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DEVELOPMENT AND FIRST RESULTS WITH A STORAGE RESONATOR ENHANCING THE SHUNT IMPEDANCE OF AN ELECTRON ACCELERATING CAVITY

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Summary

In electron storage rings where the bunch repetition rate is low the dissipation of RF power in the accelerating cavity can be reduced by modulating the RF. A scheme using the energy oscillation between a storage resonator and the accelerating cavity has been successfully tested. Results of both low- and high-power tests at 500 MHz as well as design considerations for a 352 MHz prototype are presented.

Introduction

In normal operation LEP[1] will have a bunch spacing of 25.5 μs. Since this is still shorter than the natural filling time of the accelerating cavities continuous wave operation is preferred. Hence for a very large fraction of the time RF power is dissipated without interaction with the beam. It is desirable to store the RF energy in a low-loss storage system and transfer it to the accelerating gaps only during the passage of a bunch. One approach to this is a sinusoidal oscillation of energy between a storage device and the accelerating cavity with rise and fall times faster than the natural decay time[2]. Such a device has been built and operated up to a power of 125 kW.

Principle of Operation

For LEP, five-cell slot-coupled accelerating cavities will be used and will be similar in their basic geometry to those used in SPEAR[3], PETRA[4] and PEP[5]. To the centre cell of such a cavity is coupled a low-loss resonator (the storage cavity) which is also tuned to the π-mode frequency. The coupling between the two cavities determines the frequencies of the two resonant modes ω_1 and ω_2.

$$\omega_1 = \omega_{RF} + \frac{\Delta}{2}$$

$$\omega_1 = \omega_{RF} - \frac{\Delta}{2}$$

$k = \Delta/\omega_{RF}$.

ω_{RF} is the main RF frequency, k the coupling factor and Δ the frequency spacing.

If one excites the system with both frequencies simultaneously

$$U_D = U_o \cdot \cos\omega_1 t + U_o \cdot \cos\omega_2 t$$

one obtains - since ω_1 and ω_2 are zero and π modes respectively - in one cavity (Fig. 1)

$$U_1 = 2U_o \cdot \cos\omega_{RF} t \cdot \cos\Delta/2\ t$$

and in the other

$$U_2 = -2U_o \cdot \sin\omega_{RF} t \cdot \sin\Delta/2\ t.$$

This represents an energy oscillation between the two cavities at a rate Δ. ω_1 and ω_2 have now only to be chosen in such a way that the bunches pass the accelerating cavity at the maximum of the accelerating field.

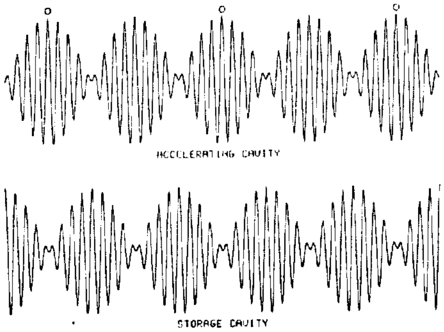

Fig. 1. Fields in accelerating and storage cavities

The total power dissipation is thus reduced by a factor q:

$$q = \frac{Q_a + Q_s}{2 \cdot Q_s}$$

Q_a = Q value of accelerating cavity
Q_s = Q value of storage cavity

For the storage cavity an H_{omn} mode is preferably used, which has low losses in order to get a low value q.

Expected Performance of LEP System

The LEP accelerating system will work at 352.21 MHz. The geometry of the accelerating cavities has been optimized with SUPERFISH by suitably shaping the cells to give a value of $ZT^2 = 26.3$ MΩ/m; the Q value was taken to be 41300 (85% of the SUPERFISH value). The spherical storage cavity with an inner diameter of 1.21 m, excited in the H_{011} mode should have a Q value of 163900 (95% of theoretical value). Using these values the effective shunt impedance will be 42.1 MΩ/m. Taking into account several factors which tend to reduce this value such as distance from the interaction points, phase and amplitude errors due to losses in the structure, non-flat field distributions and losses in the intercavity coupler, we expect the effective shunt impedance of the coupled system to be 40 MΩ/m.

