Recent progress of *T*singhua *T*homson scattering *X*-ray source(TTX)

Lixin Yan

yanlx@tsinghua.edu.cn

On behalf of TTX group of

Accelerator Lab , Tsinghua University, Beijing, 100084, China

22-25, May, 2018@Marseille, France

OUTLINE

- Motivation & brief introduction
- Recent progress of TTX
  - ✓ Upgrade and Optimization of TTX
  - ✓ Parameter measurements
  - ✓ Application experiments with TTX
- Future plans of TTX
- Summary

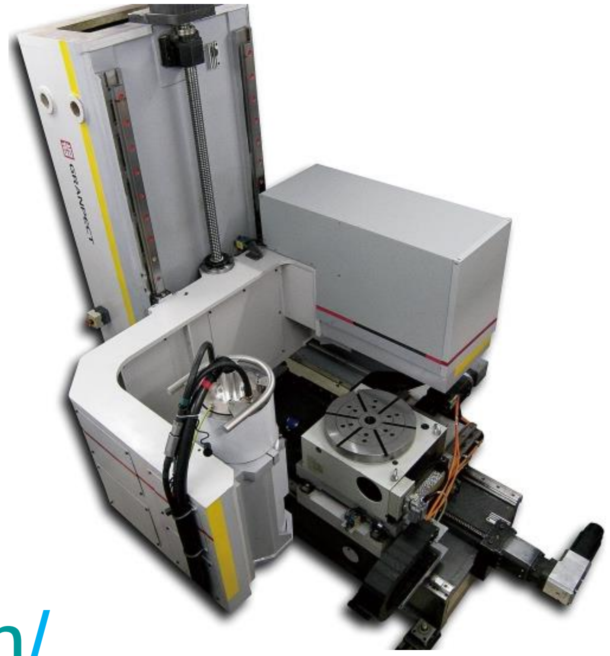
Serials of X-ray Imaging Systems Developed by Tsinghua University and NUCTECH company

- In the past 30 years, Acc lab of THU has been devoted to develop accelerator based x-ray technologies and made great contribution for industry applications

✓ Cargo Inspection systems ✓ Baggage & Industry CT



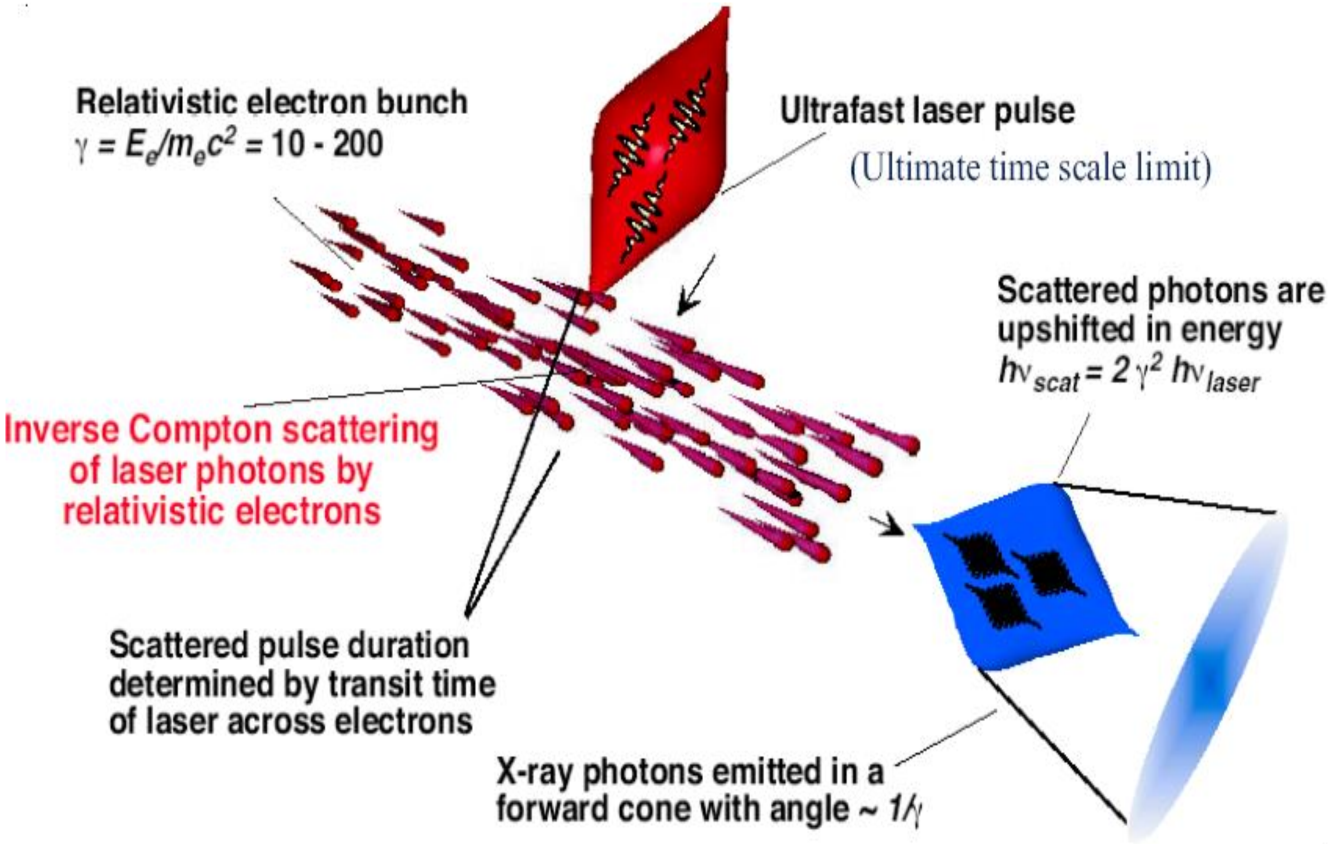




http://www.nuctech.com/

Advanced applications demand better x-ray sources. Thomson scattering x-ray is one of the candidates.

☐ Principle of TS



Head-on configuration:

$$E_X[keV] = 1.9 \times 10^{-2} E_e{}^2[MeV]/\lambda_l[\mu m]$$

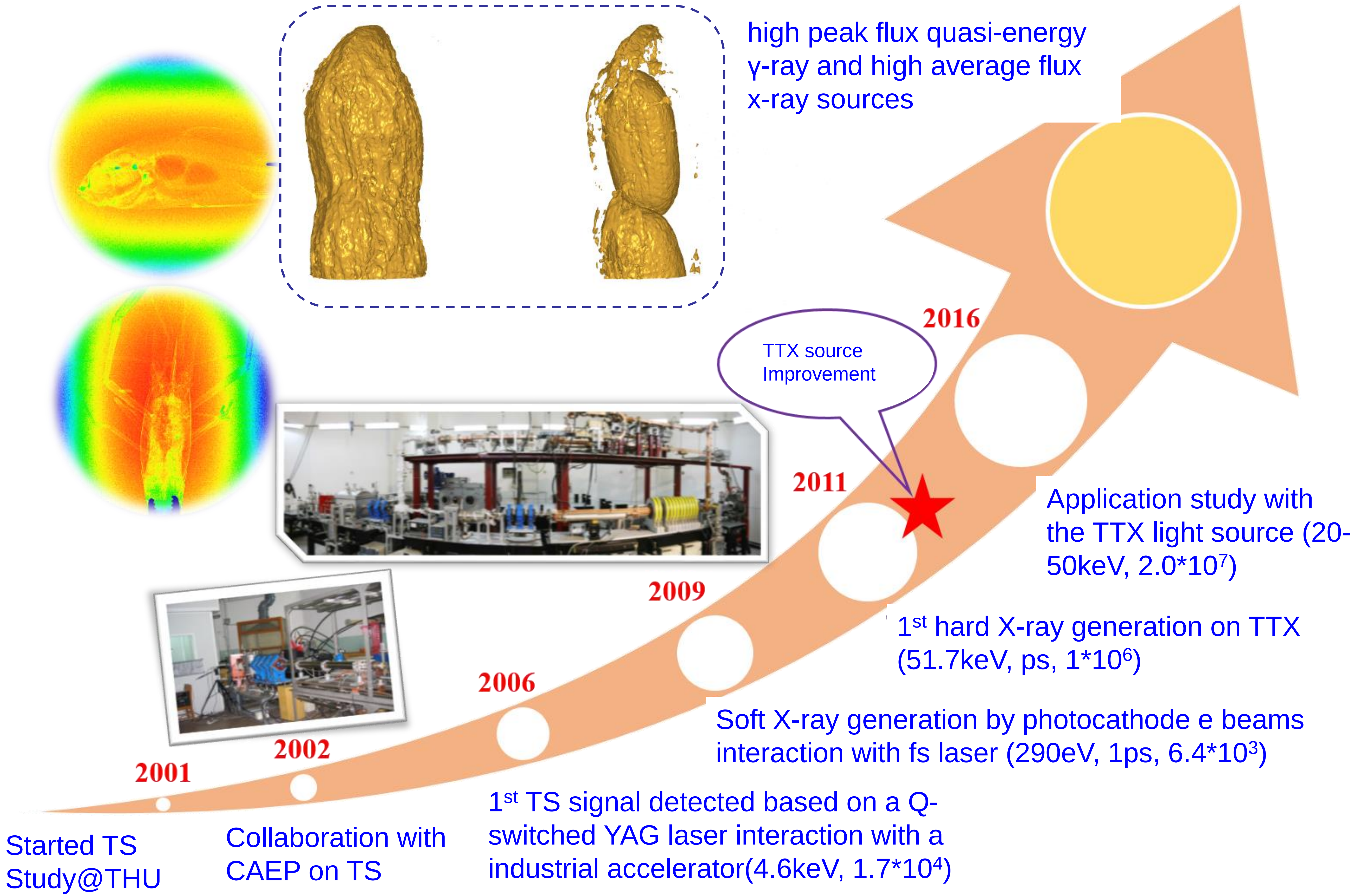
$$50keV \;@\; 46MeV \; and \; 800nm$$

☐ Advantages of TS

- ✓ Quasi-Monochromatic spectrum
- ✓ Engergy tunability (keV~MeV)
- ✓ Radiation in a small angle （～1/γ)
- ✓ Ultrashort bunch length(ps or sub-ps)
- ✓ Good synchronization for pump-probe experiments
- ✓ Small source size(~10 μm)
- ✓ High Peak Brightness
- ✓ Polarization controllable
- ✓ Compact and affordable

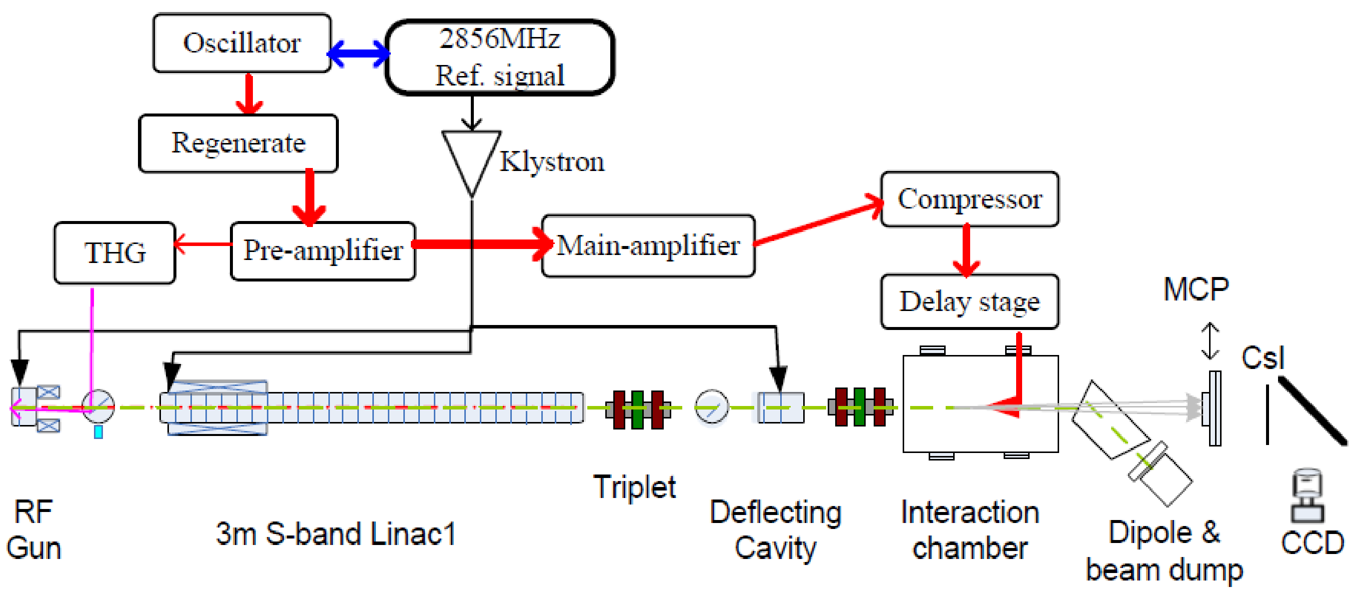
$$E_X(\theta) = \frac{4\gamma^2}{1 + a_0^2/2 + \gamma^2\theta^2} E_L$$

Milestones on the road to develop Thomson scattering X-ray source at Tsinghua University



