CERN/PS/ 88-76 (DL)
November 1988

RADIAL TRANSMISSION LINES

A. Aronson*), F. Caspers, H. Haseroth, J. Knott, W. Willis

Invited Paper
Switched Power Workshop
October 16-21, 1988
Shelter Islands, New York

*) BNL, Upton, USA

RADIAL TRANSMISSION LINES

F. Caspers, H. Haseroth, J. Knott, W. Willis
CERN, Geneva, Switzerland
S. Aronson, BNL, Upton, USA

Introduction

The principle of the switched power Linac (SPL) has raised considerable interest. Work is going on in different laboratories concerning its various aspects. At CERN, model measurements were performed to study the enhancement factors and the field distribution around the accelerating gap. Multi-frequency operation to achieve similar effects has also been tested. This paper reviews the work done at CERN over the last few years.

History

Except for the very early days, particle acceleration was performed either by DC voltages or by RF. Beam transport elements were usually powered by DC currents. Only for special cases, like injection or ejection elements, were pulsed power supplies used. With the advances in the technology of switching means, especially in the semiconductor field, pulsed power-supplies became more fashionable, even in cases where DC supplies would have done the job.

The power used in these elements is sometimes amazingly small. The power stored in a pulsed beam of low duty cycle is usually also fairly small if compared to the total power consumption of the accelerator.

Switched power has occasionally been used, for example, to replace a Cockcroft-Walton for pulsed beam applications. A step-up transformer provided the high voltage from a low voltage power-supply. This technique has difficulties, however, to compete with RF systems using cavities with high shunt impedances. Particle acceleration could benefit from the advantages of the pulsed power techniques by using extremely short pulses which are increased in amplitude by passing them from the outside to the inside of a radial transmission line[1].

Field measurements in the final geometry of the switched power Linac are somewhat difficult to make because of the small size and the correspondingly very high frequencies. Therefore, a scaled-up model has been built at CERN (Fig. 1). It consists of two gaps forming a double sided radial strip line scaled up by a factor of 10 and thus permitting the use of conveniently sized probes and commercially available high frequency instrumentation[2].

