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MODEL MEASUREMENTS FOR NEW ACCELERATING TECHNIQUES

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Reported by F. Caspers

ABSTRACT

We summarize the work carried out for the past two years, concerning some different ways for achieving high-field gradients, particularly in view of future linear lepton colliders. These studies and measurements on low power models concern the switched power principle and multifrequency excitation of resonant cavities.

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Introduction

Several technical aspects concerning the Switched Power Linac (SPL) as proposed by W. Willis [1] have been studied on a model at CERN. The use of synthetic pulse techniques as applied for studying propagation and enhancement lead to the idea of exciting a similar structure straightforward with several (harmonic) frequencies in order to obtain the desired high peak fields for the acceleration of particles.

The SPL Principle

The SPL may achieve very high accelerating gradients by switching an electron burst with a sufficiently fast laser pulse from previously charged photocathodes on the circumference of a disk structure (Fig. 1). The electromagnetic pulse increases in amplitude as it travels radially towards the centre, where it accelerates particles on the axis.

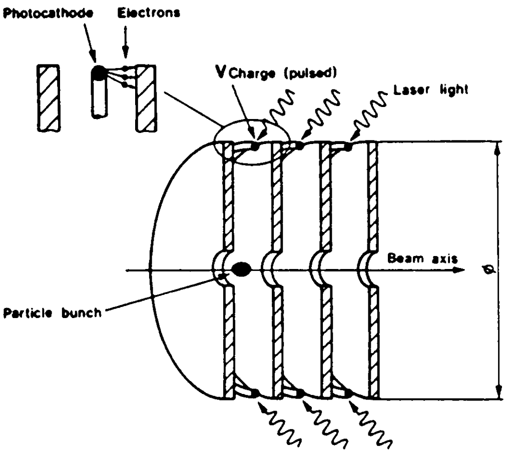

Fig. 1 - Principle of the switched power linac.

Assuming the photocathode to be charged with a -- to 100 kV pulse for up to 10 ns and then discharged by a correctly timed very short (few ps) laser pulse into an about 1 mm wide gap, we can expect accelerating fields of the order of one MV per mm to be held for only 10 ps. This would result in a compact accelerator with small structures, featuring high peak power for low stored energy.

Problems Related to the SPL

High-Voltage Breakdown

Some data exist in the literature concerning the voltage hold-off limits for the switch and at the centre of the structure. Jüttner et al. reported gradients of 1.4 GV/m with 57 μ copper gaps and 3 GV/m on 27 μ tungsten electrodes for ns pulses [2]. Recent measurements on pulsed rf at SLAC indicate peak fields of 500 MV/m at 10 GHz [3]. Properly scaled this should allow to hold several GV/m for subnanosecond pulses.

Experimental verification on geometries similar to that of the SPL are actually under way at BNL and CERN. We hope to achieve pulses of 100 kV for less than 1 ns. This will give straightforward results for the switch area and allow for extrapolation to the situation in the accelerating gap.

Fast Switching

The switch requirements are quite severe as rise-times of a few ps will be necessary in order to achieve reasonably high transformer ratios. Further, the impedance of the structure at the periphery is only about 1Ω, and, due to the short rise time the width of the emitting surface may not exceed a few tenths of a mm. Therefore, current densities of the order of 100 kA cm^{-2} are required to launch pulses of 100 kV into the structure.

These values are probably hard to achieve, but do not seem impossible at this moment [4]. Experimental studies are actually under way at BNL and some results have been reported at this Workshop [5].

Propagation and Enhancement

The gain of the radial line transformer depends on the geometry, as given by the outer radius R and the pulse rise time. As long as the concentrically travelling pulse does not merge at or near the axis, the maximum possible enhancement at a given radial position r is determined by the ratio of the respective impedances:

$$\frac{V_r}{V_R} = \sqrt{\frac{Z_r}{Z_R}} = \sqrt{\frac{R}{r}} \qquad \text{with } Z_r = \text{constant } \frac{s}{2\pi r} .$$

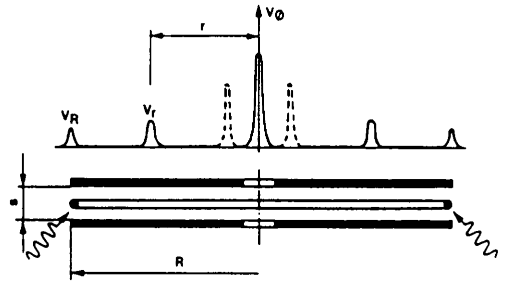

Fig. 2 - Pulse propagation in one cell of the SPL.

