Mode Identification & Cavity Stretching for the Prototype Storage Ring Cavity

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INTRODUCTION

The Advanced Photon Source (APS) storage ring uses single cell cavities (Fig. 1). As described in the paper "Coupled Bunch Instabilities in the APS Ring" by L. Emery,\(^1\) several of the higher order modes (HOM) in these cavities cause instability thresholds below the desired operating level. In order to clearly indentify these modes, an experimental method of measuring the fields is necessary. A well-known technique is measurement with probes or loops extending in from the walls, but this cannot be used in the interior. A different approach is the use of small perturbations which cause a frequency shift that is related in a known way to the local field. This perturbation can be calculated for objects of needle-shaped, spherical, and disk-shaped form.\(^2\) With proper use this method can give very accurate measurements of the direction and magnitude of the electric and magnetic fields.

This report gives examples of a method of measuring electric field strengths in a resonant cavity. It is shown that insertion of a metallic bead (needle), whose dimensions are small compared to the wavelength, perturbs the frequency of a resonant electromagnetic cavity by an amount that depends upon the local electric field at the position of the perturbing object.

In the APS storage ring, the single cell cavities could be machined to slightly different longitudinal lengths in order to stagger harmonic resonances. Cavity measurements with shims was performed and compared with calculations.

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The modes that require clear identification are the following:

<table>
<thead>
<tr>
<th>#</th>
<th>Mode</th>
<th>Frequency (MHz)</th>
<th>R (Normal Mohm)</th>
<th>Q</th>
<th>R/Q (Ohm or Ohm/m)</th>
<th>Threshold Current (mA)</th>
<th>Cyl</th>
<th>Pole</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 E-1</td>
<td>353.6</td>
<td>5.6</td>
<td>49000</td>
<td>114.3</td>
<td>80</td>
<td>E010</td>
<td>TMO-EE-1 Mono 35.6</td>
</tr>
<tr>
<td>6</td>
<td>0 M-1</td>
<td>536.7</td>
<td>1.67</td>
<td>41000</td>
<td>40.7</td>
<td>80</td>
<td>E011</td>
<td>TMO-ME-1 Mono 53.6</td>
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<tr>
<td>7</td>
<td>1 E-1</td>
<td>588.7</td>
<td>13.6</td>
<td>68000</td>
<td>200.3</td>
<td>81</td>
<td>E110</td>
<td>1-EE-1 Dipo 53.6</td>
</tr>
<tr>
<td>10</td>
<td>0 E-2</td>
<td>744.9</td>
<td>.003</td>
<td>43000</td>
<td>.11</td>
<td></td>
<td>E020</td>
<td>TMO-EE-2 Mono 74.3</td>
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<tr>
<td>11</td>
<td>1 M-2</td>
<td>761.1</td>
<td>25.6</td>
<td>53000</td>
<td>483.4</td>
<td>43</td>
<td>E111</td>
<td>1-EE-2 Dipo 75.8</td>
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<tr>
<td>16</td>
<td>0 E-3</td>
<td>922.5</td>
<td>0.62</td>
<td>107000</td>
<td>5.8</td>
<td>130</td>
<td>E012</td>
<td>TMO-EE-3 Mono 93.1</td>
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<tr>
<td>17</td>
<td>0 M-2</td>
<td>939.</td>
<td>0.23</td>
<td>42000</td>
<td>5.5</td>
<td>340</td>
<td>E013</td>
<td>TMO-EE-2 Mono 93.4</td>
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<tr>
<td>19</td>
<td>1 E-3</td>
<td>962.</td>
<td>6.1</td>
<td>54000</td>
<td>11.3</td>
<td>180</td>
<td>E112</td>
<td>1-EE-3 Dipo 95.7</td>
</tr>
<tr>
<td>20</td>
<td>1 M-4</td>
<td>1017.4</td>
<td>2.6</td>
<td>41000</td>
<td>63.4</td>
<td>320</td>
<td>E121</td>
<td>1-EE-4 Dipo 101.5</td>
</tr>
<tr>
<td>23</td>
<td>1 E-5</td>
<td>1145.1</td>
<td>2.7</td>
<td>92000</td>
<td>29.3</td>
<td>80</td>
<td>E120</td>
<td>1-EE-5 Dipo 104.7</td>
</tr>
<tr>
<td>25</td>
<td>0 E-4</td>
<td>1173.2</td>
<td>.18</td>
<td>44000</td>
<td>4.1</td>
<td>80</td>
<td>E022</td>
<td>TMO-EE-4 Mono 117.2</td>
</tr>
<tr>
<td>27</td>
<td>0 M-3</td>
<td>1210.8</td>
<td>.49</td>
<td>94000</td>
<td>5.2</td>
<td>80</td>
<td>E013</td>
<td>TMO-ME-3 Mono 120.7</td>
</tr>
<tr>
<td>28</td>
<td>1 E-6</td>
<td>1219.2</td>
<td>3.65</td>
<td>41000</td>
<td>89.3</td>
<td>430</td>
<td>E122</td>
<td>1-EE-6 Dipo 122.2</td>
</tr>
<tr>
<td>43</td>
<td>0 E-6</td>
<td>1509.1</td>
<td>0.36</td>
<td>88000</td>
<td>4.1</td>
<td>80</td>
<td>E022</td>
<td>TMO-EE-6 Mono 150.7</td>
</tr>
</tbody>
</table>