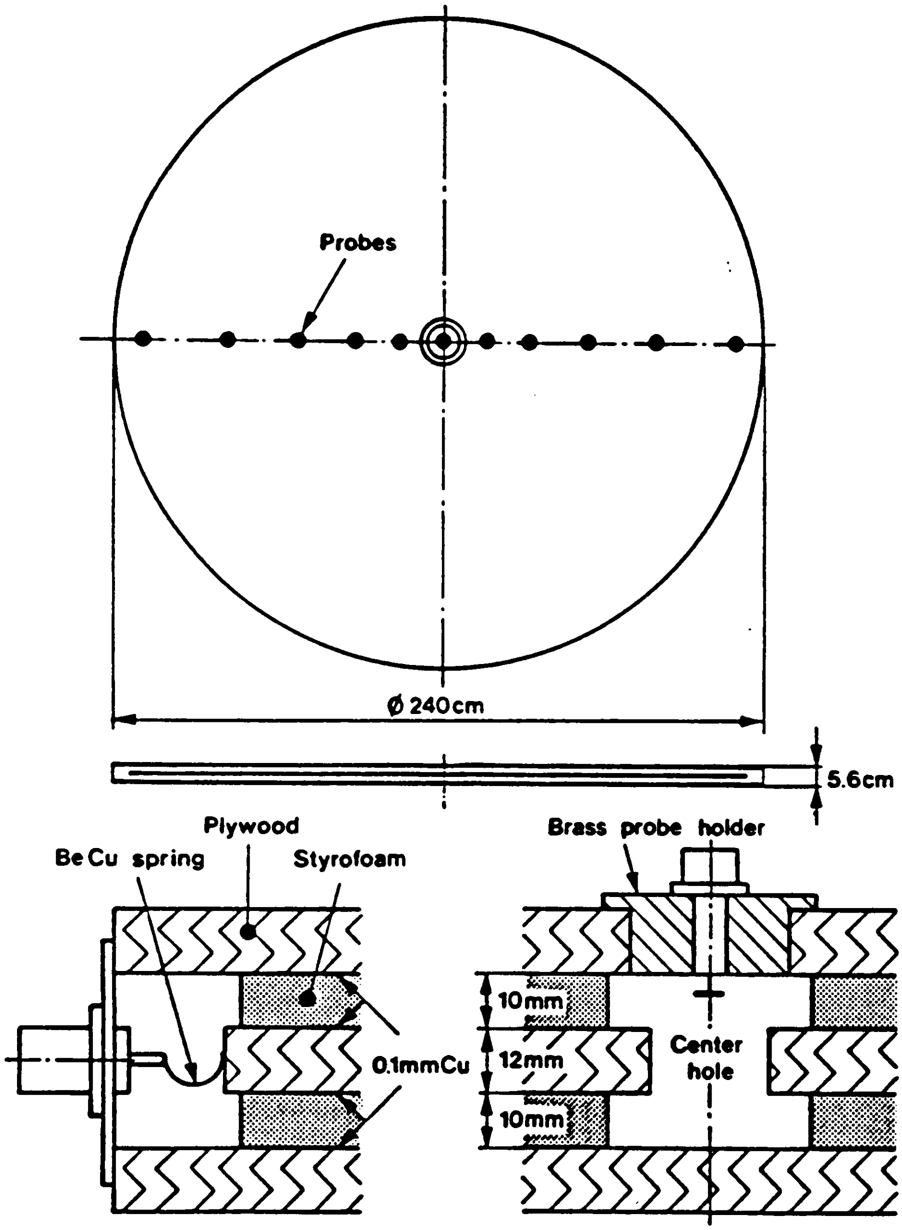


Fig. 1a

Radial power combiner structure

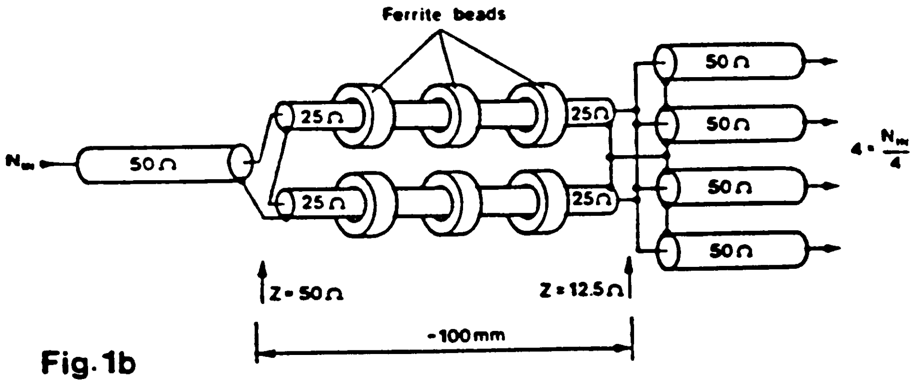


Fig. 1b

Broadband power divider/transformer

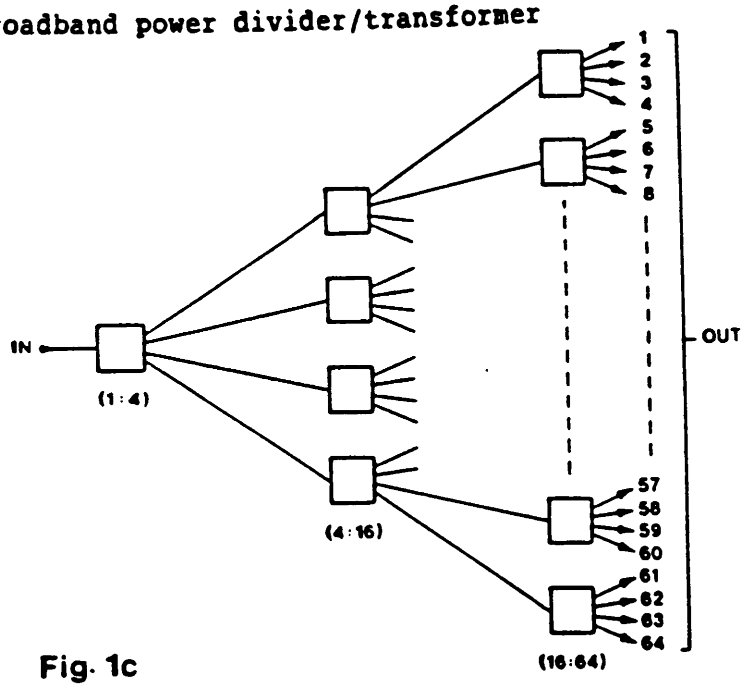


Fig. 1c

1:64 power divider network

Experimental Set-up

The model consists of a sandwich structure with two outer disks of diameter 2.4 m and a central disk separated by a 10 mm gap each side. For pulsed transmission the model can be treated as a radial transmission or double sided strip line with its impedance increasing with r^{-1} from the periphery to the center. One gap is actually fitted with probes across the diameter to study the propagation of signals. At the center a universal plug permits the use of different kinds of probes with adequate spacing, adapted to the specific need of each study. The photocathode discharge is simulated by feeding pulses to the central disk from 64 equally distributed points on the circumference.

The 64 pulses are derived from one single pulse by feeding it successively through broad-band power dividers (line transformers). They feature a 3 db band-width from 2 MHz to about 5 GHz. As a matter of fact, most of the measurements were done by using synthetic pulse techniques with a network analyser (HP 8753 A or HP 8510) able to present the results in the time domain. Complementary tests with a fast pulser and real time oscilloscopes are in good agreement with the first method. One advantage of the synthetic pulse methods is the easy choice of band limited pulses and the much better stability, dynamic range and reproducibility compared with sampling or real time systems. In Fig. 2 measured traces in the low pass mode are depicted.

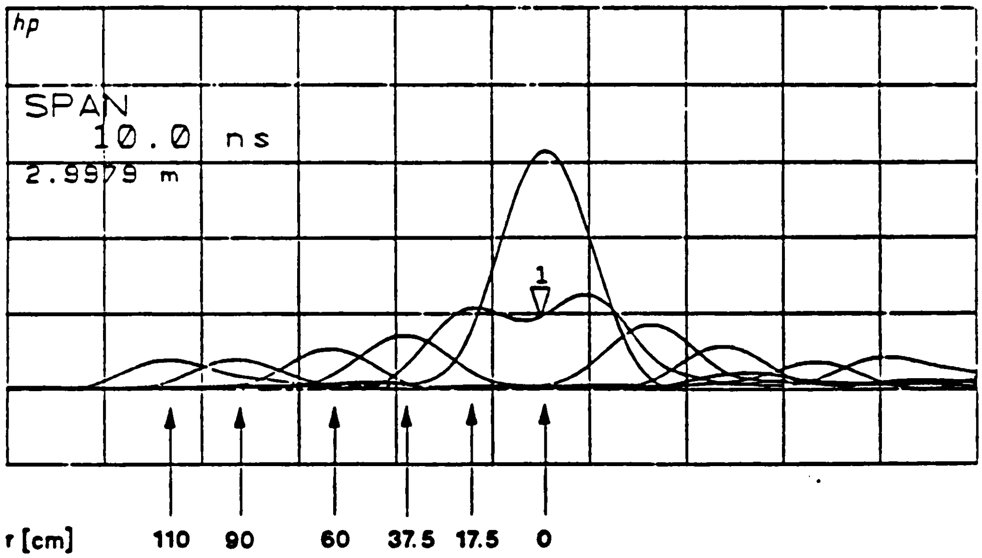


Fig.2: Pulses at different radii as measured with network analyzer

Enhancement Factor

The enhancement across the structure as a function of the radius is shown in Fig. 3:

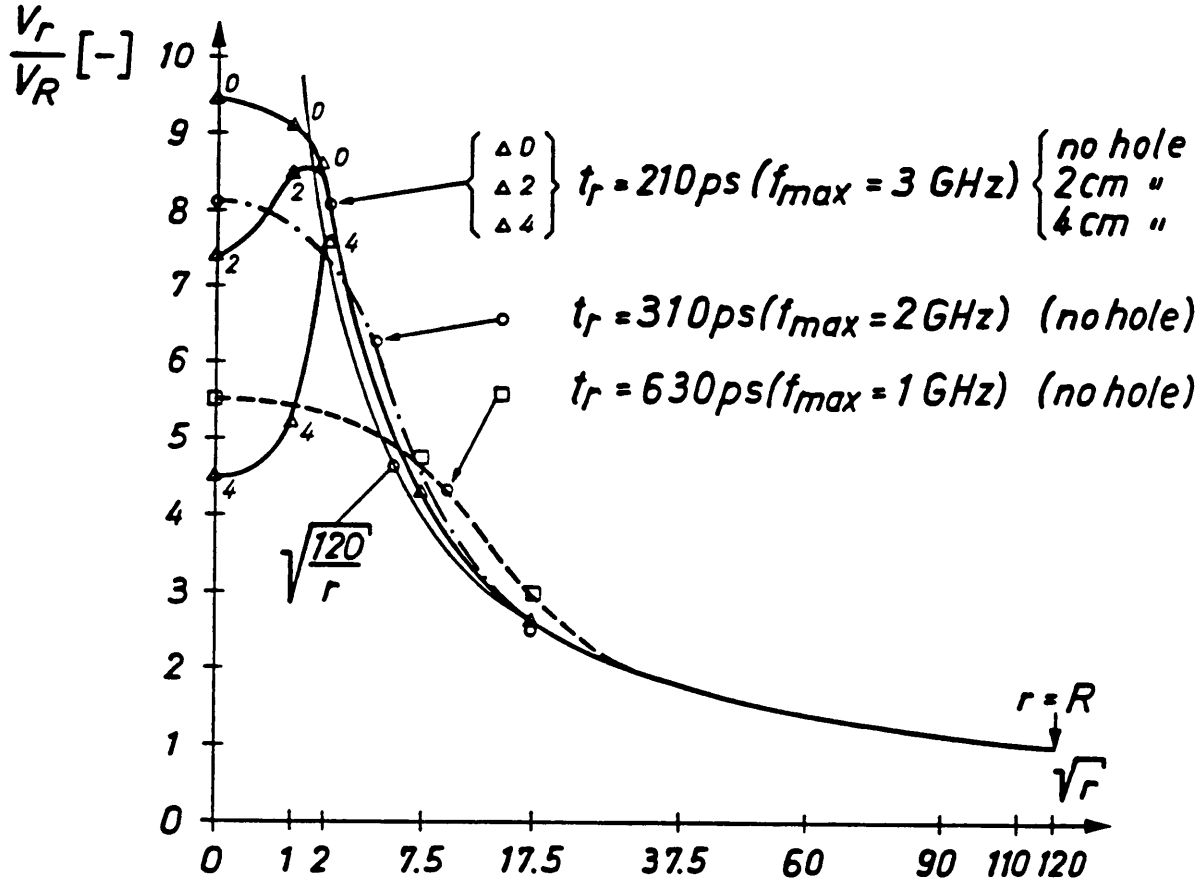


Fig. 3

Enhancement vs radius for different rise-times

The measurements are in good agreement with the theoretical curve $\sqrt{R/r}$ until the incoming pulses start to overlap near the axis. The beginning of this overlapping is of course a function of the pulse width and hence linked to the rise-time. The gain at the center is reduced as a function of the rise-time and the results are very well predicted by Cassell and Villa[3] when taking into account the distance s between the disks and the rise-time t_r :

$$\frac{V_o}{V_R} = 2\sqrt{\frac{2R}{s + ct_r}} \tag{1}$$

The enhancement at the center as a function of the rise-time (10 to 90% value) is shown in Fig. 4. An empirically corrected curve, using the equivalent half wave length instead of $c * t_r$ gives a better fit to the measured values and permits an extrapolation to shorter rise-times. It seems possible to get enhancement factors of about 15 for rise-times of the order of 5 ps. It is also clear from this curve that the stability and reproducibility of the rise-time are very important for the stability and reproducibility of the field in the center.

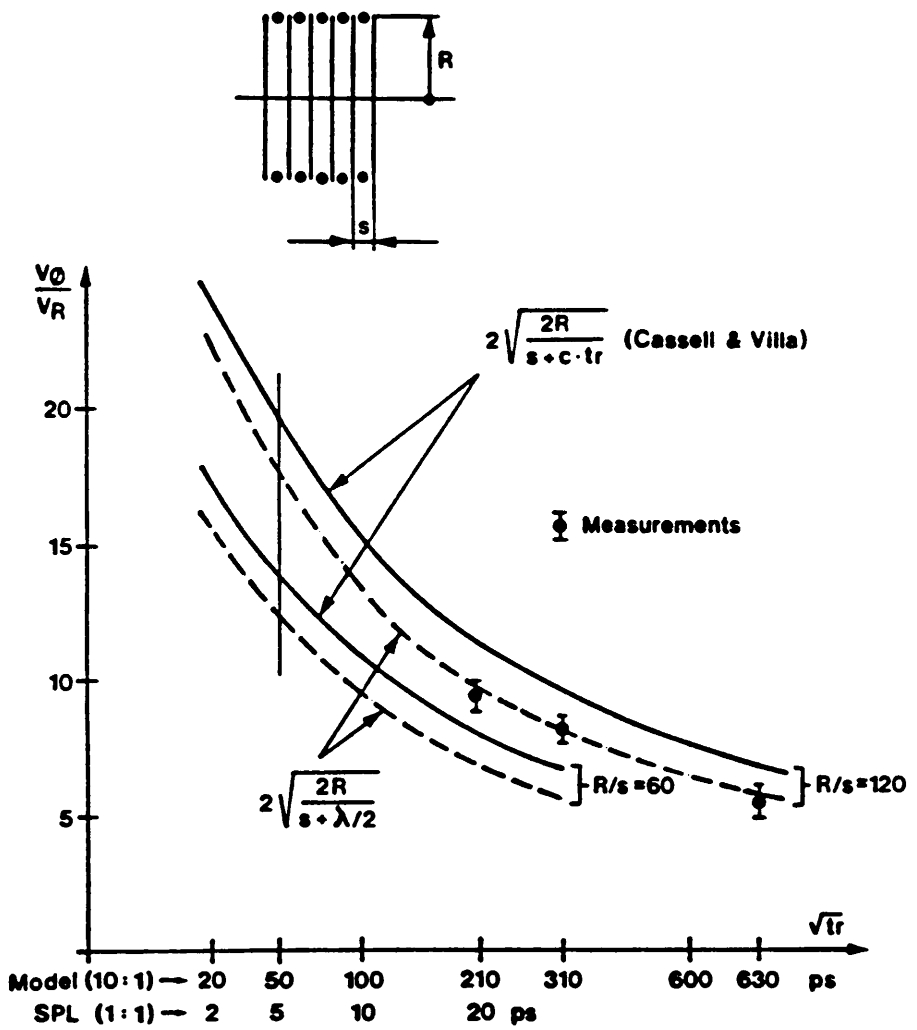


Fig. 4 Enhancement vs rise-time for different geometries

As mentioned above, there is a plug in the center that can be removed and hence measurements are possible with and without a hole for the beam :

a) Without beam hole

The measured enhancement can be as high as 9.4 (Fig. 3) when using the full 3 GHz bandwidth of the network analyser, corresponding to a synthetised pulse with an equivalent rise-time of 210 ps.

