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Investigation on repetition-rate electron beam generator for pumping non-chain HF/DF chemical laser*

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Abstract: A 1Hz repetition-rate electron beam generator is being developed to pump HF/DF chemical laser. The pulse width, peak current and peak voltage of the electron beams are 100ns, 100kA and 450kV, respectively. It uses two diodes, two water-filled pulse forming lines, three laser-triggered switches, a pulse transformer and one set of energy storage capacitors. The primary, secondary and mutual inductances of the pulse transformer are 331nH, 26.5mH and 1.9μH, respectively. The capacitance of each pulse forming line is 8.15nF. Its inductance and impedance are 300nH and 6.2Ω, respectively. The breaking factor is 0.3 at 1MV charging voltage. The output energy of a non-chain HF/DF chemical laser pulse is expected to be 250J at 3.8μm.

Key words: Repetition-rate electron beams generator; HF/DF chemical laser; Pulsed transformer

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With the recent successful application of a single pulse electron beam in pumping high energy laser in the inertial confinement fusion, inertial fusion energy and directional energy laser weapon[1~5], the repetition-rate electron-beam-pumped high energy, high power laser become very interested in these fields today. Thus many laboratories and scientists are involved in developing the repetition-rate electron beam generators to pump gas laser for the laser wavelength from 0.248mm to 10.6μm[6~9]. This paper presents our researches on the key technologies of repetition-rate electron beam generator.

1 Repetition-rate electron beam generator

The generator shown in Fig. 1 consists of a pulse transformer (PT), pulse forming lines (PFL1, PFL2), electron-beam diodes (D_1, D_2), primary capacitor (C_0), laser-triggered gas switches (G_0, G_1, G_2), and a high voltage power. The charging voltage on C_0 is 100kV, the peak voltage on the PFL is 1MV. The design parameters for electron-beams are 0.5MeV, 100kA and 100ns. The expected HF/DF laser energy is 250J at 3.8μm.

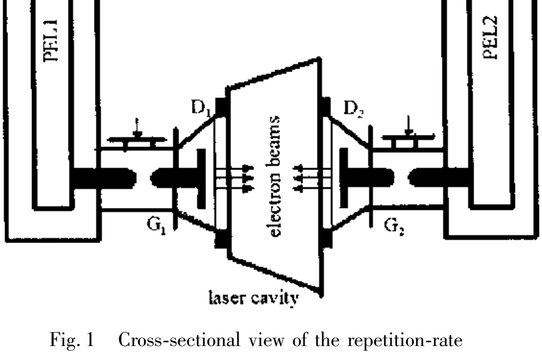

Fig. 1 Cross-sectional view of the repetition-rate electron-beams pumped non-chain HF/DF laser system

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2 Structure of the pulse forming line

For the water-filled pulse forming lines, their diameters are calculated on the breaking factors of the PFL according to the J. Martin empirical formula[10]. If the diameters of the outline and the inner-line of PFL are R and r, when a voltage pulse is applied to the PFL with a peak voltage $V_{PFL,P}$, the electric field, breakdown electric field and breaking factors on the inner surface of the outer line of the PFL are defined as

$$E_R^+ = \frac{V_{PEL,P}}{R\ln\frac{R}{r}},\quad F_R^+ = \frac{0.23\alpha}{t_{eff}^{1/3}A_R^{0.058}},\quad K^+ = \frac{E_R^+}{F_R^+} \tag{1}$$

respectively, where A_R is the area of the inner surface of outline, $t_{eff} = 0.5\mu s$ is the charging time of the voltage higher than 63% of the breakdown voltage on the PFL, α is the modified factor. It is defined as

$$\alpha = 1 + 0.12\left(\frac{R/r - 1}{R/r + 1}\right)^{1/2} \tag{2}$$

For the outer surface of the inner line, the parameters are

$$E_r^- = \frac{V_{PFL,P}}{r\ln\frac{R}{r}},\quad F_r^- = \frac{0.56\alpha}{t_{eff}^{1/3}A_r^{0.069}},\quad K^- = \frac{E_r^-}{F_r^-}$$

The dependence of K^+ and K^- on r and $\zeta = R/r$ is shown in Fig. 2. The calculation shows that only at $\zeta = 2.5$, the two curves overlaid. At $r = 8$cm, $K^+ = K^- = 0.30$. It is just the breaking factors of the PFL we chose. Here, $\zeta = 2.5$, $r = 8$cm and $R = 20$cm.