Despite the overlap of wavefronts near the centre the overall gain will be limited by finite rise times. Several analytical studies have been carried out for the case of ideal symmetric feeding [6-8] and experimental verification has been done.

SPL Model Measurements

Experimental Set-Up

For a detailed study of these problems a model has been built at CERN. It consists of two gaps forming a double-sided radial stripline scaled up by a factor of 10 in order to avoid problems arising from the possibly small dimensions of an SPL, and permitting the use of conveniently sized probes and commercially available high frequency instrumentation [9-11].

The photocathode discharge is simulated by feeding pulses via a high bandwidth divider network (Fig. 3 and Fig. 4) over 64 equally spaced connectors on the circumference (Fig. 5). The broadband power dividers (line transformers) exhibit a 3 dB bandwidth

* Work carried out in collaboration with S. Aronson (BNL), H. Haseroth, J. Knott and W. Willis (CERN).

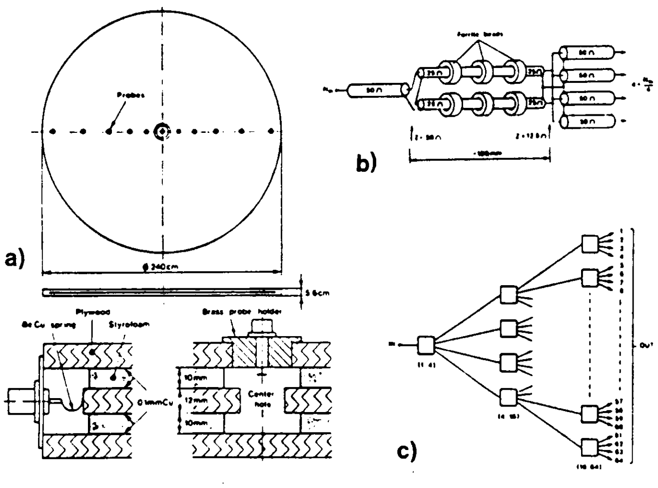

Fig. 3 - a) Radial power combiner structure.
b) Broadband power divider/transformer.
c) 1:64 power divider network.

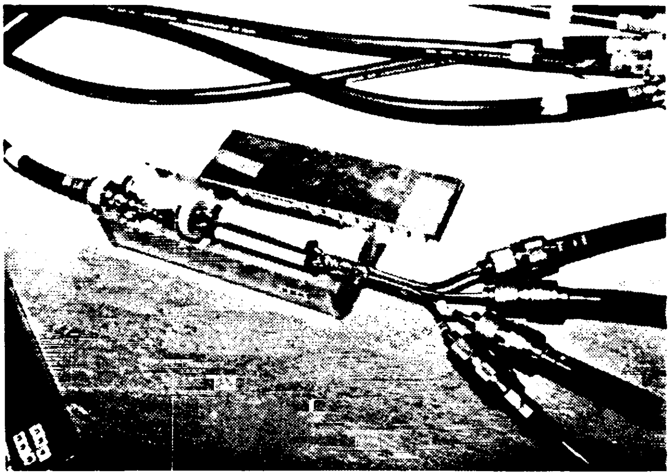

Fig. 4 - Photo of single 1:4 broadband power divider.

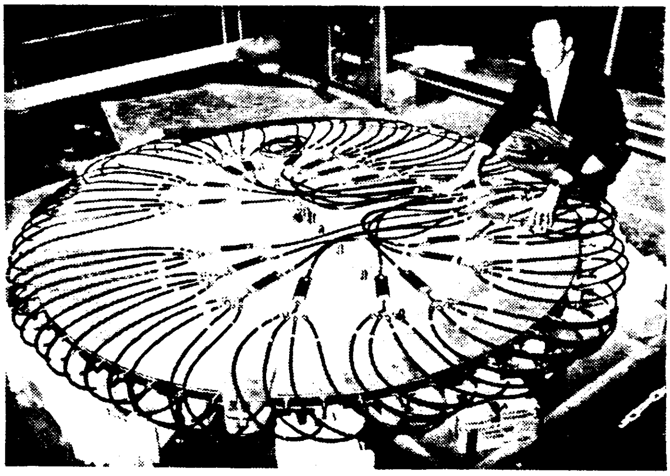

Fig. 5 - Photo of SPL model with power divider network.

from 2 MHz to about 5 GHz. One of the gaps is equipped with probes across the diameter, and exchangeable probes with closer spacing are used at the centre to obtain details of the field distribution in the supposed accelerating gap. Most of the measurements were done by using synthetic pulse techniques with a network analyser (HP 8753A 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. 6, measured traces in the lowpass mode are depicted.

