TERAHERTZ FEL BASED ON PHOTOINJECTOR BEAM IN RF UNDULATOR

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Abstract

Photoinjectors, which can produce picosecond electron bunches of MeV-level, are attractive for THz generation. Fortunately, a long distance to reach scattering power saturation in FEL is not necessary, if bunch length is shorter than the produced THz half-wavelength. However, the energy of several MeVs does not allow providing long traveling of the flying bunch without longitudinal divergence. That is why, we suggest using specific rf undulator in a form of the normal wave in the helical waveguide at 3 GHz frequency. The mentioned wave has the -1st space harmonic with transverse fields and negative phase velocity (responsible for particle wiggling). This wave has also the 0th harmonic with longitudinal field and positive phase velocity equal to bunch velocity. Due to the synchronous 0th harmonic one can effectively channel low-energy bunches (due to longitudinal focusing field) as far as several meters distance. One might also inject electron bunches in slightly accelerating field, in this case the output THz pulse obtain nearly linear frequency modulation. Such long THz pulses with the mentioned modulation of the frequency can be efficiently compressed by pair of diffraction gratings.

CONCEPTS OF THZ FEL BASED ON PHOTOINJECTOR ELECTRON BEAM

In order to produce THz radiation, we suggest to use short bunches of electrons with bunch length less than a half of THz wavelength. Such bunches can be easily produced by means of the existing rf photoinjectors which are driven by high-power picoseconds lasers [1]. Typically rf gun might release bunches of 5-10 MeV and charge up to 1 nC. In order to produce 1 THz radiation, bunch length should not exceed 0.15 mm. This bunch length means that all electrons radiate THz wave in the phased condition (coherently). Unfortunately, the desirable short bunches cannot keep longitudinal size at long distance because Coulomb force causes strong divergence of particles. That is why, one should provide longitudinal focusing of electron bunches at whole length of THz FEL. To solve this problem, we suggest to escort each bunch by slow TM_{01} wave which, being in Cerenkov synchronism with electrons, executes longitudinal focusing in proper phase (at zero longitudinal electric field) like it happens in accelerators (autophasing). Of course, longitudinal focusing inevitably makes whole FEL more complicated and expensive, because it assumes exact injection in proper rf phase. However, in rf photoinjectors particles already are assumed to be synchronized with rf field. In our case we consider THz FEL as a prolonged rf gun. Second, due to focusing one might build long FEL and to produce long THz pulses. In order to multiply power of these long THz pulses, its are appealing to be compressed by means of special pulse compressor consisted of two gratings. Principles of the mentioned pulse compressor were elaborated for high power laser systems [2, 3]. In accordance with these principles, the pulse with the chirped frequency modulation is compressed in a system with frequency dispersion shaped by two gratings operated in non-mirror regime of the reflection [4]. In case of THz FEL the necessary frequency modulation can be provided by using non-equidistant periodicity of undulator's periods. There are two opportunities. The first concept (Fig. 1) can be based on DC-magnet undulator with slow focusing TM_{01} waveguide and pulse compressor.

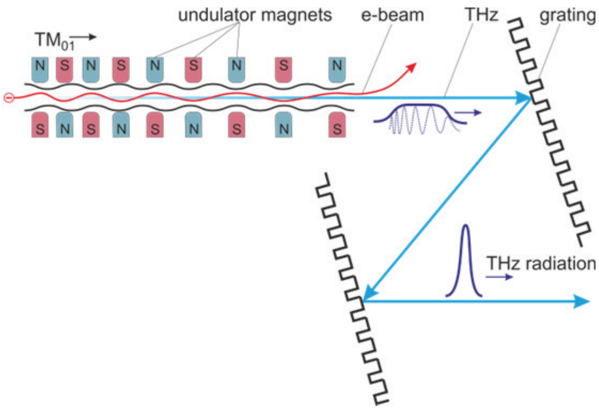

Figure 1: Concept of THz FEL with DC-magnet undulator, focusing TM_{01} waveguide, and built-in pulse compressor.

