ICFA Mini-Workshop on Novel Concepts for
Linear Accelerators and Colliders

SLAC National Accelerator Laboratory – July 8-10, 2009

COAXIAL TWO-CHANNEL HIGH-GRADIENT DIELECTRIC WAKEFIELD ACCELERATOR*, **

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G.V.Sotnikov, T.C.Marshall, J.L.Hirshfield, *Phys.Rev.ST Accel.Beams* **12, 051301 (2009).

OUTLINE OF TALK

Two-channel dielectric wake field accelerators, non-symmetric and symmetric, are discussed.

-Two channels allow separation of drive and witness beams, and achievement of a transformer ratio >>2.

-There is a tradeoff between transformer ratio and accelerating gradient.

- Breakdown threshold should be higher than for a conventional resonant structure, since exposure time to high fields is only the brief passing time of the drive bunches, with no cavity filling time.

- Quenching waves (originating at the entry boundary), that trail wake fields, cannot be overlooked (as has been the case in most prior DWFA studies).

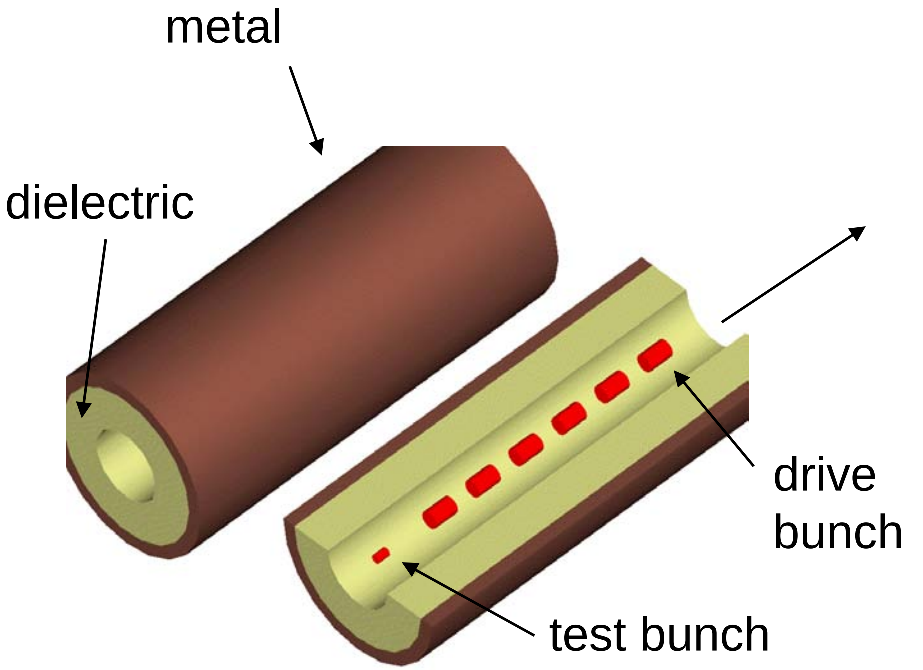
- Multi-bunch operation may not be promising, due to quenching waves, so necessary luminosity will require a high bunch rate.

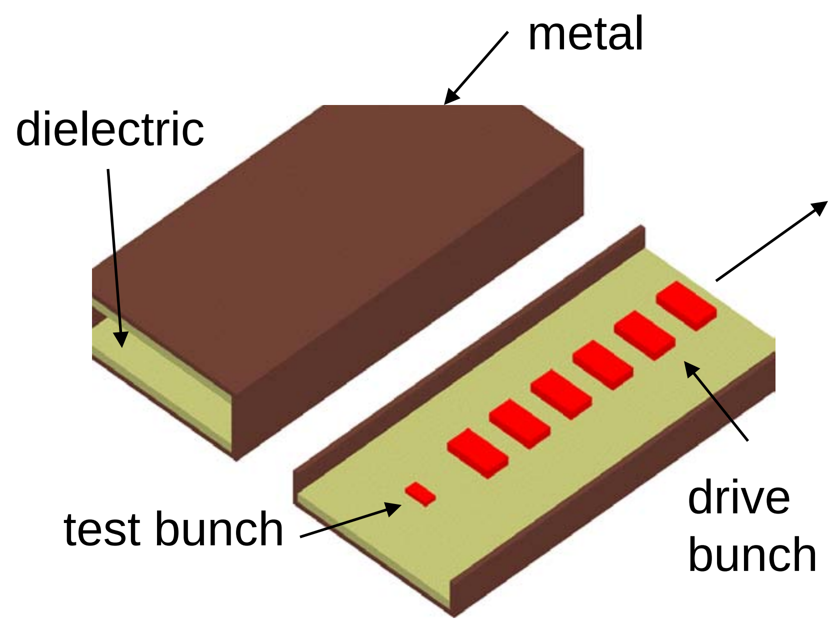
-Stability needs careful study.

-An outline is given for experiments planned at ANL-AWA with W.Gai, J.Power, M.Conde.

-A mm-scale THz symmetric (coaxial) two-channel DWFA is described with acceleration gradient of ~0.6 GeV/m and transformer ratio of ~8:1. A linear collider model based on this structure is discussed.

CONVENTIONAL SINGLE-CHANNEL DWFA STRUCTURES





single channel cylindrical structure

- transformer ratio* $T \sim 2{:}1$
- multi-bunch drive train ?
- drive bunch stability x
- superposition of wakes ?

$T = \dfrac{\text{(accel gradient for test particle)}}{\text{(average decel gradient for drive bunch)}}$

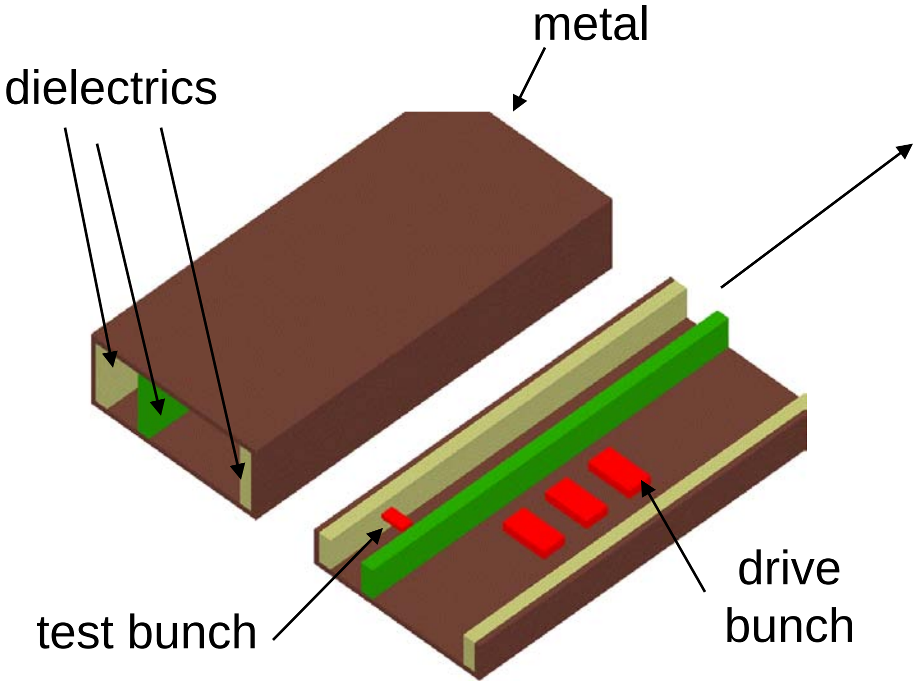
single channel planar structure

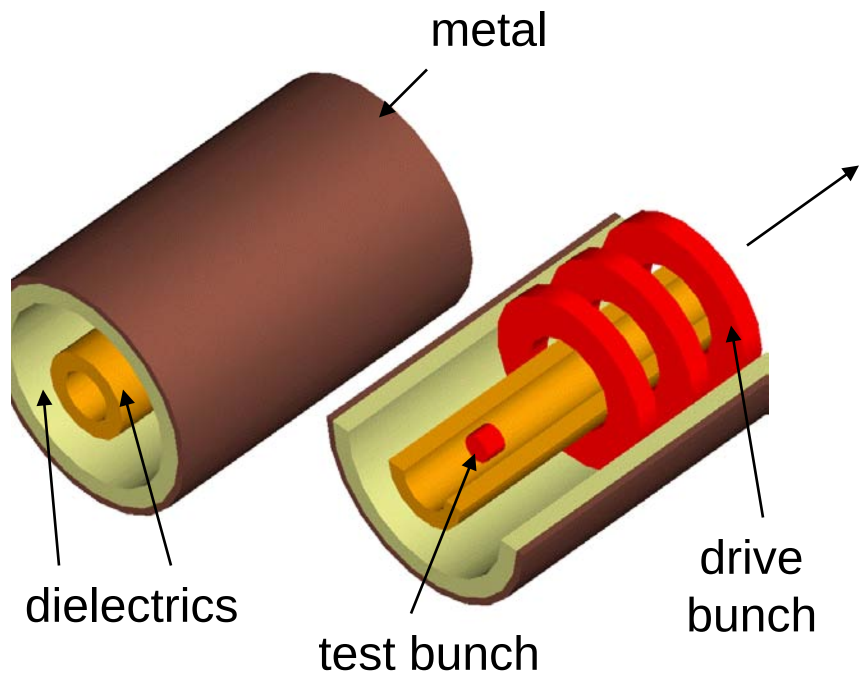
- transformer ratio $T \sim 2{:}1$
- multi-bunch drive train ?
- drive bunch stability ?
- superposition of wakes ?

