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High transformer ratio of multi-channel dielectric wakefield structures and real-time diagnostic for charging and damage of dielectrics*

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Abstract:
Dielectric wake field (DWA) accelerator concepts are receiving attention of late, on account of their promising performance, mechanical simplicity, and anticipated low cost. Interest in DWA physics directed toward an advanced high-gradient accelerator has been enhanced by a finding that some dielectrics can withstand very high fields (> 1 GV/m) for the short times during the passage of charged bunches along dielectric-lined channels. In a two-channel structure, a drive bunch train propagates in a first channel, and in the second adjacent channel where a high gradient wakefield develops, a witness bunch is accelerated. Compared with single-channel DWA's, a two-beam accelerator delivers a high transformer ratio, and thereby reduces the number of drive beam sections needed to achieve a given final test beam energy. An overview of multi-channel DWA structures will be given, with an emphasis on two-channel structures, presenting their advantages and drawbacks, and potential impact on the field. Studies that were aimed to study charging rate and charge distribution in a thin walled dielectric wakefield accelerator from a passing charge bunch and the physics of conductivity and discharge phenomena in dielectric materials useful for such accelerator applications will also be briefly presented.

Dielectric Loaded Structures advantages

1. Can sustain accelerating gradients in access of 100 MV/m in upper GHz

M. Conde et al., “High Gradient Excitation and RF Power Generation using Dielectric Loaded Wakefield Structures,” LINAC’08, Victoria, September 2008, MOP067; http://www.JACoW.org.

2. Can sustain gradients of a few GV/m in THz frequency range

M. C. Thompson et al., Phys. Rev. Lett. 100, 214801, (2008).

Foreseeable normal and superconducting structures are limited in achievable gradients… hence Dielectric Loaded structures may offer a solution

Relativistic beam transports the energy to the accelerating structures,

Difficulties of generating and distributing RF power by conventional means are decreased

Wakefields constitute RF pulses that are of short duration and high peak intensity.

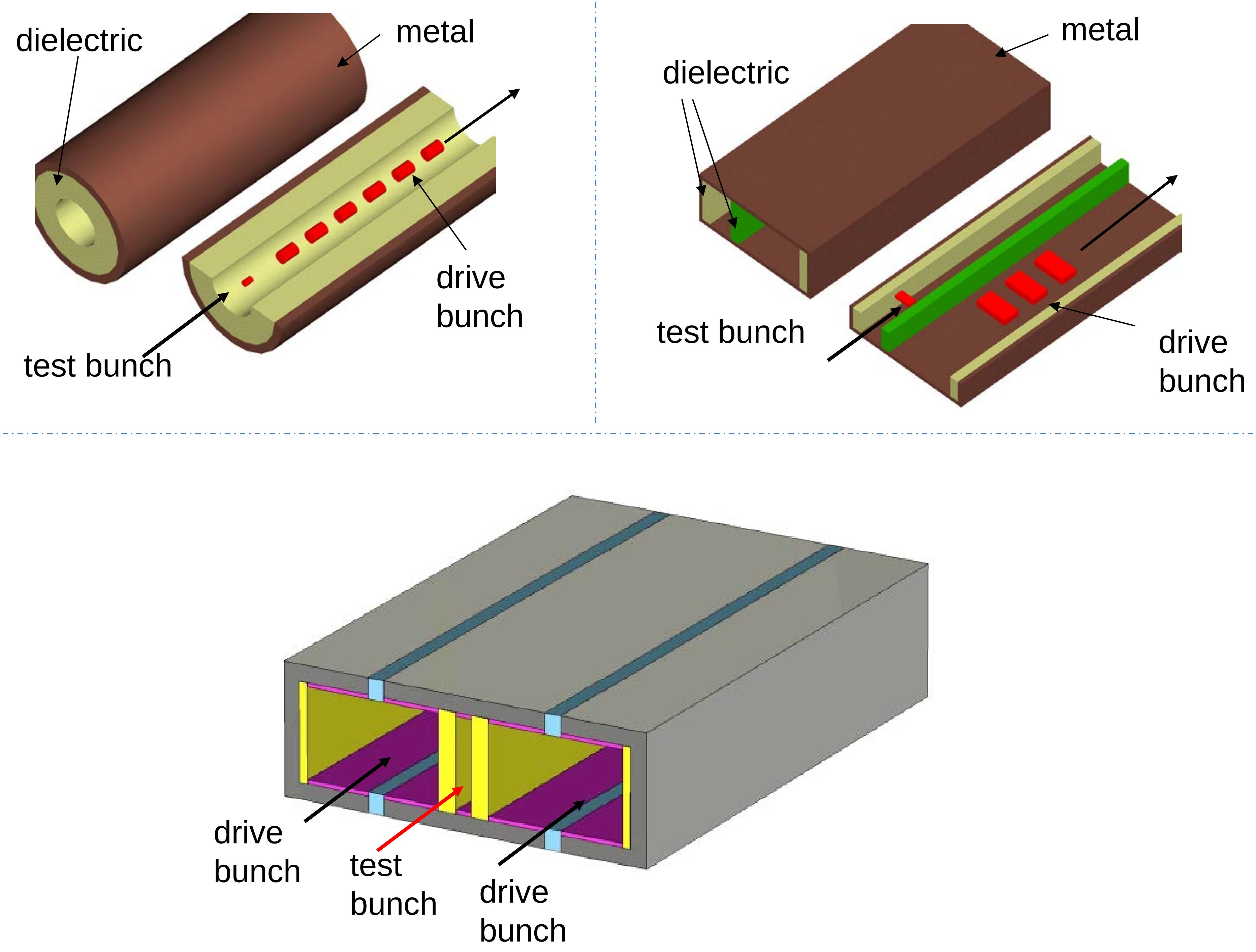
Dielectric Loaded structures offer simpler geometries, and easier fabrication

There are no features that promote field enhancement

It is possible that the accelerating field can be made nearly-uniform across the transverse cross-section

The damping of undesired modes may be more easier done, than in conventional structures

As compared to other wakefield schemes, DWA can accelerate both electrons and positrons in identical fashion


dielectric
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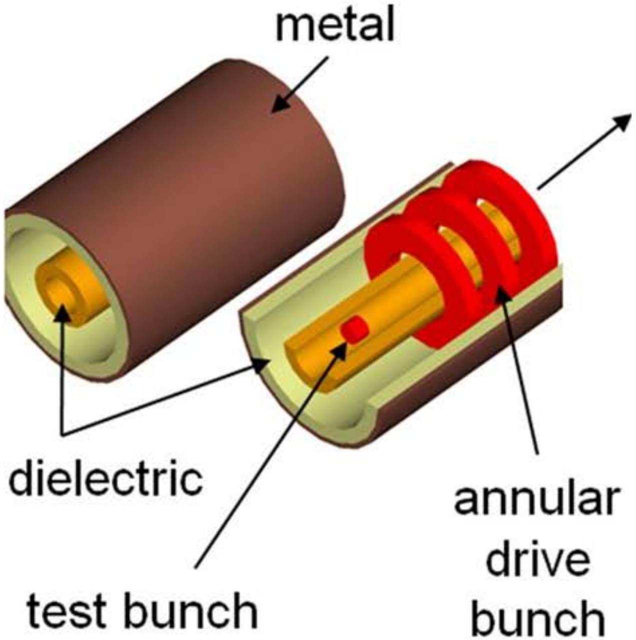
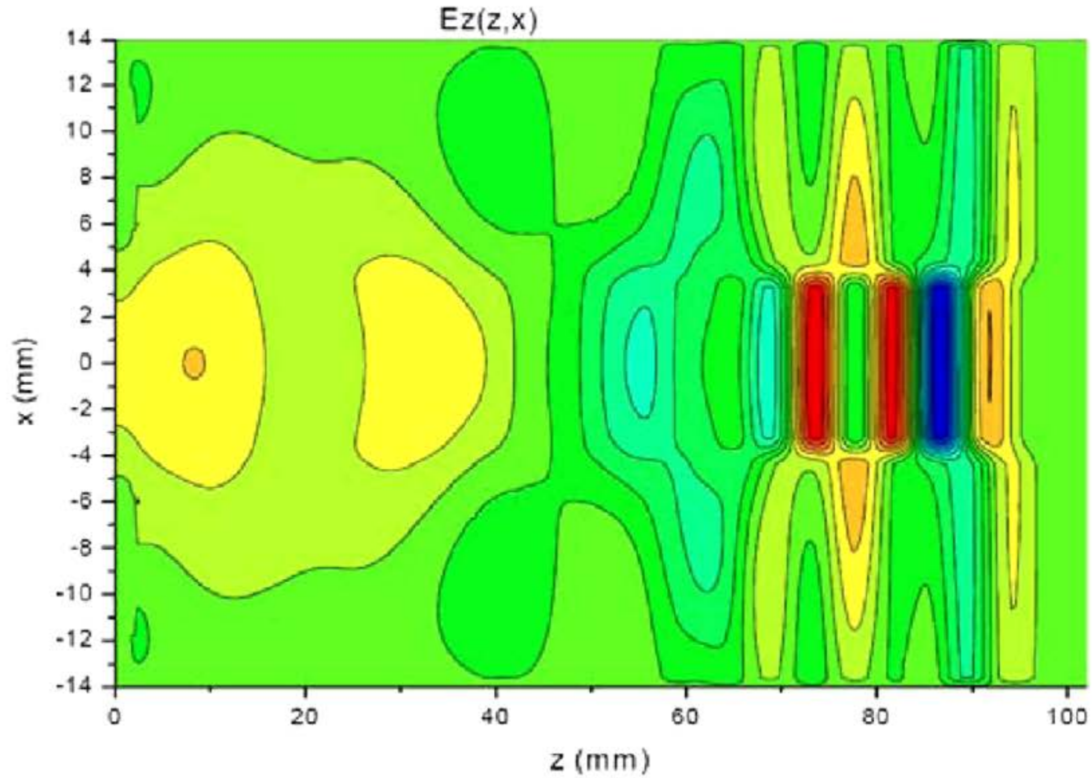




Common problem:

How to focus both the drive bunches and the test bunch ?

High gradient limits due to single bunch beam breakup in a **<u>collinear</u>** **dielectric wakefield accelerator** , C. Li, W. Gai, C. Jing, J. G. Power, C. X. Tang, and A. Zholents
Phys. Rev. ST Accel. Beams 17, 091302 (2014) - Published 16 September 2014

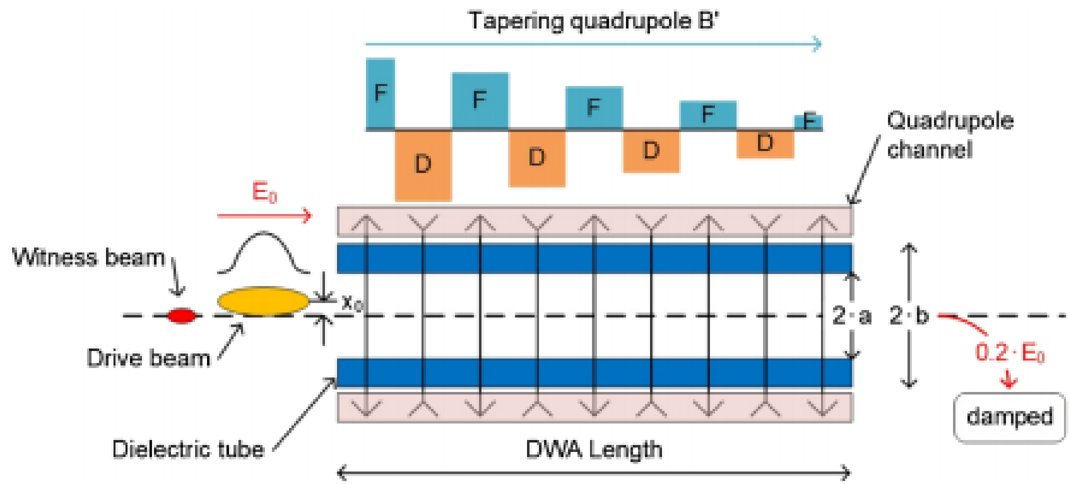


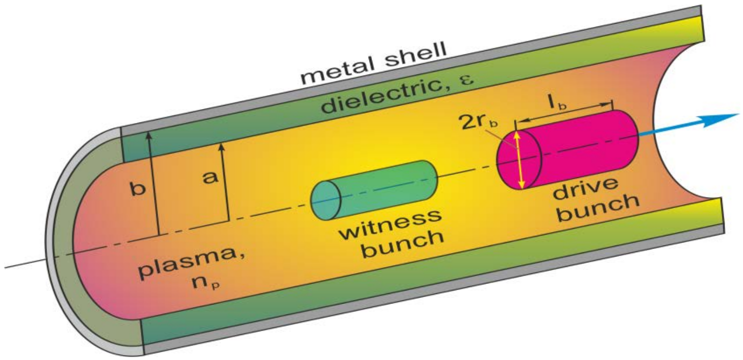
FIG. 1. Schematic of a DWA linac surrounded by a FODO lattice. The quadrupole field gradient B' is tapered to match the energy loss of the drive bunch along the linac. The final energy of the drive bunch at the end of the structure is 20% of its initial energy.

