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STUDY OF PEAK POWER DOUBLERS WITH SPHERICAL RESONATORS

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Introduction

Based on the work done at SLAC by Z.D. Farkas et al.[1] SLED, it was investigated whether a similar arrangement can be used for the LEP Injector Linac (LIL) in order to save high power klystrons by feeding, for a part of the accelerator, twice the number of accelerating sections from one klystron (LIPS = LEP Injector Power Saver). It seemed interesting to make use of the high quality factor of spherical resonators ($2...2.5 \times 10^5$) as compared to 10^5 of the cylindrical resonators used for SLED. The advantages (high Q) and disadvantages of spherical resonators (high number of competing resonant modes, problems of orientation, coupling) are discussed. Results of measurements with low power (c.w. and pulses) on single resonators and a complete model, and with high power on a prototype are presented.

Purpose of LIPS

The pre-injector for the LEP accelerator at CERN, LIL, consists of two electron/positron linacs: Linac V, in which electrons will be accelerated to 200 MeV in order to produce positrons, and further downstream Linac W, which will accelerate either electrons or positrons to 600 MeV. Most of the feeding high power klystrons were originally intended to be connected to four accelerator sections each.

In order to reduce their number, it was investigated whether a system similar to the SLED installation at SLAC could be used for part of the linac sections. SLED is essentially a radiofrequency pulse compressor, transforming a "long" (some microseconds) pulse into a "short" (about one microsecond) pulse whose peak power may be up to nine times higher. The basic theory of SLED is given in ref. 1 and 2. The idea in this case, was not to achieve higher energy gain per accelerator section, but to double the number of sections fed by a single klystron.

Need for high-Q-resonators

Calculation of the possible energy multiplication factor as defined in ref. 1, considering the data of LIL sections, and assuming that the input pulse length should not be longer than 4 microseconds, made a quality factor of 1.5×10^5 to 2×10^5 desirable (table 1).

$\frac{Q}{10^5}$	$\frac{t_3}{\mu s}$	$\frac{t_1}{\mu s}$	$\frac{t_2}{\mu s}$	βopt.	M
5	10	8.9	9	12.67	2.05
5	3.6	2.8	2.9	32.8	1.54
2	10	8.9	9	5.23	1.93
2	4	3.2	3.3	11.6	1.55
	3.8	3	3.1	12.4	1.52
	3.6	2.8	2.9	13.4	1.49
	3.5	2.7	2.8	14	1.48
	3.4	2.6	2.7	14.7	1.46
1.5	3.6	2.8	2.9	10.2	1.47
	3.5	2.7	2.8	10.6	1.45
	3.3	2.6	2.7	11.15	1.44
1	3.6	2.8	2.9	6.96	1.42

TABLE 1

Maximum energy multiplication factor for various values of LIPS cavity Q, and of input pulse length t_3. t_1, t_2 and β adjusted for optimum M.

Cylindrical resonators using the H_{015} (TE_{015}) resonance as at SLAC, will yield a theoretical Q of < 100 000. For this reason, it was necessary to look for resonators and/or resonant modes yielding a higher Q. It seemed therefore interesting to look into the application of spherical resonators. Their theory[3] will not be treated in detail here, but some of the results, which are not obvious to people familiar with rectangular or cylindrical resonators, will be explained and discussed in some detail.

Higher other modes in spherical resonators

The resonances possible in a spherical cavity may be split into two sets: The H (TE) modes, which have no electric field component in radial direction, and the E (TM) modes, which have no magnetic field component in radial direction. Assuming spherical coordinates r, ϕ, θ, the fields may be expressed as Bessel functions of half order, harmonic functions, and of associated Legendre functions of r, ϕ, and θ.

The resonant frequencies of a sphere of radius a are determined by

$$k_{ml}\, a = 2\pi \frac{a}{\lambda_{ml}} = 2\pi \frac{f_{ml}}{c_o}\, a \qquad (1)$$

where k_{ml} is given as

$$k^H_{ml} a = 1^{th} \text{ zero of } J_{m+1/2} \ (x) \qquad (2)$$

$$k^E_{ml} a = 1^{th} \text{ zero of } \frac{d}{dx}\left\{\sqrt{x}\ J_{m+1/2}\ (x)\right\} \qquad (3)$$

for H and E types, respectively.

