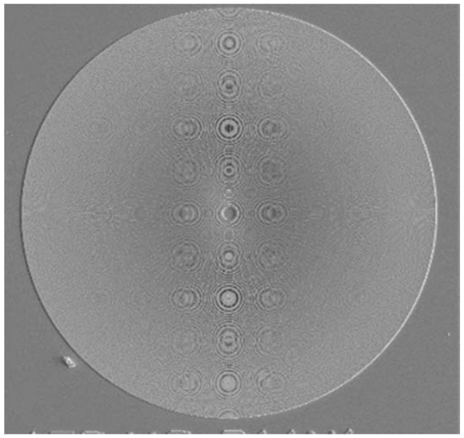
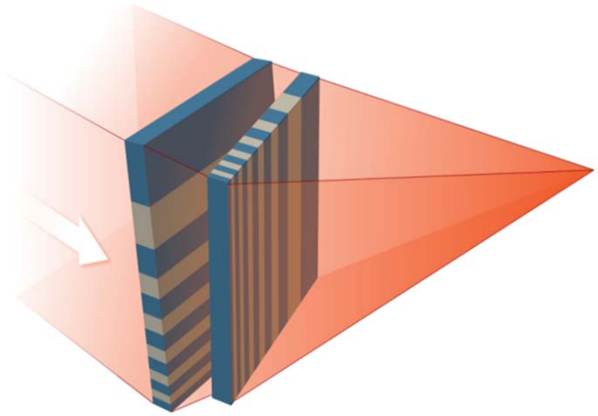
Diffractive Optics

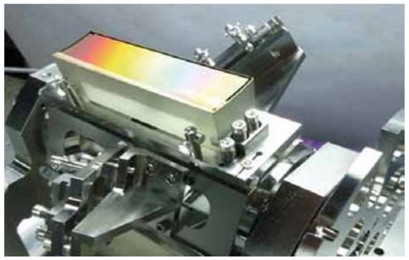
1) Focusing Optics-ZPs and MLLs
2) Reflection Gratings



Zone Plate



Multilayer Laue Lens



Grating courtesy of (Horiba/ Jobin Yvon)

Assoufid, Goldberg, Idir, Cocco, Rabedeau

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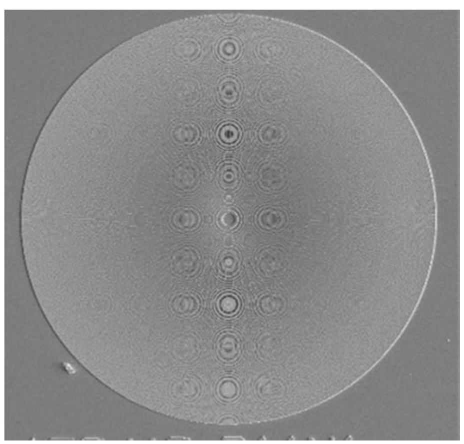
Diffractive X-Ray Optics (DXO)

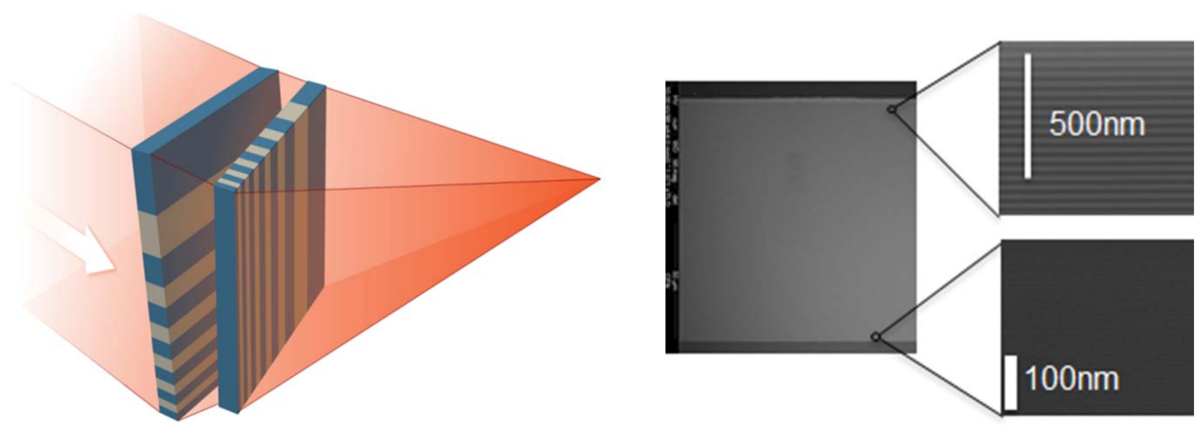
Nanofocusing diffractive optical elements are essential for many SXR & HXR applications to achieve the highest possible resolution and sensitivity. Increasing demand for high spatial resolution pushes us beyond current capabilities, with no commercial source. More concerted effort and resources would bring faster progress.