number of stages $N > W_{final}/TW_{drive}$

For 3-TeV CLIC, $T \approx 29$ and $N = 24$.
(2008 parameters)

NOVEL TWO-CHANNEL DWFA STRUCTURES





rectangular multi-layer, two-channel

- transformer ratio ~10:1
- multi-bunch drive train x
- drive bunch stability x
- superposition of wakes x

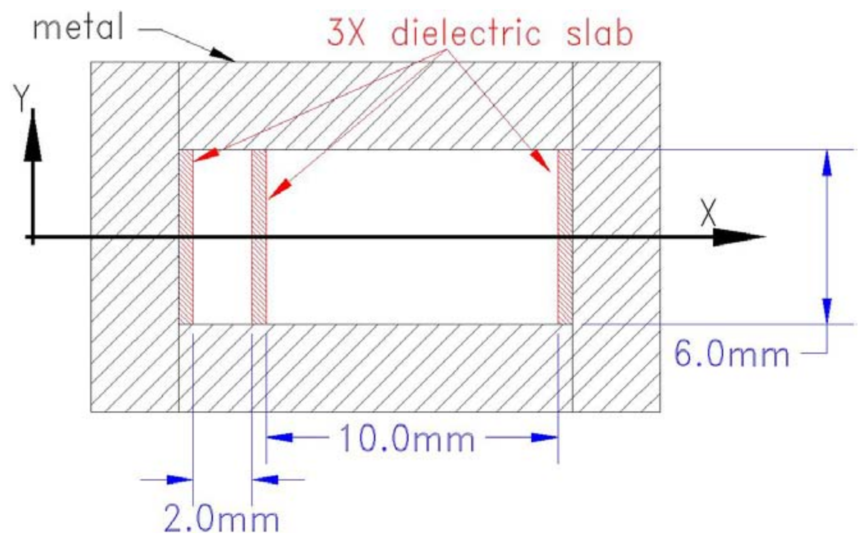
cylindrical multi-layer, two-channel

- transformer ratio* ~10:1
- multi-bunch drive train ?
- drive bunch stability ?
- superposition of wakes ?

* *larger if another dielectric annulus is added*

CROSS SECTIONAL VIEW OF 2-CHANNEL RECTANGULAR DWFA STRUCTURE

Wide channel is for high-current low-energy drive beam, while narrow channel is for low-current high-energy test beam.



Advantages:

- Separate channels can simplify separation of beam transport issues.
- Energy flow is continuous from drive beam to test beam. No coupling structures.
- Transformer ratio >>2 is possible, but at the expense of accelerating gradient.
- Axially-uniform structure is relatively simple to fabricate.

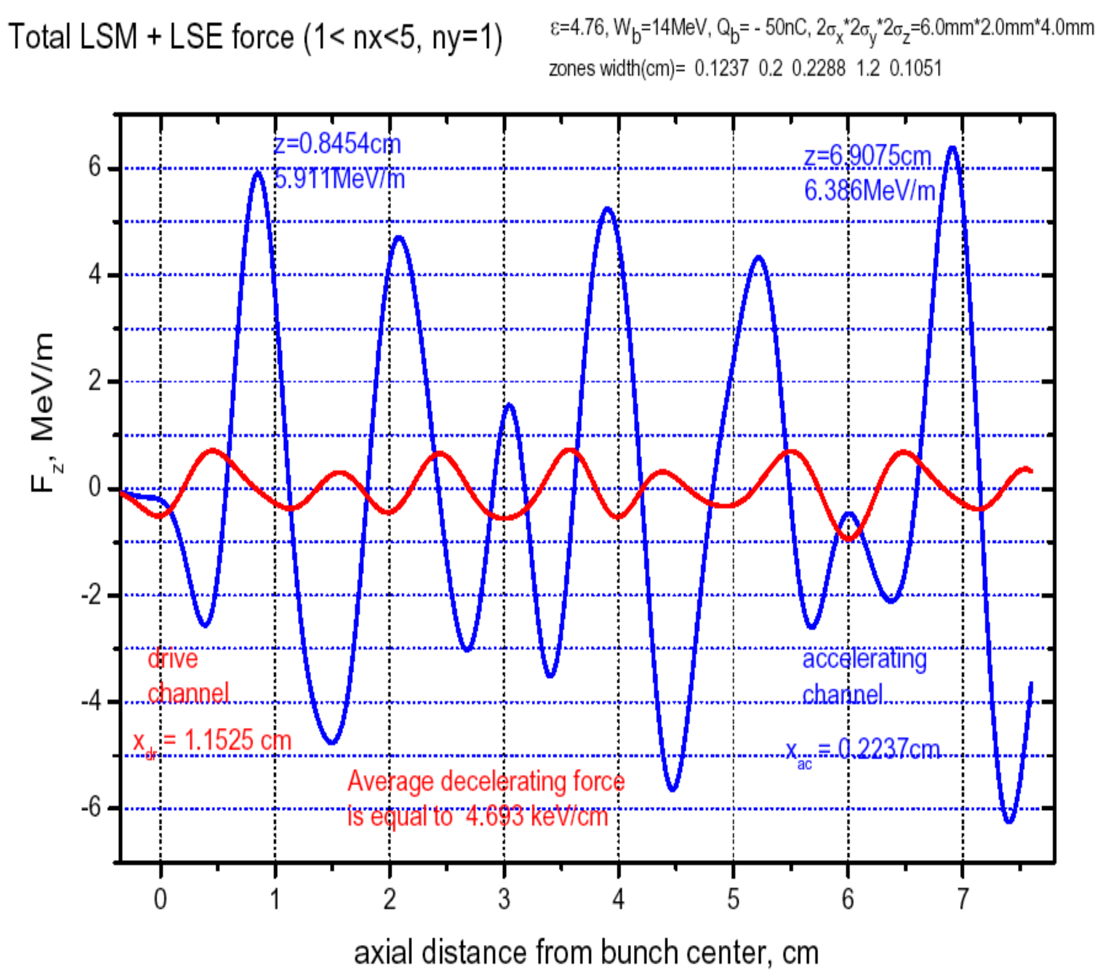
Disadvantages:

- Dielectrics can impede thermal transport, leading to cooling issues.
- Transverse asymmetry can lead to excessive deflecting forces & emittance growth.

