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HIGH SHUNT IMPEDANCE ACCELERATING STRUCTURE WITH DISTRIBUTED MICROWAVE COUPLING

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Abstract

Conventional traveling wave or pi-phase advance standing wave structures use coupling of the microwave power through the beam pipe. This feature constrains the cavity shunt impedance (efficiency) to relatively small values. As microwave power flows through the accelerating cells in such structures, the probability of breakdown in high gradient operation is greatly increased. In this paper we present results from an accelerating structure prototype with distributed microwave coupling, an approach invented at SLAC [1, 2]. These structures include one or more parallel waveguides which are loaded by accelerating cavities. In this configuration accelerating cavities are fed independently and completely isolated at the beam pipe. Thus there is no microwave power flow through the accelerating cavity, making this geometry favorable for high gradient operation and maximizing the shunt impedance.

INTRODUCTION

Future colliders require high gradient and high efficiency (i.e., high shunt impedance) accelerating structures. The SLAC National Accelerator Laboratory recently developed a series of novel accelerating structures with distributed coupling [1]. These structures include one or more parallel waveguides that are loaded by accelerating cavities. This approach allows configurations where no RF power is flowing axially through the accelerating cavity, while maintaining a high accelerating gradient. In addition, this approach allows accelerating cavities to be completely isolated at the beam pipe. Conventional traveling-wave or standing-wave structures couple the RF power through the beam pipe. This feature constrains the cavity shunt impedance to relatively small values. Without this constraint, the distributed-coupling design improves efficiency, while reducing cost and improving the operational flexibility of particle accelerators. Further in the text we refer to this structure as distributed coupling high shunt impedance (DCHSI) accelerating structure. Also, high gradient operation poses the risk of having high breakdown rates. In traditional traveling-wave structures, RF power flows through the accelerating cells. For distributed coupling structures, this risk is reduced because the absence of power flow through the accelerating cavity allows configurations where no power flows through the beam pipe, and the cavity shapes can be optimized to minimize pulsed surface heating. Finally, the distributed-coupling accelerating structure design allows one to fabricate the structures in two halves. This significantly reduces the complexity of machining, brazing, and tuning, thus reducing the cost of the structure. In addition, the traveling-wave structure is matched to the RF source, so that no circulator is needed, and the RF network is simplified.

ACCELERATING STRUCTURE DESIGN

We simulated accelerating structure cells with Master-Slave ($2\pi/3$ phase shift) boundary condition for waveguide and beam pipe ends (see Fig. 1A), and copper conductivity on all metallic walls. Another method of determining the main parameters is the usual standing-wave calculation of one and a half or three periods with simple electric and magnetic boundary conditions (see Fig. 1.B). The structure geometry was optimized to have high shunt impedance.

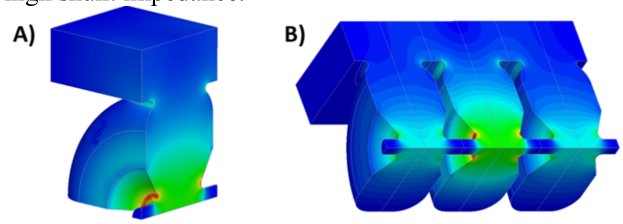

Figure 1: A) Electric field pattern for the $2\pi/3$ operating mode 9.3 GHz (Quarter-cell model, HFSS calculation with master-slave boundary conditions). B) The $2\pi/3$ operating mode field pattern in the HFSS eigenmode calculation with electric boundary conditions at ends.

We designed a 20-cell structure based on such cell (Fig. 2). Table 1 shows main accelerating parameters of the structure.

