Linac based light source activities at THU

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Content

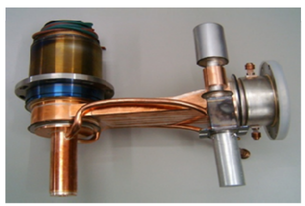
- An brief introduction
- Recent research activities on linac based light source
  - Thomson scattering X/γ-ray source and applications
  - THz generation
- Summary

Accelerator Lab in Department of Engineering physics, Tsinghua University

- Faculty
  - 16 faculties (4 full Professors)and more employee
  - About 30 graduate students
- Activities
  - Education (undergraduate and graduate)
  - Low Energy Linear Accelerators and Their Applications
  - High brightness electron sources (NC S-band photo-injector)
  - Linac based light source(Thomson scattering X/γ-ray source, THz source)
  - High gradient accelerator structure (Prof. Shi, TU1A)
  - Ultra-fast Electron Diffraction and radiography
  - Advanced Accelerating Concepts (DWS,PWFA)(Dr. Wang Dan, TU1P)
  - Compact Pulse Neutron Sources (CPHS)(Prof. Xing, THOP)
  - …

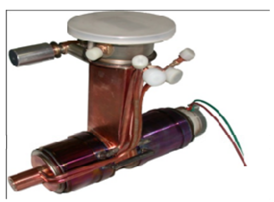
Low energy linac tubes research and applications

- More than 1000 S-, C-, X-band accelerator tubes produced with energy 0.5-20MeV in the last thirty years.



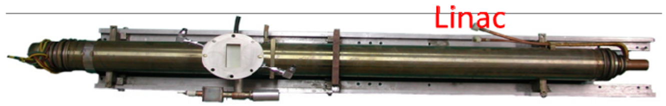
1.5 MeV SW Linac

9 MeV SW Linac

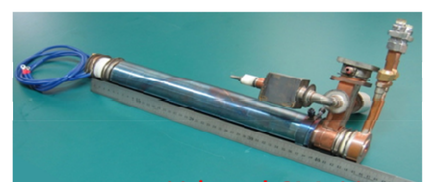


4 MeV SW Linac

6 MeV SW Linac

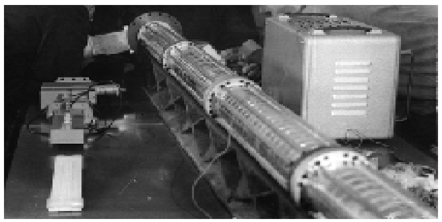
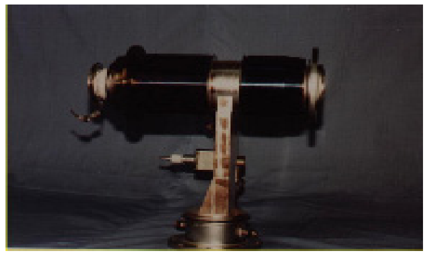
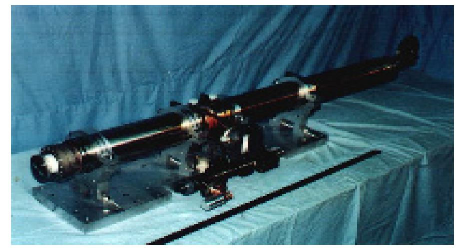


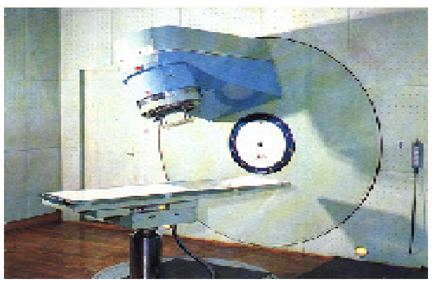
15 MeV SW Linac

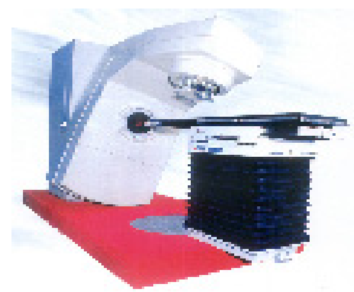
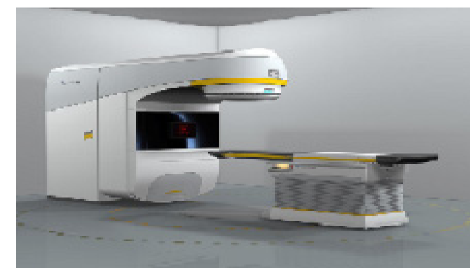


X-band 6MeV Accelerating tube

Medical Applications



TW 10MeV Linac
BJ-10

SW 6MeV Linac
WDVE-6

SW 14MeV Medical
Linac

SW 20MeV Linac
with ES

All the above medical linacs were the 1st ones in China!

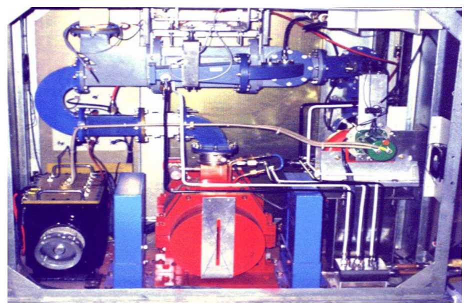
Cargo Inspection Systems

Fixed

Electron Energy: 9MeV

Dose Rate: 30 Gy/min-m

Re-locatable



Electron energy 6MeV

Dose rate ~12cGy/min

Mobile

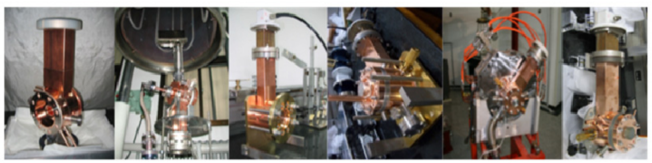
X-band 2.5MeV
SW Tube

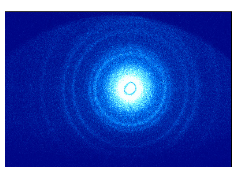
S-band 2.5MeV
SW Tube

http://www.nuctech.com/

Research activities on photo-injector linac and high brightness electron

TTX-I upgrade and applications
XGLS, Compact γ-ray source
Bunch train and coherent THz Radiation
Advanced concept acceleration



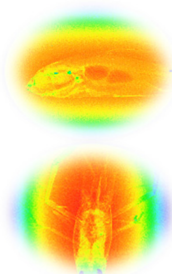


2002

Study of Photocathode RF gun

2006

First photoelectron beam generation



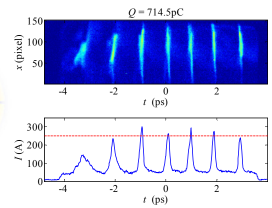
2009

MeV UED,
Soft X-ray via TS

2011

Commissioning of 50MeV photo-injector
Generation of low emittance, high charge beam

First hard X-ray generation at TTX
Linac based THz generation
XGLS proposed

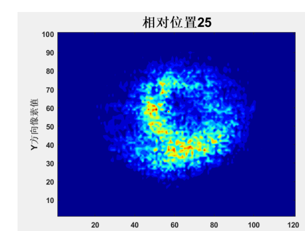


2013

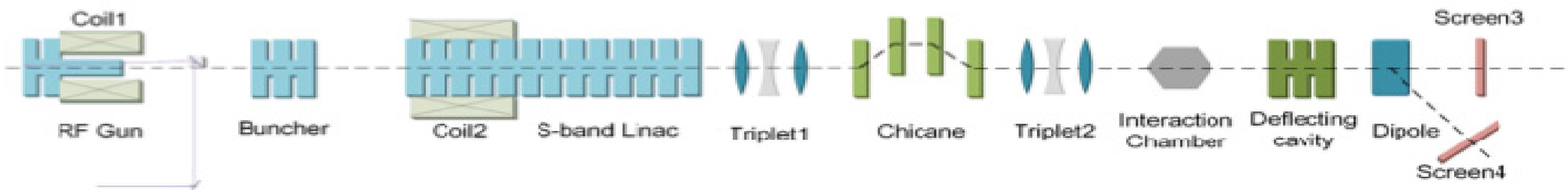
High energy radiography
Advance X-ray imaging and application

2016

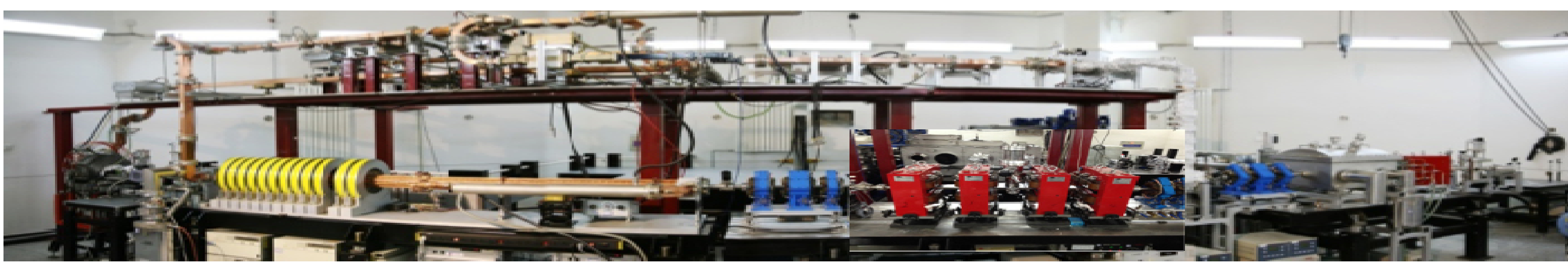
Bunch train and THz generation
(CTR/CUR/CSR/dielectric tube)
Photocathode RF gun applied on SXFEL,DCLS.....



