JLAB-TN-02-042

Estimates of the Beam Breakup Thresholds in the 10KW FEL due to HOMs

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The beam breakup thresholds for the 10KW FEL due to higher order modes (**HOM**s) have been estimated by using the measured values of the HOMs as input to the matbbu[1] and tdbbu[2] codes. The results of both codes were compared. Previous estimates were made in the absence of measured values.[3]

The HOMs values have been experimentally measured by Haipeng Wang and Ricky Campisi; the former with the HOM dampers, but without the fundamental power coupling, and the latter with the fundamental power coupling, but without the HOM dampers.

Only four cavities were measured, and it is necessary to approximate what the HOMs will be in the actual accelerator. The two HOM dampers are about 120^o apart, while the X and Y axes of the accelerator are 90^o apart, so, as a conservative estimate, the "worst" Q for each polarization was used. The actual frequency values of the HOMs in the accelerator are unknown, so a Gaussian spread on the frequencies was used to simulate the different possible accelerators.

For this first work, only the HOM values measured by Haipeng Wang (without the fundamental power coupler) were considered (Table 1).

Using the same input files as used for earlier tdbbu simulations by L.Merminga[4], matbbu was evaluated for 3 HOM ("as manufactured") combinations mode by mode using the "worst" HOM values from Haipeng Wang as of 2 July 2002. In the first case, the HOM's were Gaussian distributed with a 1 MHz sigma[5], in the second 5 MHz. The results are plotted in Figure 1a and 1b.

mode	**Frequency** [MHz]	**R/Q** [ohm/cm^2] *(mafia)*	**R/Q * $(^c/_{2\pi f})^2$** [ohm] *(used by matbbu)*	**Q**
TE1	1725.31189	0.0337	0.258	3.40E+07

1 JLAB-TN-02-044, *matbbu 2.4: A Tool for Estimating Beam Breakup due to Higher Order Modes,* K.B.Beard, L.Merminga, B.Yunn
2 JLAB-TN-02-045, *tdbbu 1.6: Another Tool for Estimating Beam Breakup due to Higher Order Modes*, K.B.Beard, L.Merminga, B.Yunn
3 JLAB-TN-01-028, *Dipole HOM Damping Requirement of New 7-Cell Cavity for the 12 GeV,* B.Yunn
4 L.Merminga, private communicaiton
5 J.Benesch, private communication, estimate based on 160 CEBAF cavities

mode	Frequency [MHz]	R/Q [ohm/cm^2] *(mafia)*	$R/Q * (^c/_{2\pi f})^2$ [ohm] *(used by* matbbu*)*	Q
TE2	1746.41895	0.0049	0.037	9.70E+05
TE3	1780.17297	0.5574	4.010	5.40E+05
TE4	1824.03320	0.3655	2.500	5.21E+06
TE5	1874.31238	13.2500	86.000	1.60E+05
TE6	1926.01416	10.9000	67.000	4.11E+05
TE7	1991.40027	0.4739	2.720	2.35E+005
TM8	2000.51636	2.9330	16.710	4.45E+005
TM9	2068.54785	0.3492	1.860	1.58E+06
TM10	2089.20215	5.7290	29.900	1.50E+06
TM11	2102.47681	5.6010	28.900	7.00E+06
TM12	2109.69775	0.2755	1.411	5.30E+06
TM13	2113.46313	1.0080	5.140	1.10E+07
TM14	2113.84692	0.1302	0.664	4.24E+07

