HELICAL WAVEGUIDES FOR SHORT WAVELENGTH ACCELERATORS AND RF UNDULATORS*

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Abstract

The short wavelength accelerating structure can combine properties of a linear accelerator and a damping ring simultaneously. It provides acceleration of straight on-axis beam as well as cooling of this beam due to the synchrotron radiation of particles. These properties are provided by specific slow eigen mode which consists of two partial waves, TM_{01} and TM_{11}. The flying RF undulator introduces a high-power short pulse, propagating in a long helically corrugated waveguide where the -1st space harmonic with negative phase velocity is responsible for particle wiggling. High group velocity allows providing long interaction of particles with RF pulse. Calculations show that RF undulator with period 5 mm, undulator parameter 0.1 is possible in 1 GW 10 ns pulse at frequency 30 GHz. These RF parameters, as it was shown experimentally, are achievable by means of the relativistic BWO. The eigen mode in a helical undulator might be slow one so that the 0th harmonic phase velocity is equal to light velocity. Such wave (with non-zero longitudinal electric field) can be excited by relativistic drive bunch in a waveguide where witness bunch follows after the drive bunch, wiggles in wakefield of the drive bunch, and generates X-rays at whole waveguide length. Helical waveguides can also be used in order to channel low-energy bunches (due to longitudinal focusing field) in RF undulator of THz FEL.

HELICAL ACCELERATING STRUCTURE

An accelerating structure, based on helical corrugated waveguide has the operating normal mode consisted of the 0^{th} spatial harmonic (with positive phase velocity), which is actually the accelerating mode, and the -1^{st} harmonic (with negative phase velocity) which is responsible for particle wiggling [1]. The transverse non-synchronous field components can provide emittance control and beam focusing due to ponderomotive force. Let us consider the shape of the accelerating structure in cylindrical system of coordinates (r, z, φ) by equation:

$$r(z,\varphi) = R + a \cdot \sin(\frac{2\pi \cdot z}{d} + \varphi)\,. \qquad (1)$$

where R – is a waveguide radius, a and L – are amplitude and period of the corrugation. Period of the corrugation is close to $2\pi/h_{TM01}$, where h_{TM01} – is a propagation constant of the partial TM_{01} mode in smooth circular waveguide of the radius R. In the normal eigen mode the TM_{01} partial wave does not perturb transverse movement of on-axis electrons [2], the TM_{11} wave does not have longitudinal E_z component on axis.

Parameters of the 28 GHz TM_{01}-TM_{11} helical structure was optimized (R=6.1 mm, a=1.25 mm, d=8 mm) to reach maxima of the accelerating field relative to maximum of surface field, $E_a / E_s^{\max} = 0.307$; and shunt impedance, R_{sh}=19 MOhm/m [1]. At acceleration gradient 100 MV/m the equivalent magnetic field is as high as 0.75 T. Field structure of the operating mode is shown in Fig. 1. The phase velocities of longitudinal component and both transverse components have opposite signs (Fig. 2).

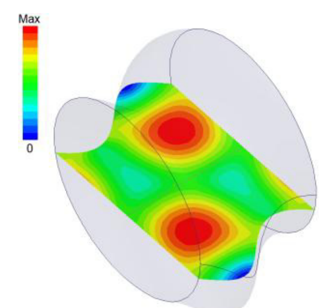

Figure 1: Module of electric field in middle plane.

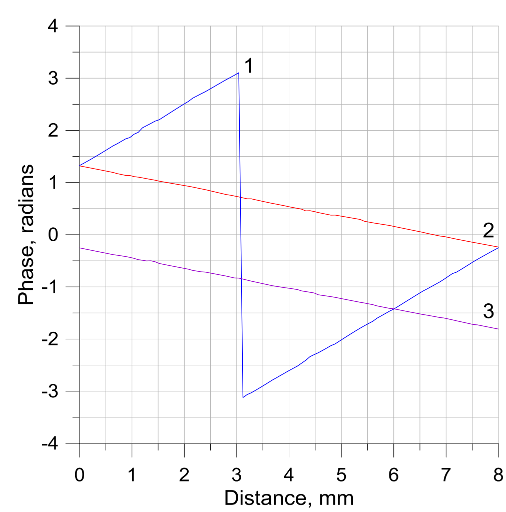

Figure 2: Phases of E_z (longitudinal) field component (curve 1) and phases of E_x (curve 2) and E_y (curve 3) field components.

The helpful feature of TM_{01}-TM_{11} helical structure is a flexible focusing of electrons due to higher space harmonics crowded to the corrugation.

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Dispersion relation for the eigen mode and spurious modes of the optimized structure is plotted in Fig. 3. Note that mode selection could be provided using thin wall absorber wire in the groove (Fig. 4) which is parallel to surface currents of the operating mode only. Calculations show that all spurious modes has noticeable extra losses in presence of this absorber.

