A simulation study of Tsinghua Thomson scattering X-ray source*

TANG Chuan-Xiang(唐传祥)[1,2,3;1)] LI Ren-Kai(李任恺)[1,2,3] HUANG Wen-Hui(黄文会)[1,2,3]
CHEN Huai-Bi(陈怀璧)[1,2,3] DU Ying-Chao(杜应超)[1,2,3] DU Qiang(杜强)[1,2,3] DU Tai-Bin(杜泰斌)[1,2,3]
HE Xiao-Zhong(何小中)[1,2,3] HUA Jian-Fei(华剑飞)[1,2,3] LIN Yu-Zhen(林郁正)[1,2,3]
QIAN Hou-Jun(钱厚俊)[1,2,3] SHI Jia-Ru(施嘉儒)[1,2,3] XIANG Dao(向导)[1,2,3]
YAN Li-Xin(颜立新)[1,2,3] YU Pei-Cheng(余沛成)[1,2,3]

1 (Department of Engineering Physics, Tsinghua University, Beijing 100084, China)
2 (Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing 100084, China)
3 (Key Laboratory of High Energy Radiation Imaging Fundamental Science for National Defense, Beijing 100084, China)

Abstract Thomson scattering X-ray sources are compact and affordable facilities that produce short duration, high brightness X-ray pulses enabling new experimental capacities in ultra-fast science studies, and also medical and industrial applications. Such a facility has been built at the Accelerator Laboratory of Tsinghua University, and upgrade is in progress. In this paper, we present a proposed layout of the upgrade with design parameters by simulation, aiming at high X-ray pulses flux and brightness, and also enabling advanced dynamics studies and applications of the electron beam. Design and construction status of main subsystems are also presented.

Key words Thomson scattering, X-ray, ultra-fast, brightness

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1 Introduction

Understanding the structural dynamics on fundamental time and length scales of atomic motion is an important frontier that inspires the developments of several scientific tools, such as X-ray free-electron lasers[1—3], ultra-fast electron diffractions[4—6], and Thomson scattering X-ray sources[7—9]. These tools are capable of producing tunable, very high brightness X-ray or electron pulses at short wavelengths (<1 Å) and short durations (<1 ps). This enables many applications in chemistry, biology, material sciences.

Although X-ray pulses from a Thomson scattering source lack transverse coherence, the compact scale and affordable cost of a Thomson scattering X-ray source make it an attractive system for various purposes, including medical and industrial applications, as well as ultra-fast science studies. A Thomson scattering source is compact enough to be used in a typical university laboratory, thus fits into a local experimenter's laboratory or a hospital.

A prototype Thomson scattering facility has been built at the Accelerator Laboratory of Tsinghua University[10]. In preliminary experiments[11], electron pulses from a 16 MeV backward traveling-wave linac collided with the 1.5 J, 6 ns, 1064 nm laser pulses from a Nd:YAG Q-switched laser system. A 6 ns X-ray pulse was generated with a peak energy of 4.6 keV and an intensity of 1.7×10^4 photons.

As the upgrade of present setup, we propose a system composed of an ultra-fast laser system, a photocathode RF gun, two sections of traveling-wave linacs capable of boosting the electron beam energy to around 50 MeV, and a four-dipole magnetic bunch compressor. In this paper, we present a simulation

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1) E-mail: tang.xuh@tsinghua.edu.cn

design of this layout, and the design and construction status of some main subsystems.

2 Tsinghua Thomson scattering X-ray source (TTX)

At the Accelerator Laboratory of Tsinghua University, the Thomson scattering X-ray source is developed in pursuit of a platform for ultra-fast science studies, and also a compact facility for medical and industrial applications. For example, the tunable, monochromatic X-ray beams from a Thomson scattering source are ideal for imaging, and thus they are promising to further improve the cargo inspection system, and the dual energy X-ray imaging and CT system developed at Tsinghua[12].

2.1 An overview of TTX

The layout of the proposed Tsinghua Thomson scattering source is shown in Fig. 1. A feature of this layout and operating condition is that the electron bunch charge density is relatively high and the beam energy is relatively low, thus the collective space charge effects play an important role all through the beam-line. While high electron bunch charge is of benefit to the resultant X-ray flux, one has to ensure good electron beam qualities for optimized X-ray brightness.