Table 1- HOM dampers only, 2 July 2002

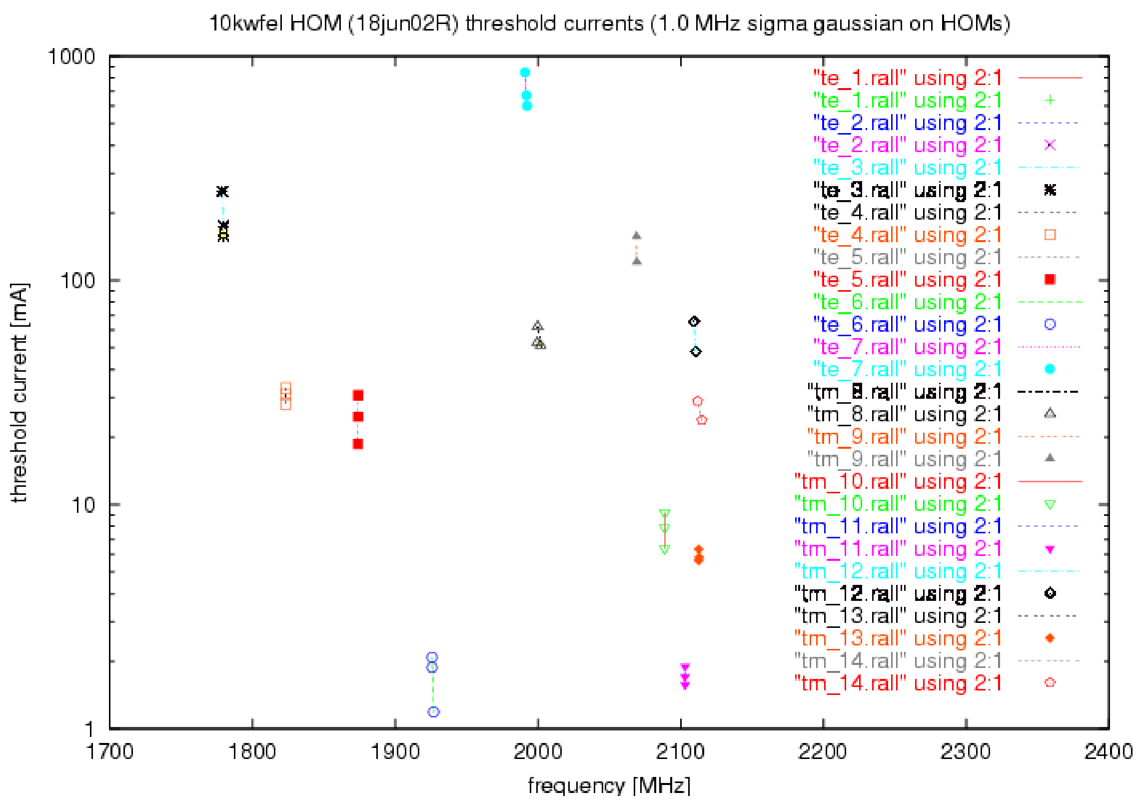

Fig.1a. 2 July 2002 measurements, 1 MHz spread

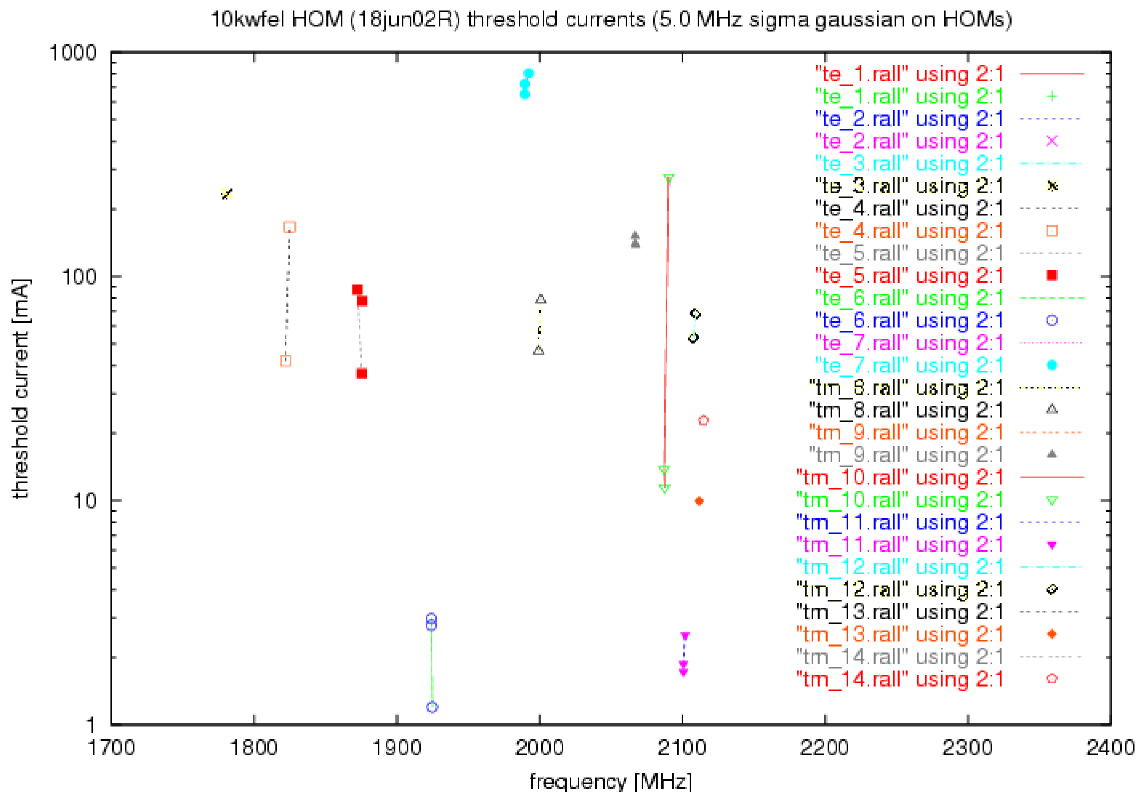

Fig.1b. 2 July 2002 measurements, 5 MHz spread

Note that in both cases some of the threshold currents are significantly below the 10 mA design goal. This was a cause of concern, and prompted further studies.

Several of the HOM measurements were repeated and those updated values were used in the subsequent studies. As a comparison, both tdbbu and matbbu were used to estimate the threshold currents (Table 2). Since the time for some tdbbu simulations was prohibitive, lower Q values were used for the comparison.

