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Nuclear Instruments and Methods in Physics Research A 483 (2002) 377–382
NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A
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An undulator with non-adiabatic tapering for the IFEL project

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Abstract

We describe the design of a planar undulator with unusually strong tapering, for the inverse FEL experiment (on the IFEL experiment at the UCLA Neptune Lab. Presented at the 2001 Particle Accelerator Conference, June 18–22, 2001, Chicago, Illinois) to be carried out in Neptune Lab. (Nucl. Instr. and Meth. A 410 (1998) 437) at UCLA. A powerful TW CO_2 laser will be used to accelerate electrons up to 50–60 MeV in 50 cm long undulator. A strong undulator tapering is needed because of the short Rayleigh length of the laser beam. Both the magnetic field and the undulator period are tapered to provide synchronicity of the laser beam interaction with a captured electron bunch along the whole undulator length. The most critical part of the undulator is the region near the laser focus. The main characteristics of the IFEL, such as the percentage of trapped electrons, energy of accelerated electrons and sensitivity to the laser focus transverse position, are given. The general principles of the design of this undulator construction can also be useful for high efficiency FEL amplifiers of intense laser modes.

PACS: 41.60.Cr; 41.75.Jv

Keywords: Undulator; Tapering; Inverse FEL; Simulation

1. Introduction

The Inverse Free Electron Laser (IFEL) physics is based on the same principles as the Free Electron Lasers. One important difference is in the range of electron energy changes during the process and another one is the problem of electron bunch trapping in a bucket during the acceleration. This problem was investigated theoretically many years ago, but only in the approximation of slowly varying magnetic field or adiabatic regime (see for example, [1,2]). Here we will consider a design with strong tapering of the magnetic fields and fast varying laser fields. The simulations were made for this non-adiabatic regime as was required by the IFEL project [3,4].

The (UCLA-RRC KI) IFEL experiment [3] proposed by the University of California at Los Angeles and Kurchatov Institute is rather unique. A CO_2 laser, with power in the Twatt range, larger than the power used in other IFEL experiments, will be used. The short acceleration length (50 cm) and the high-intensity-focused laser beam create

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0168-9002/02/$ - see front matter
PII: S0168-9002(02)00347-9

an absolutely new IFEL regime. Two key issues of this project should be underlined. The first is the acceleration gain. Due to acceleration, the electron energies will be increased by some tens of MeV. In all the other known up to date IFEL experiments (see for example, [5]), the energy gain was <1–2 MeV. Another key factor is the relatively large number of the accelerated electrons, some tens of percents of the initial number. The IFEL project details are given in Ref. [3].

The non-adiabatic, diffraction-dominated IFEL is rather unusual, difficult to evaluate analytically, and it demands a numerical simulation approach. All these circumstances require a special undulator to be constructed with a very strong and non-uniform tapering within very small magnetic field tolerances. We present here the results of the undulator design and of the IFEL behaviour obtained using numerical simulations. Some undulator design options are given to demonstrate the ways how the main IFEL characteristics can be changed to optimize it for the real experimental conditions.

2. IFEL project basic parameters and electron dynamics simulations

For the IFEL analysis, we used as the reference the laser and the electron beam parameters given in Ref. [3]. To optimize the IFEL properties we used a wide range of parameters around the reference set (see below).

The laser field is assumed to be in the fundamental Gaussian mode:

$$E(r, z, t) = \frac{E_0}{w(z-z_0)} \times \exp\left\{ \mathrm{i}\left(kr - \omega t - \arctan\left(\frac{z-z_0}{z_R}\right)\right) - r^2\left(\frac{1}{w_0^2 w^2(z-z_0)} - \mathrm{i}\frac{k}{2R(z-z_0)}\right)\right\}. \tag{1}$$

Here, r and z are cylindrical coordinates; $k = 2\pi/\lambda$ is the carrier wave number; ω the laser frequency; w_0 the mode waist (radius at $z = z_0$); and $z_R = \pi\omega_0^2/\lambda$ is the Rayleigh length; $w(z-z_0) = 1 + (z-z_0)^2/z_R^2$; $R(z-z_0) = z - z_0 + z_R^2/(z-z_0)$. The laser focus ($z = z_0$) is at the centre of the undulator. The laser beam initial parameters given in Table 1 are used for the analysis. From the laser mode, Eq. (1), and the given parameters it is clear that the laser field amplitude strongly varies along the path where the acceleration takes place. The initial electron beam parameters are given in Table 2.