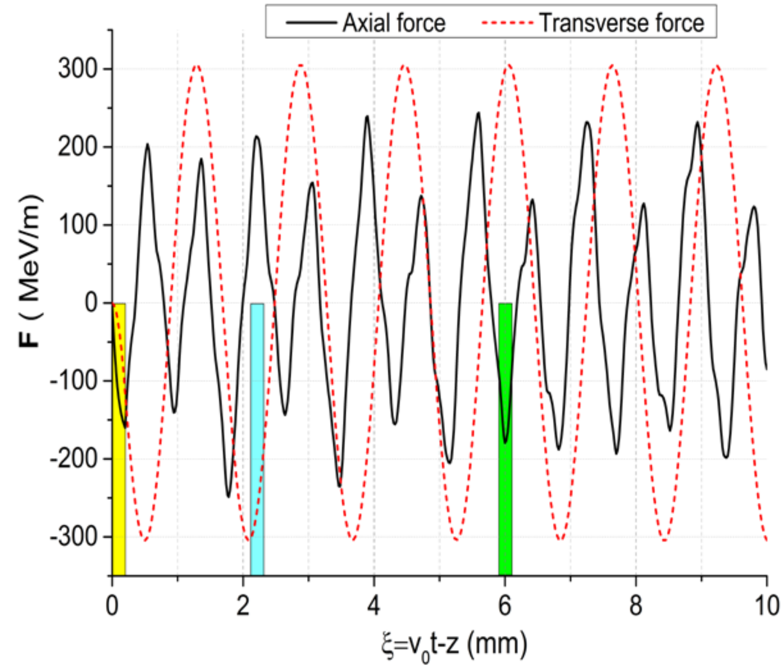
1. addresses the drive bunch focusing
2. will it be applicable to other schemes ?

Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerators

Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, Volume 740, 11 March 2014, Pages 124-129

G.V. Sotnikov, R.R. Kniaziev, O.V. Manuilenko, P.I. Markov, T.C. Marshall, I.N. Onishchenko





G > 200 MeV/m

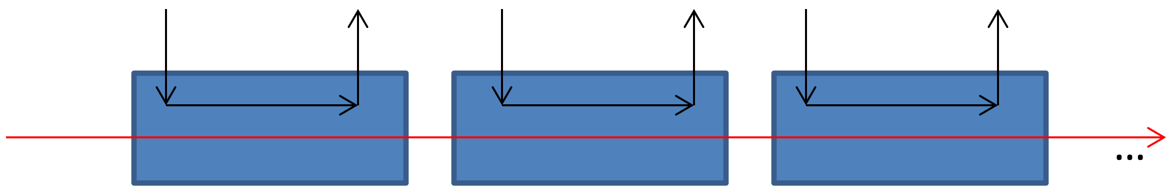
outer radius of dielectric tube	600 microns
inner radius of dielectric tube	500 microns
relative dielectric constant, ε (fused silica liner)	3.75
drive bunch charge	3 nC
drive bunch length, L_b (box distribution)	200 microns
drive bunch radius, r_b (box distribution)	450 microns
drive bunch electron density, n_b	1.47×10^{14} cm^{-3}
n_b/n_p	1/3

Collinear schemes require

1. Profiled bunches, or
2. Profiles bunch trains (RBT)

to get high transformer ratio (TR).

... but is it enough of it ?



E_d – (initial) energy of the drive bunch
η_d – efficiency
L – the length of section
n_c – number of sections
E_f – final energy of the accelerated bunch
$D_g = E_d\eta_d / L$ – deceleration gradient
$A_g = E_f / n_c L$ - acceleration gradient,
$T = A_g / D_g$ - transformer ratio

$$\mathbf{n_c = (E_f / E_d\eta_d) T^{-1}}$$

Crystal Ball :

On the Future High Energy Colliders *

Vladimir Shiltsev
Fermilab, Batavia, IL , USA
Accelerator Physics Center
August 4, 2015

Phenomenological Cost Model

$$\mathrm{Cost(TPC)} = \alpha\, L^{1/2} + \beta\, E^{1/2} + \gamma\, P^{1/2}$$

"Total Project Cost in **the US accounting**"

"Tunnels" – Cost Civil Construction

"Energy" – Cost of Accelerator Components

"Site Power"- Infrastructure

where *α,β,γ* – technology dependent constants

- **α≈ 2B$/sqrt(L/10 km)**
- **β≈ 10B$/sqrt(E/TeV)** for SC&NC RF
- **β≈ 2B$ /sqrt(E/TeV)** for SC magnets
- **β≈ 1B$ /sqrt(E/TeV)** for NC magnets
- **γ≈ 2B$/sqrt(P/100 MW)**

Let:

RPF = test pulse repetition frequency

n_t - number of test particles in one test bunch

η_t – efficiency (acceleration)

η_w – efficiency (wall plug to drive bunches)

p_0 – power per section w/o RF

M – cost (TCP)

$$M = E_f^{1/2}\left[\alpha\left(\frac{L}{E_d\eta_d}\frac{1}{T}\right)^{1/2} + \beta + \gamma\left(\frac{p_0}{E_d\eta_d}\frac{1}{T} + \frac{n_t PRF}{\eta_w\eta_d\eta_t}\right)^{1/2}\right]$$

Large **T** → Smaller cost

Multi-channel schemes

1. Can use RBT and profiled bunches !
2. Naturally deliver high TR even with a single unprofiled bunch !
3. Focusing of drive bunches and accelerated bunches ?

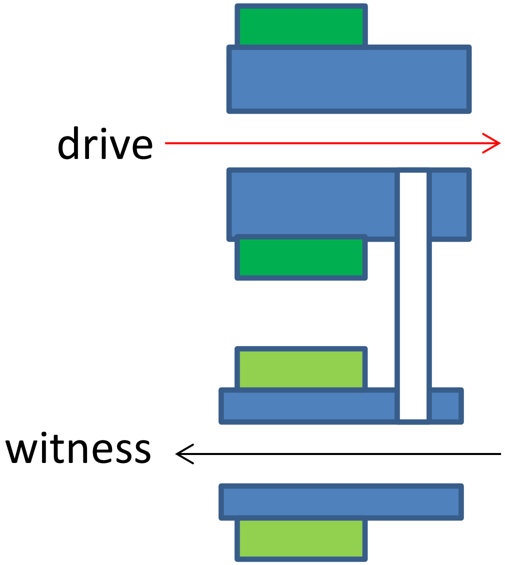
Rectangular two- and more -channel ☑

Coaxial configuration ☑

PETS-like schemes ☐

PETS-like schemes

TBA = Two Beam Acceleration



1. Independent beam-line optics → easier to design and to stage

2. Structures can be optimized independently → easier design

3. Broadband couplers and microwave-energy transmission line are required… how to ??

4. Not broadband ??

AN X-BAND DIELECTRIC-BASED WAKEFIELD POWER EXTRACTOR*

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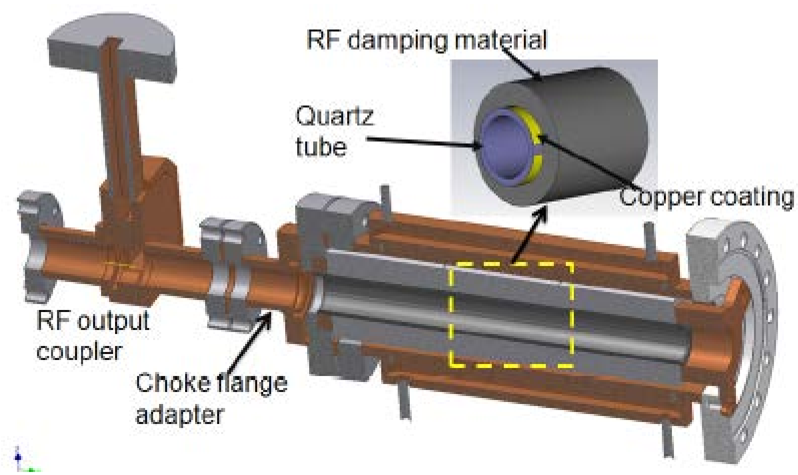
S. Weathersby, J. Lewandowski, V. Dolgashev, S. Tantawi, SLAC, Menlo Park, CA, 94309, U.S.A.
M. Conde, J. G. Power, W. Gai, ANL, Argonne, IL 60439, U.S.A.
I. Syratchev, CERN, Geneva, Switzerland

Parameters	PETS	DWPE
Beam Aperture (mm)	23	23
Effective Length (cm)	21.3	23
Group velocity	0.453c	0.485c
R/Q(ohm/m)	2290	2172
Q	7200	7317
Generated Power (MW)	135	142
Esurf(MV/m/135MW)	56	20



Required pulse length 240ns

Achieved (in RF tests) 100-120 ns at 40 MW

Issues because of multipacting

Coaxial Structure

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **12**, 061302 (2009)

Coaxial two-channel high-gradient dielectric wakefield accelerator

G. V. Sotnikov,[1,2,*] T. C. Marshall,[3,2,†] and J. L. Hirshfield[4,2,‡]

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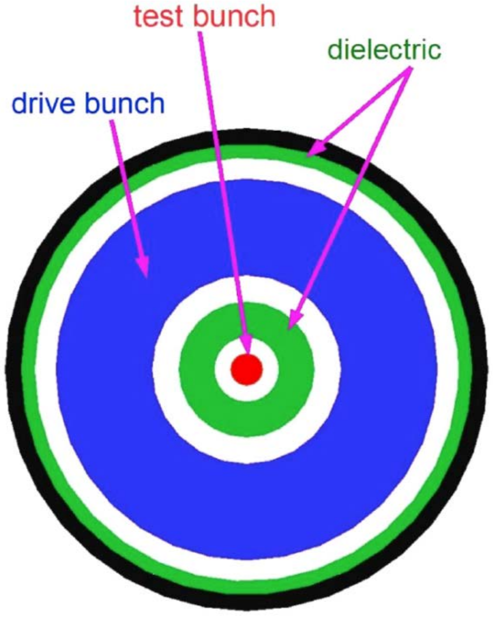
[2]*Omega-P, Inc., 199 Whitney Avenue, New Haven, Connecticut 06511, USA*
[3]*Columbia University, New York City, New York 10027, USA*
[4]*Yale University, New Haven, Connecticut 06520, USA*

(Received 27 March 2009; published 22 June 2009)

