!30 years of NSLS operation

1982-|---|---|---|---|---|---|---|---|-1992-|---|---|---|---|---|---|---|---|-2002-|---|---|---|---|---|---|---|---|-2012-|---|---**NSLS-II**

R&D 100 Awards

1986 NIST and University of Tennessee: soft x-ray emission spectrometer.

1988 BNL and the University of Chicago: an x-ray microprobe/microscope.

1988 AT&T Bell Laboratories: **high-resolution soft x-ray monochromator.**

1989 BNL NSLS: real-time: harmonic closed-orbit feedback system

1990 BNL NSLS: wavefront dividing infrared interferometer

1991 SUNY Stony Brook, BNL, LBNL, and IBM: high-resolution scanning photoelectron x-ray microscope.

1997 BNL& Quantar Technology, Inc.: Fluorescence Omnilyzer.

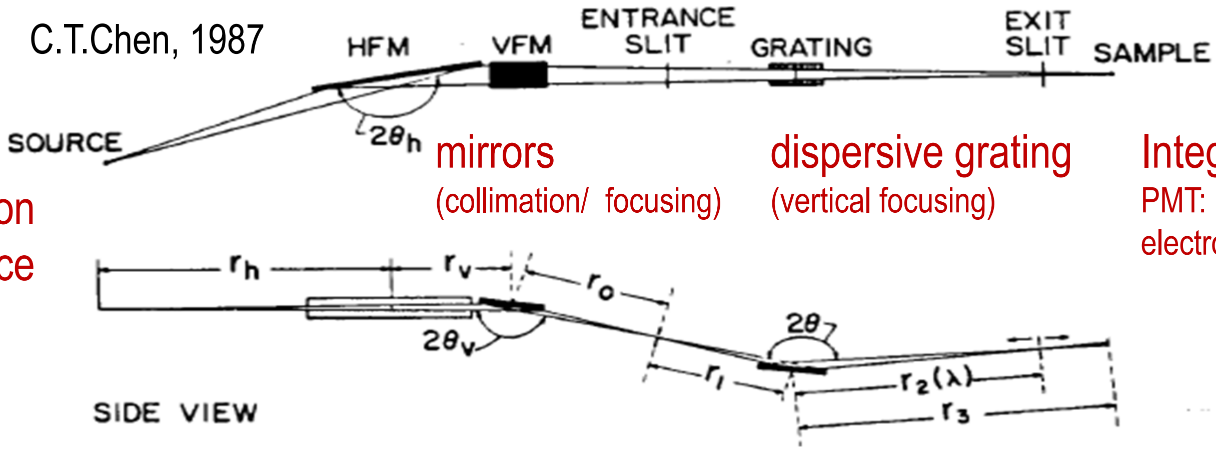
1999 SUNY Stony Brook University& Bell Laboratories: cryo scanning transmission x-ray microscope

2006 BNL NSLS: Sagittal Focusing Laue Monochromator

2011 BNL&CSIRO(Australia): Maia x-ray microprobe detector system

> continuous innovation: novel SR-based experimental techniques, pushing the boundary of the SR source, x-ray optics and detectors

C.T.Chen, 1987



second generation SR-source

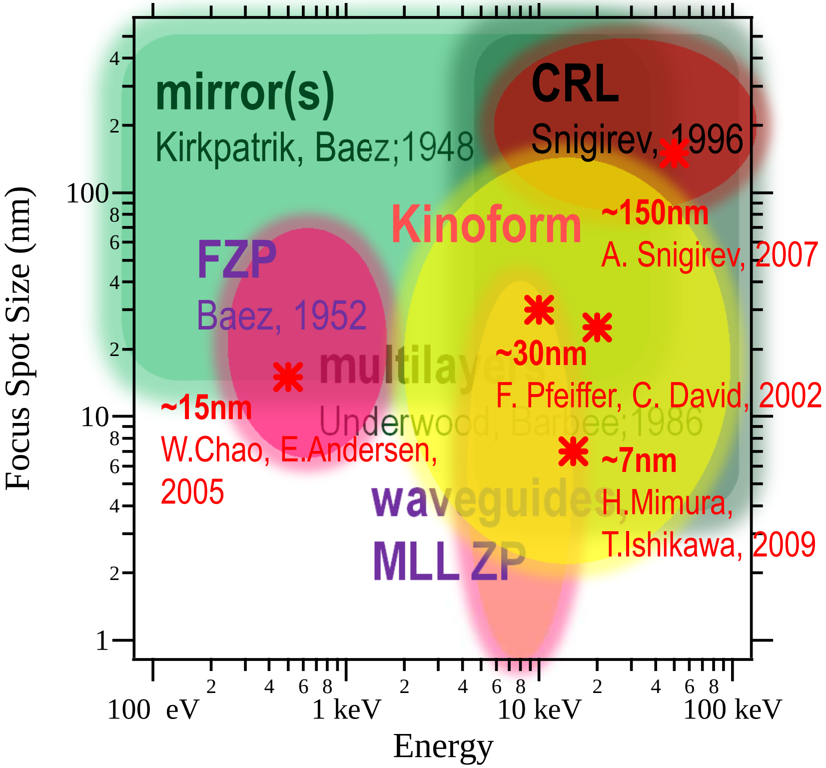
mirrors (collimation/ focusing)

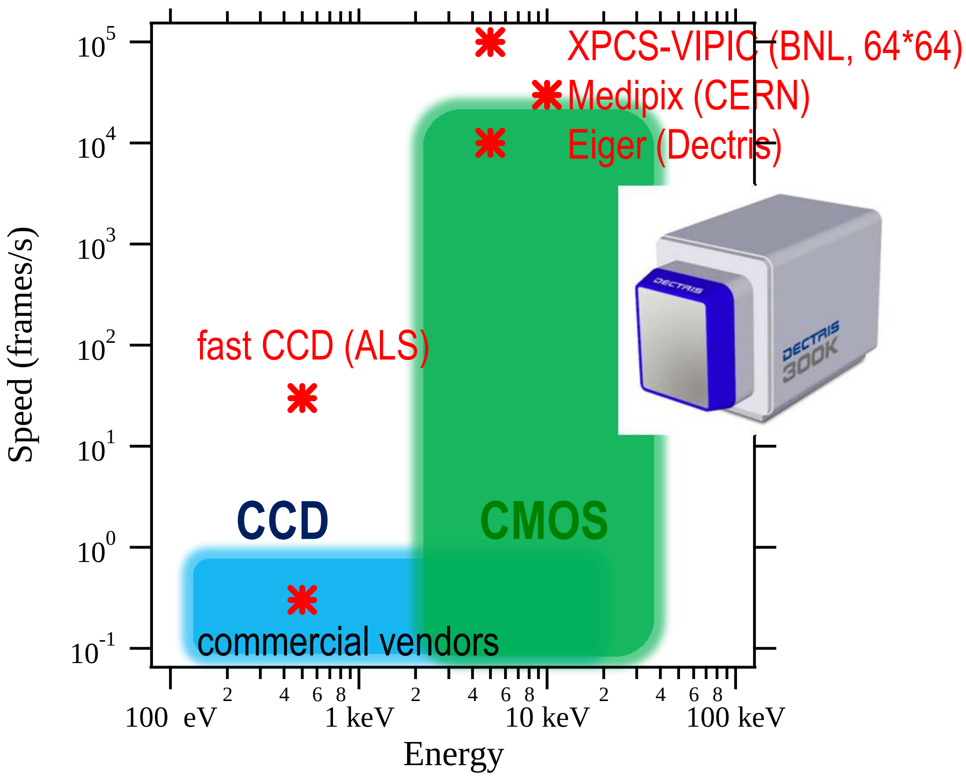
dispersive grating (vertical focusing)