Solutions for the undulator magnetic fields are found using the Radia code [6] by successive approximations. Each magnetic field version is tested, then corrected and after that tested again. For these tests calculations of a single probe electron trajectory and its synchronicity with the laser field are done with a code based on the

Table 1
The laser beam initial parameters

Laser wavelength λ	10.6 μm
Laser power range	0.4–0.8 TW
Rayleigh range z_R	3.6 cm
Laser waist w_0	0.35 mm
Laser waist at the undulator entrance $w_0 \cdot w$	2.5 mm

Table 2
Initial electron beam parameters

Electron beam energy	14 MeV
Electron beam emittance ε_n	10 mm mrad
Electron beam pulse length	6 ps
Electron beam rms radius at the focus	0.15 mm
Electron beam rms radius at the undulator entrance	0.50 mm

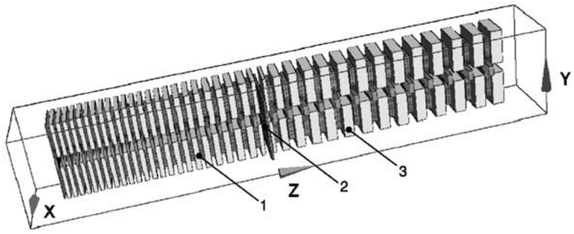

Fig. 1. Schematic design of the hybrid planar double-tapered undulator: (1) first section of the undulator; (2) intersection trajectory corrector; and (3) second undulator section.

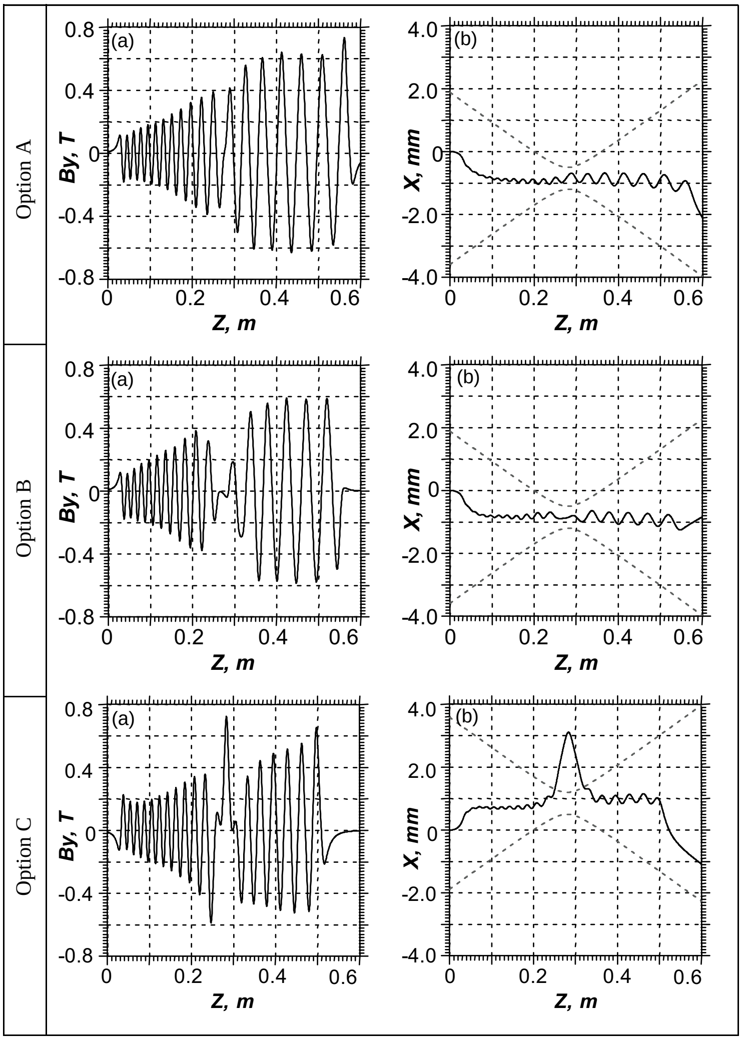

Fig. 2. Magnetic fields (a) and trapped electron trajectories (b), for the three undulator options; notice the different behaviours in the focal region.

Lorentz equations and using MathCAD.[1] This control is made on-line with the Radia simulations. A version was considered as final one when corrections of the field decreased to a level $<0.1\%$. The final solution is tested for the capture and acceleration of an electron bunch with the particle tracing 3D code TREDI, IFEL version [3].

[1] Electron dynamics equation [1] could also be useful for such a control, but only in the case of slowly varying fields well described by one or two field harmonics.