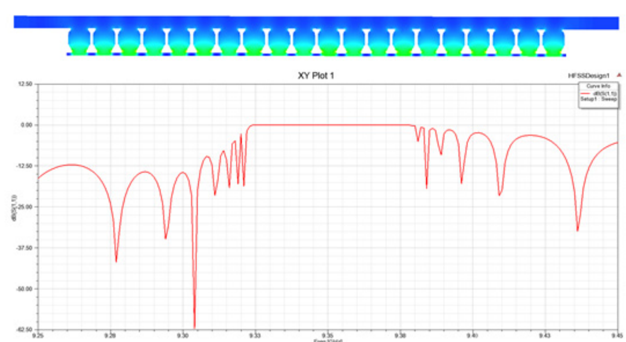

Figure 2: HFSS simulation result for the 20-cell DCHSI cavity: top is operating field balance at 9.3 GHz; bottom is reflected-wave ratio S11 vs. frequency.

MANUFACTURING AND TESTING

Because of the cell nose geometry, the DHSI structure has to be machined with a 5-axis CNC. One important design consideration was the ability to manufacture the nose geometry. We contacted two vendors for high precision machining to get feedback on the allowable

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geometries. Based on their feedback the structure was designed with a specific nose geometry.

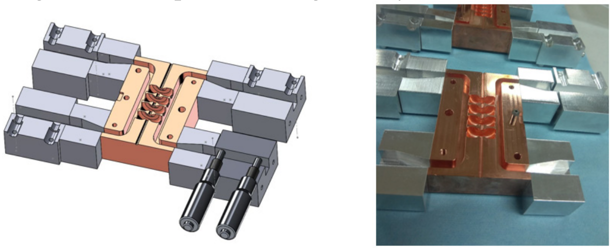

Figure 3: Left: engineering design of the 4-cell DCHSI. Right: manufactured DCHSI with waveguide converters.

Our work on the DCHSI structure was limited in time by the duration of phase I SBIR grant. Full 20-cell structure would have taken a long time to fabricate. One of our vendors could manufacture a small, 4-cell structure in a timely manner. The fabricated structure is shown in Fig. 3. We use micrometer heads for tuning the coupling.

Table 1: Accelerating Parameters of Distributed Coupling Structure

Parameter	DCHSI
Cell length, mm	10.745
Aperture radius, mm	1.14
a/λ	0.035
f, GHz	9.3
Q	6883
Phase advance per cell, degrees	120
Phase velocity, speed of light	1
Group velocity, speed of light	0.015
Attenuation length, m	1.06
Shunt Impedance, MΩ/m	143.5
R/Q, kΩ/m	20.85

The 4-cell structure required some field balance tuning (Fig. 4.A). An appropriate sequence of copper mechanical manipulation was applied to achieve a proper field balance (Fig. 4.B).

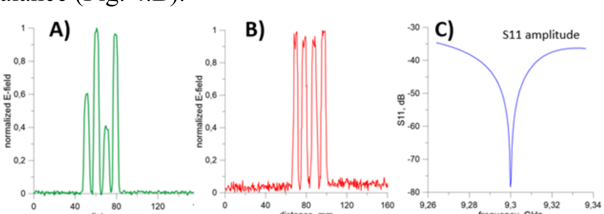

Figure 4: A) 4-cell DCHSI structure original field balance. B) Corrected field balance. C) Reflection from the structure (measured).

DCHSI – "LITE

With DCHSI structure we were limited in manufacturing time because of the complex nose-shape geometry used to maximize shunt impedance. It was decided to design a no-nose DCHSI structure, which was dubbed DCHSI–lite. The no-nose cell geometry can be machined with simple CNC, which is faster and cheaper at full scale.

The structure was designed using the same approach described in the previous section (Fig. 5). It was built in full scale (20 cells) in aluminum.

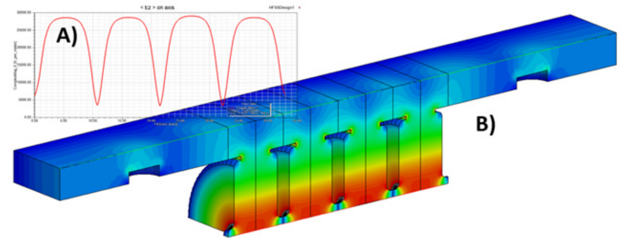

Figure 5: A) Field balance and B) Ez distribution in 3D in DCHSI–lite.