A part of an ordered list of roots of equations (2) and (3) is given in table 2. The indices of the roots correspond to those used throughout in this paper, they are marked H or E, according to whether they belong to (2) or (3). Thus, the values in table 2 can be regarded directly as a list of normalized resonant frequencies of a sphere.

E	5	2	20.27200
H	6	1	20.37130
E	2	13	20.49322
H	1	15	20.54023
E	4	7	20.61542
E	1	18	20.78209
E	3	10	20.86032
H	4	6	20.98346
E	5	5	21.28148
H	2	12	21.37397
H	3	9	21.42849
H	5	4	21.52542
E	2	14	21.62158
H	1	16	21.62922
E	6	3	21.71393
E	1	19	21.81748
H	6	2	21.85387

Table 2

Ordered list of resonances in a sphere

Generally, the E modes have lower Q factors than the H modes; the Q of the latter is simply given by

$$Q^H_{1mn} = \frac{a}{\delta} \qquad (4)$$

where δ is the equivalent depth of penetration (skin depth):

$$\delta = \frac{1}{\sqrt{\pi . f . \mu . \kappa}} \qquad (5)$$

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For copper with $\kappa = 5.8 \times 10^5\ \Omega^{-1}\ \mathrm{cm}^{-1}$ and $f = 2998.55$ MHz it is $\delta = 1.2068\ \mu$m.
Hence, the radius has to be around 30 cm in order to obtain a Q of 2.5×10^5.
For $f = 2998.55$ MHz, $k = 0.6284\ \mathrm{cm}^{-1}$.
Therefore, one has to search for a suitable zero according to (2), for $\times > 18.85$. Looking at the list in table 2, one finds 20.9835 for the H_{46} modes, a value which is 0.59 % off the nearest other root, 20.8603 of the $E_{3\ 10}$ type. At this point, some words have to be said about characteristics and peculiarities of resonant modes in spheres.

The normalized frequencies in table 2 determine only the first two indices of the corresponding resonances, and the third index, n, may be any value between zero and the second index m (inclusively). All modes are therefore "naturally degenerate", the more the higher the second index, m. Thus the H_{46n} modes constitute a "family" consisting of

$$H_{460},\ H_{461},\ H_{462},\ H_{463},\ H_{464},\ H_{465},\ H_{466},$$

all of which have the same resonant frequency and the same quality factor in an ideal sphere, although the field distributions are quite different. Schematic representations of the distribution of surface currents in the sphere are given in Fig. 1.

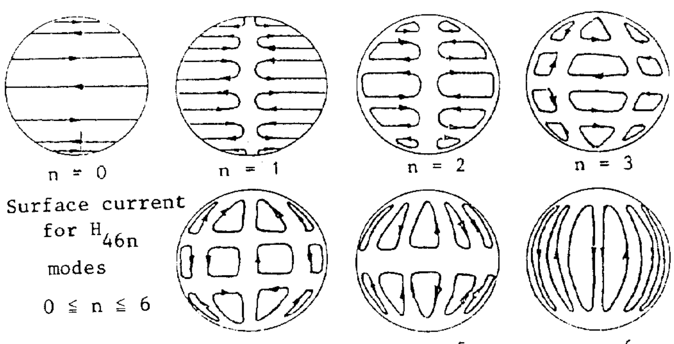


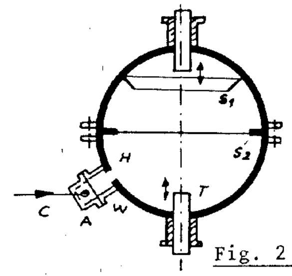
Fig. 1

Apart from the above mentioned natural degeneration, field configurations in a sphere have not a pre-determined orientation. In an ideal sphere, this means that a given mode may have any orientation (position of "axis" and "equator"); in non-ideal spheres, the resonant frequency will depend on the orientation. Thus, there may be a second type of quasi-degeneration (splitting of any mode into a multitude of modes with slightly different resonant frequencies). In practice, this has to be taken in account by providing suitable polarizers and mode suppressors, which select the wanted mode and force in to the desired position.

