中国科学院高能物理研究所

R&D of Beamlines and End-stations for BAPS (HEPS)

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Beijing Advanced Photon Source (BAPS)
5-6 GeV, 1300m ring; 6GeV, 7BA, 48pm.rad

The proposed Phase I beamlines

1. High Energy X-ray diffraction/scattering
2. Hard X-ray nano probe
3. Inelastic X-ray scattering
4. CDI and XPCS probe
5. Time-resolved X-ray probe
6. Macro-molecular crystallography
7. X-ray Spectroscopy
8. Surface/interface diffraction and scattering
9. Polarized soft X-ray probing for micro/nano magnetic properties
10. Hard X-ray imaging
11. Small angle X-ray scattering
12. High-pressure and extreme condition
13. Soft X-ray spectrum for surface, interface and electronic structures of nano-materials

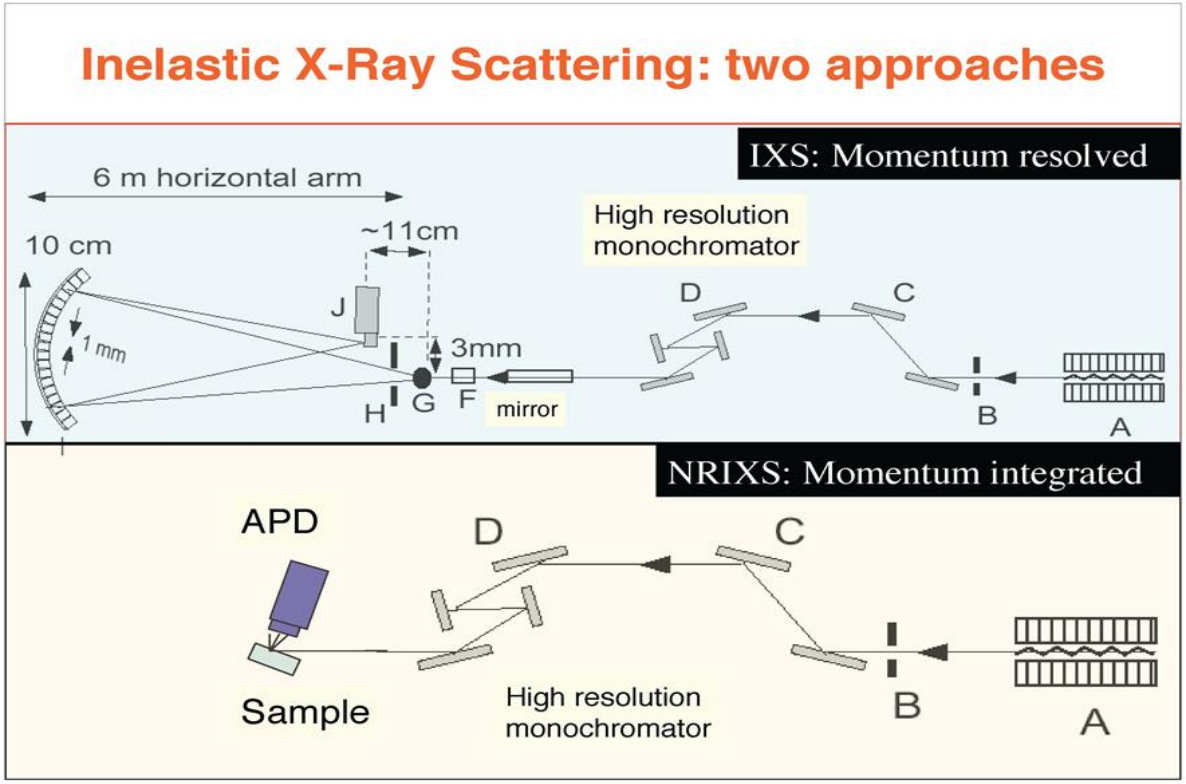
R&D for beamlines

- **High energy-Resolution monochromator: 2-3 meV**
- **High energy X-ray monochromator : 80-120 keV**
- **High Precision Bending and Metrology: 0.3/0.1μrad**
- **Nanofocusing: 10-30nm**
- **Nanopositioning, 1 nm**
- **Cryogenically cooled DCM: 800W**

1. High Energy Resolution Monochromator (HRM)

-Inelastic X-ray Scattering beamline

~meV monochromator
~meV backscattering analyzers



A prototype HRM for ^{57}Fe

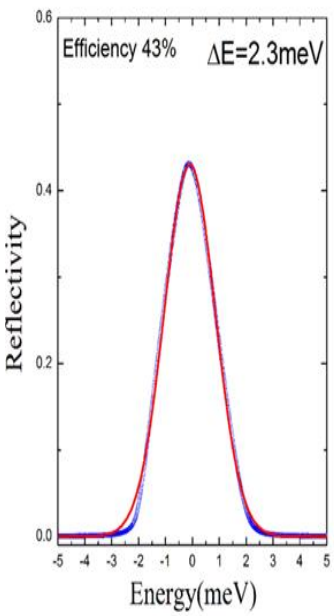
HRM	Specification
Working Energy (keV)	14.4125 ^{57}Fe
Energy resolution (meV)	3-5meV(depending upon source, optical alignment)
Spectral efficiency	~20%-30%(depending upon source, optical alignment)

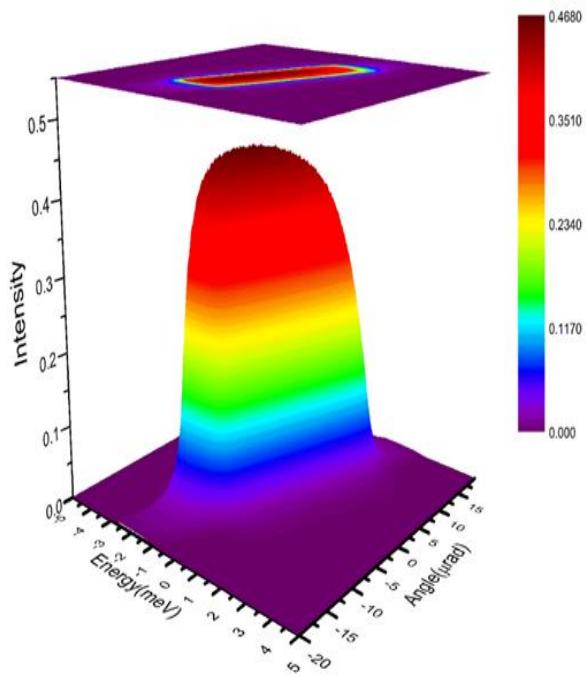
Building a prototype HRM

- Setup crystal fabrication capability and accumulating experiences
- Familiarizing High-precision mechanics

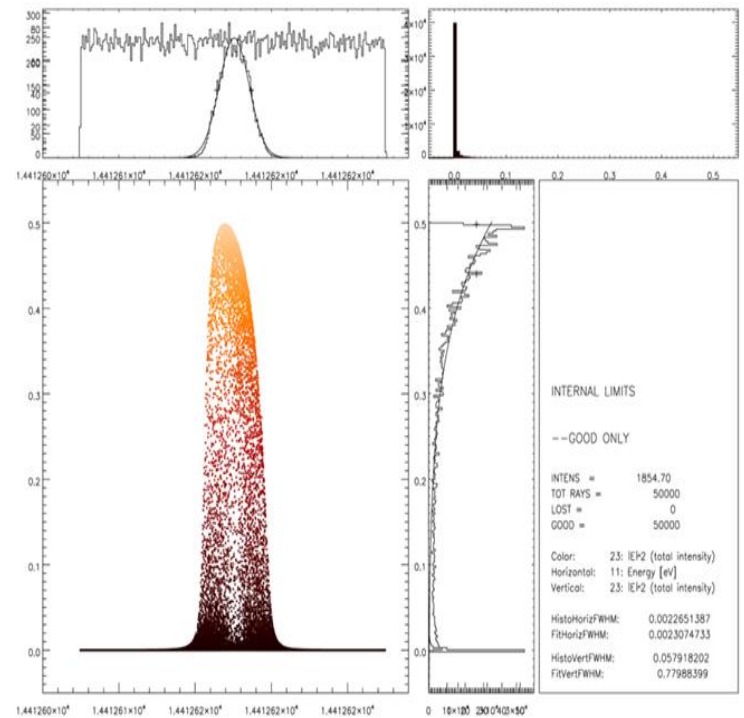
Optical and mechanical design

DDT





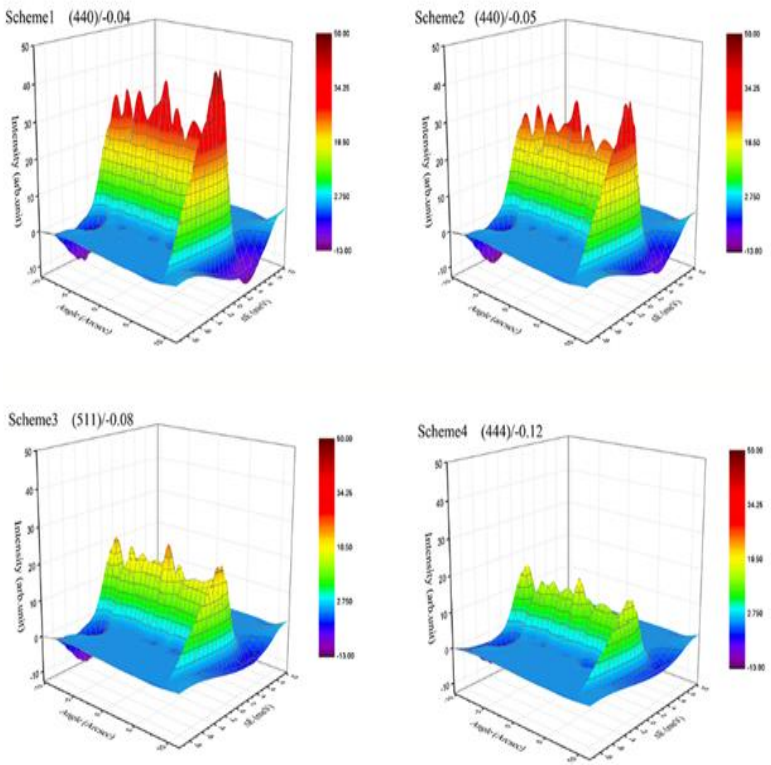
Ray tracing



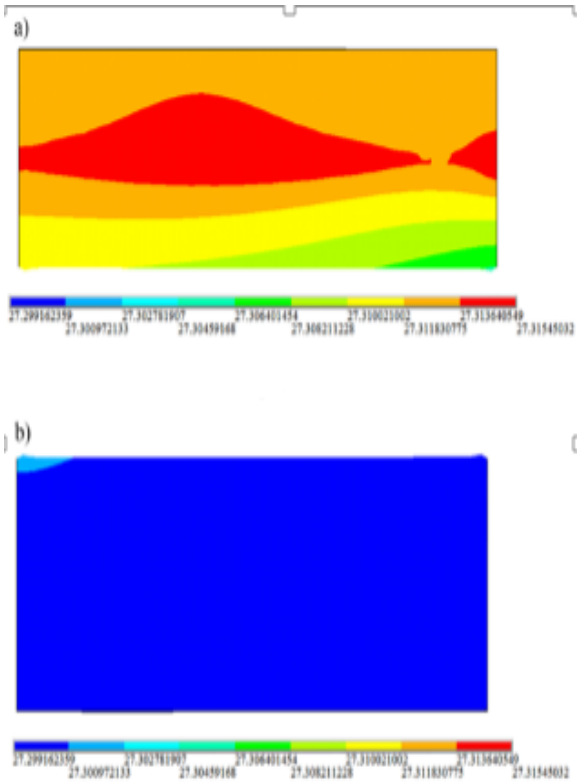
Thermal effects of nested HRM

Heat distribution/thermal stability under the way

Modeling/simulating crystal optics, by combining dynamical diffraction theory and finite element analysis



DDT



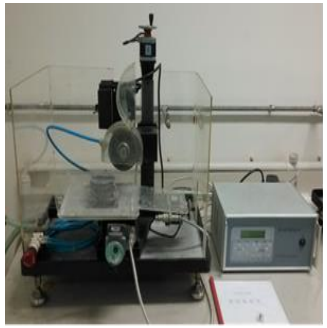
FEA

Our crystal fabricated at X-ray optics Lab of APS

Fabricated Crystal has been tested in 3-ID
2.5 meV

X-ray Optics Lab at IHEP under construction

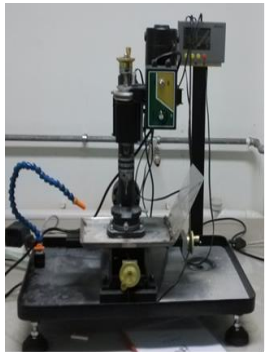
Crystal cutting/lapping



Crystal Drilling

Crystal orientation
Bragg/Laue

Crystal polishing



Chemical etching

4-point resistivity probe

Next

- High-precision mechanics ordered

- HRM crystal/ Analyzer crystal fabrication at home

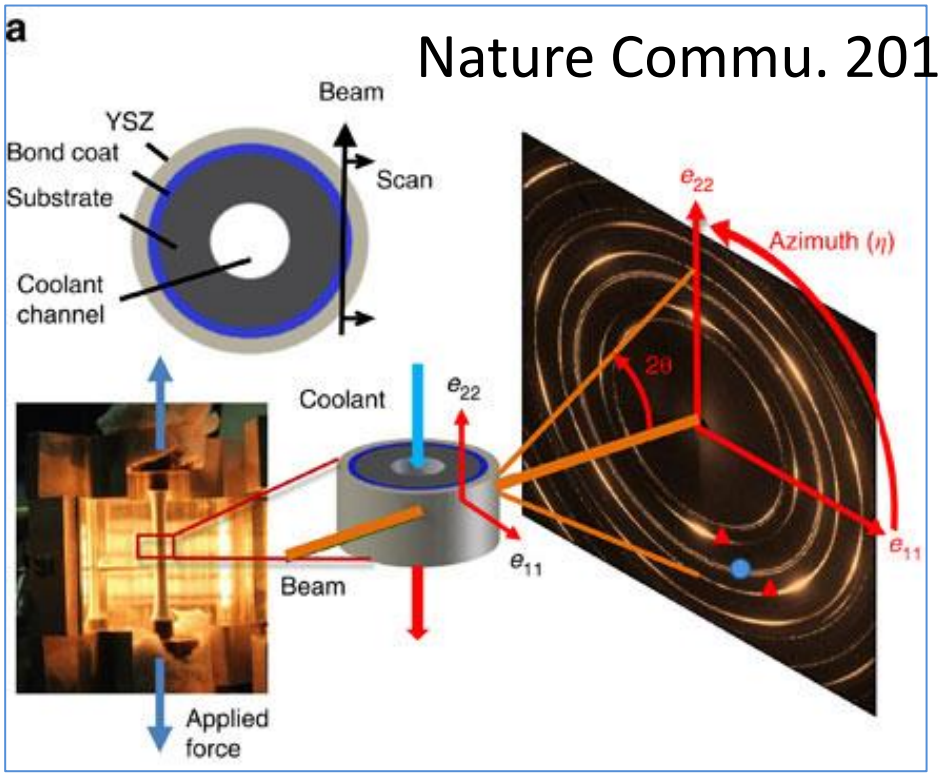
2. High Energy Monochromator

- Hard X-ray diffraction/scattering beamline

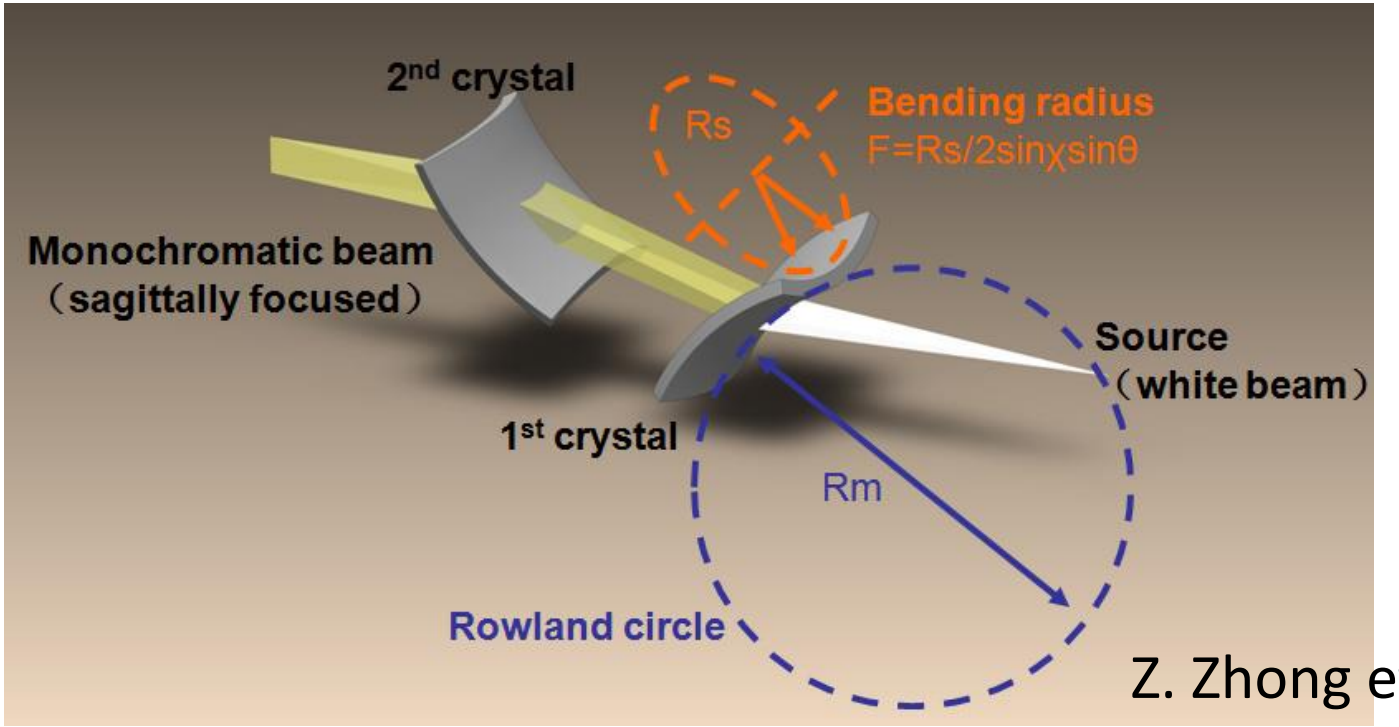
High energy X-ray application in industry is a key point in BAPS proposal

Strain response of thermal barrier coatings done at APS

Nature Commu. 2014



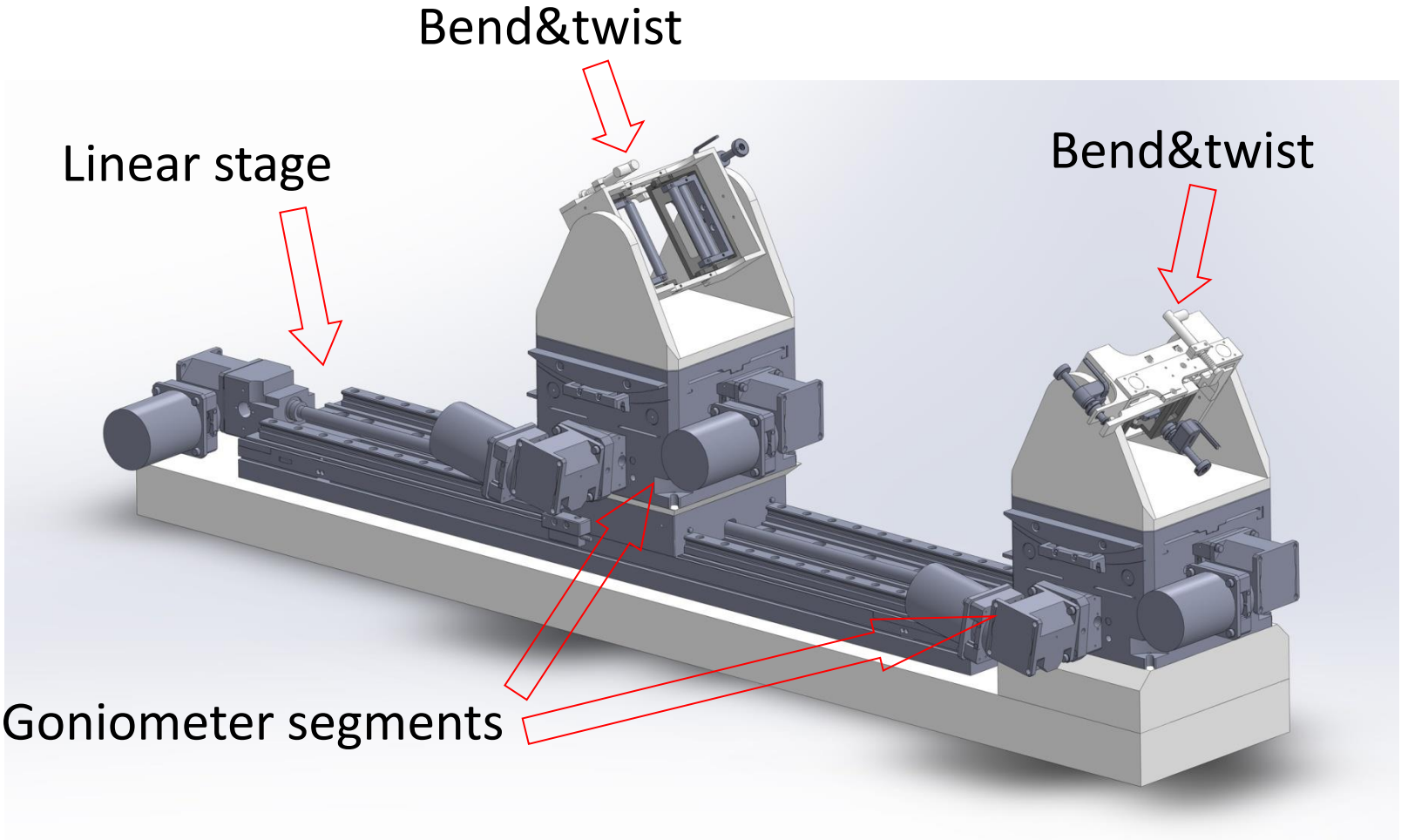
- Sagittal-focusing Laue Monochromator



Z. Zhong et al. (NSLS)

Energy range	80~120 keV
Energy resolution	$\Delta E/E \leqslant 2.8\times10^{-3}$ （@80keV）
Efficiency	≥20%
Beam size	~0.5mm（horizontal）

- Design of HEM prototype



Cryogenic cooling modeling:

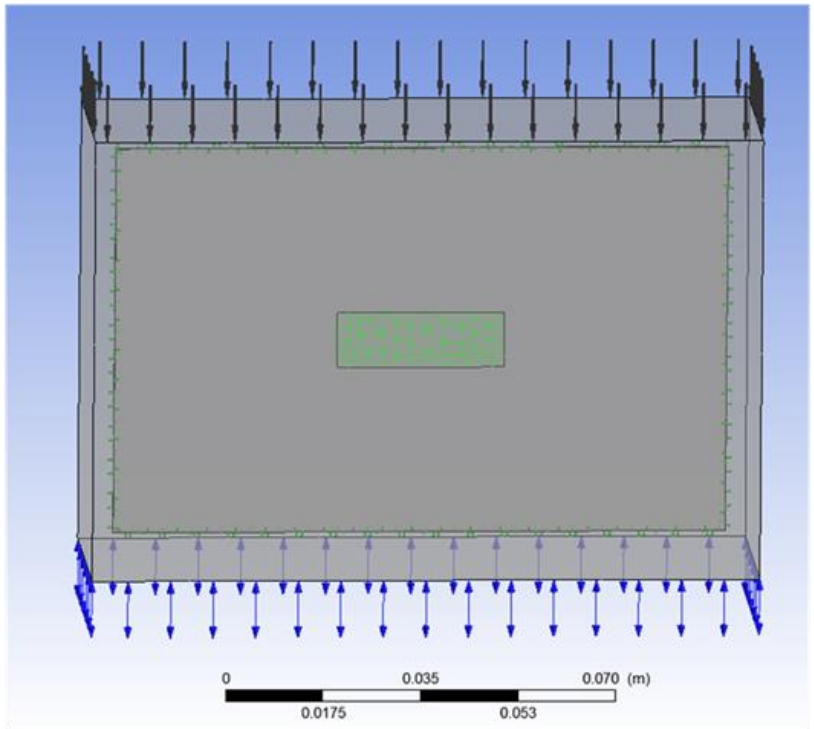
FEA：

Low temperature Helium gas stream, downward.