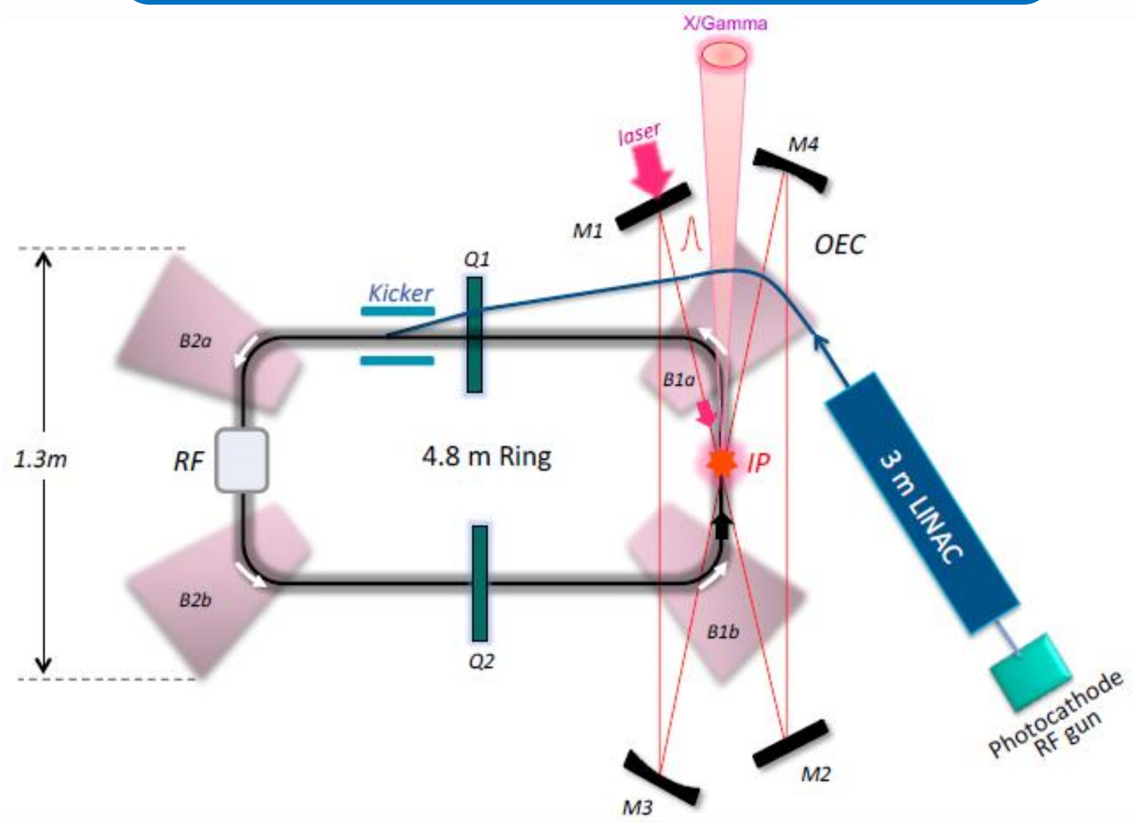
Tsinghua Thomson scattering X-ray source (TTX)

High Peak Brightness



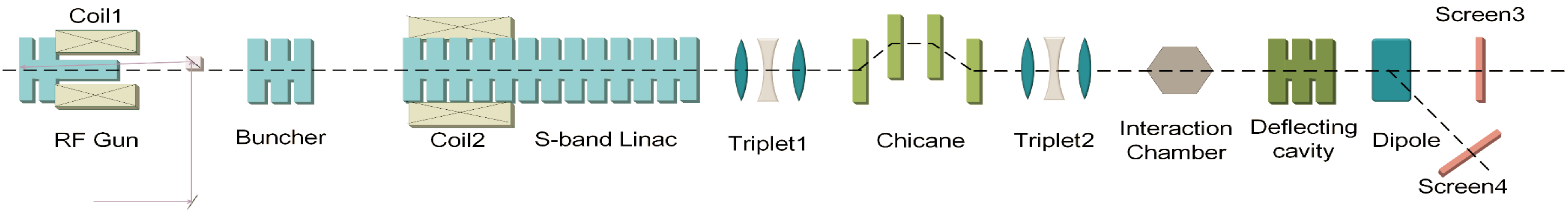
- Energy: **20-50keV**
- Repetition Rate: **10Hz**
- Average X-ray Flux: **~10^8-10^9 ph/s**
- X-ray Pulse Length: **~100fs-ps**
- X-ray beam size at IP: **~10μm**

High Average Brightness

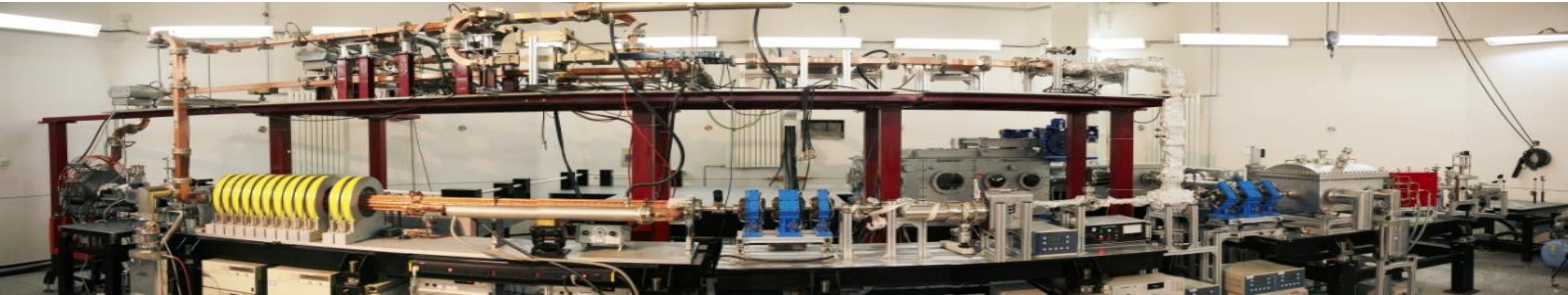


- Energy: **20-100keV**
- Repetition Rate: **~10MHz**
- Average X-ray Flux: **~10^{12} ph/s**
- X-ray Pulse Length: **~20ps**
- X-ray beam size at IP**: ~10-100μm**

The 50MeV Electron beam line of TTX



- ✓ The photocathode RF gun gradient is ~110MV/m and the bunch charge from a few pc to ~1nC;
- ✓ An S-band TW cavity (buncher) was installed for ballistic bunching before the acceleration.
- ✓ A 4-dipole chicane has been installed after the linac.
- ✓ It's able to generate ultra-short (20fs) and high intensity (10kA) beam with ballistic bunching and magnetic compression.

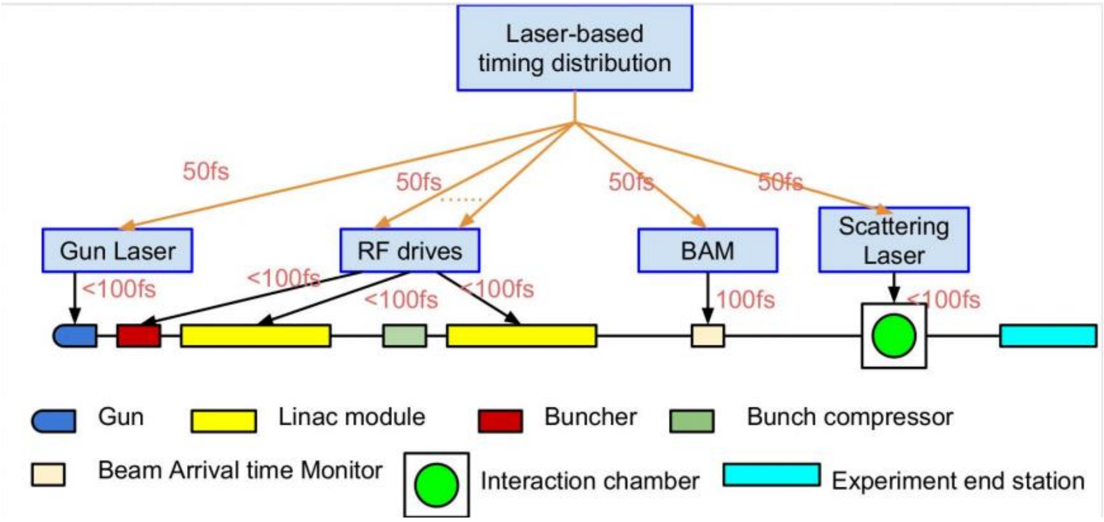


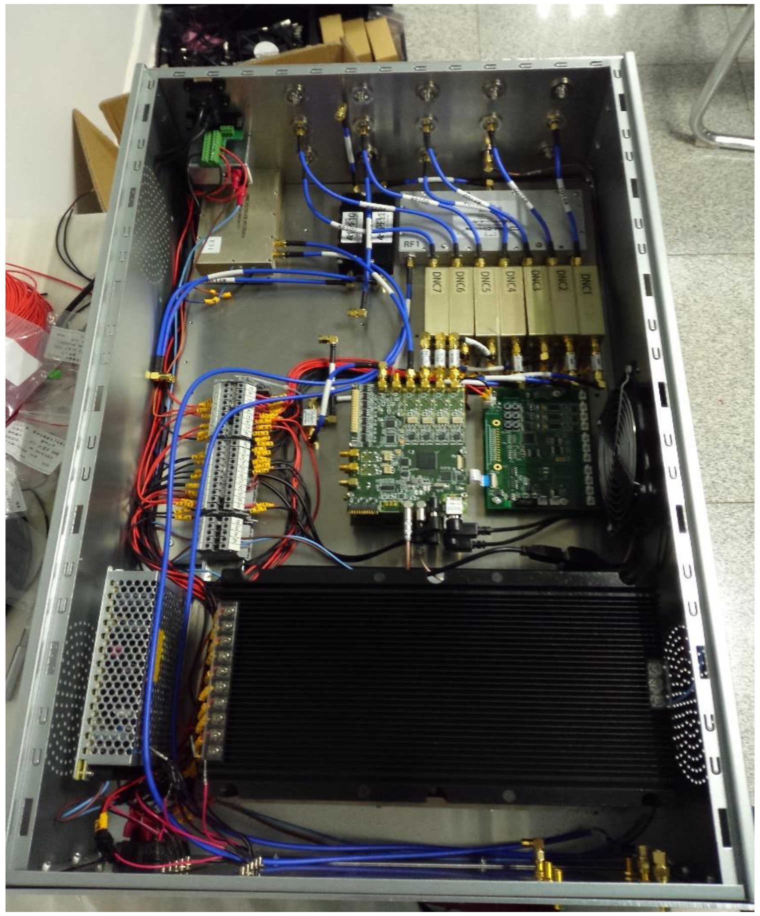
Two new laser systems were installed for stable and high quality beam generation

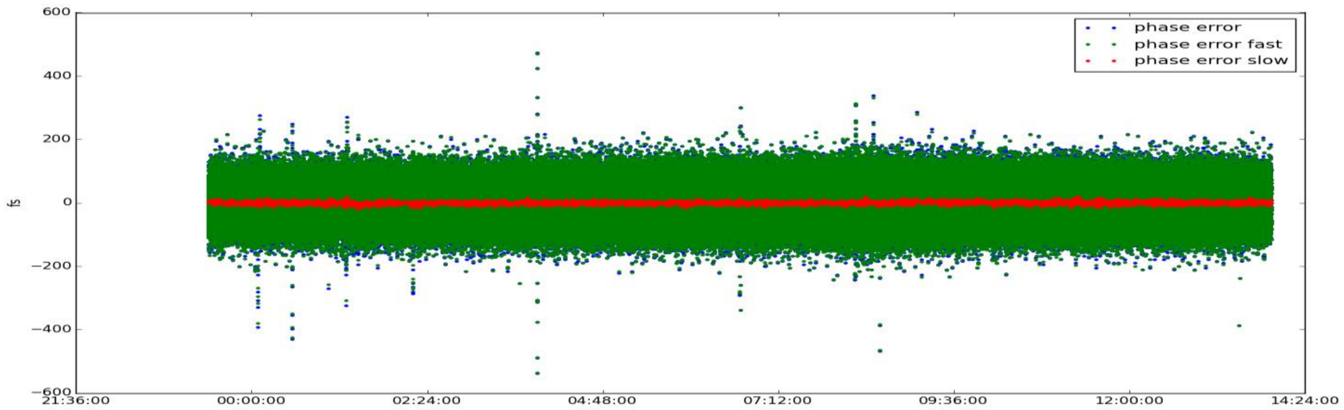
- A new laser room with stable temperature control was built
- A new driving laser system from Coherent was installed
  - ✓ The UV pulse energy jitter is reduced to ~1%
- The 20TW laser system was upgraded with a new front-end(oscillator and preamplifier) from Amplitude Technology
  - ✓ Much stable: <1% energy jitter and ~2μrad pointing jitter
  - ✓ High beam quality: focused to ~5μm, ~25fs

A new synchronization system was developed to reduce the timing jitter between the electron and laser

- A new laser-based timing distribution system was developed. ~50fs additional timing jitter for laser and RF drivers.
- The LLRF system and Laser-RF synchronization system were installed with lower jitter: <80fs
- The timing jitter between the laser and the electron beam at interaction point is achieved to be less than 300fs.

