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Practical Design of Resonant Cavity for a RF Free Electron Laser

Wang Mingchang, Wang Zhijiang, Zhou Huifen, Feng Chengshi
(Shanghai Institute of Optics and Fine Mechanics, Academia Sinica, Shanghai, China)

Abstract: Practical design of the resonant cavity for a RF free electron laser at 10.6 μm is proposed. For a given cavity length, the parameters, including the curvature of reflector, waist radius and spot size on reflectors, are calculated according to the Gaussian profile. The problem of spatial match between the radiation and the beam in a long narrow waveguide has been solved and the synchronization is discussed.

Key words: free electron laser, resonant cavity

I. Introduction

Ever since its introduction more than a decade ago, the development of free electron laser has been rapid. In order to effectively coordinate the electron beam and the mutual interaction length of laser and the inducted magnetic field, most RF free electron laser devices adopted the resonance cavity structure modified from the magnifier.[1]

A new series of problems, however, came with the change in structure.[2] For example, the electron beam would require a higher peak current to shorten the time needed to establish resonant oscillation, the electron beam should acquire sufficient pulse width to maintain a minimum number of oscillation, and adequate optical resonant cavities should be chosen to ensure matching between electron beam and radiation beam.

The difference between the resonant cavity of a free electron laser and that of an ordinary laser lies in the problem of strict time and spatial matching between electron beam and radiation beam. Ordinary laser devices usually adopt mutual-focus or semi-mutual-focus cavities with minimum divergent scattering loss because the limited dimension of the reflective mirror of the cavity is the source of divergent scattering loss. For free electron lasers, the spatial clearance of induced magnetic fields should be as small as possible to maintain high magnetic field strength, while the magnetic field should be as long as possible to ensure sufficient single-pass gain. Therefore, a long narrow waveguide will be formed in the resonant cavity. Because the dimension of the reflective mirror of the resonant cavity is generally much larger than the clearance of the induced magnetic fields, the latter will become the major source of divergent scattering loss.

The design objective of resonant cavity for free electron laser is to ensure spatial matching between electron beam and radiation beam. To accomplish this goal, the waist positions of the radiation and electron beams should overlap and the Gaussian /386 distribution of the radiation beam should cover the spatial distribution of the electron beam as much as possible. In general, the waist radius of the electron beam is small, between 0.5 and 1mm and free electron lasers usually adopt the mutual-center cavities.[3]

For the case of long narrow waveguides, because of the steep change in distribution of radiation beam in the mutual-center cavity and rapid expansion after the waist position, loss will result because of blocking of the waveguide. The distribution of radiation beam for mutual-focus cavity is less drastic but the radiation spot at the waist is bigger and matching between radiation and electron beams is less satisfactory. To solve this problem, the cavity used in this study is between the mutual-center and mutual-focus models and the dimension of the radiation spot is about 1.4 to 2.0 times that of the electron beam at the waist position.

A practical design of the resonant cavity for a 10μm RF free electron laser is introduced in this paper. Three sets of Gaussian distribution curves for fixed resonant cavity length of 2519.244mm were calculated along with their characteristic parameters: waist position, waist spot dimension, Raleigh length, and curvature of reflector. Conditions for stable optical cavity were satisfied. Also, the problem of time synchronization of pulsed electron and radiation beams is discussed. The required precision of cavity length adjustment is 1μm.

II. Design Consideration

From the standpoint of physical optics, to minimize loss due to divergent scattering the half angle spanned from the first reflector onto the second reflector a_1/L should be slightly bigger than the half angle from the far-field scattering caused by the pseudo plane wave resulted from the finite dimension of the second reflector $\lambda/2a_2$; namely $a_1a_2/\lambda L \geq 1$.

For cavity length L=2519.244mm and wavelength $\lambda=10.6\mu m$, it is required that $a_{1,2} \geq 5.2mm$. The cavity radius was greater than 10mm and the requirement was satisfied.

The capability to maintain low (divergent scattering) loss mode is related with the distance between two reflectors L and their radii of curvature R_1 and R_2. From the stability diagram of optical cavity it is clear that the resonant cavity should adopt a structure between the mutual-focus and mutual-center cavities. Stability requirement can also be satisfied by the large-R cavity structure which is between the mutual-focus and mutual-center cavities, however, the radiation spot was too big at the waist position and was not suitable for practical application. Furthermore, the mutual-center cavity ($R_{1,2}=L/2$), mutual-focus cavity ($R_{1,2}=L$), and parallel plane cavity ($R_{1,2}=\infty$) are all close to the unstable region and severe loss would result from a very insignificant deviation. The cavity structure between mutual-focus and mutual-center cavities would allow certain deviation while still maintaining stability as long as the following condition is satisfied:

$$0<(1-L/R_1)(1-L/R_2)<1 \qquad (1)$$

Considering the scattering of radiation of Gaussian distribution. For symmetrical resonant cavity we have $R_1=R_2=R$ and the dimension of the smallest spot at the waist position W_0 is

$$(W_0)_{mutual\text{-}focus}=(\lambda L/2\pi)^{1/2} \qquad (2)$$

while the dimension of the radiation spot at the mirror is

$$(W_{1,2})_{mutual\text{-}focus}=\sqrt{2}(W_0)_{mutual\text{-}focus} \qquad (3)$$

