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OPTICAL CAVITY R & D FOR LASER-ELECTRON INTERACTION APPLICATIONS

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Abstract

Laser-electron Inverse Compton Scattering X-ray source based on optical enhancement cavity is expected to produce higher-flux and better-quality X-rays than conventional sources, in addition, to become more compact, much cheaper than Free Electron Laser and Synchrotron Radiation. One X-ray source named ThomX is under construction at LAL, France. An electron storage ring with 50 MeV, 16.7 MHz electron beam will collide with a few picosecond pulsed laser to produce 10^{13} photons per second. A prototype cavity with a high finesse ($\mathcal{F}$=25,100) in the picosecond regime is used to perform R & D for ThomX. We obtained 380 kW power stored in the optical cavity and mode instabilities were observed. The EOM-based frequency modulation to measure the finesse, the influence of dust on finesse, high-power experiments and other related issues are mentioned briefly. We will also describe the TTX2 (Tsinghua Thomson Scattering X-ray source) at Tsinghua University which is in design process. TTX2 prefers using an electron storage ring and an optical cavity in order to get high X-ray flux.

INTRODUCTION

Over the last one hundred years, X-ray sources have facilitated countless important scientific discoveries. In particular, more than a dozen Nobel Prizes have been awarded for work related to X-rays [1]. Physicists are constantly searching for diverse X-ray sources of high quality and high brilliance to meet the needs of various applications. To date, several types of high-performance sources have been developed, including synchrotron radiation sources, free-electron lasers and inverse Compton scattering sources. Even great improvements in X-ray quality and brightness do not necessarily translate into greater access or productivity for individual researchers. X-rays are essential tools in many fields of fundamental applied research at universities and in both industrial and academic laboratories. However, even the cost of a single conventional synchrotron far exceeds the typical budget of a mid-size university or laboratory. The European Commission is aware of this problem and the consequent necessity to *develop bright but small and (relatively) cheap X-ray sources, not to replace synchrotrons but to complement them* [2]. A compact, room-sized apparatus based on laser-electron interaction has the most potential to bridge the gap between conventional X-ray sources and synchrotrons or FELs and thus to lower the barrier to entry for X-ray-based research.

ThomX is an *Equipex* project funded by French government to create a compact source of X-rays for applications in the health sector and for cultural heritage investigations, among other purposes. In the following section, we will introduce R & D on the prototype cavity of ThomX and the upgrading of TTX, short for Tsinghua Thomson Scattering X-ray Source.

DEVELOPMENT OF THE PROTOTYPE CAVITY OF THOMX

Measurement of Finesse

We used the EOM-based frequency modulation method to measure the finesse of the prototype cavity shown on Fig. 1. The finesse reached is as high as 25,000. The decay time method is described briefly in the following paragraph.

This method is based on Reference [3]. The idea is to determine the free space range and the bandwidth of the cavity and divide one by the other, as in the definition of the finesse. This technique uses the property that the interval of the cavity resonance frequency is equal to FSR. When the optical frequency is shifted by FSR, the resonance condition is still met. In this method, the laser oscillator is locked to the cavity, and the laser beam is modulated in phase at a frequency close to FSR.

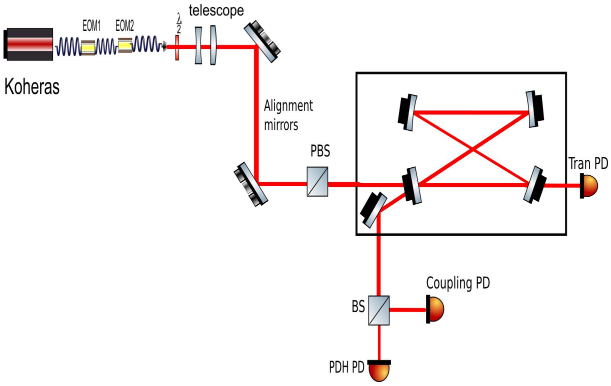

Figure 1: Schematic illustration of the experimental setup for measuring the finesse using the EOM-based method. EOM1 is used to generate the PDH error signal. EOM2 is used to modulate the laser beam in phase at a frequency close to FSR.

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Through an EOM (electro-optic modulator) frequency modulation of $\Omega = FSR$, each lateral sideband $\Omega, 2\Omega, \cdots$, can also be accumulated in the Airy peak of the cavity, and the resonance will be maximal. However, when the modulation is varied around FSR, some lateral bands will no longer be coupled to the Airy peak, and the stored power will decrease. Thus, by sweeping the resonance, one can reconstruct the Airy function. This makes it possible to precisely measure FSR and the cavity linewidth.

Fig. 1 shows the experimental setup. EOM1 is used to generate the error signal. EOM2, modulated around FSR, is used to sweep the resonance in order to reconstruct the Airy function. The speed of the frequency sweep is approximately 100 Hz per 50 ms. This scan gives the conversion ratio from the oscilloscope timebase to the frequency domain of the cavity. Finally, we obtain the curve shown in Fig. 2, which gives the Airy function of the cavity as detected by the transmission photodiode. This measurement method yields an FSR of 178.38 MHz and a linewidth of $\delta\nu = 7.1$ kHz. Hence, the finesse is 25,100.

