IL NUOVO CIMENTO **45 C** (2022) 202
DOI 10.1393/ncc/i2022-22202-9

Communications: SIF Congress 2021

Method for spatial mode shifting in an actively frequency stabilized optical cavity for dual-color X-rays generation in BriXSinO

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received 28 January 2022

Summary. — We report on the experimental proof of a technique for the implementation of dual-color X-ray generation via inverse Compton scattering in the BriXSinO project. Our technique is based on two identical optical cavities, with different interaction angles with the electron line. A fast (50 ms) shift of their fundamental modes allows an alternate Compton interaction, resulting in two alternate X-rays colors. As a proof of principle, we tested our technique on an experimental setup with the same geometry used for BriXSinO, demonstrating the feasibility of this method for a future implementation in a complete Compton source.

1. – Introduction

Monochromatic X-ray sources constitute research and diagnostic tools that find an important role in many fields such as physics, medicine, biology, cultural heritage, and materials science. In this scenario, a promising source type suitable for medical applications is based on the Inverse Compton Scattering (ICS) effect, mainly due to its synchrotron like features, but with strongly reduced costs and dimensions. In Europe, besides STAR [1], ThomX [2], MuCLS [3], Nestor [4], and Smart*Light [5], a new ICS source is supported by Università di Milano and the National Institute of Nuclear Physics (INFN) within the MariX project [6]. This source is called BriXS [7], and it will have the unique feature of a dual-energy X-ray generation. At the moment, a compact demonstrator of the final ICS system called BriXSinO is under development at the INFN LASA laboratories (Segrate, Italy), and its Technical Design Report is in preparation and will be published soon. It will provide an X-ray beam with an average energy tunable in the range 9–37 keV, a relative bandwidth of $\Delta E/E = 1$–10%, and intensities of 10^{9-11} ph/s, with a maximum repetition rate of nearly 100 MHz. A significant aspect of BriXSinO will be the implementation of dual-color X-rays imaging in vivo. Relevant medical applications, such as the K-edge digital subtraction imaging (KES), require dual-energy beams [8]. In particular, KES is based on the acquisition of two images at energies bracketing the K-edge of a certain contrast element: a proper subtraction of them allows a great contrast enhancement, strongly reducing the background noise. Although KES has been already implemented with ICS sources [9], to date, no operative ICS source allows

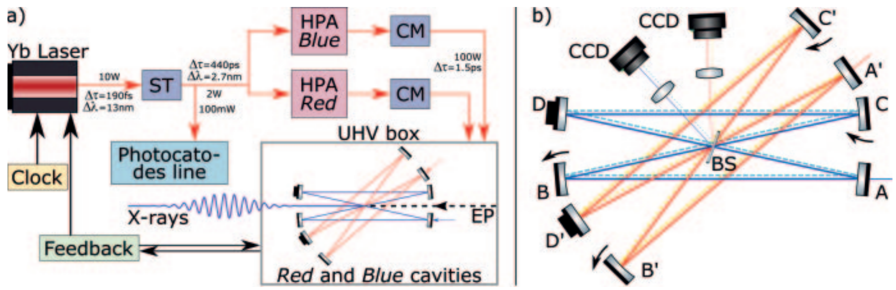

Fig. 1. – (a) Schematics of the laser line in BriXSinO. ST: Stretcher; HPA: High Power Amplifier; CM: Compressor; UHV box: Ultra-high vacuum box; EP: electrons pipeline. Laser and electronic lines drawn with red and black arrows, respectively. (b) Setup for the shift method experiment: A to D and A' to D' cavities mirrors; BS pellicle beam splitter; lenses and CCD for foci imaging system.

in vivo implementation, enabled by a fast switch between different energy levels. In this work, we propose an innovative technique to operate in dual-color mode [10], exploiting the interaction angle-dependence of the X-rays energy, using two identical optical cavities that can alternately interact with the electron beam with two different angles, producing two colors [11]. In the following sections, we briefly describe the optical system of BriXSinO, then we will present our technique with the experimental results we obtained.

