HELICAL 1T×1CM PULSED INSERTION DEVICES FOR PRODUCTION OF INTENSE POLARIZED X- & GAMMA-RAYS

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Abstract

Two types of high-field, pulse undulators are revisited as non-coherent or partially coherent sources capable of undulator factor approaching unity at substantial gap-to-period ratios exceeding 0.4 not achievable with conventional technology. One type is a microwave guide, smooth-wall undulator powered by wake-fields extracted with CLIC-type scheme adapted for the two-beam undulator (TBU). Another novel ID is represented here by a bifilar transmission line energized by a high voltage, ~ns-pulse, solid-state generator. These two devices fit well future linear colliders based on high-gradient microwave linac technology and radiation facilities respectively.

INTRODUCTION

Development of electron–positron colliders requires a source of intense polarized positron beams. Polarized positrons can be produced from polarized γ-rays irradiating a thin target (a fraction of radiation length [1]). One way is using of SC helical undulator having at least hundred meters length, limited period (<1.2cm), sufficient gap (>4–5mm), and field magnitude (>0.7T). Existing helical undulator technology is not failure-free and viable enough as requires close to critical currents (for SC undulators), has too small gaps (~1mm) implying bypassing, very limited section length because of low vacuum conductivity, gas bremstrahlung and radiation-induced desorption. Normal-conducting, pulse-current option is limited by heat deposition and pulsed power supply. Unique Cornell design [2] employs sophisticated ferrofluid cooling system and operates at <30Hz rep rate (12μs pulse length), whereas a normal-conducting linear collider operates at higher rep rates (about 100Hz).

Another possibility is photon backscattering on energetic electrons. The polarization of backscattered gammas is determined entirely by the polarization of incident electromagnetic radiation and changes a little with scattering angle or gamma-photon energy. A terawatt laser produces a deflecting force equivalent to several tens of Tesla of undulating field. However, the interaction length is limited by diffraction to about a centimeter [3]. Substantial problems [4] are related to multistaging, jitter, sustainability of optical elements, synchronized timing, dramatic reduction of the polarized gamma-photons yield for off-axis electrons.

Somewhat similar problems are related to development of IDs for intense polarized synchrotron radiation sources, applied, e.g., for circular dichroism studies.

In this paper, two novel concepts of a helical undulator are proposed: a microwave undulator powered by a microsecond- range wakefield extractor (two-team undulator, TBU), and a pulse-line undulator (PLU) powered by a ns-pulse, high-voltage source.

MICROWAVE UNDULATOR AS A PULSED, POLARIZED RADIATION SOURCE

A microwave undulator is especially suitable for long radiators of spontaneous X- and γ-ray emission. Such a waveguide-based ID does not need tapering (unlike FEL), can have shorter period and much better active/physical length ratio due to shorter interruptions (if any) compared to any conventional magnetic undulator. One can also provide a larger gap that exceeds considerably the equivalent undulator period (or operating wavelength in an oversized, open mm-wave guide [5]). It may have side openings (using open type structure) or evanescent slots/holes for better pumping and insertion of wakefield BPMs. The microwave undulator is perfectly compatible with superimposed focusing/correcting elements (quadrupoles and sextupoles). For a normal-conducting linear collider active cooling of the waveguide undulator is not a challenging problem due to larger aperture and lower power deposition than pulsed electromagnetic undulator (for the same pulse rate). Fore example, the ferrofluid-cooled, 1mm aperture, 1m length undulator consumes about a half kW power at 30Hz pulse rate [2], which is comparable to that for the two-wave undulator considered here at higher rep rates and much larger $5.6\times5.6\text{mm}^2$ cross-section at about the same peak field. Bypassing can be eliminated due to enlarged aperture and enhanced vacuum conductivity, super-imposed focusing, reduced period, and absence of undulator fields in the idle mode. That also means that the undulator physical length can be reduced from ~790m [1] down to ~150m making the physical and active undulator lengths equal.

And finally a waveguide undulator to be more robust and easier in manufacturing as the smooth-wall square or elliptical pipe tolerances are determined only by minimal reflection and insertion losses (about 1 mill tolerance at 30GHz) and the bremstrahlung radiation is less dangerous for the waveguide unlike magnetic undulators subjected to quench and/or degradation of the insulation undergoing to enormously high mechanical stress at strong X-ray and gamma-radiation background (~100MRad dose) and extremely low (for SC ID) or elevated temperatures (NC ID). On the other hand, the waveguide bremstrahlung may seed high–order multipactor to be taken into account in the design (including external magnetic fields).

