Report on High Mu National Magnetics Sample Ferrite Toroids S/N-1 to S/N-5

August 2013

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RF Department Technical Note # 95

Introduction

In order to build additional ferrite tuners for the Booster RF Cavities suitable replacement Ni-Zn ferrite toroids need to purchased that have mechanical and electrical properties as close as possible to the original Stackpole "Cermag 2285" material (referred to as the low Mu material equal to ~12.5) and the Toshiba "M4D21A" material (referred to as the high Mu material equal to ~ 20).

Since both Stackpole Carbon and Toshiba are out of the ferrite business Fermilab needed to find vendor(s) that could supply toroids that would meet our specifications. This evaluation program is designed to qualify vendor (s) that can meet our special ferrite needs. This technical note reviews the findings to date for the National Magnetics modified M3 material.

Review of 5 National Magnetics modified M3 sample toroids

Fermilab received 5 sample M3 high Mu NiZn toroids from Nation Magetics for evaluation on our low and high power test fixtures. We first measured the mechanical properties of the toroids to check conformity to our specifications for size and mass. Per our drawing number 0330-EA-5000 the ID must be 5.000" +/-0.005, the OD must be 8.000" +/-0.005, and the thickness must be 1.000" +/-0.005. Toroids with serial number 1, 2, & 4 fall just outside of our tolerance zone for the ID, though not by much. All other physical dimensions are per specification. The mass of the toroids are very similar to that of the reference Toshiba M4D21A toroid.

The low level measured Q of the toroids in the Fermilab test fixture looks reasonable as they are all greater than the minimum specification of 200 and high than the legacy Toshiba M4D21A. However, the low level Mu, as measured in the Fermilab test fixture, is low by about 30% as compared to the reference Toshiba M4D21A. See Appendix A for low power test setup and Table 1 below for summary of toroid low level measurement details.

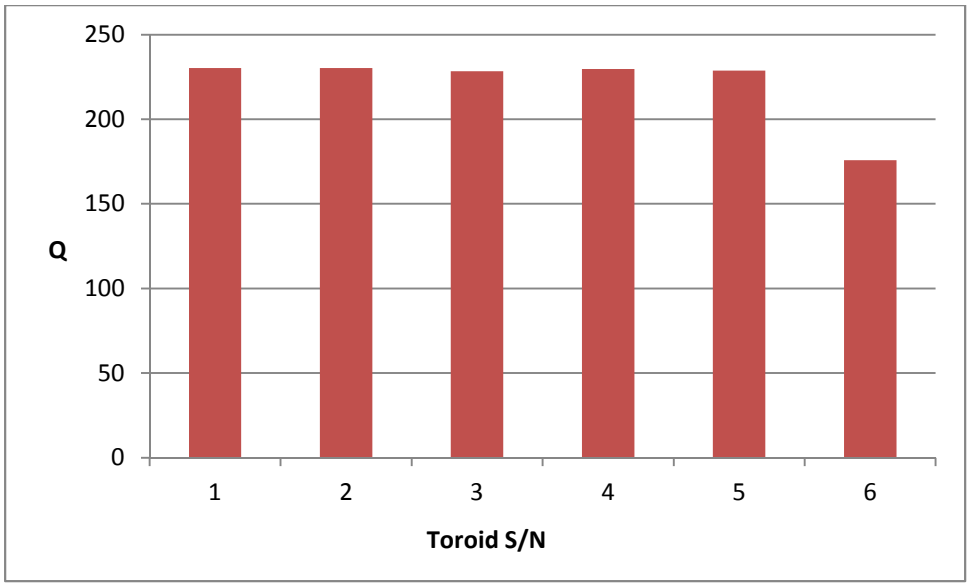
Core #	Notes	measured mu	Out Diam in	In Diam in	Thickness in	mass grams	volume cm^3	density gm/cm^3	Qo	fo MHz	Inductance
1	M3	14.75	8.000	4.992	1.004	2181	504.94	4.32	230	40.519	3.46E-08
2	M3	15.09	8.000	4.992	1.004	2202	504.94	4.36	230	40.282	3.54E-08
3	M3	15.21	8.000	5.000	1.004	2220	503.92	4.41	228	40.198	3.57E-08

4	M3	15.20	8.004	4.988	1.004	2214	506.26	4.37	230	40.202	3.56E-08
5	M3	15.14	8.000	5.000	1.004	2208	503.92	4.38	229	40.242	3.55E-08
M4D21A	Toshiba	20.19	8.001	5.000	1.000	2166	501.94	4.32	176	36.894	4.85E-08

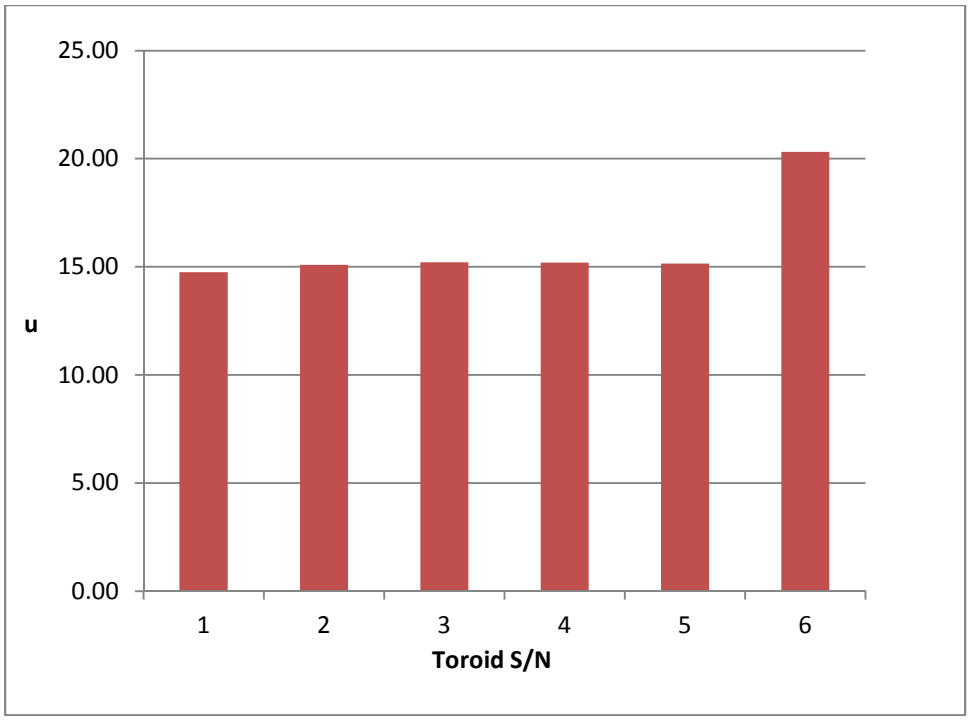
Table 1 Low level tests - National Magnetics M3 Toroids (High Mu) August 2013