With real pulses of 200 ps rise-time and a 1 GHz oscilloscope a gain of 8.5 was obtained; about the same as for synthesised pulses of 310 ps rise-time or when the network analyser bandwidth was limited to 2 GHz. All these results, though about 15 to 20 % lower than calculated, are in good agreement with the Cassell-Villa formula. By applying the empirically found correction one should be able to easily specify an optimised geometry for an efficient switched power Linac (SPL) structure.

b) With beam hole

Removing the center plug, thus allowing an aperture for the beam (Fig. 1a) reduces the field strength measured by an on-axis probe on the supposed beam axis by 50% for a 4 cm hole and by 25% for a 2 cm hole, corresponding to a diameter on the real SPL of about 4 and 2 mm respectively . This loss is certainly to some extent due to a local reduction of the electric field caused by the fringing field or the acceleration gap. Particles travelling on-axis will probably see nearly the full voltage as measured without hole. Some more detailed studies of the exact field distribution in this area can be performed on the model.

Concerning the time after the pulses arrived at the center, two points of view are possible: the pulses can be considered as having travelled through the center, or as being reflected by the center. These points of view are at least equivalent in the case of feeding the structure with a rotationally symmetric field distribution. Looking at the pulses after having crossed the center of the structure has not shown any measurable difference of the pulse shape due to the hole (Fig. 5). This should lead to the conclusion that the beam hole itself is not responsible for energy losses of the pulse. This is,

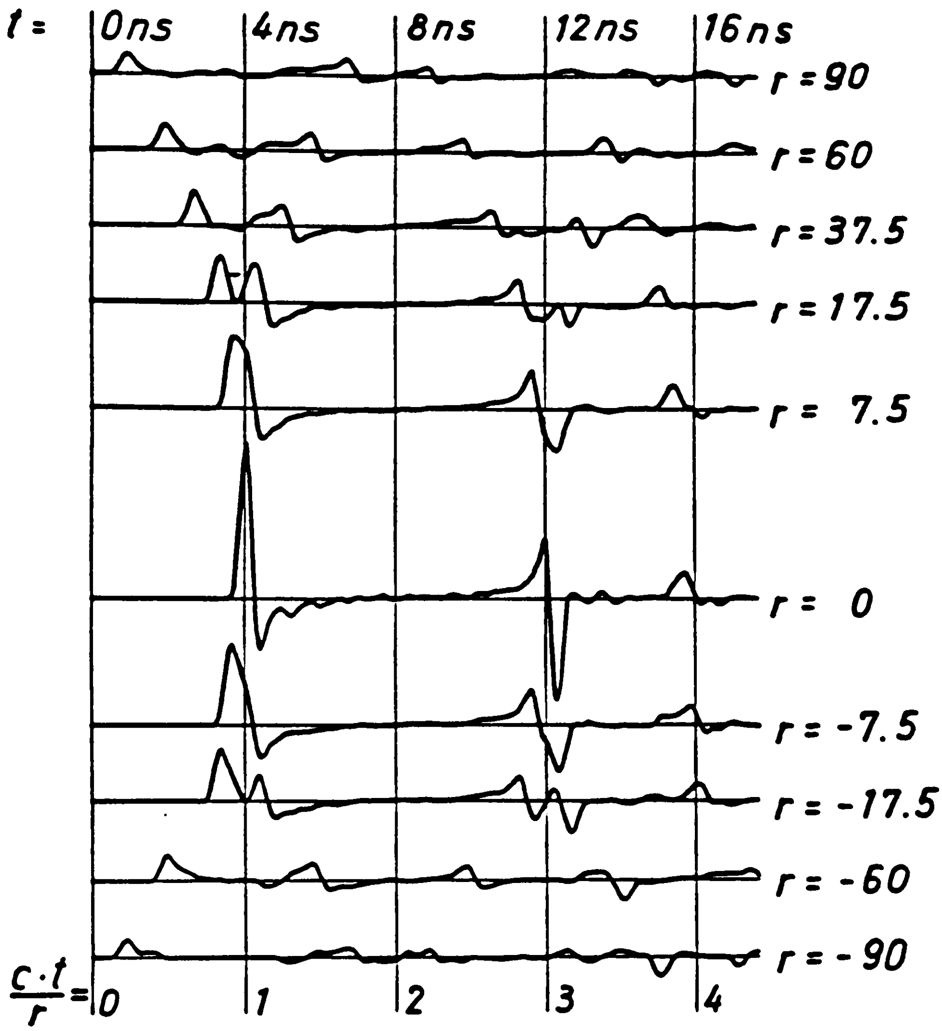


Fig. 5

Homogenous feeding

however, not in contradiction to the above mentioned observation of a reduced field level in the center of the gap, due to additional energy stored in the fringing field.

Non uniform feeding and resulting asymmetries

A critical problem for the SPL is the required geometric and temporal uniformity of the photocathode discharge. In order to simulate possible defects the number of feeds was reduced by disconnecting sectors (1/32, 1/16, etc.), and by feeding alternate quarters to study quadrupole and dipole excitation with only one half of the structure powered.

Tests were also carried out by introducing delays into parts of the feeds in order to study effects due to a possible non uniform temporal response of the photocathode switch on the circumference of the structure.

In addition to data taken with the probes across the diameter of the model, we used more closely spaced probes of the rotatable holder right in the center. Probes at the center and respectively 1 or 2 cm off-center proved to be adequate for studies in this area.

