ON RESONANT CONDITION IN A GRATING ACCELERATOR

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Abstract

The grating accelerator is a conventional linear accelerator (LINAC) but with a laser instead of a klystron or magnetron RF power source. Any linac structure must convert incoming radiation into slow modes, since only a slow mode contains longitudinal electric fields and can get coupled to a relativistic electron beam. In order to do that, the structure must be periodic. In this paper we present the resonant condition versus Lawson’s theorem for the grating accelerator.

1 INTRODUCTION

The interaction of an electron beam with a metallic grating surface produces an electromagnetic wave known as Smith – Purcell (SP) radiation. The first experimental confirmation was obtained in 1953 by Smith – Purcell [1]. Using a relativistic electron beam (I = 5 μA, r_b = 75 μm, θ = 4 mrad, L = 48 mm, E_b = 309 kV - 340 keV, λ_g = 1.67 μm) they observed a light (450 – 550 nm) strongly polarized with the electric vector perpendicular to the metal grating.

The experiments of Doucas et al [2] with a relativistic electron beam of 3,6 MeV was the first evidence for the feasibility of using high energy electrons to produce SP radiation (I = 50 – 200 mA, J = 0.35 - 1.7 A/cm^2, r_b = 1.5 - 3 mm, τ = 6 μs, f = 1Hz. , 0 = 115^0, L = 2x7 cm^2, , λ_g = 0.030.). They obtained SP radiation with wavelength λ = 0.35 – 1.86 mm.

K.Mizumo et al. in 1975 [3] suggested the realization of the inverse SP effect which leads to the electron acceleration or deceleration function of the electron particle velocity and the phase velocity of the electromagnetic wave. They consider the acceleration in the field above a linear grating when the grating is exposed to a propagating or standing wave.

Starting from experiments, several studies have been carried out exploring this effect in a view of possible application as a tunable EM source [4], in a free electron laser[5] and for particle acceleration [6]. The particle acceleration by means of the laser was first proposed in 1962 by K. Shimoda[7]. Technological advances have made possible terawatt laser systems with high intensities (≥ 10^{18} W/cm^2), modest energies (≤ 1 J) and short pulses (≤ 1 ps) [8].

The existence of a 7 MeV electron linac, a 11.5 MeV microtron and a 30 MeV betatron accelerator in the National Institute for Laser, Plasma and Radiation Physics (NILPRP) in Bucharest and the theoretical [9] and experimental [10] results obtained till now made attractive the idea of SP study on that effect by means of NILPRP accelerators [11,12]. In this paper we present some aspects regarding on the resonant condition in a grating accelerator based on inverse Smith-Purcell effect.

2 BASIC PRINCIPLES

Two papers have attemptted to employ the inverse SP effect [3],[7] by illuminating a grating from directly above with the plane parallel light and passing the particles over the surface of the grating at the right angles to the lines. Unfortunately, it has been shown by Lawson [13] that these geometries fail to accelerate relativistic particles.

A grating linac is composed of an accelerator which supplies the relativistic electron beam (REB), a metal grating (MG), a laser and cylindrical lenses for focusing the laser radiation on the metal grating, all of them located in a vacuum enclosure. The accelerator may be a linear accelerator, a microtron or an induction accelerator. The MG can be made of Aluminum, Cooper or other materials and the laser is of ultra - high intensity of Nd:YAG/Nd:glass laser type.

