

## LASER LINAC WITH GRATING

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A proposal for a laser linac with grating, is given for the miniaturizing of accelerators. A metal grating is used as periodic structure of the linac and as a reflector of a resonator of a laser device. Charged particles are accelerated by the intense electric field near the surface of the grating. The pitch of the grating and the wavelength of the laser must satisfy the phase matching

condition for the particles and the field. A preliminary experiment was performed for a part of the proposal so that the giant pulse laser oscillation was observed. The surface of the grating was destroyed by the flux of the high power laser beam. Consideration on the appropriate materials are given for this purpose.

### 1. Introduction

A proposal for a laser linac was given by Shimoda in 1962<sup>1)</sup>. The principle is to accelerate charged particles by an optical electric field in a cavity which is excited by a laser output.

However, it is rather difficult to excite the cavity at a single high order mode and to match the phase velocity of the electric field and the velocity of the charged particles.

In the present paper, an idea of a laser linac with a grating is proposed for the purpose of miniaturizing particle accelerators.

An intense periodic electric field is produced near the surface of a metal grating, which accelerates charged particles under several conditions.

### 2. Proposal of laser linac with grating

A schematic diagram of the proposed linac is shown in fig. 1.

Acceleration of electrons is discussed in this paper, but various kinds of other particles can be considered. The electrons starting from the injector enter the intense

electric-field produced by a laser along the surface of a metal grating.

As shown in fig. 1, the radiation emitted from the laser rod is incident upon the surface of the metal grating which forms the Fabry-Perot cavity with the mirror  $M_1$  for the laser oscillation.

In other words the metal grating is used for two purposes, firstly for the periodic structure of the linac and secondly for the component of the laser cavity.

Some portions of the diffracted beam from the grating are used as positive feedback for the oscillation, but others give rise to the loss of the resonator.

As the result of the interference, the electric field distribution near the grating surface is considered to become as shown in fig. 2.

Let the following three conditions be satisfied:

1. The direction of the velocity of the injected electrons is perpendicular to the direction of the grooves of the grating;

2. The direction of the main component of the electric field vector ( $E$ -vector) is also perpendicular to the direction of the grooves of the grating;

3. The relation, formula (1), is satisfied along the path of the electrons in order to obtain velocity matching between the optical field and the electrons,

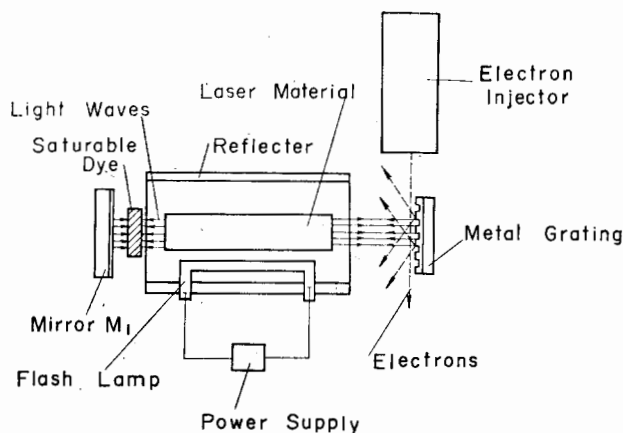


Fig. 1. Schematic diagram of "laser linac with grating".

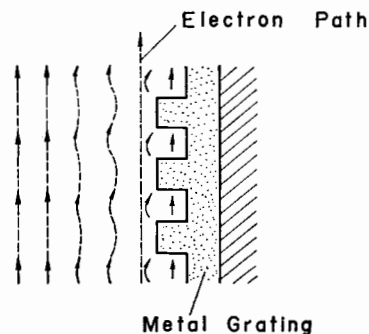


Fig. 2. Configuration of electric-field near grating surface.

$$n\lambda/c = d/v, \quad (1)$$

where  $\lambda$  is the wavelength of the laser,  $d$  the pitch of the grating,  $c$  the light velocity,  $v$  the velocity of the electrons and  $n$  is a positive integer.

Then the operation of a linac is anticipated.

When the energy of the injected electrons is high enough,  $v$  is nearly equal to  $c$  and formula (1) can be simplified in the form

$$n\lambda \approx d. \quad (2)$$

The reason why the electrons can be accelerated is the same as the well-known mechanism of an Alvarez type<sup>2</sup>). Once an electron passes a portion of the strong electric field in the accelerating phase, it passes the next portion under the strong electric field of the same phase, and so on.

An estimation of the value of the acceleration energy is shown in fig. 3. If the diameter of the light spot on the surface of the grating is about 1 cm and the internal power flow of either direction  $P$  is assumed to be  $10^6 \text{ W} \approx 10^9 \text{ W}$ , the maximum energy gain is calculated to be  $10^4 \text{ eV/cm} \approx 10^6 \text{ eV/cm}$ . However, the practical gain will be less, because of the reduction in efficiency, depending on the shape of the grating.

