AN X-BAND STANDING WAVE DIELECTRIC LOADED ACCELERATING STRUCTURE

C. Jing#, S. Antipov, P. Schoessow, and A. Kanareykin, Euclid Techlabs, Solon, OH-44139 USA
R. Konecny, Argonne National Laboratory, Argonne, IL-60439, USA
S. Kazakov, Fermi National Accelerator Laboratory, Batavia, IL 60510, USA
S. Gold, Plasma Physics Division, Naval Research Laboratory, Washington DC, 20375, USA

Abstract

An 11.4 GHz standing wave Dielectric Loaded Accelerating (DLA) structure was recently developed. The structure is designed to achieve a 120 MV/m gradient powered by a 10 MW 200 ns rf pulse from the X-band Magnicon at the Naval Research Laboratory (NRL). The structure uses on-axis rf coupling, which helps to localize the maximum EM fields within the dielectric region. Bench testing shows excellent agreement with the simulation results. In the high power rf test, multipactor was found to prevent increasing the gradient inside the dielectric cavity beyond 10MV/m. A simple model has been constructed that shows good agreement with the experiment. A new approach to completely suppress the multipactor in DLA structures using an axial magnetic field has been proposed. More experiments are planned.

MOTIVATION

The rf breakdown issue has become a major obstacle limiting accelerating structures from meeting the requirements for future high energy accelerators no matter what technology is used: metallic room temperature structures, superconducting rf cavities, dielectric based accelerators, or others. To fully understand the physics behind rf breakdown in high gradient accelerators, many well-designed experimental studies are needed, along with theory and simulations. Regarding breakdown studies of dielectric accelerators, beam driven experiments have shown very encouraging results [1]. However, direct breakdown data are not available for externally powered Dielectric Loaded Accelerating (DLA) structures. To date, a 15 MV/m gradient was reported for an X-band traveling wave DLA structure without observation of rf breakdown [2]. Breakdown occurring at the gap of a dielectric joint in another X-band traveling wave DLA structure implied that a DLA structure may be able to sustain a ~120 MV/m gradient in a gap free configuration [3]. Part of the reason that the direct observations of rf breakdown in externally powered DLA structures do not exist is because of the difficulties of eliminating gaps, in part because of length limitations in fabricating high quality ceramic tubes. A low R/Q gap free DLA structure was built for other test purposes, but the established gradient was low because of the limited rf power level available at the testing facility.

*Work supported by the Department of Energy SBIR program under Contract #DE-SC0006303 to Euclid Techlabs and by DoE grants to Argonne national Laboratory and the Naval Research Laboratory.
#jingchg@hep.anl.gov

The Standing Wave (SW) DLA structure presented in this article has the unique possibility of achieving a very high gradient with a low rf power requirement, 120 MV/m per 10 MW or 170 MV/m per 20 MW. Therefore, it will be capable of demonstrating high gradients in DLA structures or to reach its rf breakdown limit. Either result will increase the pace of dielectric accelerator development.

STRUCTURE DETAILS

The geometry of a dielectric-loaded accelerating structure is very simple; for example, a circular DLA structure may be made by just slipping a ceramic tube into a cylindrical metallic waveguide. However, other practical challenges are encountered. The major issue behind the fabrication of DLA structures is the effective coupling of the external rf energy into the devices. In the structure considered in this paper, the rf is coupled on the axis of the structure, as shown in Fig.1. A matching cell is used to adjust the coupling. This configuration has two advantages. First, we can use a standard SLAC type X-band TM_{01} mode launcher to feed rf into this structure, which will eliminate any uncertainty in terms of rf breakdown in the coupler below 20 MW. Second, this structure can be fine tuned by push-pull tuners mounted on the matching cell, which is on top of the tightly tolerance controlled machined iris. The electric field profile of the SW DLA structure is shown in Fig. 1, where we can see that the high electric field is concentrated in the dielectric region.

Major parameters for the structure are summarized in Table I. The ceramic material is a compound of Mg and Ti oxides (dielectric constant 20, loss tangent 10^{-4}). Under

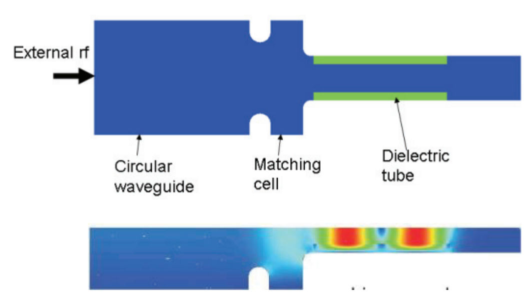

Figure 1: Top: 2D drawing of the developed SW DLA structure; Bottom: simulated E-field.

the critical coupling condition, the total loaded Q will be half of the intrinsic Q of the DLA structure, i.e. ~1125 in simulation. This means the filling time ($\tau=2Q/\omega_0$) of the

ISBN 978-3-95450-115-1

structure is around 31 ns which is far below the ~100 ns rise time of the Magnicon at Naval Research Laboratory (NRL).

