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X-ray generation at SPARC_LAB Thomson backscattering source

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Summary. — In the last years, the phase contrast X-ray imaging became a very promising technique, in particular for medical application. At this purpose, several compact and very performing X-ray sources are growing up all around the world and most of them are based upon the Thomson backscattering phenomenon. This is the context of the SPARC_LAB Thomson backscattering X-ray source, presently under commissioning at INFN-LNF. Here a head-on collision is foreseen at the Thomson Interaction Point between a 30 to 150 MeV electron beam and the 250 TW FLAME laser pulse, providing a photon energy tunability in the range from 20 to 250 keV. The first experiment foresees the generation of a X-ray beam, useful for X-ray imaging of mammographic phantoms with the phase contrast technique. In February 2014, the SPARC_LAB Thomson source produced its very first X-ray beam. The shift and the obtained results are presented.

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PACS 29.20.Ej – Linear accelerators.
PACS 29.27.Bd – Beam dynamics; collective effects and instabilities.

1. – Introduction

The X-ray imaging is essentially based on the analysis of intensity or phase variations of an X-ray beam passing through a sample in order to create its image. Nowadays, the most relevant techniques are the standard X-ray imaging and the more innovative phase contrast X-ray imaging. The standard X-ray imaging studies the attenuation of the intensity of the X-ray beam, while the phase contrast technique relies on the phase variation of the X-ray beam. This technique presents some advantages with respect to the conventional one, in particular when low-energy X-rays are required. One of them is the edge enhancement effect, a peculiarity of the phase contrast technique, that provides an increasing of the image contrast in the area immediately around the edge. For example

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this effect is very useful to improve the visibility of details in the medical imaging when it is difficult to distinguish healthy tissues from tumours because of sample features. This is the case of X-ray imaging of tissues such as the breast since, being them mostly adipose and glandular, the radiation is more absorbed, reducing the detectable signal and the sharpness of the image.

Despite the benefits, the phase contrast technique requires very performing X-ray sources that have to generate monochromatic, spatially coherent photon beam and photon flux of the order of 10^{10} photon/s. Moreover photon beam energy has to change in relation to the patient physical characteristics. Nowadays such a beam can be produced in synchrotron radiation facilities, but, due to their huge dimensions and high costs, they cannot be inserted in routine clinical practice. This problem can be fixed generating X-rays through Thomson backscattering. The sources based on this phenomenon can be very compact and, at the same time, can produce X-ray beams useful for the phase contrast technique.

At the Frascati INFN-SPARC_LAB [1] a Thomson backscattering source is presently under commissioning. Here the opportunity has been used to couple the SPARC high brightness photoinjector [2] with the 250 TW FLAME laser system [2] in order to provide a X-ray Thomson source in the range from 20 to 500 keV. In table I the SPARC_LAB Thomson source design parameters, optimized to obtain a X-ray beam useful for X-ray imaging of mammographic phantoms with the phase contrast technique, are listed [3].

In the following sections the very first shift, which took place in Frascati in February 2014, and the obtained results are presented.

Table I. – *SPARC_LAB Thomson source design parameters.*

Electron Beam		
Charge	100–800	pC
Energy	30–150	MeV
Energy spread	< 0.1	%
Pulse length	15–20	ps
Spot size	5–20	μm
Emittance	1–3	mm mrad
FLAME laser pulse		
Pulse energy	1–5	J
Wavelength	800	nm
Pulse length	6	ps
Spot size	10	μm
Repetition rate	10	Hz
X-Rays		
Energy	20–250	keV
Spot size	10	μm
BW	10	%
Photons	10^9	Number per shot

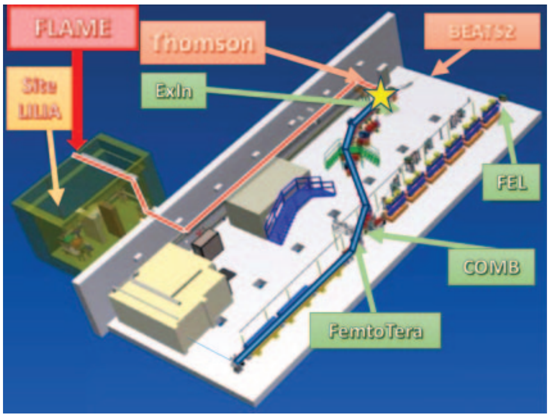

Fig. 1. – FLAME laser pulse, passing through a 20 meter long vacuum optical beamline, collides at the Thomson Interaction Point (IP) with the electron beam coming from the SPARC_LAB high brightness photoinjector.

