

Estimates of Beam Breakup Thresholds in the 10kW FEL with the Renaissance Cryomodule

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Due to damage in cryomodule *FEL03*, another cryomodule, *Renaissance* (once known as *NL11*), will be used to replace it. This new module is still being built and only a few of its cells have had their higher order modes (HOMs) measured. Based on earlier estimates of the beam breakup (BBU) threshold for a very similar design¹, it is anticipated that the threshold currents will fall short of the 10 mA goal for the infrared (IR) line and 5 mA goal for the ultraviolet (UV) line. To quote the late Johnny Carson, “How bad is it?”

Simulations of the BBU threshold using **ERLBBU**²

ERLBBU 0.3.1 code was used to simulate the threshold of multipass BBU in the JLab FEL Upgrade IR setup with the Renaissance cryomodule. The optics for these simulations was produced by C. Tennant from the original 145 MeV DIMAD file generated by D. Douglas. It was assumed in these simulations that R/Q's and Q's of HOMs of the Zone 2 and Zone 4 cryomodules were small. Therefore, no HOM of Zones 2 and 4 were included in simulations. The Renaissance cryomodule was situated between Zone 2 and 4 cryomodules instead of the current Zone 3 cryomodule. Accelerating cavities in the Renaissance cryomodule were distributed in the following order: ll-ll-ll-hg-hg-hg-hg, where “ll” and “hg” stand for low-loss and high-gradient cavities respectively. The frequency and the quality factor of HOM's measured in the vertical test were provided by H. Wang for some cavities. The experimental data for 4 HOM (A,B,C,D) couplers and "rod" tip shape was used. The feedthrough type was irrelevant to our studies, according to Haipeng. HOM R/Q's were obtained from computer RF simulations. The number of HOMs included in simulations was 16 per cavity for low-loss cavities (14 TM110 and 2 TE112 HOMs) and 28 per cavity for high-gradient cavities (14 TM110 and 14 TM111 HOMs). Because the data was available only for several cavities and because the frequency of HOMs can change after cavity tuning, a set of HOM frequencies was chosen as “initial” and then frequency of HOMs was randomly changed from its initial values in a range of ±2 MHz. Every time the frequency was changed, the threshold was recalculated. Totally, 9 distributions of the HOM frequency were generated for these simulations. Additionally, it was assumed that odd- and even-numbered modes were polarized in perpendicular planes. Because, the exact polarization angle of HOMs was unknown, two cases were simulated for each distribution of HOM frequencies: 1) odd-numbered modes were polarized in the x-plane and even-numbered modes were polarized in the y-plane, 2) opposite to previous case, odd-numbered modes were polarized in the y-plane, while even-numbered modes were polarized in the x-plane. (Note that transfer matrices were uncoupled.) This brought the total number of simulated

¹ JLAB-TN-03-035, *HOM calculations for CEBAF module SL21 and NL11 in the 10kW FEL*, K.B.Beard, B.Yunn
²E. Pozdeyev, Phys. Rev. ST Accel. Beams, V8, 054401, 2005

cases to 18. As an example, Appendix 1 presents a set of files used by ERLBBU for these simulations. Frequencies of HOMs for the other eight frequency distribution sets were obtained from the presented numbers by a random variation of the numbers within ± 2 MHz range.

The beam evolution in the FEL was simulated for 10 msec of the FEL time. Accuracy of threshold calculation in each run was approximately 1%. All the simulations were performed on a 1.6 GHz Pentium M laptop running Windows. Total time spent for simulating all the 18 cases was approximately 3 hours.

Simulation of the threshold in all the 18 cases yielded an average threshold of 3.1 mA. The lowest threshold was equal to 2.1 mA. The maximum simulated threshold did not exceed 5 mA. Figure 1 shows the simulated threshold for all the 18 frequency distributions.

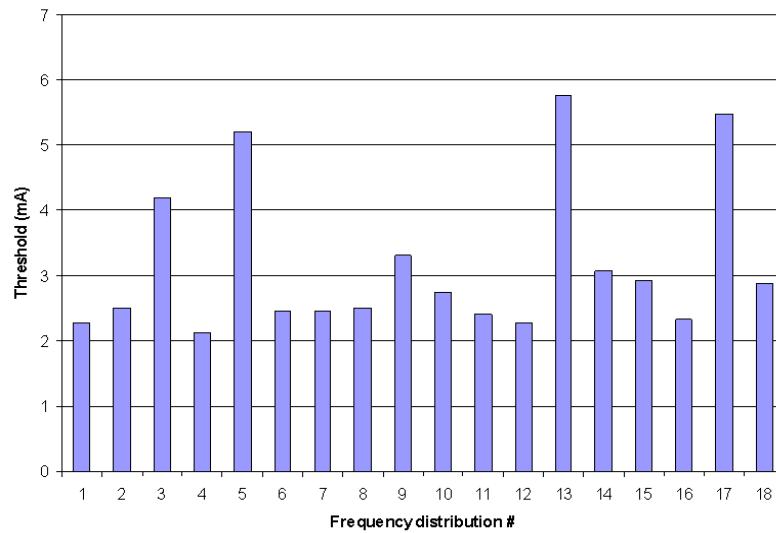


Figure 1: BBU threshold for the 18 distributions of the HOM frequency. The frequency of HOMs was randomly varied from its initial values in a range of ± 2 MHz.