Notes:

1. In column 2, a "0" means monopole, "1" means dipole.
2. In column 3, an "E" means that Ez, on axis, is, as a function of z, even about the midplane of the cavity (the plane perpendicular to its axis at its center). An "M" means that it is an odd function, so, for example, Ez will necessarily have a zero on the midplane.

The function is even or odd according as the "p" in column 9 is even or odd.

The "E" and "M" in column 3 have nothing to do with the "E" (in "Emnp") and "M"

in columns 9 and 10 respectively; but they are the same as the first "E" or "M" in the pair "-xE-", in column 10, the second of which is always an "E".

3. The "E" or "M" in the pair "-xE-" in column 10 refer to electric or magnetic boundary conditions respectively (transverse electric or magnetic fields zero respectively) at the midplane or end faces respectively of the cavity.

4. Both the "E" (in "Emnp") and "M" (in "TMO") mean that the mode is transverse magnetic.

5. The "p" in column 9 is the number of zeros of Ez inside of the cavity, along its axis (not including the beam pipe outside the ends of its axis). Column 9, and only column 9, relates to a cylinder, not to the cavity. It attempts to connect the "mp" indices for modes in a cylinder to corresponding modes in the cavity. Mode-shapes and frequencies are continuous functions of boundary deformation, (see Theorem 10 on p. 421 of "Methods of Math. Phys." by Courant & Hilbert) the correspondence could be established by a sequence of URMEL runs in which the boundary was gradually deformed from that of a cylinder to that of the cavity, but we have not had the time to make those runs. Instead the proposed correspondence is based on the symmetries which the cylinder and cavity have in common (reflection in the midplane, and rotation about the axis), and on the relative ordering of the two sequences of frequencies. At higher frequencies, where shorter wave lengths allow the mode to fit more intimately into differences of the two boundaries, the attempted correspondence is less useful. URMEL itself cannot make any such correspondence. It uses the mode designation in column 9, instead of 8, to (necessarily) avoid the attempt.

6. Shunt resistances are expressed in ohms (or megohms), as in URMEL. (If expressed in linac ohms, as in Jacob, the values listed above would have been twice as large.)

7. Shunt resistances include transit time factors, as in URMEL.
BEAD PULL MEASUREMENT SET-UP

The perturbing bead (needle) is epoxied to a silk thread. A stepping motor-driven gear pulls the needle through the cavity in programmed accurate steps. When the bead enters a region of electric field in the cavity it will lower the cavity resonant frequency by an amount proportional to the square of the electric field at the bead site. The degree of the field distortion is dependent on the size and shape of the bead and the field gradient at the site of the bead perturbation. Various probes, couplers, and tuners are located in ports on the cavity. The port numbers are identified in Figures 1 and 2. Resonant cavity phase shift is measured by a Hewlett Packard network analyzer (HP-8510B) with the following set-up:

1) The bead moves 60 centimeters in 100 steps. At each step the network analyzer makes 10 phase measurements that are then averaged.