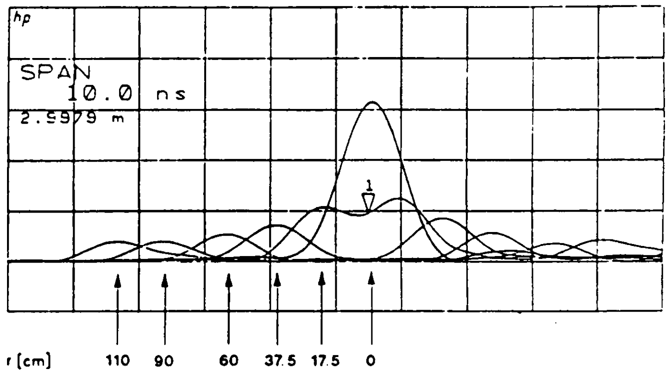

Fig. 6 - Pulses at different radii as measured with network analyser (HP 8510) radial power combiner. Here: modulus of the envelope of a carrier-modulated signal shown ≈ modulus in "bandpass" mode time-domain.

Propagation and Enhancement

The enhancement across the structure as a function of the radius is shown in Fig. 7a. Measurements follow the theoretical line $\sqrt{R/r}$ until pulses start to overlap near the axis. At the centre the gain is reduced as a function of the rise time and the results come close to those predicted by Cassell and Villa [6], by taking into account the disk spacing s and the rise time t_r:

$$\frac{V_0}{V_R} = 2\sqrt{\frac{2R}{s + ct_r}} .$$

In Fig. 7b the enhancement at the centre is plotted as a function of the rise time (10 to 90% value). An empirically corrected curve, using the equivalent half-wavelength instead of $c \cdot t_r$, gives a better fit to the measured values and permits an extrapolation to shorter rise times. As a result, enhancements around 15 seem feasible for a rise time of 5 ps, but it also shows how important the stability of the rise time will be for the repetitive performance of a future switched power linac.

Without Beam Hole

By using the full 3 GHz frequency range of the network analyser, corresponding to synthetised pulses with an equivalent rise time of 210 ps, we have measured enhancements as high as 9.4 (Fig. 7a).

With real pulses of 200 ps rise time and a 1 GHz oscilloscope we obtain a gain of 8.5; about the same as for synthetised pulses of 310 ps or the network analyser limited to 2 GHz. The difference in rise time or bandwidth is due to the different spectral composition of synthetised and real pulses.

Although about 15 to 20% lower than calculated, all these results are in good agreement with the Cassell-Villa formula. By applying the empirically found correction one should be able to easily specify an optimized geometry for an efficient SPL structure.

With Beam Hole

Introducing an aperture for the beam into the structure (Fig. 3a, centre hole) reduces the field strength measured by an on-axis probe on the supposed beam axis by 50% for a 4 cm hole and 25% for a 2 cm hole, corresponding to a diameter on the real SPL of 4 respectively 2 mm. This loss may be to some extent due to a local reduction of the electric field caused by the fringing field of the acceleration gap. Particles travelling on axis will probably see nearly the full voltage as measured without no hole for acceleration. Detailed studies of the field distribution in this area are in preparation.