THEORETICALLY-PREDICTED ACCELERATING & DRAG FORCES

for the 1st structure to be used in experiments at Argonne National Laboratory

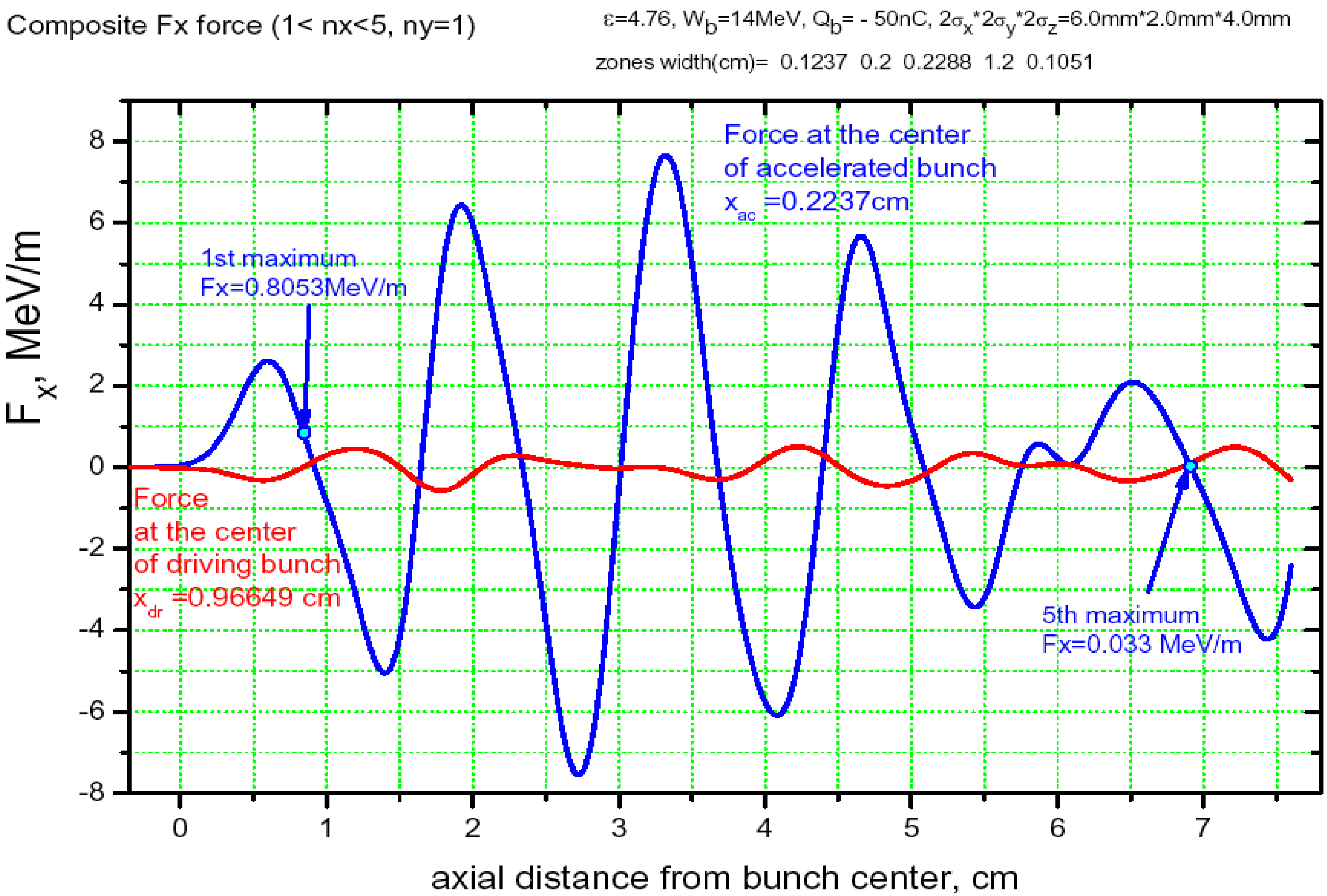
Note: the witness bunch is located at z = 0.845 cm behind the drive bunch center.



design mode	LSM_{31}
accelerating channel	2 × 6 mm^2
drive channel	12 x 6 mm^2
slab 1 thickness	1.24 mm
slab 2 thickness	2.29 mm
slab 3 thickness	1.05 mm
slab ε	4.76

drive bunch parameters	
Gaussian length	σ_z = 2 mm
energy	14 MeV
charge	50 nC
# of bunches	1
transformer ratio	~12.6

THEORETICALLY-PREDICTED TRANSVERSE FORCES IN BOTH CHANNELS

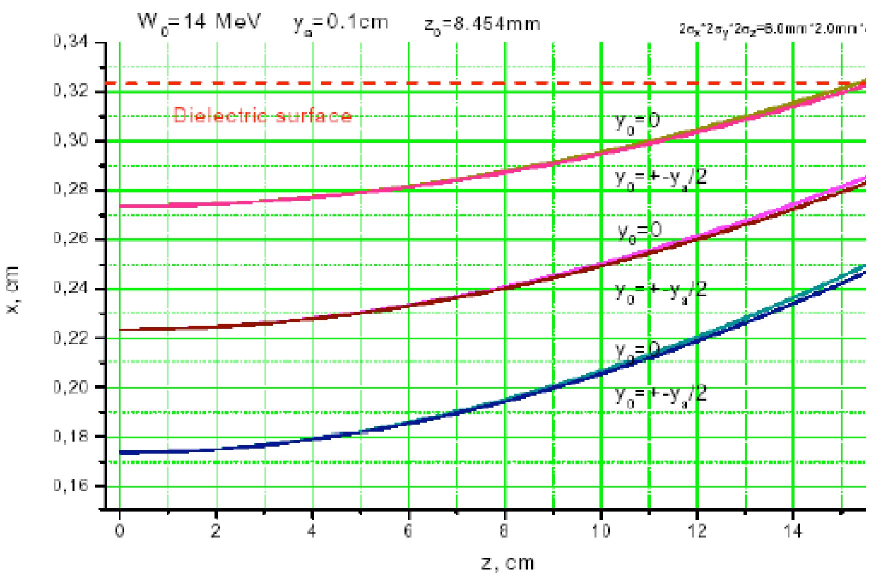


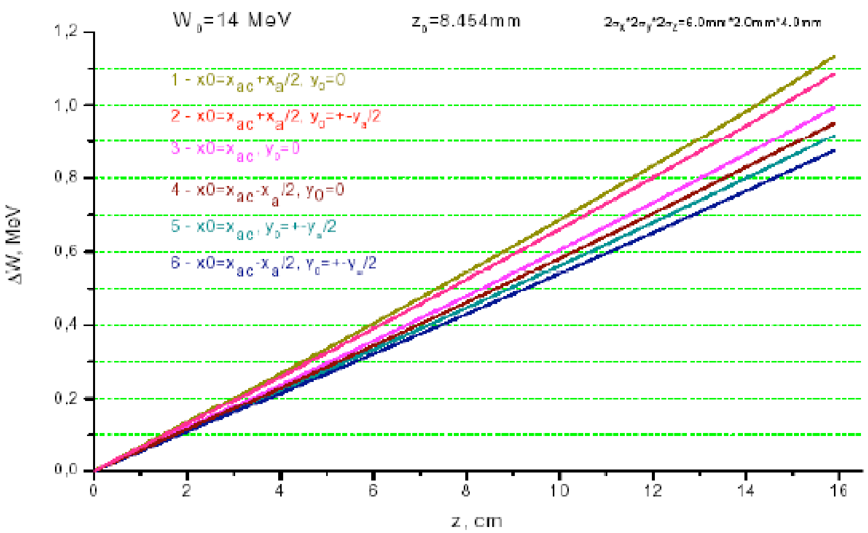
Transverse deflection is not insignificant, but witness bunch remains in its channel over its entire 12 cm length. Transverse wake forces can be greatly reduced for a three-channel structure.

Mode powers, test beam deflection, energy gain

14 MeV, 50 nC drive bunch (6x2x4 mm^3)

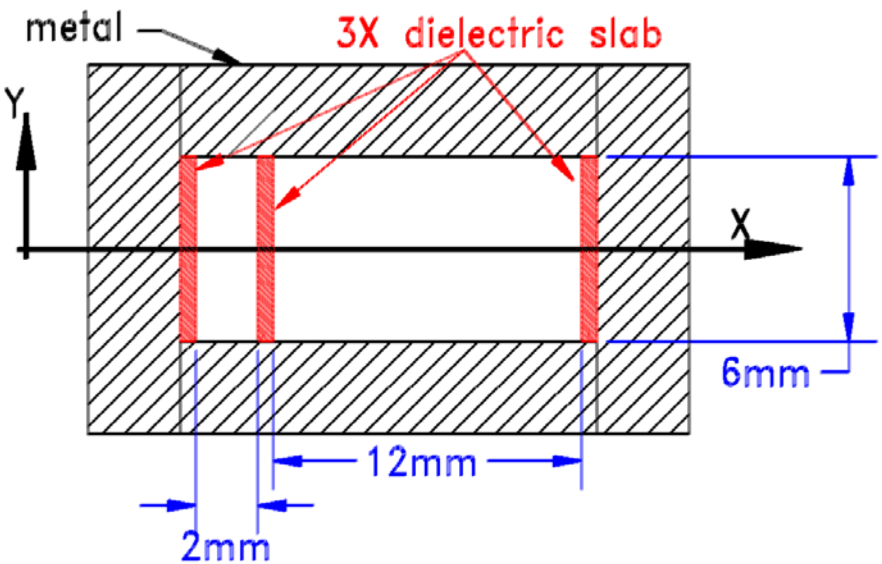
Mode	Frequency, GHz	Power, MW	Mode	Frequency, GHZ	Power, MW
LSM_{11}	24.789	0.5177	LSE_{11}	19.9566	2.499
LSM_{21}	29.9655	1.072	LSE_{21}	39.0669	0.1345
LSM_{31}	29.9969	2.412	LSE_{31}	44.6771	$9.58 \cdot 10^{-2}$
LSM_{41}	53.6052	$4.36 \cdot 10^{-2}$	LSE_{41}	45.4008	0.256
LSM_{51}	75.418	$8.36 \cdot 10^{-5}$	LSE_{51}	72.9881	$1.94 \cdot 10^{-4}$





