ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR13

HIGH-EFFICIENCY TRAVELING-WAVE ACCELERATING STRUCTURE WITH CERAMIC INSERTION*

H. Xu†, L. D. Duffy, J. W. Lewellen, K. A. Shipman, E. I. Simakov, J. Upadhyay,
Los Alamos National Laboratory, Los Alamos, NM, USA
M. R. Raya, Rice University, Houston, TX, USA

Abstract

In a radiofrequency accelerating structure with ceramic insertion, high shunt impedance (162 MΩ/m) and high group velocity (3.1% the speed of light) are achieved simultaneously. The ceramic insertion is in the form of a cylinder, sandwiched between copper endplates with the beam aperture opened at the center. We report our theoretical study on this novel type of traveling wave accelerating structure operating in a $2\pi/3$-mode at 5.7 GHz. The high shunt impedance is realized by the low-loss, highly reflective ceramic insertion confining the accelerating mode at the center. The high group velocity, or the fast radiofrequency filling time of the accelerator structure, is made possible by large side coupling slots. As a result, this novel traveling wave accelerating structure enhances the power efficiency significantly, by two means. The high shunt impedance allows providing a greater accelerating gradient for a given radiofrequency input power. The fast filling time allows an earlier start of the beam acceleration within each radiofrequency power pulse, thus potentially leading to a higher duty factor of the accelerator beam production. The design uses metallic irises, which minimizes the electric field magnitude witnessed by the ceramic component. The unique radiofrequency mode launcher design is also addressed.

INTRODUCTION

Low-loss dielectric inserts have been explored for applications in charged particle accelerators to suppress high-order modes [1] and to enhance the shunt impedance of the accelerator cavity [2–4]. The enhanced shunt impedance is the direct result of reduced radiofrequency (RF) losses. In a normal-conducting metallic structure, the RF magnetic field is supported by conduction current within the skin depth of the metal. The conduction current leads to ohmic loss. In comparison, the application of dielectric inserts allows the RF magnetic field to be borne inside the dielectric, often ceramics, components. Dielectric materials are insulators with, ideally, negligible electrical conductivity, therefore, ohmic losses are greatly reduced. However, dielectric materials, when interacting with RF electric fields, experience tangent loss. If the benefit of ohmic loss mitigation surpasses the additionally introduced tangent loss, the overall RF loss in the accelerator cavity is reduced.

Integrating ceramic components in an RF accelerator is very challenging. To date, no dielectric-assisted accelerator structure can operate at intermediate accelerating gradients (above 20 MV/m), while providing a flat-top accelerating field on a microsecond timescale. The triple-points, or the junctions where vacuum, dielectric, and metal meet, must be carefully designed to avoid excessive electric field enhancement. The peak electric field witnessed by the dielectric components must be mitigated to avoid dielectric breakdown. Appropriate coatings, such as titanium nitride or diamond-like carbon, are often used to mitigate or suppress the electron multipactor phenomenon.

At Los Alamos National Laboratory, we developed a type of ceramic-enhanced $2\pi/3$-mode traveling-wave (TW) accelerator structure at *C*-band (5.712 GHz), which addresses all the dielectric-related risks mentioned above. Therefore, we expect our ceramic-enhanced TW accelerator to operate at an accelerating gradient above 20 MV/m, with microsecond-duration RF pulses. Meanwhile, the TW structure presents a (time-dependent) shunt impedance as high as 162 MΩ/m, and a group velocity of 3.1% the velocity of light. The high group velocity leads to fast RF filling inside the TW structure. In comparison, in a conventional, entirely metallic TW accelerator structure, achieving both high shunt impedance and high group velocity simultaneously is not possible.

The ceramic-enhanced TW accelerating structure saves RF power in two ways. First, the high shunt impedance reduces the required RF power for a given accelerating gradient. Second, the fast RF filling in the accelerator structure shortens the delay needed between the turn-on of the input RF pulse and the injection of the charged particle beam. This delay is usually needed for the RF field to propagate through and stabilize in the structure, during which time the RF power is wasted.