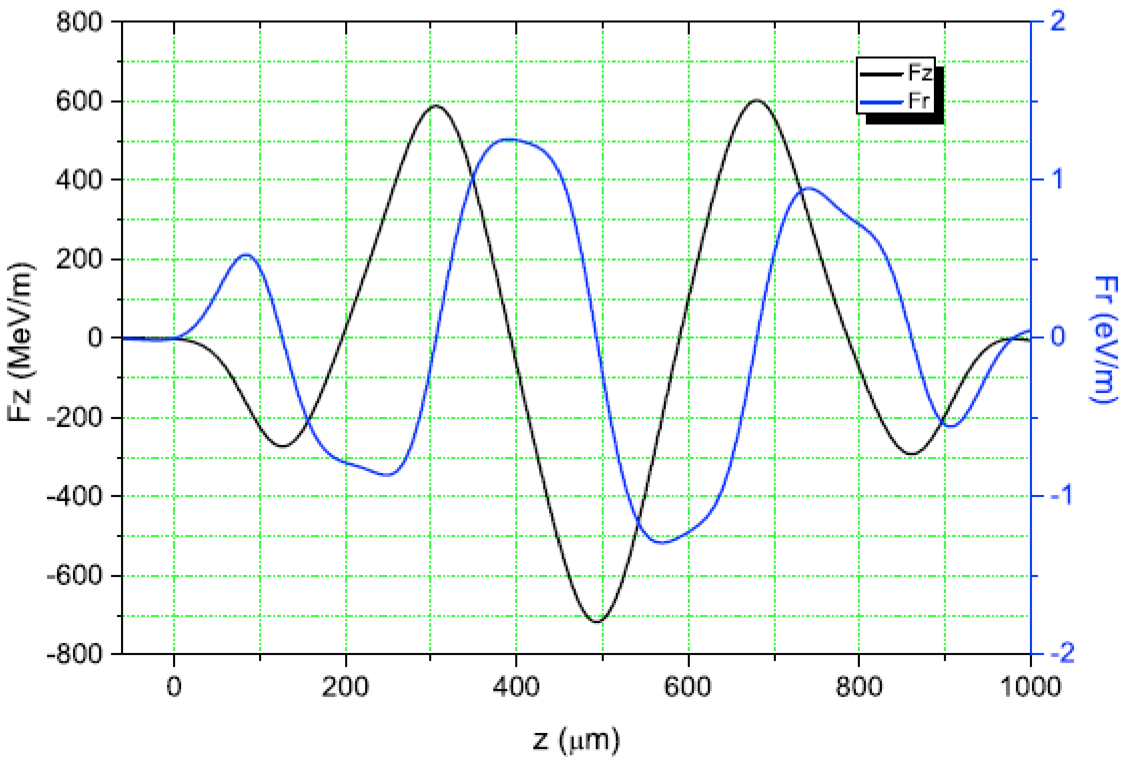


1. Medium- to high- transformer ratio;
2. No need for coupling structures to transfer the energy from the drive beam to the witness beam;
3. Inherent transverse focusing forces acting on the witness bunch
4. Nearly stable motion of the drive bunch ?

Frequency of the E_{02} design mode	912.459 GHz
External radius of outer coaxial dielectric shell r_4	1060.5 μm
Inner radius of outer coaxial dielectric shell r_3	1047.5 μm
External radius of inner coaxial dielectric shell r_2	89.5 μm
Accelerating channel radius (inner radius of inner coaxial dielectric shell) r_1	50.0 μm
Relative dielectric constant of dielectric shells ε	5.7
rms bunch length σ_z (Gaussian charge distribution)	34.64 μm
Outer drive bunch radius (box charge distribution) r_{b2}	718.5 μm
Inner drive bunch radius r_{b1}	418.5 μm
Bunch energy	5 GeV
Bunch charge	6 nC

T $\rightarrow$ 7

$\mathbf{A_g} \rightarrow$ 500 MV/m



Transverse and longitudinal forces acting on the witness bunch

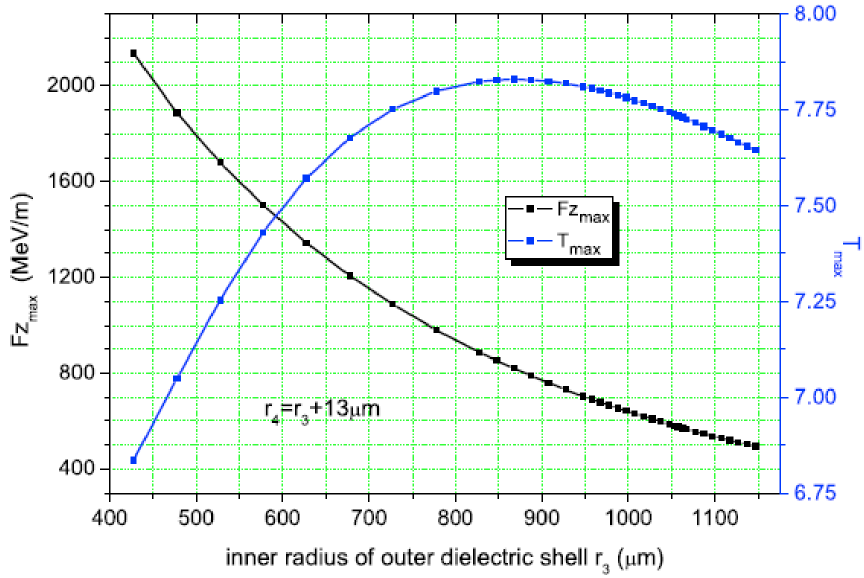


FIG. 6. (Color) The value of the composite longitudinal electric field at the first axial maximum and corresponding transformer ratio versus the dimension of the drive channel. The thickness of the outer dielectric shell is fixed and equal 13 μm. The other parameters are the same as those in Table I.

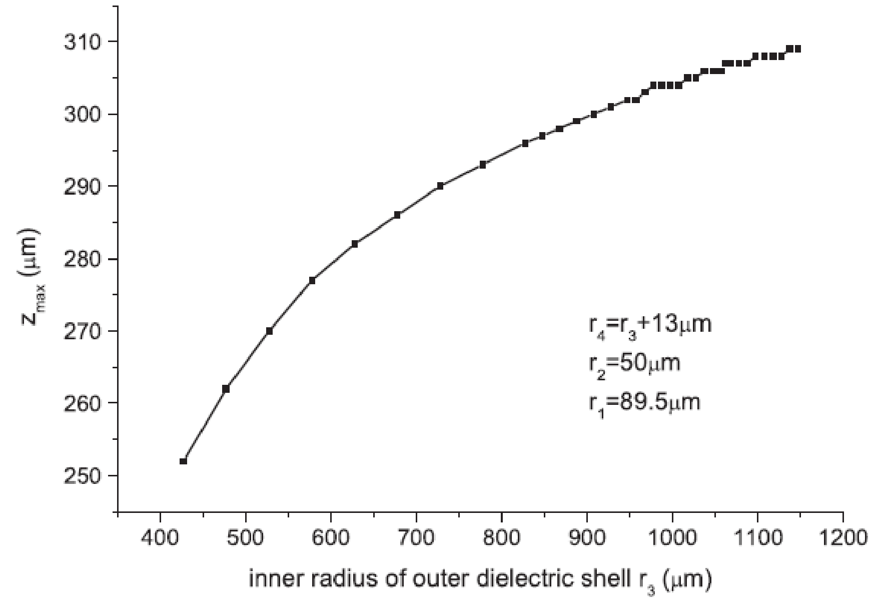


FIG. 7. The location (from drive bunch center) of the first maximum of the accelerating field versus the width of the drive channel. The thickness of the outer dielectric shell is fixed and equal to 13 μm. The other parameters are as in Table I.

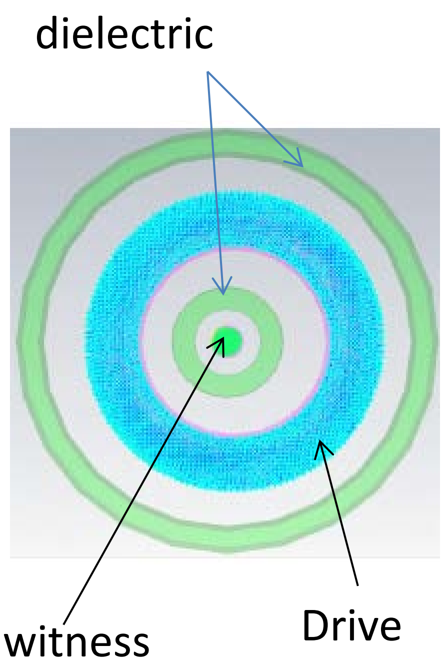
What about asymmetries in the drive bunch distribution, and/or the device geometry ?

AIP | Conference Proceedings

Accelerated Bunch Stability in a Coaxial Dielectric Wakefield Structure When its Symmetry is Broken

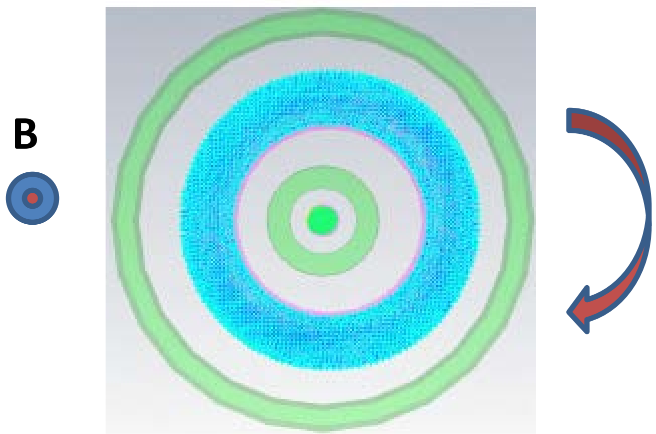
G. V. Sotnikov, T. C. Marshall, J. L. Hirshfield, and S. V. Shchelkunov

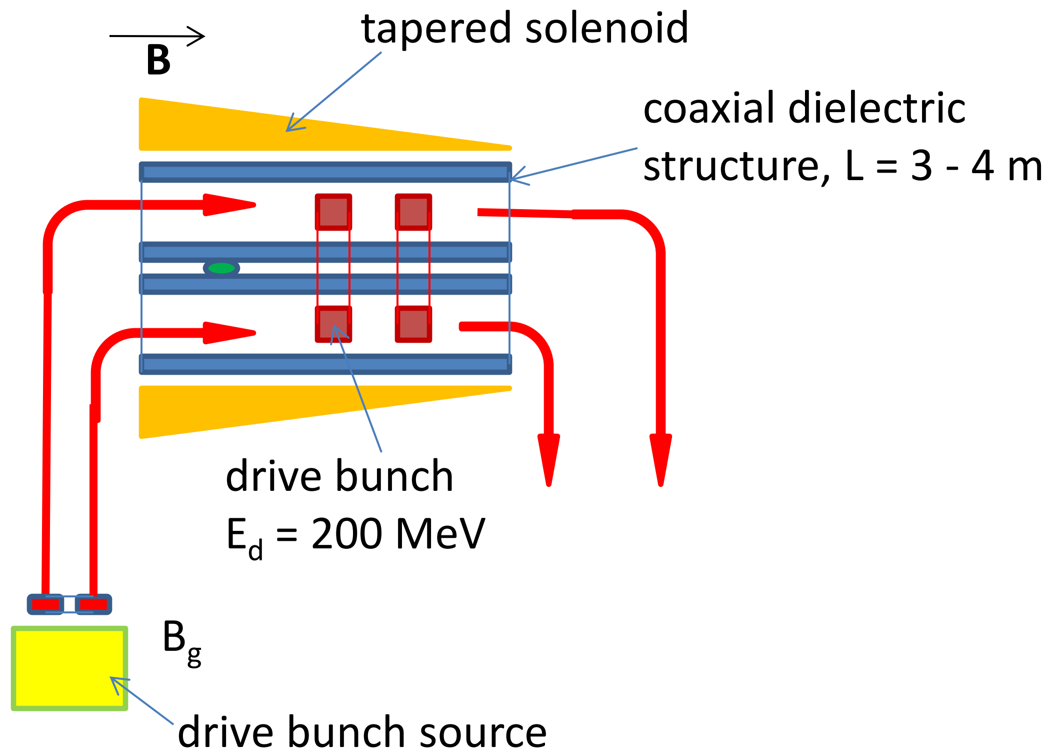
Citation: AIP Conference Proceedings **1299**, 342 (2010); doi: 10.1063/1.3520340
View online: http://dx.doi.org/10.1063/1.3520340



Drive bunch charge = 6nC;
Displaced by 5 microns;
The witness gets displaced by 50 microns over 1 m.

