Structure-Based Beam-Driven Accelerator

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Yale University

Omega-P R&D, Inc.
Accelerator Physics & Technology

(ATF) to provide

1) number of bunches	> 300 - 400;
2) charge per bunch	2 nC;
3) bunch size, transverse	< Ø 2mm @ IP;
4) bunch size, longitudinal	< 2mm @ IP;
5) bunch energy spread, Pk-Pk	as suitable for beam transport;
6) frequency	2.856 GHz for bunch spacing;
7) bunch energy	~10 MeV;
8) total beam power, peak	~ 56 MW;
9) beam power, average	~ 8 W @ 1Hz;

10)conservative number of klystrons at 20 MW = 3;

(Omega-P R&D) note: the frequencies of our structure =
11.424GHz + third harmonic, (by design); or
22.+ GHz + third harmonic, (by design)

"Detuned-Structure-Based Beam-Driven Accelerator”,
Yong Jiang, Xiangyun Chang, Sergey Shchelkunov, Jay L. Hirshfield, Proc. of the 18th Advanced Accelerator Concepts Workshop (AA2018, Breckenridge, Colorado, Aug. 12-17, 2018; eds. E.I. Simakov, N. Yampolsky, and K.P. Wootton); ISBN: 978-1-5386-7721-6; pp. 176 - 180

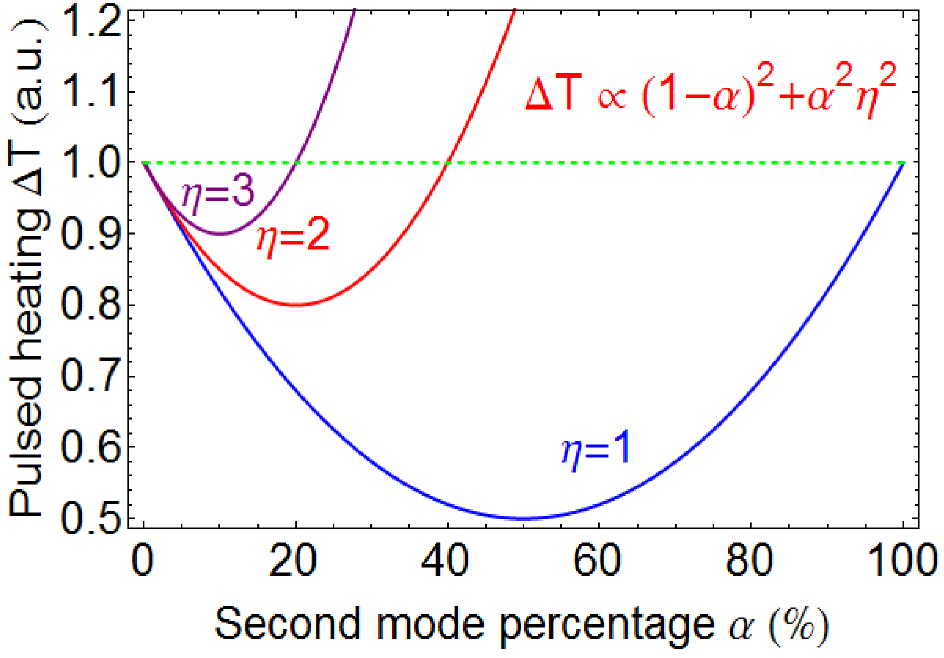
"Structure-based, high transformer ratio collinear two-beam accelerator",
Yong Jiang, Sergey V. Shchelkunov, and Jay L. Hirshfield, AIP Conference Proceedings 1812, 070003 (2017); http://doi.org/10.1063/1.4975883
http://aip.scitation.org/doi/pdf/10.1063/1.4975883

“Multi-harmonic test setup for RF breakdown studies”,
Y. Jiang et al., Nucl. Instrum. Methods Phys. Res. A, 657, 71–77 (2011)

“High-gradient two-beam accelerator structure”,
S. Yu Kazakov, S. V. Kuzikov, Y. Jiang, and J. L. Hirshfield
Phys. Rev. ST Accel. Beams **13**, 071303 (2010)

Suppression of Surface Pulsed Heating

"Quadratic Dependence" Effect



$$E_{total} = (1-\alpha)E_1 + \alpha E_2$$

$$H_{total} = (1-\alpha)H_1 + \alpha H_2$$

E_1 , E_2 normalized to the same acceleration gradient

α is the percentage of the 2nd mode

$$\Delta T \propto (1-\alpha)^2 < H_1^2 > +\alpha^2\sqrt{f_2/f_1} < H_2^2 > =< H_1^2 > [(1-\alpha)^2 + \alpha^2\eta^2]$$

where $\eta = \sqrt{(f_2/f_1)^{1/2} < H_2^2 >/< H_1^2 >}$

$$\exists\alpha \qquad (1-\alpha)^2 + \alpha^2\eta^2 < 1$$

also, modified Poynting vector S_c and total RF power P_{total} are reduced.

Two harmonic mode superposition could suppress pulsed heating – a possible precursor to breakdown.

TM_{010}+TM_{012} Cavity

a/λ=0.10 π mode standing wave effective gradient E_{acc}=100 MV/m	TM_{010} + TM_{012} Bimodal Cavity 1st harmonic alone	 3rd harmonic alone	 84% 1st +16% 3rd	Pillbox A 1st harmonic only	Pillbox B 1st harmonic only	Nose-cone 1st harmonic only
frequency (GHz)	11.9942	35.9826		11.9942	11.9942	11.9942
effective shunt impedance (MΩ/m)	100.73	24.65	▲ 124.19	100.43	99.18	127.7
transit time factor	0.753	0.633		0.762	0.758	0.749
max E_{surf} (MV/m)	209.8	359.2	▼ 178.0	206.7	178.0	218.6
max H_{surf} (MA/m)	0.309	0.776	0.339	0.309	0.309	0.267
max S_c (W/μm²)	2.365	9.700	▼ 1.670	3.190	3.181	3.68
max ΔT (K) @ 200ns pulse length	24.46	261.8	▼ 19.15	24.46	24.46	17.65
wall loss (MW)	1.241	5.069	▼ 1.006	1.244	1.260	0.979

2-mode superposition compared to fundamental mode alone in the same cavity :

- ◊ pulsed heating temperature ↓22%
- ◊ effect shunt impedance ↑23%
- ◊ peak surface E-field ↓19.4%
- ◊ modified Poynting vector ↓30%
- ◊ total RF power ↓ 19%

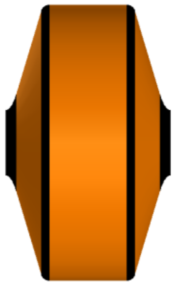
	Bimodal (16%)	Nose-cone	
effective gradient E_a	150	150	MV/m
effective shunt impedance	124.2	127.7	MΩ/m
max E_{surf}	267	327.9	MV/m
max H_{surf}	0.509	0.401	MA/m
max S_c	3.76	8.28	W/μm²
max ΔT @ 200ns pulse length	43.1	39.7	K
wall loss	2.26	2.20	MW

Bimodal Cavity for Pulsed Heating Suppression

TM_{010}+TM_{012} (f + 3*f*)

