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The ThomX ICS source

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ABSTRACT

ThomX is a new generation Compact Compton Source. It is currently commissioned by and at the IJCLab (Laboratoire de physique des 2 infinis - Irène Joliot-Curie (UMR9012)) at Orsay. The first beam is expected at the begining of 2021. The aim of ThomX is to demonstrate the characteristics of an intense and Compact (lab-size) X-ray source based on Compton Scattering. The performances are mostly driven by the laser optical system which is above the state of the art of stored laser power. Proof of principle of various X-ray techniques will be performed thanks to the versatile ThomX beamline. Firstly, this article presents the machine description. Secondly, the issues and limits of the laser system are discussed. Then, the ThomX beamline is described and the machine status conclude the ThomX presentation. Finally, the expected performances for the next years and the possible experiments that can be made with this new machine are detailed.

1. Introduction

There is a growing demand on access to bright, monochromatic and tunable X-ray sources in cultural heritage (masterpiece studies), medicine (imaging and therapy) and industrial applications (material science). Synchrotron Radiation facilities are the best quality sources in both brightness and tunability criteria. But their significant dimensions, their building and operation costs, and the available time of beamline access are strong constraints on their usage and large diffusion. Nevertheless, Compact Compton Scattering (CCS) machines could provide a quasi-monochromatic X-rays beam whose compactness remains compatible with an experimental room for moderate costs compared to Synchrotrons. Recent developments on laser and optical system open the way to reach high X-ray flux and consequently high brightness with these machines compared to the present lab-size X-ray sources [1,2].

Different Compton machines are in construction or are already delivering X-ray beam. For instance at low energies (from 15 keV to 35 keV) the Compact Light Source (CLS) from Lyncean Technologies in Munich [3,4] provides daily X-ray beams for users with a flux of about $10^{10} - 10^{11}$ ph/s. In the order of magnitude of 50 keV, Tsinghua Thomson Scattering X-ray Source (TTX) [5] has already delivered its first beam with a flux of 10^7 ph/s. At higher energies (from 20 to 140 keV) the STAR project [6] is under construction to deliver an X-ray flux around 10^9 ph/s. To the end, the Extrem-Light-Infrastructure Nuclear-Physics Gamma-Beam-Source project (ELI-NP-GBS) [7–9] had to deliver X-ray beams with energies ranging from 0.2 to 20 MeV with a flux of 10^8 ph/s. For a wider energy range NESTOR in Ukraine from 10 keV to 900 keV with an X-ray flux of 10^{13} ph/s and SPARC in Italy from 20 keV to 500 keV with an X-ray flux of 10^{10} ph/s has just start their commissioning [10,11]. All these machines present different designs for the electron beam and the laser system: a Linear Accelerator (linac) or a storage ring for the electron beam, a single shot, an optical multipass or a Fabry-Pérot cavity for the laser beam. A non-exhaustive list of different Compton machines and their design and performances could be found in Refs. [2, 12,13].

Among the Compton machines, the ThomX project aims at providing a complementary bright and tunable X-ray source in a non-expert environment (museums, hospitals, laboratory). The compact source, under construction at the Irène Joliot-Curie Laboratory (IJCLab) in the Orsay campus of Paris-Saclay University, is designed to produce a total flux of 10^{13} ph/s and a brightness of 10^{11} ph/s/mm^2/mrad^2/0.1% bandwidth with a tunable energy ranging from 45 keV to 90 keV on the X-ray beam axis. Thanks to the kinematic of the Compton process with this total flux and the ThomX machine parameters, one can obtain 10^{11} ph/s in 2–3% of bandwidth with the sole use of a diaphragm having an angular aperture of 1 mrad (1% from the Compton process, 1–2% from the electron and laser beams characteristics). To reach these performances, both electron bunches and laser pulses will be stacked respectively in a storage ring and in a high gain Fabry-Pérot cavity.