Problem ?
Need corrections to the trajectory by other means every meter.



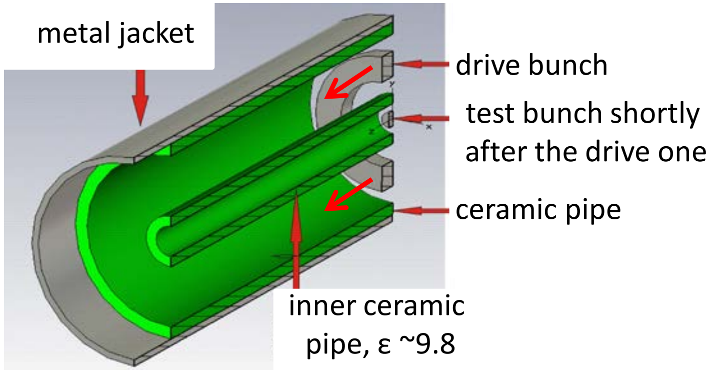


γ_d = 400 (initial)
D_g = 50 - 65 MV/m
A_g = 400 – 500 MV/m

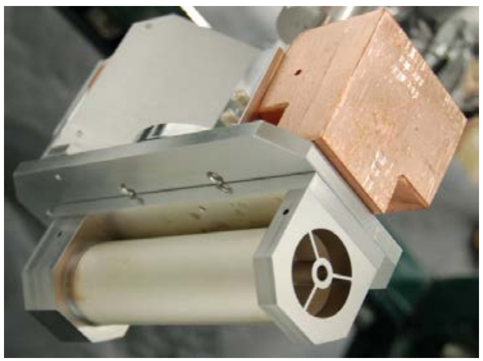
B = 1 T (entrance)
B_g = -1 T (at the source)

one revolution of the drive bunch over 3 – 4 m

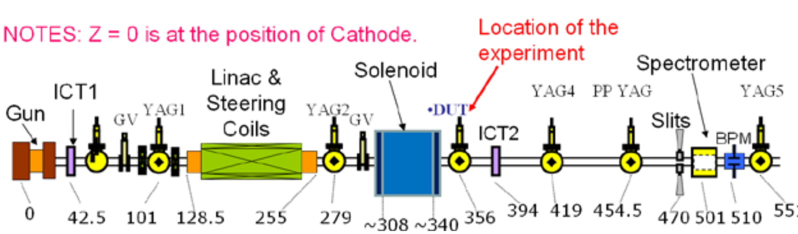
Proof-of-Principle Experiment

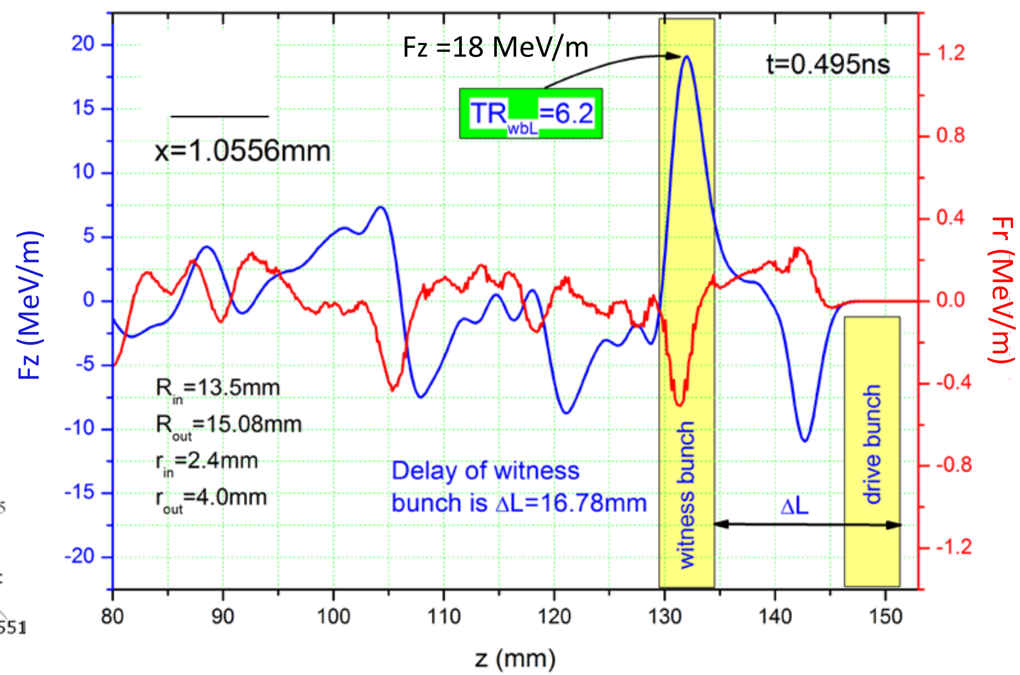


E_{02} design mode	18.82 GHz
TR	~6
External radius of outer coaxial cylinder R_{out}	15.08 mm
Inner radius of outer coaxial waveguide R_{in}	13.5 mm
External radius of inner coaxial cylinder r_{out}	4 mm
Inner radius of inner coaxial waveguide r_{in}	2.4 mm
Dielectric permittivity (Alumina)	9.8
drive/witness bunch energy	14 MeV
drive bunch charge	50 nC
outer drive bunch radius (Box distribution)	< 10.75mm
inner drive bunch radius	> 6.75mm
witness bunch charge	< 1 nC
witness bunch radius (Box distribution)	< 1.2 mm



AWA beam-line





PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **14**, 031302 (2011)

Improved ramped bunch train to increase the transformer ratio of a two-channel multimode dielectric wakefield accelerator

G. V. Sotnikov[1,2,*] and T. C. Marshall[2,3,†]

A recipe:

-- to have **high TR in a coaxial multimode [a few-mode] structure**, and

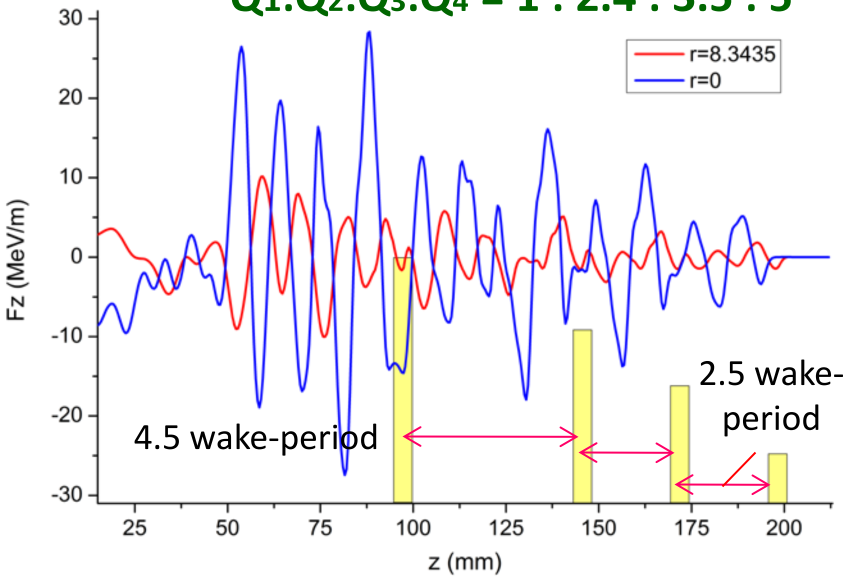
-- to have **all the drive bunches to have the same deceleration** (so that the drive train can be use efficiently)

A) Take the 1st bunch;
compute TR_1;
find acceleration peak;

B) Place 2nd bunch there ;
select the charge of 2nd bunch = Q_1 *[1+ TR_1];

C) To work w/ many bunches do the following:
... for the bunch train w/ n-1 bunches find TR_{n-1};
... find closest acceleration peak
... place there nth-bunch w/ $Q_n = Q_1 * [1 + TR_{n-1}]$

$Q_1:Q_2:Q_3:Q_4$ = 1 : 2.4 : 3.5 : 5

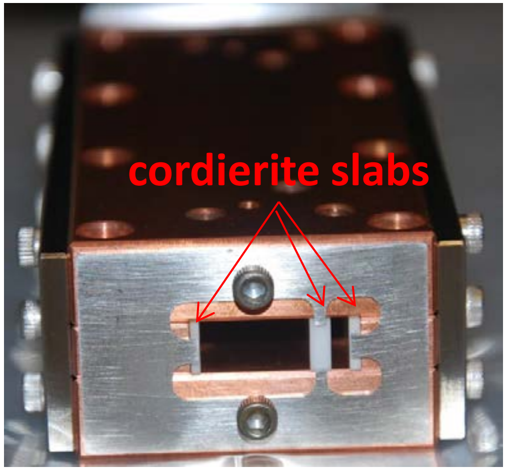


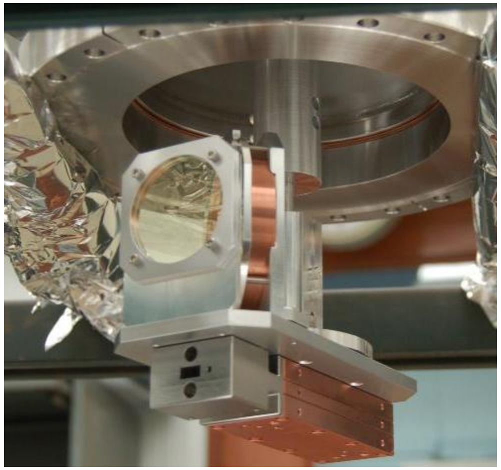
Demonstrated (theoretically) that T can be enhanced by a factor of almost 5 with 4 ramped drive bunches

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **15**, 031301 (2012)

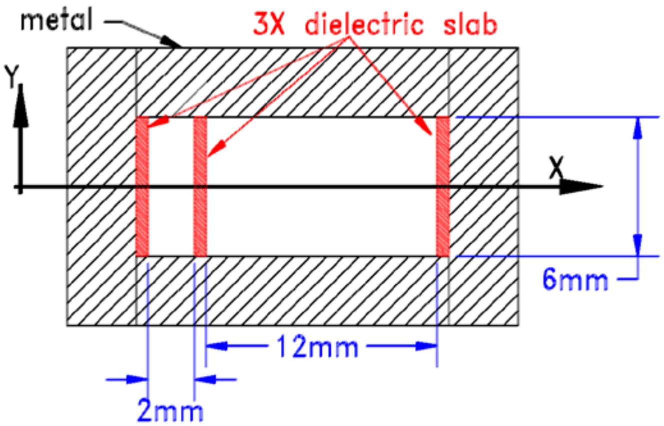
Comparison of experimental tests and theory for a rectangular two-channel dielectric wakefield accelerator structure

S. V. Shchelkunov,[1] T. C. Marshall,[2] G. Sotnikov,[2,3] J. L. Hirshfield,[1,2] Wei Gai,[4] M. Conde,[4] J. Power,[4] D. Mihalcea,[4] and Z. Yusof[4]