For ordinary resonant cavity with fixed L/R ratio, the ratio of the spot dimension at the mirror to the minimum spot dimension for mutual-focus cavity is[4]

$$\frac{W_{1,2}}{(W_{1,2})_{\text{mutual focus}}}=\left\{\frac{1}{(L/R)[2-(L/R)]}\right\}^{1/4} \qquad (4)$$

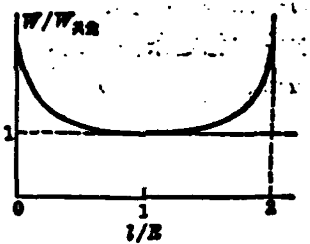

Figure 1: Ratio of spot size at mirror of symmetrical resonant cavity to spot size at mirror of mutual-focus (1/R=1) cavity

Figure 1 shows the ratio of spot dimension for various cavity structures. To minimize the dimension of radiation spot at the mirror and to avoid blocking by vacuum tube channel due to small clearance of the induced magnetic field of free electron laser, the cavity should resemble mutual-focus cavity as much as possible.

The Raleigh parameter for symmetrical resonant cavity is

$$Z_0 = \left[\frac{(2R-L)L}{4}\right]^{1/4} \qquad (5)$$

and the dimension for the minimum spot is

$$W_0 = (\lambda Z_0/\pi)^{1/2} \qquad (6)$$

and the dimension for the spot at mirror is

$$W_{1,2} = \left(\frac{\lambda L}{2\pi}\right)^{1/2}\left[\frac{2R^2}{L(R-L/2)}\right]^{1/4} \qquad (7)$$

Based on the R templet and the given spot dimension and the scattering equation for the Gaussian distribution mentioned above, a set of parameters were calculated (see table 1).

Table 1: Calculated value of cavity parameters (mm)

R	1282.3	1312.2	1522.2	1438.8	1700.0
Z0	168.9	257.4	575.1	475.0	744.8
W0	0.76	0.98	1.39	1.26	1.59
W1,2	5.68	4.66	3.35	3.59	3.12

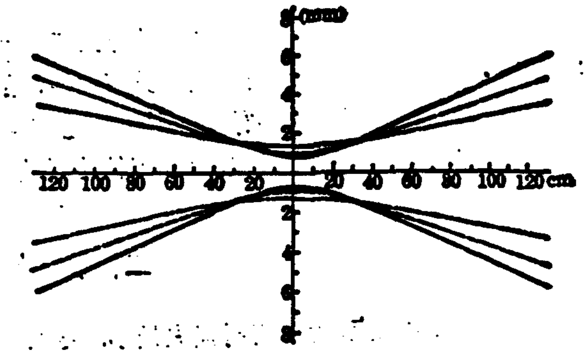

Figure 2: Gaussian beam distribution in a resonant cavity. Solid line-W_0=0.76, R=1282.3, dashed line-W_0=0.93, R=1312,2, dot-dashed line-W_0=1.39, R=1522.2

Figure 2 shows the calculated data based on the in-cavity transmission of Gaussian distribution.

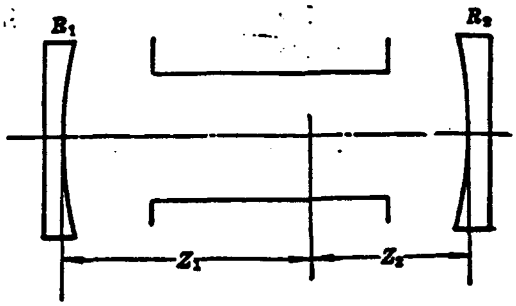

Figure 3: Waist position for asymmetrical resonant cavity

For the general case of asymmetrical resonant cavities, figure 3 shows the reflectors with radii of curvature R_1 and R_2 placing at positions Z_1 and Z_2 from the waist. The sign convention adopted was that negative values would be assigned when the center of curvature is at the right-hand side of the mirror. Therefore, in this figure Z_1 and R_1 both are negative values and the cavity length $L=-Z_1+Z_2$. For fixed Z_0 the radii of curvature of the reflectors can be calculated by

$$\left.\begin{aligned} R_1 &= Z_1 + Z_0^2/Z_1 \\ R_2 &= Z_2 + Z_0^2/Z_2 \end{aligned}\right\} \qquad (8)$$