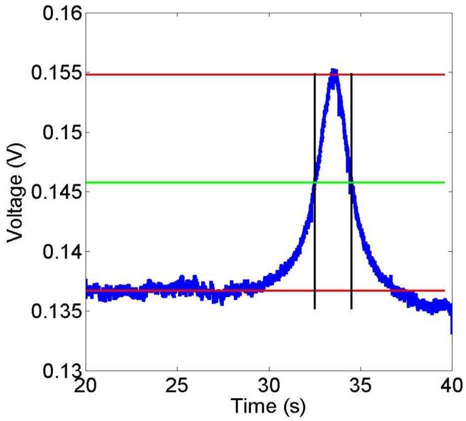

Figure 2: Finesse measurement results. The obtained cavity Airy function corresponds to $FSR = 178.38$ MHz and a linewidth of 7.1 kHz.

Influence of Dust on Finesse

Dust deposited on the cavity mirror surfaces has a great effect on the cavity finesse, which can lead to an enormous decrease in the cavity gain. We measured the surfaces of the cavity mirrors of ThomX and another cavity named Mightylaser, as shown in Fig. 3. The mirrors of ThomX are new, and we can see that the mirror surfaces are very clean. The luminous regions near the edges of each mirror in Fig. 3 correspond to reflection from the mirror mounts. By contrast, the surfaces of the Mightylaser cavity mirrors are somewhat dirty because they have been in use for a long time, and some small amount of dust has been deposited in the centers of these mirrors. We attempted to clean the Mightylaser mirrors by wiping them and using First Contact cleaner, which is specially designed for cleaning precision optics, mirrors and surfaces in use. Unfortunately, it was impossible to clean the Mightylaser cavity mirrors to the level of those of ThomX. It is possible that these mirrors were damaged under high laser power.

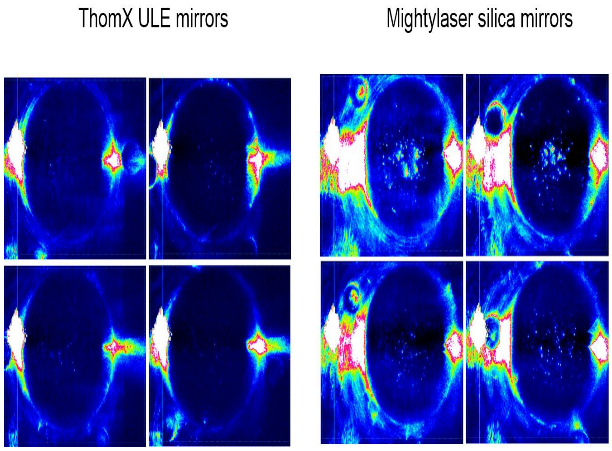

Figure 3: The surfaces of the cavity mirrors of ThomX are shown on the left. The surfaces of the cavity mirrors of Mightylaser are shown on the right.

The experimental finesse is approximately 25,100, very close to the theoretical finesse of 28,000. By contrast, the finesse of the Mightylaser cavity is approximately 9,000, which is much lower than its theoretical value of 40,000. These findings provide an intuitive understanding of the effect of dust on the cavity finesse.

To keep the optical setup clean and avoid the deposition of dust on the cavity mirrors, it is necessary to take several steps. In addition to using an ultra-clean vacuum chamber, we also assemble all parts and perform all experiments in a clean room.

Before bringing any element into the clean room, we clean it with acetone and alcohol. In addition, we use a nitrogen-based ionizing pistol to remove residual particles. A full clean suit, including hat, gloves and body suit, is necessary for all personnel working in the clean room.

High-Power Experiments

Our group performed several high-power experiments on the prototype S-Box cavity. The experimental setup is shown in Fig. 4. Before entering the amplifier, the laser pulse duration is stretched to 250 ps by a CVBG, and the output power of the amplifier can reach as high as 40 W. The injected laser beam is coupled to the cavity after passing through the four-cylindrical-mirror telescope. A PDH error signal is used to lock the laser to the cavity. The cavity finesse is approximately 25,000. The repetition frequency of the Onefive oscillator is 133 MHz.

