HIGH POWER TESTS OF OVERMODED WAVEGUIDE FOR THE ILC KLYSTRON CLUSTER SCHEME*

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Abstract

A Klystron Cluster Scheme [1] has been proposed for the ILC Main Linacs in which the rf power from up to thirty, 10 MW, 1.3 GHz klystrons is combined in a single 0.5 m-diameter circular waveguide in a surface building and transported down to and along the accelerator tunnel, where it is periodically tapped-off, over nearly a kilometer, to power groups of SC accelerator cavities. This scheme eliminates the need for a separate linac service tunnel and simplifies the linac electrical and cooling distribution systems. In the past two years, proof-of-principle testing on two short prototype circular waveguides, 10 m and 40 m long, has been performed at SLAC. In this paper, we'll review the circular waveguide test setup and the results.

INTRODUCTION

The Klystron Cluster Scheme (KCS) is an option for powering the ILC Main Linacs without having to accommodate rf production equipment underground [1]. To test of the scheme's feasibility, a series of circular aluminium pipes with an inner diameter of 0.48 m, the envisioned KCS main waveguide, was assembled at SLAC and resonantly powered by a pulsed (1.2-1.6 ms) L-band (1.3 GHz) klystron at 3-5 Hz. RF was coupled in through a magic T and a device called a coaxial tap-off (CTO) [1] configured to serve as a TE_{01} mode launcher. Fig. 1 shows the input end of the initial 10 m long pipe test setup. The pipe was made in 8 foot lengths and the inner diameter was bored with an accuracy of about 1 mm.

Figure 1: Photograph of the test setup of the nitrogen filled, aluminium, circular pipe in which power enters from the top via WR650 waveguide and is split with a magic T to feed the mode launcher.

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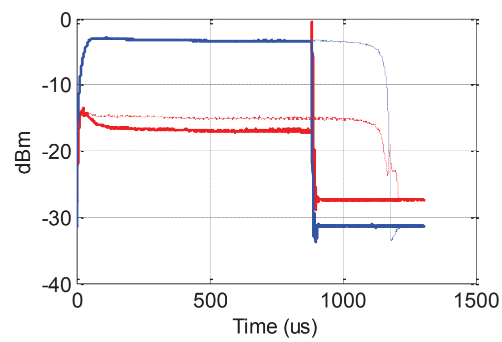
EXPERIMENTAL SETUP

The circular waveguide was operated in the azimuthally symmetric TE_{01} mode, chosen for its low loss and its lack of surface electric field. Both features are important for an application so ambitious both in transport distance and power handling. While intended ultimately for one-way transmission, it is not feasible at this stage to assemble the equipment required to provide it with the full rf power. Instead, equivalent field levels were established by testing it resonantly. It was powered on resonance with a shorting plate on the far end, so that a very high electric field standing wave was built up inside.



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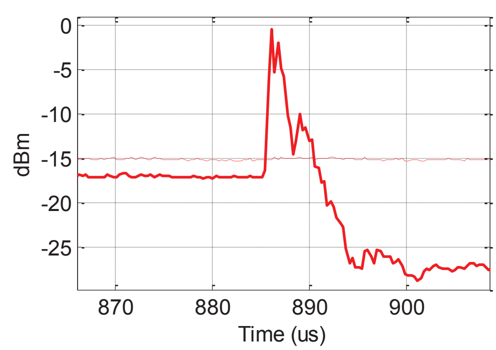

b)

Figure 2: a) Typical un-calibrated waveforms from the pipe resonance, where the blue and red traces are respectively the input rf power and the power to the terminated magic T 4th port in normal operation (dashed) and for a breakdown event (solid), and b) a finer-scaled view of the magic T waveforms.

In normal operation, there is by symmetry very little power flow to the fourth port of the magic T through which the dual CTO inputs are fed. However, in the event of a breakdown, some stored rf energy is scattered into asymmetric modes and flows to that port as illustrated in Fig. 2, allowing this signal to be used to interlock for rf breakdown. The pipe was pressurized with N_2 to raise its breakdown field threshold.

HIGH POWER TEST RESULTS

Initially, a 10 m resonant pipe of 6061-T6 aluminium was assembled and tested. Theoretical calculation gives an expected unloaded Q value of ~192,000 for this setup. Critically coupled, it would require only 315 kW input rf power to produce, via a 75 MW standing wave, antinode field levels equivalent to those of a 300 MW travelling wave. Initial network analyser cold tests, however, revealed a puzzlingly low Q_0 of 146,000.

