Dielectric-Lined Wakefield Radio Frequency (DWARF) Undulator with Plasma-Filled Drive Channel

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The RF undulator concept we propose for a light source/FEL overcomes common issues with conventional RF undulators where it is difficult to devise a configuration that can compete with short-period (~1 cm) permanent magnet (PM) undulators, because of problems of generating sufficient microwave power at short wavelengths, and because of limitations due to structure heating and RF breakdown. An undulator period equivalent to that of a PM undulator with period typically 3.3mm or less can be achieved by DWARF, with K = 0.65.

The DWARF we present has at least two important new advantages, namely:

(a) the structure is filled and emptied with radiation at the **group velocity that is close to velocity of light**, minimizing heating and breakdown issues; and

(b) a plasma-filled drive channel provides stability for the drive bunch train.

(c) Also: the Plasma-Filled DWA, when configured in a symmetric single-channel cylindrical unit, could provide a stable high energy bunch train to a FEL.

DWARF undulator presentation can be presented as a series of questions and answers:

What is already known about RF undulators?

-- Short review of conventional work to set the stage; including paper by Kuzikov et. al.

Is the DWARF possible?

--Yes, a counter-streaming bunch that emits FEL radiation can undergo transverse deflections from a certain DWA wakefields that are set up by a forward moving, lower-energy drive bunch .

However, transverse force is needed to wiggle the counter-streaming bunch:

-- Symmetric wakefield mode (customary in single channel) is of no use.

-- Use two-channel rectangular DWA device to develop asymmetric mode.

Also, ***Need*** a single mode with ~ uniform transverse fields, e.g. LSM11.

-- Use a DB train of several bunches, appropriately spaced, that generates the desired single wakefield mode.

-- Wiggling motion can be driven by a LSM11 mode

Item [4] implies need for stable DB train

-- Use plasma stabilization in DB channel

-- PDWA will be described in part two of this talk

Some of our earlier work which is a precursor to this project:

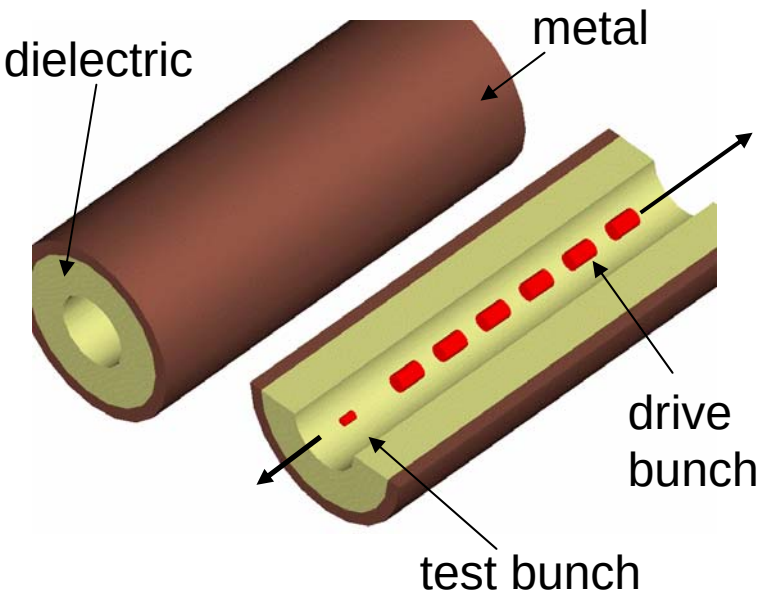
[1] **S.V. Shchelkunov, T.C. Marshall, G. Sotnikov, J.L. Hirshfield, Wei Gai, M. Conde, J. Power, D. Mihalcea, and Yusof, Phys. Rev. ST Accel. Beams 15, 031301 (2012).**

[2] **S.V. Kuzikov, Y. Jiang, et al., "Configurations for Short-Period RF Wigglers", Phys. Rev. ST Accel. Beams 16, 070701 July (2013)**