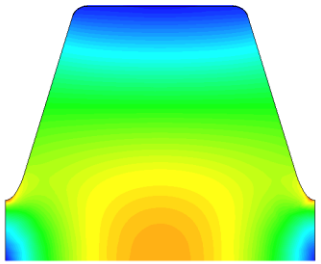
elliptical cavity

a/λ=0.1



TM_{010} 12 GHz

E



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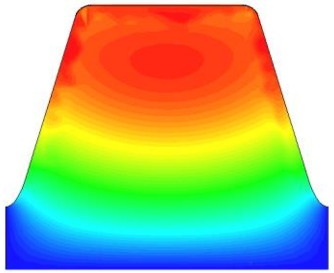
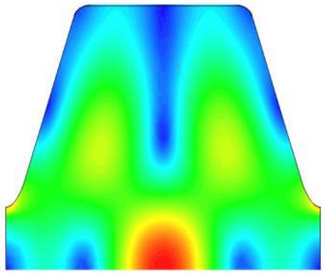


TM_{012} 36 GHz

E



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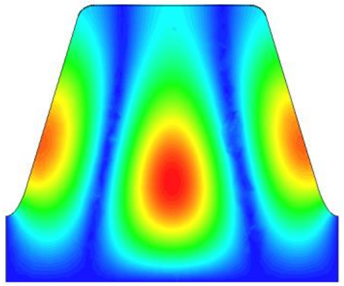
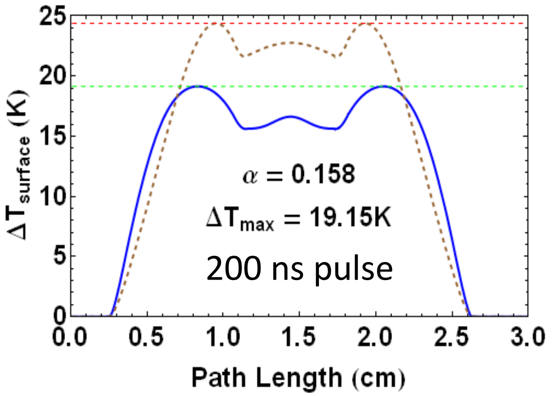
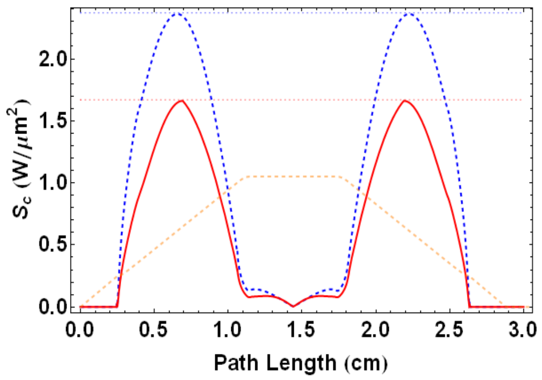


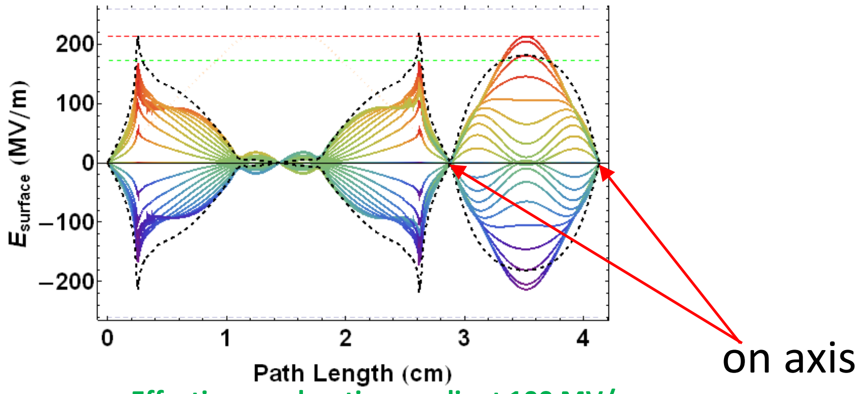
pulsed heating temperature



modified Poynting vector S_c



surface E-field along periphery

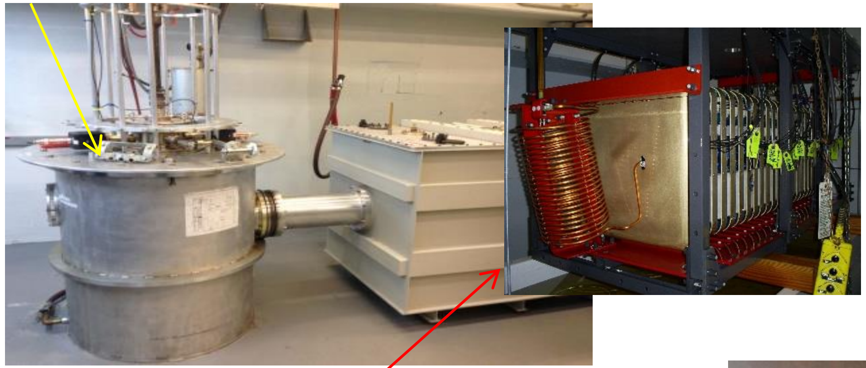


Effective acceleration gradient 100 MV/m

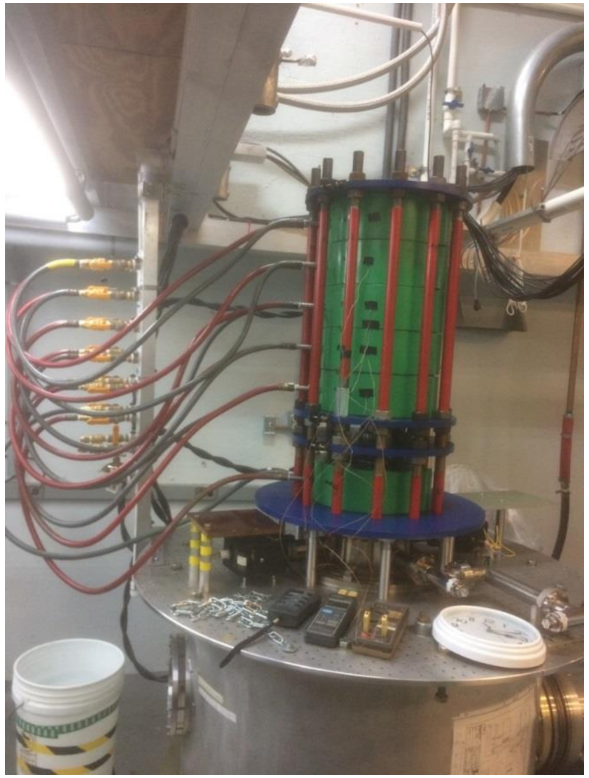
2-mode superposition compared to fundamental mode alone in the same MHC :