Model Measurements

A test set-up for low-power measurements on a coupled system was built first. A 500 MHz accelerating cavity was generously lent to us by DESY. A copper cylinder whose H_{011} resonance was at 500 MHz was used as storage resonator. The coupling element was a coaxial double loop coupler. The unloaded Q values of accelerating and storage resonator were

Q_a = 28 900
Q_s = 109 800

resulting in a measured Q_c of the coupled system in modulation mode of

$$Q_c = 45\ 600.$$

The coupling factor k was adjusted by rotating the intercavity coupler to give

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$$k = 2.6 \times 10^{-4}$$

The distribution of the accelerating fields in the five cells of the accelerating cavity was uneven and different for the two resonant frequencies, which lead to a non-perfect energy exchange. They differed particularly in the centre cell. The relative values of the maximum fields in the cells were measured to be for ω_1 and ω_2:

	C_1	C_2	C_3	C_4	C_5
$E(\omega_1)$	1.07	1	0.93	1.03	1.08
$E(\omega_2)$	0.98	1	1.09	1.02	0.98

The different voltage distributions for the two modes gave rise to an incomplete modulation in the accelerating cells and in the storage cavity and hence to a loss in shunt impedance. The maximum loss in shunt impedance due to this effect was 1.8% (calculated from measured fields). With the results of these measurements the reduction of dissipated power was q = 0.6, a value close to what was expected.

Periodically Switched System

As shown before, the bunch spacing T_b is a multiple of half the modulation period T_m.

$$T_b = n \cdot T_m/2 \qquad n = 1, 2, \ldots.$$

For n greater than 1 there will be energy beats in the accelerating cavity when no bunch passes. These could be suppressed by switching the coupling periodically on and off (Fig. 2).

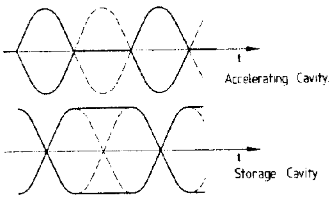

Fig. 2. Fields with switched coupler

Such a switched system has losses

$$P^{\Omega} = \frac{1}{2n} P_a + \left(1 - \frac{1}{2n}\right) P_s$$

where P_a and P_s are the CW losses in the accelerating and storage cavities respectively. The decrease of losses compared to the modulated system without switch is

$$g = \frac{P - P^{\Omega}}{P} \cdot 100\% = \left(1 - \frac{1}{n}\right) \frac{1 - P_s/P_a}{1 + P_s/P_a} \cdot 100\%$$

Because of the length of the RF stations the modulation period T_m cannot be chosen to be very short, i.e. n is restricted to 2 or 3. This yields theoretical gains g of 30% and 40% respectively for LEP with 2x4 bunches and 45% and 60% respectively for LEP with 2x2 bunches. These values do not take into account additional losses due to the switch or to the different power feeding systems.

For n = 2 and 2x4 bunches the requirements for the switch are: frequency 40 kHz, rise time 1-2 μs, power handling capacity 1 MVA (product of peak current times peak voltage). Five different principles were looked at:

1) non-reciprocal ferrite devices (at least one wavelength long, heavy, high losses)
2) gas discharge devices (recovery time ∿ 100 ms)
3) multipactoring (technology not reliable enough)
4) pulsed electron beams (high energies and densities)
5) PIN-diodes

The PIN-diode switch was chosen as being the most promising solution and a model with 30 diodes has been developed. It consists of a ridged circular waveguide as inter-cavity coupler and a shunt mounted coaxial stub line of length $\lambda/2$ (Fig. 3). The coaxial line is tapered in order to provide enough space for the diodes mounted circumferentially at $\lambda/4$ distance. By means of a movable short circuit one can adjust the length of the line and thus compensate for the diode capacitance. The bias is supplied via an RF rejection filter and movable pistons which are dc-isolated by having an anodized surface.