Based on the available optical templet and the R_1 and R_2 values, the Raleigh distance can be calculated:

$$Z_0^2 = \frac{L(-R_1-L)(R_2-L)(R_2-R_1-L)}{(R_2-R_1-2L)^2} \qquad (9)$$

and the dimension for the minimum spot can be obtained from equation (6). The dimension for the spot at mirror is

$$W_{1,2} = W_0\left[1+\left(\frac{Z_{1,2}}{Z_0}\right)^2\right]^{1/2} \qquad (10)$$

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III. Results and Discussion

For a resonant cavity with $R_1=R_2=1522.2$mm, the waist position is at the center of the cavity. The spot at waist position is $W_0=1.39$mm and is about 1.5 times bigger than the assigned minimum radius of the electron beam ($r_0=0.5-1.0$mm) and the requirement is satisfied. At the exit of the induced magnetic field Z=750mm, spot radius W=2.29mm and is smaller than the minimum dimension of 2.90mm for the waveguide and blocking would not occur.

For asymmetrical resonant cavity, the waist position was chosen to be $Z_1=1509.62$ and $Z_2=1009.62$. From equations (6), (8)-(10) a set of parameters satisfying the requirement was obtained: $R_1=1762.0$mm, $R_2=1312.2$mm, $Z_0=575.5$mm, $W_0=1.39$mm, $W_1=3.91$mm, and $W_2=2.81$mm.

The resonant cavity adopted the structure of an exterior cavity. The vacuum tube channel was sealed by ZnSe Bush window. The index of refraction for the material at 10.6μm is 2.4023 and the Broost angle is 67.40°. The absorption coefficient was about 1.2×10^{-3}cm^{-1}. The reflecting mirrors of the resonant cavity were ZnSe mirror with multiple-layer coatings. The mirrors at one end were total reflecting mirrors and the mirrors at the output end had transmittance of 1% and 3%, respectively. Therefore, the theoretical in-cavity compound loss (not including coupling output) should be less than 3%.

One of the characteristics of the vibrators of RF free electron laser is the higher precision required for cavity length adjustment. Assuming that the electron beam pulse of 4μs duration was composed of a series of micro-pulses with equal duration. If the acceleration frequency were 2856MHz the separation of the micro electron beam pulses was $\Gamma_e=1/f_e=0.35$ns. The requirement for oscillation was that after traveling for one cycle within the cavity the radiation could still maintain strict synchronization with the following micro pulses. Therefore, the cavity length was adjusted by a servo system and the range of adjustment was determined by pulse separation Γ_e. At present, the range was about 10.5cm. Considering the error of measurement of a 2.5m cavity, the actual range of adjustment can be reduced to about 2cm.

The width of the micro pulse determined the accuracy of adjustment of cavity length. At present, the width was $\Gamma_p=4$ps, corresponding to 1.2mm in distance. The accuracy of cavity length adjustment should guarantee that after traveling one-cycle within the cavity the radiation could still fall into the second micro pulse. Because of the "sliding" effect of the pulse of RF free electron laser,[5] the problem of accuracy became more complicated. The sliding effect is that the traveling period of radition trough each induced magnetic field is sliding one wavelength ahead of the electron beam pulse. Choosing the number of periods of induced magnetic field as N=50 then the sliding distance is 530µm. For micro pulses with 4ps duration the pulse would have slided about one-half ahead and the effect of sliding is significant.

If 10% of the radiation beam would be allowed to slide from the micro pulses then the sliding distance would be 120µm. If the in-cavity radiation oscillated 100 times, then the error for cavity length adjustment would be 1.2µm. If the in-cavity oscillated 200 times then the error for cavity length adjustment would be 0.6µm.

In practicality, there is a certain range for cavity length adjustment. The experiment at Los Alamos showed that laser output was possible when the length adjustment range was limited to 40µm. However, the output amplitude was different and there existed a maximum output. Obviously, considering the sliding effect the micro pulse of 4ps duration is indeed too narrow and oscillation would be difficult.

An open-loop servo system was used to accurately adjust cavity length. The power supply for the servo machine was manually controlled during experiment to drive a servo motor which rotated 1.5° each step. The motor drove a clearance-diminishing gear deceleration system (deceleration ratio 1:2). After deceleration a system (auxiliary rotation 0.5mm) was engaged to induce horizontal movement of mirrors along the guiding rail. The accuracy for horizontal movement was 1µm. The guiding rail was polished to guarantee that the tilting angle associated with horizontal movement of the mirrors is less than 10". This is also the adjustment accuracy of the servo system. The moving distance of mirrors was directly recorded by a optical grating indication system with discerning capability of 5µm at present. After improvement the accuracy was improved to within 1µm.

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