ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-WEPRO008

A BEAM-DRIVEN MICROWAVE UNDULATOR FOR FEL

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Abstract

We propose a microwave/THz undulator with an electron beam powering the microwave waveguide instead of the ~ GW level external high frequency RF source otherwise required for these devices. We plan to use a dielectric loaded or a corrugated copper structure, exploiting the well-developed technology of the beam-driven wakefield accelerator for high power RF generation. A key element of the proposed design is that the drive beam that generates the high power RF propagates opposite the undulating beam inside a decelerating waveguide.

INTRODUCTION

The idea of beam-driven accelerators, where intense electron beams are used directly to drive electromagnetic fields that accelerate probe or "witness" electron beams has been known for some time. An area that has received particular theoretical, computational, and experimental emphasis is that of *wakefield* accelerators. In this paper we unveil the next logical step in the application of wakefields, using intense electron beams to create fields that directly guide and periodically deflect "witness" electrons, causing them to radiate photons. This is a new application of wakefield principles that may be used in the near future to develop compact undulators. A combination of both a compact accelerator and a compact undulator could lead to a compact X-ray FEL that would represent an important research tool becoming available to a much wider group of scientists.

Microwave undulators have features that make them attractive to use in FELs: a relatively large beam aperture; short undulator period; the capability of producing both circular and planar polarization; and fast dynamical control of the polarization, wavelength, and the undulator parameter *K* [1-3]. The disadvantage can be a limited tunability for spontaneous radiation and FELs (a limited range of values of the undulator parameter). High power microwave sources with precise and stable amplitude and phase are expensive; handling of tens of GW of circulating microwave power is challenging and the design of the waveguide/cavity structure can be complicated [1-3]. RF limitations of microwave undulators also include the very large required field amplitudes, the loss factor on metallic surfaces, and drive power levels exceeding those from available sources [1-4].

Microwave waveguides can in principle be used for undulators with periods less than 1 cm. These devices are capable of generating x-rays from a few nanometers to the Ångstrom wavelength region [1,2]. Meanwhile, intensive work has been done recently by S. Tantawi's group at SLAC and their BNL collaborators on RF undulator development; successful experimental results have been reported recently [3].

In this paper we propose a beam driven design for an undulator based on an electron bunch train powering a microwave or mm waveguide. The drive bunch train propagates towards the undulating beam inside a dielectric loaded [5,6] structure or corrugated waveguide [3,7] generating high power RF. The beam driven undulator provides strong phasing between the undulating beam and the RF wave because the wakefield generated by the driver propagates along the undulator waveguide with phase velocity equal to the speed of a ultra-relativistic drive beam, V~c. The "smart" waveguide design [8] and a proper bunch spacing of the electron drive beam train [9] provide single mode generation of the high magnitude undulating field that gives an undulator parameter in the range of K~1 for a high frequency device.

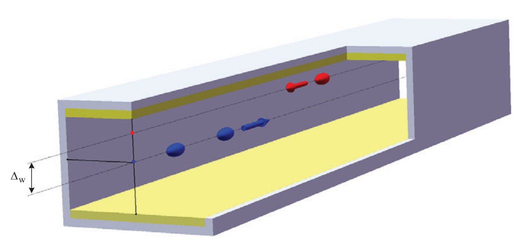

Figure 1: Conceptual design of a beam-driven short period FEL undulator.

It is also important that this type of undulator is not limited to some specific frequency, and short period undulators can be realized with Ka-band, W-band and potentially THz range power extractors [5,6] installed at various facilities equipped with high current short bunch electron linacs. Recently a collinear dielectric wakefield accelerator was proposed as the source of a high repetition rate, high current drive beam for a future FEL X-ray light source [11]. This technique provides >100 kHz drive beam for the FEL. Therefore a beam driven wakefield structure can be used as a unique, extremely short period undulator for high repetition rate X-ray sources [11].