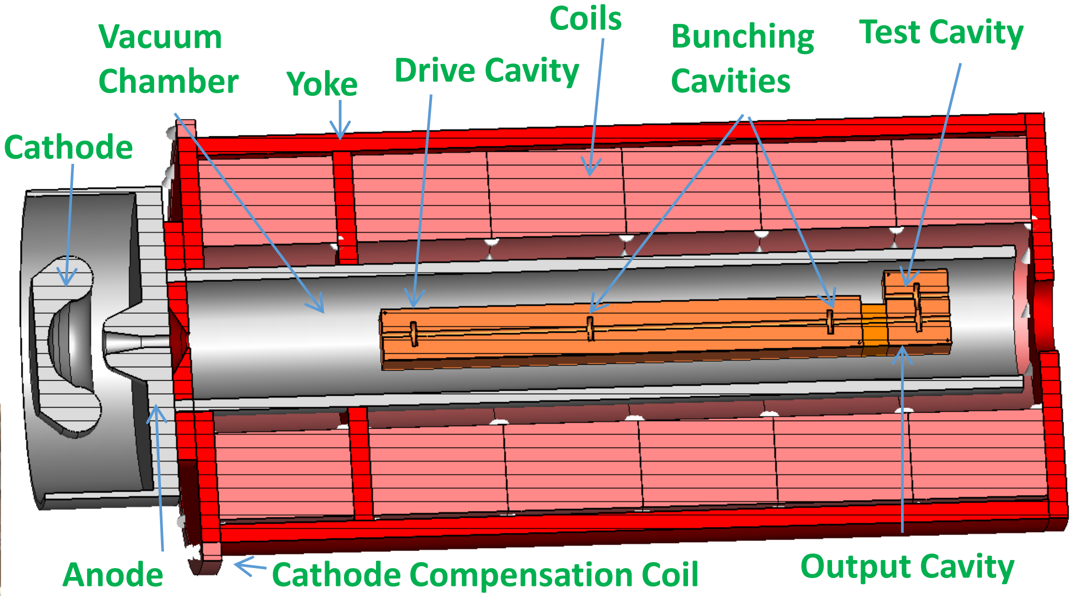
- ◊ pulsed heating temperature ↓22
- ◊ peak surface E-field ↓19.4%
- ◊ total RF power ↓ 19%
- ◊ effect shunt impedance ↑23%
- ◊ modified Poynting vector ↓30%

Electron Gun 350-500kV; 129-220 A



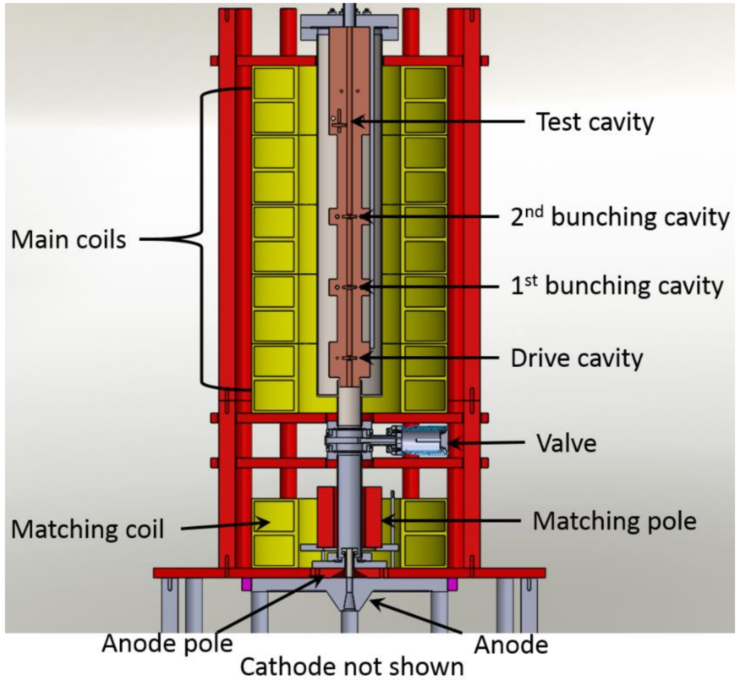
Solid State Marx Modulator
500kV, 250 A, 1.2 µs, 5 Hz

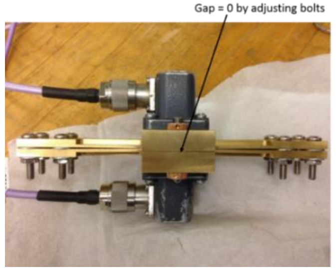


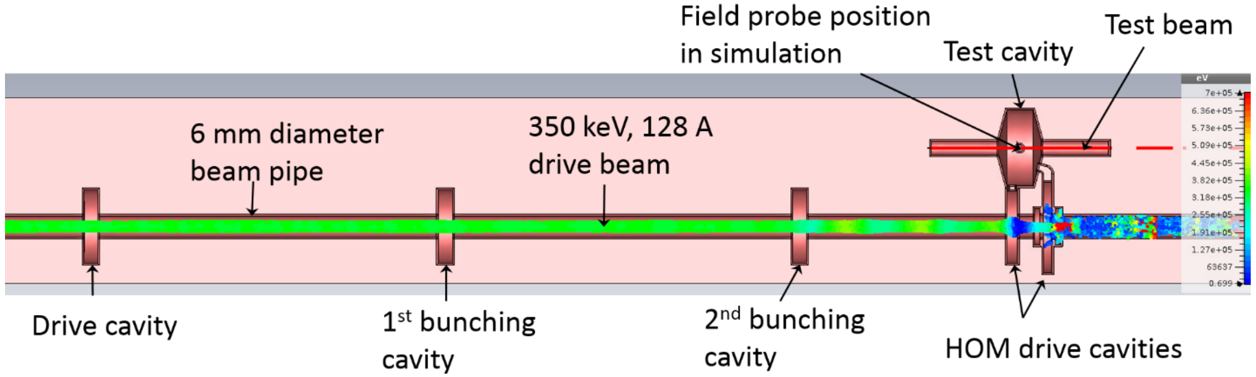


Challenge: High Current Drive Beam
Solution: Thermionic Beam using Klystron-like Bunching without actual X-band Klystron

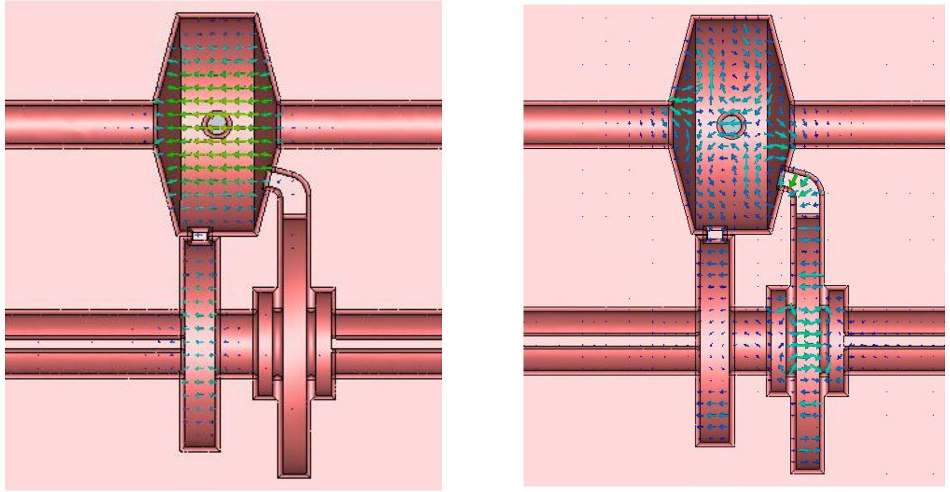
Challenge: Low Energy Drive Beam (0.5 MeV) can be reflected by high field (1.8 MeV loss)
Solution: add a two-frequency output cavity and couple to test cavity