Summary of low power results

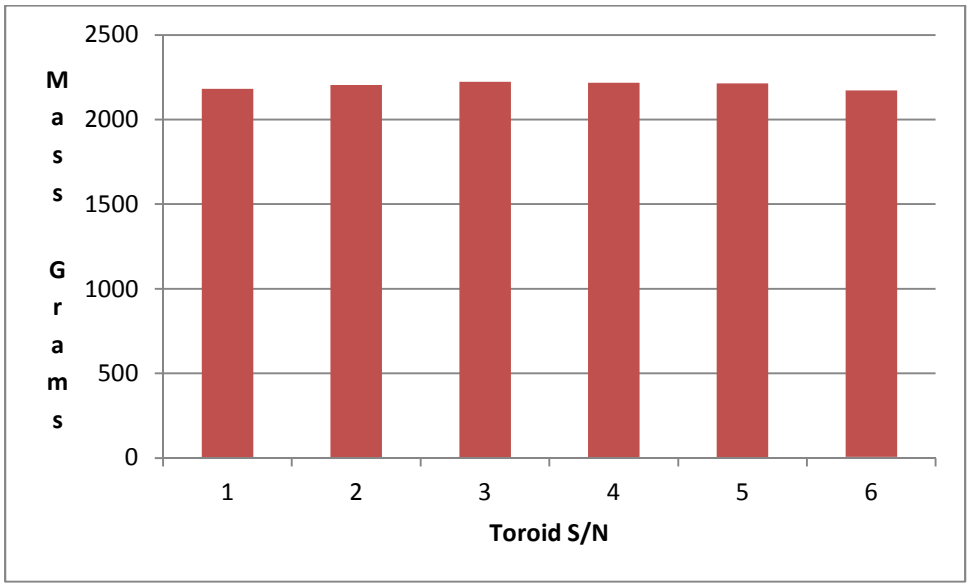
1. The Q of the 5 M3 toroids is in general higher than that of the Toshiba M4D21A where toroid S/N 6 is the Toshiba M4D21A.



2. The Mu of the M3 toroids is low by ~30% compared to the legacy M4D21A (toroid S/N-6).



3. Mass of the Toroids are consistent and comparable to the Toshiba M4D21A (toroid S/N-6).



High power measurement procedure

Following the low level measurements the torolds were inserted one at a time into our high power half wave test cavity. See appendix B for high power test setup. Each toroid test consisted of:

1. Measuring Q at zero bias by exciting the cavity with about 4 kWatt of rf power.
2. Biasing the torold up to 10,000 amps and back down to zero amps.

3. Measure toroid characteristics at bias levels of 1000A, 3000A, 5000A, & 10,000Amps at two power levels, ~ 3 kW and ~ 4.3 kW. Note onset of high loss by a drop in cavity voltage as shown in the picture below.

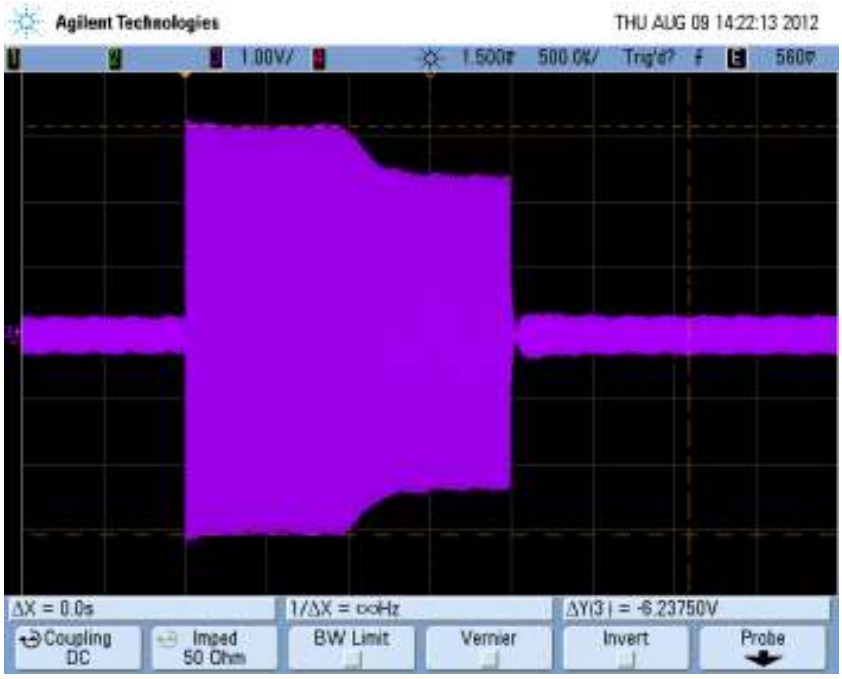


Figure 1 - Shows a typical high loss effect (HLE) as seen by the cavity RF voltage in the coaxial cavity. The HLE occurs about 1 ms into the RF pulse. The RF amplitude should remain flat across the whole RF pulse, but with the onset of high loss a distinct drop in cavity voltage is observed. Our test RF pulse is typically 2 ms long, with a forward power between 3-5 kW. The RF pulse is gated on near the center of the bias flattop portion of the current pulse. The 2 ms pulse is repeated every 10 seconds. See appendix A for test setup.

4. Measure Q at 10,000 amps.

All 5 of the M3 toroids were tested in our half wave high power test fixture. Data for the 5 toroids plus the legacy Toshiba M4D21A is below.

