CERN – EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CLIC Note 552

VARIABLE HIGH POWER RF SPLITTER AND RF PHASE SHIFTER FOR CLIC

I. Syratchev

Abstract

During the routine operation of CLIC a way has to be found to divert RF power from a single accelerating structure that is continuously breaking down. One way to do this is to use a device, which re-directs or splits the RF power between the structure and the RF load. An extensive development programme of such devices is under way at SLAC [1], however, there is no reliable device available to date which can handle a few hundred MW at the CLIC high frequency of 30 GHz. Ultra-fast switching times are not required for CLIC, it is sufficient that the power be diverted. The device however should be extremely reliable. A novel design of a mechanically – driven high-power RF splitter/divider and RF phase shifter that satisfies the CLIC requirements is presented.

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Abstract.

During the routine operation of CLIC a way has to be found to divert RF power from a single accelerating structure that is continuously breaking down. One way to do this is to use a device, which re-directs or splits the RF power between the structure and the RF load. An extensive development programme of such devices is under way at SLAC [1], however, there is no reliable device available to date which can handle a few hundred MW at the CLIC high frequency of 30 GHz. Ultra-fast switching times are not required for CLIC, it is sufficient that the power be diverted. The device however should be extremely reliable. A novel design of a mechanically – driven high-power RF splitter/divider and RF phase shifter that satisfies the CLIC requirements is presented.

1 BASIC FEATURES OF THE SPLITTER

The standard configuration for such a device is shown in Fig. 1. Depending on the RF phase ratio between the two inputs to the 3-dB hybrid (φ1 and φ2), the resulting output signal is sent either to the accelerating structure or to the RF load, or is split between them. The NLC design of one of these devices is shown in Fig. 2, the NLC team call it a planar phase shifter/attenuator [1] and the adjustments are made using mechanically driven moveable short-circuits. It has a simple layout but has to withstand operation at high power levels and many mechanical cycles. The insertion losses of these devices should be as small as possible because they unavoidably reduce overall efficiency.

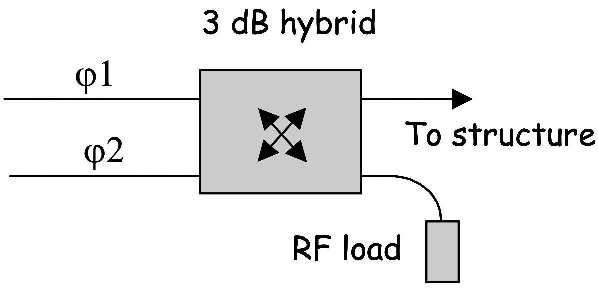

Figure 1. RF power splitter layout.

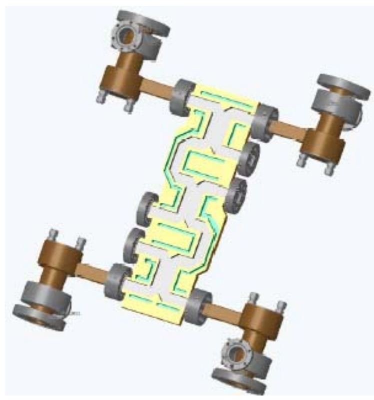

Figure 2. NLC planar splitter

The CLIC team has developed an alternative device; it eases construction and reduces ohmic losses. The basic idea is to exploit the polarization properties of the fundamental H_{11} mode in a circular waveguide. It is well known that with the transformation of the circular waveguide into an elliptical one, the initial H_{11} mode degenerates into two orthogonal modes. The split of energy between these two modes is regulated by the angle between the original H_{11} mode polarization and the orientation of the main axes of the elliptical waveguide. When the two degenerate modes are converted back into a single mode in a subsequent piece of circular waveguide, the resulting H_{11} mode will have changed its original polarization. To minimize the transformation length, the cross-section of the elliptical waveguide is normally chosen such that at a given frequency the ratio between the two polarization wavelengths is about 1.5. The second important feature of the splitter is that the RF power that is extracted is sensitive to polarization. All the component parts have been optimised separately with HFSS. All the results presented here are from simulations. The final splitter assembly is shown in Fig. 3 together with the electric field patterns for two regimes of operation: total rejection (Fig. 3 left) and total transmission (Fig. 3 right). Rotating the "polarizer" by 45 degrees makes the commutation between the two regimes. The S – parameters for both these cases are shown in Fig. 4. One can see that the isolation is about – 17.5 dB with a matching better than – 30 dB. The fact that the RF power splits equally between ports P3 and P4 over a wide frequency band is an advantage that will be discussed later. The overall length of the splitter is about 5 wavelengths, which makes it rather compact and hence efficient.

