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Citation: AIP Conference Proceedings **1812**, 070003 (2017); doi: 10.1063/1.4975883
View online: http://dx.doi.org/10.1063/1.4975883
View Table of Contents: http://aip.scitation.org/toc/apc/1812/1
Published by the American Institute of Physics

# Structure-Based, High Transformer Ratio Collinear Two-Beam Accelerator

Yong Jiang[1, a)], Sergey V. Shchelkunov[1, 2], Jay L. Hirshfield[1, 2]

[1]Yale University, New Haven, CT, USA; [2]Omega-P R&D, Inc., New Haven, CT, USA;

[a)] Corresponding author: yong.jiang@yale.edu

**Abstract.** A novel concept for a structure-based collinear two-beam accelerator is described. By employing a structure composed of multi-harmonic detuned cavities, this new accelerator can provide a high acceleration gradient with a high transformer ratio and a low breakdown probability. An experimental research project, with theoretical and computational support, is being conducted at the Yale University Beam Physics Laboratory. Furthermore, this project will support construction of a unique university-based facility for exploring a range of beam-driven acceleration ideas, including plasma and dielectric wakefield concepts.

## INTRODUCTION

A multi-TeV future lepton collider is considered necessary for exploration in the energy range per elementary constituent that cannot be reached by LHC. The CLIC Study Group has made compelling arguments that favor a two-beam accelerator (TBA) approach for a multi-TeV collider [1]. But issues of RF breakdown and pulsed heating pose difficult limitations to achieve a working acceleration gradient of 150 MeV/m or greater in metallic accelerator structures, as is considered desirable for a multi-TeV machine that could be built on a practical real-estate footprint.

Any mechanism that shows promise for obtaining low RF breakdown probability at high acceleration gradient is of great interest to the accelerator physics community. Recently, we proposed a class of novel cavity designs with unconventional spatiotemporal distributions using multi-harmonic mode superposition to suppress RF breakdown [2] and pulsed heating [3]. Multi-harmonic cavity structures can, in principle, be powered by two or more types of klystrons at two or more harmonic frequencies [4]. But we have reached the conclusion that the two-beam configuration is more appealing for a large-scale high-gradient accelerator, based on the same arguments put forward by the CLIC group [1]. However, the transfer of RF power from a PETS [1] to an accelerator structure, as in CLIC, requires a sophisticated and costly waveguide system and transfer structure, which can provide sites for RF breakdown. A novel two-beam accelerator consisting of detuned cavities was proposed by us recently to allow the drive beam and test beam to propagate collinearly through the structure, without need for either a PETS or a power transfer structure [5]. By applying the multi-harmonic cavity concepts, realization of a high gradient TBA structure with low breakdown probability is conceivable, allowing a reliable acceleration gradient in an X-band structure to reach 150 MeV/m, without exceeding the empirical limits [6], namely a peak surface electric field < 260 MV/m and pulsed heating temperature rise < 56 °K. Another compelling reason to use bimodal cavities in a TBA structure is that the short length for electron bunches that is dictated by the need for high luminosity automatically implies high magnitude harmonic frequency components in the beam current. Thus, one's ability to extract energy carried in higher harmonic components—in addition to that in the fundamental--should boost energy efficiency of the TBA.

## BIMODAL CAVITY TO SUPPRESS RF BREAKDOWN

A multi-harmonic cavity (MHC) concept, with the eigenfrequency of the higher mode equal to a harmonic of the fundamental $TM_{010}$ mode, is proposed by us as a means to suppress RF breakdown [2-3]. Surface field emission and

*Advanced Accelerator Concepts*
AIP Conf. Proc. 1812, 070003-1–070003-5; doi: 10.1063/1.4975883
Published by AIP Publishing. 978-0-7354-1480-8/$30.00

surface pulse heating are two major processes that likely precede and induce RF breakdown, and thus limit accelerating gradients. The time varying nature of RF fields with multiple-frequency mode superposition introduces a possibility to suppress RF breakdown. Cavities that support multi-mode superposition, with one or more frequencies at harmonics of the fundamental $TM_{010}$ mode frequency, serve as vehicles to explore this possibility. For example, a profiled cavity is shown in Fig. 1, supporting a combination of the $TM_{010}$ mode and its 3rd harmonic $TM_{012}$ mode, both non-deflecting acceleration modes. Its RF properties have been described in Ref. [3].

