Detuned-Structure-Based Beam-Driven Accelerator

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***Abstract*—An experimental research is being conducted at the Yale University Beam Physics Laboratory, aiming to confirm fundamental aspects of an as-yet untested two-beam collinear electron accelerator concept employing a detuned bimodal cavity structure. The features of this novel beam-driven accelerator concept include (i) interleaving of bunches of the low-current accelerated beam with bunches of the high-current drive beam, while both beams move along the same central axis in the structure; (ii) excitation by the drive beam of two modes of each cavity in the structure, with the frequency of the higher mode equal to three times the frequency of the fundamental TM_{010} mode; and (iii) detuning of the cavity modes away from the frequency of the accelerated and drive beam bunches, and their third harmonic. Advantages that are anticipated from this approach include (a) operation at higher acceleration gradient with lower breakdown and pulsed heating rates than for a structure of single-mode cavities at the same acceleration gradient, due to the unconventional spatiotemporal field distributions in the bimodal cavities; (b) realization of a transformer ratio well above two, due to the detuning of the cavity modes; and (c) greater system simplicity and lower cost than for a two-beam accelerator with separate drive and accelerated beam-lines. The recent R&D progress is presented.**

Keywords—two-beam accelerator, detuned structure, beam driven

I. Introduction

RF breakdown poses fundamental limitation to achieve a working acceleration gradient of 150 MeV/m or greater in conventional metallic accelerator structures, as is considered desirable for a multi-TeV machine that could be built on a practical real-estate footprint. And surface RF pulsed heating is considered as one of the major causes which trigger the onset of RF breakdown. Recently, we proposed a class of novel cavity designs with unconventional spatiotemporal distributions using multi-harmonic mode superposition to suppress pulsed heating and RF breakdown [1-4].

A multi-harmonic cavity (MHC) can support the fundamental mode TM_{010} as well as the higher mode with the eigen-frequency equal to the harmonic of the fundamental mode. For example, the RF electromagnetic field distributions are shown in Fig. 1, supporting a combination of the TM_{010} mode and its 3rd harmonic TM_{012} mode, both of which are acceleration modes. Its RF properties and features in RF breakdown suppression have been described in Ref. [3-4]. The time varying nature of RF fields with multiple-frequency mode superposition introduces a possibility to suppress RF breakdown. As additional constraints are imposed on the cavity design optimization, certain characteristic quantities, such as quality factor or shunt impedance, of each individual mode might be inferior to the designs without such constraints; however with two-mode superposition, the overall performance can be superior to that of a single mode, in terms of effective acceleration gradient and RF breakdown suppression. Such analogy could be straightly following the strategic move in CPU industry where multi-core integration is used to increase CPU performance and beat Moore's law.

Multi-harmonic cavity structures can, in principle, be powered by two or more types of klystrons at two or more harmonic frequencies [3]. But the common accepted argument is that the two-beam accelerator (TBA) configuration is more appealing for a large-scale high-gradient accelerator [5]. The limitation due to the paucity of high power RF sources can also be overcome using beam-driven excitation of a cavity or

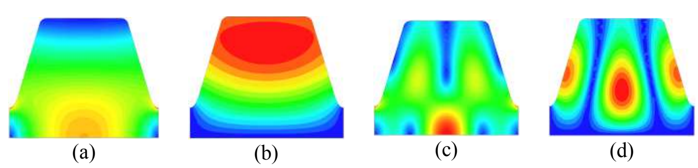

Fig. 1. The RF electromagnetic field distributions of a bimodal cavity in the beam-driven accelerator structure, with (a) RF electric field, (b) magnetic field of the TM_{010} mode, (c) electric field and (d) magnetic field of its 3rd harmonic TM_{012} mode.

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accelerator structure. A novel two-beam accelerator consisting of detuned cavities [4, 6] was proposed recently to allow the drive beam and test beam to propagate collinearly through the structure, without need for a sophisticated and costly waveguide system and transfer structure which can provide sites for RF breakdown [5]. Incorporated with the multi-harmonic cavity concepts, realization of a beam-driven high gradient TBA structure with low breakdown probability [4] is conceivable, allowing a reliable acceleration gradient in an X-band structure to reach 150 MV/m, without exceeding the empirical limits [7], namely a peak surface electric field < 260 MV/m and pulsed heating temperature rise < 56 °K. The high transformer ratio is also expected to be larger than 10.