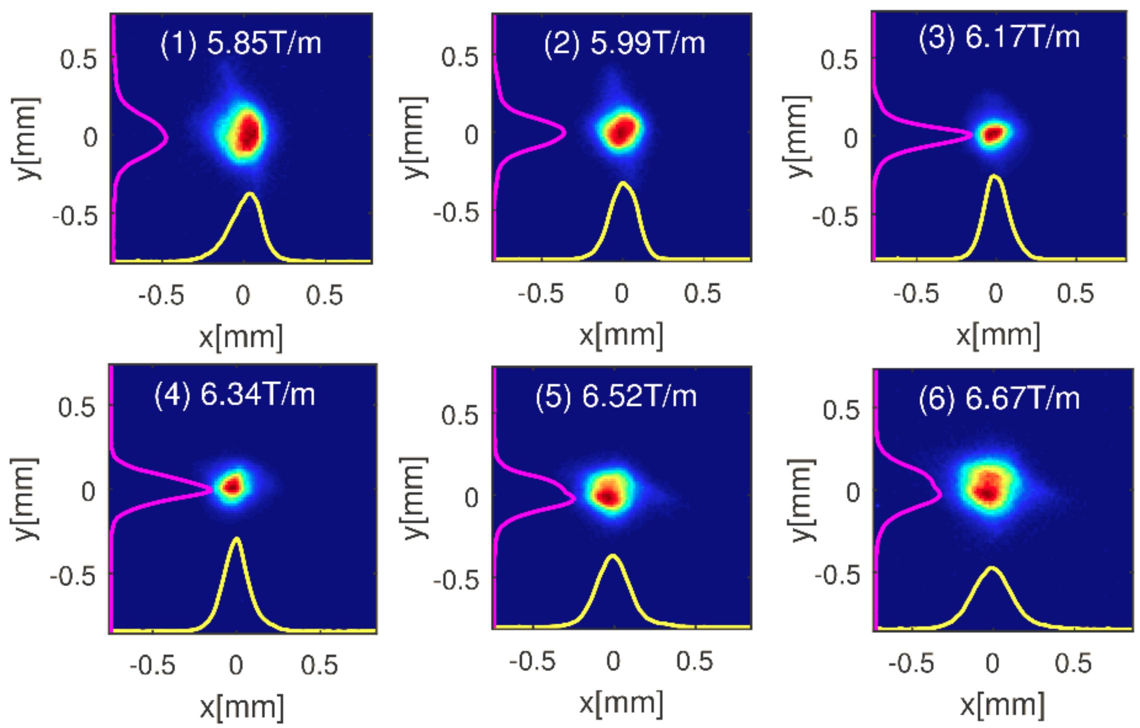


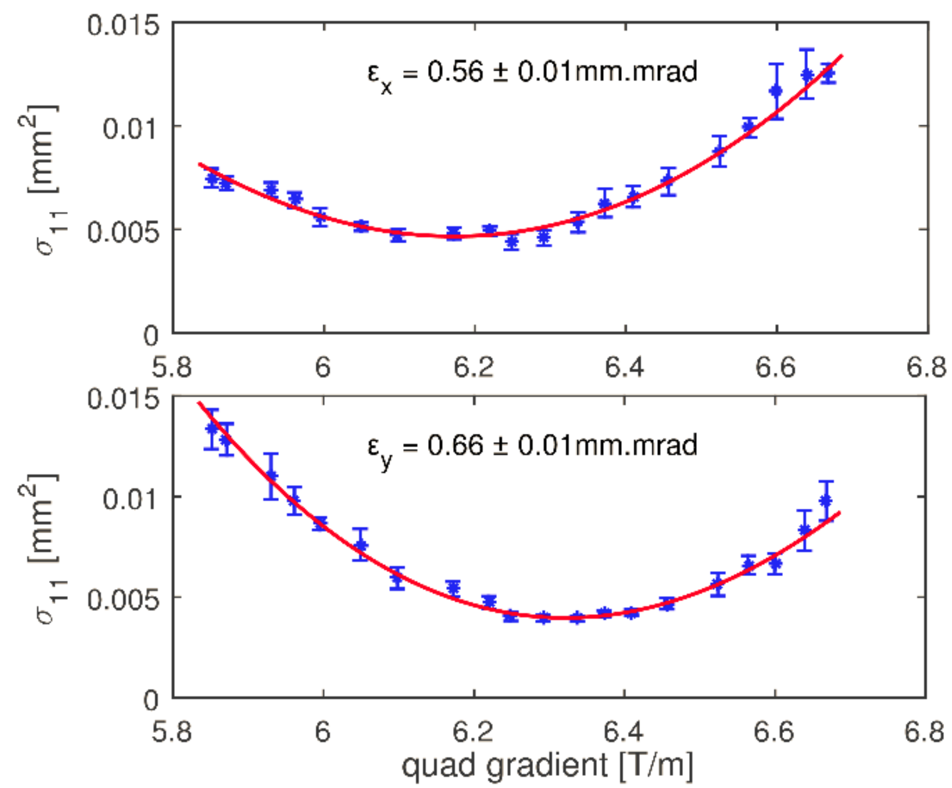




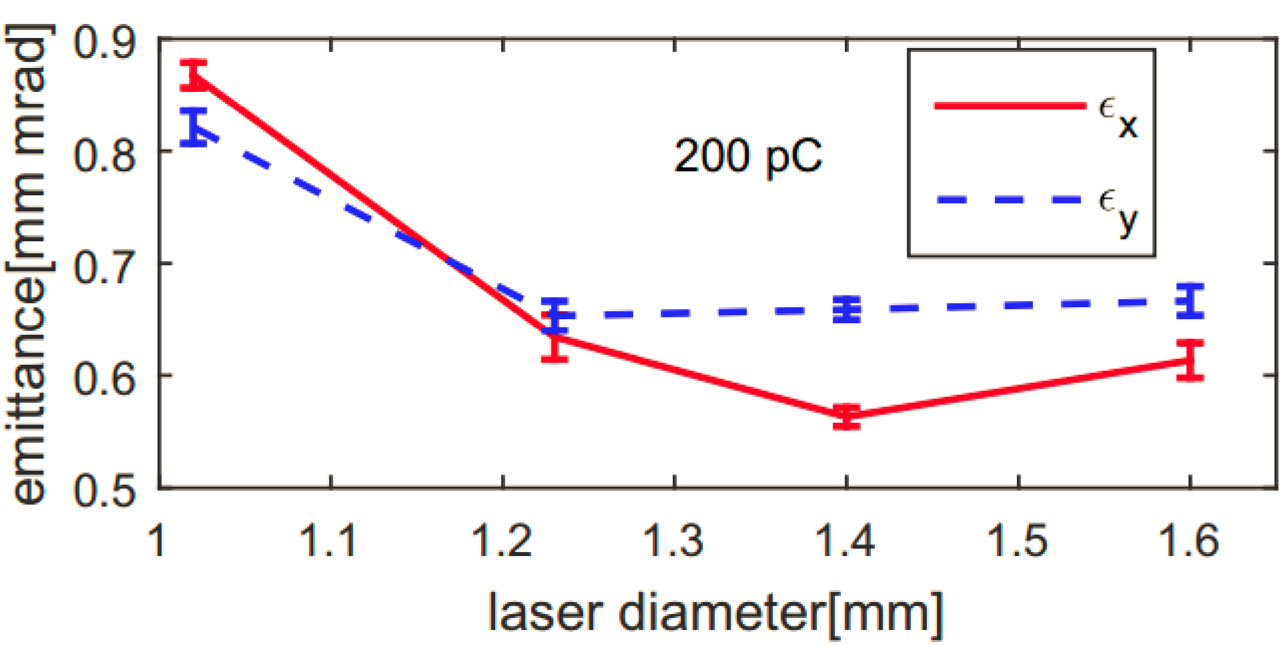
Emittance measurement and optimization

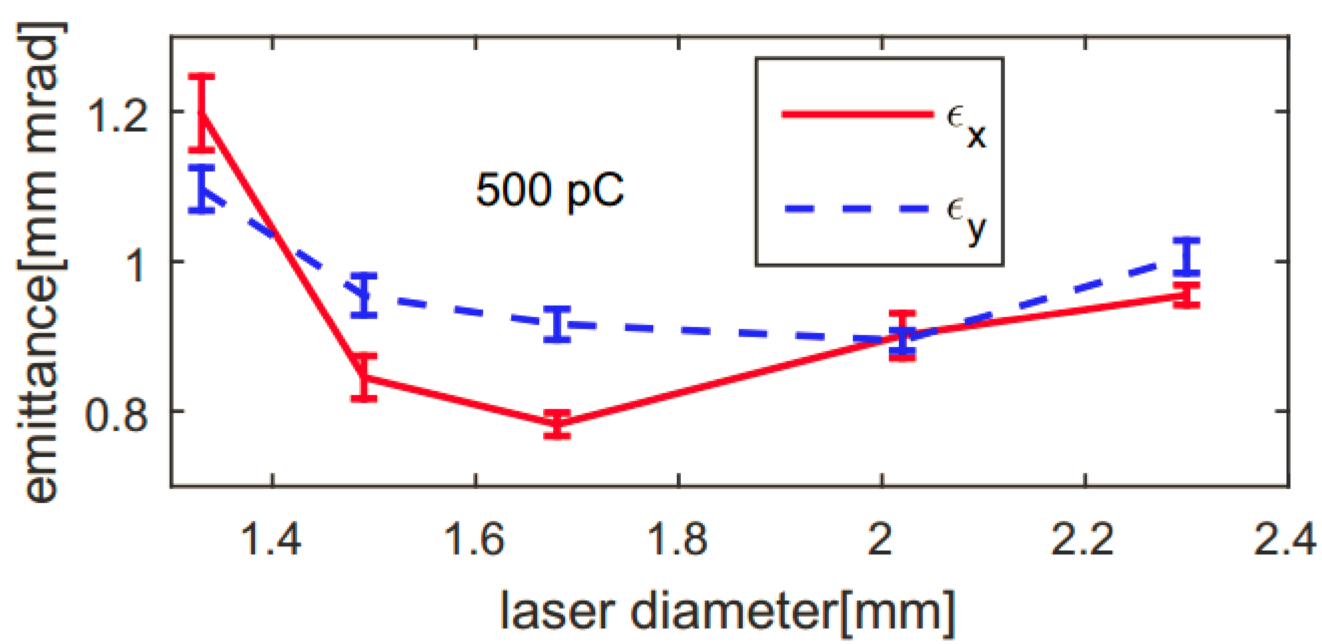
- QE scan technique to measure the beam emittance



