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CRYOGENIC DIELECTRIC STRUCTURE WITH GΩ/m LEVEL SHUNT IMPEDANCE

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Abstract

Shunt impedance is one of the most important parameters characterizing particle acceleration efficiency. It is known that RF losses are reduced at cryogenic temperatures. For example, a record high shunt impedance of 350 MΩ/m was demonstrated recently for all metal X-band accelerating structure, which is more than 2 times higher than that at room temperature. In this article we present a novel hybrid dielectric structure which can achieve even higher shunt impedance due to the fact that losses in dielectric materials reduced much more than in pure copper.

MOTIVATION

Very recently, researchers at SLAC reported a new world record for accelerating gradient in an X-band copper accelerating structure, 150 MV/m of stable beam acceleration [1]. The structure was tested in a cryostat at 77 K, which doubles the Q-factor compared to room temperature, and achieved the highest recorded shunt impedance of 350 MΩ/m in a metallic accelerating structure, one important figure of merit for accelerators. The effort was initiated a few years earlier with a destructive breakdown test of a shorter structure at 45 K, where a gradient of 250 MV/m was reached [2]. This improved performance compared to room temperature structures supports the hypothesis that the breakdown rate can be reduced by immobilizing the crystal defects and decreasing the thermally induced stresses. An investigation in a pulsed DC system demonstrated a similar improvement at cryogenic temperatures [3]. Concurrently, a new ceramic material that has extremely low rf loss at room temperatures ($\tan\delta \sim 6\times10^{-6}$ at X-band, more than one order of magnitude improvement compared to $\tan\delta \sim 1\times10^{-4}$ for conventional alumina) was used in a Dielectric-Assisted Accelerator (DAA) [4], which achieved a shunt impedance of 617 MΩ/m in C-band. It is well known that the microwave loss of many dielectric materials (e.g., Mg-TiOx-based materials and ultrapure Al_2O_3) can be reduced by a factor of ~10 compared to room temperature at liquid Nitrogen temperature or slightly below [5–7]. If we consider the development of an accelerating structure using this new ceramic material at cryogenic temperatures, a GΩ/m level of shunt impedance may be achievable, which is almost comparable with SRF accelerators, but at a much lower cost. In fact, in 2019 the same group that developed the DAA structure published a simulation result [8], in which they showed a Q factor of 765,000 and a shunt impedance of 3.8 GΩ/m could be achieved at a temperature of 27 K. However, that structure uses the TM_{02} mode, and can suffer from lower order mode excitation, and thus mode conversion can reduce the overall efficiency. Also, the DAA structure is quite complicated in terms of dielectric fabrication and must be built in sections; as a result, the unavoidable gaps between adjacent dielectric structures are vulnerable to RF breakdown.

In the last two decades, the theoretical and experimental investigations of dielectric accelerating structures have predominantly used a dielectric-lined waveguide (i.e., dielectric-loaded accelerator, DLA), due to its simple geometry and low fabrication cost [9]. However, in comparison with the prevailing metallic disk-loaded accelerators, the dielectric-lined waveguide suffers from a lower Q-factor and lower shunt impedance. The reason for the low shunt impedance of a conventional DLA structure is the high magnetic field of the TM_{01} mode near the copper surface, which leads to high wall currents and ohmic losses. Recently we have proposed and studied two different variations of dielectric accelerators for cryogenic temperatures (70K or 45K) operation: 1) the Cryogenic Dielectric Corrugated Accelerator (CDCA, Fig. 1a); 2) the Cryogenic Dielectric Disc Accelerator (CDDA, Fig. 1b). Both of them can achieve ~550 MΩ/m of shunt impedance at X-band.

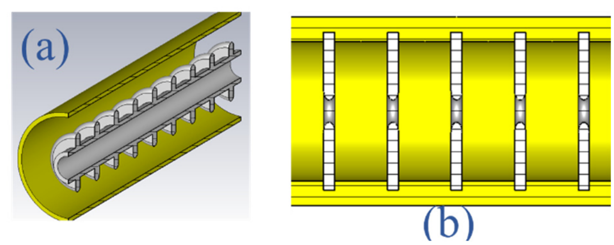

Figure 1: Conceptual view of two variation of dielectric accelerators: a) dielectric corrugated accelerating structure and b) dielectric disk accelerating structure. The grey area represents the dielectric material, and the yellow represents the copper housing for terminating the electric fields and sealing the vacuum.