Simulations of the BBU threshold using MATBBU and TDBBU

Another set of BBU simulations was run using the `matbbu`³ and `tdbbu`⁴ codes. Since the exact HOMs are not known, a few typical cases were generated based on the best available HOM values⁵. Based on the sample, a gaussian width of 3 MHz was assigned to the frequencies of all the HOMs. HOMs lacking R/Q values were omitted from this calculation.

Renaissance consists of two kinds of cavities; the low loss (LL) and high gradient (HG).

³ 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

⁴ 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

⁵ Hiapeng Wang, private communication

The upstream 3 will be of the LL type, the downstream 5 of the HG type. They are described in the following tables:

R/Q [W/cm^2]	R [ohm]	frequency [MHz]	Qbar
0.81	5.029E+00	1920	1.33E+04
0.81	5.010E+00	1923.55	6.37E+03
0.01	6.063E-02	1925.43	4.88E+03
0.01	6.046E-02	1928.11	3.10E+03
0.74	4.448E+00	1941.77	4.81E+04
0.74	4.440E+00	1943.48	8.69E+03
0.03	1.591E-01	1969.36	1.12E+05
0.03	1.589E-01	1970.3	1.62E+04
6.82	3.882E+01	2000.81	1.53E+05
6.82	3.880E+01	2001.23	2.81E+04
10.06	5.515E+01	2039.75	3.71E+05
10.06	5.514E+01	2040.01	9.35E+04
0.88	4.646E+00	2077.15	4.94E+05
0.88	4.645E+00	2077.32	1.71E+05
2.56	1.284E+01	2133.14	1.75E+05
2.56	1.284E+01	2133.39	2.26E+05
0.00	7.063E-04	2151.73	1.62E+05
0.00	7.061E-04	2152.15	1.81E+05
7.18	3.459E+01	2175.73	1.67E+05
7.18	3.454E+01	2177.37	1.33E+05
15.10	7.133E+01	2196.94	5.93E+05
15.10	7.131E+01	2197.21	1.37E+06
8.17	3.805E+01	2211.89	9.98E+05
8.17	3.804E+01	2212.08	2.67E+06
0.58	2.670E+00	2221.43	1.07E+06
0.58	2.669E+00	2221.69	3.24E+06
0.07	3.198E-01	2226.9	5.14E+06
0.07	3.197E-01	2227.29	7.30E+06
38.08	1.018E+02	2920.59	2.68E+05
38.08	1.017E+02	2921.77	2.13E+05
3.99	1.064E+01	2921.96	8.10E+05
3.99	1.064E+01	2922.39	7.00E+05
2.82	7.524E+00	2922.8	1.10E+06
2.82	7.520E+00	2923.52	2.77E+05
0.49	1.294E+00	2928.43	3.62E+05
0.49	1.290E+00	2932.81	6.67E+05
0.80	2.120E+00	2935.78	1.20E+07
0.80	2.115E+00	2939.32	1.51E+07
0.02	6.019E-02	2941.45	2.03E+06
0.02	6.013E-02	2942.96	7.91E+06

Table 1. HOMs for the Low Loss cavities.

R/Q [ohm/cm^2]	R/Q [ohm]	HG004 freq [MHz]	Q	-
2.14E-02	1.39E-01	1867.97	1.64E+04	
2.14E-02	1.39E-01	1869.57	1.05E+03	
2.13E-01	1.37E+00	1883.16	3.20E+03	
2.13E-01	1.36E+00	1888.74	9.61E+02	
1.23E-01	7.71E-01	1906.52	7.33E+05	
1.23E-01	7.54E-01	1927.25	1.25E+03	
6.52E+00	3.97E+01	1934.84	1.47E+04	
6.52E+00	3.95E+01	1940.02	4.46E+03	
1.59E+01	9.32E+01	1972.75	3.64E+05	
1.59E+01	9.30E+01	1974.86	1.05E+04	
5.13E+00	2.89E+01	2012.27	2.06E+04	
5.13E+00	2.89E+01	2013.58	2.62E+04	
3.23E-01	1.76E+00	2047.26	1.05E+04	
3.23E-01	1.76E+00	2048.87	4.64E+04	
4.49E+00	2.42E+01	2056.96	1.63E+04	
4.49E+00	2.42E+01	2057.81	1.97E+04	
6.67E-02	3.34E-01	2132.87	1.83E+06	
6.67E-02	3.34E-01	2133.17	1.81E+06	
4.97E+00	2.46E+01	2145.97	3.36E+06	
4.97E+00	2.46E+01	2146.43	2.22E+06	