There are two proposed options for nanofocusing diffractive optics to achieve the goals of the DOE light sources: zone plates (ZP) and multilayer Laue lenses (MLLs). For both, efforts to achieve 5-nm focus with high efficiency is required.

Though there are different sets of requirements depending on X-ray energy, beamline, experiment, etc., there are also fundamental similarities in achieving the desired focus which should drive collaboration between the labs.



Zone Plate



Multilayer Laue Lens

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1) the issues and challenges faced

Diffractive focusing optics

I) HXR ZPs

1) High resolution, high efficiency HXR ZPs are challenging: nanoscale width + microscale thickness.
   MACE (developed at SLAC/Stanford) solves the problem of high efficiency, but not ultra high resolution.
2) Current tech: ~15-20 nm focal spot, low efficiency.
3) Specialized fab: 7 nm focus, *lower* efficiency.

Need to develop new/improved fabrication methods or new optical systems to deliver nm-size spots.

II) SXR & Tender X-Rray ZPs

1) Current technology: 9-nm STXM, 10-nm TXM resolution.
2) Development of wavefront encoding optics tailored to specific applications. (Applies to HXR as well).
3) **Key challenge: Small structures with adequate aspect ratios**
4) Limitations come from patterning materials and processes

What is the limit required in the SXR?

III) HXR MLL Optics

1) Current tech: 11-nm line focus, 15x15-nm imaging @ 12 keV.
2) Roadmap to diffraction-limited 50-µm-aperture MLL & 100-µm-aperture flat MLL has made progress
   but has not yet been realized.

Fabrication of wedged MLLs needs development

Explore material systems with low cumulative stress for MLLs with large aperture, >100 µm

1) the issues and challenges faced (continued)

Zone plates: Soft X-Ray vs. Hard X-Ray—different requirements.

Requirements	**Soft/Tender X-Ray**	**Hard X-Ray**
Focal spot size	<5 nm or <100 nm with very high efficieny	5-10 nm
Energy range	Up to 6 keV	Up to a few 10s of keV
Aperture	> 100 um imaging ZP > 10 mm condenser ZP	> 100 um imaging ZP > 1 mm condenser ZP
Aspect ratio	> 20:1	>100:1
Smallest zone with	< 5 nm	<5 nm
Efficiency	As high as possible	As high as possible
Vacuum requirements	Depends on application	Depends on application

1) the issues and challenges faced (continued)

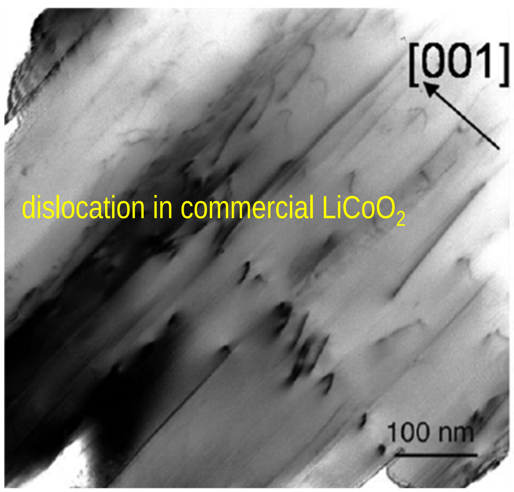
MLLs

Requirements	Hard X-Ray
Focal spot size	~5 nm
Energy range	Up to a few 10s of keV
Aperture	> 100 microns
Aspect ratio	No intrinsic limitation
Smallest zone with	~2 nm
Efficiency	Theoretical limit ~50%
Vacuum requirements	NA

