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EVOLUTION OF THE INVERSE COMPTON SCATTERING X-RAY SOURCE OF THE ELSA ACCELERATOR*

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Abstract

The Inverse Compton Scattering (ICS) X-ray source of ELSA accelerator at CEA-DAM, presents an efficient approach for generating X-rays with a compact linac. The source consists of a 30 MeV, 15 ps rms, up to 3 nC electron beam and a table-top Nd:YAG laser. X-rays are produced in the 10-80 keV range, higher X-ray energies achieved with frequency doubling of the laser. The yield is increased by a factor of 8 thanks to an optical mirror system developed at CEA, folding the laser beam path and accumulating successive laser pulses. We present a new version of the device, with improvement of mechanical constraints management, adjunction of motorized mirrors, and a new imaging system. A Chirped Pulse Amplification (CPA) system was also designed, enabling higher amplification levels without exceeding laser damage threshold. The uniqueness of this CPA system lies in its use of a short wavelength bandwidth, ±250 pm after Self-Phase Modulation (SPM) broadening, and a line density of 1850 lines/mm for the gratings of the compressor. The pulse will be stretched with a chirped fiber Bragg grating (CFBG) before amplification in Nd:YAG amplifiers, and compressed by a double pass grating compressor.

ELSA X-RAY SOURCE

ELSA Accelerator

ELSA produces X-rays for studies of detectors used in facilities like the Laser Megajoule at CEA CESTA. The ICS source will be used to produce high flux in both single-shot and recurrent modes in the 10-80 keV range. The main goal is to produce 20 ps X-ray pulses in single-shot mode, with a flux of 10^{18} ph/s/cm^2. First experimental results have been published in 2010 and 2016 [1, 2], still far from the ultimate goal, but showcasing potential for scaling up the X-ray flux. The accelerator (Fig. 1) is an electron linac featuring a 144 MHz photoinjector, 433 MHz accelerating cavities to reach 17 MeV, and a 1.3 GHz to reach 30 MeV, delivering 0.1 to 3 nC bunch trains typically at 1 Hz [3]. Double alpha magnets compress bunches from 80 to 28 ps before the final acceleration stage and the Inverse Compton Scattering (ICS) interaction point (IP). The accelerator can currently supply 10^4 bunches per train at 17 MeV, or 300 bunches per train at 30 MeV, and can also deliver single bunches.

Compton Laser

The laser dedicated to the ICS emits laser pulses at the same rate as the electron bunches, with similar temporal shape. It consists of a 144 MHz mode-locked Nd:YVO_4 oscillator at 1064 nm, a pulse selector, three Nd:YAG amplifiers, and eventually a KTP or LBO crystal for frequency doubling to 532 nm. Quadrupling can be achieved by the addition of a BBO crystal but is not implemented yet. The laser system can presently deliver up to 150 mJ per train at 1 Hz at 532 nm.

SMILE Device

At the interaction point (Fig. 2), our SMILE system (System Multipass Interaction Laser Electrons) focuses and superimposes 8 successive laser pulses going back and forth between two planes, reflecting on a series of spherical mirrors separated by a distance allowing a round trip time equal to the emission period of the laser pulses (Fig. 3). Thus eight successive pulses can interact with one electron bunch at the same time.