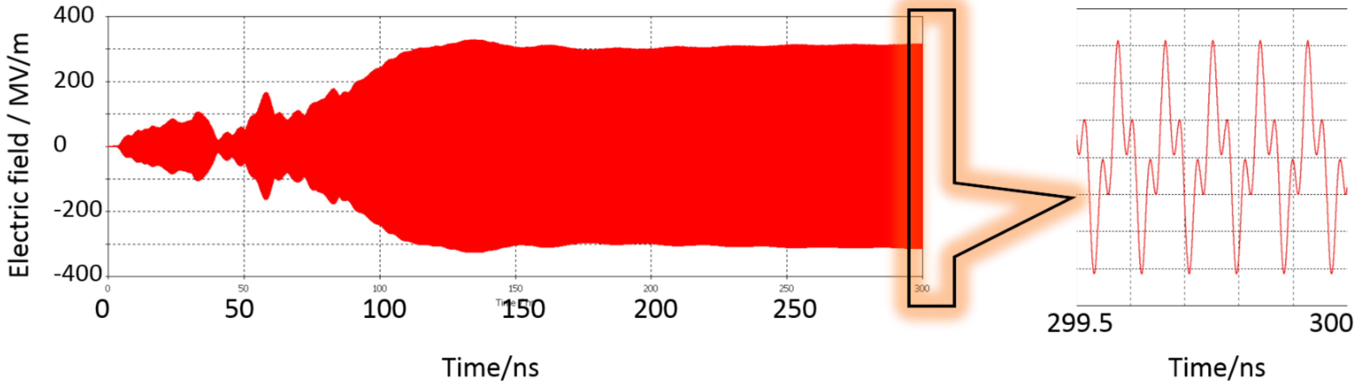




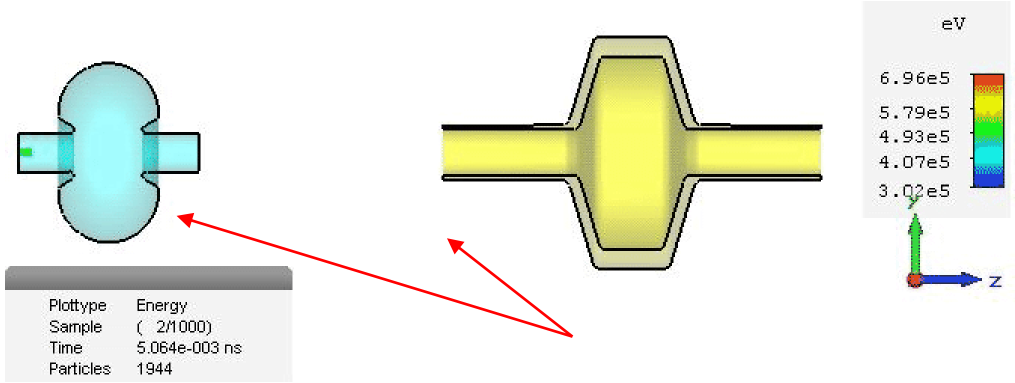
Steady state of a 350 keV, 128A beam going through the system. Drive power in drive cavity is 30 W, beam radius is 2 mm, and longitudinal magnetic field is 3000 G. A high energy (100 MeV), negligible current (1 pA), and small size (0.4 mm diameter) test beam is sent through the test cavity to test the acceleration.

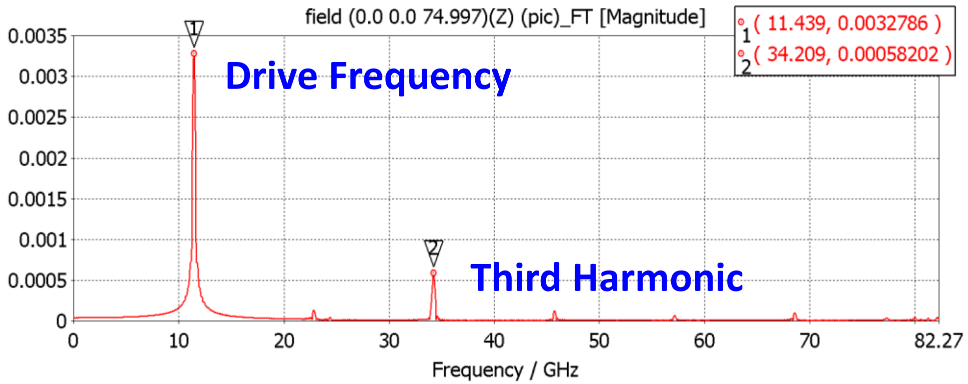


Left: Fundamental mode field pattern.
Right: 3rd HOM field pattern.



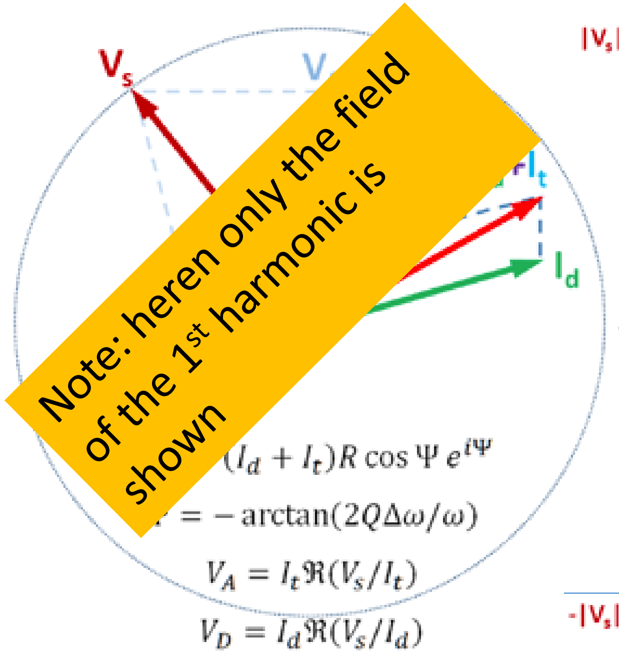
Electric field vs. time at probe location of figure 11. The peak field reaches 313 MV/m. The peak energy gain of the test beam is 1.92 MeV.

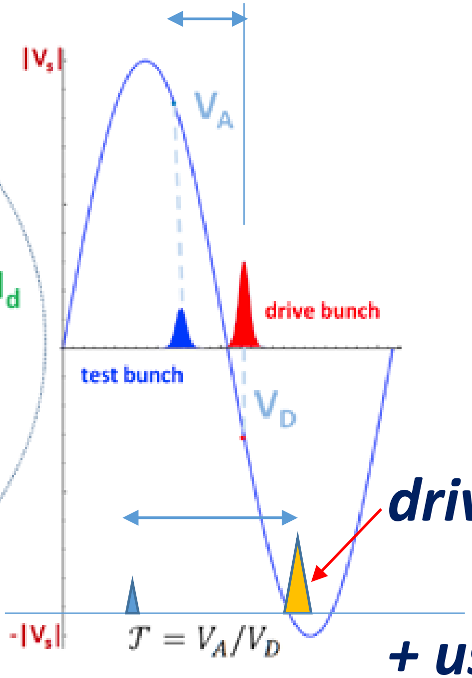


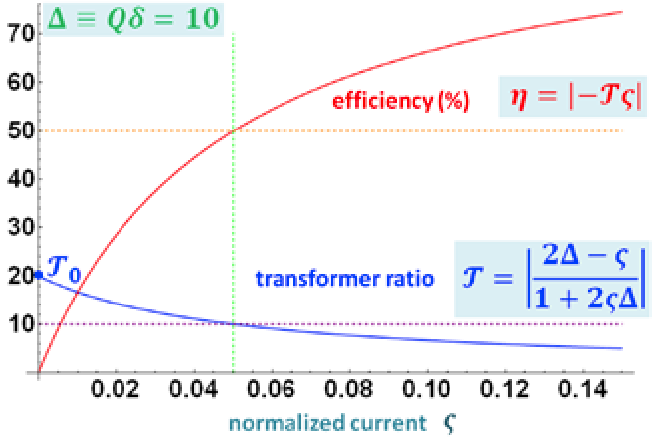


to test these directly… we need something else;

recall: special case ΔΦ (drive-to-test) = 90°







drive here → low detuning → lesser drive charge is needed

+ use a variable ΔΦ to map the accelerating/decelerating fields on axis

lesser drive
same gradients
same wall fields
almost no test bunch – low beam loading (low efficiency), but we can…