UNIT-CELL DESIGN

The TW accelerator unit-cell design and CST [5] eigenmode RF simulation results are provided in Fig. 1. As illustrated in Fig. 1(a), the unit cell consists of a pair of copper endplates sandwiching a ceramic tube, with a cylindrical copper wall defining the outer diameter of the cell. On the endplates, four slots are opened along the azimuth, allowing the RF fields in one cell to be coupled to the next. The beam aperture is formed within the nose cones, which were designed to further boost the shunt impedance.

The unit cell was designed to operate at 5.712 GHz, with a phase advance of $2\pi/3$ radian per cell, for accelerating ultra-relativistic electron beams. As shown in Fig. 1(b) and

---

* Work supported by U.S. Department of Energy through the Laboratory Directed Research and Development program of Los Alamos National Laboratory, under project number 20210083ER.

† haoranxu@lanl.gov

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-MOPR13

(c), the RF fields are largely confined at the central region of the cell, within the inner diameter of the ceramic tube. In the central region of the cell, the distribution of the RF fields is very similar to that of a TM_{010} mode, except that the mode is not confined by a metallic sidewall, but by a wall of low-loss ceramic. As mentioned in the previous section, because there is, ideally, no ohmic loss induced in the ceramic material, and the tangent loss is low, the shunt impedance of our TW accelerator cell is enhanced. Beyond the outer diameter of the ceramic tube, the RF fields are comparatively low. However, the coupling slots opened on the endplates were designed to be large enough to allow sufficient RF coupling between neighboring cells, yielding a high TW group velocity.

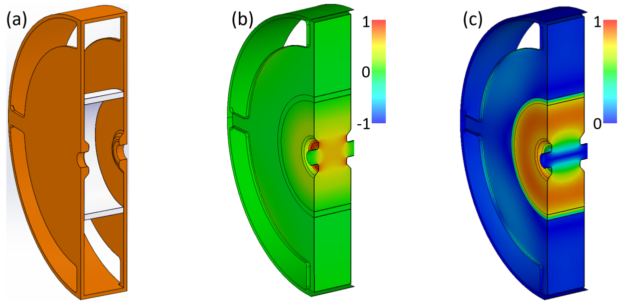

Figure 1: Ceramic-enhanced $2\pi/3$-mode traveling-wave linear accelerator unit cell design, half-section view. (a) 3D model of the unit cell design; (b) normalized longitudinal RF electric field distribution; (c) normalized RF magnetic field magnitude distribution.

To concentrate the RF fields in the central region, a high permittivity of the ceramic material is desired. To minimize loss, the loss tangent of the material needs to be small. In our design, we used the Trans-Tech D-3500 ceramic material, with a relative dielectric constant of $\epsilon_r = 35.5$ and a loss tangent of $\tan\delta = 1.1 \times 10^{-4}$. Meanwhile, the ceramic tube inner and outer diameters must be designed carefully to maximize the RF fields in the central region, thus maximizing the shunt impedance.

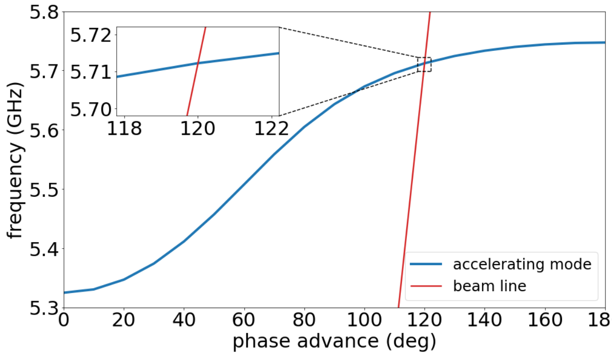

Figure 2: Dispersion relation of the ceramic-enhanced traveling-wave accelerator unit cell.

The dispersion relation of the unit-cell design of the ceramic-enhanced traveling-wave accelerator is provided in Fig. 2. The dispersion relation shows a positive group velocity. The dispersion of an ultra-relativistic electron beam is also plotted, and a detail plot of the interception point is provided. The interception point represents the wave-beam synchronization condition, which denotes that the design operates with a 120-degree phase advance per cell at 5.712 GHz.