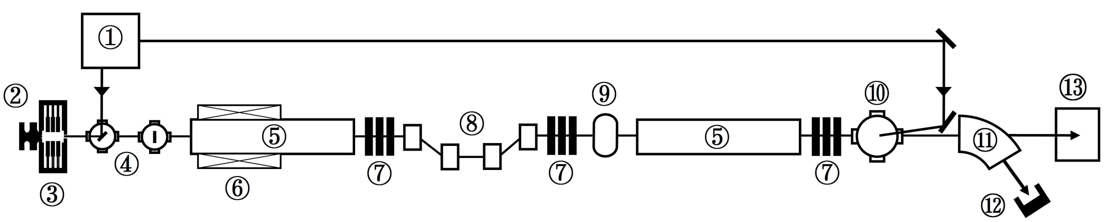

Fig. 1. Layout of the Tsinghua Thomson Scattering X-ray Source (not to scale). 1: laser system; 2: photocathode RF gun; 3: magnetic solenoid; 4: laser incidence and electron beams diagnostics chamber; 5: 1.5 m traveling-wave linacs; 6: solenoid; 7: focusing triplets; 8: four-dipole magnetic bunch compressor; 9: RF deflecting cavity; 10: Thomson scattering interaction chamber; 11: spectrometer dipole; 12: electron beam dump; 13: X-ray beam detector.

An ultra-fast laser system generates both the 266 nm ultraviolet (UV) pulses for electrons production and the 800 nm infrared (IR) pulses for scattering interaction. These two pulses are virtually jitter-free. The laser system is synchronized with the RF system through a timing circuit, with a timing jitter no greater than 200 fs.

Short UV laser pulses incident on the cathode nearly perpendicularly, and generate electron pulses with corresponding spatial distribution and bunch charge. The electron bunches are accelerated rapidly by high amplitude electric fields in the photocathode RF gun and reach 5 MeV at the gun exit. As mentioned above, the high charge density beam undergoes so-called emittance oscillation[13], and its projected normalized emittance can be compensated[14] by tuning the strength of the gun solenoid, the strength of the solenoid around the first linac tube, and the phase and amplitude of the first linac tube.

A four-dipole magnetic bunch compressor is used to compress the rms bunch length to lower than 1 ps, for the purpose of ultra-fast phenomena observation. The compression ratio is such chosen that the space charged induced emittance growth and energy jitter induced timing jitter are kept at an acceptable low level. The pole-face angles of the first and fourth dipole are adjusted to avoid over-focusing in the vertical direction. The first linac is run off-crest to introduce an energy chirp necessary for bunch compression, and the second one is used to eliminate the correlated energy spread and to boost the electron energy for desired X-ray wavelength.

An S-band RF deflecting cavity[15] is located after the bunch compressor. It is used for bunch length measurement and also monitoring the arriving time jitter of electron bunches induced by the laser-RF timing jitter and RF amplitude fluctuation. The deflecting cavity also allows advanced beam phase space manipulation, such as longitudinal pulse shaping[16] and emittance exchange[17], which foresee promising applications in plasma-based acceleration and high brightness light sources.

2.2 Simulation and design parameters

Simulated main parameters of the facility operation, and electron beam and X-ray beam parameters are listed in Table 1. We use the code PARMELA[18] for electron beam dynamics and the code CAIN[19] for Thomson scattering interactions.

Table 1. Simulated parameters of the proposed Tsinghua Thomson scattering X-ray source.

initial electron bunch parameters	
bunch charge	0.75 nC
bunch length/(Gaussian, rms)	2.0 ps
bunch radius (Uniform, hard-edge)	1.0 mm
main machine parameters	
repetition rate	10 Hz
gun RF field amplitude	97 MV/m
electron energy at gun exit	4.7 MeV
gun solenoid strength	0.20 Tesla
linac solenoid strength	0.10 Tesla
RF amplitude of 1st linac	19 MV/m
RF phase of 1st linac	-30°
RF amplitude of 2nd linac	21 MV/m
RF phase of 2nd linac	50°
electron bunch parameters at IP	
energy at IP	50 MeV
energy spread at IP (rms)	0.34%
bunch length (rms)	0.68 ps
normalized x emittance ϵ_x	2.8 mm-mrad
normalized y emittance ϵ_y	3.0 mm-mrad
spot-size in x direction (rms)	57 μm
spot-size in y direction (rms)	24 μm
laser parameters at IP	
wavelength	800 nm
bandwidth (FWHM)	3.8%
pulse energy	0.6 J
pulse duration (rms)	30 fs
spot-size (rms)	50 μm
generated X-ray parameters	
maximum photon energy	60 keV
single-shot photon count	3.2×10^7
peak photon flux	1.9×10^{19} s^{-1}
peak brightness/(s·mm^2·mrad^2·0.1%BW)$^{-1}$	5×10^{17}

In Fig. 2 we show changes of the normalized rms transverse emittance and rms spot-sizes with beam-line position z. A schematic of the layout is attached below indicating the corresponding beam-line components.

