CONCEPTS FOR SHORT PERIOD RF UNDULATORS

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Abstract

Two concepts for room-temperature RF undulators, fed by cm- or mm- wavelength radiation and aimed to produce ~1 nm wavelength radiation using relatively low energy electron beams, are considered. In accordance with the first considered concept each undulator segment introduces a high-Q cavity fed by its own multi-megawatt RF source. The 30 GHz pulsed gyroklystron or gyrotrons at 30 - 300 GHz, already elaborated and tested in IAP RAS, are appealing candidates. These sources can provide the effective undulator period of 0.5 - 0.05 cm, the undulator parameter up to 1, and the effective field length of 50 cm for each segment. The second concept implies using high-power short pulse propagating in a long helically corrugated waveguide where the -1st field harmonic is responsible for particle wiggling. High group velocity of this pulse allows providing long interaction of particles with RF fields.

RF UNDULATORS BASED ON HIGH-QUALITY CAVITIES

RF undulator in comparison with traditional undulator, consisting of DC magnets, introduces a strong appeal to use less energetic electron beam, in order to produce the same wavelength of Compton's scattered radiation [1-3]. For example, in order to achieve radiation of nanometer wavelength instead of 1-2 GeV beam in conventional undulator with several centimeters period, one can use several hundreds of MeV beam in RF undulator with period ~1 cm [4]. The inevitable payment for this evident advantage is a necessity to provide high power level of microwaves, in order to have acceptable undulator parameter to be competitive with conventional undulators. In Ka-band the necessary power of the wave (to be counter-propagating to electrons) in waveguide of ~1 cm size reaches GW level. That is why, the modern projects of RF undulators assume cavities of high Q-factors to be powered by existing RF sources (klystrons, gyroklystrons, magnikons) which itself are able to provide tens of megawatts. According to such a concept full RF undulator consists of many relatively short sections to be mutually phased ones. At centimeter wavelength range the bimodal TE_{01}-TE_{02} resonator looks promising [4], at millimeter or sub-millimeter range a multi-mirror Gaussian beam resonator is preferable.

High-Q cavities bring a threat of destroying phenomena like RF breakdown and pulsed heating [5-6]. In order to avoid these undesirable phenomena, a short-pulse RF radiation of GW power level is appealing. In particular, experiments carried out with particle accelerators show that nanosecond RF pulses of GW level can travel through electrodynamic structure without breakdown [7].

There are necessary RF sources of GW power level based on relativistic BWOs [8]. Such sources can deliver more than 1 GW power in X-band and about 1 GW in Ka-band in pulses of 0.1-20 ns duration with repetition rate as high as several kHz. It was proven in experiments that phases of separate sources might be mutually locked [9].

SHORT-PULSE, TRAVELING WAVE RF UNDULATOR BASED ON HELICAL CORRUGATED WAVEGUIDE

A short RF pulse of duration τ, propagating in a smooth waveguide with group velocity closed to light velocity c and directed toward an ultrarelativistic electron bunch, causes wiggling of particles at length $L_{eff}^{count} = c\tau/2$. If one takes 10 ns RF pulse, the interaction length does not exceed 2 m. Interaction distance can be much longer, if RF pulse is co-propagating with electrons. In this case the effective interaction length is:

$$L_{eff}^{co} = \frac{v_{gr}\tau}{1 - v_{gr}/c}, \tag{1}$$

where v_{gr} – is a group velocity along electron beam.

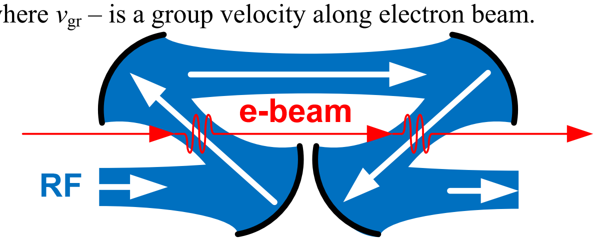

Figure 1: Mirror transfer line employing the "flying" RF undulator.

Of course, the co-propagating RF pulse in a smooth waveguide does not promise considerable Doppler's frequency up-shift. This problem is solved by using a so-called "flying" RF undulator, where a wavebeam spends a part of time moving toward electrons (Fig. 1).

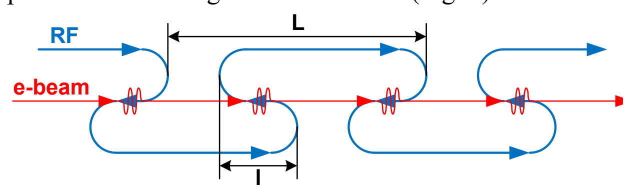

Figure 2: Equivalent scheme of "flying" RF undulator.