mode	$(R/Q)_{Mafia}$ [ohm/cm²]	R [ohm] $(R/Q)_{Mafia}*(c/2\pi f)$	$F_{nominal}$ [MHz]	$Q_{nominal}$	Q_{run}	tdbbu runtime [uS]	tdbbu Cray CPU [hr/run]	I_X [mA] tdbbu (matbbu)	I_Y [mA] tdbbu (matbbu)	notes	Ricky's Q_L TN-01-028	extrapolated I_X [mA]	extrapolated I_Y [mA]
T5	13.25	86.0	1889.4	2.7E6	2.7E6	5000	3	1.6 (1.6)	2.4-2.8 (2.6)		4.61E6 -- 1.37E5	0.9 -- 32	1.5 -- 51
T6	10.09	67.0	1928.9	4.E5	4.E5	650	0.4	15 (13.6)	20 (19.1)		1.20E5 -- 3.76E5	45 -- 14	64 -- 20
T10	5.729	29.9	2098.5	1.5E6	1.5E6	2500	1.5	11 (8.3)	11 (10.8)		8.60E5 -- 3.94E6	14 -- 3	19 -- 4
T11	5.601	28.9	2114.8	7.E6	1.E5	150	0.9	128 (120.7)	120 (147.2)				
T11			2114.8	7.E6	3.E5	450	0.3	44 (39.8)	48 (48.7)				
T11			2114.8	7.E6	1.E6	1500	0.9	13 (11.9)	15 (14.6)				
T11			2114.8	7.E6	2.E6	3000	1.8	(6.0)	(7.3)				
T11			2114.8	7.E6	7.E6	11400	7	(1.7)	(2.1)		2.16E6 -- 1.01E6	6 -- 11	7 -- 13

