Metrology of X-ray Optics for Brightness Preservation and Nano-Focusing

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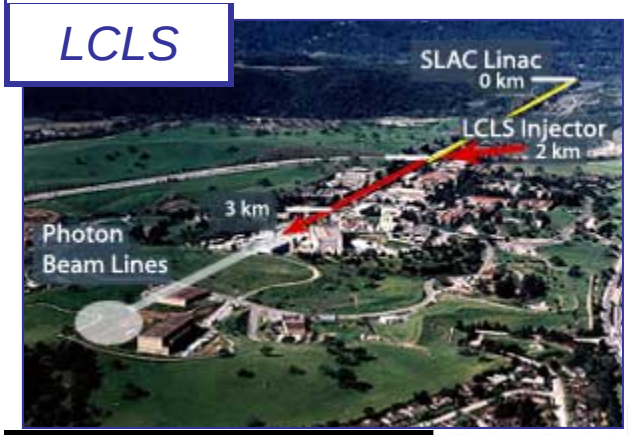
New Sources require a new generation of optics and metrology to harness high brightness

BERKELEY LAB

LCLS



New state-of-the-art X-ray facilities are designed to deliver world leading brightness, flux, spectral, spatial, and temporal resolution

Coherent, short pulses of x-ray light sources require diffraction limited optics.

Specification of figure error of diffraction-limited X-ray mirrors for LCLS (a Strehl ratio of 80%)

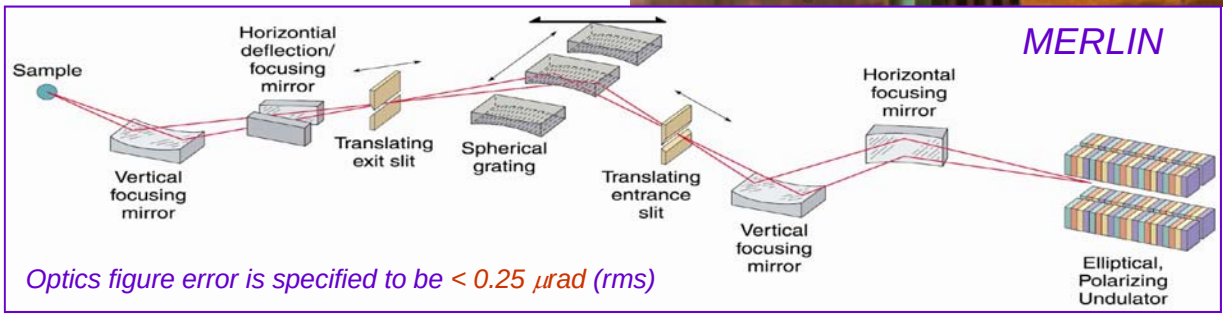
~ 0.1 μrad (rms)

Low emittance top-off ALS

Mirrors with slope error ~ 0.2-0.3 μrad are available right now, e.g. from InSync Inc.

APS and upgrade

MERLIN



Optics figure error is specified to be < 0.25 μrad (rms)