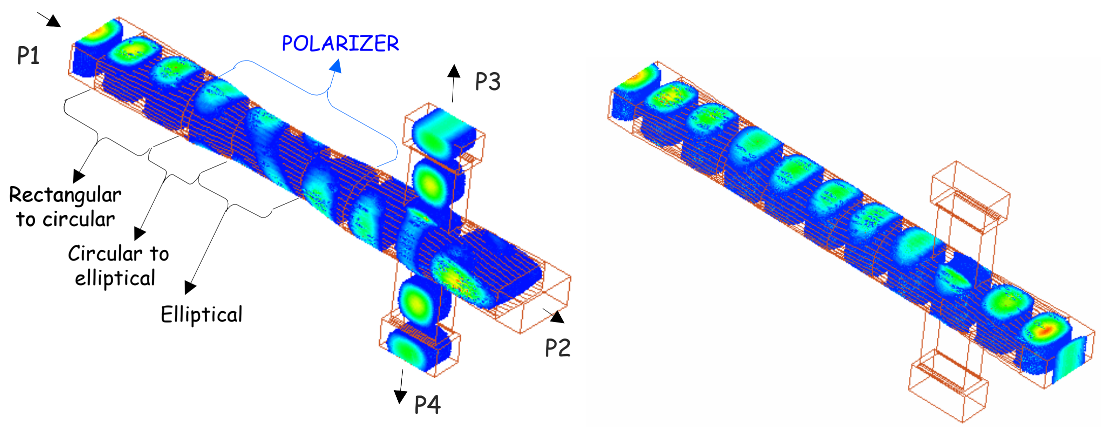

Figure 3. The electric field patterns for two regimes of splitter operation: rejection (left) and transmission (right).

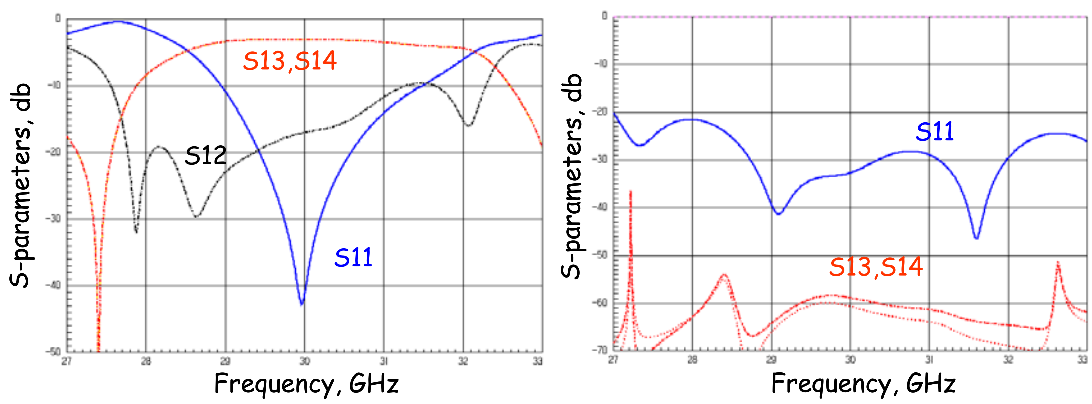

Figure 4. S-parameters for both regimes.

From a mechanical point of view the most critical question is how to rotate the "polarizer" under vacuum in the presence of very high RF power levels. One possibility considered was to deform a thin-walled (0.5 mm) stainless-steel circular waveguide. Unfortunately, for the waveguide profile required, the induced stress exceeded the elastic limit by a large factor [2]. With the proper choice of material this method may be made to work but for the moment this solution was not retained. For practical reasons, the well-known choke-type connection was chosen and optimised. With this solution there is no need to have an electrical contact between the two circular waveguides because the choke provides a cavity that traps the electromagnetic field within itself without any external radiation through the slot. The electric field pattern in such a junction is shown in Fig. 5. The S-parameters are shown in Fig. 6. Note that in the HFSS simulation, a waveguide port with eight propagating modes represented the end of the slot.