6.84E+00	3.36E+01	2152.85	3.00E+06
6.84E+00	3.36E+01	2153.1	6.12E+06
7.06E-01	3.46E+00	2157.41	1.19E+06
7.06E-01	3.45E+00	2157.82	1.49E+06
9.13E-01	4.46E+00	2159.37	2.60E+06
9.13E-01	4.46E+00	2159.77	2.35E+06
3.51E-01	1.72E+00	2160.68	7.61E+06
3.51E-01	1.71E+00	2161.08	4.23E+06
2.38E-02	6.69E-02	2848.21	4.32E+03
2.38E-02	6.69E-02	2848.62	4.08E+03
5.03E-02	1.39E-01	2874.25	2.24E+03
5.03E-02	1.39E-01	2876.77	2.10E+03
2.97E-01	8.08E-01	2894.31	1.88E+06
2.97E-01	8.02E-01	2905	3.48E+05
2.63E-04	7.11E-04	2905.34	8.08E+03
2.63E-04	7.10E-04	2907.82	2.95E+03
3.64E-01	9.82E-01	2908	7.08E+05
3.64E-01	9.82E-01	2908.45	5.14E+06
1.86E-01	4.91E-01	2936.91	1.44E+06
1.86E-01	4.90E-01	2939.78	1.24E+03
3.74E-01	9.71E-01	2963.79	6.51E+02
3.74E-01	9.70E-01	2965.57	7.27E+03

Table 2. HOMs for the High Gradient cavities.

The recirculation matrices for the IR and UV lines was taken from the most recent DIMAD⁶ file by D.Douglas⁷. Note that the recirculation time is slightly longer for the UV line (1313 half-RF cycles) than the IR line (1297 half-RF cycles). A test run indicated that while the IR recirculation matrix is slightly different from earlier runs⁸, the results were pretty much the same.

```
569
-0.1017264E+01  0.2562799E+02 -0.2685950E-15  0.2643892E-14
-0.1246576E+00  0.2157478E+01  0.3827638E-16 -0.6593188E-15
-0.5707719E-15  0.1391415E-13  0.1541742E+01 -0.1341357E+02
 0.6601658E-16 -0.1742299E-14 -0.3052009E+00  0.3303947E+01
```

Table 3. IR recirculation delay and matrix in DIMAD units.

```
585
-0.6656959E+00  0.1893122E+02  0.6617143E-15 -0.8343985E-14
-0.2696691E-01 -0.7352959E+00 -0.4356890E-16  0.3547394E-15
-0.2189724E-15 -0.1555449E-14 -0.1140809E+01  0.6555733E+01
-0.2431680E-16  0.4154796E-15  0.8725853E-01 -0.1378008E+01
```

Table 3. UV recirculation delay and matrix in DIMAD units.

All the HOMs for *Renaissance* were inserted into the file, but none for the existing two older cryomodules (zones 2 and 4), as previous simulations showed their modes produced no troublesome thresholds.⁹ No attempt was made to optimize the speed by removing HOMs, and matbbu was allowed to automatically choose its regions-of-interest (RoI). The effect of lasing was not included, but previous studies using tdbbu 3.1 that includes the lasing effect indicate that it only increases the threshold by ~20%. Since the HOM orientations are unknown, each HOM was assigned to both the X and Y. A typical input file is in Appendix 2.

⁶ file:/group/casa/FEL/beard/dimad/CURRENT/DOC/index.html

⁷ D.Douglas, private communication

⁸ C.Tennant, private communication

⁹ K.Beard, private communication

The first file was run in tdbbu 1.6h2f4; because of the high Q values, it runs slowly (about 15 days on a 733 MHz Pentium III), but eventually produced a result of 2-2.4 mA threshold on the X axis and 3-5.6 mA on the Y axis.

Running with matbbu was a feasible alternative; those runs also took quite a while (about 3 days on a 2.8 GHz Pentium 4 per case). A total 4 runs for the IR and 3 for the UV lines were run. The results are summarized in the following plots.

