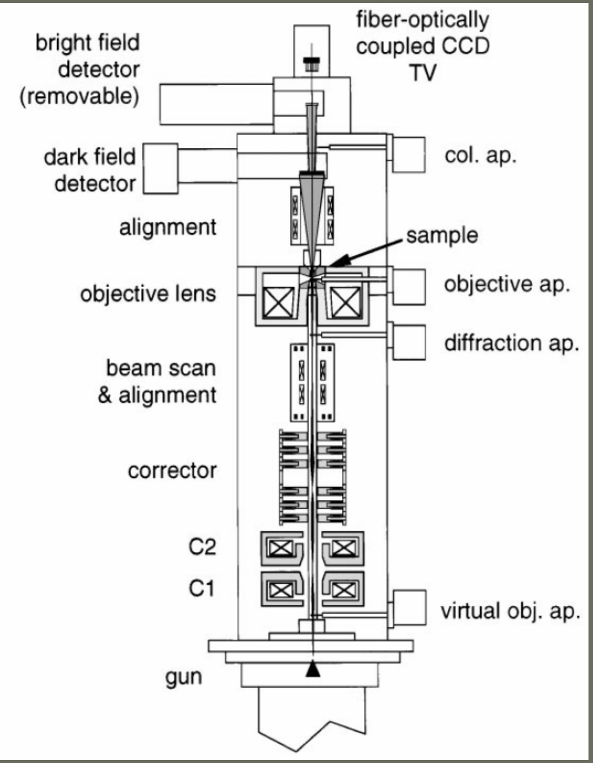
The TEAM Project

TEAM: Transmission Electron Aberration-Corrected Microscope



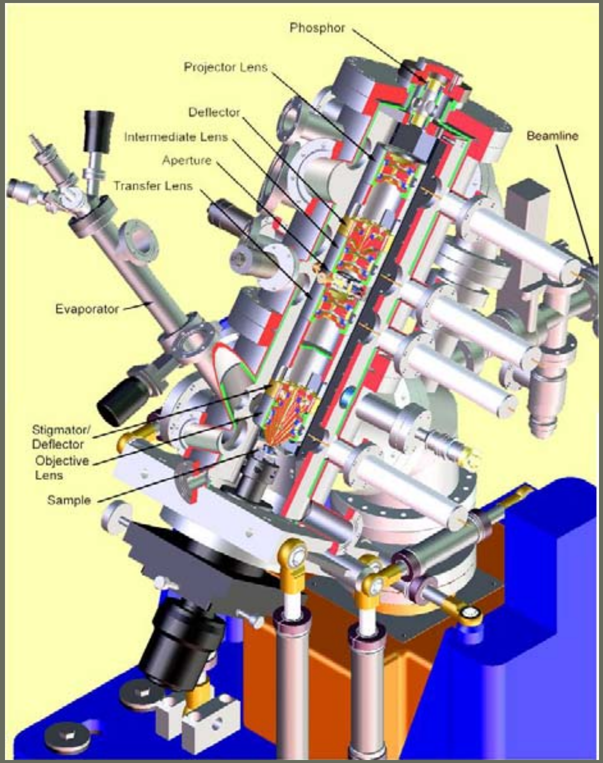
Electron Microscopes: Basics

- Transmission electron microscope (TEM)
- Scanning transmission electron microscope (STEM)
- Photoemission electron microscope (PEEM)
- Low energy electron microscope (LEEM)
- Scanning Electron Microscope (SEM)



Krivanek et al, UltraMicrosc **78**, 1 (1999)

Philips CM200, NCEM LBNL

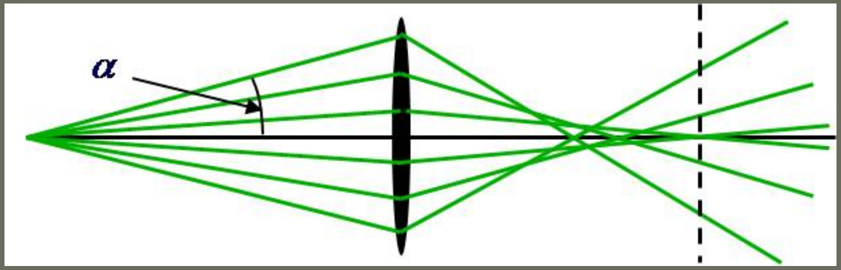


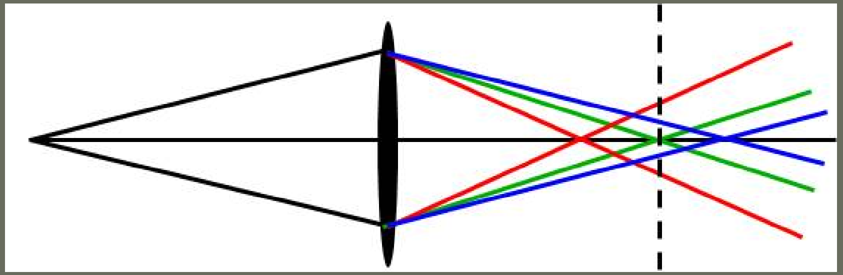
PEEM2, ALS LBNL

Electron Microscopes: Optics

- Round lenses: fewest allowed aberrations
- Magnetic lenses: > 100 kV
- Electrostatic lenses: < 50 kV
- Round lenses are always focusing

Most important aberrations:





Spherical: $\Delta r = C_s \alpha^3$

Chromatic: $\Delta r = C_c \alpha \Delta E/E$

Scherzer' theorem: $C_s < 0$, $C_c > 0$

(Scherzer, Z. Phys. **101,** 593 (1936))

Aberration Reduction vs Correction

Aberration reduction:

- Lenses optimization: 30s-80s, done
- Resolution for TEM/STEM: 1Å
- Resolution for LEEM: 4 nm
- Resolution for PEEM: 20 nm

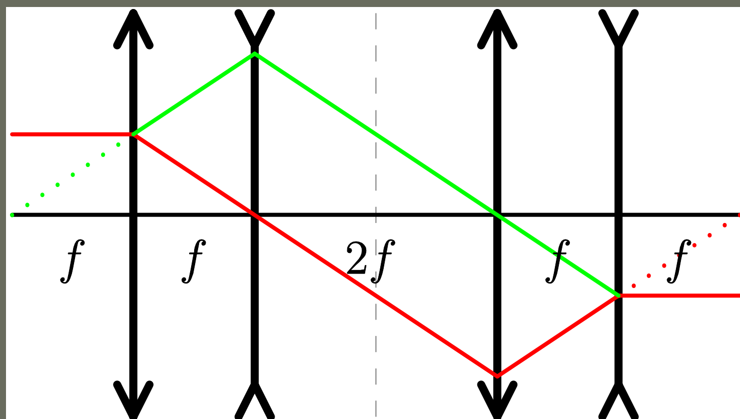
Aberration correction:

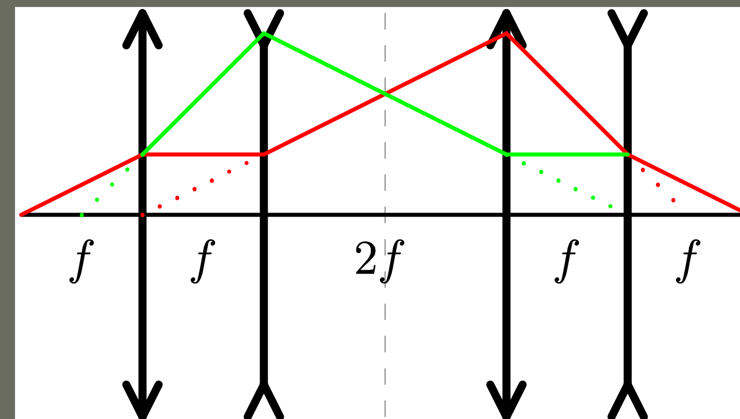
- Possibility #1: multipoles
- Possibility #2: mirror
- Known for decades
- Became feasible in the past decade

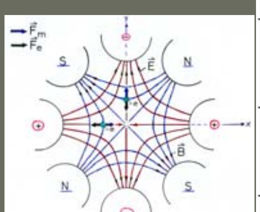
Rose, J. Electron Microsc. Advanced Access (2009)