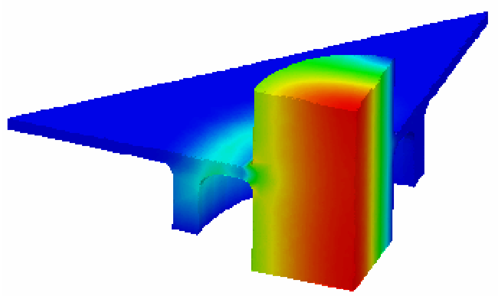

Figure 5. Electric field distribution in the choke junction (quarter symmetry).

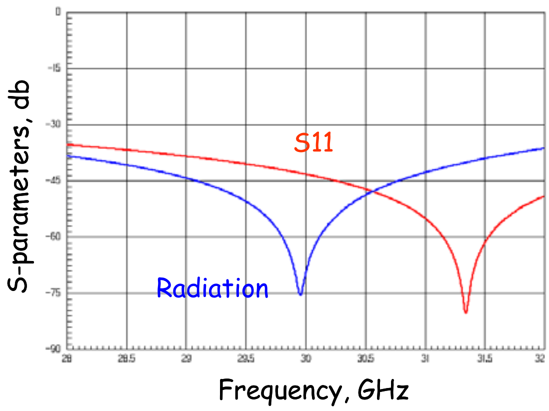

Figure 6. S-parameters of the choke

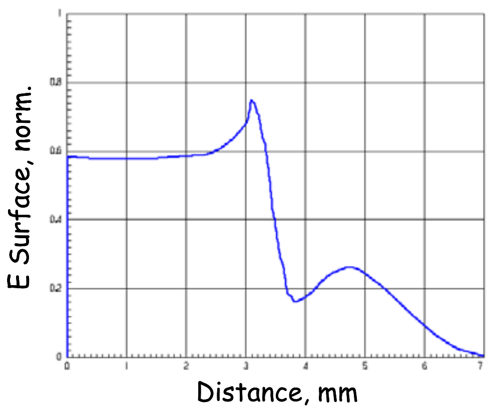

Figure 7. Electric surface field distribution in a choke normalized to the maximum surface field in a rectangular waveguide.

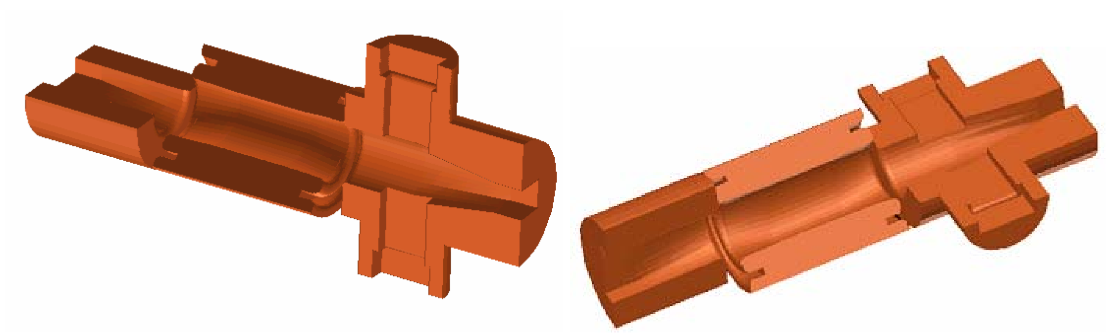

Figure 8. Artistic views of the variable high RF power splitter.

The trouble with any choke junction is a possible electric field enhancement due to its shape and size. In our particular design this problem did not occur. The maximum surface electric field in the area of the inner choke radius was about 75 % of that in a standard rectangular waveguide (see Fig. 7). Artistic views of the splitter with the incorporated chokes are shown in Fig. 8.