The DCHSI–lite structure (Fig. 6) was assembled and prepared for cold test. A phase shifter and attenuator were used to make sure both waveguides (shoulders) were properly powered at the correct amplitude and phase.

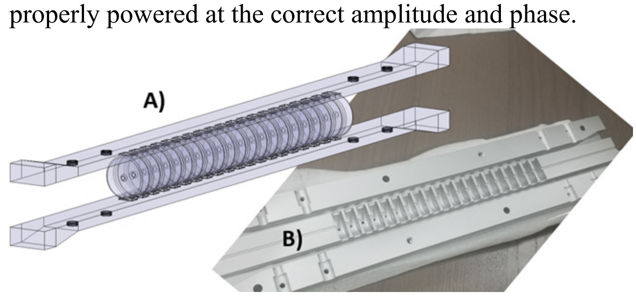

Figure 6: A) Engineering design of the DCHSI–lite and B) Fabricated prototype.

Figure 7 shows the bead pull measurement that was achieved with this structure. The prototype tuning procedure consisted of three main steps. First, detach both waveguide shoulders from the cavity prototype and attach them to directional couplers with waveguide loads or waveguide/coaxial adapters. Using attenuators to equalize amplitude output power S21 in the shoulders. Measure S21 phase in one of the shoulders at the operating frequency (probably 9.3 GHz). Use phase shifter and attenuators to obtain 180^0 difference and equal amplitude in the shoulders at the operating frequency. Second, keep the tuned settings of the waveguide shoulders to attach them to the cavity. Make sure that all 40 tuning bolts and 8 waveguide micrometric tuners (MWTs) in the cavity have the same position. Use only the MWTs to equalize, as much as possible, the S21 signal from the 10 dB directional couplers in the band 9300±25 MHz, with a minimum at the operating frequency or around (±10 MHz) points in both shoulders. Finally, thread a bead-pull line through the CP beam pipe. Using only MWTs, adjust the previously obtained S21 minimums and S21 shapes in the waveguide directional couplers.

The DCHSI-lite cavity bead pool measurements are based on non-resonance perturbation techniques. The on-axis electric field amplitude and phase are proportion to square root of the S21 measurement. The results of the bead pull test are shown in Fig. 7.

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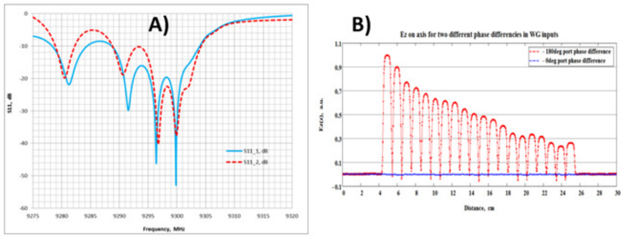

Figure 7: A) Measured HSI 20-cell cavity S-parameters (left is S11 for both shoulders; right is S21 for one shoulder). B) Electric field balance vs. phase difference in waveguide input ports.

There is a noticeable attenuation along the structure. This fact was unexpected and surprizing at the beginning. It turned out that the structure was bead blasted after fabrication to conceal the tool marks. This was a default procedure by our vendor and this fact was overlooked. Increased surface roughness made attenuation length significantly shorter – about 20 cm.

In summary, we designed a high shunt impedance accelerating structure with distributed coupling, and manufactured a 4-cell prototype. This prototype was cold tested, and measurements showed that the required parameters were achieved. We also designed a simplified, “lite” distributed coupling structure, and manufactured it at full size in aluminum. Apart from unexpectedly short attenuation length which was determined by the increased roughness produced by a bead blast, the structure performed as expected. These novel high gradient high efficiency accelerating structures can become structures of choice for next generation compact x-band accelerators for medical radiology and cargo inspection.

ACKNOWLEDGEMENT

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[1] V. Dolgashev, US patent US9380695 B2.
[2] V. Dolgashev, in *Proc. LINAC’16*, East Lansing, MI, Sept. 2016, pp. 48-51.