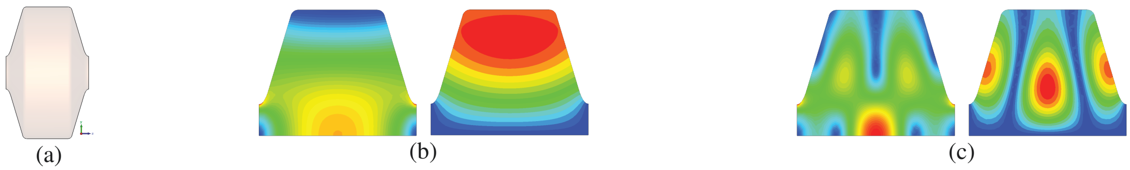



**FIGURE 1.** (a) Preliminary optimized bimodal cavity profile. Electromagnetic field patterns are shown of (b) the $\pi$-mode $TM_{010}$ mode, and (c) its $3^{rd}$ harmonic $TM_{012}$ mode. At left in (b) and (c) are *E*-fields, at right, *H*-fields.

But currently, tests using high power RF sources at high frequencies have not received much support, due partly to the paucity of these sources. This limitation can be overcome using beam-driven excitation of a cavity or accelerator structure. In fact, recent SLAC mm-wave RF breakdown tests were carried out at FACET using single-bunch excited wakefields to infer a maximum accelerating gradient of 0.3 GV/m without breakdown in the frequency range 115 to 140 GHz [7]. The SLAC experiments were limited by available FACET beam time, and by use of single-bunch beams. As an alternate approach, a facility sited at Yale University is currently under construction to provide a high-current long bunch train for extensive beam-driven accelerator studies, including RF breakdown, with bunch train lengths that exceed the cavity or structure filling times. Our initial experiments will be on a novel acceleration mechanism relying on detuned multi-harmonic cavities, and on related accelerator structures, that are predicted to reach gradients at X-band >150 MV/m for hard copper structures and towards 200 MV/m for CuAg alloy, without increasing the breakdown rate, and possibly even higher gradients at higher frequencies.

## DETUNED-CAVITY TWO-BEAM ACCELERATOR

The concept of the detuned-cavity TBA, developed by us [5], can be illustrated in Fig. 2. The general concept is to use a high-current relativistic electron beam to drive a structure composed of a chain of detuned RF cavities, in which strong electric fields are excited to accelerate a co-propagating lower-current, higher energy test beam. An analogy for the test (i.e., accelerated) bunches is that of dolphins riding on a ship's wake. The phase delay between the drive beam and the excited field, arising from the imposed detuning, allows drive beam bunches to ride near a node of the excited electric field as the beam propagates, while test beam bunches ride on or near the crest of the field. Hence, the drive bunches experience a small decelerating electric field and deposit a small increment of energy into the wakefield, while the test bunches experience a high accelerating electric field; together, these imply a high transformer ratio $\mathcal{T}$. $\mathcal{T}$ is the ratio of energy change per unit charge between a test bunch and a drive bunch. This situation is exactly what prevails when any resonator is driven at a frequency away from its natural resonance frequency, so that the voltage and current differ in phase by an amount determined by the degree of detuning. Of course, this picture only applies during steady state, i.e. after filling of the resonator. This TBA configuration allows for transfer of energy directly from a high-current drive beam to a low-current accelerated beam, without need for a separate structure for generating intense RF fields, or for an intermediate transfer structure, as in CLIC [1].