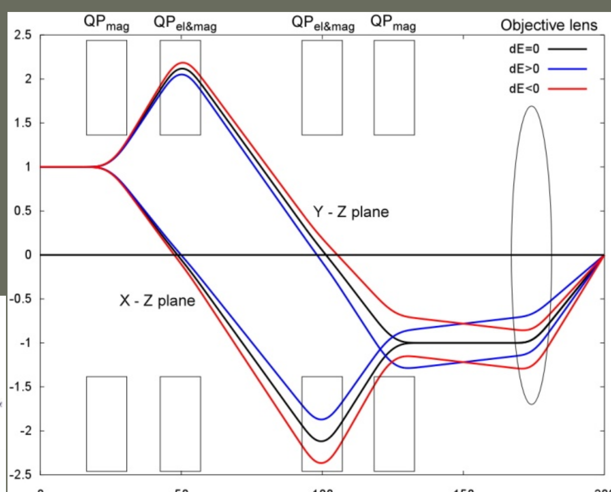
A Simple Multipole Corrector

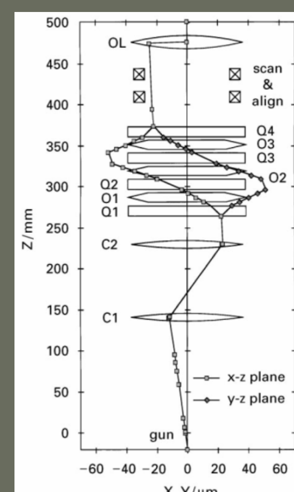
Dymnikov & Yavor, Sov. Phys. Tech. Phys. 8, 639 (1963)

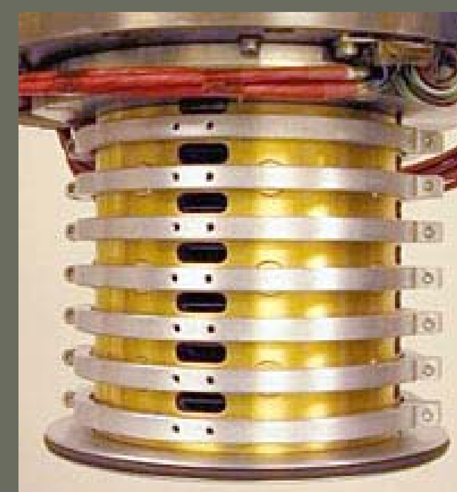








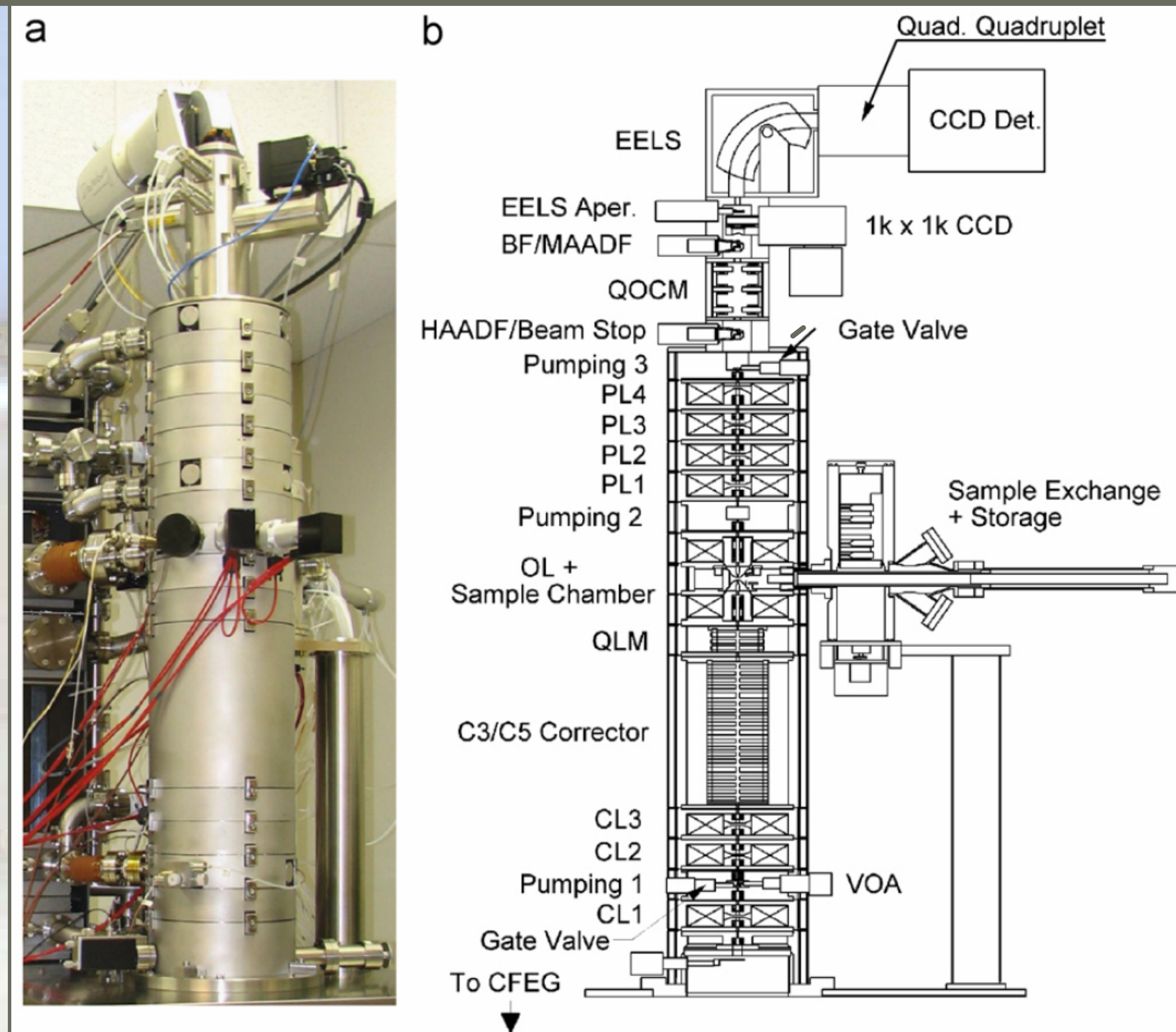




C_c Corrector for SEM
Zach & Haider, NIMA **365,** 316 (1995)

C_s Corrector for STEM
Krivanek et al, UltraMicrosc **78**, 1 (1999)

