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.\textsuperscript{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 \times 10^5 to 2 \times 10^5 desirable (table 1).

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<th>\Delta \text{us}</th>
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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

\[ Q_{1mn}^H = \frac{a}{\delta} \]  

where \( \delta \) is the equivalent depth of penetration (skin depth):

\[ \delta = \frac{1}{\sqrt{\pi f \mu c}} \]
For copper with $K = 5.8 \times 10^5 \text{ n}^{-1} \text{ cm}^{-1}$ and $f = 2998.55 \text{ MHz}$, it is $\delta = 1.2068 \mu \text{m}$.

Hence, the radius has to be around 30 cm in order to obtain a Q of $2.5 \times 10^5$.

For $f = 2998.55 \text{ MHz}$, $k = 0.6284 \text{ cm}^{-1}$.

Therefore, one has to search for a suitable zero according to (2), for $x > 18.85$. 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 $E_{310}$ 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.

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 it into 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 $\phi$ coordinate, it was intended to force it into position and detune the competing $H_{46n}, 0 < n < 6$ by attaching short conical rings inside the sphere at places where $\phi = 0$ ($r = 0$ 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)

![Fig. 1](https://via.placeholder.com/150)

![Surface current](https://via.placeholder.com/150)

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 $\theta = 30^\circ$.

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 unsuccessful because they not only detuned the unwanted $H_{46n}, n > 0$ 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](https://via.placeholder.com/150)

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.

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.

The best reproduceable measurement yielded a Q of $2.2 \times 10^5$, compared to the theoretical value of $2.7 \times 10^5$. The coupling factor was set, by choice of the coupling iris, to a value $\beta \approx 13.4$, the calculated optimum for $2 \times 10^5$ and a total input pulse length of $3.6 \mu s$ (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 $\beta$ 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°, 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).

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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).

High power LIPS pulses

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