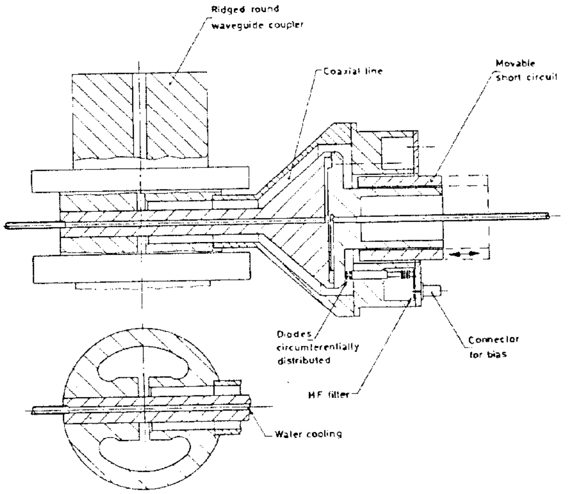

Fig. 3. Switched coupler

The switch has been tested at low power on the 500 MHz cavity test stand and has worked very satisfactorily. Fig. 4 shows the field pattern in the storage and accelerating cavities.

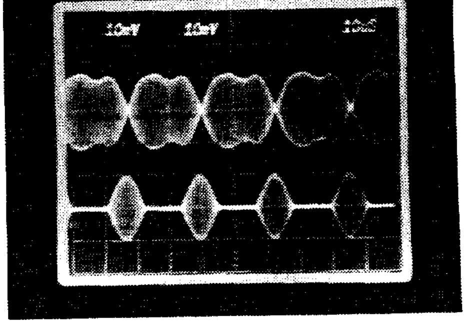

Fig. 4. Measured fields in storage (top) and accelerating (bottom) cavities

Design of the Storage Cavity

The layout of the LEP coupled cavity system is shown in Fig. 5.

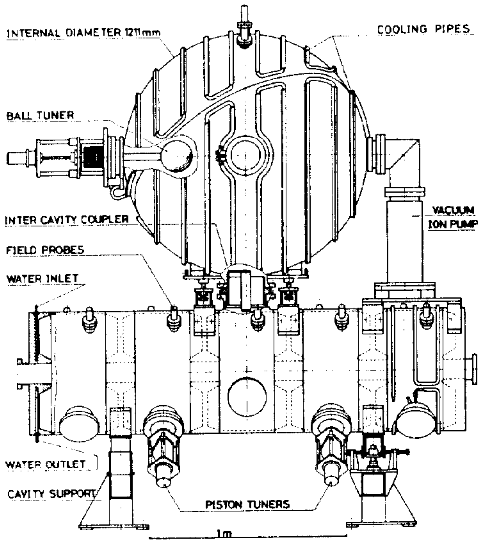

Fig. 5. Arrangement of coupled cavity system for LEP

A sphere of 1.21 m diameter operating in H_{011} mode was chosen as the storage cavity. The following considerations determined the design.

At present it is foreseen that the storage cavity will be operated under vacuum. Since the RF sections are close to the physics interaction regions we aim for an exceptionally good vacuum so the storage cavities should be bakeable to 200°C. For good heat transport properties of the wall as well as high electrical conductivity an all-copper solution as opposed to copper-plated or copper-clad steel was chosen. The poor mechanical properties of OFHC copper at high temperatures can be considerably improved by using a phosphorous deoxidized high-conductivity copper with an addition of 0.1% silver.

The cavity has to be stiff enough and sufficiently well cooled that deformations produced by vacuum and thermal expansion are small enough to be compensated with a fine-tuning device. The stiffness requirements can best be fulfilled with a sphere. Adequate cooling is obtained by brazing cooling pipes on the external surface. The power dissipation under normal conditions will be 23 kW and with a switch 50 kW. Consideration of the vacuum-induced deformation caused by amplification of initial manufacturing imperfections, the level of stress at 200°C, elastic and plastic stability, the creep deformation at 200°C and cooling requirements, led to a wall thickness of 5 mm.

The sphere is produced out of two spun hemispheres which are electron-beam welded together. Due to the tolerances associated with this technique of forming the sphere has to be brought to resonance by successively machining the hemispheres to reduce their height before welding them together. The sphere has outlets for the intercavity coupler, a tuner, a power coupler, a vacuum pump in a field-free region, an RF monitoring probe and a vacuum gauge.

