THE RADIOTHOMX PROJECT

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Abstract

The goal of this project is to develop a compact device which can produce an intense flux of monochromatic X-rays for medical applications. It is based on Compton back-scattering resulting from collisions between laser pulses and relativistic electron bunches. Intense laser beams can be obtained with a high gain Fabry-Perot cavity coupled with either a high average power fiber amplifier or a high average power conventional bulk amplifier. Such a scheme is going to be developed by CELIA, Thalès and LAL laboratories. The accelerator design to produce high repetition rate electron bunches at 50 MeV is under study. Two possibilities are being investigated: either a storage ring operating at an injection frequency high enough to preserve the electron beam characteristics or a high average current ERL. Both accelerator configurations aiming at producing X-ray fluxes higher than 10^{12} photons/s will be presented.

INTRODUCTION

In collaboration with Thalès, CELIA and LOA, a program is underway at LAL to develop a source for generating monoenergetic, tunable X-rays. The goal is to provide photon fluxes higher than 10^{12} ph/s dedicated mainly to medical applications.

In the X-ray application field, there is a strong need for high brightness beam and this is the main driver for technological improvements: the standard X-ray tube evolving towards higher performance brilliant X-ray synchrotron and micro-focus sources [1]. This trend is linked to the need for better imaging needed for non invasive imaging, high resolution protein imaging and medical applications (among other). Synchrotrons are today the best suited machines for such applications but, they are costly, lack of compactness and they offer limited access time. For these reasons, projects considering a compact machine [2] are being developed around the world.

Besides the high resolution radiography, these compact machines will be innovative devices for cancer treatment [3]. As an example, a localized dose enhancement can be produced thanks to the Auger cascades generated by the interaction between a monochromatic X-ray beam and a contrast agent (such as iodine or gadolinium).

This kind of compact machines can be also used in cultural heritage science.

The compactness results from Compton effect by colliding a low energy electron beam (50 MeV) with a high power, infrared laser beam (10-30 mJ per pulse). The backscattered photons will be in the multi-keV energy range, determined by the electron beam energy and the laser beam one. Since emission angle and energy are correlated, the produced X-ray beam can be collimated to reach 5 to 10 % of spectral bandwidth.

The particularity of this project is high brilliance provided by using an intense laser beam with a high gain Fabry-Perot cavity [4] coupled with a high average power fiber or bulk laser beams presently under development. To maximise the Compton flux, the electron beam should be matched with the laser beam, which constrains the electron beam at the interaction region. Moreover, the Compton interaction damages the electron beam quality. For these reason, the main accelerator under study is a ring, which will store the beam during a time short enough to avoid the degradation of the beam quality induced by Compton interactions. An alternative design can be an energy recovery linac, for which the electron beam is renewed at each interaction.

In this paper, we describe two preliminary accelerator designs and impact their potentiality as monochromatic X-ray generator.

SYSTEM CONSTRAINTS

The main goal of the project is to provide an X-ray source for radiography and radiotherapy at around 50 keV. The choice of the laser device and its wavelength at 1.03-1.064 μm imposes the 50-60 MeV electron energy. To obtain a flux higher than 10^{12} ph/s, it is necessary to produce high energy laser pulses (10-30 mJ). Such parameters can be achieved by means of a high gain Fabry-Perot cavity coupled with a pulsed laser [4]. This imposes that the frequency of the light pulse in the optical cavity be matched with the pass frequency (or one of its harmonics) of the electron bunches at the interaction point. The interaction frequency should be in the 50 MHz range to provide the desired high flux of X-rays with the described characteristics of the laser and of the electron beam.

To avoid the degradation of the cavity mirrors [5], we should foresee a collision angle between the photons and the electron. To maximise the longitudinal and transverse overlap between the electron bunch and the photon pulse, the rms transverse size in both planes should be on the order of 50 μm (laser waist 100 μm), and its length should be in the domain of 10 ps (FWHM). Because of the small transverse size involved, transverse displacements of the electron bunch trajectory must be strictly limited. In addition due to the energy spread growth, it is better to minimize the dispersion function at the interaction point.