T13	1.008	5.14	2124.7	1.8E8	1.E5	150	0.9	185 (627.0)	122 (961.5)	other modes contribute X: (147)@1890.3 Y: (85)@1893.5			
T13			2124.7	1.8E8	3.E5	450	0.3	180 (207.8)	120 (323.9)	other modes contribute: X: (148)@1890.3 Y: (85)@1893.5			
T13			2124.7	1.8E8	1.E6	1500	0.9	69 (62.2)	117 (97.6)				
T13			2124.7	1.8E8	2.E6	3000	1.8	30-32 (31.1)	55-60 (48.8)				
T13			2124.7	1.8E8	1.8E8	270000	160	(0.4)	(0.6)		4.59E6 -- 3.04E6	16 -- 24	24 -- 36
T14	0.1302	0.664	2125.5	1.5E8	1.E5	150	0.9	168-183 (>1000)	100-118 (>1000)	other modes			
T14			2125.5	1.5E8	3.E5	450	0.3	174-190	113-123	other modes			
T14			2125.5	1.5E8	1.E6	1500	0.9	174-190 (704.7)	103-113 (800.9)	other modes			
T14			2125.5	1.5E8	2.E6	3000	1.8	168-183 (260.7)	109-119 (393.0)	other modes			
T14			2125.5	1.5E8	1.5E8	225000	140	(3.5)	(5.2)		2.07E6 -- 1.45E6	253 -- 362	377 -- 538

Table 2. Comparison of matbbu and tdbbu simulations.

It can be seen from the table that there is very good agreement between the codes, but it should be noted that while matbbu can be "told" to be sensitive to only certain frequency ranges, tdbbu "sees" all of them with a file.

It was then suggested that since Ricky Campisi had done earlier HOM measurements using only the fundamental power coupler, his measurements and Haipeng Wang's could be added in parallel. The calculations were repeated and the results are in Table 3 and Figure 2. Note that mode 15 was not measured; the Q is just an estimate.

A 5 MHz frequency spread was taken on the HOMs of interest and three "accelerators as manufactured" cases were run:

mode	R	(R/Q)-MAFIA	**Mafia freq**	Ricky's freq	Ricky's	Haipeng's worst	1/(1/Ricky+1/Haipeng)	mean threshold
	Ohm	ohm/cm^2	**MHz**	MHz	Q	Q	Q	mA
1	2.58E-01	3.37E-02	**1725.31**	1719.92	2.48E+06	3.84E+06	1.51E+06	>1000
2	3.70E-02	4.95E-03	**1746.42**	1741.56	8.92E+05	4.94E+06	7.56E+05	>1000
3	4.01E+00	5.57E-01	**1780.17**	1778.31	1.92E+05	3.03E+06	1.81E+05	567.08
4	2.50E+00	3.66E-01	**1824.03**	1823.68	1.62E+05	5.21E+06	1.57E+05	572.04
5	8.60E+01	1.33E+01	**1874.31**	1874.23	4.61E+06	2.70E+06	1.70E+06	2.69
6	6.70E+01	1.01E+01	**1926.01**	1928.36	1.20E+05	4.06E+05	9.26E+04	58.03
7	2.72E+00	4.74E-01	**1991.40**	1997.75	2.18E+06	3.29E+05	2.86E+05	521.01
8	1.67E+01	2.93E+00	**2000.52**	2006.27	5.48E+06	4.45E+05	4.12E+05	54.64
9	1.86E+00	3.49E-01	**2068.55**	2079.17	4.73E+05	1.58E+06	3.64E+05	549.5

10	2.99E+01	5.73E+00	**2089.20**	2099.32	8.60E+05	1.50E+06	5.46E+05	22.68
11	2.89E+01	5.60E+00	**2102.48**	2111.38	2.16E+06	7.05E+06	1.65E+06	7.08
12	1.41E+00	2.76E-01	**2109.70**	2118.45	4.05E+06	5.30E+06	2.30E+06	118.2
13	5.14E+00	1.01E+00	**2113.46**	2121.56	4.59E+06	1.06E+07	3.20E+06	22.23
14	6.64E-01	1.30E-01	**2113.85**	2123.11	1.45E+06	1.52E+08	1.44E+06	462.99
15	2.98E+01			2953.11			1.00E+06	8.51

Table 3. RC and HW measurements added in parallel.