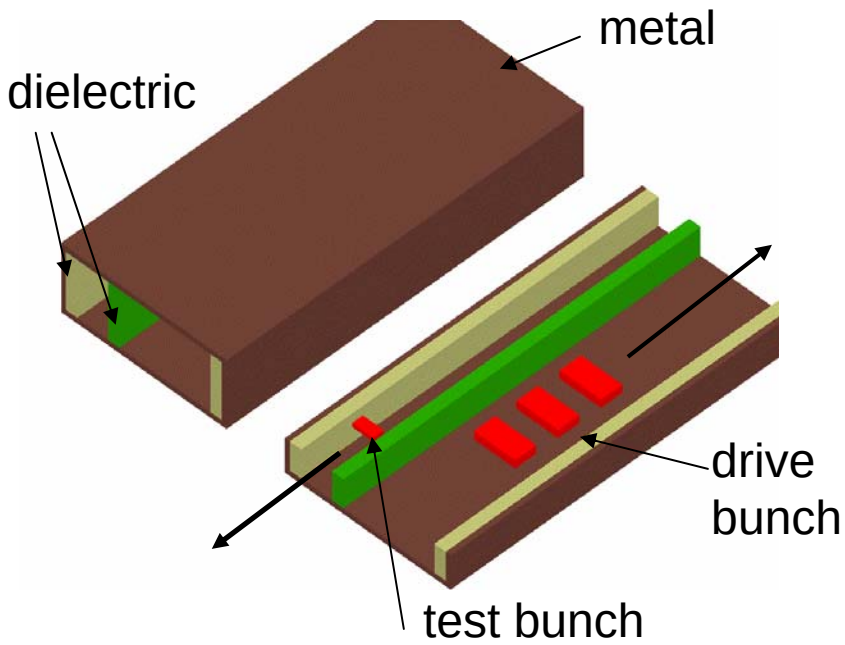
[3] **G.V. Sotnikov et al., "Analytical and Numerical Studies of Underdense and Overdense Regimes in Plasma Dielectric Wakefield Accelerators", Proc. Of EAAC2013, La Biodala, Isola d'Elba Italy, (June 2013) [to be publ., J. Nucl. Instrum. & Methods, Nov. 2013].** http://dx.doi.org/10.1016/j.nima.2013.10.087

Some of work by others (which recently has came to our attention):

[4] **poster WEPAC16 at NA-PAC13 by Kanareykin A., Baturin S., Jing C.-J., and Zholents A.**



Symmetric ***w***akefield ***m***ode (customary in single channel) is of ***n***o ***u***se for DWARF

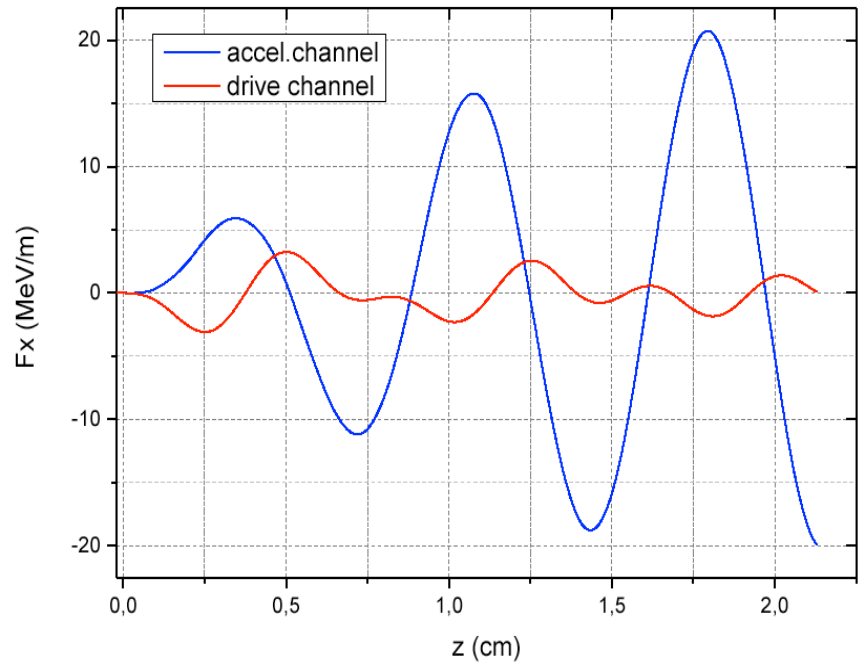


counter-streaming test bunch can undergo periodic transverse deflections from a DWA wakefield set up by a drive bunch train

short period, intense, no heating/breakdown

Accl. channel dimensions $2a_1$	2.00 mm
drive channel dimensions $2a_2$	10 mm
structure height $2d$	8 mm
transformer ratio	5.73
slab-1 thickness	0.343 mm
slab-2 thickness	0.513 mm
slab-3 thickness	0.1812 mm
slab relative dielectric constant	4.0
bunch size	$1.8 \times 1.8 \times 1.5\ mm^3$
bunch energy	14 MeV
bunch charge	50 nC
bunch charge density	$10.3\ nC/mm^3$
bunch number	1
bunch center location, x	7.856 mm

A single drive bunch traversing this rectangular two-channel unit will excite a number of LSM and LSE modes of this structure: half of these modes are symmetric, and half non-symmetric. The drive bunch will mostly excite two non-symmetric modes, the LSM11 and LSE11, as well as the symmetric LSM31 mode. It is the non-symmetric modes that cause the transverse deflecting force on a witness bunch in the accelerating channel.



Total transverse wake force Fx (the sum of all LSE and LSE modes) *vs* axial distance *z* in the drive and acceleration channel centers of the structure specified by Table (at left), excited by ***one*** 50-nC drive bunch located here at z = 0 cm

a) The wakefields set up by a single drive bunch are not monochromatic; interfering modes are excited by the drive bunch, as well as transient effects that originate from the entry of the drive bunch into a structure of finite length

b) Nevertheless, an RF undulator should be monochromatic.