Another point to take into account is the deterioration caused by the Compton back-scattering process on the electron beam. Since the Compton flux is dependent on the quality of the electron beam, the Compton flux decreases rapidly as a function of time as long as the electron bunch is not renewed [6]. This led us to explore two different accelerator schemes:

- A low frequency electron RF photocathode gun (between 10 and 50 Hz) followed by an accelerating section (LIL type) used to inject electron bunches into a storage ring. A Fabry Perot optical cavity fed by a pulsed laser is suitable in one of the ring straight section to provide electrons/photons collisions. The electron beam will be renewed before the X-ray flux is too much impaired.
- A superconducting linac coupled with a DC electron gun, which produces directly a high frequency electron beam. In order to save RF power, the linac will operate in the energy recovery mode (ERL). The optical cavity can be installed in the recirculation loop.

A COMPACT ACCELERATOR

Ring Configuration

The linac will be composed of a rf photocathode gun [7], which can give a 5.9 MeV electron beam. The characteristics of the electron beam depend on the characteristics of the laser, which lights the photocathode. By considering a Gaussian laser shape and a transverse dimension of 1 mm, the emittance will be 9 π mm mrad for 1 nC electron beam charge and its length will be 3.4 ps. Then a 4.5 m long section [8] with an accelerating gradient of 14 MV/m will bring the energy at 57 MeV with an energy spread of 0.4%. An improvement of the emittance can be realized with a shape of the laser (beer can or ellipsoidal) [9] down to 2 π mm mrad.

The electron beam will then be injected in the ring, where it will be stored during about 200 ms (or less for reasons given above) in order to maintain the characteristics of the electron beam coming from the linac.

In order to fit in a medical environment, the ring should be as small as possible. But this must not be achieved at the expense of the electron beam stability. First, different configurations as racetrack and hippodrome have been studied. The main difficulty with these ring types is that their straight sections are too long to place the optical cavity mirrors at both ends of such sections. Thus enough space should be provided between quadrupoles for this cavity. In addition, these optics have only one symmetric cell, and are not satisfactory as far as stability is concerned. It is better to have short sections to put the cavity mirrors outside the ring dipoles and to increase the number of symmetries. For these reasons an octagon ring is under study. The drawback of such a configuration is that the ring circumference must be increased from 7 m to about 12 m.

ERL Configuration

RadioThomX ERL consists in a linear accelerator, whose electron bunches are recirculated once to restore the energy to the high frequency structure. The electron bunch characteristics are preserved for each new collision with the photon pulses. In the Energy Recovery Linac (ERL) mode, high average current can be obtained. A high current operation requires a CW gun based on a DC photoinjector (JLab type) [10], which provides a 10-100 MHz pulsed electron beam of 0.1 - 1 nC charge. A booster is necessary to accelerate the beam to 10 MeV before it is injected in an ERL loop. The low energy required for the interaction gives a simple design to the loop. The linear accelerator needs only one (or two) ELBE type cryomodule [11] surrounded by quadrupole triplets. Our RadioThomX ERL design takes into account various requirements, particularly those bearing on the transverse focusing, and maximize the Beam Break Up current threshold [12]. Due to the reduced dimensions of the ERL, a constant gradient focusing scheme is chosen.

The transverse transport of the ERL configuration is calculated under the thin lenses approximation and the electron beam shape transport. The accelerator parameters and the optical functions are adjusted. The calculated Beam Break up current is on the order of 100 mA. As a consequence, an operation can be viewed with a charge of 100 pC and a 100 MHz repetition rate. In fact, the calculated Beam Break Up threshold current is larger than 10 mA and does not limit the current of the ERL operation. In a futuristic, very advanced configuration, one may consider a 100 mA operation.

RadioThomX ERL appears feasible as a similar ERL is already under operation at Daresbury [13]. The main difficulty resides in its DC gun. Furthermore, the room needed for the cryogenic devices may be difficult to accommodate in a hospital environment.