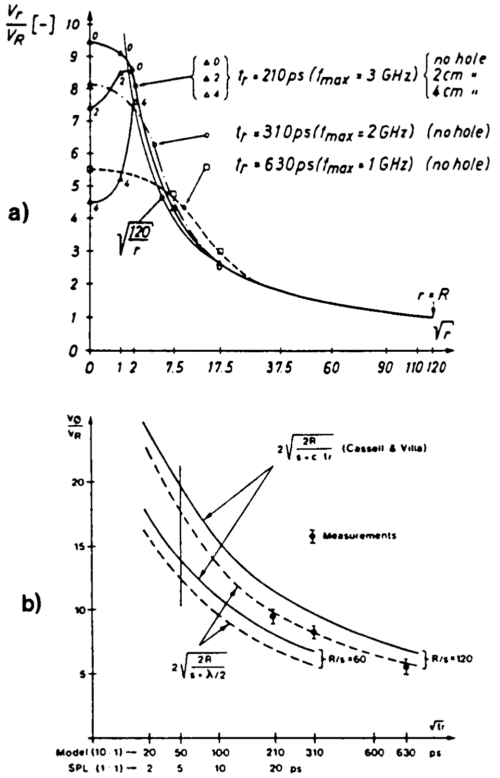

Fig. 7 - a) Enhancement vs radius for different rise times. b) Enhancement vs rise time for different geometries.

Looking at the pulses after having crossed the centre of the structure has not revealed any visible ference of the pulse shape due to the hole (Fig. 9). s might lead to the conclusion that the beam hole itself is not responsible for energy losses of the pulse. However, the accelerating voltage could be reduced by the additional energy stored in the fringing field.

Asymmetries and Non-Uniform Feeding

An additional challenge for the SPL is the required geometric and temporal uniformity of the photocathode discharge. To simulate possible defects we have reduced the number of feeds by either disconnecting sectors (1/32, 1/16, etc.), or feeding alternate quarters to study quadrupole or dipole excitation with only one half of the structure powered.

Introducing delays into part of the feeds allowed to study effects due to different temporal response of the photocathode switch along the circumference.

In addition to data taken with the probes across the diameter of the model, we used more closely spaced probes on the rotatable holder right in the centre. Probes at the centre and one, respectively two centimetres off-centre 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 straightforward the individual maxima as done in the earlier published results [9].

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

As can be seen from Figs. 8a and 8b, 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,respectively lesss than 1%. Without the beam hole the difference is even less pronounced.

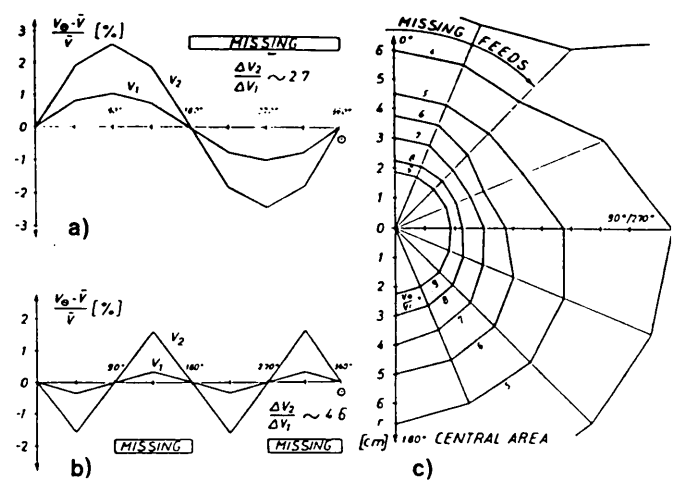

Fig. 8 - a) Dipole excitation. b) Quadrupole excitation c) Field distribution across the model with 1/8 of the feeds missing.

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 require to improve the central geometry of the disks.

The distribution on the structure with 1/8 of the power disconnected is shown on Fig. 8c. As the probes outside the centre are only fixed ones, these 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 centre of the disk structure is shown in Fig. 9.

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 centre. One notes that pulses having travelled through the centre look differentiated. As already stated before, the

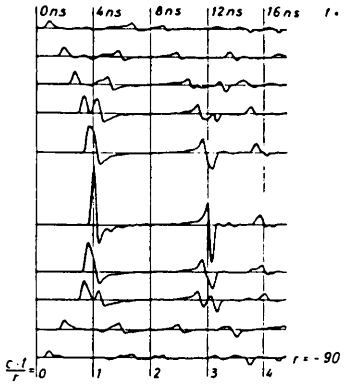

Fig. 9
Homogeneous feeding.

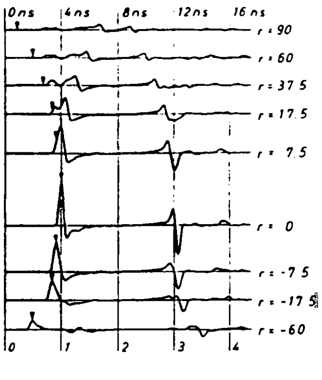

Fig. 10
1/4 of the feeds missing.