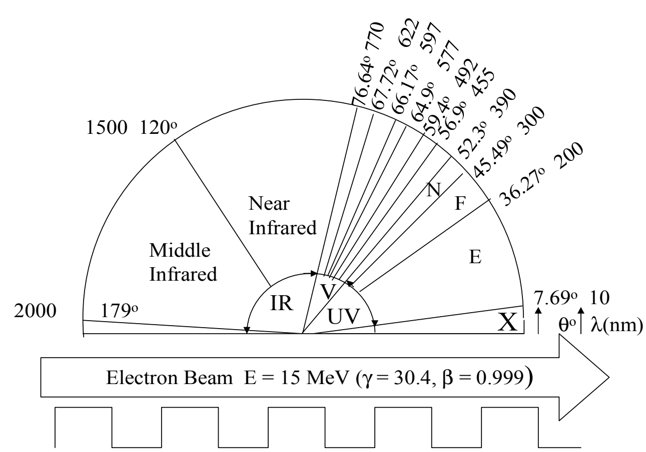

Fig.1 The spectral angular distribution of SP radiation

Consider a MG, that consists of an electrically perfectly conducting surface (Fig.1). The surface is periodic in the x direction of a Cartesian coordinate system. The y direction is parallel to the grating rulings. The space above the grating is situated in vacuum. The top of the grating is in the (x,y) plane and the metal grating profile is described by a periodic function $z = f(x) = f(x + \lambda_g)$, where λ_g is the spatial period of the MG. The electron beam moves with velocity $v = v_o\, i_x$ (i_x is the unit vector in the x direction) along the trajectory y = o and $z = z_o$ = const. Therefore, both the geometrical configuration and all field quantities are independent of y and the problem is two dimensional (2D).

Figure 1 illustrates the angular distribution of Smith-Purcell radiation for an electron beam of 15 MeV which moves perpendicularly to the MG rulings with spatial period $\lambda_g = 1$ µm

The basic principle of a grating accelerator is to focus an intense light beam from a laser at normal incidence onto a grating structure ("inverse Smith – Purcell Structure") in order to accelerate an electron beam which is passing parallel to the grating plane, distant not more than a wavelength. If a laser beam of wavelength λ is incident on a metal grating at an angle θ, so that λ and θ fulfill the SP condition, an electron beam of velocity v_e grazing over the MG, should synchronously interact with the electromagnetic wave, leading to the electron acceleration or deceleration function of the electron particle velocity and the phase velocity of the electromagnetic wave. If the electrons are faster than the wave velocity, they will be decelerated and their lost kinetic energy converts into light amplification.

The energy which transfers to an electron is given by the relation:

$$\frac{d}{dt}(\gamma m_0 c^2) = q\,v\,E \qquad (1)$$

where q = - |e| is the electric charge, v is speed of the electron in the direction of E laser field that remains in phase with the particle over a long time (or distance)

$$E_s\,(\text{TeV/m}) = 2.7\text{x}10^{-9} I^{1/2} (\text{W/cm}^2) \qquad (2)$$

where I is the laser intensity, λ is the laser wavelength.

3 RESONANT CONDITION

For the electrons traveling perpendicular to the grating rulings , in condition

$$\frac{dE}{dy} = 0, \qquad (3)$$

the fields above the surface in the x direction of electron motion of the electron can always be given as a sum of fields of the type [12]:

$$E_x = A_n \exp j(k_{x,n}x + k_{z,n}z), \qquad (4)$$
$$E_y = 0, \qquad (5)$$
$$E_z = A_n\,(k_{z,n}/k_{x,n})\,j(k_{x,n}x + k_{z,n}z), \qquad (6)$$

where

$$k^2_{z,n} = k_0^2 + k^2_{x,n} \qquad (7)$$

The requirements that the fields remain in phase with an electron of velocity v = βc is

$$k_{x,n}\,\beta = k_o \qquad (8)$$

and in this case the Eq. (7) becomes:

$$k_{z,n} = \frac{k_o}{\beta}(\beta^2 - 1)^{1/2} \qquad (9)$$

As the energy of the particle increases, β approaches 1 and from Eq(9) we see that $k_{z,n}$ approaches zero. From Eqs. (4) and (6), then we see that can be no net acceleration. The reason for that is that the only wave consistent with the symmetry, that stays in phase with a particle traveling at the velocity of light, is a simple propagating plane wave traveling in the direction of the particle. Such a wave is always transversely polarized and therefore it cannot accelerate in its direction of propagation. In order to overcome that restriction, we must break the symmetry condition (3) and consider the wave traveling at an angle to the beam direction. If, for instance, we simply rotate the grating by an angle ψ with respect to the beam, the condition for synchronism beams (8) is given by:

$$k_{x,n}\beta\cos\psi = k_0 \qquad (10)$$

with

$$k_{z,n} = \sqrt{1 - \frac{1}{(\beta\cos\psi)^2}} \qquad (11)$$

Now $k_{x,n}$ and $E^r_{n,x}$ no longer approach zero as β approaches unity. Thus we see that Lawson's theorem, though showing that the proposed geometries do not work it, does not rule out all acceleration in the fields above a grating. An alternative to a skew grating is to employ a skew intral wave. In this case, although the grating lines are perpendicular to the electron beam, the induced surface waves can still be at an angle to the beam and E_q (9) still applies. Notice that all the space harmonics exist at a given frequency ω. Once $k_{x,o}$ is known, by choosing the velocity of the electron beam v_o to be equal to the phase velocity of the fundamental space harmonic, $v_o = \omega / k_{x,o}$, $k_{x,n}$ is known. Moreover each space harmonic has a different phase velocity given by

$$v_{p,n} = \omega / (k_{x,o} + nk_g) \qquad (12)$$

and the group velocity of the nth harmonic $v_{g,n} = (d\omega/dk_z) = v_g$, the same for all harmonics.

4 GRATING ACCELERATOR

At present there is an increased interest to develop advanced acceleration techniques capable of continuing progress in high energy accelerator physics. One of them is the use of inverse SP effect for acceleration.

When the synchronous condition is satisfied, an actual interaction must occur between the REB and the EM wave, leading to the electron acceleration. If the electron suffers net acceleration over a period of time then EM field energy is converted into electron kinetic energy resulting in an accelerator. Grating accelerators will have the unique property of providing high acceleration gradients because of the intense fields that can be obtained. An accelerator of the order of 10 GeV.m^{-1} was anticipated by Palmer [6]. In table 2 the Palmer's parameters of a very hypotetical 50 + 50 TeV grating accelerator are given.

Table 2

Main parameters of grating accelerators

Energy	E	2 x 50 TeV
Length	L	2 x 5 km
Gradient	G	10 GeV/m
Specific emittance	ε_s	3.10^{-12} m.rad
Number of particle/bunch	N	$3.2.\ 10^7$
Spot size	σ	1 nm
Bunch length	d	1 cm
Focus,	$\beta^\bullet$	1 cm
Frequency,	f	24 kHz
Beam power	P	2 x 6 10^6 W
Luminosity	L	10^{33} cm^{-2} s^{-2}

Such a wave is always transversely polarized and thus it cannot get accelerated in its direction of propagation.

It is convenient to consider the case when the incident wave direction lies in a plane perpendicular to the beam direction (see Fig.2)

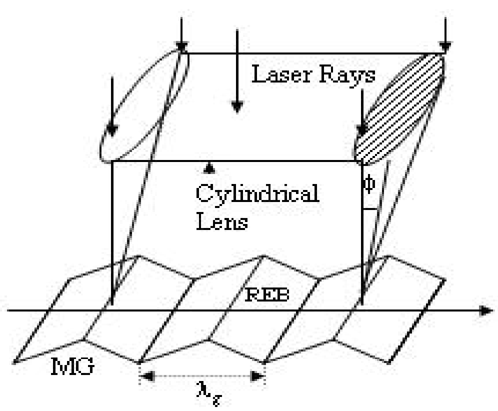

Fig. 2 General geometry for particle acceleration

Till the parameters may be reached, it is necessary to imagine some technical and technological solutions capable to be implemented with the existing accelerators in own lab.

5 CONCLUSIONS

In this paper, some theoretical and practical aspects of the inverse Smith-Purcell effect for particle acceleration in the high energy domains have been presented. The acceleration of particles in the fields above the grating is possible if either particle travel skew to the grating rulings or if radiation is falling at a skew angle onto the grating. The acceleration fields can be obtained using lasers. The grating accelerator has a very high acceleration gradient and it represents a type of accelerator which is worth researching and implementing.

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