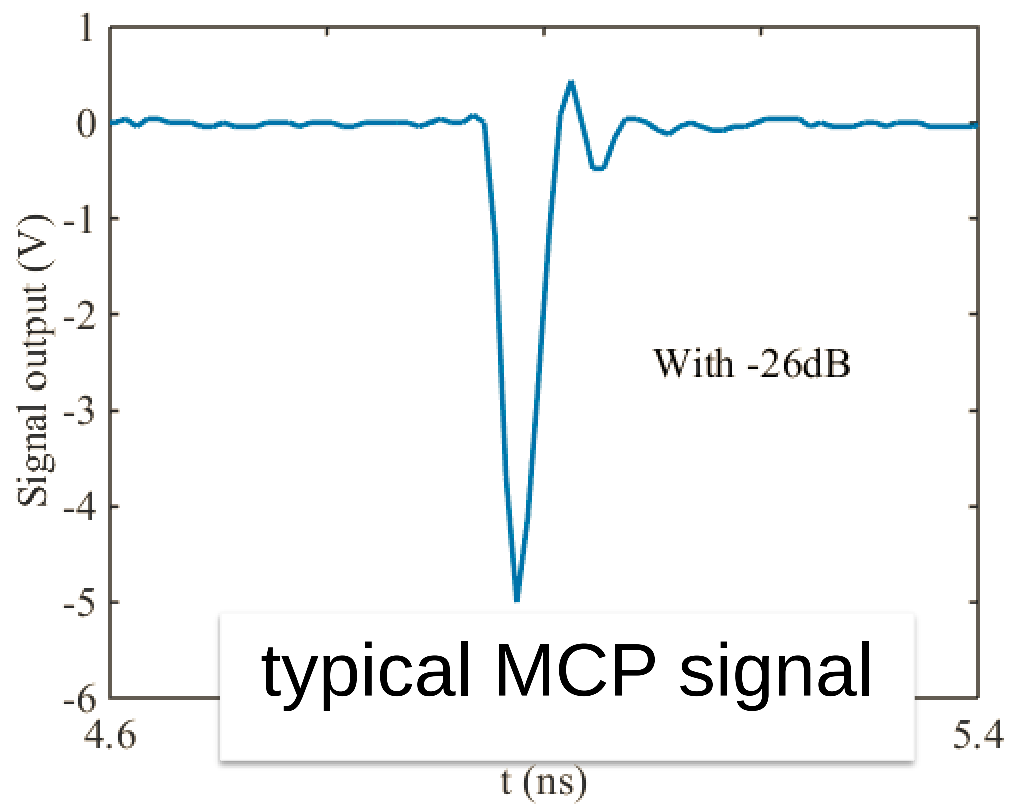


- Emittance optimization results for 200pC and 500pC

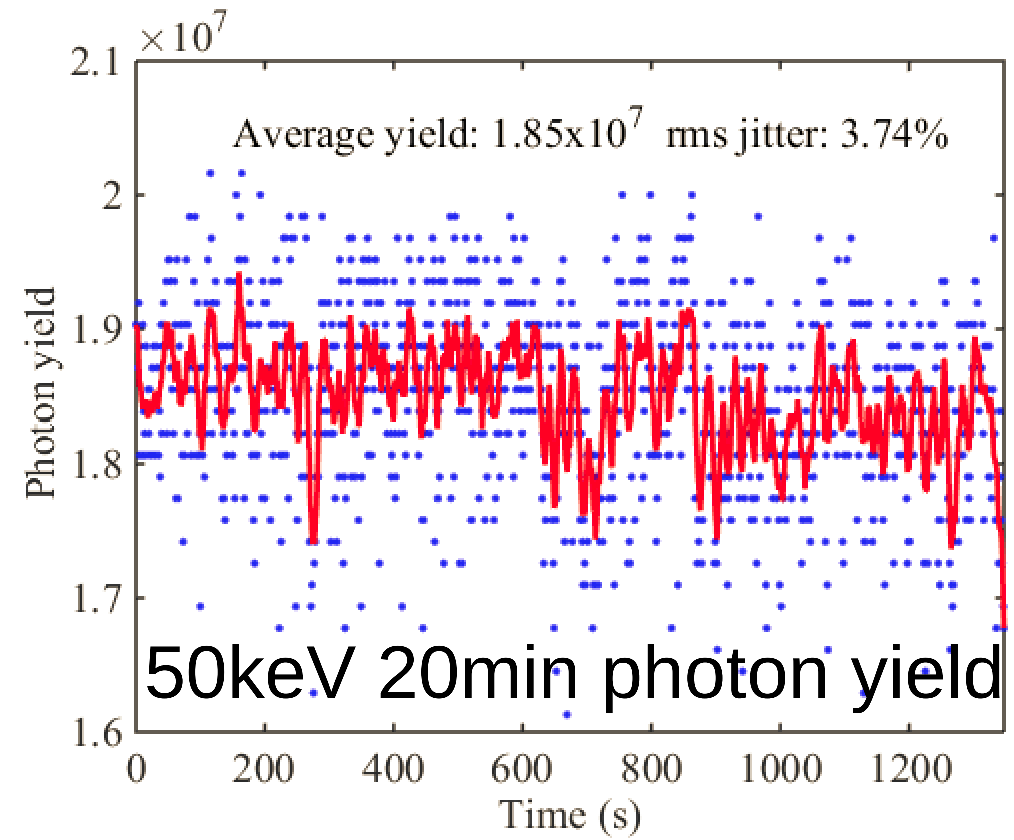




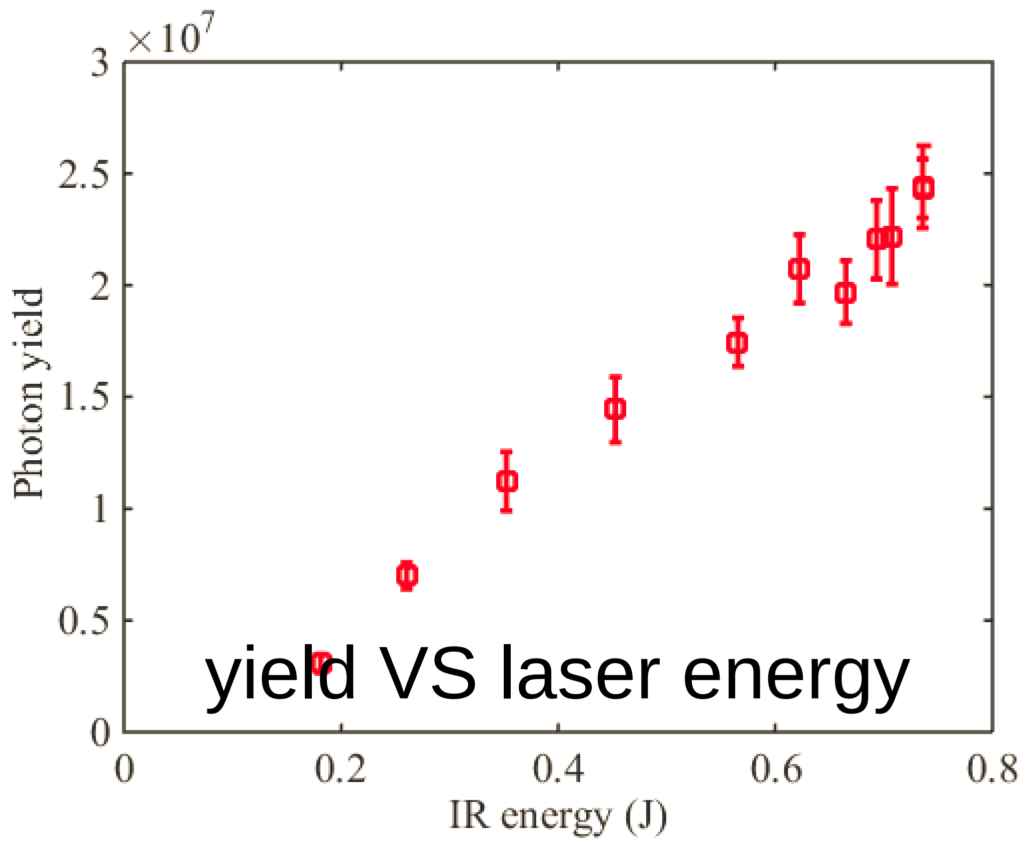
X Photon yield measurements with an MCP



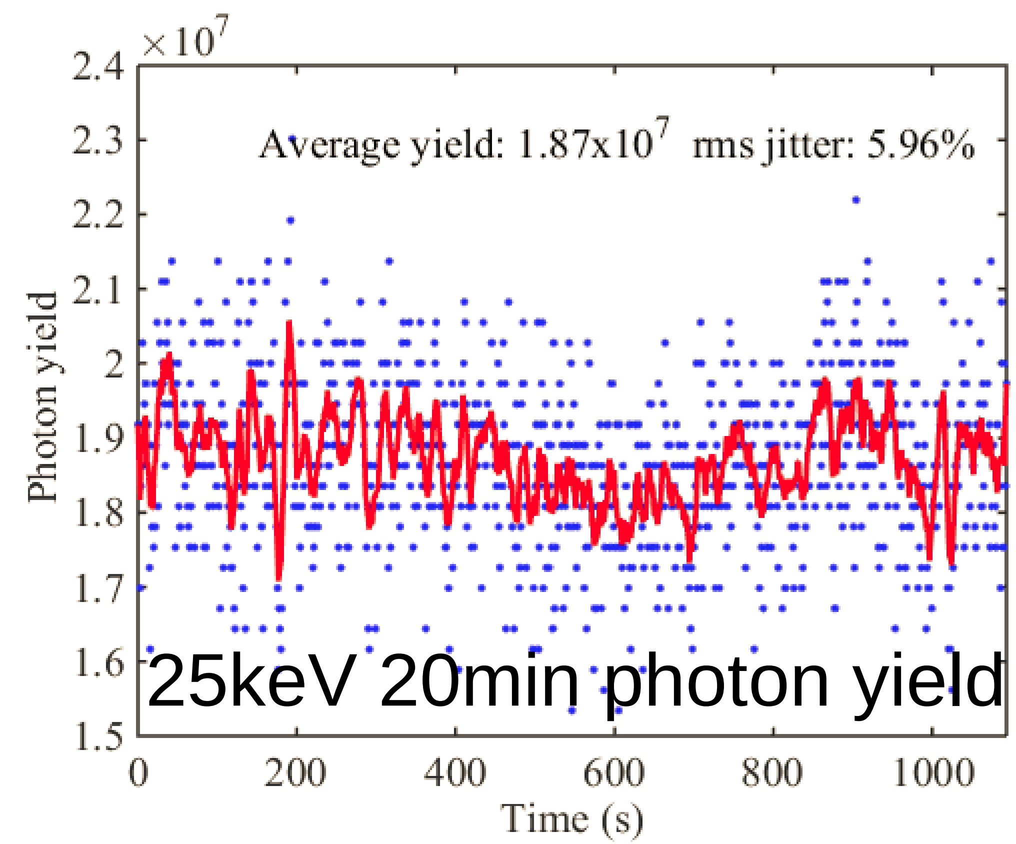
typical MCP signal



50keV 20min photon yield

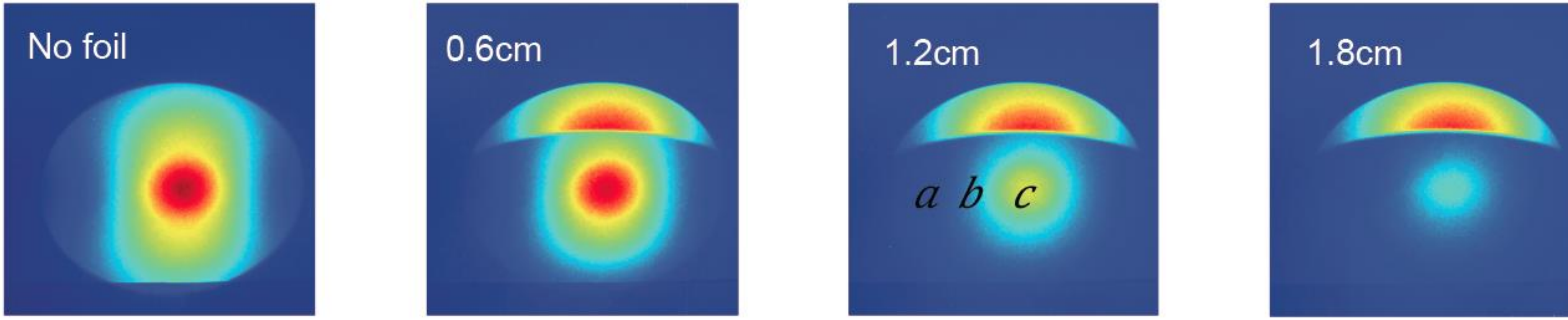


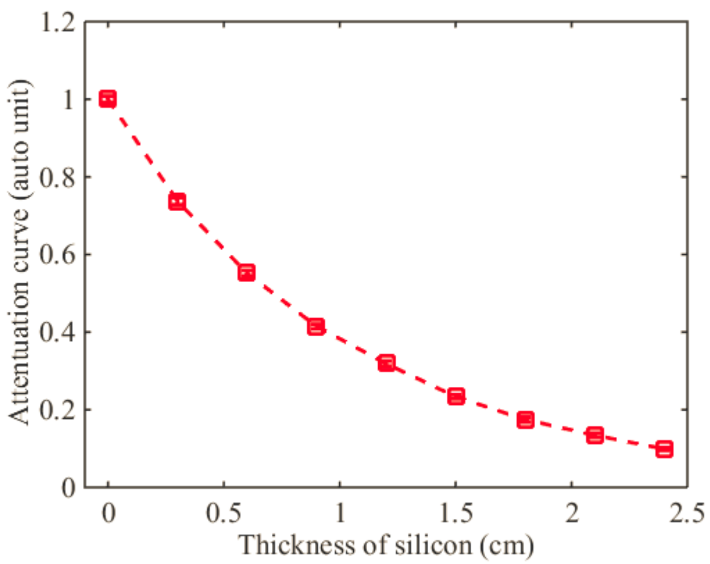
yield VS laser energy



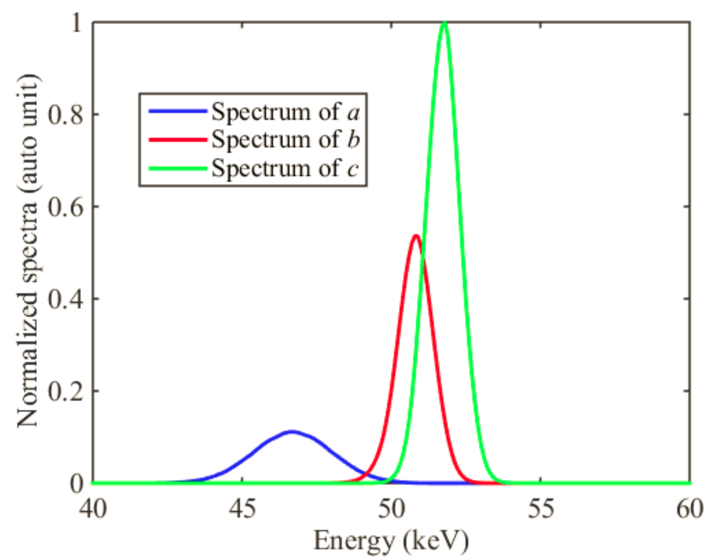
25keV 20min photon yield

Reconstruction the Spectra of X-ray by the attenuation curve through silicon foils