Data were normalised by correlating them in time to the maximum of the undisturbed enhancement rather than to take the individual maxima directly as done in the earlier published results[4].

Generally, the missing or delayed feeds cause an equivalent power loss in or near the center, as expected. But the overall distribution near the axis is astonishingly uniform, even for extremely asymmetric feeding.

As can be seen from Figs. 6a and 6b, the dipole excitation is attenuated to 5% at $r = 2$ cm and only 2% at 1 cm. For the quadrupole mode (alternate quarters disconnected) the damping is even stronger with only 3 and less than 1% respectively. Without the beam hole the difference is even less pronounced.

It is of particular interest that the dipole effect, as measured at the center, is in phase with the simulated edge defect, whilst for the quadrupole it is 180° out of phase.

These variations are already of the same order as those introduced by imperfections of the actual model. For this reason detailed measurements are required to improve the central geometry of the disks.

The distribution on the structure with 1/8 of the power disconnected is shown in Fig. 6c. As the probes outside the center are only fixed ones, these

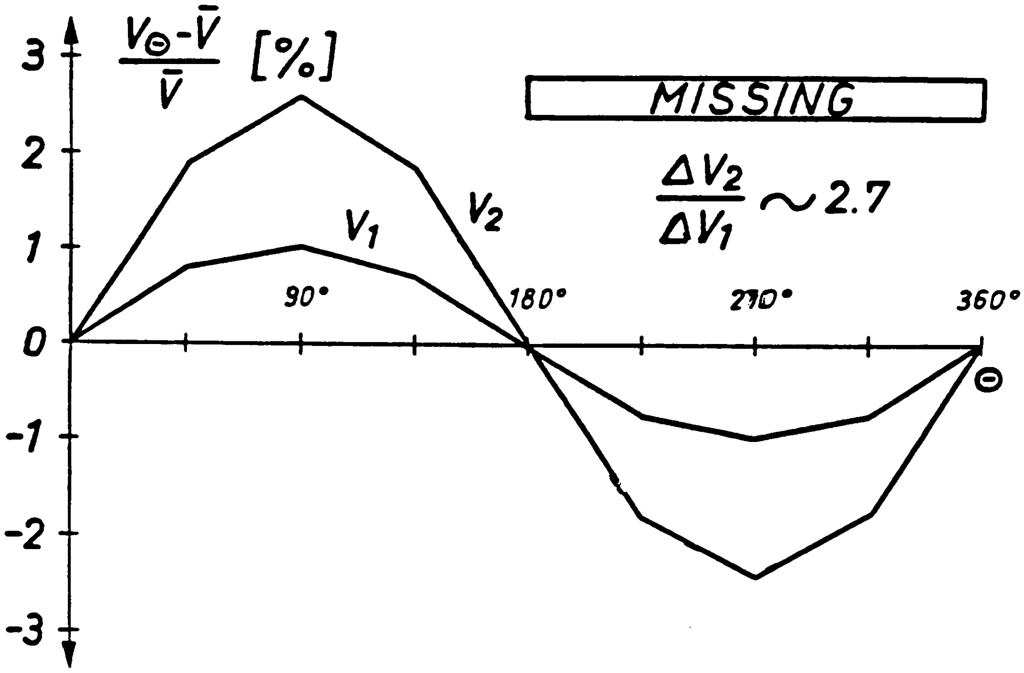


Fig. 6a   Dipole excitation

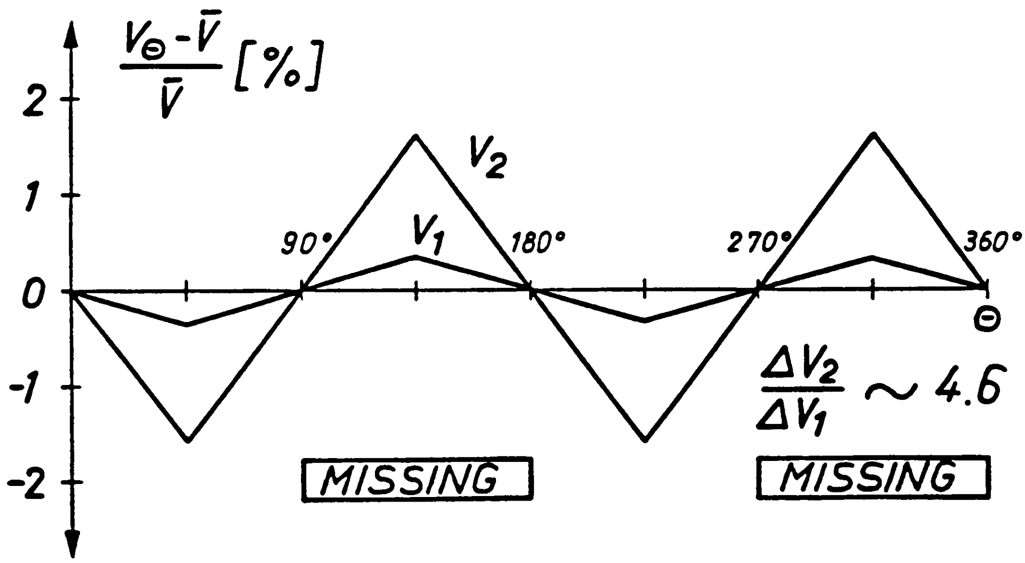


Fig. 6b   Quadrupole excitation

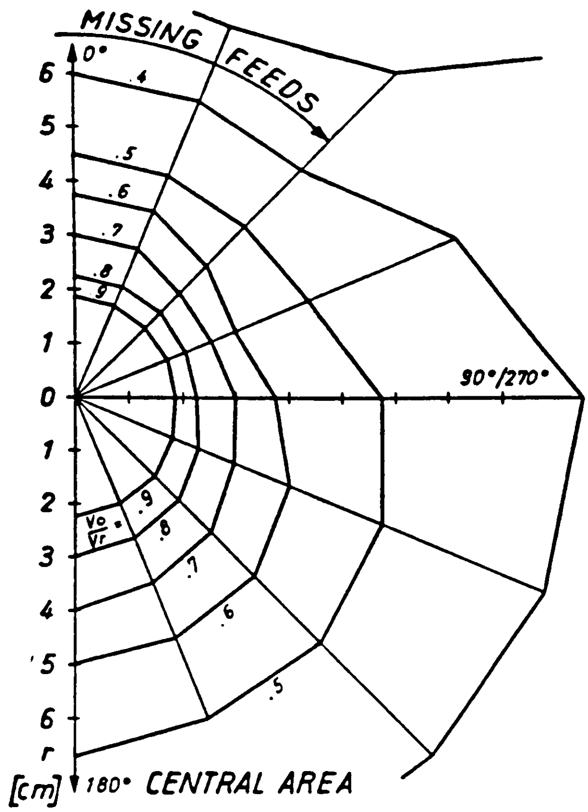


Fig.6c

Field distribution across the model with 1/8 of the feeds missing

results have been obtained by moving the feed defect around the circumference of the model.