Rectangular two-channel structure to demonstrate high transformer ratio *T*

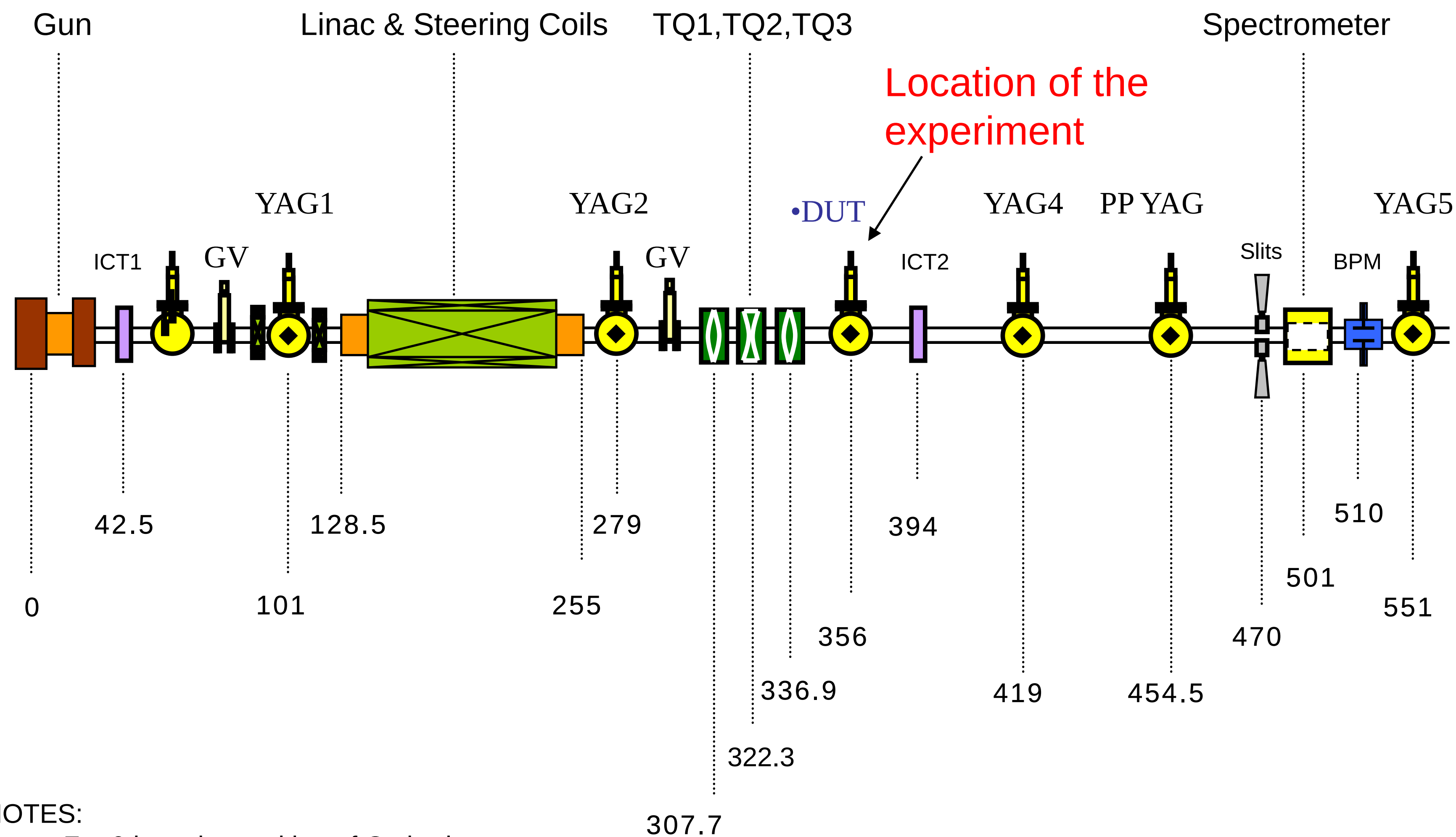
- Dielectric-lined (Cordierite supplied by Euclid Concepts, LLC, $\varepsilon \approx 4.76$) to have spatially localized wake-fields to achieve high gradient w/o breakdowns.
- Experimental objective: To test 2-channel dielectric wakefield structure and compare results with theory model predictions.



- Double-pulse rf photocathode to make a timed, delayed test bunch.
- Two channels to provide a high transformer ratio
- What will be measured: energy gain of witness bunch electrons; and microwave radiation spectrum generated by the drive bunch.

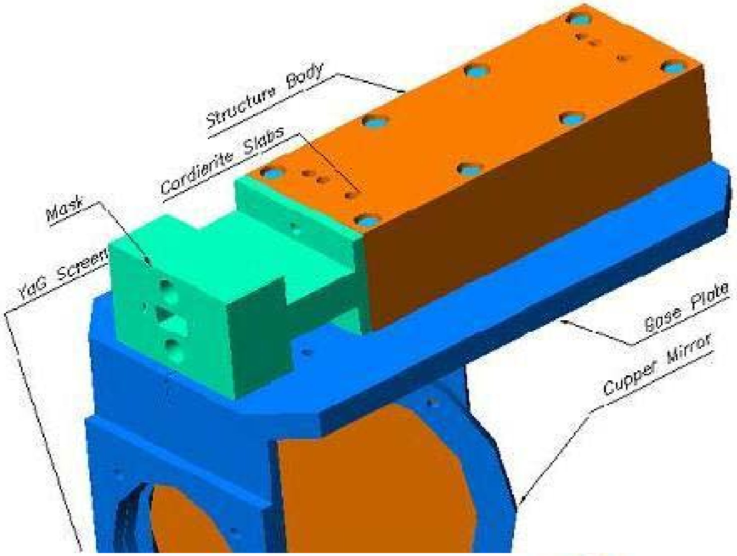
Experiment location is AWA Beam-line

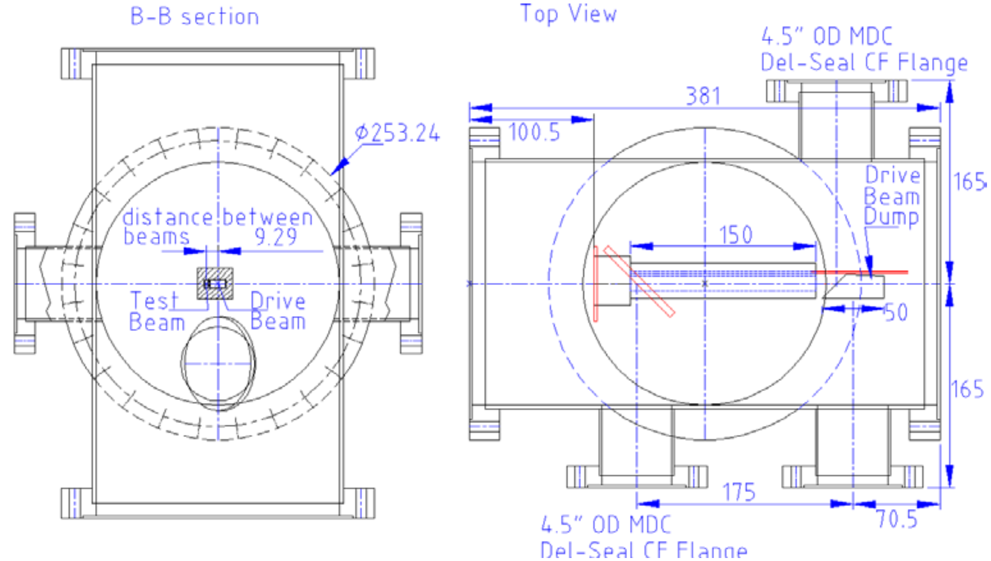
(courtesy of John Power)