2) The tuner is in port 3, adjusted so that the fundamental is 351.929 MHz.

3) The input coupler is in port 1, rotated so that the impedance looking into the cavity is 50 ohms at the fundamental frequency. (The input impedance match is shown on the Smith Chart in Figure 3.)

4) Ports 5 and 7 are covered with aluminum plates.

5) All bead pulls start from outside port 9.

6) Probe orientation labeling:
   90 Deg. = H probe plane parallel to the Z axis.
   0 Deg. = H probe plane perpendicular to the Z axis.

The maximum distance the test set-up allows to pull beads that are radially offset but parallel to the Z axis is 3.5 centimeters. All monopole data shown were taken on axis. Dipole data shown were taken off axis at the maximum distance of 3.5 cm. All dipole modes tested in this report were also run on axis and had no perturbation. All measurements were taken with the cavity bolted together at 20 inch pounds and before the inner surface was properly cleaned. After cleaning and correct torquing of the knife edge (RF contact), the cavity Q is expected to increase.
Figure 1
Prototype Storage Ring Cavity
Viewed from side.
BERGLIN CAVITY - PORT LOCATION

Figure 2
Prototype Storage Ring Cavity
Viewed on-axis.
The tuner in port 3 is adjusted so the cavity resonant frequency is at 351.92 MHz. The input coupler in port 1 is then rotated so the impedance looking into the cavity is 50 ohms at that frequency. The 3.42 ns delay is the electrical length of the transition from N to input coupler done in the low pass time domain on the H.P. 8510 network analyzer.
MEASUREMENT RESULTS

The following figures show the resonant frequency, the E-field, the product of $H$ and radius, and results of the bead pull measurements for the fundamental frequency and higher order modes at the following frequencies:

Figure 4, 351.93 Mhz,
Figure 5, 535.98 Mhz,
Figure 6, 736.98 Mhz,
Figure 7, 915.02 Mhz,
Figure 8, 932.91 Mhz,
Figure 9, 1161.63 Mhz,
Figure 10, 1209.63 Mhz,
Figure 11, 1500.64 Mhz,
Figure 12(a) & (b), 581.57 Mhz,
Figure 13, 757.70 Mhz,
Figure 14(a) & (b), 954.20 Mhz,
Figure 15(a) & (b), 1017.60 Mhz,
Figure 16(a) & (b), 1132.32 Mhz,
Figure 17, 1209.31 Mhz,
LuLL-LuLu

input coupler 8 port 1 - term.

SHUNT RESISTANCE = 1.87E+6 OHMS  Q = 5988

Figure 4
Figure 5
**Figure 6**

- **N736987**
  - FREQUENCY: 0.736987 GHz
  - 6 May 1991
  - SHUNT RESISTANCE: 270 OHMS
  - $Q = 2768$

- **N737797**
  - FREQUENCY: 0.737797 GHz
  - 6 May 1991
  - SHUNT RESISTANCE: 117 OHMS
  - $Q = 3053$
Figure 8
Figure 11
Figure 12(b)
Figure 13
Figure 14(b)
Figure 15(b)
**Figure 16(b)**

N1139755  
**FREQUENCY** = 1.139755 GHz  
**FREQUENCY** = 1.139651 GHz  
**FREQUENCY** = 1.140442 GHz  
**FREQUENCY** = 1.140396 GHz  
8 May 1991  
8 May 1991  
8 May 1991  
8 May 1991  
**Q = 8695**  
**Q = 5714**  
**Q = 12903**  
**Q = 12820**  
**SHUNT RESISTANCE** = 9420 OHMS  
**SHUNT RESISTANCE** = 2630 OHMS  
**SHUNT RESISTANCE** = 11000 OHMS  
**SHUNT RESISTANCE** = 8460 OHMS  
25.4 mm needle; port B - H7 (45 deg.); port 13 - H4 (30 deg.);  
off axis - max low; input coupler & port 1 - term.;  
25.4 mm needle; port B - H7 (45 deg.); port 13 - H4 (30 deg.);  
off axis horiz. - max toward port 1; input coupler & port 1 - term.;  
25.4 mm needle; port B - H7 (45 deg.); port 13 - H4 (30 deg.);  
off axis horiz. - max toward port 1; input coupler & port 1 - term.;  
25.4 mm needle; port B - H7 (45 deg.); port 13 - H4 (30 deg.);  
off axis horiz. - max toward port 1; input coupler & port 1 - term.;
(1E-6)