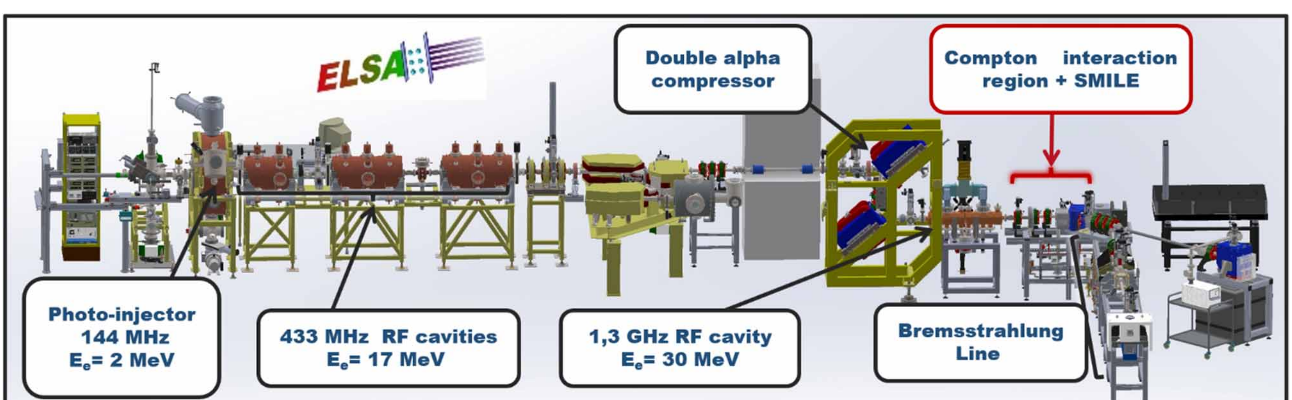

Figure 1: Layout of the ELSA Accelerator.

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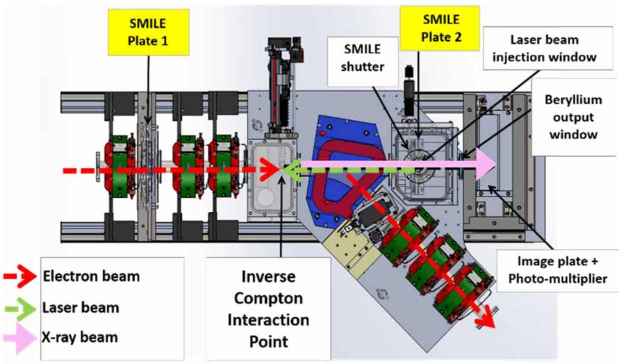

Figure 2: Top view of the Compton interaction Region.

For clarity, only forward trajectories are shown in Fig. 3. Forward paths pass through the interaction point whereas backward paths go around the interaction point (Fig. 4) therefore lying outside of the trajectory plane.

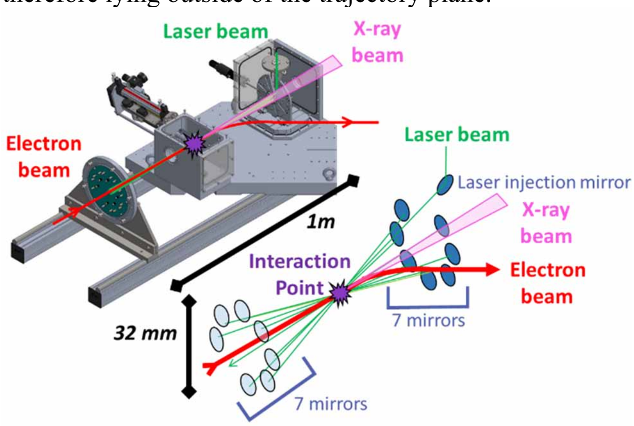

Figure 3: 3D view of the SMILE and schematic (not to scale) with highly exaggerated angle.

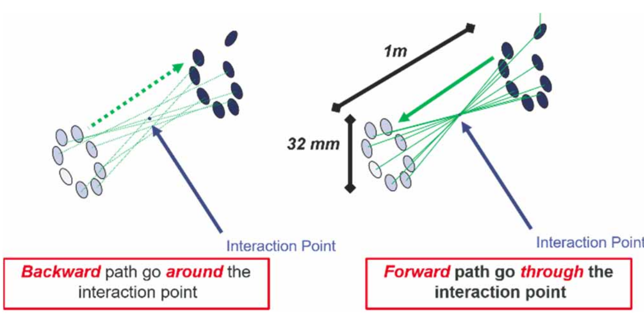

Figure 4: Trajectories of laser beams in the backward and in the forward direction.

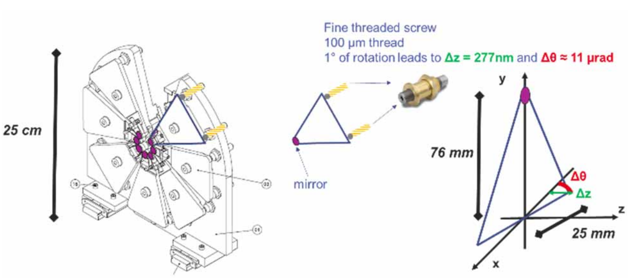

Figure 5: 3D view of the SMILE and schematic.

The SMILE device optomechanical system was designed for high angular precision. Mirrors are placed at the end of lengthy triangular metallic plates, with fine-threaded screws adjusting the plate orientation at the other two ends to achieve µrad precision (Fig. 5).