The 50MeV electron photo-injector linac beam line



- The maximum gradient of the gun is ~110MV/m and the bunch charge from a few pC to ~1nC.
- An S-band TW cavity was installed for ballistic bunching before the acceleration.
  - The acceleration phase is set at ~-90° to introduce an energy chirp
  - Simulations show the emittance can be preserved when compression factor $C<3$
- A 4-dipole chicane has been installed after the linac
  - The bend angle can be varied up to ~15°.
- The combination of ballistic bunching and magnetic compression enable us to generate ultrashort (rms<20fs) and high-intensity (~10kA) electron beam.



UV and IR Laser system

UV driver laser for
photocathode RF gun

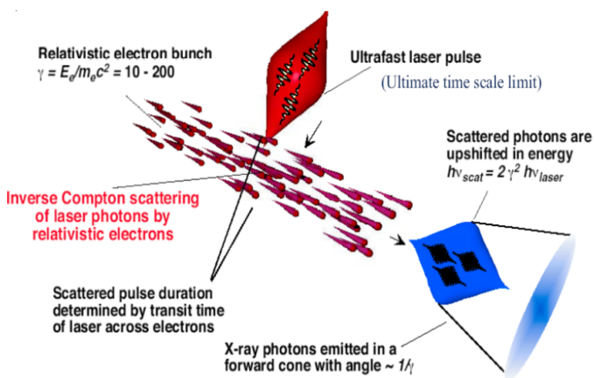
30TW 800nm scattering laser,
25fs, 0.75J

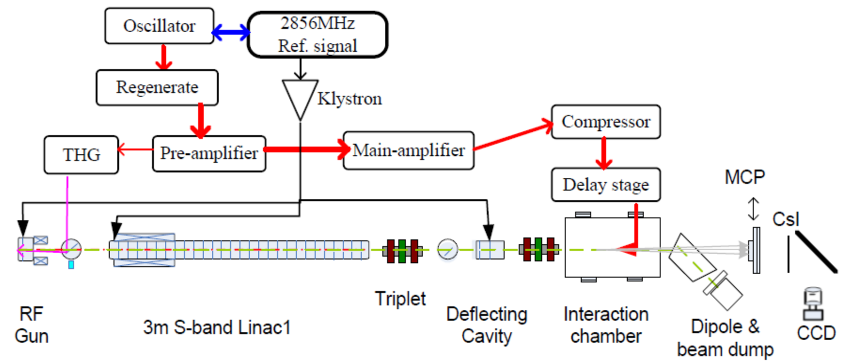
Synchronized with RF and electron beam
with jitter less than 100fs

Linac based light sources developed in THU

- Thomson scattering X/γ-ray source and applications
  - Activities of Tsinghua Thomson scattering X-ray source
  - The projects of ICS sources by THU
- Linac based THz source
  - Bunch train generation
  - Coherent THz radiation with bunch train

Tsinghua Thomson scattering X-ray source (TTX)

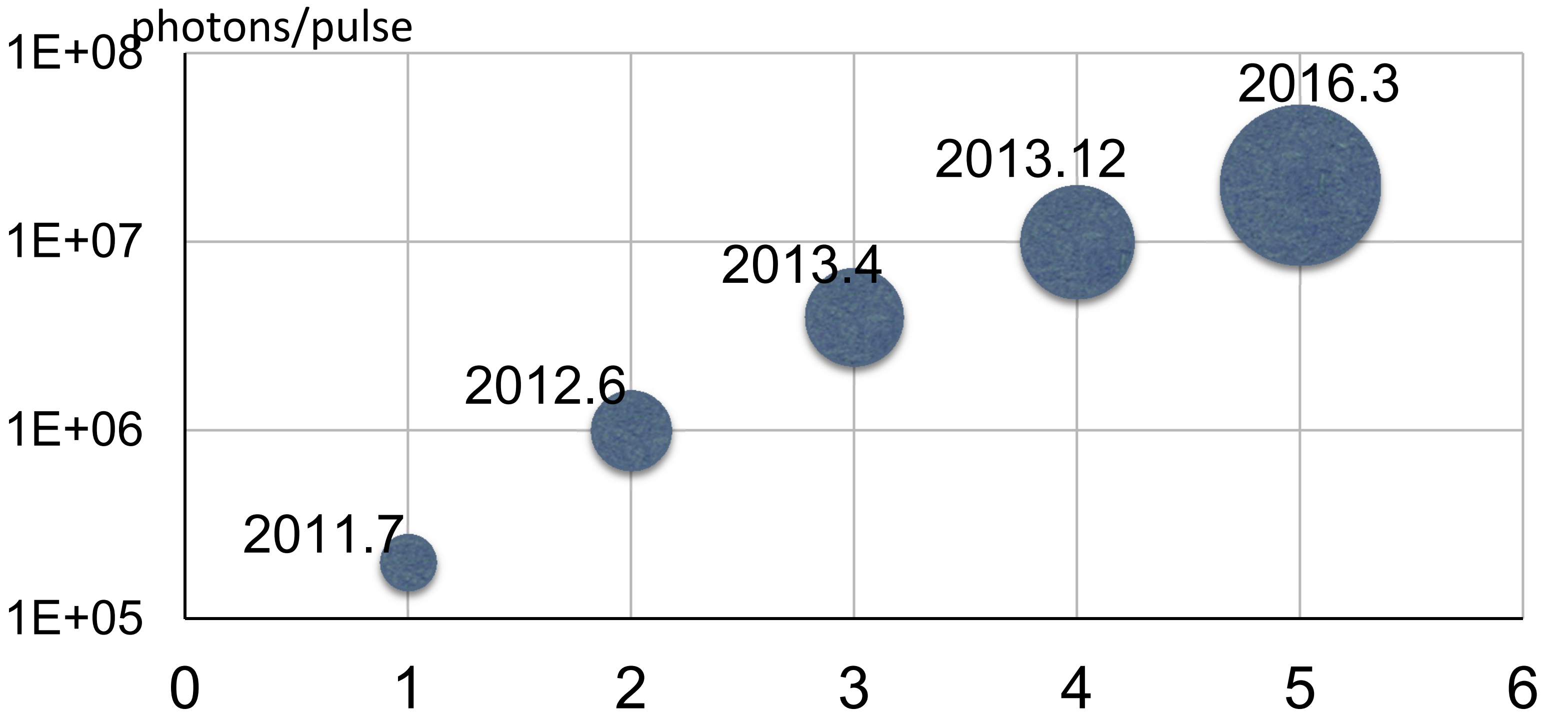




- **Quasi- monochromaticity**
- **Energy tunability(kev-MeV)**
- **Small spot-size (~10um)**
- **Precisely controllable polarization**
- **ps or sub-ps bunch length**
- **Relative high brightness**
- **Compact and relative low cost**

