TRANSVERSE DYNAMICS OF A RING BEAM IN A COAXIAL TWO-CHANNEL DIELECTRIC WAVEGUIDE

A. Altmark, Electrotechnical University, Saint-Petersburg, Russia
A. Kanareykin, Electrotechnical University, Saint-Petersburg, Russia and EuclidTechlabs LLC, Gaithersburg, MD,USA

Abstract

The most critical issue of wakefield accelerating schemes is transformer ratio (maximum energy gain of the witness bunch/maximum energy loss of the drive bunch) which cannot exceed 2 in collinear wakefield accelerator with use of Gaussian bunches. We observe new scheme of wakefield acceleration in collinear two-channel waveguide, where accelerating field created by electron bunch with annular charge distribution passing in vacuum layer. This radiation is used for acceleration of witness beam which passing through central vacuum channel. These vacuum areas separated by dielectric tube. Transformer ratio for this scheme can be much greater than 2.

The main problem of wakefield accelerators is transverse beam dynamics of the driver bunch, because of high value of its charge and low energy of the particles. We present results of the beam dynamics calculation of the annular drive beam by “macroparticle” method based on analytical expressions for Cerenkov radiation. The upgraded BBU-3000 code has been used for calculation of the beam dynamics in coaxial dielectric wakefield accelerating structures. It is shown that dynamics depends on radial and azimuthally structures of HEM modes excited by the drive beam there. Initial beam imperfections to the beam dynamics was carried out.

INTRODUCTION

A new application of microwave and THz Cherenkov radiation has been proposed and studied in the last decade to be used for high energy physics colliders and X-ray FELs, the Dielectric Wakefield Accelerator, or DWA [1-3].

In a general sense, a high gradient is desirable for a TeV level linear collider design because it can reduce the total linac length and hence the cost. Recently a high energy linear collider based on a short rf pulse (~22 ns flat top), high gradient (~267 MV/m loaded gradient), high frequency (26 GHz) dielectric two beam accelerator scheme has been proposed. The major parameters of a conceptual 3-TeV linear collider based on a DWA have been developed and are presented in reference [4].

X-ray free-electron lasers (FELs) are expensive instruments and the accelerator contributes the largest portion of the cost of the entire facility. Using a high-energy gain dielectric wakefield accelerator instead of a conventional accelerator may facilitate reduction of the facility size and significant cost savings. It has been shown that a collinear dielectric wake-field accelerator can accelerate low charge and high peak current electron bunches to a few GeV energy with up to 100 kHz bunch repetition rate [5].

Dielectric loaded accelerator (DLA) structures using various dielectric materials [6] and excited by a high current electron beam or an external high frequency high power RF source have been under extensive study recently [1-3]. The basic wakefield RF structure is very simple - a cylindrical, dielectric loaded waveguide with an axial vacuum channel is inserted into a conductive sleeve. Following at a delay adjusted to catch the accelerating phase of the wakefield is a second electron (witness) beam. The witness beam is accelerated to high energy by the wakefield produced by the drive beam [1].

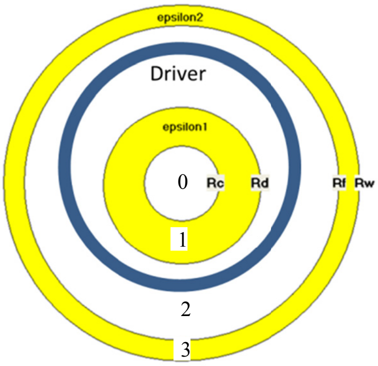

Figure1. Wakefield acceleration by ring driver beam in coaxial cylindrical waveguide

A series of proof of principle experiments have been successfully performed at Argonne’s Advanced Accelerator providing accelerating gradient in the range exceeding 100 MV/m at X-band [1-3,6]. THz wakefields of ~ GV/m magnitude range have been successfully generated by the UCLA-SLAC collaboration as well [7].