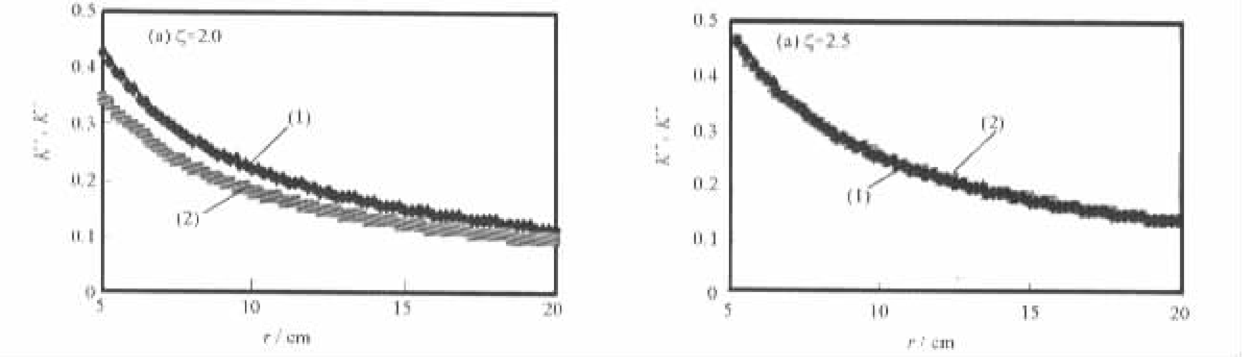

Fig. 2 Breaking factors of the PFL, K^+ (1) and K^- (2) versus the radius of the inner liner

For propagation time $\tau = 100$ns in PFL, its geometrical length $L = 1.68$m as $\tau = \sqrt{\varepsilon_r}\frac{2L}{C}$, where $C = 2.998 \times 10^8$m/s is the velocity of light in vacuum, $\varepsilon_r = 80$ is the dielectric constant of the de-ionized water. Thus, the capacitance (C_{PFL}), inductance(L_{PFL}) and impendence (Z_{PFL}) of each PFL are given by the following equations

$$C_{PFL} = \frac{\varepsilon_r}{18}\frac{L}{\ln\frac{R}{r}} = 8.15\text{nF},\quad L_{PFL} = \frac{\mu_0}{2\pi}L\ln\frac{R}{r} = 330\text{nF},\quad Z_{PFL} = \frac{60}{\sqrt{\varepsilon_r}}\ln\frac{R}{r} = 6.2\Omega \tag{4}$$

where, $\mu_0 = 4\pi \times 10^{-7}$H/m is the magnetic permeability in vacuum the unit of L is m. All of the parameters of the PFL are listed in table 1.

Table 1 Parameters of each pulse forming line and the parameters of the repetition rate pulsed transformer

L /m	R /m	r /m	C_{PFL1} /nF	L_{PFL1} /nH	Z_{PFL1} /Ω	τ_1 /ns	V_{PFL1} /MV	E_{PFL1} /kJ	Z_{PFL1} /Ω	d_p /cm	d_i /cm	L_p /nH	L_s /mH	M /mH
1.68	0.20	0.08	8.15	100	6.2	100	1	7	6.2	36.6	16	331	26.5	1.9

3 Structure of the pulsed transformer

The air core pulsed transformer is shown in Fig. 3.

The windings are composed of 15-turn 2mm thick copper sheet and multi-layer high density polyethylene (HDPE) films. The physical performances of this material and other available insulation films for our test are listed in table 2. Because the HDPE has a relatively high breakdown field, 370 kV / cm and small dissipation factor, 0.08×10^{-3} at 1MHz, we chose it as the first candidate material. The 2mm thick copper sheet is successively wound on a stainless steel cylinder-transmission line of secondary high voltage pulse. HDTL thin film is used as the turn-to-turn insulation material. The widths of the copper sheet of the primary and secondary coils are 40cm, $W_p = W_s = 40$cm. The width of HDTE film is 60cm. The outermost turn of the 15-turn windings is the single primary coil. Other 14 turns are the secondary coils of the pulsed transformer. The diameter of the innermost turn is $d_i = 16$cm. The interval distance between turns is 5mm. The total thickness of the secondary windings is 10.3cm. The diameter of the primary single turn is $d_p = 36.6$cm. The total thickness of the transformer windings is 12cm. The average diameter of the secondary coil is defined as