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

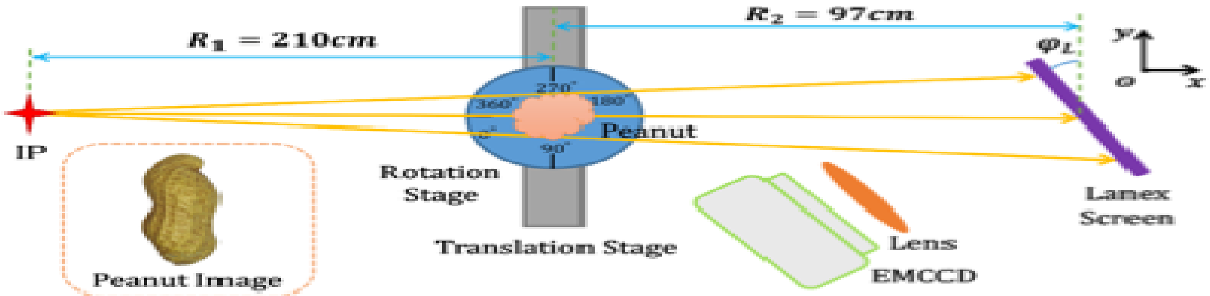
Performances of TTX

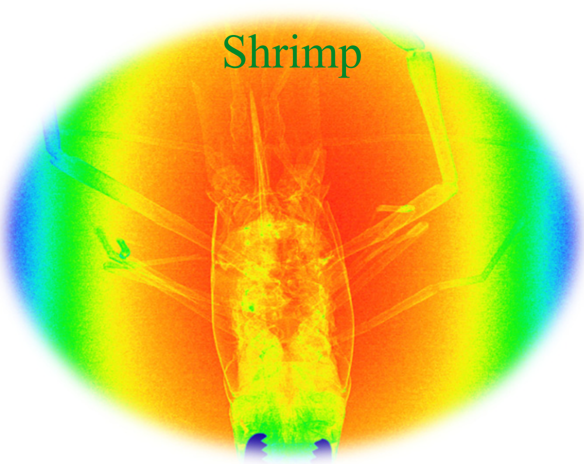


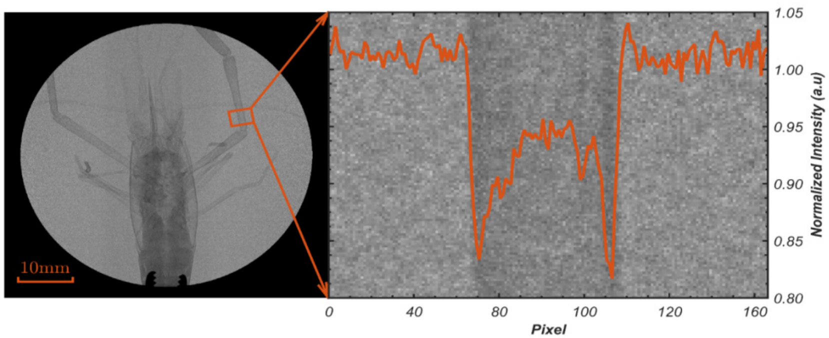
NIM A 608 (2009), NIM A637(2011), RSI 84, 053301(2013), NIM B402(2017)

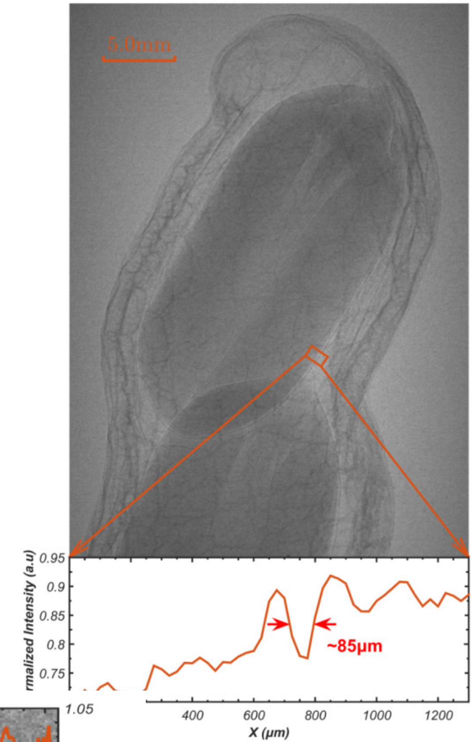
Experiments with TTX

- In-line phase contrast imaging



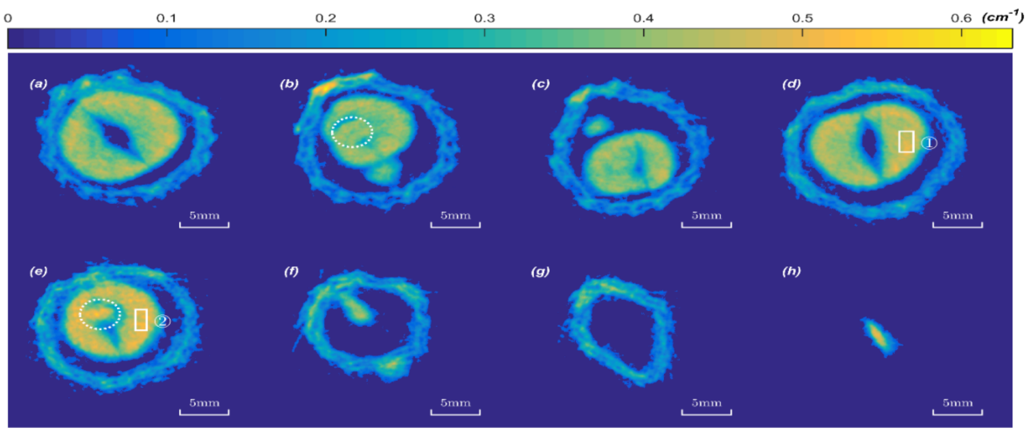






Proc. SPIE 10391(2017)

☐ Mono-energetic X-ray CT imaging at TTX



There is no beam hardening effects , the attenuation coefficients can be retrieved directly.

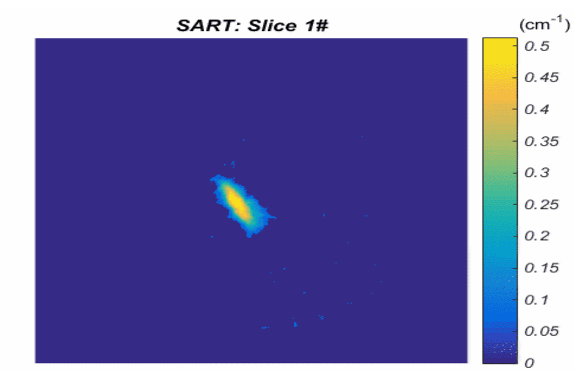
$$\left(\frac{\mu}{\rho}\right)_{mix} = \sum_{i=1}^{n} \omega_i \left(\frac{\mu}{\rho}\right)_i$$

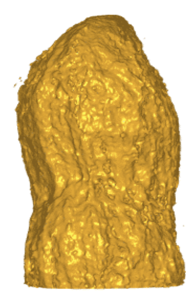
E. C. McCullough, Med. Phys., 1975

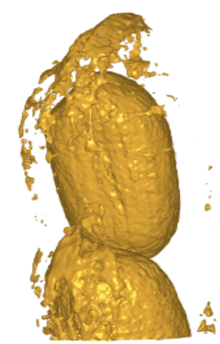
$$\mu_{theory} = 0.538cm^{-1}$$

$$\mu_{ROI,1} = 0.459cm^{-1}$$

$$\mu_{ROI,2} = 0.486cm^{-1}$$

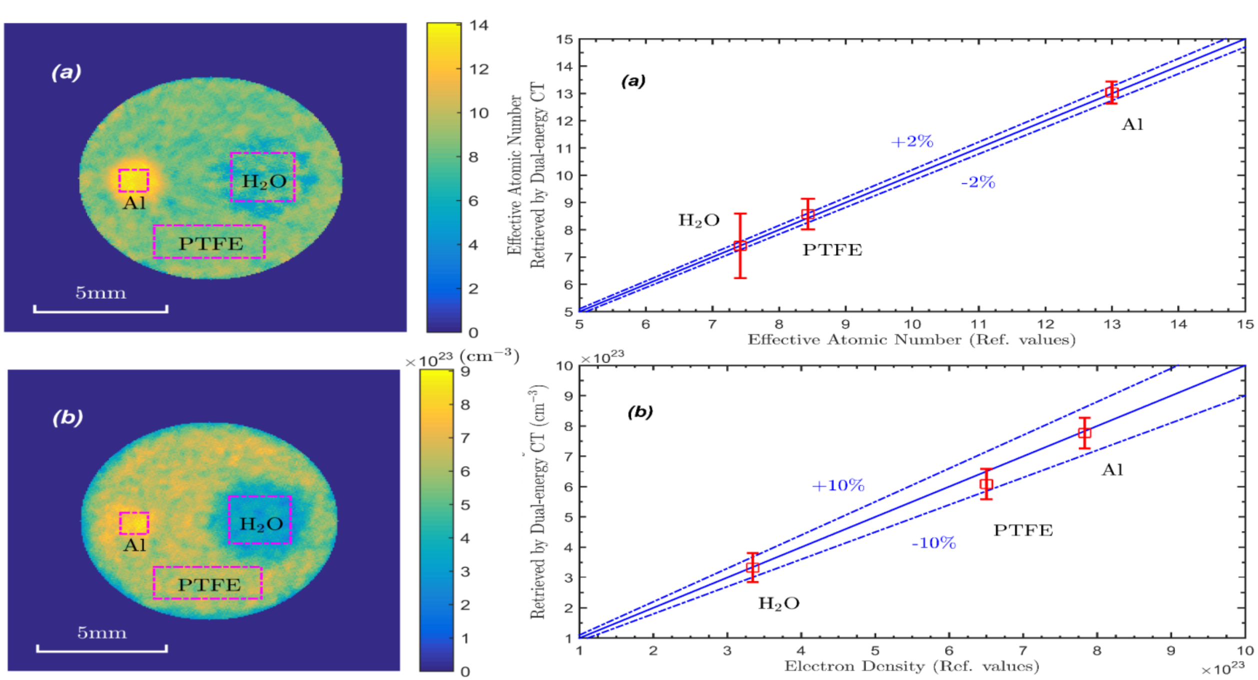






NIM B402(2017

◻ Dual-Energy Mono-energetic X-ray CT Imaging



The effective atomic number Z_{eff} and the electron density ρ_e can be retrieved