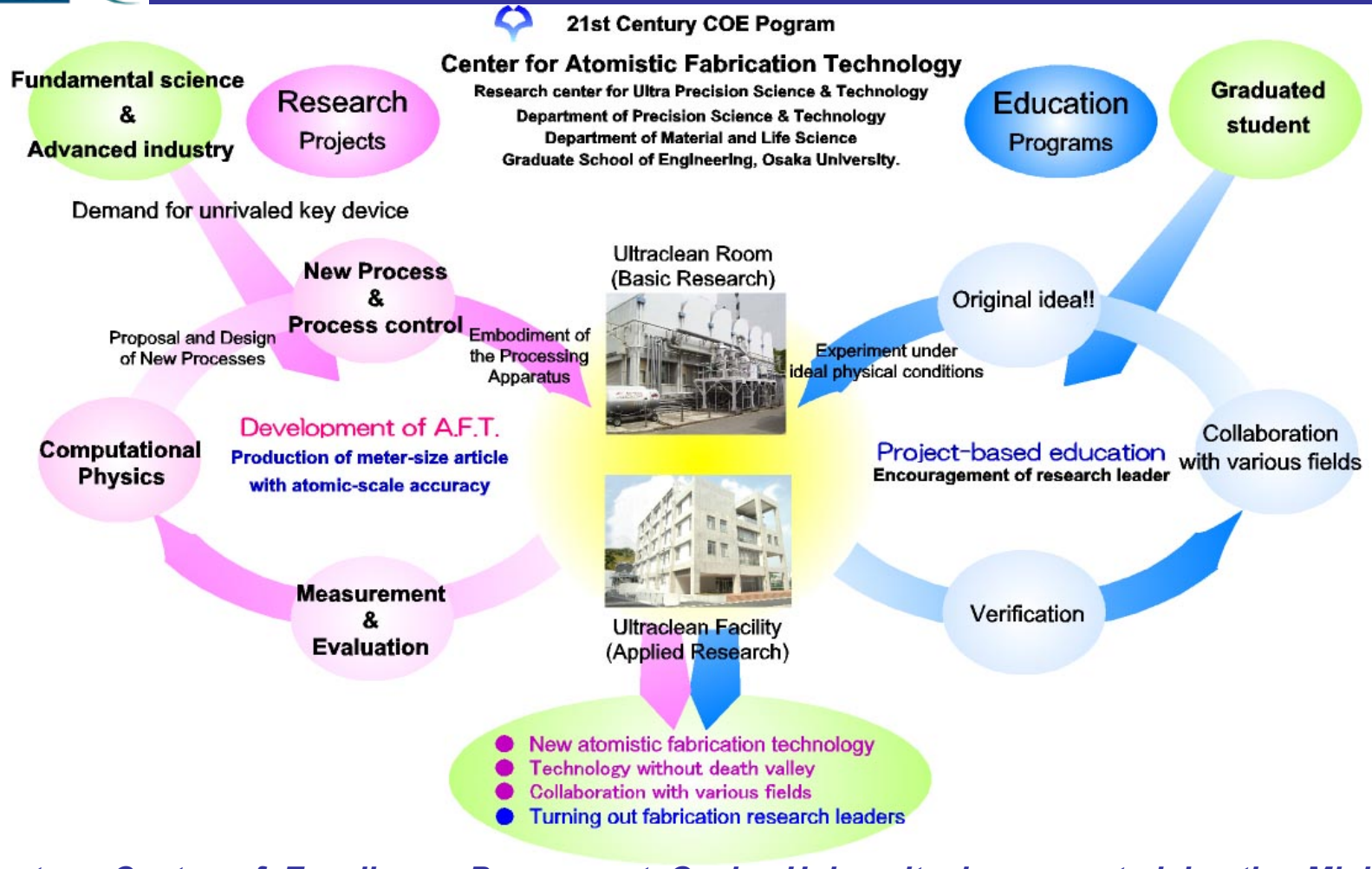
RMS mirror figure error [μrad]	0.0	0.1	0.5	1.0	2.0
Vertical focus size, FWHM (μm)	1.7 / 4.0	2.9 / 6.9	11.9 / 28.5	23.6 / 56.5	47.0 / 112.9
Horizontal focus size, FWHM (μm)	25.7 / 70.5	25.7 / 70.7	27.3 / 75.1	31.8 / 87.5	45.5 / 125.2
Monochromatic intensity at 12 keV (ph/sec/μm^2)	5.5×10^{12} / 8.5×10^{11}	3.3×10^{12} / 5.0×10^{11}	7.5×10^{11} / 1.2×10^{11}	3.3×10^{11} / 5.0×10^{10}	1.1×10^{11} / 1.6×10^{10}

Table 4.1.3 *Expected "real-world" performance of an NSLS-II X-ray crystallography/scattering beamline (including mirror figure error and transmission losses for the monochromator, mirrors, and beamline windows) for different values of mirror figure error. The expected performance in both high and low demagnification modes of operation of the KB assembly is shown as high/low values.*

NSLS-II

from NSLS-II Proposal

Japan has invested in integration of advanced metrology and optics



-21st Century Center of Excellence Program at Osaka University is supported by the Ministry of Education, Culture, Sports, Science and Technology