### 3. A preliminary experiment for our proposal

An experiment as shown in fig. 4 was carried out for the purpose of a preliminary study of the system shown in fig. 1. The main purpose of the experiment is: to observe the giant pulse oscillation in the resonator formed with a metal grating and a mirror, and to investigate the material of the grating.

The grating is the "Echelle" one" made of a thin aluminum layer on glass. The pitch  $d$  of the grating is  $0.6944 \mu\text{m}$  and almost equal to the wavelength  $\lambda$  of the ruby laser ( $0.6943 \mu\text{m}$ ).

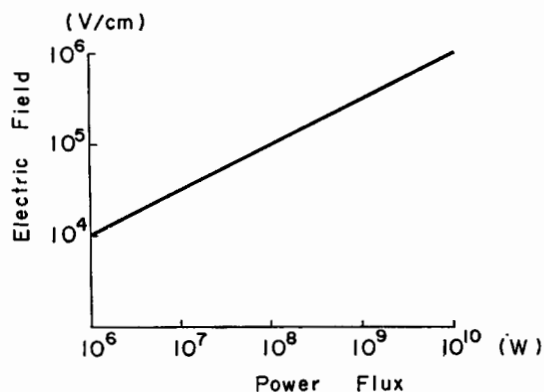


Fig. 3. Relation between electric-field vs laser power flux (laser spot diameter is assumed to be 1 cm).

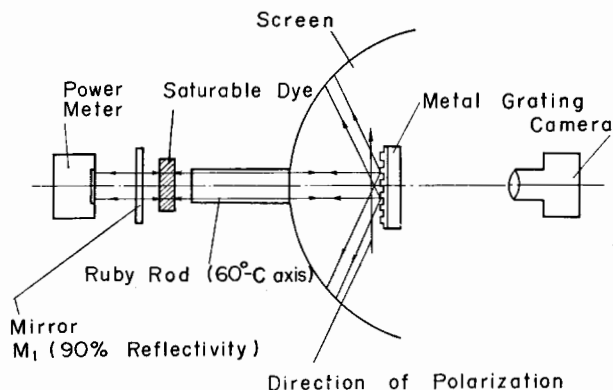


Fig. 4. Schematic diagram of experimental setup.

Saturable Dye (cryptocyanine in methyl alcohol) is used for the  $Q$ -switching of the laser. The reflection coefficient of the zero-order interference (at  $0.6943 \mu\text{m}$ ) from the surface of the grating is about 45% which is large enough to sustain oscillations of the ruby laser. The ruby rod has an angle of  $60^\circ$  between the  $C$ -axis and the rod axis so that the radiated laser light is almost completely polarized.

The direction of the  $E$ -vector of the laser field is adjusted so as to be perpendicular to the groove direction of the grating. The side view of our experimental set up is shown in fig. 5.

The diffracted (+1 and -1 order) spectrum were observed on the screen as shown in fig. 6. Fig. 7 shows the background spectrum of the xenon flash-light reflected by the grating when the ruby is not lasing.

The peak power of the giant pulse oscillation is measured to be about  $10^6 \text{ W/cm}^2$  and the pulse duration is about 50 ns.

The surface of the metal grating is found to have been partially damaged after the laser oscillations.

### 4. Discussions

Now we come to the problem of destruction of the metal surface by the laser pulse. In the above stated experiment, we used a grating made of thin metal on glass. But in order to reduce the local heating by the laser pulse, the grating should be made of thick metal plate, so we will discuss this case in some detail.

#### 4.1. TEMPERATURE RISE OF A METAL SURFACE BY LIGHT ABSORPTION

We must estimate the temperature rise of a metal surface caused by absorbed light.

Let  $T(z,t)$  be the temperature rise in degree [a function of time  $t$  (sec) and the distance from the surface  $z$  (cm)] and  $Q$  be the rate of the absorbed energy