As discussed in Ref. [5], this concept also applies for multi-mode cavities. The detuned-cavity TBA structure is composed of cavities with a geometry similar to what is shown in Fig. 1. The cavity frequencies are detuned from the drive-beam frequency and its higher harmonic frequency. The combination of the $TM_{010}$ mode, and its $3^{rd}$ harmonic, $TM_{012}$, was chosen because of its superior performance in RF breakdown suppression, and to achieve phase synchronization for $\pi$-mode phase advance in the detuned cavity structure. The electric field patterns for each mode in the structure are shown in Fig. 3(a), and a snap shot of the axial electric fields experienced by bunches in the test and drive beams is shown in Fig. 3(b). Given the cavity RF properties [3] and a drive bunch width of 5 ps, the $3^{rd}$ harmonic percentage $\alpha$ is about 11%; with 25 A drive beam current and 2 A test beam current (current ratio 0.08), the effective acceleration gradient is 150 MeV/m, the loaded transformer ratio is 7.9, and the beam-to-beam power transfer efficiency is 60%. In this example, the unloaded transformer ratio is chosen to be 20 by designing the proper cavity detuning and cavity quality factor. By cooling the structure to increase the cavity quality factor, it is possible to study scenarios with different unloaded transformer ratios, and hence different efficiencies as a straightforward way to implement a future upgrade to boost to higher intensity and energy of the accelerated beam. In additional to the high gradient feature, the maximum pulsed heating temperature rise is reduced by 20%, the modified Poynting vector is reduced by 30%, and the peak surface *E*-field is reduced by 19%, as compared to a structure at the same acceleration gradient with only the fundamental mode excited [3].

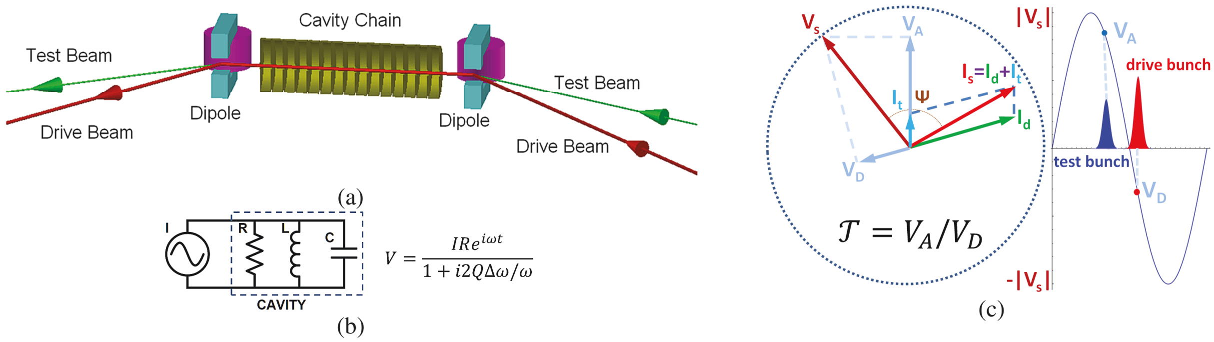



**FIGURE 2.** (a) Cartoon version of a collinear detuned-cavity TBA; (b) Circuit model for a beam-driven cavity, where the lumped elements *R*, *L* and *C* are as is typical for an RF cavity, and where the voltage excited by the current will have phase advance or delay, depending on the frequency detuning; and (c) A phasor diagram of induced acceleration and deceleration voltages imposed on the test current and drive current. The currents $I_d$ and $I_t$ are the drive and test beam currents along the cavity axis, which induce the total voltage $V_s$ in the cavity, with its projections $V_A$ and $V_D$ as acceleration and deceleration voltages. The ratio of $V_A$ to $V_D$ gives the transformer ratio $\mathcal{T}$. The beam loading is intrinsically included, since the total voltage is induced by the total current, $I_s=I_d+I_t$, as the interleaved drive and test beams are propagating in the same structure. Drive and test bunches both enjoy the proper phase of voltages to maintain longitudinal phase stability. Plot at right shows how drive and test bunches can experience voltages of differing amplitudes and signs, on account of detuning.

