A SHORT-PERIOD RF UNDULATOR FOR A NANOMETER SASE SOURCE

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Abstract

An undulator made of static magnets typically has a period of a few centimeters. In order to produce synchrotron radiation of short wavelengths (~ 1 nm) in such undulator a 1.5 GeV electron beam is necessary. Instead of expensive high energetic electron beam a beam of a moderate energy (≤ 300 MeV) in RF undulator with period ranging from several millimeters to sub-millimeters is appealing. Additionally the RF undulator can provide fast dynamic control of polarization, wavelength, undulator K parameter, can have wide aperture (~ 1 cm), and to bring other attractive features [1-3].

In order to become a competitive alternative to the traditional undulator, the RF undulator must, of course, have as high strength of wiggling fields as magnetic fields in existing permanent magnets (B ~ 1 T). In particular, the K parameter should be about unity in RF undulator of the 10 mm period. Because powers of modern millimeter and sub-millimeter RF sources like a magnicon or a relativistic gyroklystron are limited by several tens of megawatts, necessary undulator fields can be obtained in so-called storage cavities only. Design of such cavities should take into account many constraints like: emittance growth in presence of powerful RF fields, Ohmic wall losses, breakdown, and surface pulse heating.

TRAVELLING WAVE RF UNDULATORS

A travelling wave undulator can be made of low-loss resonant ring where an operating wave moves toward the beam which traverses one of arms. Among low-loss waves there are TE_{01} mode in smooth circular cross-section waveguide and HE_{11} in corrugated waveguide of the impedance type. Both modes have low surface fields in an oversized waveguide. Because the first mode requires bigger diameter to turn [4] and consequently requires higher RF power and energy, the HE_{11} mode is preferable.

The 34 GHz room-temperature RF undulator which exploits superposition of the HE_{11} and HE_{12} modes to minimize diffraction losses in mitre bends is shown in Fig. 1. Calculations show, in order to obtain parameter K = 0.4 in the waveguide of L = 250 mm length, about 120 MW input power, 470 ns filling time (loaded Q-factor is $5.1\cdot10^4$ at waveguide radius 26.5 mm) are necessary. Surface electric field is ~ 20 MV/m. Ohmic quality ($Q_{ohm} = 31\cdot10^4$) here is twice more than diffraction quality ($Q_{diff} = 15.2\cdot10^4$) caused by scattering in mitre bends. The mentioned high input power level is explained by big total volume which cannot be reduced because waveguide radius reduction causes more diffraction losses.

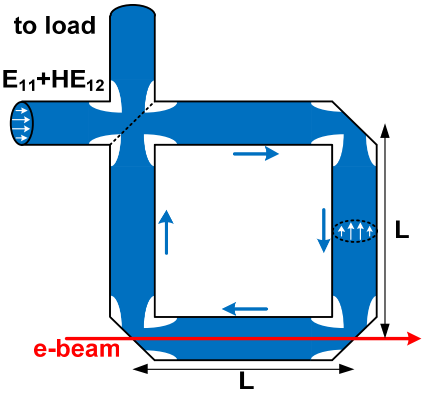

Figure 1: HE_{11} resonant ring.

BEAM DYNAMICS IN A STANDING WAVE RF UNDULATOR

In the standing wave RF undulator an operating mode consists of a co-propagating wave and a counter propagating wave (Fig. 2). Transverse oscillations in such undulator can be described by equation:

$$\frac{d^2X}{d\vartheta^2} = \frac{K}{\gamma}(\alpha\cdot\delta\cdot e^{-i\delta\vartheta} + e^{-i\vartheta})\cdot e^{-i\varphi}, \quad (1)$$

where X – is a dimensionless transverse particle position, ϑ – is a normalized longitudinal coordinate, K and γ - are undulator parameter and Lorentz factor, φ - is an injection phase, α - is an amplitude of the co-propagating wave. Here we used a definition:

$$\delta = \frac{k-h}{k+h}, \quad (2)$$

where h – is a propagation constant in a waveguide, and $k=\omega/c$.

The counter propagating wave causes the desired FEL quiver electron motion with relativistic Doppler up-shift of Compton photons. The forward co-propagating wave also interacts with the electrons and generates low frequency microwave radiation. Unfortunately, this wave produces beam oscillations which by factor $1/\delta$ bigger than oscillations caused by the counter propagating wave.

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The view along the beam axis in Fig. 2, obtained by means of Microwave CST Studio, shows such beam motion. The reason of this instability is that co-propagating wave in oversized waveguide moves synchronously with moving electrons far enough so that some electrons acquire the positioning shift in one direction, other electrons do the shift in the opposite direction.