Integrated Detector
PMT: abs./ fluorescence; electrometer, total e- yield

Novel approaches in the SR beamline design

progress in x-ray optics and detectors

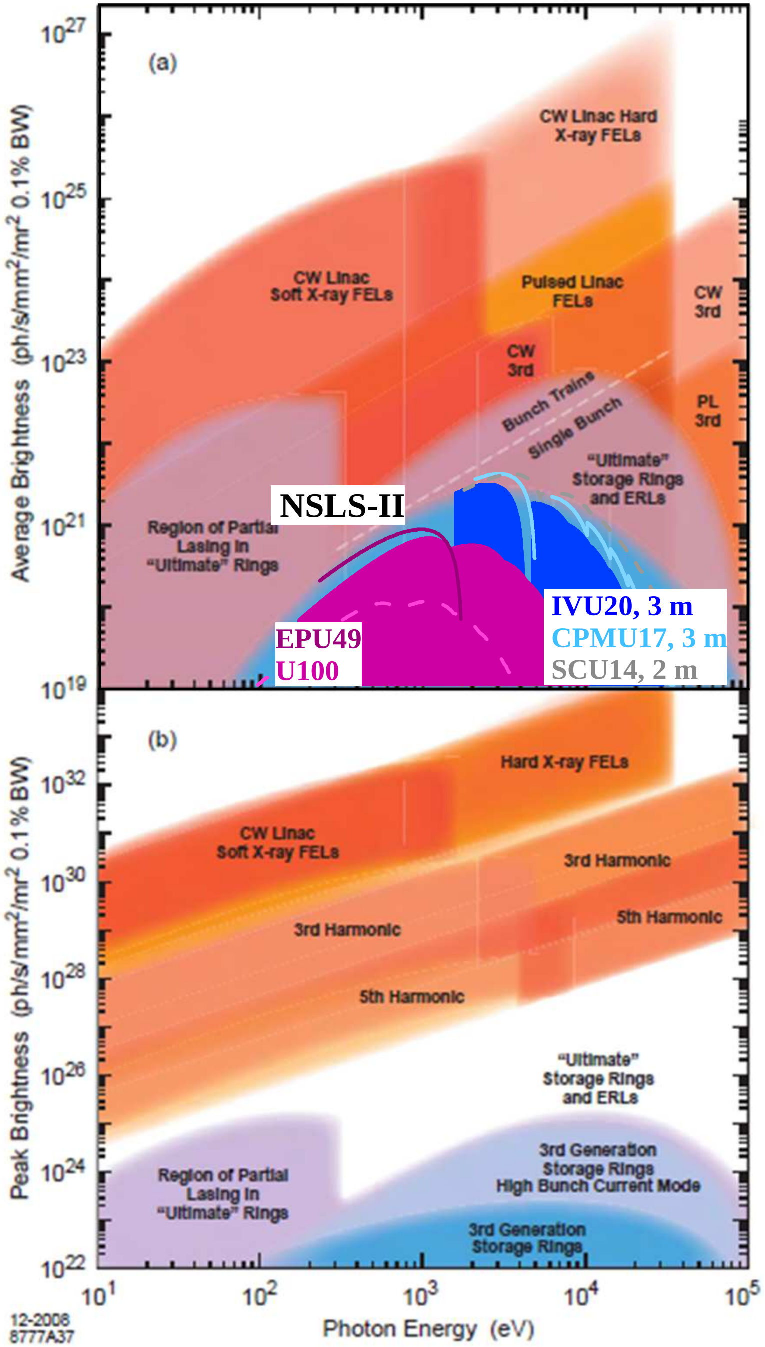


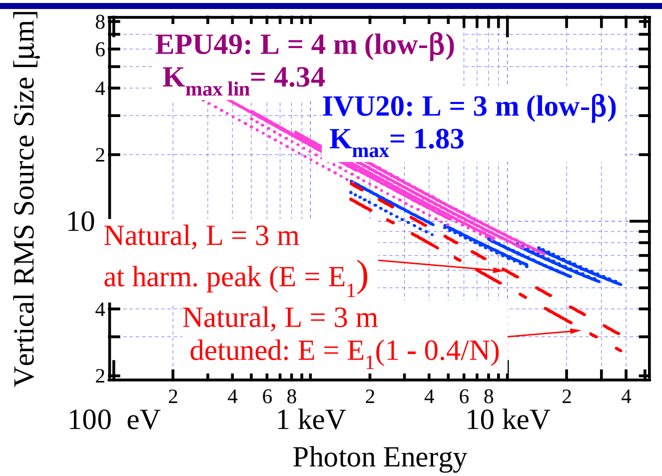


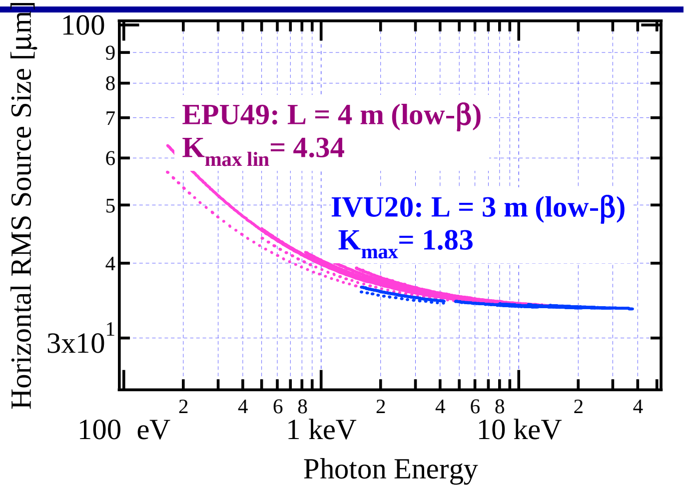
> A tremendous progress was made for all type of x-ray optics: reflective (mirrors), refractive (CRL, Kinoforms), and diffractive (ZP) optics breaks **100 (10) nm** barrier while retaining high efficiency

> **2D x-ray detectors** with direct x-ray photon readout become common. Continuous shift to CMOS technology will produce detector with an efficiency of single x-ray photon counting, almost no background and high dynamic range

new x-ray sources-> new scientific frontiers







scientific challenges:

- mastering energy/information flow at nanoscale with capability rivaling living things (~nm, sub-meV@keV)
- exploration of complex correlations between spin, orbit, lattice and electronic excitations in (non-crystalline) materials and understanding of systems far from equilibrium (femtosecond dynamic)