As a conservative assumption and based on some the recent experimental results[20], the initial longitudinal distribution of electron bunches is taken to be Gaussian. The rms length is chosen to be 2.0 ps. The initial transverse distribution is assumed to be uniform, with a hard-edge radius of 1.0 mm, since a uniform distribution leads to a linear correlation of the space charge forces with radial offsets, thus benefiting to the emittance compensation process, and the transverse shaping of the UV laser pulse is relatively easier to implement. Ideally, the bunch charge also has to be adjusted together with other parameters for optimized X-ray pulse durations and brightness. Our strategy is to set the bunch charge to a reasonable value, i.e. 0.75 nC at present, which is well achievable with the upgraded laser system (to be discussed below) and a Cu cathode, and then to optimize the downstream parameters.

The magnetic solenoid is a critical component for the control of the transverse emittance of electron bunches, for its focusing effects in combination with the space charge de-focusing forces within a single electron bunch make different longitudinal slices realign in the transverse phase space, and thus the projected normalized emittance is minimized. Downstream of the solenoid are several chambers for laser normal incidence and electron beam diagnostics. The entrance of the first linac is located at 1.5 m. The strength of gun solenoid is carefully tuned, in combination with the linac solenoid, and the RF phase and amplitude of the first linac tube. As shown in Fig. 2, the normalized transverse emittance ϵ_x and ϵ_y undergo oscillation and are damped adiabatically toward a minimum value of 2 mm·mrad.

Due to room limitation of the experimental hall, the whole beam-line can not exceed 10 m, thus we employ two identical linac tubes, which is the first half of a normal 3 m SLAC type traveling-wave structure. These two tubes are used to introduce and compensate the longitudinal energy chirp, respectively. The RF amplitude in linac tubes is limited no higher than around 20 MV/m for technical reasons, and these two 1.5 m tubes are adequate to boost the electron beam to 50 MeV for hard X-ray generation. By tuning the RF phases and amplitudes of the two linacs, the electron beam can reach energies lower than 50 MeV, thus the generated photons continuously extend to soft X-ray wavelengths. However, the bunch charge has to be reduced accordingly since space charge effects are more severe at lower energy.

Two focusing triplets are placed before and after the bunch compressor, respectively, for beam matching. A third triplet is located after the second linac tube for final focusing of the electron beam to an ultra-small spot-size for scattering at the interaction point (IP). The triplets also have applications in bunch length measurement using deflecting cavity, contributing to the transformation matrix or as that used in Ref. [21].

The dynamics of a short duration, high intensity bunch inside a bunch compressor is expected to be rather sophisticated. Since the bunch is chirped and dispersed, and electrons move along curved pathes,

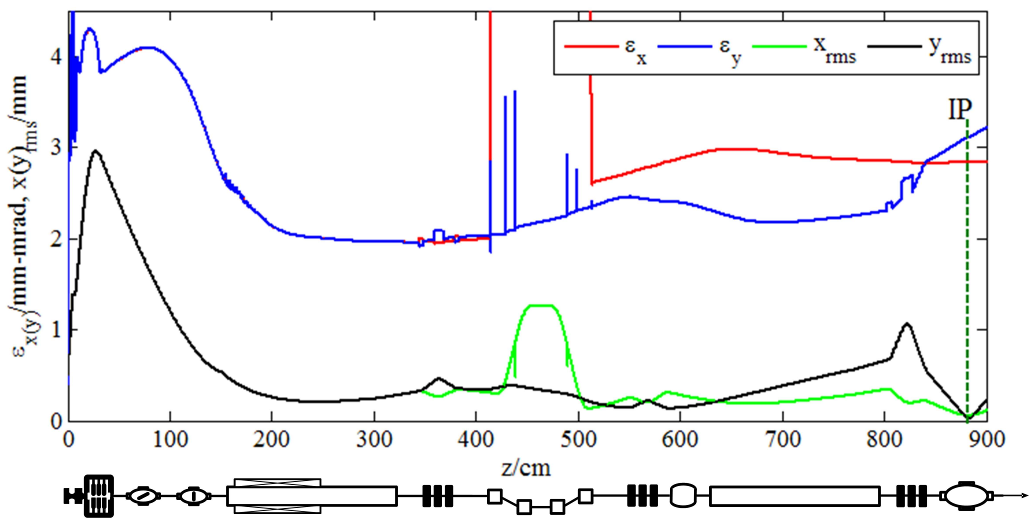

Fig. 2. Normalized transverse emittance (rms) and spot-size (rms) as functions of beam-line position z. A schematic of the layout is attached indicating corresponding components.

