The ThomX Project

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on behalf of the ThomX Collaboration#

Abstract

ThomX is a Compton source project in the range of the hard X rays (40 ÷ 90 keV). The machine is composed of an injector Linac and a storage ring where an electron bunch collides with a laser pulse accumulated in a Fabry-Perot resonator. The final goal is to provide an X-rays average flux of 10^{11}÷10^{13} ph/s. The emitted flux will be characterized by a dedicated X-ray line. Different users are partners in the ThomX project, especially in the area of medical science and cultural heritage. Their main goal will be the transfer of all the experimental techniques developed on big synchrotron rings to these more compact and flexible machines. The project ThomX has recently been funded and will be located on the Orsay University campus. In this article the project and its associated scientific interest are presented.

INTRODUCTION

Compton backscattering (CB) is the physical effect that most efficiently boosts the photon energy. In the head-on configuration the backscattered photon frequency is increased by a factor 4 γ^2 where γ is the relativistic factor. Therefore, by colliding a laser beam and relative low energy electron bunches, it is possible to provide hard X rays, in the tenths of keV range. In the past, the Compton cross section value did not allow the development of a CB-based source owing to the low flux achievable. Nevertheless the impressive technology performance increase in the area of fibre lasers [1], optical resonators [2] and particle accelerators is boosting different projects in this context. An interest in these machines has been shown by different users attracted by compact and relative low cost sources that have a high photon energy cut-off, even though they cannot provide the same brilliance and flux as synchrotrons. Moreover, owing to the energy-angle dependence, CB allows monochromaticity of the order of percent by only using a diaphragm system.

In this framework the French project ThomX [3] has recently been financed and a collaboration between different institutes and an industrial partner has been set-up. ThomX will be a CB compact light source composed of a 50 - 70 MeV storage ring and a high average power fibre laser amplified in a passive optical resonator. For the two working energies a spectrum cut-off of respectively ~45 and 90 keV is expected. This will enable the scientific partners to exploit this new source performance and to transfer the experimental techniques developed in synchrotrons to the specificity of the CB sources.

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Scientific case

Different phases have been planned for the ThomX project. First it will work as a demonstrator exploring the subtleties of the beam dynamics under Compton scattering regime. In the following phase it will provide X-beams to the users. In this context two fields will be explored by the communities involved in the baseline ThomX program, medical science and cultural heritage preservation.

As far as the former is concerned the imaging field is very promising. Providing a quasi-monochromatic beam concentration charts can be obtained by energy (K-edge) or temporal substraction by means of contrast agents (Gd, I, Xe, Au) [4]. The physiopathology and the in-vivo histology are provided by the synchrotron radiation (SR) dynamics contrast enhancement [5]. Studies on the contrast agents as specific function nanoparticles-vectors are extremely promising (as for example in convection enhanced delivery [6] where the drug targets only the tumoral cells) not only for the imaging, but also for the new therapy technique, the synchrotron stereotactic radiotherapy [7]. The latter is a technique developed in ESRF, where tuning the spectrum cut off on the k-line of the contrast agent will allow a local increase in the deposed energy in the tumor with respect to the other tissues. One of the most important immediate applications is given by the phase contrast imaging. This can be applied to mammography [8], microtomography [9], histology and biological tests.

In the cultural heritage preservation field the very important added value of a CB source is the compactness, and consequently the possibility to be installed in a museum giving the masterpieces direct access to the laboratory (in situ analysis) thus avoiding very expensive and complicated transport procedures. In this framework there are many different possible monochromatic X-rays experimental techniques complementary to the existing ion beam analysis (IBA) [10]. Physico-chemical analysis of heavy elements, their environment and the material organisation should be possible thanks to X-ray diffraction and scattering. Phase contrast imaging interest in palaeontology on fossils and amber samples have already been demonstrated [11]. Many other applications are possible with a state-of-the-art CB source [12] (absorption, tomography, XANES, magnification..), targeting a total material analysis and therefore having a deep impact on the research activity of art historians and restorers.

THE THOMX SOURCE

The Accelerator Complex

The ThomX accelerator complex is divided in three parts: the injector, the transfer line and the storage ring.