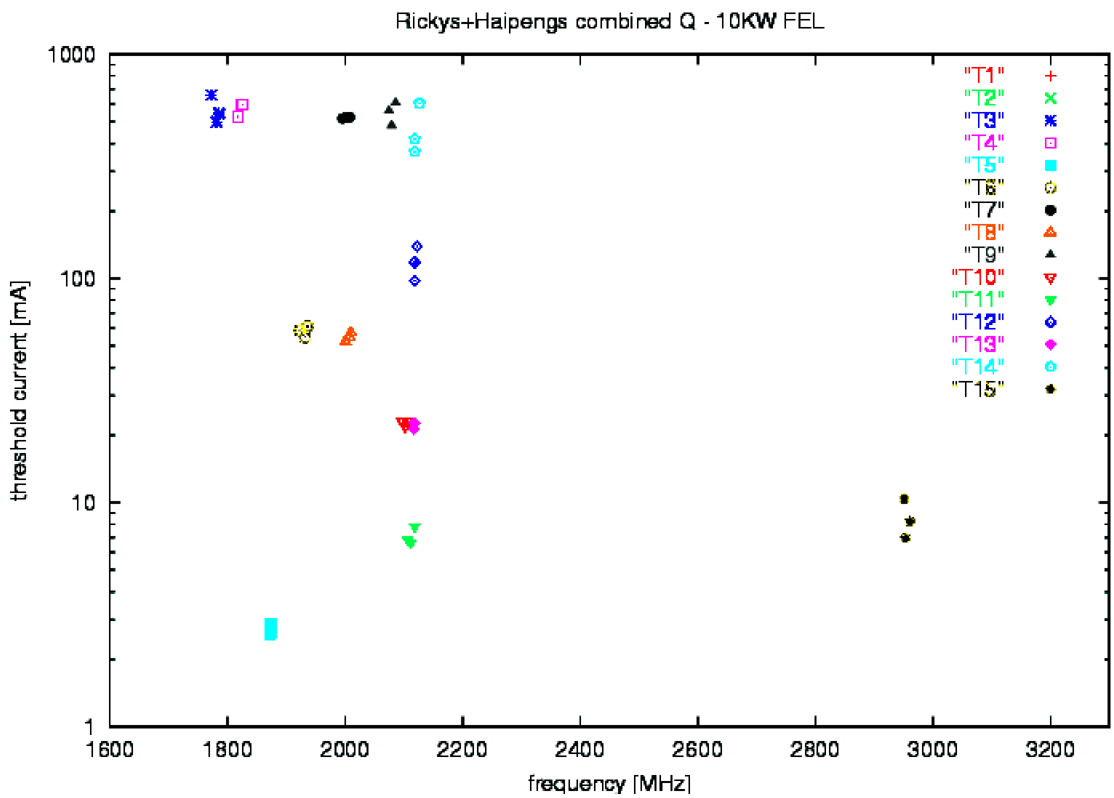

Figure 2. Combined Qs from Ricky's and Haipeng's measurements.

It is clear that mode#5 was cause for concern. To address that concern, an additional HOM damper was added to a model to see if it made a difference and new measurements were made. The results are in Fig 3.

Mode	Frequency	Q
1	1712.077	5.70E+06
2	1738.549	2.40E+05
3	1772.647	8.90E+06
4	1820.901	8.90E+04
5	1871.4	2.60E+04
6	1926.353	1.90E+05
7	1996.75	7.10E+05
8	2012.766	2.10E+04
9	2065.24	1.40E+05
10	2092.078	1.40E+06
11	2106.5	4.70E+06
12	2115.429	8.80E+06
13	2121.2	7.30E+06

Table 3. Combined measurements with additional HOM damper.