Beam size:

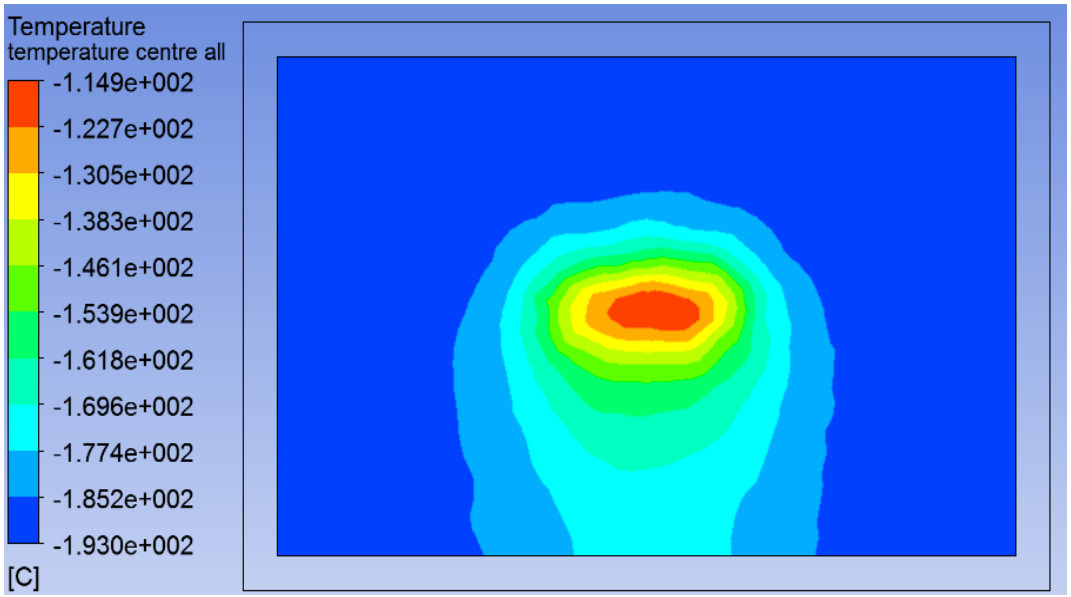
30mm×10mm；

Heating power: 100W.

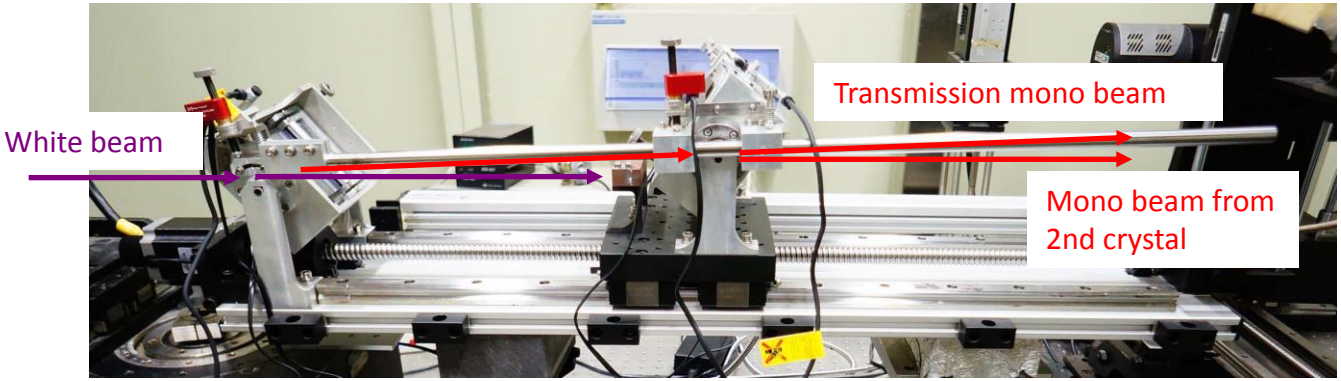


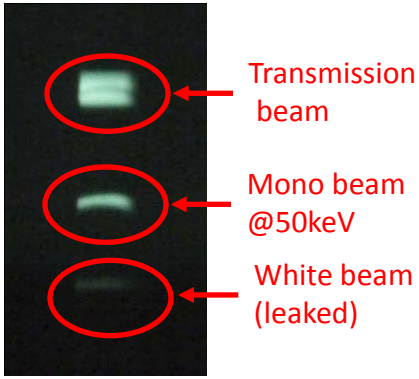
Helium temperature -193° C

speed=10m/s



- Prototype 1





Optics：

Energy range 20～80keV

Crystal orientation (111)/(100)

Crystal thickness 0.65mm

Bending radius 1.2m

Focus length 13m

Mechanism：

4-bar bender

Boomerang coupled

Independent twist

No cooling

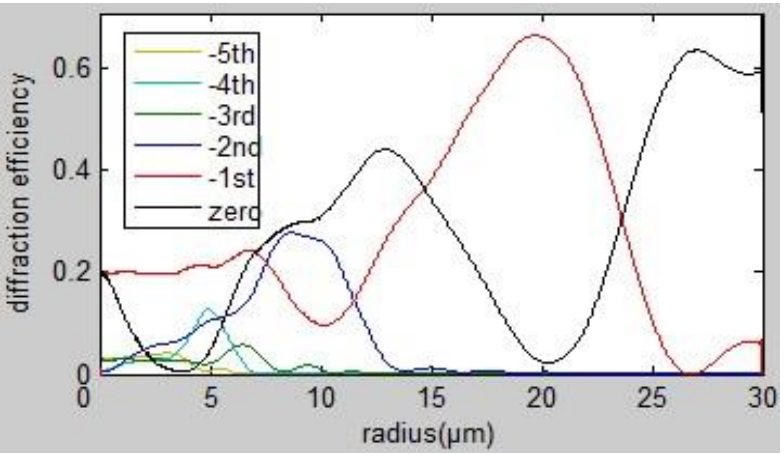
3. Nano and Micro-focusing Optics

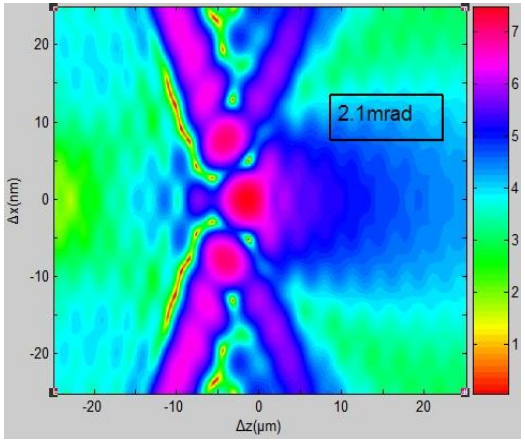
	Optics	X-ray Energy	Focus
Nano-focusing	MLL	10~20keV	10 ~ 30 nm
Micro-focusing	HECRL	> 80 keV	1 ~ 100 μm

MLL : Multilayer Laue Lens

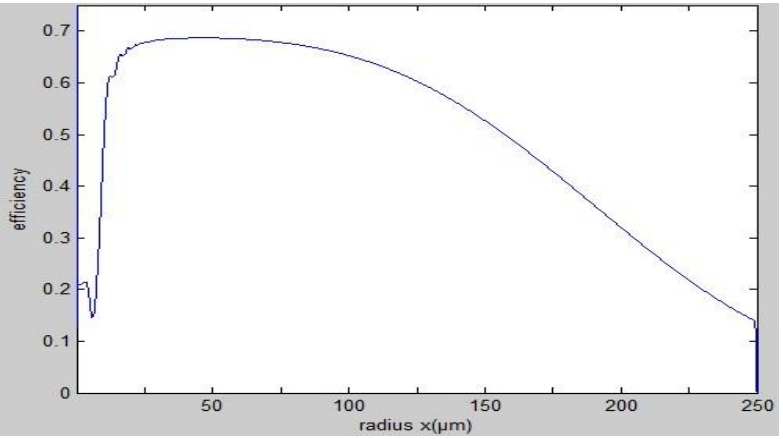
HECRL: High Energy X-ray Compound Refractive Lenses

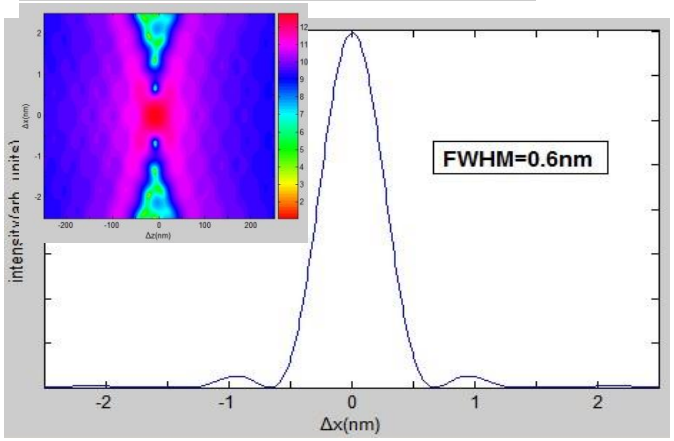
3.1 MLL



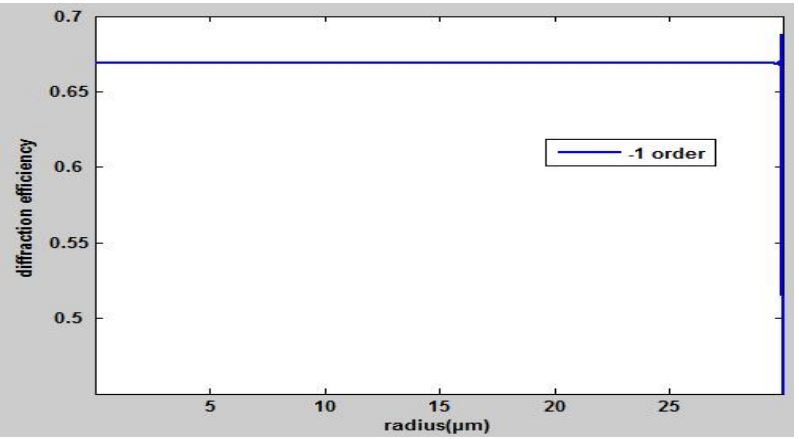


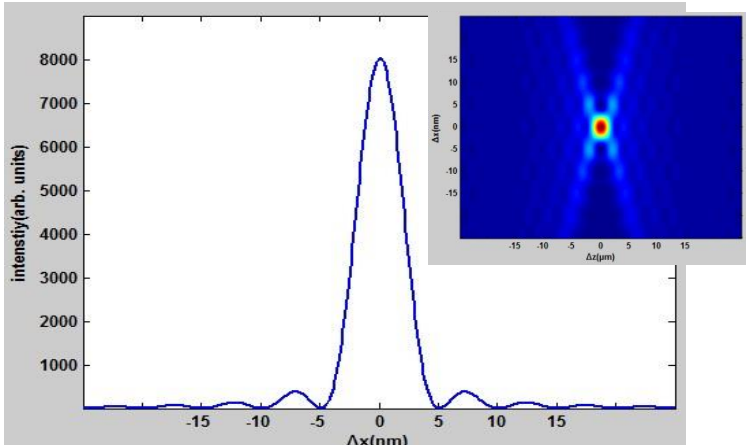
Tilted MLL





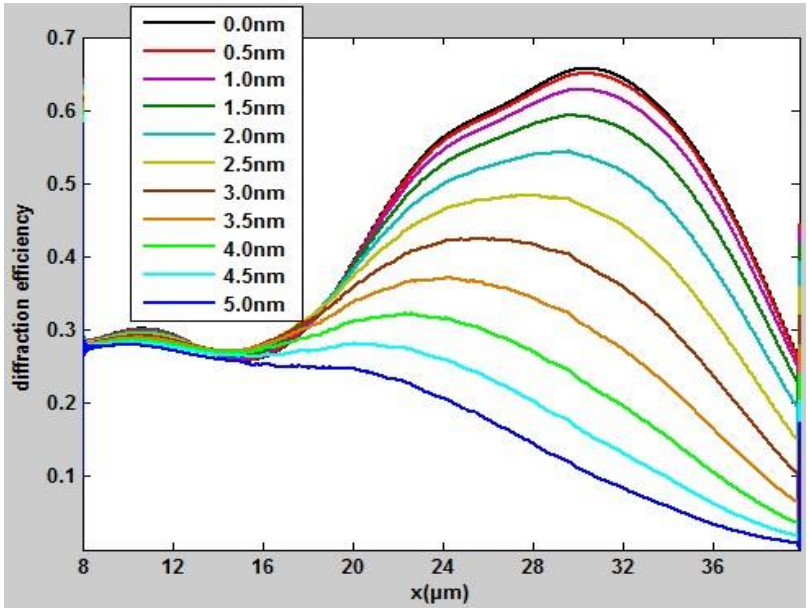
Wedged MLL

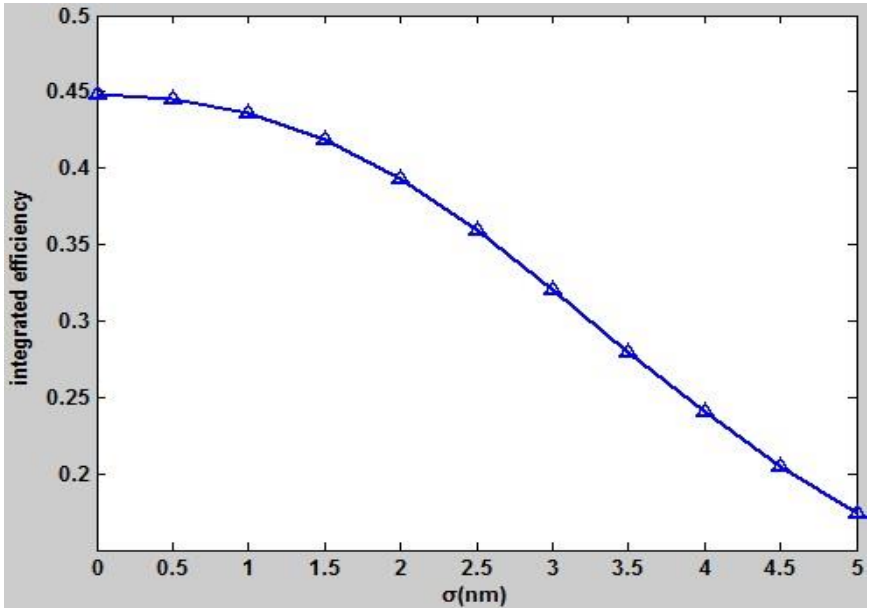




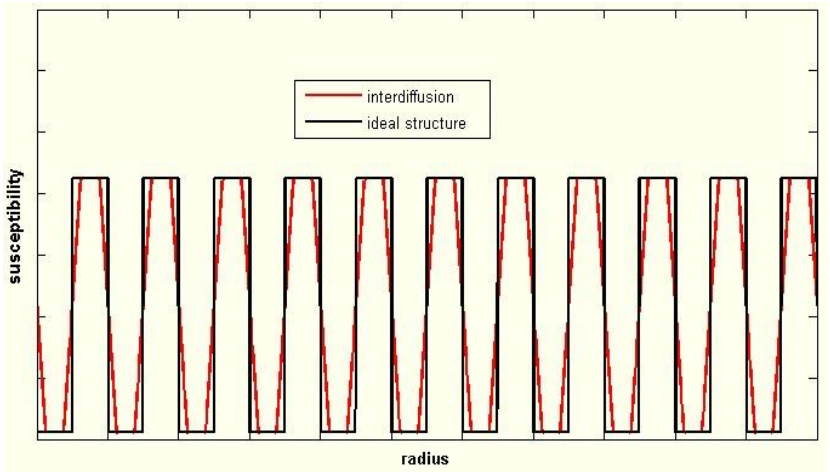
Curved MLL

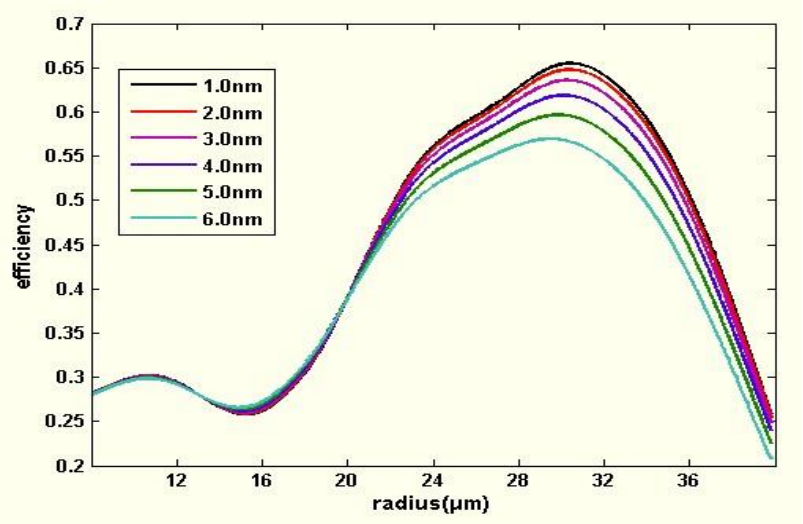
Effect of roughness and interface diffusion on MLL's performance





The local diffraction intensity and total efficiency with different roughness

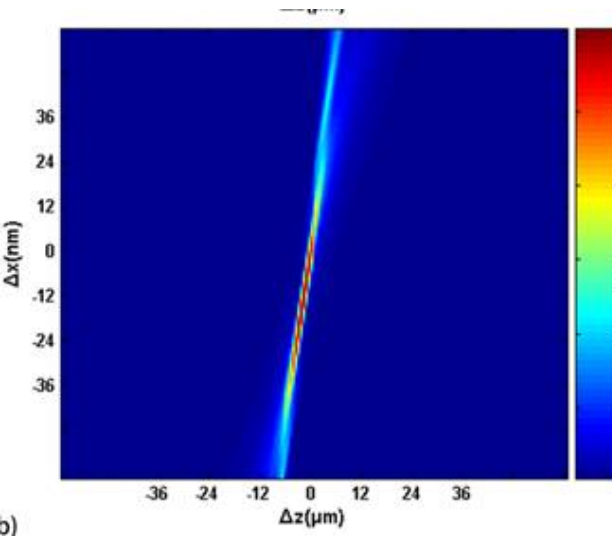


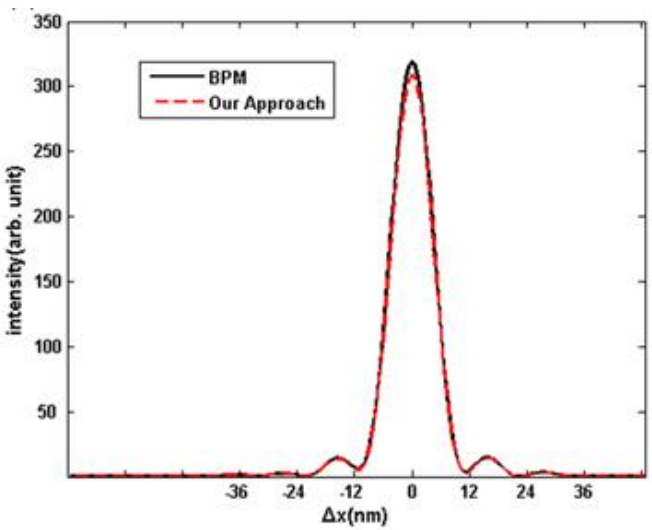


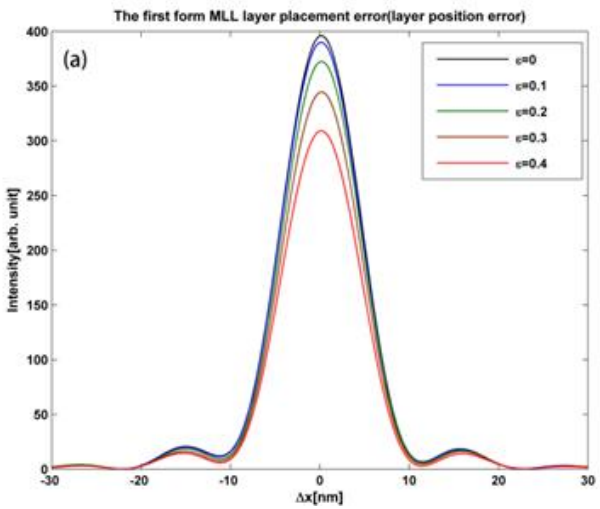
Effect of interface diffusion on the local diffraction intensity

Effect of the first form of layer placement error on MLL's performance

Based on the CWT and new assumptions, a new dynamical modeling approach to calculate focusing performance of MLL with layer placement errors.