ISBN 978-3-95450-125-0

The microwave source framework is represented by decelerator sections extracting high power (~462MW at 30GHz, ~130ns in CLIC [6]) from the driving beam with inherently proper timing. The microwave power in a traveling wave undulator can be subsequently reused in corresponding high-power network to enhance overall efficiency. The accelerating module is replaced by counter-propagating traveling wave undulator module. One can distinguish in Figure 1 the following variants: (a) direct scheme with two decelerators feeding one undulator section (one decelerator per polarization—-horizontal or vertical); (b) one decelerator per one undulator section; and (c) continuous waveguide with partial power recuperation.

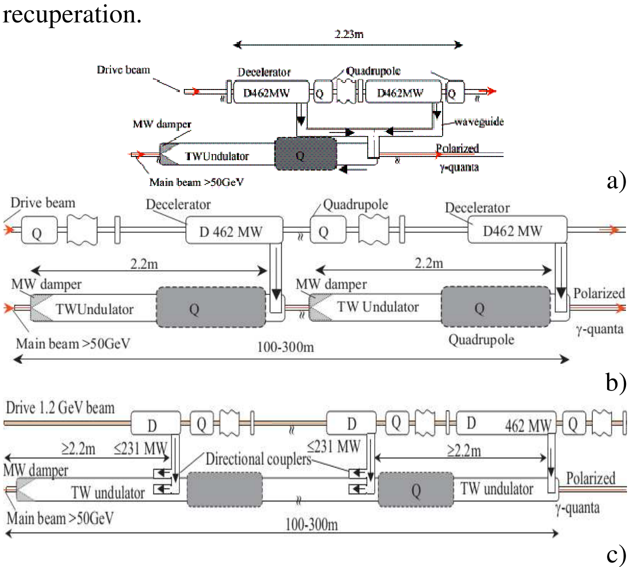

Figure 1: TBU schematic layouts: (a) one module (period) of two-beam undulator (TBU); (b) two modules of sectioned TBU and reduced field and power budget; (c) TBU with a continuous long waveguide and partial RF power recuperation.

Such a partial recuperation of the power losses is possible if the microwave pulse length exceeds at least twice the sum of filling time and beam time-of-flight of a single unit (2.2m in our example). These two amounts of power can be made equal and properly phased. It gives reduction of power required by about of factor of two and keeping about the same rms deflection force or increasing the deflecting force by ~√2 for the same power budget.

For quadratic guide operating $TE_{01}+TE_{10}$ modes at 30GHz we estimate the optimal dimension as 5.6mm at λ_w=6.9mm.

For the CLIC PETS scheme a 2×462MW maximum power corresponds to 2.23m length (see Figure 1a.) and equivalent helical undulator field Bw=1.1T.

At least few MeV energy radiated by the polarized photons per electron per meter is required for a linear collider. For the Figure 1a scheme we obtain ~2.8 MeV/m at relatively moderate 50GeV beam energy and ~1.1dB/m attenuation (with copper waveguide) resulting to 5kW power deposition per undulator section. Another option (see Figure 1b) gives still substantial equivalent field Bw=0.76T or 1.4 MeV/m photon energy per meter. Minimum pulse length required is $L(1/\beta+1/\beta gr)/c$=24ns which is much less than the CLIC drive beam pulse length ~130ns making feasible the coherent recuperation of microwave energy (see Figure 1c). Thus the power consumption per unit length of TBU can be at least as twice as smaller than that in CLIC TBA [6].

Circular polarization is usually considered as two cross-polarized, 90°-shifted waves coupled to the undulator pipe. The waveguide can be square rectangular or circular. Circular waveguide pipe perfectly fits the cases of Figure 1a,b and offers maximum simplicity at higher series impedance and lower losses. Besides, a simplified coupler without splitter can be used (tapper with bend) along with a $TE_{10}^{\square}$-$TE_{11}^{\circlearrowleft}$ transducer to circularly polarized wave (see Figure 2). The transducer can be placed on the decelerator output allowing transporting the circular polarized wave to the undulator via a circular pipe.

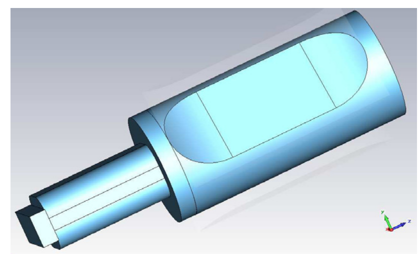

Figure 2: Transducer design that provides circular polarization in a circular waveguide. .

PULSE-LINE UNDULATOR

A microwave source capable to provide hundreds of megawatts of microwave peak power to energize the high-field, traveling wave undulator is a part of normal conducting TBA linear collider but not available on synchrotron radiation facilities. A high-voltage short pulse can be used to energize bifilar transmission line structure. A table-top solid-state pulser from FID technology produces up to 250–500kV voltage and up to 100 J energy for close to Gaussian nanosecond pulses at 50–100Ω load and rep rates up to tens kHz [7]. Both generator and terminator to be broad-band matched with the transmission line impedance. In the conceptual design we assumed 1cm period, 4mm aperture diameter, ~3.8 dielectric constant for the insulator, and 0.2×2mm^2 cross-section of the helical conductor (see Figure 3).