It is surprising to see how all these possible perturbations are finally attenuated by the radial line structure and how close the maximum of the enhanced pulse stays to the supposed beam axis.

Pulse Propagation

The behaviour of the radial line transformer and the development of the pulses propagating from the periphery to the center of the disk structure is shown in Fig. 5.

The amplitude increases steadily until the two wave fronts start to overlap at $r = 7.5$ cm, resulting in the expected high peak right in the center. Note that pulses having travelled through the center look differentiated. As already stated before, the presence of a beam hole is apparently of no influence on this effect.

These waveforms are in reasonable agreement with the simulations carried out by M.E. Jones[5]. Slight differences are due to a different spectral composition of the pulses and the fact that our model represents a short circuit for the pulses reflected at the periphery (ct/r = 2,4, etc.), whereas Jones' calculations are done for a more realistic open structure.

Fig. 7 shows the propagation with 1/4 of the feeds missing equally on both sides of one row of the radial probes, similar to Fig. 6c. The wave fronts from the nearest working feeds arrive with an appropriate delay and a reduced amplitude with respect to the expected pulse, as indicated by the markers. Arriving finally nearly on time in the central area and after having merged with the undisturbed pulse, they continue with their smaller amplitude on the other side of the structure; a strong indication that pulses travel across the center rather than being reflected from it.

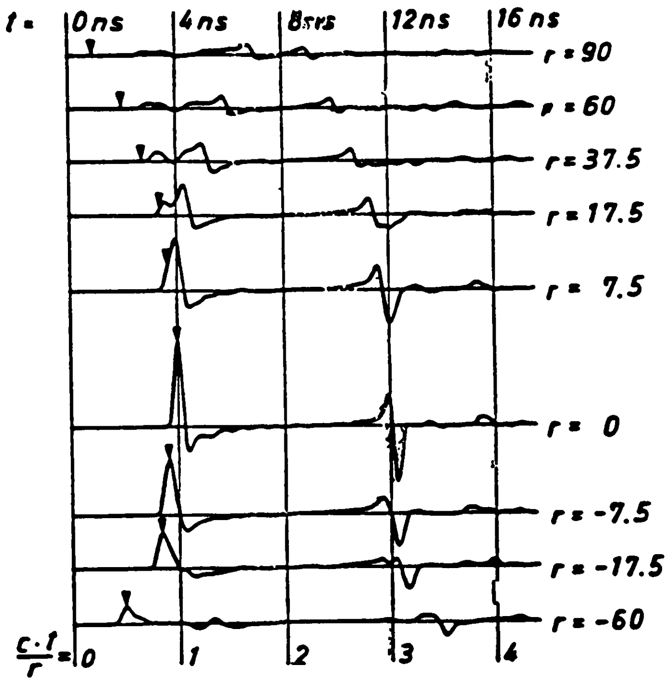


Fig.7

1/4 of the feeds missing

Multi-frequency operation of the radial transmission line

The radial transmission line can also be considered as a sort of resonant structure in the sense that the outgoing pulses are again being reflected from the outer limit of the structure. The pulses being fed in once thus keep going on through the structure for several cycles. Hence, repetitive excitation seems possible. Repetitive pulses can of course be Fourier synthesised with higher integer harmonics of a given fundamental frequency. Because the Eigen-frequencies of the radial transmission line are not integer harmonics of the fundamental frequency, some tests were made using superimposition of the first few Eigen-frequencies[6]. This does not yield a nice square pulse propagating radially the cavity, but, if at a certain moment all the maximum amplitudes of the individual Eigen-frequencies are in phase, the maximum field will occur at the center of the cavity.

We are mainly interested in this particular moment and a priori it is not important what happens before or afterwards. In a way, we have then given up the picture of a pulse moving towards the center of the cavity to gain its amplitude as described before with the switched power principle.

Multi-mode excitation

The orthogonal properties of the Eigen-frequencies guarantee the mutually undisturbed operation of the different RF generators, provided that they are mutually independent and isolated using frequency filters, corresponding to the appropriate mode. This permits a linear superposition in space and time of the corresponding individual field patterns in the cavity. In general, there is no rational ratio of the Eigen-frequencies. To obtain, nevertheless, a periodic excitation one can choose as operational frequencies integer multiples of a certain base frequency f_0 which are near enough (within the 3 dB bandwidth) to the corresponding Eigen-frequency. This is equivalent to having a comb generator with a comb spacing $\Delta f = f_0$ and selecting only those frequency lines which fall within the 3 dB bandwidth of the resonance frequency of the mode to be considered. With a defined phase relation between the frequencies thus selected, electric field maxima will be obtained at equally spaced time intervals f_0^{-1} at the center.

Power considerations

For most cavities the R/Q decreases rapidly for higher order modes but this decay turns out to be very slow for a flat pillbox (Tables 1 and 2).

This means that we can easily add higher modes in order to achieve high gradients. Assuming constant Q and R/Q the maximum accelerating field will increase proportionally to the input power and not only with the square-root as for single frequency operation.

Assuming conventional cavities, the total power involved is still considerable. The advantage is, nevertheless, the high gradient which can be obtained this way, as compared to the single-frequency operation at the same total power level. In particular, higher gradients can be held when the pulses are shorter. It should be noted that this method seems to offer some control of the pulse shape.