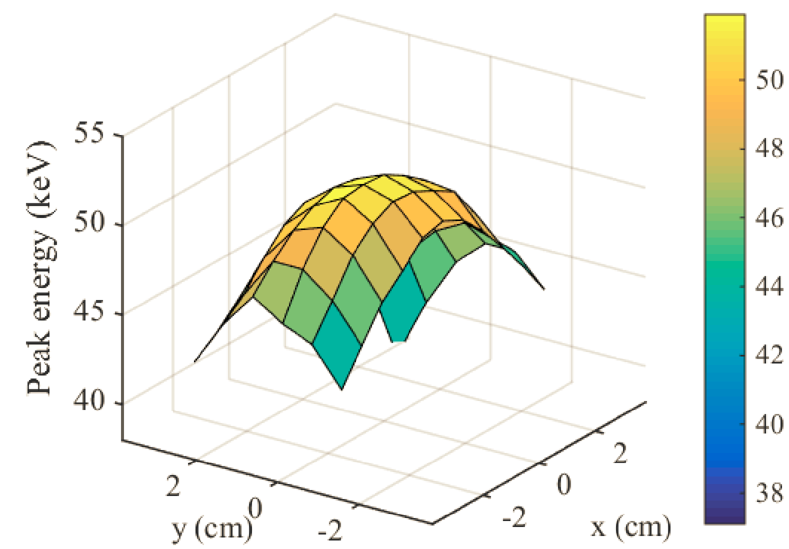




Attenuation curve of point *a*



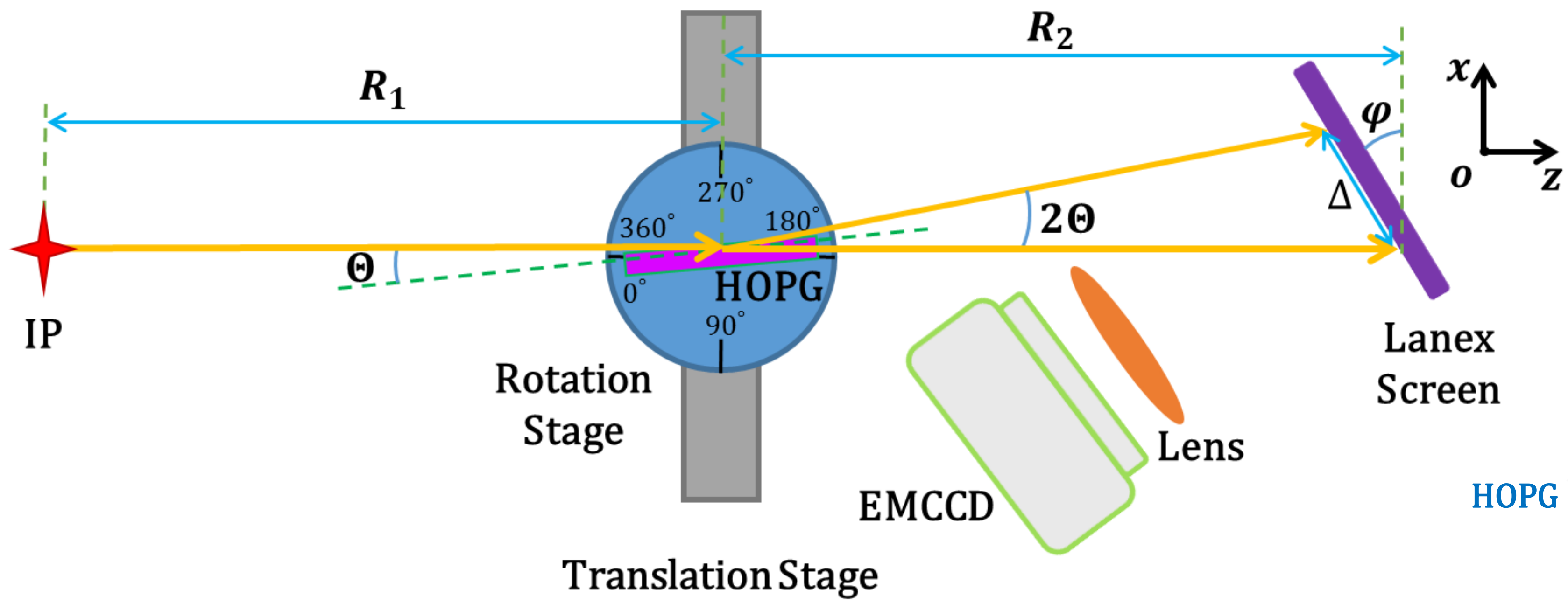
Reconstructed spectra of the point *a,b,c*

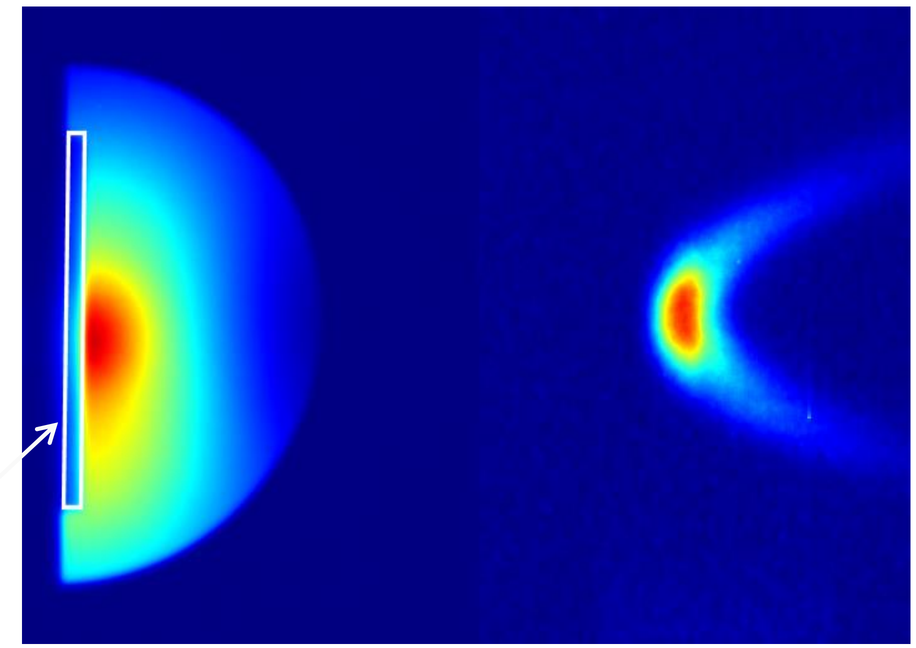


Peak energy distribution

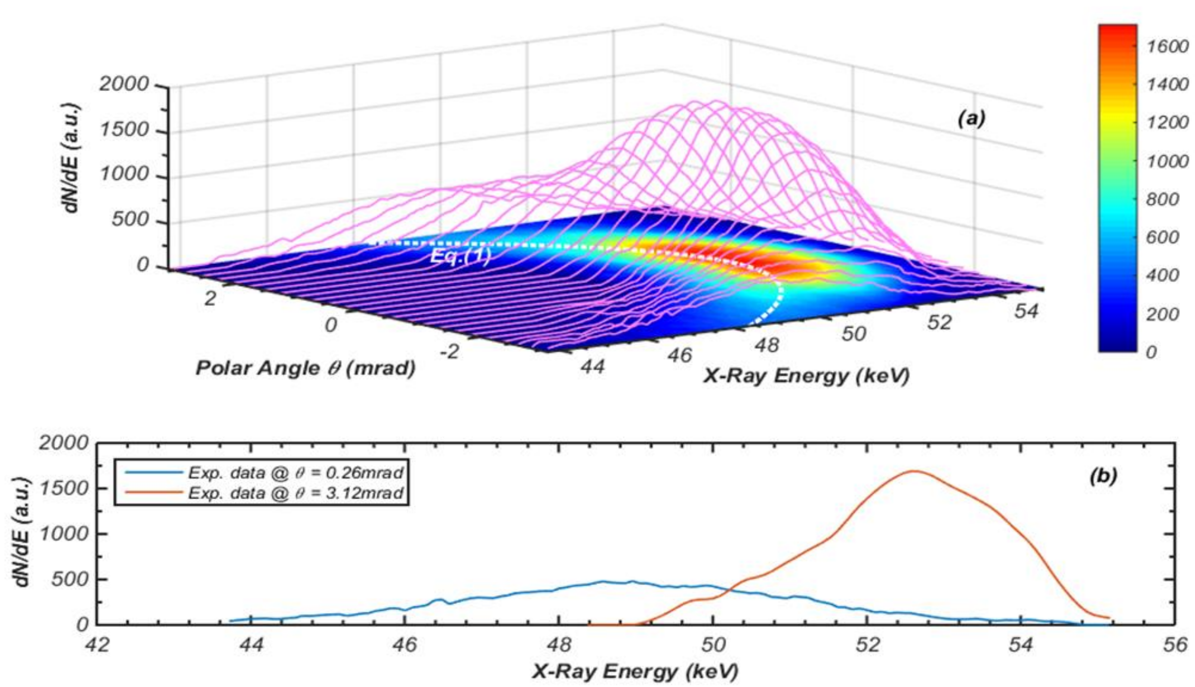
- By measuring the attenuation through silicon foils with different thickness, we reconstructed the spectra of X-ray

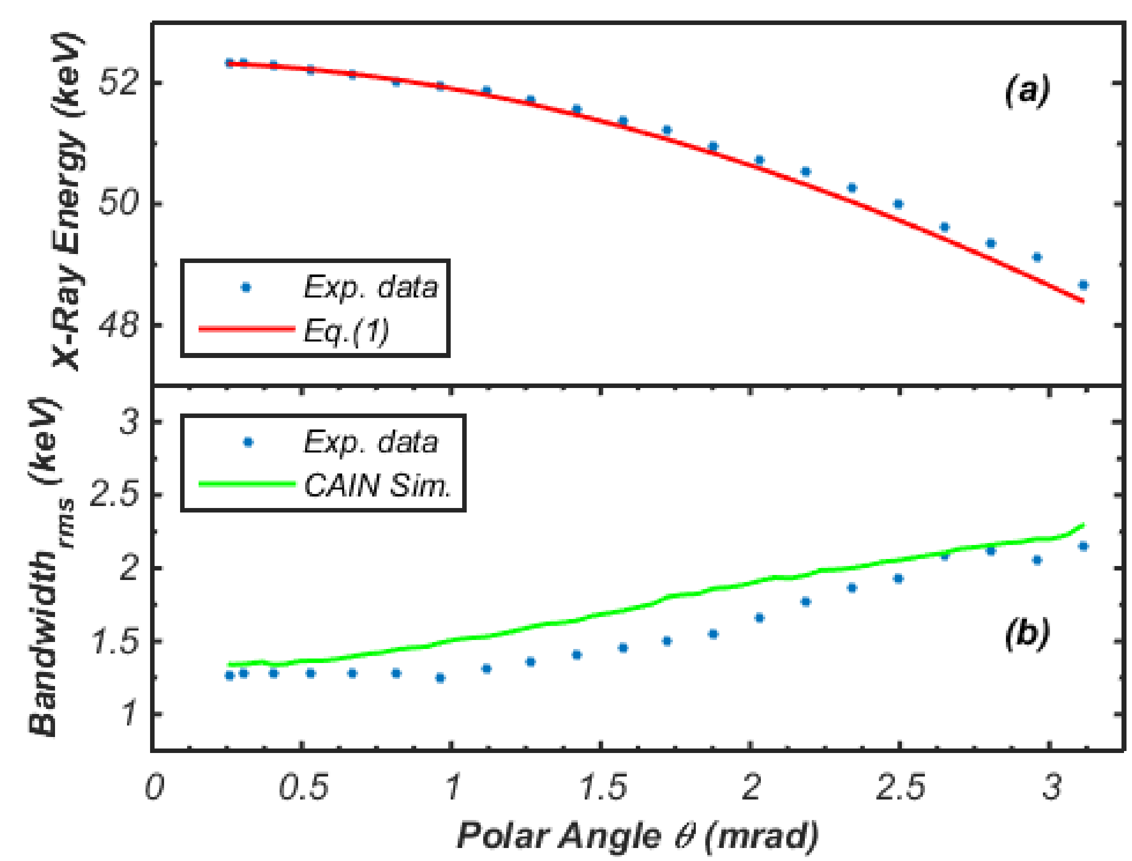
Reconstruction the Spectra of X-ray by the Bragg diffraction of Highly Ordered Pyrolytic Graphite (HOPG) crystal



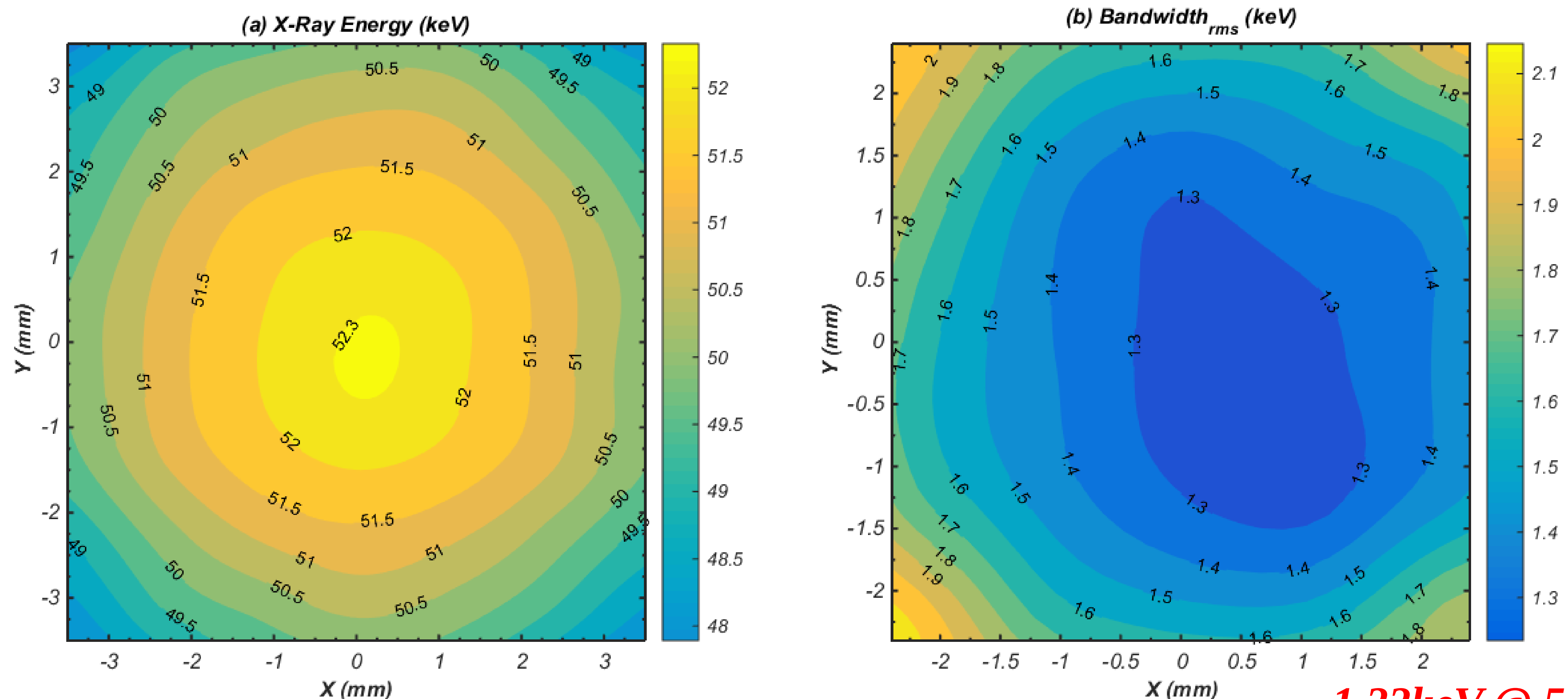


$$E_X = \frac{hc}{2d\,\sin\left\{\frac{1}{2}\arcsin\left(\frac{\Delta\cos\varphi}{\sqrt{\Delta^2+R_2^2-2\Delta R_2\sin\varphi}}\right)\right\}}$$