…demonstrate that BDR is reduced (as the 1st step);
+ we can use a small test charge to map the fields on axis to show that they are a real combo of the 1st and 3rd harmonics

1) number of bunches =	**300 or about;**
2) charge per bunch =	**2 nC;**
3) bunch size, transverse	< Ø 2mm;
4) bunch size, longitudinal	< 2 - 3 mm;
5) bunch energy spread, Pk-Pk	< as needed for transport;
6) frequency =	2.8 GHz for bunch spacing;
7) bunch energy =	10 MeV;
8) total beam power, peak	~ 56 MW;

9) conservative number of klystrons at 20-**30 MW** = 3 - 2;

Plasma Dielectric Wakefield Accelerator

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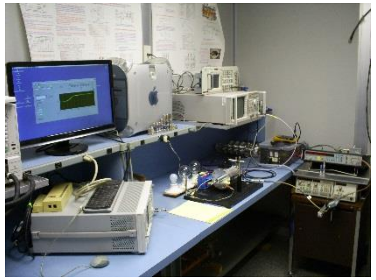
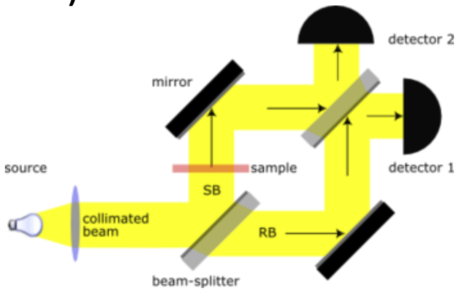
Yale University   Columbia University   NSC KIPT   Omega-P R&D, Inc. Accelerator Physics & Technology

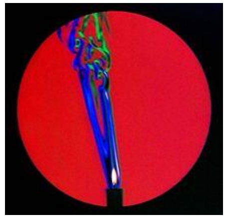
1)



2)



3)



(ATF) to have in –house “plasma diagnostic”

-- possible types

1) Microwave cavity over an open section of DWA;

2) Interferometer (e.g. Mach-Zehnder) based;

3) Using Schlieren

1) the average plasma density is measured by the microwave resonator method (probably at 12GHz);

2) to pass an IR or visible laser beam down the axis of the PDWA;

the plasma would form a leg of an interferometer to count fringes;

3) some information about the radial electron density profile using schlieren (advanced shadowgraph)

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

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

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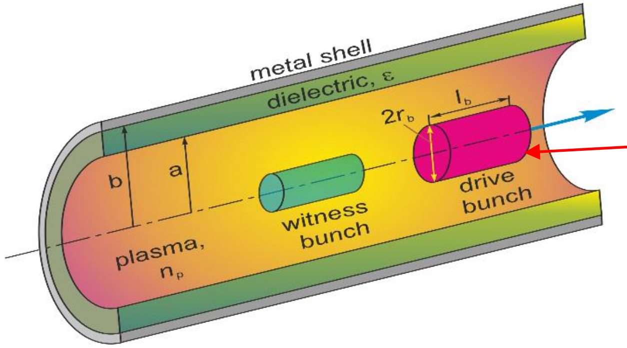
ARTICLE INFO

Keywords:
Wakefield
Acceleration
Blowout
Underdense plasma
Overdense plasma
Particle-in-cell

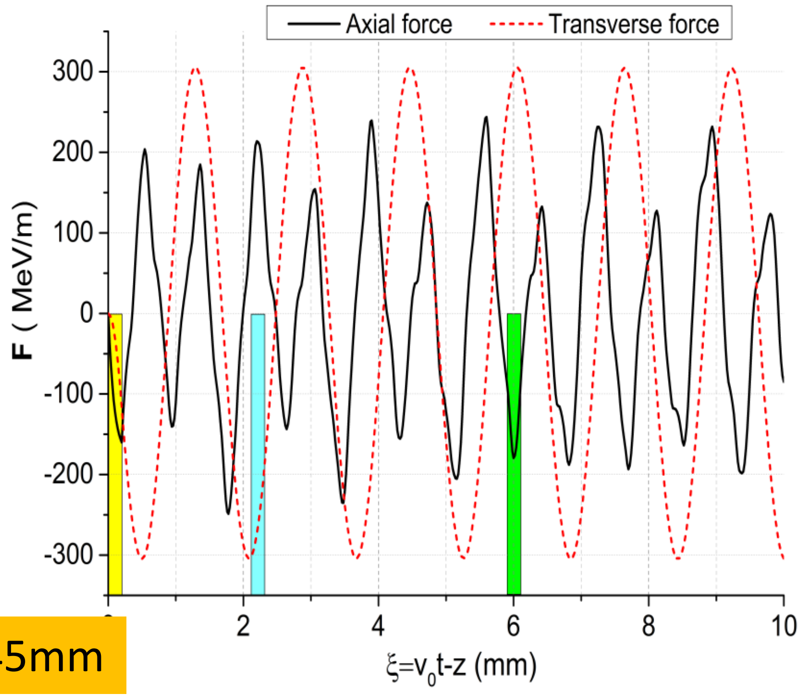
ABSTRACT

We present the results of analytical studies and numerical simulations of a plasma-dielectric wakefield accelerator (PDWFA). The plasma-dielectric structure under investigation is a dielectric-lined circular waveguide that has a transport channel filled with isotropic plasma. In the linear theory approximation (overdense plasma) the total field is represented as a sum of the plasma wave, the eigenwaves of the dielectric waveguide, and the quasistatic field of the bunch. It is shown that at a certain plasma density the superposition of the plasma wave and the dielectric waves allows the acceleration of the witness bunch by the field of the dielectric wave together with simultaneous focusing by the plasma wave. For the overdense plasma regime the results of analytical investigations coincide well with results of particle-in-cell (PIC) simulations. Also, we carried out a PIC simulation of the underdense (blowout) regime of wakefield excitation in the unit. In this regime a focusing is provided by ions remaining in the drift channel after pushing out from it plasma electrons.

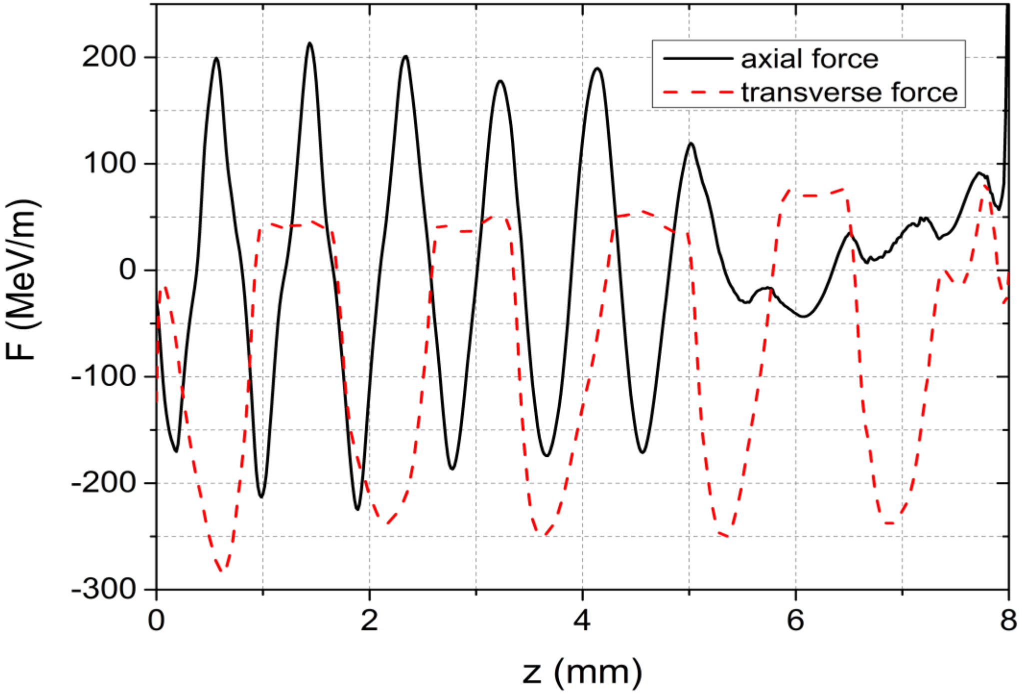


one drive,
or a few

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 x 10^{14} cm^{-3}
n_b/n_p	1/3



