Recent Advances in X-ray Photoelectron Microscopy

Raymond Browning

3D+ XPS Microscope a new '**class**' of microscope

High resolution XPS images for general materials analysis and special applications:

Complex, rough, insulating surfaces
Large depth of focus and angled surfaces
3D+ chemical and phase imaging
XPS, UPS, PEEM, ARPES
HAXPES depth profiles, and more….

Being developed under NIST SBIR at NSLS NATIONAL SYNCHROTRON LIGHT SOURCE

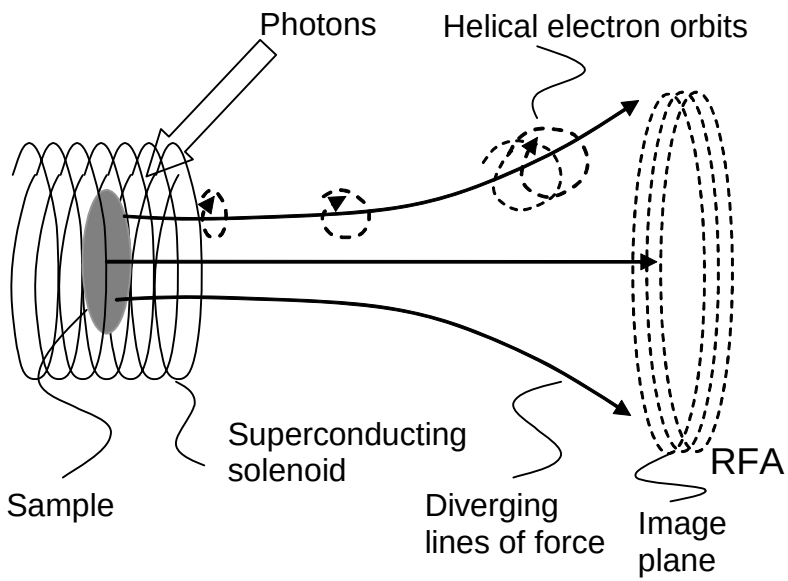
3D+ XPS microscope based on Turner magnetic projection microscope and later implementations at Surface Science Inst. and SSRL

Pianetta, Lindau, King, Keenlyside, Knapp, Borg, Kim, Kelly, and Browning (1985-1995)

Turner microscope:

Projects photo-electrons along diverging magnetic field lines to form a real magnified image

$$Magnification = \sqrt{\frac{B_{sample}}{B_{image}}}$$



Advantages:

High collection angle, simple electron optics, and a real image

Disadvantages:

Magnetic field is difficult to terminate at an electron spectrometer
Spatial resolution fixed by cyclotron radius at sample,1-10µ

Turner microscope has found limited application

New approach to improve performance and spatial resolution:

Required two key developments:

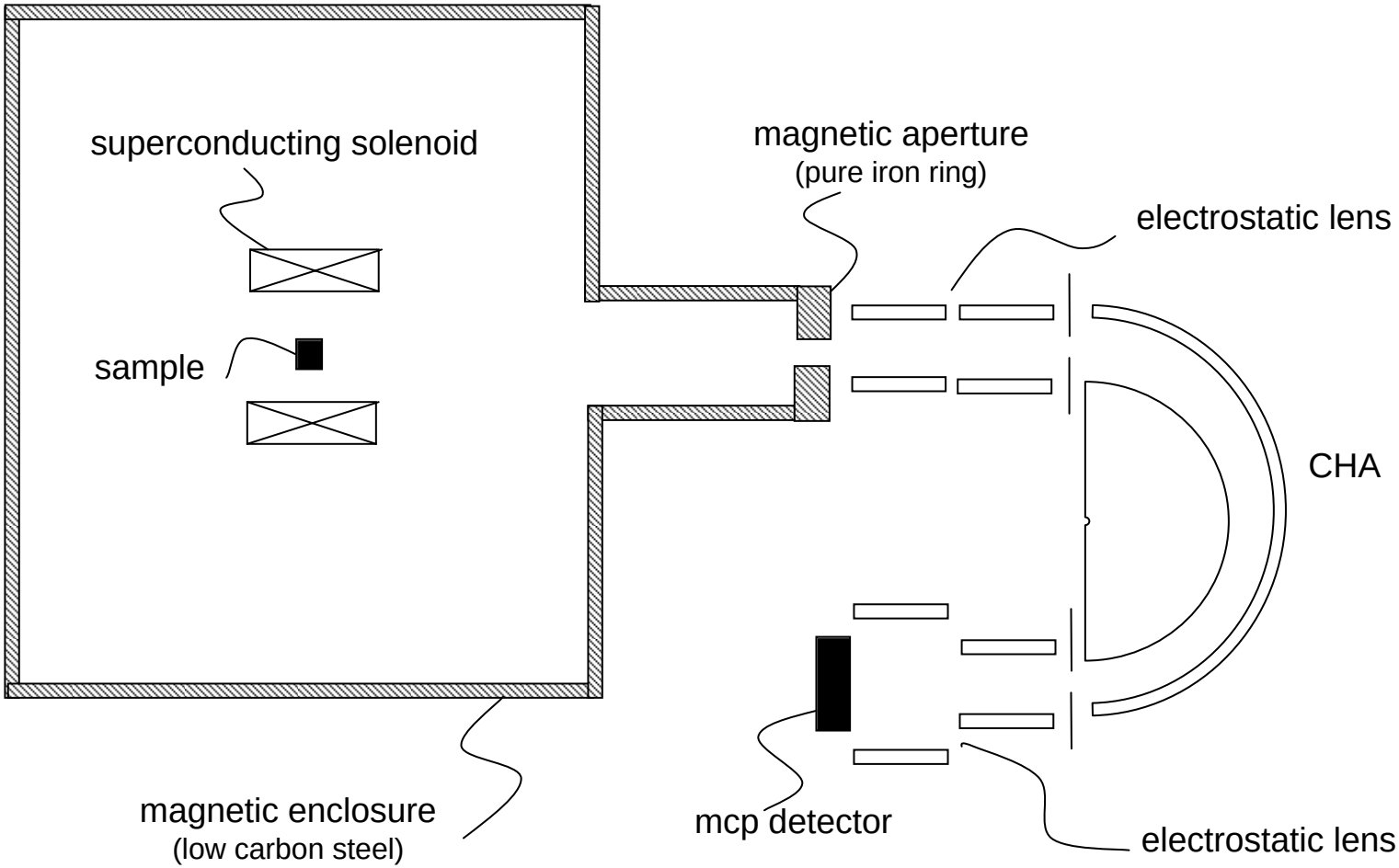
1. Termination of the magnetic field

2. Filter to limit size of electron cyclotron radii

Talk Outline:

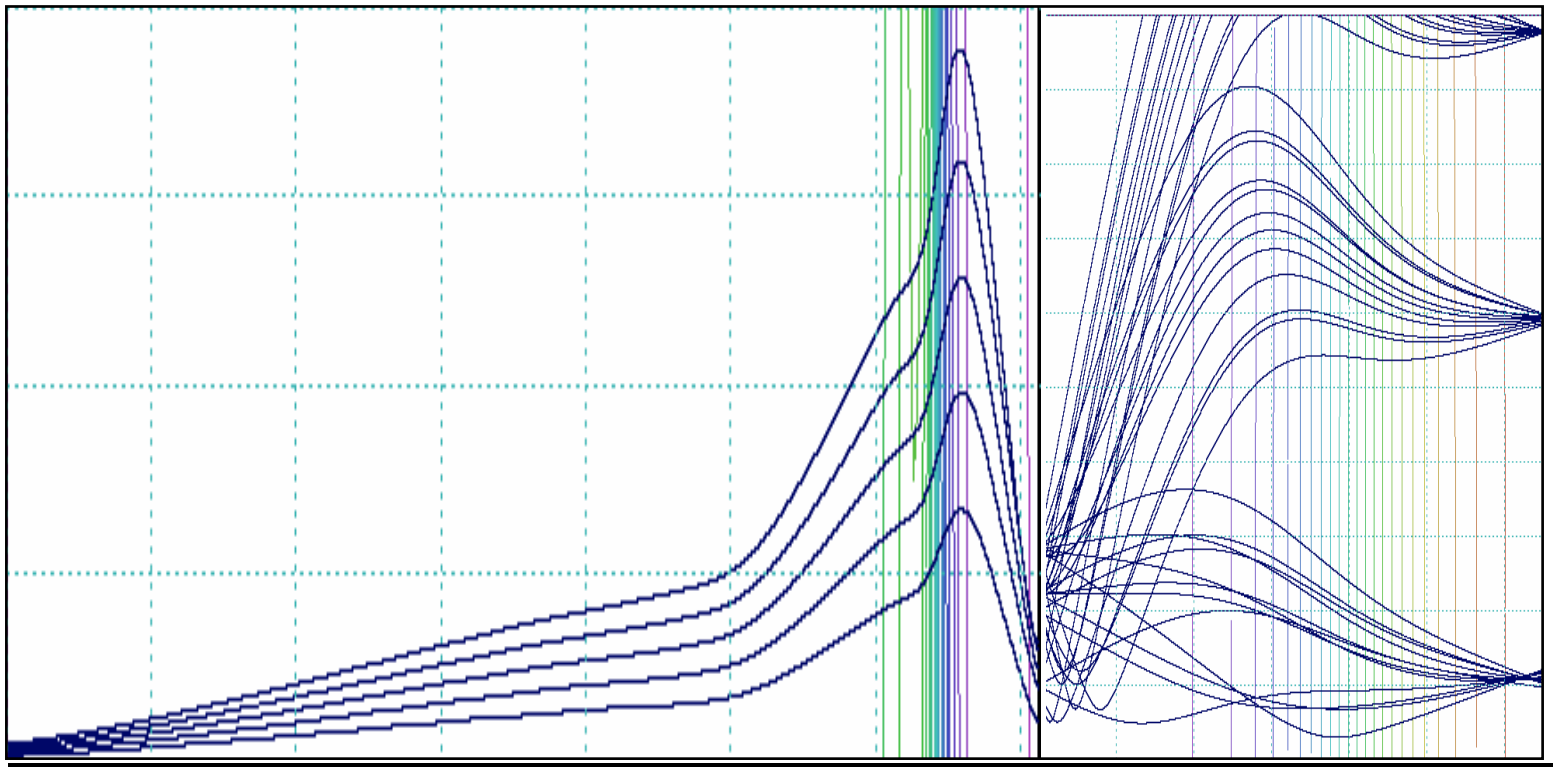
Magnetic and spectrometer solutions
Spatial Resolution
CORF – cyclotron orbit radius filter
Signal to Noise
and a bit of speculation

1. Magnetic field solution and imaging analyzer



Magnetic field solution and imaging analyzer

- Magnetic aperture terminates field – twist and astigmatism
- Electrostatic lens produces an angular (virtual) image at the CHA
- Image is energy analyzed: 250 meV
- Angular image focused as a real image onto a detector: 400 lines