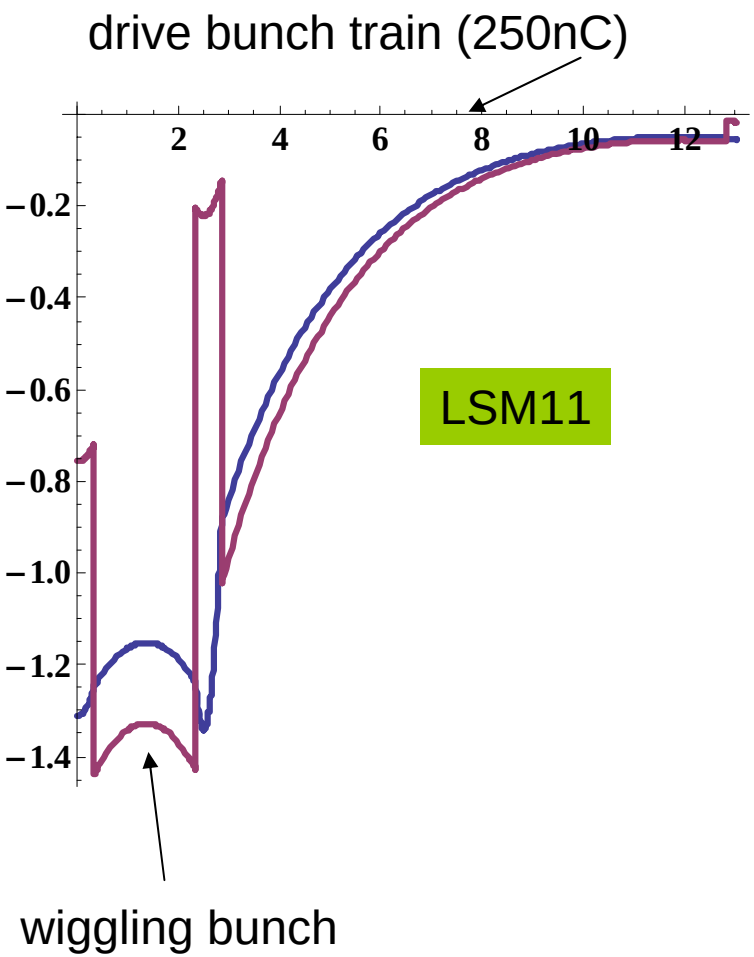
c) The way to produce the monochromatic wakefields in a DWA is to use of a train of a few drive bunches, spaced by the [sub]- period of the desired wakefield mode; the radiation power into a given mode is proportional to the bunch interference factor

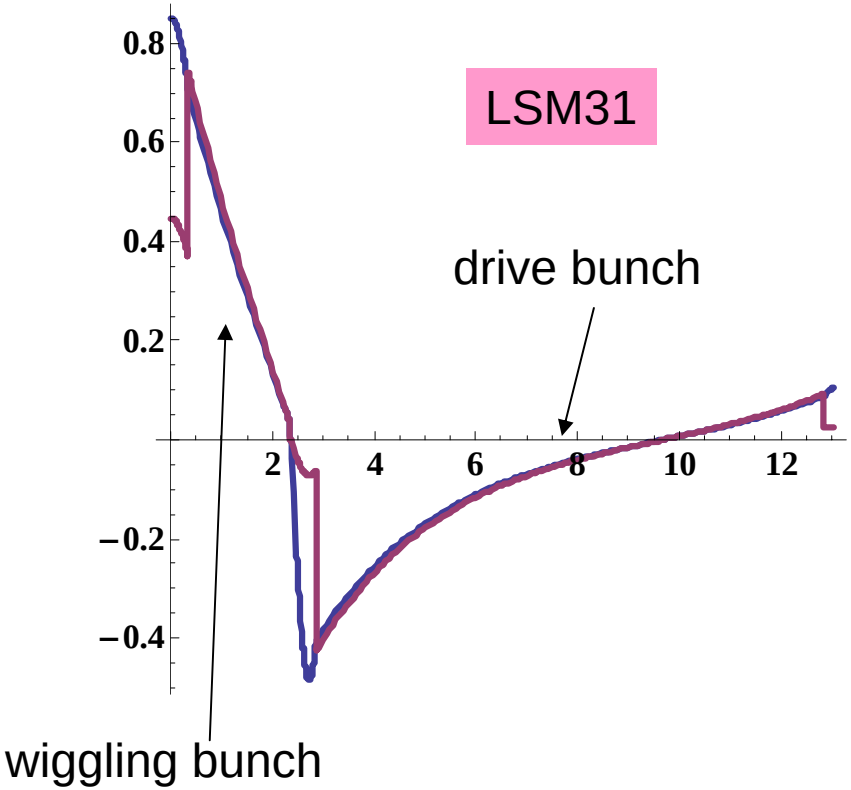
$$C_b = \sin^2 (N_b k_{z,mn} L_b/2)/\sin^2(k_{z,mn} L_b/2) ,$$