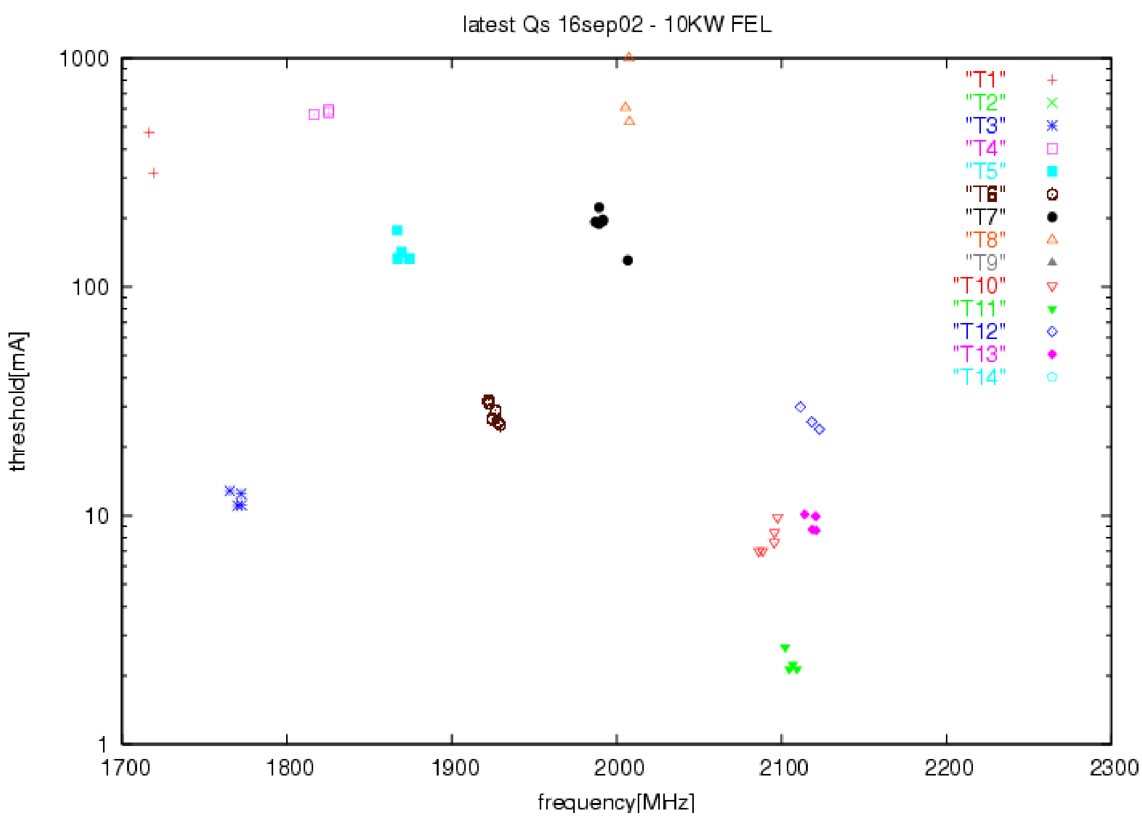

Fig 3. Combined Q's with additional damper.

Mode 5's Q was greatly increased, but mode 11's Q was decreased, and the latter became the limiting current. It should be noted that for these high Q (>10^6) values, the threshold current is essentially inversely proportional to Q.[6]

6 B.Yunn, private communication

In conclusion, we have used the matbbu and tdbbu codes to estimate the beam breakup thresholds for the 10 KW FEL using the measured higher order modes (HOMs). We found that the codes are in good agreement and that the threshold approximately scales inversely with the Q for high Q values.

We predict that mode#5 (1874 MHz), mode#11 (2102 MHz), and mode#15 (2953 MHz) can induce beam breakup at less than 10 mA. The uncertainty in these thresholds is believed to less than a factor of 2.[7]

Acknowledgements

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7 B.Yunn and L.Merminga, private communication

8 This research used resources of the National Energy Research Scientific Computing Center, which is supported by the Office of Science of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