Medical science applications are expected in the imaging field with standard radiography or with 3D tomography [14]. Thanks to the directionality and quasi-monochromaticity of the beam, other very promising developing fields are the K-edge imaging, the phase contrast imaging and the radiotherapy [15]. Operation of the source in hospitals can lead to an enormous increase in the number of treated patients. Different X-rays techniques could be used to provide a thorough material analysis for cultural heritage studies as well [16]. The result concerns works of art dating, employed techniques, attribution, primitive sketches detection and underlying drawings analysis. Other applications would be able to benefit from ThomX source, and CCS sources more generally, in such fields as crystallography, lithography, chemistry, metallurgy and biology. An energy scale-up can also explore applications in the nuclear fields (waste management and processing, nuclear spectroscopy, nuclear nonproliferation, etc) [17,18].

2. ThomX project

2.1. Machine description

The ThomX machine layout is represented in Fig. 1 and detailed in Ref. [19]. An electron beam of 5.3 MeV is produced by a photo-injector and then it is accelerated to a final energy range of 50 MeV–70 MeV by a S-band accelerating section. The 50–70 MeV electron beam is injected to and extracted from the storage ring at 50 Hz. The storage ring has a revolution frequency of 16.6 MHz. An optical resonator with a high finesse of about 40,000 is chosen at the Interaction Point (IP). It provides a gain around 10,000 to reach about 1 MW average laser power inside the cavity. The range of parameters available at ThomX is detailed in Table 1.

The electron source of the linac is a homemade photo-injector (2.5 cells, 3 GHz) placed between two solenoids for emittance compensation and focusing at the entrance of the accelerating section. The energy of 5.3 MeV is achieved with an 80 MV/m electric field gradient. Different cathodes materials will be available to provide the electrons by photo-emission. We will first start with a metallic cathode as Copper or Magnesium. Then, semi-conductor cathodes (i.e. CsTe) are foreseen with a preparation chamber.

In order to reach 50 MeV a LIL accelerating section, designed in-house and lent by synchrotron SOLEIL, the major partner of the project, was chosen. The LIL accelerating section is a quasi-constant gradient traveling wave structure. The energy gain in the section is 45 MeV, corresponding to an average effective accelerating gradient of 10 MV/m for an input RF power of 9 MW. However the linac should reach higher electron beam energies in order to produce X-rays beyond 45 keV. Since the maximum targeted X-ray energy is 90 keV, the linac design should allow an electron beam energy of 70 MeV, corresponding to an RF power of 20 MW. Thus, taking into account the RF system efficiency, the specification for the total RF power is set at 35 MW. The ThomX project is in the process of procurement of its own accelerating section with the same goals: final electron beam energies ranging from 50 MeV to 70 MeV.

To favour flexibility and compactness, the ThomX ring design is based on a Double Bend Achromats (DBA) configuration with a two-fold symmetry including eight dipoles, two long and two short straight sections. The Fabry-Pérot optical cavity is integrated in between the adjacent dipoles of one of the short straight sections. Other equipment as RF, feedback and injections pulsed magnets are accommodated in the dedicated two long sections.

The ThomX optical cavity is a four-mirror cavity in a bow-tie configuration with two planar mirrors and two spherical mirrors. The high finesse of this cavity allows to store up to 1 MW average laser power with only 100 W incident laser power.

After a first mechanical design phase, the full integration of the machine was assessed. Considering the final set-up, the calculated mechanical stresses on the bellows were taken into account to find a more flexible solution. For this reason it was decided to lengthen the ring circumference passing from 16.8 m to 18 m. Consequently, the ring passes from the 28th to the 30th RF harmonic of the 500 MHz RF system [20]. This impacts essentially the ring and the Fabry-Pérot cavity repetition frequency, thus reducing respectively the available average current and laser circulating power. The ring optical functions (see Fig. 2) were adjusted to fit the new length constraints, preserving the β^* of 0.1 m at the IP to keep the luminosity constant. In this context, the Betatron tunes and the momentum compaction factor were slightly modified compared to the original design [19]. The new parameters are listed in Table 1. Considering the new parameters, a linear scaling allows estimating at a negligible 7% the reduction of the emitted flux due to the reduced current. Moreover, in this framework, one should also take into account that the bandwidth of the optical resonator is proportional to the repetition frequency, therefore the cavity gain should be slightly reduced too.