Summary of high power Results

1. The onset of the high loss effect vs bias current at RF power level of ~ 3 kW.

Toroid #	0 Amps	1000 Amps	3000	5000	10000
1	No HLE	No HLE	HLE	HLE	No HLE
2	No HLE	No HLE	HLE	-	No HLE
3	No HLE	HLE	-	HLE	No HLE
4	No HLE	HLE	-	HLE	HLE
5	No HLE	HLE	-	HLE	No HLE

M4D21A	No HLE	HLE	HLE	No HLE	No HLE

2. The onset of the High loss effect vs bias current at a RF power level of ~ 4 kW.

Toroid #	0 Amps	1000 Amps	3000	5000	10000
1	No HLE	No HLE	No HLE	No HLE	No HLE
2	No HLE	No HLE	HLE	HLE	No HLE
3	No HLE	HLE		HLE	HLE
4	No HLE	HLE	HLE	HLE	HLE
5	No HLE	HLE		HLE	No HLE
M4D21A	No HLE		HLE		No HLE

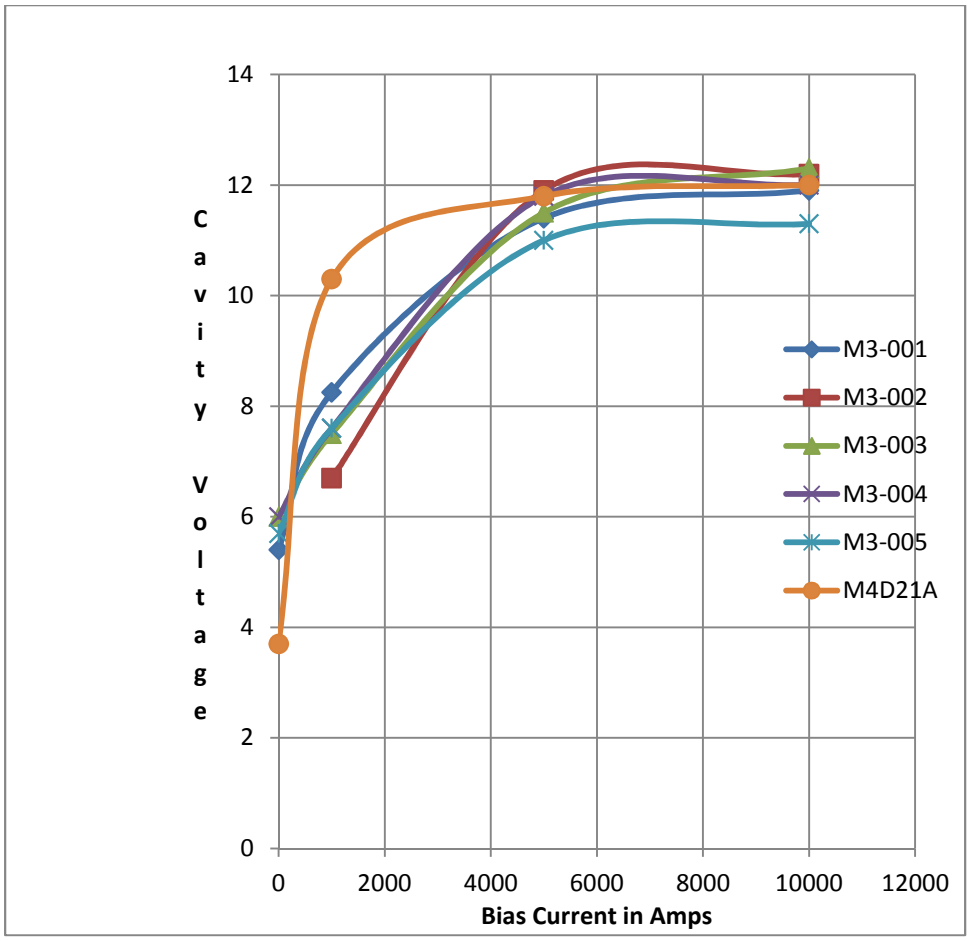
3. Q before and after biasing toroids to10,000 amps.

	Q Before biasing	Q at 10,000 amps	Q after biasing
Toroid #	0 Amps	10,000 Amps	0 Amps
1	233	543	284
2	222	693	296
3	252	704	269
4	238	-	268
5	247	-	257
M4D21A	336 ?	766	-

4. Resonant Frequency vs Bias Current

Frequency	Fo MHz	Fo MHz	Fo MHz
Toroid #	0 Amps	5000 Amps	10,000 Amps
1	40.562	42.648	42.925
2	40.57	42.664	42.941
3	40.51	42.665	42.945
4	40.54	42.662	42.925
5	40.508	42.661	42.945
M4D21A	38.487		42.89

5. Cavity voltage as a function of bias current



Conclusion

The overall results from the low and high power testing suggest the following improvements are needed to bring the special M3 material closer to the properties of the Toshiba M4D21A.

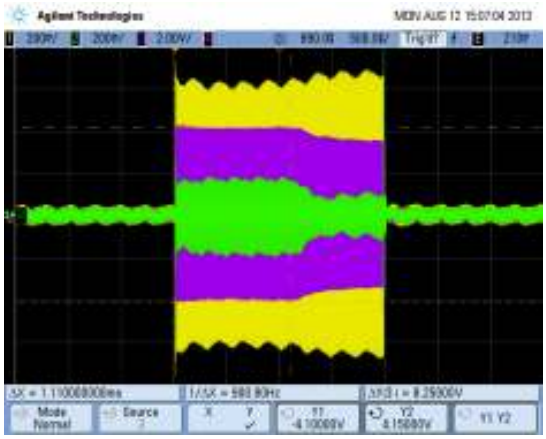
- **Need to try and improve the Mu by 10 to 20 percent.**
- **Keep the mass the same as the sample toroids, 2150 to 2250 grams.**
- **The onset of the high loss effects (HLE) was the best in sample toroid number 1. I do know if there was anything different about toroid #1 but having future toroids similar to this one is desirable.**
- **For the next batch of sample toroids I recommend that National Magnetics supply 10 toroids which would be enough for construction of a complete tuner assembly. They should try and improve the Mu by 10 to 20 percent while keeping the mass in the 2150 to 2250 gram range.**