If current development work on a vacuum-tight intercavity coupler proves to be successful the storage cavity could be operated under atmospheric pressure, which would considerably simplify the design.

Due to the spherical geometry the polarization of the H_{011} mode is not determined. To achieve polarization and tuning at the same time a ball tuner was built which consists basically of a watercooled sphere of 120 mm diameter which is fixed to a rod. The present tuner has a stroke of 150 mm and a total tuning range of 3 MHz.

Control of the System

The cavities are kept in tune with piston tuners in cells 2 and 4 and a ball tuner in the storage cavity. A block diagram of the system is shown in Fig. 6, with the drive input to the storage cavity.

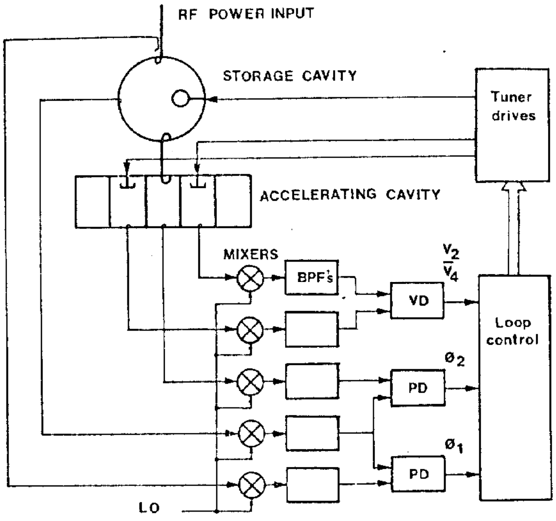

Fig. 6. Block diagram of control system

Detuning of the coupled cavity (the accelerating cavity in this particular case) changes the phase between both cavities ϕ_2 as well as the phase between the forward running wave of the drive and the driven cavity ϕ_1, whilst detuning of the driven cavity results only in a change of ϕ_1. This phenomenon is used to determine which cavity has become detuned.

Sample signals are taken from the storage resonator and each cell of the accelerating cavity via inductively coupled loops, the drive being sampled via the forward output of a directional coupler in the waveguide. The phase discriminators PD sense the incremental phase changes of ϕ_1 and ϕ_2 and after processing and amplification these signals drive the tuners. An additional control loop compares the fields in cells 2 and 4 and keeps field symmetry along the structure by driving the piston tuners differentially.

To run the system in both modulated and CW modes phase and amplitude information is taken from only one of the two frequency components of the modulated signals. This is done by converting down to a lower frequency where phase and amplitude information is retained and the increased fractional separation makes it possible to isolate one frequency component with a band pass filter (BPF). These filtered signals are fed into the phase and amplitude discriminators of the control system.

High-power tests

A coupled cavity system working at 500 MHz was built to carry out tests up to 125 kW RF power. A photo of the set-up is shown in Fig. 7.

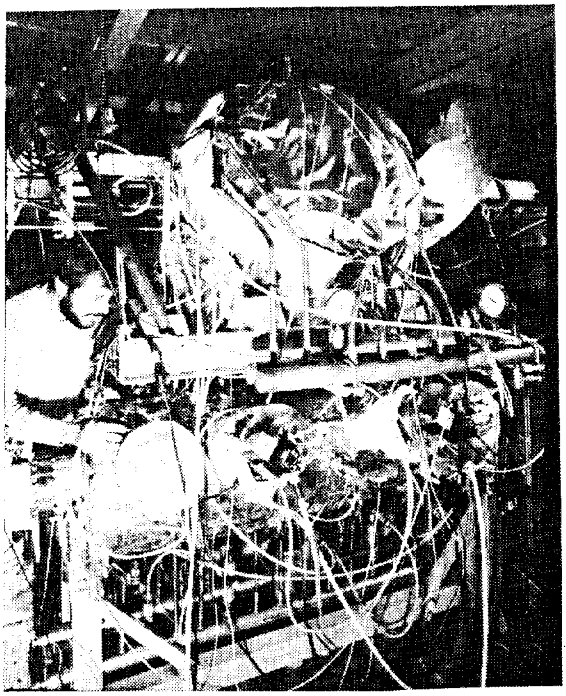

Fig. 7. Test set-up for 500 MHz power tests

As accelerating cavity we use a copper five-cell structure; the storage cavity is a copper sphere of 858 mm inner diameter.