T = 12.6 :1

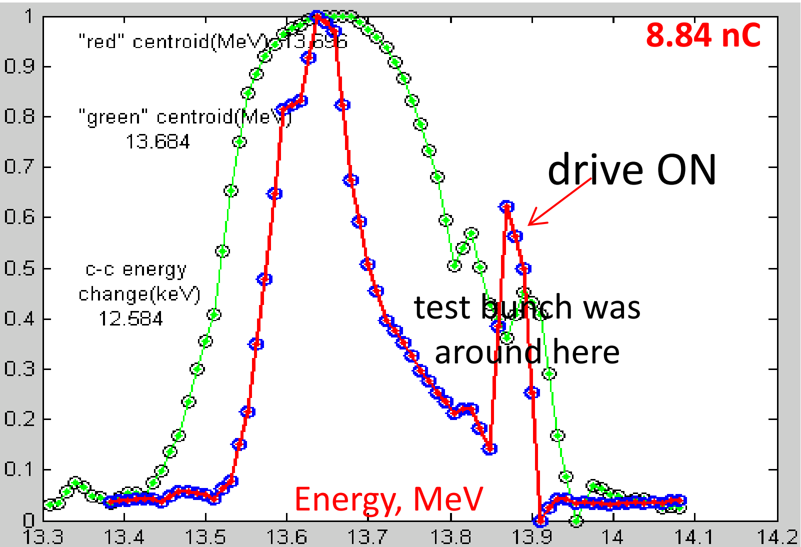


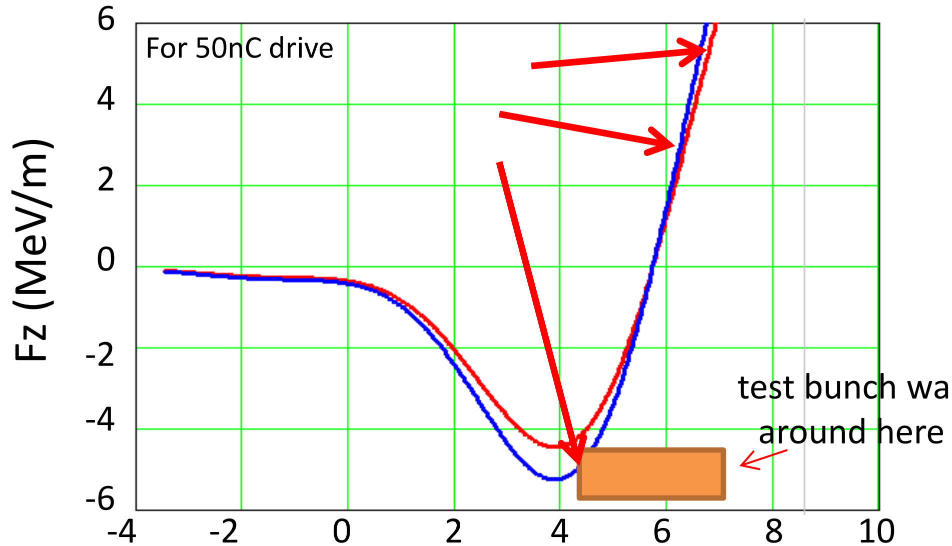
Design mode	**LSM_{31}, 30GHz**
Accel. ch	**2 x 6 mm**
Drive ch	**12 x 6 mm**
Slab 1 THK	**1.25 mm**
Slab 2 THK	**2.3 mm**
Slab 3 THK	**1.06 mm**
Slab ε	**4.76**
Length	**10 cm**

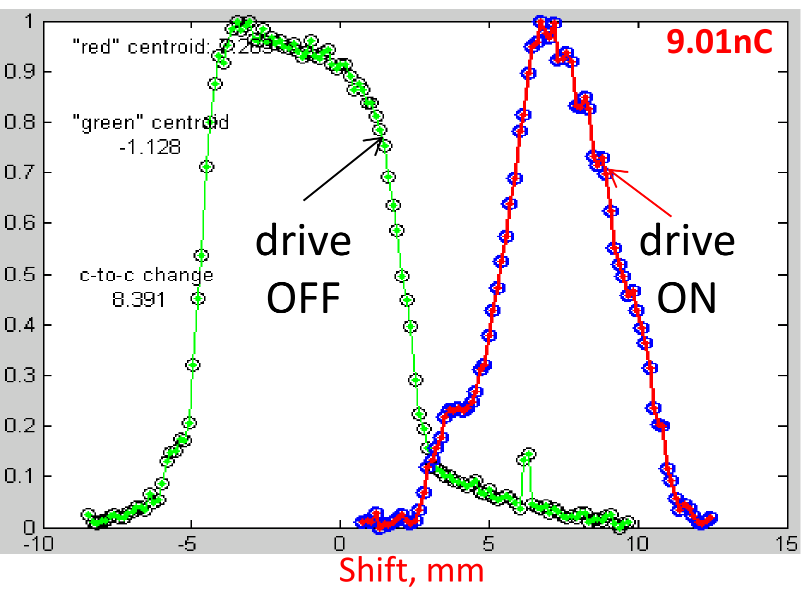
Energy loss up to **50 – 100 keV**
Energy gain up to **90 - 100 keV**
Energy change (average) ~0 keV
X-kick about **6.18 – 6.8 mrad**

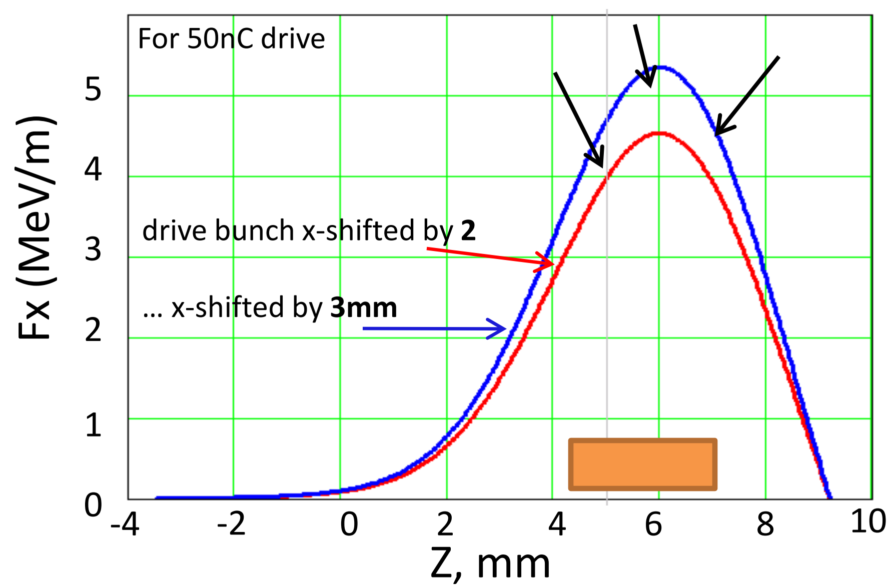
Recalculating for the 50nC of drive and normalizing per 1m:
To have loss , Fz must be up to -4.95 / - 5.5 MeV/m
To have gain, Fz must be up to **+2.75 / 5.5 MeV/m**

To have X-kick Fx must be about **4.65 / 5.12 MeV/m**









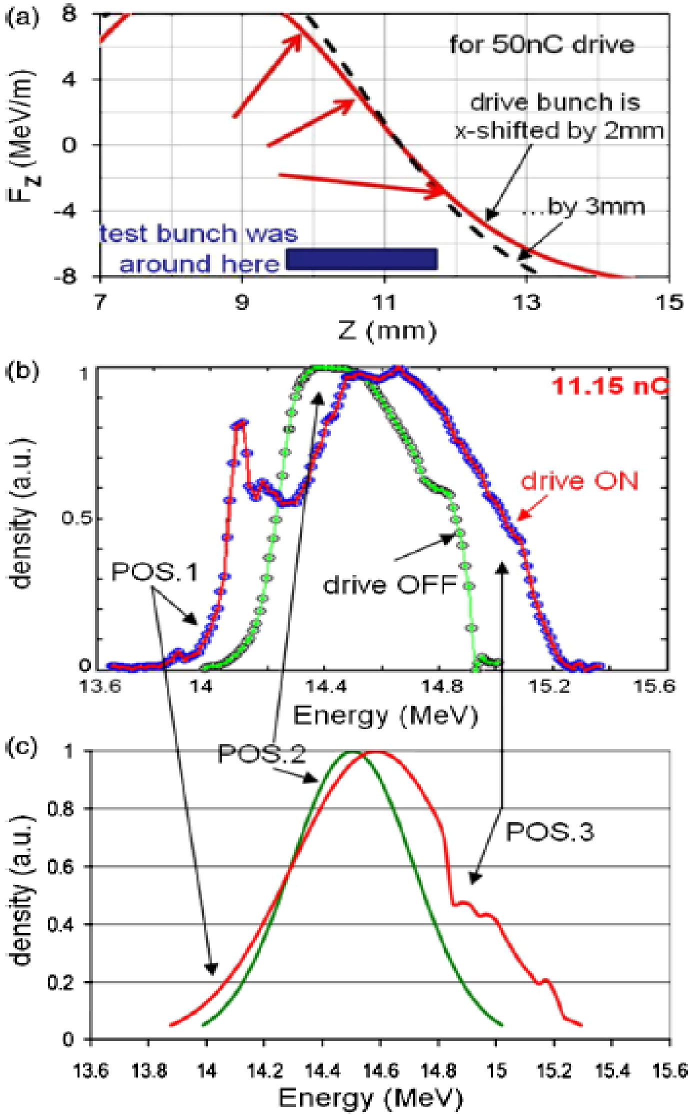


FIG. 13. (a) Simulations of F_z for the test channel [values are renormalized to 50 nC (see explanations in the text)] for the delay 10.7 mm. (b) Typical energy distribution (observed in 80% of shots; normalized to 1). (c) CST MICROWAVE STUDIO simulations to predict changes in the energy distribution [for case #2 in Table V, and the drive bunch being shifted off the center of its respective channel by 2 mm (toward the test channel)].

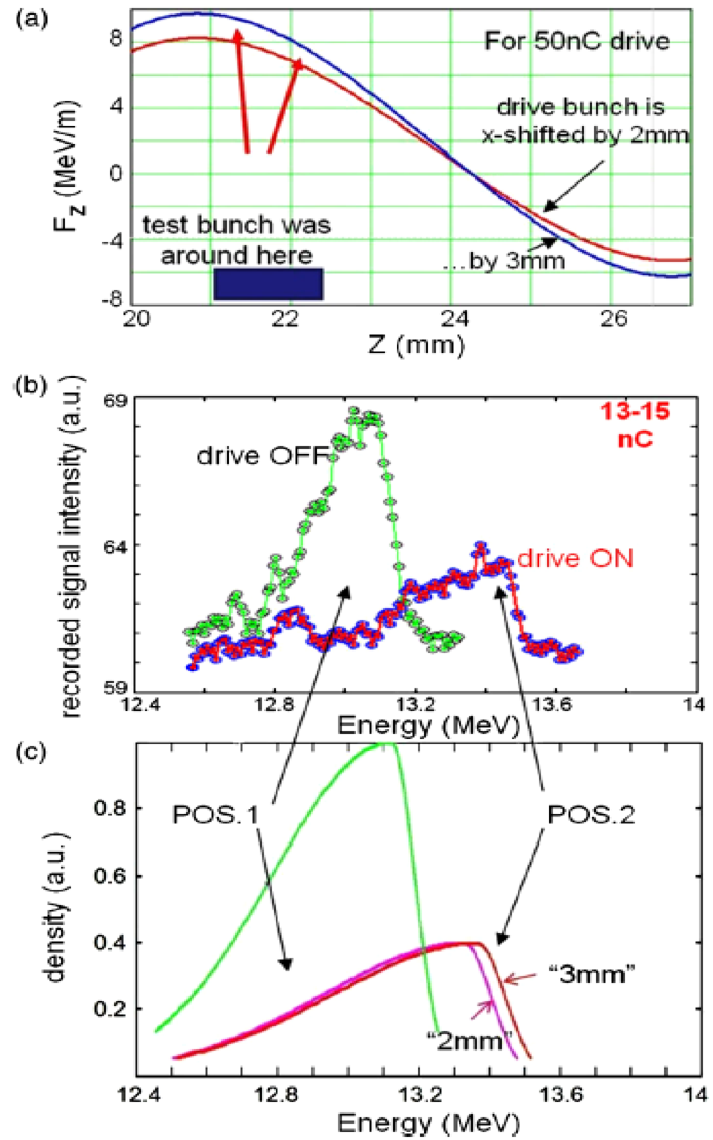


FIG. 14. Simulations of F_z for the test channel [values are renormalized to 50 nC (see explanations in the text)] for the delay 21.7 mm. (b) Typical energy distribution (observed in 80% of shots; raw intensity data are shown). (c) Simulations to predict changes in the energy distribution (for case #3 in Table V).