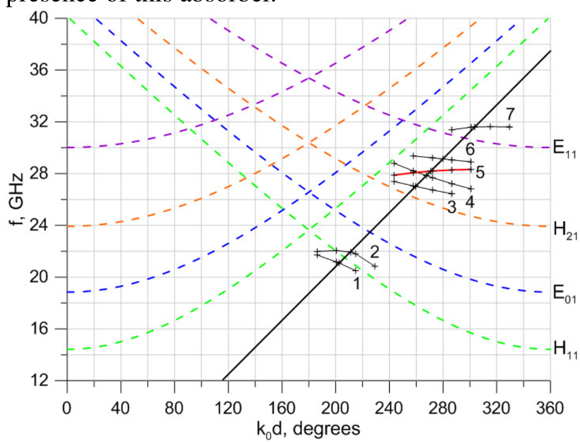

Figure 3: Dispersion characteristics in helical waveguide: light cone line (black); 1,2,3,4,6,7 – spurious modes; 5 – operating TM_{01}-TM_{11} wave.

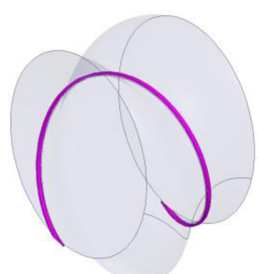

Figure 4: Helical structure with spiral absorbing groove.

FLYING RF UNDULATOR

In a helical corrugated waveguide (Fig. 5) bunch wiggling in short high-power RF pulse can be provided in the long section [3, 4]. Here we consider the 32 GHz fast TM_{01}-TM_{11} mode in the described helical structure which exists in frame of the parameters: R=6.1 mm, a=0.3 mm, d=6 mm. Such wave has group velocity as high as $v_{gr}/c=0.7$ (Fig. 6) and the effective undulator period 5.4 mm. Such 10 m long RF undulator, fed by 10 ns RF pulse of 1 GW power, has undulator parameter K=0.12 and is equivalent of 25 m of usual DC-magnet undulator with undulator period 3 cm and K=0.5.

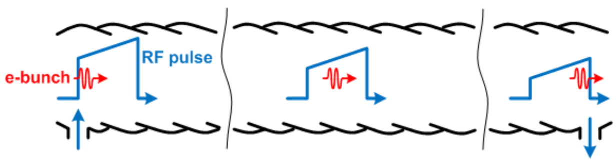

Figure 5: Flying" RF undulator in form of helical corrugated waveguide section.

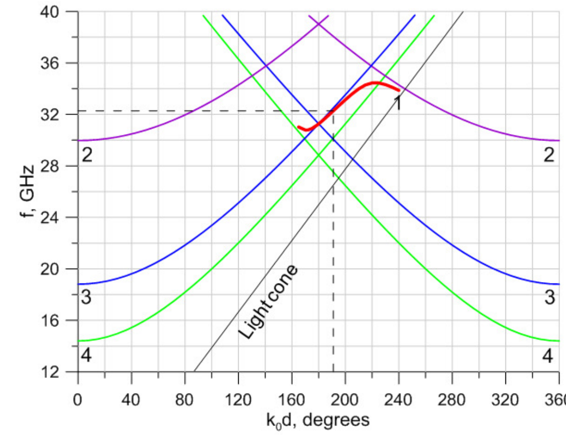

Figure 6: Dispersion characteristic of normal TM_{01}-TM_{11} wave in helical waveguide (red curve 1); dispersion curves of TM_{11} (2), TM_{01} (3), and TE_{11} (4) partial waves in the smooth circular cross-section waveguide.

In Fig. 7 results of simulations for short RF pulse propagation in the proposed helical undulator are shown. One can see that power loss (spread) of RF pulse, caused by frequency dispersion in the structure, are low.

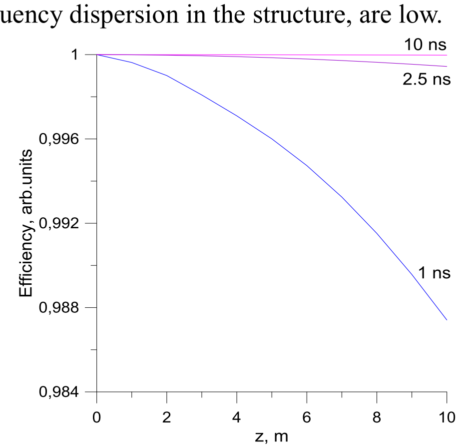

Figure 7: Efficiency of propagation for 32 GHz pulses of different durations in 10 m long helical undulator.

FLYING RF UNDULATOR FED BY DRIVE BUNCHES

Because in the considered slow-wave helical accelerating structure we assumed that 0th harmonic phase velocity equals to electron velocity, it is appealing to excite the operating wave by high-current relativistic drive bunches. Witness bunches should be injected near zero longitudinal electric field (Fig. 8). Witness bunches in this case naturally see counter-propagating wave (-1st space harmonic) with strong transverse field strength (Fig. 9).