The unloaded Q value for the sphere was measured to be 138500 which is 96.2% of the theoretical value.

The difference in frequencies between atmospheric pressure and vacuum due to the change in dielectric constant is +150 kHz; a value of +165 kHz was measured which indicates almost negligible deformation under vacuum.

At its operating point the ball tuner accounts for 1.2% of the total power losses in the storage cavity.

As intercavity coupler a ridged waveguide coupler is used (Fig. 8).

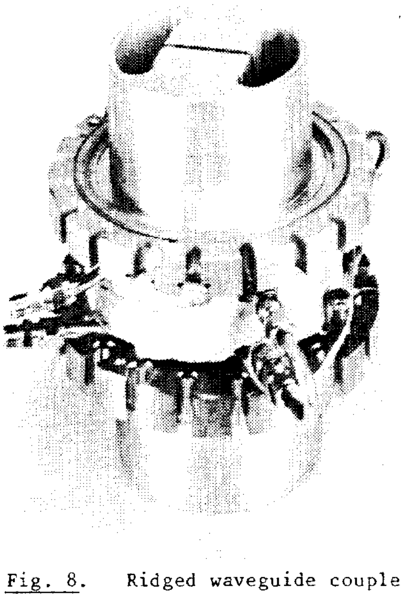

Fig. 8. Ridged waveguide coupler

The main RF power is fed via a WR 1800 waveguide into the storage cavity with a newly developed coaxial loop coupler mounted on a waveguide to 50 Ω coaxial transition of the doorknob type. The vacuum RF window is a cylindrical ceramic tube between the doorknob and the outer conductor of the coupler.

The power source is a 500 MHz, 250 kW klystron driven by the modulated signal $U = \sin\omega_1 t + \sin\omega_2 t$ via a 100 W linear amplifier. In this mode the klystron efficiency is unacceptably small for LEP. In a later stage however two klystrons will be used for one group of coupled cavities[6]. Both klystrons will be continuously operated in saturation where the efficiencies are expected to be at least 70%. The outputs of the two klystrons of which one will supply ω_1 and the other ω_2 will be combined via a magic tee, whose outputs will supply the sum and difference signals. These will be fed into the accelerating cavities and the storage cavities respectively.

By machining off the end faces the intercavity coupler was adjusted to a coupling factor of 2.26×10^{-4}; the two resonant frequencies are at 499.614 and 499.727 MHz. After several hours of conditioning (the accelerating cavity had been previously conditioned to 150 kW) an average input power of 125 kW was achieved. An oscilloscope photo of the fields in the two cavities at 125 kW is shown in Fig. 9.

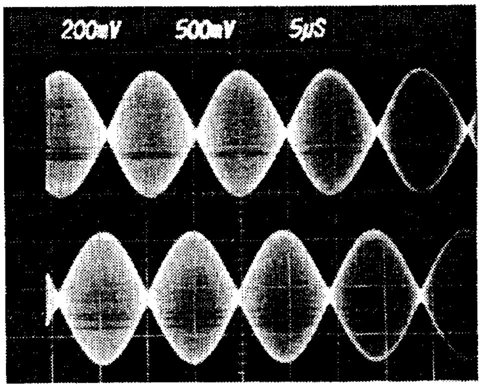

Fig. 9. Fields in prototype at 125 kW (accelerating cavity bottom, storage cavity top)

Up to now the system has run satisfactorily for 150 hours under power with approximately 100 hours above 100 kW.

Since a local discharge in the gap of the intercavity coupler was observed, the coupler was replaced by a coaxial double loop coupler which is now under test.

The storage cavity has also been powered separately under atmospheric pressure up to 60 kW. A switched coupler for high RF power is presently under development.

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