C_s (C_3/C_5) Corrector for STEM

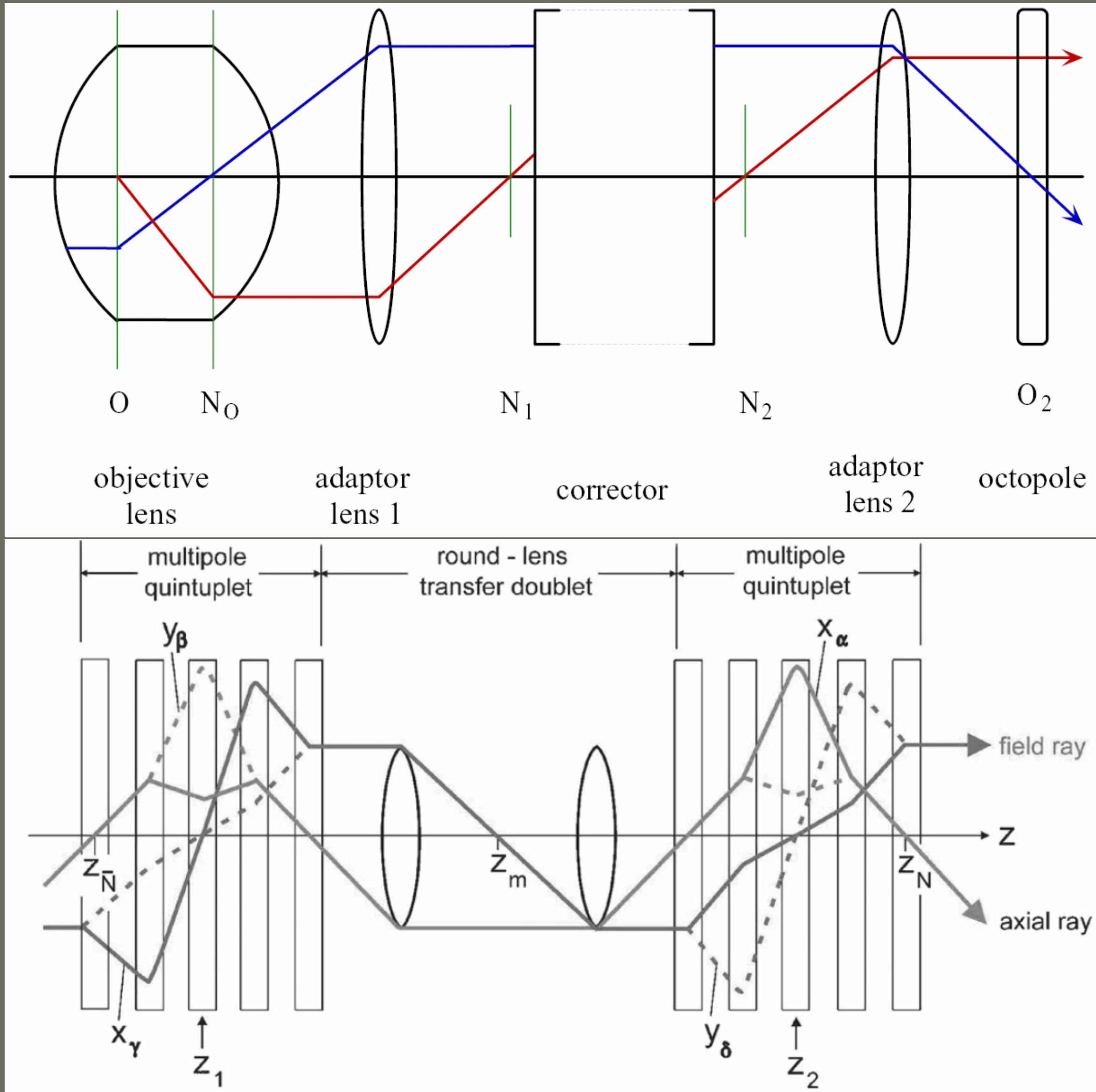


Krivanek et al, UltraMicrosc **108**, 179 (2008)

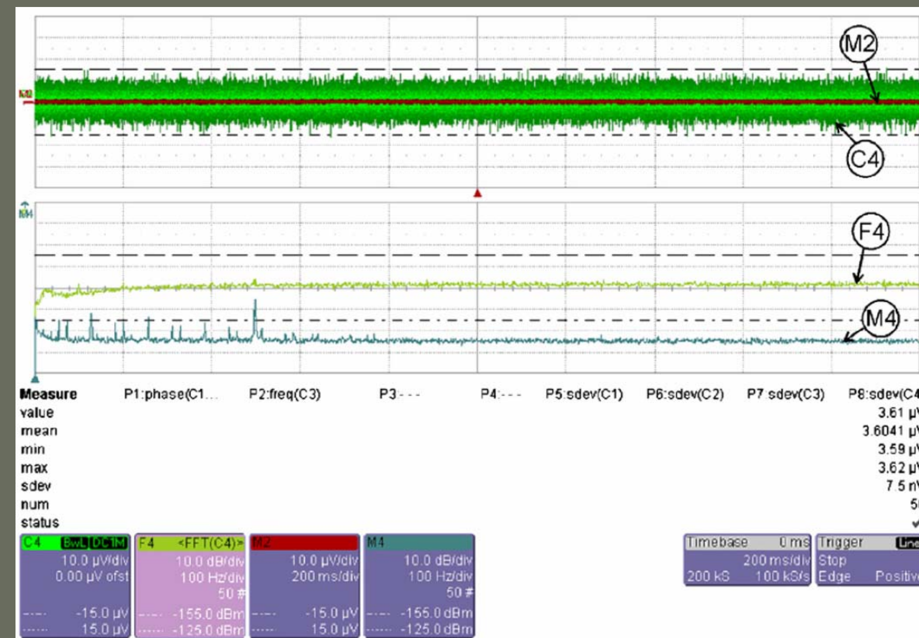
C_s/C_c Corrector for TEM

Rose, J. Electron Microsc. Advanced Access (2009)

- Center magnets: electrostatic and magnetic dodecapoles
- One more octupole to corect the cross term
- First-order Wien filter to correct C_c
- Voltage stability: < 4e-8!
- Current stability: < 1.5e-8!



Stability Demonstrated!

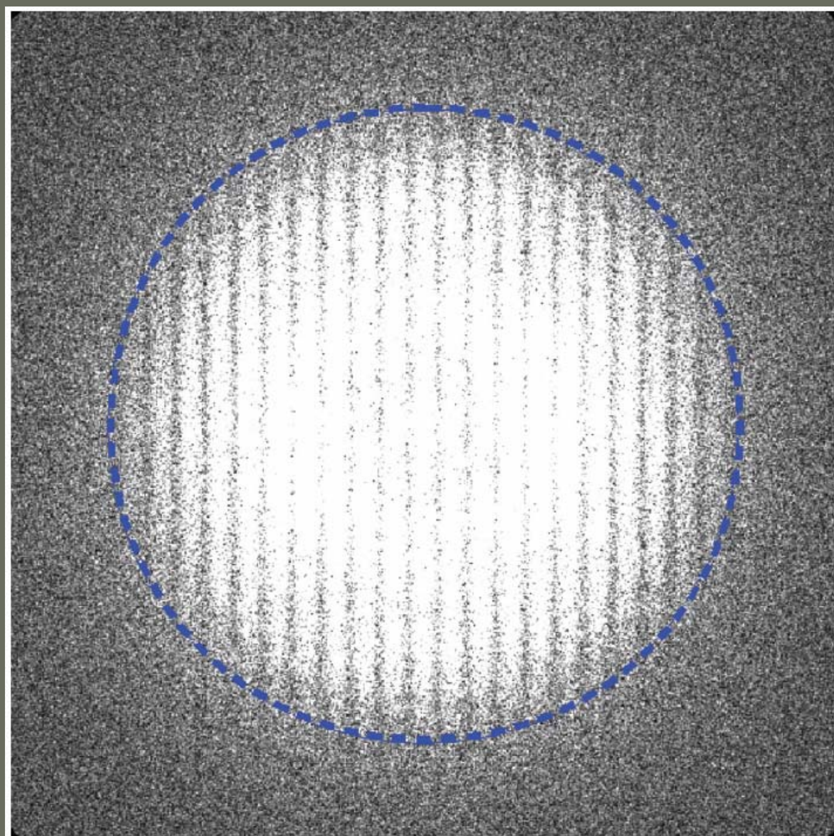


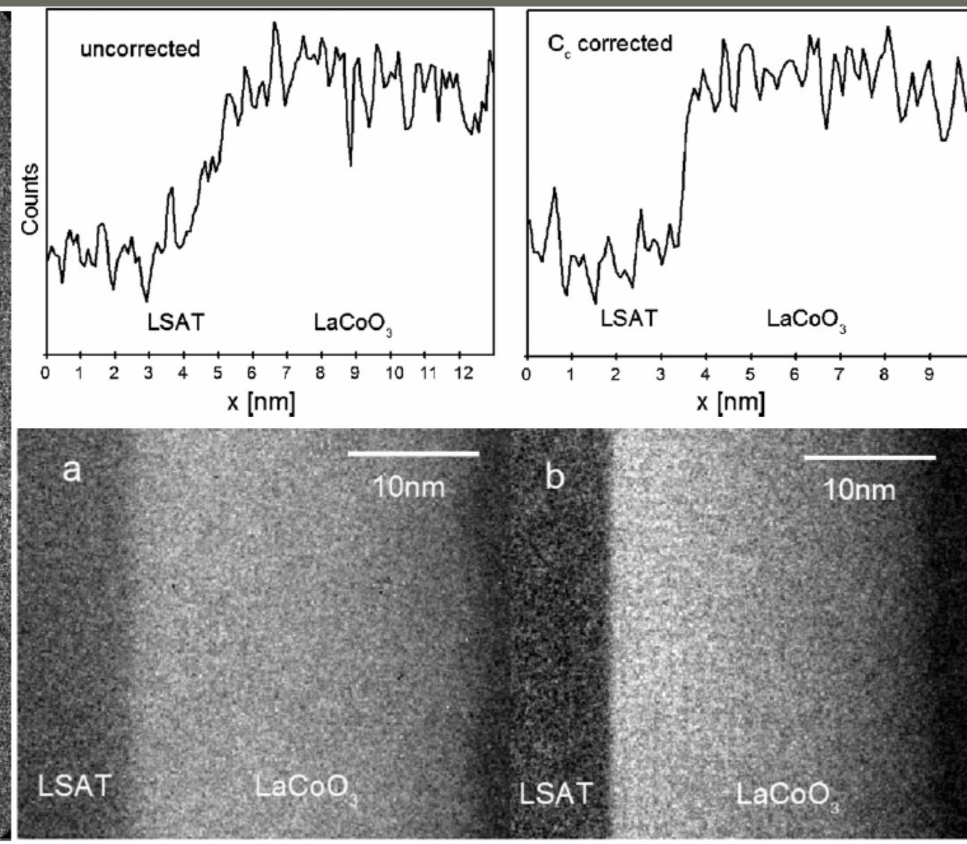
$\Delta I/I=8.1e\text{-}9$

$\Delta V/V=3.6e\text{-}9$

Haider et al, UltraMicrosc **108**, 167 (2008)

