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TAPERED FLYING RADIOFREQUENCY UNDULATOR

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Abstract

The x-ray free electron laser (x-FEL) efficiency, measured as a fraction of the electron beam power converted into light, is typically below 0.1% for most of the x-FEL facilities presently in operation. Undulator tapering techniques can be used to improve the conversion efficiency by 1-2 orders of magnitude. However at present there are no robust tapered undulator x-FEL schemes operating at 10% efficiency. In this paper we report on the development of tapered radiofrequency (RF) undulator. An RF undulator is a microwave waveguide in which strong RF field is excited that interacts with a charged particle beam forcing it to radiate coherent x-rays while undergoing a wiggling motion. RF undulators are attractive for use in x-FELs due to their large beam aperture and a short undulator period. Simulations and tests have shown that by decreasing the corrugation periodicity one can vary an equivalent undulator period by 50%. We also discuss a so-called non-resonant trapping regime not requiring phase locking for feeding RF sources.

FLYING RF UNDULATOR

The RF undulator based on a travelling wave benefits from a Doppler up-shift when the electron beam interacts with oncoming microwaves. In [1] an RF pulse co-propagating (with the electron beam) was proposed where a benefit of the Doppler up-shift of Compton scattering is not lost due to the mode having strong -1st spatial harmonic transverse fields at axis of a helical corrugated waveguide (Fig. 1). In this "flying" undulator the effective interaction length L_{eff} of a pulse with length τ and group velocity v_{gr} is proportional to $(1-v_{gr}/c)^{-1}$. For a large group velocity L_{eff} can be much larger than the pulse length.

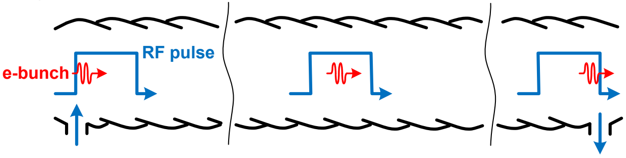

Figure 1: Flying RF undulator geometry (helical corrugation) and interaction timing structure.

In [1-2], a 30 GHz, 10 ns, 1 GW relativistic backward wave oscillator powers a 10-meter long RF undulator with effective undulator strength $K = 0.3$ and undulator period $\lambda_u \approx 5$ mm. There are high power Ka-band BWO's which are good candidates for powering of the proposed flying undulator [3-4].

Figure 2 shows the dispersion characteristic of the operating mode of the TE_{11}-TM_{01}-TM_{11} RF undulator for the following geometrical parameters: R_0=6.1 mm, periodicity D=6 mm and corrugation depth a=0.3 mm (red solid curve). The dashed curve is the dispersion characteristic of the same mode in the waveguide with smaller corrugation period, 5.4 mm. Therefore, a tapered undulator can be built near 34 GHz using adiabatic variation of corrugation period so that the effective undulator period change is as high as 10%.

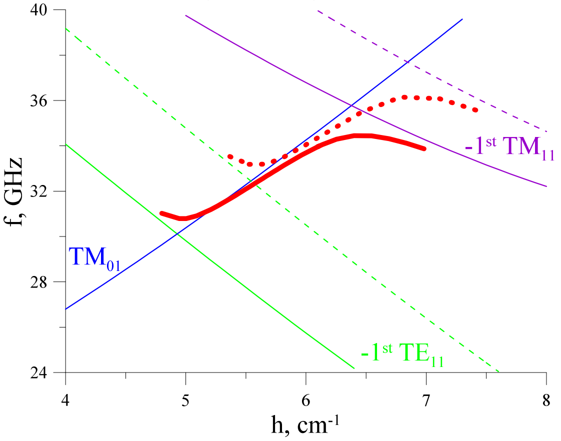

Figure 2: Dispersion of the operating mode (red solid curve) of the helical undulator with period of corrugation 6 mm and dispersion of this mode (red dashed curve) of the undulator with period of corrugation 5.4 mm.

HIGH-EFFICIENCY, TAPERED FLYING RF UNDULATOR

For a high efficiency free electron laser we consider a string of tapered flying undulators (Fig. 3). Each RF undulator section is assumed to be a helical corrugated structure with periodicity and corrugation depth changing as a function of z (coordinate along electron beam propagation).

In each undulator section geometrical parameters are varied to maintain the resonant condition ($\lambda \approx \lambda_u/2\gamma^2$) with particles losing their energy from γ_0 to γ_{min}, which defines the maximum efficiency $\eta = \Delta\gamma/(\gamma-1)$.