High Power Data

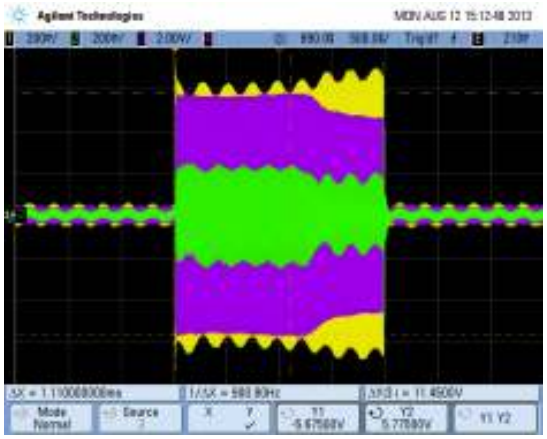
Note 1: HLE is High Loss Effect, seen when the cavity voltage drops during RF pulse.

Note 2: For all photos, yellow is forward voltage, green is reflected voltage, violet is cavity voltage.

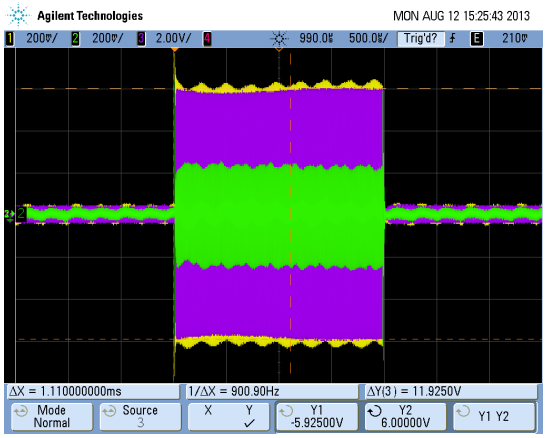
001-M3-2013 (after biasing)											
Bias Current (A)	Setting (dBm)	Res. Freq. (MHz)	Forward Power (V)	Reverse Power (V)	Forward Power (kW)	Reverse Power (W)	Cav. V before HLE	Cav. V after HLE	Time @ start of HLE (ms)	Loop position (in.)	Picture #
0	4.0	40.562	1.14	0.28	3.248	196	5.6	NO HLE		3-1/4	
1000	4.0	41.644	1.13	0.34	3.191	289	7.5	NO HLE		3	
1000	7.0	41.641	1.30	0.35	4.224	306	8.3	HLE	1.2	3	1
3000	4.0	42.396	1.16	0.24	3.363	144	9.6	7.5	1.3	1-3/4	
3000	7.0	42.396	1.32	0.34	4.355	289	10.4	7.7	1.0	1-3/4	
5000	4.0	42.648	1.10	0.38	3.024	361	10.2	HLE		1-1/2	
5000	7.0	42.648	1.30	0.44	4.224	484	11.4	HLE	1.3	1-1/2	2
8000	4.0	42.859	1.10	0.31	3.024	240	10.2	NO HLE		1-1/2	
8000	7.0	42.859	1.22	0.37	3.720	342	11.6	HLE just	starting	1-1/2	
9500	4.0	42.914	1.10	0.43	3.024	462	9.2	NO HLE		1-1/2	
9500	7.0	42.914	1.30	0.40	4.224	400	11.9	NO HLE		1-1/2	3



Picture 1 – M3 S/N -1 , @ 1000A Bias



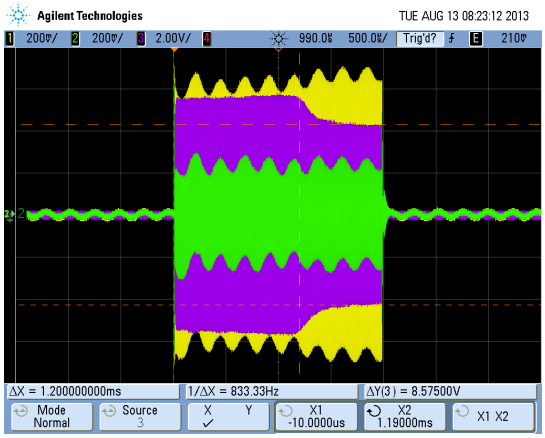
Picture2 – M3 S/N -1 , @ 5000A Bias



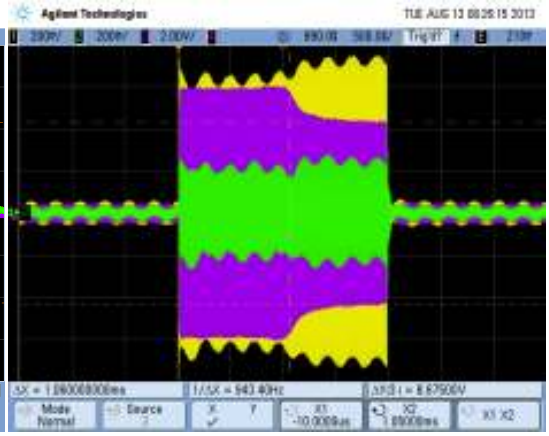
Picture 3 – M3 S/N -1 , @ 9500A Bias

001-M3-2013 (after biasing)			
Q measurement			
Bias Current (A)	0, before	10000	0, after
SG setting (dBm)	7.0	7.0	4
Max Cavity Voltage (V)	5.4	10	5.6
Resonant frequency (MHz)	39.789	42.925	40.594
f1	39.746	42.882	40.544
f2	39.917	42.961	40.687
Q	**232.7**	**543.4**	**283.9**