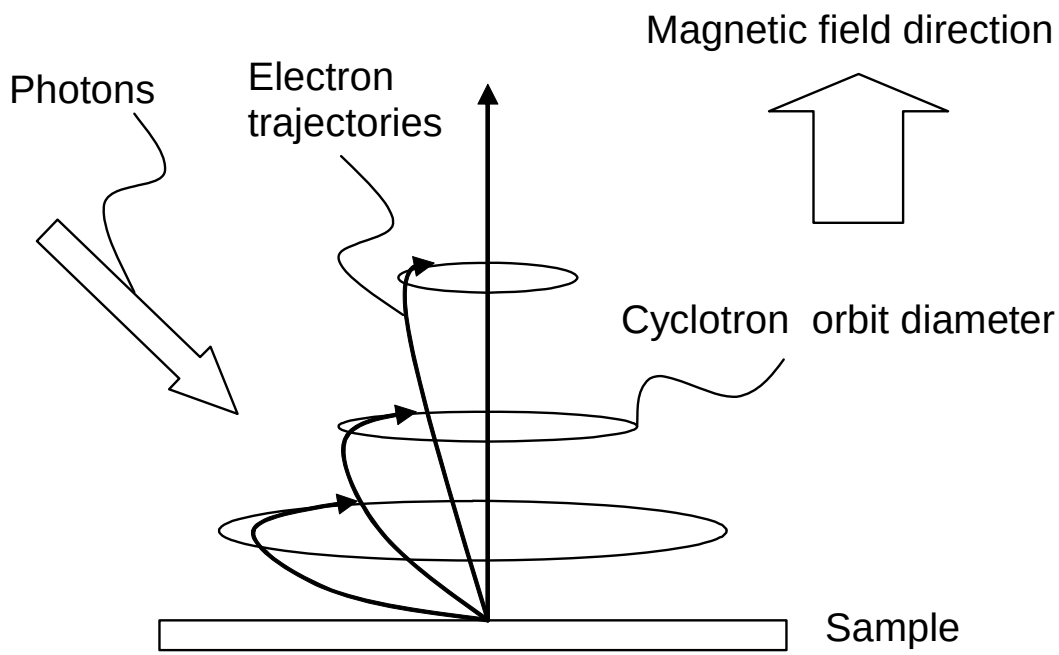


The point spread function (PSF) of the magnetic projection lens is limited by the cyclotron radius of the electrons emitted from the surface

The cyclotron radius with total energy *E* emitted at an angle *θ* to the magnetic field direction is:

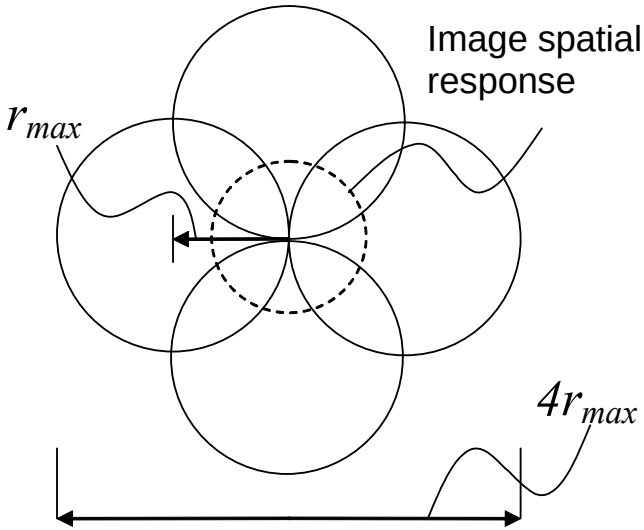
$$r = \frac{3.375 E^{1/2} \sin(\theta)}{B}$$

Where *r* is in μ, *E* is in eV, and *B* in Tesla.



Radial energy, eV	2T	10T
0.00355	0.1μ	20nm
0.088	0.5μ	100nm
0.355	1.0μ	200nm
1.0	1.7μ	337nm

The PSF is determined by the combination of cyclotron electron orbits in all directions around an emission point.



$$r_{\max} = \frac{(2mE)^{1/2}}{eB}$$

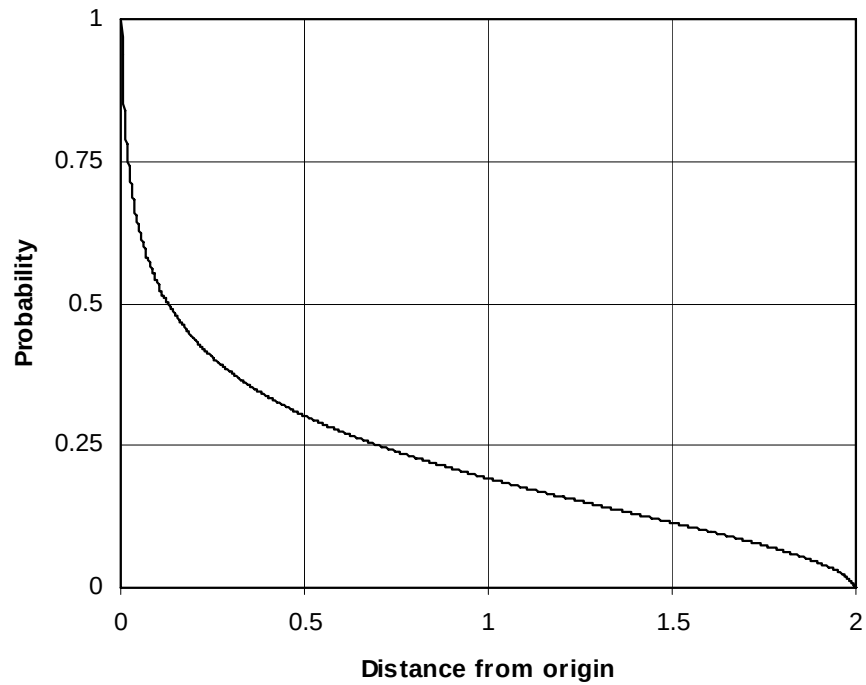
More than 50% all electrons are at greater than $0.5r_{max}$ from origin.