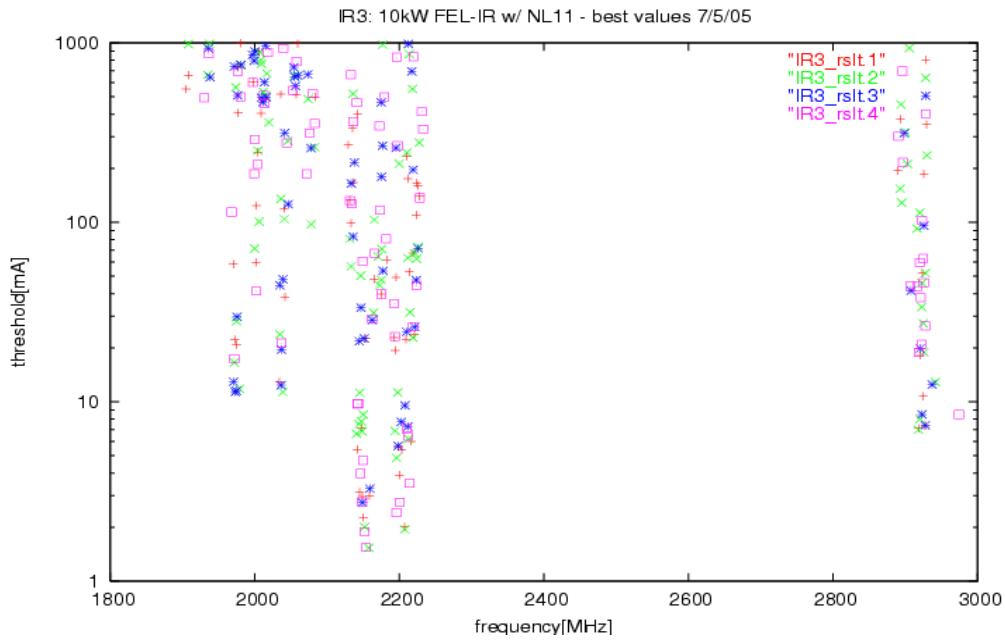


Figure 1. Summary of matbbu IR-line simulations; the thresholds are between 1.5-2 mA.

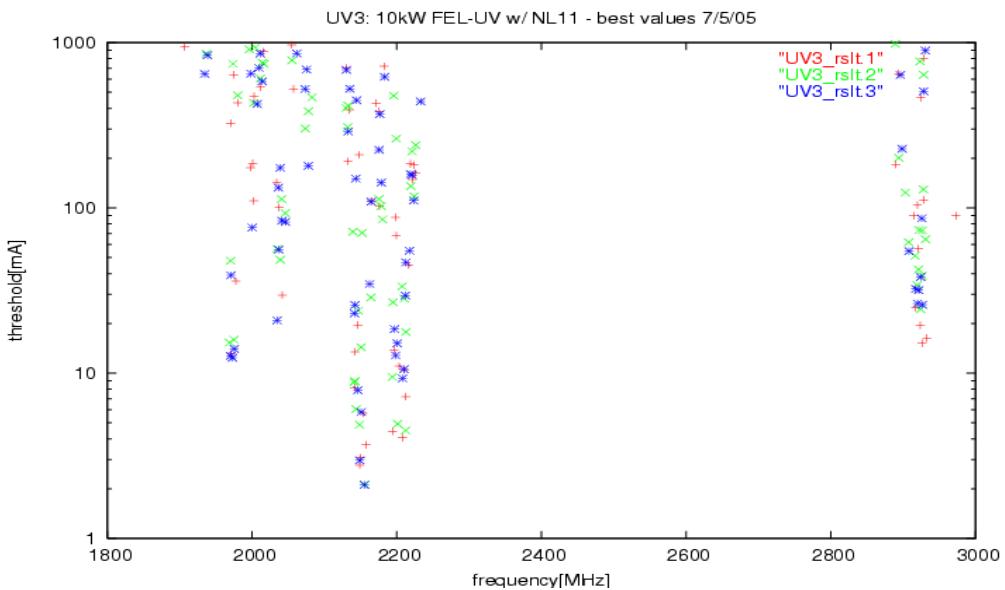


Figure 2. Summary of matbbu UV-line simulations; the thresholds are between 2-3 mA.

Summary

In summary, with the best available values of the higher order modes in the *Renaissance* module, the beam breakup thresholds would be about 1.5-3 mA for the IR line and 2-3 mA in the UV line if no steps are taken to mitigate the problem. These values are well below the design goal of 10 mA in the IR line and 5 mA in the UV line.

While adding a simulation of active HOM feedback is a fairly straight forward modification in `tdbbu`, implementing it as other than as a reduced Q is problematic in `matbbu`. Any attempt to insert beam rotation or similar “tricks” requires discarding the assumption inherent in both `tdbbu` and `matbbu` that the X and Y HOMs are totally decoupled; a recent estimate is that they would be couple by about 1°.¹⁰

¹⁰ Haipeng Wang, private communication, referring to SLAC results

Appendix 1. ERLBBU files

Files used by ERLBBU for the presented simulations included the main parameter file (parameters.txt) and five files describing the FEL optics and the HOMs (linac.txt, recirc.txt, module1.txt, module2.txt, and module3.txt). The meaning of the files and parameters is explained in the program help.

