

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

K.B.Beard, L.Merminga, B.Yunn, TJNAF
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The beam breakup thresholds for the 10KW FEL due to higher order modes (**HOMs**) 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° apart, while the X and Y axes of the accelerator are 90° 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.Merminga⁴, `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 sigma⁵, in the second 5 MHz. The results are plotted in Figure 1a and 1b.

mode	Frequency [MHz]	R/Q [ohm/cm²] (mafia)	R/Q * ($c/2\pi$)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 communication

5 J.Benesch, private communication, estimate based on 160 CEBAF cavities

mode	Frequency [MHz]	R/Q [ohm/cm ²] (mafia)	R/Q * (c/2πf) 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

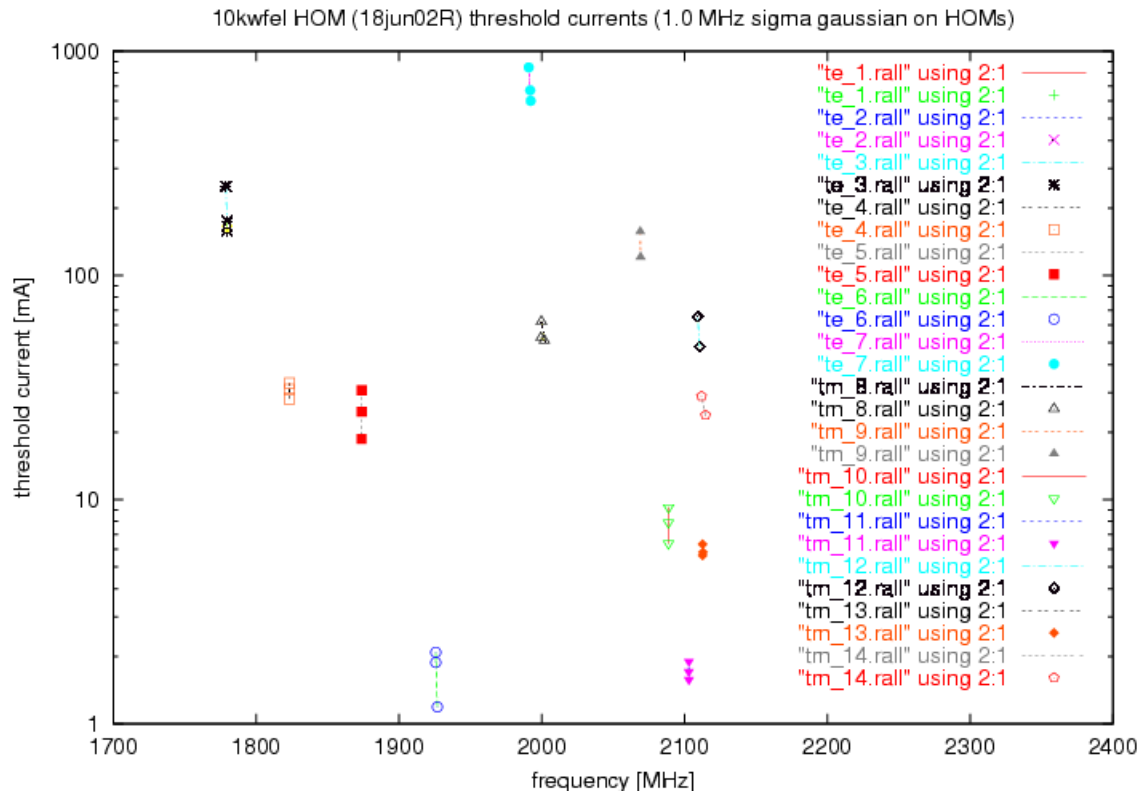


Fig.1a. 2 July 2002 measurements, 1 MHz spread

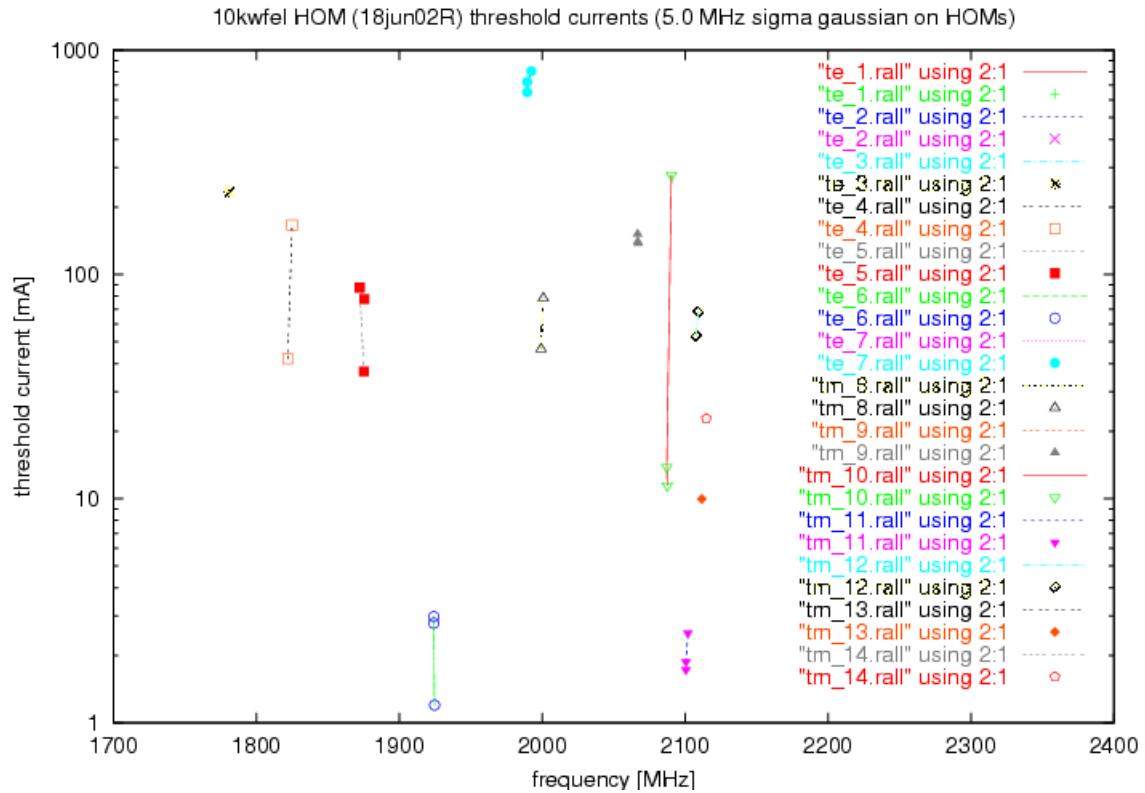


Fig. 1b. 2 July 2002 measurements, 5 MHz spread

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/cm ²]	R [ohm] $(R/Q)_{Mafia} \cdot \frac{c}{2\pi f}$	$F_{nominal}$ [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	extrapolate d I_x [mA]	extrapolate d 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.