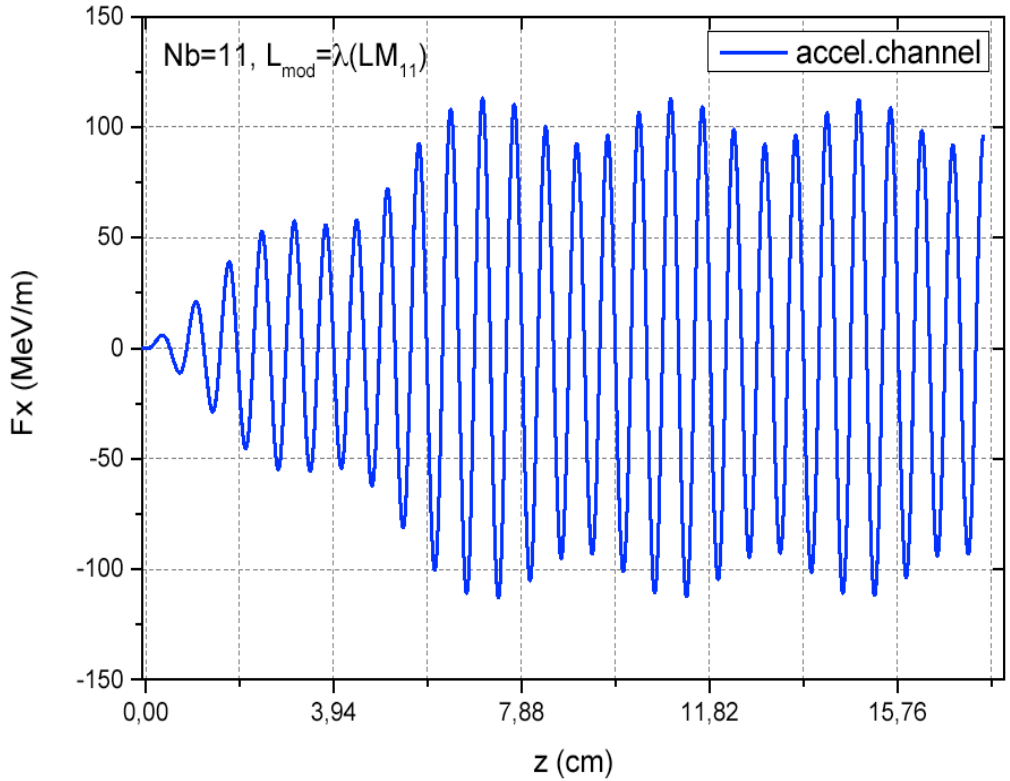
where N_b is the number of drive bunches, spaced by L_b, and $k_{z,mn}=2\pi/\lambda_{mn}$, with λ_{mn} being the axial period of the m-nth wakefield mode. Radiation from competing (non-synchronous) modes from a train of periodic bunches will be much reduced if the ratio C_b/N_b^2 is small enough. The forces from the individual drive bunches will then superimpose in a linear fashion, so that a train of several modest-size drive bunches will produce a large deflecting force.

B_y and E_x/c (Tesla)

graphs of $B_y(x)$ $E_x(x)/c$ for LSM11 to show asymmetry, also LSM31 to show symmetric mode doesn't work.