Implies: **Spatial resolution ~r_{max}**

(Knife edge resolution test 80%-20%)

For a uniform distribution of radii up to r_{max} the distribution of electrons crossing the image plane is:

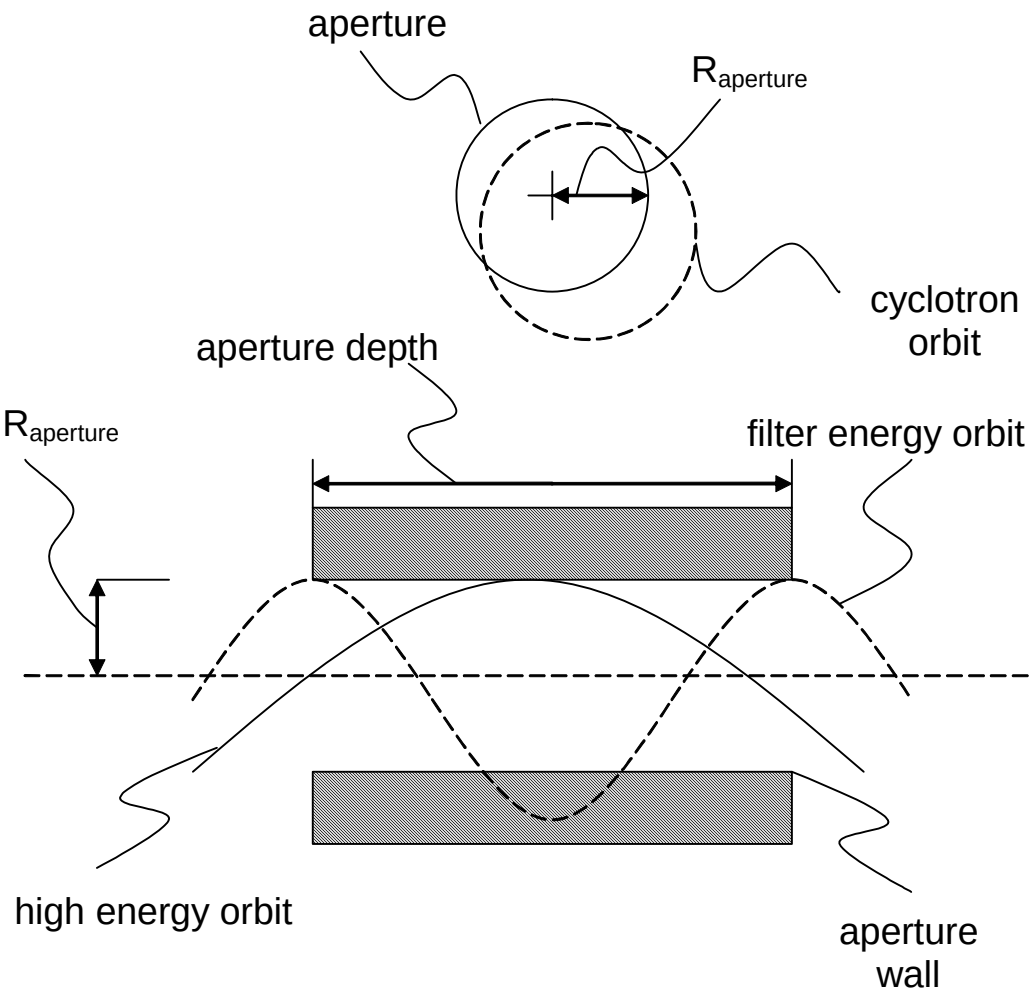
$$P(dx) = \int_{x/2}^{r_{\max}} \frac{xdx}{2r^2\pi\left(1-(1-\frac{x^2}{2r^2})^2\right)^{1/2}} dr$$

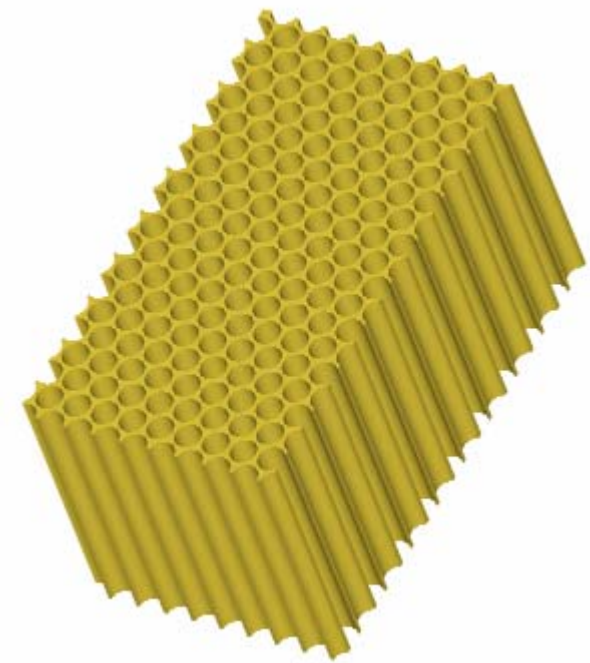


New approach to improve spatial resolution:

2. Filter to limit size of electron cyclotron radii

CORF: cyclotron orbit radius filter

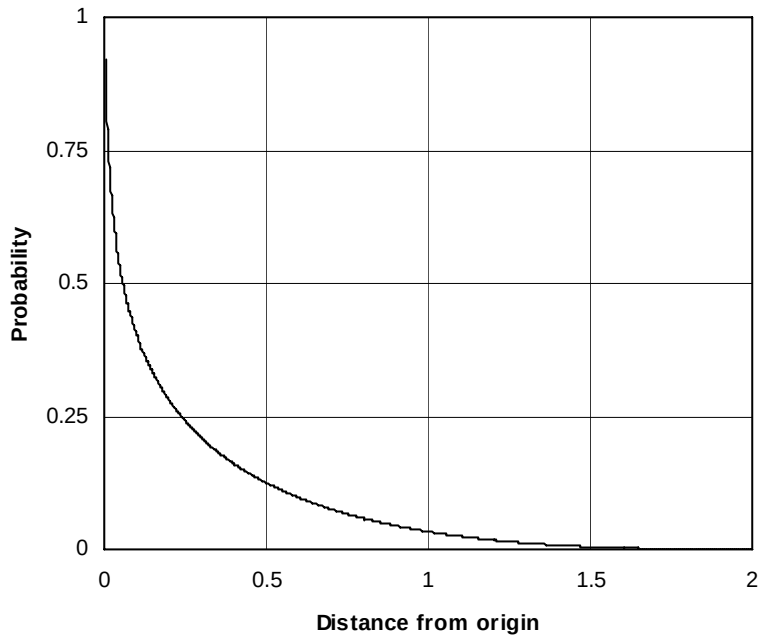


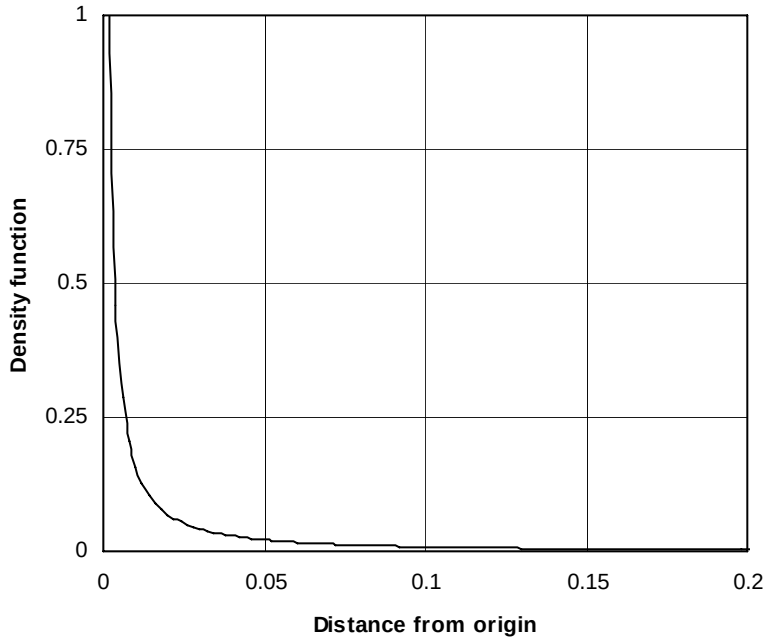


$R_{aperture}$ is new r_{max}

The PSF is determined by the combination of projection lens and **CORF** response.

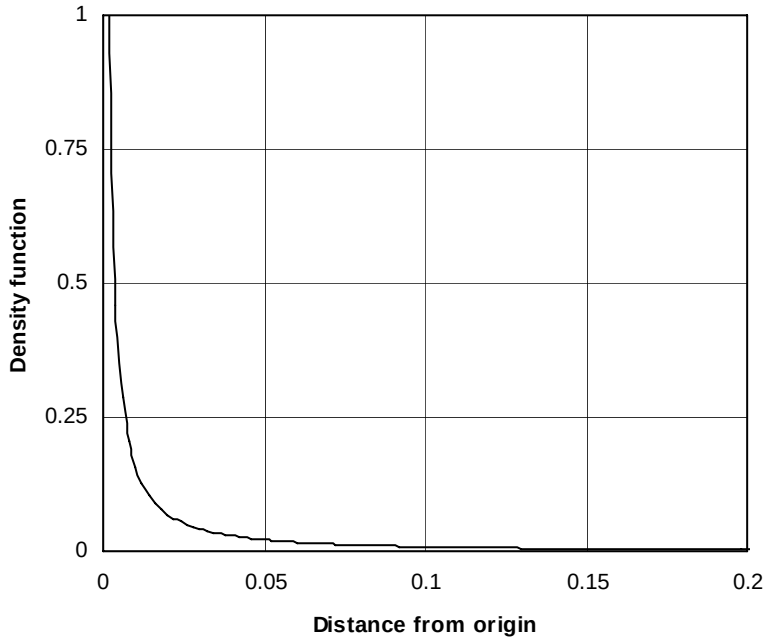
$$P(dx, r_{\max}) = \int_{x/2}^{r_{\max}} \frac{(r_{\max} - r)^2}{r_{\max}^2} \times \frac{xdx}{2r^2\pi\left(1-(1-\frac{x^2}{2r^2})^2\right)^{1/2}} dr$$

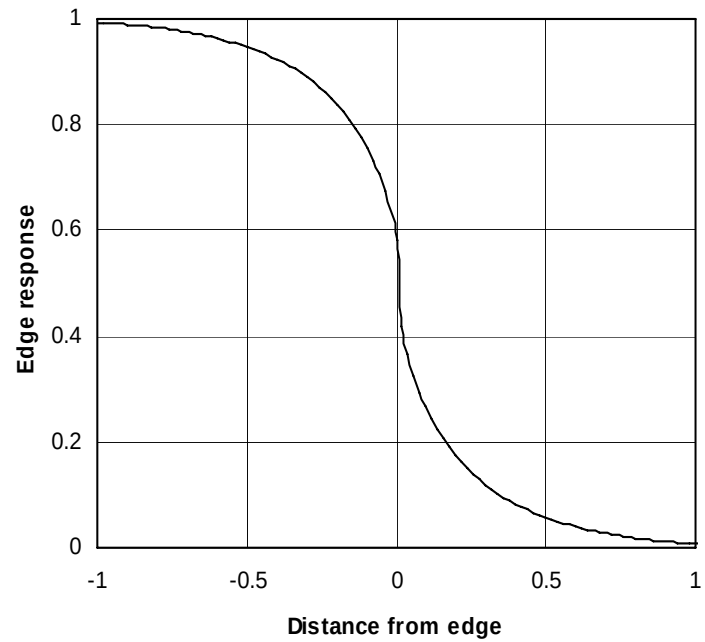




More than 50% all electrons are at less than $0.25r_{max}$ from origin.