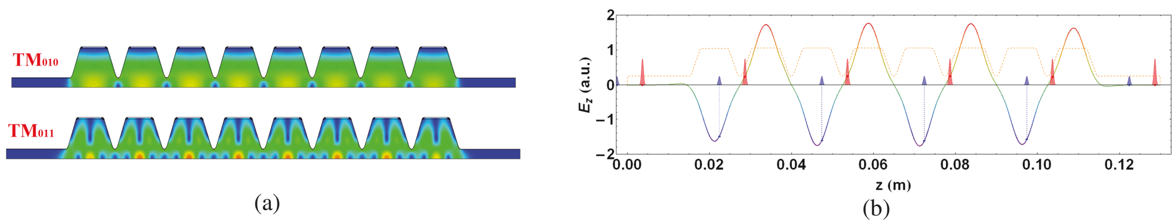
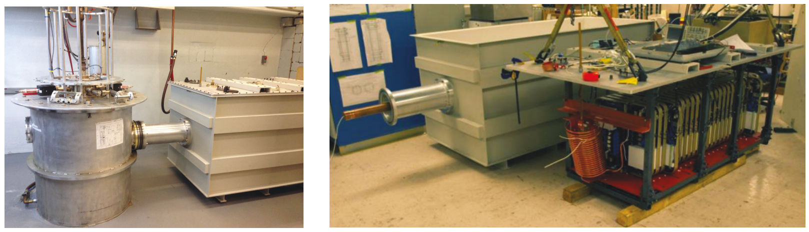



**FIGURE 3.** (a) The electric field patterns for each mode in a short version of the TBA structure; and (b) snapshot of axial electric field experienced by the test bunches (blue) and drive bunches (red).

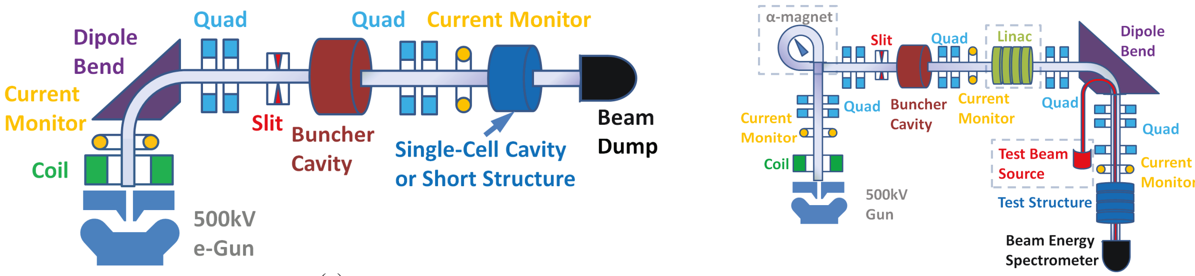
## PLANNED EXPERIMENTAL SETUP

Ideally, to demonstrate the high acceleration gradient and RF-breakdown-suppression features of a detuned-cavity TBA, one should measure the energy gain/loss of high intensity relativistic test/drive beams after they propagate through the structure, and study the statistics of RF breakdown events. However, there is no user-facility in the United States that we are aware of that could provide the required high-current, long drive-bunch train (a µs-long bunch train is typically needed to exceed the fill time) to excite the accelerator structure to reach steady state. Hence, a test facility at the Beam Physics Lab (BPL) of Yale University is under construction for long bunch train beam-driven accelerator experiments, by benefiting from the availability of facilities and equipment in BPL, as shown in Fig. 4, including a 500-kV, 200-A thermionic electron gun and an all-solid-state Marx modulator. As shown in Fig. 5, the experimental near-term objectives are (a) to construct an electron beam source to provide a high-current long bunch train; (b) to apply such a bunch train to excite a single-cell bimodal test cavity and study the phase and amplitude relation between the beam-driven harmonics; and (c) further to carry out construction of the beam-driven multi-cell accelerator structure using bimodal detuned cavities, and to measure its transformer ratio and acceleration gradient. This beam line can also be configured to drive the test structure on-resonance to achieve even higher gradient (but at a lower transformer ratio [5]), which provides a means to study RF breakdown properties and verify anticipated superior performance of bimodal cavity structure due to two-mode superposition as compared with single-mode operation.