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 [8]. Slight differences are due to 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. 10 shows the propagation with 1/4 of the feeds missing equally on both sides of one row of the radial probes, similar to Fig. 8c. 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 centre rather than being reflected from it.

Simultaneous Multifrequency Operation of rf Structures

The Principle

In the context of the previously described new accelerating techniques considered for single pass colliders and the application of synthetic pulse methods we have also considered the possible operation of a cavity in a phase-locked multifrequency mode [12]. The purpose is to obtain high accelerating gradients with smaller average losses than in the conventional single-frequency operation scheme. The resonant frequencies are not harmonically related to each other. Assuming finite Q-values one can always find a frequency f_0 such that within a 3 dB bandwidth all resonances considered are at integer multiples of f_0. For the gap voltage one obtains in this case periodic pulses with a spacing $\tau = 1/f_0$. Assuming similar shunt impedances will result in power losses proportional to V_{peak} compared to $P_{loss} \sim V^2_{peak}$ for single-frequency operation.

Resonant Excitation

Pulses fed into the model cavity travel several times through the structure without too much attenuation or deformation. This observation suggested some form of resonant excitation with a pulse train. This pulse train could be Fourier-synthetised with the corresponding frequencies of CW transmitters.

The dispersive character of the cavity, however, will result in a successive deformation of the pulse. As we are not interested in the exact behaviour of the pulse but in a maximum field in the centre, the use of the Eigen-frequencies may be an interesting alternative.

This will not yield a nice square pulse bouncing through the cavity, but, if at a certain moment all the maximum amplitudes of the individual Eigen-frequencies are in phase, the maximum field gradient will occur at the centre of the cavity.

We are mainly interested in this very moment and a priori it is not important what happens before or after. 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 centre.

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
MO-EE-10	5757.87	6.315	11071

Table 2 - Pillbox with nose-cones

R = 15 mm, s = 20 mm,
Beam hole = 5 mm, $N_{nose-cone}$ = 10 mm

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

The total energy involved is comparable in 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 limiting possible applications seriously.

Fig. 11 shows the electric field as a function of time at the centre.

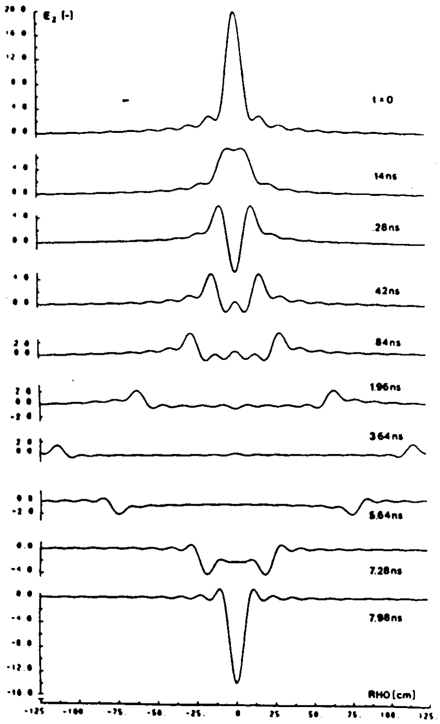

Fig. 11 - Electric field in the cavity at different times.

Multifrequency Model Measurements

Experimental Set-Up

Preliminary measurements have been carried out on a pillbox cavity built for this purpose (Fig. 12). Eleven probes are located along one radius. In the centre there is one probe coupling mainly to the longitudinal E-field. Eight positions on the circumference are used for coupling loops. Figure 13 shows the initial experimental set-up, used to test the feasibility of simultaneous excitation of the cavity on several Eigen-frequencies. Preliminary tests were limited to two frequencies. It turned out that in each feedback path a pin-diode limiter is required after the amplifier as a nonlinear element which gives rise to very little harmonic distortion. In case the amplifiers are driven into saturation thus limiting the oscillation amplitude, strong mutual interactions occur between different feedback loops (intermodulation) despite the bandpass filters. Using a network analyser we were able to demonstrate the radial enhancement for the first five Eigen-frequencies. Figure 14 shows the resulting field levels as function of time at three radial positions.