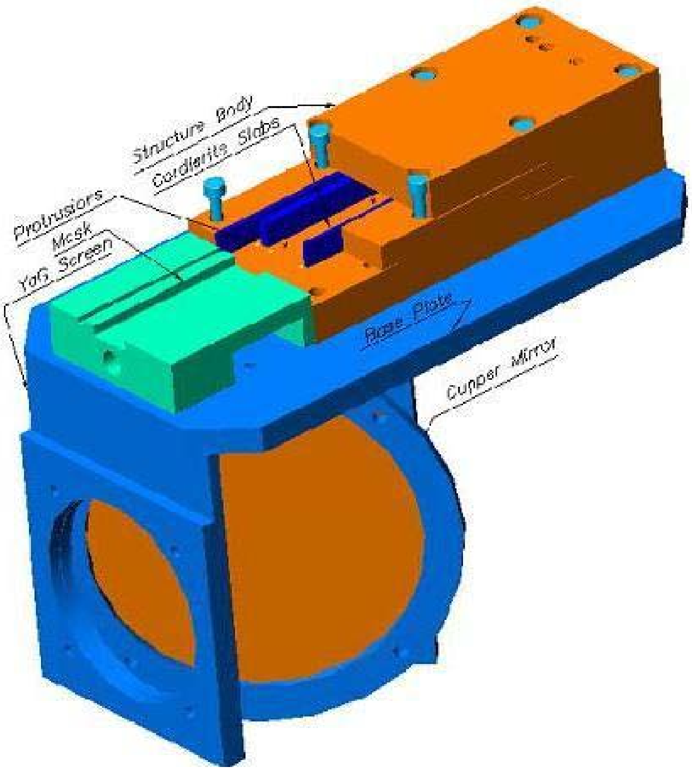


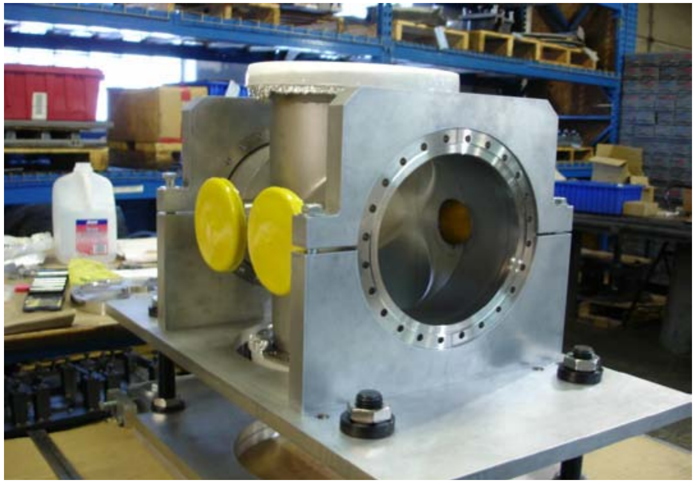
NOTES:

Z = 0 is at the position of Cathode.


Structure Body
Cordierite Slabs
Mask
YaG Screen
Base Plate
Cupper Mirror


B-B section
Top View
4.5" OD MDC
Del-Seal CF Flange
381
100.5
ϕ253.24
distance between
beams
9.29
Test
Beam
Drive
Beam
150
Drive
Beam
Dump
165
165
50
175
70.5
4.5" OD MDC
Del-Seal CF Flange


Structure Body
Cordierite Slabs
Protrusions
Mcsk
YaG Screen
Base Plate
Cupper Mirror

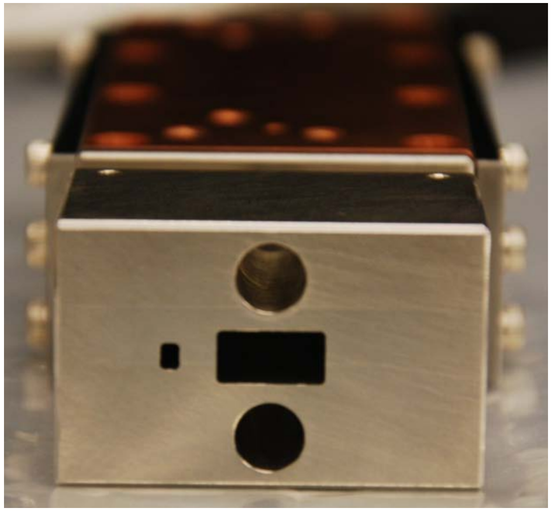


Photos of rectangular two-channel DWFA

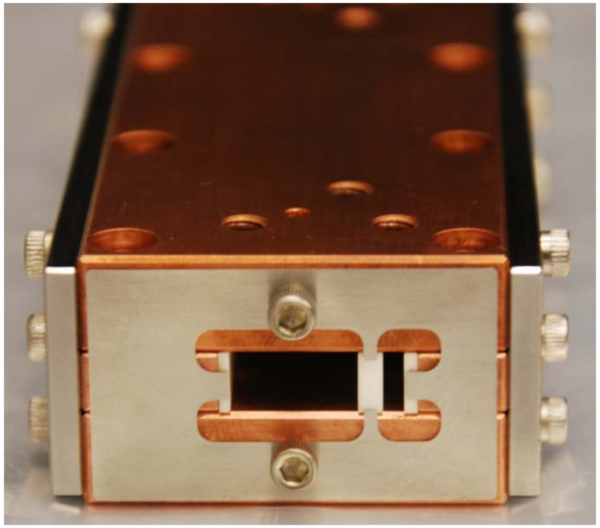
channels are 2 x 6 mm^2 and 12 x 6 mm^2, 150 mm long

side view, showing beam scraper at left and accel structure at right

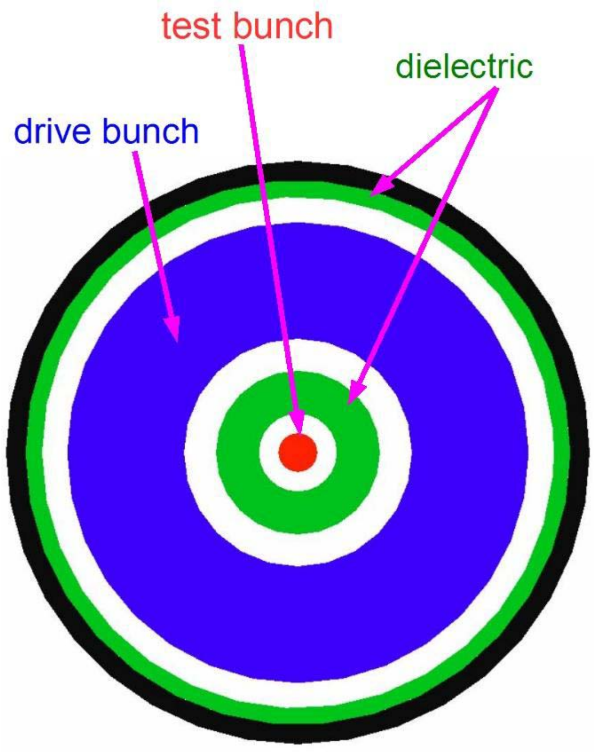
front view



rear view



A TWO-CHANNEL DWFA WITH GOOD SYMMETRY
(requiring a stable high-charge annular drive bunch)