TEAM C_c Corrector: First Test





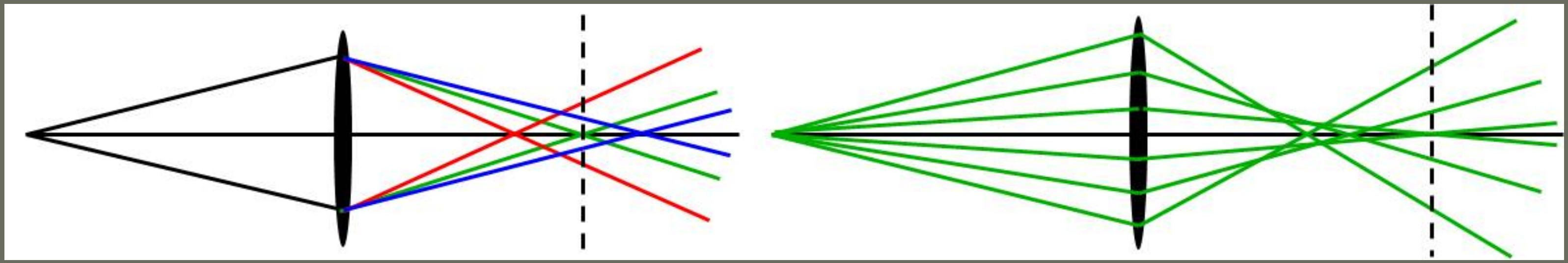
Blue circle: 1Å

Elemental map of La:
a) uncorrected; b) corrected

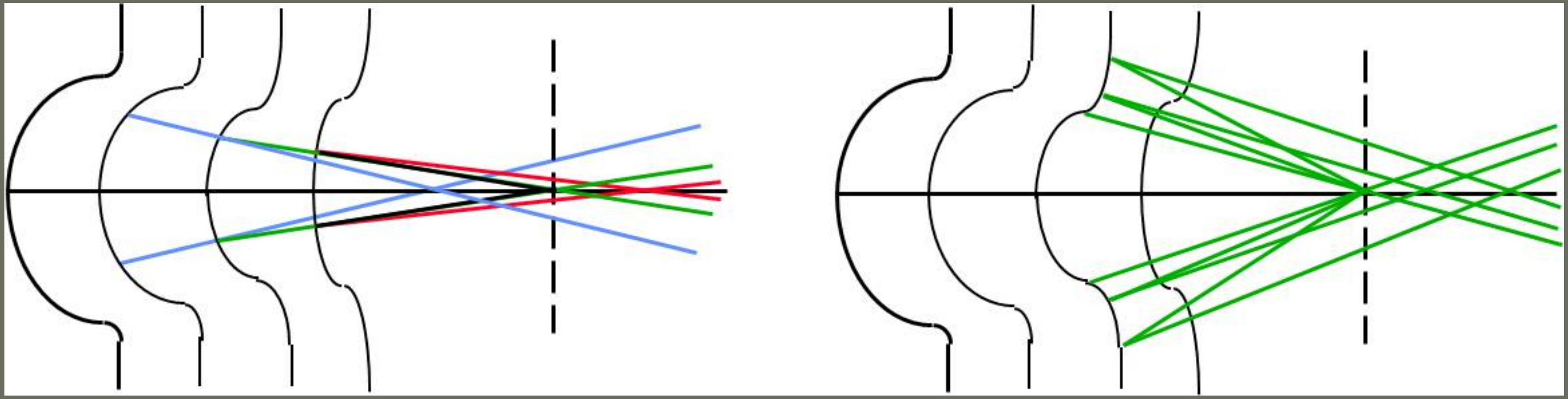
Kabius et al, J. Electron Microsc. Advanced Access (2009)

How Does an Electron Mirror Work?