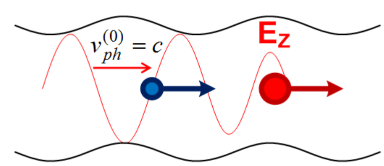

Figure 8: Mutual positions of drive bunch (red) and witness bunch (blue) in longitudinal electric field of

operating mode.

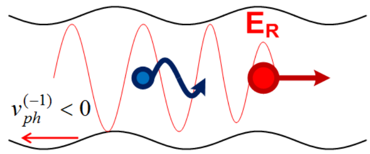

Figure 9: Mutual positions of drive bunch (red) and witness bunch (blue) in transverse electric field of operating mode.

The most appealing feature of the described scheme is that the effective interaction length of witness particles with the excited by drive bunches wake fields might be very big. Obviously, the higher group velocity of the operating wave, the shorter the producible wakefield magnitude and the higher effective undulator field as well.

In simulations we used the 27.15 GHz helical waveguide mode with 0.17*c* group velocity (*R*=6 mm, *a*=1.5 mm, *d*=10.5 mm) which was excited by three equidistant bunches with bunch length equal to a half of the wavelength. The distance between bunches was $2\pi/h_0$. Results of simulations (Fig. 10) show that desirable wake fields are able to be excited. High undulator parameter *K*~1 is also reachable using ~ 1 nc drive bunches. All bunches in Fig. 10 move from right to left side.

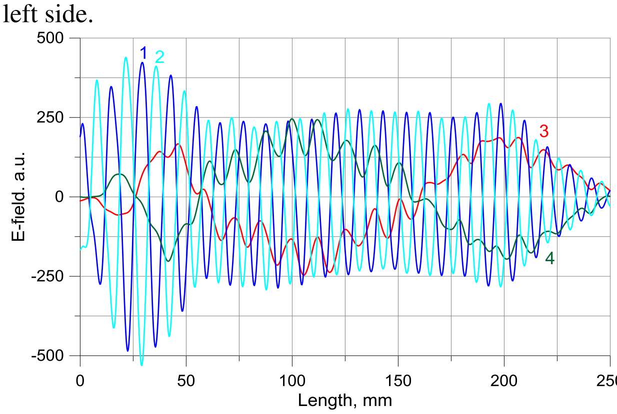

Figure 10: Excitation of flying mode by three drive bunches: 1 – E_z field at t=0; 2 – E_z field at t=1/2f, 3 - E_r field at t=0; 4 – E_r field at t=1/2f.

TERAHERTZ FEL

In order to produce THz radiation, we suggest to use short bunches of electrons with bunch length less than a half of THz wavelength [5]. Such bunches can be easily produced by means of the existing rf photoinjectors which are driven by high-power picoseconds lasers. In the conceptual scheme (Fig. 11) the helical waveguide supports synchronous with electron bunch eigen mode consisted of two main space harmonics. The 0th harmonic represents focusing TM_{01} wave, the -1st harmonic is TM_{11} wave with negative phase velocity which causes wiggling of electrons. In such structure pulses with the chirped frequency are obtainable using injection of particles in slightly accelerating rf field so that particles with growing energy naturally radiate undulator radiation with growing frequency. The reached chirped THz pulses might then be compressed by means of pulse compressor consisted of two gratings like in existing powerful laser systems.

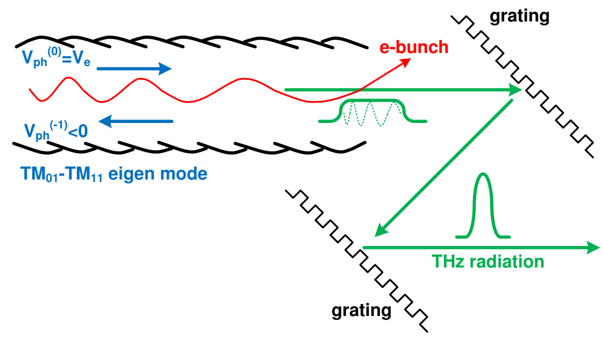

Figure 11: Concept of THz FEL with helical rf undulator and built-in pulse compressor.

CONCLUSION

In a helical waveguide there are eigen modes consisted of the partial waves with comparable amplitudes and different transverse structures. Such eigen modes might be slow ones. In this case helical structure is good at acceleration of electrons with a possibility to control beam emittance and energy spread due to synchrotron radiation of particles in strong transverse field of the counter-propagating space harmonic. This wave might be also excited by drive bunches. In this case the described operating wave can introduce flying RF undulator for witness bunches moving behind drive bunches. The effective interaction distance could be as long as necessary. The fast eigen mode of the described type in the helical waveguide is also appealing for RF undulator fed by external RF source. This also allows large effective length for compact undulator. The mentioned slow wave in helical structure is also attractive for THz FEL where axial field component is used to avoid expansion of short bunches in longitudinal directions.

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