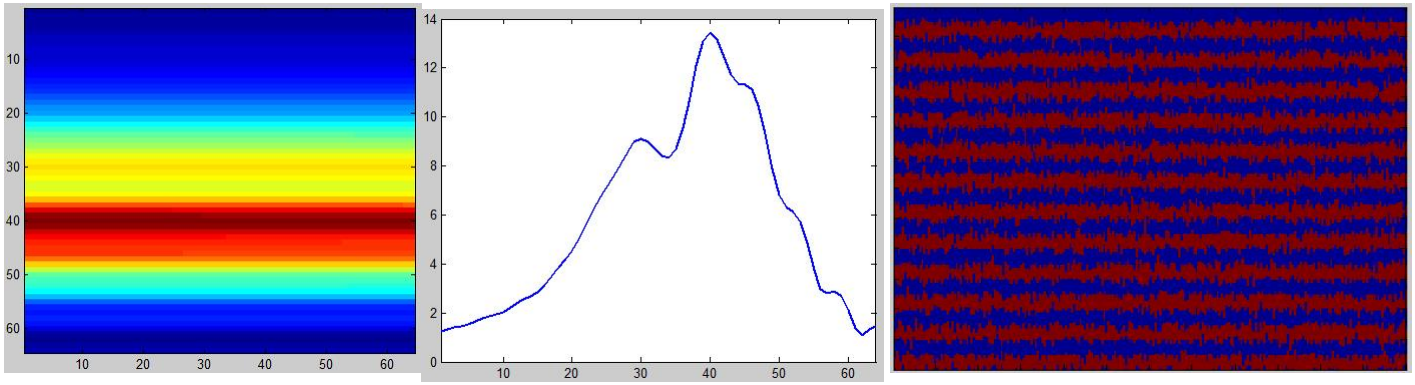




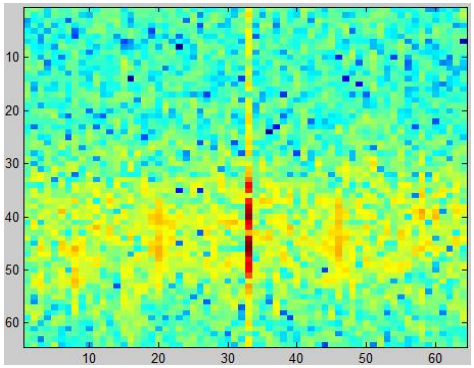


JSR 2014, submitted

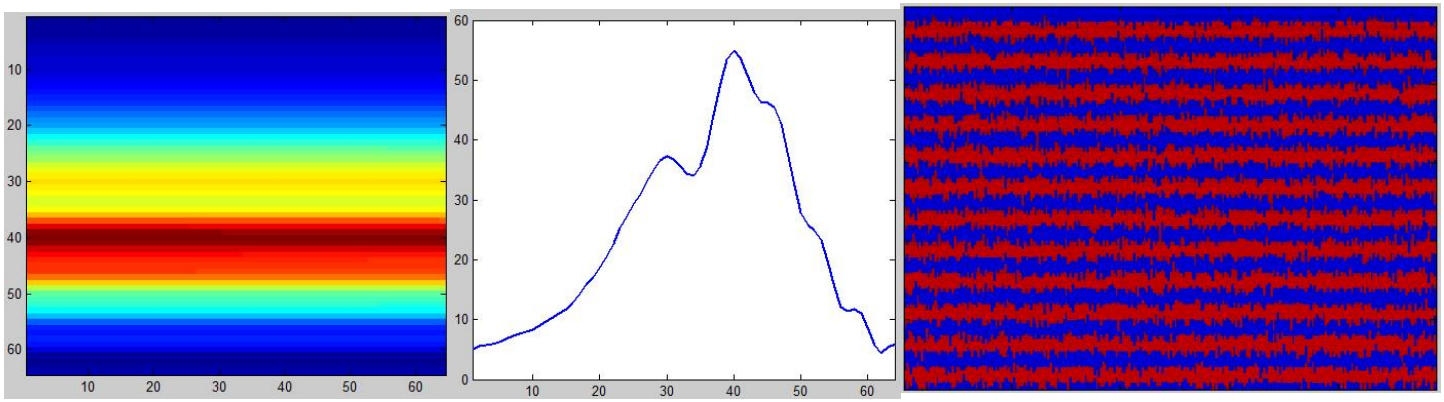
Simulation of Ptychography



Simulated probe function, object



Simulated diffracted pattern

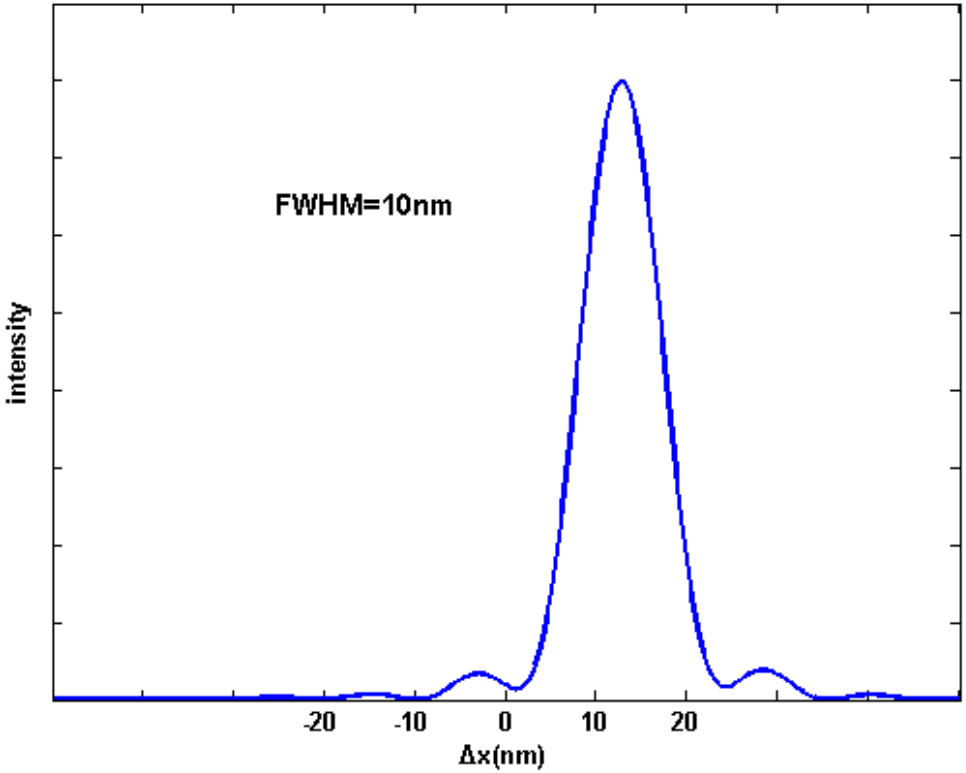


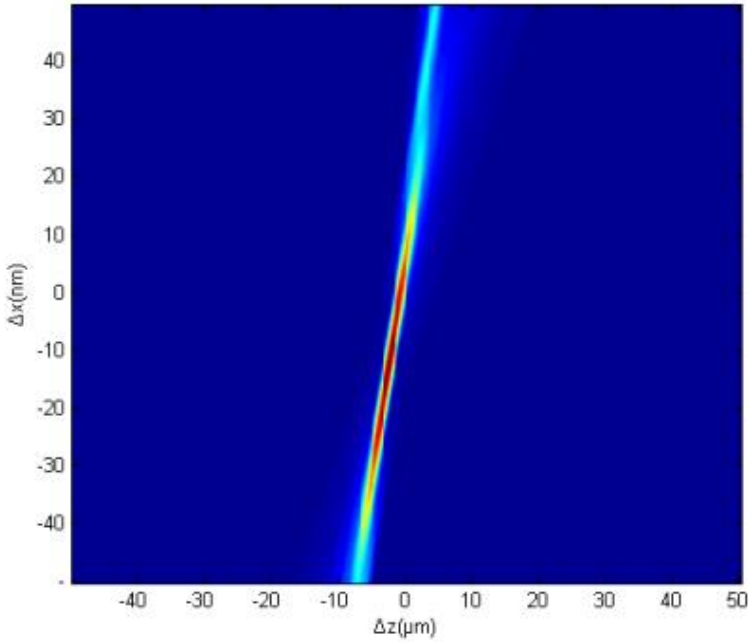
Reconstructed probe function and object.

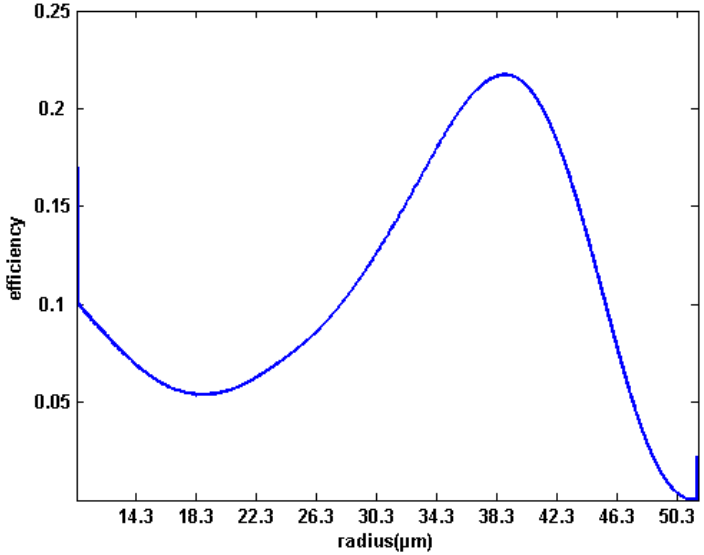
Optimization and design of partial MLL for 10nm focusing

Energey type	Focal length (mm)	E (Rs/R)	Working distance (mm)	Aperture size (μm)	Outermost/ innermost zone width (nm)	Number of zones	ΔE/E ($\times 10^{-4}$)	Si(111) ($\times 10^{-4}$)	Section depth (μm)	Efficiency/ tilting angle
tMLL/ (12.0keV)	4.0	0.2	0.8	41.3	4-20nm	6200	1.6	1.3	5.0	10.7% 4.9mrad
tMLL/ (14.0keV)	4.67	0.2	0.93	41.3	4-20nm	6200	1.6	1.3	6.0	12.5% 4.2mrad
tMLL/ (19.5keV)	6.5	0.2	1.3	41.3	4-20nm	6200	1.6	1.3	8.5	14.7% 3.0mrad

tMLL@12.0keV

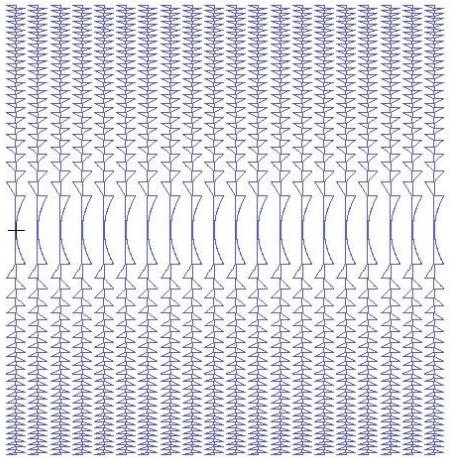

FWHM=10nm
intensity
-20
-10
0
10
20
Δx(nm)


40
30
20
10
0
-10
-20
-30
-40
Δx(nm)
-40
-30
-20
-10
0
10
20
30
40
50
Δz(μm)


0.25
0.2
0.15
0.1
0.05
efficiency
14.3
18.3
22.3
26.3
30.3
34.3
38.3
42.3
46.3
50.3
radius(μm)

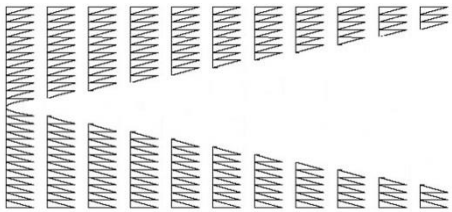
3.2 CRL for High Energy X ray (HECRL)

	Type 1（Ni）	Type 2（Ni）
Accept Apeture D(μm)	1082.4	3882.4
Gain	11.86	36.92



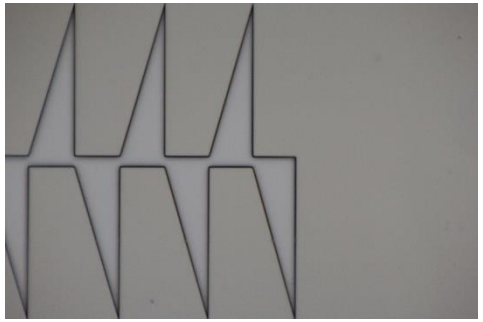
Type 1

Focus length: 5m

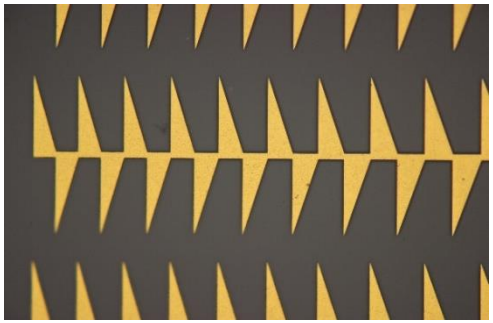


Type 2

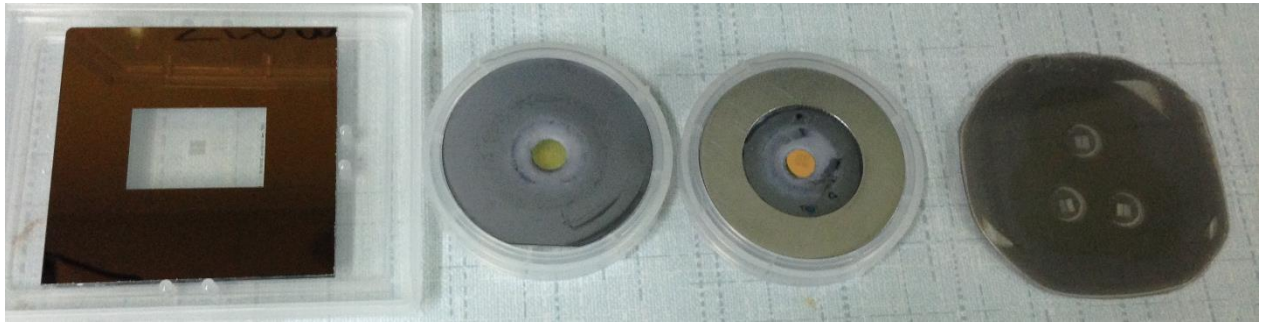
Fabrication of the HECRL: in our LIGA beamline

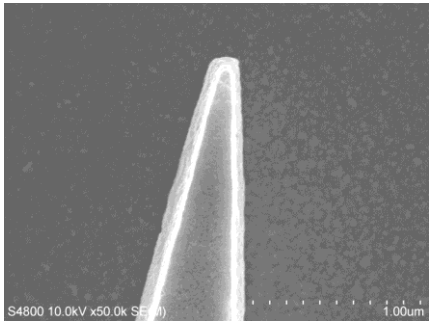


Primary Mask for LIGA

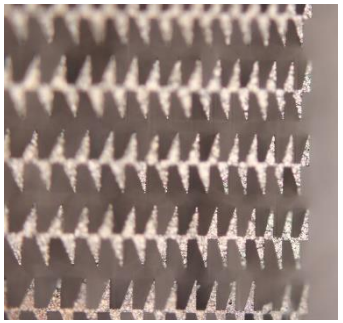


Secondary Mask

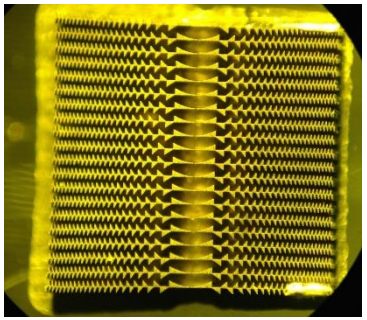




Pyramid Head ~100nm

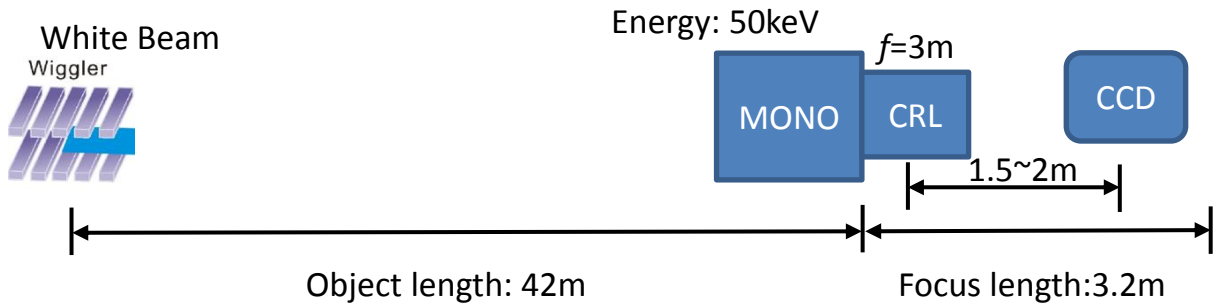


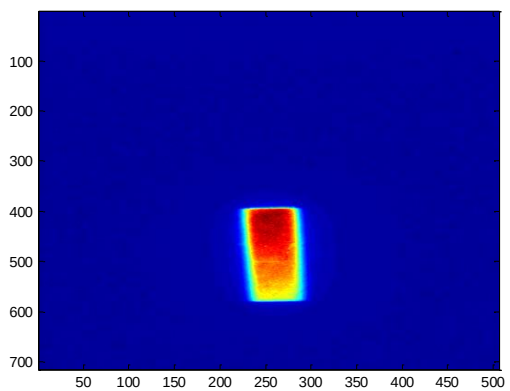
HECRL (Ni)



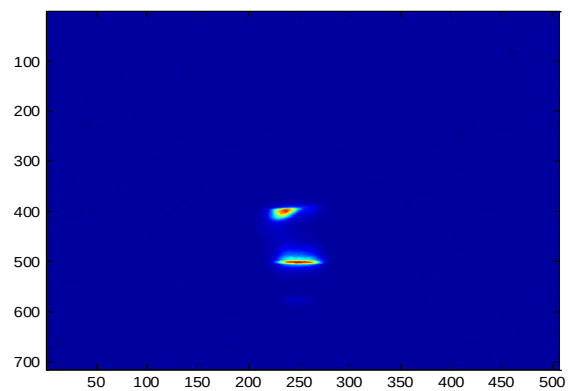
HECRL (Ni)

Beamline Testing： 4W1A (BSRF)



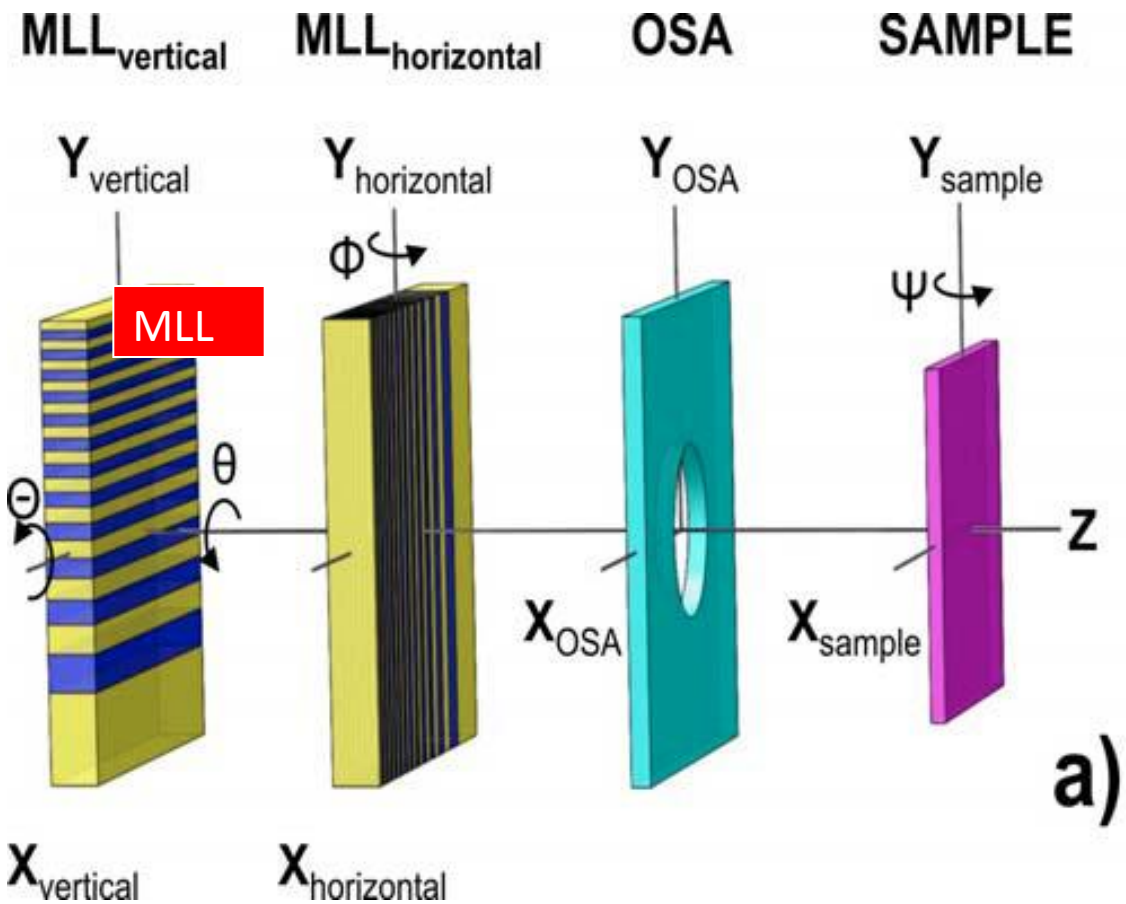


without HECRL



with HECRL

4. Nanopositioning for the hard x-ray nanoprobe



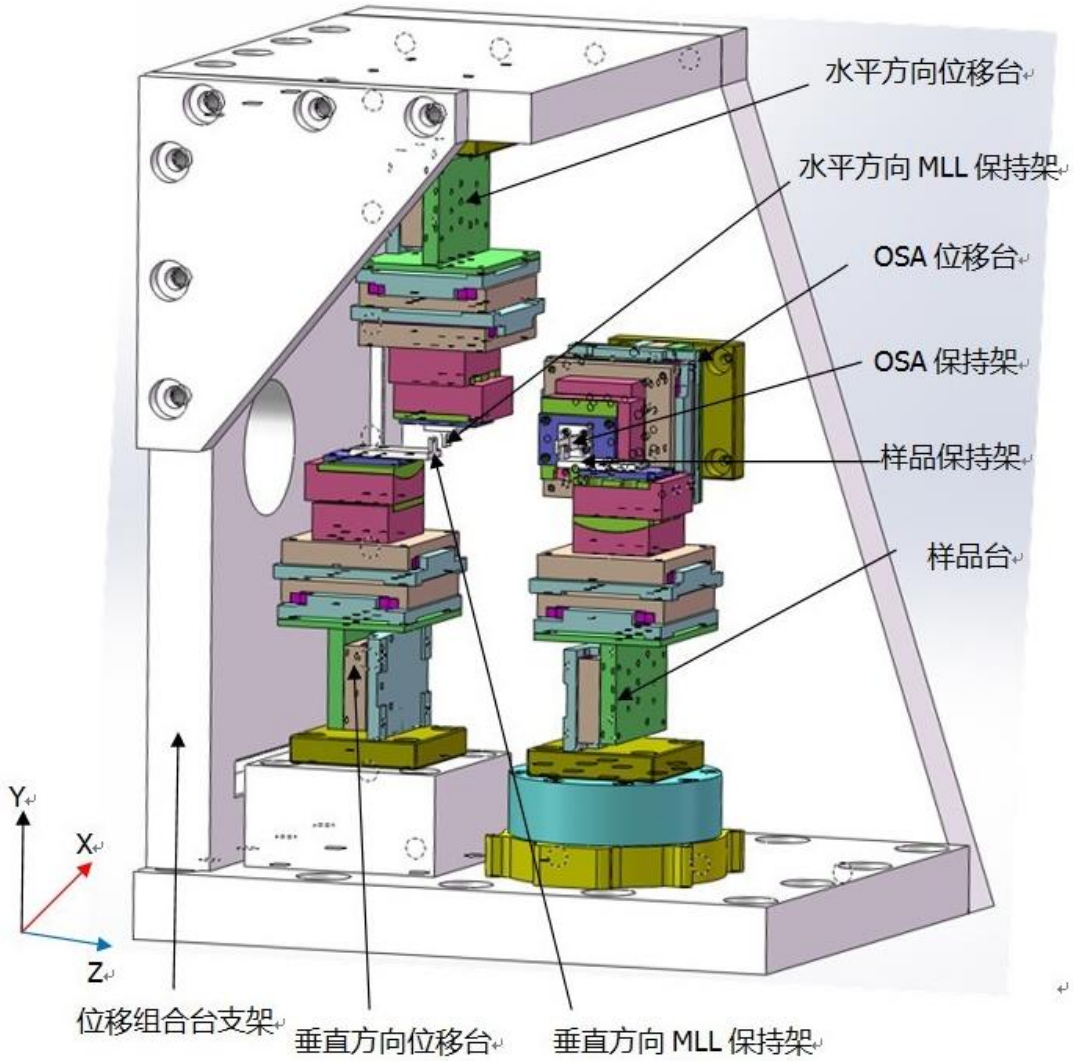
The MLL module together with the sample module for a 1-axis diffraction (NSLSII CD0)

- Nanopositioning resolution: =<1nm
- Laser interferometer resolution, <0.2 nm;

Stability

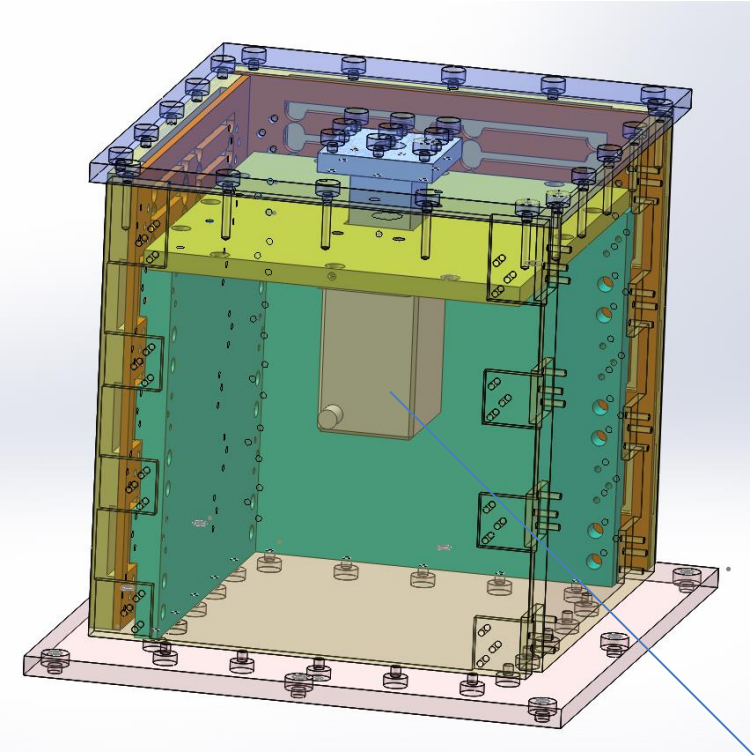
- Substantially compact with high mechanical stiffness;
- High temperature stability;
- No amplification of floor vibration

