Politecnico di Milano

School of Industrial and Information Engineering

Engineering Physics

The S.T.A.R. Accelerator: Structure and Applications

Extended abstract

Asaf Maiblatt

Student Number: 937439

Supervisors: Professors Ezio Puppin and Luca Serafini

March 2025

The S.T.A.R is a new backscattering Compton X-ray source, currently under construction in the University of Calabria in Cosenza, Italy.

It is based on a scattering interaction between an electron beam and an infrared laser.
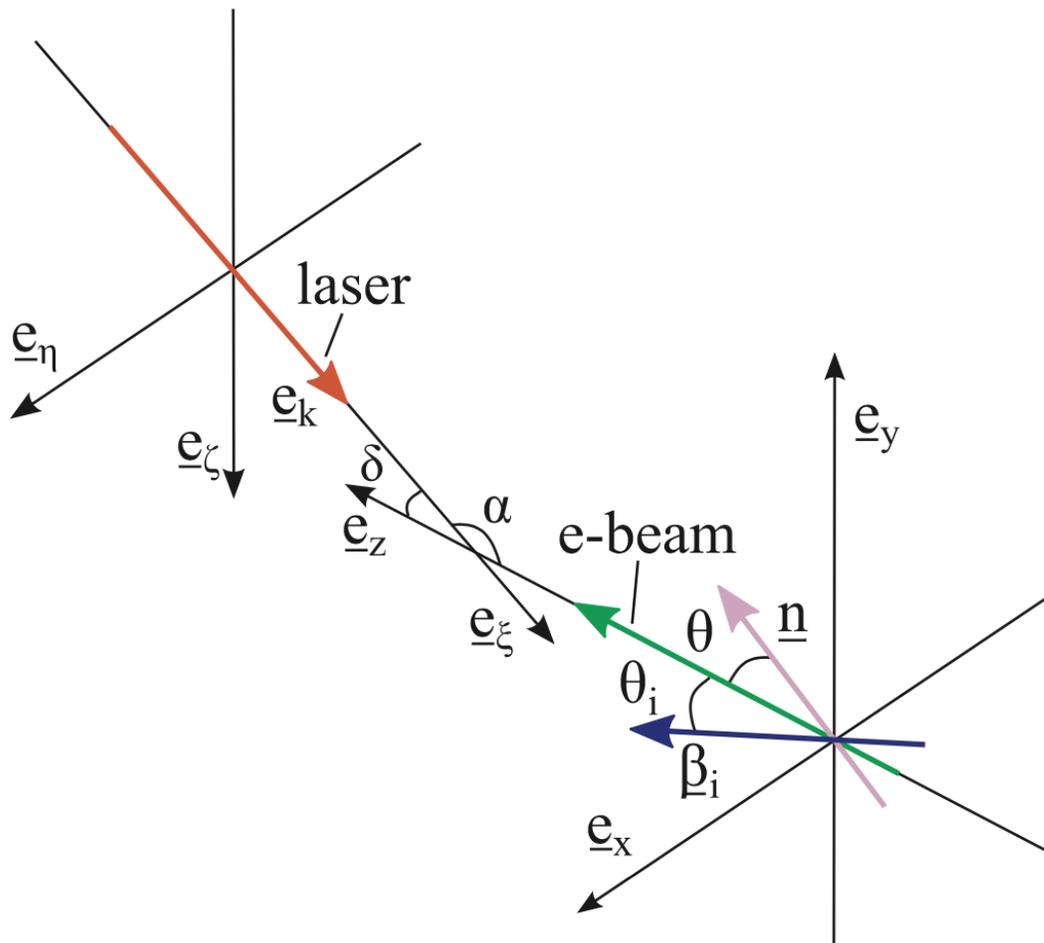
Thompson model[1]

Figure 1. Geometry of laser-electron beam interaction. p. 111.

[1] from **Photon flux and spectrum of γ-rays Compton sources**. pp. 110-112.

The radiation frequency produced by the interaction is $\omega_X = \frac{\omega_L(1+\cos\alpha)}{1-\beta\cos\theta+2\hbar\omega_L/(mc^2\gamma)}$

where $\hbar$ is the reduced Planck constant, $\beta = {v_e}/{c}$ v_e is the electron velocity, c is the speed of light, m is the electron mass, γ is the Lorentz factor of the electron[2].