strong space charge interactions take place in a complicated geometry configuration, and coherent synchrotron radiation (CSR) may also affect the beam qualities in a coupled manner. PARMELA calculates space charge effects with reasonable bench-marked accuracies, while it lacks the capacity to take electron-radiation interaction into account, thus the results shown in Table 1 and Fig. 2 are estimations ignoring possible CSR effects. Subsequent design work will include introducing a self-consistent code that is able to deal with both space charge and radiation effects in three-dimensions.

Downstream of the exit of the third focusing triplet, strong emittance growth is observed in y-direction. This results from the intense focusing in y-direction, reducing the spot-size $y_{\rm rms}$ from 1.0 mm to 24 μm, thus increasing strong space charge forces blow up the divergence in y-direction. Electron bunches are focused to beam waist in both transverse planes at the IP position, and scatter with the laser pulses at 90° or nearly head-on. Scattered X-ray pulses propagate along the forward direction of electron pulses before scattering, and are collected by a detector or used for experiments. While electron pulses are bent by a spectrometer for energy and energy spread monitoring. Laser pulses parameters and X-ray pulses qualities predicated by code CAIN are shown in Table 1.

Simulation studies show that with the above properly chosen and technically achievable parameters, the proposed TTX source layout can produce short (0.7 ps) X-ray pulses with peak brightness exceeding 10^{17} photons/(s·mm^2·mrad^2·0.1%BW), there by enabling new capacities in many interested applications.

2.3 High average brightness X-ray source design

As discussed above, the linac based Thomson scattering layout offers X-ray pulses with very high peak brightness and short durations which are highly demanded for ultra-fast science studies, while the average flux is relatively low due to the limited repetition rate of high power RF and laser systems. A novel approach[22] suggests store electron pulses in a compact storage ring, and laser pulses in a optical cavity, respectively. The repetition rate of scattering interactions thus easily reaches tens of MHz, and the average flux will be dramatically increased. Several groups[23—26] around the world are investigating this approach, and we include this as part of the proposed TTX source. Lattice design and beam dynamics studies of this TTX compact laser-electron storage ring are presented in Refs. [27, 28].

3 Status of TTX

In parallel with simulation work of operation parameters optimization, some main subsystems have been built or purchased, or under commissioning.

The ultra-fast TW laser system is built by the Institute of Physics, the Chinese Academy of Sciences. It is capable of generating 266 nm UV pulses with 1 ps to 12 ps continuously adjustable durations, and with energy up to 1 mJ. The 800 nm IR pulses for scattering are in commissioning by the time we prepare this paper. Detailed design, status, and subsequent pulse shaping schemes of the laser system are discussed in Ref. [29].

A 1.6 cell S-band BNL/SLAC/UCLA type photocathode gun and an S-band deflecting cavity have been fabricated locally. Both structures are now being vacuumed and connected to the waveguide system, and are ready for baking and RF conditioning.

The RF system consists of a 320 kV, 50 Hz modulator, a Toshiba 50 MW klystron, and waveguides including power dividers, phase shifters, etc. The modulator and klystron have been conditioned to their full specifications. Waveguide system has been installed and vacuumed, and now under baking.

Installation and alignment of beam-line components are also scheduled.

4 Summary

In this paper, we introduce the proposed upgrade of the Tsinghua Thomson scattering X-ray facility as a compact, tunable, monochromatic, high brightness X-ray source. The layout, operation parameters, and qualities of electron and X-ray pulses are studied by simulations. Short duration (<1 ps), high brightness (>10^{17} photons/(s·mm^2·mrad^2·0.1%BW)) X-ray pulses are expected on this design, which has promising applications in ultra-fast science studies. While for medical and industrial applications which require high average flux, we include a compact laser-electron storage ring in TTX design. Main subsystems have been prepared or in commissioning. Beam experiments are foreseen before the end of 2008.

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