IL NUOVO CIMENTO **46 C** (2023) 150
DOI 10.1393/ncc/i2023-23150-6

Communications: SIF Congress 2022

Intracavity intensity noise suppression in the inverse Compton scattering source BriXSinO exploiting carrier-envelope offset manipulation

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received 31 January 2023

Summary. — We report on a technique that exploits the control of the carrier-envelope offset to suppress the frequency-to-intensity noise conversion in the locking of a mode-locking laser against a high-finesse optical enhancement resonator. A proper combination of the laser carrier-envelope offset and the resonator finesse allows the improvement of the signal-to-noise ratio of the optical intensity trapped into the optical resonator. In this paper, we show the application of this technique in the laser system of the inverse Compton scattering source BriXSinO, currently under development in Milan, Italy, demonstrating the possibility of achieving an intracavity intensity noise reduction of a factor of 20.

1. – Introduction

Inverse Compton Scattering (ICS) sources are promising tools for the generation of monochromatic X-rays, which play an increasingly important role in many scientific fields, in particular physics, medicine, materials science, and cultural heritage, thanks to their reduced dimensions and costs [1-4]. In the area of Milan, the realization of a new ICS source is supported by Università degli Studi di Milano and Istituto Nazionale di Fisica Nucleare (INFN) within the framework of the BriXSinO project [5]. This source will be a test bench for a new kind of Energy Recovery Linac (ERL) based on a push-pull scheme [6], implementing at the same time unique features such as fast dual-energy X-ray generation [7, 8]. BriXSinO will provide X-ray beams 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. One of the main requirements for these ICS facilities is the high stability of the laser, in particular its average intensity in the interaction point with the electron bunches. In BriXSinO, the limit for the intracavity laser intensity noise has been set to the 2% level by the users [5]. One of the main sources of amplitude noise is given by the frequency-to-intensity conversion that happens intracavity. In this work, we apply a novel solution to reduce the residual frequency-to-intensity noise conversion, and we demonstrate its effectiveness in the BriXSinO test laser system.

2. – Theory and setup

The core of our technique resides in the dependence of the frequency-to-intensity noise conversion on the carrier-envelope offset of the laser. A detailed description of the related theory can be found in [9], and it has been presented at SIF Congress 2022. Both the mode-locking laser and the enhancement cavity have a comb spectrum, and their modal frequencies can be written, respectively, as [10] $\nu_m^{(\text{laser})} = m\, f_{\text{rep}} + f_{\text{ceo}}$ and $\nu_n^{(\text{cav})} = n\,\text{FSR} + f_{\text{cav}}$. Here m and n are integers, f_{rep} is the repetition rate of the laser, FSR is the Free Spectral Range of the cavity, and f_{ceo} is the carrier-envelope offset of the laser, while f_{cav} is the offset of the enhancement cavity containing the contributions of the Guoy phase, the air, and the mirrors' dispersion. In stacking the laser pulses into the cavity, the highest coupled power is achieved when the two combs are matched [11]. This condition is satisfied and maintained via the well-known Pound-Drever-Hall (PDH) technique [12], which, in our setup, stabilizes FSR so that $\nu_{m_0}^{\text{laser}} = \nu_{n_0}^{\text{cav}}$, with $n_0 = m_0$, and where ν_{m_0} corresponds to the barycenter of the laser spectrum. This means that $\text{FSR} = f_{\text{rep}} + f_0/m_0$, where we introduced $f_0 = f_{\text{ceo}} - f_{\text{cav}}$ as the relative offset between the laser and the cavity combs. We have that detuning between the teeth of order m of laser and cavity is $\Delta\nu_m = f_0(m - m_0)/m_0$, and thus it directly depends on f_0. Since we are interested in intracavity power fluctuations, we write the expression of intracavity gain as $\Gamma = \frac{1}{N}\sum_m S_m \Gamma_m(\Delta\nu_m)$. Here $\Gamma_m(\Delta\nu_m) = (1-R_1)[1+R-2\sqrt{R}\cos(2\pi\Delta\nu_m/\text{FSR})]^{-1}$ is the gain of the single tooth m, S_m is the amplitude of the laser spectrum as a function of the tooth m, and $N = \sum_m S_m$. This means that the total gain is the sum of the single tooth gains, weighted on the laser spectrum. If we introduce a frequency fluctuation δf equal for all the teeth, then detuning becomes $\Delta\nu_m + \delta f$. Supposing that δf follows a Gaussian distribution with variance $\sigma_{\delta f}^2$, then the corresponding variance of the gain fluctuations can be found to be $\sigma_\Gamma^2 = \langle\delta\Gamma^2\rangle - \langle\delta\Gamma\rangle^2 = \alpha^2\sigma_{\delta f}^2 + 2\beta^2\sigma_{\delta f}^4$, where $\alpha = \frac{1}{N}\sum_m S_m \frac{\mathrm{d}\Gamma_m}{\mathrm{d}\nu}|_{\Delta\nu_m}$ and $\beta = \frac{1}{2N}\sum_m S_m \frac{\mathrm{d}^2\Gamma_m}{\mathrm{d}\nu^2}|_{\Delta\nu_m}$. If the PDH signal is 0, then $\alpha = 0$, so that the frequency-to-intensity conversion factor of interest is β. In the expression of β, however, the contribution of the teeth m in the sum depends on f_0 through Γ_m. If $f_0 \neq 0$ one can demonstrate that the contribution of the teeth far from m_0 and the one of the teeth near m_0 cancel out, so that β decreases and σ_Γ as a consequence, too. On the other hand, also the gain Γ decreases when f_0 differs from 0, but less than σ_Γ, so that the trend is advantageous in terms of the relative noise of intracavity power $\sigma_{\Gamma,\text{rel}} = \sigma_\Gamma/\Gamma$. Indeed, once a desired gain Γ is fixed, it is convenient to set the cavity with a higher gain value $\tilde{\Gamma}$ (*i.e.*, a higher finesse), and then increment f_0 until Γ is reached: in this condition, the relative intracavity power noise is lower than the one in a cavity with a gain Γ and $f_0 = 0\,\text{Hz}$. Figure 1 shows a simulation of this technique. Here we take $\Gamma = 1130$ and $\tilde{\Gamma} = 2680$, corresponding to finesse values of 1800 and 4300, respectively, with a frequency noise $\sigma_{\delta f} = 5\,\text{kHz}$. By incrementing f_0 to 30 MHz, the gain of $F = 4300$ drops to 1130, the same of $F = 1800$ (panel (a)), but the relative noise drops by a factor of 6 (panel (b)).