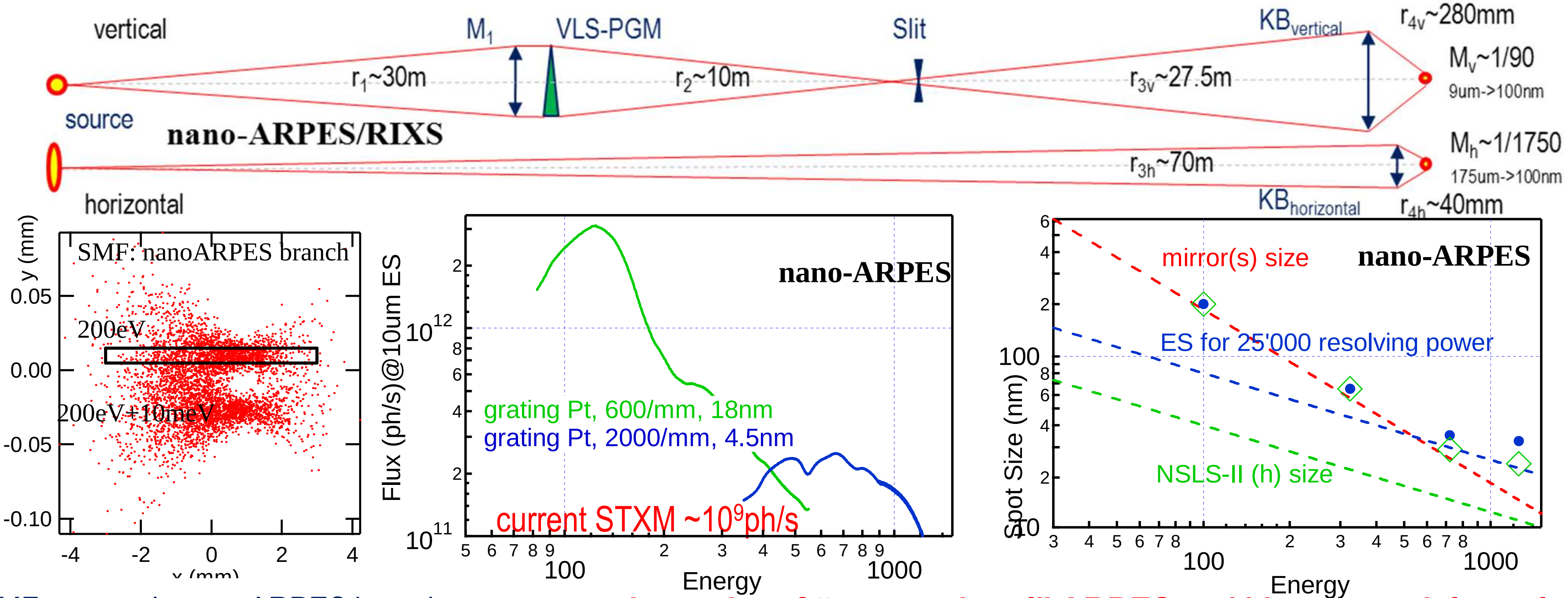
SR technology advances (coherence and instant power):

- ultimate III generation storage rings (0.1nm*rad/1A)
- ERL(1pS<) and FEL

SR-based novel experimental techniques

- **microscopy** (KB<10nm) and **coherent scattering** (ultralow scattering optics (CRL: λ(1A)/25)
- **high-energy-resolution spectroscopy** (IXS: resolving power of 10^6-10^8 for both soft and hard x-rays)
- precise **dichroic** measurements
- pump-and-probe or **time-resolved measurements** (utilization of XFELs and e^- seeding, ~0.1eV/atom, 100fS)

spectroscopy-> microscopy

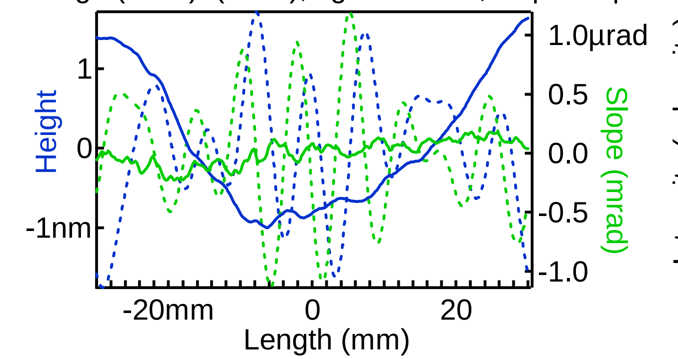


SMF proposal: nano-ARPES branch

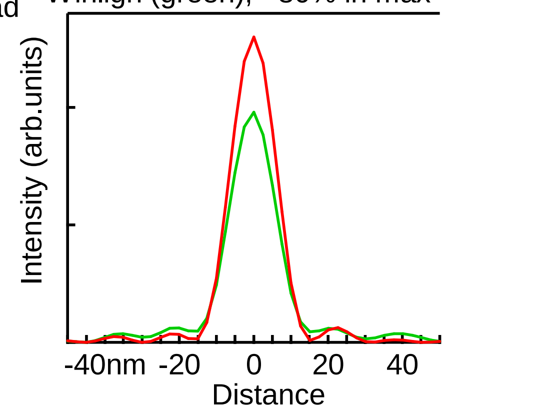
> intensity of "conventional" ARPES at 100nm< spatial resolution

…but mirror (soft x-ray) requirements

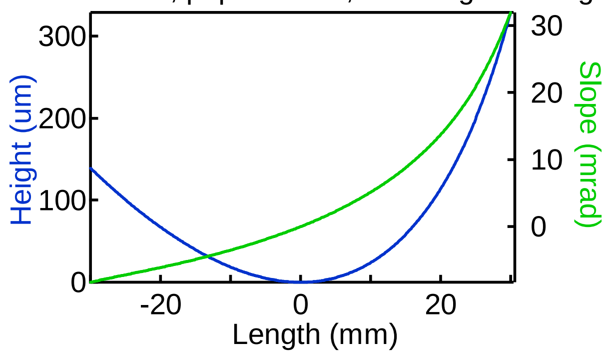
JTEC(solid): (RMS), figure 0.7nm; slope 0.1µrad
Winlight(desh): (RMS), figure 0.9nm; slope 0.5µrad



ideal (black), FWHM~20nm@1000eV
JTEC (red)~ideal
Winligh (green), ~80% in max



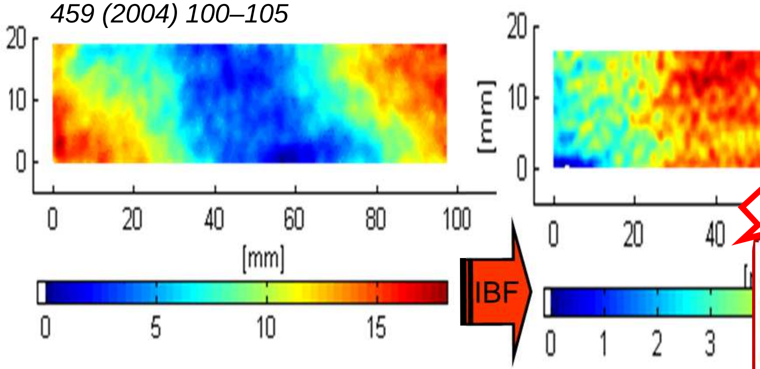
entrance 70m, exit 40mm, grazing 1.9deg
NA 41mrad, pupil 3.3mm, max angle 3.7deg



>current mirror fabrication capability (<1nm RMS), in principle, is sufficient to reach KB ultimate performance (~30nm), problem with **large sag** (mirror size) remains

ion beam assisted reactive erosion- at the SR facility?