Our TW unit cell design is advantageous in terms of protecting the ceramic inserts. As indicated in Fig. 1(b), the electric field magnitude that the ceramic tube witnesses is minimized to less than 10% of the peak electric field inside the unit cell. The minimized electric field exposure significantly reduces the dielectric breakdown risk. Meanwhile, the ceramic tube is located far away from the beam axis, which reduces the likelihood of beam halo interception onto the ceramic surface. For a first test, we plan to assemble the structure in a clamped manner, without using any grooves for the ceramic tubes to be inserted in. The ceramic tubes will be held in place by only static friction. The purpose of this assembly scheme is to minimize the triple-point risk. Lastly, secondary electron yield of the ceramic surfaces will be reduced by using diamond-like carbon coatings.

MODE LAUNCHER

As Fig. 1 indicates, there is little RF coupling across the beam aperture at the center, and the inter-cell RF coupling is achieved through the side coupling slots. Therefore, it will be desirable if the input RF power can be filled into the cavity through the side slots in the first cell of the TW accelerating structure consisting of an array of the abovementioned unit cells. To realize the initial side-slot RF filling from the standard WR187 waveguide into the uniquely designed cavity, an RF mode launcher is needed.

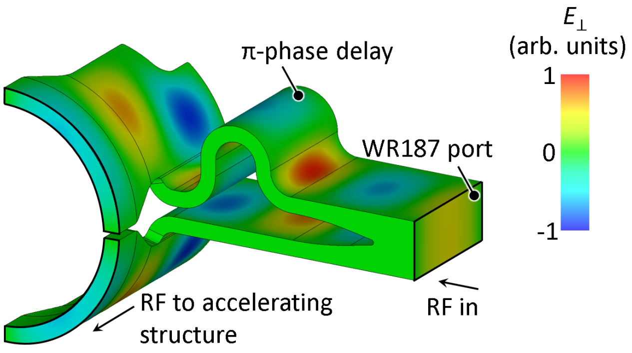

Figure 3: Vacuum volume design of the RF mode launcher for the ceramic-enhanced traveling-wave accelerator. One half of the entire mode launcher design is presented. Normalized electric field perpendicular to the metal faces is plotted.

We designed an RF mode launcher using the CST High Frequency Solver, the vacuum volume of which is provided in Fig. 3, along with the normalized surface-normal RF electric field magnitude. The input RF to the mode launcher is through a standard WR187 rectangular waveguide port. The

RF input is then divided into two equal channels in the mode launcher. One portion is fed to one of the four side-coupling slots, after a 90-degree bend. We designed the 90-degree bend referring to the design guidance provided by a previously published study on distributed-coupling linear accelerator [6]. The other portion feeds another side-coupling slot as well, but the RF phase is delayed by 180 degree. The 180-degree phase delay was designed to ensure that the desired electric field orientations, from the two divided RF portions, are achieved at the side-coupling slots. The simulation results showed less than -60-dB reflection at the input WR187 port.

FULL STRUCTURE

We then integrated the RF mode launcher models onto a 24-cell ceramic-enhanced constant-impedance traveling-wave accelerator structure. The full structure half-section view is provided in Fig. 4. One RF mode launcher is used on each end of the linear accelerator. On each end of the accelerator, between the 24-cell structure and the RF mode launcher, there is a matching cell, wherein the dimensions of the slots and of the ceramic tube were tailored to ensure that a uniform, 120-degree phase advance is realized in each cell in the 24-cell TW accelerating structure. The two WR187 ports of one RF mode launcher are combined by a T-split. Therefore, the accelerator is powered by one single WR187 port. Because the full structure is assembled by clamping, one degree of freedom is required for the vacuum chamber enclosure on the outside. Therefore, we involved a bellow section in designing the vacuum system for the accelerator.