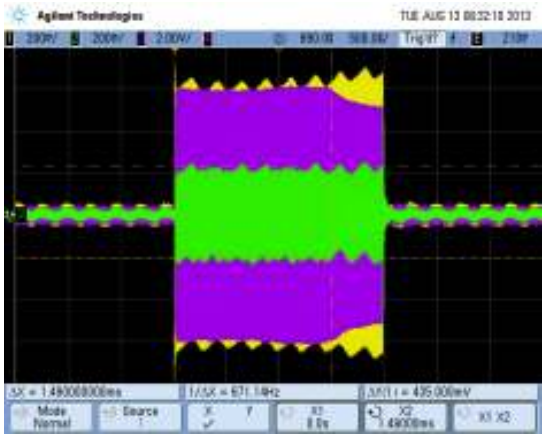
002-M3-2013 (after biasing)											
Bias Current (A)	**Setting (dBm)**	**Res. Freq. (MHz)**	**Forward Power (V)**	**Reverse Power (V)**	**Forward Power (kW)**	**Reverse Power (W)**	**Cav. V before HLE**	**Cav. V after HLE**	**Time @ start of HLE (ms)**	**Loop position (in.)**	**Picture #**
0	4.0	40.570	1.10	0.27	3.024	182	5.4	NO HLE		3	
1000	7.0	41.680	1.20	0.55	3.599	756	6.7	HLE?		2-3/4	
3000	4.0	42.397	1.10	0.27	3.024	182	9.3	7.2	1.2	2	
3000	7.0	42.397	1.31	0.34	4.289	289	10.4	7.4	0.9	2	4
5000	4.0	42.662	1.30	0.42	4.224	441	11.9	8.6	1.1		5
5000	7.0	42.664	1.25	0.37	3.905	342	11.1	8.5	1.2	1-1/2	
8000	7.0	42.864	1.20	0.42	3.599	441	11.2	10.7	1.8	1-1/2	6
9500	7.0	42.924	1.30	0.47	4.224	552	12.2	11.4	1.8		7
10000	7.0	42.941	1.30	0.48	4.224	576	12.2	12.0	1.9	1-1/2	8
10000	9.0	42.941	1.30	0.52	4.224	676	12.2	11.6	1.7	1-1/2	9



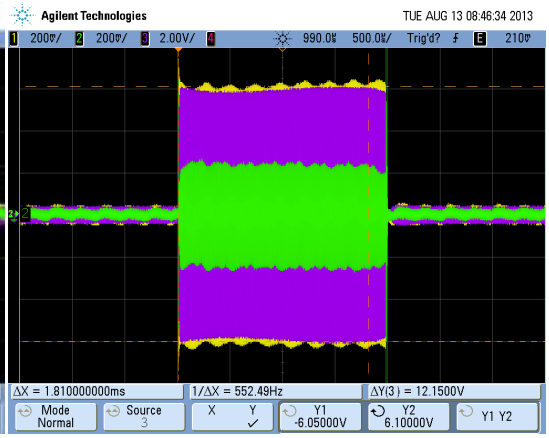
Picture 4



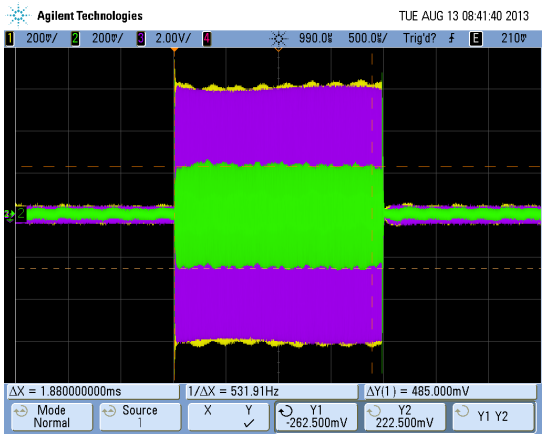
Picture 5



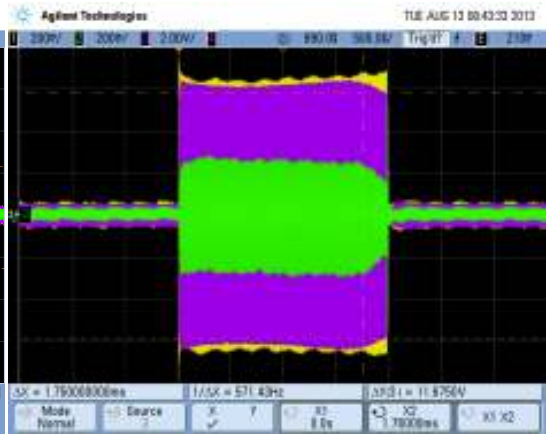
Picture 6



Picture 7



Picture 8

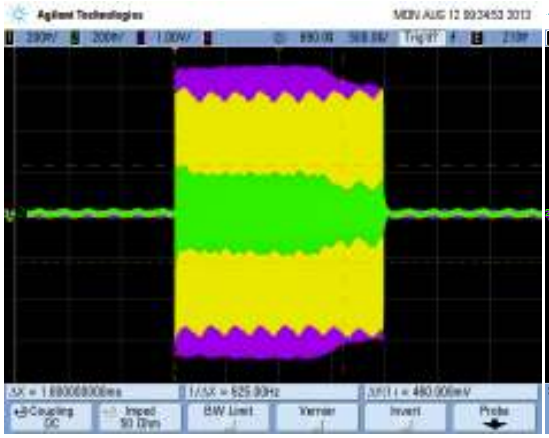


Picture 9

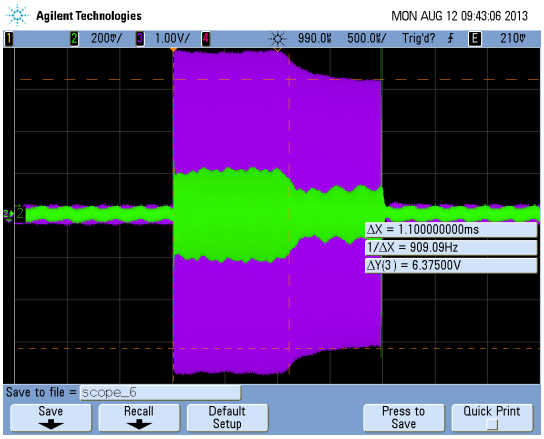
002-M3-2013 (after biasing)