File parameters.txt:

```
logfile      log.txt
unitstransport
ndim 2
linac        linac.txt
recirc       recirc.txt
frf   1.497e09
h    20
pl   648.5
ibeam 3.0e-03
einj 10e06
xinj 1.0e-3
asinjx     0.0
finjx      0.0
phinjx     0.0
arinjx     0.0
yinj      1.0e-3
asinjy     0.0
finjy      0.0
phinjy     0.0
arinjy     0.0
txon       0.0
txoff      1.0e-04
tsim       1.0e-02
iout       100
opmode      x
opvopt      x
oplist      0
ofn  tmp.txt
accy 1.0e-2
exec C:\projects\proj1\erlbbu\erlbbu0_3_1\erlbbu0_2_1\Release\ERLBBU0_2.exe
```

File recirc.txt

```
0.4435479E+00 -0.1814799E+02 -0.1001278E-15 -0.4149872E-16
0.4100764E-01  0.5766990E+00 -0.1136603E-16  0.3338902E-15
0.1561075E-15 -0.2286973E-14 -0.1152552E+01  0.1768565E+02
-0.4038847E-17 -0.1580106E-15  0.3581095E-01 -0.1417150E+01
endfile
```

File linac.txt

```
nmodules 3
0.1000000E+01  0.1000000E+01  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.1000000E+01  0.0000000E+00  0.0000000E+00
0.0000000E+00  0.0000000E+00  0.1000000E+01  0.1000000E+01
0.0000000E+00  0.0000000E+00  0.0000000E+00  0.1000000E+01
```

0.7414750E+00	0.2121481E+01	0.0000000E+00	0.0000000E+00
-0.2281665E+00	0.6958417E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.6697584E+00	0.2559150E+01
0.0000000E+00	0.0000000E+00	-0.2273726E+00	0.6242839E+00
0.9467644E+00	0.2748303E+01	0.0000000E+00	0.0000000E+00
-0.3527887E-01	0.9538202E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9575124E+00	0.2551689E+01
0.0000000E+00	0.0000000E+00	-0.3031868E-01	0.9635762E+00
0.1000000E+01	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.1000000E+01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.1000000E+01	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.1000000E+01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.9674935E+00	0.2529694E+01	0.0000000E+00	0.0000000E+00
-0.2737630E-01	0.9620182E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.8990428E+00	0.2707222E+01
0.0000000E+00	0.0000000E+00	-0.7585703E-01	0.8838714E+00
0.7985270E+00	0.2700492E+01	0.0000000E+00	0.0000000E+00
-0.1266887E+00	0.8238647E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.7795089E+00	0.2258672E+01
0.0000000E+00	0.0000000E+00	-0.1624990E+00	0.8120087E+00
0.1000000E+01	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.1000000E+01
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01

```

module1    module1.txt
module2    module2.txt
module3    module3.txt

```

endfile

File module1.txt

ncavs 8			
nhoms 2			
0.1000000E+01	0.5341000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.5341000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.7731799E+00	0.6002923E+00	0.0000000E+00	0.0000000E+00
-0.1013222E+00	0.7833952E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.7731799E+00	0.6002923E+00
0.0000000E+00	0.0000000E+00	-0.1013222E+00	0.7833952E+00
0.8210782E+00	0.9912318E+00	0.0000000E+00	0.0000000E+00
-0.5427544E-01	0.8479172E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.8210782E+00	0.9912318E+00
0.0000000E+00	0.0000000E+00	-0.5427544E-01	0.8479172E+00
0.8805048E+00	0.6668182E+00	0.0000000E+00	0.0000000E+00
-0.3378631E-01	0.8830193E+00	0.0000000E+00	0.0000000E+00

0.0000000E+00	0.0000000E+00	0.8805048E+00	0.6668182E+00
0.0000000E+00	0.0000000E+00	-0.3378631E-01	0.8830193E+00
0.8939900E+00	0.1053531E+01	0.0000000E+00	0.0000000E+00
-0.2304726E-01	0.9050290E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.8939900E+00	0.1053531E+01
0.0000000E+00	0.0000000E+00	-0.2304726E-01	0.9050290E+00
0.9190264E+00	0.6923877E+00	0.0000000E+00	0.0000000E+00
-0.1672280E-01	0.9200995E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9190264E+00	0.6923877E+00
0.0000000E+00	0.0000000E+00	-0.1672280E-01	0.9200995E+00
0.9250736E+00	0.1082354E+01	0.0000000E+00	0.0000000E+00
-0.1268612E-01	0.9310575E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9250736E+00	0.1082354E+01
0.0000000E+00	0.0000000E+00	-0.1268612E-01	0.9310575E+00
0.9387960E+00	0.7059309E+00	0.0000000E+00	0.0000000E+00
-0.9952991E-02	0.9393805E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9387960E+00	0.7059309E+00
0.0000000E+00	0.0000000E+00	-0.9952991E-02	0.9393805E+00
0.9415782E+00	0.1168483E+01	0.0000000E+00	0.0000000E+00
-0.8016891E-02	0.9459151E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9415782E+00	0.1168483E+01
0.0000000E+00	0.0000000E+00	-0.8016891E-02	0.9459151E+00
0.1000000E+01	0.5341000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.5341000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.1017320E+01	0.7631574E+00	0.0000000E+00	0.0000000E+00
-0.9577754E-03	0.1017354E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1017320E+01	0.7631574E+00
0.0000000E+00	0.0000000E+00	-0.9577754E-03	0.1017354E+01
0.1017518E+01	0.1181617E+01	0.0000000E+00	0.0000000E+00
-0.1029385E-02	0.1017977E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1017518E+01	0.1181617E+01
0.0000000E+00	0.0000000E+00	-0.1029385E-02	0.1017977E+01
0.1018608E+01	0.7641503E+00	0.0000000E+00	0.0000000E+00
-0.1109337E-02	0.1018647E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1018608E+01	0.7641503E+00
0.0000000E+00	0.0000000E+00	-0.1109337E-02	0.1018647E+01
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0.0000000E+00	0.0000000E+00	-0.1198980E-02	0.1019369E+01
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0.0000000E+00	0.0000000E+00	-0.1414224E-02	0.1020995E+01
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-0.1693102E-02 0.1022918E+01 0.0000000E+00 0.0000000E+00
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File module2.txt