2.2. Issues and limits of the Fabry-Pérot cavity

The enormous optical power stored (1 MW) permanently inside the Fabry-Pérot cavity induced huge thermal effects on the mirrors. One of the most limiting effect appears to be the transverse mode degeneracy [21,22] induced by thermo-elastic deformation of the mirror surfaces [23,24]. This degeneracy implies that different transverse optical modes are present at the same time inside the cavity, hence decreasing the available power at the interaction point.

The method used for ThomX to overcome this issue is to induce losses to higher order modes. We proposed a solution adapted from Ref. [25] that accounts for elliptical mode shapes and, high-finesse, low loss optical resonator. Instead of an intra-cavity pinhole, that could be damage at high average power, and in turn pollute the cavity mirrors, a pair of movable D-shape mirrors are used to induce large losses on high-order transverse modes while keeping the high finesse for the fundamental mode.

Table 1
Main nominal parameters of the ThomX machine [20].

Parameter	Unit	Value
Electron machine		
Injection frequency	Hz	10–50
Bunch charge @50 hz	nC	0.05–1
Cathode material		Cu, Mg, CsTe
Electron energy	MeV	50–70
Rms transverse size @IP	μm	45–100
Normalized beam emittance @IP	mm.mrad	2–9
Bunch length	ps	10–20
Ring revolution frequency	MHz	16.6
Optical cavity		
Laser wavelength	nm	1030
Incident average power	W	100
Stored average power	MW	1 (20–30 mJ/pulse)
Rms transverse size @IP	μm	40
Repetition frequency	MHz	33.3
X-ray beam		
Total flux	ph/s	10^{12}–10^{13}
Brightness (in 0.1% bw)	ph/(s.mm^2.mrad^2)	10^{10}–10^{11}
Rms transverse source size	μm	40
X-ray max. Energy	keV	45–90

The performances of these D-shape mirrors were evaluated with the power stored inside the cavity. If multi-mode operation occurs, the locking system fails to maintain the resonant condition and coherent power stacking cease abruptly. The results obtained on a test cavity demonstrate that without D-shape mirrors the power was held about 1 s and with D-shape mirrors the power stacking never cease during the whole experimental time. Moreover as the D-shape mirrors prevent the transfer of laser power to the higher order modes the luminosity of the interaction between electron bunch and laser pulse is maximized with a better overlap integral of the two beams. These results are very promising for a reliable usage of the X-ray source ThomX.

2.3. The ThomX beamline

The ThomX beamline named “X-line” is an original part of ThomX. The ThomX beamline is not a dedicated application beamline as usually done in synchrotron center. On the contrary the X-line is a versatile beamline for various applications. The X-line is composed of two main optical tables located after the interaction point on both sides of the concrete wall of the accelerator bay as shown in Fig. 3 and detailed in Fig. 4.