As the pipe was heated up by the rf, its resonance quickly drifted, as shown in Fig. 3, where the average power lost to the pipe walls is 2.2 kW. Due to the very high Q of the system, this detuning was significant. An automatic tracking program was thus implemented to tune the rf source frequency by minimizing the reflected power. This made temperature stabilization through water cooling and insulation unnecessary.

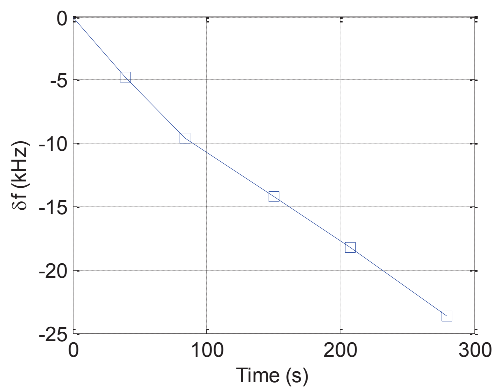

Figure 3: Frequency shift of the resonant 10 m long pipe vs. time with 2.2 kW average rf power dissipation.

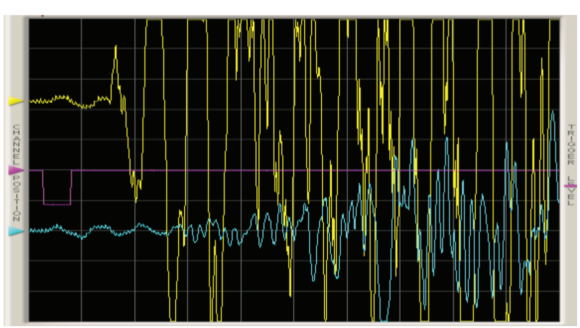

Figure 4: The pink line represents the rf signal, and the yellow and light blue lines are breakdown waveforms from the two sensors, which were 2.5 m apart. The relative signal start times is about 1.3 ms.

The pipe was pressurized to 15 psig N_2 and tested for a couple of hundred hours, during which it incurred many breakdowns. A pair of acoustic sensors was mounted on the pipe in an effort to localize the breakdown sites. Typical breakdown waveforms from the sensor pair are shown in Fig. 4, where one can see a clear difference in the signal start times. From these time differences, we were able to conclude that most breakdowns were in the CTO mode launcher. After disassembly, we found breakdown pits in the CTO although they were in an area where there should have been no surface electric fields.

We also found that there were extensive "scorch" marks (small beads of melted aluminium) around the flange faces of the pipe, as seen in Fig. 5, but they were not the cause of the rf breakdown noted above. The flange joint was designed with two grooves on one side, the outer groove accommodating a canted-coil rf seal and the inner one a rubber O-ring pressure seal. This ordering, determined by available sizes, proved unfortunate. Simulation suggests that the inner groove provided a choke-mode type resonance near our rf frequency. Thus, although TE_{01} shouldn't see small flange gaps, imperfections or parasitic mode content (degenerate TM_{11}) must have driven high enough fields in them to cause localized arcing. Re-machining the flange faces with a slight angle to guarantee contact at the ID solved this problem. After reassembly, the measured Q_0 was 168,000, still somewhat low, perhaps due to a parasitic mode bump seen at the edge of the resonance.

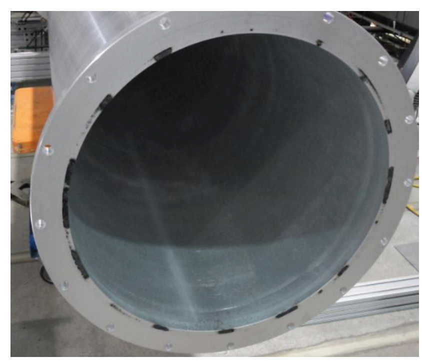

Figure 5: The "scorched " flange face from high power testing. This problem was fixed.

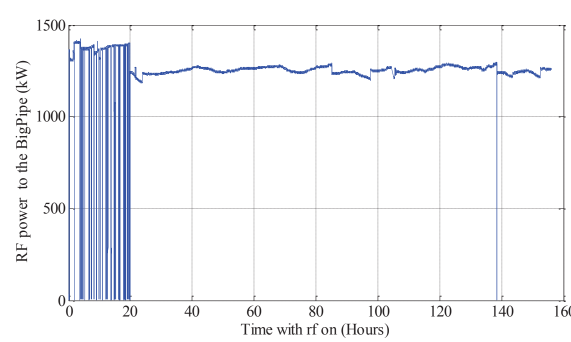

Figure 6: The input power to the circular pipe with a 90° overmoded rectangular bend, where the fast drop of the power represents rf breakdown.