2. – Experimental setup

In February 2014, the SPARC_LAB Thomson source produced its very first X-ray beam. A laser pulse, provided by FLAME laser system, collides at the Thomson Interaction Point (IP) with the counterpropagating electron beam, coming from the SPARC_LAB high brightness photoinjector (see fig. 1).

2·1. *The electron beam.* – At SPARC_LAB the electron beam is generated by a 50 mJ Ti:Sapphire laser pulse hitting on a Cu photocathode placed in a 1.6 cell S-band RF gun. At the gun exit the beam energy is $\sim 5\,\text{MeV}$ and the three following TW SLAC type S-band sections carry the electron beam up to the required energy. Then the beam, passing through a double dogleg transport line, reaches the Thomson IP. The R_{56} parameter of the dogleg can be set in the range of $\pm 50\,\text{mm}$([1]).

At the linac exit 6D phase space measurement is provided by a S-band RF deflecting cavity [5] and the beam envelope is captured all along the source. Emittance measurements can be done with the quadrupole scan technique at the end of the LINAC and at each straight section of the Thomson transfer line. The energy and the energy spread measurements are performed using a 14° by-pass dipole.

For the commissioning phase a 50 MeV, 200 pC electron beam has been chosen. In order to minimize the effects of power amplitude jitters from the feeding Klystrons, the phases of the accelerating sections have been set as follows to : $\Phi S_1 = -26.2°$,

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([1]) The following of a charged particle beam through a beam transport line can be represented by matrix treatment. At any position s, measured along a reference trajectory, a charged particle can be described by a 6×1 vector $X(s) = (x(s), x'(s), y(s), y'(s), z(s), \Delta p/p_0)$ where: $x(s)$, $y(s)$ and $z(s)$ are the horizontal, vertical and longitudinal displacements of the trajectory (with respect to the central trajectory); $x'(s)$ and $y'(s)$ are the angles this trajectory makes in the horizontal and vertical plane; $\Delta p/p_0$ is the longitudinal momentum deviation of the trajectory (with respect to the central trajectory). The R-matrix is the transfer matrix between two locations, $s1$ and $s2$, of the charged beam along the transport line, whose elements depend on the transport between $s1$ and $s2$ and on the size of the beam (for computing space-charge forces) in this interval [4]. R_{56} represents the correlation between z and $\Delta p/p_0$.

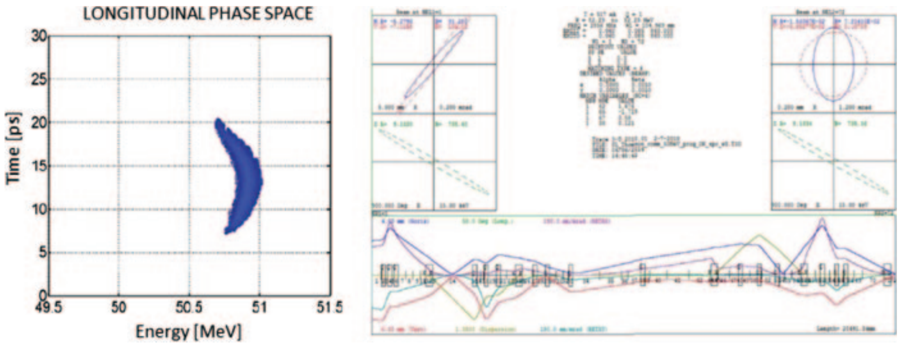

Fig. 2. – Measured longitudinal phase space at the exit of the LINAC provided by the S-band RF deflecting cavity on the left. Trace 3D Simulation of the beam envelope from the exit of the LINAC to the IP on the right.