Q measurement			
Bias Current (A)	0, before	10000	0, after
SG setting (dBm)	4.0	4.0	4.0
Max Cavity Voltage (V)	4.75	10.2	5.55
Resonant frequency (MHz)	39.775	42.935	40.592
f1	39.724	42.896	40.539
f2	39.903	42.958	40.676
Q	**222.2**	**692.5**	**296.3**

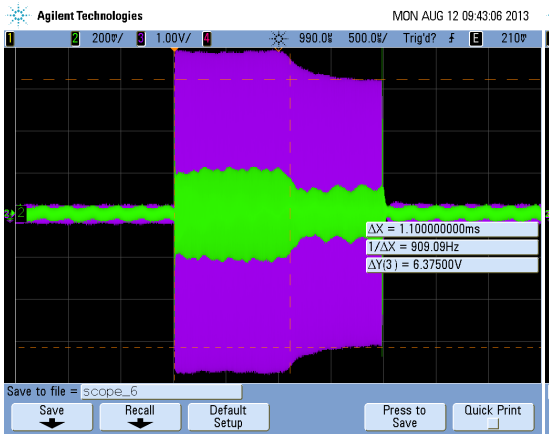
003-M3-2013 (after biasing)											
Bias Current (A)	**Setting (dBm)**	**Res. Freq. (MHz)**	**Forward Power (V)**	**Reverse Power (V)**	**Forward Power (kW)**	**Reverse Power (W)**	**Cav. V before HLE**	**Cav. V after HLE**	**Time @ start of HLE (ms)**	**Loop position (in.)**	**Picture #**
0	4.0	40.510	1.10	0.27	3.024	182	5.3	NO HLE		3	
1000	4.0	41.633	1.10	0.36	3.024	324	6.9	6.0	1.45	2-3/4	10
1000	7.0	41.633	1.30	0.45	4.224	506	7.5	6.4	1.1	2-3/4	11
5000	7.0	42.665	1.30	0.37	4.224	342	11.5	8.5	1.1	1-1/2	
10000	4.0	42.945	1.10	0.37	3.024	342	10.4	NO HLE		1-1/2	12
10000	7.0	42.945	1.30	0.46	4.224	529	12.3	11.2	1.7	1-1/2	13
10000	9.0	42.945	1.30	0.48	4.224	576	12.6	11.4	1.7	1-1/2	14



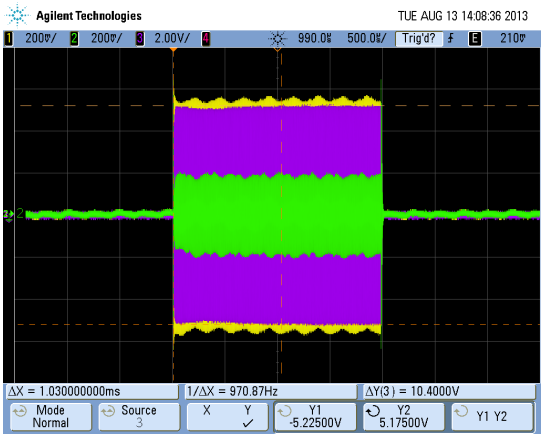
Picture 10



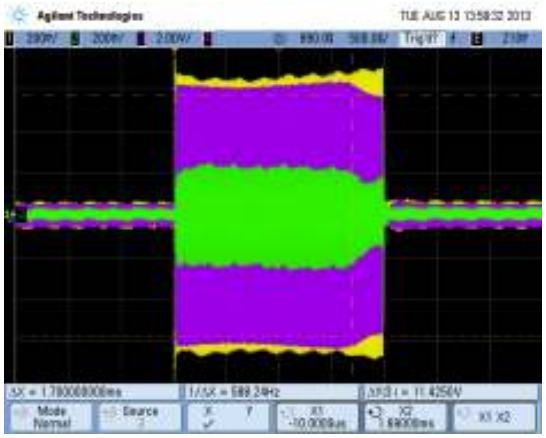
Picture 11



Picture 12



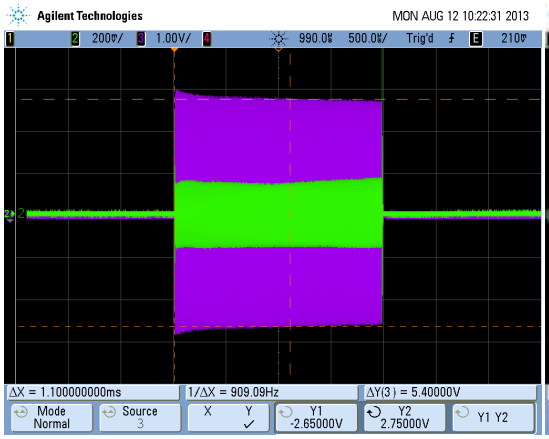
Picture 13



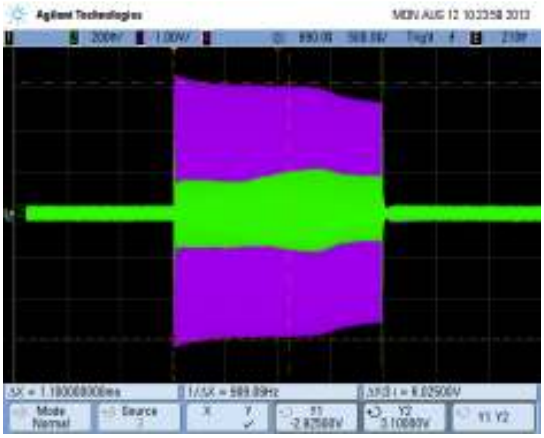
Picture 14

003-M3-2013 (after biasing)			
Q measurement			
Bias Current (A)	0, before	10600	0, after*
SG setting (dBm)	4.0	7.0	NA
Max Cavity Voltage (V)	4.87	11.8	NA
Resonant frequency (MHz)	39.737	42.944	43.060
f1	39.697	42.913	42.990
f2	39.855	42.974	43.150
Q	**251.5**	**704.0**	**269.1**