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nhoms 28

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9.684490e-001	7.080000e+005	2.925184e+009 0.0
9.660628e-001	5.140000e+006	2.928794e+009 90.0
4.919217e-001	1.440000e+006	2.933927e+009 0.0
4.864476e-001	1.240000e+003	2.950389e+009 90.0
9.755635e-001	6.480000e+002	2.954261e+009 0.0
9.613231e-001	7.270000e+003	2.976062e+009 90.0
2.407200e+001	1.630000e+004	2.060668e+009 0.0
2.407894e+001	1.970000e+004	2.060370e+009 90.0
3.284612e-001	1.830000e+006	2.150115e+009 0.0
3.282174e-001	1.810000e+006	2.150913e+009 90.0
2.436099e+001	3.360000e+006	2.155121e+009 0.0
2.431823e+001	2.220000e+006	2.157015e+009 90.0
3.340295e+001	3.000000e+006	2.159118e+009 0.0
3.333608e+001	6.120000e+006	2.161283e+009 90.0

3.440962e+000	1.190000e+006	2.161241e+009 0.0
3.445223e+000	1.490000e+006	2.159904e+009 90.0
4.457291e+000	2.600000e+006	2.159438e+009 0.0
4.447715e+000	2.350000e+006	2.161761e+009 90.0
1.710771e+000	7.610000e+006	2.161218e+009 0.0
1.712898e+000	4.230000e+006	2.159875e+009 90.0
6.589425e-002	4.320000e+003	2.867514e+009 0.0
6.586920e-002	4.080000e+003	2.868059e+009 90.0
1.371657e-001	2.240000e+003	2.889363e+009 0.0
1.366192e-001	2.100000e+003	2.895136e+009 90.0
7.977834e-001	1.880000e+006	2.911230e+009 0.0
7.946864e-001	3.480000e+005	2.916897e+009 90.0
7.021745e-004	8.080000e+003	2.920090e+009 0.0
7.011903e-004	2.950000e+003	2.922138e+009 90.0
9.692915e-001	7.080000e+005	2.923912e+009 0.0
9.661628e-001	5.140000e+006	2.928643e+009 90.0
4.914290e-001	1.440000e+006	2.935397e+009 0.0
4.860548e-001	1.240000e+003	2.951581e+009 90.0
9.771022e-001	6.480000e+002	2.951934e+009 0.0
9.606301e-001	7.270000e+003	2.977135e+009 90.0
2.404872e+001	1.630000e+004	2.061665e+009 0.0
2.405832e+001	1.970000e+004	2.061253e+009 90.0
3.284125e-001	1.830000e+006	2.150274e+009 0.0
3.282751e-001	1.810000e+006	2.150725e+009 90.0
2.432557e+001	3.360000e+006	2.156689e+009 0.0
2.434780e+001	2.220000e+006	2.155704e+009 90.0
3.344774e+001	3.000000e+006	2.157672e+009 0.0
3.339614e+001	6.120000e+006	2.159339e+009 90.0
3.441211e+000	1.190000e+006	2.161163e+009 0.0
3.444457e+000	1.490000e+006	2.160144e+009 90.0
4.455465e+000	2.600000e+006	2.159880e+009 0.0
4.449174e+000	2.350000e+006	2.161407e+009 90.0
1.709566e+000	7.610000e+006	2.161979e+009 0.0
1.708514e+000	4.230000e+006	2.162644e+009 90.0
6.589018e-002	4.320000e+003	2.867603e+009 0.0
6.587462e-002	4.080000e+003	2.867941e+009 90.0
1.371750e-001	2.240000e+003	2.889265e+009 0.0
1.368391e-001	2.100000e+003	2.892809e+009 90.0
7.962661e-001	1.880000e+006	2.914003e+009 0.0
7.965861e-001	3.480000e+005	2.913417e+009 90.0
7.025130e-004	8.080000e+003	2.919386e+009 0.0
7.004999e-004	2.950000e+003	2.923578e+009 90.0
9.692924e-001	7.080000e+005	2.923911e+009 0.0
9.660723e-001	5.140000e+006	2.928780e+009 90.0
4.914521e-001	1.440000e+006	2.935328e+009 0.0
4.857412e-001	1.240000e+003	2.952534e+009 90.0
9.760536e-001	6.480000e+002	2.953519e+009 0.0
9.620030e-001	7.270000e+003	2.975010e+009 90.0
6.98088346e06	0.0	180.0