In this paper, we consider the use of a dielectric loaded accelerating structure, exploiting the well-developed technology of the dielectric wakefield accelerator (DWA)

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for high power RF generation. Two types of dielectric loaded waveguide geometries are being considered: rectangular and cylindrical. Each structure has separate vacuum regions for the drive and undulating beams. The high current low energy drive beam traverses the structure generating a high amplitude transverse monochromatic wakefield on the axis of the undulating bunch, which passes through the structure in the opposite direction.

BEAM DRIVEN UNDULATOR CONCEPTS

The new design of the mm-wave/THz undulator, which we will refer to as the "beam driven undulator", is based on an electron beam powering a microwave or mm-wave waveguide. This type of undulator could be also called a "wakefield undulator", analogous to a wakefield accelerating structure powering a two-beam CLIC-like or collinear wakefield accelerator [7,8]. The beam driven undulator has to be supplied with a 60-80 MeV, 20-60 nC, relatively short (1-2 mm) bunch train from a linac, like the 75 MeV linac that has recently been commissioned at ANL (Argonne Wakefield Accelerator facility) [12].

A beam driven undulator possesses all the advantages of wakefield accelerators: no complicated high power RF coupling required; a microwave or mm-wave wakefield structures can sustain much higher fields because of the relatively short RF pulse generated by the drive beam [5,6]. This allows the use of corrugated all-metal [3,7] structures or dielectric based waveguides [5,6] exploiting the technology of the dielectric wakefield accelerator for high power high frequency RF generation. It should be noted that a dielectric loaded structure is a 2D waveguide and it does not exhibit any parameter variation along the structure length compared to an all-metal disk loaded or corrugated waveguide that requires precise machining tolerances resulting in high costs of the all-metal device.

The drive beam that generates the high power RF propagates towards the undulating beam inside a dielectric loaded waveguide. A simplified design with the drive and undulating beams propagating towards each other inside a rectangular dielectric structure is shown in Fig. 1. The ultra-relativistic driving beam (blue) generates a transverse deflecting wakefield, which propagates towards the undulating beam (red) with the speed of light. The undulating beam sees double the wakefield frequency $\omega_u=2\omega_y$, where ω_y is the transverse wakefield frequency in the laboratory frame. As a result of the Lorenz transformation the wavelength of the transverse deflecting field is half that of the transverse undulating field wavelength in laboratory coordinates. By applying a double Lorentz transfor-mation, first to the frame comoving with the transverse wakefield and then back to the lab coordinates to the equation of motion of an undulating beam, one can obtain the undulator effective parameters: wavelength λ_u, effective undulator magnetic field B_u and undulator parameter K.

The wakefield generated by the drive bunch in the beam driven undulator section has to be monochromatic with a relatively short wavelength, provide a sufficiently strong transverse magnitude along the undulating bunch trajectory, and the undulator parameter K has to be close to unity, K~1. This requires a special waveguide design using field concentrator elements like additional dielectric components with high dielectric constants [8]. Some of the designs considered in this project are presented in Fig. 2 and Fig. 3, where each structure has separate vacuum regions for the drive and undulating beams. The high current low energy drive beam traverses the structure generating a high amplitude transverse monochromatic wakefield on the axis of the undulating bunch, which passes through the structure in the opposite direction.

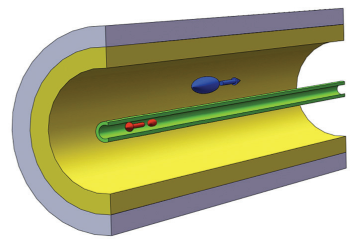

Figure 2: A beam driven undulator with a field concentrator. A cylindrical coaxial design with the undulating beam passing through the structure along the central axis.

Cylindrical Structure

Figure 2 shows a coaxial field concentrator design with an additional dielectric tube along the central symmetry axis (the undulating beam path); the transverse undulating field is generated by the drive beam passing along a parallel axis in a separate vacuum gap between the dielectric tubes. For the cylindrical case we use the HEM (hybrid electromagnetic) mode generated by a drive beam with the AWA accelerator parameters, bunch length 0.15 cm, total bunch train charge 100 nC (we plan to use a train of 4×75 MeV bunches of 25 nC each according to the new AWA linac parameters) [12]. The structure has a 6 mm aperture with a 1.7 mm beam offset for the driver pass.