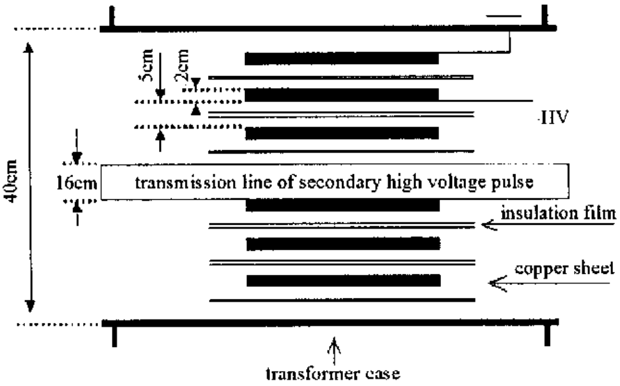

Fig. 3 Structure and the dimension of the pulsed transformer

Table 2 Available insulation films for the high voltage pulsed transformer

	dielectric constant at 1MHz	dielectric strength /(kV · mm^{-1})	dissipation factor at 1MHz
HDPE	2.34	37	0.2×10^{-3}
PTFE	2.1	48	0.5
FET	2.1	24	0.5
PET	4.0	42	20

$$\bar{d}_s = \left(\frac{3 + d_i^2 + 2 \times d_p \times d_i + d_p^2}{6}\right)^{1/2} = 23.4\text{cm} \tag{5}$$

The primary and secondary inductances, the coupling coefficient and mutual inductance of the pulse transformer are get from the following equations[11,12]

$$L_p = \frac{\mu_0 \pi}{4}\frac{d_p^2}{W_p}K_L = 331\text{nH}, \quad L_s = \frac{\mu_0 \pi}{4}\frac{d_s^2}{W_s}K_L = 26.5\mu\text{H}$$
$$K = \frac{\bar{d}_s}{d_p}\left(\frac{W_s}{W_p}\right)^{1/2} = 0.64, \quad M = K\sqrt{L_p L_s} = 1.9\mu\text{H} \tag{6}$$

where, $n = 14$ is the turns of the secondary coil, $K_L \approx 1$ is the inductance-modified factor[12]. All of the parameters of the transformer are listed in table 1.

4 Equivalent circuit model and analysis

The electrical circuit of the system is shown in Fig. 4a. C_0 and R are the primary capacitor and the charging resistor. G_0, G_1 and G_2 are laser-triggered gas switches. L_p and L_s are the inductances of the primary and secondary windings of the pulse transformer. C_{PFL1} and C_{PFL2} are the capacitances of PFL1 and PFL2. C_{T1} and C_{T2} denote the capacitances of the transmission lines of the secondary high voltage pulse on the left side and right side, respectively. C_{PT} is the total distributed capacitance of the copper sheets in the pulsed transformer. Z_{D1} and Z_{D2} are the impedances of the two field-emission diodes.

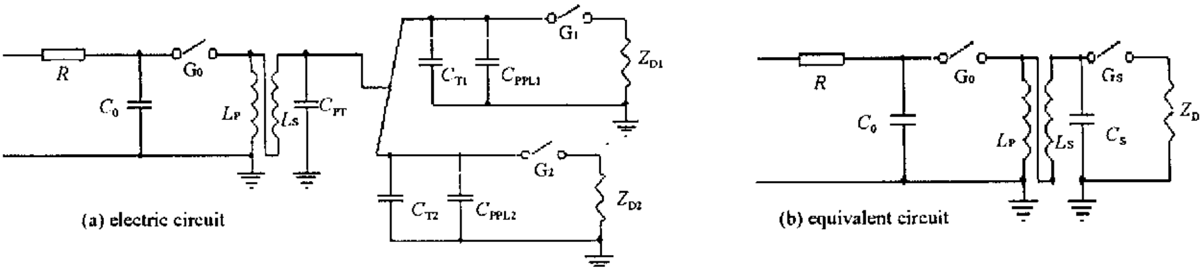

Fig. 4 Schematic of the electric circuit (a) and the equivalent circuit of the electron beams generator (b)