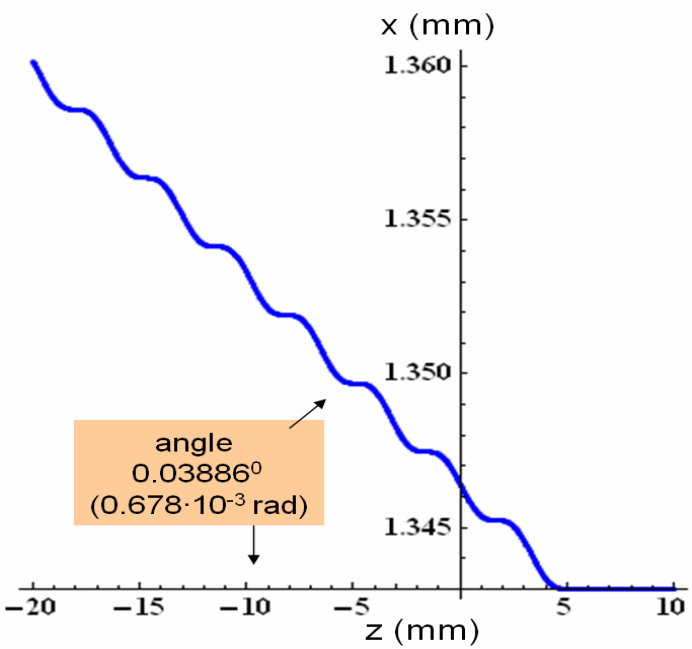




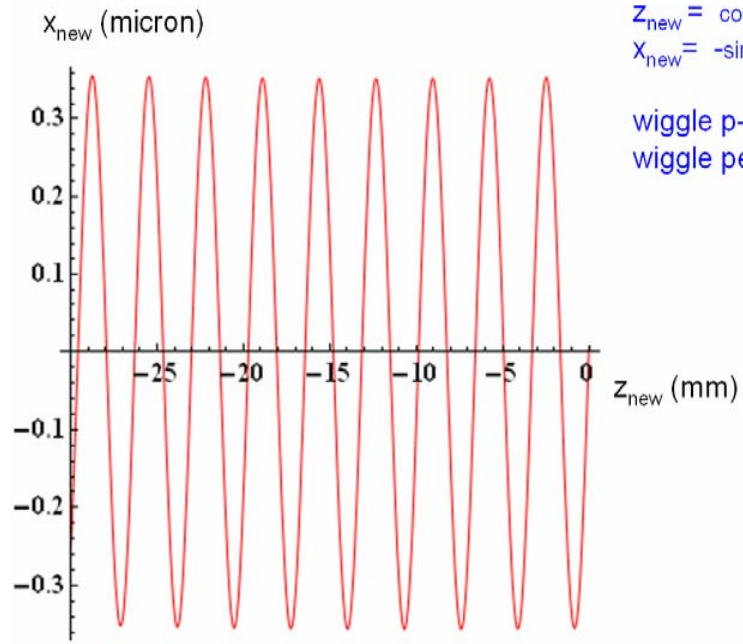
Total transverse wakefield force Fx vs. axial distance z at the center of the acceleration channel, excited by 11 identical 14MeV bunches, spaced by 6.6mm. (An actual device would use a more lengthy train of smaller-charge drive bunches.)

Additional mode filtering/ damping is need…
???
…subject to further studies and geometry modifications that accommodate mode dampers

Trajectory of single electron entering in the middle of test channel



If we rotate the coordinate system by $\Theta = -0.03886^0$ the trajectory looks like a set of wiggles about a straight line



$z_{new} = \cos(\Theta)\cdot z + \sin(\Theta)\cdot x$

$x_{new} = -\sin(\Theta)\cdot z + \cos(\Theta)\cdot x - 1.343$ mm

wiggle p-p amplitude (micron) ~0.71

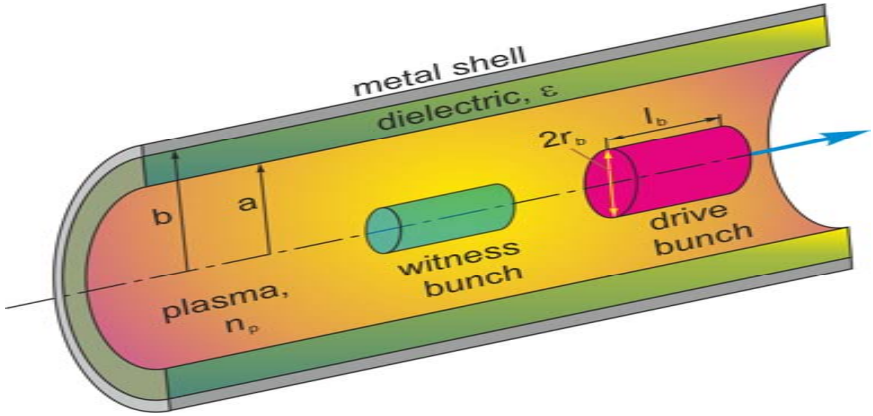
wiggle period (mm) ~ 3.286

(left) Orbit of a wiggling electron in the fields of a LSM11 mode set up by a point drive bunch, having energy 14MeV and total charge 250nC (this also could be achieved by using a bunch train having aggregate charge 250nC). The forces (magnetic, By ≈ 1T, and electric, Ex/c ≈ 1.2T) experienced by the test, 500MeV electron are periodic, and for a counter-propagating electron, the Lorentz forces from these two fields add. Particle oscillation with a period 3.3mm and amplitude several tenths of a micron is obtained here. The drift (sloping line) is caused by the particle entering the undulator fields abruptly; **(right)** the orbit of a test particle in this rf undulator after the coordinate system has been rotated by a small angle indicated to compensate for the drift. The oscillation is superimposed on a small uniform drift of the electron, which commonly occurs in undulators that have no entry taper; a gradual taper will correct the drift effect. K = 0.65 is obtained here.