Energy transfer efficiency from the drive to witness bunches is a critical issue for wakefield acceleration techniques. The transformer ratio R is defined as the ratio of the maximum energy gain of the witness bunch to the maximum energy loss of the drive bunch. There are two major classes of wakefield accelerator geometries, collinear and two beam. For a collinear wakefield accelerator, R is less than 2 under very general conditions: linear media; a relativistic, longitudinally symmetric drive bunch; and identical paths through the system of both drive and witness beams [8-9]. A number of techniques have been proposed to overcome the transformer ratio limitation. Some of the methods that can be employed to obtain R>2 for the dielectric based accelerator include: a triangular longitudinal drive bunch profile [8]; a train of Gaussian drive bunches of progressively increasing

ISBN 978-3-95450-125-0

charge (ramped bunch train) [10-11]; and use of a proton drive beam so that the particles can change positions within the bunch during deceleration [12].

Another way to achieve high transformer ratio is by designing separate drive and witness beam lines with different shunt impedances. This technique has been considered in [13] for all-metal structures and initially proposed for dielectric based high gradient accelerator in [14], where a multichannel structure with an annular drive beam propagating through a coaxial outer vacuum channel and a witness beam through a central channel has been considered.

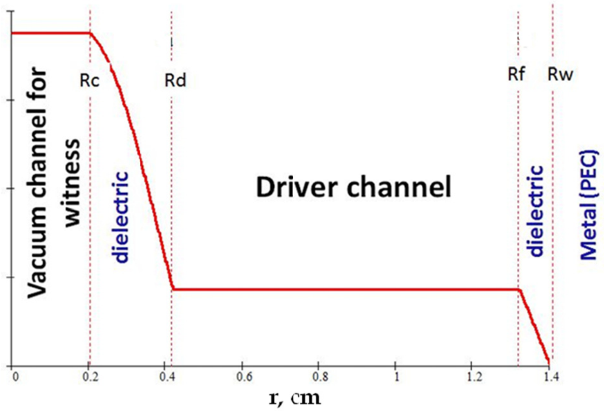

Figure 2. Accelerating TM01-mode field of the structure presented in Fig.1.Transformer ratio =4.5.

Recently the coaxial scheme [14] was considered again for high-gradient wakefield acceleration, and detailed analytical studies for this type of coaxial dielectric-loaded structure have been presented [15-17]. Transformer ratio values as large as R=4.5 were predicted, Fig. 2.

In [16], the coaxial scheme initially proposed in [14] has been considered for the THz frequency range and for the SLAC FACET drive bunch parameters. The structure geometry correspond to THz frequency range wakefields (~ 0.1 mm witness beam aperture) and can be found in reference [16].

ANALYTIC RESULTS AND COMPARISON WITH NUMERICAL SIMULATIONS

The coaxial geometry proposed in [14] for transformer ratio enhancement of the dielectric based wakefield structures is considered here for GHz Ka-band [15] and THz acceleration [16-17]. At the same time, dynamics of the beam in structure-based wakefield accelerators leads to beam stability issues not ordinarily found in other machines. In particular, the high current drive beam in an efficient wakefield accelerator loses a large fraction of its energy in the decelerator structure, resulting in physical emittance growth, increased energy spread, and the possibility of head-tail instability for an off axis beam, all of which can lead to severe reduction of beam intensity [18]. Beam breakup (BBU) effects resulting from parasitic wakefields provide a potentially serious limitation to the performance of dielectric structure based wakefield accelerators as well [18-19].

Correspondingly, the transverse stability of the annular driver beam can be a critical issue for a coaxial high transformer ratio DWA [17]. We report on beam breakup study results for the coaxial Ka-band DWA currently planned to be tested at Argonne Wakefield Accelerator (AWA). Recently we have developed a particle-Green's function beam breakup code (BBU-3000) that allows rapid, efficient simulation of beam breakup effects in advanced linear accelerators [19]. The goal of this work is foremost to design mitigation techniques for BBU and to test these concepts as part of an ongoing series of experiments at ANL/AWA, BNL/ATF and SLAC/FACET.