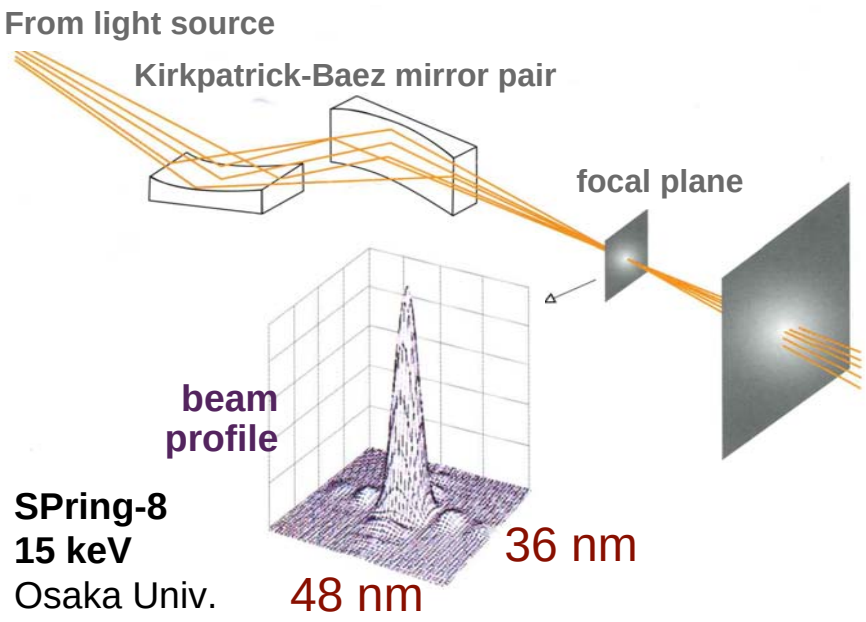
- "Center for Atomistic Fabrication Technology" started in 2003

- combines ultra-precision metrology with ultra-precision manufacture; metrology is the key

Japan is now leading the world in integration of advanced metrology and optics

Focusing System for Synchrotron Radiation

Hard-x-ray diffraction-limited nanofocusing



- *Surfaces measured and manufactured to nm accuracy over 100 mm;*
- *Best focus achieved is ~30 nm at 15 keV: very close to diffraction limit;*
- *Technology now available to Japanese FEL and SR light sources.*

Metrology and fabrication technology also feeds:

- *EUV optics (for lithography)*
- *Ground and satellite-based telescopes*
- *Ultra-low-scatter mirror for high-power lasers*

Ultra-precision optics are seen as an important technology base for the Japanese economy in the 21st century

High precision X-ray optical metrology in Europe

No equivalent X-ray optics effort in U.S.A.

BESSY (Germany)

Nanometer-Optical component measuring Machine (NOM) for 0.05 µrad accuracy metrology

PTB (Germany)

Extended Shear Angle Difference (ESAD) instrument with ~0.1 µrad accuracy

ESRF (France)

Development of metrology using x-rays developed to 20 nrad (Hartman methods)

PSI (SLS)

Development of SXR shearing interferometry, < 0.1 µrad

CARL ZEISS

- *Local polishing with a computer controlled polishing robotic arm*
- *Local ion beam figuring*
- *Direct figuring of complex shapes by computer-controlled polishing*

- ***Very large investment made by major institutions in metrology and optics***

  Note that center for manufacture of EUV optics now moved to Europe

- ***Next evolution in Europe is to be the formation of an EU optics network between all the major institutions***

  COST P7 collaboration

- ***Investment in optics seen as key technology for ultra-bright light sources and as a technology base for industry***

