MECHANICAL STABILITY ANALYSIS ON OPTICAL CAVITY USED FOR TTX*

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Abstract

Due to the great applications of ultrafast X-ray in detecting the micro-world, the X-ray sources develop rapidly. One of X-ray sources named Laser-Electron X-ray Machine (LEXM) based on the Inverse Compton Scattering of optical cavity is very promising. Accelerator Lab of Tsinghua University has finished the basic prototype design. This paper compares the different kinds of X-ray source, such as SR, FEL, X-ray tubes and LEXM. And this paper optimizes the optical lengths of four mirrors structure optical cavity and analyses the mechanical stabilities of two mirrors and four mirrors structure optical cavity used for TTX. According to the simulation results, we choose the four mirrors structure optical cavity.

INTRODUCTION

X-ray diffraction and scattering, X-ray crystallography, and X-ray spectroscope are widely used in life science[1], material science[2], and medical diagnosis[3]. High-quality and high-brightness X-rays are a strong requirement to improve the applications. Scientists are making efforts to look for new X-ray sources. With the development of new technology, so far, X-ray source generators have X-ray tube, Synchrotron Radiation (SR), Free Electron Laser (FEL) and Laser-Electron X-ray Machine (LEXM). Figure 1 shows the history of X-ray sources.

X-ray tubes are cheap and compact but not monochromatic. SR has a high X-ray flux and costs a lot because of tens of GeV electron storage ring. More than 70 synchrotrons in operation or under construction locate in more than 30 countries. Nowadays, FEL has got the highest brightness and intensity. However, due to the high cost, many fundamental and applied research organizations cannot afford an SR or a FEL. LEXM based on Inverse Compton Scattering can fill the gap between SR/FEL and X-ray tubes.

LEXM has many advantages, such as compact instrumentation, low cost, good beam direction, acceptable luminosity and so on. Nevertheless, an L-LEXM based on CPA (chirped pulse amplification), which has been in operation at Tsinghua University, produces the low-repetition-rate X-ray (tens of hertz). An H-LEXM with high-repetition-rate (several hundred MHz), which contains an electron ring and an optical enhancement cavity (OEC), will be constructed. 10^4-10^5 photons per collision and average flux of 10^{12}-10^{13} photons per second can be reached.

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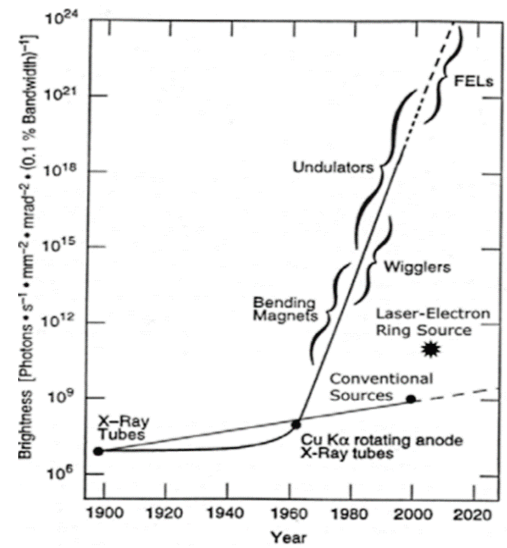

Figure 1: X-ray source brightness versus time[4].

This paper is organized as follows: first we will compare the different kinds of X-ray source (SR, FEL, X-ray tubes and LEXM) and find that LEXM based on Inverse Compton Scattering can fill the gap between SR/FEL and X-ray tubes. LEXM is a very promising X-ray source. Figure 2 is the schematic diagram of H-LEXM. Next, we introduce the basic theory of Inverse Compton Scattering and the mechanical stability analysis for optical cavity. Based on the theory, in order to compare the mechanical stability of two-mirror and four-mirror optical cavity, firstly we optimize the four-mirror optical cavity to get the most X-ray flux and by using the parameters of four-mirror optical cavity, then, we do the simulations of two-mirror and four-mirror mechanical stabilities.

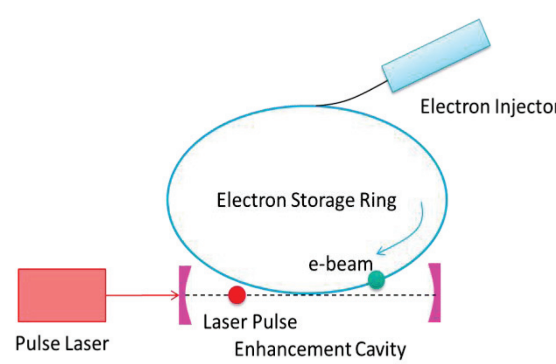

Figure 2: Schematic diagram of H-LEXM.