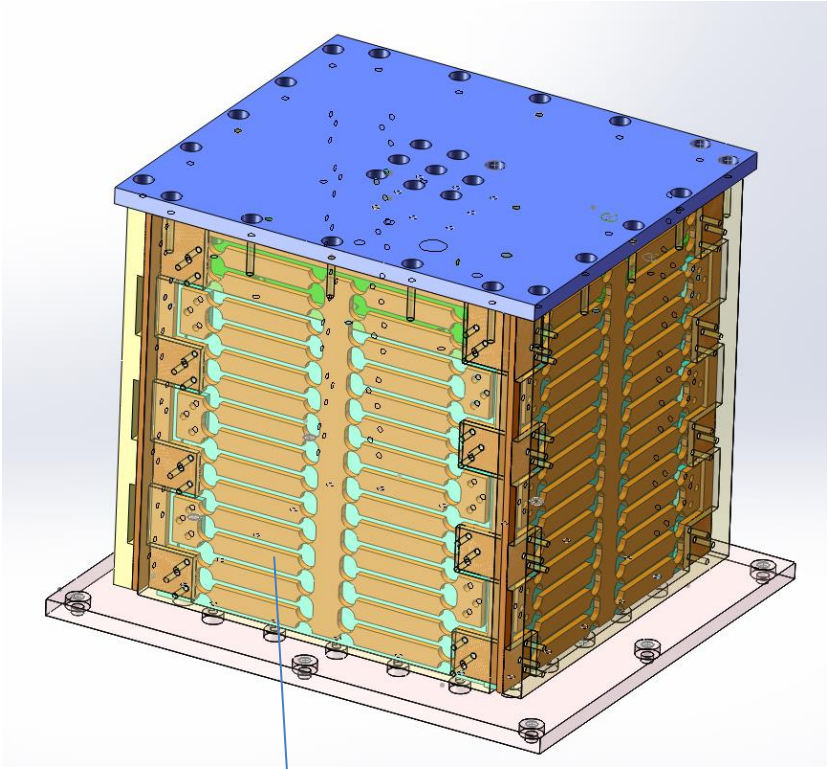
Design of the HXN stage



Moving Feedback control by Laser interferometer

Weak-link assembly

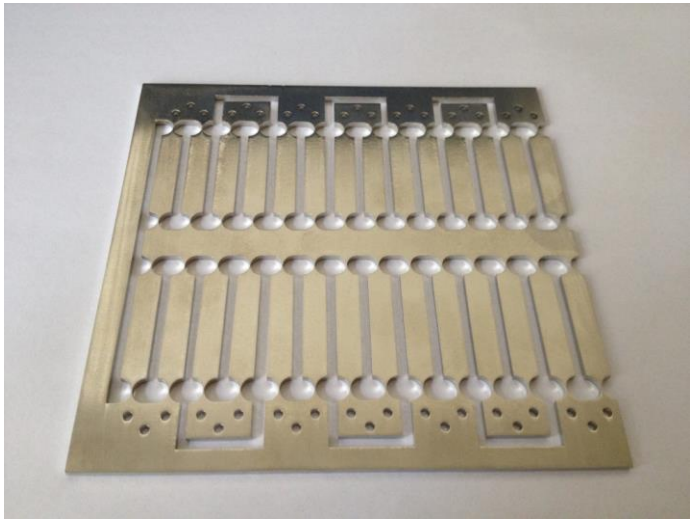




$160*140*131mm^3$

PZT driver

Weak-link



304 PH17-7

Weak-link (120mm*120mm*2mm) by laser cutting

Next: Large load nano-positioning stage, 800g

5. High Precision Bending and Metrology

The DLSR requires very high surface precision for reflective optical element.

Emittance 0.05nm・rad ~ Surface precision:

<0.02μrad for lower than ~4cm spatial frequency

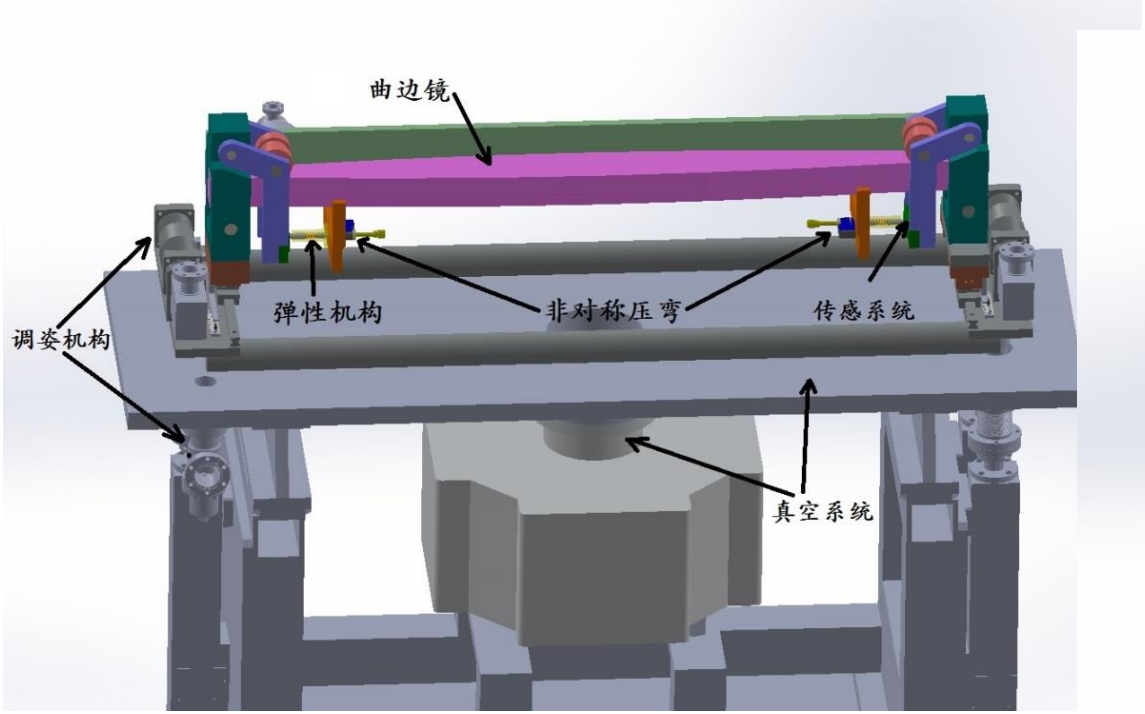
<1nm for higher than ~4cm spatial frequency

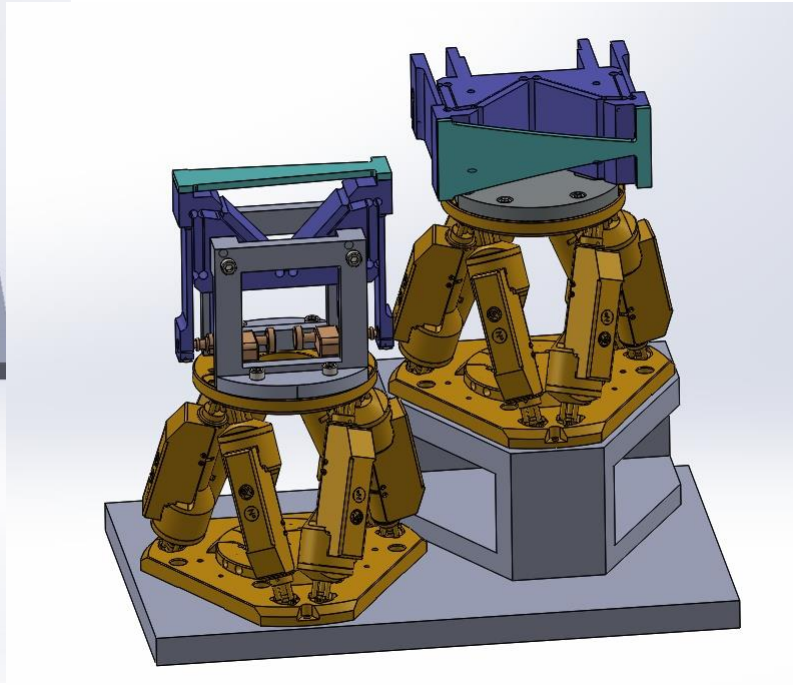
Current technology not good enough.

5.1 Bent Mirrors

- Ellipse surface profile
- Gravity adaptive
- Variable width mirror
- Asymmetric bending moment - for long mirror
- No axial force bending – for long mirror
- Finite Element Analysis auxiliary system optimization
- High resolution bending
- High stability bending
- Large adaptation scope for focusing condition
- 1m long mirror
  ~ 0.5μrad RMS bending surface precision
- 120mm long mirror
  ~ 0.3μrad RMS bending surface precision

Bent Mirrors





5.2 Optical Metrology

High precision LTP for low-to-middle frequency slope errors

70 nrad RMS plane measurement accuracy and 5mrad range

Stitching interferometer

Fizeau laser interferometer and Michelson white light interferometer for middle-to-high frequency surface ripples

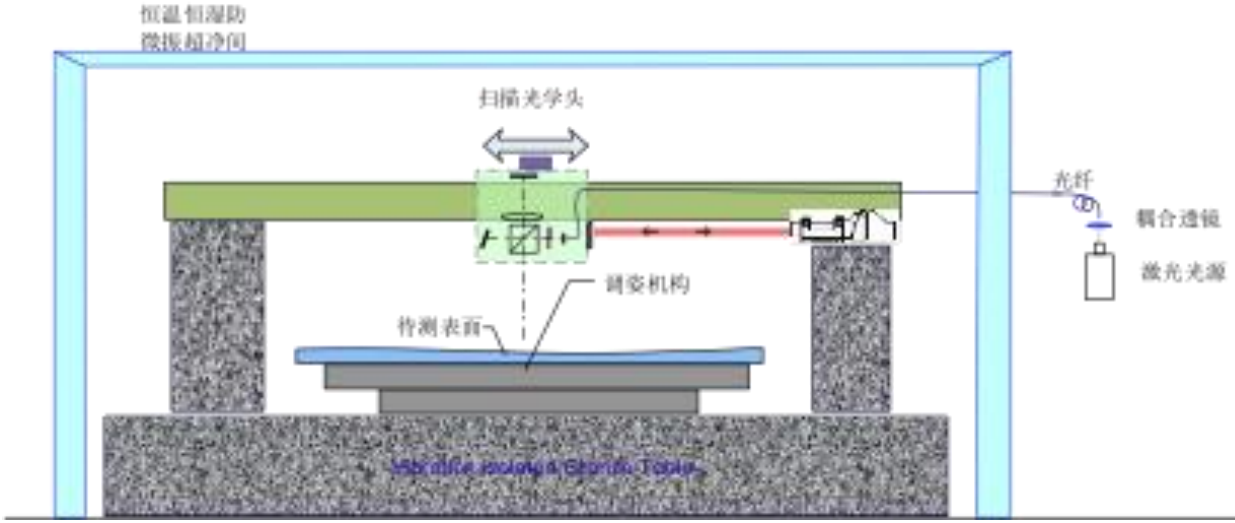
For 500mm plane, 2nm RMS measurement accuracy

High Temperature/vibration stability laboratory under construction

~0.05°C stability and uniformity

RMS 20nm ground vibration

High stability compressed air supply

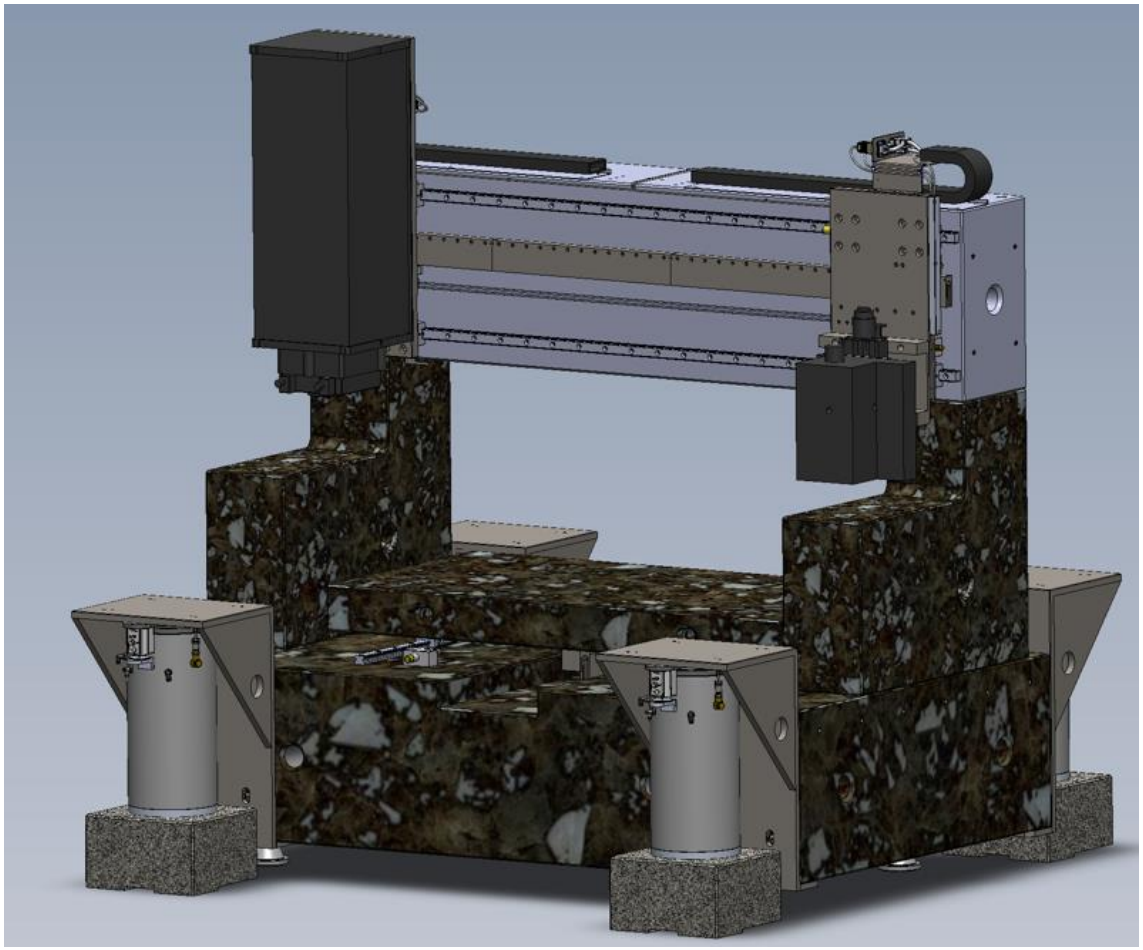


LTP

- Double Optical Head
  - Optimized structure
- High-quality optics, detectors
  - H5 class, 1nm surface precision, low noise detector

Stitching Interferometer

- Combined stitching technology
- Active vibration isolation technology
- High stability laboratory environment



6. Cryogenically Cooled DCM

Heat Load:

800W, Power Density 10W/mm^2

Energy Range: 5 up to 28keV

Energy Resolution: $\sim 10^{-4}$

Flow Rate of LN_2: up to 25Liters/min

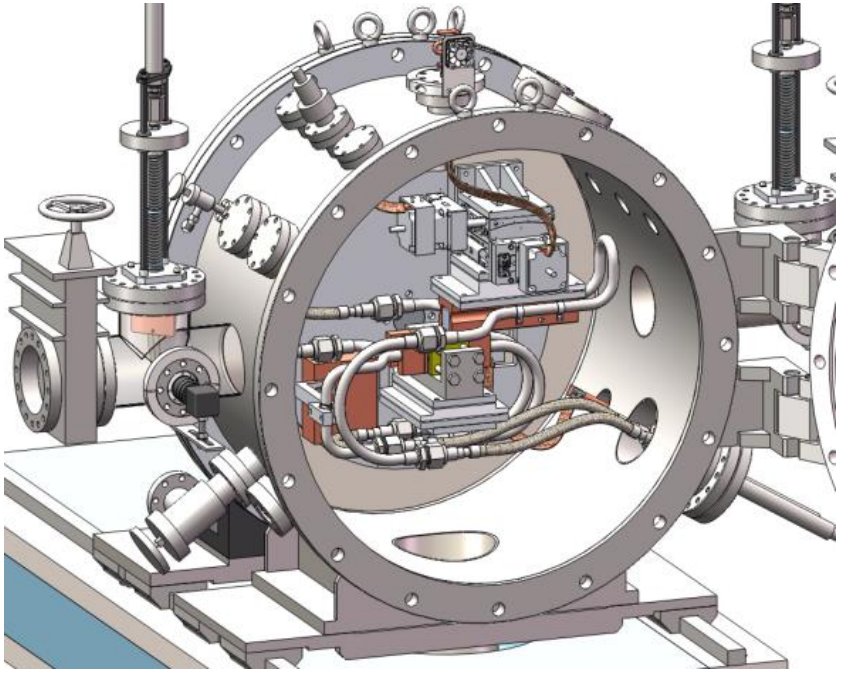
Pressure Instability: $<$1.5kPa

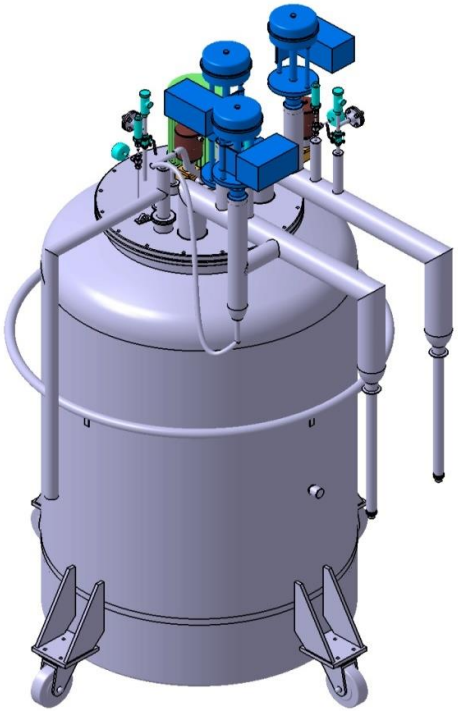
New Crystal cooling design

Cryogenic design

Vibration control

A Prototype will be finished next year





R&D for end-stations

- Ultrafast X-ray probe
- dynamics extreme conditions (P-T)
- X-ray detector, point and 2D
- Imaging
- Experimental apparatus for engineering materials

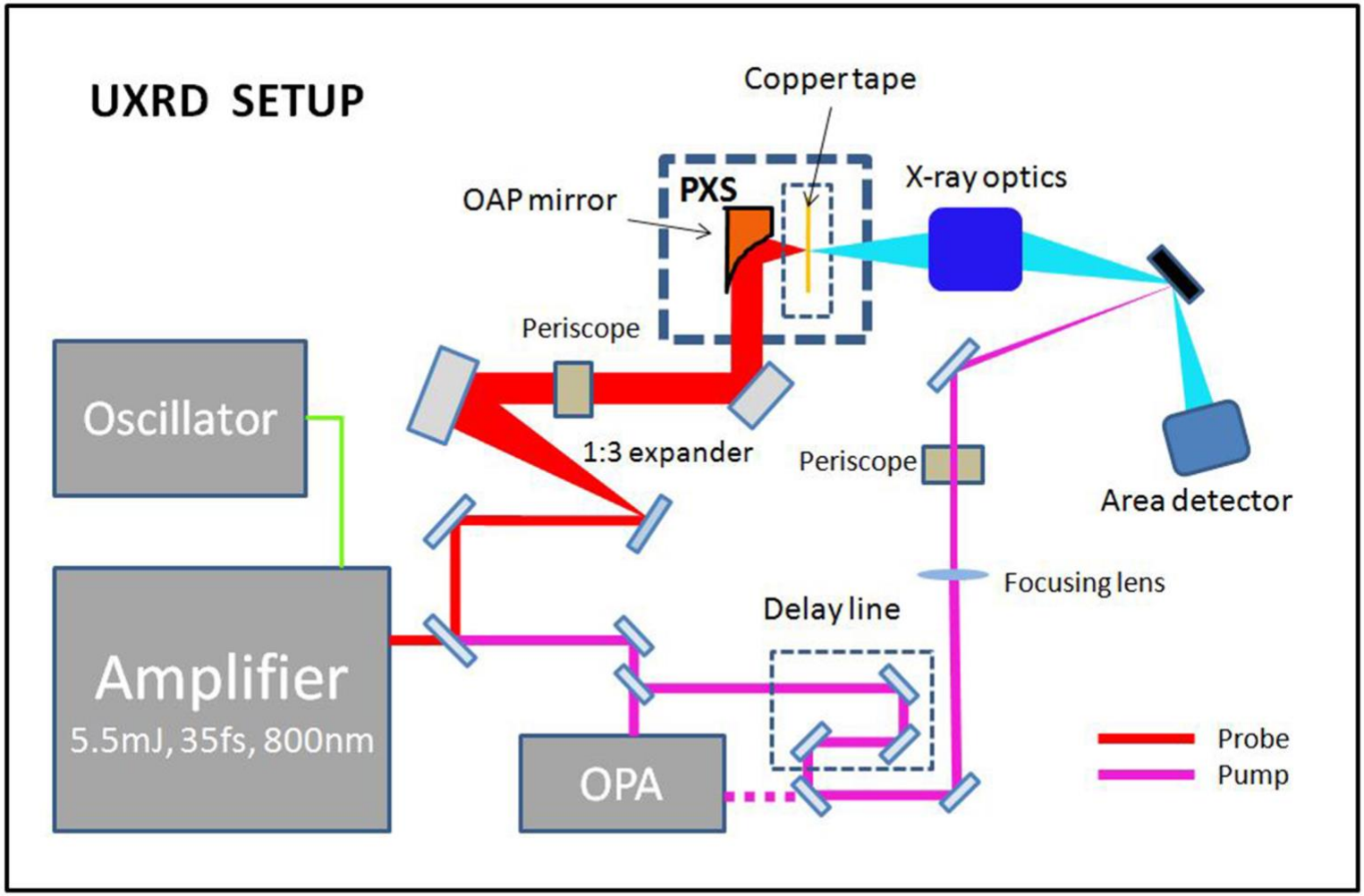
7. Ultrafast time-resolved X-ray development

Sub-ps to 100ps

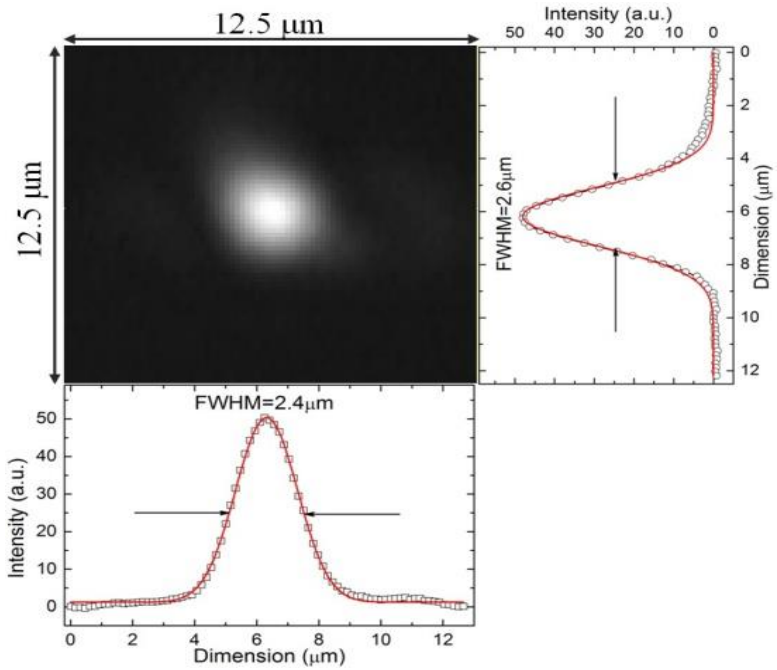
Phase I: **1kHz sub-ps XRD**， based on Laser-driven plasma X-ray source, finished