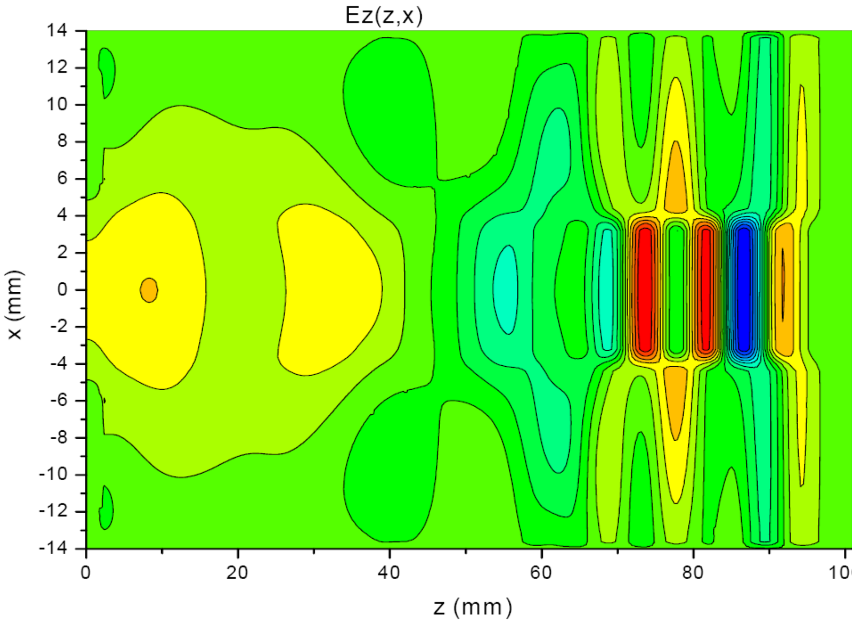


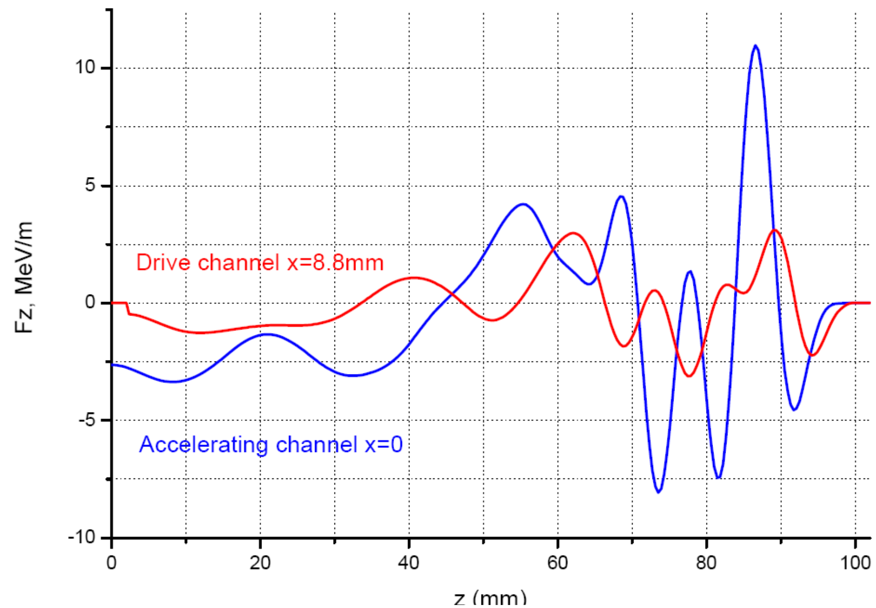
Design mode	~30 GHz
Metal waveguide radius R	14.0 mm
Accl. channel radius a	2.0 mm
Inner drive channel radius b_1	4.215 mm
Outer drive channel radius b_2	13. 15 mm
Relative dielectric constant ε	4.76
Bunch axial RMS dimension $2\sigma_z$ (Gaussian charge distributition)	4.0 mm
Outer drive bunch radius (Box charge distributition)	11. 8575 mm
Inner drive bunch radius	5. 8575 mm
Bunch energy	14 MeV
Bunch charge	50 nC
Number of bunches	1

AXIAL FORCES ON DRIVE AND TEST BUNCHES IN COAX DWFA

4-mm long, 50 nC annular drive bunch head is at z = 100 mm; test bunch is at z = 86 mm; transformer ratio ≈ 11/1.1 = 10:1.

Note that after about two periods, wake field is wiped out by quenching wave.

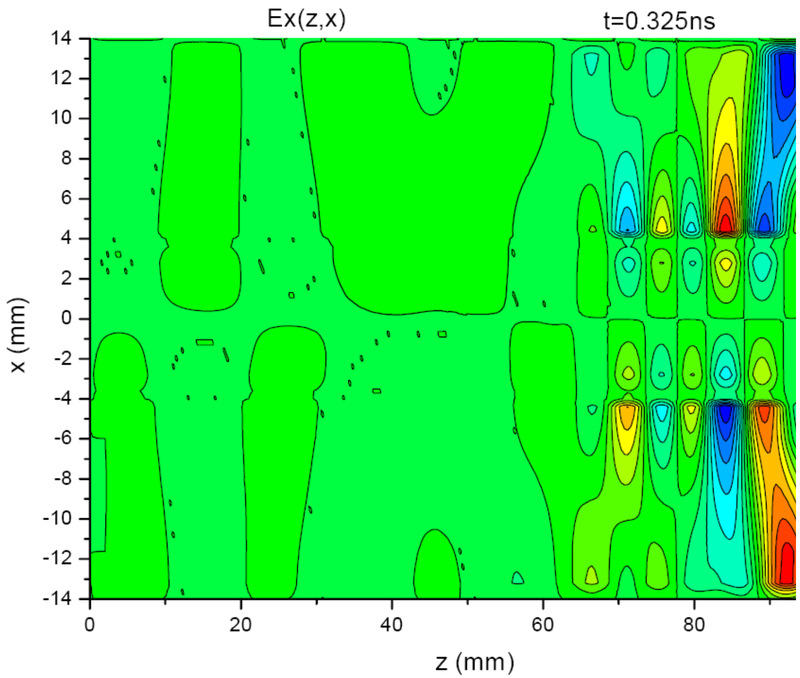


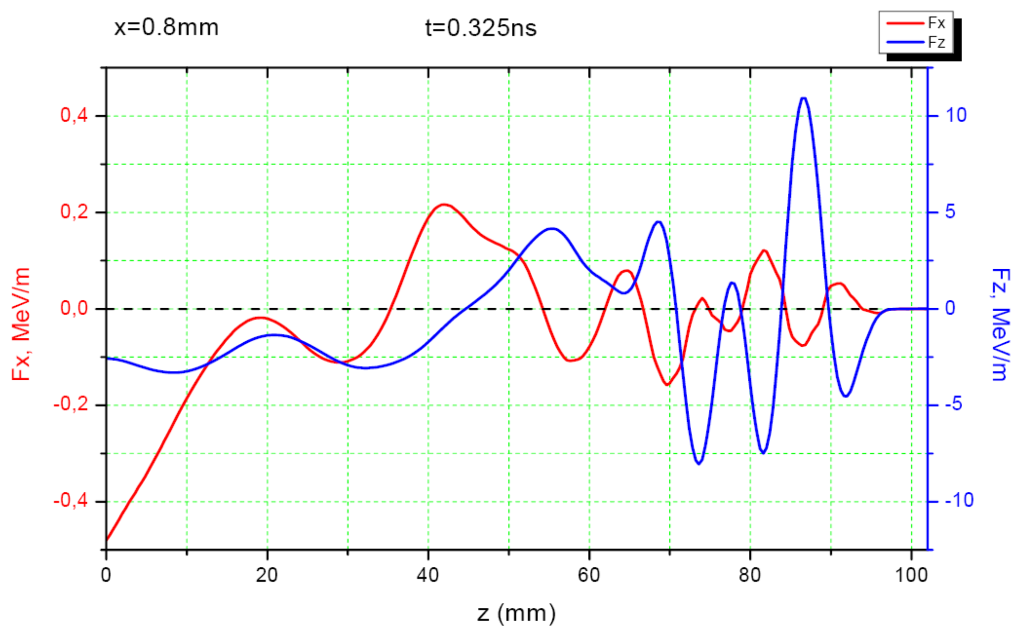


TRANSVERSE FORCES ON DRIVE AND TEST BUNCHES IN COAX DWFA

4-mm long, 50 nC annular drive bunch head is at z = 100 mm; test bunch is at z = 86 mm, r = 0.8 mm; transformer ratio ≈ 10

Note that transverse force on test bunch is *stabilizing!*



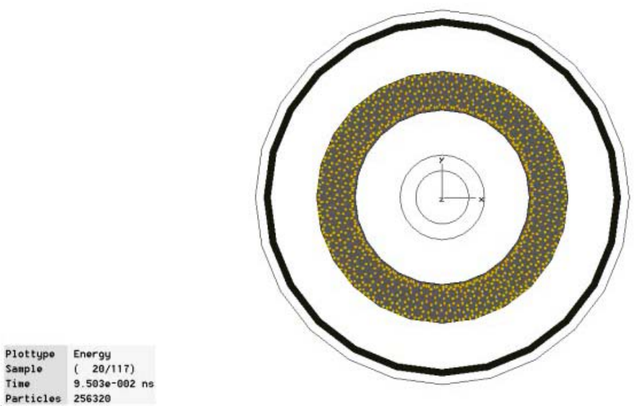


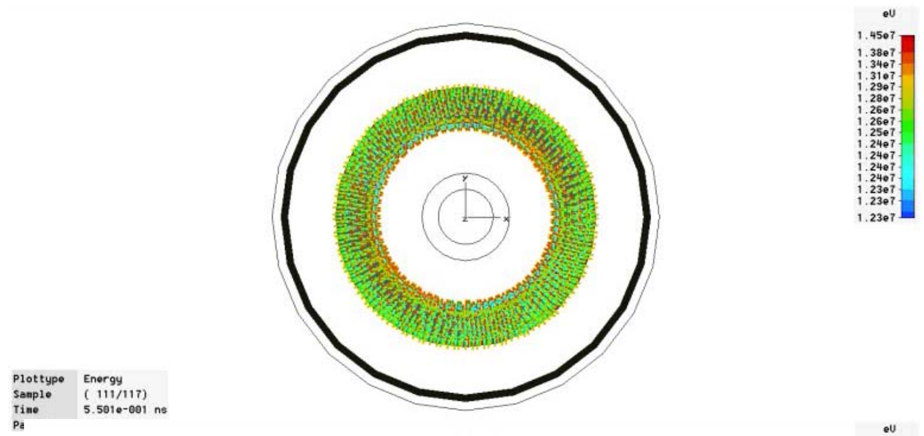
PIC code results for multiple drive bunch stability (4 bunches) in a 30-GHz structure. Note no distortions in annular drive bunches, even after off-axis injection and travel.