The coaxial, two-channel DLA structure of figure 1 has an inner vacuum region "0" (r < a) for the witness beam and an outer vacuum region "2" (b < r < c) for the drive beam. The drive beam used to excite the DLA is azimuthally asymmetric; this is necessary to excite dipole modes which cause beam instabilities. In this paper, we will concentrate on the dipole wakefield excitation due to a non-uniform ring of electrons.

BEAM DYNAMICS SIMULATIONS

BBU-3000 represents an approach to beam dynamics computations which is complementary to the usual electromagnetic PIC (Particle in Cell) approach.

Table 1. Parameters of the coaxial waveguides used in the transverse beam dynamic analysis.

#	Rc, cm	Rd, cm	Rf, cm	Rw, cm	ε_1	ε_2	f, GHz (TM_{02})
1	0.2	0.60	1.00	1.40	4.76	4.76	13.84
2	1e-5	0.06	1	1.4	24	4.76	23.89

Table 2. Parameters of the annular drive beams used in the transverse beam dynamic analysis

#	Q, nC	σ_z, cm	σ_r, cm	offset, cm	R, cm	W, MeV
1	10	0.2	0.01	0.02	0.8	10
2	10	0.2	0.01	0	0.8	10
3	50	0.1	0	0.8	-	14
4	10	0.1	0.01	0.41	-	15

Particle pushing is done in the same fashion as a PIC code but the wakefields caused by the charged particles are computed using the known analytic expressions for the Green's functions in a dielectric tube [18]. Details of the scalar code for the Gaussian shaped beam have been published elsewhere [19]. Here we focus on the recent work on the annular electron beam simulation.

It should be noted that for the annular beam the offset value is limited in comparison with ordinary Gaussian beam because of intrinsic large diameter (relatively to a witness beam aperture) of a vacuum channel of the coaxial DWA structure. Consequently, the beam dynamics of the annular drive beam will be dominated by dipole mode fields, or HEM modes with ν=1 with the field structure presented in figure 3. In this paper, the beam breakup of the annular driving bunches has been studied with respect to its both azimuthal and radial asymmetries.

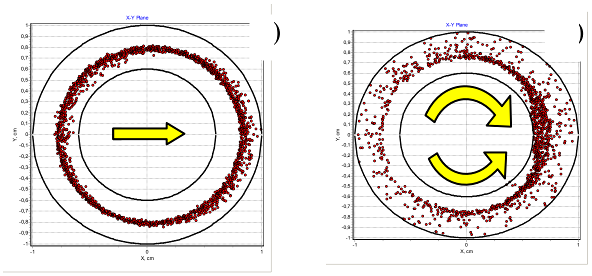

Figure 3. Beam dynamic simulations of an annular beam passing through coaxial dielectric wakefield structure presented in figure 1, region 2: (a) azimuthally symmetric beam with offset (table 1, structure #1; table 2, beam # 1); (b) azimuthally symmetric beam with no offset (table1,structure # 1; table 2, beam # 2).

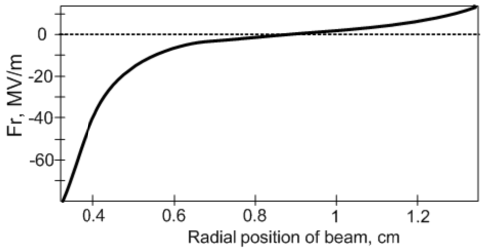

Figure 4. Transverse deflecting field vs. radial position of the Gaussian beam in region 2 for the structure # 1 of table 1, for the beam # 3 of table 2.