The splitter can operate not only in an ON/OFF mode, but also as a variable divider. This brings extra flexibility to the RF power distribution system of the linear accelerator. In general, the RF power distribution between the 3 output ports of the splitter are determined by the following relationships:

$$\begin{aligned} P_2 &= P_1 \cos^2(\alpha) \\ P_3 + P_4 &= P_1 \sin^2(\alpha) \quad (1), \\ P_3 &= P_4 \end{aligned}$$

where α is the rotation angle of the "polarizer" and the indexes correspond to the numbers of the ports (see Fig. 3). HFSS simulations confirmed these relationships. The RF power distribution as a function of "polarizer" angle is shown in Fig. 9, left. The normalized extra RF phase advance of the transmitted signal (P2) due to "polarizer" rotation is shown in Fig. 9, right. The RF phase of the signals in ports 3 and 4 remains constant. The simulated matching for all cases was better than – 33 dB.

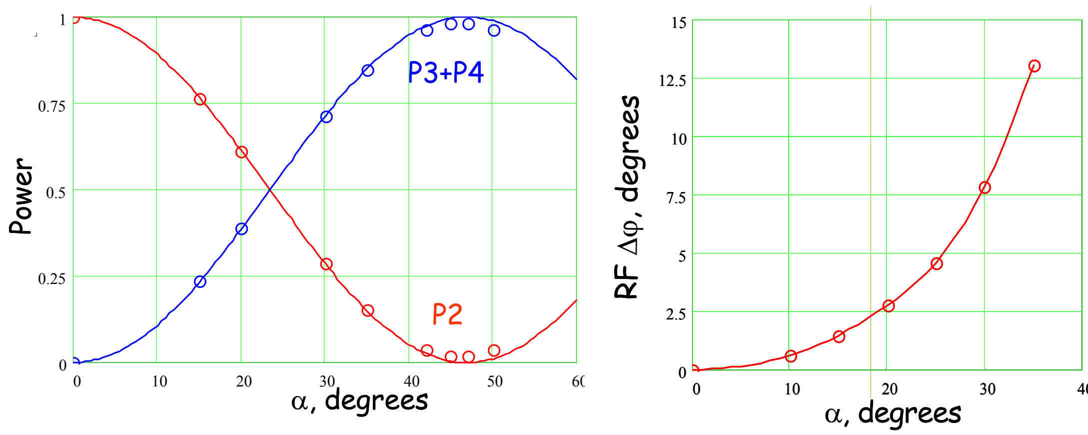

Figure 9. RF power distribution between 3 output ports vs. rotation angle of the "polarizer" (left). Normalized extra RF phase advance of the transmitted signal (P2) due to the "polarizer" rotation (right). The circles correspond to HFSS simulations and dash line (left) represents cos² function.

In a few of the present linear accelerator designs one RF feeder is used to feed a few accelerating structures. For CLIC [3], with its newly developed accelerating structure [4], this number would be 4 or 5. For NLC there would be 3 travelling-wave structures [5], or 10 standing-wave structures [6]. This variable power splitter is easily incorporated into the RF distribution system and is easily adjusted to optimise the performance. It has the advantage that it consists of identical components. A possible layout for CLIC is shown in Fig. 10. In this configuration the rotation angle for each of the identical "polarizers" should be chosen to provide the required RF power at each extraction point.

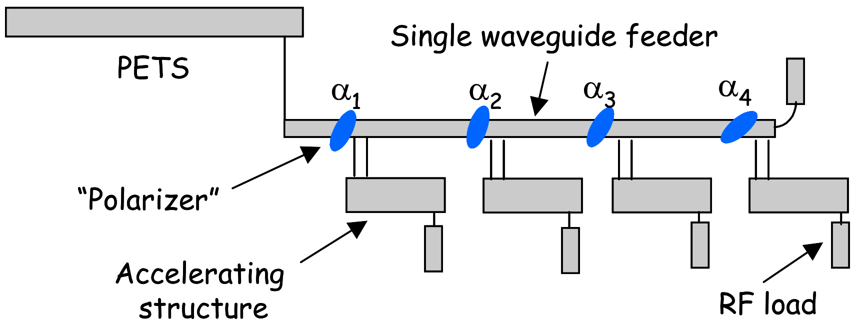

Figure 10. A possible layout for one CLIC accelerating module.

This is summarized in Fig. 11, which gives the angle for each "polarizer" as a function of the structure number for different total numbers of structures (6 at most). It is assumed that each structure is fed symmetrically through ports 3 and 4; the polarizer angle is given by the following expression:

$$\alpha_m = \arcsin\left(\sqrt{\frac{1}{2(N-m+1)}}\right) \quad m = 1..N \quad (2),$$

where N is the total number of the structures in one module and m is the structure number.