The 50 Hz injector consists of a high brilliance electron gun and a LIL-type S band accelerator section. The RF power will be supplied by a 35 MW klystron pulsed by a solid state IGBT switch modulator. A directional coupler will split the power towards the gun and the accelerating structure through a phase shifter and a variable attenuator. The gun design is similar to the existing 'CTF3 sonde' [13] with a Q factor of 14400, a pulse length of 3 μs, a R_s of 49 MΩ/m giving 100 MV/m at 9.4 MW. An Mg cathode will allow the emission of 1 nC bunches once triggered by a 100 μJ, λ = 266 nm laser. At the gun exit Parmela simulations show a normalised r.m.s. emittance smaller than 5 π mm mrad and an energy spread of about 0.7 %. Other beam dynamics simulations have been worked out taking into account the accelerating structure and both a Gaussian and a flat shaped laser beam for 50 and 70 MeV final energy. At 50 MeV, in the flat top case, a normalised emittance of 4 π mm mrad and an energy spread of 0.36 % with 3.7 ps bunch length were obtained which fit the ThomX's injector specifications. A similar performance with reduced emittance (~ factor 2) was obtained in the 70 MeV injection. At the end a dedicated beam diagnostic line (OTR, Yag and Cerenkov radiator for respectively beam sizes, emittance, and bunch length measurements) will allow the beam characterization.

The transfer line is based on the same magnetic elements family as the ring. A first diagnostic station, in a dispersive region, will be used for the energy spread measurement. Another one, before the septum, will provide the transverse and longitudinal emittances, the dispersion matching and the orbit steering for the injection optimisation. Since for the different scientific users it is important to minimize the environmental noise, it was chosen to inject and properly extract towards a beam dump using three pulsed magnets in the same straight section: one kicker for the beam extraction, the septum for both injection and extraction and one kicker for the injection. In order not to impact on the SR length, the pulsed magnets active lengths have been reduced to 250 mm. The small gap field transverse homogeneity and the minimization of the septum stray field is a challenge. So we chose to develop an in vacuum eddy current septum, excited by full sine pulses of current, associated with a magnetic shielding around the stored beam inner pipe. With this solution a very low stray field (a few μT.m) is expected [14]. The realization of the kicker magnets pulsed power supplies will be the subject of a development program based on a fast solid-state switches prototype, owing to the short pulse length (56 ns) and the very high current rate of rise required (~20 kA/μs).

The storage ring optics [15] is based on a four-fold symmetry Double Bend Achromat. The revolution frequency is ~ 17.8 MHz. To improve the compactness and the critical aspect of the optical cavity integration, the Interaction Point (IP) was inserted in the middle of two adjacent dipoles, in the zero dispersion region (see fig.1). This appealing design introduces the feasibility of a second interaction region and frees the straight sections for the injection, the RF and the feedbacks. Due to the injection mismatching, the CSR effect and the absence of synchrotron damping the longitudinal and transverse feedbacks performance will be decisive for the beam stability (~ 5 μs for longitudinal stabilization). A 500 MHz (harmonic 28) ELETTRA-type cavity, powered by a 40 kW SOLEIL-type solid state amplifier [16], will provide the 300÷500 kV necessary for the required energy acceptance. The HOM tuning is achieved with a precise control of the cavity temperature and a movable plunger on the equator. The LLRF will consist of a conventional set of slow frequency, phase and amplitude loops. In addition a high gain direct RF feedback and a fast phase loop will generate a strong longitudinal damping. The bucket and dynamical acceptance are respectively 10% and 2.4 % (at 300 kV). The transverse feedback will be provided by a dedicated stripline. In fig.1 the layout of the ThomX accelerator complex is illustrated.

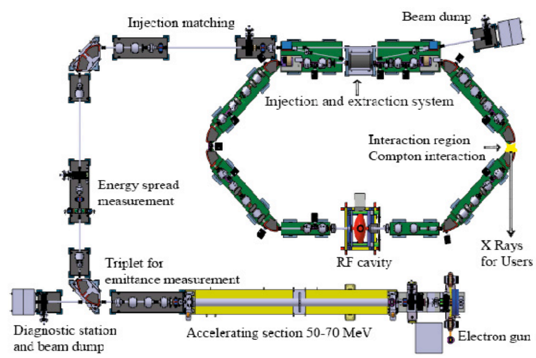

Figure 1: Layout of the ThomX accelerator. The main different parts of the machine are illustrated.