Table 1 - Flat pillbox

R = 250 mm, s = 10 mm, Ø = 5 mm

Mode Type	Frequency MHz	(R/Q)/Ohm at R_0	Q_0
MO-EE-1	458.923	7.391	3114
MO-EE-2	1053.01	7.466	4718
MO-EE-3	1649.60	7.411	5906
MO-EE-4	2245.40	7.325	6892
MO-EE-5	2839.35	7.212	7753
MO-EE-6	3430.70	7.071	8526
MO-EE-7	4018.82	6.912	9232
MO-EE-8	4603.11	6.730	9886
MO-EE-9	5182.99	6.529	10494
MP-EE-10	5757.87	6.315	11071

<u>Table 2</u> - Pillbox with nose-cones

R = 15 mm, s = 20 mm

Beam hole = 5 mm, $N_{\text{nose-cone}}$ = 10 mm

Mode Type	Frequency MHz	(R/W)/Ohm at R_0	Q_0
TM0-EE-1	906.488	31.038	7861
TM0-EE-2	2045.47	34.245	11665
TM0-EE-3	3162.02	32.399	13915
TM0-EE-4	4282.97	24.680	15397
TM0-EE-5	5434.69	16.167	16740
TM0-EE-6	6619.58	10.154	18209
TM0-EE-7	7828.05	6.538	19743
TM0-EE-8	9050.72	4.422	21285
TM0-EE-9	10281.1	3.160	22813
TM0-EE-10	11515.1	2.385	24328

The total energy envolved is comparable within about a factor 2 to that of the switched power Linac if we assume that the RF for the cavity is switched on according to its filling time. During the filling about an equal amount of energy would be lost in the cavity. After filling the stored energy should be equivalent to the switched power Linac, provided that an "equivalent" number of frequencies is being used. However, to reduce the amount of stored energy, one would need to use small structures such as the 30 GHz main Linac structure in the CLIC concept or the 12 cm radius of the SPL. This involves very high frequency components (above 20 GHz) with high peak power. In the normal conductivity case such an approach would certainly not be competitive for the time being. On the other hand, superconducting structures are not efficient above, say 5 GHz, thus seriously limiting possible applications. Fig. 8 shows the electric field in the cavity at different times.

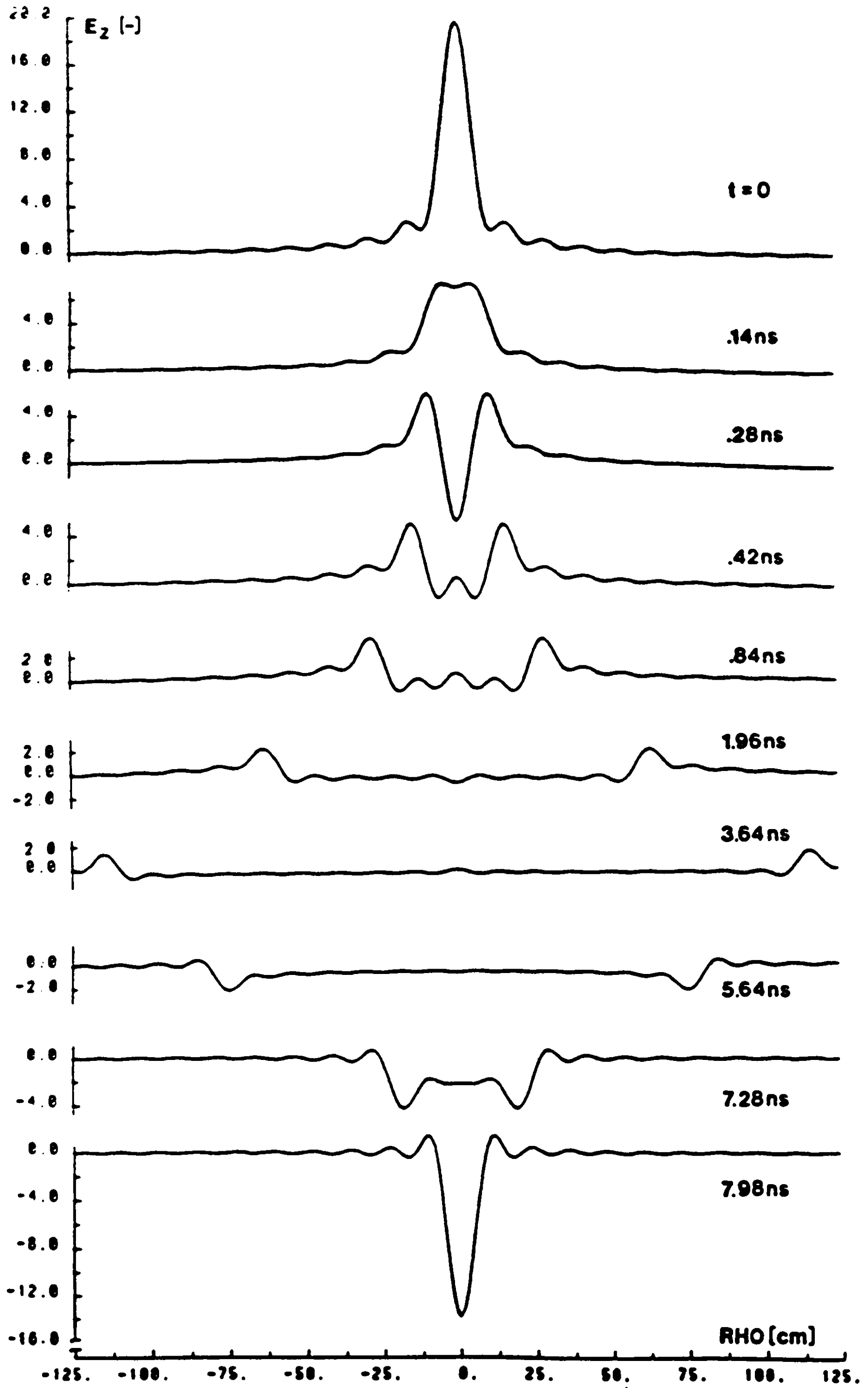
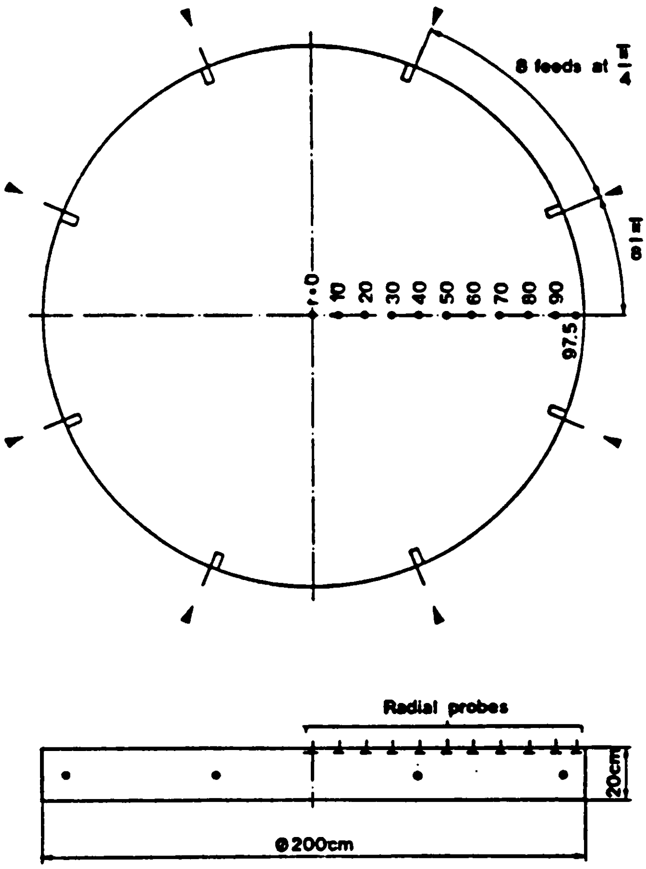