The first table shown in Fig. 4a is just after the interaction point about

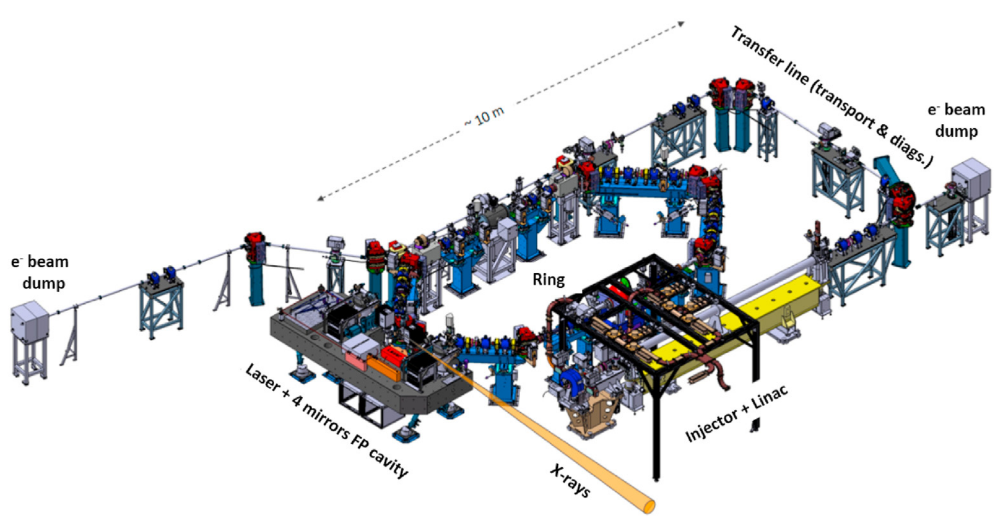


Fig. 1. ThomX layout.

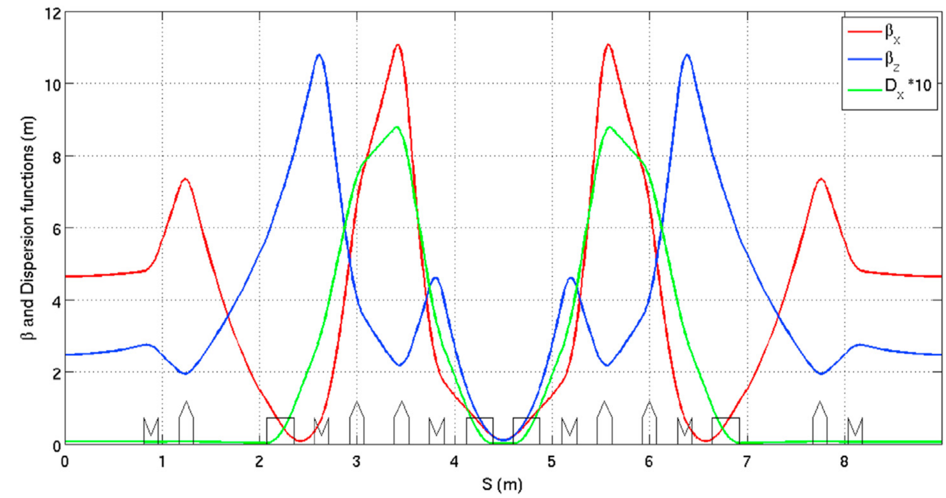


Fig. 2. Optical functions for the ThomX ring [20]. The IP is located at the center of the plot where the optical functions are minimal.