  BESSY NOM profiler cost ~$5M + 5 people × 3 years

Needs for precision metrology X-ray optics

Not only Optical Metrology has to be developed

Optical Metrology is good for

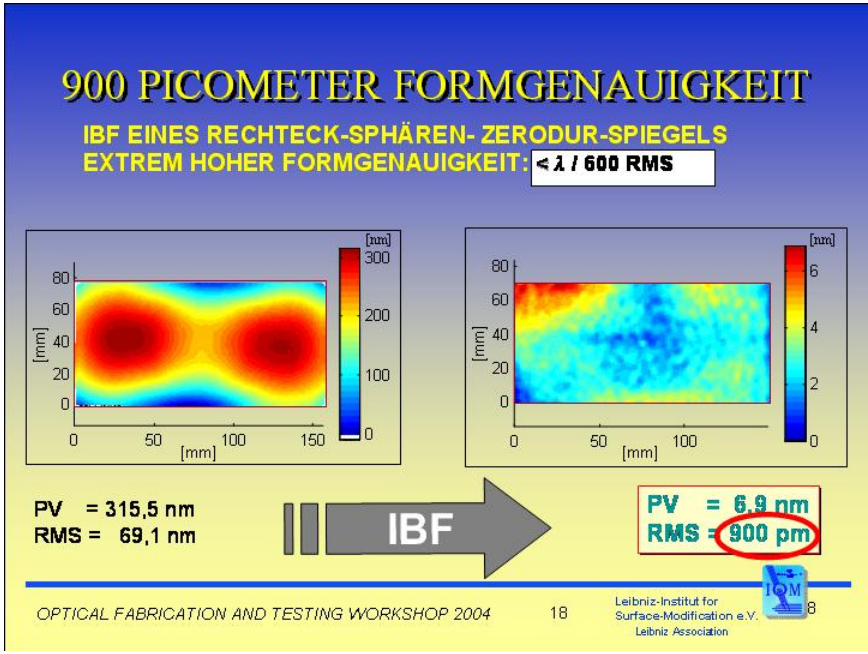
- **surface figure and finish investigation**

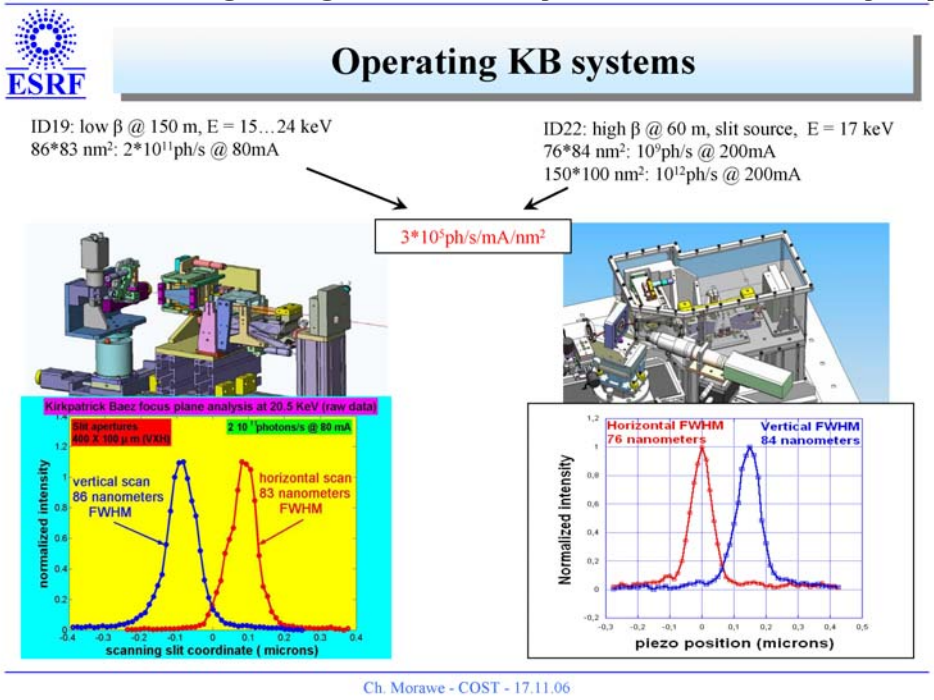
  to cross-check with vendor's optical metrology

  to provide the data for *local correcting re-polishing*;