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After these tests, a longer (40 m) version of the setup was built using the original CTO but new pipe with the improved flange design. The longer pipe increased the stored energy, which could potentially cause more damage during breakdown events. This pipe was first tested resonantly up to high electric fields (300 MW traveling wave equivalent). No rf breakdown occurred with a nitrogen pressure of 22 psig.

The pipe was later terminated with a 90° overmoded. 34.9 cm high, rectangular TE_{20} mode, H-plane bend [2], which would also be needed for KCS. The unloaded Q of the resulting resonant line was 181,300, within ~3% of theoretical value (including HFSS bend simulation), and the coupling beta was 1.30. The anomalous loss due to parasitic/gap resonance was completely eliminated. With 1.19 MW input power, the corresponding equivalent field in the pipe is that for the 300 MW transmission required for ILC. The pipe was pressurized to 30 psig of nitrogen to raise the rf breakdown threshold. It was then tested at ~1.25 MW (equivalent of 315 MW transmission) for more than 100 hours with only one breakdown as shown in Fig. 6. It was thus demonstrated that field levels equal to those for the 300 MW transmission required for ILC could be reliably sustained.

This test setup was then operated at various power levels and pressures. During this period, the breakdowns appeared to occur in the 90 degree bend based on the origin of the sound they made. The peak electric field in the bend at 300 MW is 3.34 MV/m, terminating on the top and bottom of the waveguide. During the tests, it was run as high as 4 MV/m, corresponding to 430 MW TW-equivalent fields, driven with an input power of 1.71 MW. The rf breakdown rate did not improve over time, suggesting that it may not be a metal surface phenomenon. After the high power test, we examined the bend surface and did not find any clear breakdown marks. Nevertheless, as it represents the highest field region, we believe that the breakdowns events are associated with the H-plane bend.

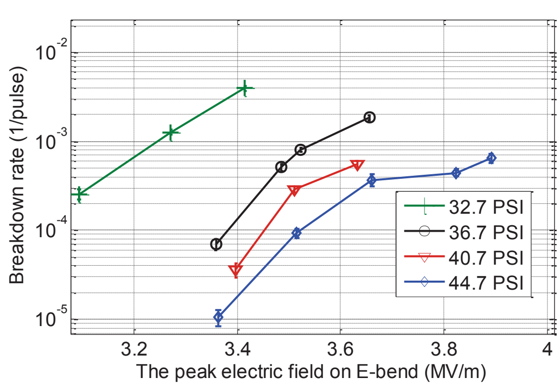

Figure 7: The breakdown rate dependence on the peak surface electric field of the bend at different N_2 pressures.

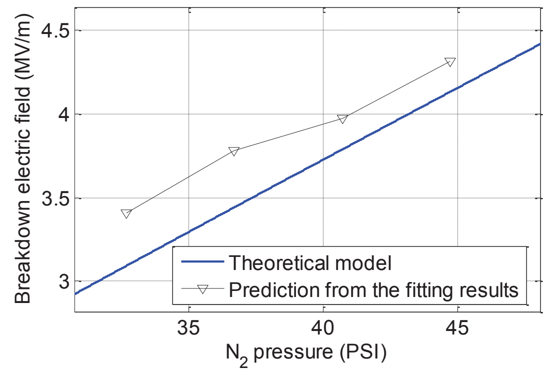

Figure 8: The peak bend field at a fixed breakdown rate versus the nitrogen gas pressure. The triangles are the experimental data and the solid blue line is obtained from a theoretical model.

The breakdown rate as a function of the nitrogen pressure and peak electric surface field in the bend is shown in Fig. 7. The rate has strong dependence on the electric field as well as on the gas pressure. It is clear that increasing the pressure lowers the rate for a given field level, as expected. We also found that the breakdown rate depends linearly on the rf pulse width. Finally, as shown in Fig. 8, the peak field at a fixed breakdown rate has a slope with pressure that follows a model of rf breakdown in gas as presented in reference [3].

SUMMARY

We have resonantly tested two short (10 m and 40 m) pressurized versions of the KCS circular main waveguide. The experimental results have demonstrated that the KCS option is suitable for ILC-like power levels. We also observed that the breakdown rate has a strong rf electric field and gas pressure dependence.

ACKNOWLEDGEMENTS

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