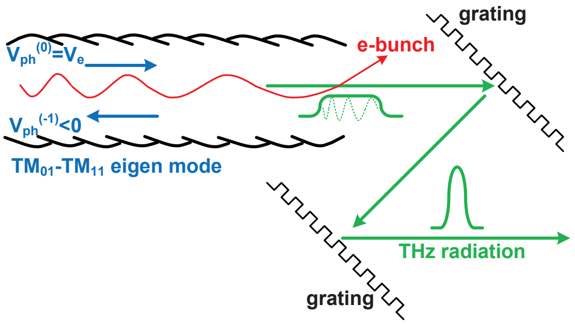

Figure 2: Concept of THz FEL with helical rf undulator and built-in pulse compressor.

In the second scheme (Fig. 2) the helical waveguide supports slow eigen mode consisted of two main space harmonics. The 0-th harmonic is represented by focusing

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TM_{01} wave, the -1st harmonic is TM_{11} wave with negative phase velocity which causes wiggling of electrons. The chirped pulse in this case is obtained using injection of particles in slightly accelerating rf field so that particles with growing energy naturally radiate power with growing frequency.

BEAM DYNAMICS IN LONG WAVEGUIDE SECTION

Principle of longitudinal bunch focusing is shown in Fig. 3. Here slow TM_{01} wave with phase velocity close to bunch velocity guides particles so that electrons near front are slightly decelerating, but back electrons are placed in slightly accelerating field.

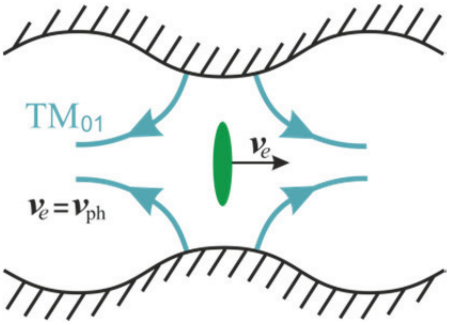

Figure 3: Scheme of bunch focusing in longitudinal direction.

As one can see in Fig. 3 there are no forces which prevent transverse expansion of particles in the bunch. Moreover, there are deflecting radial electric field component, E_r, which causes transverse defocusing. Although azimuth component of magnetic field, H_φ, mitigates the mentioned divergence, one should provide longitudinal DC magnetic field, in order to avoid loss of current density due to defocusing phenomenon. That is why, in simulations of bunch dynamics with parameters, shown in Table 1, we used 2.5 GHz TM_{01} wave with 100 MV/m E_z amplitude (typical values for rf gun) and axial DC magnetic field as high as 1 T magnitude.

Table 1: Bunch Parameters

Parameter	Value
Charge, nC	0.1
Energy, MeV	5
Length, mm	0.15
Radius, mm	1.5

Results of simulations for this case are presented in Fig. 4 (XZ-plane) and in Fig. 5 (XY-plane) respectively. 250 particles were used in simulations. Red dots describe incident bunch, blue ones show particle distribution behind 0.5 m, the green particles corresponds to approximately 1 m distance behind photoinjector. Note that in DC magnetic field particles slowly rotate around z-axis (Fig. 5). The far an electron from axis, the bigger is angle of the rotation. The Figures 4 and 5 confirm that high-charge bunches can be efficiently guided at long distances (>1 m) in longitudinally focusing TM_{01} mode and in guiding DC magnetic field simultaneously.

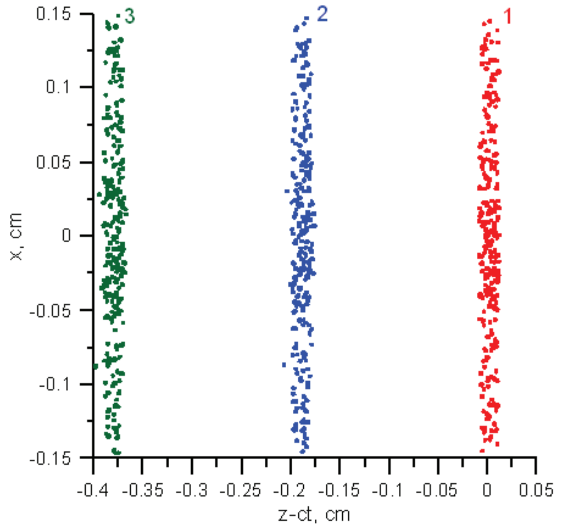

Figure 4: Space distribution of particles in plane XZ for bunch flying in waveguide with focusing TM_{01} wave: 1 – t=0, 2 - t=1.65 ns, 3 - t=3.33 ns.