THE PRODUCED RADIATION

ERL and Ring Configuration

The X-ray flux (ph/s) produced by Compton interaction depends on the repetition rate f_{rep}, the number of photons per laser pulse N_l, the number of electrons per bunches N_e, the Compton X-section σ_{th} and on the transverse dimensions of the electron and laser beam σ (considering a perfect overlap): $F_{ph} = \frac{N_e N_l}{4\pi\sigma^2}\sigma_{th} f_{rep}$

Assuming that the number of photons, the transverse size and the colliding transverse dimensions can be the same in both accelerator configurations, the ratio between the ERL flux and the ring flux reads:

$$F_{ring} / F_{erl} = Q_{ring} f_{ring} / Q_{erl} f_{erl}.$$

For a realistic accelerator design, the electron bunch charge can reach 1 nC (Q_{ring}) at 30-60 MHz (f_{ring}) in the ring configuration and 0.1-1 nC (Q_{erl}) at 100 MHz (f_{erl}) in the ERL configuration. Under these assumptions, the ring flux is three to six times larger than the ERL one, if presently achieved ERL performances are used (0.1 nC, 100 MHz); and the ERL flux may turn out two to three times larger than the ring one, if we take into account the future developments of ERL.

The choice of the accelerator also depends on the room available in the medical environment, on the timescale of the project realisation and on the difficulty of operation of the overall device. Concerning the ERL configuration the main issue is the fact that the ERL technology (to achieve a high average current) is still under development to reach optimal flux performance [14] and one lacks experience in its operation. However in the ERL configuration, the difficulty to insert an optical cavity device is minimized, the crossing angle can be reduced, the energy beam dump is lower and the tunability is easier. Concerning the ring configuration, the technology is well known but the implementation of the Fabry Perot cavity within the ring structure is quite challenging. In addition, the Compton back-scattering process involves important recoil effects and thus a rapid increase of both the energy spread and the length of the electron bunch.

Beam Sizes and Source Quality

A careful parameter optimisation must be carried out especially those concerning the transverse overlap between the two beams. If it is not possible to decrease the transverse sizes of the two beams, decreasing only the laser ones improve considerably the source brilliance for a fixed aperture of the collimator.

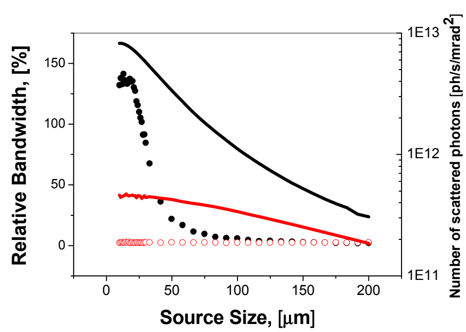

Figure 1: Spectral widths (dots, left axis) normalized to the central X-ray energy of the scattered photons and number of scattered photons (solid lines, right axis) versus the transverse sizes of either the laser beam (red) or the electron beam (black). Red dots and red solid line correspond to changes of the laser transverse size while electron one remains constant and equal to 165 µm (FWHM); black dots and black solid line correspond to changes of electron transverse size while the laser one remains constant and equal to 35 µm (FWHM).

In figure 1 the spectral widths normalized to the central X-ray energy and fluxes of scattered radiation versus transverse source sizes are shown for the cases when either the electron or the laser beam transverse sizes are changed while the others remain constant. This figure shows that a change of the laser transverse dimensions practically does not influence the spectral bandwidth. In contrast, changing only the electron transverse sizes leads to an enhancement on the flux in spite of an enlargement of the spectral width. In fact, decreasing the transverse sizes of the electron beam increases its angular divergence. As a consequence, the X rays, which go through the collimator are the most energetic ones anymore. Divergence of laser beam has a very little influence on the energy spread and divergence of scattered X-rays. In contrast, the divergence of the electron beam is strongly connected with scattered X-ray beam brilliance [15].

As an example, with a 70 µm (RMS) electron beam transverse size and a 15 µm (RMS) transverse laser spot size, an X-ray flux of 5 10^{11} ph/s/mrad² can be obtained with a quasi mono-energetic spectral bandwidth of 2-3 %.

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