Use plasma to stabilize the drive bunch train in the adjacent DB channel

-- Yet to be studied for applications with DWARF

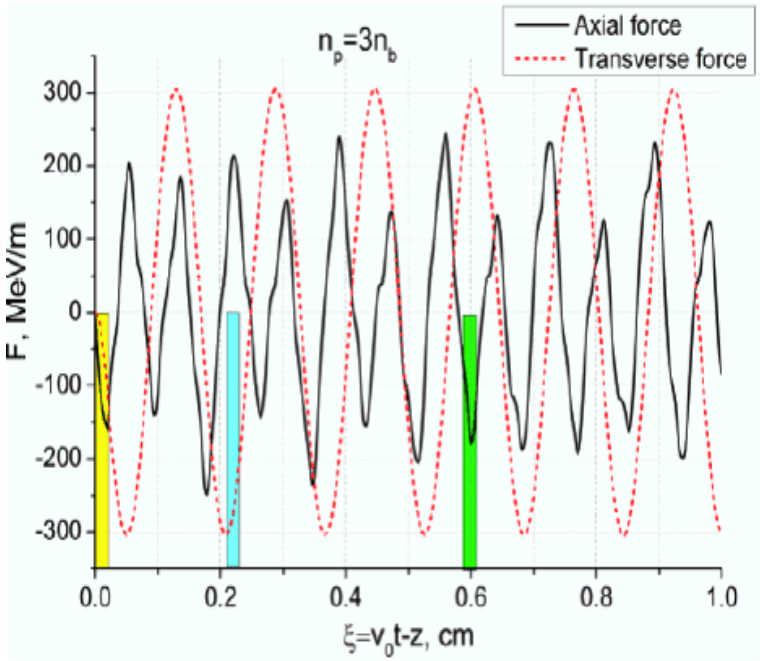
-- Herein we describe PDWA in simple model suitable for an <u>accelerator</u>

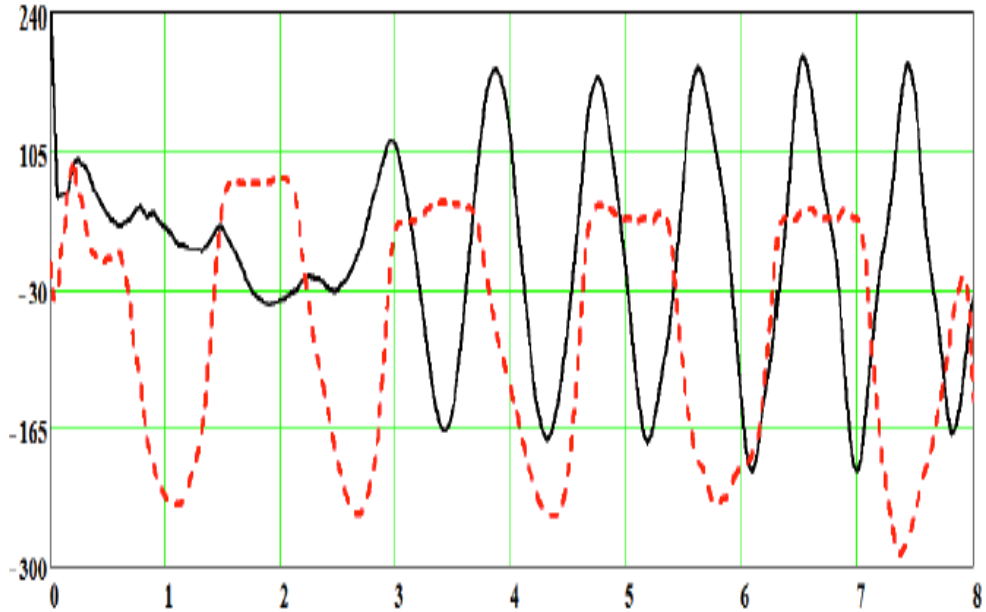


G > 200 MeV/m for 3nC drive bunch (see table)

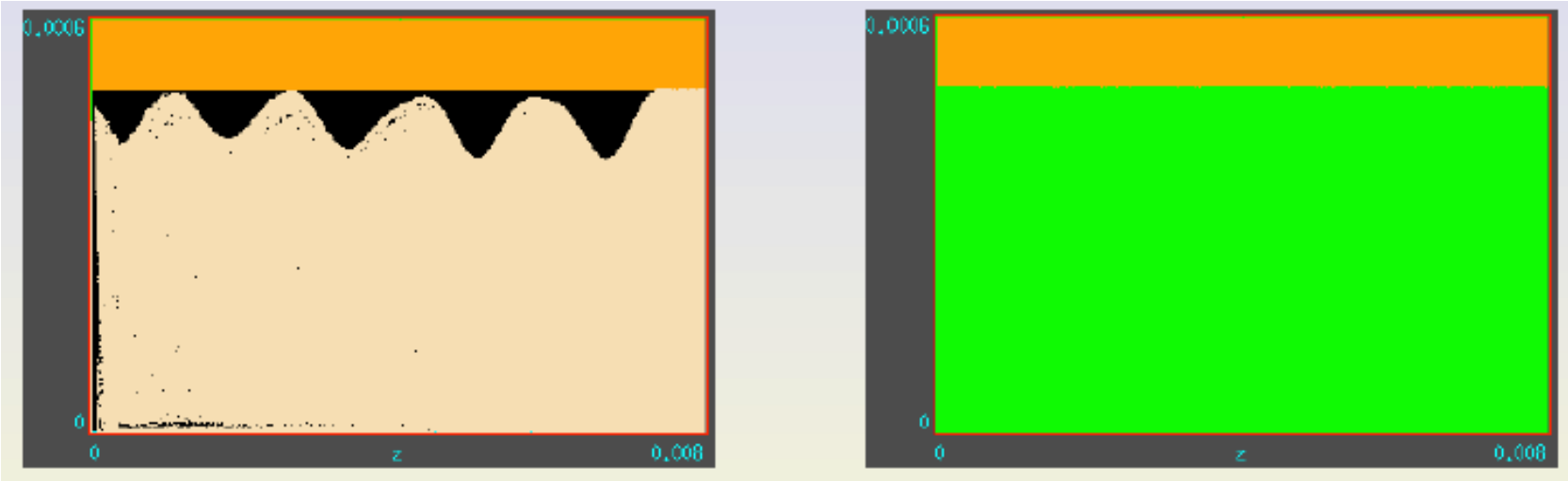
Parameters of a PDWA unit that uses a high-energy drive bunch