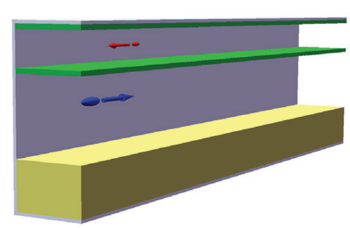

Figure 3: A rectangular waveguide beam driven undulator with a field concentrator. The high dielectric constant plate (green) separates the drive and undulator sections of the structure.

We use a field concentrator based on a dielectric waveguide for the undulator beam. The proposed design provides effective parameters λu=5.6 mm, Bu=21.3 kG corresponding to undulator parameter K=1.1 for a two

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bunch drive beam train. Structure parameters are presented in Table 1.

Table 1: Structure Parameters for AWA Experiment

Parameter	Cylindrical structure	Rectangular structure
Witness channel, a	1 mm,	0.5 mm× 3 mm
Concentrator thickness, b-a	Tube thickness 0.25 mm	Plate thickness 0.150 mm
Concentrator permittivity, ε_1	35.7	35.7
Driver channel, c	6 mm	3 mm×3 mm
Driver gap, c-b	2.25 mm	3 mm
external layer permittivity, ε_2	5.7	5.7
external layer thickness, d-c	1.5 mm	1.5 mm
Driver offset	1.7 mm	0.7 mm

The undulating beam passes along the centre axis of the structure where the HEM_{11} hybrid is the dominant mode. Calculations of the undulator parameters for this structure geometry and beam charge and bunch length leads to the effective undulator parameters for two drive trains, Tab.2.

Rectangular Structure.

For the rectangular structure case we use the first undulating mode generated by a drive bunch train. We consider the same drive parameters as for the cylindrical waveguide above (AWA beam parameters) σ_z =0.15 cm drive length, bunch train charge Q=100 nC, drive bunch train passing the structure at a 2.5 mm offset from the drive's channel center. Structure parameters are: presented in Table 1.

The undulating beam traverses the structure along the central axis. The drive bunch train position is offset by 700 μm from the drive gap center line. Using a 12.81 cm separation distance between the first and the second drive trains the transverse force at the undulating beam position after the second driver will be fully monochromatic and amplified. In this case the K-parameter will be increased by a factor of two, and the effective undulator parameters presented in Table2:

Table 2: Undulator Parameters

Structure	λ_u	B_u	K
cylindrical	0.56 cm	21.3 kG	1.10
rectangular	0.43 cm	26.25 kG	1.06

Note that the concept also allows a significant reduction in the undulator wavelength. Consider total bunch train charge Q=100 nC passes through the structure with a 1.6 mm offset. The structure parameters according to Table 1 are: a=350 μm, b=375 μm c= 2.1mm, d= 2.85 mm, dielectric permittivity of the inner tube ε_1 =35.7 and of the outer layer ε_2 =5.7. Undulator parameters for this configuration are, Table 3.

Table 3: Short Wavelength Undulator Parameters

λ_u=0.29 cm	B_u= 47.6 kG	K=1.28

In this paper, we have discussed only the conceptual design of the beam-driven undulator. The next step will be to model the energy loss and corresponding increase in energy spread of the drive beam as it propagates. Note that as long as the driver train is still relativistic its energy loss will not affect the transverse component of the wakefield radiation. The uniformity of the undulating field along the wake has to be studied as well. The undulator length limitations caused by drive beam break-up (BBU) effects are expected to be in the 1-10 m range. The total undulating field pulse length has to correspond to the required number of undulating cycles (of order 10^3.) The parameters of the proposed beam-driven undulator concept are being studied in our ongoing research.

SUMMARY

We propose a new kind of undulator that makes use of a second electron beam to deflect the primary beam. The two beams propagate in opposite direction through a dielectric or corrugated wakefield structure. The primary advantage of the wakefield undulator is its capability of developing short effective deflection wavelengths. A light source based on this concept would be able to produce radiation for which the output wavelength and polarization are continuously variable by controlling the characteristics of the drive beam. We plan to test this approach experimentally at the ANL/AWA.

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