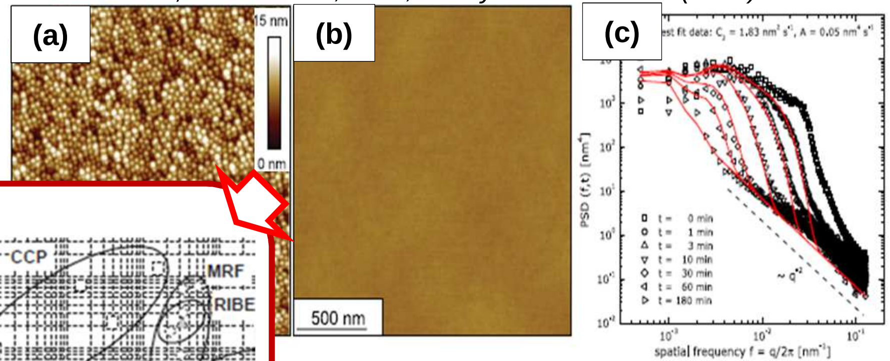
Large field optical metrology measurements of mirror figure before (a: PV 50nm) and after (b:PV 5nm) IBF, *after F Frost, et al., Thin Solid Films 459 (2004) 100–105*

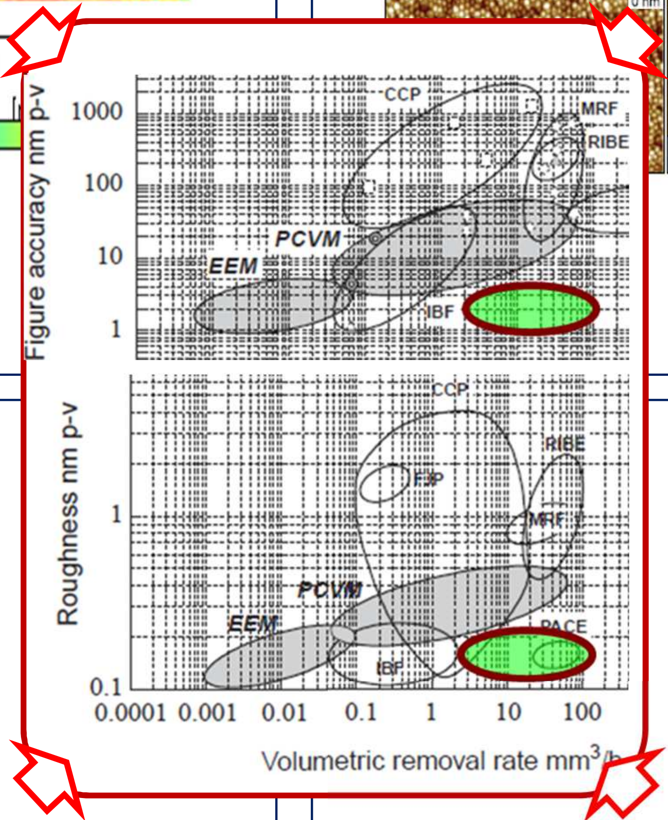


ion beam figuring

deterministic to nm-accuracy, spatially resolved (error map polishing)

AFM images before (a: σ(rms)~2.2nm) and after (b: σ~0.2nm) IBF and PSD variation, *after F Frost, et al., J. Phys.:Cond.Mat.21 (2009) 224026*





ion beam assisted Si diffusion

IB gun / parameter-specific need experiments

several commercial vendors

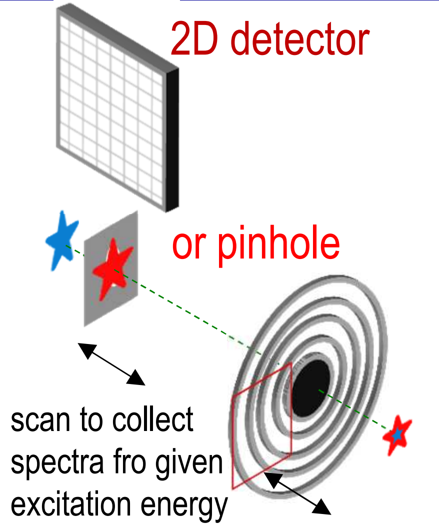
Zeiss, SESO, Winlight

+process is compatible with at-wavelength metrology

reactive ion etching and profiled sputtering

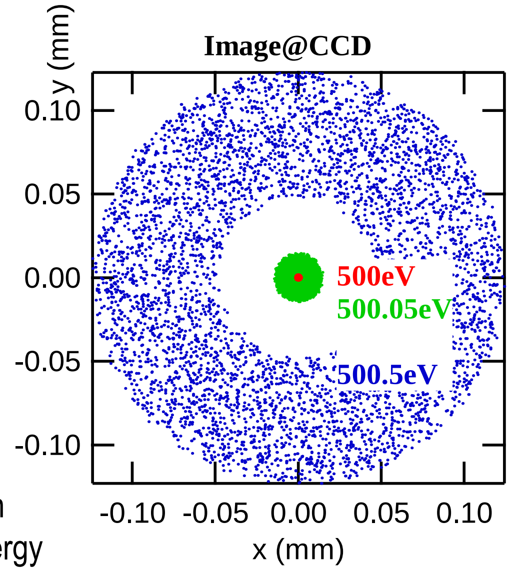
semiconductor industry: existing technology (Bosch, cryo-etching) for deep etching

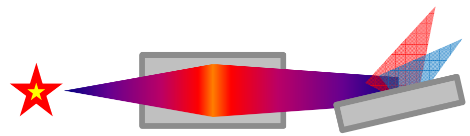
transmission grating based spectrometer

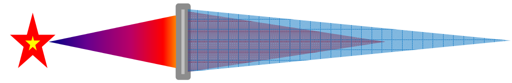


scan to collect spectra fro given excitation energy Δ50eV@500eV~2 50mm

scan to match excitation energy





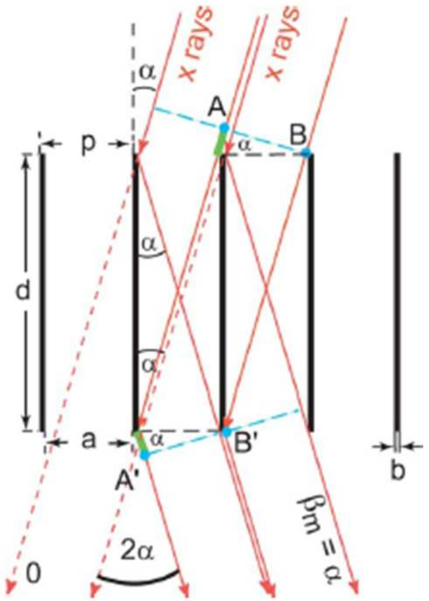


few mrad	for 25nm ZP and low energy can be as high as 0.2rad
limited by system aberration or optics imperfections (~10'000)	~number of zones (few thousands)
semi-parallel collection	small aberrations, simple mechanics and alignment

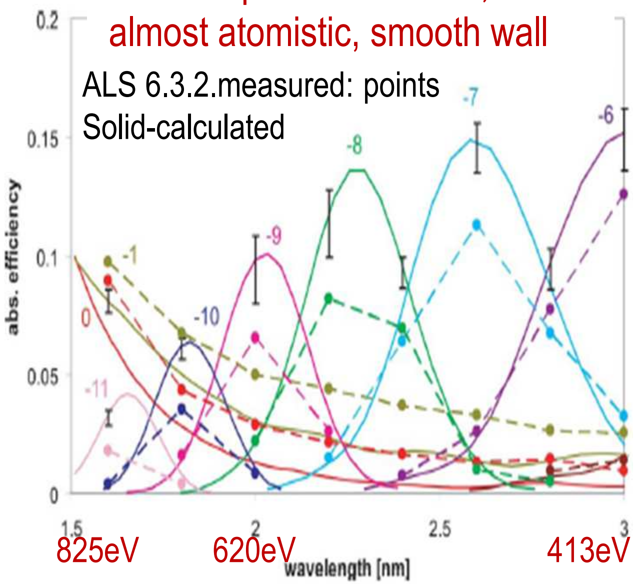
RIXS ZP-based spectrometer operation

>large collection angle
>medium energy resolution
20mm (10^5 grooves) at 1m~20mrad acceptance
>?not limited by (grating) slope errors
>low aberration
>robust alignment

Chandra: Heilmann et al, ApplOpt50(2011):1364 (M.Schattenburg group MIT)

