“Flying” rf undulator

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***Abstract*— A concept for the room-temperature rf undulator, designed to produce coherent X-ray radiation by means of a relatively low-energy electron beam and pulsed mm-wavelength radiation, is proposed. The “flying” undulator is a high-power short rf pulse co-propagating together with a relativistic electron bunch in a helically corrugated waveguide. The electrons wiggle in the rf field of the -1st spatial harmonic with the phase velocity directed in the opposite direction in respect to the bunch velocity, so that particles can irradiate high-frequency Compton’s photons. A high group velocity (close to the speed of light) ensures long cooperative motion of the particles and the co-propagating rf pulse.**

I. CONCEPT OF THE FLYING UNDULATOR

We suggest an rf undulator based on co-propagation of an electron bunch and a short high-power rf pulse without a loss in Doppler’s up-conversion of the frequency,

$$\omega/\omega_{\rm u} \sim 2\gamma^2(1 - V_{\rm e}/V_{\rm phase,u}).$$

This “flying” undulator has the following effective undulator length:

$$L_{\rm eff}^{\rm co} = \frac{V_{\rm gr}\tau}{1 - V_{\rm gr}/c}$$

which is longer by factor $(1+V_{\rm gr}/c)/(1-V_{\rm gr}/c)$ than the interaction distance of the counter-propagating particles and the rf pulse with the same duration. The sectioned scheme shown in Fig. 1 illustrates the main idea of the “flying” undulator. Electrons and the rf pulse (which naturally contains counter-propagating wave subsections, where $V_{\rm phase,u}$ is negative) can move together over a long distance. However, the length of the counter-propagating subsections is small as compared to the length of the whole undulator.

In a helical corrugated waveguide (Fig. 2), wiggling can be provided in the long section. We consider the “flying” rf undulator based on a normal mode of the corrugated waveguide, which is formed by teo partial waves, namely, the co-propagating 0-th harmonic with positive propagation constant h_0 and phase velocity, and the -1-st harmonic with the negative propagation constant h_{-1} and the negative phase velocity. The group velocity is positive and and close to the speed of light for the both spatial harmonics. Therefore, the rf wave propagates together with the e-beam. At the same tame, the -1-st spatial harmonic of the normal wave is used as the wiggler. As its phase velocity is negative, a high Doppler’s up-conversion of the frequency is provided.

The co-propagating partial wave of the “flying” undulator can cause large-scale perturbation of electron motion and spoil the X-FEL radiation spectrum. In order to avoid this, the 0-th and -1-st harmonics should be represented by modes with different transverse structures. The 0-th harmonic should be chosen so that it does not have transverse fields in the center, where a thin electron beam is injected. Waves like TE_{mn} or TM_{mn} with the azimuth index $m \neq 1$ satisfy this requirement. Of course, the operating (“wiggling”) fields of the -1-st harmonic should be as high as possible. Therefore, the -1-st harmonic should preferably be a wave with m=1. In particular, we consider the rf undulator based on the helical corrugated waveguide, where the TM_{01} wave is actually the $0^{\rm th}$ harmonic, the rotating TM_{11} is the -1-st harmonic in the one-thread ($\overline{m}=1$) helical waveguide.

II. CORRUGATED WAVEGUIDE MODES

We study a helical corrugated waveguide with the surface described in the cylindrical system of coordinates (*z*-axis coincides with waveguide center) by the formula $r(z,\varphi) = R_0 + a\sin(2\pi z/D + \overline{m}\varphi)$, where R_0 is the average waveguide radius, *a* is the corrugation amplitude, *D* is the period, and $\overline{m}$ is the number of helical threads. In this corrugated waveguide, there is an infinite number of the s Floquet’s spatial harmonics with propagation constants $h_{\rm n} = h_0 + 2\pi n/D$ (here *n* is the harmonic number) and phase velocities $v_{\rm ph} = \omega/h_{\rm n}$ (they could be either positive or negative relative to the electron velocity sign). Particles oscillate in the transverse fields of the -1-st harmonic. The equivalent undulator period is given by the formula $\lambda_{\rm u} = 2\pi/(|h_{-1}| + k)$. Note that $|h_{-1}|$ can be close to the vacuum wavenumber k, or even bigger (for slow -1$^{\rm st}$ harmonic). Therefore, the equivalent undulator period might be favourably as short as it is in the case of the counter-propagating rf pulse (when the equivalent undulator period is close to the half-wavelength, $\lambda_{\rm u} = 2\pi/(h+k) \approx \lambda_{\rm rf}/2$).