We locked the oscillator to the cavity and observed some strange mode shapes at different powers, as shown in Fig. 5. When a low amount of power is stored in the cavity, the mode seems to be TEM_{00}, and it is very pure. At higher powers (50 kW and 70 kW), it seems that the TEM_{00} mode overlaps with higher-order modes. This effect restricts the

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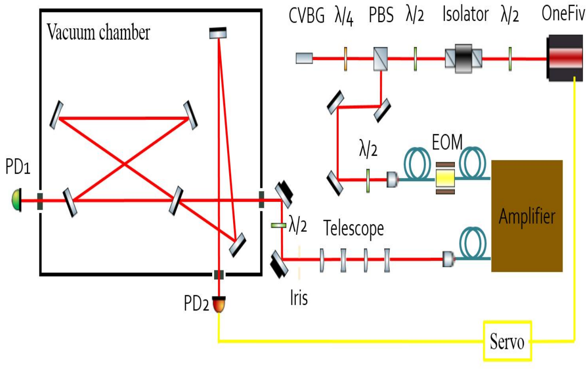

Figure 4: Schematic illustration of the setup for the high-power experiments. The red line represents the light path. The yellow line represents the electrical signal.

stacked power in the cavity to approximately 70 kW and strongly limits the coupling. This effect may originate from the heating of the mirror mounts due to the scattering at high power and mode degeneracies [4] due to the thermal effect. After placing the aluminum covers in front of the mirror mounts, we achieved a stable power as high as 383 kW and reached a maximum power of 400 kW for several seconds, with a cavity gain of 10,000.

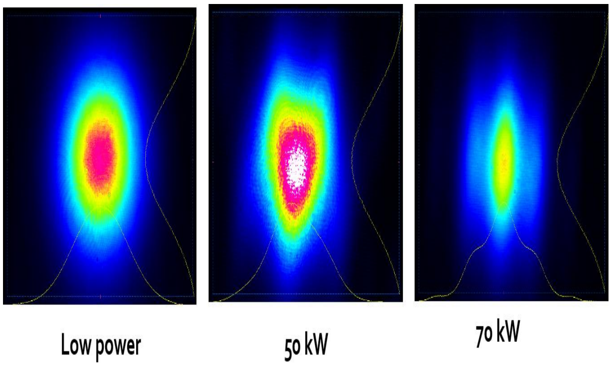
Low power 50 kW 70 kW

Figure 5: Beating of transverse modes at different powers.

To achieve such performance, it is necessary to realign at every step. This is because under high power, the cavity losses alignment very quickly. In fact, we were not limited by the amplifier, but we nevertheless could not stack more power in the cavity. Modal instabilities is limiting this power. This remains an open question.

Another group at the Max Planck Institute in Germany [5] achieved 670 kW in their cavity, but they used a low-finesse cavity and a high input laser power. Their system is much more expensive than ours. Ours is more complex and difficult to operate, mainly because of the feedback loop.

TTX2

Tsinghua University hosts a compact low-repetition-frequency X-ray source called TTX, which is based on a linac system and a terawatt femtosecond laser system. The next step of the project will be to upgrade TTX to a high-repetition-frequency X-ray machine named TTX2, consisting of an optical cavity and an electron storage ring. The prototype optical cavity for TTX2 was designed shown in Fig. 6 at Tsinghua University in order to gain the necessary experience for this upgrade. The installation will begin this year.

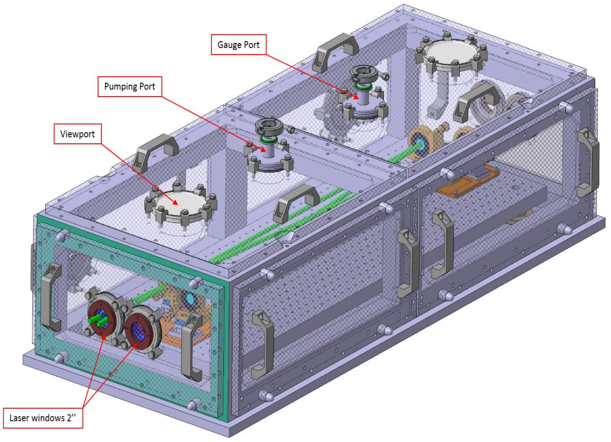

Figure 6: Model of the prototype optical cavity for TTX2.

CONCLUSION

Laser-electron Inverse Compton Scattering X-ray source based on optical enhancement cavity is one promising light source to bridge the gap between conventional X-ray sources and synchrotrons or FELs. The prototype cavity of ThomX project was introduced. An EOM-based frequency modulation method to measure the cavity finesse, the influence of dust on finsse, high-power experiments and other related issues are discussed. We obtained 400 kW at 25000 finesse in pulsed regime and observed that modal instabilities is limiting this power. We also describe the other one named TTX2 at Tsinghua University. TTX2 based on an electron storage ring and an optical cavity to get high X-ray flux is our next step.

REFERENCES

[1] Karlsson, Erik B. "The Nobel Prize in Physics." The Nobel Prize: The First 100 Years. 2001. 31-69.

[2] European Cooperation In Science and Technology, `http://www.cost.eu/COST_Actions/mpns/MP0601`

[3] Locke, C. R. et al. "A simple technique for accurate and complete characterisation of a Fabry-Perot cavity." Optics Express 17.24 (2009): 21935-21943.

[4] Bullington, A. L. et al. "Modal frequency degeneracy in thermally loaded optical resonators." Appl Opt 47.15(2008):2840-51.

[5] Carstens, Henning, et al. "Cavity-Enhanced 196 kW Average-Power Infrared Pulses." Mid-Infrared Coherent Sources 2013.