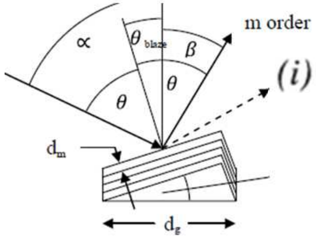


>200nm period achieved, almost atomistic, smooth wall



ultra-high resolution soft x-ray spectrometer

$m\lambda = d_0(\sin\alpha + \sin\beta)$: single grating equation (infinite grating)



need to balance

source size | *optics imperfection* | *optical scheme (acceptance) aberrations*

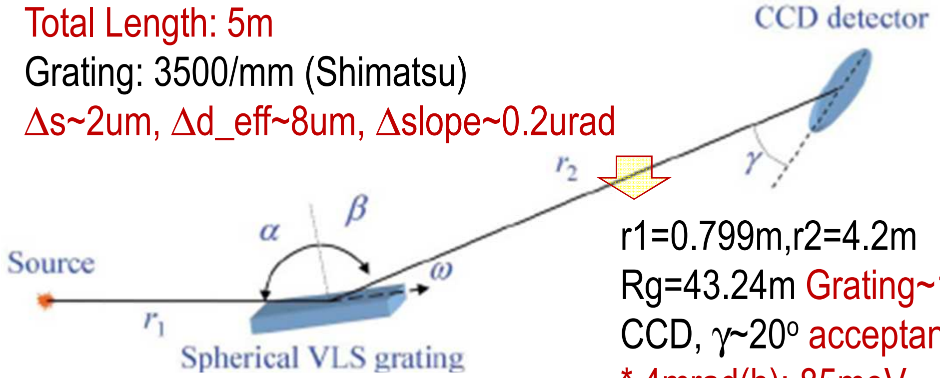
(i) Entrance slit (width S_1) *(iv) Slope error $\Delta\phi$ (of imperfectly made grating):* *(iii) Aberrations (of perfectly made grating):*

+fabrication concern: how well it can be made

$$\Delta\lambda_{S1} = \frac{S_1 d\cos\alpha}{mr} \quad . \qquad \Delta\lambda_{SE} = \frac{d(\cos\alpha + \cos\beta)\Delta\phi}{m} \quad . \qquad \Delta\lambda_{A} = \frac{\Delta y' d\cos\beta}{mr'} = \frac{d}{m}\left(\frac{\partial F}{\partial w}\right) \quad .$$

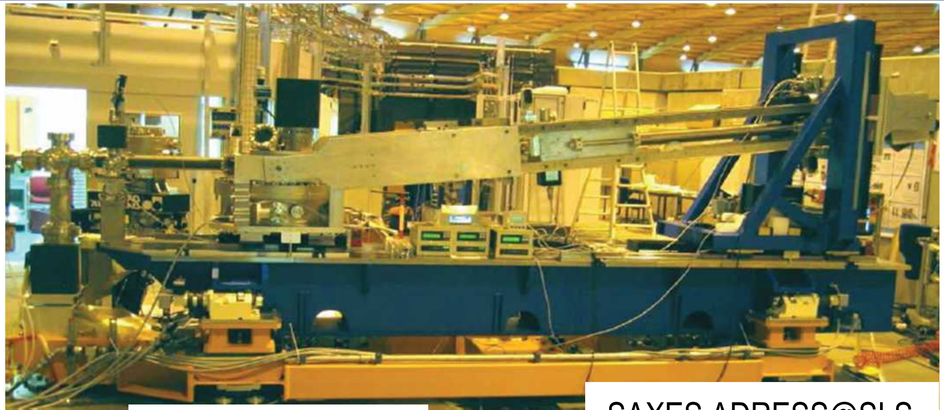
$\eta(m,\lambda) \sim \mathbf{R(\Theta,\lambda)} * \mathrm{Eff}(\text{groove profile}, m, h/\lambda)$: scalar approximation

Total Length: 5m
Grating: 3500/mm (Shimatsu)
Δs~2um, Δd_eff~8um, Δslope~0.2urad



r1=0.799m,r2=4.2m
Rg=43.24m Grating~120mm,
CCD, γ~20° acceptance~5.5mrad
* 4mrad(h); 85meV

V. Strocov et al., JSR18(2011):134

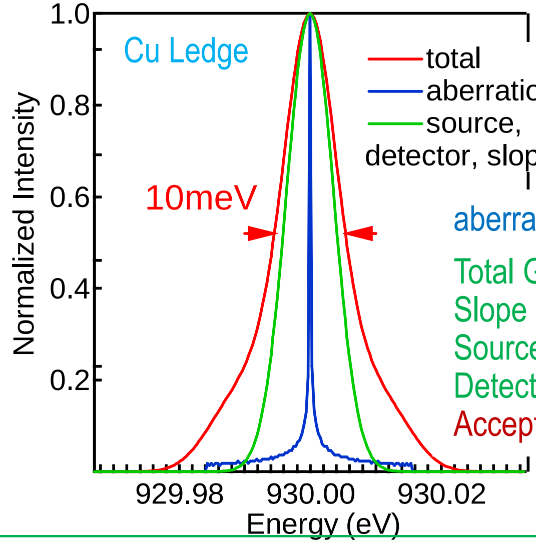


SAXES ADRESS@SLS

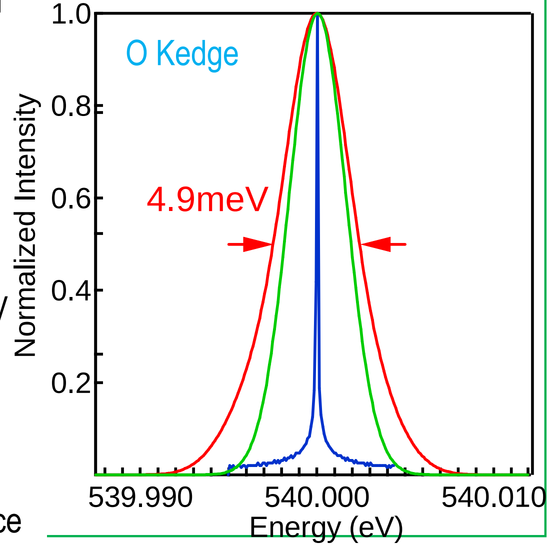
RIXS SIX@NSLS-II

Total Length: 10m
Grating: 3500/mm (Shimatsu)
Δs~0.7um, Δd_eff~2.5um, Δslope~0.1urad

r1=1.464m,r2=8.554m
Rg=81.54m Grating~120mm,
CCD, γ~20° acceptance~3mrad
VLS: a1=0.284/mm, a2=-0.313E-3



aberrations: 7.4meV
Total Gauss: 8.5meV
Slope (0.1urad RMS): 6meV
Source:3.5meV
Detector(2.5um eff):5meV
Acceptance (v)~3mrad



V. Strocov, VLSTrace

> 10^5 resolving power can be reached with "conventional design', assuming: grating slope error~0.1urad+ very dense CCD