Density function is radial distribution divided by area of dx i.e. $1/2\pi xdx$





Edge spatial resolution (80%-20%) $0.32r_{max}$

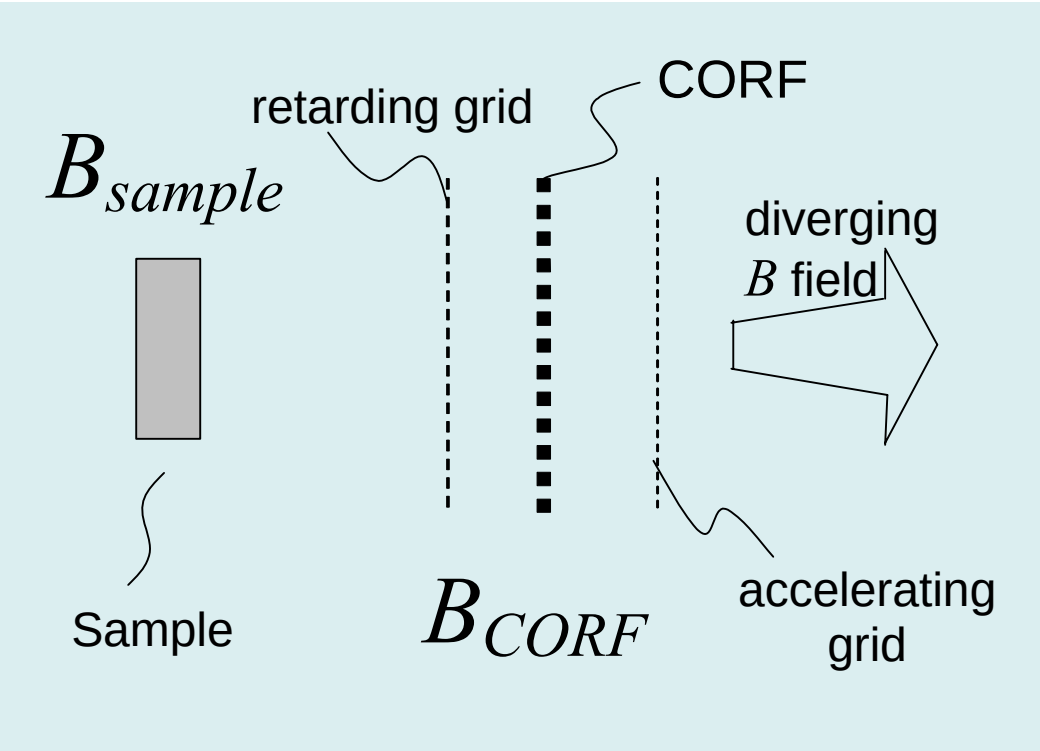
Pixel resolution much higher < $0.16r_{max}$

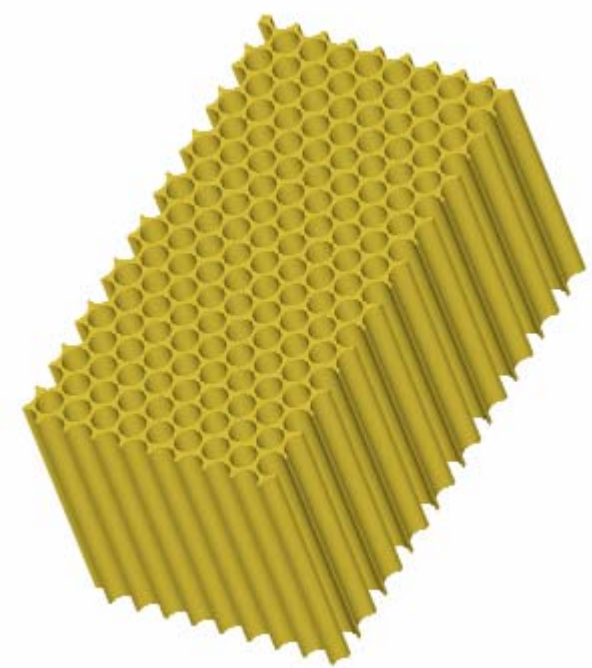
The PSF is very non-Gaussian

The modulation transfer function will have very high frequencies

Spatial filtering will produce higher resolution images (depending on S/N)

CORF: cyclotron orbit radius filter



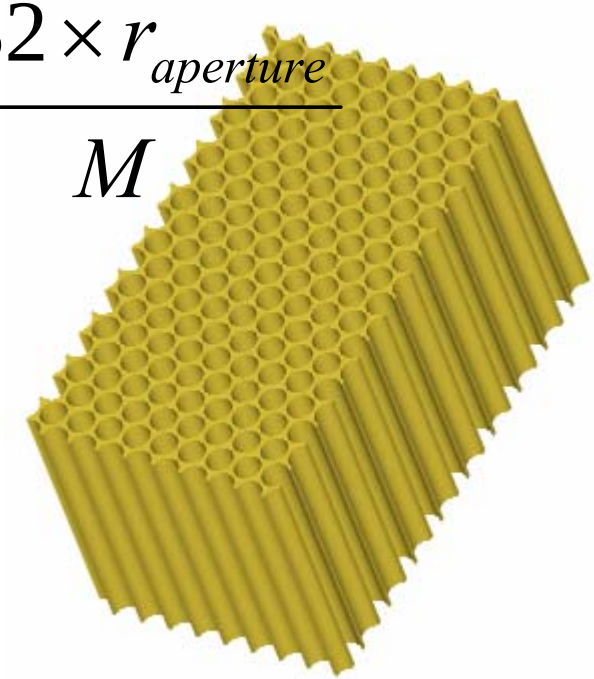


$$M = \sqrt{\frac{B_{sample}}{B_{CORF}}}$$

$$S_{20-80} = \frac{0.32 \times r_{aperture}}{M}$$

CORF: cyclotron orbit radius filter

$$M = \sqrt{\frac{B_{sample}}{B_{CORF}}} \qquad S_{20-80} = \frac{0.32 \times r_{aperture}}{M}$$



Current project target:

- 7 Tesla sample field,
- 2 Tesla CORF field
- 1μ diameter apertures in 5.5μ Au foil