3. Designed undulator properties

The undulator must satisfy the requirements of the UCLA-RRC KI project [3]. This means that it must provide the following:

1. Transparency for both the electron and the laser beams.
2. Synchronism between the electron and the laser wave along the whole undulator length, including the focus region, where the Guoy phase shift takes place.

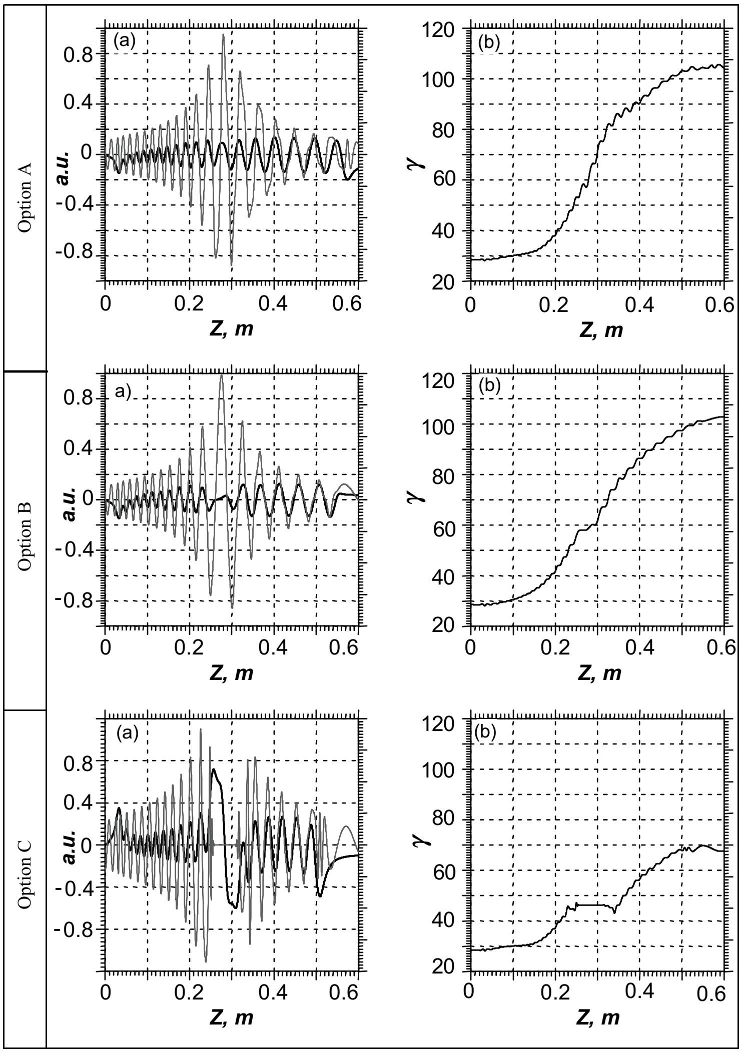

Fig. 3. Synchronization curves (a) and energies of accelerated electrons (b) along the undulator. Dotted curve in (a)—laser fields seen by one of the trapped electrons; solid curve—transverse velocity of the same electron.

3. Maximum acceleration rate and maximum electron energy gain at the exit.
4. Maximum captured fraction and electron beam trapping for the acceleration up to the final energy not <0.95 of the maximum electron energy in the bunch.
5. Small sensitivity to possible transverse displacements of the laser focus (jitter) within mms.

To provide the transparency the undulator gap is made large, 12 mm. To fulfil the other requirements a double tapering of both the magnetic field strength and the undulator periods is used. A schematic view of the hybrid planar undulator design is shown in Fig. 1. The first and the second undulator sections are strongly but monotonically tapered. A special tapering is necessary for the central focal region. Three hybrid undulators, respectively A, B and C, were designed to solve the focal region problem in different ways. The basic undulator parameters are given in Table 3.

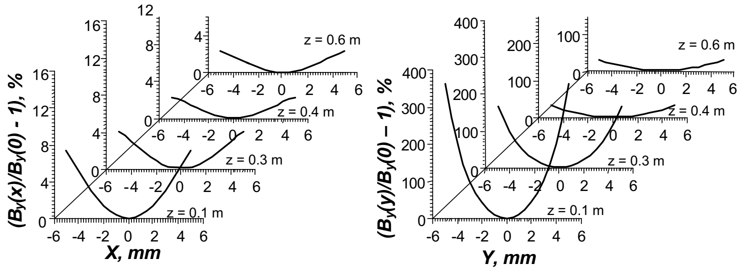

Fig. 4. Transverse magnetic field profiles for the undulator option A showing the ability of additional electron beam focusing by own undulator fields.