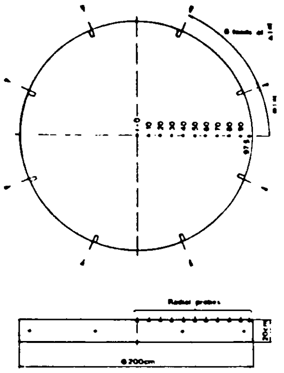

Fig. 12 - Test cavity for multimode excitation

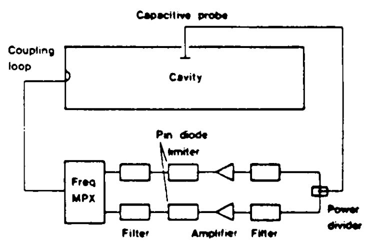

Fig. 13 - Initial test set-up

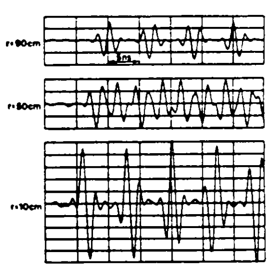

Fig. 14 - Radial enhancement for different radii

Concerning the problem in the frequency domain, the operating frequency of each individual oscillator circuit may be slightly varied by means of an electronic or mechanic phase shifter located in the feedback path. By making sure that within the possible tuning range of about a 3 dB bandwidth a spectral line of the virtual comb generator mentioned above in the description "multimode excitation" can be found, phase locking is possible using a PLL circuit (Fig. 15).

The operating frequency can and must be allowed to jump from one comb line to the other, in case of detuning due to mechanical deformation or thermal effects, but must always stay within the 3 dB bandwidth of the corresponding Eigen-frequency.

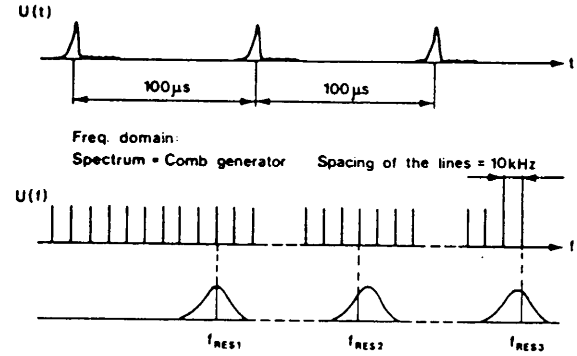

Fig. 15 - Multifrequency excitation for non-harmonically related resonance frequencies (e.g. pillbox). Example: SPL (Switched Power Linac). Rep. rate = 10 kHz.

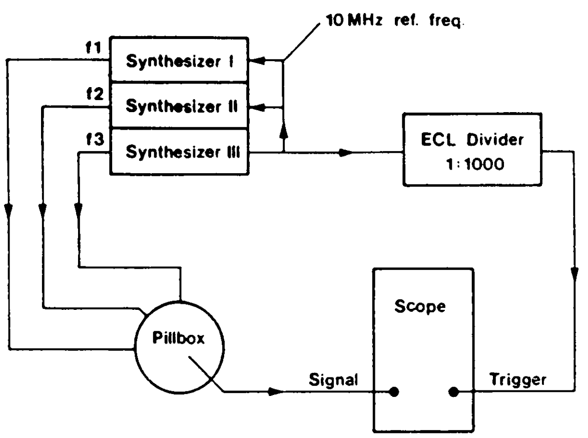

Fig. 16 - Block diagram for phase-locked multifrequency excitation. For the model (pillbox): f_1 = 113.91 MHz, f_2 = 261.47 MHz, f_3 = 409.49 MHz.

Superconducting Cavities

General Considerations

It is obvious that high gradients will require high rf power. The use of superconductivity would be very interesting in order to keep the losses low and to recover the residual energy that has not been taken out by the beam . For field emission high field superconductivity is limited by the rf losses and by the existence of certain maximum magnetic field levels. In the multimode excitation, however, the high gradients are very limited in space and time. Hence the rf losses are reduced as in the normal conducting case.There may also be the possibility to exceed certain superconducting field limits if the time of the applied pulse is sufficiently short (e.g. about 200 ps for an assumed upper frequency of 3 GHz). We consider to explore these possibilities at least with type II superconductors [13, 14]. Even if superconductivity is not to be used with high gradients for acceleration, the multimode scheme will be an interesting means to study in general the behaviour of superconductors at high fields with short pulses. Results from Campisi et al. [15] indicate that limitations due to field emission may be possible to overcome.