2. – Optical system

The laser line plays a crucial role in BriXSinO. Indeed, it will provide the high-average power photons required for the ICS, but it will also generate the electron bunches and set the synchronization reference of the whole system. A schematic of the BriXSinO laser line is shown in fig. 1(a). The laser source is a mode-locked Yb-doped fiber laser (Menlo Orange) with a central wavelength $\lambda_0 = 1035\,\mathrm{nm}$, 20 nm bandwidth, a repetition rate of 92.857 MHz, and an average power of 10 W. Since the ICS interaction cross-section is very low ($6.652 \times 10^{-29}\,\mathrm{m}^2$), a high average power, typically above 100 kW, is necessary to obtain a significant flux of X-rays. At the same time, the power level must be stable, with fluctuations below 2% for BriXSinO. In order to satisfy these requirements, the 10 W laser output is amplified in two steps: actively, with a fiber amplifier, then passively, exploiting pulse stacking in an optical cavity. Following the scheme of fig. 1(a), a fraction of the laser beam is deviated to the photocatodes line where the electrons will be generated, while the remaining power is split in two identical lines, which go into the two corresponding optical cavities (labeled *Red* and *Blue*). Here, ICS takes place in their focal point. The active amplification is based on the famous CPA technique, so a stretcher is placed before the two identical Yb-fiber amplifiers (NKT Aerogain Base 1.2). Pulses are then compressed to 1.5 ps, and have an average power of 100 W, and finally go into *Red* and *Blue* cavities, surrounded by an ultra-high vacuum chamber. In order to allow pulse stacking up to a passive power gain of 10^3, the cavities are kept resonant with the laser using the PDH technique [12]. *Red* and *Blue* cavities are geometrically identical (3-meter long 4-mirror, 2 flat and 2 curved, crossed cavities) and have the same Finesse (~ 6000). The interaction point is the same for the two cavities and coincides with their foci, as it clearly appears in fig. 1, thus the only difference between them is the interaction angle with the electrons. In particular, it is 7° for the *Blue* cavity, and 30° for the *Red*. A fast switch of the interaction between one cavity to the other would allow the generation of 31.8 keV and 34 keV X-rays for the *Red* and the *Blue*, respectively, in BriXSinO. A challenging task is to maintain the intracavity power constant during switching, so that the X-rays will not suffer from efficiency losses. Furthermore, intracavity power must be maintained stable also when out of alignment with the electrons, in order to avoid detrimental thermal instabilities. In sect. **3**, we provide details about the implementation of the method to quickly alternate the cavity interacting with the electron bunch by simply shifting both the cavities foci positions, while maintaining the resonance with respect to the laser. Aiming at the realization of the final laser system of BriXSinO, different R&D lines have been developed in the last years. The main goals of the R&D activities are the characterization at a high repetition rate of the photocatodes used for the generation of the electron bunches, and the realization of both the high-power amplification system and the high-Finesse cavities. The technique that we are presenting for the dual-color implementation has been demonstrated using an experimental setup simpler than the final one, consisting of a similar Yb laser, and two actively stabilized cavities operating in air. The laser is a 200 mW Menlo Orange, with a repetition rate of 100 MHz, and with the same wavelength and spectrum as the laser for BriXSino. In this experiment, the two cavities have a Finesse of 1800, with an intracavity average power of nearly 100 W.