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.

Hence the MHC serves as a vehicle to suppress surface field emission and surface pulse heating.

II. Experimental Design

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 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. This experiment centers on the availability of facilities and equipment in the Beam Physics Lab (BPL) of Yale University including a 500-kV, 200-A thermionic electron gun and an all-solid-state Marx modulator, as shown in Fig. 2.

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 [6]), 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.

Our initial experiments will be on a novel acceleration mechanism relying on detuned multi-harmonic cavities, and on

Fig. 2. The 500 kV, 200 A electron gun connected to a 500 kV, 250 A Marx modulator in the Beam Physics Lab at Yale University.

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.

It is very challenging to generate bunched drive beam with high average current and long train. One solution is to use a single high power RF cavity, for example, Compact Energy Recovery Linac (ERL) buncher cavity developed at the High Energy Accelerator Research Organization (KEK) [8], but a high power RF driver is needed. Another solution is to use klystron-like bunching scheme consisting of an input cavity and gain cavities chain. In this way, only small amount RF drive power (< 200 W) is needed. The drive cavity modulates the electrons' velocity, depending on the RF phase when the electrons arrive at the cavity. At a certain drift distance, due to the velocity modulation, the faster electrons catch up to the slower ones, creating the "bunches". To reinforce the bunching,

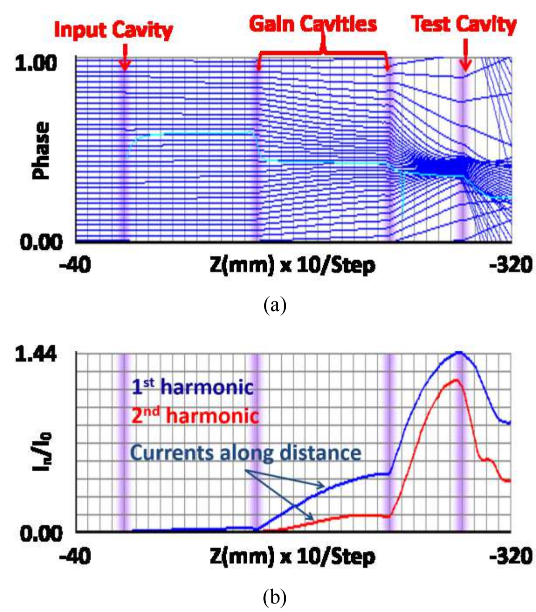


Fig. 3. Generation of high current bunched beam. (a) Electron phase plot of beam wave interaction simulation using AJDISK [9]. (b) Beam current plot given by AJDISK. Input power is 100 W; the frequency of the first Gain Cavity is 11430 MHz, and the second Gain Cavity frequency is 11465 MHz; The input beam energy is 300 keV and the beam current is 101 A.

additional bunching cavities, or so-called gain cavities, can be inserted along the beam axis, as shown in Fig. 3. The bimodal test cavity is located at the bunching length after the bunching cavities. 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 3rd 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 [7]. 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 larger than 100 MΩ/m [3, 4], only several amperes of drive current should be sufficient to generate high enough gradients for the RF breakdown study, if driven on resonance. As an example, assuming a bunch current of 40 A, the effective acceleration gradient is expected to be higher than 200 MV/m with the normalized detuning $2Q\delta = 20$ where δ is the relative detuning $\Delta\omega/\omega$. The relative amplitude and phase of the third harmonic mode compared to the fundamental mode can be adjusted and optimized by modifying several parameters, including the injection beam parameter, bunching cavity RF parameter, and the drive power. The resulting bunching structure of the electron beam can be frozen with additional acceleration structures and applicable to the future higher-energy beam-driven experiment.

III. R&D Status

To demonstrate the plausibility of the selective harmonic excitation in such an experimental setup, preliminary simulations using CST Particle Studio® was carried out. Rather thorough validations of the simulations are carried out and cross-checked with theoretical predication and experimentally verified.

PIC simulations with self-consistent beam-cavity interaction are implemented to model the bunching process of high current electron. As shown in Fig. 4, great efforts have been spent on validating the simulation by extrapolating the results from textbook analytics solution of 1-D ballistic model to realistic 3-D region with the strong space charge and the complex structure. To ensure the X-band RF field and its third harmonic field are well concentrated within the cavities, the beam pipe size is chosen to be 8 mm in diameter that puts a stringent requirement on the maximum beam size. The beam matching configurations have been investigated at various cathode emission conditions with different beam voltages and currents, where the beam voltages range from 100 kV up to the 500 kV, and currents from 20 A up to 218 A. With multiple solenoids to generate magnetic lens sets, the stable beam size is observed along the trajectory without the mismatch-induced scalloping when bunching cavities are not activated (as shown in Fig. 5b).

