FAR-FIELD ACCELERATION SCHEME

A.V. Smirnov
Russian Research Center «Kurchatov Institute», 123182 Moscow, Russian Federation

Abstract

A novel method for acceleration of relativistic particles is proposed. It is based on a resonance interaction of a straightforward charged particle beam passing through a wiggling electromagnetic beam.

Electromagnetic beam guiding can be provided in a vacuum waveguide or in overdense plasma channels under stimulated hose instability. Main parameters of acceleration process are estimated. The method proposed allows acceleration of both low energy electrons and high energy relativistic particles, absence of conventional undulator at low synchrotron radiation losses and enhanced acceleration rate compared with Inverse Free Electron Laser (IFEL).

1 INTRODUCTION

A number of mechanisms utilising high power laser radiation for particles acceleration were proposed almost from the very beginning of lasers appearance. Some of the various schemes can be found in references [1,2,3,4,5].

One of the most known schemes studied both theoretically [5] and experimentally [6] is the Inverse Free Electron Laser (IFEL) proposed by Palmer [7]. The main disadvantages of such schemes are the limitations imposed on energy or current by synchrotron [5] or coherent undulator radiation [8].

To facilitate the limitations critical for high energy physics application we proposed here a somewhat inverse scheme. It foresees a straightforward relativistic particle beam propagating through an electromagnetic wiggling beam guided, for example, by periodically \`slowly\` curved walls. The last circumstance allows to consider the scheme as non-violating the Lawson-Woodward theorem [9].

2 THE PRINCIPAL SCHEME AND ASSUMPTIONS

The principal scheme is shown in the Fig. 1. The waveguide (or channel) provides a periodic change of the angle between particle beam axis and e.m. beam wave vector. The field can have linear or circular polarisation. The waveguide structure can be performed as both rectangular waveguide having sinusoidal deformation and helically curved circular waveguide. Note, from the conceptual point of view such an accelerator can use both mm-wave or laser beams propagating in such a waveguide/cavity and laser beams propagating in a periodic plasma channel.

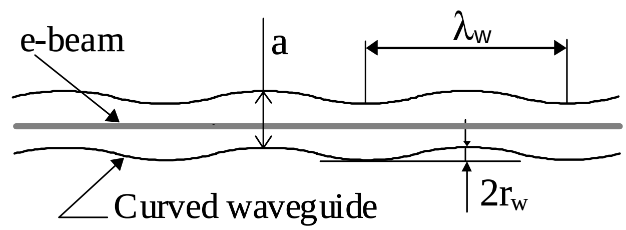

Figure 1. Schematic drawing of an accelerator with a wiggling field.

We will consider below acceleration of relativistic electrons by traveling wave in rectangular waveguide at short wavelengths $\lambda_s << \lambda_w$.

Similar to the IFEL scheme [5] high power losses of TE modes can be considerably reduced in case of EH mode propagation. It takes place under proper dielectric coating of the metal walls of the waveguide structure [10,11] provided the angles between incident rays and reflecting surface are small, i.e. $r_w << \lambda_w$. In other words low-loss waveguides can be used only at the glancing angles to provide low-loss propagation.

3 BASIC RELATIONSHIPS

To analyze beam interaction with EH_{11} mode we impose an additional condition $a << \lambda_w$. Then wavevector ***k*** of propagating e.m. beam follows the sinusoidal function:

$$k_z = k\cos\theta(z), \quad k_y = k\sin\theta(z),$$
$$\theta(z) = d(r_w \sin k_w z)/dz = k_w r_w \cos k_w z,$$

where $k=2\pi/\lambda_s$ is the e.m. beam free space wavenumber, $\theta(z)$ is the angle between the particle beam axis and e.m. beam axis, $k_w=2\pi/\lambda_w$, r_w is the amplitude of the e.m. beam centroid wiggling propagation.

For a straightforward particle beam propagating along OZ axis it gives the following expression for the phase slippage between the e.m. and particle beams over the period λ_w:

$$\Delta\varphi = 2\pi \frac{\lambda_w}{\lambda_s}\left(\frac{1}{\beta} - J_0(2\pi \frac{r_w}{\lambda_w})\right), \qquad (1)$$

where β is the particle beam velocity related to the speed of light c, J_0 is the conventional Bessel function.

Resonant interaction between e.m. and particle beams can take place when $\Delta\varphi=2\pi n$, where n is integer parameter of synchronism. Note, non-zero acceleration/deceleration can take place only for odd n. For small angular amplitudes $k_w r_w << 1$ we derive:

$$r_w = \frac{\lambda_w}{\pi}\sqrt{1 - \frac{1}{\beta} + n\frac{\lambda_s}{\lambda_w}}\,. \qquad (2)$$

By variation of the last expression over beam energy γ and integer parameter n one can obtain an important relationship between the key parameters of the scheme and energy spread that still keeps the synchronism:

$$\frac{\lambda_W}{\lambda_S}\frac{\Delta\gamma}{\beta^3\gamma^3} << 1\,. \qquad (3)$$

This relationship means, that low-energy injection (a few MeVs) requires monoenergetic beams (e.g. electrostatic accelerators with energy spread of the order of 10^{-4}-10^{-3}).