ACCELERATOR DESIGN

Design of an X-band CDCA

The strategy of CDCA structure for high shunt impedance contains i) introduction of a vacuum gap to reduce the magnetic field near the copper surface (in order to do this, a corrugation has to be introduced, since otherwise the phase velocity of the TM_{01} mode cannot be slowed down to the speed of light), and ii) cooling of the structure to cryogenic temperatures to obtain an extremely low loss tangent in the dielectric material, in order to further reduce the RF loss in the dielectric by a large factor. The trade-off cost of the CDCA structure, in comparison to a conventional DLA structure, is the larger transverse size and a higher ratio of the electric field on the dielectric surface divided by the acceleration gradient. In order to implement a CDCA structure in a practical way, as shown Fig. 2a, we can use the end wall to 1) hold the position of the corrugated

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dielectric tube and 2) establish a path for conduction cooling of the dielectric tube. In terms of fabrication, the copper jacket can be made in two halves, and then brazed along with the ceramic tube. Figure 2b is the simulation (accelerating field on axis) of a DCA prototype that operates in a pi-mode standing wave. The shunt impedance of this 12-cell DCA structure is ~550 MΩ/m at 77 K, which is more than 5 times higher than for the same structure at room temperature. Major simulation parameters are the following: f=11.7 GHz, beam aperture 2a = 2.6 mm, TM_{01} π-mode standing wave, dielectric constant = 9.8, loss tangent=3e-6, Q=1.11e5. It is worth pointing out that, without the end-walls (as shown in Fig. 1a), we have previously reported ~1GΩ/m of shunt impedance. Because of the surface current-induced loss at the end walls, the shunt impedance is lower, but it is still a significant, almost 10-fold improvement over a conventional dielectric-loaded accelerator at the same frequency.

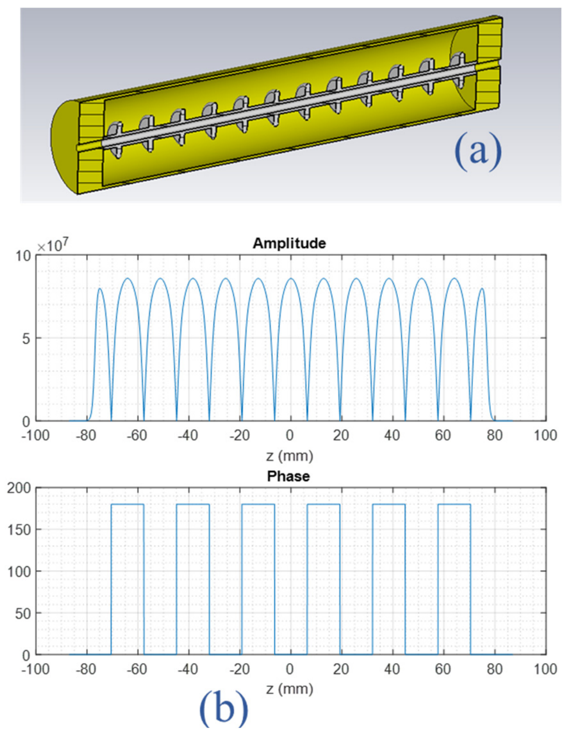

Figure 2: An X-band standing wave pi mode DCA prototype: a) model in CST®; b) plots of the simulated accelerating gradient on axis and its phase. The simulation is normalized in 1 J of total energy.

Design of an X-band CDDA

The DDA itself is not a new concept. It uses very high dielectric constant material (e.g., 50 or higher) to concentrate the field thus enhance the shunt impedance. The most important property of the DDA is that it maintains such high shunt impedance at a relatively high group velocity, which is critical for Short-Pulse, Two-Beam Wakefield Acceleration, since the short-pulse TBA requires a short RF filling time in order to achieve a high RF-to-Beam efficiency. As shown in Fig. 3, noses were introduced on the dielectric iris to improve shunt impedance. The noses usually will result in higher surface fields, but due to the geometry optimization we were able to keep the electric field enhancement factor below 2.5 (Rsh~550 MΩ/m). The simulation results in Fig. 3 are normalized to 1J of stored energy which corresponds to E_{acc}=264 MV/m of accelerating gradient. Shunt impedance as high as 706 MΩ/m can be obtained for the electric field enhancement factor of 5.