$\Phi S_2 = +78.5°$, $\Phi S_3 = -111°$. In these conditions the electron beam energy spread was less than 0.1 % and the emittance in the range 1–3 mm mrad.

The beam transport line of such a beam has been simulated from the exit of the LINAC to the IP to obtain a 10–50 μm beam spot size. Simulations, made with the Trace 3D code [6], have the aim to properly correct the horizontal dispersion in the double dogleg and to match the beam, coming from the LINAC, to the Thomson Interaction Point focusing system. Simulated Twiss parameters, useful for matching the beam, are reported in fig. 2 on the right.

Because of a limit in the magnet cooling system, unfortunately, the solenoid upstream the IP could be used at 70% of its nominal value. In this condition the minimum rms spot size was of about 90 μm, nevertheless, due to a poor overlap of the colliding beams, the best result has been obtained for an enlarged electron beam spot size of $\sigma_x y = (240–160 \pm 10)\,\mu$m. All working point parameters are presented in table II.

2˙2. *FLAME laser pulse*. – FLAME is a 250 TW Ti:Sa laser system which provides a 800 μm wavelength laser pulse in a 60–80 nm bandwidth. The 10 Hz FLAME laser pulse can reach a maximum energy on a target of 5 J with a pulse duration between 25 fs and 10 ps.

The laser system is located in a clean room in a building adjacent to the SPARC laboratory. From here an optical transfer line in vacuum ($P = 10^-6$ Torr) carries the beam up to off-axis parabola mirror that focuses the beam in a 10 μm diameter (FWHM) spot at the interaction point. The parabolic mirror is holed in its center, in order to allow the passing through of the scattered radiation and of the electron beam (see fig. 3).

In the very first Thomson Source experiment FLAME provided a 0.5 J laser beam at IP with 6 ps pulse width and 10 μm beam spot size. The working point parameters are listed in table II.

2˙3. *X-ray beam diagnostic*. – Since in first collisions the radiation signal could be not optimised, a detector having a high sensitivity and a wide dynamic range has been selected: a CsI(T1) crystal coupled with a photomultiplier tube (Hamamatsu, mod. R329-02), placed 4 meter away from the source along the X-rays propagation axis. The detector has been calibrated to detect, for a 60 keV monochromatic radiation, the signal produced by a single photon up to the one due to pulses containing about 10^6 photons.

TABLE II. – *SPARC_LAB Thomson source working point parameters.*

Electron Beam		
Charge	200	pC
Energy	50	MeV
Energy spread	0.1 ± 0.03	%
Pulse length	3.1 ± 0.2	ps
Spot size	90 ± 3	μm
Emittance	1.5–2.2 ± 0.2	mm mrad
FLAME laser pulse		
Pulse energy	0.5	J
Wavelength	800	nm
Pulse length	6	ps
Spot size	10	μm
Repetition rate	10	Hz

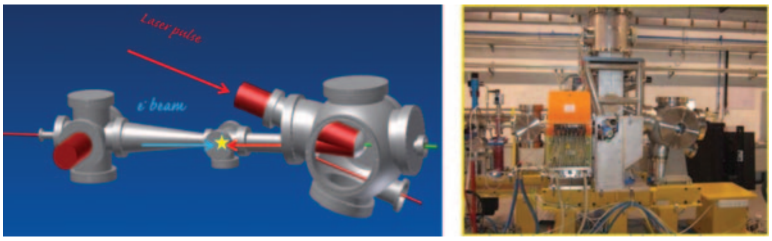

Fig. 3. – 3D CAD drawing of the Thomson Interaction vacuum chamber setup, on the left. Lateral view of the implemented interaction chamber and parabolic mirror vacuum chamber, on the right.

Two types of measurements are foreseen for X-rays: a 20 GHz BW oscilloscope for a fast response and a multichannel analyser (MCA-8000, Amptek, US) to acquire an integral measurement over various interactions. Therefore, an information on the energy distribution is required to evaluate the number of photons in each pulse.

The diagnostic tool will be upgraded, with techniques specifically developped [7, 8], in order to provide a full characterization of the source.