9 This work supported by the Department of Energy, contract DE-AC05-84ER40150 http://www.jlab.org/hpc/home/

Appendix

Both the matbbu and tdbbu codes share the same input file format, which is described in some detail elsewhere.[10] The file below is a typical case for mode#5.

```
1TITLE 10kW IR FEL 145 MeV, April 2002 3CMs [5,7,5]cells (generic)
 DATA
 APRTR    100000.   2.0
 REF      0.       600.0      355.00   700.00    500.0     0.0
 BEAM     10.0      2994.0     40.0     0.0       1.0       0.0
 XPRNT    2.0       203.0     1.0
 YPRNT    2.0       203.0     1.0
#CMPNT     4400.0   0.0       0.0       0.0       0.0       0.0
>DRIFT  1.100.0     0.0
1DRIFT  1. 63.41    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.82    17000.    1812.510  90.0
1CAVITY    13.77    7000.     1816.220  .0
1CAVITY    22.32    120000.   1882.830  90.0
1CAVITY    22.24    8000.     1885.840  .0
1CAVITY    48.42    5000.     1963.530  90.0
1CAVITY    48.27    2600.     1966.660  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.64    10000.    1825.020  90.0
1CAVITY    13.60    5100.     1827.260  .0
1CAVITY    22.04    83000.    1894.660  90.0
1CAVITY    22.01    7300.     1895.980  .0
1CAVITY    47.94    2300.     1973.270  90.0
1CAVITY    47.76    1700.     1976.980  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.68    24000.    1821.940  90.0
1CAVITY    13.66    3100.     1823.560  .0
1CAVITY    22.12    210000.   1891.120  90.0
1CAVITY    22.08    4300.     1892.920  .0
1CAVITY    48.17    3400.     1968.680  90.0
1CAVITY    47.99    1400.     1972.210  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.74    45000.    1818.320  90.0
1CAVITY    13.70    2500.     1820.930  .0
1CAVITY    22.21    400000.   1887.240  90.0
1CAVITY    22.15    4300.     1889.910  .0
1CAVITY    48.29    3000.     1966.180  90.0
1CAVITY    48.09    1600.     1970.160  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.59    10000.    1828.330  90.0
```