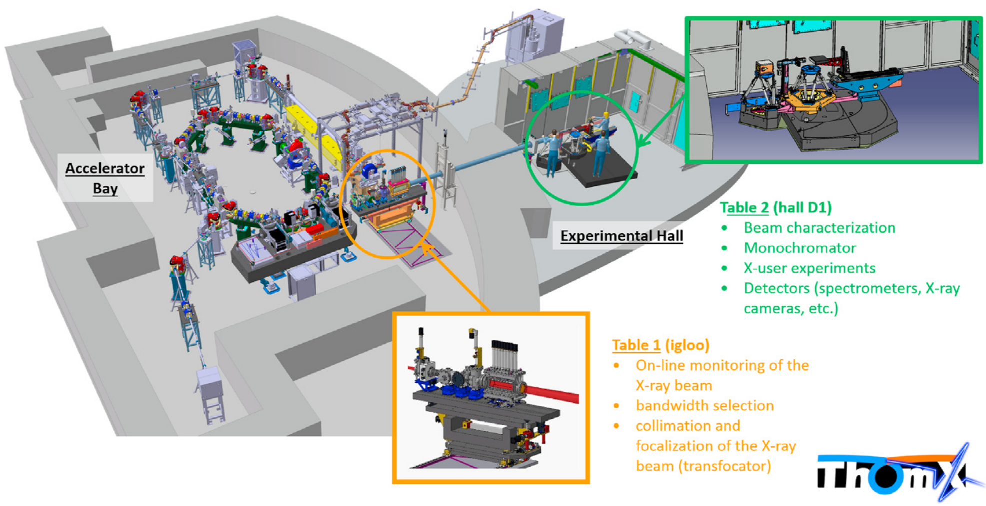


Fig. 3. The ThomX beamline: the "X-line" main components.

1 m downstream in the accelerator hall. It is used to monitor online the X-ray beam in position and intensity by means of redundant detectors:

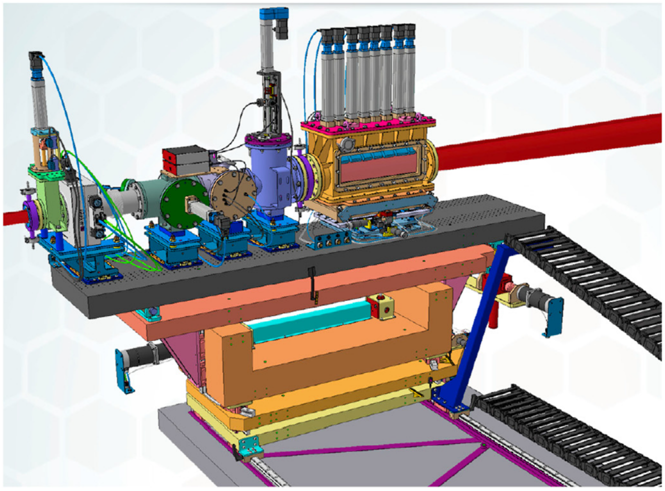
- a fluorescent screen coupled with a camera and a photodiode for the beam spatial profile and intensity,
- a diode detector based on the scattering of the X-ray on a thin sheet of kapton and 2 photodiodes in front of each other for beam intensity and vertical position,
- a wire detector for beam intensity and vertical (or horizontal) position, in the X-ray range of the apparatus developed in Ref. [26].

All these elements were carefully tested on CRG-FAME beamline at ESRF before installation to ensure their performances with the ThomX beam. The first table aims also to shape the beam for experiment. For instance there are a beam shutter for background correction, a pair of slits for beam bandwidth or spatial selection and at the extreme end of the table an optical refractive device (called a transfocator) to focalize or collimate the beam on samples.

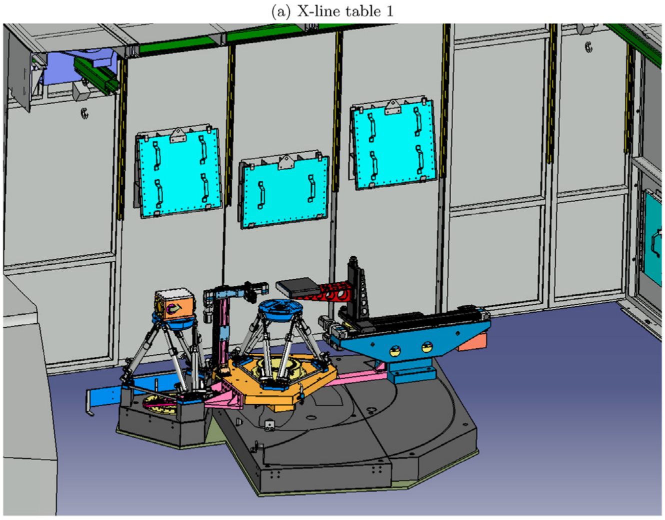
The second table shown in Fig. 4b is installed inside the experimental hall (the X-Hutch) located after the safety beam shutter and the concrete wall of the accelerator bay (for radiation protection purpose). This table is totally dedicated to users and experiments. It aims to position the samples in front of the detectors inside the X-ray beam. The second table is composed of two high precision hexapods (6 degrees of freedom positionner), one for a monochromator to reach 10^{-4} in relative energy bandwidth of the X-ray beam and one dedicated to the sample positioning. These two hexapods are mounted on an ultra-high precision goniometer for $\theta - 2\theta$ rotation. To complete the pair of hexapods, a second goniometer centered on the sample holds a detector arm. The X-line is mainly based on standard Synchrotron beamlines and it provides a wide panel of detectors for X-ray experiments which account for:

- two silicon based low energy spectrometers for X-ray fluorescence measurements,
- a CdTe based high energy spectrometers for X-ray fluorescence and X-ray beam characterization,
- a scintillation sCMOS camera with high resolution (few tens of microns) for medical imaging,
- a CdTe camera with lower resolution (hundred microns) for X-ray diffraction pattern or imaging,
- a calibrated Si photodiode for absolute X-ray flux measurements.

As for all the ThomX machine, the X-line is fully operated under Tango Controls protocol [27]. This integration allows users to access, to the different motors and detectors, through a unique protocol interface. It makes the experimental scan and data acquisition easier by avoiding



(a) X-line table 1



(b) X-line table 2 inside the X-Hutch

Fig. 4. CAD images of the two tables of the ThomX X-ray line.

complicated and time consuming development of interface programs or scripts to merge the information from different third-party softwares. One can notes that Tango is not the only controls-commands protocol available for scientific machine (e.g. EPICS), but it is the protocol already used by the ThomX collaboration partners Soleil and ESRF.

2.4. Machine status

ThomX project has been approved and financed in the framework of the EQUIPEX program of the French National Research Agency (ANR-10-EQPX-51). After a first study phase a Conceptual Design Report has been provided [28] summarizing the main aspects of the scientific case, the accelerator complex, the lasers and the users' X-line. This phase was followed by a detailed study of the expected parameters and of all the technical systems of the machine leading to the publication of the Technical Design Report [19]. In parallel, an important decision was taken concerning the infrastructure. ThomX will be integrated with another EQUIPEX accelerator project of the Orsay campus, ANDROMEDE, in the former "IGLOO" building creating the new IGLEX research platform. After the studies period in 2015, the infrastructures civil works started in 2016 and was finished in middle of 2017. At the same time, the majority of the equipment was delivered during this year. Its integration inside the building has followed and it is expected to be complete in summer 2020. The radiation protection studies related to the facility (shielding design, assessment of radiological exposure, radioprotection system design, radiation zoning and commissioning phases) were dealt with a CNRS specialist unit (iRSD) and IN2P3 [29]. The ThomX light source is awaiting for the technical approbation of the French nuclear authority ASN (Nuclear Safety Authority) and the delivery of the licence by the ASN is expected in the begining of 2021.

3. Expected performances and first experiments

3.1. Commissioning phases

The ThomX commissioning is based on three phases (cf. Table 2):

1. the first beams
2. power up
3. final performances.

Three stages were firstly defined to comply with the radiation protection objectives and PSS (Personal Securty System) validation planned in agreement with ASN and secondly to tune the different parts of the machine and their feedbacks step by step. During the commissioning phase, the first experiments will be carried out using the beam with reduced parameters. Experimental workload will progressively increase with the evolution of the machine parameters. The table 2 sums up the three phases parameters and performances.

3.2. First experiments

The commissioning of the light source will take some time, estimated to few years. During the first phase, the X-ray beam will not be stable and good enough to be used for reliable data acquisition. Moreover, during this phase, the machine will be permanently tuned to improve its performances and so the X-ray beam characteristics may be changed too. It is planned to use the first phase to take over the X-ray line and all its equipments.

Then ThomX will be ready to achieve first X-ray experiments as soon as a stable X-ray beam will be delivered. The first experiments planned on ThomX are the characterization of the X-ray beam in terms of flux, size and position, stability over time, angular spectrum and flatness (homogeneity).