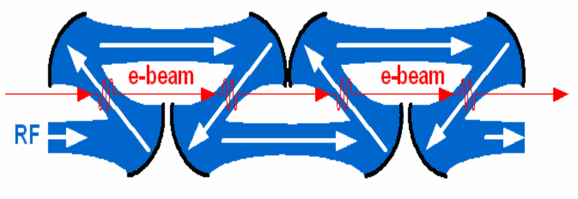

Figure 1: Periodic mirror transfer line with the “flying” rf undulator.

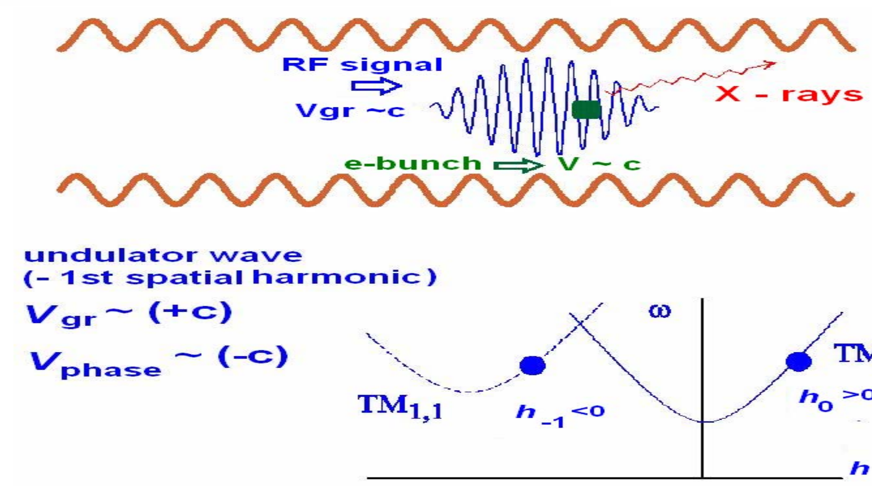

Figure 2: “Flying” rf undulator based on the helical waveguide.

We investigate the operating TM_{01}-TM_{11} wave. Figure 3 illustrates the dispersion curve of this normal wave for the following parameters: R_0=6.1 mm, *D*=6 mm, and *a*=0.3 mm. The dispersion curve of our normal wave is close to linear within the phase interval between 170° and 220°. At these points, the dispersion curve of the partial TM_{01} mode has intersections with the dispersion curves of the partial TM_{11} and TE_{11} waves, correspondingly. Note that the operating point is placed approximately between the mentioned TM_{01}-TM_{11} and TM_{01}-TE_{11} Bragg’s resonances, so that the TE_{11} fields contribute also to the field structure of the operating normal wave.

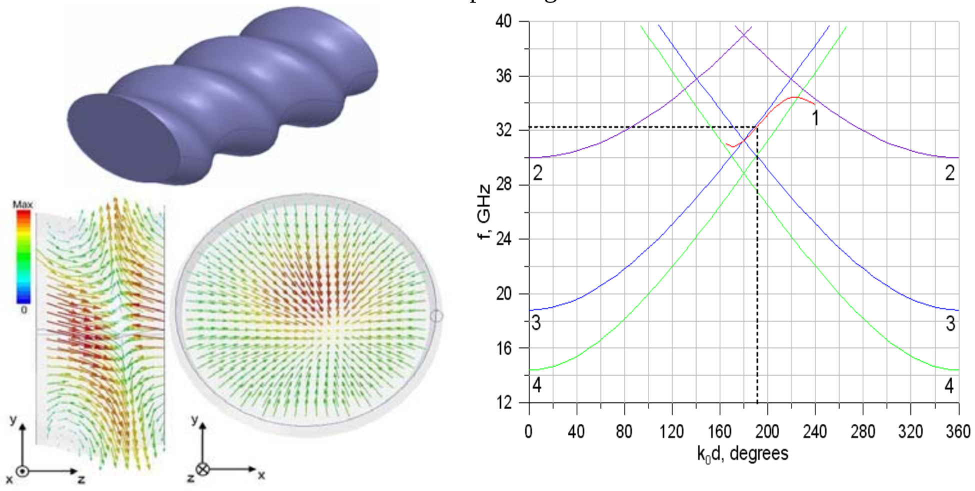

Figure 3: Helically corrugated waveguide, electric field structure of the TM_{01}-TM_{11} operating normal wave , and dispersion characteristic of the normal TM_{01}-TM_{11} wave in the helical waveguide (curve 1); dispersion curves of TM_{11} (2), TM_{01} (3), and TE_{11} (4) partial waves in the smooth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