  to provide the input data for *beamline performance evaluation* of x-ray optics

- **setting, alignment, adjustment of x-ray optics**





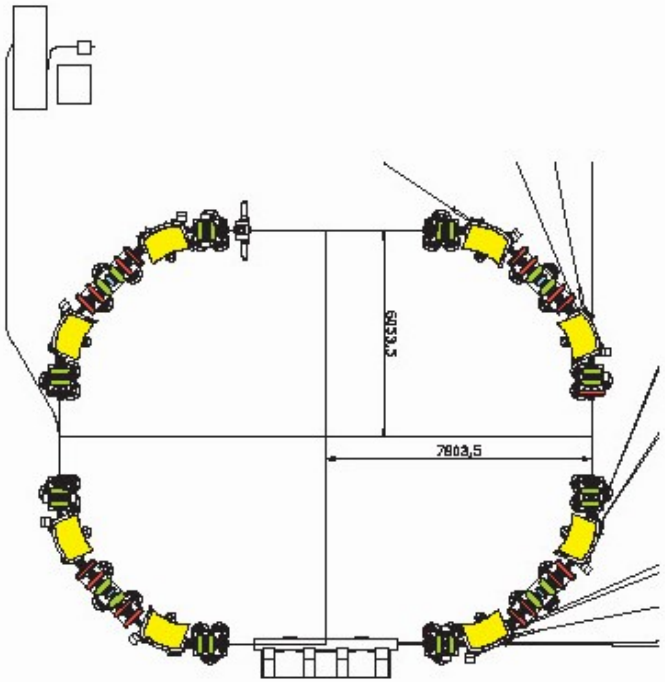
EUV and x-ray metrology is good for

- **investigation quality of multilayer x-ray optics, gratings, Fresnel zone plate optics**

  to provide the input data for *beamline performance evaluation* of x-ray optics

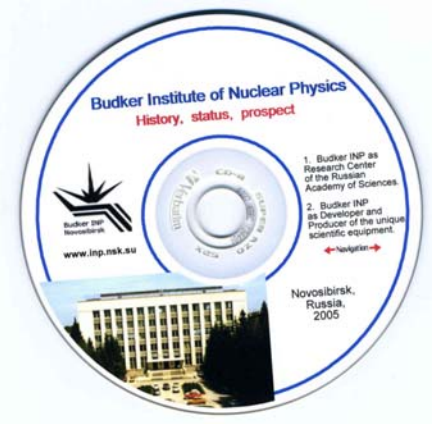
- **setting, alignment, adjustment of x-ray optics *on the beamline***

PTB Metrology Light Source



Low-energy (600 MeV) electron storage ring, named 'Metrology Light source' (MLS)

- *It is dedicated to metrology and technological development in the UV and VUV spectral range*
- *User operation of the MLS is scheduled to begin in 2008.*
- *Almost all electron optical devises were designed and manufactured at the Budker Nuclear Physics Institute (Novosibirsk, Russia).*



Direction of high precision optical metrology in US

Concentrate resources in a national center

Do not design unique metrology instruments at each facility

Perform a systematic R&D investigation of factors limiting performance of instruments for X-ray optical metrology

Do not use unique test and calibration procedures at each facility

Develop experimental methods and national standards for test and calibration of metrology instrumentation

Do not focus on optical instrumentation alone

Develop theoretical approaches for evaluation of beam-line performance of X-ray optics based on metrology data

Do not concentrate solely on the immediate goals of a local facility

Collaborate to use national and world-wide resources and experience

Catalyze R&D with industry in the manufacture and correction of optics

Close the loop with manufacturers to develop what we need using agreed measurement methodologies

DOE has to take national leadership, direct development of the core instrumentation and organize a national center for x-ray metrology and advanced manufacture

Osaka in Japan; BESSY/PTB in Europe; DOE Labs in the USA

Metrology development at LBNL to meet US needs

base established; enhancement needed

modified the LTP-II to the accuracy of ~0.3 μrad (rms); systematic investigation of LTP performance to reach 0.1 μrad measurements required by brightness preserving optics for ALS, LCLS, NSLS-II…

standards based on a Binary Pseudorandom Grating for precise calibration of interferometric microscopes and Universal Test Mirror for LTP/NOM calibration

developed theory of X-ray scattering by rough surfaces for evaluation of the beam-line performance

developed power spectral density analysis of metrology data in order to analyze figure and finish simultaneously from advanced manufacturing

collaborating with vendors (InSync) in order to advance US manufacturing technology, new materials, new bonding techniques