The simplified equivalent scheme of the "flying" undulator in Fig. 2 allows writing group velocity along beam in the mirror line:

$$v_{gr} = \frac{c}{1 + 2l/L}. \tag{2}$$

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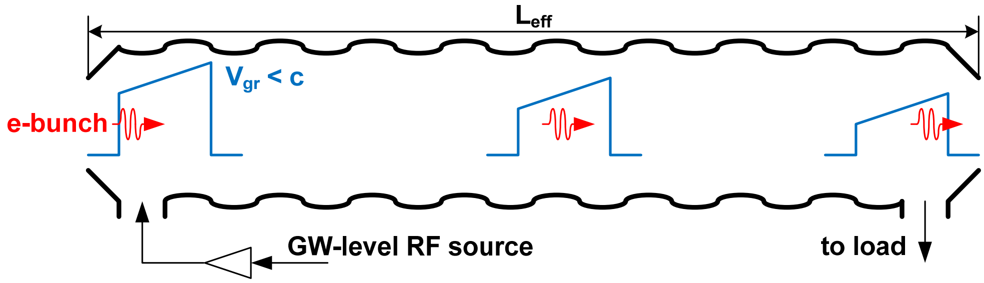

Figure 3: “Flying” RF undulator in form of helical corrugated waveguide section.

Any undulator can be described by dimensionless undulator parameter K, which is proportional to deflecting field amplitude. In an undulator with parameter K the optical radiation (in small signal approach) grows along electron path on z coordinate as $\sim \exp(K^{2/3} z)$ [4]. Let us introduce gain parameter as $\eta = K^{2/3} \cdot L_{eff}$, which can be used, in order to compare the “flying” RF undulator with the undulator, where RF pulse is counter-propagating. Ratio of gain parameters η_F (for the co-propagating ‘flying’ RF pulse) and η_0 (for the counter propagating RF pulse) is given using equations (1) and (2):

$$\frac{\eta_F}{\eta_0} = \frac{L}{l}. \tag{3}$$

If the condition $l=L$ is satisfied, then the “flying” RF undulator does not have advantages in comparison with smooth undulator with counter-propagating wave. Maximum of the ratio (4) is achievable, if l goes to zero. In this case the effective interaction length goes to infinity. However, there are big gaps where the interaction is absent at all. Such klystron-type configuration is more sensible to energy spread and beam emittance than configuration with simple counter-propagating wave [10].

In Fig. 3 the improved concept of the “flying” RF undulator, based on helical corrugated waveguide, is shown. Here bunch has continuous interaction with RF fields. In comparison with undulator based on counter-propagating wave in smooth waveguide (with parameter K_0), undulator parameter K in the corrugated waveguide is less, so let us take $K=K_0 \cdot \chi$. Nevertheless, the effective interaction is longer so that normalized gain parameter:

$$\frac{\eta_F}{\eta_0} = 2\chi^{2/3} \frac{v_{gr}/c}{1 - v_{gr}/c}, \tag{4}$$

is more than unity, if group velocity is high enough:

$$\frac{v_{gr}}{c} > \frac{1}{1 + 2\chi^{2/3}}. \tag{5}$$

In a corrugated waveguide of the fundamental period D there is an infinite number of the spatial harmonics those phase velocities could be either positive or negative relative to sign of electron velocity. Let us consider the “flying” RF undulator where co-propagating 0-th harmonic has the positive propagation constant h_0 and phase velocity, but -1-st harmonic has the negative propagation constant h_{-1} and negative phase velocity. The group velocity is less than c, positive and constant for all spatial harmonics. Particles oscillate in the transverse fields of the -1-st harmonic with equivalent undulator period:

$$\lambda_u = \frac{2\pi}{|h_{-1}| + k}, . \tag{6}$$

where $h_{-1} = h_0 - 2\pi / D$, $k=\omega/c$ – is a vacuum wavenumber.

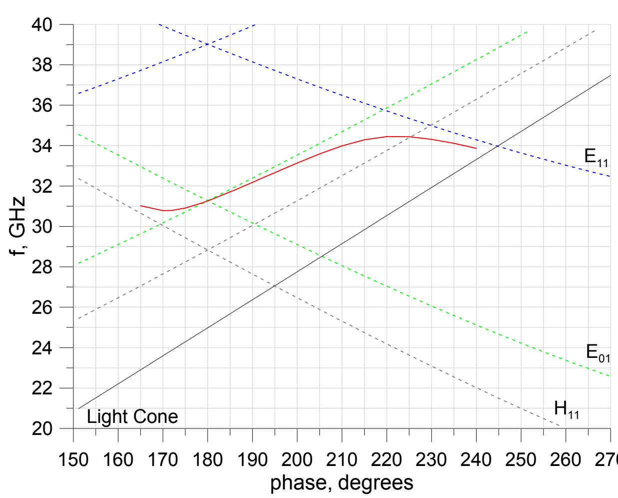

Figure 4: Dispersion characteristic of normal TM_{01}-TM_{11} wave in helical waveguide (red curve).