Investigations of the H_{46n} modes

The resonant mode envisaged to be used was the H_{460} mode. Its field does not depend on the ϕ coordinate, it was intended to force it into position and detune the competing H_{46n}, $0 < n \leq 6$ by attaching short conical rings inside the sphere at places where $E_\phi = 0$ ($I_\phi = 0$ on the surface) - (Fig. 2).

Coupling was intended to be made by a hole on the latitude of the first current (electric-field) maximum counting from the equator. (Indicated in Fig. 2)



C = coaxial connection
A = adapter coax/waveguide
W = short piece of waveguide
H = coupling hole
T = Tuning cylinders
S_1 = possible mode suppressor (conical)
S_2 = possible mode suppressor (ring)

Fig. 2 Spherical resonator

Manufacture of resonators and low-power tests

Four hemispheres were manufactured out of copper sheet by spinning. They were equipped with flanges at the "equators", flanges for mounting piston tuners at the "poles", and one of them with a coupling flange at $\theta = 30^0$.

For a long time, it was tried to separate and measure the H_{460} type. Finally, this idea was abandoned, mainly for the following reasons.

Parasitic mode suppressors, tried in the form of thin rings of various widths, mounted at the equator such that they protruded into the sphere, tended to prove unsucessful because they not only detuned the unwanted H_{46}, $n > 0$ modes but displaced neighbouring electrical and magnetic modes such that the spectrum in the neighbourhood of the wanted mode became more crowded than before (Fig. 3).

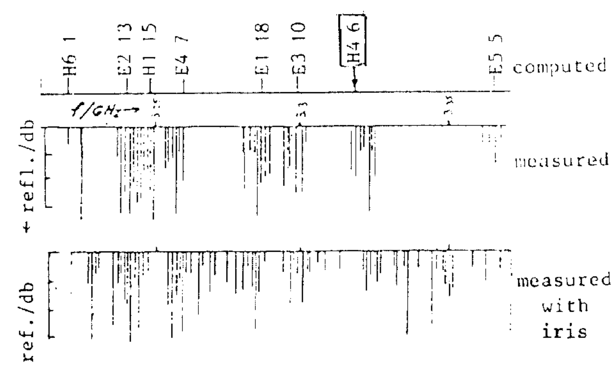


Fig. 3

Spectrum as measured on undisturbed sphere and with equatorial iris

The positioning of the tuning pistons proved to be extremely critical, because they acted not only as tuners, but apparently also changed the position of the field inside the cavity. This could be seen from the fact that the coupling factor depended very strongly on the tuner positions.

It was then decided to try to use the H_{461} type, which is the only one of the family to have a strong electric field at the poles (Fig. 1). Feeding was foreseen at one of the poles, suppressing the tuning piston there, and only leaving the tuner at the opposite pole. The idea was to detune the wanted mode without affecting the other members of the family, to a place sufficiently clear of these and other competing modes, rather than leaving the wanted mode at its frequency and trying to detune the competing ones.

After considerable experimental (cut and try -) effort, this idea proved to be successful. The cavities were optimised for the wanted mode by turning the coupling flange with respect to the hemisphere on which it was mounted, and by turning the hemispheres with respect to each other.

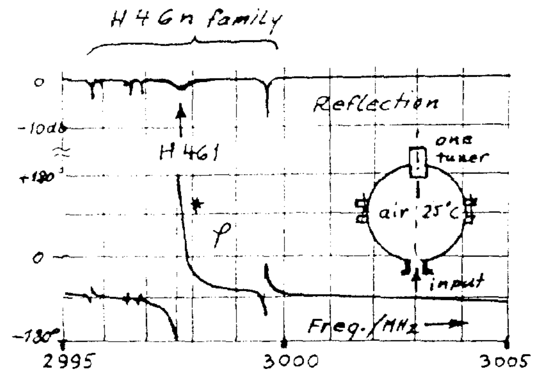


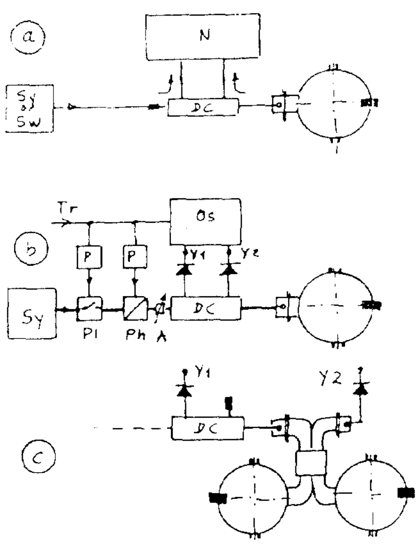
Fig. 4

Spectrum of resonator, diameter 660 mm
optimized for H_{461}
penetration of tuner raises
the freq. of the H_{461} only