Later experimental validation of the beam will be performed with standard experiments as X-ray diffraction on a calibrated powder, X-ray fluorescence of well-known materials, X-ray imaging of a phantom (medical calibrated sample) and phase contrast imaging of the phantom. In this way, it is possible to measure the transverse coherence, the monochromaticity and the focal spot size of the beam achievable with ThomX. Each characterization is a complex scientific experiment. The ThomX consortium, which is made of 8 partners, includes some French

Table 2
The ThomX parameters and performances during the three phases.

Parameter	Phase I	Phase II	Phase III
Electron machine			
Bunch charge	50 pC	100 pC	1 nC
Electron energy	50 MeV	50 MeV	50–70 MeV
Repetition frequency	10 Hz	50 Hz	50 Hz
Optical cavity			
Incident average power	50 W	100 W	100–150 W
Stored average power	100 kW	500 kW	1 MW
X-ray beam			
Total flux	10^{10} ph/s	10^{11} ph/s	10^{13} ph/s
Brightness (in 0.1% bw)	10^{8} ph/(s.mm^2.mrad^2)	10^{9} ph/(s.mm^2.mrad^2)	10^{11} ph/(s.mm^2.mrad^2)
X-ray max. Energy	45 keV	45 keV	40–90 keV

CNRS laboratories as LAMS and Néel Institute, in the cultural heritage domain, GIN or ESRF in the medical field. These partners will be the first users. In the future the ThomX light source will be opened to the X-rays users community.

The ThomX X-ray beam could be employed in two different ways depending on the requirements of the experiment [2]:

- a wide conical beam configuration dedicated for X-ray imaging that does not required small bandwidth but large field of view (exposed area). It could be used for X-ray tomography, medical imaging or for radiation therapy research.
- a focalized beam configuration, thanks to the transfocator that produces a small beam size and divergence, which is more specific for experiments that required high precision and small bandwidth. X-ray diffraction is one of these targeted applications.

The table 3 gives some parameters of these two beam usages.

A simulation of the expected X-rays position distribution on the sample plane after focalization for 50 MeV electron beam energy is represented in Fig. 5 (emittance effects are not considered). In this configuration, one can note that the energy spread comes from the intrinsic energy spread of the X-ray (about 5% RMS for ThomX emittance effects considered) and not from the angular energy dependence of the Compton scattering. This implies that the beam is homogeneous in energy.

Once the first experiments have been completed and the ThomX machine tuned, users from other laboratories could come on ThomX to exploit the X-ray beam of the future platform, and explore the limits of the machine. This phase is not planned before end of 2022.

3.3. *Why such a source is interesting for scientific fields*

The particularity of the Compton machine sources is their very high and broad energy range (i.e. from a few tens of keV up to a few tens of MeV class X-ray beam) which distinguishes it from the majority of synchrotron lines which rarely go above 30 keV and are not tunable over large energy range.

On the one hand, the high energy sources (around 100 keV) allow access to the threshold of heavy elements such as lead, tungsten and rare earths. High energy also brings a high penetration power, considering the characterization of absorbent and/or thick materials such as a turbine blade or an engine block. From an experimental point of view, high energy diffraction offers the possibility to perform pdf (partial distribution function) experiments including a wider range of the reciprocal lattice and thus a finer information of well or poorly crystallized materials. On the other hand, the high X-ray energy above 80 keV allows research in radiotherapy.

The monochromaticity and low near-natural divergence of the central cone beam provides a monochromatic, parallel decimetric beam size. This unique characteristic makes it possible to consider a clearly improved quality of radiography and/or tomography compared to the traditional sources used. Moreover, the chemical sensitivity is enhanced due to the possibility of scanning the X-ray energy around an absorption line energy of a chemical element of interest (K edge imaging).