10 JLAB-TN-02-043, *TDBBU and MATBBU Input File Format*, K.B.Beard, L.Merminga, B.Yunn

```
1CAVITY    13.59    2500.     1828.120  .0
1CAVITY    22.02    160000.   1895.390  90.0
1CAVITY    21.97    3500.     1897.480  .0
1CAVITY    48.04    2600.     1971.200  90.0
1CAVITY    47.84    1800.     1975.430  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.70    12000.    1820.640  90.0
1CAVITY    13.66    2000.     1823.190  .0
1CAVITY    22.14    200000.   1890.370  90.0
1CAVITY    22.08    3900.     1892.960  .0
1CAVITY    48.20    3500.     1968.080  90.0
1CAVITY    48.01    1500.     1971.830  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.81    38000.    1813.290  90.0
1CAVITY    13.75    3700.     1817.350  .0
1CAVITY    22.29    39000.    1884.000  90.0
1CAVITY    22.18    9000.     1888.460  .0
1CAVITY    48.10    800.      1970.000  90.0
1CAVITY    47.94    1000.     1973.360  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.64    12000.    1825.000  90.0
1CAVITY    13.59    4700.     1828.080  .0
1CAVITY    22.04    36300.    1894.570  90.0
1CAVITY    21.98    12300.    1897.200  .0
1CAVITY    47.79    1000.     1976.500  90.0
1CAVITY    47.69    2100.     1978.460  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 63.41    0.0
1DRIFT  1. 85.1     0.0
1LENS   1.-3.597509 15.0
1DRIFT  1. 37.4     0.0
1LENS   1. 6.755323 15.0
1DRIFT  1. 37.4     0.0
1LENS   1.-3.597509 15.0
1DRIFT  1. 38.38    0.0
1DRIFT  1. 51.64    0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1722.4622   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1718.5032    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1714.5313   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1715.5314    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1713.5778   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1721.7893    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
```

```
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1719.8063   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1718.9666    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1716.2150   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1716.1320    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1723.6415   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1718.1343    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1722.0447   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1711.3800    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 30.      0.0
1DRIFT  1. 35.      3.4375
1CAVITY 0.0.2580E+000.1510E+07 1723.2881   90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2580E+000.1510E+07 1724.6337    0.00000.0000E+000.0000E+000.0000E+00
1DRIFT  1. 35.      3.4375
1DRIFT  1. 57.02    0.0
2DRIFT  1. 38.38    0.0
2LENS   1. 1.294342 15.0
2DRIFT  1. 37.4     0.0
2LENS   1.-2.550615 15.0
2DRIFT  1. 37.4     0.0
2LENS   1. 1.294342 15.0
2DRIFT  1. 85.1     0.0
1DRIFT  1. 63.41    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.65    20700.    1824.210  90.0
1CAVITY    13.65    20700.    1824.560  .0
1CAVITY    22.06    145000.   1893.540  90.0
1CAVITY    22.06    145000.   1893.780  .0
1CAVITY    48.05    2800.     1971.030  90.0
1CAVITY    48.05    2800.     1971.230  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.63    17000.    1825.590  90.0
1CAVITY    13.63    17000.    1825.230  .0
1CAVITY    22.04    4300.     1894.690  90.0
1CAVITY    22.04    4300.     1894.040  .0
1CAVITY    48.02    2500.     1971.680  90.0
1CAVITY    48.02    2500.     1971.210  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.72    18400.    1819.610  90.0
1CAVITY    13.72    18400.    1819.340  .0
1CAVITY    22.14    106000.   1890.270  90.0
1CAVITY    22.14    106000.   1890.530  .0
1CAVITY    48.01    3000.     1971.880  90.0
```

```
1CAVITY    48.01    3000.     1971.520  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.76    31000.    1816.550  90.0
1CAVITY    13.76    31000.    1816.430  .0
1CAVITY    22.22    189000.   1886.840  90.0
1CAVITY    22.22    189000.   1886.900  .0
1CAVITY    48.26    2600.     1966.820  90.0
1CAVITY    48.26    2600.     1966.210  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.65    15800.    1823.820  90.0
1CAVITY    13.65    15800.    1823.640  .0
1CAVITY    22.07    16100.    1893.390  90.0
1CAVITY    22.07    16100.    1893.900  .0
1CAVITY    48.03    4100.     1971.400  90.0
1CAVITY    48.03    4100.     1971.210  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.62    14200.    1826.140  90.0
1CAVITY    13.62    14200.    1826.590  .0
1CAVITY    22.07    11300.    1893.350  90.0
1CAVITY    22.07    11300.    1893.920  .0
1CAVITY    48.04    3900.     1971.360  90.0
1CAVITY    48.04    3900.     1971.020  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 66.06    0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.63    30000.    1825.290  90.0
1CAVITY    13.63    30000.    1825.980  .0
1CAVITY    22.06    56000.    1893.690  90.0
1CAVITY    22.06    56000.    1893.540  .0
1CAVITY    48.07    2000.     1970.760  90.0
1CAVITY    48.07    2000.     1970.030  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 25.      0.0
1DRIFT  1. 25.      2.5
1CAVITY    13.73    12300.    1818.510  90.0
1CAVITY    13.73    12300.    1818.630  .0
1CAVITY    22.20    69000.    1887.830  90.0
1CAVITY    22.20    69000.    1887.450  .0
1CAVITY    48.22    5000.     1967.640  90.0
1CAVITY    48.22    5000.     1967.980  .0
1DRIFT  1. 25.      2.5
1DRIFT  1. 63.41    0.0
2DRIFT  1.100.0     0.0
$RECIRC 1.
$CALC     0.
0.1,0.,0,0.0,0.,0
0.1,0.,0,0.0,0.,0
1093
0.893024  -18.6171  0.0 0.0
-0.00198  1.161135  0.0 0.0
0.0 0.0 -1.08916  18.46925
```

0.0 0.0 .024832 -1.33922
0.0,0.,0,0.,0.,0
0.0,0.,0,0.,0.,0