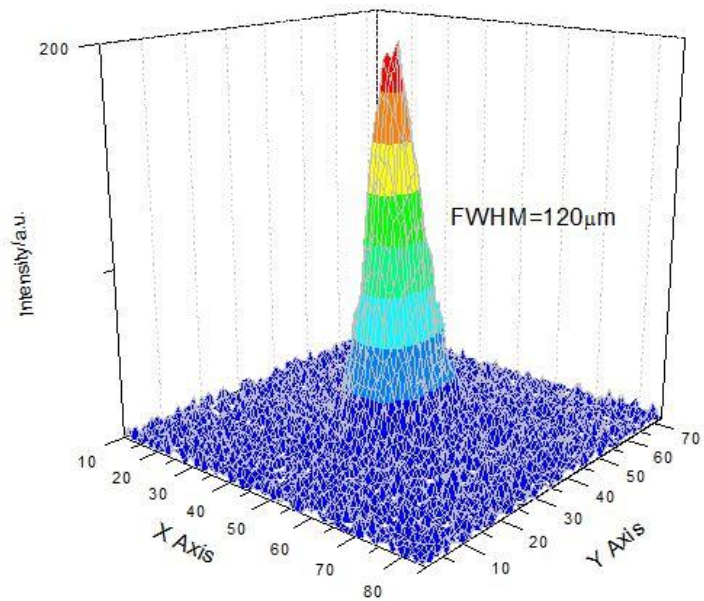
Phase II: **MHz repetition ps X-ray spectroscopy and scattering**, based on SR, under the way

Phase I: 1kHz sub-ps XRD setup, table-top source -based on Laser-driven plasma X-ray source



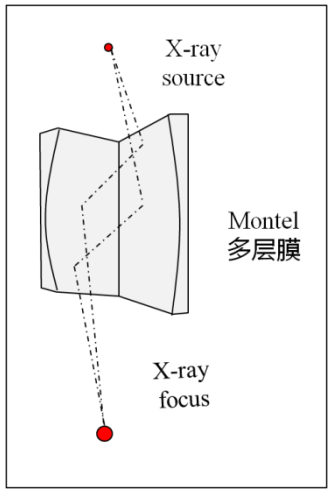
Laser		X-ray	
Pulse energy (mJ)	**5.5**	Photon energy (keV), Cu Kα	**8.04**
Repetition (kHz)	**1**	Flux on sample (ph/s)	**10^5-10^6**
Pulse duration (fs)	**35**	Pulse duration (fs)	**100~300**
Laser focus (FWHM) (μm)	**3**	X-ray focus (FWHM) (μm)	**120**

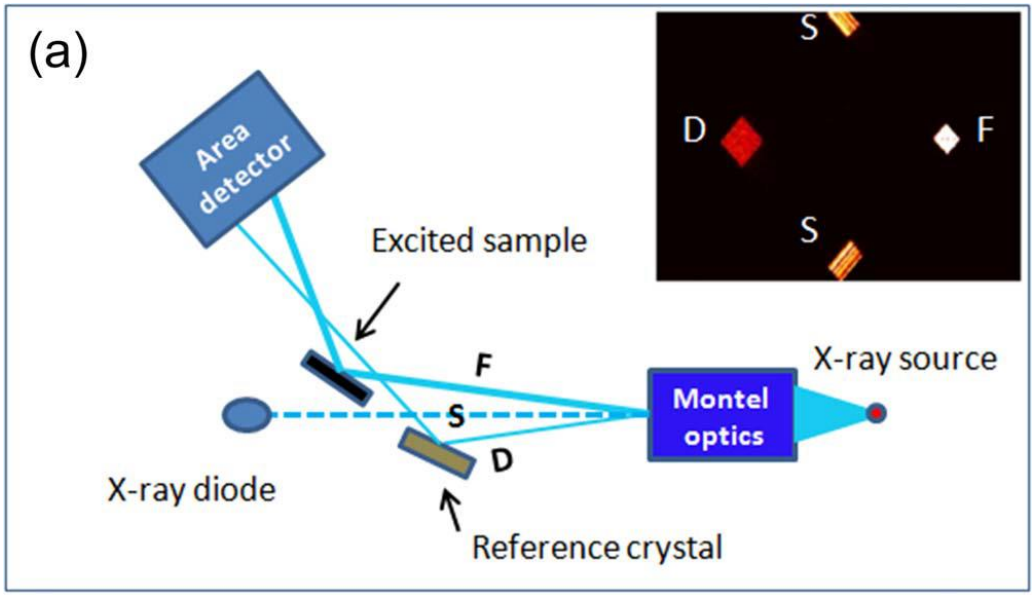


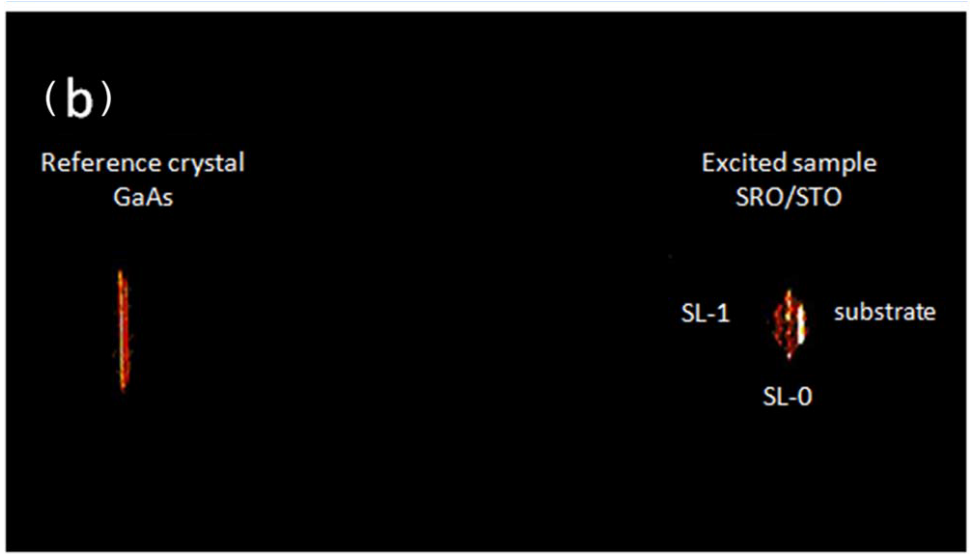


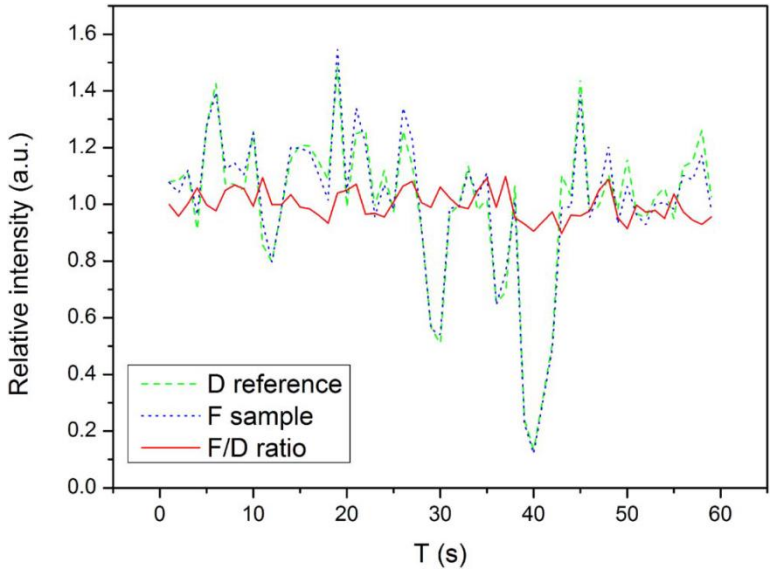
Fluctuation suppression-novel normalization

Montel multiplayer mirror





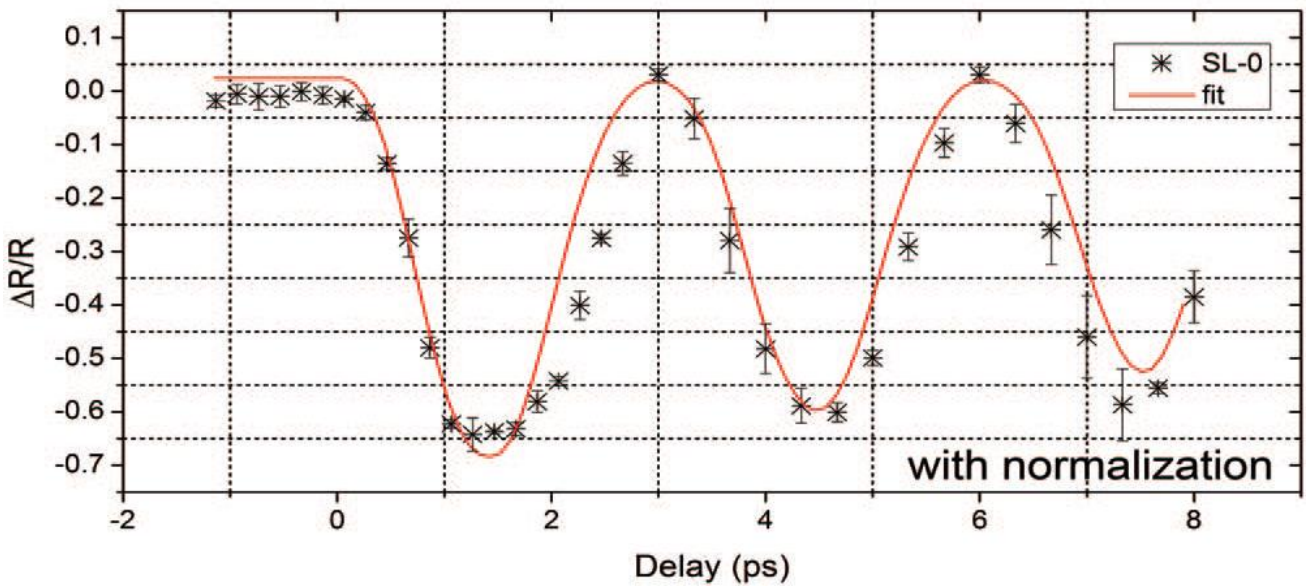




B.Zhang, *Rev. Sci. Instrum.* 85, 096110 (2014)

Sub-ps XRD:

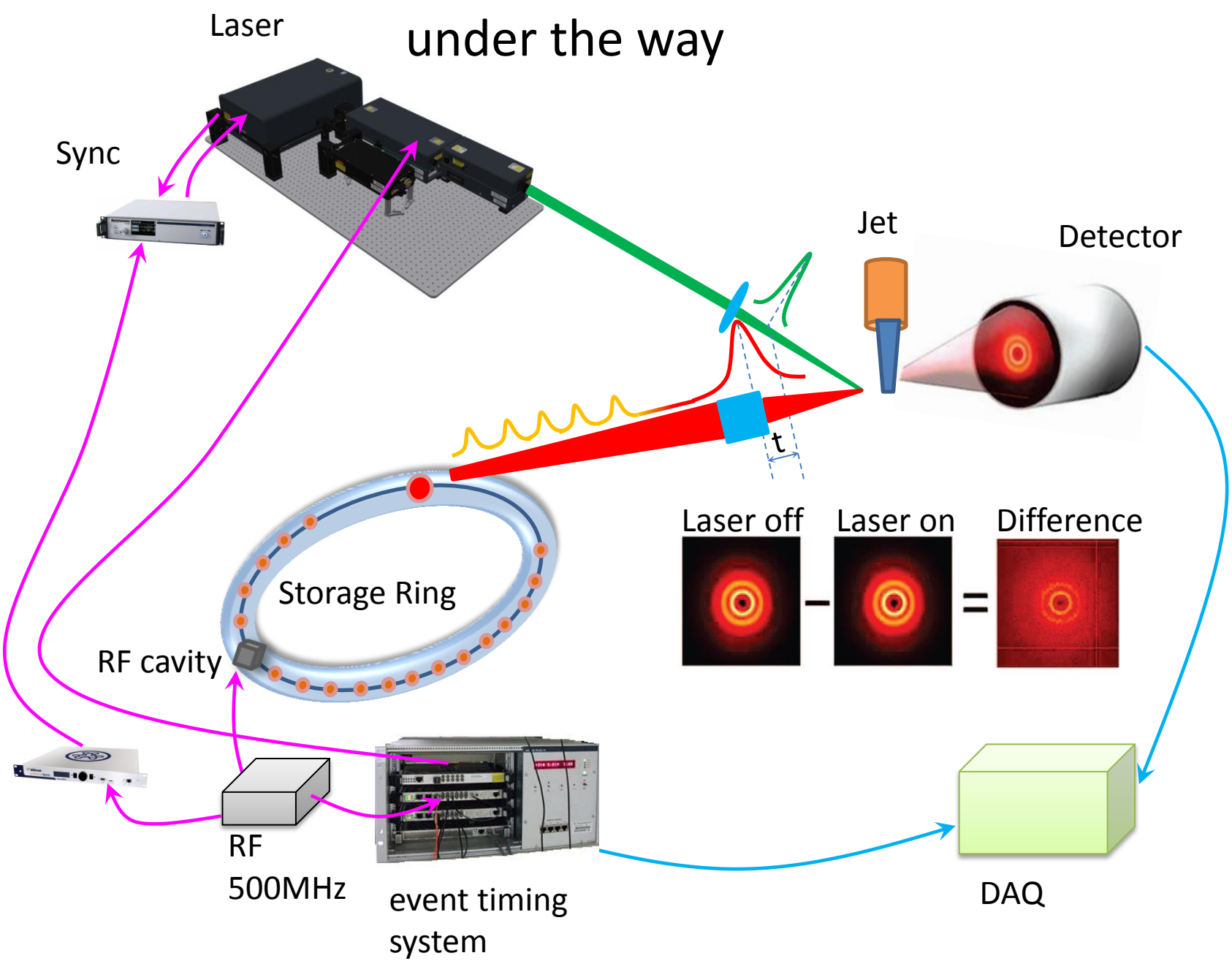
Superlattice: 10 pairs of metallic SrRuO3 (SRO, d_{SRO}=7.5 nm) and dielectric $SrTiO_3$ (STO, d_{STO}=15.0 nm) layers.

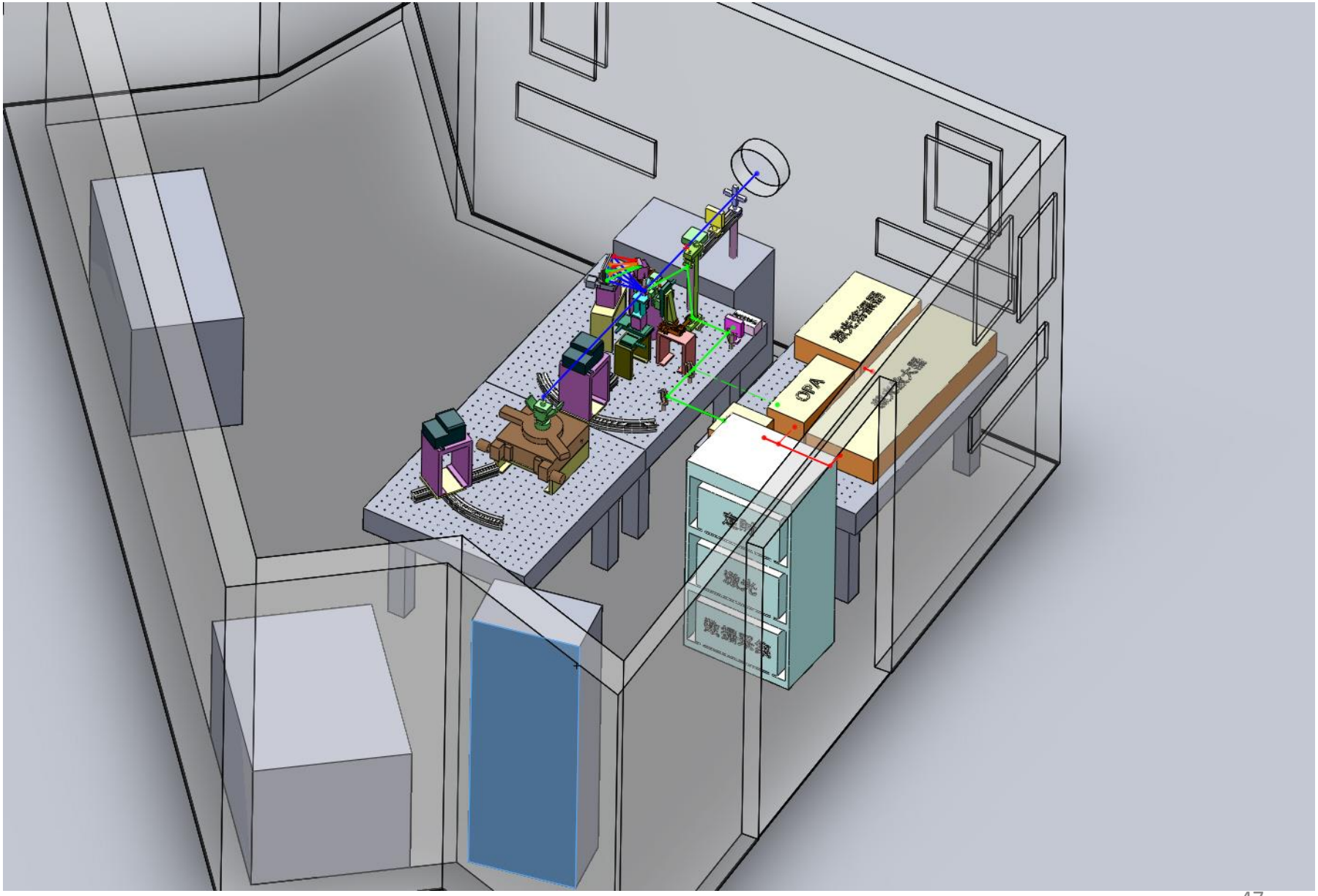


SRO/STO superlattice Phonon oscillation

B.Zhang, *Rev. Sci. Instrum.* 85, 096110 (2014)

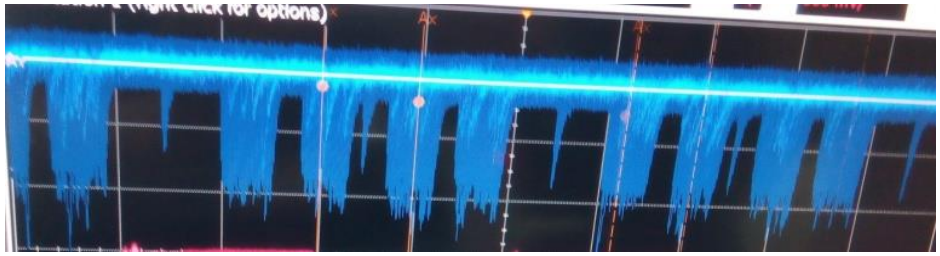
Phase II: MHz repetition rate pump-probe under the way



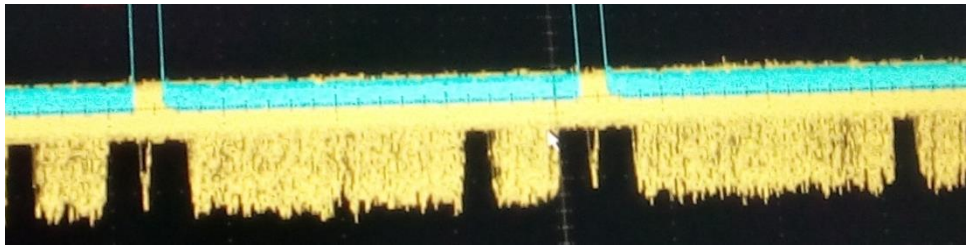

OPA

Acquisition R&D for Scattering: gated 2D detector

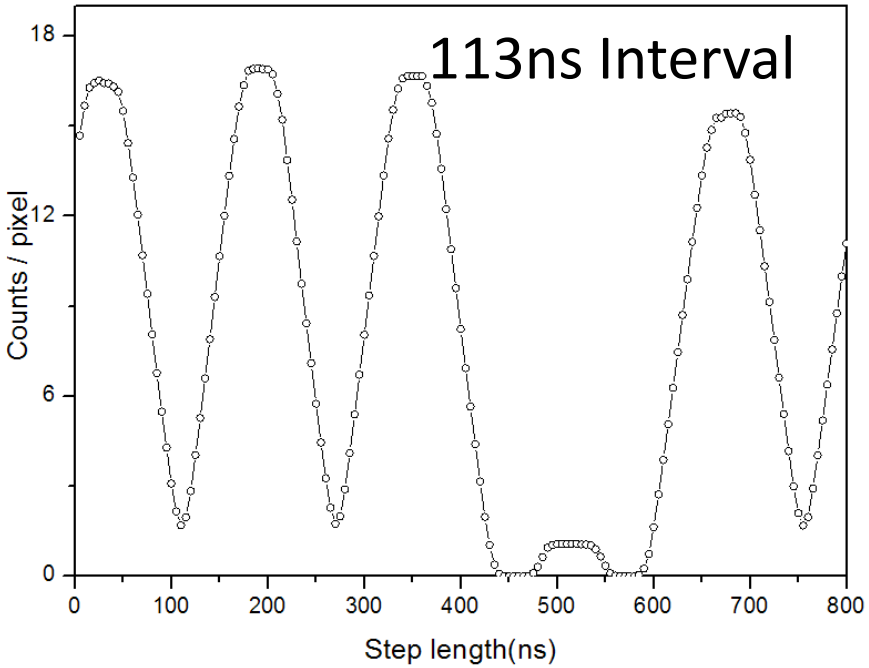
113ns Interval at sides of camshaft bunch