3. – Experimental setup and results

This research has been developed in the framework of the BriXSinO ICS source, schematized in fig. 2(a). The laser system used for the Compton interaction is basically formed by a mode-locking oscillator, amplified firstly by a fiber amplification module,

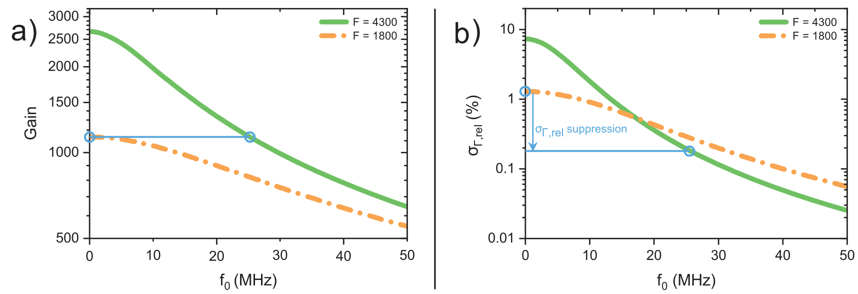

Fig. 1. – Simulations of the gain (a) and the relative noise (b) as functions of f_0, for finesse values of 1800 and 4300. f_0 can be exploited to obtain a fixed gain (1130), but a lower relative intensity noise.

then by a four-mirror crossed enhancement cavity. At the moment, a low power version of the final laser system is implemented, and its simplified scheme is shown in fig. 2(b). Exploiting this setup and the technique described in [13] to measure the finesse and to calculate the cavity gain, we acquired the Relative Intensity Noise (RIN) of the intracavity pulses through the transmitted beam for two different configurations. The first corresponds to a low finesse value of 1800 and zero offset, while the second to a high finesse value of 4300 and an offset different from zero. Notice that in this last configuration, we changed the offset to $f_0 = 45\,\text{MHz}$, until the same gain of 1140 of the first configuration was reached. For a significant comparison, we kept the PDH feedback parameters constant in the two configurations (they were optimized for the first configuration). However, a third measurement has been performed in the high-finesse and high-offset configuration and with the feedback parameters optimized for that case. Results are shown in fig. 3(a). Starting from the upper curve, in orange we have the configuration with $F = 1800$ and $f_0 = 0\,\text{MHz}$, then in green the configuration with $F = 4300$ and $f_0 = 45\,\text{MHz}$, then in blue the configuration with $F = 4300$, $f_0 = 45\,\text{MHz}$ and the feedback parameters optimized, and finally in gray the external laser noise, which is our background. The direct comparison between the orange and green curves shows a noise improvement of 10 dB (on average) between 100 Hz and 10 kHz, and a difference of 20 dB in the range 10–50 kHz. The resulting integrated noises are $\sigma_{\Gamma,\text{rel}} = 8\%$ and $\sigma_{\Gamma,\text{rel}} = 2.5\%$, respectively. Since the intracavity power is the same in the two cases, we demonstrated that our method can be