endfile

File module3.txt

nhoms 2

0.1000000E+01	0.5341000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.5341000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.9763648E+00	0.7325639E+00	0.0000000E+00	0.0000000E+00
-0.1612928E-02	0.9764422E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9763648E+00	0.7325639E+00
0.0000000E+00	0.0000000E+00	-0.1612928E-02	0.9764422E+00
0.9768259E+00	0.1134701E+01	0.0000000E+00	0.0000000E+00
-0.1474300E-02	0.9775015E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9768259E+00	0.1134701E+01
0.0000000E+00	0.0000000E+00	-0.1474300E-02	0.9775015E+00
0.9784056E+00	0.7340473E+00	0.0000000E+00	0.0000000E+00
-0.1352806E-02	0.9784697E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9784056E+00	0.7340473E+00
0.0000000E+00	0.0000000E+00	-0.1352806E-02	0.9784697E+00
0.9787879E+00	0.1136823E+01	0.0000000E+00	0.0000000E+00
-0.1245735E-02	0.9793581E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9787879E+00	0.1136823E+01
0.0000000E+00	0.0000000E+00	-0.1245735E-02	0.9793581E+00
0.9801221E+00	0.7352982E+00	0.0000000E+00	0.0000000E+00
-0.1150890E-02	0.9801761E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9801221E+00	0.7352982E+00
0.0000000E+00	0.0000000E+00	-0.1150890E-02	0.9801761E+00
0.9804441E+00	0.1138623E+01	0.0000000E+00	0.0000000E+00
-0.1066479E-02	0.9809317E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9804441E+00	0.1138623E+01
0.0000000E+00	0.0000000E+00	-0.1066479E-02	0.9809317E+00
0.9815859E+00	0.7363671E+00	0.0000000E+00	0.0000000E+00
-0.9910254E-03	0.9816319E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9815859E+00	0.7363671E+00
0.0000000E+00	0.0000000E+00	-0.9910254E-03	0.9816319E+00
0.9817928E+00	0.1212368E+01	0.0000000E+00	0.0000000E+00
-0.9233052E-03	0.9822825E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.9817928E+00	0.1212368E+01
0.0000000E+00	0.0000000E+00	-0.9233052E-03	0.9822825E+00
0.1000000E+01	0.5341000E+00	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.1000000E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1000000E+01	0.5341000E+00
0.0000000E+00	0.0000000E+00	0.0000000E+00	0.1000000E+01
0.1050610E+01	0.7894889E+00	0.0000000E+00	0.0000000E+00
-0.8961088E-02	0.1050834E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1050610E+01	0.7894889E+00
0.0000000E+00	0.0000000E+00	-0.8961088E-02	0.1050834E+01
0.1051663E+01	0.1227956E+01	0.0000000E+00	0.0000000E+00
-0.1127206E-01	0.1056551E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1051663E+01	0.1227956E+01
0.0000000E+00	0.0000000E+00	-0.1127206E-01	0.1056551E+01
0.1063401E+01	0.8000226E+00	0.0000000E+00	0.0000000E+00

-0.1460823E-01	0.1063703E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1063401E+01	0.8000226E+00
0.0000000E+00	0.0000000E+00	-0.1460823E-01	0.1063703E+01
0.1064471E+01	0.1248252E+01	0.0000000E+00	0.0000000E+00
-0.1968022E-01	0.1072897E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1064471E+01	0.1248252E+01
0.0000000E+00	0.0000000E+00	-0.1968022E-01	0.1072897E+01
0.1084758E+01	0.8182161E+00	0.0000000E+00	0.0000000E+00
-0.2794172E-01	0.1085128E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1084758E+01	0.8182161E+00
0.0000000E+00	0.0000000E+00	-0.2794172E-01	0.1085128E+01
0.1084254E+01	0.1285900E+01	0.0000000E+00	0.0000000E+00
-0.4276459E-01	0.1102116E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1084254E+01	0.1285900E+01
0.0000000E+00	0.0000000E+00	-0.4276459E-01	0.1102116E+01
0.1127171E+01	0.8571614E+00	0.0000000E+00	0.0000000E+00
-0.7353967E-01	0.1126976E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1127171E+01	0.8571614E+00
0.0000000E+00	0.0000000E+00	-0.7353967E-01	0.1126976E+01
0.1092659E+01	0.1463672E+01	0.0000000E+00	0.0000000E+00
-0.1554494E+00	0.1164771E+01	0.0000000E+00	0.0000000E+00
0.0000000E+00	0.0000000E+00	0.1092659E+01	0.1463672E+01
0.0000000E+00	0.0000000E+00	-0.1554494E+00	0.1164771E+01
00.00	2610000.	2102.607e06	0.0
00.00	3100000.	2113.355e06	90.0
00.00	6110000.	2106.007e06	0.0
00.00	6660000.	2116.585e06	90.0
00.00	2170000.	2115.201e06	0.0
00.00	2170000.	2115.201e06	90.0
00.00	1940000.	2104.683e06	0.0
00.00	1970000.	2114.708e06	90.0
00.00	5210000.	2114.156e06	0.0
00.00	5210000.	2114.156e06	90.0
00.00	2490000.	2104.201e06	0.0
00.00	2880000.	2115.384e06	90.0
00.00	2880000.	2115.384e06	0.0
00.00	2880000.	2115.384e06	90.0
00.00	2570000.	2105.565e06	0.0
00.00	3060000.	2116.055e06	90.0
5.077089683e06	0.0	180.0	