$$\mu(E) = a_1 \frac{1}{E^3} + a_2 f_{KN}(E)$$

$g_1 Z^3 \rho_e$

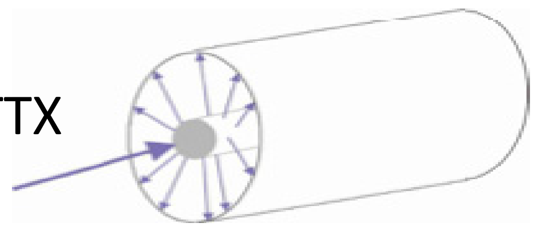
$g_2 \rho_e$

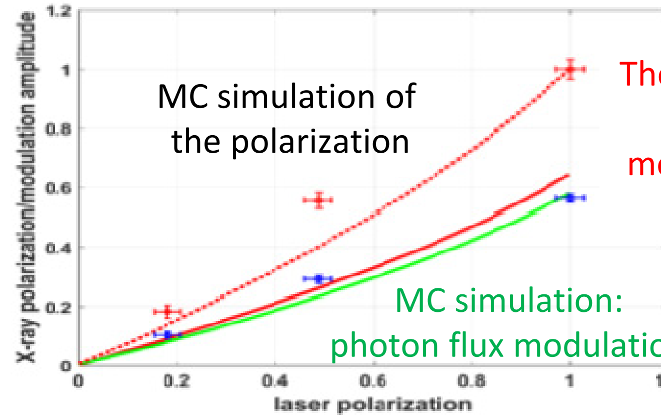
X-ray energy: 29keV and 68keV

accepted by JSR

X-ray polarization modulation and measurement

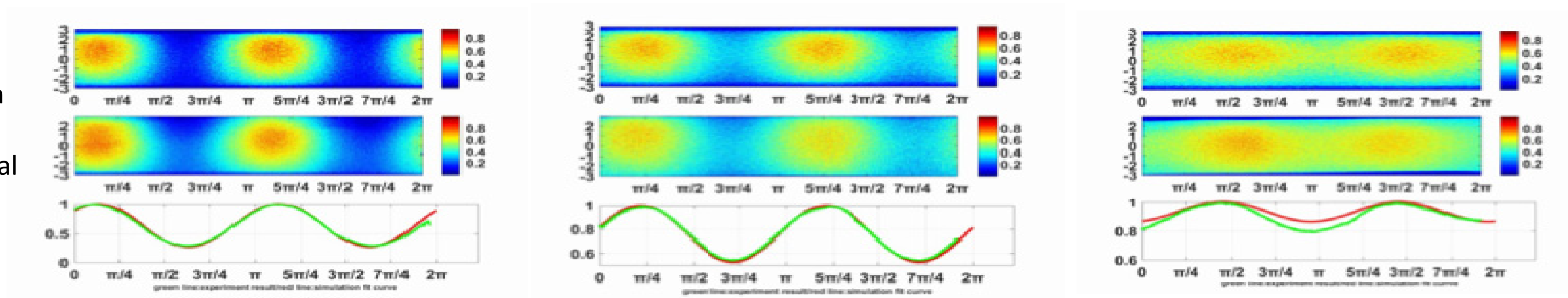
X-ray from TTX





MC simulation

Experimental results



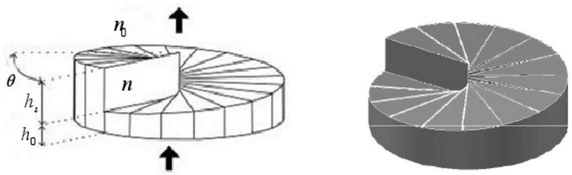
$\lambda = 0.5703$ $\quad p = 1$ $\qquad \lambda = 0.3173$ $\quad p = 0.5564$ $\qquad \lambda = 0.1047$ $\quad p = 0.1836$

Hongze Zhang, et al, "Experimental Polarization Control of Thomson Scattering X/γ-ray Source" arXiv:1612.09403v2

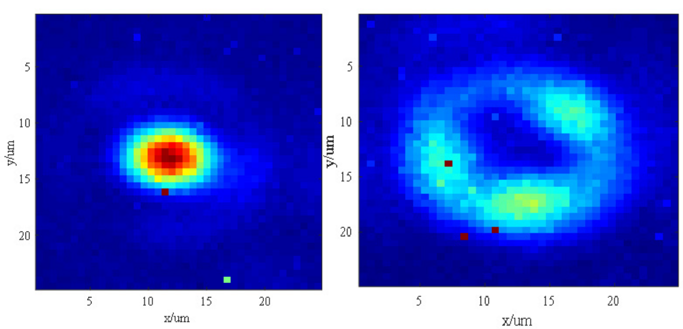
☐ Orbit Angle Momentum(OAM) X/γ-ray generation

Experimental demonstration OAM X-ray generation via Thomson scattering

Space Phase Plate (SPP)

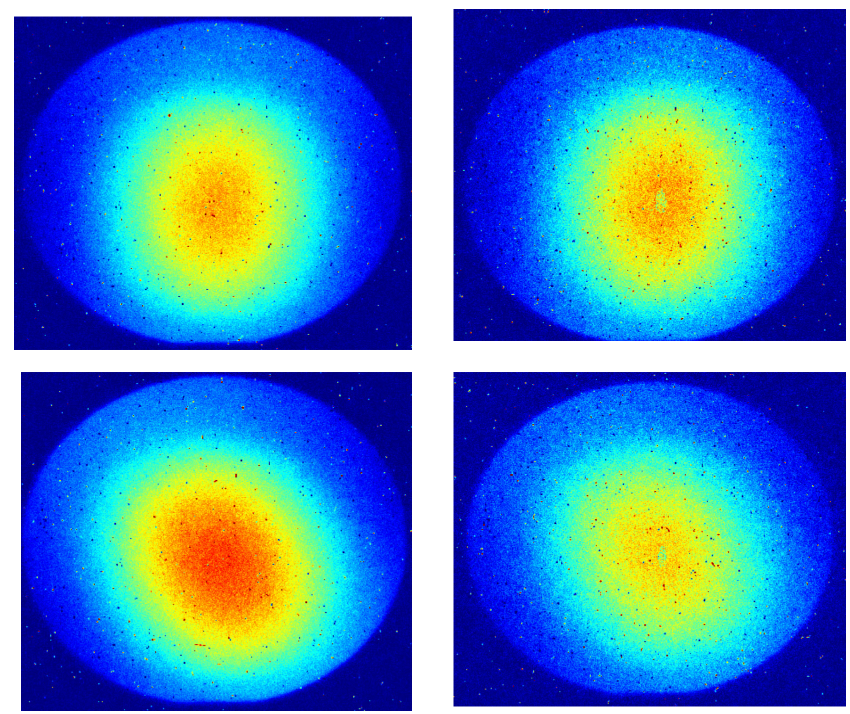


Laser profile



W/O SPP with SPP

X-ray profile



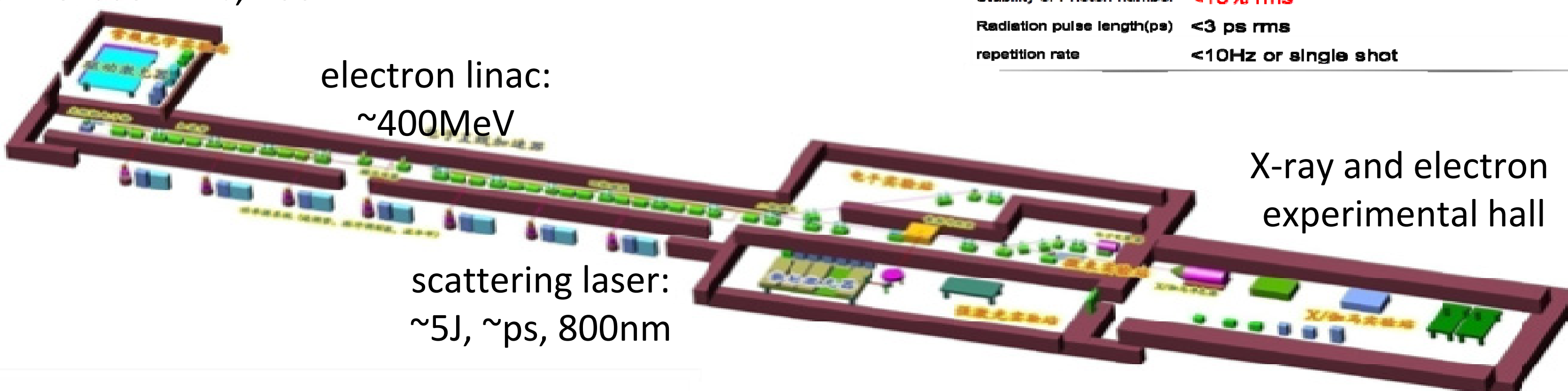
W/O SPP with SPP

The projects of ICS source by THU

◻ XGLS: a 3MeV ICS gamma-ray source

- Mono-Chromatic Mode

Photon energy (MeV)	0.1	0.665	1.25	2.0	2.5	3.0
Energy stability	<1%					
Photons per shot	>1×10⁷	>10⁸				
Collimation angle (mrad)	1.26	0.49	0.36	0.28	0.25	0.23
Bandwidth in collimation angle	<3% rms					
Stability of Photon number	<10% rms					
Radiation pulse length(ps)	<3 ps rms					
repetition rate	<10Hz or single shot					