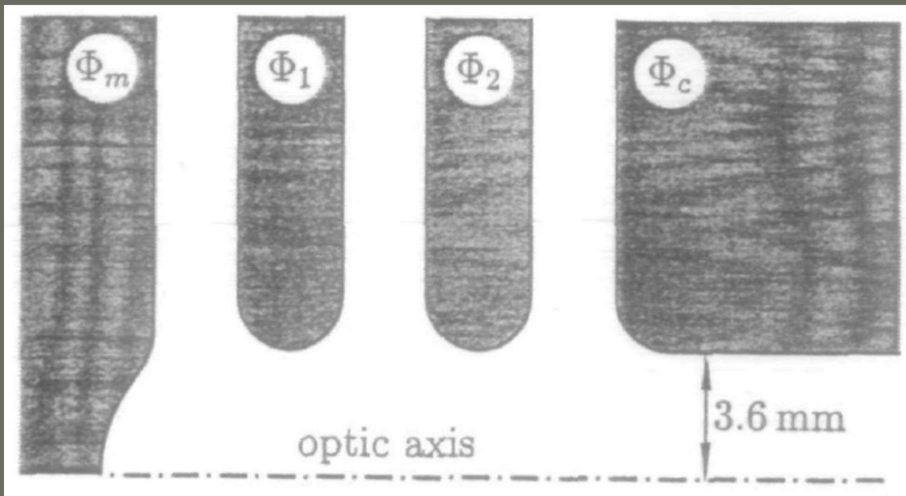
Round lens



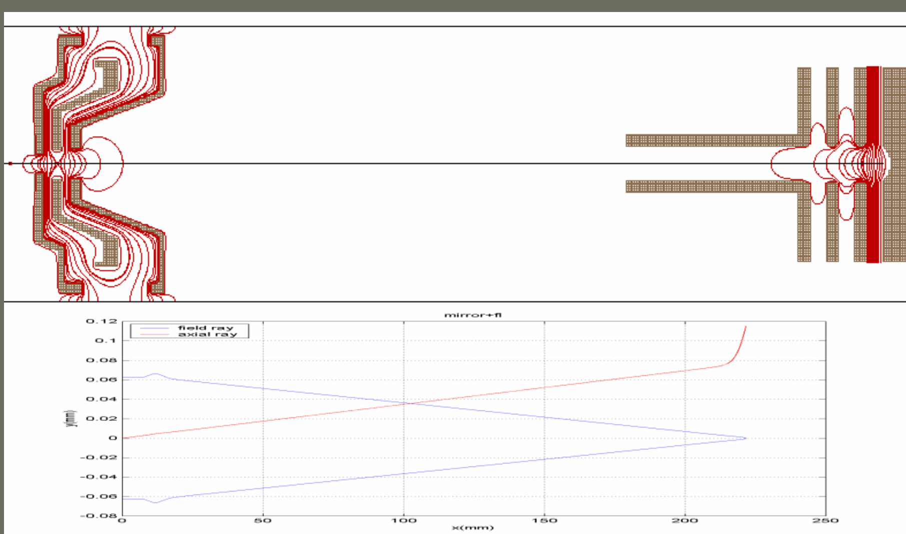
Electron mirror



Aberration Correction for PEEM/LEEM

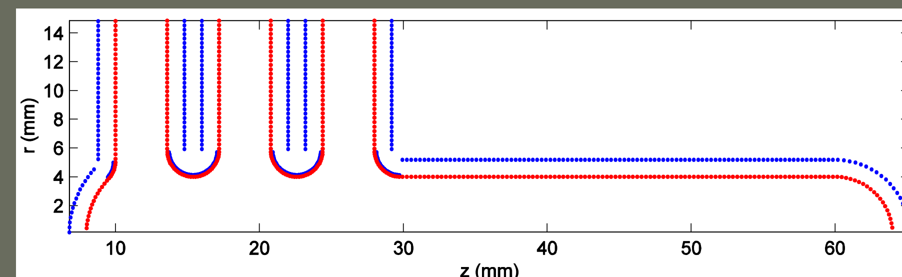


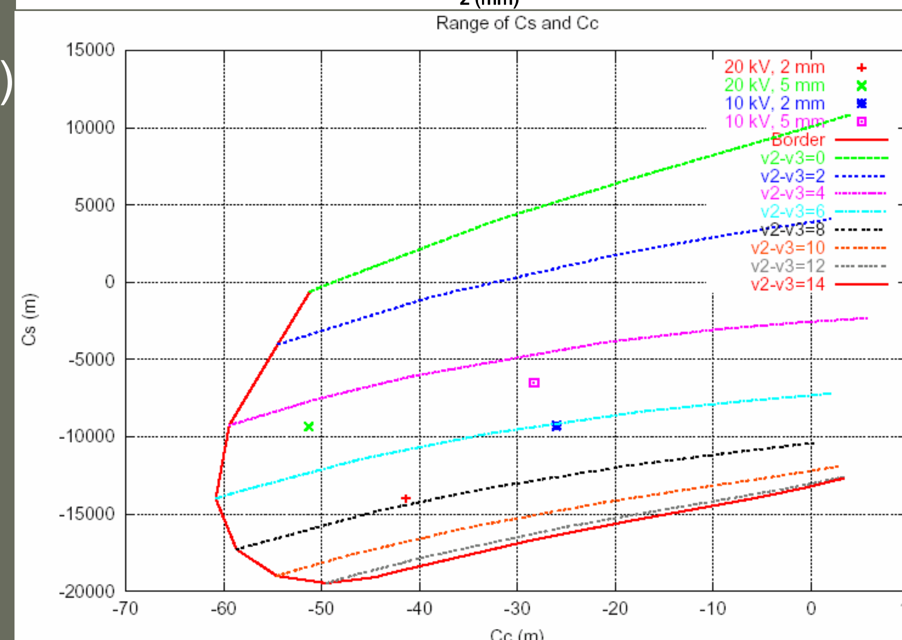
Preikszas & Rose, J. Elec. Microsc. **1**, 1 (1997)



courtesy of J. Feng

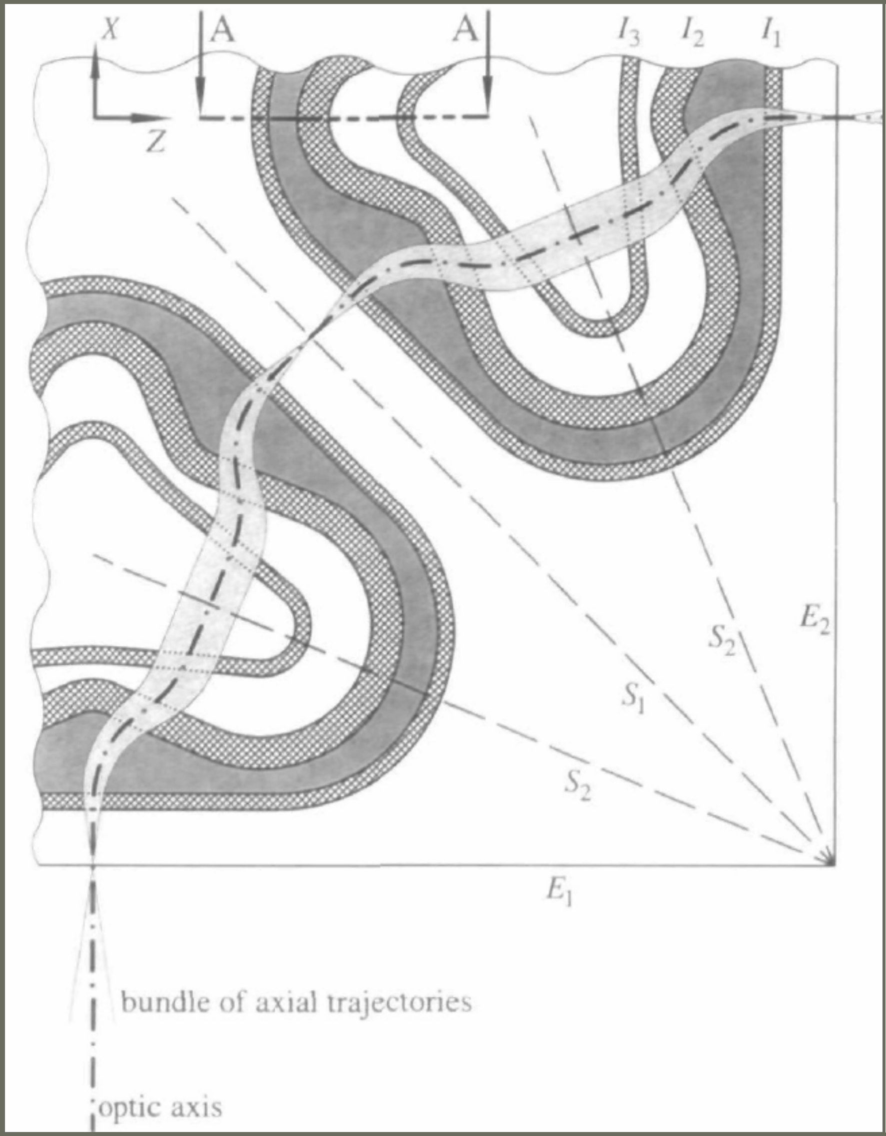
- Rotational symmetry
- Large field of view

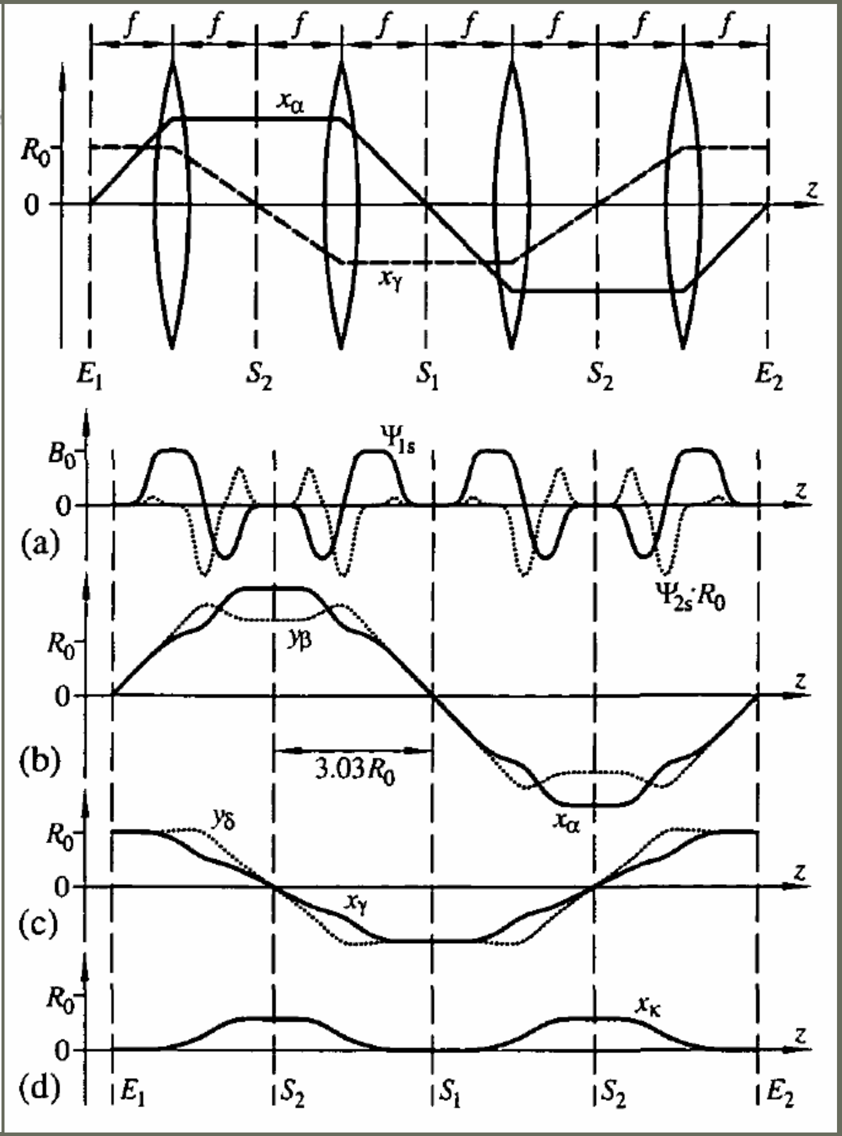




Wan et al, NIMA 519, **222** (2004)