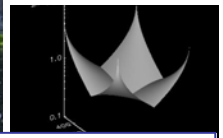
collaborating with metrology teams at BNL, BESSY, PTB, CLS, ESRF, ELETTRA and organizing the Virtual Optical Metrology Laboratory (VOML) to share the developed techniques, methods, designs, and results

Super high resolution gratings for soft x-rays

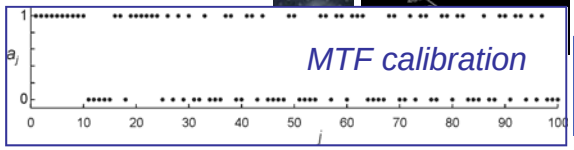
LBNL LDRD-2008 project pending:
HIGH-PERFORMANCE METROLOGY OF X-RAY OPTICS

Micromap-570

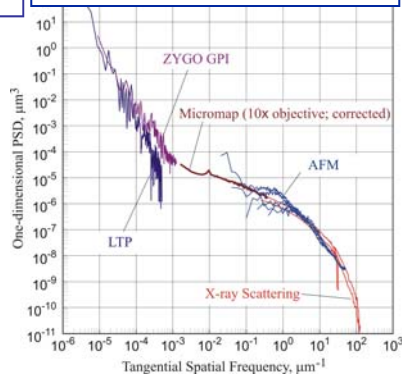
Software for beam-line performance evaluation



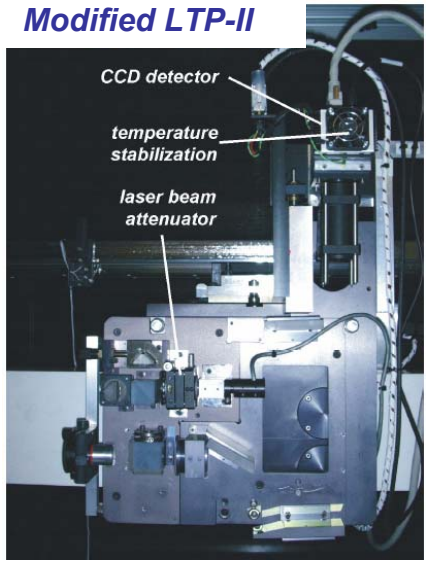
ZYGO GPI



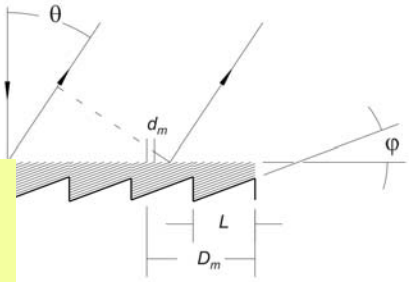
Characterization of X-ray optics with 2D PSD



Modified LTP-II



Super dense grating



Needed for upgraded ALS, LCLS, NSLS-II, but is a very heavy load for ALS budget.

Program needs to be expanded to meet expected needs.

SUMMARY

1. ***New X-ray Sources require a new generation of optics and metrology to harness high brightness and coherence:***
   - ***≤ 100 nrad slope error:*** *beyond the limits of available metrology;*
   - ***"If you can't measure it, you can't make it."***

2. ***Dedicated in situ and ex situ metrology and adjustment techniques have to be developed:***
   - ***'traditional' optical metrology methods: LTP, interferometers, interferometric microscopes***
   - ***Hartmann wavefront sensing, shearing interferometry … at x-ray and optical wavelengths;***
   - ***methods that can be replicated and incorporated into various beam line designs;***
   - ***theoretical methods and metrology data analysis for beam-line performance evaluation;***
   - ***techniques for testing super high resolution diffractive optics and dedicated beam lines.***

3. ***Ultra-precision optics and dedicated metrology are seen to be an important technology base for economy development in the 21st century;***
   - ***help and stimulate industry to develop new technologies for fabrication of x-ray optics.***