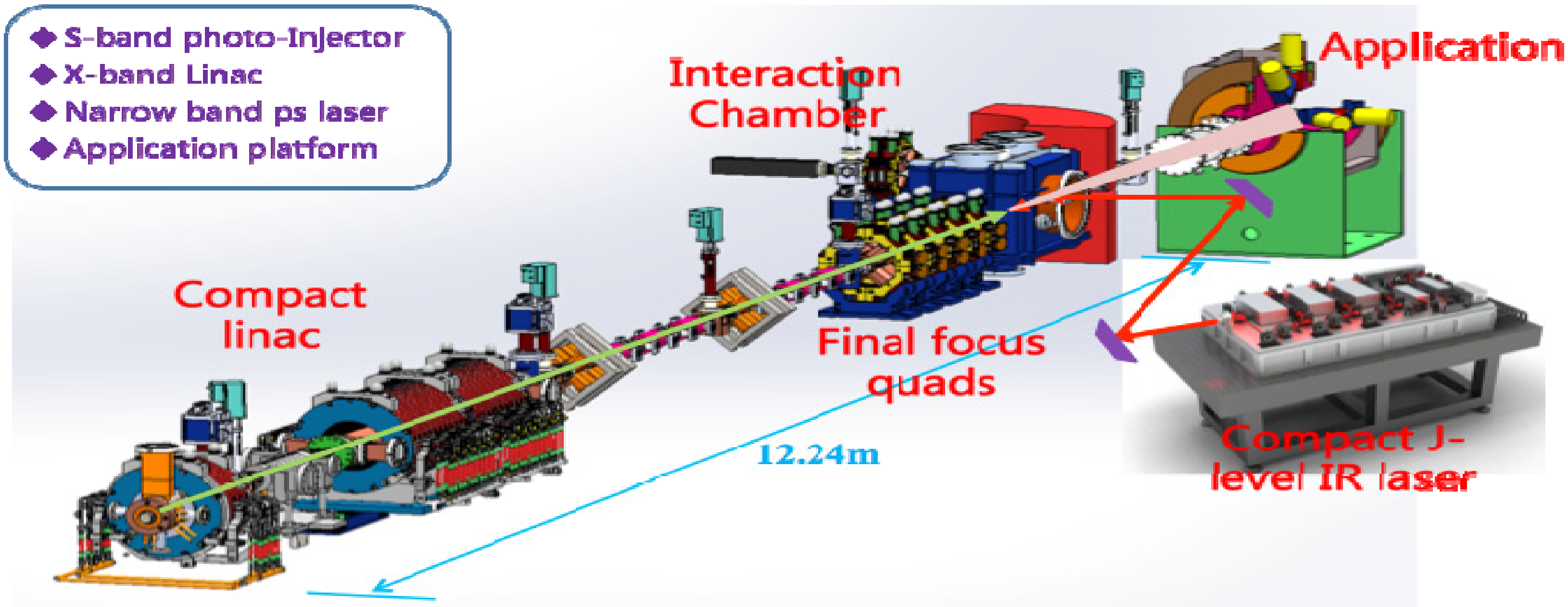
- Ultra-short pulse Mode

Photon energy	0.5MeV< E < 3MeV
Photons per shot	> 1.0×10⁷
Pulse length	<250fs rms

☐ Status of the XGLS

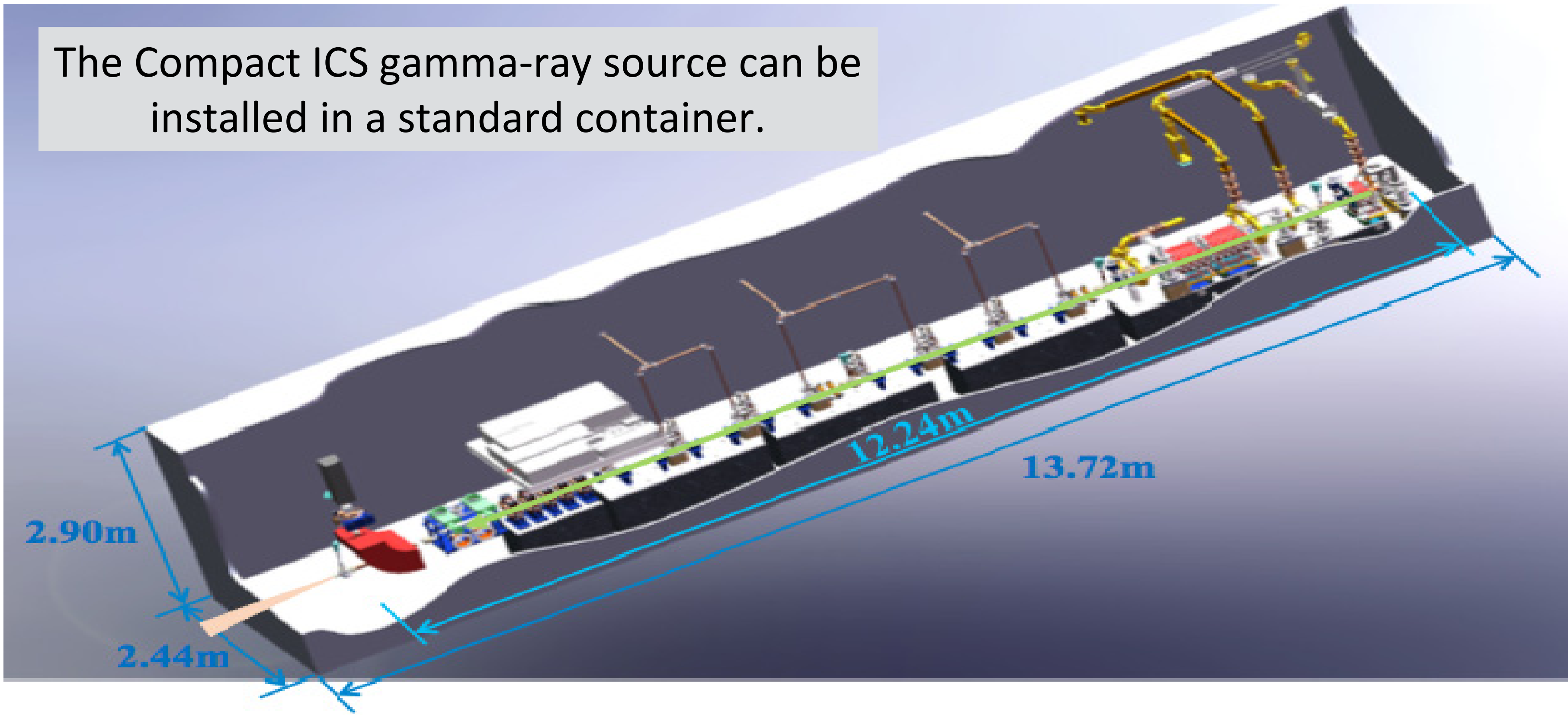
S-band photon-injector has been installed and under commissioning now.
Charge: >500pC, Energy: ~110MeV, emittance: ~0.6mm mrad

A Compact ICS Gamma Ray Source



γ-ray energy: 0.2-4.8MeV
Bandwidth with collimator : <1.5%
Total photon flux(ph/s): $>4\times10^8$@0.2-2.4MeV; $>1\times10^8$@2.4-4.8MeV
Photon flux with 1.5% Bandwidth(ph/s): $>4\times10^6$@0.2-2.4MeV; $>1\times10^6$@2.4-4.8MeV
controllable polarization from linear to circle

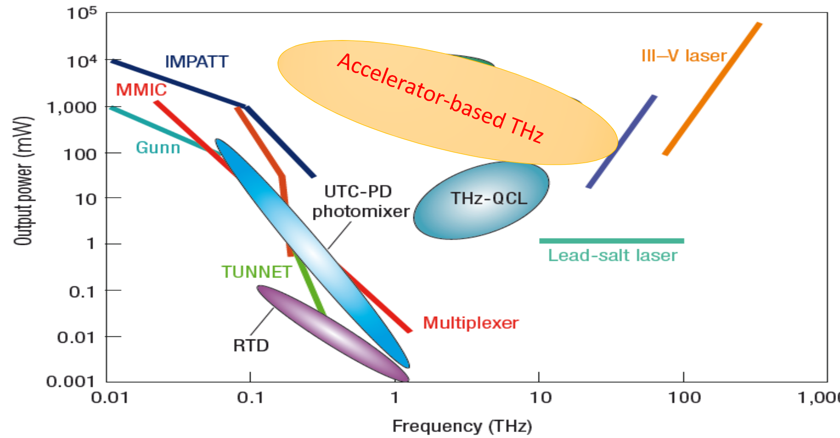
The Compact ICS gamma-ray source can be installed in a standard container.