Table 3
Basic undulator parameters

Total undulator length	524.49 mm
Undulator period at the entrance	15.16 mm
Undulator period at the exit	52.10 mm
Initial field strength	0.115 T
Field strength at the exit	0.626 T

Fig. 2 shows the magnetic field profiles and the probe electron trajectories. The respective synchronization curves and the energy of the accelerated electron are given in Fig. 3. The electron velocities and the laser field strengths acting on the electron at the position z are given. The synchronization is provided if the velocity and the laser field have the same sign. The option A synchronizes, in the focal region, only electron phases and does not decrease the electron oscillation amplitudes, which in this case are large near the focus. It gives the maximum electron energy gain at the exit. The option B provides smaller oscillation amplitudes in the focal region, while the electron trajectories are more straight. The option C produces a "hook" trajectory in the central undulator part. Because of this the electrons leave the laser field in the laser focus and do not interact with the laser. This was done with the purpose to decrease the sensitivity to a possible jitter, as required in point 5. The options A, B, C have different not only trajectories, but also other characteristics. To find the optimum one should consider the complete set of properties.

Fig. 4 gives the transverse profiles of the undulator field for the option A. The analysis of

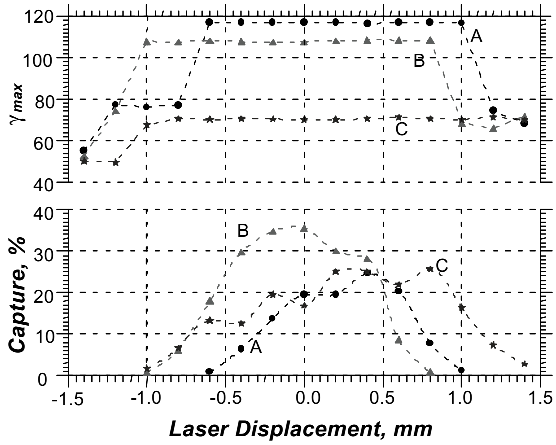

Fig. 5. Dependence of IFEL characteristics on jitter (laser focus transverse displacement) for options A, B and C. Initial electron energy is $\gamma_0 = 28.5$.

the undulator focusing field effects [7] shows in fact that it gives a small improvement in the capture efficiency. Fig. 5 shows the sensitivity to the laser focus displacement (jitter). The option A gives maximum acceleration but with a smaller number of trapped electrons (captured fraction) and more restrictive limits on the laser jitter. The options B and C have a large capture ratio, and more tolerance to the laser jitter, than A, but smaller final electron energies.

The dependence on the laser power has also been investigated. It is found that the maximum energy of the accelerated electrons grow linearly with the laser power up to 0.8 TW, with nearly the

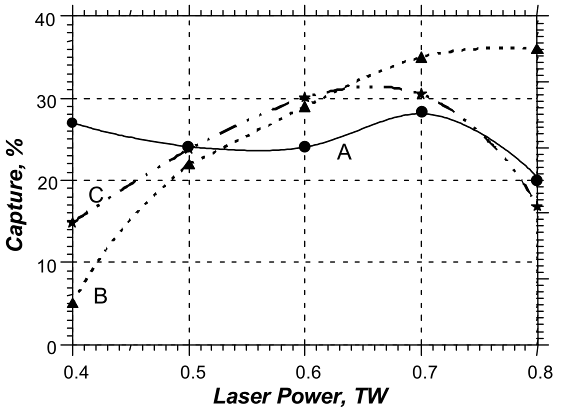

Fig. 6. Dependence of the relative number of trapped electrons on the laser power for options A, B and C, respectively. Initial electron energy is $\gamma_0 = 28.5$.

same average rate of acceleration for all three options. The results on the capture ratio given in Fig. 6 show that, for the option A, it slowly decreases when the laser power increases. At a laser power <0.5 TW, the option A provides higher captures than other options. At laser power more than 0.5 TW the option B is the most efficient.

4. Conclusion

The results of the numerical simulations and analysis show that the existing undulator technology enables the construction of an undulator with very strong tapering in undulator periods and magnetic field strengths. This undulator can be satisfactorily used in IFELs with the highly accelerating gradients obtained by focusing a high-power laser to a short Rayleigh range. The effect of the Guoy phase shift at the laser focus on the electron acceleration can be controlled by proper undulator tapering. On the other hand, this type of IFEL has a strong sensitivity to the magnetic field shapes, requiring tight tolerances on the magnetic field. Since the problem is non-linear and depends on many parameters a real optimization can be made only by numerical simulations. For the UCLA-RRC KI project [3], the option A is the preferred one for the laser energy of 0.4 TW unless the jitter is worse than it looks now.

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