As it was proven in the paper [3], the co-propagating wave causes large-scale particle motion and dramatically spoils radiation spectra in RF undulator. In the proposed RF undulator the 0-th harmonic always exists and cannot be avoided. Nevertheless, in a helical corrugated waveguide the 0-th and -1-st harmonics can be represented by modes of different transverse structures.

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The 0-th harmonic should be chosen so that it does not possess transverse fields in the center where the thin electron beam travels. We suggest RF undulator based on TM_{01} (0^{th} harmonic) – TM_{11} (-1^{st} harmonic) in the one-thread helical waveguide. Dispersion curve of this operating normal wave, i.e. eigen frequency Vs phase h_0D in degrees, is shown in Fig. 4 for parameters: the average radius is R_0=6.1 mm, the period is D=6 mm, and the amplitude of corrugation is a=3 mm. The dashed curves correspond to partial modes in the smooth circular waveguide. The light cone is shown by black solid curve.

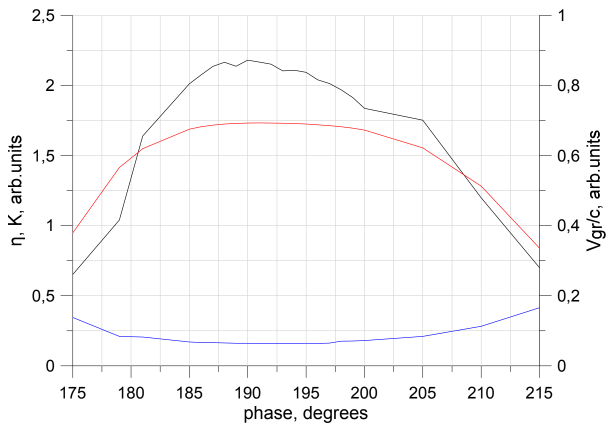

Figure 5: Normalized characteristics of TM_{01}-TM_{11} wave. The blue curve is undulator parameter. The red curve describes group velocity. The black curve is gain factor.

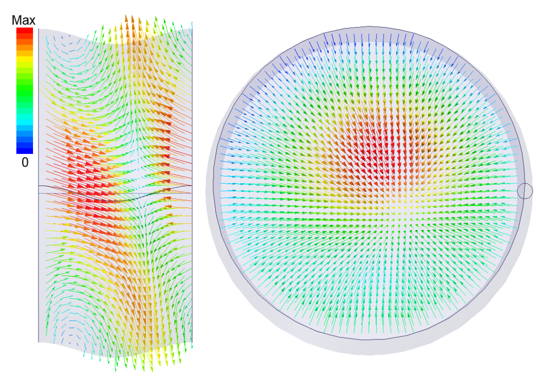

Figure 6: Instantaneous field structure of TM01-TM11 operating wave at phase 190 degrees.

In Fig. 5 K-parameter is plotted for the mentioned waveguide parameters and 1 GW RF power in dependence on the phase. In the same figure one can see group velocity and gain parameter also plotted in dependence on the phase. The highest value of parameter η (near 190 degrees in Fig. 5) corresponds to moderate fields, λ_u=5.4 mm, and group velocity about 0.7c. So we suggest to choose the point 190° as operating one. Such "flying" undulator is the equivalent of 10 m of usual undulator. Field structure of the operating TM_{01}-TM_{11} mode is shown in Fig. 6. Note that at the operating frequency partial TM_{11} mode is evanescent in the smooth circular waveguide.

The surface fields near phase 190° are 2.5 times higher than fields at axis so that Ohmic losses are not negligible. At phase=190° the power loss corresponds to factor $\alpha=6\cdot10^{-2}$ m^{-1} at room temperature. This loss is as high as about 60% of the incident RF power in 10 m helical waveguide. That is why, the pulse shape with the higher amplitude in front in comparison with the rear part of the pulse is desirable (Fig. 3). This pulse shape might provide constant acting fields for the electron bunch at whole undulator.

Schemes TE_{21}-TM_{11} and TM_{01}-TE_{11} are also possible.

CONCLUSION

The proposed concept, based on using GW level, 10-20 ns pulses in Ka-band, makes possible to use alone or a few number of RF sources in long enough "flying" undulator in order to create effective SASE XFEL.

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