(a) (b)

**FIGURE 4.** (a) 500 kV, 200 A electron gun connected to 500 kV, 250 A Marx modulator; and (b) untanked modulator with the circuit plates visible.




(a) (b)

**FIGURE 5.** (a) Schematic of the beamline setup for this proposal. (b) Schematic for a future upgrade.

Figure 5 shows schematics of the proposed experimental beamline setups. The single-cell bimodal test cavity will use a geometry similar to that in Fig. 1. The test cavity will support a fundamental mode at X-band, 11.424 GHz, and its 3$^{rd}$ harmonic at Ka-band, 34.272 GHz, allowing for a short filling time (about 200 ns) and providing the RF-breakdown statistics, which can be directly benchmarked with the existing data at X-band [6]. The buncher cavity modulates the electrons' velocity, depending on the RF phase when the electrons arrive at the cavity. If the buncher cavity is designed to operate at S-band and driven by an S-band RF driver with input power of 400 W (sub-harmonic of X-band), the bunching length for a 500 keV beam is about 2 meters, where the electrons are mostly compressed into bunches to generate a high peak current; for a X-band buncher cavity, the bunching length is about 0.7 m. After exiting from the gun, the electron beam goes through beam focusing elements and a collimating slit before passing through the buncher cavity. The bimodal test cavity is adjustably located at the bunching length after the buncher cavity. The high-current, short-bunch trains will excite high amplitudes of both the fundamental mode and third harmonic mode in the test cavity. As the effective shunt impedance of the bimodal cavity is 124 MΩ/m, only several amperes of drive current should be sufficient to generate high enough gradients for the RF breakdown study, if driven on resonance. The relative amplitude of the third harmonic mode can be adjusted by changing the bunching parameters of the buncher cavity to modify the bunch shape. Assuming a bunch current of 40 A, the effective acceleration gradient is expected to be 240 MV/m with the normalized detuning $2Q\delta = 20$. As the bunch will eventually become unbunched after drifting beyond the bunching length, for the setup in Fig. 5, the test structure will be limited in length. It will be composed of only a few cavities, but include end matching cells, as in a full accelerator structure, all located within the region where the bunch structure is still well maintained. As shown in Fig. 5(b), a future upgrade is envisioned.

To demonstrate the plausibility of selective harmonic excitation in such an experimental setup, a preliminary simulation using CST Particle Studio® Particle In Cell solver was carried out, based on a simplified model, as shown in Fig. 6. A 500 keV mono-energetic beam is injected in a buncher cavity with beam current of 2 A in this example. The buncher cavity is a scaled version of the KEK Compact ERL buncher cavity [8] with eigenfrequency of 11.43 GHz and the unloaded quality factor $Q$ of 12475. To minimize the required mesh size and corresponding computation run times, excessive drive power (22 kW) for the buncher cavity was used in the simulation to achieve bunching in a rather short distance (70 mm) to shorten the overall length. A uniform 0.2 T magnetic field is used to transport the bunched beam, instead of quadrupoles, in order to simplify the simulation. A multi-harmonic test cavity is centered at 70 mm downstream of the buncher cavity, with its geometry and field distribution shown in Fig. 6 and material of annealed copper. Wall loss and space charge effect are included in the simulation. The Fourier transform of excited electric fields in the multi-harmonic cavity shows clear evidence of the excitation of both the fundamental mode $TM_{010}$ and the third harmonic $TM_{012}$, with other harmonics (up to the 7th as shown) highly suppressed. The simulated beam time is only 5 ns, far short of the cavity filling time (about 250 ns) to reach steady state. The excited field will be at a much higher amplitude after reaching steady state, as suitable for RF breakdown tests and particle acceleration study. The preliminary simulation shown in Fig. 6 is only meant for illustration and proof of the principle. Thorough optimization will be required to achieve the desired bunch profile, harmonic field amplitude, and realistic beam transport scheme. In Fig. 6(b), HOM's and possible spurious modes due to coarse mesh are also present. Non-resonant spurious modes are expected to be highly suppressed after reaching steady state.