The electron beam enters each undulator section at such time that it ends up in the tail of the RF pulse. As electrons travel along the undulator at virtually the speed of light they pass the RF pulse which has a group velocity slower than speed of light. By the time the electron beam reaches the head of the RF pulse it has arrived at the exit of the undulator section. Electrons interact with both the RF field of the undulator and x-ray field generated by the electrons themselves. This interaction in a tapered undulator section can be represented in a phase space as a typical pendulum behavior with stationary buckets in which electrons are trapped (have finite trajectories). The center of the bucket corresponds to a resonant energy, and its size in energy is proportional to a current undulator parameter $K(z)$ as well as x-ray wave amplitude. Due to a finite signal rise and fall time electron beam sees initially a very small bucket due to low RF field. As it passes the RF pulse, at the exit of the undulator the bucket collapses again due to RF field roll off.

In the traditional resonant trapping scheme, considered for XFELs, electrons were assumed to be trapped in the bucket and stay in the same bucket the whole time, decreasing their energy from γ_0 to γ_{min}. For resonant trapping with RF undulators all undulator sections have to be at the same RF phase, meaning that all RF sources have to be phase locked.

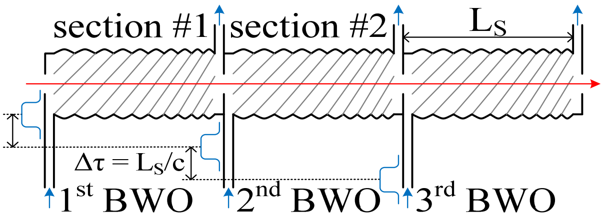

Figure 3: FEL scheme based on tapered RF undulators with decreasing equivalent undulator period.

We propose a so-called *non-resonant* trapping of electrons to relieve the stringent requirements on phase locking [5, 6]. In this scenario, not all electrons fall into the bucket at the entrance of the section. The ones that are trapped in a bucket stay trapped, and collapse inside the bucket, decreasing their energy due to radiation. The energy of other electrons does not change and they don't radiate. In the following sections another portion of electrons are trapped and decelerated. Going from section to section most of the electrons will end up decelerated.

Let us consider an example of XFEL calculations on a base of the described principles. In this example we take a 600 MeV ($\lambda \approx 2$ nm), 100 pC electron bunch of 0.167 ps length and 30 μm diameter. The energy spread is 0.1%. According to 1D FEL theory, Pierce parameter is as high as $\rho = 5\times10^{-4}$ (gain length $L_g \approx 0.5$ m). The FEL consists of 16 sections, each 10-meter long, each section has sine-like tapering of the corrugation amplitude with undulator parameter $K_{max}=0.25$ in maximum. In the Fig. 4 one can see variations of undulator period along the XFEL.

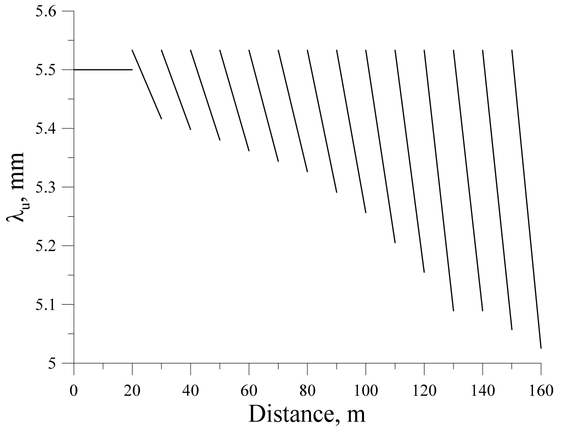

Figure 4: FEL scheme based on tapered RF undulators with decreasing equivalent undulator period.

The first two sections (first 20 m) with λ_u=5.5 mm are necessary, in order to excite initial x-ray wave which is to be amplified in next sections. All other sections are tapered ones. In these sections the magnitude of tapering increased along the distance. The further a given section from the entrance, the stronger it's tapering magnitude. This law is necessary because in the beginning of the FEL the x-ray amplitude is rather small so that effective trapping of particles is not available.

As the amplitude of the x-ray wave grows up the stronger tapering becomes possible which promises higher efficiency. In the considered example the last 16th section has 10% variation of the undulator period. The efficiency of the FEL (Fig. 5) was calculated using 1D theory equations. In the Fig. 5 the black curve #1 corresponds to the simulation where all sections were phase locked. In this simulation the highest efficiency (0.8%) was obtained. Other simulations (curves 2-6) were performed using only two first sections phase being locked, all other 14 sections had uniform [0-2π] random distribution of RF phases from one section to another section. Note that calculated in these cases efficiencies are high, in the worst case (curve 4) the efficiency is approximately 15% less than in the best case (curve 1).