OD of outer dielectric tube	600 microns
ID of outer dielectric tube	500 microns
Relative dielectric constant, ε (fused silica, http://www.technicalglass.com/technical_properties.html)	3.75
Bunch energy	5 GeV
Bunch charge	3 nC
Bunch length, L_b (box distribution)	200 microns
Bunch radius, r_b (box distribution)	450 microns
Drive bunch electron density, n_b	1.47×10^{14} cm^{-3}
n_b / n_p	1/3





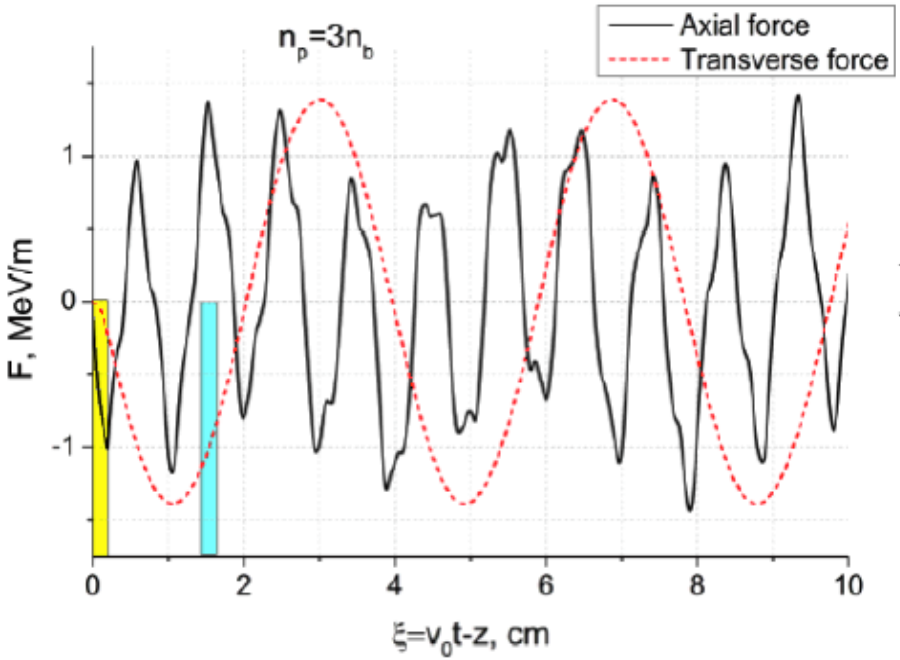
(left) Linear theory model: axial and transverse (at *r* = 0.45 mm) forces on relativistic particles in a PDWA (parameters as in Table). Drive bunch (yellow) moves toward left; note differing periods of wakefield and plasma waves. An electron witness bunch is shaded blue, a positron witness bunch is shaded in green; **(right)** Axial profiles of the longitudinal force (MeV/m, black line) and transverse force (red dotted line), the latter at *r* = 0.45 mm, as given by our PIC code. The bunch is located at z = 8 mm. The truncation of the plasma wave is caused by the removal of plasma electrons (but not the positive ions) by being pushed against the absorbing wall (a nonlinear plasma-rearranging effect).