3. – Shift method for dual-color ICS

With our technique we want to demonstrate the possibility of implementing the in vivo dual-color operation with an ICS source, exploiting the modal shift of two optical cavities as mentioned above. For this reason, we aim to a switch between the two cavities faster than 100 ms. The proposed technique is based on the curved mirrors synchronous rotation of both cavities, as schematized in fig. 1(b). Indeed, the rotation of mirrors B and C induces a shift of the entire optical axis of the cavity, resulting in a rigid movement of the cavity modes and, in turn, of the focal point, so that the cavities can alternately interact with the electrons. The effect of the curved mirrors rotation can be demonstrated by applying the well known ABCD matrix formalism, that takes into account misalignments and disalignments [13]. In our case, the rotation of the curved mirrors is around a horizontal axis, thus the shift of the focus is in the vertical direction. In order to be compatible to an in vivo ICS application, these movements must be performed while maintaining the maximum intracavity power, and thus the resonance to the external laser. Experimentally, we controlled the rotation of each curved mirror via piezoelectric actuators, where in particular we tested two different types of mounting on the two cavities: gimbal mountings on the *Red* cavity, and standard mountings on the *Blue*. Gimbals rotate around the incidence point of the beam on the mirror, not affecting the cavity length, while standards rotate around an axis far from this incidence point, changing also the cavity length, that must be compensated by the PDH stabilization system. Each actuator was controlled by an ad hoc Labview® program that allows synchronizing movements to the 100 μs level. All the system dedicated to the modal shift has been calibrated and optimized following the procedure described in [10]. In order to characterize our shift method, and verify that it is compatible to an ICS application, we monitored both the spatial shift of the focus and the duration of the movement. The first point has been tested by directly performing an imaging of the focal points of the two cavities: a pellicle beam splitter has been placed near the focal points and two calibrated imaging systems monitored the *Red* and the *Blue* cavities, respectively, as depicted in fig. 1(b). While maintaining the resonance with the external laser, we performed a shift of the two focal points, obtaining the results shown in fig. 2(a). We obtained a shift of 135 μm for the *Red* cavity, and 77 μm for the *Blue*, where the latter was limited by the PDH actuator dynamics, that had to compensate the variation of the cavity length caused by

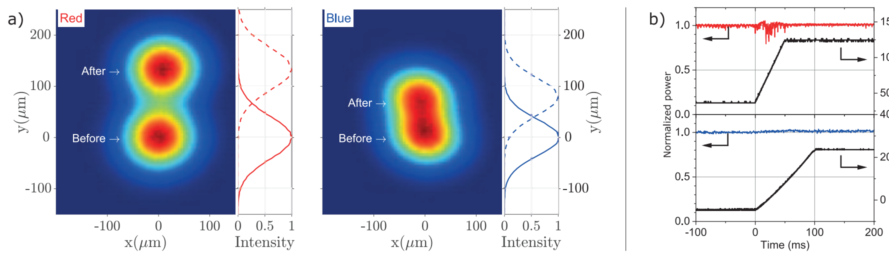

Fig. 2. – (a) Imaging of the focal points of *Red* (left) and *Blue* (right) cavities, and corresponding profiles in $x = 0\,\mu$m, before and after their shift. (b) Normalized intracavity powers of red (above) and blue (below) cavities, as a monitor of the power losses, and corresponding monitor of the mirrors rotation (black). Focus movements and power losses are 50 ms and 1% for the *Red* cavity, while 100 ms and 1.4% for the *Blue*.

the standard mounts. The $135\,\mu$m shift is sufficient to cancel the overlap between laser and electrons. After removing the pellicle beam splitter, the intracavity power is at maximum. Then, we repeated the cavity mode shift monitoring the voltages on the Gimbal actuator on mirror C of the *Red* cavity and on the PDH piezoelectric actuator of the *Blue* cavity (voltage on SmarAct mounts is not accessible), while acquiring the corresponding transmitted powers inside the two cavities. In this way, we were able to measure the shift durations and the intracavity power losses, respectively. Results are shown in fig. 2(b). We obtained a very low variation of the transmitted beam, of 1.0% for the *Red* cavity and of 1.4% for the *Blue* cavity, with a very fast movement: 50 ms and 100 ms, respectively, compatible with spatial coupling losses. During the synchronous shifts, both cavities remained in resonance with the external laser, fulfilling an in vivo dual-color application.

4. – Conclusions

In this work, we presented and demonstrated a technique to implement a dual-color method in the BriXSinO ICS facility, performing a synchronous and controlled movement of the focal points of two high-Finesse crossed cavities. In particular, we demonstrated a movement of the focus of $135\,\mu$m in a time of 50 ms. The cavities were stabilized during the movement, and the variation in the stored power before and after the movement was negligible for our application (1.0%). Our method, once implemented in a working ICS facility like BriXSinO, will allow generating dual-color X-rays compatible to in vivo applications for the first time.

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