Spectral bandwidth of X-ray was measured and agree well with the total contributions of the four factors



1.22keV @ 52.35keV

$$\frac{\Delta E_\gamma}{E_\gamma} = \sqrt{4\left(\frac{\varepsilon_n}{\sigma_e}\right)^4 + 4\left(\frac{\Delta\gamma}{\gamma}\right)^2 + \left(\frac{\Delta E_L}{E_L}\right)^2 + \left(\frac{1}{4}\left(\frac{\lambda_0}{\pi\omega_0}\right)^2\right)^2} = 2.33\%$$

Electron emittance 0.5%

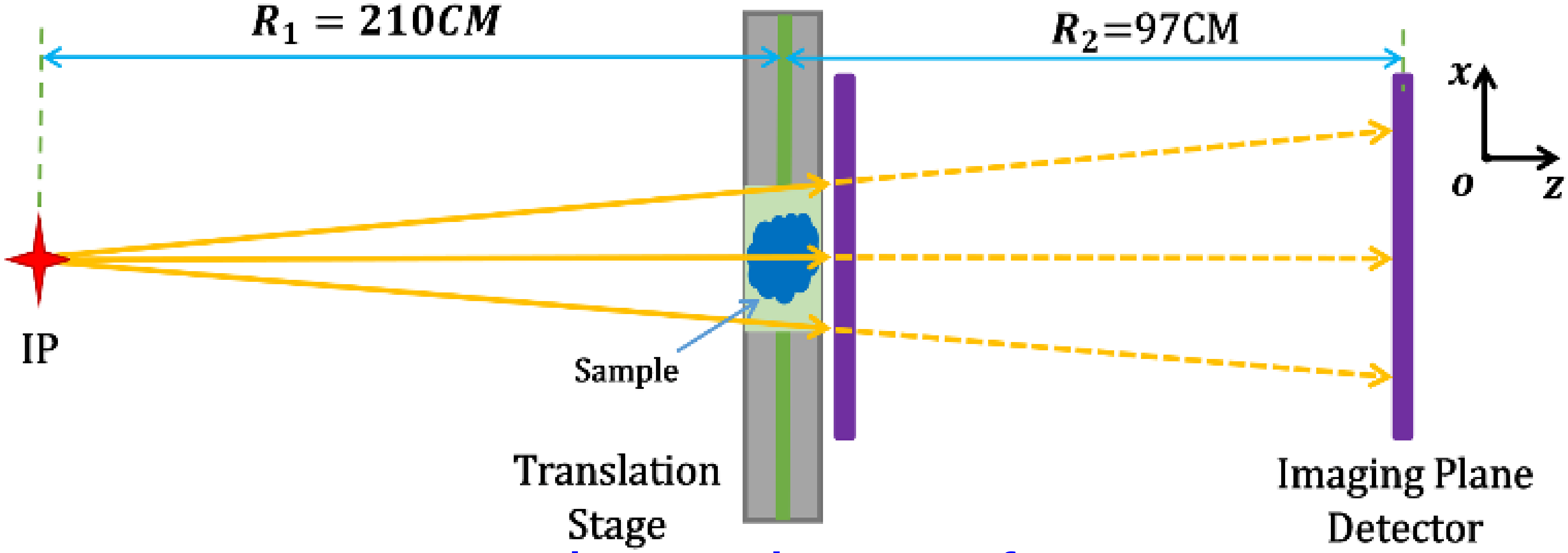
Electron energy spread 0.6%

Laser bandwidth 2.2%

Laser focusing geometry 0.045%

Y. Du et al, Rev. Sci. Instrum., 2017

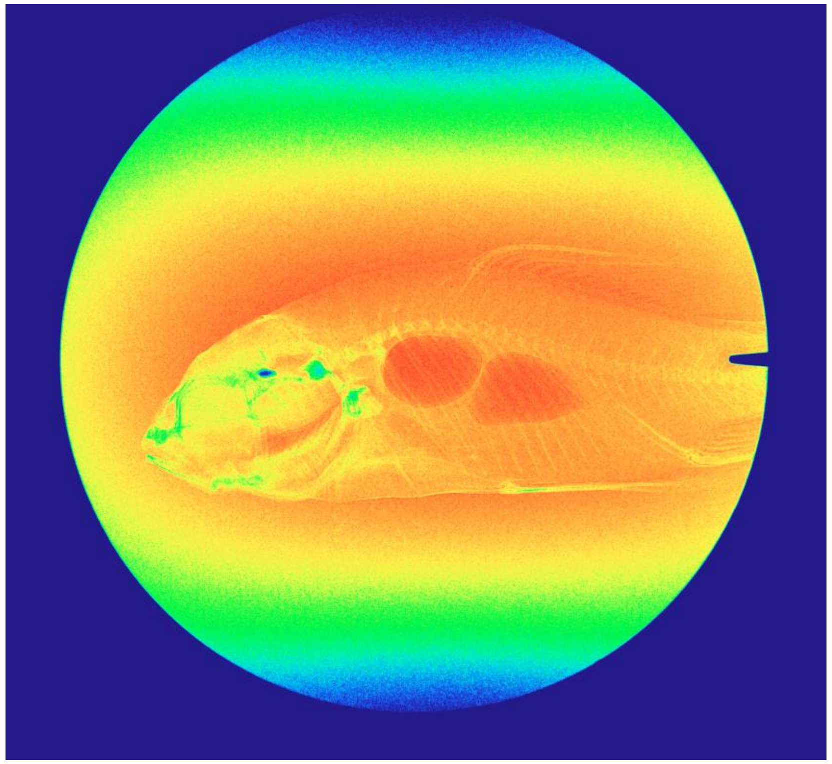
In-line phase contrast imaging with TTX



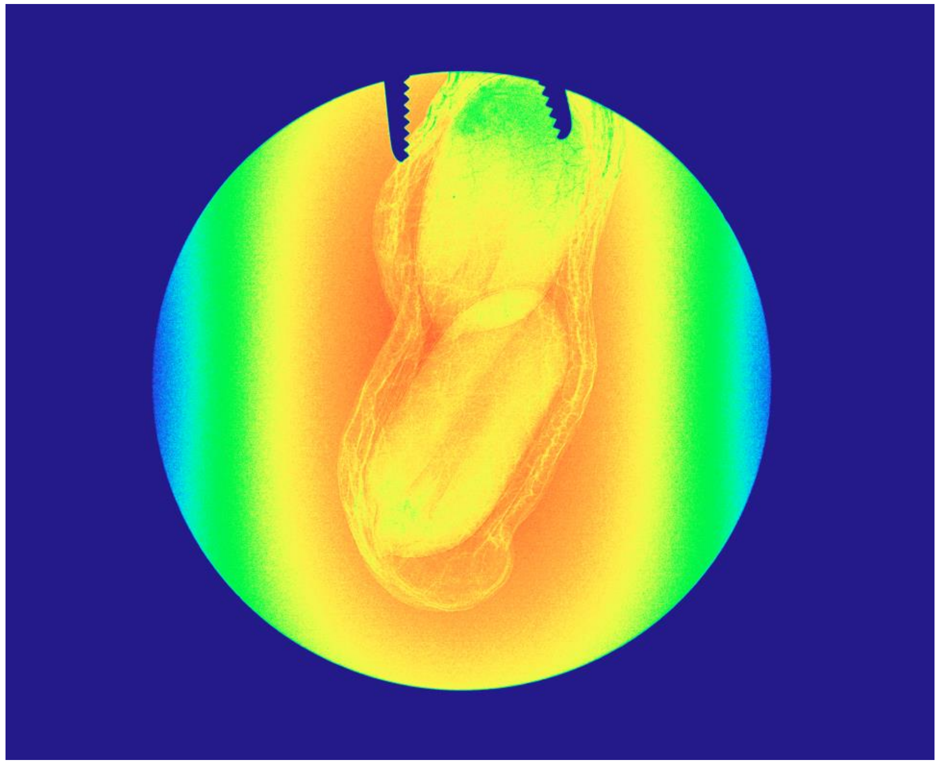
Experimental Setup for PCI:

X-ray penetration, detection by imaging plane at proper distance.