New Challenge: Beam Separator

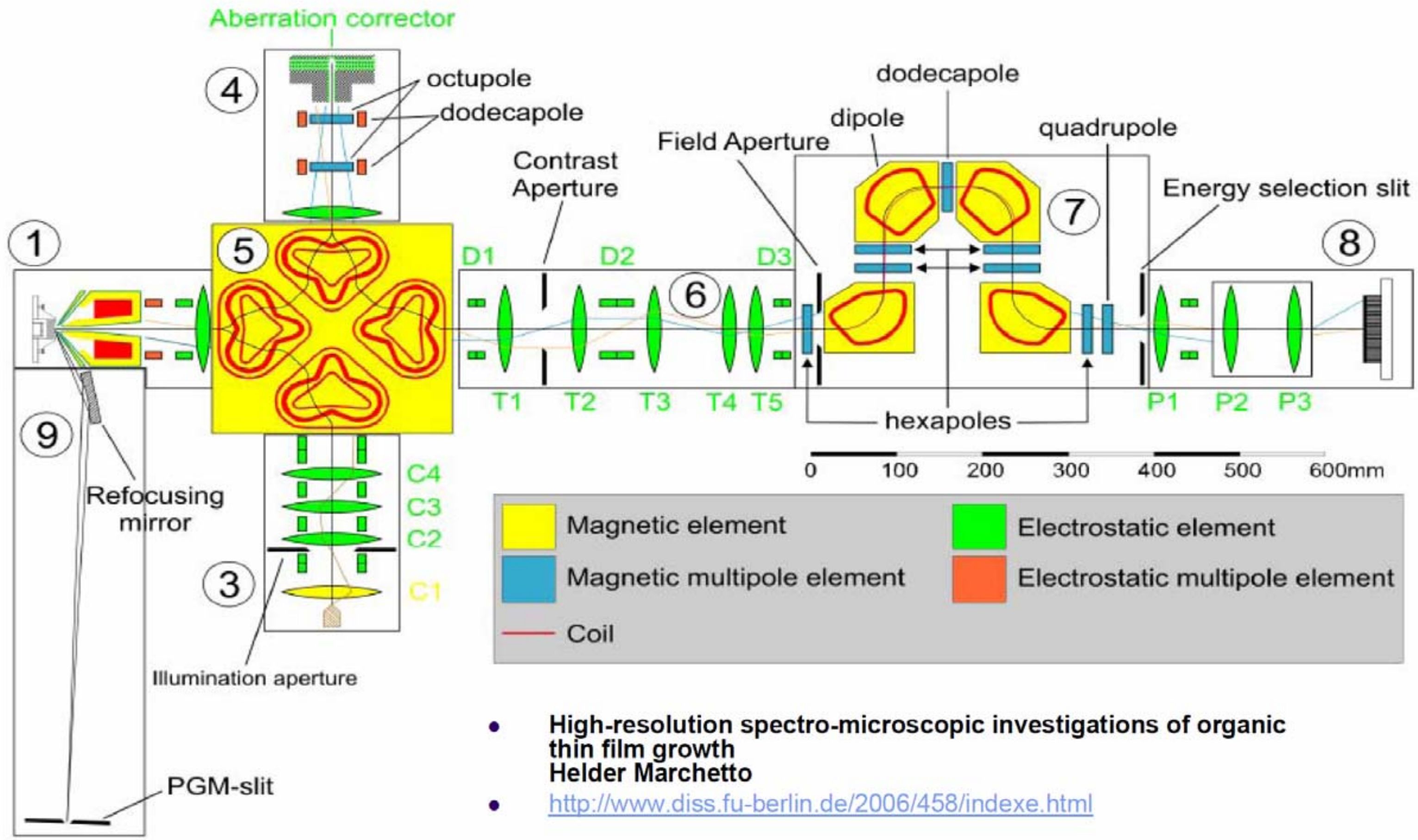




Müller et al, J. Electron Microsc. **48**, 191 (1999)

SMART at BESSY II

Target resolution: 1 nm

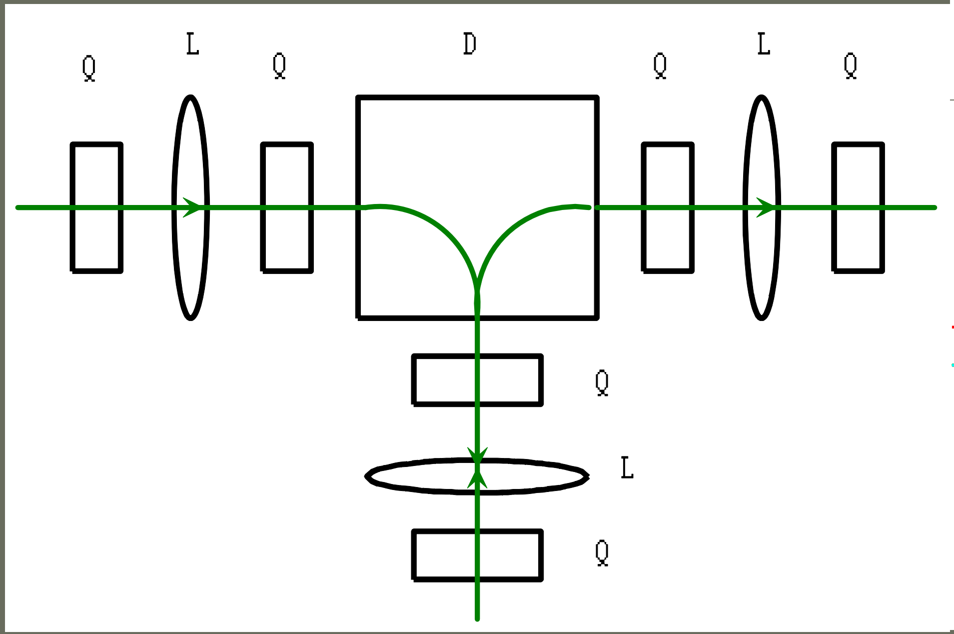


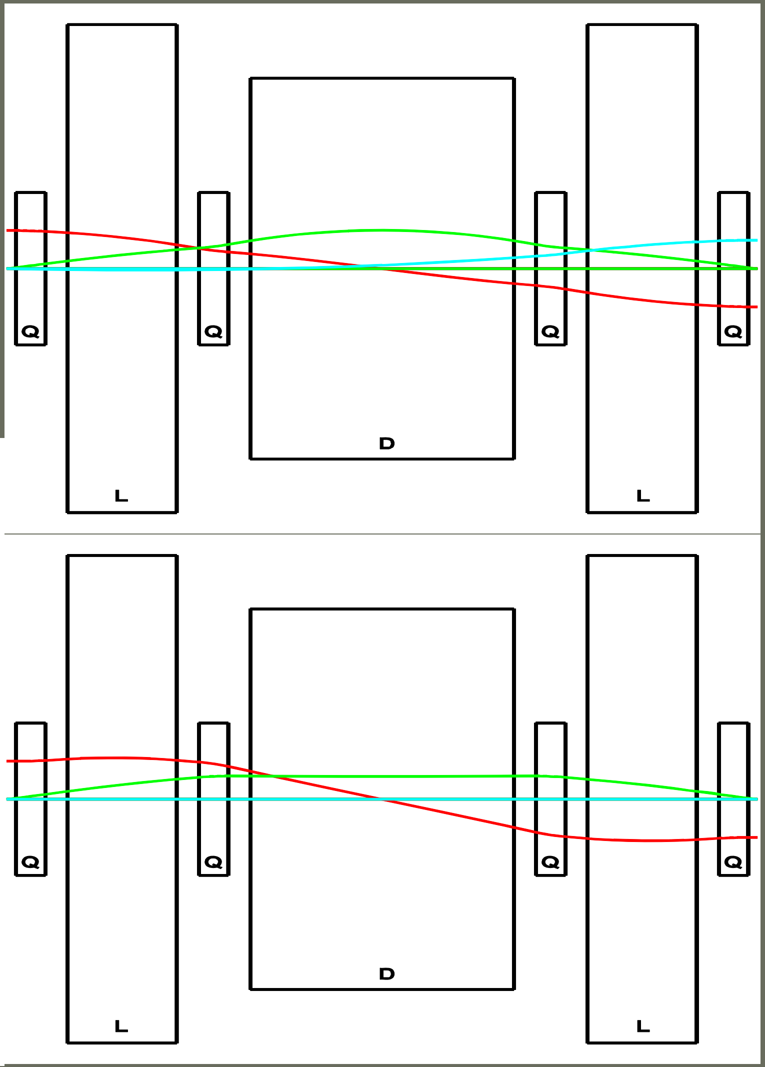
- **High-resolution spectro-microscopic investigations of organic thin film growth**
  Helder Marchetto
- http://www.diss.fu-berlin.de/2006/458/indexe.html