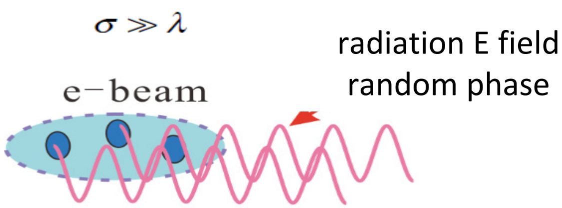
Linac based coherent THz Source

Advantages:

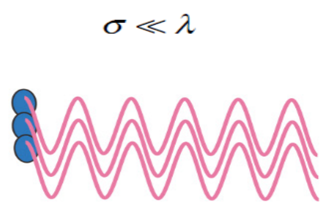
- High average and peak power
- 0.1-30THz
- Broad or narrow bandwidth



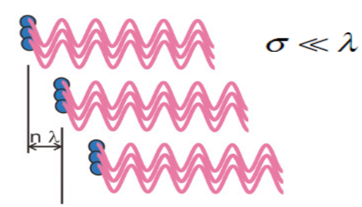
- Coherent radiation for ultra-short bunch and bunch trains



Incoherent radiation for a single bunch



Coherent radiation for a single bunch



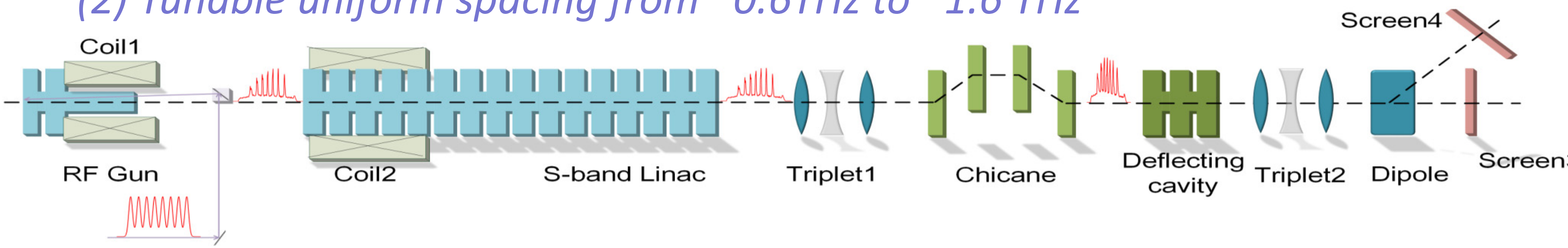
Coherent radiation for bunch train

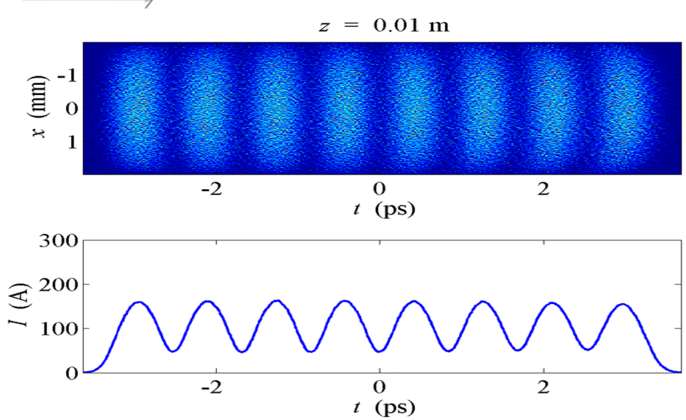
☐ Train generation by nonlinear space-charge oscillation

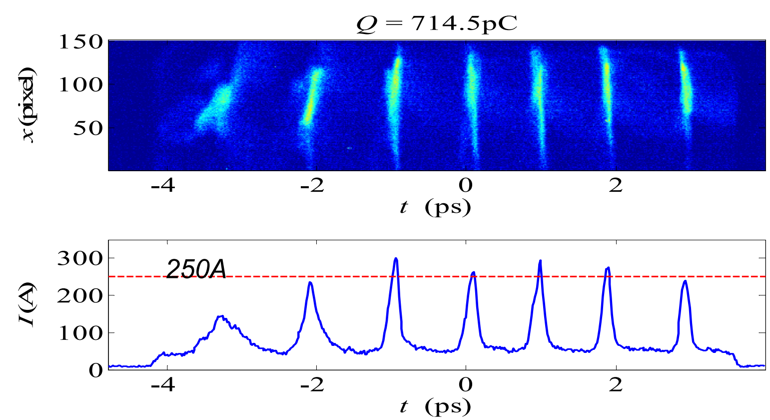
- We take advantage of NLSCO to generate multi-bunch trains with

  (1) Large charge (~700pC) and high peak current (~300A)

  (2) Tunable uniform spacing from ~0.6THz to ~1.6 THz





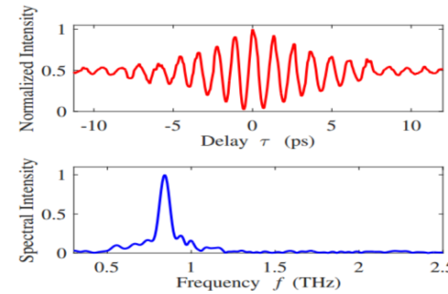


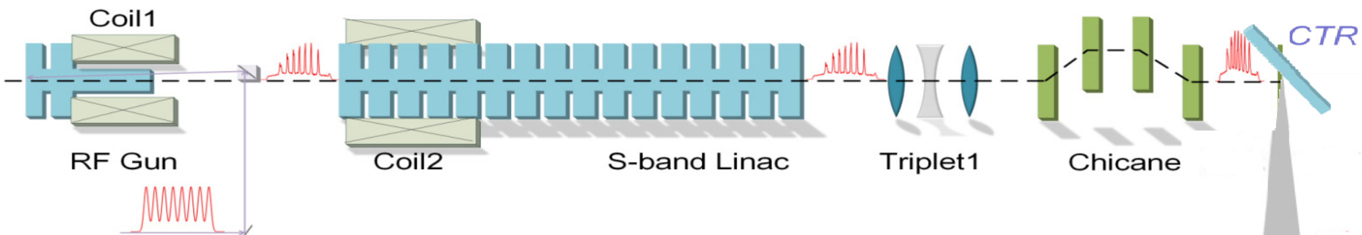
Train generation by nonlinear space-charge oscillation

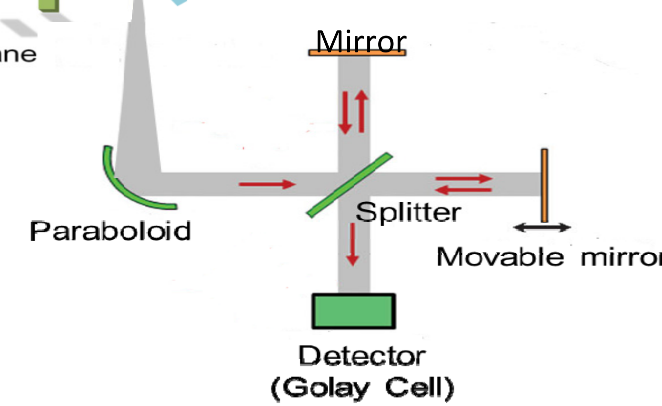
- CTR radiation and THz Autocorrelation Measurement :

  (1) Narrow bandwidth

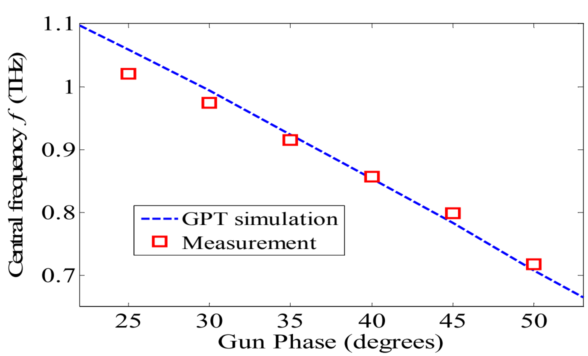
  (2) Tunable frequency from ~0.6THz to ~1.6 THz