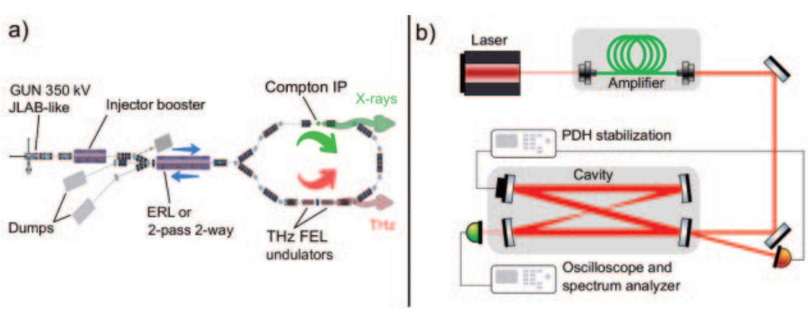

Fig. 2. – (a) Scheme of the BriXSinO machine [5]. The enhancement cavity will be centered in the Compton Interaction Point (IP) to generate X-rays. (b) Simplified scheme of the laser line. A Yb mode-locking laser is fiber-amplified up to 1.1 W, and stacked in a cavity. A PDH feedback loop locks the cavity to the laser.

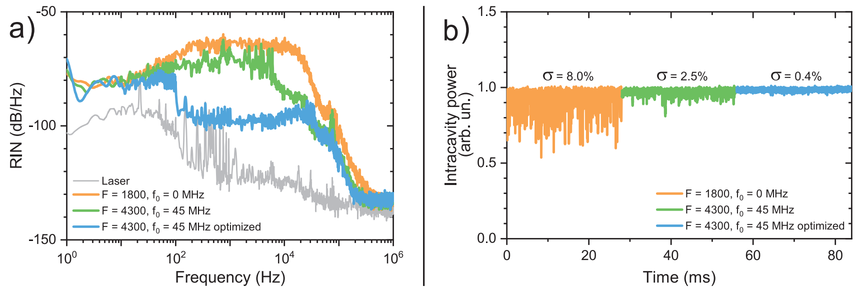

Fig. 3. – (a) RIN of the intracavity power in three different configurations with the same gain $\Gamma = 1140 \pm 30$. From top to bottom: (orange) $F = 1800$ and $f_0 = 0\,\text{MHz}$, (green) $F = 4300$ and $f_0 = 45\,\text{MHz}$, (blue) $F = 4300$, $f_0 = 45\,\text{MHz}$ and feedback optimized, (gray) external laser background. (b) Temporal traces of the intracavity power in the same three configurations of panel (a). From left to right: orange, green, blue. The relative noise is reduced by a factor 20, while the intracavity power remains the same.

effectively used to reduce the relative noise. Moreover, optimized feedback parameters for the high-finesse and high-offset configuration (in blue) leads to an even lower noise of 0.4%. Note that the noise reduction of $-20\,\text{dB}$ occurs within the feedback bandwidth below 10 kHz. To better highlight the noise reduction obtained with our technique, in fig. 3(b), we show the temporal trace of the intracavity power, measured by exploiting the transmitted beam (configurations and colors correspond to the ones of panel (a)).

4. – Conclusions

In conclusion, we have demonstrated the suppression effect of f_0 on the frequency-to-intensity noise conversion of a pulsed laser-cavity locked system. In particular, we showed that an increase in f_0 causes a considerable reduction in intensity noise, which we could experimentally reduce by a factor of 20, while maintaining a constant average intracavity gain $\Gamma = 1140$. Thus, once the necessary gain Γ is fixed, one could set a higher nominal gain $\tilde{\Gamma}$, and then increase f_0 until Γ is reached, resulting in lower intracavity power fluctuations than operating with a nominal gain Γ and maximizing spectral coupling ($f_0 = 0\,\text{MHz}$). Our technique can be effectively implemented in every optical system, where a high average intracavity power and a low intensity noise are necessary, such as in ICS sources like BriXSinO.

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