Fink et al, J. Electron Spectrosc. Relat. Phenom. **84**, 231 (1997)

Simplifying the Beam Separator

- Single pass dispersive
- Separate elements
- Simple magnet
- Conventional lenses

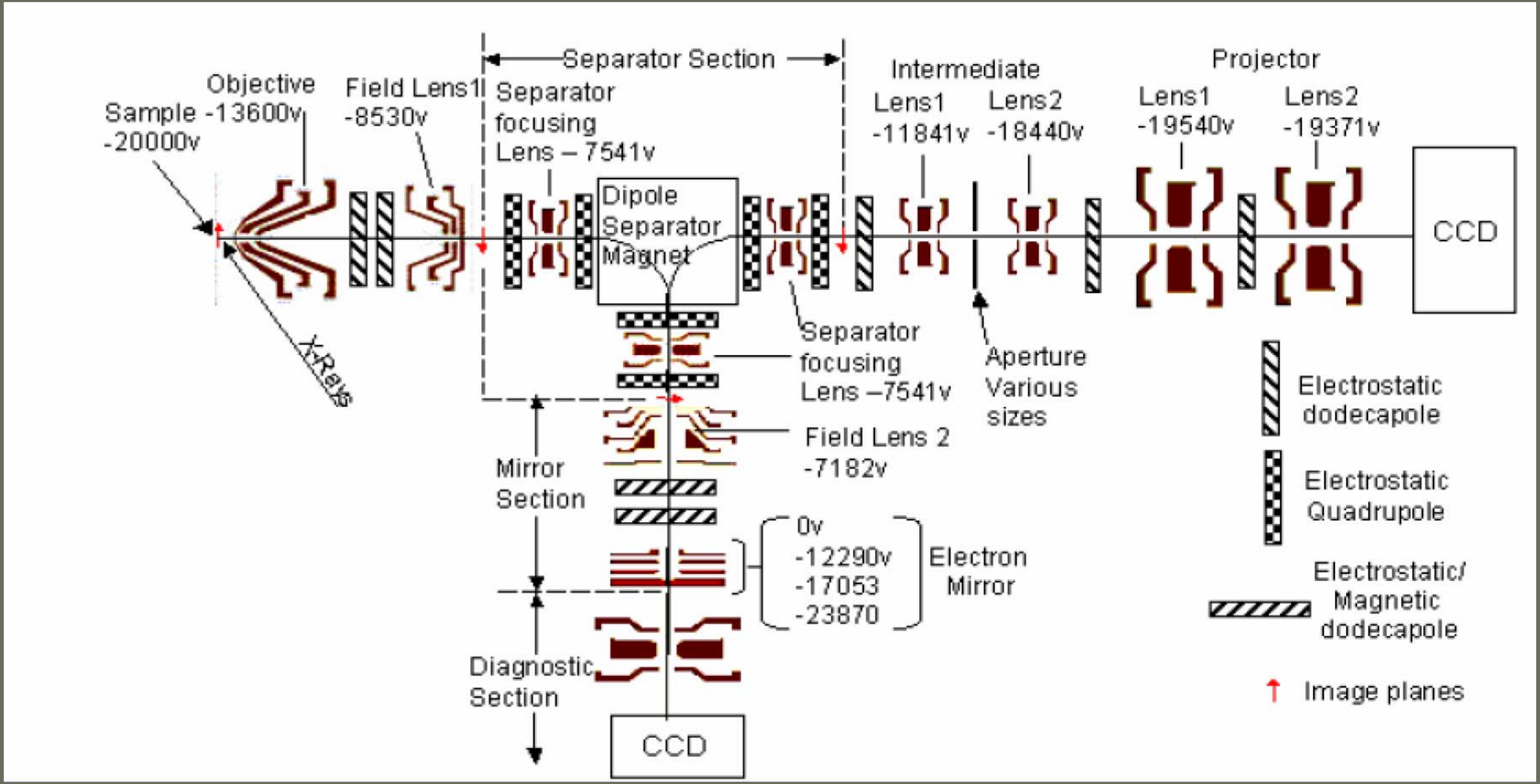




Wan et al, NIMA **564**, 537 (2006)