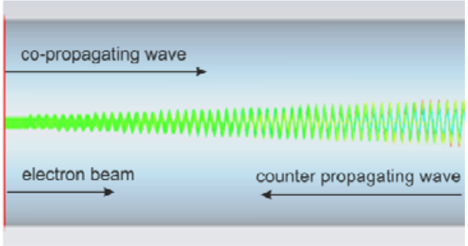

Figure 2: Electron beam motion in standing wave undulator with identical co-propagating and counter propagating waves (f = 34 GHz, K = 0.1, γ = 13, R = 14 mm).

The mentioned high-magnitude oscillations can cause beam transportation problems and can cause undesirable light power loss due to a fact that different parts of electron beam radiate power in different phases (incoherence). Criteria for maximum acceptable transverse beam deflection are given by obvious Fresnel parameter:

$$s_{\max} \le \frac{\sqrt{\lambda L}}{2\gamma}, \qquad (3)$$

where λ - is a wavelength of the deflecting RF radiation, and *L* – is an undulator's length. Note that increasing of Lorentz factor γ helps one to solve beam transportation problem due to a reduction of a magnitude of oscillations. However, equation (3) shows that acceptable average beam deflection reduces linearly with γ decreasing.

A CAVITY WITH DIFFERENT CO- AND COUNTER PROPAGATING MODES

In order to avoid the mentioned undesirable instability a co-propagating mode should have a transverse structure which excludes an interaction with the beam. In Fig. 3 the counter propagating mode is the TE_{01} wave which has almost maximum fields at beam location, the co-propagation mode TE_{02} has zero fields at this place (Fig. 4). Both modes do not have normal to wall fields.

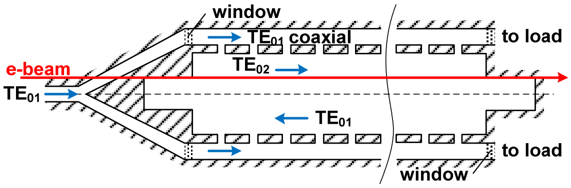

Figure 3: Conceptual sketch of the two-mode undulator.

The TE_{01} and TE_{02} modes are converted each to other by ladder-like converters in both ends of the undulator. Calculations show that very high conversion efficiency (diffraction losses at level – 50 dB) is achievable. Input coupler in a form of the perforated section couples selectively the TE_{02} mode in undulator with the TE_{01} coaxial mode. Parameters of the 34 GHz undulator with $K = 0.4$ are summarized in the Table 1.

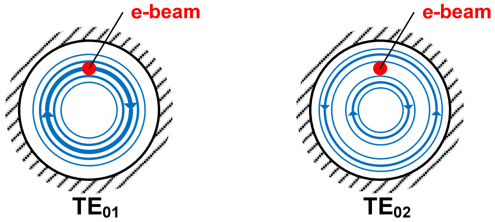

Figure 4: Cross-section of the resonator showing azimuthal transverse electric fields of co- and counter propagating modes and a location of electron beam.

Table 1: Parameters of the 34 GHz Undulator

waveguide radius, R	12 mm
main section length, L	250 mm
Ohmic quality, Qohm	67800
loaded quality, QL	33900
coupling, χ	0.8%
RF pulse duration, τ	320 ns
beam shift off axis, rb	6.55 mm
RF input power, Pin	34 MW
temperature rise, ΔT	133°C

Beam dynamics in such undulator is described by solution of the equation (1) under α=0:

$$X = \frac{K}{\gamma}\left(e^{-i\vartheta} - i\vartheta - 1\right)\cdot e^{-i\varphi}, \qquad (4)$$
$$\frac{dX}{d\vartheta} = i\frac{K}{\gamma}\left(e^{-i\vartheta} - 1\right)\cdot e^{-i\varphi}.$$

Analysis of equations (4) shows that there are injection phases (φ=0 and φ=π) which at length of undulator $\vartheta_{end}=2\pi n$, corresponded to an integer number of oscillations n, provide zero transverse position and velocity at output simultaneously.