STRATEGY FOR OPTIMIZATION

A global analysis was done to bring out the pitfalls of the source and build a global strategy encompassing multiple domains. The planned improvements are: (i) a SMILE upgrade to reduce mechanical constraints including a redesign of the interaction area, (ii) the development of a remote alignment method compatible with IR laser, (iii) a Chirped Pulse Amplification (CPA) system to avoid laser damage risks in the laser amplifiers, (iv) Twiss parameters and charge optimization, (v) the linearization of the accelerating field by a decelerating 1.3 GHz cavity for bunch compression enhancement and (vi) an upgrade of the 1.3 GHz accelerating cavity and klystron system. Only the 3 first items are addressed in this article. First results for item (iv) have been published at IPAC'23 [4].

Re-designing the Interaction Area

The SMILE exhibited two key shortcomings. Firstly, the mechanical components supporting the mirrors displayed slight shifts when transitioning from atmospheric pressure to vacuum conditions and drifted along the day. The whole mechanical system was redesigned, thoroughly isolating constraints on the mirror plates (Fig. 6) and on the laser injection mirror (Fig. 7). Secondly, alignment used to be done manually, forbidding further fine adjustments and necessitating frequent disruption of vacuum conditions. The fine thread screws were replaced by piezo actuators (Fig. 7), enabling the ability to align the mirrors directly in vacuum.

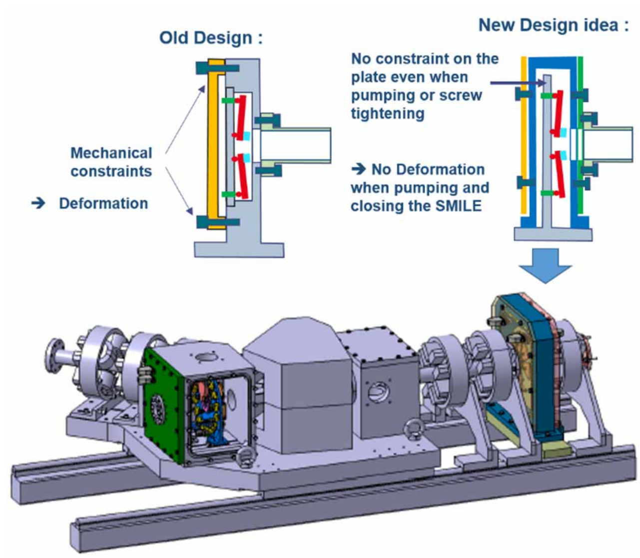

Figure 6: New mechanical design of the SMILE with better mechanical constraints management.

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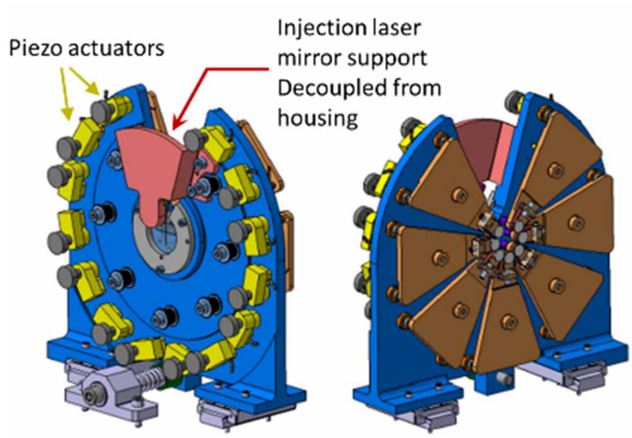

Figure 7: New design for the injection laser mirror and addition of piezo actuators

Remote Alignment Method for IR Laser (1064 nm)

It is often preferable to use IR photons (1064 nm) to maximise the X-Ray flux when using the source in the 5 – 20 keV range, as the frequency doubling yield is only about 30%. In this case alignment with direct eye observation is not possible anymore.

A new alignment method using three CCD cameras and the piezo actuators was developed, allowing, in the near future, the implementation of a real time automatic adjustment to compensate for the various environmental drifts.