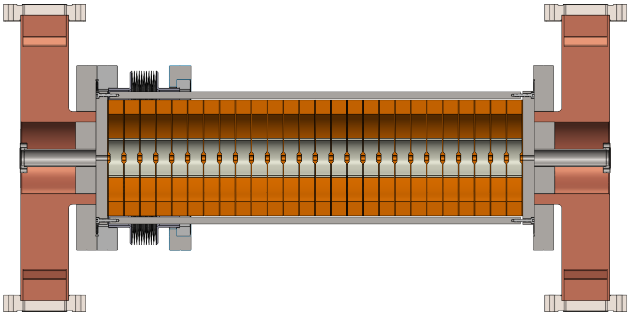

Figure 4: Half-section view of the full structure assembly design.

We studied the RF performance of the entire accelerator assembly, from the power-input WR187 port to the output port, in the CST High Frequency Solver. The RF reflection at the input port was −21 dB, or less than 1% reflected power. We studied the on-axis electric field distribution, the amplitude and phase of which are plotted in Fig. 5, for a nominal accelerating gradient of 20 MV/m. The accelerating field amplitude shows a uniform distribution across the multi-cell structure, with a slowly decreasing trend, as expected in a constant-impedance structure. At each end, the field amplitude is halved in the matching cell, where the phase advance is 115 degree.

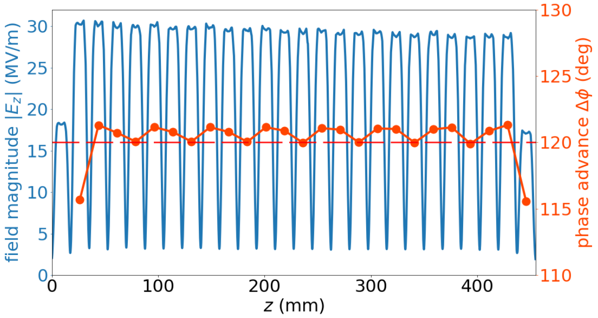

Figure 5: Amplitude and phase distribution of the longitudinal electric field on the beam axis in the ceramic-enhanced traveling-wave accelerator structure.

CONCLUSION

We presented our theoretical research and design study on a type of traveling-wave radiofrequency linear accelerator with ceramic inserts. The structure presents a high shunt impedance and a high group velocity, which allow the structure to operate with a high efficiency of RF power utilization. The design meanwhile minimized the operating risks of the ceramic inserts in the accelerator cavity.

In order to effectively drive the accelerator structure, an RF mode launcher was designed to launch the RF into the accelerator through the side slots opened on the endplate of the first accelerator cell.

We presented a 24-cell ceramic-enhanced linear accelerator structure that appears promising for operating at or above an intermediate accelerating gradient level of 20 MV/m.

REFERENCES

[1] J. X. Zhang *et al.*, "High power experimental studies of hybrid photonic band gap accelerator structures," *Phys. Rev. Accel. Beams*, vol. 19, no. 8, p. 081304, Aug. 2016. `doi:10.1103/PhysRevAccelBeams.19.081304`

[2] S. Mori *et al.*, "Multipactor suppression in dielectric-assist accelerating structures via diamondlike carbon coatings," *Phys. Rev. Accel. Beams*, vol. 24, no. 2, p. 022001, Feb. 2021. `doi:10.1103/PhysRevAccelBeams.24.022001`

[3] B. Freemire *et al.*, "Development of X-band single-cell dielectric disk accelerating structures," *Phys. Rev. Accel. Beams*, vol. 26, no. 7, p. 071301, Jul. 2023. `doi:10.1103/PhysRevAccelBeams.26.071301`

[4] J. Upadhyay *et al.*, "Design of a ceramic enhanced normal conducting standing wave accelerator structure for high shunt impedance," *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 1034, p. 166669, Jul. 2022. `doi:10.1016/j.nima.2022.166669`

[5] CST Studio Suite, `http://www.3ds.com/products/simulia/cst-studio-suite`

[6] S. Tantawi *et al.*, "Design and demonstration of a distributed-coupling linear accelerator structure," *Phys. Rev. Accel. Beams*, vol. 23, no. 9, p. 092001, Sep. 2020. `doi:10.1103/PhysRevAccelBeams.23.092001`