Fig.8: Electric field in the cavity at different times

Multi-frequency measurements on a model pillbox

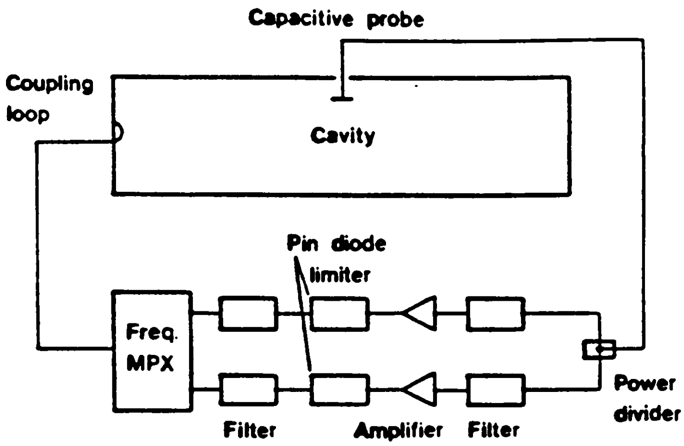
Some measurements were performed on a cavity built for this purpose (Fig. 9). Eleven probes are located along one radius. Eight positions around the circumference are used for coupling in different frequencies. Fig. 10 shows the initial experimental set-up which was limited to 2 frequencies. Pin diode limiters were required after the amplifiers to avoid driving the amplifiers into saturation.

Using a network analyser it was possible to demonstrate the radial enhancement for the first five Eigen-frequencies. Fig. 11 shows the resulting field levels as function of time for three radial positions.



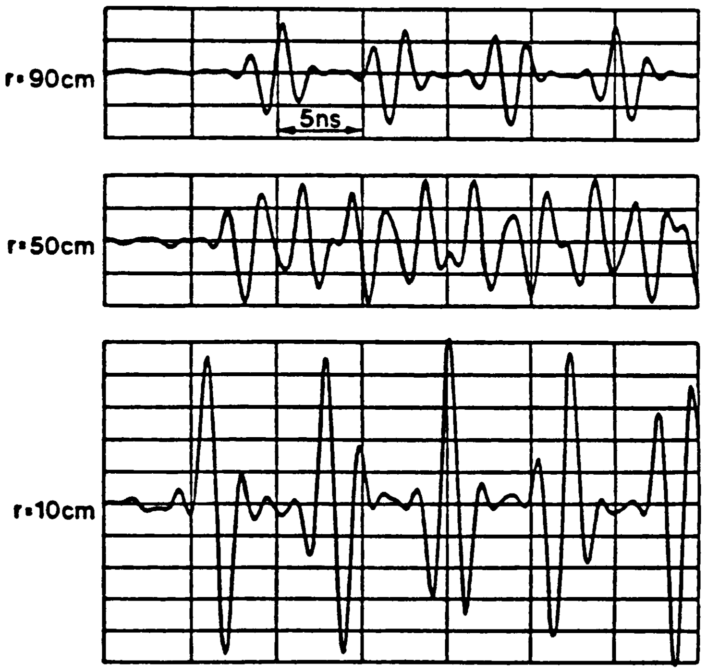
Test cavity for multi-mode excitation

Fig.9



Initial test set-up

Fig. 10



Radial enhancement for different radii

Fig. 11

Conclusions

Model measurements on the radial transmission line have not only confirmed the theoretical calculations but have provided a good insight into the requirements which have to be fulfilled by the photo-cathode switch. Multi-frequency operation of the radial transmission line may turn out as an interesting alternative.

Acknowledgements

It is a pleasure to thank V. Radeka, I. Stumer and B. Zotter for discussions and comments, J.-P. Romero for assembling the models, E. Tanke for extensive calculations and J.L. Vallet for help with the measuring set-up.

References

1. Willis, Proc. Workshop on Laser Acceleration of Particles, Malibu, AIP No. 130, p. 421 (1985)
2. S. Aronson, F. Caspers, H. Haseroth, J. Knott, W. Willis, Model Measurements for a Switched Power Linac, CERN/PS 87-29 (LI) (1987) and 1987 IEEE Particle Accelerator Conference, Washington
3. R. E. Cassell, F. Villa, SLAC-PUB-3804 (1985)
4. S. Aronson, Status of Switched Power Linac Studies at BNL and CERN, Symposium on Advanced Accelerator Concepts, Wisconsin University, Madison (1986)
5. M.E. Jones, Particle Accelerators 21, p. 43 (1987)
6. F. Caspers, H. Haseroth, J.Knott, High Gradients by Simultaneous Multi-frequency Operation of RF Structures, CERN/PS/87-30 (LI) and 1987 IEEE Particle Accelerator Conference, Washington.