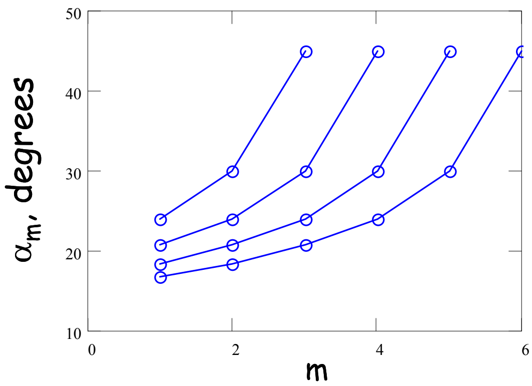

Figure 11. "Polarizer" rotation angle vs. structure number

Different operational scenarios may also be considered. For the most advanced version, one could foresee all "polarizers" to be actively tuned during accelerator operation. This would enable the RF power to be diverted away from a defective structure in a module. In this case all the "polarizer" angles would have to be re-tuned to re-direct the extra RF power towards the RF load at the end of the waveguide feeder line. Implementation of such a scenario would however require a rather complicated network, and it is therefore more probable that a complete module would be sacrificed in the event of a single structure failure. In such a case all the "polarizer" angles would be fixed and another dedicated variable "polarizer" would be introduced between the PETS and the module.

2 RF PHASE SHIFTER

The variable RF phase shifter for fine-tuning of the input RF phase of the accelerating structure itself is another important device. It is required to compensate parasitic RF phase deviations during machine operation. For example at 30 GHz, a temperature change of the waveguide by 5 C^0, leads to an extra RF phase advance by 3 degrees over a length of 1 m, the required RF phase stability for CLIC is less then ±0.2 degrees [7]. A new high-resolution RF phase-tuning device has been developed. The design has many of the design features of the previously described RF splitter. It consists of two "polarizers" in series which rotate together providing the effect of an "RF chicane" - the mode polarization bounces back and forth resulting in an RF phase delay that depends on the "polarizer" angles. An example is shown in Fig. 12, the HFSS electric field patterns are shown for "polarizer" angles of 30 and 60 degrees. The RF phase delay as a function of the "polarizer" angle is shown in Fig. 13 on the left. The matching of the RF phase shifter over the tuneable range is shown in Fig. 13 on the right.

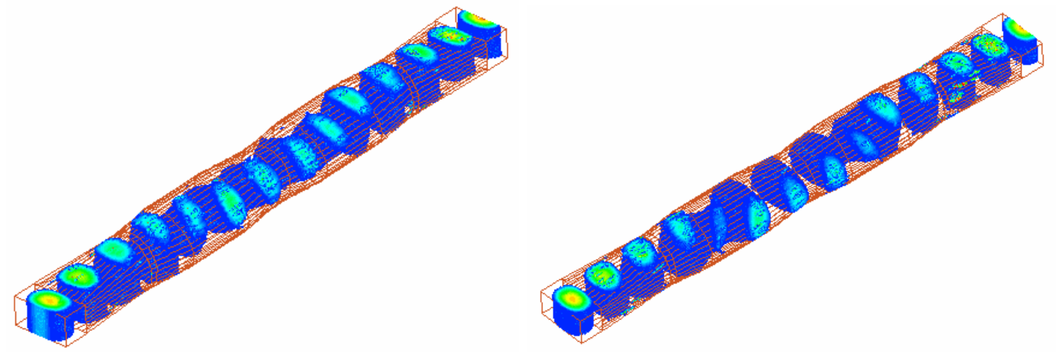

Figure 12. HFSS electric field patterns in the RF phase shifter for "polarizer" angles of 30 degrees (left) and 60 degrees (right).