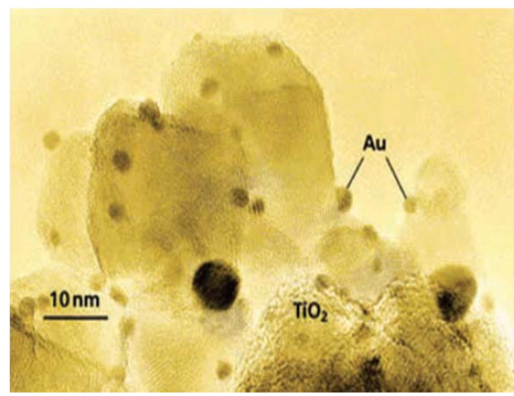
2) The impact of solving those challenges

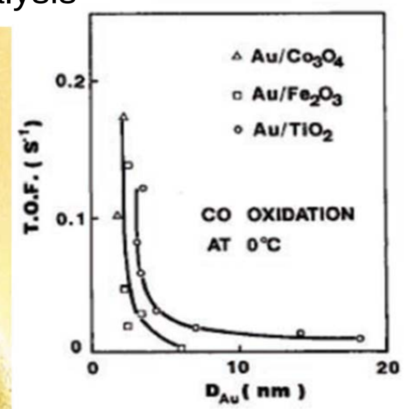
- The dramatic increase in coherent flux enabled by or expected from the new generation light sources will provide transformative imaging and spectroscopy capabilities at very high spatial resolution with close to atomic sensitivity.
- Exploiting the new capabilities from next generation of light sources cannot be accomplished without the availability of highly efficient diffractive focusing optics that are able to deliver focused beams with spot sizes in the <10 nm range.
- Enhance capabilities of experiments using nanofocusing optics, especially those requiring a thin-single optic.
- Imaging with X-ray energy beyond 30 keV.
- Two examples of science problems below:

Energy Storage Materials



Catalysis





- **Multi-scale Hierarchical 3D “Buried” Structures**
- **In-situ/In-operando investigation**

3) current status of work in these areas at the 4 labs

LBNL: ALS / ALS-U

CXRO efforts in zone plates

- Nanofab. **dedicated facility** for nano-diffractive optics.
- The only e-beam tool **designed for ZP patterning**
- **Partnership** w/ Molecular Foundry on nano-patterning
- New tools for **engineered wavefront encoding**
- New **ZP wavefront interferometer**
- **Partnering w/ industry** on EUV diffractive optics dev.

BNL: NSLS-II / NSLS-II

ZPs

- ZPs obtained from collaborators

MLLs

- **Wedged MLLs**, fabricated over the last 4 years.
- BNL effort is underway to **bond MLL optics**
- MLL with **15 nm x 15 nm focus** in routine user operation at HXN beamline @ 12 keV

ANL: APS / APS-U

MLLs

- R&D on AA monitoring, material systems, deposition processes for higher aperture, efficiency, and precision (collaboration with BNL)

ZPs

- APS-U funded R&D to develop 20-nm focusing stacked ZP system.
- Fabrication capabilities down to 14-nm zone-width with 20 aspect ratio
- Demonstrated ZP stacking with **80 nm @ 27 keV, 28% focusing efficiency**.

SLAC: LCLS /SSRL/ LCLS-II

ZPs

- Early career development project for MACE process
- Nanofabrication facility under construction

Gratings

- Improve precision VLS grating measurements
  – support the development of domestic vendor and R&D project
- Early stage R&D project to produce shallow blaze angle with ultra-high resolution

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4) Specific ways in which we can work together across the complex—complementing, not duplicating.