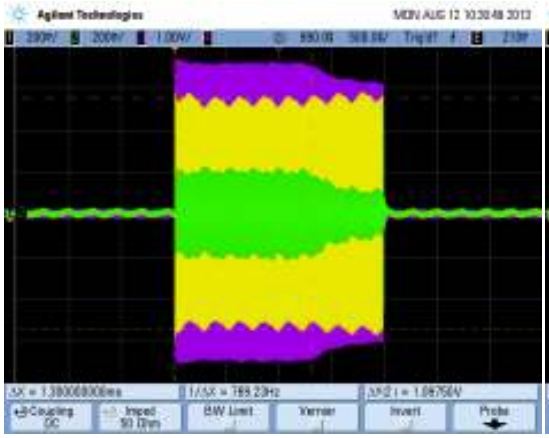
004-M3-2013 (after biasing)											
Bias Current (A)	Setting (dBm)	Res. Freq. (MHz)	Forward Power (V)	Reverse Power (V)	Forward Power (kW)	Reverse Power (W)	Cav. V before HLE	Cav. V after HLE	Time @ start of HLE (ms)	Loop position (in.)	Picture #
0	4.0	40.540	1.10	0.31	3.024	240	5.4	NO HLE		3	15
0	7.0	40.505	1.30	0.36	4.224	324	6.0	5.2	1.5	3	16
1000	4.0	41.629	1.10	0.38	3.024	361	7.0	6.2	1.3	2-1/2	17
1000	7.0	41.629	1.30	0.39	4.224	380	7.6	6.5	1.1	2-1/2	18
5000	7.0	42.662	1.30	0.44	4.224	484	11.8	8.6	1	1-1/2	19
10000	7.0	42.925	1.30	0.45	4.224	506	12.0	11.5	1.9	1-1/2	20
10000	9.0	42.925	1.30	0.49	4.224	600	12.5	11.2	1.7	1-1/2	21



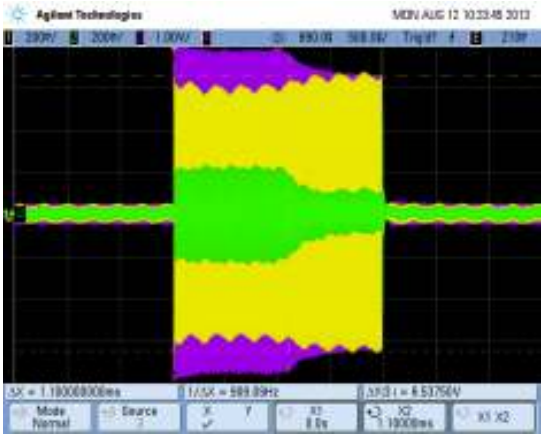
Picture 15



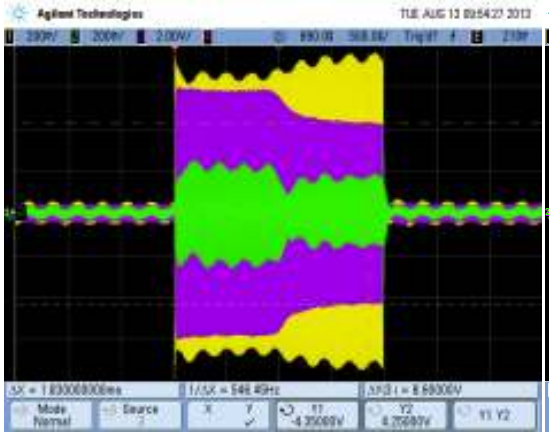
Picture 16



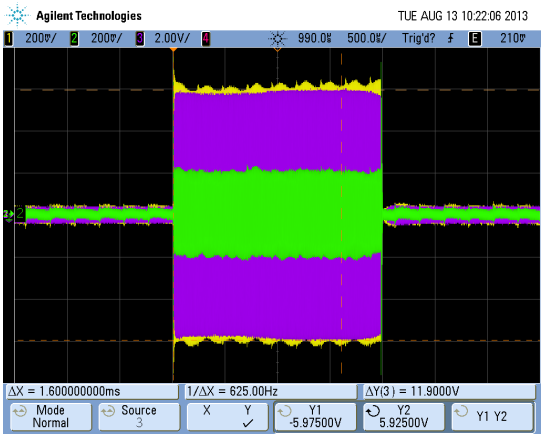
Picture 17



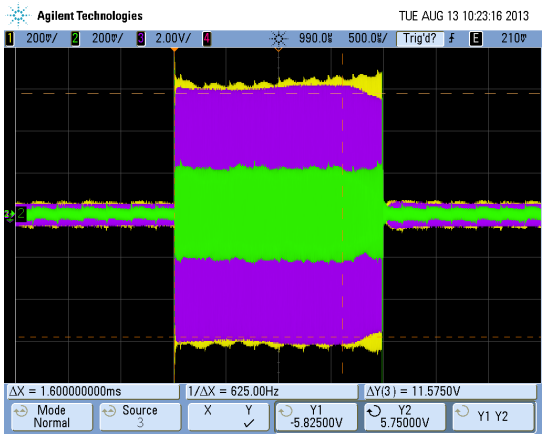
Picture 18



Picture 19



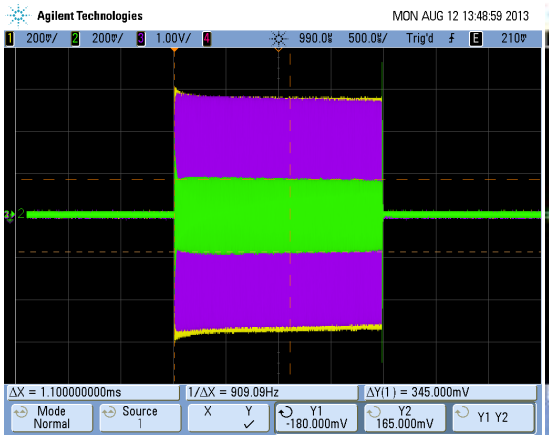
Picture 20



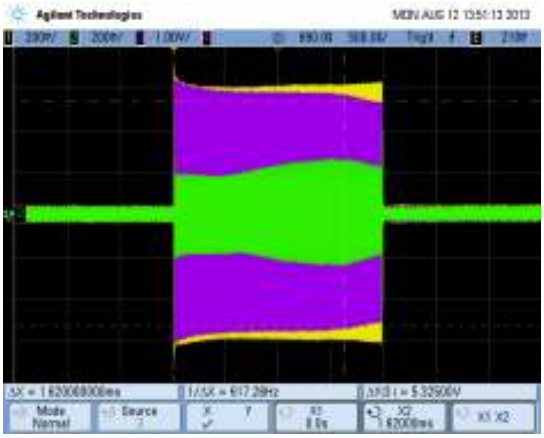
Picture 21

004-M3-2013 (after biasing)			
Q measurement			
Bias Current (A)	0, before	10000	0, after*
SG setting (dBm)	4.0		NA
Max Cavity Voltage (V)	4.96		NA
Resonant frequency (MHz)	39.747		42.960
f1	39.703		42.880
f2	39.870		43.040
Q	**238.0**		**268.5**