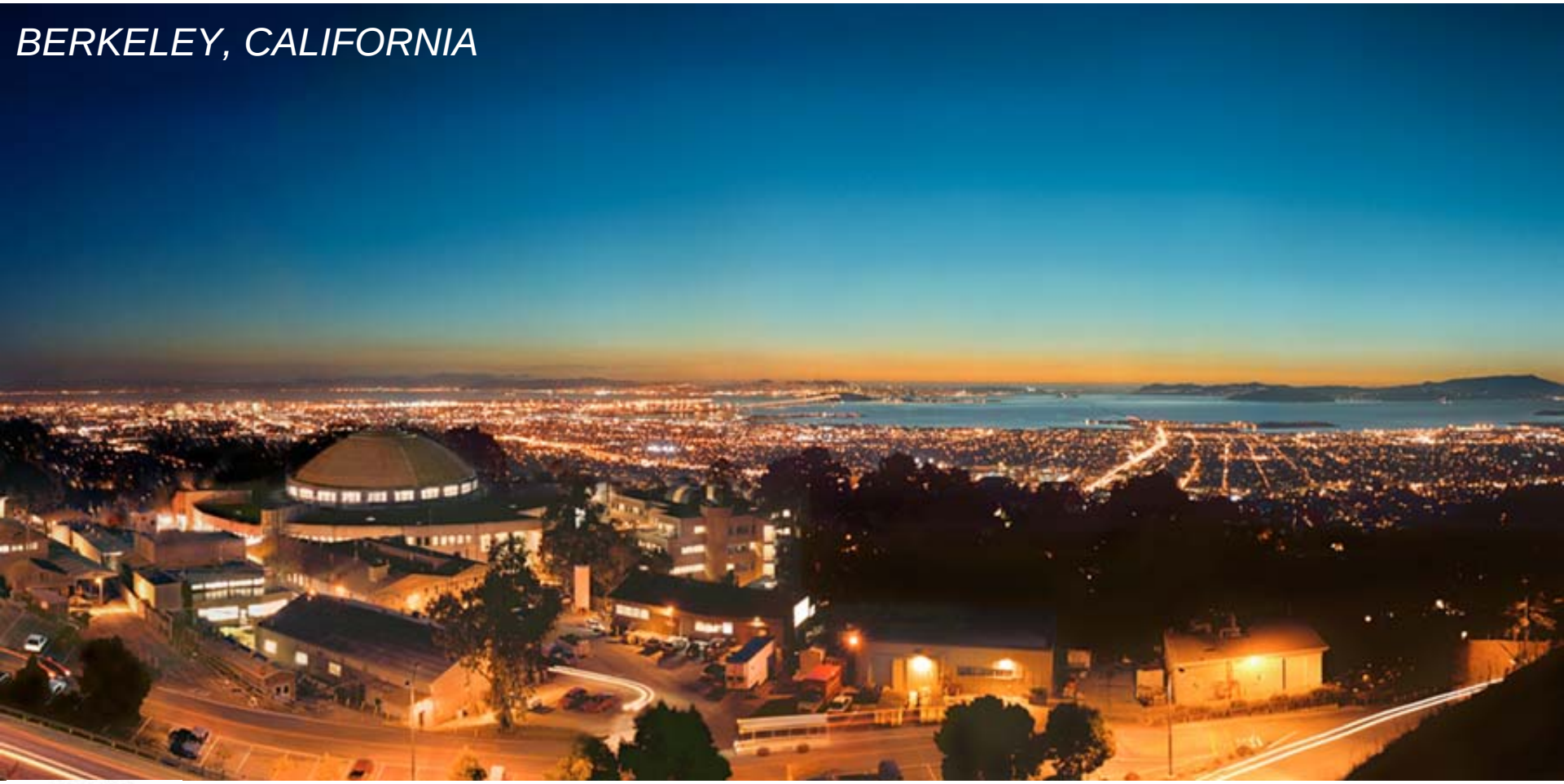
4. ***The complexity and importance of this task demands centralization of efforts in a national center.***

5. ***DOE has to take national leadership, direct development of the core instrumentation and organize a national center for x-ray metrology and advanced manufacture.***

DOE Center(s) for X-ray Metrology

Welcome to discuss on Metrology Workshop at the ALS User Meeting, October 2007

THANKS!