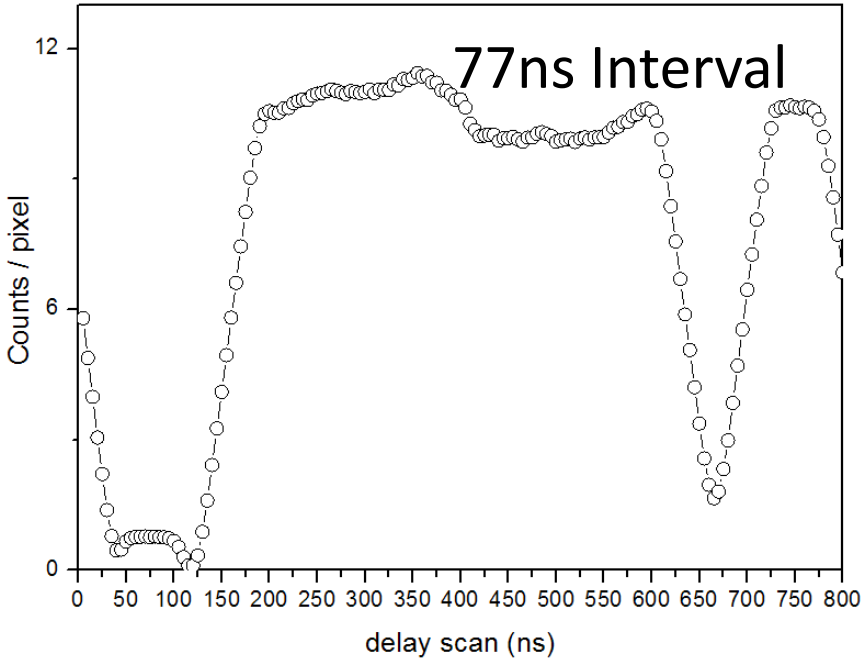


77ns Interval



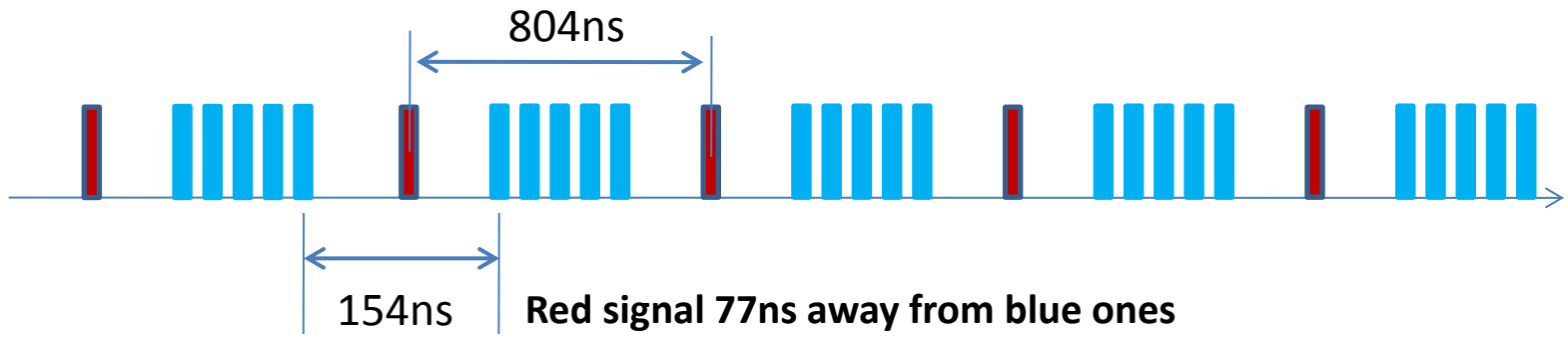
Signal from camshaft bunch gated out by Pilatus at 1.24MHz



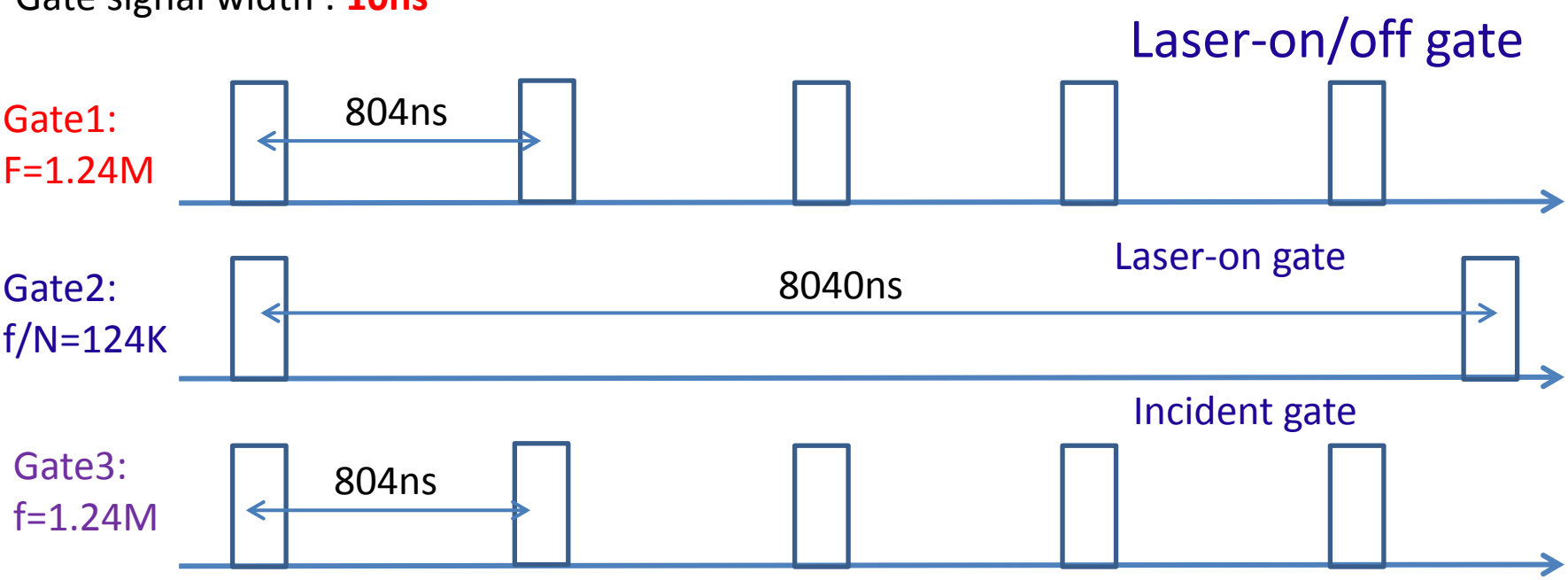


Acquisition R&D for X-ray Spectroscopy:

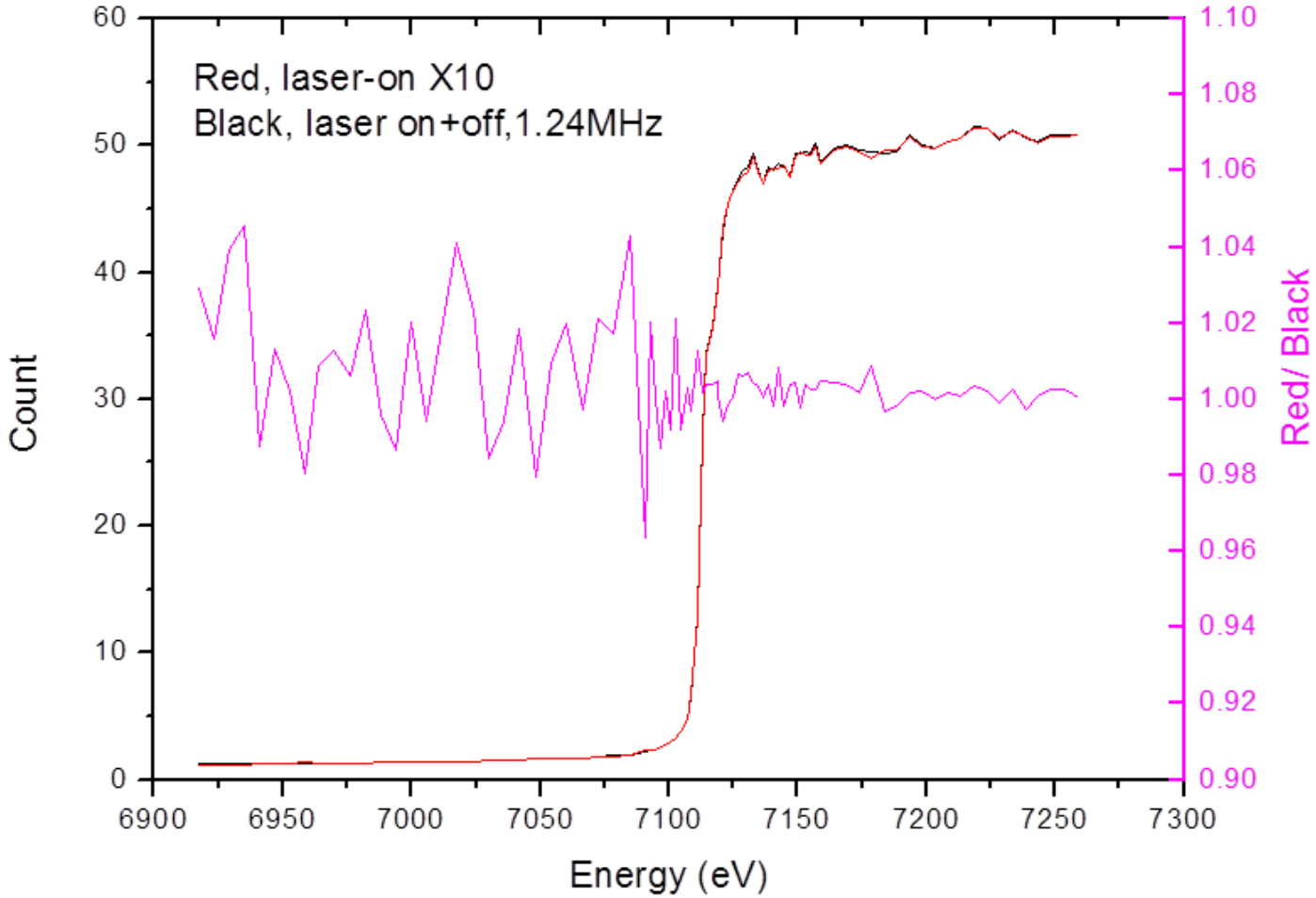
Period: 804ns, revolution frequency: 1.243MHz



Gate signal width : **10ns**



Simulate the 100kHz laser on detection out of 1.24MHz



Lay foundation for Ultafast X-ray at BAPS:

in-situ, in-operanto, real material

Nanoscale (1-10nm) dynamic, 1-100ps

Sensitivity, 1mM $\rightarrow$ <0.1mM

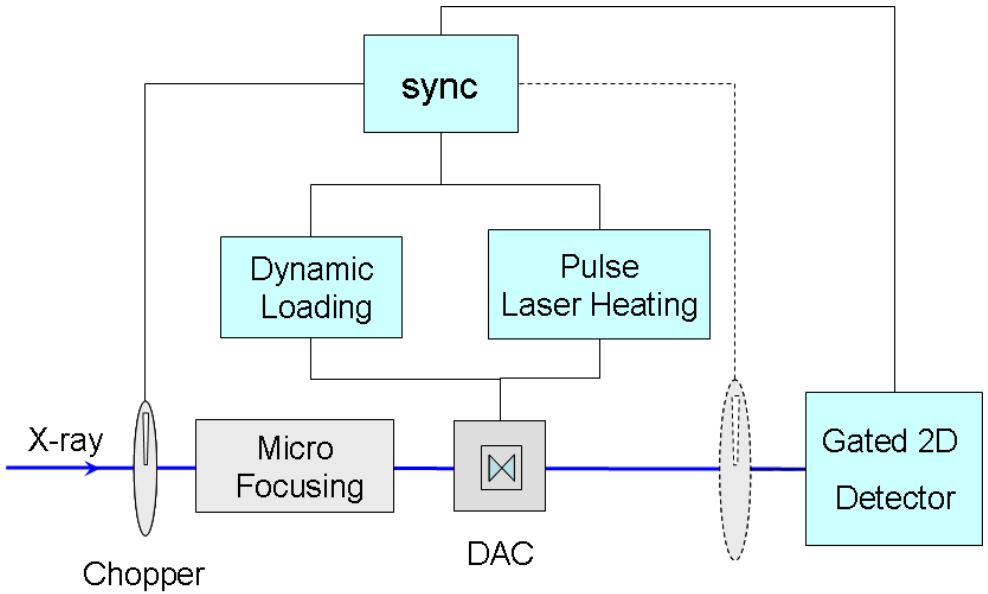
New excitations

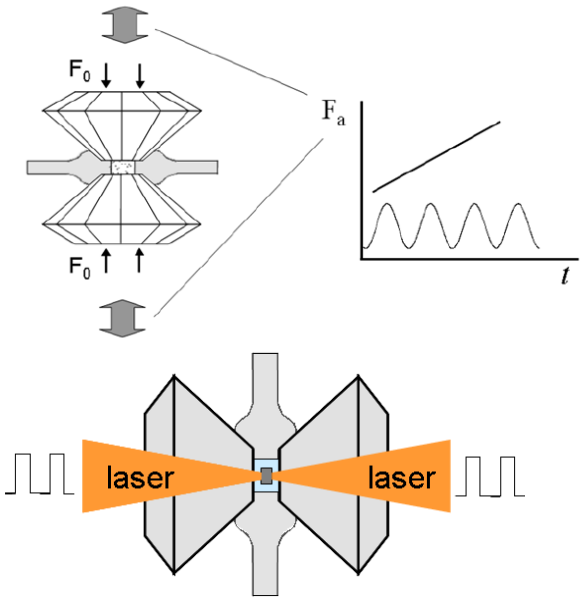
Irreversible process

Short pulse: 1-10ps

Laser slicing	**Low α mode**	**Crab cavity**	**Electron beam slicing**	**SRF harmonic cavity**	**Linac injector**

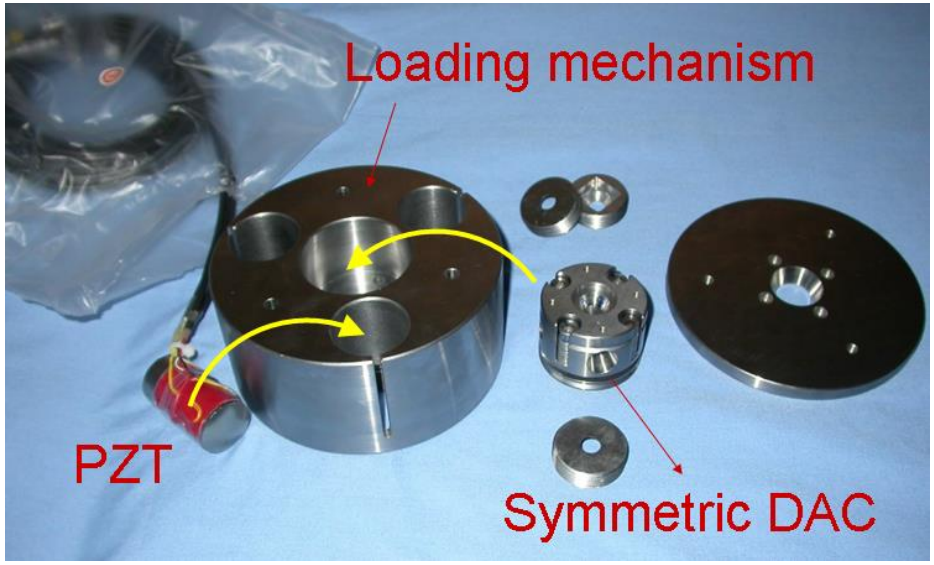
8. Dynamics Research under Extreme Conditions

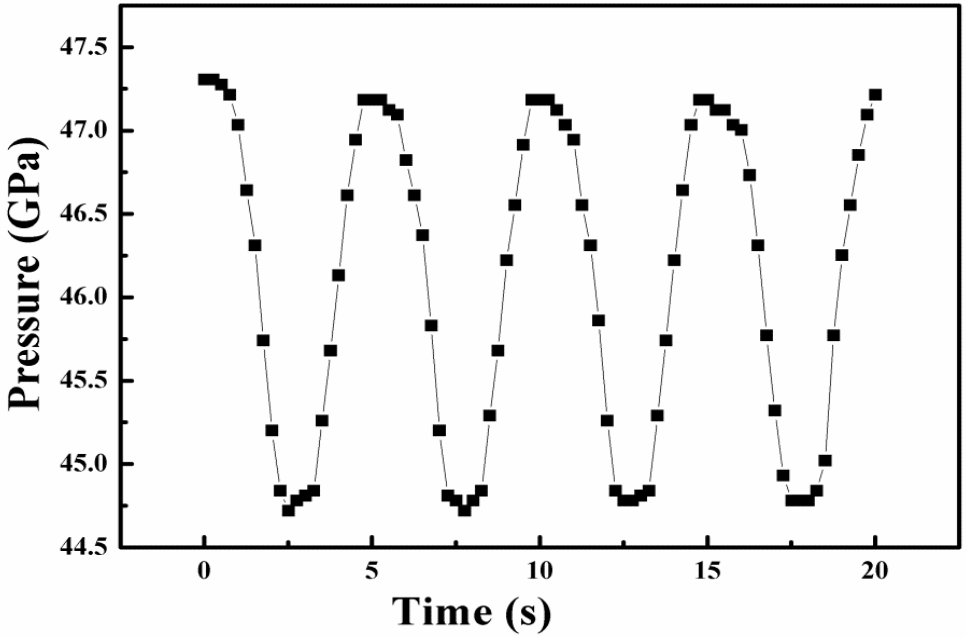


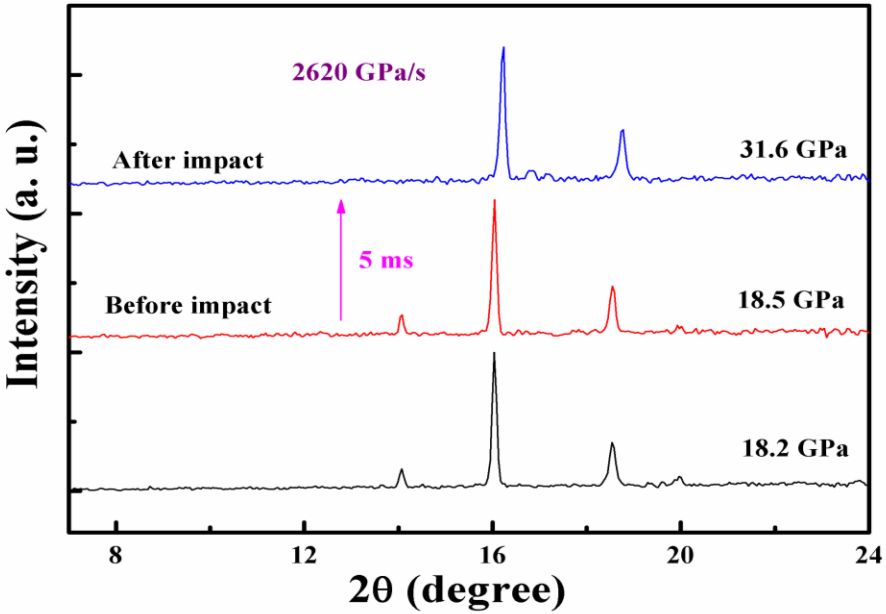


Dynamic DAC: use piezo actuators or gas-membranes, ***Pulse laser heating:*** ~10 μs laser pulses for high instantaneous temperatures (>3000 K) at over 100 GPa.

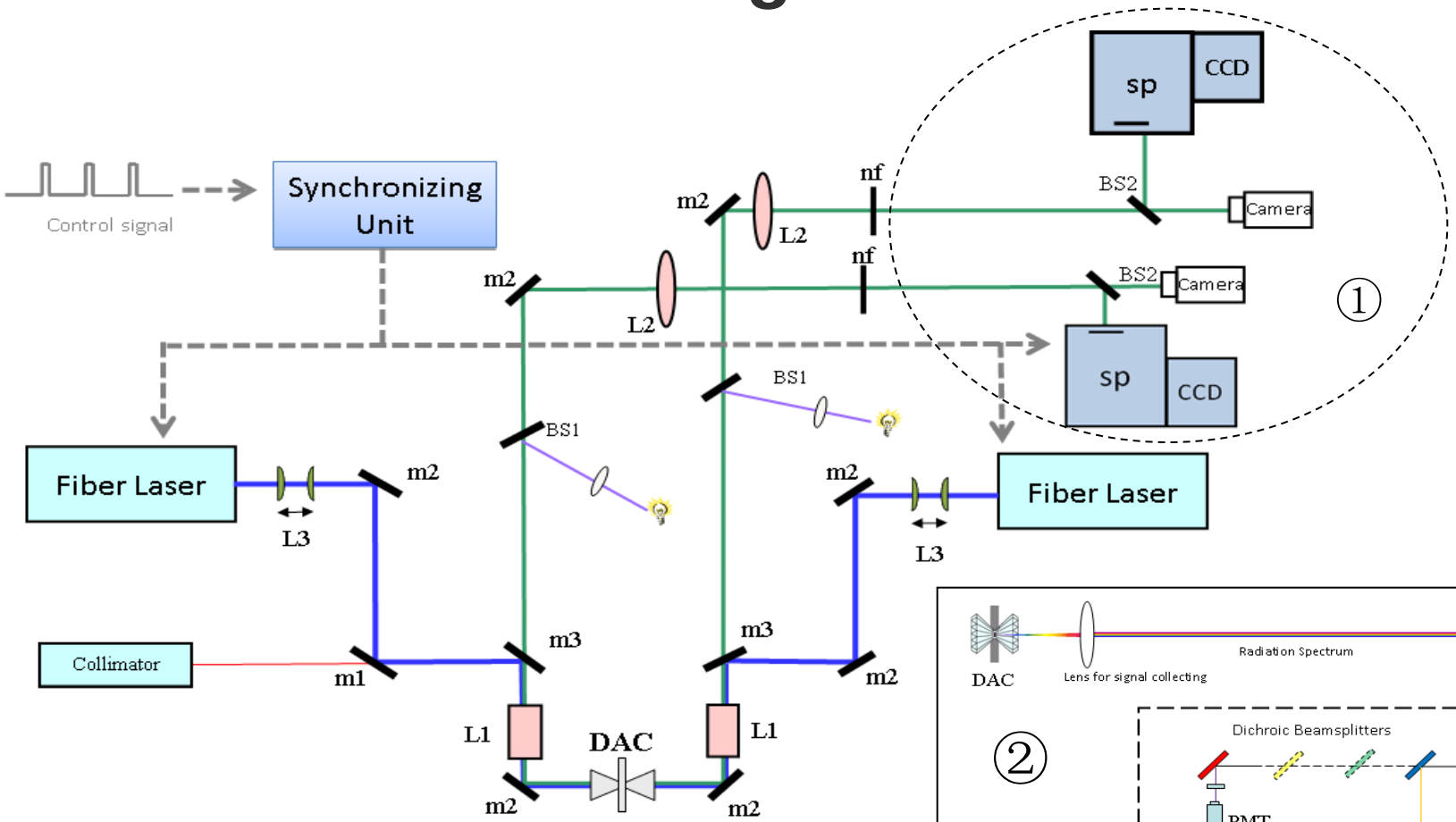
- ***Time-resolved X-ray diffraction:*** high-speed large area detector (e.g. Pilatus) and x-ray chopper , μs- subsecond.