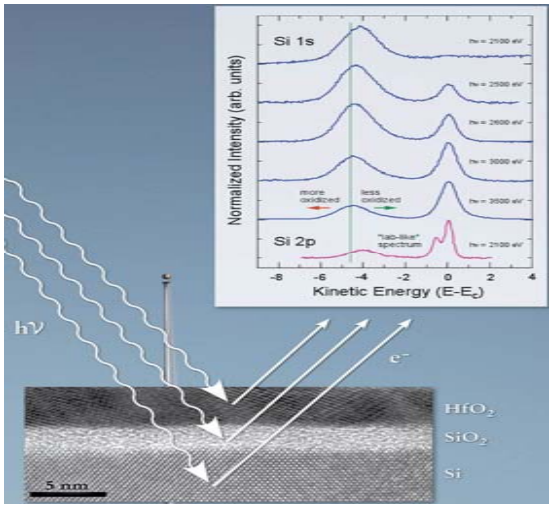
$$M = \sqrt{\frac{7T}{2T}} \qquad S_{20-80} = \frac{0.32 \times 0.5}{1.87} = 0.083\ \mu$$

HAXPES 3D imaging

NSLS II – 10^{11} photons/sec/μ^2

Magnetic field: Sample 18T,CORF 2T

<100 sec per image



Si 1s, **3.5keV** photons

r_{CORF}	Rmax	Angle radians	Accepted fraction	electrons emitted per pixel/sec	cps/pixel	secs/pixel 4counts	Pixel size, μ
0.75	0.25	0.0327	8.8E-05	5.60E+03	4.95E-01	8.1E+00	0.040
0.5	0.17	0.0218	3.9E-05	2.49E+03	9.77E-02	**4.1E+01**	**0.027**
0.25	0.08	0.0109	9.8E-06	6.22E+02	6.11E-03	6.5E+02	0.013

Si 1s, **2.0keV** photons

0.75	0.25	0.1056	9.2E-04	4.80E+03	4.41E-00	9.1E-01	0.040
0.5	0.17	0.0703	4.1E-04	2.13E+03	8.70E-01	4.6E+00	0.027
0.25	0.08	0.0351	1.0E-04	5.33E+02	5.43E-02	**7.4E+01**	**0.013**

Si 2p, 400eV photons

0.25	0.08	0.0257	5.4E-05	7.11E+03	3.86E-01	**1.0E+01**	**0.013**

Defining Spatial Resolution, or spatial response

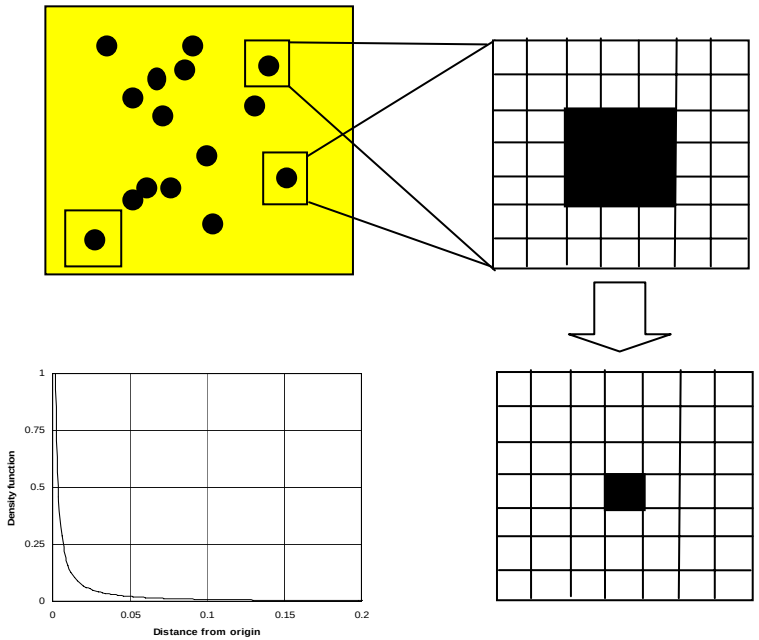
Thought experiment:

Finely dispersed catalyst
1% of surface area

1000x1000 pixel image

4 counts/pixel on $C_{catalyst}$

40,000 counts/image



Partition image with strong signal and

deconvolute co-imaged weak signals with PSF

Real high frequency components, not Gaussian

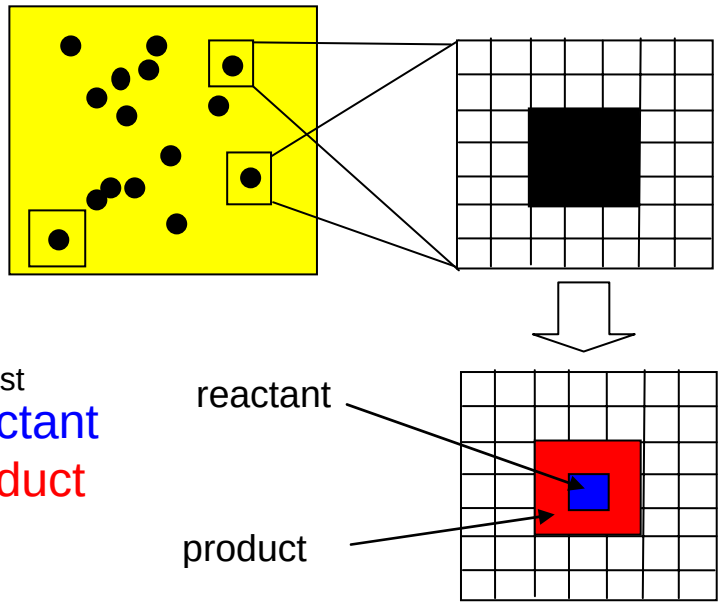
Defining spatial resolution, or spatial response

Thought experiment:

Finely dispersed catalyst
1% of surface area

1000x1000 pixel image

4 counts/pixel on XPS $S_{catalist}$
2 counts/pixel on XPS Sreactant
5 counts/pixel on XPS Sproduct
50 counts/pixel on UPS line