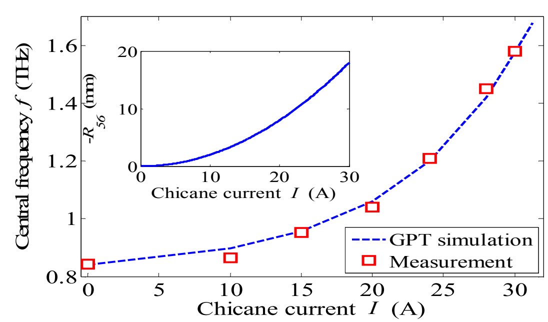




Velocity bunching



Magnetic compression

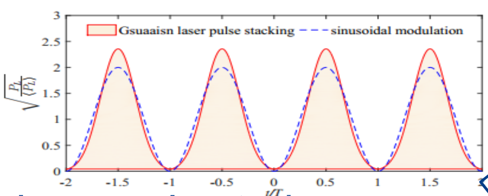


Z Zhang, LX Yan, et al., PRL, 116, 184801(2016)

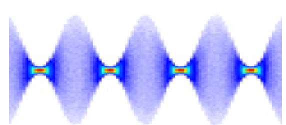
☐ Train generation by slice energy modulation

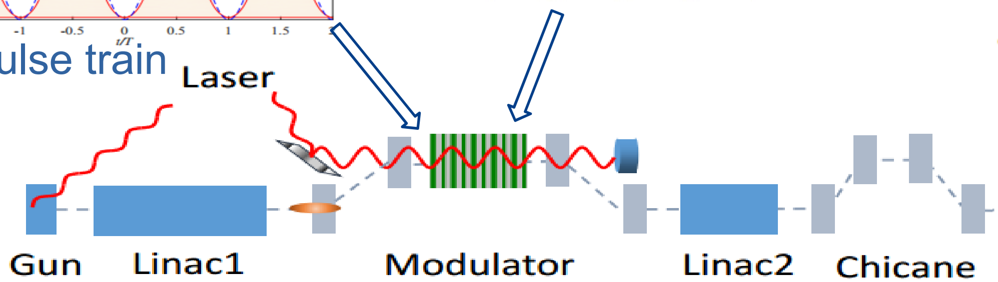
- Limitations of NLSCO: f<2THz; bunching factor<0.2

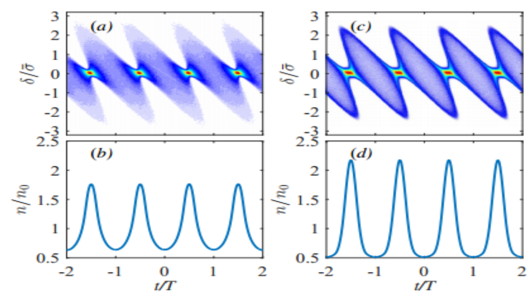
✓We propose a new method to generate electron bunch train with *wide frequency range* (1~10THz) and *large bunching factor* (~0.4),suitable for *large beam charge*.



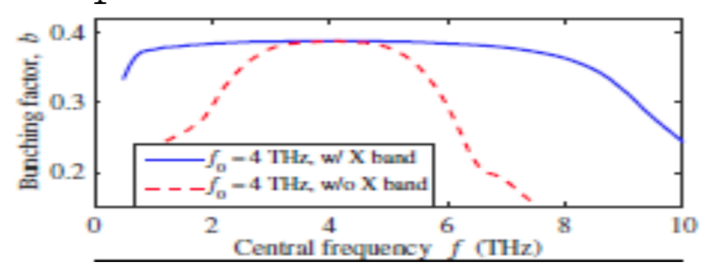
laser pulse train







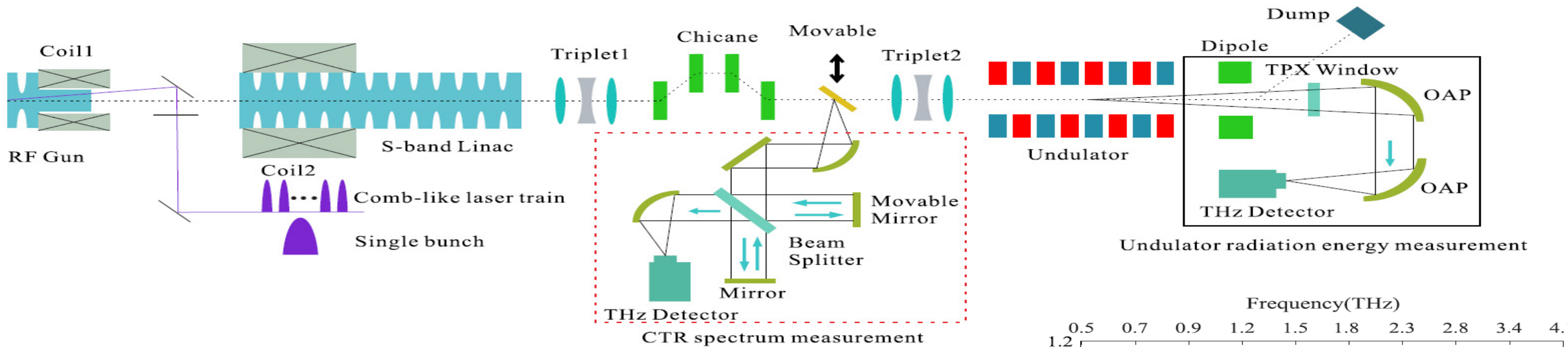
$b_1 \approx 0.27$ $b_1 \approx 0.4$



Z Zhang, LX Yan, et al, PRAB, 20, 050701(2017)

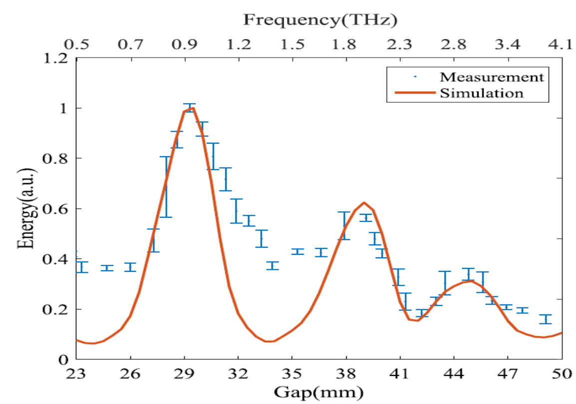
Coherent THz radiation from Undulator

- Experiments on THz radiation from an eight-period undulator by the electron bunch trains has been conducted at our lab.



Parameters of the undulator

Parameter		Value
Undulator period	λ_u	100 mm
Number of periods	N	8
Magnetic gap range	g	23-75 mm
Peak magnetic field	B	0.99-0.15 T
Undulator parameter	K	9.24-1.39

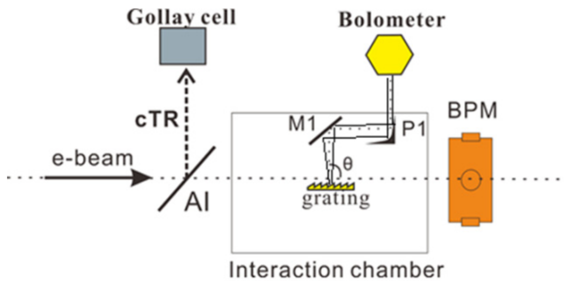


Measurement of pre-bunched beams' form factor based on radiation from a gap-tunable undulator

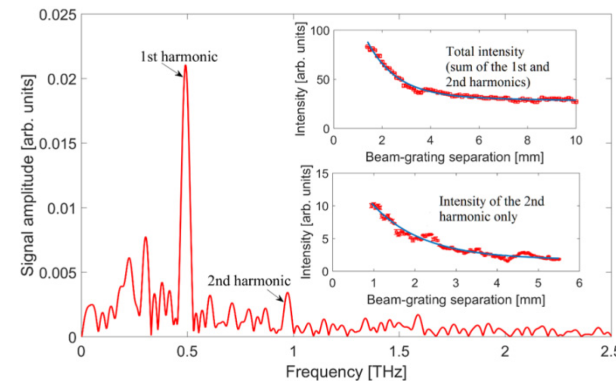
XL Su, et al, Rev. Sci. Instrum. 89, 013304(2018)

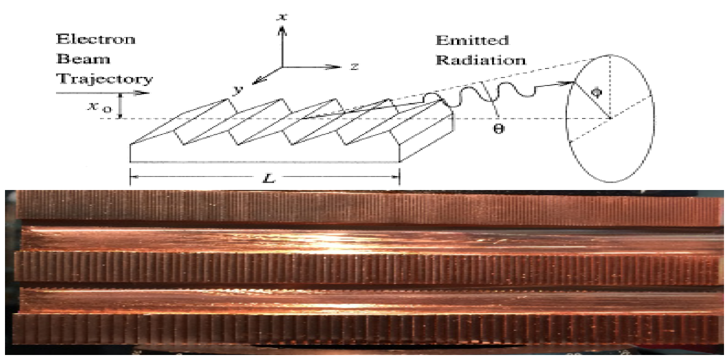
Coherent THz radiation from Smith-Purcell