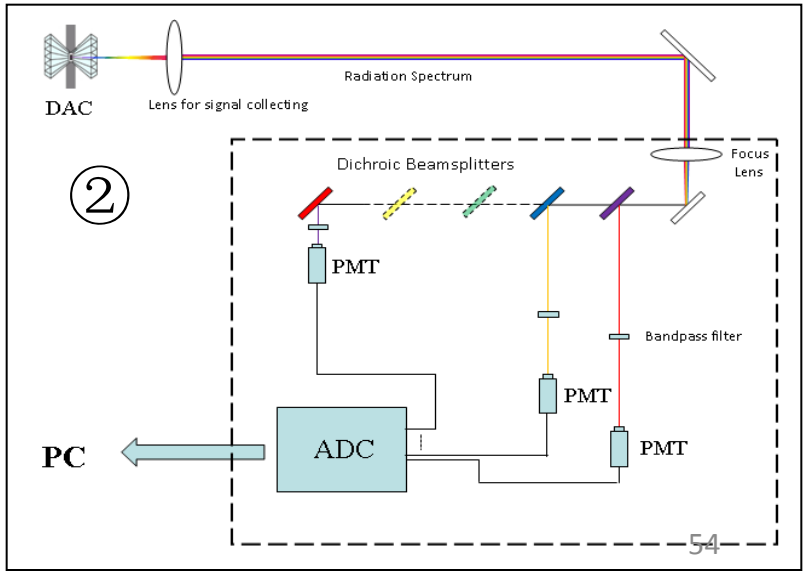

Loading mechanism
PZT
Symmetric DAC


Pressure (GPa)
47.5
47.0
46.5
46.0
45.5
45.0
44.5
0
5
10
15
20
Time (s)


2620 GPa/s
After impact
31.6 GPa
5 ms
Before impact
18.5 GPa
18.2 GPa
Intensity (a. u.)
8
12
16
20
24
2θ (degree)

Pulse Laser Heating



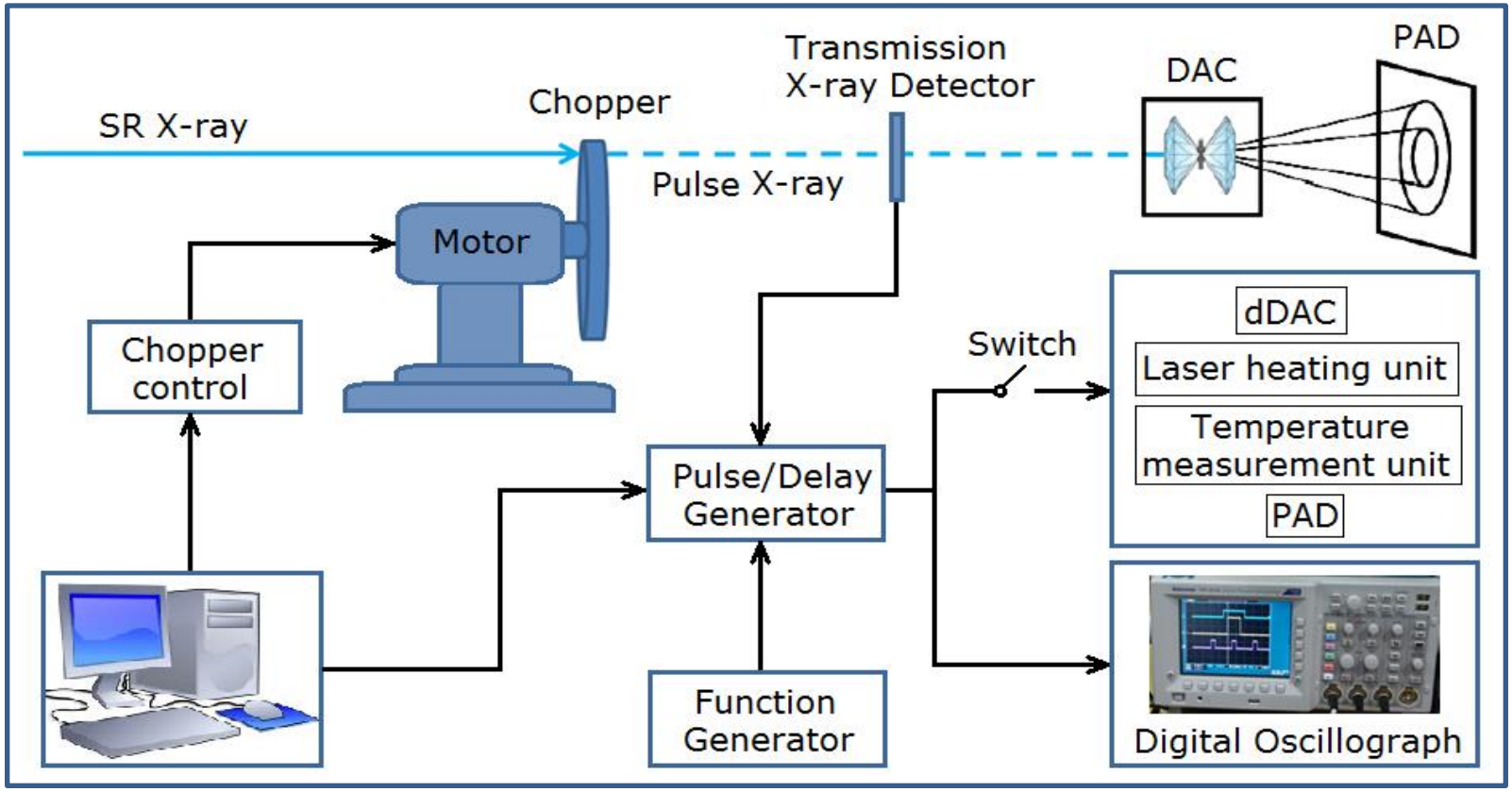


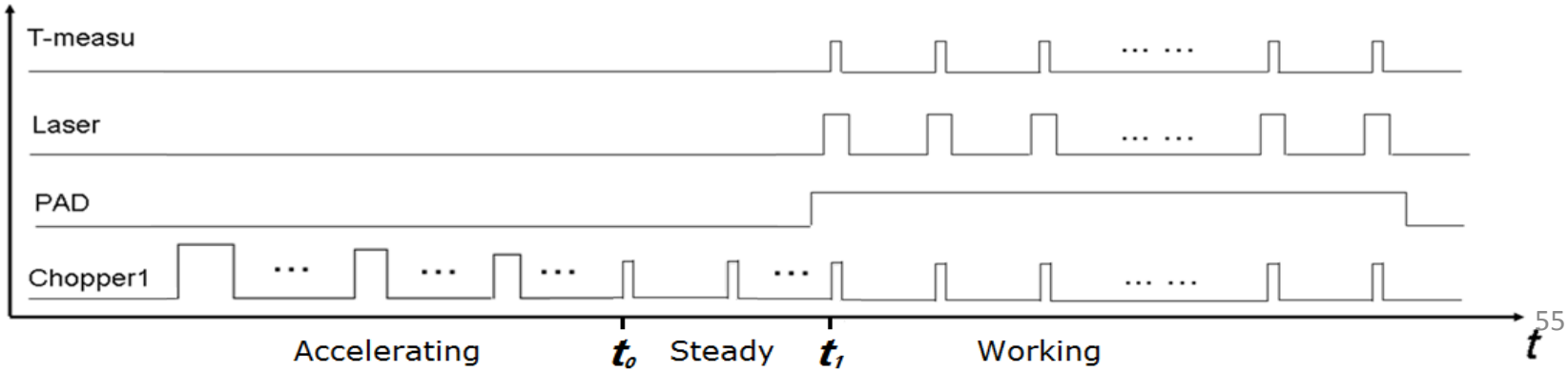
Temperature Measurement

① CCD: sub-millisecond

② PMT: sub-micro second

Time-resolved XRD





9. X-ray Detectors

A small step in detector a leap in X-ray measurement

Nuclear electronics lab for high energy physics detector

$\rightarrow$ Detectors for photon science

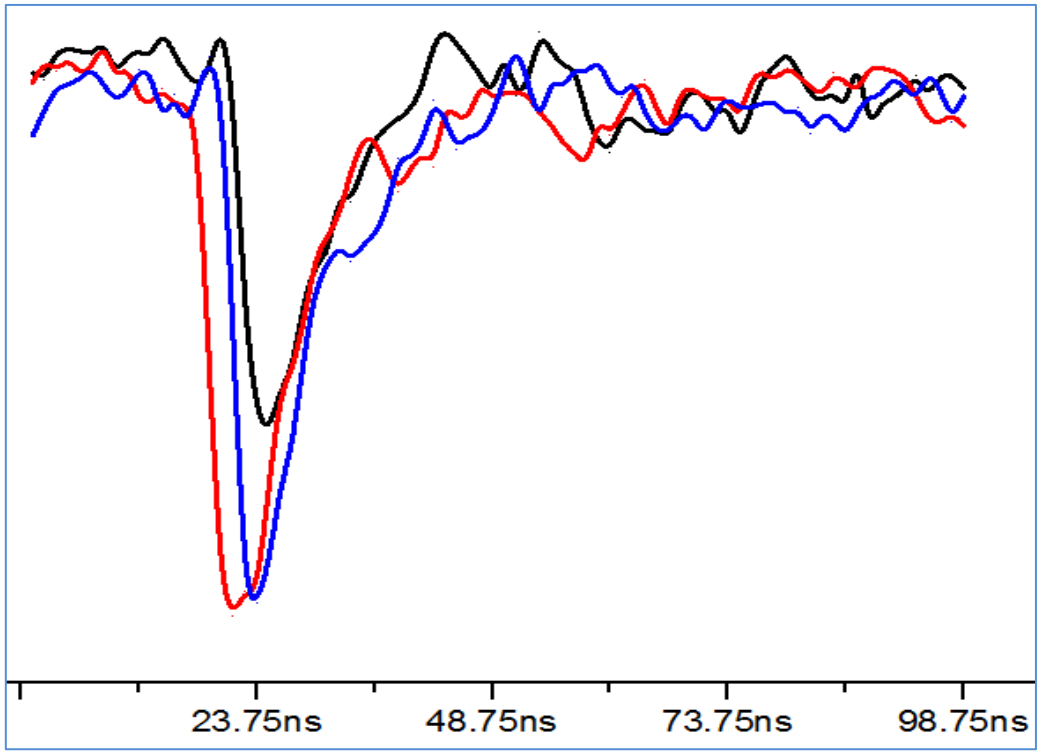
- APD (Avalanche Photodiodes), Ultrafast XAS, NRS
- PAD (Pixel Array Detector)
- others: SDD, Imaging detector

9.1 APD

APD pre-amplification electronics,

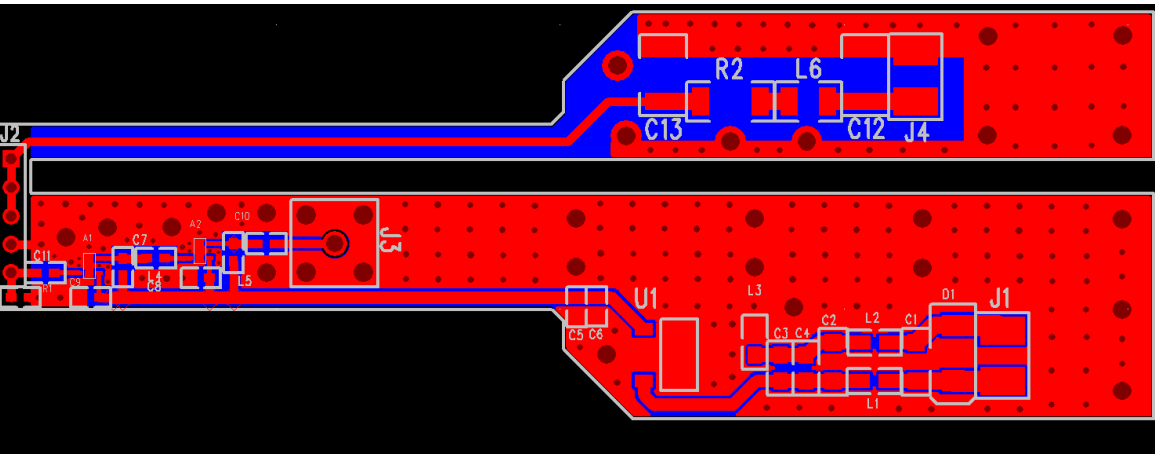
Gain: 1000

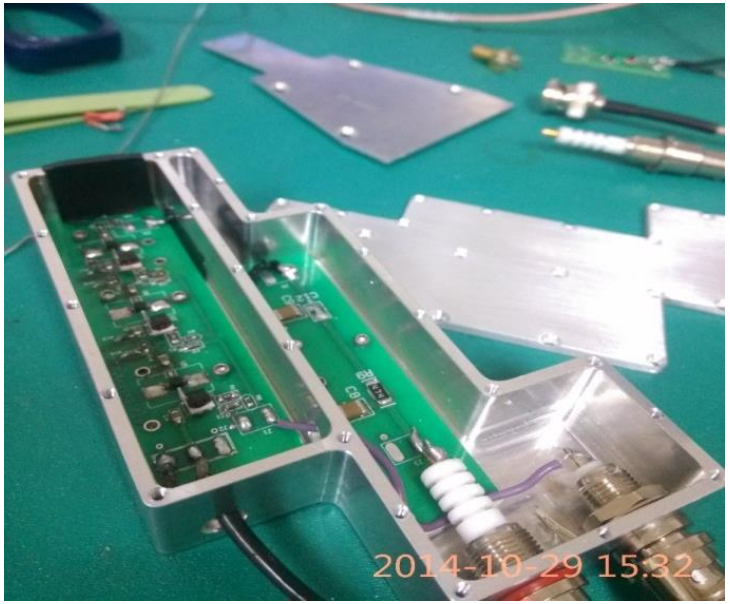
Rising edge: ~3ns



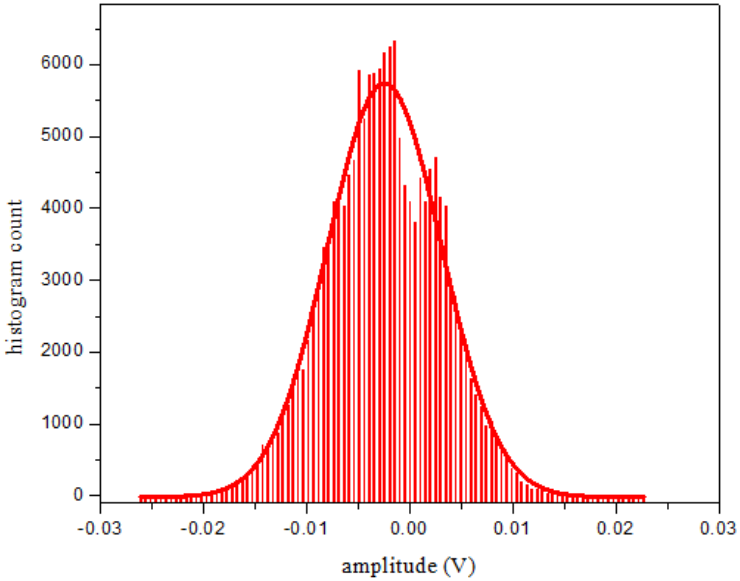
5th version design: oscillation tackled, noise could be better

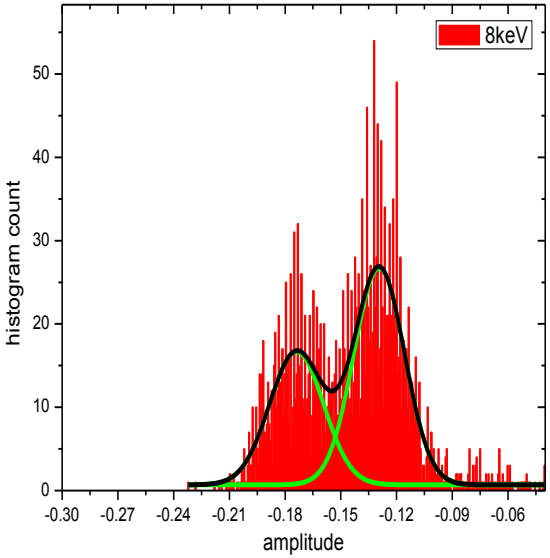
Pre-amp PCB



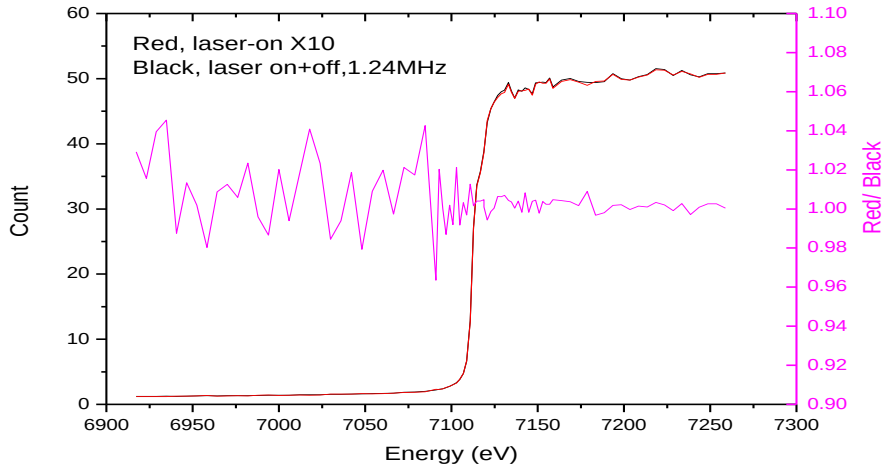


Noise and signal statistic





Used in ultrafast XAS measurement and bunch purity measurement



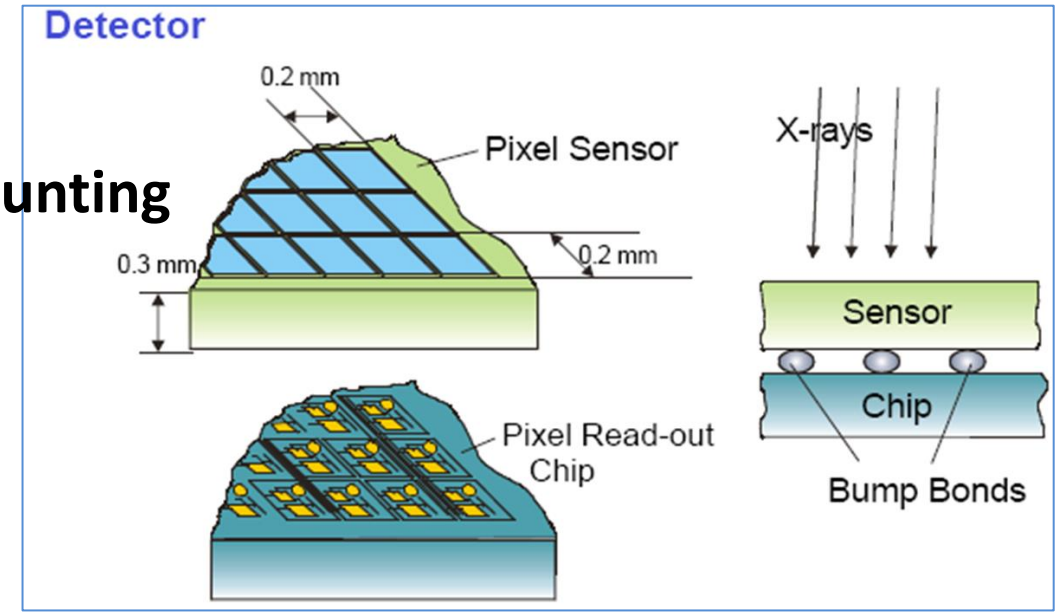
Next, APD array

APD sensor , pre-amp electronics

ASIC for array APD under design

9.2 XPAD

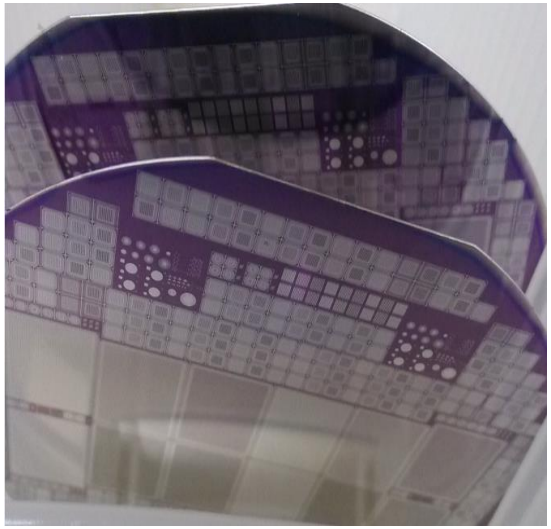
Single photon counting



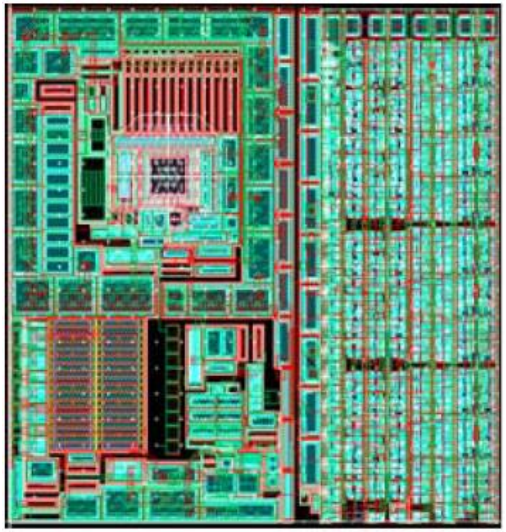
Sensor thickness (μm)	300 (Si-Pin)
Pixel size (μm)	150 X150
Dynamic range (bit)	20
Frame rate (Hz)	1000
Module size (mm)	72X104