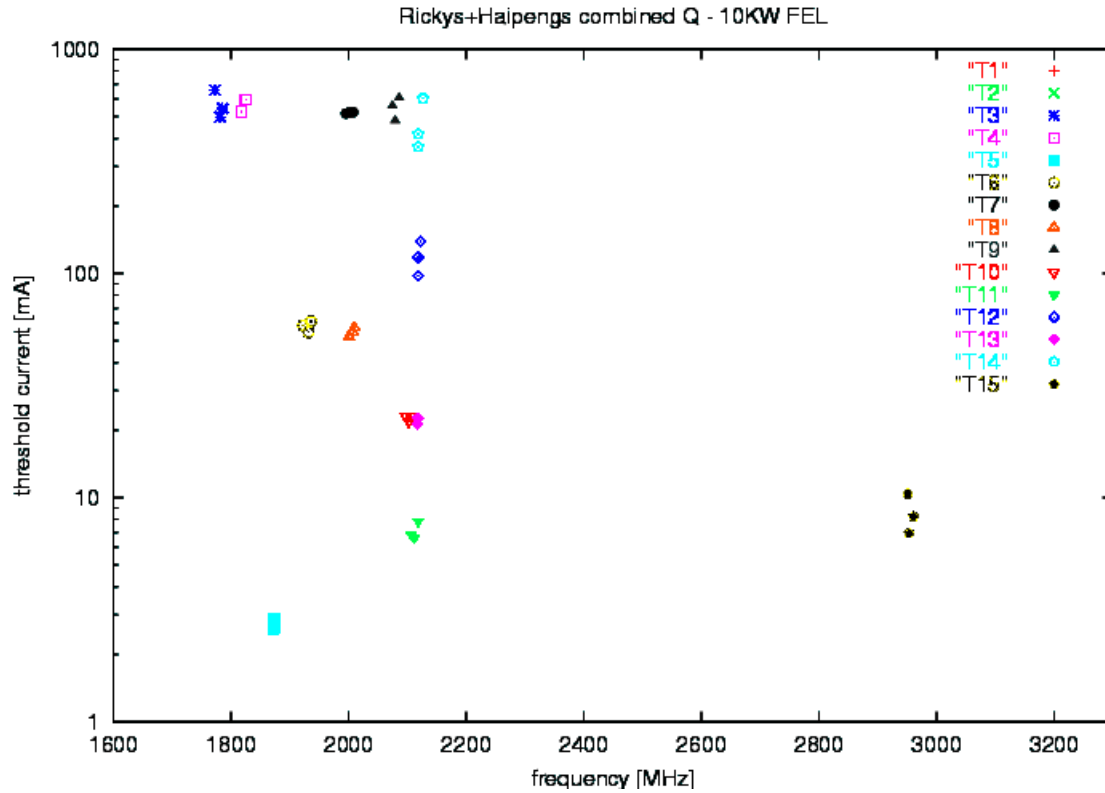


Figure 2. Combined Qs from Ricky's and Haipeng's measurements.

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.

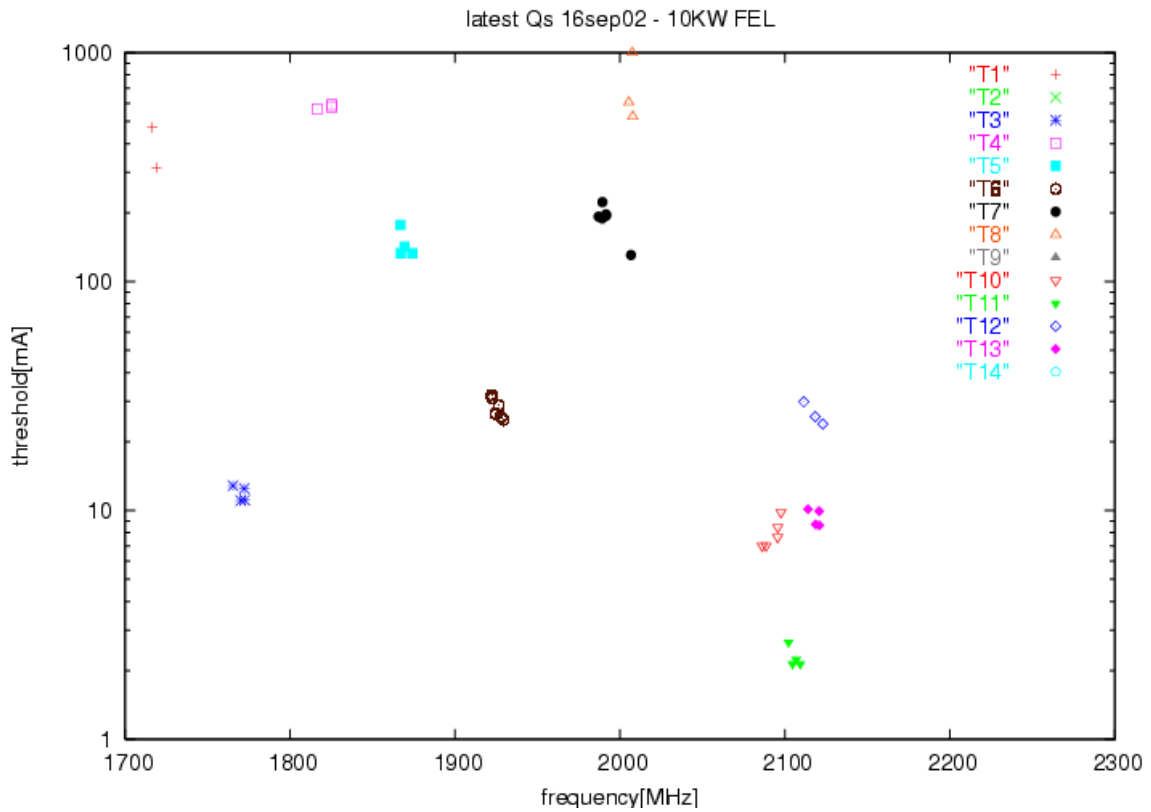


Fig 3. Combined Q's with additional damper.

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 `tbbu` 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 10000. 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
 IDRIFT 1.25. 2.5
 IDRIFT 1.25. 0.0
 IDRIFT 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
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 IDRIFT 1.66.06 0.0
 IDRIFT 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
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 IDRIFT 1.25. 0.0
 IDRIFT 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
 IDRIFT 1.25. 2.5
 IDRIFT 1.66.06 0.0
 IDRIFT 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
 IDRIFT 1.25. 2.5
 IDRIFT 1.25. 0.0
 IDRIFT 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
 IDRIFT 1.25. 2.5
 IDRIFT 1.63.41 0.0
 2DRIFT 1.100.0 0.0
 \$RECIRC 1.
 \$CALC 0.
 0.1,0.,0,0,0.,0
 0.1,0.,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