@ r=0.45mm



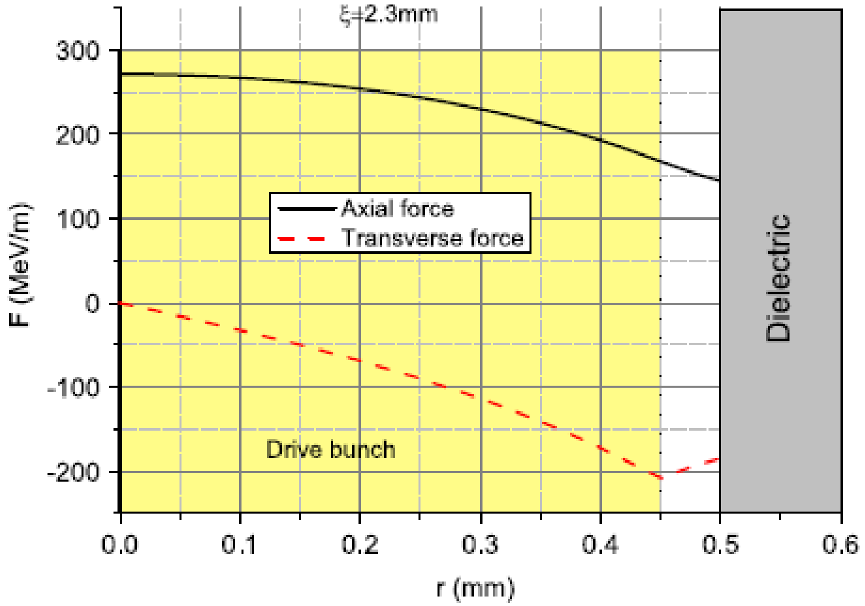
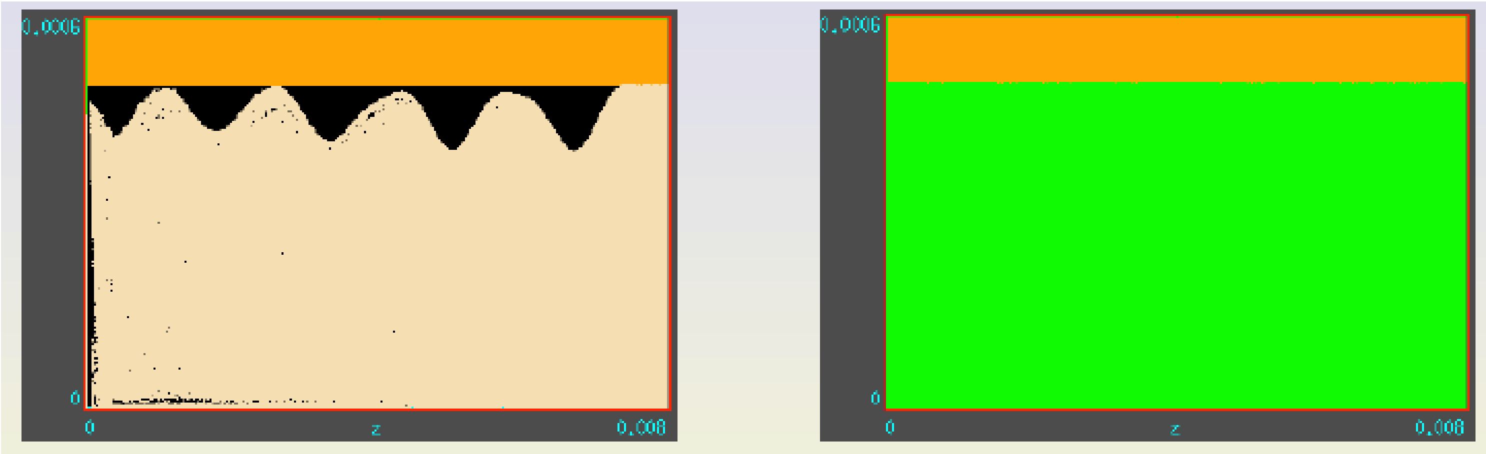
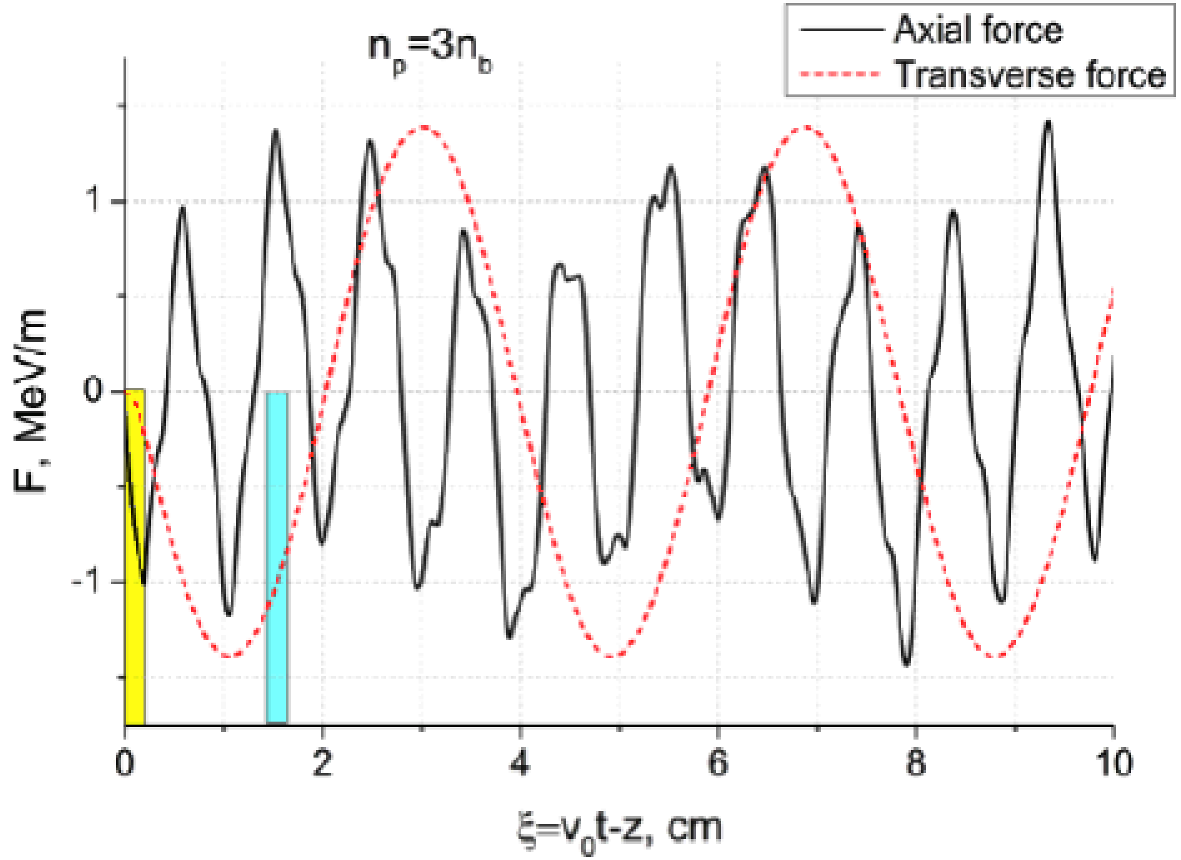