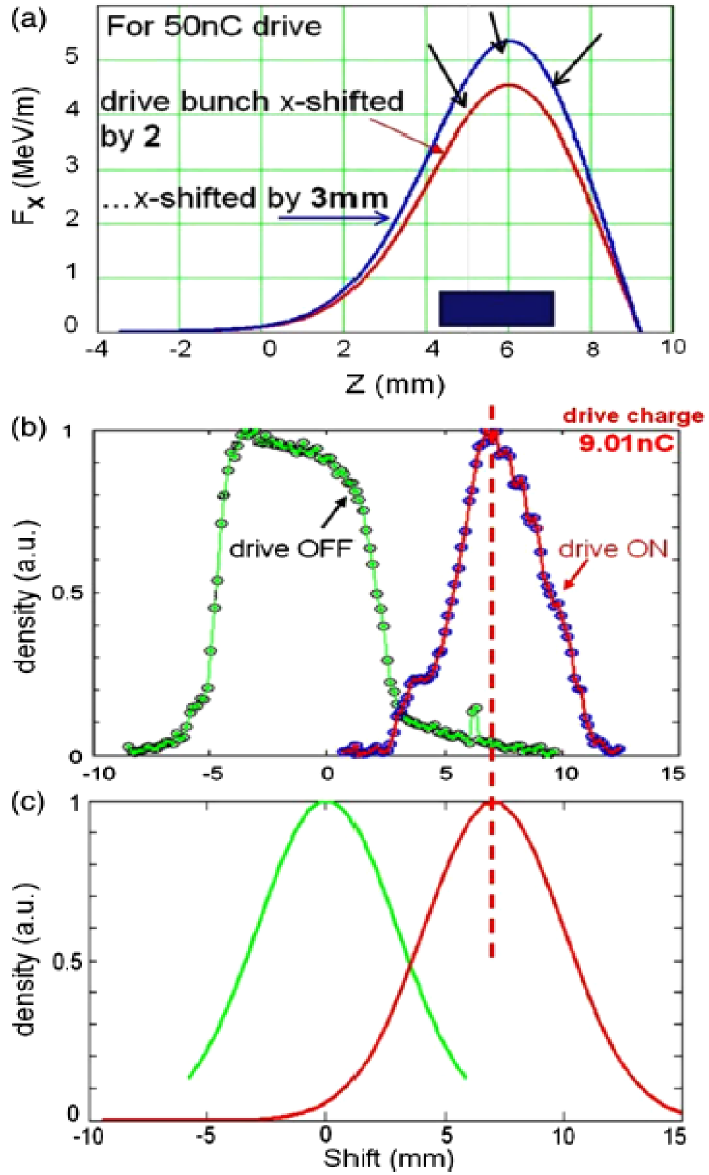


FIG. 15. (a) Simulations of F_x for the test channel. (b) Typical bunch horizontal distribution (observed in 80%–85% of shots, normalized to 1) for the delay was 5.7 mm. (c) Simulations that predict changes in the horizontal distribution [for case #1 in Tables V and VI, for the drive bunch being shifted off the center of its respective channel by 2 mm (toward the test channel)].

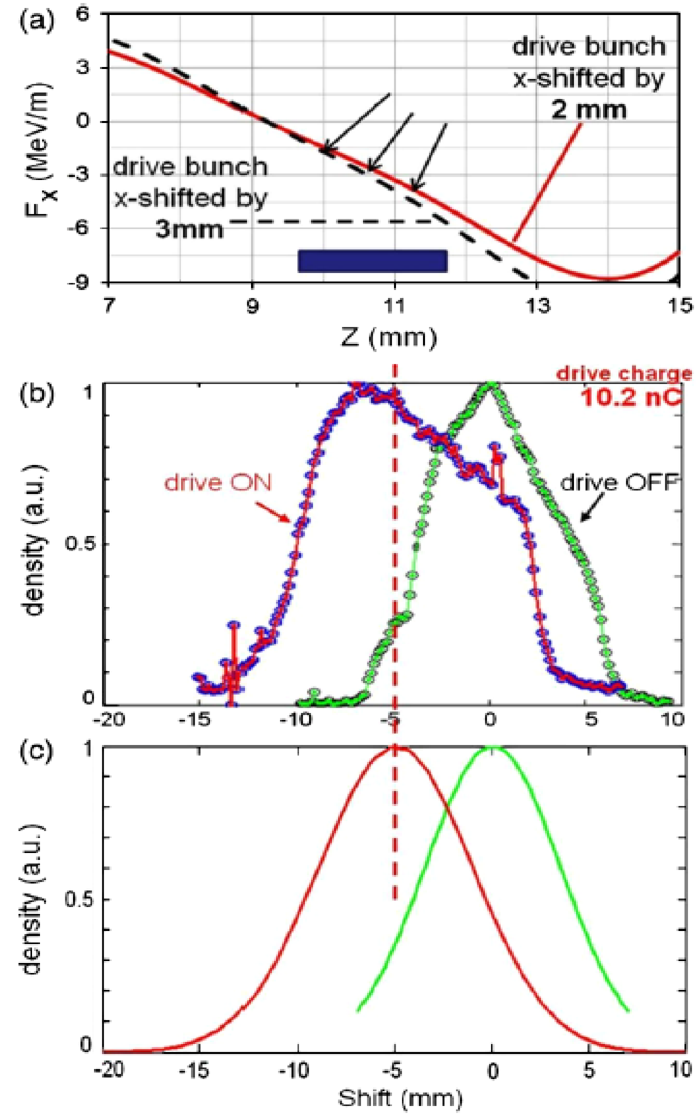
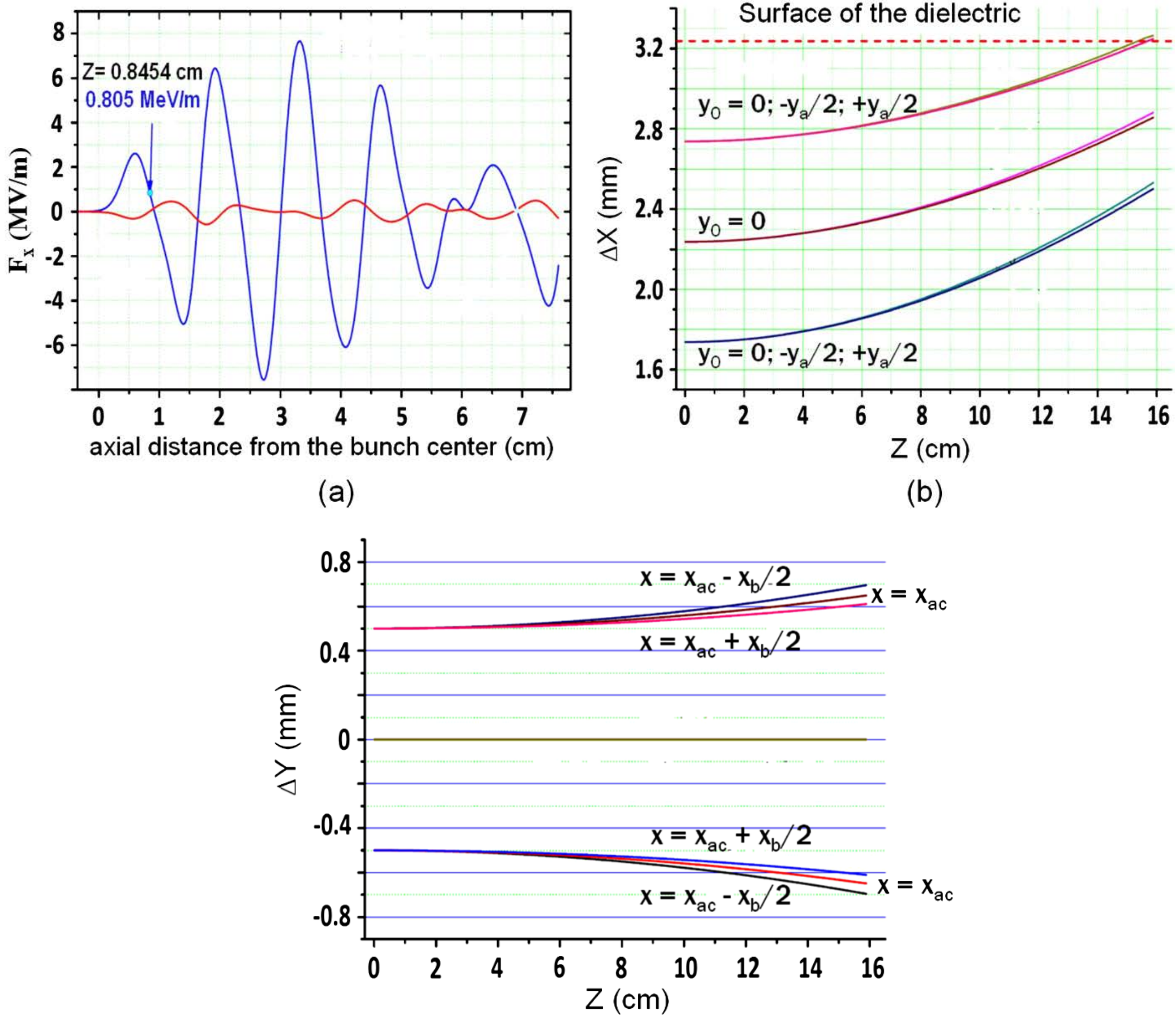


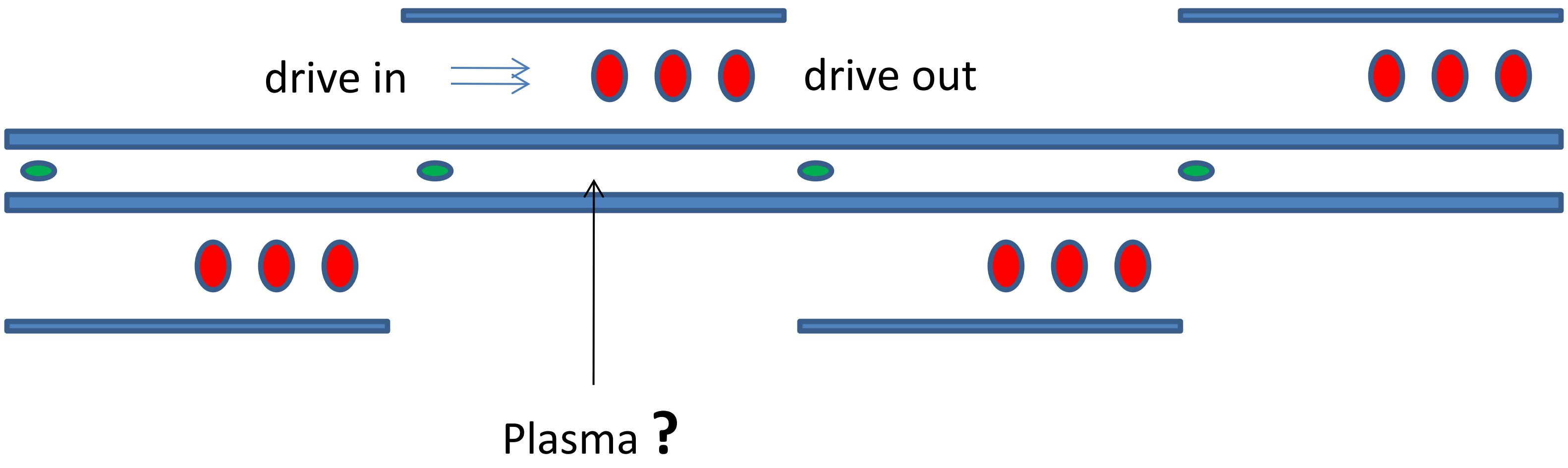
FIG. 16. (a) Simulations of F_x for the test channel. (b) Typical bunch horizontal distribution (observed in 80% of shots, normalized to 1) when the delay was 10.7 mm. (c) Predicted changes in horizontal distribution [case #2 in Tables V and VI with the drive bunch being shifted off the center of its respective channel by 2 mm (toward the test channel)].