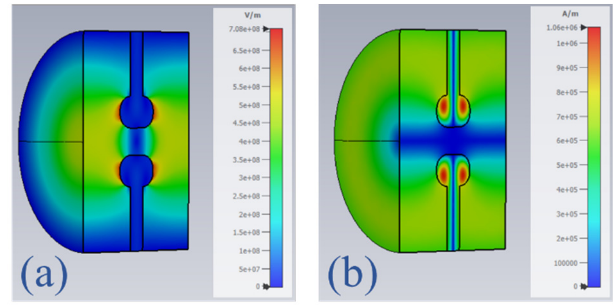

Figure 3: 3D EM modelling of the newly proposed CDDA structure: contour plot of Ez field a) and magnetic field b).

THERMAL ANALYSIS

The X-band CDCA

We have carried out a preliminary examination of whether the two end walls can provide enough conduction cooling for the entire CDCA structure. Let us take as an example the prototype CDCA structure shown in Fig. 2. The thermal simulation result is shown in Fig. 4. The heat load of the simulation is based on the 28 W average power dissipation that is expected for a low duty-cycle (Q~10^{-6}) case while supporting a 100 MV/m accelerating gradient. Note that the thermal conductivity of alumina peaks at around 60~80 K, as shown in the NIST database [10]. Here we use the thermal conductivity of alumina at 77 K = 100 W/m/K and copper conductivity at 77 K = 3.0×10^{8} S/m. The simulation indicates that the entire dielectric section can maintain 77 K with the copper jacket in contact with the cryocooler head.

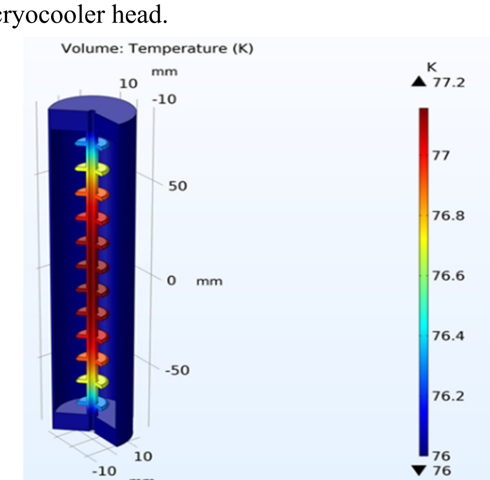

Figure 4: The thermal simulation of the X-band DCA prototype under 100 MV/m of gradient and 28 W of heat load.

The X-band CDDA

As an example, Fig. 5 presents the thermal simulations of conduction cooling of a single cell (two disks) CDDA

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structure operating at 100 MV/m and duty factor of 10^{-6} taking into account 10ns pulse length available at AWA (Argonne Wakefield Accelerator facility) at 100 Hz repetition rate. The temperature rise is insignificant in this case. By scaling, the temperature rise of only up to 72 K is expected in the case of 10^{-5} duty factor (1ms long pulse, 10 Hz repetition rate) if powered by a klystron, which is also negligible. It is worth to mention, that the CDDA concept provides the best colling approach out of all other dielectric based concepts. The feasibility of fabricating a dielectric disk with nose is within the current ceramic fabrication technologies.

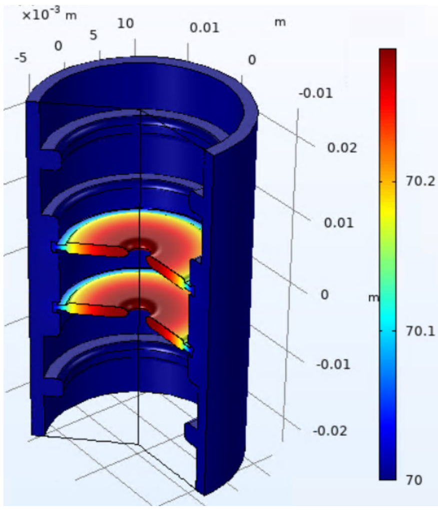

Figure 5: The thermal simulation of the X-band CDDA prototype with assumption of the base temperature is 70 K.

CONCLUSION

We investigated two different types of dielectric accelerators. Promising results has been achieved: shunt impedance as high as 550 MΩ/m while being operated at cryogenic temperature (77 K). Further optimization and detailed studies are needed.

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