- Manipulation of sub-picosecond bunch train to study the characteristics of coherent SP radiation



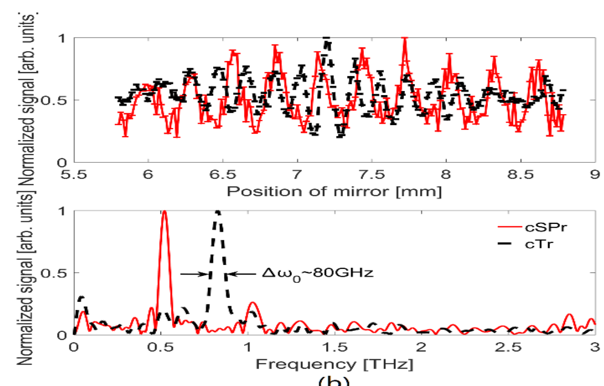
SP radiation with single bunch





Gratings:110mm long, period 0.3/0.6mm

SP radiation with bunch train



Y. Liang et al., Appl. Phys. Lett. 112, 053501 (2018)

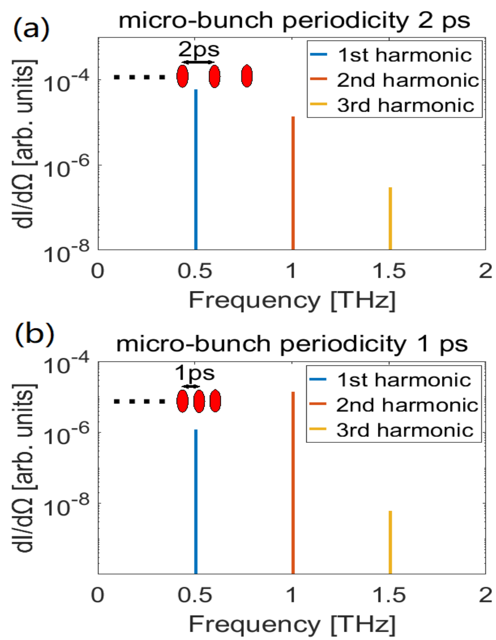
☐ Coherent THz radiation from Smith-Purcell

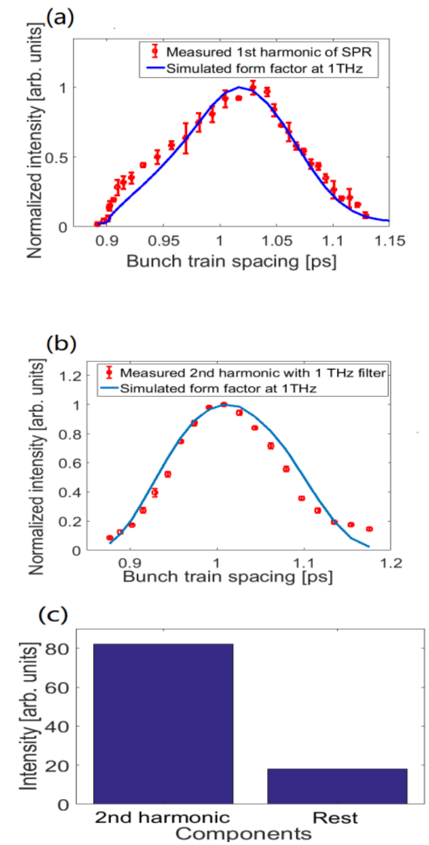
- Demonstrate the selective (resonant) excitation and control of coherent SP THz radiation generation.

$$\left(\frac{dI}{d\Omega}\right)_{N_b} = \left(\frac{dI}{d\Omega}\right)_1 \left(N_e S_{inc} + N_e^2 S_{coh}\right) \left[\frac{\sin\left(\frac{\pi N_b \lambda_b}{\lambda}\right)}{\sin\left(\frac{\pi \lambda_b}{\lambda}\right)}\right]^2$$

$$\left(\frac{dI}{d\Omega}\right)_1 = 2\pi q^2 \frac{Z}{d^2} \frac{m^2 \beta^3}{(1-\beta\cos\theta)^3} R^2 \exp\left(-\frac{2x_0}{\lambda_e}\right)$$

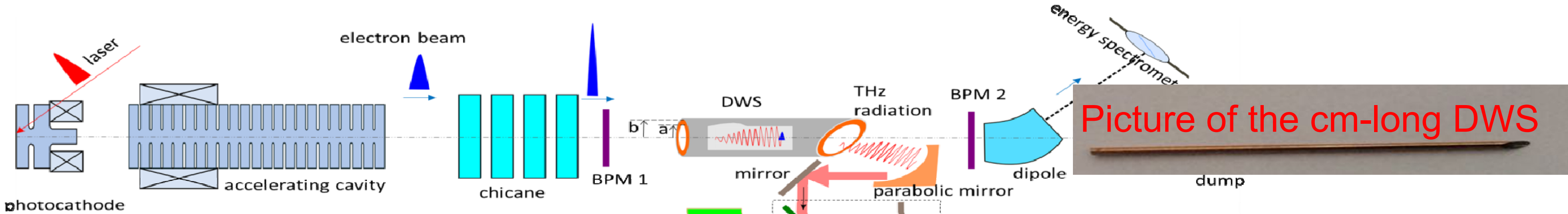
Coherent SP radiation by bunch trains

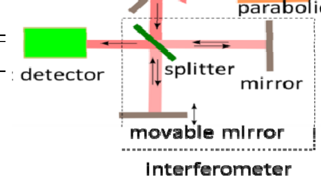




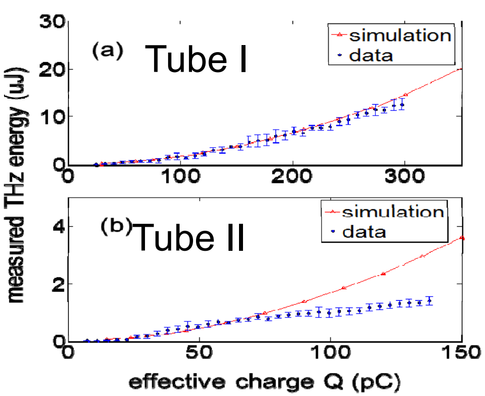
Y. Liang et al., Appl. Phys. Lett. 112, 053501 (2018)
YF Liang et al., submitted

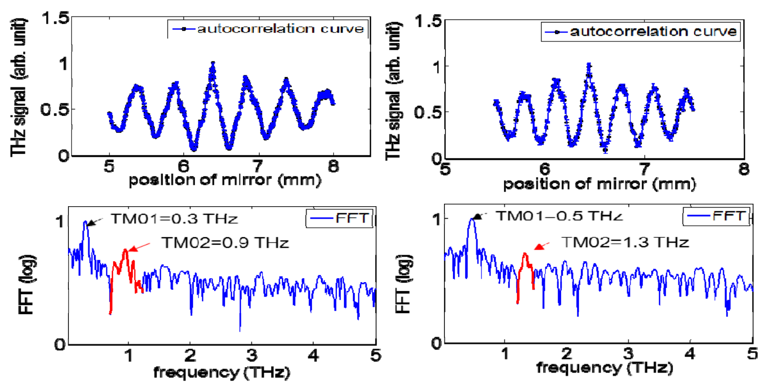
❑ THz radiation from dielectric wakefield structure





parameter	DLW No.1	DLW No.2
inner diameter 2a	0.9 mm	0.4 mm
outer diameter 2b	1.1 mm	0.52 mm
waveguide length L	30 mm	20 mm
frequency of TM_{01} mode	0.3 THz	0.9 THz
frequency of TM_{02} mode	0.5 THz	1.3 THz





Tube I

Tube II

✓Tens of μJ THz pulse energy has been measured with several hundred pC.

✓Second order mode of the THz radiation is clearly seen with short drive beams.

Dr. Dan Wang, TU1P02
September 18

D. Wang, LX Yan, et al., submitted

Summary

- At Accelerator laboratory of Tsinghua, a 50MeV photo-injector linac has been built and high brightness electron beam is generated and applied in various fields.
- X/γ-ray source based on Thomson scattering(inverse Compton scattering) has been demonstrated successfully in THU. Preliminary applications such as advance X-ray imaging are also tested. MeV ICS sources are proposed.
- Various methods to generate high-peak current electron bunch/train and coherent THz radiations have been studied for THz source development.

Accelerator Laboratory, Advanced Radiation Source and Application Laboratory, Tsinghua University (TTX &CPHS)

Facility Tour to Accelerator Laboratory & Tsinghua University

Time: 13:30-17:00, Friday, 21 September

Thanks!

清華大學
Tsinghua University