For synchronous particle one can easily estimate the approximate value acceleration rate:

$$\frac{dW}{dz} \approx eE_0\frac{r_W}{\lambda_W}\,,$$

where E_0 is the electric field amplitude on the waveguide axis.

It can be seen, that for long wavelengths of cm-mm range the coupling coefficient r_w/λ_w between the acceleration rate and e.m. field amplitude is lower then that for slow-wave structures. For IR and visible range this value can be comparable or even higher then that for IFEL scheme.

For near-field variant of the scheme this coefficient can be comparable with unity because the 'vacuum far-field' condition $r_w << \lambda_w$ is not required. For example, for such a scheme based on plasma channels in terms of hose instability [12] the estimated coupling strength is 0.18 for n=1, wiggling amplitude r_w=10 µm (typical plasma channel radius) and plasma wavelength λ_w=133 µm.

4 NUMERICAL RESULTS

Assuming negligible synchrotron radiation and EH_{11} dominant mode one can obtain the following equations of motion:

$$\begin{cases} \dfrac{d\gamma}{d\xi} = A_o f(\xi)\left(f_{nx}(\xi) + \dfrac{\beta_x}{\beta_z} f_{nz}(\xi)\right)\cos\varphi \\ \dfrac{d\varphi}{d\xi} = \lambda_W k\left(\dfrac{\beta_x}{\beta_z} f_{nx}(\xi) + f_{nz}(\xi) - 1\right) \\ \dfrac{d\gamma\beta_x}{d\xi} = A_o f(\xi)\left(f_{nx}(\xi)^2 + \left(\beta_z^{-1} - f_{nz}(\xi)\right) f_{nz}(\xi)\right)\cos\varphi \end{cases} \qquad (4)$$

where $A_o = \dfrac{eE_o\lambda_W}{m_o c^2}$, $x(\xi)=r_w\cos(2\pi\xi)$, $f(\xi)=\cos(\pi x(\xi)/2a)$, $f_{nx}(\xi)=\sin(k_w x(\xi))$, $f_{nz}(\xi)=\cos(k_w x(\xi))$, $\gamma^{-2}=1-\beta_x^2-\beta_y^2$, e and m_0 are the particle charge and rest mass.

To calculate the main parameters for far-field accelerator scheme we used the following input parameters: injection energy W=1.2GeV, a=0.4cm, laser wavelength λ_s=1µm, λ_w=4cm, $E_0=1.5\cdot10^9$ V/cm that corresponds to overall traveling wave power density $3\cdot10^{15}$ W/cm^2. For small losses (of the order of 10^{-5} dB/m) such power density can be transmitted without damaging of the waveguide [5].

One can see from the figs. 2, 3, 5, 6 that the acceleration rate estimated for n=1 is 0.52 GeV/m that exceeds the value 0.25 GeV/m calculated for the IFEL scheme under the same value of power density [5] and waveguide cross-section.

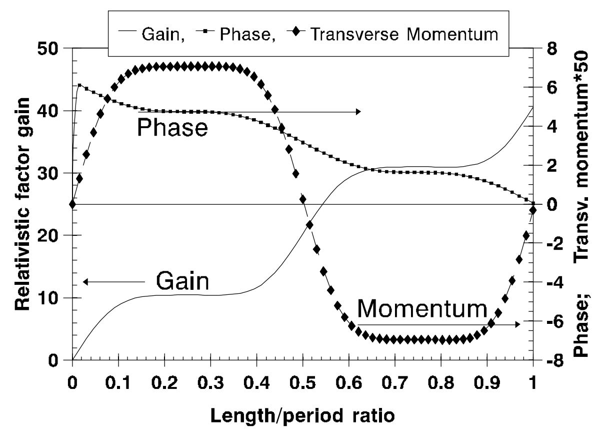

Figure 2. Energy gain $\gamma(z)$-$\gamma(0)$, transverse momentum $\gamma\beta_x$ and resonant phase φ behaviour along the accelerator cell for n=1, λ_s=1µm. Calculated effective undulator factor K_w=0.12.

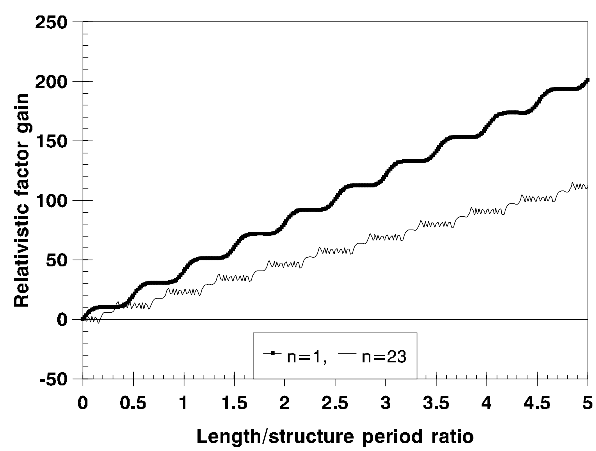

Figure 3. Energy gain $\gamma(z)$-$\gamma(0)$ behaviour along the accelerator for two different numbers n=1, 23 characterising the synchronism.