**NL220838**

**FREQUENCY = 1.220838 GHz, 22 May 1991**

**SHUNT RESISTANCE = 6640 OHMS**

**Q = 23088**

25.4 mm needle; port 22 - H4 (0 deg.); port 21 - H6 (0 deg.);
off axis horiz. - max toward port 1; input coupler & port 1 - term.
Temp = 85 deg. F

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**Figure 17**
FREQUENCY SHIFT OF FUNDAMENTAL AND HIGHER ORDER MODES DUE TO DIMENSIONAL CHANGES IN AXIAL DIRECTION

Figures 18 and 19 show graphically the calculated values of the first four odd and first four even modes, respectively, as a function of stretching the cavity dimension in the longitudinal direction.\(^3\)

Table 1 lists measured data for .042" and .062" shims between the center part of the cavity and one of the end pieces for two conditions. In the first, conducting metal tuners fill the four large ports so that the cavity wall looks flush (this is the closest geometry to the 2-D cylindrically symmetric computer calculations). The second condition is with the matched input coupler in port 1 and a metal tuner in port 3 inserted to a point that the cavity resonates at 351.93 Mhz (the storage ring operating frequency). Table 2 lists the calculated vs. measured frequency shifts for these modes.

\(^3\) Calculations provided by L. Emery, Advanced Photon Source, Accelerator Physics Group
(First five even modes only)

Mode Frequency Shift as a function of Cavity Stretching
Mode Frequency Shift as a Function of Cavity Stretching
(First Four Odd Modes Only)

Figure 19
Table 1

PROTOTYPE STORAGE RING CAVITY - COPPER SHIMMING VS FREQUENCY SHIFT
(SHIMS ON ONE SIDE OF CAVITY)

<table>
<thead>
<tr>
<th>8-Jul-91 TLS</th>
<th>PORTS 1,3,5,7 = ALL TUNERS IN FLUSH</th>
<th>PT.1 = INPUT COUPLER (term-matched)</th>
<th>PT.3 = TUNER ADJUSTED</th>
<th>PT.5-7 = BLANKED OFF-ALUM. PLATE</th>
</tr>
</thead>
<tbody>
<tr>
<td># MODE</td>
<td>NO SHIMS</td>
<td>.042&quot; SHIMS</td>
<td>.062&quot; SHIMS</td>
<td>.042&quot; SHIMS</td>
</tr>
<tr>
<td></td>
<td>79.0° F (MHz)</td>
<td>80.4° F (MHz)</td>
<td>78.7° F (MHz)</td>
<td>85.0° F (MHz)</td>
</tr>
<tr>
<td>0 E-1</td>
<td>352.714</td>
<td>352.718</td>
<td>352.737</td>
<td>351.929</td>
</tr>
<tr>
<td>0 M-1</td>
<td>536.252</td>
<td>535.437</td>
<td>535.180</td>
<td>534.921</td>
</tr>
<tr>
<td>0 E-2</td>
<td>744.622</td>
<td>743.937</td>
<td>743.712</td>
<td>737.136</td>
</tr>
<tr>
<td>0 E-3</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>914.306</td>
</tr>
<tr>
<td>0 M-2</td>
<td>936.078</td>
<td>935.357</td>
<td>934.656</td>
<td>932.650</td>
</tr>
<tr>
<td>0 E-4</td>
<td>1173.283</td>
<td>1171.725</td>
<td>1171.098</td>
<td>1160.255</td>
</tr>
<tr>
<td>0 M-3</td>
<td>1209.414</td>
<td>1207.075</td>
<td>1205.807</td>
<td>1207.269</td>
</tr>
<tr>
<td>0 E-6</td>
<td>1507.618</td>
<td>1505.230</td>
<td>1503.877</td>
<td>1498.637</td>
</tr>
<tr>
<td>1 E-1</td>
<td>586.408</td>
<td>586.192</td>
<td>586.299</td>
<td>586.996</td>
</tr>
<tr>
<td>1 M-2</td>
<td>758.444</td>
<td>757.677</td>
<td>757.355</td>
<td>756.766</td>
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<tr>
<td>1 E-3</td>
<td>958.849</td>
<td>957.880</td>
<td>957.354</td>
<td>957.355</td>
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<tr>
<td>1 M-4</td>
<td>1014.850</td>
<td>1014.656</td>
<td>1013.597</td>
<td>1016.512</td>
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<td>1 E-5</td>
<td>1140.891</td>
<td>1139.397</td>
<td>1138.844</td>
<td>1137.900</td>
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<tr>
<td>1 E-6</td>
<td>1220.077</td>
<td>1218.720</td>
<td>1217.834</td>
<td>1218.769</td>
</tr>
</tbody>
</table>