Chirped Pulse Amplification

A CPA system was designed to avoid laser induced damage in the amplifiers, limit non-linear effects, and shorten laser pulses (Fig. 8). The specificity of this design is the narrow bandwidth (0.03 nm) Nd:YAG laser chain. A similar system was designed to use as a pump for near and mid-IR OPCPA [5], but never used for an ICS source. All parts were actually delivered, and are now in the process of installation and alignment, with tests scheduled in the following weeks. The narrow bandwidth is an advantage for ICS source, as the ΔE/E is kept small.

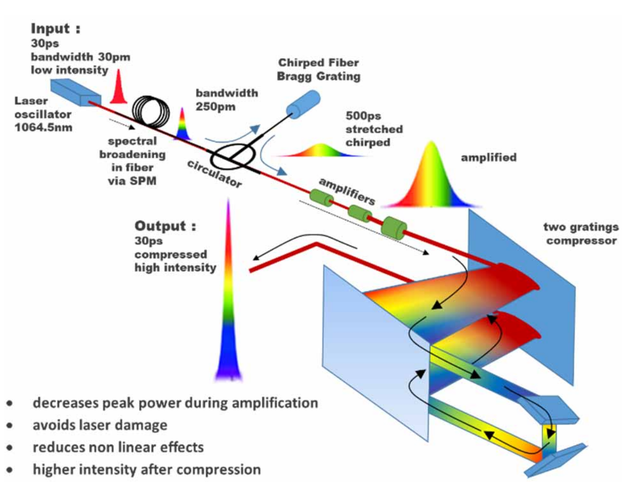

Figure 8: Principle of the new CPA system under development.

We present here the main features of the design of our CPA (Fig. 8). First the laser spectrum is broadened to 0.25 nm by self-phase modulation (SPM) in a 6.6 µm-core monomode fiber. Then the laser pulse duration is stretched to 500 ps by a Chirped Fiber Bragg Grating (CFBG) before amplification in three Nd:YAG modules. The pulse is then compressed by a double-pass gratings compressor using high line density (1850 l/mm, Fig. 9), high laser resistance high efficiency (> 96%, Fig. 10) gratings at an angle of incidence of 78°, 2° apart from the Littrow angle to enhance dispersion. The distance between the gratings is 1.7 m. These parameters were used to maximise diffraction efficiency and dispersion, in order to keep the system compact.

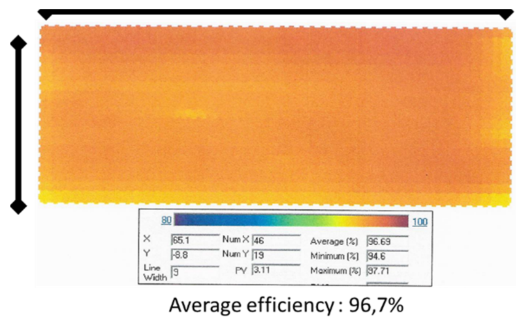

Figure 9: Scanning of the diffraction efficiency over the surface of the grating. Excellent efficiency was achieved. Courtesy: Plymouth Grating Laboratory

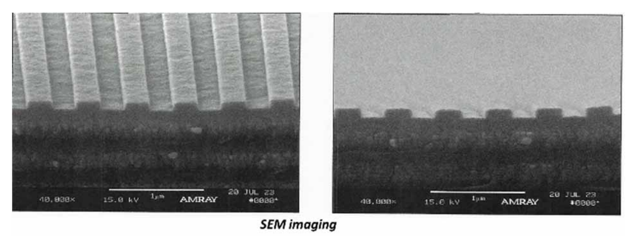

Figure 10: SEM imaging of the grating. Courtesy: Plymouth Grating Laboratory

CONCLUSION

The ICS source of ELSA is undergoing deep improvements on several fronts. They include the upgrade of the laser pulses piling up system SMILE with better mechanical constraints management to improve alignment maintaining, the use of IR laser pulses which led us to develop a camera-based alignment system, and the development of a CPA system to avoid optical damage in the laser amplifiers. The main features of the design of these improvements were presented in this proceedings paper. All parts have been actually delivered and are now being installed and tested in the laboratory. Final tests on the ELSA accelerator are scheduled by the end of the year. Other optimizations are also carried out simultaneously on other aspects, namely the optimization of the electron beam Twiss parameters and current, the optimization of bunch compression by a field linearizing 1.3 GHz cavity, and an upgrade of the 1.3 GHz accelerating cavity and klystron system. All these enhancements will contribute to a more versatile, user-friendly source with significantly improved yield.

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