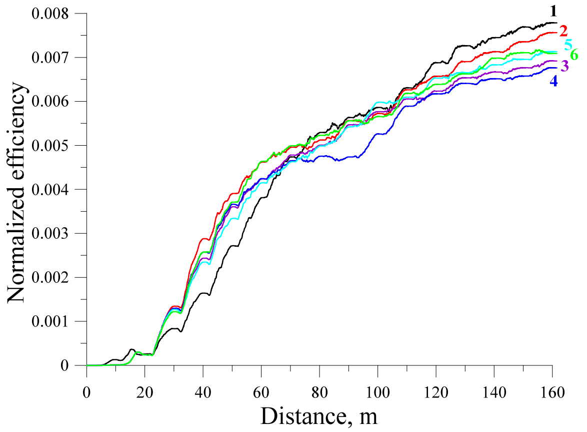

Figure 5: Efficiency of lasing along FELs for in-phase undulator sections (black curve#1) and for 5 different sets of sections with randomly distributed phases (curves 2-6).

The longer the XFEL, the higher efficiency could be reached. In the non-resonant trapping case, electrons that missed the bucket because of phase, frequency or amplitude drift are not lost completely as they have a chance to be trapped in the following section.

Simulations show that high efficiency is achievable in presence of the considerable energy spread. The higher necessary efficiency the stronger tapering is required in last sections. Tapering of *K*-parameter is not convenient in RF undulator (if one tries to vary an amplitude of RF wave, it will automatically change period, the magnitude of *K*-tapering is limited, variations of *K* lead to variations of electron-wave interaction strength). Tapering is not efficient until X-ray wave amplitude is low. Non-resonant trapping regimes assume rather long FEL. Short, compact, high current bunches produced by laser-plasma accelerators are appealing even taking into account large energy spread (~10%).

The 1D FEL theory results were also tested by Genesis. In order to simulate the variation of the period, we used variation of the K-parameter. Genesis simulations confirmed that efficiency grows up adding section with an increase of tapering.

LOW-POWER TEST

For low-power test we produced a simplified prototype of RF undulator sections based on elliptical standing wave TE_{11} mode (Fig. 6). In this undulator we smoothly reduce one waveguide size for tapering and increase the size of the opposite axis to obtain good field flatness. In order to change the undulator period, one needs to vary the ellipticity of the waveguide. The smaller the elliptic axis perpendicular to the electric field, the bigger the undulator period will be.

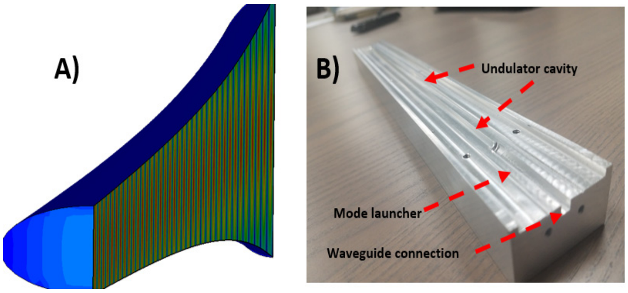

Figure 6: Elliptical standing wave TE_{11} tapered undulator.

In elliptical TE_{11} undulator, the period tapering was measured at about ~50% by bead pull technique. Wigner data representation shows linear tapering was achieved (Fig. 7).

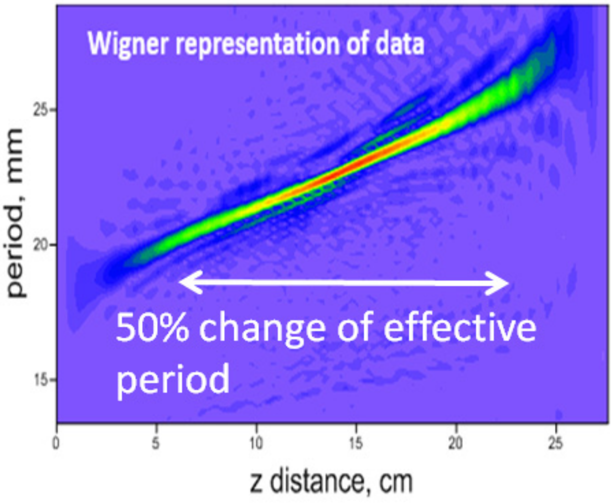

Figure 7: The Wigner representation of measurement.

CONCLUSION

Calculations show that high efficiency (1%-10%) is achievable in the non-resonant trapping regime even in presence of considerable (0.1%-10%) energy spread. This regime allows to reduce considerably number of RF sources, to avoid phase locking of sections, to provide operation to be not sensible to field balance within a section. The carried out low-power tests with strongly tapered RF undulator prototype showed that more than 50% variation of undulator period is obtainable.

ACKNOWLEDGEMENT

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