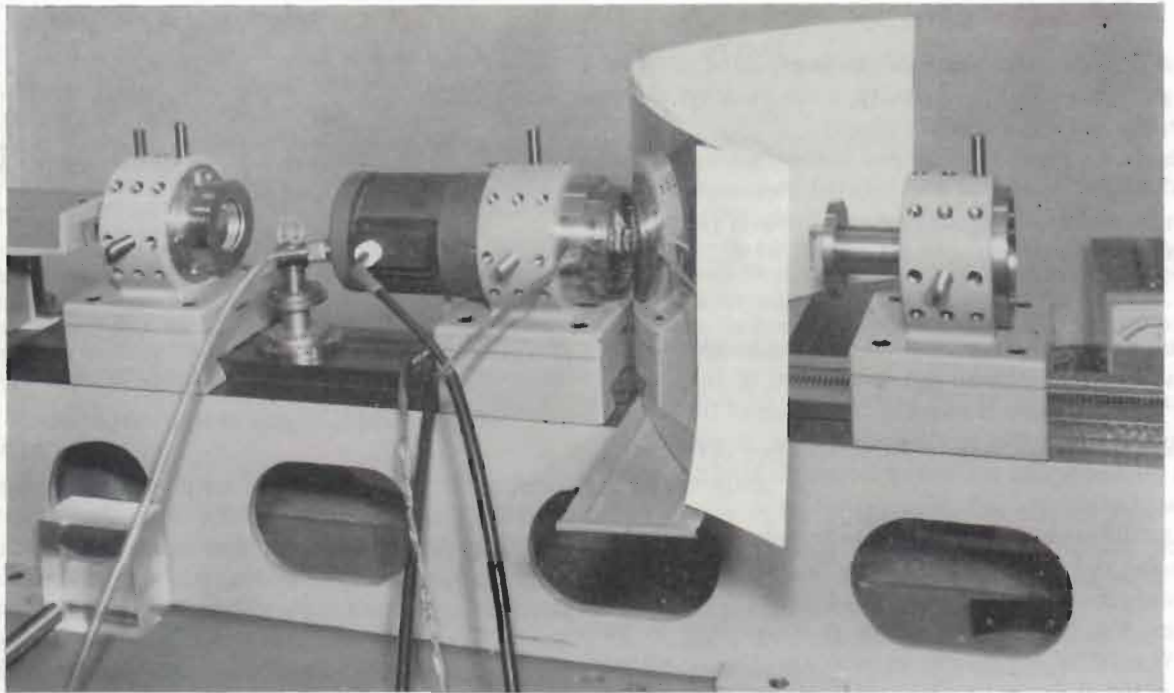


Fig. 5. Side view of our experimental setup.

of the laser light in cal/sec; the relation is known to be<sup>3)</sup>

$$T(z,t) = \{2Q/(\pi a^2)\} \{(kt)^{1/2}/K\} \cdot [\text{ierfc}\{z/(kt)^{1/2}\} - \text{ierfc}\{z^2 + a^2)/(kt)^{1/2}\}], \quad (3)$$

where

$a$  : the radius of the laser (cm);

$k$  : heat diffusion constant (diffusivity) (cm<sup>2</sup>/sec) =  $K/(\rho C_p)$ ;

$K$  : heat conductivity (cal/cm<sup>2</sup>·°C·sec);

$\rho$  : density (g/cm<sup>3</sup>);

$C_p$  : specific heat (cal/°C·g);

The numerical values of  $\text{ierfc}(x)$  are given by tables in ref. <sup>3)</sup>. The constants  $k$ ,  $K$ ,  $\rho$ ,  $C_p$ , and the melting point  $T_m$  of several kinds of metals are given in table 1<sup>3)</sup>.

If  $t$  is the pulse width of the giant pulse oscillation (about  $5 \times 10^{-8}$  s) and  $a$  is 0.5 cm, the maximum allowable rate of the absorbed energy of the metal surface  $Q_{\max}$  which will cause a temperature rise  $T = T_m - 20^\circ\text{C}$ , is calculated in table 2.

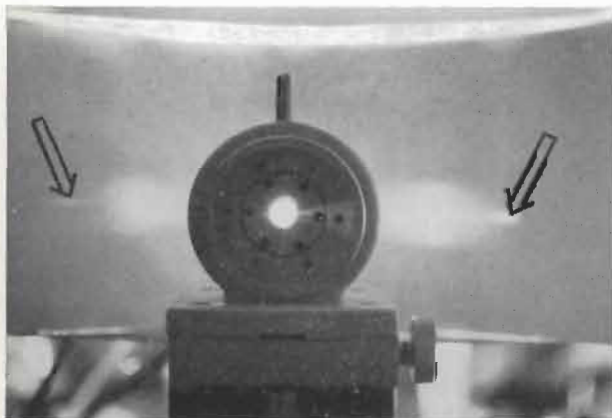


Fig. 6. Giant pulse oscillation and its spectrum observed on the screen.

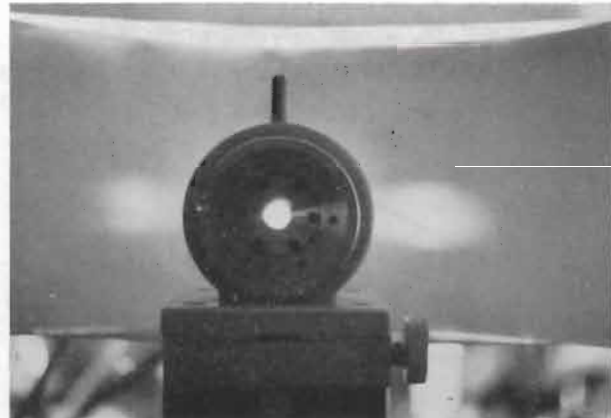


Fig. 7. Background noise of xenon lamp spectrum.