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THEORY

There exist a set of electromagnetic fields which have a spherical wavefront and Gaussian amplitude, and the fundamental mode TEM_{00} propagating along the z direction is we want.

Luminosity is determined by the space-time distributions of beam particles, the collision angle, and the collision frequency:

$$L = f_c \iiint \int_{-\infty}^{\infty} N_e \rho_e (x,y,z,t) \, N_l \rho_l (x,y,z,t) \, dxdydzdt,$$

where N_e, N_l, and f_c are the number of electrons in a bunch, the number of photons in a pulse, and the number of collisions per second; ρ_e, ρ_l are the distributions of an electron bunch and laser pulse.

When neglecting the variation of the beam size and supposing two round beam, luminosity becomes[5]:

$$L = N_e N_l f_c \frac{(1-\beta\cos(\theta))}{2\pi} \times \frac{1}{\sqrt{\sigma_{ye}^2+\sigma_{yl}^2}} \frac{1}{\sqrt{\sigma_{xl}^2(-\beta\cos(\theta)+1)^2+\sigma_{xe}^2(\beta-\cos(\theta))^2 +(\sigma_{ze}^2+\sigma_{zl}^2)\sin^2(\theta)}},$$

where N_e, N_l, f_c, $\sigma_{x,y,z,e}$, $\sigma_{x,y,z,l}$, and θ indicate, respectively, the number of electron and photons per bunch, the repetition frequency, the three-dimensional bunch root-mean-square sizes for the electron (index *e*) and laser photon (index *l*) bunches, and the collision angle.

Because of the tiny laser waist size (about 100um), in experiments it will be necessary to shift the optical cavity to look for the interaction point. So it is important to analyse mechanical stability to decide to choose 2-mirror or 4-mirror cavity.

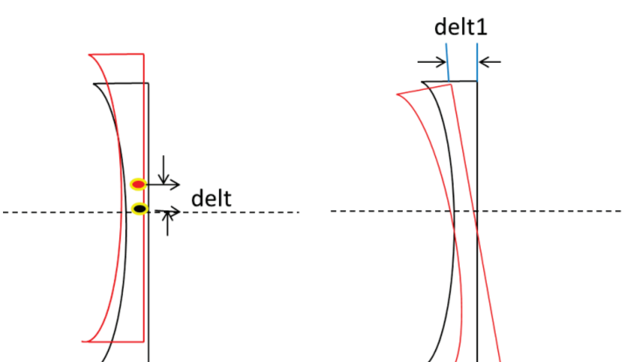

Figure 3: schematic diagram of vertical error and angle error.

For alignment analysis, we can use the ABCD transfer matrix method by introducing the E, F error element. A mirror mechanical error includes vertical error (delt1) and angle error (delt), as shown in Figure 3.

The corresponding transfer matrix of the mirror is[6]

$$T_i = \begin{bmatrix} A & B & E \\ C & D & F \\ 0 & 0 & 1 \end{bmatrix},$$

where E=0 , $F = \frac{2\times delt}{\rho} + 2delt1$

In one period, we can get the final transfer matrix by inversely multiplying the part matrix, supposing **T**=$\begin{bmatrix} A & B & E \\ C & D & F \\ 0 & 0 & 1 \end{bmatrix}$. Then the waist size, the optical axis offset displacement and optical axis offset angle are expressed as follows[6]:

$$w_0 = \sqrt{\frac{\lambda}{\pi} * \frac{2 * \mathrm{Abs[B]}}{\sqrt{4-(\mathrm{D}+\mathrm{A})^2}}}$$

$$r_0 = \frac{(1-\mathrm{D}) * \mathrm{E} + \mathrm{B} * \mathrm{F}}{2-\mathrm{A}-\mathrm{D}}$$

$$r_{01} = \frac{(1-\mathrm{A}) * \mathrm{F} + \mathrm{C} * \mathrm{E}}{2-\mathrm{A}-\mathrm{D}}$$

By using the ABCD matrix method, it is easier to calculate the waist size shift and the spot shift on the mirror. As we have known, mechanical error for mirrors is not avoidable and the analysis has referential meaning.