For n>1 the e-beam undergoes successive deceleration and acceleration (see Fig. 3, 4), and the acceleration rate reduces as n increases (see Fig. 6) at fixed period λ_w of the wiggling e.m. centroid. The minimal injection energy increases as n increases.

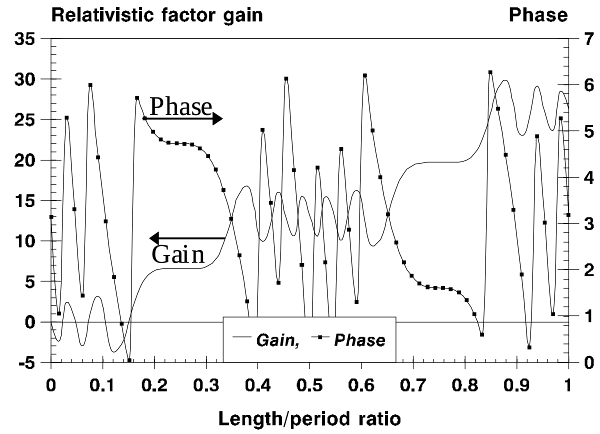

Figure 4. Energy gain $\gamma(z)$-$\gamma(0)$ and resonant phase behaviour along the accelerator cell for n=11.

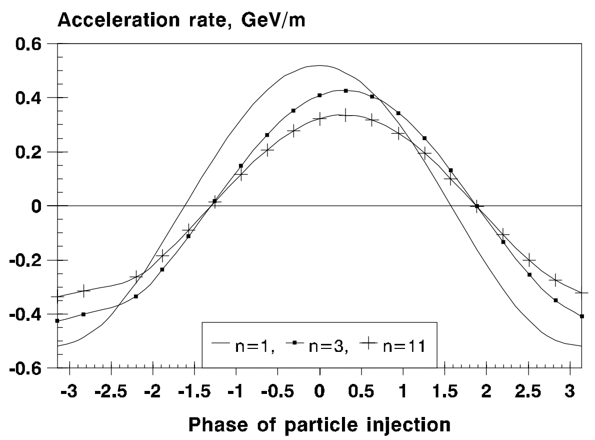

Figure 5. Acceleration rate averaged over period λ_w as a function of injection phase for three different numbers n characterising the synchronism.

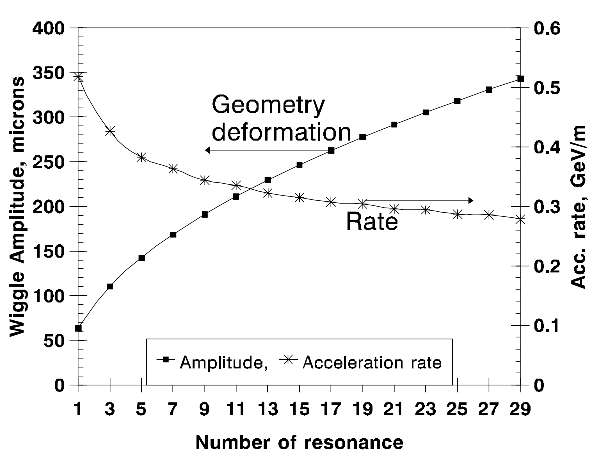

Figure 6. Wiggle amplitude r_w and acceleration rate $\Delta\gamma m_0c^2/\Delta z$ versus number n characterising the synchronism.

Similar conventional RF-linacs phase motion is negligible for relativistic particles, and output energy spread depends on phase length of the input beam. (see Fig. 5). It means that phase motion and bunching are negligible, while the resonant energy does exist and is defined by the expressions (1, 2).

5 CONCLUSION

Calculated coupling strength between the averaged acceleration gradient and laser field amplitude has reached 0.0035, that is comparable or exceeds the value for other known far-field accelerators: IFEL and Inverse Cherenkov Accelerator (ICA) schemes.

The method considered allows acceleration of both low energy (~nMeVs) electrons and high energy relativistic particles.

Synchrotron radiation losses are low because effective undulator strength $K_w \leq 1$, whereas for IFEL $K_w >> 1$. Special external undulator having the same period can eliminate the radiation losses due to compensation of periodical beam deflection.

Stimulated hose instability in overdense plasma channels to be considered as a non-vacuum application of the mechanism considered.

To provide reasonable capture a special prebuncher-IFEL is required.

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