PEEM3 at ALS

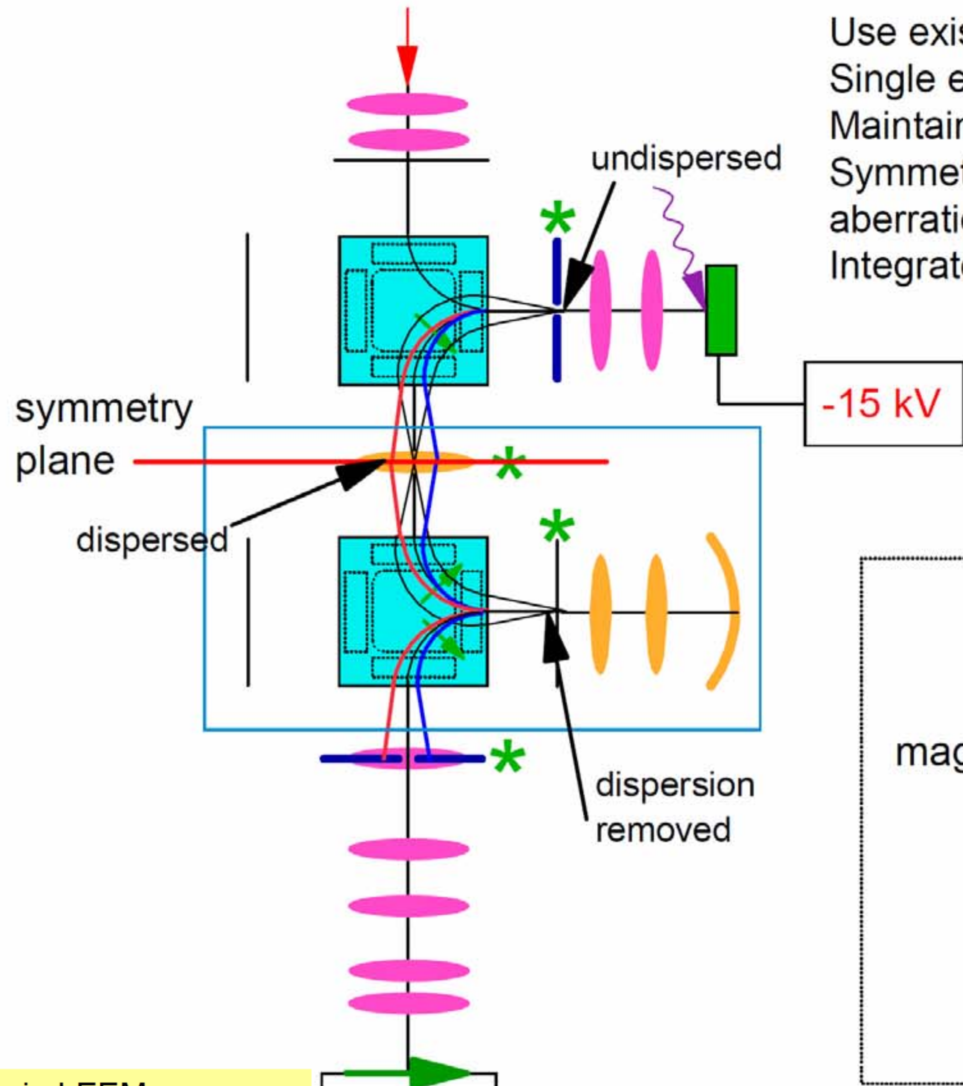
Target resolution: 4 nm

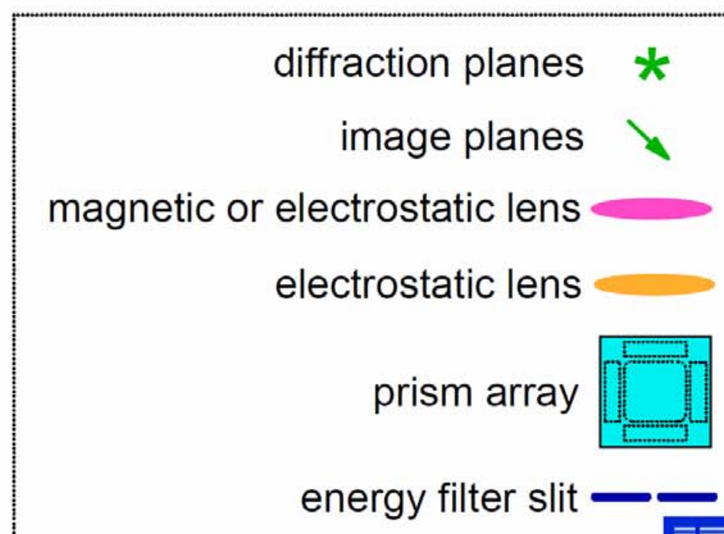


courtesy of J. Feng

Simplified aberration-corrected + energy-filtered LEEM

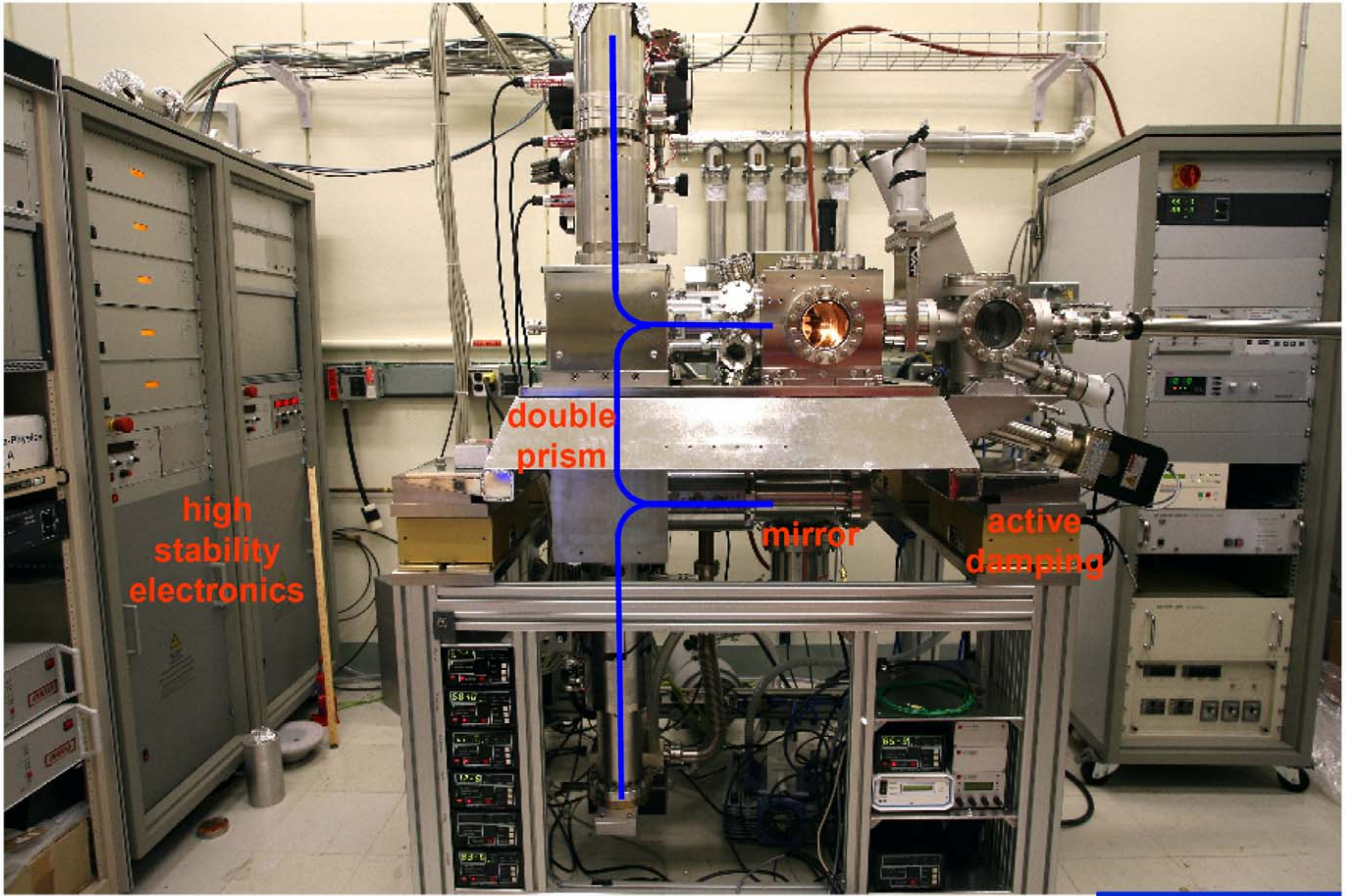
Use existing, simple prism array design
Single electrostatic lens couples prisms
Maintains straight column layout
Symmetry cancels dispersion, all 2nd order aberrations, as well as chr. ab. of magnification
Integrated energy filter without additional optics





< 1.5 nm in LEEM
< 4 nm in PEEM (>10eV)

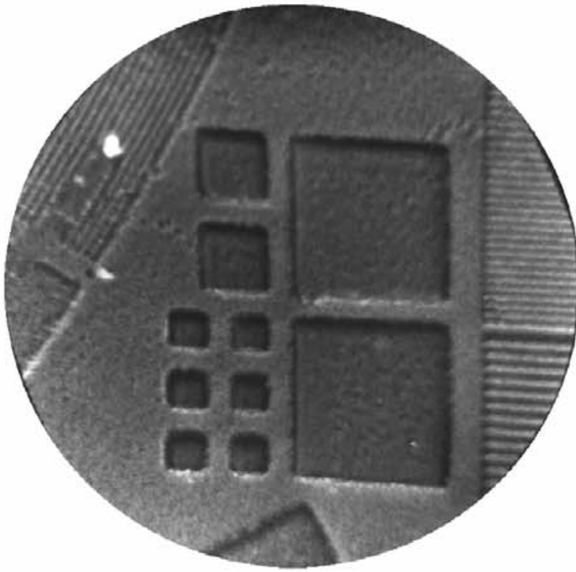
courtesty of R. Trump



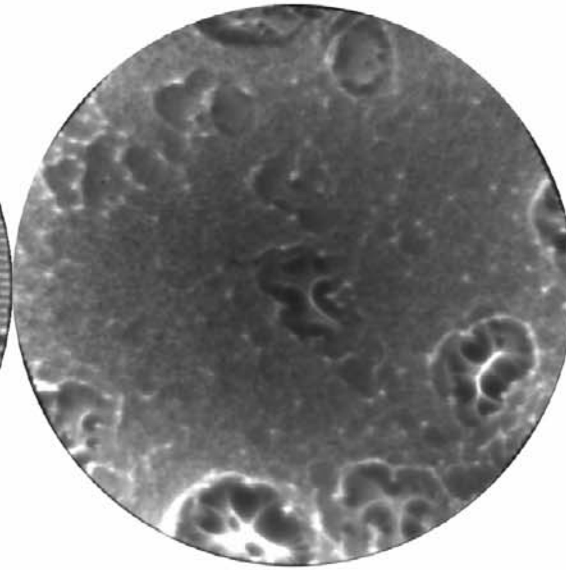
SPECS FE-LEEM P90 + Aberration corrector

courtesty of R. Trump

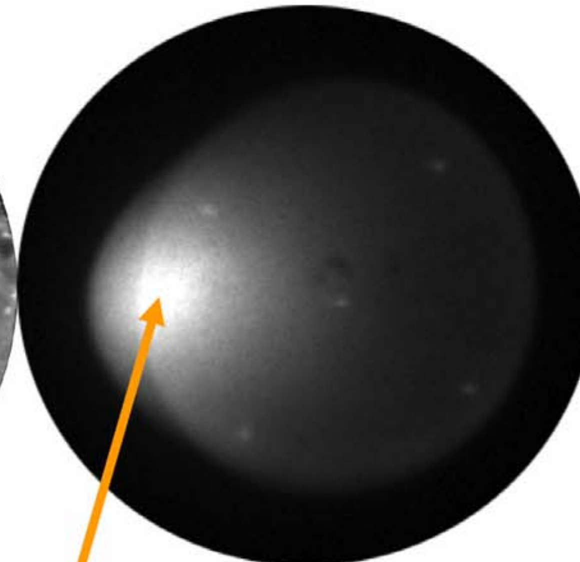
First results: everything works as expected



PEEM 80 μm



LEEM dirty Si 2.7 μm



LEED dirty Si

Note dispersion of secondary electrons after 2^{nd} pass through prism: restores energy filter function

courtesty of R. Trump

Summary

- Aberration correction in electron microscopes has become a reality
- Technological advancement over the past decade has been phenomenal
- Great science is being done using these devices and much is coming