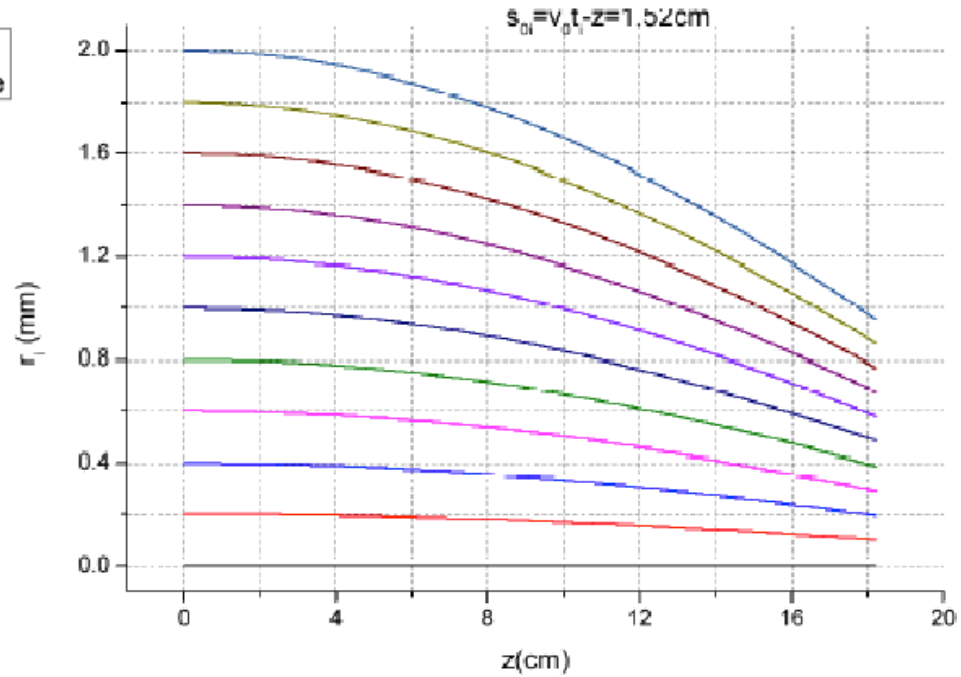


Configuration space (*r*, vertical; *z*, horizontal) plot of the electrons (left, tan dots) at t = 26.7 psec; dielectric wall is shown in orange. At the right, positive ions (green dots) are shown. Drive bunch is at the right-hand side of the figures. The net positive charge of these regions reduces the defocusing force of the plasma wave at the corresponding z locations

GHz PDWA suitable for a demonstration experiment at AWA.

OD of outer dielectric tube	10.22 mm
ID of outer dielectric tube	8.0 mm
relative dielectric constant, ε (fused silica)	3.75
bunch energy	14 MeV
bunch charge	1 nC
bunch length, L_b (box distribution)	2.0 mm
bunch radius, r_b (box distribution)	2.0 mm
drive bunch electron density, n_b	2.5×10^{11} cm^3
plasma radius	4.0 mm





(left) Drive bunch has moved 10 cm and is at the far left. The transverse force, showing a trailing plasma oscillation, is measured at *r* = 2 mm. Blue box is the witness bunch location. Results were obtained using the parameters of Table II for a device to test this device. **(right)** Radii of test witness bunch electrons accelerated by the wakefield of a drive bunch. Initially they are located at the center of the witness bunch (at a distance 1.5 cm behind the head of the drive bunch).

…an experiment conducted, for example, at AWA could provide guidance for the validation of this concept as a high energy accelerator component, e.g. for a FEL, which would be only a few m in length.

Summary (given for the reader references):

We have presented the concept of a Dielectric-lined Wakefield Radio Frequency Undulator (DWARF). This is a structure which has two rectangular adjacent channels lined with dielectric slabs [1], one channel being wide and the other narrow; the wide channel is filled with plasma of specified density. The structure is to be excited by injection of train of sub-harmonic drive bunches in the wide channel, where plasma fields provide stability for the drive bunch train. The narrow vacuum channel conveys a train of highly relativistic bunches which move counter to wakefields excited by the drive train, and thus emit X-ray FEL radiation. The concept overcomes common issues with conventional RF undulators [2] where it is difficult to devise a configuration that can compete with short-period (~1 cm) permanent magnet (PM) undulators, because of problems of generating sufficient microwave power at short wavelengths, and because of limitations due to structure heating and RF breakdown. The DWARF we have presented has at least two important advantages, namely (a) the structure is filled and emptied with radiation at the group velocity of light, minimizing heating and breakdown issues; and (b) the plasma-filled drive channel provides stability for the drive bunch train [3]. An example of a proposed DWARF would operate in the LSM-11 mode to provide an RF undulator period of 6.6 mm, which can be be compared with a PM undulator that must have a period of 3.3 mm to produce X-rays of equal wavelength. The main parameters of the DWARF we have studied are: drive channel height/width are 8 and 10 mm, undulator channel height/width are 8 and 2 mm, dielectric slab thicknesses are 0.34, 0.51 and 0.18 mm (dielectric constant 4), 14 MeV drive bunch train aggregate charge is 250 nC, and the operating wakefield frequency is 46 GHz over a length of 5 m. We have presented our recent progress on studies of this concept, including investigation of 500 MeV particle orbits in this type of undulator, stability of drive bunch trains in plasma-filled channels, excitation of wakefields by sub-harmonic injection of drive bunches, radiation spectrum, and synchronization of the plasma wave and wakefield periods.