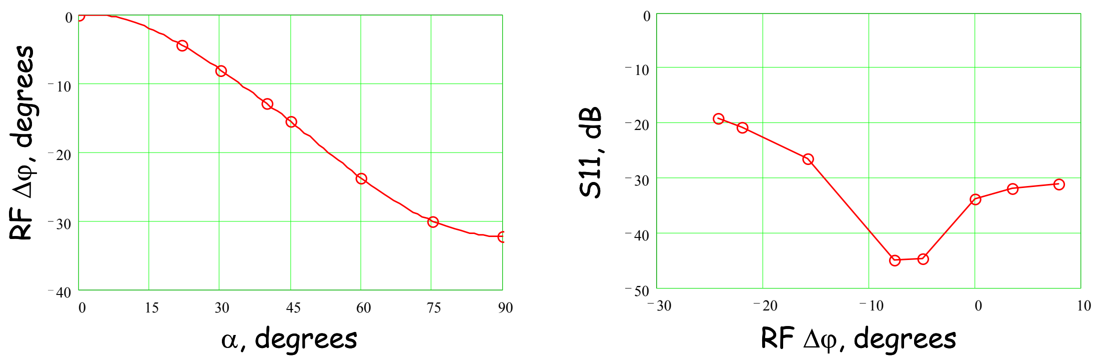

Figure 13. The RF phase delay vs. "polarizer" angle (left). The matching of the RF phase shifter in the tuneable range (right). The circles correspond to HFSS simulations

The device has a total tuning range of 32 degrees of RF phase. During operation, the RF phase should however be guaranteed to be constant. Setting the zero point to the 30 degrees of "polarizer" angle and keeping the matching of the RF phase shifter better than –25 dB, the RF phase tuning range goes from –16 to +8 degrees. The tuning accuracy is about 0.4 degrees of RF phase per 1.0 degree of the "polarizer" rotation angle, this satisfies the CLIC specification. In this particular design we tried to keep the basic elements the same as for the splitter. If it is necessary to increase the tuning range, this could be achieved by a simple lengthening of the elliptical part of the "polarizer".

When combined together (see Fig 14.) the RF power splitter and the phase shifter can provide a tight control of both the RF power level and the RF phase. As an example, the rotation angles of the "polarizers" for the RF power splitter (α_D) and the RF phase shifter (α_Φ) are shown if Fig. 15 as a function of RF power output level (P2) for a constant output RF phase.

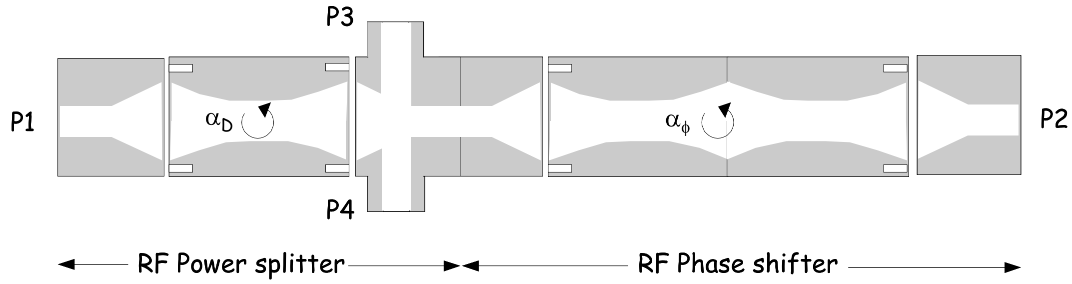

Figure 14. Schematic layout of the CLIC variable high RF power attenuator.

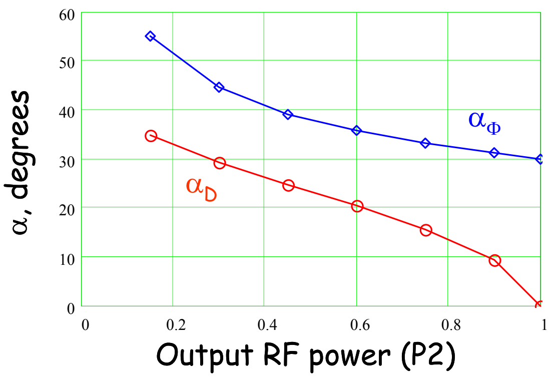

Figure 15. The rotation angles of the "polarizers" for the RF power splitter (α_D) and the RF phase shifter (α_Φ) vs. RF power output level (P2) for a constant output RF phase.

Novel designs of a CLIC high power RF attenuator and RF phase shifter have been developed which satisfy the CLIC requirements. Detailed studies to design mechanically reliable cost-effective systems are under way. The author would like to acknowledge H. H. Braun, S. Heikkinen, I. Wilson and W. Wuensch for many useful discussions.

3 REFERENCES

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