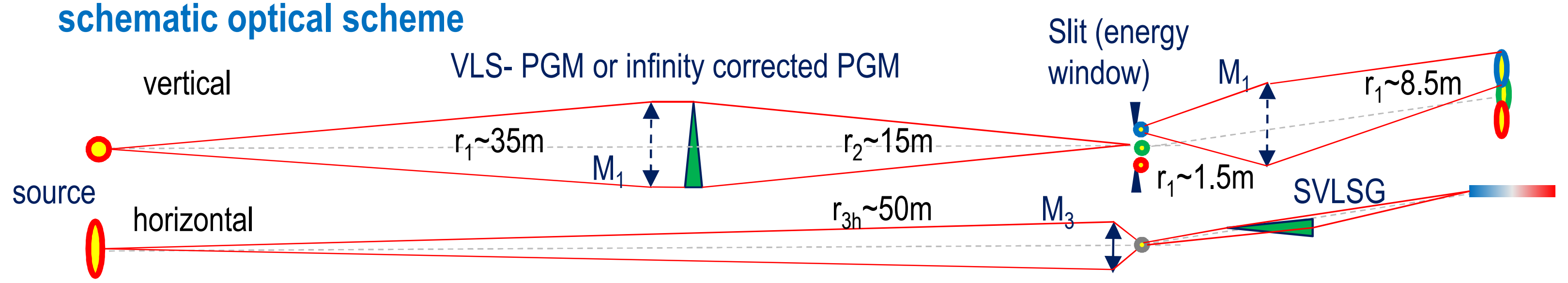
poly-dispersive RIXS

see also **V. Strocov, hv² design**

poly-dispersed RIXS

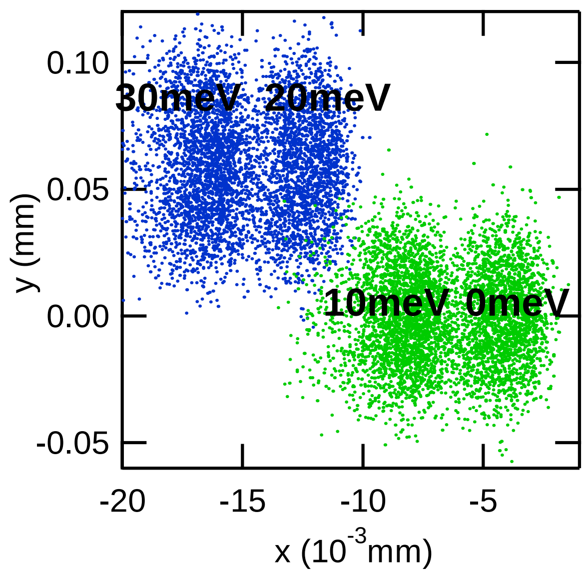
>> yes, even more, we can use pre-mirror to focus the light in non-dispersive direction and use prime mono poly-disperse light

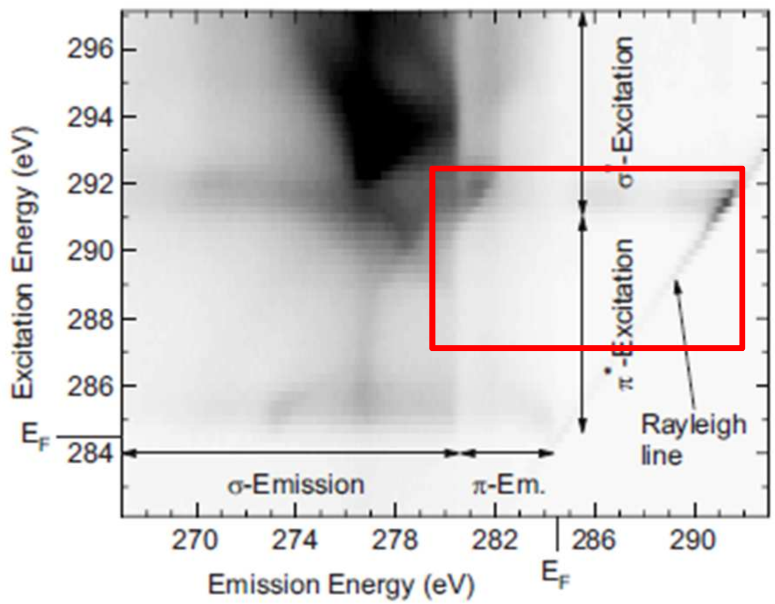
schematic optical scheme



~4eV or 400spectra (v) along 10eV (2K) @10meV

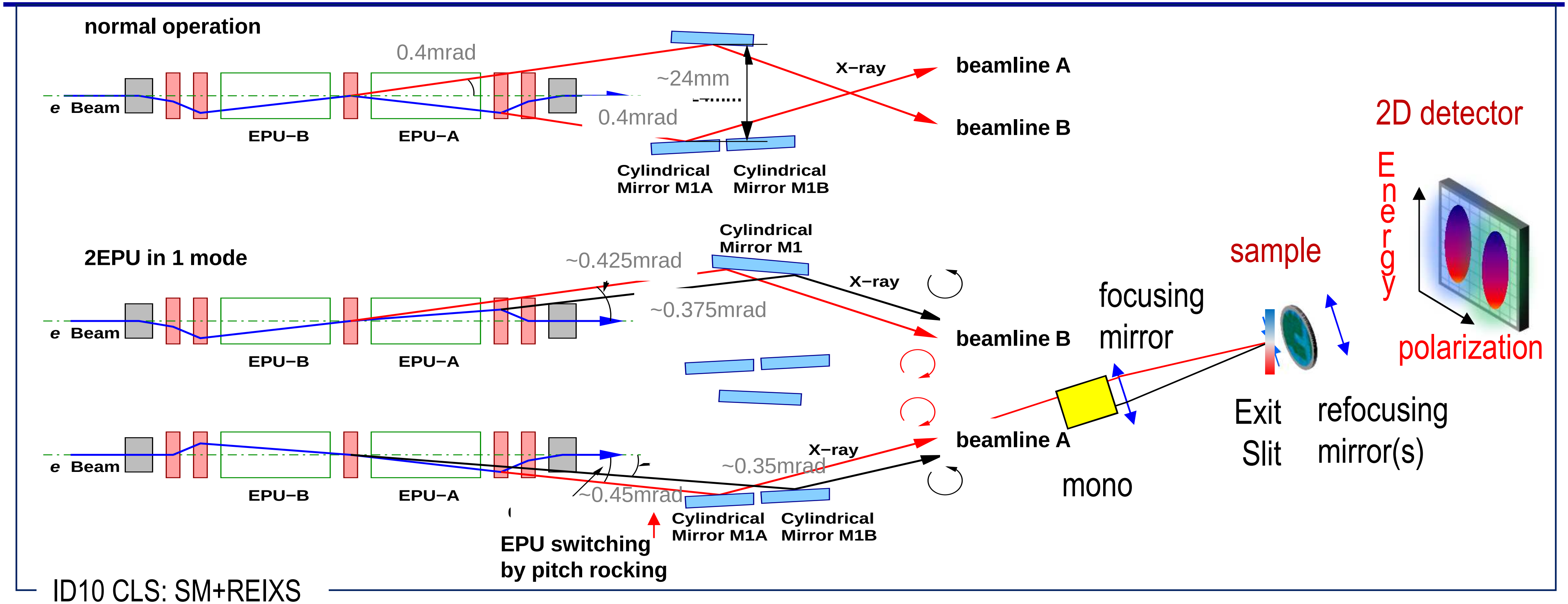
Prime mono:
Resolution 10meV
Linear dispersion ~2mev/um
or 5um apart
Further magnified (by x6)
spectrometer





>> permit us to collect ~500 individual spectra at once and further improve the vertical collection angle to 10mrad

e^- beam chicane: to take the best of "shearing"