Fig. 4. Transverse profile of the longitudinal force (black solid line) and transverse force (red dashed line), acting on a witness electron, located at a distance of 2.3 mm ($\xi \equiv v_0\tau = v_0 t - z$) from the head of the drive bunch. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)



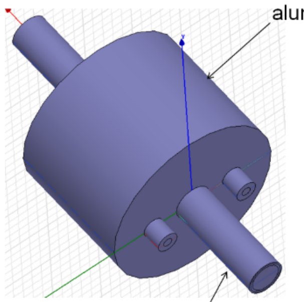
Configuration space (*r*, vertical; *z*, horizontal; dimension unit is meter) plot of the electrons (left figure, tan shading representing computed discrete dots for particles) at t = 26.7 psec; dielectric wall is shown in orange. In the right figure, positive ions (green shading) are shown. The drive bunch is at the right-hand side of the figures, and the wakefield trails left. The transverse force has pushed plasma electrons to the wall in the wavy black region adjacent to the wall that remains filled with positive ions, thereby producing the periodic plasma wave. Plasma fills the entire unit up to the dielectric wall.

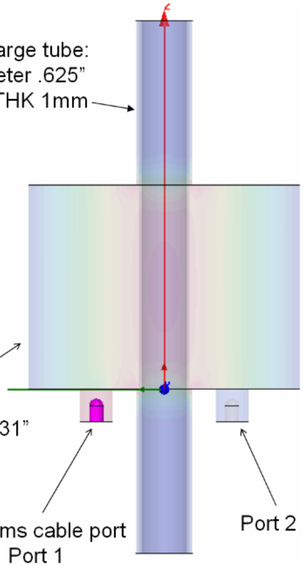
OD of dielectric tube	10.22 mm
ID of dielectric tube	8.0 mm
relative dielectric constant, ε (fused silica)	3.75
drive bunch charge	1 nC
drive bunch length, L_b (box distribution)	2.0 mm
drive bunch radius, r_b (box distribution)	2.0 mm
drive bunch electron density, n_b	2.5×10^{11} cm^3
plasma radius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

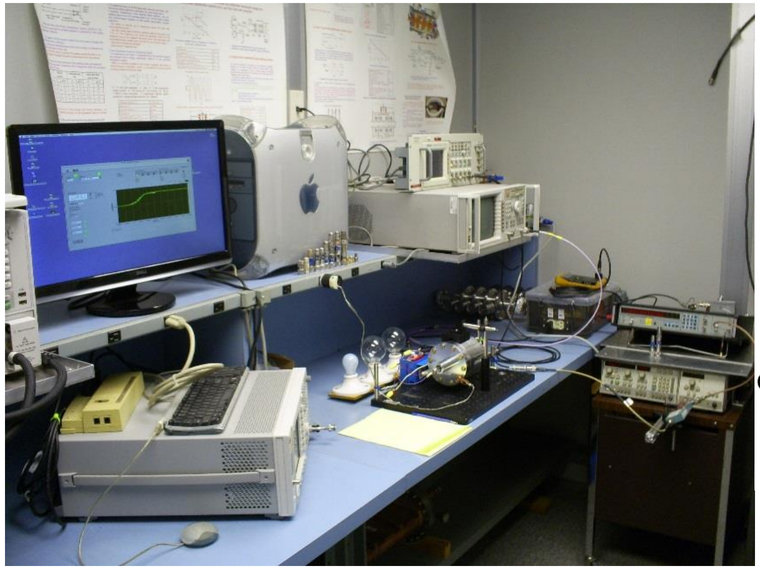


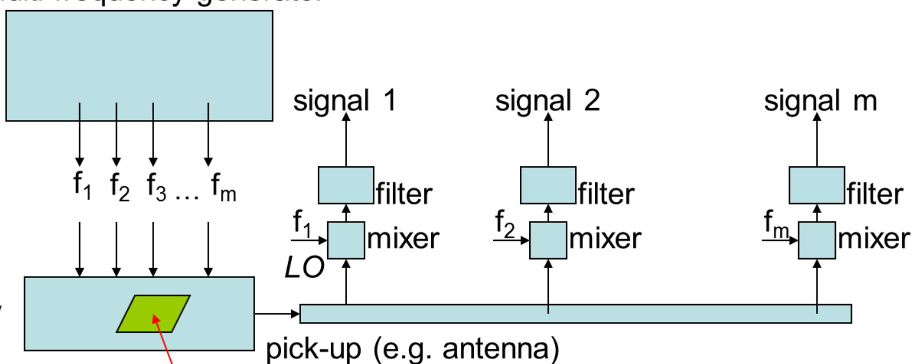
Thus, an experiment conducted at ATF could provide validation of this concept as a high energy accelerator, even though the predicted acceleration gradient is not high, but the motion of test particles distributed at a typical witness bunch location shows focusing action upon sample particles following the drive bunch at the location of the witness bunch…

1 -- Microwave cavity over an open section of DWA



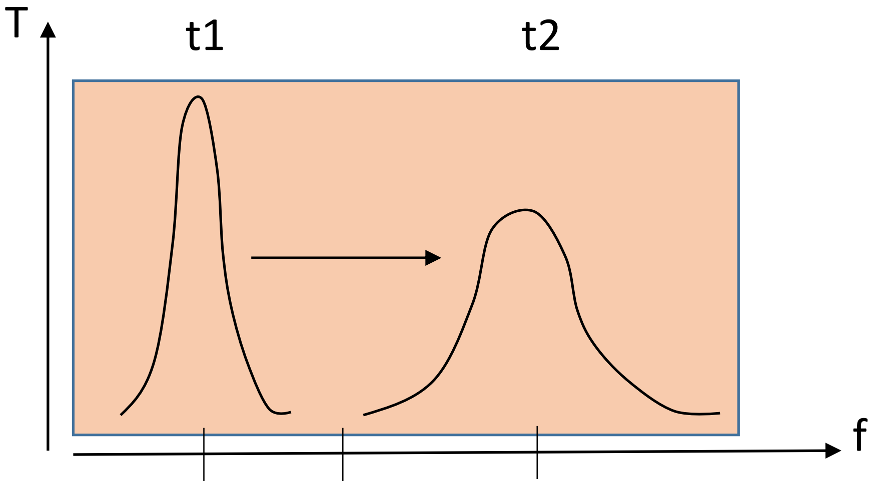


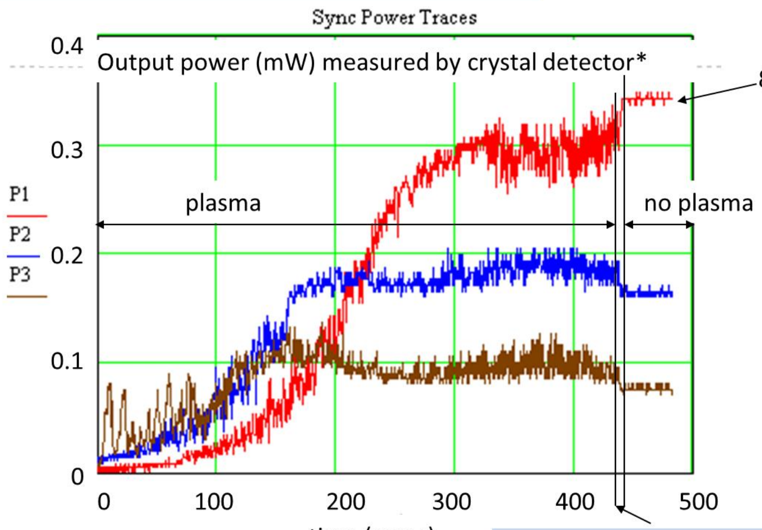




Traces were recorded at three observer frequencies:

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



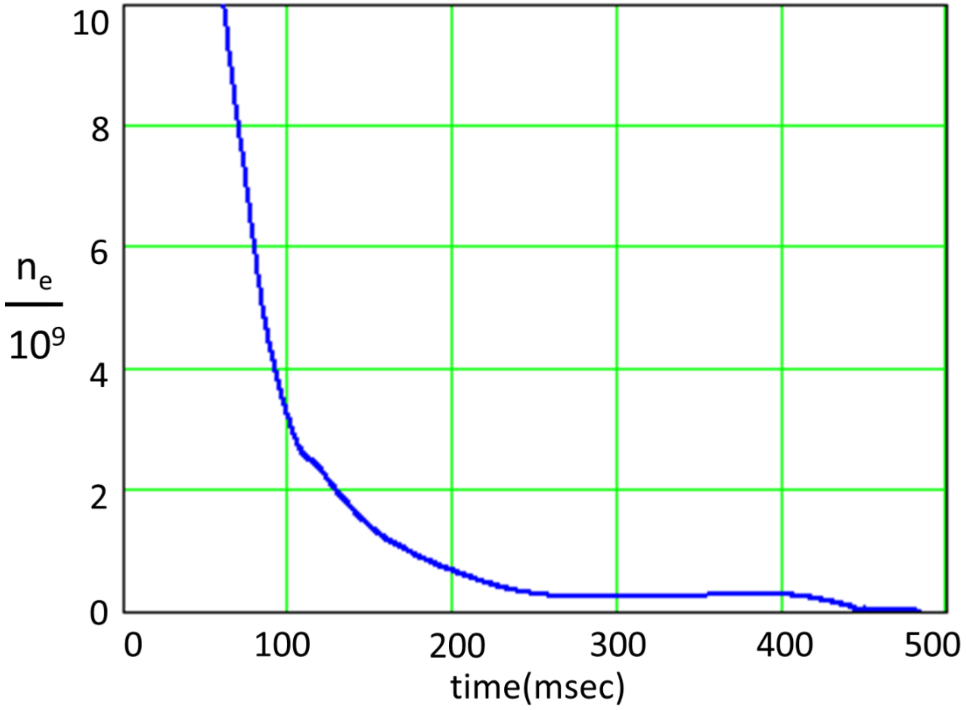


*Input power stays the same

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

$$\varepsilon_{\mathrm{Re}} = 1 - \frac{n_e \cdot e^2}{m_e \varepsilon_0 (2\pi F_\xi)^2} \frac{1}{1 + (F_{coll}/F_\xi)^2}$$

$$\varepsilon_{\mathrm{Im}} = \frac{n_e \cdot e^2}{m_e \varepsilon_0 (2\pi F_\xi)^2} \frac{F_{coll}/F_\xi}{1 + (F_{coll}/F_\xi)^2}$$



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Nuclear Instruments and Methods in Physics Research A

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ELSEVIER

Real-time diagnostic for charging and damage of dielectrics in accelerators

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ARTICLE INFO

Keywords:
Dielectric wakefield accelerator
Beam halo
Charging effects
Real time diagnostic

ABSTRACT

We report on the progress made during the initial stage of our research to study charging rate and charge distribution in a thin walled dielectric wakefield accelerator (DWA) from a passing charge bunch and the physics of conductivity and discharge phenomena in dielectric materials useful in accelerator applications. The issue is the role played by the beam halo and intense wakefields in charging the dielectric, possibly leading to undesired deflection of charge bunches and degradation of the dielectric material: the effects that may grow over many pulses, albeit perhaps differently at different repetition rates. During the initial stage of development, a microwave apparatus was built and signal processing was developed to observe time-dependent charging of dielectric surfaces and/or plasmas located on or near the inner surface of a thin-wall hollow dielectric tube. Three frequencies were employed to improve the data handling rate and the signal-to-noise. The test and performance results for a plasma test case are presented; in particular, the performance of the test unit shows capability to detect small changes ~0.1% of a dielectric constant, which would correspond to the scraping-off of only 0.3 nC to the walls of the dielectric liner inside the cavity from the passing charge bunch.

The lower electron density limit can be improved by increasing the cavity Q-factor. This follows from the fact that, at low densities of free electrons, $n_e \sim BW_\xi$. In our present setup, Q ~1000, and the minimum density $n_{e,\ min} \sim 10^8$ cm^{-3}; If one works, however, with Q ~3000-5000, this will still allow us to capture the processes on the *micro*-sec time-scale, yet to detect $n_{e,\ min}$ $2 \div 4 \times 10^7$ cm^{-3}.

2 -- Interferometer (e.g. Mach-Zehnder) based

The Mach–Zehnder interferometer's relatively large and freely accessible working space, and its flexibility in locating the fringes has made it the interferometer of choice for visualizing flowin wind tunnels[6][7] and for flow visualization studies in general. It is frequently used in the fields of aerodynamics, plasma physics and heat transfer to measure pressure, density, and temperature changes in gases.

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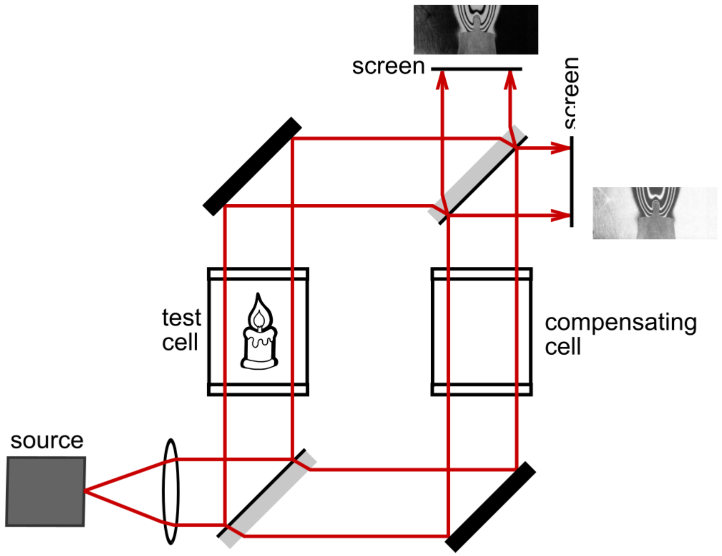

3 -- Using Schlieren

A typical application in gas dynamics is the study of shock waves in ballistics and supersonic or hypersonic vehicles. Flows caused by heating, physical absorption[6] or chemical reactions can be visualized. Thus schlieren photography can be used in many engineering problems such as heat transfer, leak detection, study of boundary layer detachment, and characterization of optics.

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