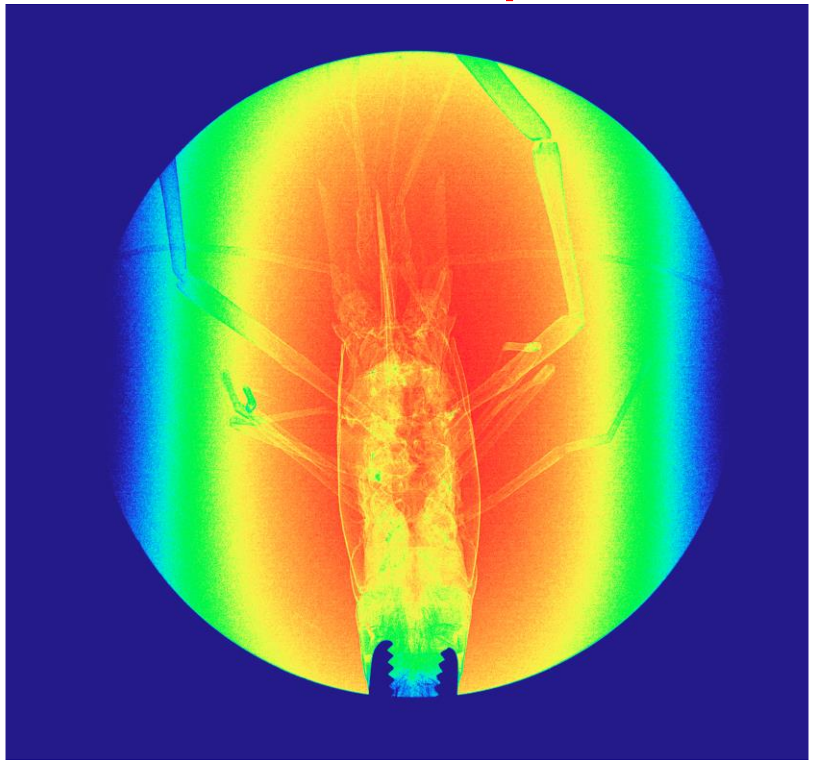
fish



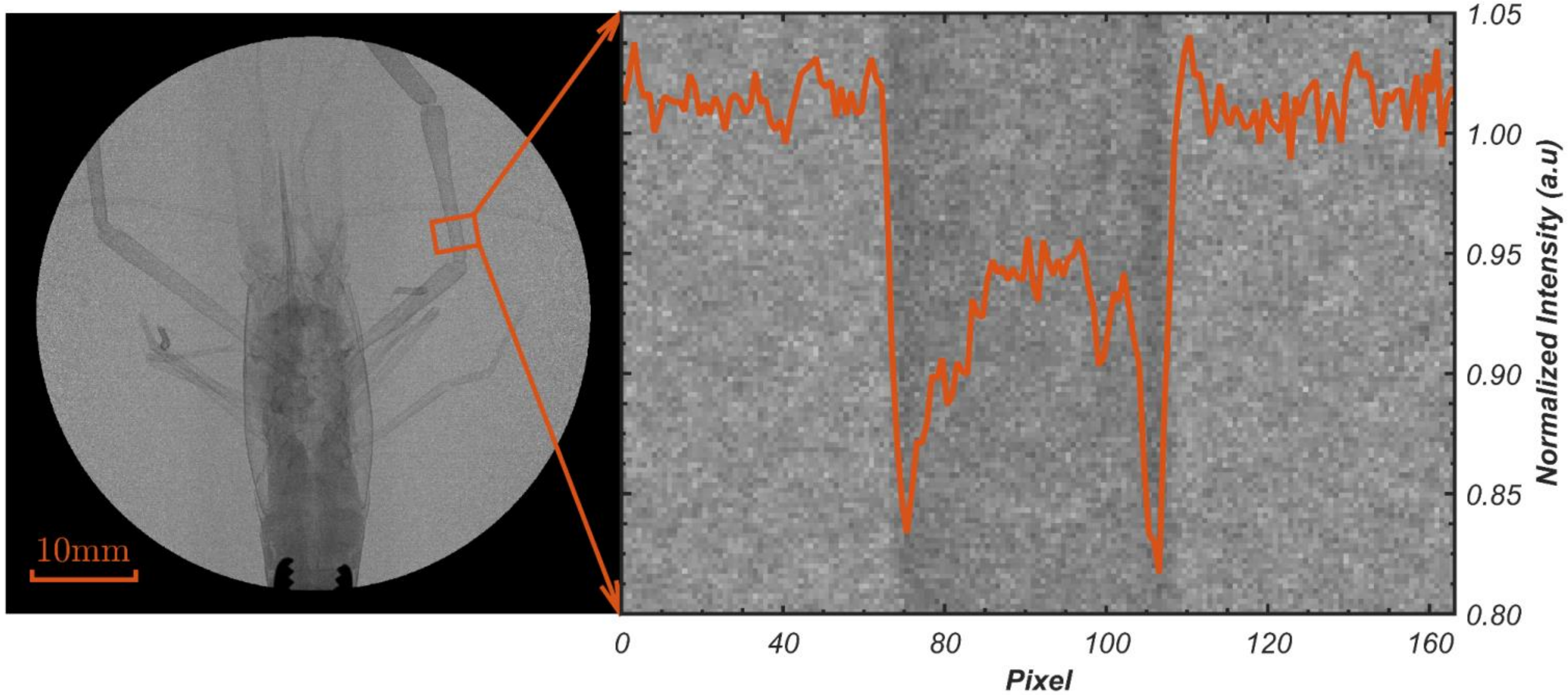
peanut

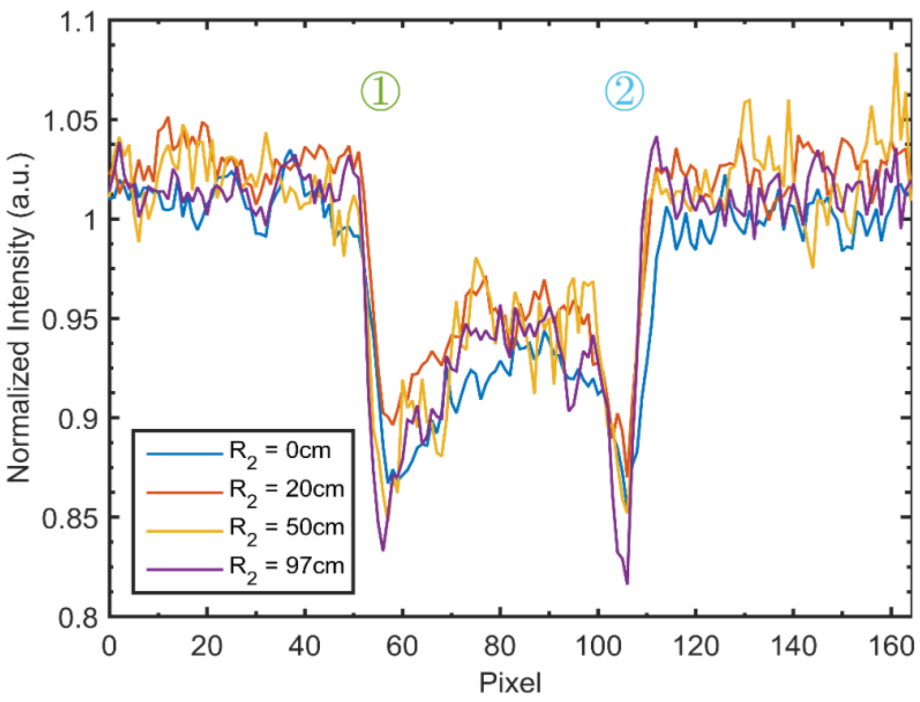


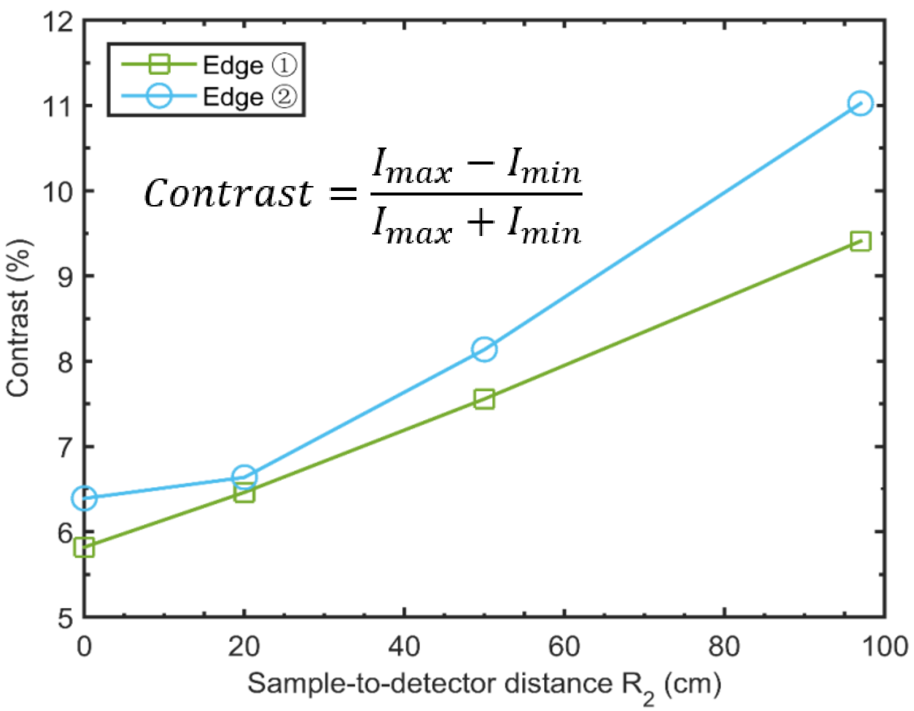
shrimp



Edge-enhancement can be clearly observed

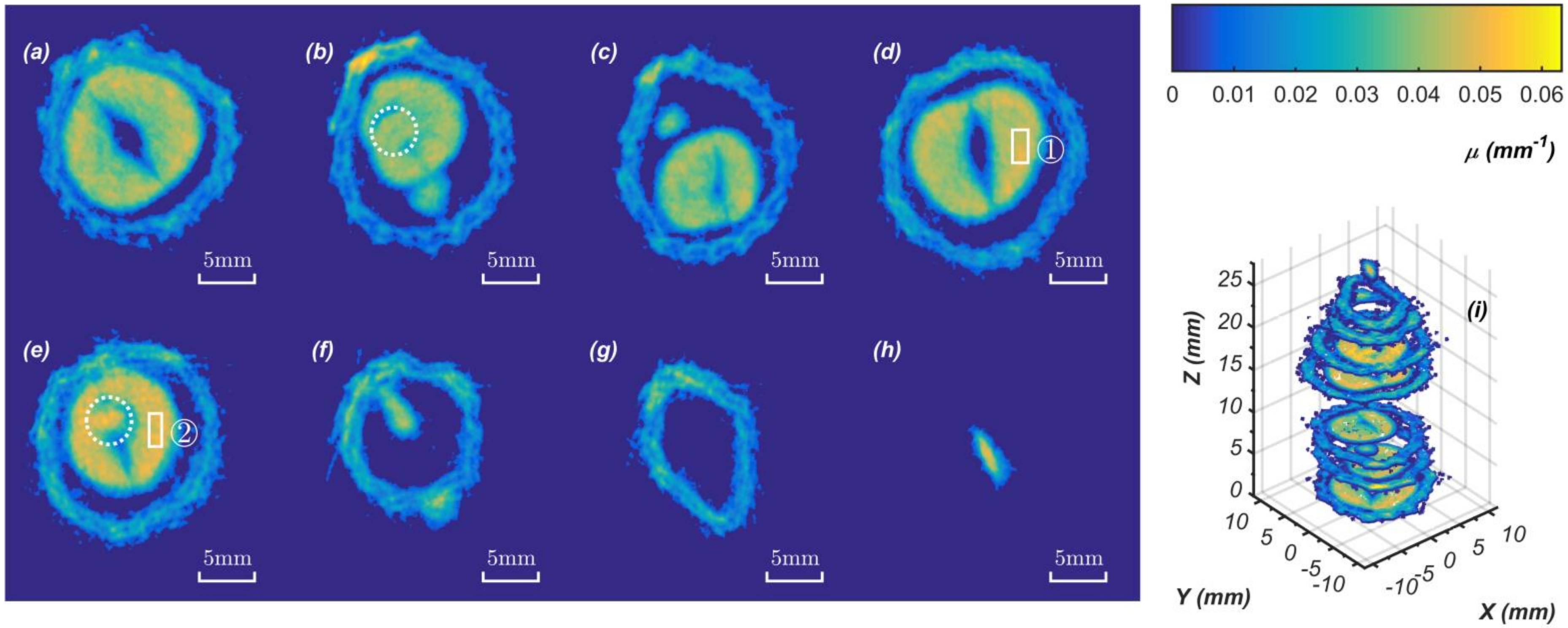






- We optimize the distance between the imaging plane and the sample(shrimp), to find the highest contrast for the edges.