In spite of the fact that, seen in the spectral representation, the competing modes were still uncomfortably close (below 1 MHz, Fig. 4), tests with simple square, and phase-switched square pulses proved that utilisation of the resonators was feasible.

Low power measurements and results

Low power measurements were done in a set-up shown in Fig. 5, using a reflection method.



a) for phase and magnitude of reflection

b) for pulse with one sphere

c) for pulse with LIPS assembly

Fig. 5

Measuring set-up

Sy : synthesizer	Tr : trigger	Y_2 : reflected signal or out-put pulse
Sw : sweeper	os : oscilloscope	
Dc : directional coupler	Pl : PIN-switch	
	P : pulsegen	A : attenuator
N : network analyzer	Y_1 : ref.-signal	Ph : bi-phase mod. ($0/180^0$)

The best reproduceable measurement yielded a Q of 2.2×10^5, compared to the theoretical value of 2.7×10^5. The coupling factor was set, by choice of the coupling iris, to a value near $\beta \simeq 13.4$, the calculated optimum for 2×10^5 and a total input pulse length of $t_3 = 3.6\,\mu s$ (table 1). The intended operation was simulated by feeding a single cavity with phase-switched r.f. pulses; the reflectometer allowed to see that the reflected signal was according to predictions; its evaluation permitted a check of the Q and β values.

High power tests

After two single spheres had been optimized with low power, they were prepared for evacuation and mounted together with a 90^0, 3 dB coupler to a complete working set-up, which was again tested and adjusted with low power. As an appropriate high power source was not available at CERN, the set-up was transported to LAL at Orsay, where it was installed to be tested with r.f. power from one of the linac klystrons (Fig. 6)[4].

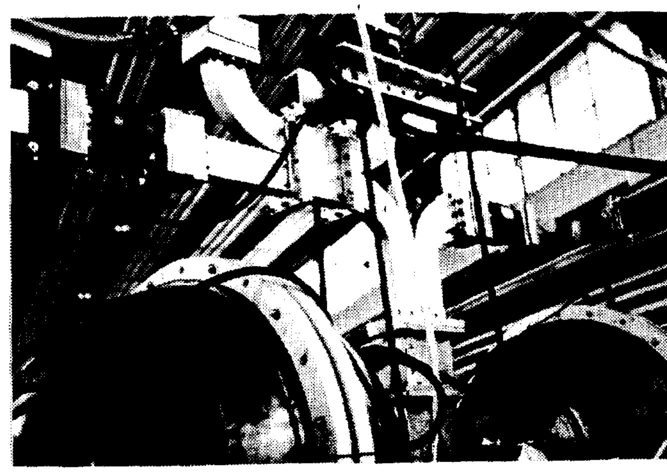


Fig. 6 - Detail of high power test set-up

After the considerable effort which it had taken to get the resonators working with low level r.f., it was amazing how quickly they were functioning with high power. Only occasional sparks, probably in the coupling orifices and some X-radiation indicated the presence of high voltage. With an input power of up to 22 MW, a peak output power of 110 MW was achieved (Fig. 7).

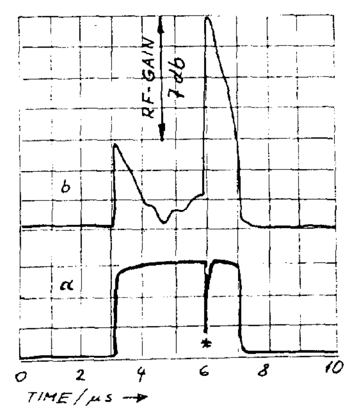


Fig. 7

High power LIPS pulses

a) out-put of klystron: 22 MW peak

b) out-put of LIPS: 110 MW peak

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