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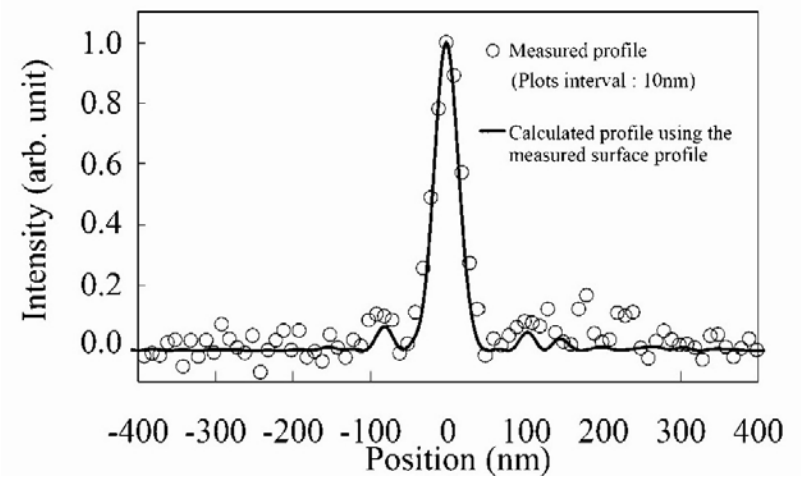
Diffraction-limited x-ray focusing at Spring-8/RIKEN (Japan)

- ***The incident beam is almost perfectly coherent*** *(coherent length, W, greater than mirror size, L)*
- ***Diffraction-limited focal spot diameter:***

$$D \approx \frac{2\lambda r'}{L \, Sin\theta} \leq 30\,nm; \qquad \lambda \approx 0.8\ \text{Å}.$$

- *Deterministic Fresnel-Kirchhoff diffraction integral calculation of the intensity profile in focal plane*
- *based on metrology with stitching interferometry over spatial wavelength range from 0.1 mm to L*



Intensity profile measured under best focusing conditions at an x-ray energy of 15 keV

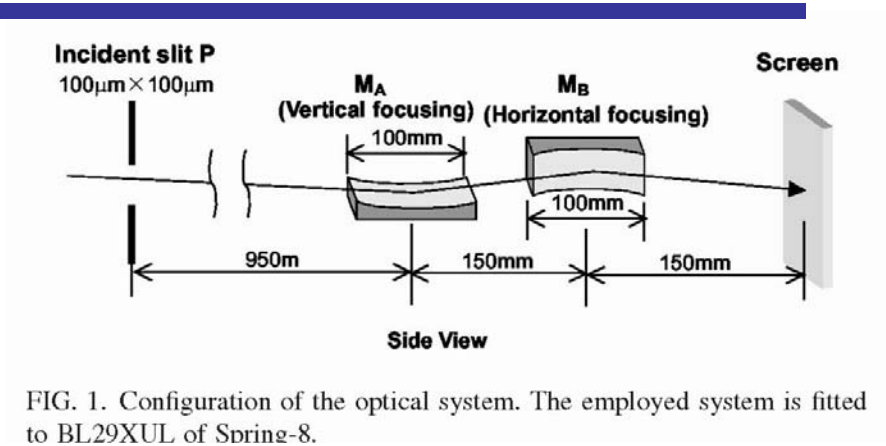


FIG. 1. Configuration of the optical system. The employed system is fitted to BL29XUL of Spring-8.

Japanese collaboration project on fabrication and metrology of elliptically figured mirrors for focusing hard x-rays to size less than 30 nm

- *Osaka University*
- *Research Center for Ultra-precision Science and Technology*
- *Spring-8/Japan Synchrotron Radiation Research Institute (JASRI)*
- *Spring-8/RIKEN*

…The mirrors are fabricated with a computer-controlled fabrication system using plasma chemical vaporization machining and elastic emission machining, on the basis of surface profiles accurately measured by combining micro-stitching interferometry with relative angle determinable stitching interferometry…

Rev.Sci. Instrum. 76, 045102 (2005); Rev.Sci. Instrum. 76, 063708 (2005)..