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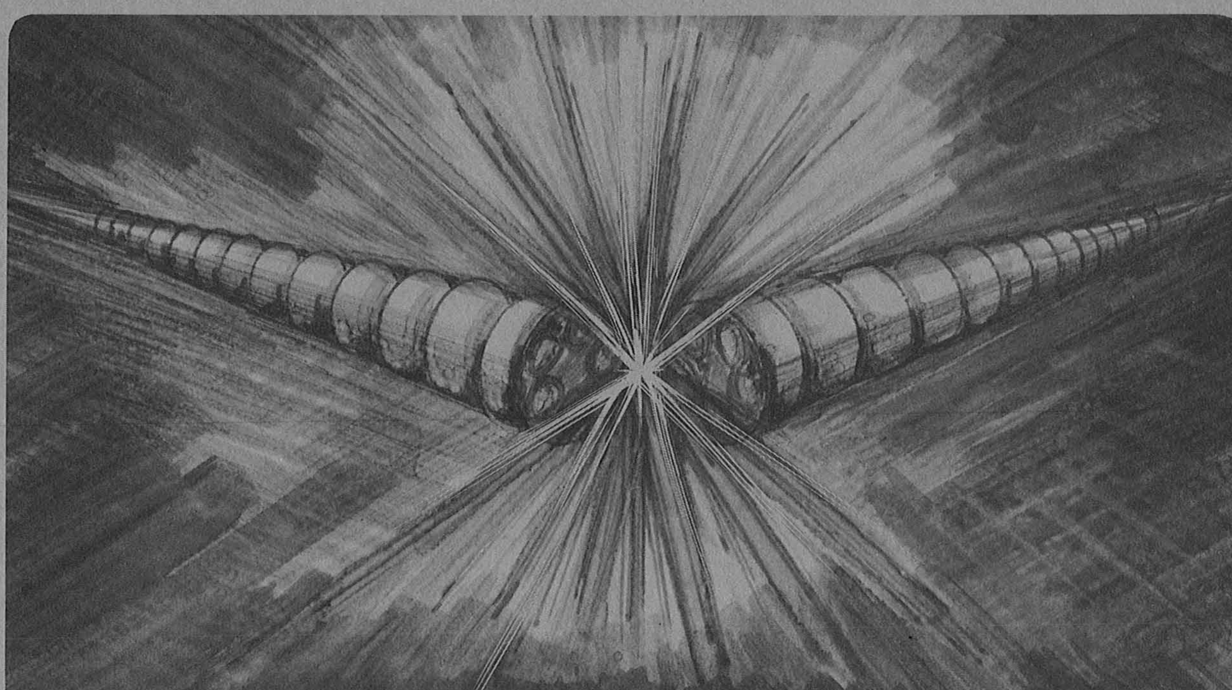

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Measurement and Computation of the Higher Order Modes of the ALS 500 MHz Accelerating Cavities*

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Abstract

Higher order modes in the accelerating cavities are expected to drive coupled bunch instabilities in the ALS, which will be overcome by a bunch-by-bunch feedback system. Computations of the cavity higher order modes using the URMEL-T and MAFIA codes are presented. Damping of the higher order modes is achieved by filters in the high power feeder waveguide which is aperture coupled to the cavity. Measurements of the modes in an ALS 500 MHz cavity are presented and compared with the computed values for an isolated, un-damped cavity. The resources of the Lambertson Beam Electrodynamics Laboratory of the Center for Beam Physics at LBL were used to perform these studies.

I. INTRODUCTION

The design current of the ALS storage ring is 400 mA in multibunch mode, leading to coupled bunch instabilities with growth rates faster than the radiation damping rate for typical RF cavity higher order mode (HOM) impedances [1].