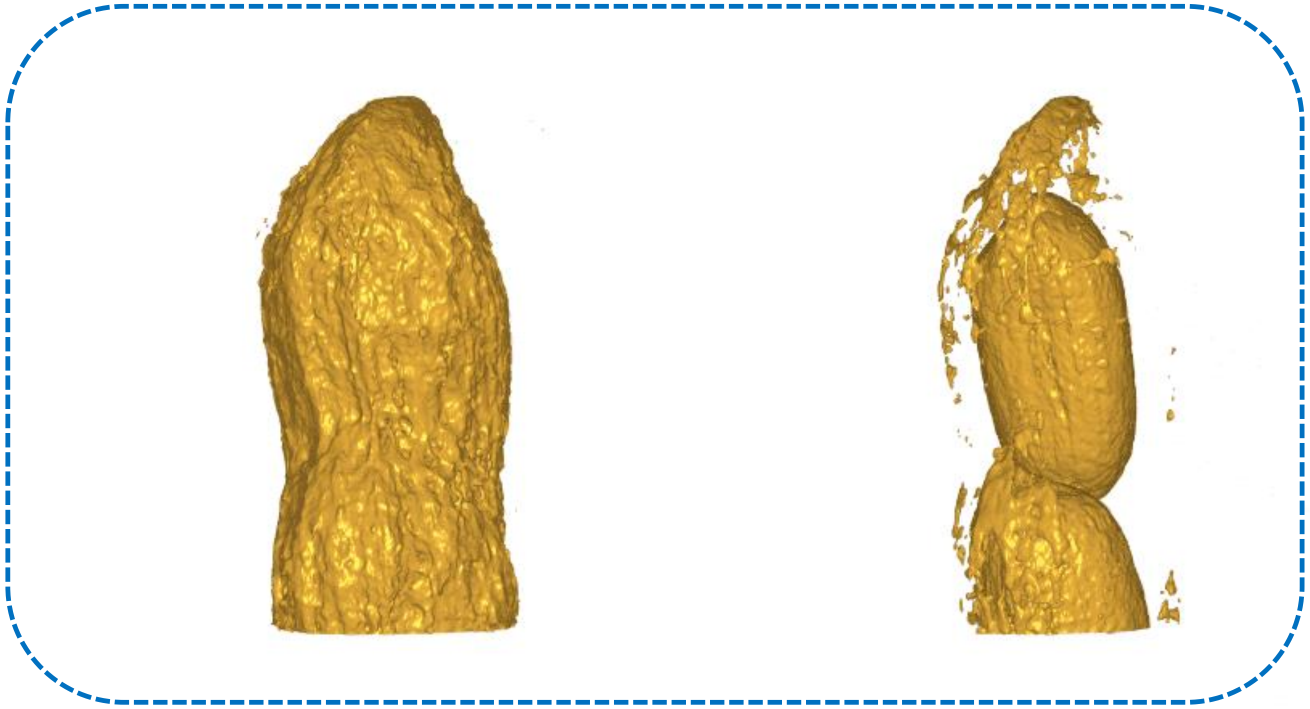
Mono-energy X-ray CT imaging with TTX



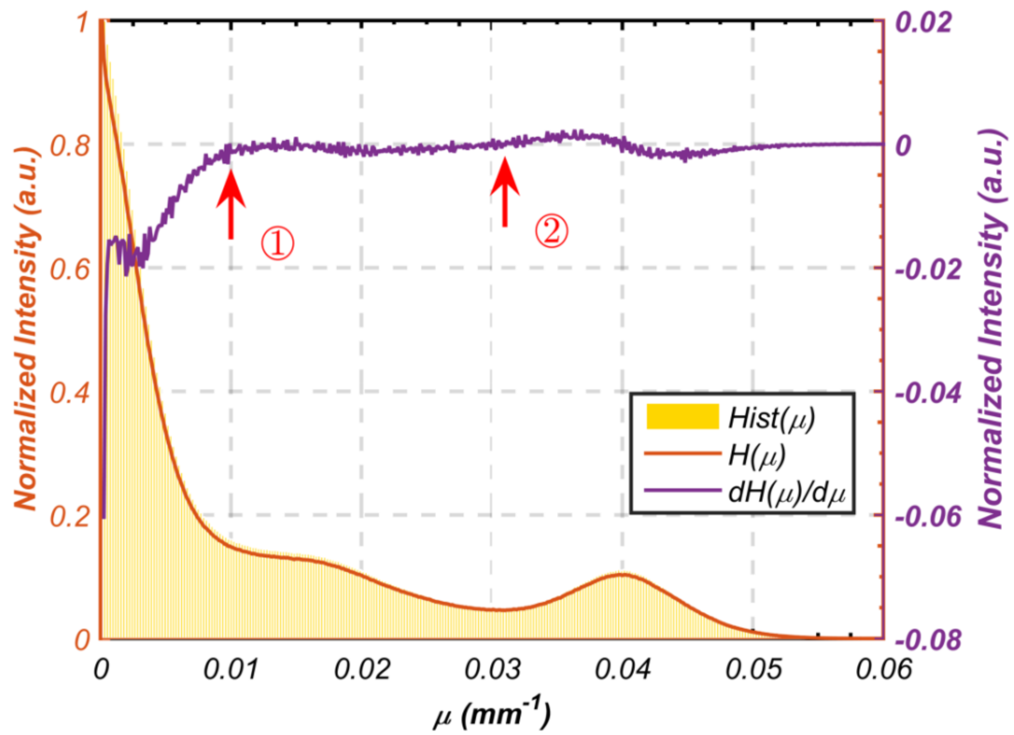
Peanut

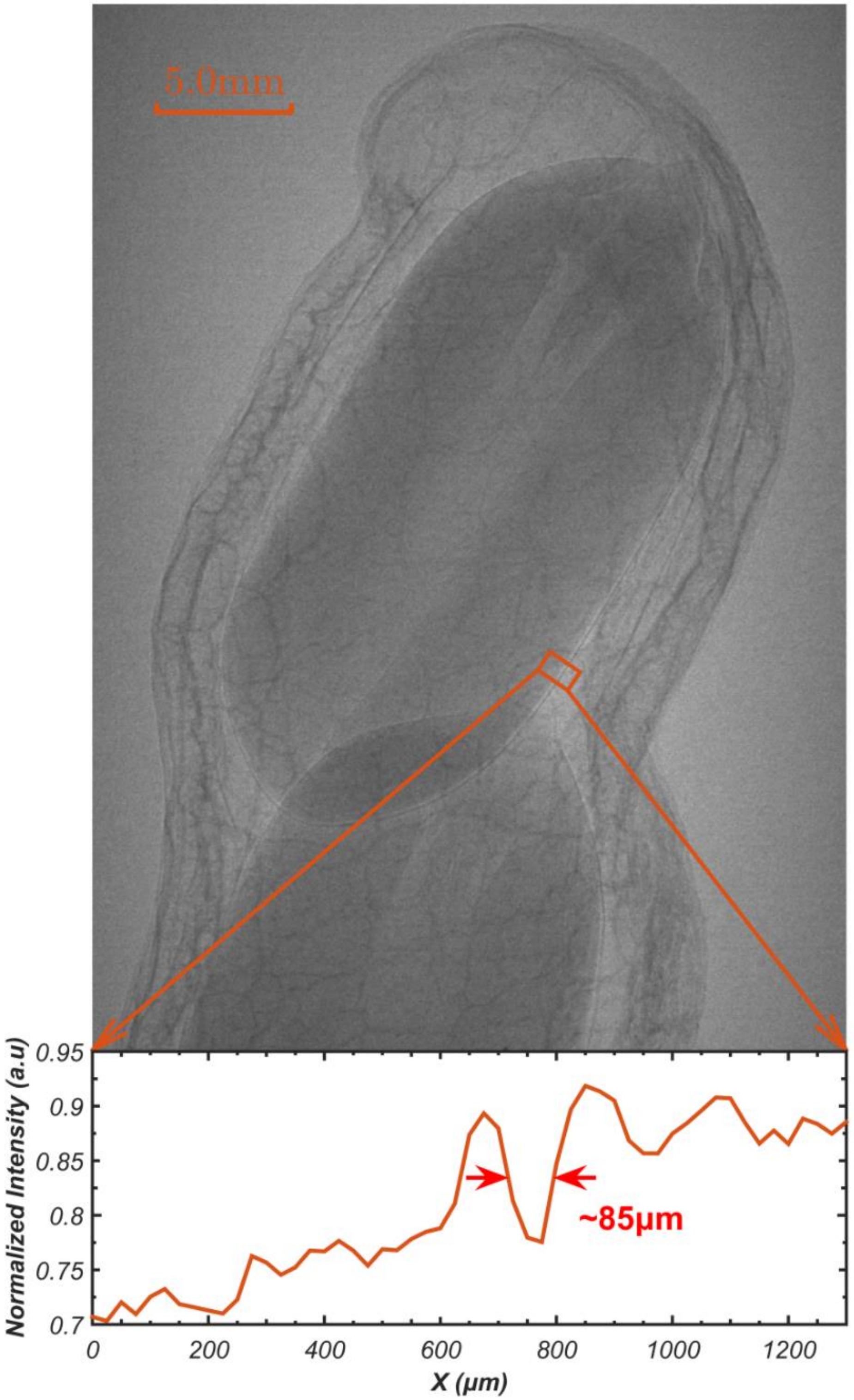
Parameter	Value
X-ray Central Energy/keV	23.96
Beam Divergence/mrad	9.2 (filtered by aperture)
Repetition Rate/Hz	10
Source-to-Detector Distance/m	3.07 (R_1: 210cm; R_2: 97cm)
Detector	EMCCD coupled with phosphor (67×65μm^2)
Projection Number	36 over 360° (1.5min per projection), SART

Mono-energy X-ray CT imaging with TTX



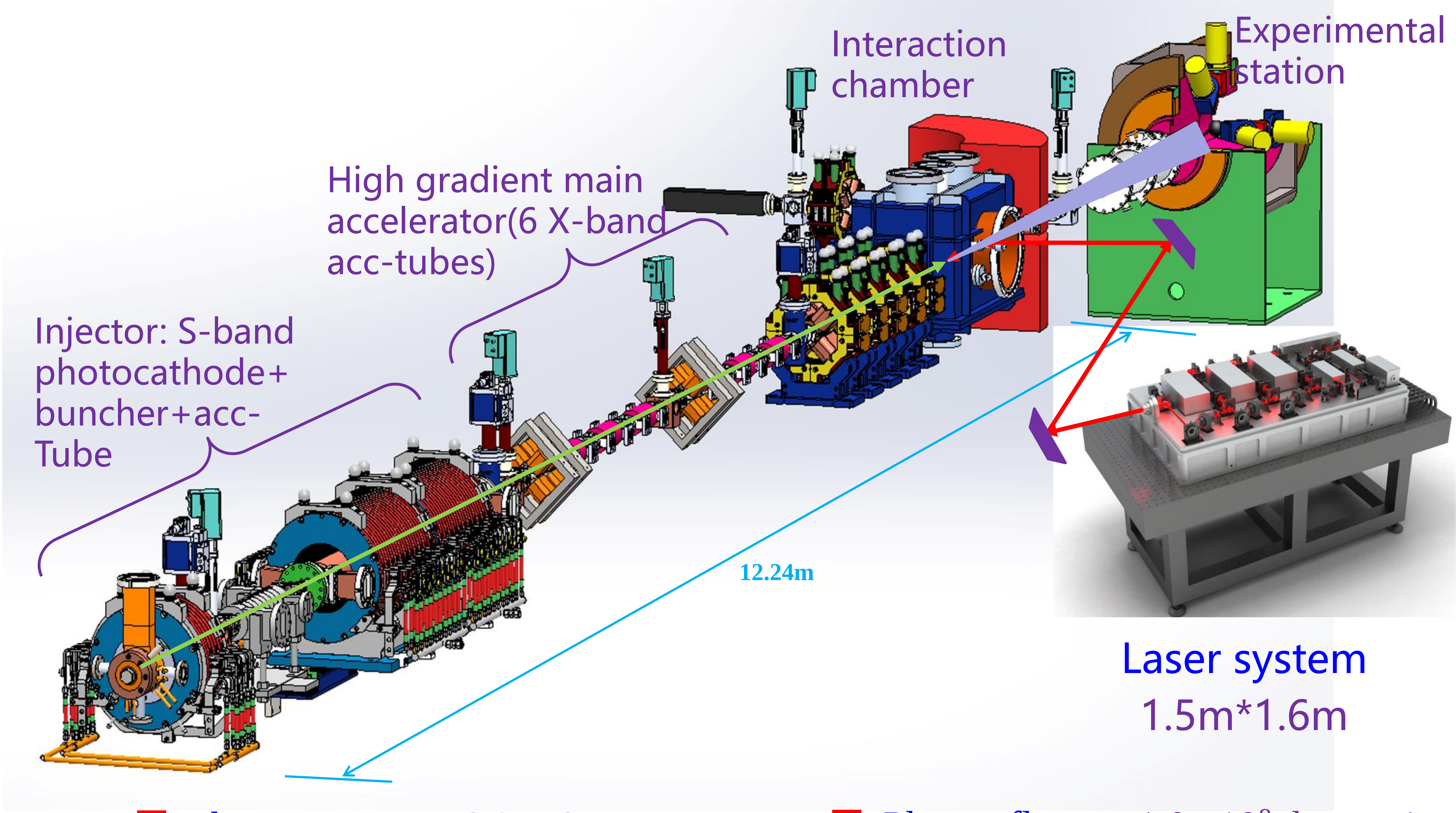
3D-Rendering





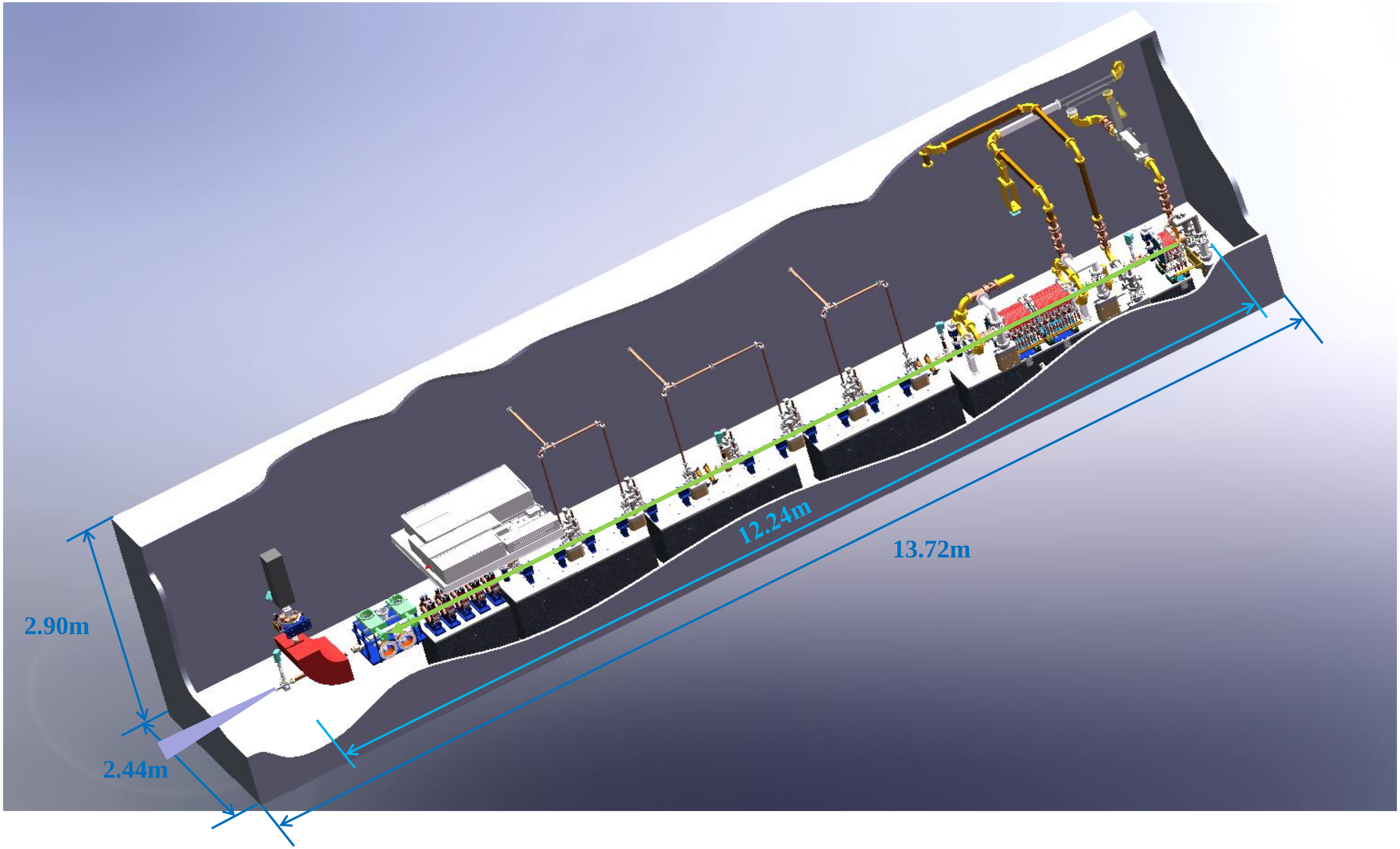
- After enlarging the PCI image of the peanut, the skin of the peanut can be clearly resolved.

Plan to develop a very compact γ-ray source for Nuclear Resonant Fluorescence Imaging



- Photon energy： 0.2-4.8MeV
- Photon flux： >1.0×10^8photons/s
- Spectral bandwidth: ≤1.5%
- Compactness： 12.24m

The very compact quasi-mono-energy γ-ray source for Nuclear Resonant Fluorescence Imaging



Main structures can be installed into a standard container.

Summary

- Thomson scattering x-ray sources can generate x-ray pulses with excellent performances, such as monochromaticity, continuous energy tunability, high brightness, small source size, controllable polarization, and ultrashort pulse length, which would find important applications in scientific research.
- Based on a 50Mev high-brightness linac and a TW laser system, Tsinghua University has built up TTX. With TTX delivered hard X-ray, preliminary experiments have been carried out, i.e. monochromatic CT, dual-energy, K-edge, and phase contrast imaging et al.
- In the next few years, we plan to develop a very compact γ-ray source with a specially designed compact accelerator for Nuclear Resonant Fluorescence Imaging applications.

Acknowledgement

- Zhijun Chi, Yingchao Du, Zheng Zhou, Zhen Zhang, Dong Wang, Qili Tian, Lianmin Zheng, Hongze Zhang, Yan You, Xing Liu, Huan Wang, Jianfei Hua, Jiaru Shi, Wenhui Huang, Huaibi Chen, Chuanxiang Tang

- Work supported by the National Natural Science Foundation of China (Grant No. 11135004, 11375097, 11475097).

Thanks for your attention！