Z= 0.8454 cm
0.805 MeV/m
F_X (MV/m)
axial distance from the bunch center (cm)
(a)
Surface of the dielectric
y_0 = 0; -y_a/2; +y_a/2
y_0 = 0
y_0 = 0; -y_a/2; +y_a/2
ΔX (mm)
Z (cm)
(b)
x = x_ac - x_b/2
x = x_ac
x = x_ac + x_b/2
x = x_ac + x_b/2
x = x_ac
x = x_ac - x_b/2
ΔY (mm)
Z (cm)

GHz –scale structure can be scaled down to a THz-scale structure with nearly the same **T**

… but what to do with the witness bunch deflection (X) and weak-defocusing (Y) **?**



AIP Conference Proceedings

Analysis of a Symmetric Terahertz Dielectric-Lined Rectangular Structure for High Gradient Acceleration

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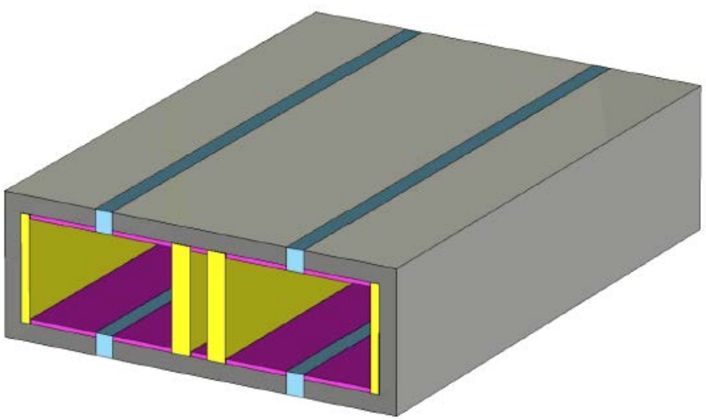
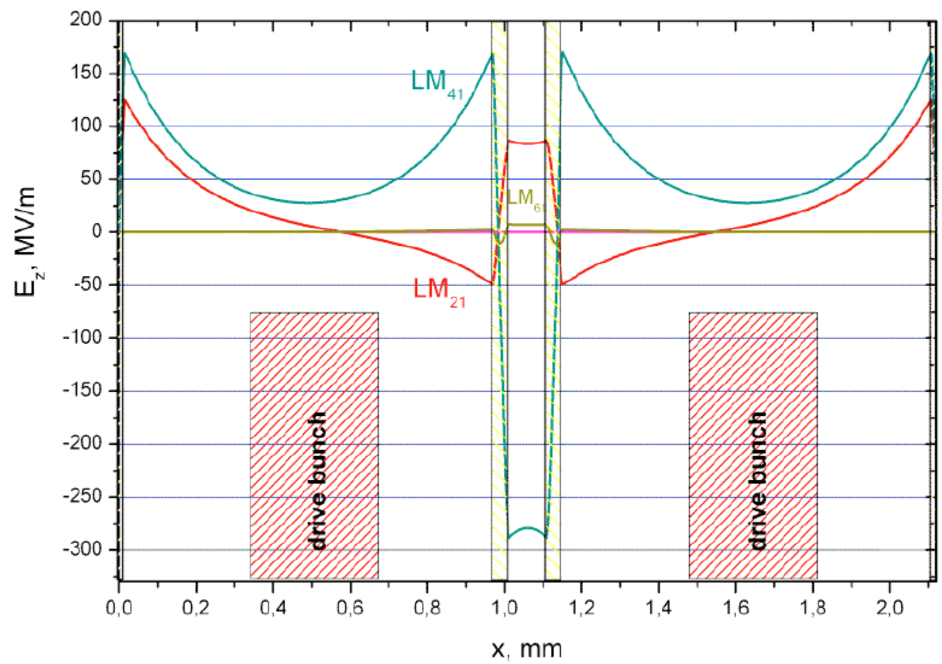




T = 18 – 20

A_g ~ 350 MV/m

driven by two bunches that propagate in sync in parallel drive channels

TABLE I. Parameters for a three-channel symmetric dielectric wakefield accelerator module.

LSM_{41} design mode eigenfrequency ($v_{phase} = c$)	1003.43 GHz
drive channels dimensions $2a_1 = 2a_3$	0.958 mm
Accl. channel dimensions $2a_2$	0.1 mm
structure height $2d$	0.6 mm
transformer ratio	~20
slab-1 and slab-4 thickness	0.013 mm
slab-2 and slab-3 thickness	0.0395 mm
slab relative dielectric constant	5.7
bunch size	$0.3 \times 0.3 \times 0.12\ mm^3$
bunch energy	5 GeV
bunch charge	3 nC
bunch charge density	$277.8\ nC/mm^3$
peak beam current	7.5 kA
number of bunches in each drive channel	1
first drive bunch center location, x	0.492 mm
second drive bunch center location, x	1.629 mm

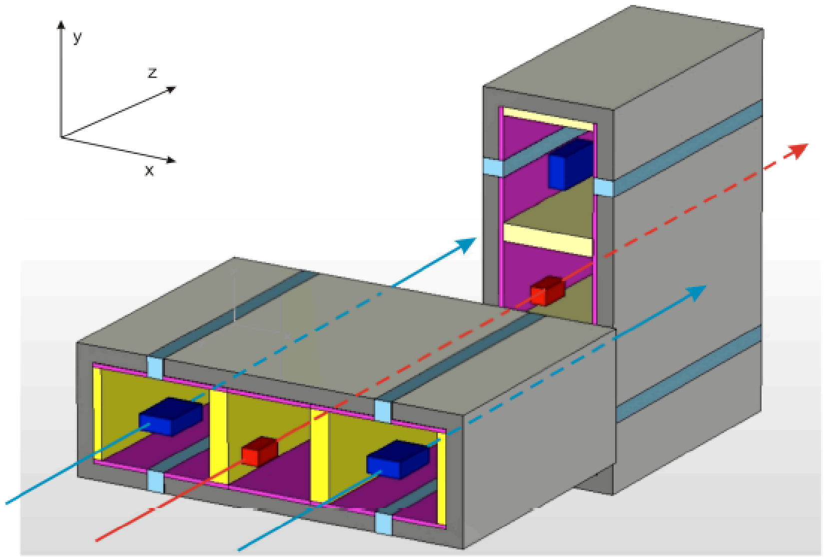


FIGURE 6. Two sections of a modular accelerator showing the 90 degree rotation about the axis of the witness bunch channel which provides dynamical stabilization for the witness bunches in a pair of units.

This can address the issues of how to have a stable witness bunch motion

However, speaking of the drive bunches…
… how to focus, or at least keep them weakly-unstable remains a big question ?

Having two sync drive bunches in parallel makes it very difficult to design a focusing scheme.

In short:

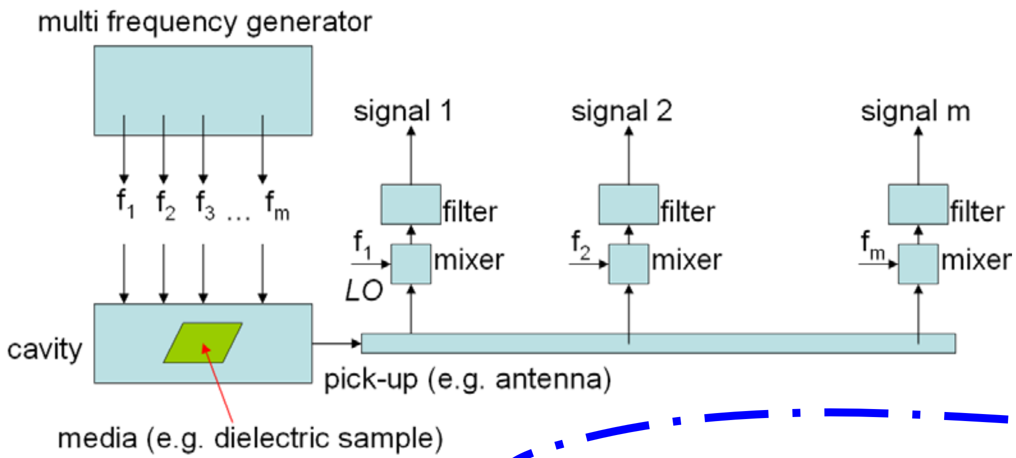
1. Multi-channel schemes can deliver large T (transformer ratio)

2. Which results in large cost-savings when building the machine

3. THz-scale (mm-scale) structures can deliver gradients 300 -500 MV/m

4. However, the problems with keeping the witness bunches stable,
and at least keeping the drive bunches unstable…
… are still to be addressed

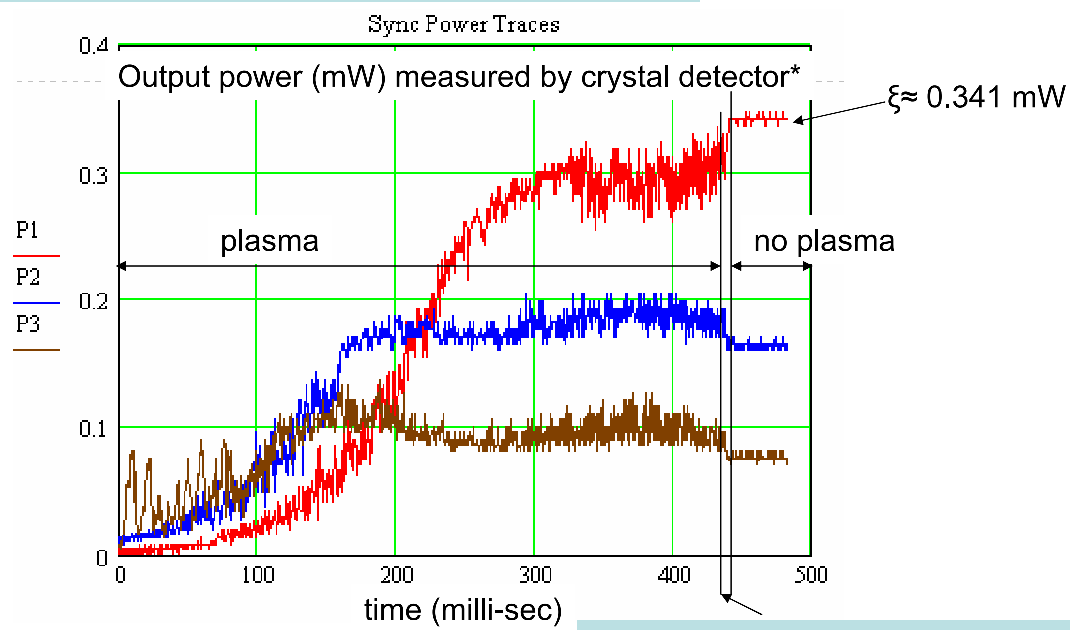
5. Charging effects, or effects of strong wakefields on dielectrics…
… are still to be investigated/ discovered



Generic schematic of the measurement system. Only principal elements are shown.