Zone Plates

- **Collaborate on R&D to develop ZPs with 5-nm focus and toward maximum efficiency.**
- **Stacked ZP system** at APS will continue and pushed further to achieve <10 nm focus
- Collaborate on R&D of **fabrication methods**
- Methods to **pattern sub-5 nm structures over large area** (all facilities)
- **High aspect ratio ZPs** fabricated at SLAC/Stanford via MACE. Such ZPs are available for the entire DOE complex. New nanofabrication laboratory will be available in 2018.

MLL

- Start formal discussion on the needs on sharing resources and leveraging capabilities and expertise
- MLL deposition systems for R&D and fabrication available at both BNL and APS (Modular Deposition System/MDS)

Both ZPs and MLLs

- Collaborate on shared platform for developing **control-software** options and integration
- Collaborate on **standard mounting** and manipulation/alignment micro/nanomechanics on a limited set of general devices

5) Thoughts on investment required to take the next steps

Meeting DOE lightsource needs in diffractive optics requires ongoing investment in R&D and state of the art facilities. These needs cannot be met by industry, the business case is not there for industry invest in the needed research and facilities.

- Start with **maintaining and leveraging existing facilities** and expand as budgets allow
- Goal: make diffractive nano-focusing optics **cost effective and readily available**. Invest in effort to catalogue optics for beamline use.
- **Hire** dedicated scientist(s)/post-doc(s) to accelerate the progress to meet the light sources needs
- Partner with vendors to develop commercial sources.
- SBIR / STTR possible, if suitable partners can be identified.