In the limit $4\hbar\omega_L/(mc^2) << 1$ the last term on the denominator is negligeable and the process is classical so $\omega_X \approx \frac{\omega_L(1+\cos\alpha)}{1-\beta\cos\theta}$. If we aspire for a head-on collision, $1 + \cos\alpha \approx 2$ and the increase of the frequency of the scattered beam will be mostly due to bringing $\beta = \frac{v}{c}$ closer to 1, which means that the faster the electron beam will travel, the higher the frequency of the scattered beam would be. To decrease the effect the changing θ angle will have on the frequency, it is common to place the sample a long distance (few meters) away from the laser-electron beam interaction point. This will guarantee an almost monochromatic X-ray beam hitting the sample. If we wish to calculate the energy of the scattered X-ray photons, we can use this formula[3]:

$$E'_{ph} = \frac{4E_L\gamma^2}{1 + X + \theta^2\gamma^2}$$

E'_{ph} is the scattered photon energy. E_L is the laser photon energy, in the lab frame. $\gamma = E_e/(m_ec^2)$ where E_e is the energy and m_e the mass of the electron in the electron beam. $X = \frac{4E_eE_L}{(m_ec^2)^2}$ is the representation of electron recoil, after the laser-electron beam interaction. $m_ec^2 \approx 511\ keV$ is the rest mass of the electron and c being the speed of light in vacuum. Similarly to the frequency calculation, placing the samples a few meters away from the laser-electron beam interaction point will reduce θ to 0, and the formula would be

$$E'_{ph} = \frac{4E_L\gamma^2}{1 + X}$$

[2] see **State of the Art of High-Flux Compton/Thomson X-rays Sources**, p 2.
[3] see **Simulation of inverse Compton scattering and its implications on the scattered linewidth**, p. 030701-2

In this case, E'_{ph} is almost monochromatic and is the maximum energy of scattered X-ray photon achievable. Again, we can see a strong correlation between the energy of the scattered X-ray photon and the electron's energy in the electron beam. Since the energy of the electron is far greater than that of the photon, the recoil factor X is negligible.

We can achieve the goal of a substantial increase in the frequency of the scattered beam.

In the S.T.A.R accelerator the wavelength of the laser is 1030 nm, which gives each photon the energy of 1.2 eV. The electron beam is either of energy of 65 MeV per electron, which will produce 120 keV scattered X-ray beam, or of 150 MeV per electron, which will produce 350 keV scattered X-ray beam.

In table 1 we see a comparison between existing X-ray sources and what is expected of the S.T.A.R accelerator. The energy of the X-ray photons is substantially higher, which could lead to the development of new technologies.

ICS	Electron Energy (MeV)	λ_{las} (μm)	Laser Energy (J)	X Energy (keV)	X Flux	Bandwidth	Rep. Rate (Hz)
BNL [2]	64–72	10	2	7–8.9	$2 \cdot 10^8$	<5%	<10
T-ReX [4]	116	0.532	0.15	0.1–0.9	10^5	15%	10
Sparc [5]	30	0.8	5	13	$1.4 \cdot 10^6$	20%	10
AIST [6]	42	0.8	0.14	40	10^6	4–10%	10
TTX [7]	46.7	0.8	0.3	51.7	10^6	10%	100
Elbe [10]	23	0.8	2.25	13–25		25%	10
STAR-II-HE [35]	140	1.03	0.5	350	10^7	6%	100

table 1. Comparison between S.T.A.R accelerator and existing X-ray sources, **State of the Art of High-Flux Compton/Thomson X-rays Sources,** p. 5.

The resulting X-ray beam is coherent, quasi-monochromatic and preserves the polarization of the laser, which makes it beneficial for many applications[4].