The ability to excite at high energy and to scan around the threshold of an element makes X-ray absorption spectroscopy experiments feasible, which until now have only been carried out on synchrotrons. Determining the chemical speciation of an element is essential in understanding the active sites of metalloproteins (life sciences), the active sites of catalysts (energy science), the colored sites in cultural heritage science, etc. Thanks to this new source, it will be possible to carry out structural (DRX, SAXS), chemical (XAS) in-situ or in-operando characterization experiments and thus to determine, for example, the functionality of a catalyst or a battery.

Table 3
Parameters on sample for the two ThomX X-ray beam usages (at the final machine performances at 50 MeV electron beam energy).

parameter	Conical beam	Focalized beam
total flux	$10^{11} \rightarrow 10^{13}$ ph/s	$10^{6} \rightarrow 10^{8}$ ph/s
beam size (rms)	35 mm	150 μm
beam divergence (rms of dispersion angle)	3.2 mrad	22 μrad
bandwidth	5–12%	10^{-4} - 5%

4. Conclusion

The ThomX machine is a novel Compact Compton Source aiming a brightness of 10^{11} ph/(s.mm^2.mrad^2) in 0.1% of bandwidth which is above the state of the art of these actual machines in terms of X-ray brightness (10^9 ph/(s.mm^2.mrad^2) in 0.1% of bandwidth) [3,4]. Those performances are ensured by a compact electron storage ring and a high finesse optical cavity. The choice of the storage ring setup, is driven by the 16 MHz repetition frequency of the X-ray production. The ThomX design phase is achieved and the ThomX project will enter the commissioning phase when the ASN licence is delivered. The commissioning time will be used also to take over the X-ray line equipment when X-ray of 45 keV will be available in 2021. Then when stable X-ray will be delivered, first proof of principles will be held. Finally once the commissioning is done, first academic users will be welcomed. The optimization towards nominal performances phase is expected to last 2 years from the moment when the first electrons are produced.

CRediT authorship contribution statement

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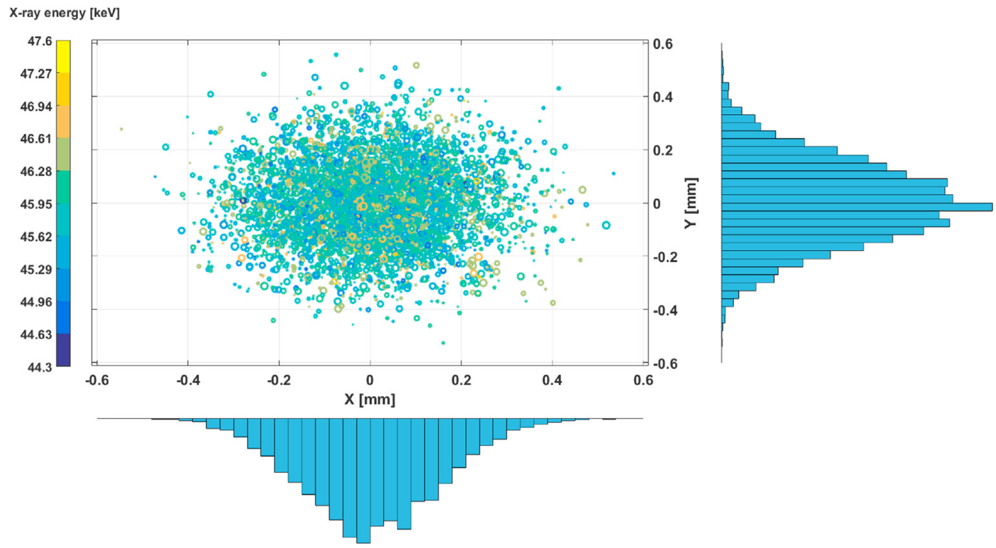

Fig. 5. The X-rays position distribution on the sample plane for 50 MeV electron beam energy. Circle size represents the flux of the macro-photon and circle color the relative energy of the X-ray.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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