Traces were recorded at three observer frequencies:

f1 = 2479.1936 MHz (≈ resonant frequency) (RED)
f2 = 2480.276 MHz (BLUE)
f3 = 2481.141 MHz (BROWN)

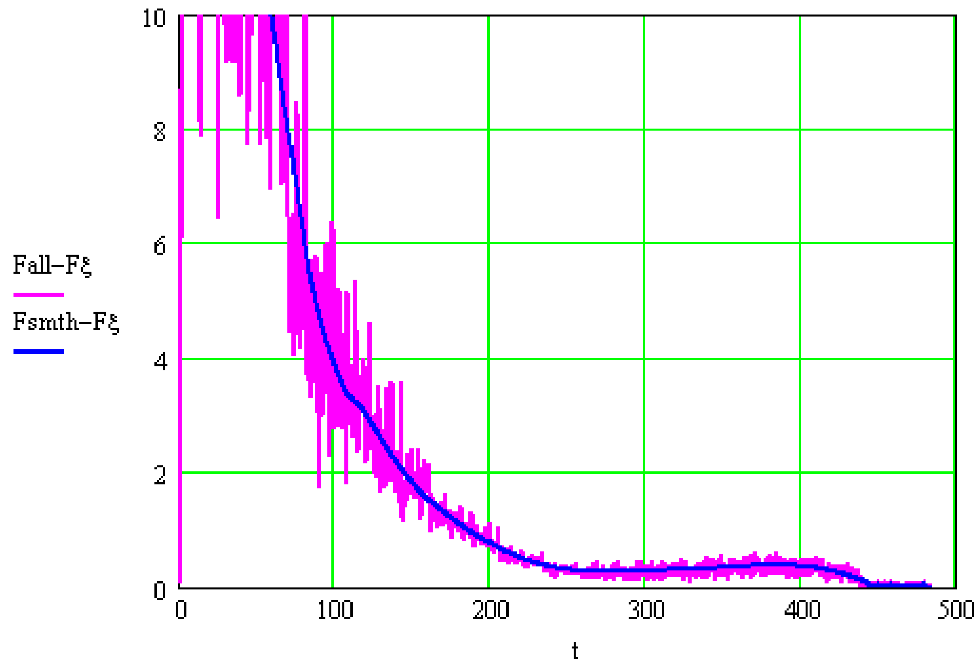


This "jump" in the traces data points will give us our sensitivity

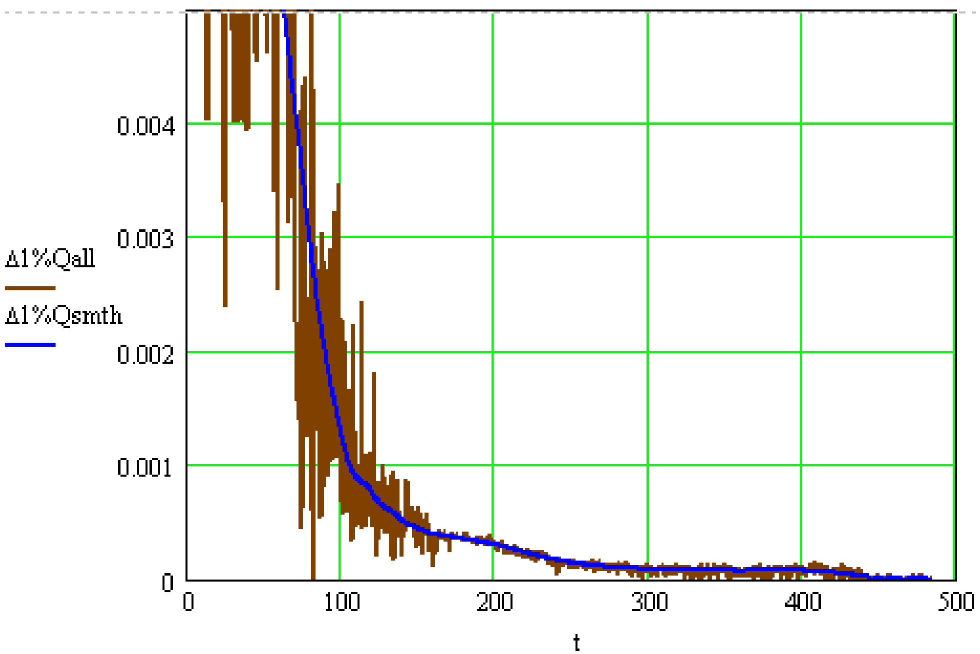
*Input power stays the same

From transmission data at different frequencies

1. One knows the changes in the Q-factor and resonant frequency (F) of the cavity
2. Known the geometry, one knows the changes in the complex electric permittivity, and so on

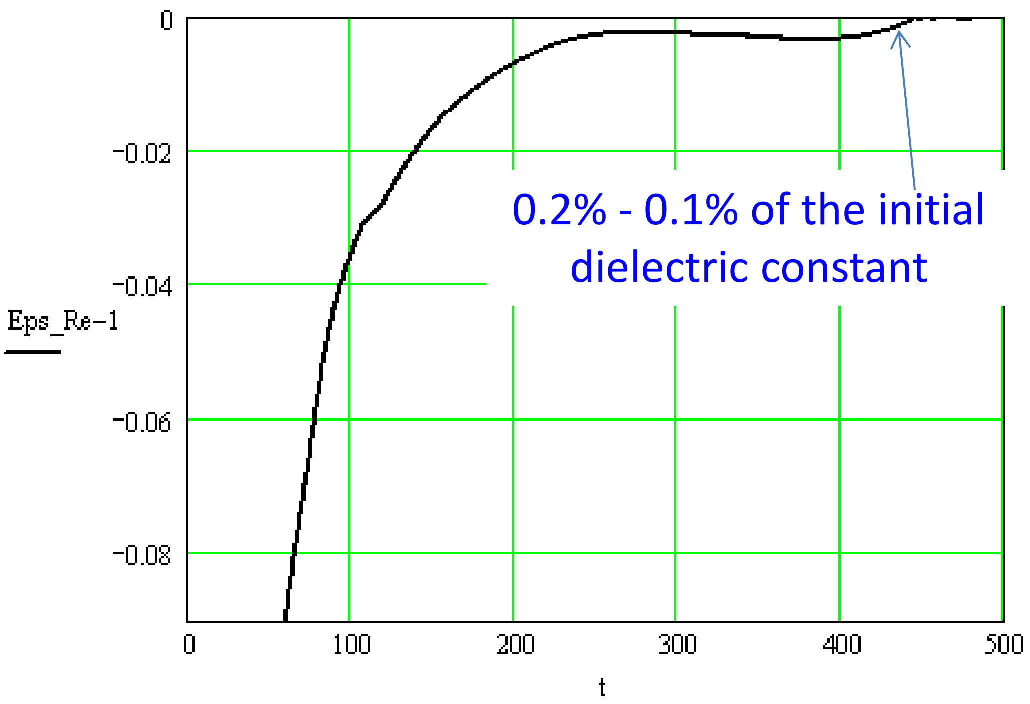


Changes in the resonant Frequency (MHz) vs. Time (ms)

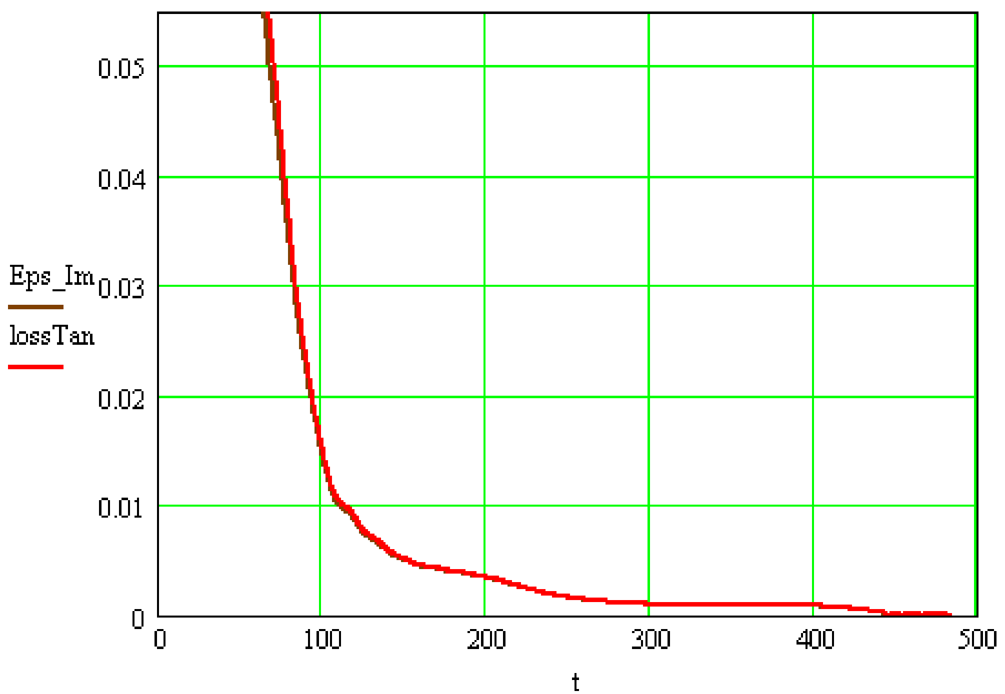


Changes in the Q-factor vs. Time (ms).

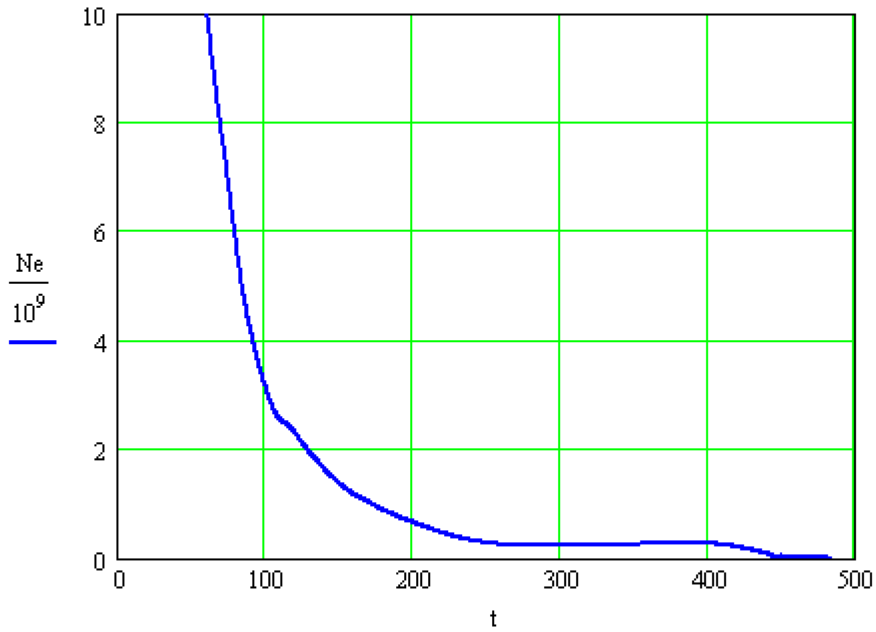
This is plotted as ($1/Q-1/Q_{\xi}$), where the latest in the Q-factor when there is no plasma



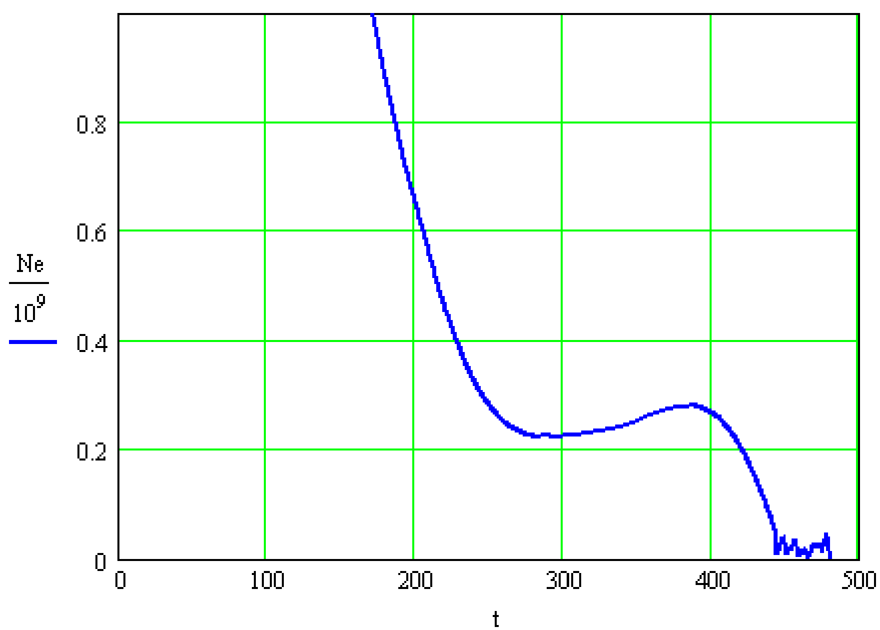
Changes in Real part of dielectric constant vs. Time (ms)



Changes in the loss-tan and the Imaginary part of dielectric constant vs. Time (ms)



Electron density (×10^9 cm^{-3}) vs Time



- **can detect the densities at or even above 10^{10} cm^{-3}**
- **can detect electron density at or even below ~ 10^8 cm^{-3}**
- **modifications are possible to push to 3×10^7 cm^{-3} at micro-sec time scales**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