Suppression of coupled bunch instabilities will be achieved by a bunch-by-bunch feedback system, described elsewhere [2]. The required gain of the feedback system is determined by the strongest driving impedance, and for nominal operation it has been assumed that the longitudinal HOM's can be damped such that the total shunt impedance R_s at frequency ω_p is:

$$R_s \frac{\omega_p}{\omega_{rf}} \leq 120\ \mathrm{k}\Omega$$

where ω_{rf} is the frequency of the RF system (500 MHz). In the transverse case a maximum transverse impedance of $4\ \mathrm{M}\Omega\ \mathrm{m}^{-1}$ is assumed.

Calculations using the URMEL-T electromagnetic design code suggest that without damping a single ALS cavity would have higher order modes of up to 1.9 MΩ shunt impedance (at 800 MHz) and $30\ \mathrm{M}\Omega\mathrm{m}^{-1}$ transverse impedance.

In order to better quantify the impedance of the cavities, measurements were made of a spare cavity, identical to the cavities in the storage ring, with waveguide coupler and higher order mode filters included in the measurements.

Higher order modes were identified using a perturbation method, and Q-values measured. Impedance was determined from multiplying the measured Q by the R/Q determined by URMEL-T computations.

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II. HOM DAMPING IN THE FEEDER WAVEGUIDE

The ALS radiofrequency accelerating system uses two 500 MHz cavities with reentrant nosecone geometry, aperture coupled to the feeder waveguide. A detailed description is given elsewhere [3]. A single klystron feeds the cavities, via a magic-tee junction, and in the the waveguide sections between magic-tee and each cavity are H-plane and E-plane low-pass filters. These filters consist of right-angle tee-junctions with one arm of the tee a bifurcated waveguide section. A metal plate along the center of the broad wall prevents propagation of the 500 MHz wave, but allows higher frequency waveguide modes to pass on either side. At the ends of these bifurcated tee sections are placed loads made of absorbing material cast into a section of bifurcated waveguide. A similar arrangement exists behind the bifurcated matching stub. The system is designed to absorb higher order mode power coupled out of the cavity into the waveguide, providing damping of those HOM's that couple to the filters.

III. NUMERICAL COMPUTATIONS

Since there is no simple method of modelling the cavity with feeder waveguide and loads included, the longitudinal and transverse (dipole) modes were computed using the URMEL-T code [4] for the basic cavity geometry. This two-dimensional model computes modes in an isolated cavity with cylindrical symmetry, with no feeder waveguide or coupling aperture. The results are shown in table 1 for longitudinal modes and in table 2 for transverse (dipole) modes, up to the cut-off frequencies of the beam tubes (2.5 GHz for dipole modes, 3.3 GHz for longitudinal (monopole) modes).

The required damping factor indicates the reduction in impedance necessary to ensure that higher order modes in the cavities do not drive coupled bunch instabilities beyond the capabilities of the feedback system to damp the motion. This makes the conservative assumption that the two cavities in the storage ring have exactly the same higher order mode spectrum and thus HOM's coincide in frequency.

MAFIA computations of a three-dimensional cavity model including coupling aperture were useful in identifying HOM's. In particular the three-dimensional modelling allows determination of the orientation of the two polarizations of the dipole modes, and also gave some indication of which modes would couple most effectively into the waveguide.

Table 1
Longitudinal Higher Order Modes Computed by URMEL-T

Frequency (MHz)	R/Q (Ω)	Q	R (MΩ)	Required damping factor
797.61	50.95	37526	1.912	50.8
1024.0	1.189	38997	0.046	1.6
1295.1	15.53	36473	0.566	24.5
1343.1	9.724	81292	0.791	35.4
1559.6	7.679	37260	0.286	14.9
1785.8	4.551	55690	0.253	15.1
1870.7	0.418	103768	0.043	2.7
1871.9	3.215	47754	0.154	9.6
2108.1	4.191	39387	0.165	11.6
2246.9	0.248	76392	0.019	1.4
2324.9	3.497	87683	0.307	23.8
2423.5	0.786	99820	0.078	6.3
2427.3	3.507	41225	0.145	11.7
2611.7	0.094	52421	0.005	
2743.9	0.090	89671	0.008	
2781.8	1.602	54646	0.088	8.1
2808.1	4.689	80873	0.379	35.5
2968.0	0.054	107891	0.006	
2979.2	0.047	44478	0.002	
3149.2	0.747	83910	0.063	6.6
3183.6	1.235	61187	0.076	8.0
3243.0	0.020	74974	0.001	
3252.4	0.539	56151	0.030	3.3
3256.0	7.693	27527	0.212	23.0
3257.6	8.055	27948	0.225	24.5