Significant efforts are invested to study the bunching process. Good confidence in the simulation capability is established after the validations in multiple test scenarios. The simulation result indicates the bunching ratio (harmonic current versus DC current) and the location of bunching peak are affected by the space charge effect significantly. These observations match empirical experience in the klystron design

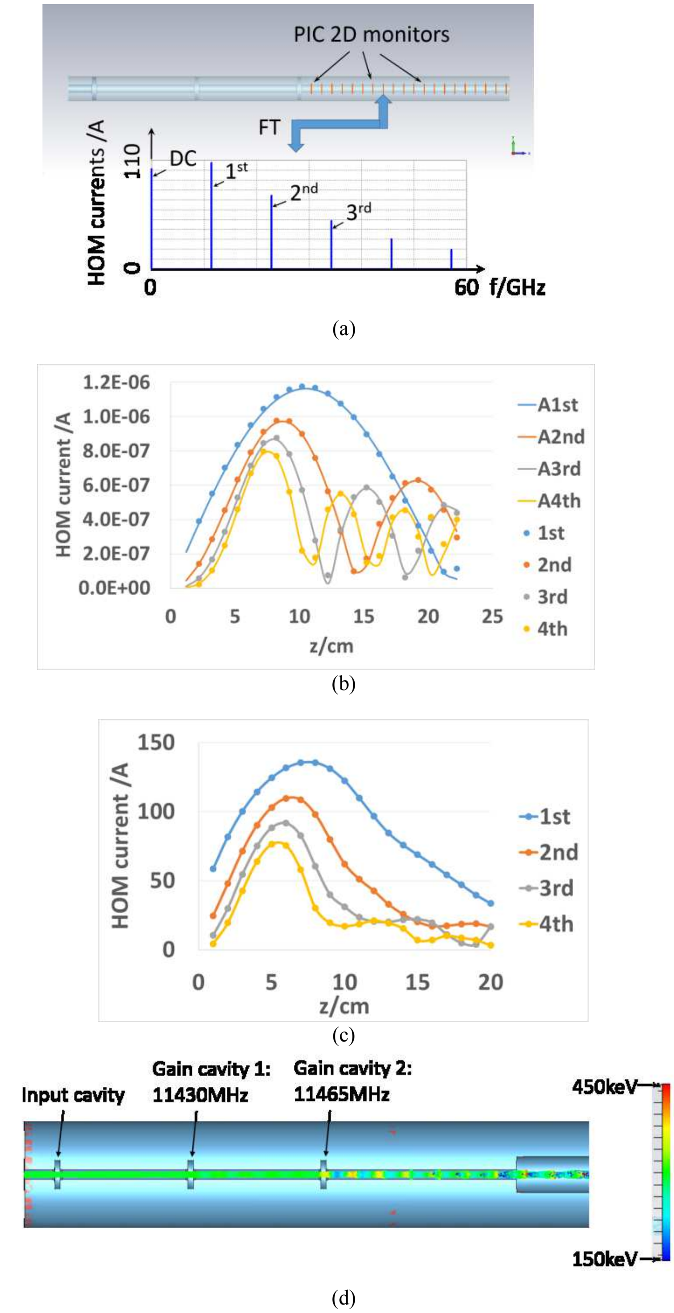
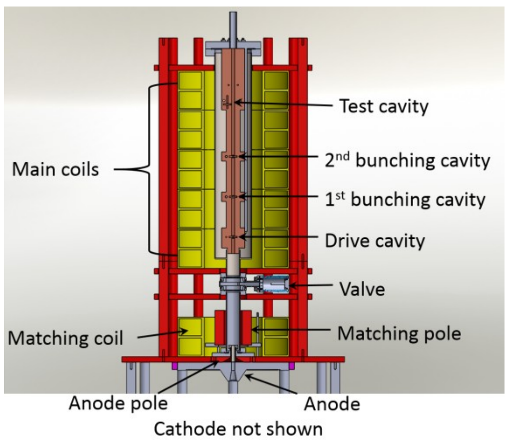