endfile

Appendix 2. matbbu and tdbbu files

The file felIR3x.4 is a typical example of the input files used in the simulation with matbbu and tdbbu. Typical commands were:

```
$> matbbu +-DIMAD -i felIR3x.4 -C cavmat_OLD -v -v  
$> tdbbu +-DIMAD -i ren2c.1 -C cavmat_OLD -G -S 400.:40. -a -v -v
```

File felIR3x.4

```
1TITLE 10kW IR FEL 145 MeV, 6/7/05 3CMs [0,7,0] cells  
DATA  
APRTR    100000.    2.0  
REF      0.        1500.    1500.00    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. 53.41    0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 5.      0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 46.06   0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 5.      0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 46.06   0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 5.      0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 46.06   0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 5.      0.0  
1CECAV   1. 0.0     0.0  
1DRIFT   1. 53.41   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. 65.1    0.0  
1DRIFT   1. 53.41   0.0  
1CECAV   1. 0.0     0.0  
1CAVITY  0.0.5029E+010.1330E+05 1919.3288  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.5010E+010.6370E+04 1922.7723  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.6063E-010.4880E+04 1924.9983  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.6046E-010.3100E+04 1932.5287  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.4448E+010.4810E+05 1937.5509  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.4440E+010.8690E+04 1948.3409  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.1591E+000.1120E+06 1968.7007  
0.00000.0000E+000.0000E+000.0000E+00  
1CAVITY  0.0.1589E+000.1620E+05 1968.6300  
0.00000.0000E+000.0000E+000.0000E+00
```

1CAVITY 0.0.3882E+020.1530E+06 1995.9011
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3880E+020.2810E+05 1996.6710
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5515E+020.3710E+06 2044.3021
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5514E+020.9350E+05 2040.5001
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4646E+010.4940E+06 2083.1500
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4645E+010.1710E+06 2080.3558
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1284E+020.1750E+06 2134.1912
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1284E+020.2260E+06 2133.0257
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7063E-030.1620E+06 2148.1534
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7061E-030.1810E+06 2150.7887
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3459E+020.1670E+06 2177.7190
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3454E+020.1330E+06 2174.6299
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7133E+020.5930E+06 2193.9951
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7131E+020.1370E+07 2200.4224
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3805E+020.9980E+06 2210.6982
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3804E+020.2670E+07 2211.3235
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2670E+010.1070E+07 2224.4948
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2669E+010.3240E+07 2223.6505
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3198E+000.5140E+07 2228.8002
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3197E+000.7300E+07 2226.1223
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1018E+030.2680E+06 2922.4877
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1017E+030.2130E+06 2923.6067
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1064E+020.8100E+06 2916.7470
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1064E+020.7000E+06 2924.3285
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7524E+010.1100E+07 2924.1354
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7520E+010.2770E+06 2922.4840
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1294E+010.3620E+06 2926.9048
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1290E+010.6670E+06 2934.8240
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1CAVITY 0.0.2120E+010.1200E+08 2936.3052
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.2115E+010.1510E+08 2936.8320
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.6019E-010.2030E+07 2940.8731
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.6013E-010.7910E+07 2941.9747
0.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5029E+010.1330E+05 1919.8190

90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5010E+010.6370E+04 1919.7873
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.6063E-010.4880E+04 1926.1385
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.6046E-010.3100E+04 1931.0869
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4448E+010.4810E+05 1945.7223
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4440E+010.8690E+04 1946.0865
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1591E+000.1120E+06 1970.0531
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1589E+000.1620E+05 1966.5850
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3882E+020.1530E+06 2003.0013
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.3880E+020.2810E+05 2001.8755
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5515E+020.3710E+06 2037.5452
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.5514E+020.9350E+05 2037.8051
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4646E+010.4940E+06 2076.9145
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.4645E+010.1710E+06 2079.9418
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1284E+020.1750E+06 2131.5326
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.1284E+020.2260E+06 2137.4189
90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7063E-030.1620E+06 2152.6399
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1CAVITY 0.0.7061E-030.1810E+06 2156.7304
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1CAVITY 0.0.3459E+020.1670E+06 2173.9131
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90.00000.0000E+000.0000E+000.0000E+00
1CAVITY 0.0.7133E+020.5930E+06 2201.2930
90.00000.0000E+000.0000E+000.0000E+00
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 0.00000.0000E+000.0000E+000.0000E+00
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