Table 2
Dipole Higher Order Modes Computed by URMEL-T

Frequency (MHz)	$R/Q*1/(kr^2)$ (Ω/m)	Q	R (MΩ/m)	Required damping factor
705.55	4.91	51229	0.25	
815.57	307.0	57906	17.78	8.9
1118.8	528.9	53646	28.37	14.2
1182.4	5.06	52833	0.27	
1243.8	2.51	103047	0.26	
1388.8	70.76	66585	4.71	2.4
1513.9	220.5	44481	9.81	4.9
1592.0	47.09	102317	4.82	2.4
1645.2	16.91	59163	1.00	
1781.6	2.15	116675	0.25	
1788.1	550.2	52854	29.08	14.6
1850.5	2.61	89109	0.23	
1943.3	5.38	38636	0.21	
2044.1	47.60	108366	5.16	2.6
2138.0	2.26	112062	0.25	
2138.7	1.82	115129	0.21	
2196.0	166.1	78218	12.99	6.6
2202.3	58.36	37136	2.17	1.1
2338.2	13.45	81679	1.10	
2375.8	6.78	121562	0.82	
2448.2	44.81	38486	1.72	
2504.3	23.58	113974	2.69	1.4
2537.1	19.67	37545	0.74	
2539.5	5.77	23015	0.13	

IV. MEASUREMENTS OF THE TEST CAVITY

A spare cavity identical to the storage ring cavities was used for the measurements of the higher order modes. A coupling waveguide together with cylindrical ceramic window was mounted onto the cavity, and the higher order mode filters, created by bifurcated waveguide sections, were attached to either end of the coupling waveguide. The layout used in the measurement is a reasonably accurate simulation of the real configuration, although neglecting the effects of waveguide bends, tee-junctions, magic-tee and the circulator.

Modes were excited in the cavity by using electric probes inserted into the beam pipes, one on either side of the cavity. The probes were held near to the beam pipe wall on an acrylic support structure which allowed rapid adjustment of the position of the probes. By adjusting the azimuthal position of these probes while monitoring the S_{21} signal the longitudinal and transverse cavity modes were excited. The frequencies at which to look for particular modes were found in the URMEL-T and MAFIA computations. The Q-value of each mode was measured from the width of the S_{21} resonance curve, at the half power points.

In order to identify the modes a perturbation method was used. A hollow cylindrical needle was threaded onto a nylon line strung inside the cavity between adjustable supports mounted on the beampipe flanges. The needle was drawn through the cavity at various displacements with respect to the cavity axis (on-axis, horizontally and vertically off-axis), with the long dimension of the needle parallel to the cavity axis. Using a needle of aspect ratio (length to diameter) 29:1 the longitudinal electric field was perturbed. Qualitative observations of the perturbation patterns allowed identification with the corresponding computed mode. A longitudinal mode would exhibit no significant difference in perturbations when the needle was on axis or any position off axis. A dipole mode would show maximum perturbation off axis at one azimuth, with negligible perturbation either on axis or off axis displaced 90°.

Since the asymmetry of the real cavity splits the degeneracy of the dipole modes, we have two modes for each dipole mode predicted by URMEL-T. These modes are found at slightly different frequencies and with different azimuthal orientations of the fields. For most dipole modes measured the field distributions were such that the mode would couple principally to either horizontal or vertical motion of the beam, hence the modes were designated as H or V.