To achieve the high energy electrons needed for the scattering interaction, a particle accelerator is used. The S.T.A.R accelerator is a radio frequency (RF) electron accelerator. It is entirely water cooled. The electrons are produced by a laser beam pointed at a metal sheet, which uses the electro-optic effect to release electrons from the metal sheet. The electron beam is then accelerated by a standing wave linear accelerator (LINAC)[5], followed by three traveling RF wave acceleration units[6].
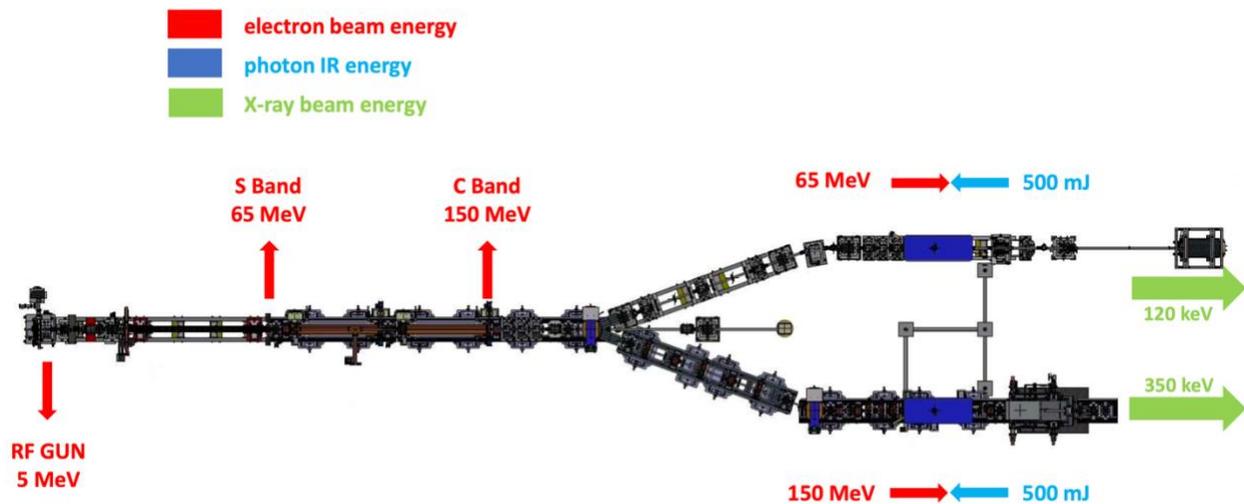

Figure 2. A summary of the energy layout of the accelerator and scattered X-ray beam at S.T.A.R, provided by **Joseph Beltrano** from the University of Calabria.

---

[4] A list of references for various relevant articles is available in **State of the Art of High-Flux Compton/Thomson X-rays Sources,** p. 2
[5] **RF Linear Accelerators for Medical and Industrial Applications** by Sammy Hanna, pp. 27-32
[6] **RF Linear Accelerators for Medical and Industrial Applications** by Sammy Hanna, pp. 32-34

The source for the RF microwave that accelerates the electrons in the different acceleration units in S.T.A.R. are two Klystrons[7]. The RF microwave is then guided to the proper location at the various acceleration units by rectangular waveguides[8]. Focusing and guiding of the electron beam is done using magnetic fields[9]. My thesis assignment was to configure the variable attenuator, which is a MACH-ZEHNDER INTERFEROMETER[10] used to control the magnitude of the RF microwave radiation entering the standing wave LINAC, and to configure the phase shifter, which is used to control the phase of the RF microwave radiation entering the standing wave LINAC. The control is done in both cases by changing the optical path of the radiation using computer-controlled stepper motors.

---

[7] From **RF Linear Accelerators for Medical and Industrial Applications** by Samy Hanna, p. 52

[8] From **Particle accelerator Physics, 4th edition,** by Helmut Wiedemann, p. 605

[9] **Particle accelerator physics, 4th edition, Helmut Wiedemann** pp. 99, 102-105

[10] **Fiber Optic Communications** by Gerd Keiser pp. 405-407

Bibliography

K. Achterhold, et al., "Monochromatic computed tomography with a compact laser-driven X-ray source", *Scientific Reports* 3, 1313 (2013)

Jens Als-Nielsen and Des McMorrow, *Elements of Modern X-ray Physics*, Second Edition, 2010

Zhijun Chi, et al., "Linearly polarized X-ray fluorescence computed tomography based on a Thomson scattering light source: a Monte Carlo study", *Journal of Synchrotrone Radiation* 27 (2020), pp. 737-745

Samy Hanna, *RF Linear Accelerators for Medical and Industrial Applications*, 2012

Gerd Keiser, *Fiber Optic Communications*, 2021

Chin-Lin Chen, *Foundations for Guided-Wave Optics*, 2007

Vittoria Petrillo, et al., "Photon flux and spectrum of γ-rays Compton sources", *Nuclear Instruments and Methods in Physics Research A*, 693 (2012), pp. 109-116

Vittoria Petrillo, et al., "State of the Art of High-Flux Compton/Thomson X-rays Sources", *Applied Sciences* 13, 752 (2023)

N. Ranjan, et al., "Simulation of inverse Compton scattering and its implications on the scattered linewidth", *Physical Review Accelerators and Beams* 21, 030701 (2018)

Helmut Wiedemann, *Particle Accelerator Physics*, Fourth Edition, 2019