- All cavity bolts are torqued to 20 inch pounds with or without copper shims
- In @ Port 8 - H7 (45°) Out @ Port 6 - H2 (45°)
### Table 2

**CAVITY STRETCHING - FREQUENCY SHIFT**
**(CALCULATION VS. MEASURED DATA)**

<table>
<thead>
<tr>
<th>(O E-1)</th>
<th>$\frac{353.93MHz - 353.62MHz}{18\text{mm}} = 0.017$</th>
<th>CAL = $0.017\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{-0.004MHz}{1.07\text{mm}} = -0.0037$</td>
<td>$0.042&quot; = -0.004\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{-0.023MHz}{1.57\text{mm}} = -0.015$</td>
<td>$0.062&quot; = -0.015\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O E-2)</th>
<th>$\frac{749MHz - 738.5MHz}{18\text{mm}} = 0.538$</th>
<th>CAL = $0.538\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{0.685MHz}{1.07\text{mm}} = 0.640$</td>
<td>$0.042&quot; = 0.640\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{0.910MHz}{1.57\text{mm}} = 0.580$</td>
<td>$0.062&quot; = 0.580\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O E-3)</th>
<th>$\frac{932.5MHz - 912.5MHz}{18\text{mm}} = 1.11$</th>
<th>CAL = $1.11\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{914.306MHz - 913.642MHz}{1.508\text{mm}} = 1.31$</td>
<td>MEAS. = $1.31\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O E-4)</th>
<th>$\frac{1184MHz - 1161MHz}{18\text{mm}} = 1.28$</th>
<th>CAL = $1.28\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{1.56MHz}{1.07\text{mm}} = 1.46$</td>
<td>$0.042&quot; = 1.46\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{2.18MHz}{1.57\text{mm}} = 1.39$</td>
<td>$0.062&quot; = 1.39\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O M-1)</th>
<th>$\frac{537MHz - 530MHz}{10\text{mm}} = 0.700$</th>
<th>CAL = $0.700\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{0.815MHz}{1.07\text{mm}} = 0.762$</td>
<td>$0.042&quot; = 0.762\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{1.07MHz}{1.57\text{mm}} = 0.681$</td>
<td>$0.062&quot; = 0.681\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O M-2)</th>
<th>$\frac{940MHz - 928.8MHz}{10\text{mm}} = 1.12$</th>
<th>CAL = $1.12\text{MHz/mm}$</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{0.721MHz}{1.07\text{mm}} = 0.674$</td>
<td>$0.042&quot; = 0.674\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{1.42MHz}{1.57\text{mm}} = 0.904$</td>
<td>$0.062&quot; = 0.904\text{MHz/mm}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(O M-3)</th>
<th>$\frac{1210.5MHz - 1191MHz}{10\text{mm}} = 1.95$</th>
<th>CAL = $1.95\text{MHz/mm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\frac{2.34MHz}{1.07\text{mm}} = 2.19$</td>
<td>$0.042&quot; = 2.19\text{MHz/mm}$</td>
</tr>
<tr>
<td></td>
<td>$\frac{3.61MHz}{1.57\text{mm}} = 2.30$</td>
<td>$0.062&quot; = 2.30\text{MHz/mm}$</td>
</tr>
</tbody>
</table>