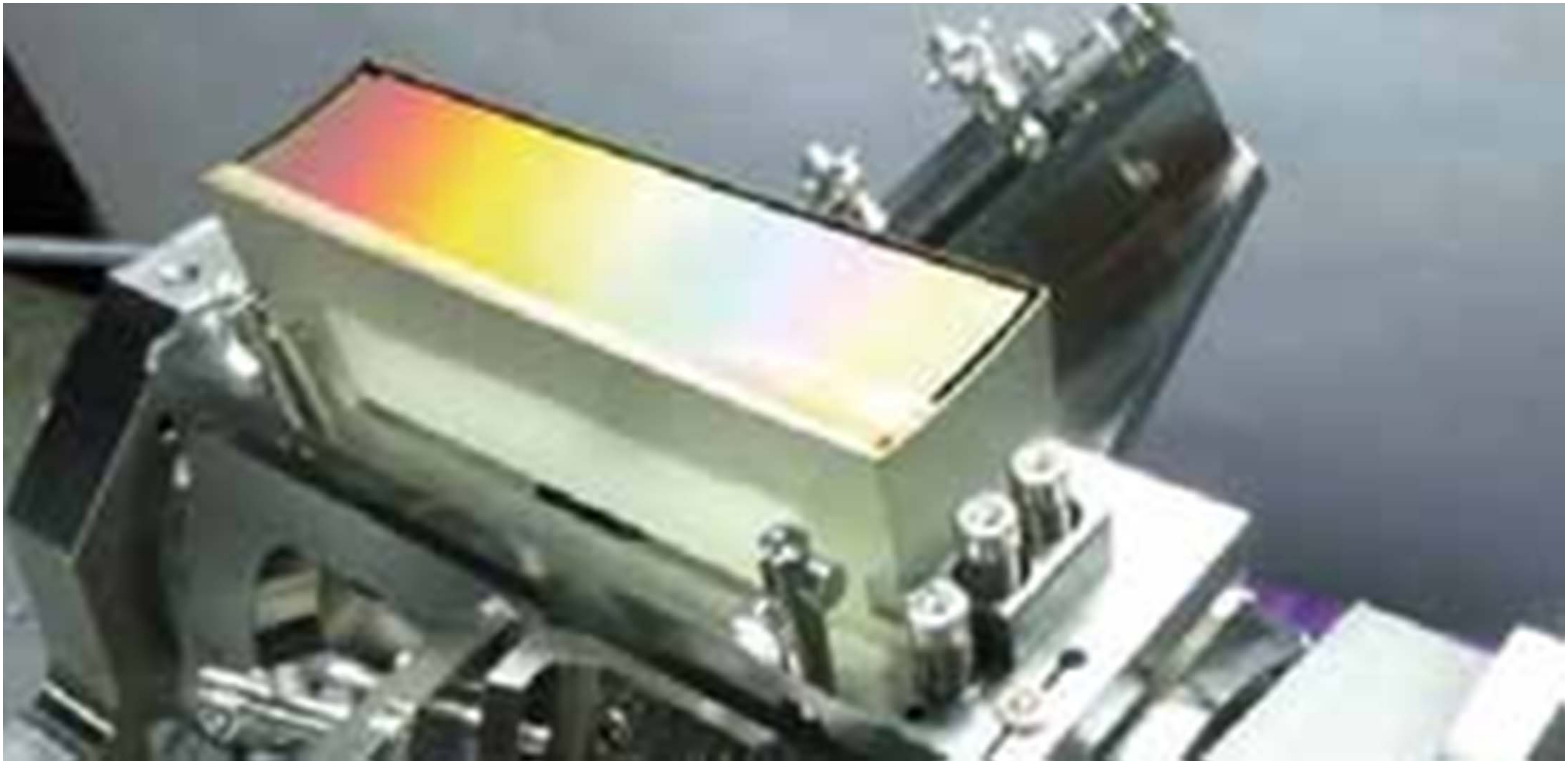
Take away message

- There is obvious demand and scientific cases from existing and emerging light sources for sub-10-nm resolution focusing diffractive optics.
- Each of the DOE lightsources has specialized and complementing abilities, but progress towards these optics has been impeded by the lack of coordinated effort or viable commercial sources.
- Only through collaborative effort with suitable funding can the desired goals for diffractive nanofocusing optics be achieved.

2) Diffractive Optics: Gratings

Diffractive X-Ray Gratings (DXO)

Gratings are the key element in all VUV and SXR beamlines. The demand for diffraction gratings is growing. Poor availability is constraining the design and implementation of monochromators and spectrometers. It is essential to improve the availability and quality of these key components.



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[Goldberg, Cocco, Idir, Assoufid, Rabedeau]

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1) the issues and challenges faced

Diffraction gratings

- Higher resolution is required for **SXR RIXS** and material studies..
  - Laminar grating with good precision can be produced by a limited number of vendors: *Horiba/Jobin Yvon*, *Shimadzu*, *ZEISS*
  - Blazed gratings are produced in the **USA by two vendors: *Inprentus* and *Bach***. *Inprentus* can produce very good gratings, but resolving power (RP) above 20,000 not yet demonstrated.
  - Ongoing R&D effort at LBNL is promising but is still a work in progress to reach RP ≥ 50,000
    - Blazed gratings are needed to reduce the length of spectrometer (by using higher diffraction orders), withstand the pulse energy (damage issues), and increase efficiency
- **Research in blaze gratings (LBNL), should be supported.**
- **Investment in supporting US vendors is important** since they are working to support our needs—
  - Work with vendors to develop metrology to support fabrication and give them the opportunity to test gratings at-wavelength.
- Research in multilayer gratings is also promising, to increase the efficiency and bridge the gap between gratings and crystal monochromators.

3) current status of work in these areas at the 4 labs

LBNL: ALS / ALS-U

High Resolution RIXS and ALS-U needs.

In House R&D for gratings that we cannot buy

– VLS gratings w/ ultraprecise g1, g2, g3, coefficients
– ultra-small blaze angles
– ML blazed gratings for high-res, high-eff spectroscopy

New Processes for grating production

– thin-film growth on surfaces
– nano-imprint for large area

Metrology development for VLS gratings

– interferometry for measurement
– scanning deflectometry

BNL: NSLS-II / NSLS-II

- **Development of metrology tools** for precision VLS gratings based on stitching interferometry and Slope measuring system.
- Possible R&D on multilayer grating

ANL: APS / APS-U

- Limited effort in metrology for VLS gratings

SLAC: LCLS/SSRL / LCLS-II

Gratings

- Improve **measurement precision of VLS gratings**. Support development of domestic vendor & R&D
- R&D project to produce **shallow blaze angle** with ultra-high resolution in early stage.

End