Accomplished

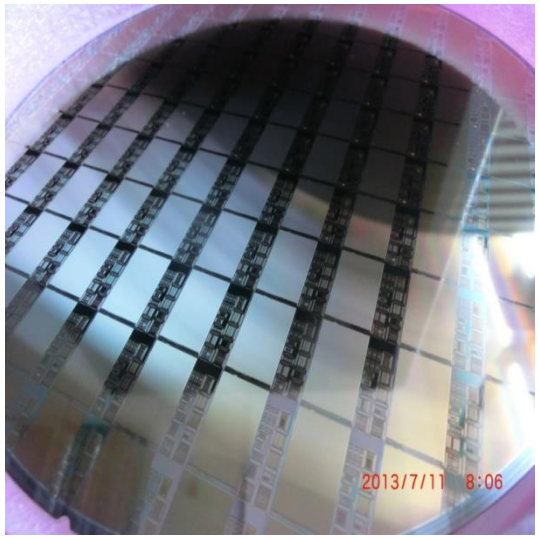
Sensor Array



ASIC

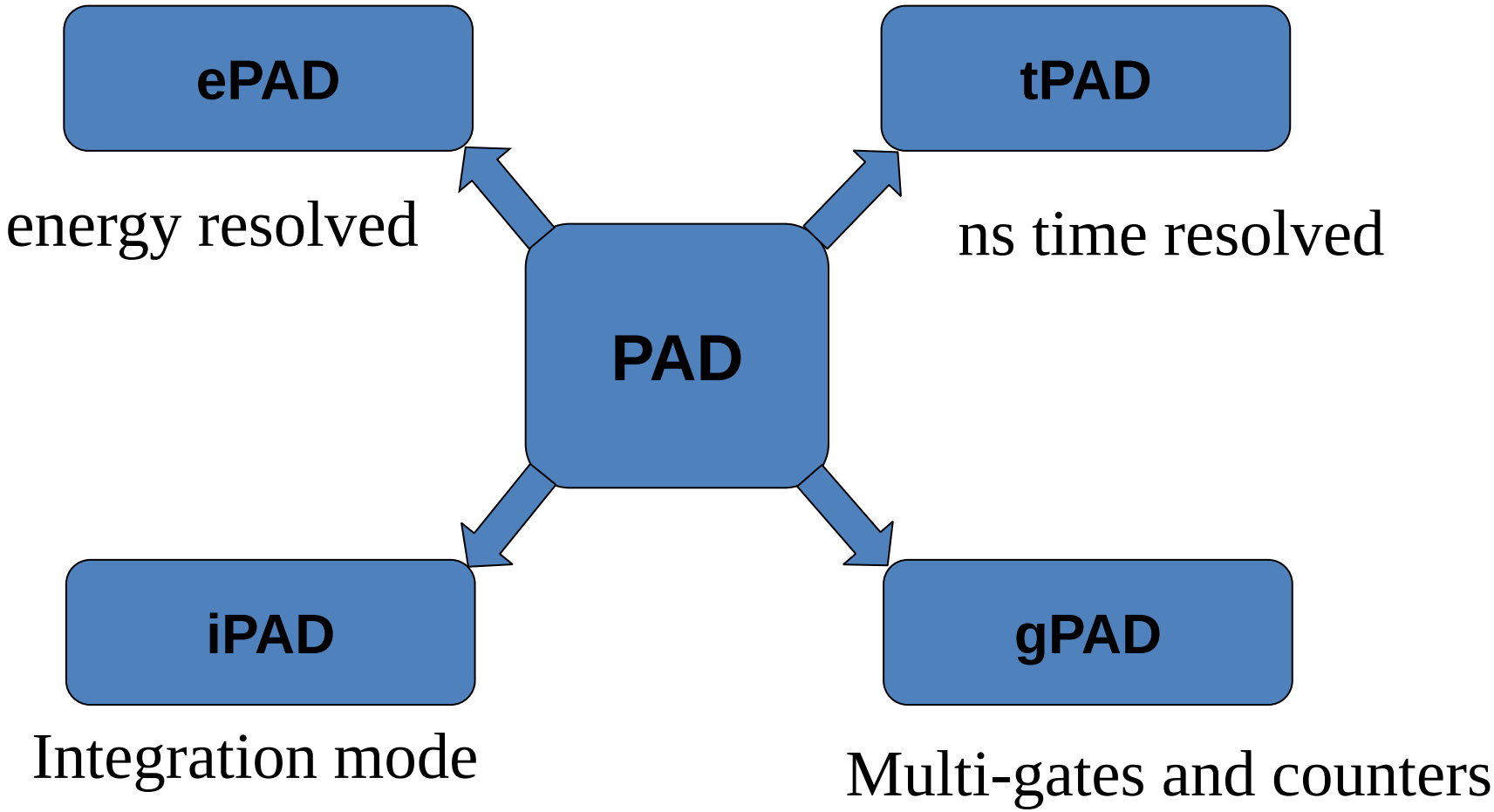


Bump Bonding



A Prototype module will be available next year

Based on XPAD, specific PAD

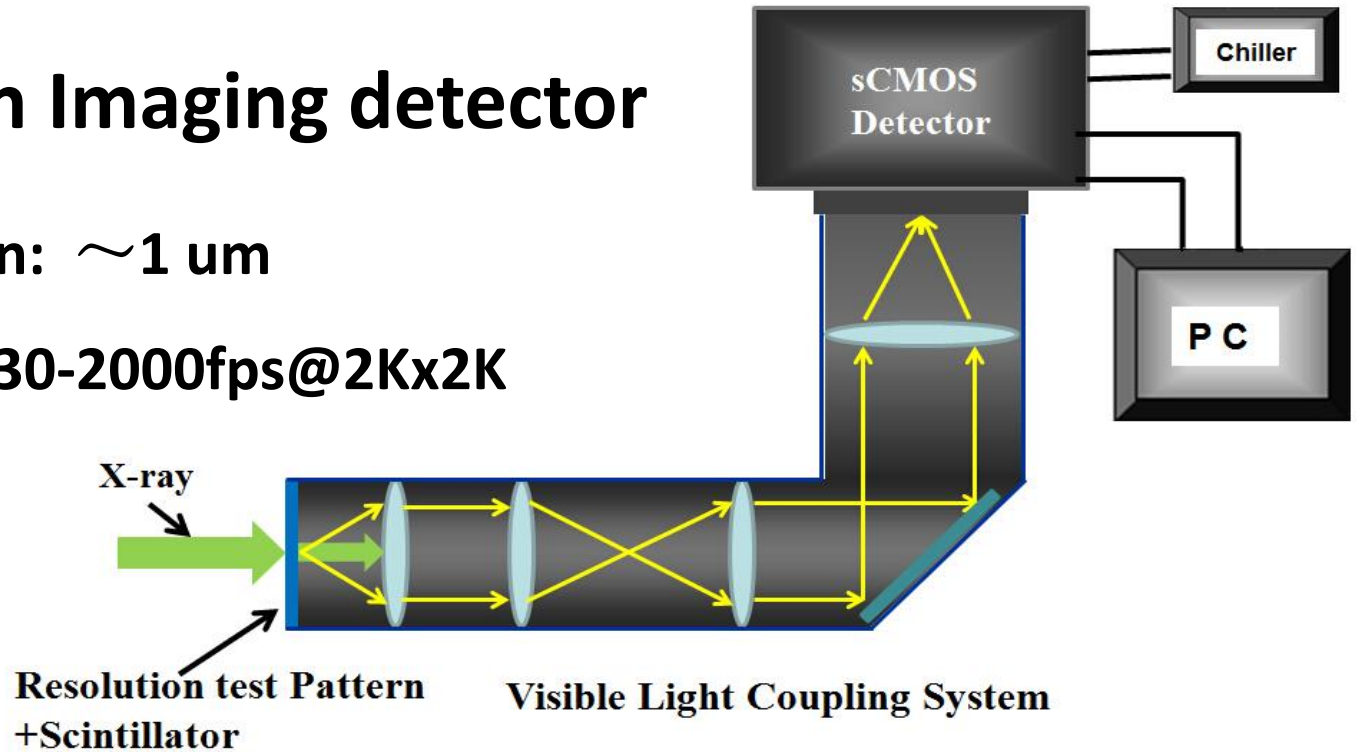


9.3 other detectors

High resolution Imaging detector

Spatial resolution: ～1 um

Readout speed: 30-2000fps@2Kx2K



SDD array for spectroscopy

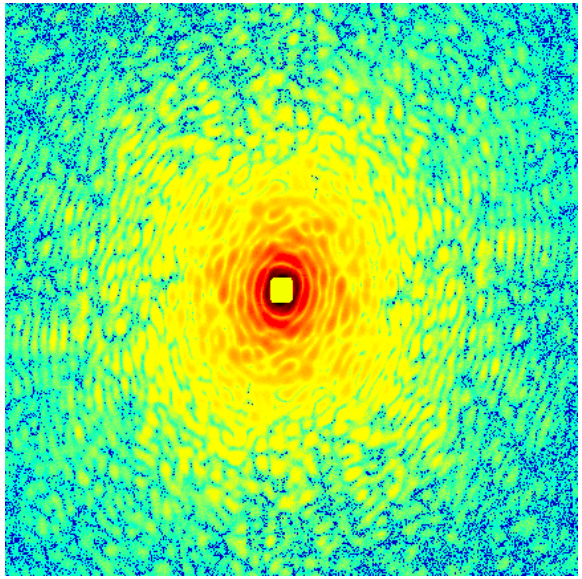
High energy resolution mode (<180eV, 1-10MCps)

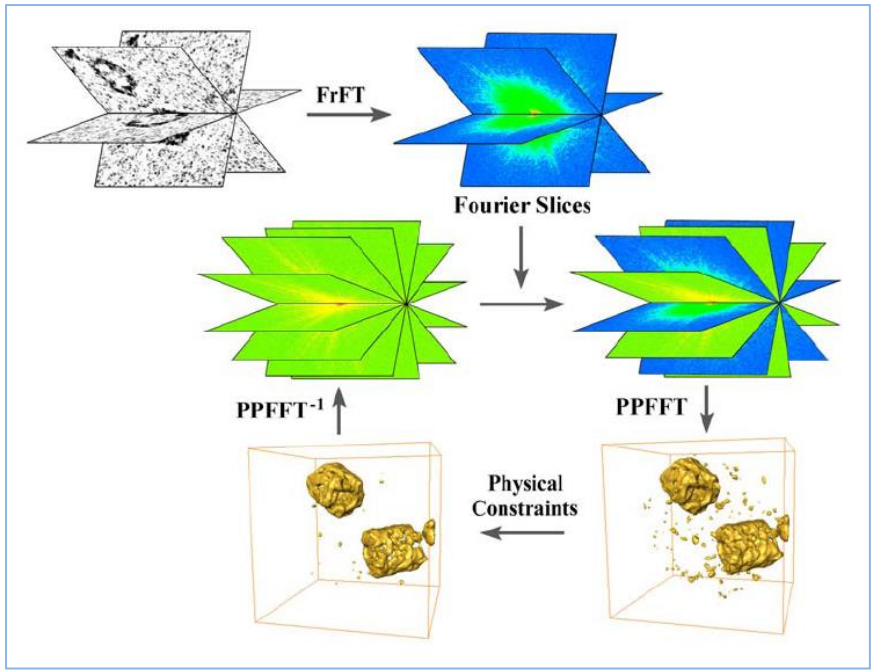
High counting mode (<300eV, 10-100MCps)

10. Imaging method

10.1 CDI

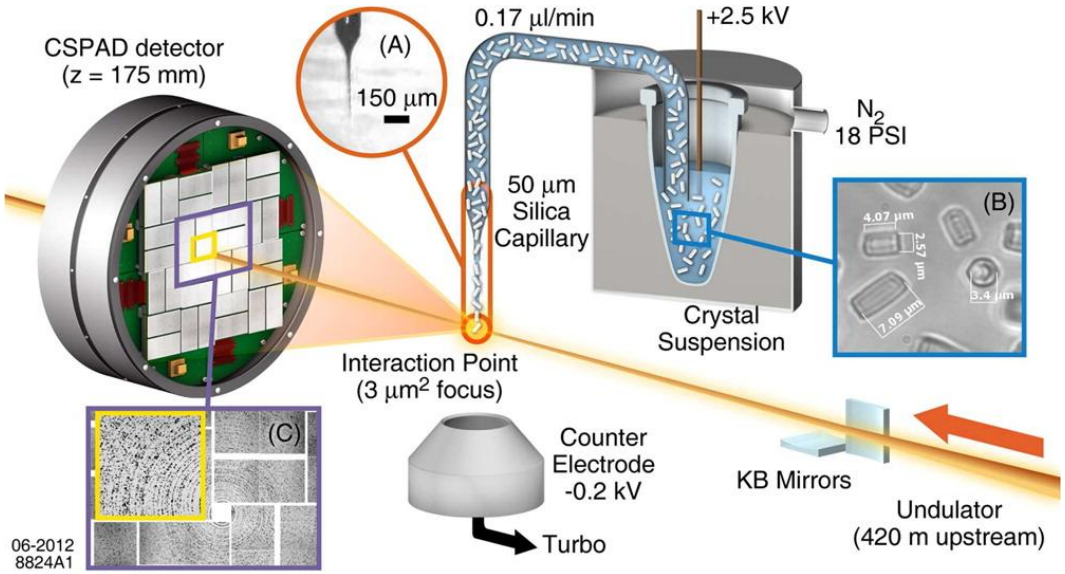
- **Methodological development in phase retrieve, based on oversampling method.**
- **Overcoming the problem of “losing region” due to beamstop, via compressive sensing theory.**
- **3D structure reconstruction.**

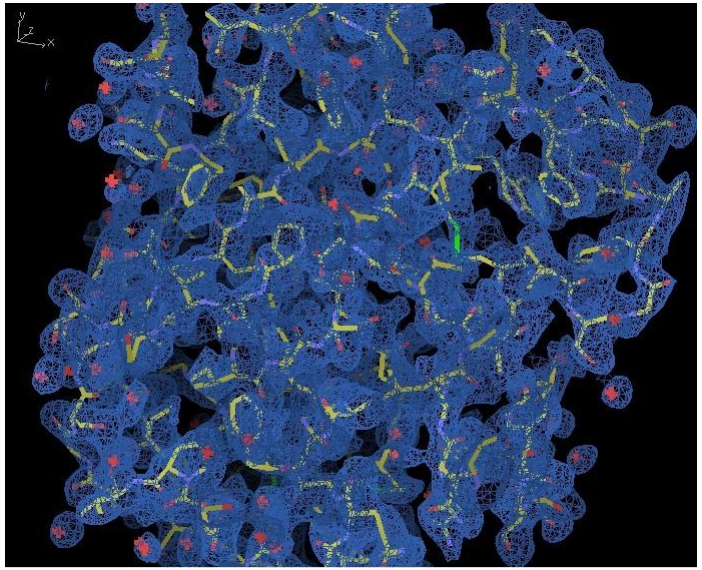




Micro liquid jet

- **Similar to XFEL, one tiny crystal should obtain one or few diffraction patterns in high-brilliance X-ray beam.**
- **Therefore the sample should be delivered by micro liquid jet instead of mounting due to radiation damage.**
- **Data processing, structure determination methods need to be developed.**





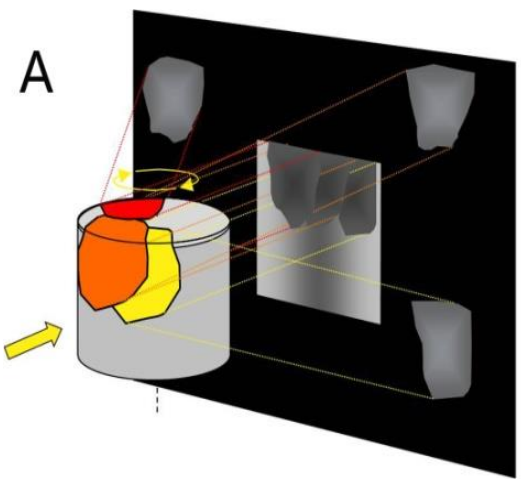
10.2 Diffraction Contrast Tomography (DCT)

Bragg diffraction of the grains as imaging contrast

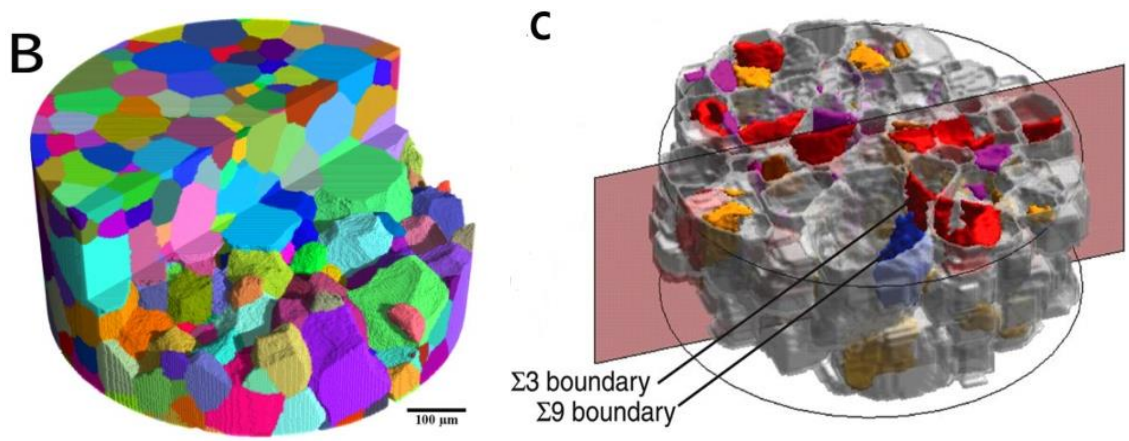
Information of polycrystalline bulk material nondestructively

3D shape and orientation of grains and grain boundaries,3D distribution

Investigate the relationship between the grains and grain boundaries 3D microstructures and the service performances.

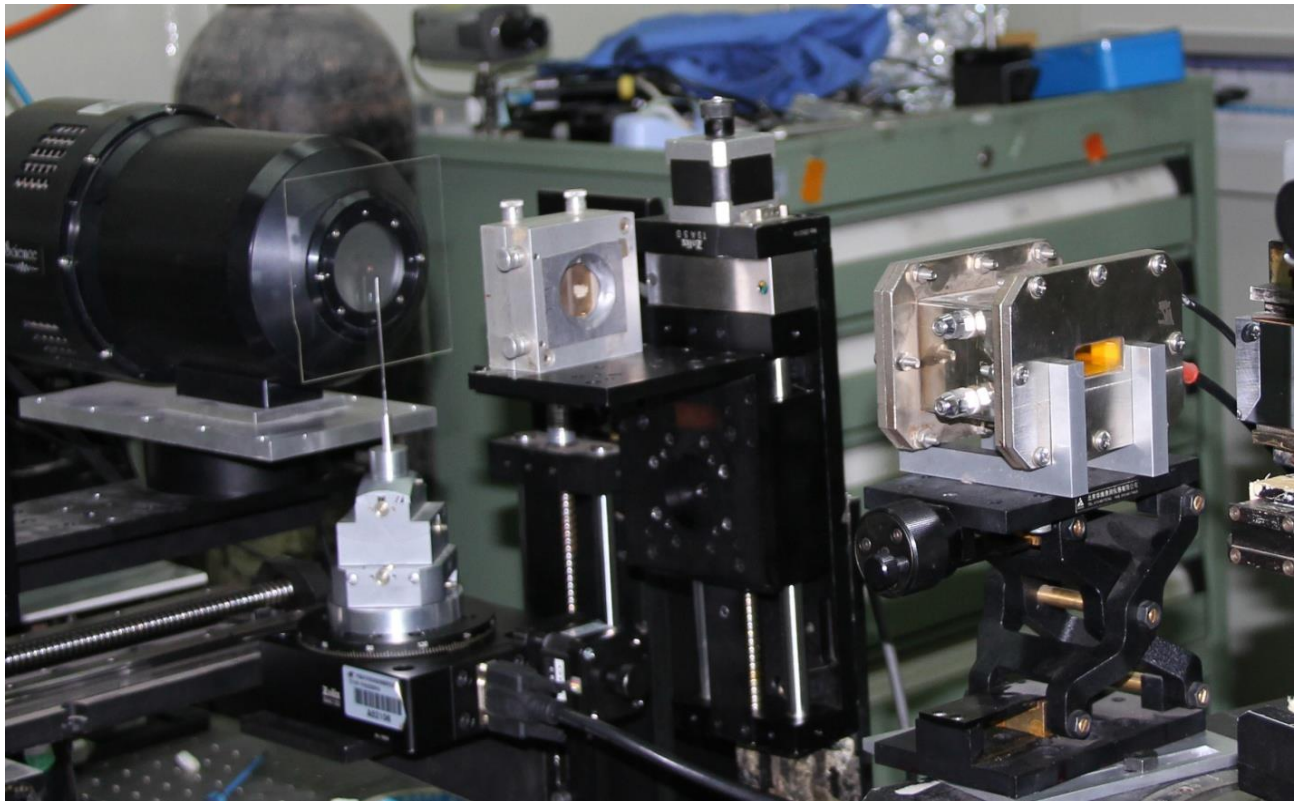


From W. Ludwig



Crystal boundary of Stainless steel
A. King et al. *Science* 2008

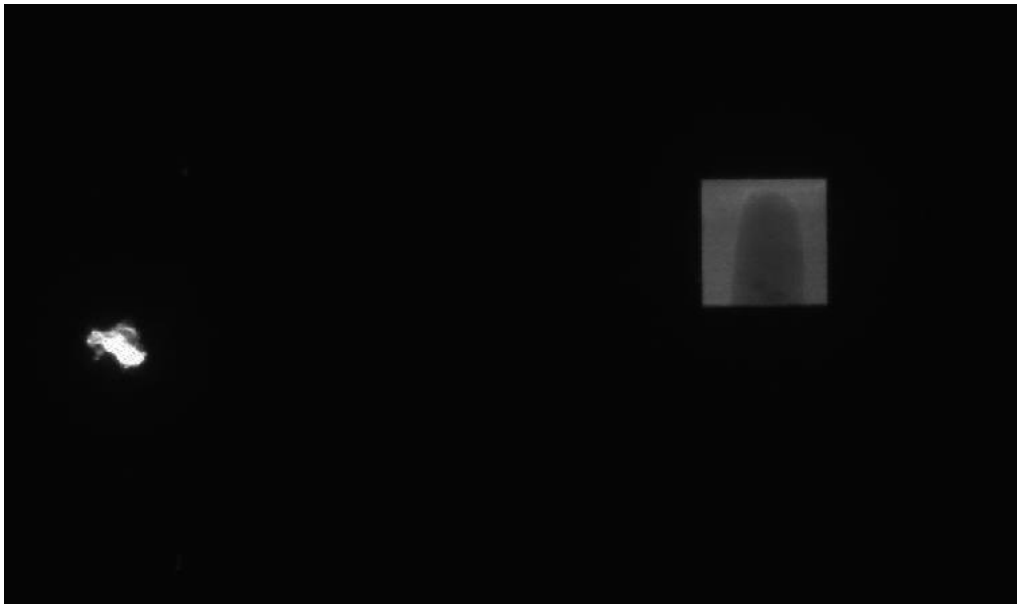
DCT setup at BSRF



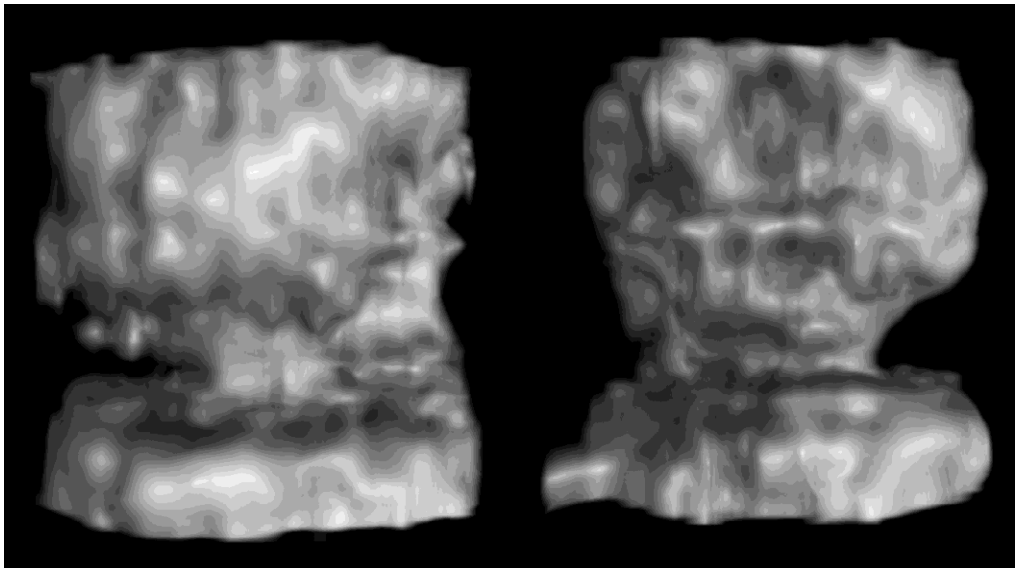
The sample used in this study is AZ31 Mg alloy. The average grain size is 150µm.
A double Si(111) monochromator , 17 KeV; The beam size: 1x1mm.
X-ray 2D detector: 7.5 µm effective pixel size.
The sample was continuously rotated through 360° , and 6000 projection images were taken.

Diffraction contrast imaging of Mg alloy

The extinction and the corresponding diffraction spots



Three-dimensional reconstruction of the single grain



JSR, 2014, submitted.

11. Experimental apparatus for engineering materials

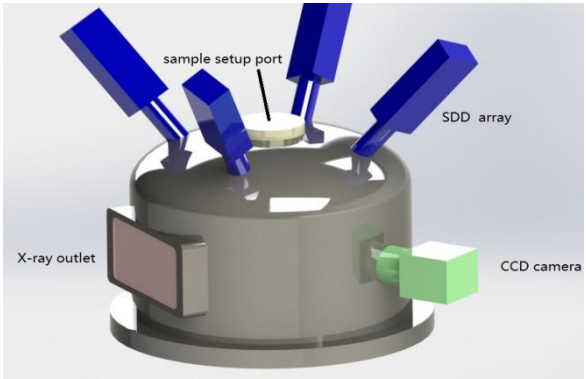
Collaoration with Univ. of Science and Technology of Beijing

High energy X-ray scattering and imaging

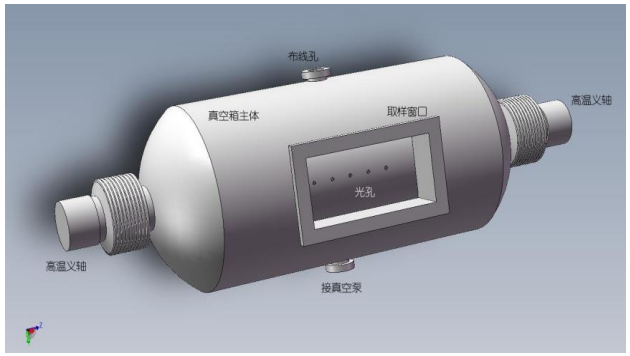
Metal smelting process (*in situ*)

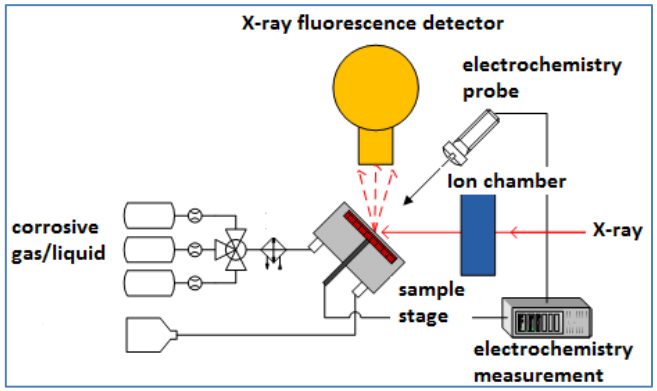
Deformation simulation

In operando measurements: service process



Temperature Up to
1400 degree
Load 2.5 Ton





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Hongwei Zheng, Nanopositioning
Jing Liu, Dynamic high Pressure
Ye Tao, laser pump/X-ray probe
Peng Liu, X-ray detectors
Gang Li, DCT,
Yuhui Dong, Engineering material & CDI

Thanks for your attention

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