3. – Commissioning results

For the commissioning phase the beams described in table II have been chosen to collide at the Thomson IP. In these conditions, in the very first 4-week shift, with an electron beam spot size of $\sigma_x y = (240\text{–}160 \pm 10)\,\mu$m, a clear, but not optimised, X-ray signal has been collected on the detector [9].

The detected signal has been measured both with a 20 GHz BW oscilloscope, for a fast response, and a multichannel analyser, to acquire an integral measurement over various interactions. The 20 Ghz BW oscilloscope has been mainly useful to synchronise the electron beam and FLAME pulse and allows to measure the 150 fs relative temporal jitter between them. The multichannel analyser provided the evaluation of average energy of X-ray and of the number of photons produced in the interaction. The detected signal, integrated over 1200 pulses, is shown in fig. 4 on the left.

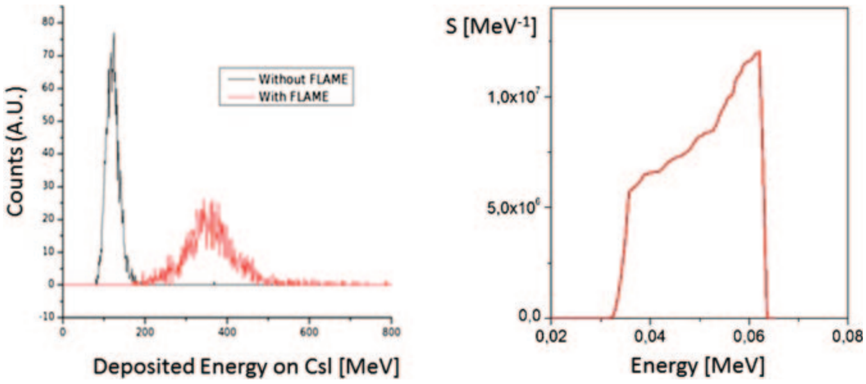

Fig. 4. – Thomson X-rays signal in red, in black the electron background signal (without FLAME laser), integrated over 120 s (1200 pulses), on the left. Spectral density S (MeV^{-1}) *vs.* photon energy, on the right.

In fig. 4 on the left the red signal is due to the Thomson X-rays, instead the black one is due to the background noise in case of FLAME pulse switched off. The backgroud is synchronous with Thomson X-rays and it is mainly due to radiation produced in the electron beam dumping section located downtream the parabolic mirror vacuum chamber, being it too much close to the X-rays radiation extraction. The average energy of Thomson X-rays, released in the crystal by each pulse, is of about 235 MeV.

By CAIN simulation of the interaction has been possible to evaluate that the average energy of the photons reaching the detector was 60 keV with an average number of photons per each pulse interacting with the detector sensitive area of 6.7×10^3.

This result has been confirmed by simulations made with a code based on the classical theory [10]: in case of a 50 MeV electron beam with 200 pC charge, 5 mm mrad of emittance and 150 μm spot size rms head-on colliding with a 500 mJ laser pulse with 30 μm beam waist, should be produced a X-ray signal of 2×10^5 photons per pulse in a bandwidth of about 19%. The predicted photon energy edge is of 63 keV given by $E_p \sim 4E_L\gamma^2$. The result is reported in fig. 4 on the right.

Poor overlap conditions due to some misalignment of the interaction vacuum chamber can explain the difference between the measured number of photons for each pulse and the one expected from the theory.

4. – Conclusions

As very first commissioning results X-rays were obtained with

1. average energy = 60 keV,

2. BW = 19%,

3. number of photons per shot of 6.7×10^3.

In the next shut-down the problems related to the solenoid cooling system will be fixed together with the misalignment of the interaction chamber and the electron dumping section. In particular the electron beam dumping will be changed and located upstream the parabolic mirror vacuum chamber.

A new experiment at INFN-SPARC_LAB is planned in 2015. The aim is to upgrade to the interaction between a 30 MeV electron beam and a FLAME laser pulse, to produce a stable X-ray signal and to fulfill a complete characterization of the X-ray source in terms of flux, energy distribution, spatial distribution and beam stability.

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This work has been on behalf of the SPARC_LAB team.

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