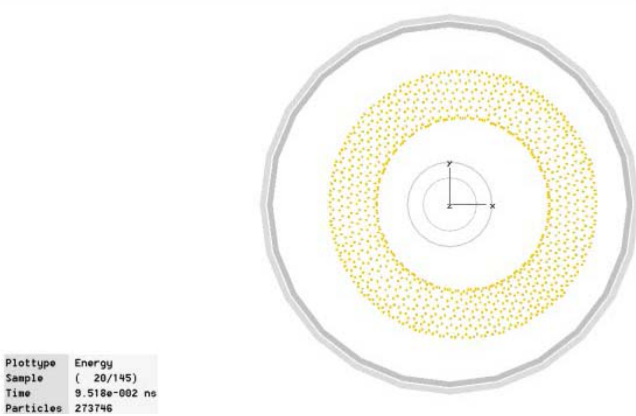
Structure dimensions were chosen so quenching waves move more slowly than the wake fields, allowing good superposition away from the entry; and that fields are flat in drive channel.

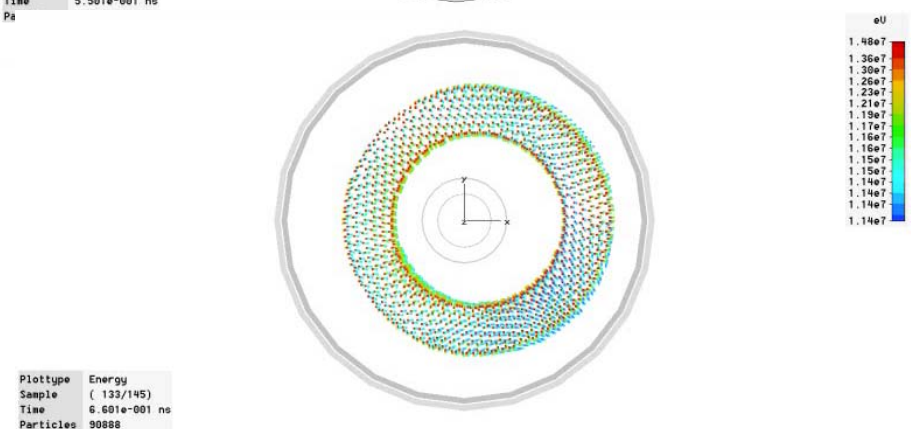
projection of particle locii at injection (4 bunches)

projection of particle locii at exit (4 bunches)







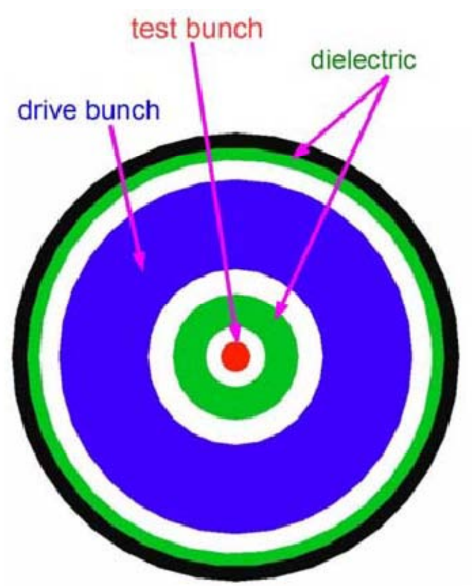


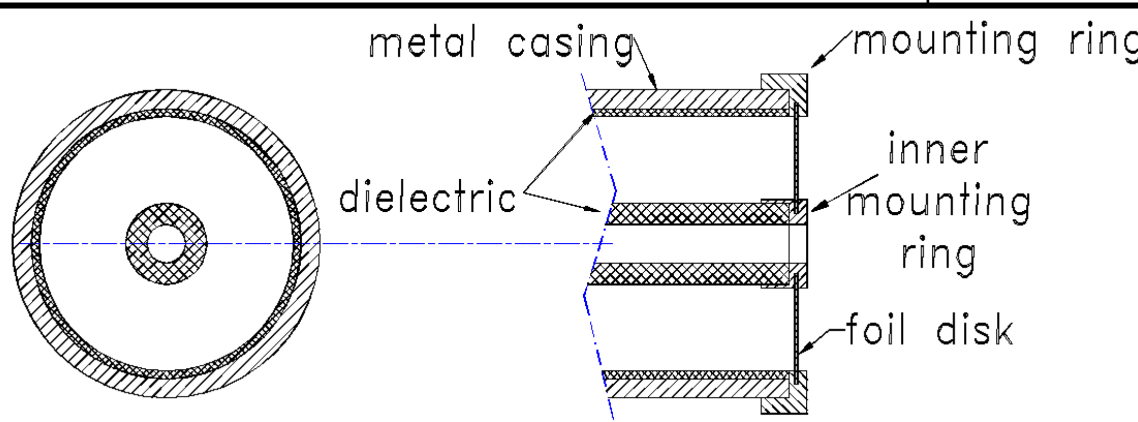
Cylindrical two-channel THz structure to demonstrate the posssibility of GeV/m scale acceleration

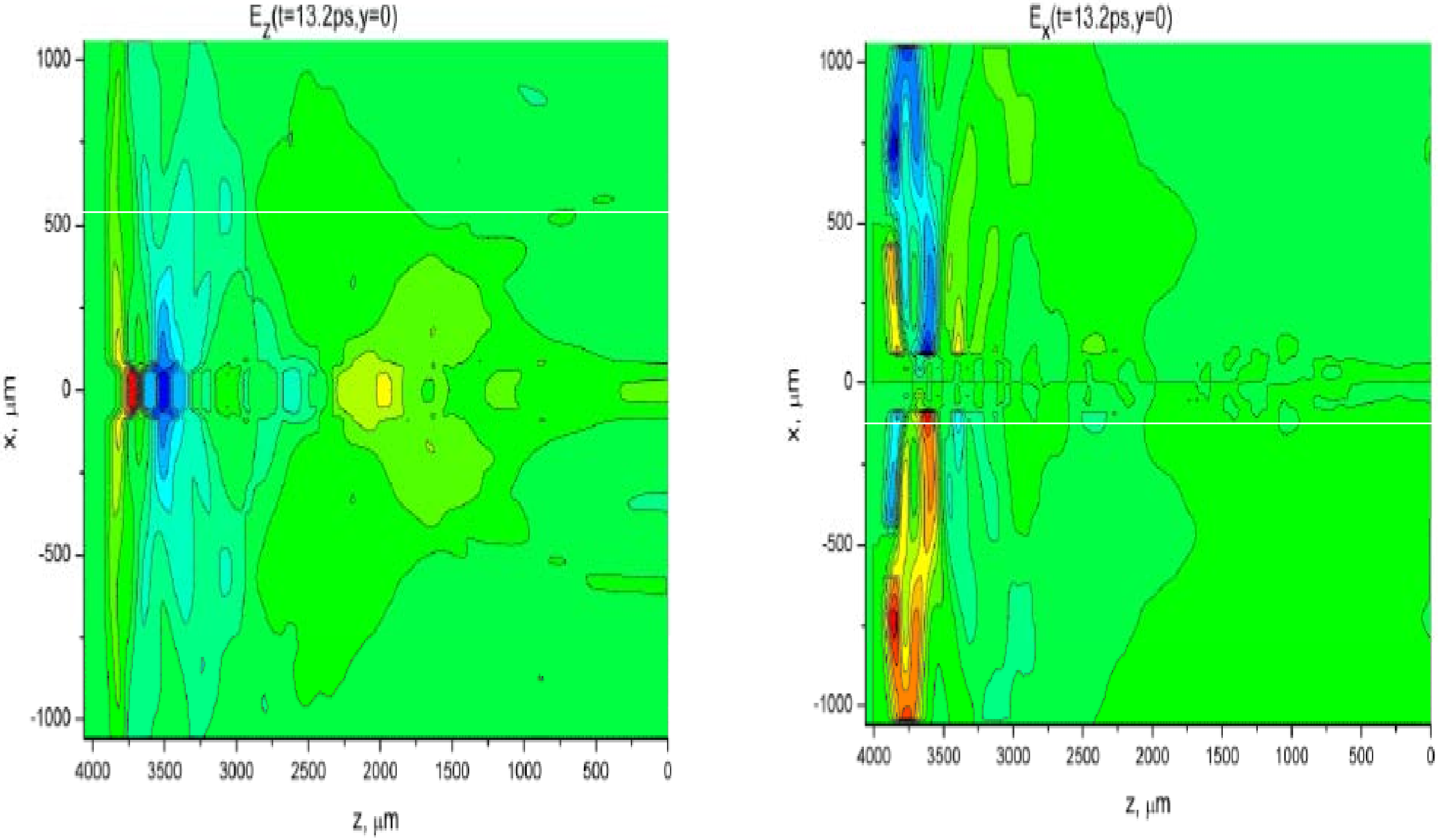
Analytic theory + numerical computation +PIC code numerical simulation.