For 2m oil transmission line ($\varepsilon_r = 2.3$), its capacitance is 0.56nF, thus $C_{T1} = C_{T2} = C_T/2 = 0.28$nF. For the transformer windings, the capacitance between the innermost two turns of the coil is

$$C_{\mathrm{T-T}} = \frac{\varepsilon_{\mathrm{r}}}{18}\frac{W_{\mathrm{s}}}{\ln\frac{r_1+\Delta r}{r_1}} = 0.9\mathrm{nF} \tag{7}$$

thus, the series capacitance of the windings is

$$C_{\mathrm{PT}} \approx \frac{1}{n+1}C_{\mathrm{T-T}} = 0.06\mathrm{nF} \tag{8}$$

and the total capacitance on the secondary side of the transformer is

$$C_{\mathrm{s}} = C_{\mathrm{PFL1}} + C_{\mathrm{PFL2}} + C_{\mathrm{PT}} + C_{\mathrm{TL1}} + C_{\mathrm{TL2}} = 16.9\mathrm{nF} \tag{9}$$

and the equivalent circuit can be simplified as in Fig. 4(b). For the 100% energy transfer from C_0 to C_{s}, $L_{\mathrm{p}}C_0 = L_{\mathrm{s}}C_{\mathrm{s}}$ and $K = 0.6$ must be satisfied in the primary and secondary circuits in the double resonant charging model. Thus, the capacitance of the primary energy storage capacitor(C_0) is calculated to be $C_0 \approx 1.4\mu\mathrm{F}$ from above condition and the resonant frequency in these two circuit loops is $\omega = 1/(L_{\mathrm{p}}C_0)^{1/2} = 1/(L_{\mathrm{s}}C_{\mathrm{s}})^{1/2} = 1.5\mathrm{MHz}$. The voltage gain of the secondary side to the primary side is $\alpha = V_{\mathrm{s}}/V_{\mathrm{p}} = (C_0/C_{\mathrm{s}})^{1/2} = (L_{\mathrm{s}}/L_{\mathrm{p}})^{1/2} = 9$. The voltage waveform on the secondary capacitor versus time is as[13,14]

$$V_{\mathrm{s}}(t) = \frac{\alpha V_0}{2}\left[\cos\frac{\omega t}{\sqrt{1-K}} - \cos\frac{\omega t}{\sqrt{1+K}}\right] \tag{10}$$

where, V_0 is the primary voltage on C_0. The normalized output voltage waveform is shown in Fig. 5. We can see that the charging waveform inverts the time $t_1 = 1.77\mathrm{ms}$ and reaches the maximum value on C_{s} at $t_2 = 2.65\mathrm{ms}$. The rise-time of the voltage pulse from t_1 to t_2 is 880ns.

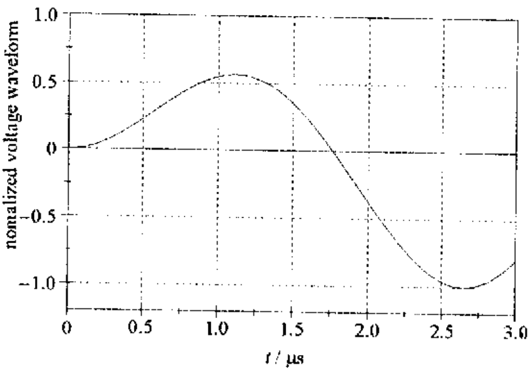

Fig. 5 Normalized charging voltage waveform on the secondary capacitor *vs* the charging time

5 Conclusion

In the double resonant charging model, the effective charging time is 0.88μs. It is short enough for the de-ionized water-filled pulse forming line. With the pulse transformer, the voltage gain is 9. The transformer windings have enough capacitance to prevent the coil from electrical breaking. If the coefficient of the energy from the electricity to laser is 3.3% [15], the output energy of HF/DF laser can reach to 250J at 3.8μm. The high-energy laser can run at 1Hz repetition-rate.

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用于泵浦非链式 HF/DF 化学激光器的重复频率电子束发生器研究

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摘 要： **正在研究的 1Hz 重复频率电子束泵浦 HF/DF 化学激光器，预期产生的电子束能量为 0.5MeV、束流强度为 100kA、束流脉冲宽度为 100ns。在该系统设计中，使用了一个脉冲变压器来对脉冲成形水线进行双共振充电。脉冲变压器的初级、次级电感与互感分别为 331nH，26.5μH 与 1.9μH。脉冲成形线的电容、电感与阻抗分别为 8.15nF，300nH 与 6.2Ω。脉冲成形线在 1MV 的峰值充电电压下的击穿因子为 0.3。在 3.3% 的能量转换效率条件下，预期可以产生的 HF/DF 激光脉冲能量为 250J 以上。**

关键词： **重复频率电子束发生器； HF/DF 化学激光器； 脉冲变压器**