ID10 CLS: SM+REIXS

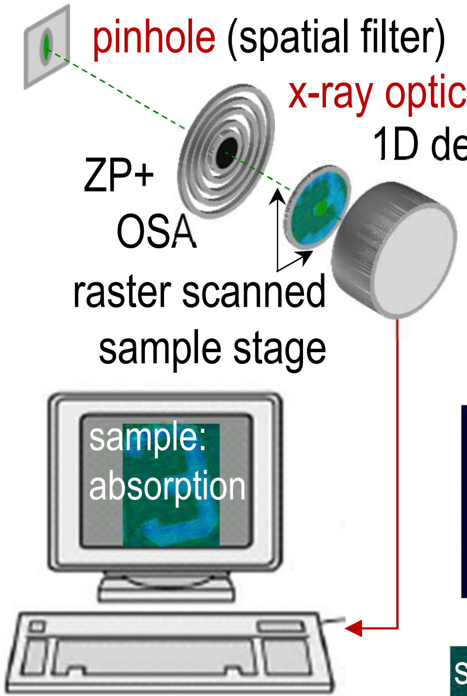
> **Shearing** the straight between two "similar beamlines not only increases total productivity, but permits novel acquisition modes: measuring extended polarization map at once, or using chicane modification (e-beam or photon beam steering) as a function of time to study dynamic while collecting dichroic signal

Parallel High Resolution X-ray Microscopy

motivation: ***bridge the gap between low resolution/ sensitivity "industrial imaging" and modern x-ray microscopy***

SR-based:

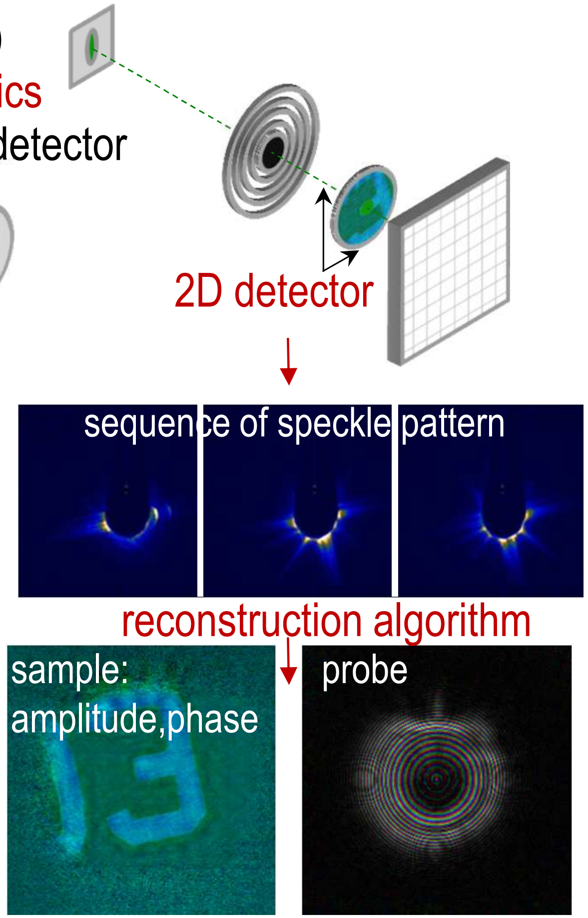
(i) scanning x-ray microscopy (ii) coherent diffraction imaging



Resolution: focus size (~**λ/NA optics, diffraction limited, 15nm**

Instant FofV: **pixel**

Scan Size: **arbitrary** k*l pixels



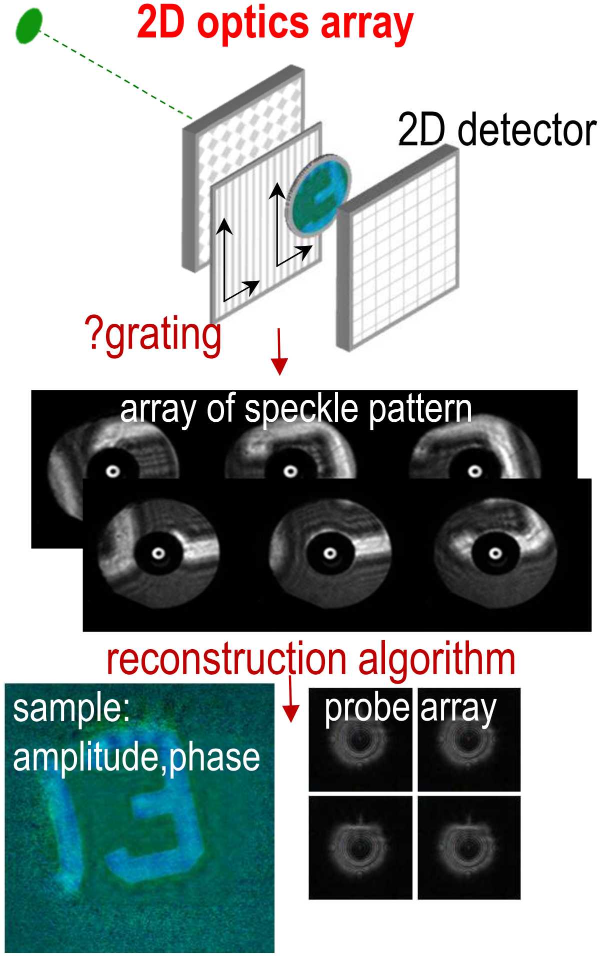
Resolution: ~**λ/NA detector, diffraction limited ~5nm**