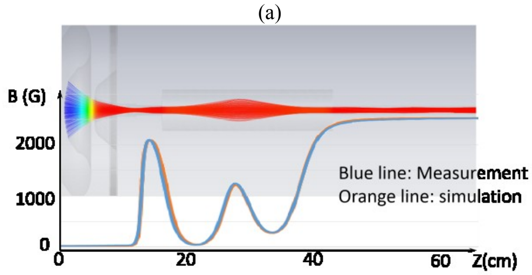
Fig. 4. Validation of the simulation results. (a) To compare with the analytic prediction of harmonic current components after the bunching chain, Fourier transform of the current montior signal in CST Studio simulation is used to extract such the information. (b) Validation of the simulation with textbook analytics solution of 1-D ballistic model, where idealized beam is used with beam radius 0.2 mm, beam energy 100 keV and beam current 1 µA. Curves with labels starting with the letter "A" are analytics solutions for each harmonic components, and the bold points are of the results from PIC simulation. (c) HOM currents at locations after the second gain cavity, as results from CST simulation. Beam radius is 2.5 mm, beam energy 300 keV and beam current 101 A, which are the same as the parameters of Fig. 3. The result is also consistent with the AJDISK result in Fig. 3. (d) Beam envelope of CST simulation with input cavity, and two gain cavities, where clear beam bunching can be observed with full beam transmission through the cavity chain.

and provide useful instruction on how to optimize the bunching cavity locations when multiple bunching cavities are used to increase the bunching ratio and higher harmonic current component.

To accommodate the highly-compressed high current electron beam generated by the electron gun, the beam matching and transport system is quite challenging while dealing with the strong space-charge effect. The beam matching and transport system has been designed, manufactured and assembled, shown in Fig. 5. The magnetic lens system composed of the matching coil and matching poles is used. The on-axis magnetic field distributions with different solenoid current settings for different beam current scenarios are measured with an excellent agreement to the design. To ensure the safety of long hour operation, the solenoid temperature during operating was measured to be less than 50 ^{o}C and within expectation.



(a)



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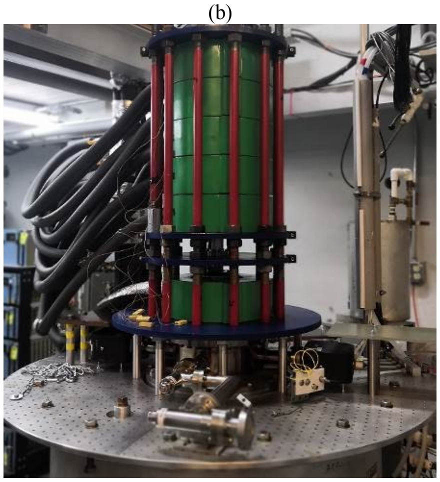
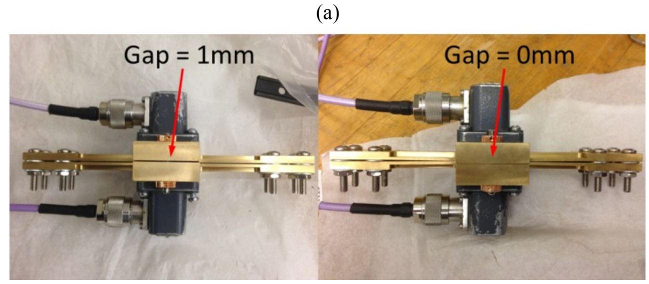


(c)

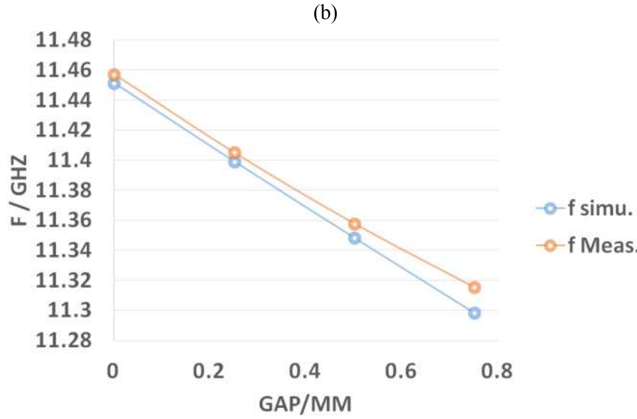
Fig. 5. (a) Engineering design of the experimental setup, including bunching cavity chain, test cavity, beam matching and transport system. (b) Front-to-end simulation of beam matching section and magnetic field distribution. The measurement of magnetic field distribution matches the simulation very well. (c) Assembly of the experimental setup with the electron gun.