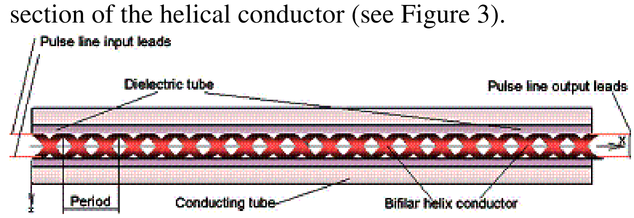

Figure 3: Schematic view of PLU based on a bifilar helical conductor made as an internal coating of an insulating tube enclosed by a conducting cylinder. The period is 1cm, length 10cm, and aperture ID is 4mm.

ISBN 978-3-95450-125-0

In the quasi-static system the characteristic wavelength related to ns-pulse duration would be much longer than the transverse dimension of the structure and hence the pulse can co-propagate with the electron beam, which would undergo periodic impact with spatial period close to the structure period.

A HV nanosecond range, Gaussian, 0.62ns rms length pulse is considered here. The transverse electric and magnetic fields along the undulator axis simulated at different longitudinal positions are given in Figure 4.

A ‘‘snapshot’’ of the periodic pattern of transverse fields on the axis is given in Figure 5 at t=3.65ns.

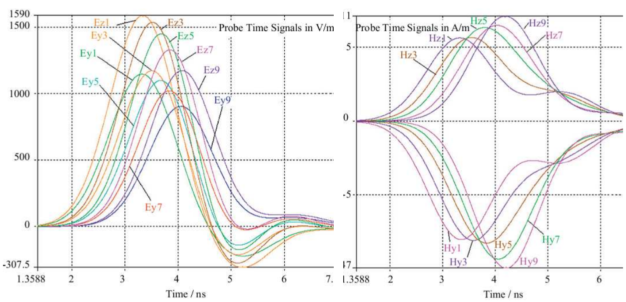

Figure 4: Transverse on-axis components of electric (on the left) and magnetic (on the right) fields at 0.8V excitation. The temporal profiles are given for the 1st through the 9th odd numbers of periods along the undulator length.

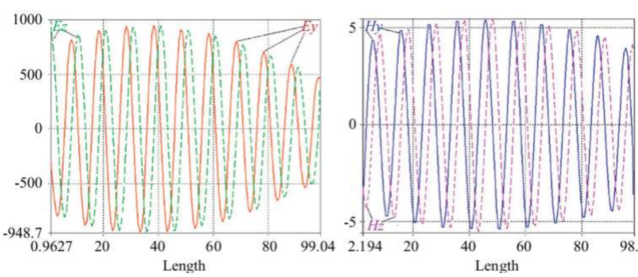

Figure 5: Horizontal and vertical transverse components for electric (V/m, on the left) and magnetic (A/m, on the right) fields along the axis (mm) at t=3.65ns and 0.8V magnitude excitation (see figure) applied to the input leads of the PLU (see figure)

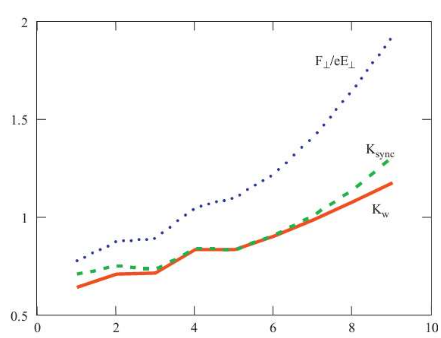

Figure 6: Longitudinal profiles for undulator factor Kw seen by relativistic beam (solid line), undulator factor Ksync seen by a synchronous β=0.32 beam (dashed), and deflecting force related to electric field (dotted) at 100kV voltage magnitude applied to the PLU input.

The undulator factor based on such a direct calculation (i.e. using peak fields only) would correspond to a synchronous motion of the particle and the pulse. In our example the pulse propagation velocity along the PLU is β=0.32. Relativistic bunch will undergo some slippage that decreases the effective force. Let us assume that the beam is synchronized with the pulse in such a way that there is no slippage in the undulator center. Resulting plots for the actual force related to the electric field and undulator factor with and without slippage are given in Figure 6 for 100kV applied peak voltage of the Gaussian incident pulse. One can see that a substantial undulator factor is produced by applying relatively moderate voltage 100kV and pulse energy (less than a few joules).

Similar to pulse DC [8] and DC-RF injectors [9,10] the key enabling feature of the PLU is that the breakdown threshold is much higher for shorter pulses and may considerably exceed a GV/m level for ns pulses.

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ISBN 978-3-95450-125-0