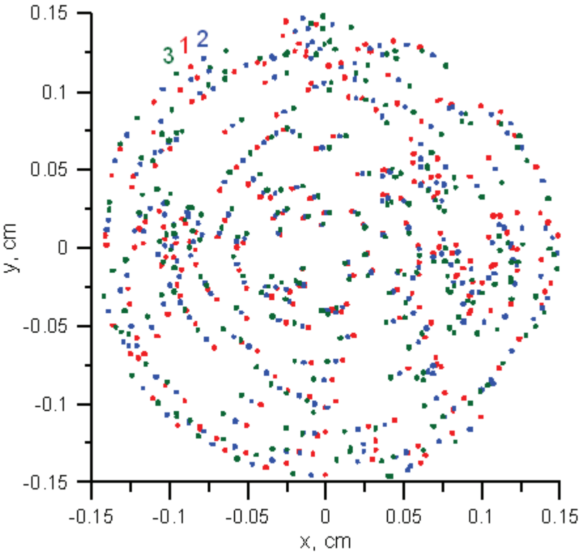

Figure 5: Space distribution of particles in plane XY for bunch flying in waveguide with focusing TM_{01} wave: 1 – t=0, 2- t=1.65 ns, 3 - t=3.33 ns.

The used amplitude of focusing TM_{01} wave is comparable with fields in rf gun. This value means that necessary rf power is high enough. Therefore, it seems appealing to use this power for bunch guiding as well as for provision of particle's wiggling at once. Principles of such rf structure, which plays a role of an accelerator and undulator simultaneously, were investigated recently [5-7]. The mentioned periodic structure has helical corrugation (Fig. 6). One of the eigen modes in this corrugated waveguide is the mode consisted predominantly of the partial TM_{01} wave (0th space harmonic) and partial TM_{11} wave (-1st harmonic) as well.

In the slow eigen mode the phase velocity of the 0th harmonic is assumed to be equal (or close) to bunch velocity (Fig. 7). This harmonic does not have transverse deflecting fields exactly at axis so that perturbation of transverse bunch dynamics is minimized [8]. The -1st harmonic has negative phase velocity and strong transverse electric and magnetic fields at axis. This harmonic provides wiggling of electrons and production of radiation with essential Doppler's frequency up-shift. In particular, in the 2.5 GHz structure the bunch with parameters, shown in Table 1, can radiate photons with frequency close to 1 THz.

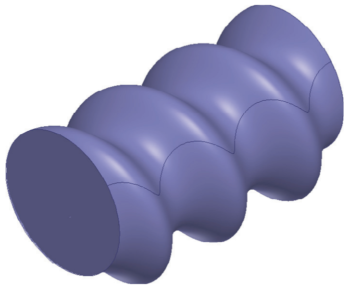

Figure 6: 3D view of helical accelerating section.

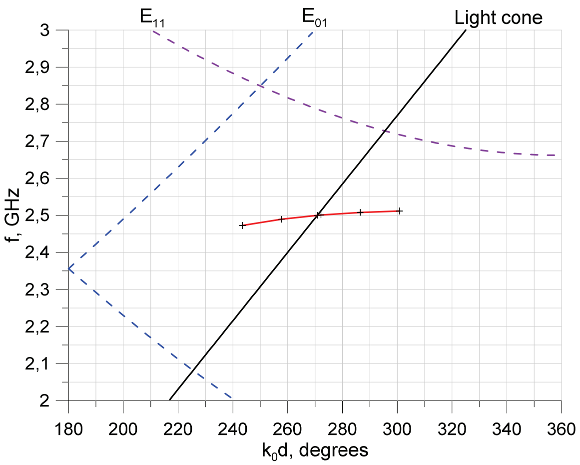

Figure 7: Dispersion of TM_{01}-TM_{11} normal eigen mode in helical accelerating structure (solid red curve) and dispersion curves of partial weaves in cylindrical waveguide (dashed curves).