Partition image with strong signal and

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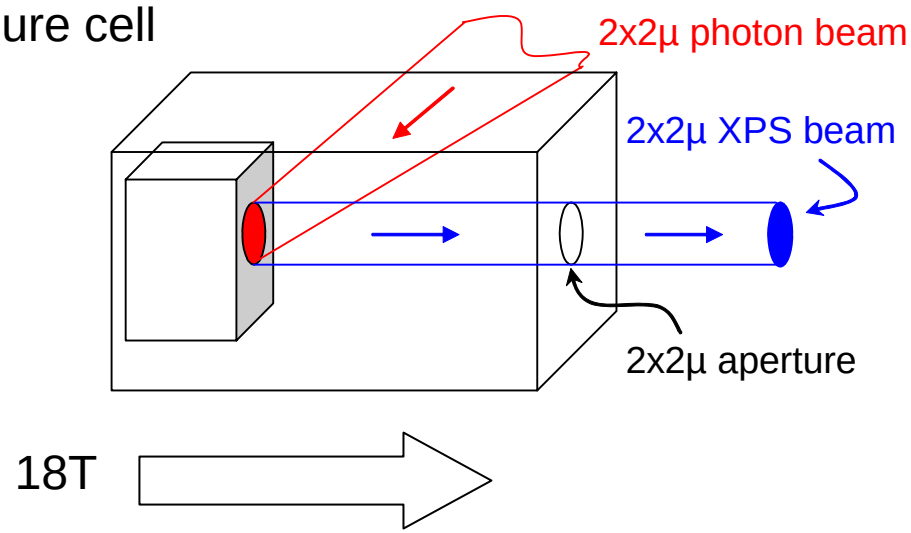
Real high frequency components, not Gaussian

More on: why make yet another XPS microscope? YAXPEM

Ambient pressure cell



It's different

3D+ NIST XPS microscope -1st light August09

Target Specifications:

Spatial Resolution:

(2009) 100nm

(2010) <50nm

(2015+) 10nm (NSLS II)

Energy Resolution:

250meV

Depth of focus:

2mm

Field of view, 400 line image:

(2009) 1mm - 40 micron

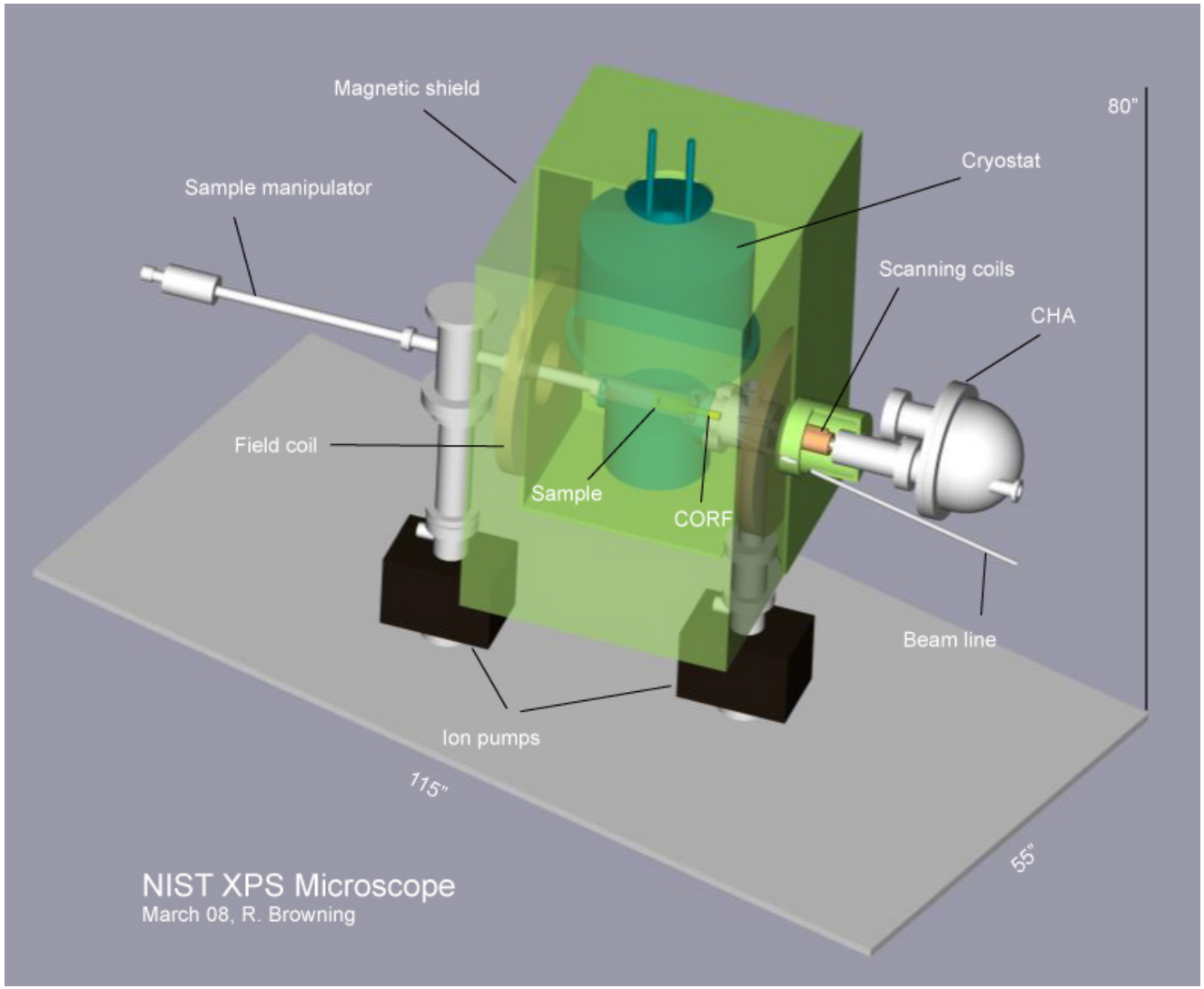
Imaging Modes:

XPS, UPS, PEEM, NEXAFS, ARPES, 3D HAXPES, Multi-photon

Multi-spectral imaging from <100nm features

Area assay from cluster diagrams

XPS and HAXPES require a high brightness source for reasonable image times, $>10^{11}$ photon/sec/μ^2 for 1-10^3 second images.



Thanks to:

Dan Fischer NIST – originated SBIR

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