Table 1: Parameters of 11.424 GHz SW DLA Structure

Parameters	Value
ID/OD	6 mm /9.134 mm
Dielectric constant	20
Loss tangent	1×10^{-4}
Length of dielectric tubes	25.8 mm
Frequency	11.424 GHz
R/Q of TM_{011} mode	8.8 (kΩ/m)
Q of TM_{011} mode	2249

Figure 2 shows the finished structure. The whole SW-DLA structure is designed in three separate parts: an rf feed in a matching cavity, a dielectric-loaded waveguide cavity and an end plug. In order to connect to the SLAC high power mode launcher (rf coupler), a 2-3/4" SLAC rf flange is brazed to the rf feed-in side. The matching cell has four push-pull tuning divots for final tuning of the structure if needed. The copper end plug is a separate part which has an ID 0.002" smaller than the OD of the dielectric tube to hold the ceramic tube in position. The induced rf reflection from this tiny bump is negligible. The end plug is locked by two vented screws. The large gap between the OD of the end plug and the copper housing is to maximize the pumping capability.

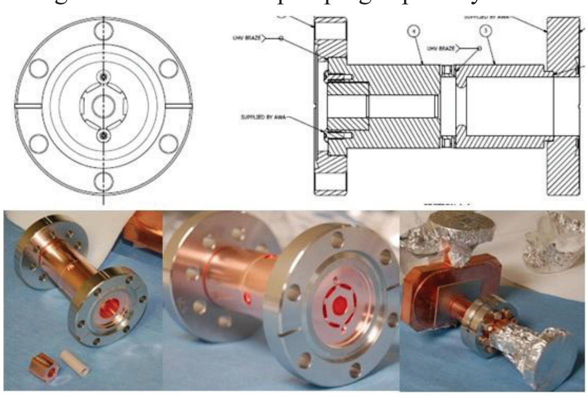

Figure 2: Top: mechanical drawing of the developed SW DLA structure; Bottom: finished structure.

To evaluate the performance of the developed SW DLA structure after the machining and assembling process was completed we performed a series of rf bench tests. Figure 3a shows the result of the S11 measurement of the SW DLA structure. The resonant frequency is exact at 11.424 GHz at room temperature. The loaded Q of the structure can be calculated from the measured S11 curve and coupling coefficient β can be read off the other display formats available for the S11 measurements, the VSWR or Smith Chart. The measurement indicates that the structure is slightly under coupled. The loaded Q is ~1190 and β is ~0.94 at room temperature. The beadpull results are shown in Fig. 3b, in which we can see that the electric field at 11.424 GHz shows very good agreement with the simulation in Fig. 1. The highest gradient appears only in the dielectric region. A small standing wave is built up inside the rf coupler and the input circular waveguide, but the gradient will be very small considering the 10 MW rf input used in the high power rf test.

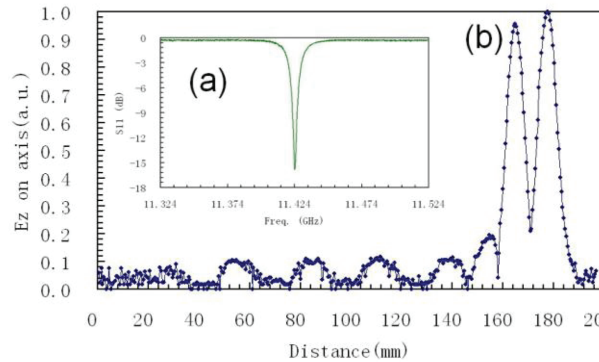

Figure 3: a): The measured S11 curve of the SW DLA structure; b): the bead-pull measurement results.

HIGH POWER RF TEST

The high power rf test was conducted at NRL in January 2012. During the test, the temperature of the structure remained below room temperature, at 15°C (considering the better performance of the Magnicon when it operates slightly above 11.424 GHz). The critical issue with a SW DLA structure observed in the high power rf test is the effect of multipactor loading. There exist two stages of multipactor. The first stage is the multipactor occurring in the matching copper cavity, which is similar to the situation during the conditioning of any standing wave linac in the low gradient regime. In this stage, the rf resonant frequency will change because of the multipactor loading, but for any copper cavity the resonant frequency will stabilize as the multipactor disappears with increasing gradient. For example, in the experiment we observed that the resonant frequency increased by around 1.5 MHz when the input rf increased from 6 kW to 10 kW due to multipactor in the copper matching cavity. The magnicon at NRL has a >5 MHz tuning range so that we can change the drive frequency during the test to ensure that the structure is driven at the resonance or close to it. Our judgment was based on the shape of the reflected signal.

The second stage of multipactor during the test of the SW DLA structure occurs in the dielectric region when the gradient exceeds a few MV/m. In this stage, the multipactor loading is very strong and accompanied by light emission. The equivalent Q of the structure drops dramatically, and thus the reflection signal increases accordingly.