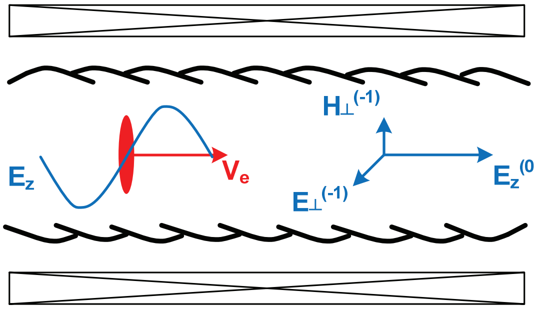

Figure 8: RF undulator based on helical waveguide.

The principal scheme of the described rf undulator is shown in Fig. 8. In the 2.5 GHz helical waveguide with parameters (average radius – 68.7 mm, period of corrugation – 90.2 mm, amplitude of corrugation – 14.1 mm) with E_z=100 MV/m longitudinal focusing field of the 0th (TM_{01}) harmonic the effective undulator parameter, determined by fields of the -1st harmonic, is as high as $K \approx 1$. This value allows to obtain ~5 MW power at 1 THz behind the undulator (about 1 MV/m field strength).

UNDULATOR WITH NONUNIFORM PERIODICITY AND THZ PULSE COMPRESSOR

We propose compression of a frequency modulated THz pulse by means of pair of diffraction gratings employed in the autocollimator regime [4]. The modulated input signal can be obtained from an undulator in which DC magnets are arranged with a variable spatial period. In rf undulator necessary frequency modulation is reached using bunch injection in slightly accelerating field (Fig. 9) or using slightly asynchronous wave relative to electron bunch.

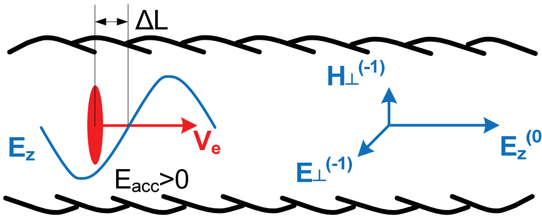

Figure 9: Injection of particle bunch in accelerating phase of E_z field component.

In accordance with pulse compression scheme after the first grating different frequency components of the wavebeam are reflected with different angles relative to the grating plane and travel different distances to the second grating (Fig. 10). After the second grating all frequency components propagate in the common direction and become phased ones, i.e. rf pulse is compressed.

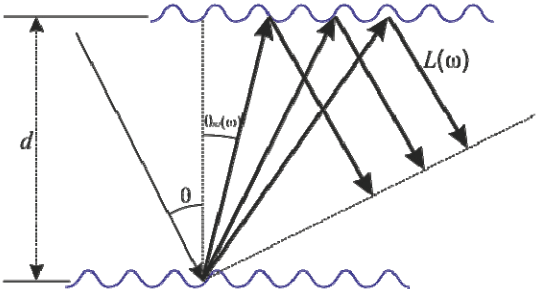

Figure 10: Paths of rays in system of two paired gratings.

In the proposed design, parameters of the gratings should be selected so to provide scattering to the -1st diffraction maximum only. Path length L in the compressor, defined according to Fig. 10, depends on frequency ω:

$$L(\omega) = \frac{d(1+\cos(\theta+\theta_{-1}(\omega)))}{\cos(\theta_{-1}(\omega))}, \qquad (1)$$

where d is the distance between the gratings, θ is the angle between the incident wave and the normal of the first grating, $\theta_{-1}(\omega)$ is the angle of the scattered wave which depends on frequency as follows:

$$\theta_{-1}(\omega) = \arcsin(\sin\,\theta - \frac{2\pi}{kD}), \quad (2)$$

where D – is a period of the corrugation, $k=\omega/c$, c – is the light velocity.

In the computer simulation initial pulse had the linear frequency modulation:

$$A_{\text{in}}(t) = A_0 \exp(-\frac{t^2}{2T^2}(1 - i\Delta\omega t) - i\omega t), \quad (3)$$

where t is current time, T is pulse length, $\Delta\omega$ is a difference of frequencies at the start and at the end of the input pulse (frequency modulation). Simple estimations in aberration-free approximation give the formula for compression coefficient:

$$C = \frac{T}{T_{out}} = 2\pi N \frac{\Delta\omega}{\omega}, \quad (4)$$

where T_{out} – is a length of the output pulse, N – is a number of field periods in the input pulse.