MECHANICAL STABLITY ANALYSIS

In our design, the circumference of the electron storage ring is 3.6 meters, so two-mirror optical cavity length is 3.6 meters and four-mirror optical cavity length is 7.2 meters. Figure 4 shows the basic structure of four-mirror cavity. In order to analysis the mechanical stability of four-mirror structure, firstly, optimize the four-mirror structure lengths (L_1-L_4) to get the most X-ray flux.

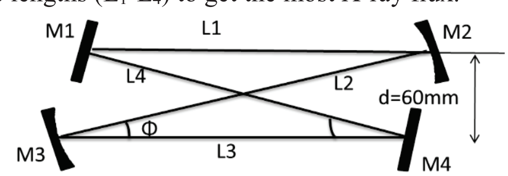

Figure 4: Schematic diagram of four-mirror optical cavity structure.

As shown in above figure, the input wavelength is 1064nm, cavity length is L_1+ L_2+ L_3+ L_4=L_{cav} and the curvature radius of the mirror is 2.0m.

To get the most X-ray, we optimize the L_1, L_2, L_3, L_4 and Φ. Using the method of exhaustion, set L_2 different value expanding from small to large. From Figure 5, we can find that when L_2 is less than 2000 mm, the cavity is unstable. And when L_2 is more close to 2000 mm, optical cavity can get more flux.

The final simulation result is in Table 1, and the X-ray flux is as high as 10^{10} order.

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Table 1: Four-mirror Cavity Optimal Parameters

X Flux	L_1 (mm)	L_2 (mm)	L_3 (mm)	L_4 (mm)	Φ(rad)
12.542×10^9	1799.5	2000.3	1799.5	1600.7	fai=0.03

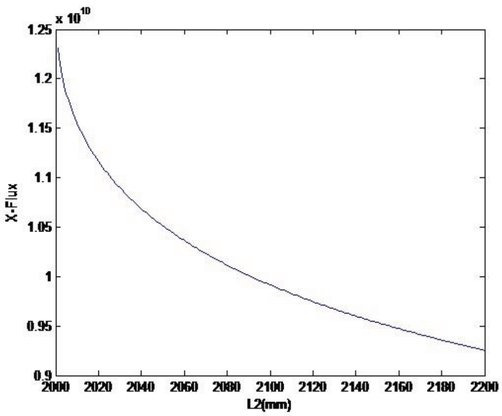

Figure 5: X-Flux versus L_2.

After getting the four-mirror optical cavity optimal parameters, it is convenient to continue to analysis the mechanical stability. We suppose the waist size is 100um. For convenience, we suppose once the mirror installation error happens for mirror vertical or angle error, the uniform absolute value is 10^{-6} m(rad), that is |delt|=1um, |delt1|=1urad. If no error, |delt|=0,|delt1|=0.

For two-mirror structure, there are 3^4 kinds of error combination. According the simulation results, no matter which one error combination is, the spot on the mirror is fixed (about 6 mm). However, we just care about the greatest error. When Mirror 1 and Mirror 2 vertical and angle errors are (-1um,-1um) (-1urad,-1urad) and (1um,1um) (1urad,1urad), the greatest displacement of the waist is 2.8 um. But the spot displacement on the mirror is as high as 10.08 mm. Because of the mirror size, the two-mirror is too mechanically unstable.

For four-mirror structure, there are 3^8 kinds of error combination. No matter which one error combination is, the spot on the mirror is also fixed(x-direction 5.1 mm y-direction 8.3 mm). However, we just care about the greatest error. As in Table 2, the greatest displacement of the waist is 5.0 um. But the spot displacement on the mirror is as small as 10.08 um. So four-mirror has good mechanical stability.

Table 2: Mechanical Stability Comparison

		Waist size	Waist displacement	Spot displacement
Two mirror		59.3um	0.0028mm	10.01818mm
Four mirror	X	65.6um	0.0050mm	10um
	Y	40.5um	0.0050mm	10um

Without doubt, Optical Fermat Principal is also suitable for error analysis. Fabian Zomer[7] has finished the work, and the results are close to this paper. This has verified the answer is correct. That is why most optical cavity (KEK LAL) choose 4-mirror rather than 2-mirror cavity.

CONCLUSION

This paper finishes the simulation of four-mirror optical cavity structure to get the most X-rays. And we carefully conducted the mechanical stability of two-mirror and four-mirror optical cavity. We found four-mirror was suitable for TTX. Tsinghua University has finished the proto-type design for H-LEXM.

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