The ThomX ring is extremely challenging since it explores a new domain of beam dynamics: low energy, no synchrotron damping, mismatched injection, Compton recoil induced longitudinal spread, IBS, residual gas scattering, ions instabilities together with the ring impedance and high electron bunch density. The simulations show that after the injection a longitudinal turbulent regime appears (see fig.2) that must be controlled by the feedbacks. The equilibrium is reached for 20 a ps bunch length and a 0.4% ΔE/E. Fig. 2 a,b,c displays respectively a beam before (a) and immediately after (b) the injection and at the equilibrium (c) after the feedback stabilization (1000 turns).

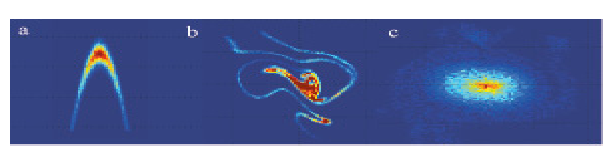

Figure 2: Beam longitudinal dynamics different phases.

The Laser System

To provide a significant X-rays flux it is essential to have at one's disposal a very intense laser pulse at the accelerator revolution frequency. To this end a system based on a high average fibre laser coupled with a high gain Fabry-Perot optical resonator is under development in the framework of the Mightylaser experiment [17].

The laser architecture will be based on the Chirped Pulse Amplification (CPA). The main parts will be a laser fundamental harmonic oscillator (35.7 MHz), a stretcher unit, a 100W Yb-doped fibre amplifier, a compressor and the injection in the optical resonator. To be able to lock the very high finesse Fabry-Perot cavity the laser must provide a stable, Gaussian, low phase noise pulse. This is a challenge owing to the high pulse energy. Therefore, an on-going R&D program aims at providing an all-fiber integrated amplifier working on mode adapters, fibre connectors and splicing, high power combiners and the fibre end facet preparation. In parallel a great effort is put forth in technology for larger core design, integration of the stretcher-compressor units and the evaluation of hybrid architectures (fibre and bulk). The goal is to achieve 2.6 µJ per pulse with $\Delta\lambda$ = 1nm at λ = 1032 nm.

The Fabry Perot resonator is based on a four mirrors design and the experience on the vacuum integration aspects acquired in Mightylaser. In the ThomX case, the cavity length imposes two monolithic mirrors supports where tilting actuators will be in charge of the feedback corrections. The cavity is designed to have a two degree collision angle and 30000 finesse thanks to the insertion of high reflectivity mirrors. Recently in LAL this has been achieved with an excellent stability on a long period and 50 % injection coupling. The resonator locking is based on the Pound Driver Hall technique with errors signals provided by three different parts of the cavity spectrum. Eight 14 bits ADC channels with a clock of 100 MHz are connected to the core of the system, a digital VirtexII FPGA with 60 ns latency time. A 100MHz digital system will be used to achieve the needed stability. The errors signals will be read by 14 bits ADC connected to a FPGA digital core including the locking acquisition and the feedbacks between the accelerator, the Fabry-Perot resonator and the laser. The corrections signals will be split to different actuators drivers by 14 bits DAC. The global latency of the digital system will be below 1µs allowing more than 200kHz of bandwidth. At present the Mightylaser cavity is installed in the ATF ring (KEK Tsukuba, Japan) and with a low input laser power and locking at a finesse of 3000 more than one photon per crossing at 178.5 MHz has been produced [17]. An increase in the stored power is planned for the winter run.

The X-ray Line

The X-ray line has two different missions. In the first phase it will characterize the X beam as far as flux, beam profile, spectrum and brilliance are concerned. Subsequently, it will be dedicated to scientific users. For the beam measurements a slit system will allow the selection of the angles and therefore of the spectrum. The beam characteristics will be measured respectively by: an in-out fluorescent screen for the beam detection, a kapton foil with a 2 diodes system for the intensity and a wire beam profiler for the beam sizes and position. In the latter the introduction of a special powder should provide a spectrum measurement.

Conclusions

At present there is a strong interest in the scientific community to explore the performance and the experimental applications of the Compton Backscattering light sources. In this framework the ThomX project has provided a collaboration framework for different French institutes. It has recently been funded and the construction phase will start next year. Thanks to diverse expertise and the R&D programs on high average power laser and high gain optical resonator the expected performance is very ambitious in respect to existing projects. Moreover, after the demonstrator phase, an effort to assure the reliability of the ThomX source is expected to provide beam time for the scientific users.

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