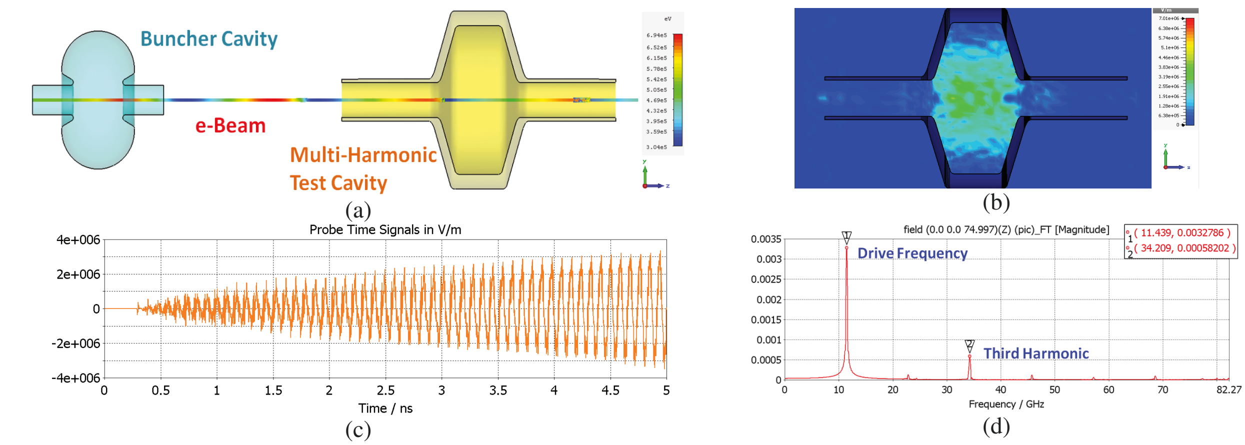



**FIGURE 6.** (a) Preliminary particle-in-cell (PIC) simulation of multi-harmonic cavity excitation by bunched beam, obtained using CST Particle Studio®. The 500-keV, 2-A DC electron beam is bunched by a buncher cavity, with clear velocity modulation seen. Wall loss and space-charge effects are included in the simulation; (b) Excited electric field pattern in the multi-harmonic cavity after around 5 ns of bunched beam traversal, i.e., less than the cavity fill time; (c) Electric field probe signal, with the probe located at the cavity center; and (d) Fourier transform of probe signal in (c), showing dominant 1st and 3rd harmonics.

## SUMMARY

A detuned-cavity TBA can have distinct advantages, as compared to an accelerator that uses discrete external high-power RF sources to energize structures, including less complexity, fewer components, and likely lower overall cost. Use of bimodal cavities, with superposition of two harmonically-related cavity modes, allows widely variable unconventional spatiotemporal field distributions to be excited in the cavity. Field emission and pulsed surface heating are believed to be precursors to RF breakdown. Successful suppression of these is expected to lead to warm accelerator structures with higher accelerator gradient and lower breakdown probability than can be realized with single-mode cavities.

## ACKNOWLEDGMENTS

The authors gratefully acknowledge the support from the U.S. Department of Energy, Office of Science, Office of High Energy Physics, under Award Number DE-SC0010699, and U.S. National Science Foundation, Division of Physics, Accelerator Science Program, under Award Number 1632588.

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