The Fig. 11 shows the input pulse and the output (compressed) pulse with central frequency 1 THz, $N = 50$ periods, $\theta = 45^o$, and $\Delta\omega / \omega = 0.1$. These parameters correspond to parameters of THz radiation which could be obtained by undulator discussed in the previous text. As it follows from Fig. 11, the power in output pulse is roughly 10 times more in comparison with power in input pulse. This means that already considered undulator supplemented with pulse compressor is able to reach 50 MW power level.

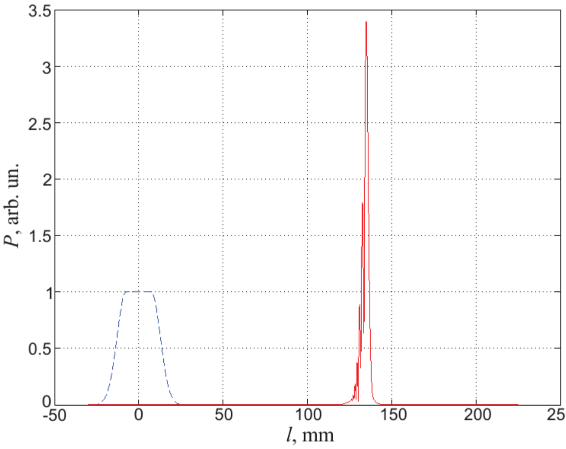

Figure 11: Pulse compression by means of two gratings: incident 1 THz pulse (blue dashed curve) and the compressed pulse (red solid curve).

Note that frequency modulation cannot be increased too much in comparison with the used value, because autocollimation regime of diffraction grating has the limited bandwidth. Nevertheless, one is able to increase pulse length (N) in a more long undulator, in order to obtain more power. In addition, there is a possibility to focus output THz wavebeam by means of the metallic focusing mirror. In already considered example wavebeam waist is close to transverse bunch size (1.5 mm), so due to focusing to size $\sim \lambda \times \lambda$ one can multiply power by factor $\sim 10^2$. In particular, in wavebeam, produced by the undulator of 10 m length, the field strength in minimal possible size of the wavebeam can reach ~1 GV/m.

CONCLUSION

Short electron bunches with charge ~0.1 nC, injected from photocathode, can be efficiently guided in the long waveguide (>1 m) with focusing synchronous S-band TM_{01} mode. Such bunches do not require microbunching to saturate output power, because they are shorter than the half-wavelength of the produced THz radiation. Necessary focusing field magnitude is ~100 MV/m, which is comparable with accelerating field in the existing S-band photoinjectors. In order to increase output field and power of THz radiation, it is appealing to use undulator (DC-magnet or rf) which allows forming pulses with chirped frequency. Such pulses could be compressed by factor 10^1-10^2 by means of grating's pair. Using additional space focusing of THz wavebeam by mirror, one is able finally to reach in mirror focus more than 100 MV/m THz field.

REFERENCES

[1] L. Faillace, Recent advancements of RF guns, Physics Procedia, 52, 2014, pp. 100 – 109. http://www.sciencedirect.com/science/article/pii/S1875389214000261#

[2] Bahk S. W. et al., "Generation and characterization of the highest laser intensities", Opt. Lett., 29, (24), 2004, pp. 2837–2839.

[3] V. Yanovsky, et al. "Ultra-high Intensity-300-TW Laser at 0.1 Hz Repetition Rate", Opt. Express, V.16. № 3. 2008, pp. 2109–2114.

[4] Electromagnetic Theory of Gratings, Ed. by R. Petit. Berlin; Heidelberg: New York; Springer Verlag, 1980.

[5] S.V. Kuzikov et al, Helical Self Focusing and Cooling Accelerating Structure, Proc. of of PAC2013, Pasadena, CA USA, 29 September -4 October 2013, pp. 1049-1051.

[6] S.V. Kuzikov et al, Concepts for Short Period rf undulators, Proc. of of PAC2013, Pasadena, CA USA, 29 September -4 October 2013, pp. 1046-1048.

[7] S.V. Kuzikov et al, "Flying radio frequency undulator, Applied Physics Letters", Vol. 105, Issue: 3, 2014, pp. 033504 - 033504-4.

[8] S.V. Kuzikov et al, "Configurations for Short Period rf Undulators", Phys. Rev. ST Accel. Beams 16, Issue 7, 070701 (2013).