Fig. 3 shows the results of BBU300 simulation for the azimuthally symmetric annular beam with offset and the beam with no offset but with azimuthal charge asymmetry. One can see radial deflection for the azimuthally symmetric beam caused by center of mass shift (offset of the beam) while the azimuthal deflection is still compensated by the charge density symmetry. At the same time, the azimuthal asymmetry generates F_θ components strong enough to increase dramatically the charge density along the line of structure center – maximum of charge density distortion, Fig.3. Fig. 4 presents the transverse deflecting field vs. radial position of the beam particle: one can see the flat region where there is no force increase. Fig. 5 presents simulation results for the gaussian beam passing through coaxial structure of Fig. 1. Note strong deflection to both inner and outer dielectric surfaces.

SUMMARY

The software effort is based on development of the BBU-3000 code upgrade. A number of new features have been incorporated including a coaxial cylindrical dielectric based structure capabilities. The results of the simulations show that the contribution to the transverse deflecting field in coaxial waveguide for annular beam is made by both azimuthally and radial forces. The sign of radial force is changed when along radial coordinate in the drive beam channel.

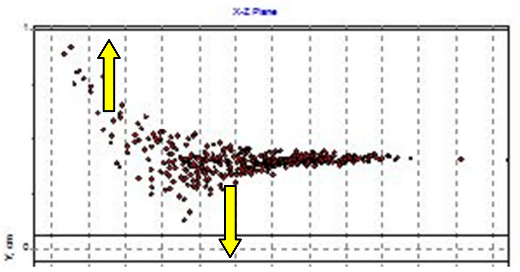

Figure 5. Beam dynamic simulations of an gaussian beam passing through coaxial structure presented in Fig.1, structure # 2 of table1, beam # 4 of table 2.

REFERENCES

[1] W.Gai, et al. Phys. Rev. Lett. **61**, 2756 (1988)
[2] W.Gai, AIP Conference Proceedings **1086**, 3 (2009)
[3] A. Kanareykin Journal of Physics, Conf. Ser., **236**, 012032 (2010)
[4] C.Jing, A.Kanareykin, J.G.Power, A.Zholents Proc. IPAC'11, 1485 (2011)
[5] C.Jing, S.Antipov, A.Kanareykin et al. Proc. PAC'11, New York, NY, 2279 (2011)
[6] A. Kanareykin, AIP Conf. Proc., **1299**, 286 (2010)
[7] M. Thompson et al., AIP Conf. Proc. **877**, 903 (2006)
[8] K. L.Bane, P.Chen, and P. B. Wilson, SLAC Report No. SLAC-PUB-**3662**(1985)
[9] J. G.Power, W.Gai, and P. Schoessow, Phys. Rev. E **60**, 6061 (1999)
[10] E.Laziev, V.Tsakanov, and S.Vahanyan Proceedings EPAC'88. IEEE, 523 (1988)
[11] C.Jing, A.Kanareykin, J. G.Power, M.Conde et al., Phys. Rev. Lett. **98**, 144801 (2007)
[12] J. B.Rosenzweig, P.Schoessow, B.Cole, W.Gai et al. Phys. Rev. A **39**, 1586 (1989)
[13] Voss G.A. and Weiland T. 1982 DESY M-82-10
[14] R.Keinigs, M.Jones,Proc. 7th Int. Conf. High-Power Part. Beams, Beams'88, Karlsruhe, Germany, **864**, (1988)
[15] W. Liu and W.Gai, Phys. Rev. ST Accel. Beams **12**, 051301 (2009)
[16] G. V.Sotnikov, T. C.Marshall, and J. L. Hirshfield Phys. Rev. ST-AB **12**, 061302 (2009)
[17] G.V. Sotnikov and T.C. Marshall. Phys.Rev.ST-Accel.Beams**14**,031302 (2011)
[18] W.Gai, A.Kanareykin, A.Kustov and J. Simpson Phys. Rev. E **55**, 3481 (1997)
[19] P.Schoessow et al., Proc. AAC'10, AIP Conference Proceedings, N.Y, **1299**, 262 (2010).