Test Set-Up for Multifrequency Excitation of a Superconducting Cavity

In order to investigate experimentally the properties of a superconducting cavity for multifrequency excitation, we are actually preparing an experiment with the Wuppertal University. A single-cell Nb-cavity with elliptic cross section will be operated at its fundamental mode (1.49 GHz) and three higher order (high) Q modes ($Q > 10^8$ at 4.2 K) at about 2.7 GHz, 2.9 GHz and 3.3 GHz. Initially the rather simple oscillator circuits (Fig. 13) will be used in order to eliminate tuning problems. The 3 dB bandwidth of each mode will be of the order of some Hz. Adjusting the complex such that all four modes are not too far away from being critically coupled (i.e. $Q_{load} = Q_0/2$) an rf power of about 10 W for each frequency should be sufficient to approach the H_c limit in the cavity. Phase-locked operation is not necessary since one can predict from a statistics point of view the probability that the field of all modes interfere constructively. After having measured the loaded Q for each mode separately versus rf power level, a comparison between these single mode data and the multifrequency excitation data versus power can be carried out. Due to the rather weak coupling to the rf generator ($Q_{ext} \approx Q_0$) this method should be very sensitive to changes in Q_0.

Initial Synthetiser Tests with the Pillbox Model

First tests with the set-up in Fig. 13 and resonance frequencies of the individual modes between about 110 and 700 MHz and a proper phase lock to f_0 = 10 kHz (i.e. the spacing of comb lines) gave no satisfactory result in the time domain because the jitter or phase noise for this type of indirect synthesis turned out to be unacceptably high. This effect may possibly be reduced by means of multiple PLL circuits. An even better approach seems to be the use of Direct Digital Synthetisers (DDS) which permit a quite easy control of amplitude, phase and frequency with a precision of about 1 Hz. These relatively cheap circuits are actually commercialised for clock rates up to 300 MHz and output frequencies of 130 MHz.

Compared to indirect synthetisers, the DDS can carry out instantaneous frequency changes without phase jumps by switching just at the maximum of a sine/cosine wave. A simple criterion to switch to an adjacent comb line is the phase of the actually considered mode as measured in transmission. A change in frequency is required if the phase deviation exceeds approximately ±45°, where the sign determines the direction of frequency change (increase or decrease).

In a test set-up the direct analog synthetiser (i.e. laboratory instrument) has been operated in a phase-locked mode (locked via the 10 MHz clock) and frequencies were adjusted corresponding to a 10 kHz comb generator. The measured electric field strength in the centre of the test cavity for this case is shown in Fig. 17. Here, the amplitude of each generator was adjusted to 2 units vertical deflection (peak-peak). Perturbative effects such as drifts in resonance frequencies were simulated by mechanically deforming the test cavity (the drift behaviour is in general different for each mode) and applying the above-mentioned phase criterion for switching to an adjacent frequency. After renormalisation of the amplitude (changes due to 3 dB bandwidth) no visible differences within the time window shown in Fig. 17 were noted.

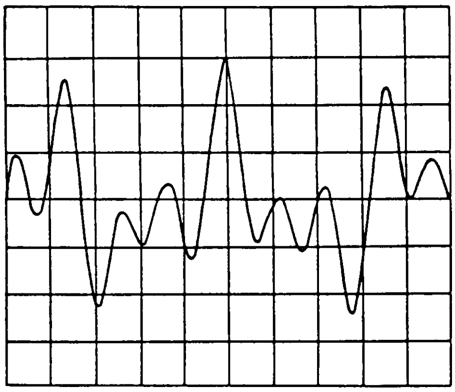

Fig. 17 - *Electric field strength in the centre of the test cavity using 3 modes. Hor. scale: 2ns/div.*

Conclusions

The actual studies have tried to give a guess ... the feasibility of some alternative ways for achieving high field gradients, particular in view of future single pass colliders.

For the Switched Power Linac average accelerating gradients of the order of 1 GeV m^{-1} seem quite reasonable, provided that we can develop reliable switches to achieve uniform and repetitive high current densities. Another important subject to study is the radial field components on the accelerated beam and their possible influence. Concerning the multifrequency approach we had a proof of principle by operating the model with a few harmonic frequencies. Extension to more frequencies and high field tests, in particular with superconducting cavities are still required.

Both methods will need further investigations on the field gradients which can be hold in practice in an accelerating structure.

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