To obtain gradients > 1 GeV/m, we study a THz structure approximately 2mm in diameter.

Design mode	921 GHz
External radius of outer coaxial cylinder	1060.5 µm
Inner radius of outer cylinder	1047.5 µm
External radius of inner coaxial cylinder	89.5 µm
Accel. channel radius	50 µm
Relative dielectric constant	5.7
Bunch axial rms-dimensions $2\sigma_z$ (Gaussian distribution)	69.3 µm
Outer drive bunch radius (box charge distribution)	718.5 µm
Inner drive bunch radius	418.5 µm
Bunch energy	5 GeV
Bunch charge	6 nC
Number of bunches	1



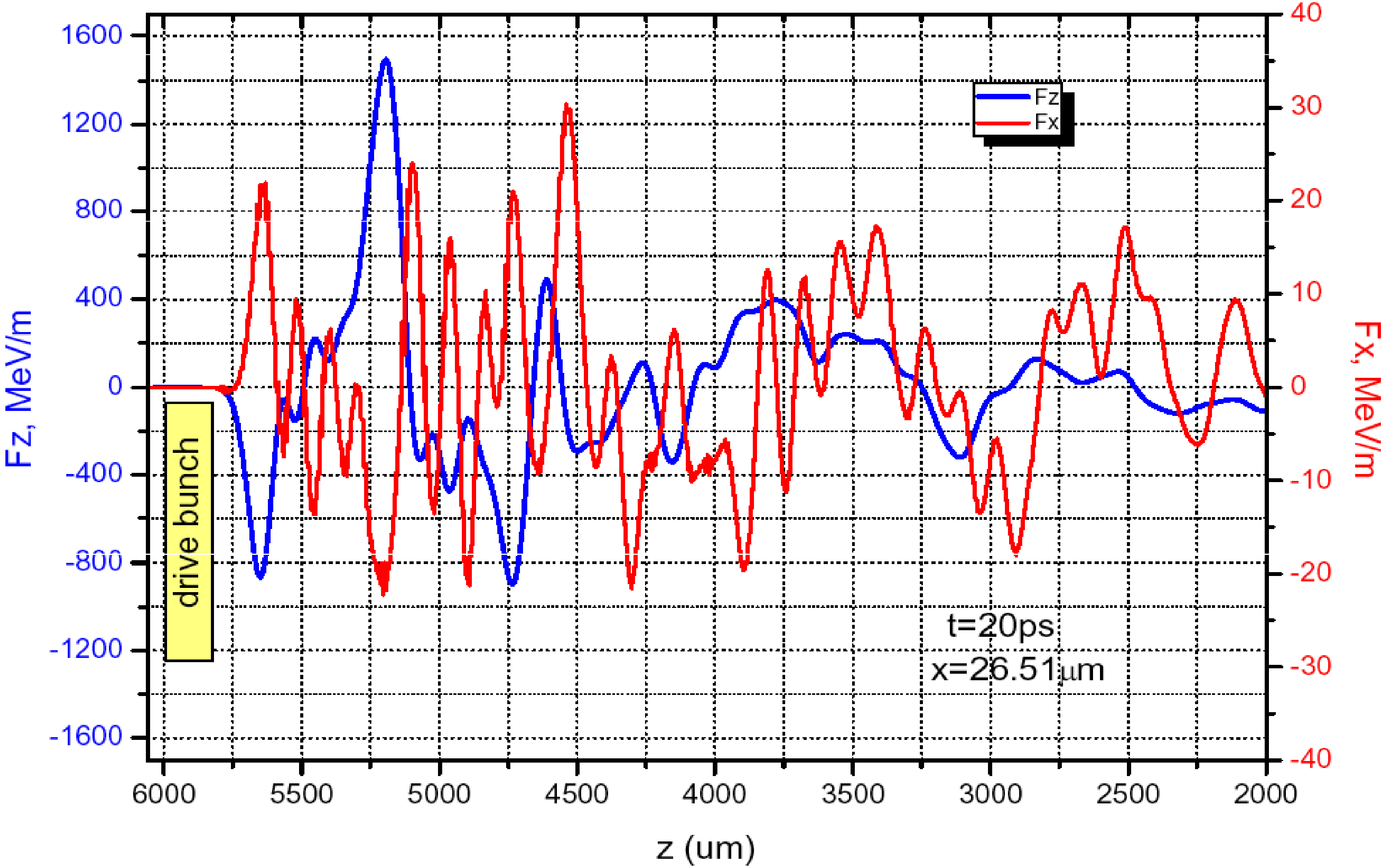




Profile map of $E_z(r,z)$ from a single drive bunch at z = 4 mm

Transverse field profile map.

Above are PIC code simulations. Observe the quenching wave (z < 3.25 mm), the striking contribution of which to the total field pattern has not been considered until lately in theoretical treatments.



Longitudinal (r = 0) and transverse (r = 26.5um) forces on a witness bunch. Note quenching wave disturbing the wakefield for z < 5 mm

Collider considerations (per Workshop charge) for coaxial two-beam dielectric wake field accelerator

Drive beam parameters: 5 GeV, 6 nC, 70 MW, I_{av} = 14 mA, 2.3×10^6 bunches/sec, or at 50 Hz prf, 46.7×10^3 bunches/pulse, which at 3 GHz gives a pulse length of 15.5 μs, and I_{pulse} = 18 A.

Accelerated beam parameters: ΔE = 1500 GeV for E_{cm} = 3 TeV. G = 0.5 GeV/m, so active length L_{ac} = 3000 m = 3 km.* With transformer ratio T = 6, number of sections N = 1500/5x6 = 50, and energy gain/section = 30 GeV. So $L_{section}$ = 60 m. [Clearly it needs to be divided into small ~1 m sub-sections.] Higher T is desirable (add another annulus, perhaps to double T). For beam power = 14 MW, I_{av} = 9.3 μA, I_{pulse} = 12 mA, or 4.06 pC/bunch. Assumed beam-to-beam efficiency η = 20%.

*Gives overall machine length 2x3 + 2x3 (ip) + … ≈ 15 km.

Issues: creation, stable transport and chopping of annular drive beam; fabrication and precision of mm-scale structure; vacuum integrity; removal of 70-14 = 56 MW, or 18.7 kW/m (~300 W/cm^2) of heat from structure; others???. Partial remedy: increase T and η.

Summary for two-channel DWFA's

Properties of 2-channel rectangular DWFA have been simulated and calculated for experiments based on ANL-AWA bunch parameters.

Double-pulse RF photocathode is to create a 50 nC drive bunch and a smaller time-delayed test bunch.

Energy gain and radiation spectrum will be measured in experiments at ANL-AWA.

This is the first experiment designed to elucidate the performance of a two-channel, two-beam DWFA.

The rectangular two-channel structure may be a good candidate for a fast kicker.

Evolution into a working accelerator requires invention of a multi-channel structure with higher symmetry than the rectangular structure. Coax structure is a good candidate.

Preliminary simulations for coax DWFA show good symmetry with a high transformer ratio and intrinsic transverse stability of the drive and test bunches.

A ~ 2-mm diameter THz structure can set up >1 GV/m gradient using a single 6-nC, 5-GeV annular drive bunch. This gradient level compares favorably with what is found in plasma or laser wake field experiments. A cm-scale structure is under study for proof-of-principle experiments at ANL-AWA.

The quenching wave will complicate the superposition of wakefields from multiple bunches near the entrance to a DWFA structure, but it poses less of a problem for a long accelerating module, since the wake fields can outrun the quenching wave.

Preliminary very rough estimates suggest that a future 3-TeV e^+-e^- collider might be built based on the coaxial DWFA concept, with parameters comparable to CLIC, but in an overall length of ~15 km. But serious practical issues abound....