A CAVITY WITH A TM MODE NEAR CUT OFF

In this undulator the operating TM_{11} mode is excited in barrel-like cavity (Fig. 5). Near cut off frequency both co- and counter propagating modes have high phase velocities and can not be in synchronism with electron beam long time. Beam dynamics simulations show that mentioned beam instability is avoided in this case. In cavity, those length equals tens of wavelengths, an electric field consists mainly of E_z component, so the surface field is not high. A corrugation is necessary, in order to provide coupling of the TM_{11} mode with TE_{11} waves of two powering phase-locked RF sources. Polarization of the operating mode can be easily controlled by polarizations of the input TE_{11} waves. The cavity has the smallest volume in comparison with TM_{11} undulator where the operating mode is far from cut off. This factor leads to relatively small input power and input pulse duration. For example, 34 GHz undulator with $K = 0.4$ and effective length 250 mm (cavity radius $R = 5.33$ mm) requires $P_{in} =$ 20 MW and $\tau = 70$ ns. These parameters provide low surface electric field (~ 1 MV/m) and comfortable temperature rise (16°C). A disadvantage of this scheme is that frequency of output photons is proportional to $2\gamma^2$ (γ – is a Lorentz factor) like in a DC undulator instead of $4\gamma^2$ like in RF undulators with far from cut off waves.

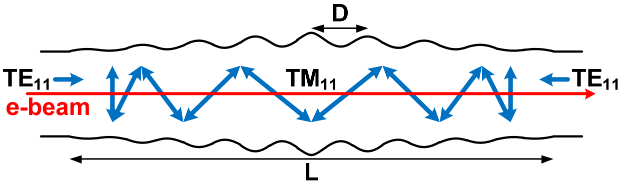

Figure 5: Conceptual design of the cavity with near to cut off TM_{11} mode.

It is remarkable that field structure in a cavity with near to cut off TM_{11} mode has smooth growing part in the beginning and dropping part in the end. Such natural field shaping allows provide small transverse shift and velocity at output for arbitrary values of the injection phase as it is shown in Figs. 6 and 7. This allows, in principle, to use long electron bunches (longer than a half of wavelength) or even to apply continuous beams.

“COLD” RF UNDULATOR

In order to reduce input power, it is natural to reduce Ohmic losses by using cryogenically cooled systems. Because a superconducting RF undulator is rather expensive and is able at relatively low RF frequencies ≤ 1 GHz, it is attractive to use at Ka-band a copper undulator to be cooled by liquid nitrogen (T≈80° C). In particular, the copper cooling down to liquid nitrogen temperatures promises more than 2 times loss reduction with anomalous skin effect taken into account. This predicted loss reduction was demonstrated experimentally with 34 GHz TE_{02} test cavity [5].

CONCLUSION

Among the considered schemes the HE_{11} resonant ring is distinguished by simplest design, low surface fields, but the feeding requires huge RF power. The TE_{01}/TE_{02} resonator (off-axis beam) with short efficient mode converters and coaxial coupler requires a moderate power, has low surface fields, in case of smoothly profiled RF field it can be operated in a regime of long pulses, but pulse heating temperature is rather high. The undulator with near to cut off TM_{11} mode has frequency up-shift two times less in comparison with other considered versions , but it is very attractive due to many reasons (low input power, low surface fields, simple design, and a possibility to be operated in a regime of long bunches.

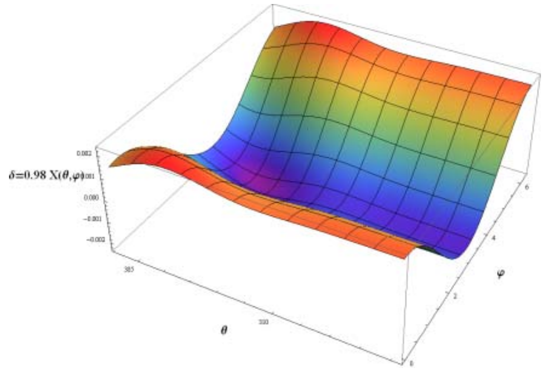

Figure 6: Transverse position of electron at output of 50 cm long undulator section ($\vartheta_{end}=100\pi$) as a function of length and injection phase (f = 34 GHz, K = 0.4, γ = 13).

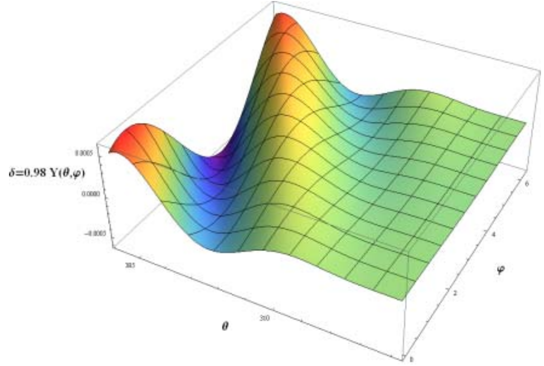

Figure 7: Transverse velocity of electron at output of 50 cm long undulator section ($\vartheta_{end}=100\pi$) as a function of length and injection phase (f = 34 GHz, K = 0.4, γ = 13).

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