Engineering design of bunch cavity chain with parameters optimized in beam dynamic simulation has been implemented. Inspired by the open cavity design developed at Compact Linear Collider (CLIC) [10], open cavity geometry is used in the design for the potential benefit of wakefield damping and the ease of cavity tuning, as well as avoiding the error-prone brazing procedure. To validate the mechanical design and RF performance, a prototype cavity is designed, fabricated and measured, as shown in Fig. 6. This mockup cavity has been constructed by combining two halves split along the cavity axis together with certain gap between them. Ultra-fine-thread studs are used to adjust the gap and fine tune the cavity frequency. The material of the mockup cavity is Brass instead of Copper. The conceptual design of the cavity structure with multiple bunching cavities and output/test cavity is developed, as shown in Fig. 5a.

(a)



(b)



(c)

Fig. 6. (a) Half plate of a mockup version of the open cavity. (b) Gap adjustment of the open cavity. The gap distance range is from 0 to 1 mm. (c) Measured frequency (labeled as *f Meas.*) vs. the simulation frequency (labeled as *f simu.*) at the different gap distances.

IV. Conclusions

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. The use of bimodal cavities with the superposition of two harmonically-related cavity modes, allows widely variable unconventional spatiotemporal field distributions to be excited in the cavity, as a means to suppress the field emission and pulsed surface heating which are believed to be the precursors to RF breakdown. The outcome of this experiment is expected to lead to warm accelerator structures with the higher accelerator gradient and lower breakdown probability than can be realized with single-mode cavities.

References

[1] S.V. Kuzikov, S. Yu. Kazakov, Y. Jiang, and J. L. Hirshfield, “Asymmetric bimodal accelerator cavity for raising RF breakdown thresholds”, Phys. Rev. Lett., vol. 104, p. 214801, 2010.

[2] Y. Jiang, S.V. Kuzikov, S.Yu. Kazakov, and J. L. Hirshfield, "Multi-harmonic test setup for RF breakdown studies", Nucl. Instrum. Methods Phys. Res. Sect. A, vol. 657, pp. 71-77, 2011.

[3] Y. Jiang and J. L. Hirshfield, “Multi-harmonic accelerating cavities for RF breakdown studies”, Proceedings of NA-PAC'13, WEPMA28, pp. 1040-1042, 2013.

[4] Y. Jiang, S. V. Shchelkunov, and J. L. Hirshfield, Structure-based, high transformer ratio collinear two-beam accelerator, AAC2014, AIP Conf. Proc., vol. 1812, p. 070003, 2017.

[5] G. Guignard (editor), “A 3 TeV e^+e^- linear collider based on CLIC technology”, CERN, Geneva, CERN Report No. CERN 2000-008, 2000.

[6] S. Yu Kazakov, S.V. Kuzikov, Y. Jiang, and J. L. Hirshfield, "High-gradient two-beam accelerator structure", Phys. Rev. Accel. Beams, vol. 13, p. 071303, 2010.

[7] A. Grudiev, S. Calatroni, and W. Wuensch, New local field quantity describing the high gradient limit of accelerating structures, Phys. Rev. Accel. Beams, vol. 12, p. 102001, 2009.

[8] T. Takahashi, Y. Honda, T. Miura, T. Miyajima, H. Sakai, S. Sakanaka, K. Shinoe, T. Uchiyama, K. Umemori, M. Yamamoto, “Development of a 1.3-GHz buncher cavity for the compact ERL”, Proceeding of IPAC2014, Dresden, Germany, THPRI045, pp. 3866-3868, 2014.

[9] A. Jensen, M. Fazio, J. Neilson, G. Scheitrum, “Developing sheet beam klystron simulation capability in AJDISK”, IEEE Trans. Electron Devices, vol. 61, no. 6, pp. 1666-1671,2014.

[10] T. Argyropoulos et al, "Design, fabrication, and high-gradient testing of an X-band, traveling-wave accelerating structure milled from copper halves", Phys. Rev. Accel. Beams, vol. 21, p. 061001, 2018.