In metal accelerating cavities, the multipactor region can be easily bypassed with an increase of the rf power beyond a certain level. However, in the test of SW DLA structure, we found out that the onset of dielectric multipactor occurred before the metal multipactor

ISBN 978-3-95450-115-1

disappeared. Indications of dielectric multipactor include visible light emission and a large rf reflection. Features of a typical reflected rf signal of filling the cavity at the beginning of rf pulse and discharging at the end of rf pulse completely disappeared once the dielectric multipactor started. Figure 4 shows the measured rf signals when the rf power level was in the dielectric multipactor region. The small notch shown in the reflected rf signal (~300 ns in Fig. 4) indicates the start of dielectric multipactor, which is very similar to our observations in previous tests of traveling wave DLA structures.

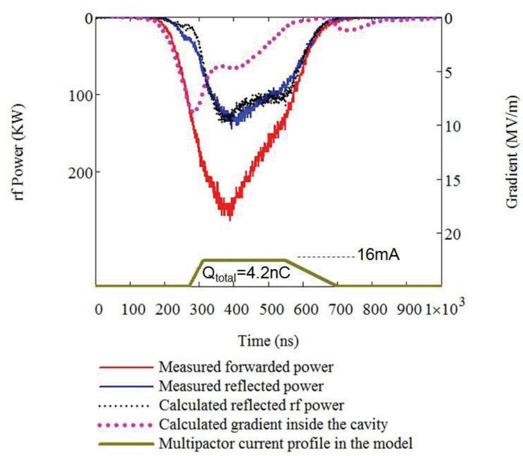

Figure 4: Comparison of the measured and calculated signals under dielectric multipactoring.

In an unloaded structure, the cavity fill time and the circulating power (or equivalently the stored energy) can be calculated directly from the incident power, the intrinsic quality factor Q_0, the external quality factor associated with the coupling iris Q_e, and the cavity coupling β. However, once the dielectric multipactor occurs, the secondary electron cloud will absorb a fraction of the incident power and dissipate it in collisions with the wall, lowering Q_0. This will change the reflected power, which is a function of β, and also reduce the power circulating in the cavity, where the accelerating electric field is proportional to the square root of the circulating power.

In order to understand this phenomenon, we used a simple RLC circuit model (shown in Fig. 5) in which we treated the SW DLA structure similarly to a pillbox cavity but with a multipactor current source (i_{mp}(t)) as a second excitation (mathematically equivalent to ordinary beam loading) in addition to the external voltage drive, V_F(t).

The calculated reflected power and voltage inside the SW DLA structure shown in Fig. 4 are results of this model. In Fig. 4 an applied power of ~250 kW (see the red curve) would normally generate an accelerating gradient of ~19 MV/m in the steady state. Unfortunately, only the incident and reflected power could be measured, since this first standing-wave structure had no provision for measuring the power inside the cavity. We use the simple model (Eqn. (13)) to predict the gradient inside the cavity under the condition of varying the multipactor current until good agreement between the measured and calculated reflected signal is obtained. The pink curve shows the calculated accelerating gradient as a function of time. It peaks at ~9 MV/m as the multipactor turns on, and then settles to only ~5 MV/m at the peak of the incident rf pulse. The beam loading current equivalent to this level of multipactor loading was calculated to be 16 mA.

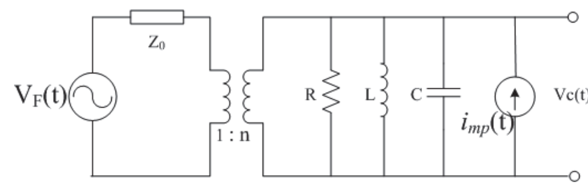

Figure 5: A simplified circuit model to represent a SW DLA structure with the multipactor loading current.

THE NEXT STEPS

Although relatively good agreement has been reached between the modeled and measured reflection signals, it would be better if we could directly compare the measured and calculated cavity signals. This motivates us to add a rf probe to the next SW DLA structure to have a quantitatively better understanding of multipactor. More importantly, the findings of a strong multipactor effect in the first round of high power rf testing allowed us to redesign the structure and experimental plan so that we can suppress multipactor to reach the principal goal of this project, determining the high gradient breakdown limit of dielectric accelerating structures.

Very recently a new approach, using an applied solenoid field to completely terminate multipactor in DLA structures, was suggested by Chao Chang [4], supported by the results of analytical models and PIC code simulations. Based on this model, an external DC magnetic field in the longitudinal direction can continuously reduce the period for secondary electrons hopping on the dielectric surface (and thus spoil the resonance condition) when the ratio of the gyro-frequency to rf frequency is in the range of 0.25 to 2. The optimal range which may completely block multipactor is 0.7~1, which is equivalent to a solenoid field ranging from 2.8 kG to 4 kG for an X-band DLA structure. This approach is more attractive than other techniques since it can maintain all the advantages of regular DLA structures, and it is independent of the accelerator parameters other than the operating frequency.

REFERENCE

[1] M. C. Thompson, *et al. Phy. Rev. Lett.* 100, 214801 (2008).
[2] C. Jing, *et al, IEEE, Trans. PS,* 38, 6, (2010):1354-1360.
[3] C. Jing, *et al, IEEE, Trans. PS,* 33, 4, (2005):1155-1160.
[4] C. Chang, *et al, J. Appl. Phys.* 110, 063304 (2011).

ISBN 978-3-95450-115-1