TABLE 1  
Thermal properties of metals.  
(Units are cg, cal. and °C).

	Gold	Silver	Aluminum	Copper	Platinum	Steel
Diffusivity, $k$	1.18	1.71	0.86	1.14	0.25	0.12
Conductivity, $K$	0.70	1.00	0.48	0.93	0.17	0.11
Density, $\rho$	19.30	10.49	2.70	8.94	21.46	7.85
Specific heat, $C_p$	0.0308	0.0556	0.206	0.0914	0.0315	0.12
Melting point, $T_m$	1063	960.5	658.8	1083	1773	1400

TABLE 2  
Maximum allowable rate ( $Q_{max}$ ) of the absorbed energy.  
(Pulse width:  $5 \times 10^{-8}$  sec; dia. of energy source: 1 cm).

	Gold	Silver	Aluminum	Copper	Platinum	Steel
(cal/sec)	$2.1 \times 10^6$	$2.3 \times 10^6$	$1.0 \times 10^6$	$2.9 \times 10^6$	$1.8 \times 10^6$	$1.4 \times 10^6$
(W)	$8.83 \times 10^6$	$9.65 \times 10^6$	$4.2 \times 10^6$	$12.2 \times 10^6$	$7.56 \times 10^6$	$5.9 \times 10^6$

TABLE 3  
Optical constants of metals. ( $R$ : reflectance;  $n$ : index of refraction;  $k_0$ : extinction coefficient).

$\lambda$ ( $\mu\text{m}$ )	Gold*	Silver*	Aluminum*	Copper*	Platinum <sup>+</sup>
$R$					
0.7	0.967	0.987	0.888	0.966	0.59 ( $\lambda$ :0.668)
1.0	0.981	0.989	0.912 ( $\lambda$ :0.95)	0.981	0.77
10.0	0.974 ( $\lambda$ :9.9)	0.991	0.980	0.988 ( $\lambda$ :10.25)	—
$n$					
0.7	0.131	0.075	1.55	0.15	2.91 ( $\lambda$ :0.668)
1.0	0.179	0.129	1.75 ( $\lambda$ :0.95)	0.197	3.42
10.0	25.2 ( $\lambda$ :9.9)	10.69	26.0	11.0 ( $\lambda$ :10.25)	—
$k_0$					
0.8	3.84	4.62	7.00	4.05	3.66 ( $\lambda$ :0.668)
1.0	6.04	6.83	8.50 ( $\lambda$ :0.95)	6.27	6.3
10.0	55.9 ( $\lambda$ :9.9)	69.0	67.3	60.6 ( $\lambda$ :10.25)	—

\* evaporated; + sputtered.

TABLE 4  
Maximum allowable light power flux ( $P_m$  in  $10^8$  W) onto the surface of metals.  
(Pulse width:  $5 \times 10^{-8}$  sec; dia. of energy source: 1 cm).

$\lambda$ ( $\mu\text{m}$ )	Gold	Silver	Aluminum	Copper	Platinum
0.7	2.7	7.4	3.8	3.6	19
1.0	4.7	8.8	4.8	6.4	33
10.0	3.4	10.7	2.1	10.0	—

#### 4.2. REFLECTION AT A METAL SURFACE

The reflection coefficients of metals vs  $\lambda$  can be obtained from experiments<sup>4</sup>). Several important values of  $R$ ,  $n$  and  $k_0$  vs  $\lambda$  are shown in table 3<sup>5</sup>). The most com-

mon lasers of high intensity are a ruby laser ( $\lambda = 0.6943 \mu\text{m}$ ) and a neodymium doped glass laser ( $\lambda = 1.06 \mu\text{m}$ ). Then we calculate the maximum allowable power onto the surface of the metals, which are the materials of the grating, from tables 2 and 3. The results are shown in table 4. It is possible to take a combination of the layers of different kinds of metals.

The results in table 4 show that these metals can stand large enough powers which are required for the laser linac, if the surface properties of these metals are given by the constants in tables 2 and 3.

As a next step of the preliminary study of the laser linac, we are trying to inject a fine beam of electrons along the grating surface.

Technical difficulties for the production of the ap-

appropriate grating and for injection of electrons into a narrow region can be largely reduced if a longer wavelength is used. High power lasers in the infrared and far-infrared may be employed for the laser linac.

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#### References

- 1) K. Shimoda, *Appl. Optics* **1** (1962) 33.
- 2) L. Smith, *Handbuch der Physik* **44** (Springer, 1959).
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