Although the R/Q for the HOM's in the real cavity may vary from the idealistic case of cylindrical symmetry, the error involved in assuming that R/Q is unchanged with the addition of the aperture coupled waveguide is generally small [5].

Measurements were made at the nominal operating temperature of 40°C, with the fundamental mode tuned to the RF frequency. For those modes driving the strongest coupled bunch motion the frequency over a range of 5 mm tuner movement was recorded at 40 °C, and the frequency variation with temperature was also measured over ± 5°C.

V. RESULTS

Measurement results are given in table 3 for the longitudinal modes, and table 4 for dipole modes. Almost all of the predicted modes were found, and a comparison with tables 1 and 2 shows that the damping via the feeder waveguide is very effective for most modes.

The Q values of modes above 2.8 GHz were difficult to measure due to the presence of fields at the ends of the beam pipes, and conservative estimates of the Q values are given.

Table 3
Measured Longitudinal Higher Order Modes

Frequency (MHz)	Q	R (kΩ)	kHz/°C	kHz/mm	Required damping factor
808.44	21000	1050	-20	37	28
1007.96	840	1.76	70		
1280.10	3000	33.0	-45	276	1.4
1309.34	810	5.51	35		
1553.55	3400	26.52	-28	-118	1.4
1807.68	2900	13.34	-33		
1846.72	2200	0.88	-15		
2122.61	1800	7.56	10	-155	
2266.6	2200	0.55			
2349.8	5100	17.8	-31	-35	1.4
2416.3	7000	5.53	-27	-78	
2484.94	2400	8.40	19		
2625.9	1500	0.14			
2769.1	1500	0.14			
2817.4	≤1000	1.60			
2847.82	≤4000	18.8	-32	-6	1.8
2968	<1500	0.08			
2979	<1500	0.08			
3149	<1500	1.125			
3183	<1500	1.86			
3243	<1500	0.03			
3252	<1500	0.81			
3256	<1500	11.54			1.2
3257	<1500	12.1			1.3

The longitudinal mode at 808 MHz (TM_{011}) does not couple strongly into the feeder waveguide and may drive coupled bunch instabilities beyond the damping capabilities of the feedback system. Six other longitudinal modes have impedances marginally greater than the feedback design criteria. Three transverse modes remain with impedance greater than 2 $M\Omega\ m^{-1}$.

Table 4
Measured Dipole Higher Order Modes

Frequency (MHz)	Q	R (kΩ/m)	kHz/°C	kHz/mm	*	**
810.08	48000	14800	-12	-23	H	7.4
1121.77	7000	3700	-21	34	V	1.8
1122.72	17000	9000	-18	-3	H	4.5
1183.20	800	4			V	
1189.85	1800	92	-18	-3	H	
1369.83	3700	260	-17	-13	V	
1518.60	300	67			V	
1529.00	1800	200	-22		H	
1597.36	8400	400	-16	-38	H	
1648.00	600	10			H	
1726.90	900	2			H	
1739.00	500	1			V	
1796.64	1200	660	-23		H	
1801.61	2000	1100	-17	-52	V	
1966.11	4000	22	-31		H	
2136.97	16000	36	-31		H	
2141.08	9000	20	-20		V	
2151.34	2500	5	70		V	
2156.70	2400	4			H	
2178.98	1700	280	-32	-110	H	
2335.56	4800	65	-48		45°	
2504.20	500	12			H	

* orientation
** required damping factor

Variations of cavity temperature and tuner position may overcome coupled bunch instabilities driven by these modes, however it may be difficult to solve the problem for all modes simultaneously. The stability of coupled bunch motion in the ALS is discussed elsewhere [2].

Damping of the strongest HOM's using probes in the cavity pumping port will be investigated as a solution to this problem.

VI. ACKNOWLEDGEMENTS

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