III. FLYING UNDULATOR OPTIMIZATION

In the corrugated waveguide described above, the highest value of the gain of the SASE FEL operation is achieved near 190° at f=32 GHz. This point corresponds to $\lambda_{\rm u} = 5.4$mm and $v_{\rm gr}/c \approx 0.7$. In the case of the 1 GW rf wave signal, the undulator factor is $K \approx 0.15$. As the wiggling component of the rf field of the “flying” undulator, has circular polarization, the effective undulator parameter twice as high, $K_{\rm eff} = 2K$.

Let us compare this “flying” rf undulator created on the basis of a 10 ns rf pulse with $\lambda_{\rm rf} = 1$ cm and with the DC-magnet undulator ($K = 0.5$ and $\lambda_{\rm u} = 3$ cm). Due to $v_{\rm gr} = 0.7c$, the “flying” undulator provides electron wiggling within the distance $L_{\rm eff} \approx 10$ m with the effective undulator period $\lambda_{\rm u} = 0.58\lambda_{\rm rf}$. At a fixed target radiation wavelength $\lambda \approx \lambda_{\rm u}/2\gamma^2$, the ratio of the required electron energies is ~ 2.5. Due to this fact, the “flying” undulator has a 2-3 times higher gain factor. Thus, the “flying” rf undulator with $L_{\rm eff} \approx 10$ m provides the gain, which is equally as high as the referenced DC undulator with the length $L \approx 25$ m, and requires significantly lower electron energy.

We should mention an additional advantage of the “flying” undulator, namely, its focusing properties. The transverse fields of its co-propagating partial wave TM_{01} (0-th spatial harmonic) component have minimum (zero) at the waveguide axis (the e-beam position). Therefore, the pondermotive Miller force caused by this non-synchronous wave is directed to the centre.

IV. RF SOURCE FOR THE FLYING UNDULATOR

As a prototype of the rf source, a relativistic Cherenkov backward-wave oscillator based of the 550 kV / 4 kA e-beam is being under creation (Fig. 4). A tubular beam of rectilinearly moving particles passes through the corrugated waveguide in a guiding magnetic field of 6 T and excites the backward travelling mode TM01. A special resonant reflector is placed at the waveguide input; this is needed to provide output of the rf power.

According to simulations, realization of the simplest scheme of such rf oscillator at the operating frequency of 35 GHz can be a way for creation of a source of a 20 ns rf pulse with the peak power of about 0.5 GW; the corresponding electronic efficiency amounts ~20%. According to simulations, the use of a sectioned operating cavity can enhance the output power up to 700-800 MW.

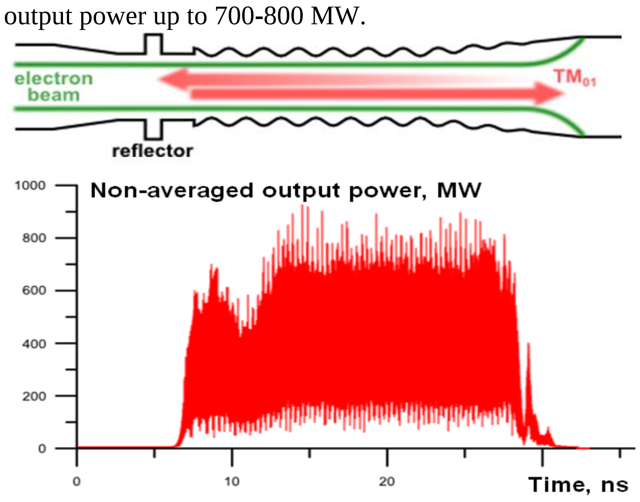

Figure 4: Schematic of the relativistic Cherenkov backward-wave oscillator, and calculated non-averaged output power versus the time.