Instant FofV: ~**probe spot size**/2

Scan Size: **arbitrary** k*m/2*l*n/2 pixels

proposed Parallel Imaging

2D optic array + sample scanning



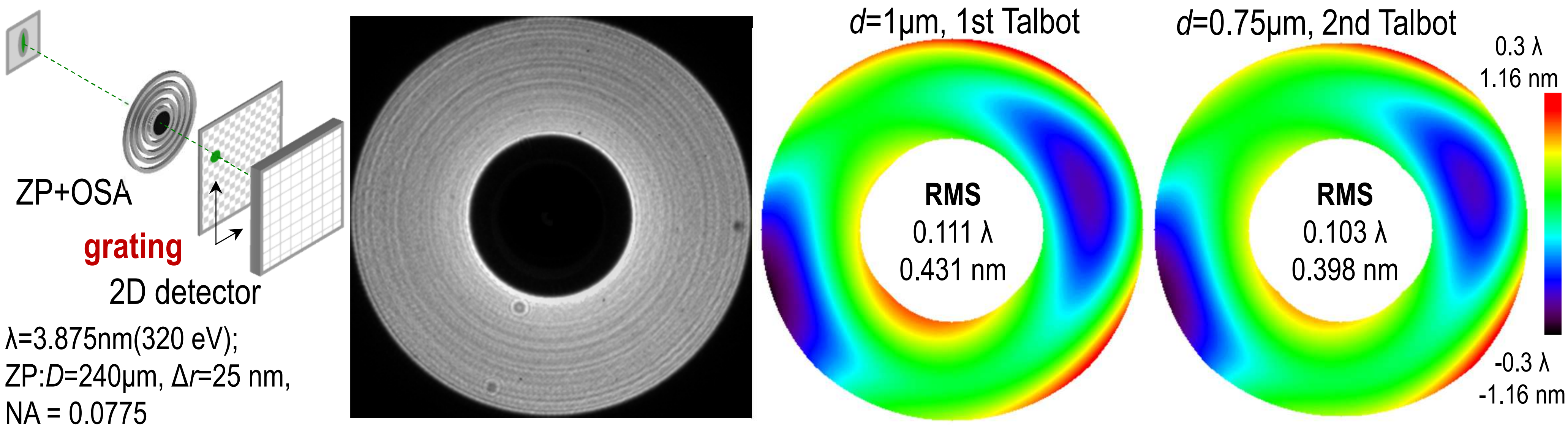
Resolution: **~100nm target**

Instant FofV: **~*i*j*probe spot size**/2

Scan Size: **~n/i m/j**

soft x-ray shearing interferometry

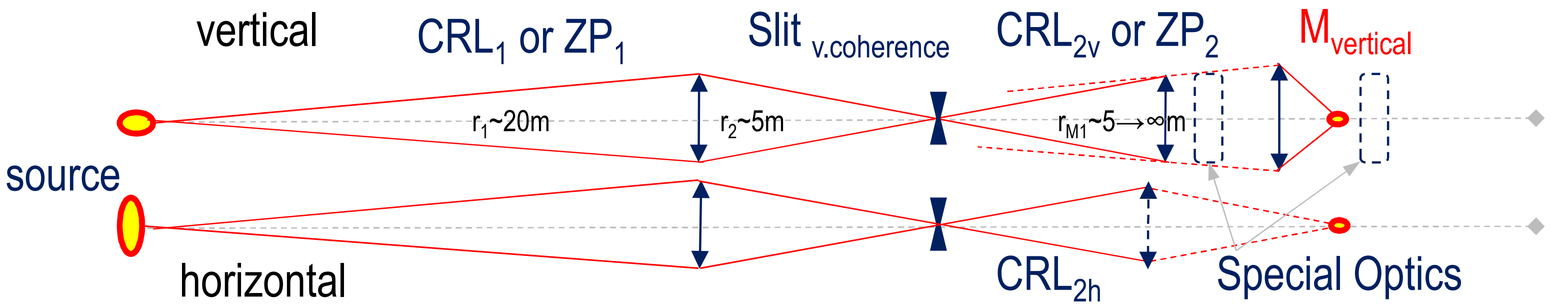
Data Analysis: 3/23/12, **Kenneth Goldberg**, KAGoldberg@lbl.gov

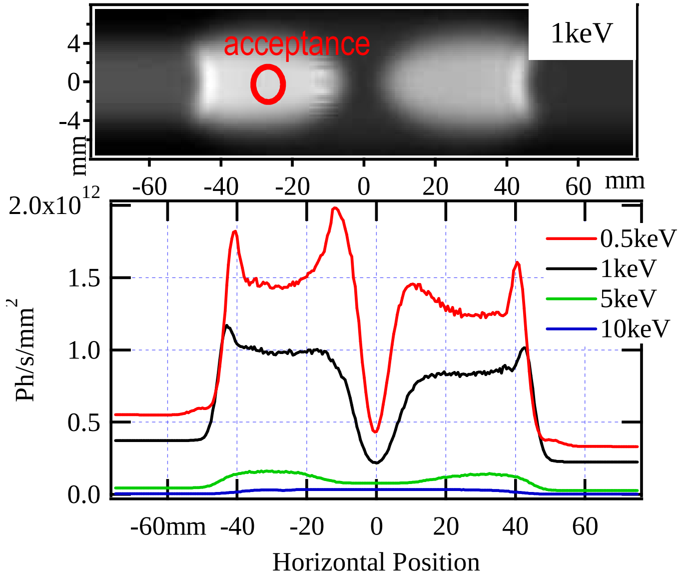


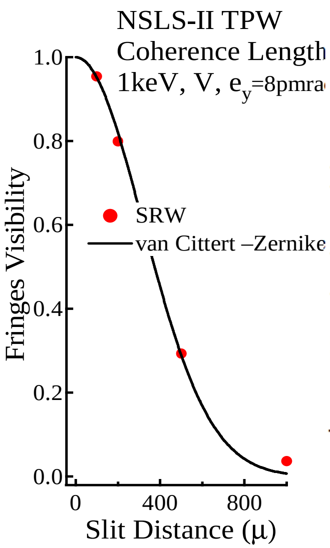
SM CLS STXM

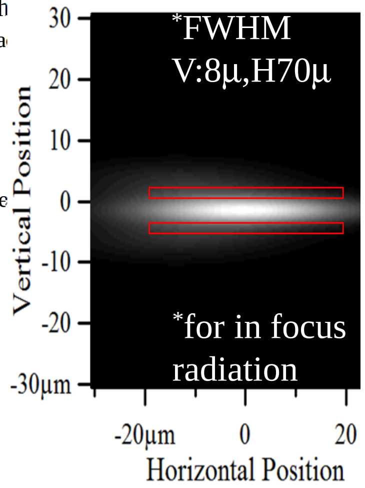
> Absolute accuracy (repeatability) of **low frequency wavefront reconstruction exceeds λ/100**, so great sensitivity make shearing interferometry attractive for x-ray phase imaging.

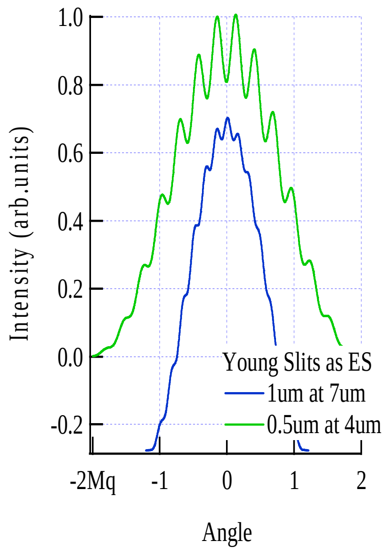
NSLS-II beamline dedicated to at-wavelength metrology

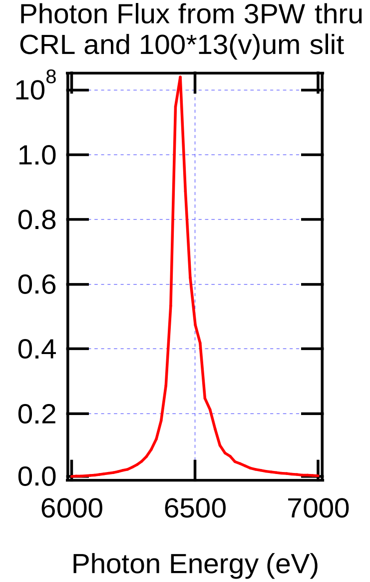












- Typical mirror/ pupil size ~280/6.5mm (soft x-ray) and 250/0.8mm (hard x-ray).
- Coherence length is 15µm (h)/190µm (v) (for E~6keV) and can be further increased by closing the slit.
- Combination of x-ray lens (CRL or ZP) with entrance slit provides light monochromaticity of 10^{-2}.
- Flux will reach 10^8ph/s/mm^2 (hard x-ray).

> simple and versatile, as (i) virtual source distance can be matched to the requirements of the optics under test (ii) coherence vs. flux can be efficiently traded

concluding remarks

Novel approaches in the SR design:

- close to diffraction limited performance of novel SR sources gives a possibility to transform “full flux” experiments to “x-ray microscopy” without penalty. Optics (and detectors) might still be a limited factor, but the progress is steady.
- an idea of “parallel acquisition” gives a fresh look to beamline design principles
- there is a rapid progress in wave-field analysis: source properties and direct propagation, as well as inverse problem solution (ptychography, x-ray interferometry, phase imaging)
- for many components, the final performance can only be verified by at-wavelength metrology. It bears ultimate accuracy and sensitivity. ?It can be used in combination with *in situ* (fine) figuring, but “combined” resources are needed to put it into the practice.

Acknowledgement:

your attention

funding: DOE Contract No. DE-AC02-98CH10886

colleagues:

- optical design (Oleg Chubar (SRW), Tony Warwick and Vladimir Strokov)
- microscopy (David Shapiro and Tolek Tyliszczak)
- x-ray interferometry (Ken Goldberg and Mourad Idir)
- x-ray metrology and optics development (Mourad Idir and Ray Conley)