005-M3-2013 (after biasing)											
Bias Current (A)	Setting (dBm)	Res. Freq. (MHz)	Forward Power (V)	Reverse Power (V)	Forward Power (kW)	Reverse Power (W)	Cav. V before HLE	Cav. V after HLE	Time @ start of HLE (ms)	Loop position (in.)	Pictire #
0	4.0	40.508	1.10	0.34	3.024	289	5.5	NO HLE		3-1/4	22
0	7.0	40.508	1.30	0.38	4.224	361	5.7	5.3	1.6	3-1/4	23
1000	4.0	41.632	1.10	0.41	3.024	420	7.0	6.2	1.36	3	24
1000	7.0	41.632	1.30	0.39	4.224	380	7.6	6.5	1.1	3	25
5000	7.0	42.661	1.30	0.42	4.224	441	11.0	8.6	1.1	1-1/2	26
10000	4.0	42.945	1.10	0.37	3.024	342	10.7	NO HLE		1-1/2	27
10000	7.0	42.945	1.30	0.43	4.224	462	12.0	11.3	1.7	1-1/2	28
10000	9.0	42.945	1.30	0.48	4.224	576	12.4	11.2	1.6		29



Picture 22



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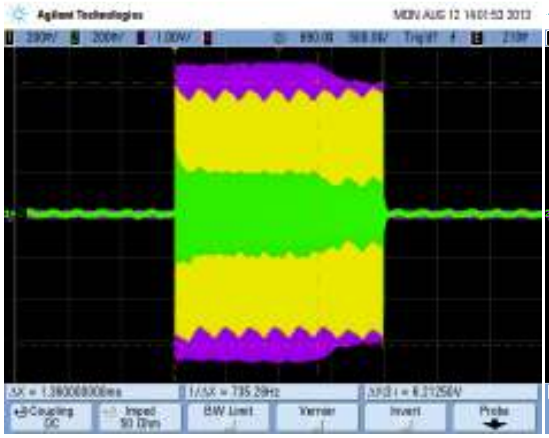

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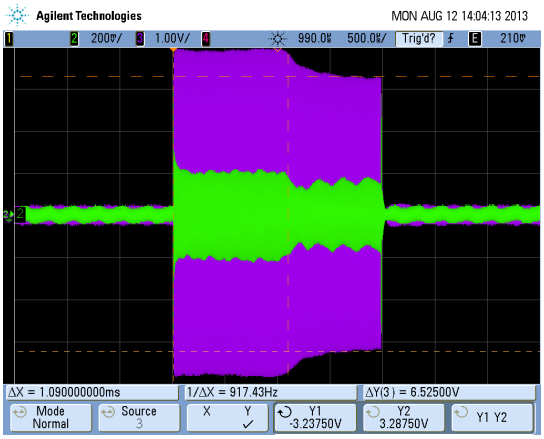
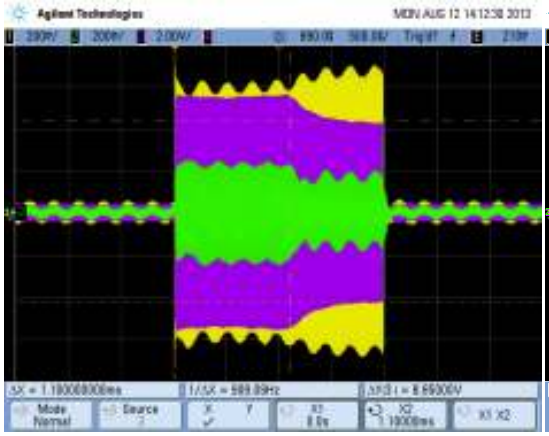


Picture 25



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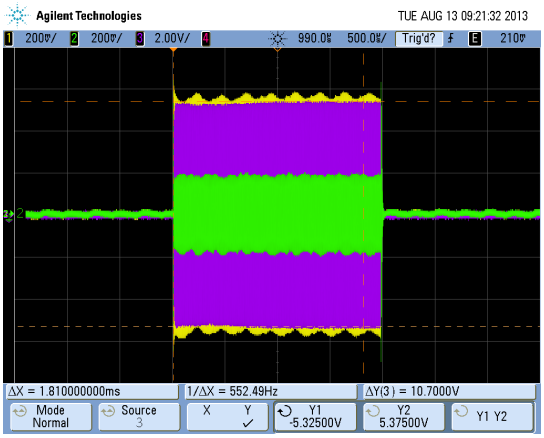
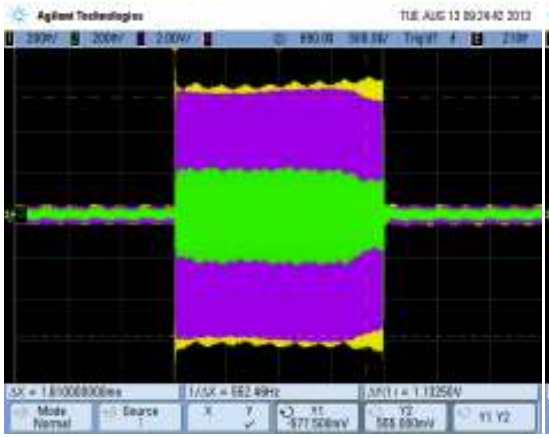
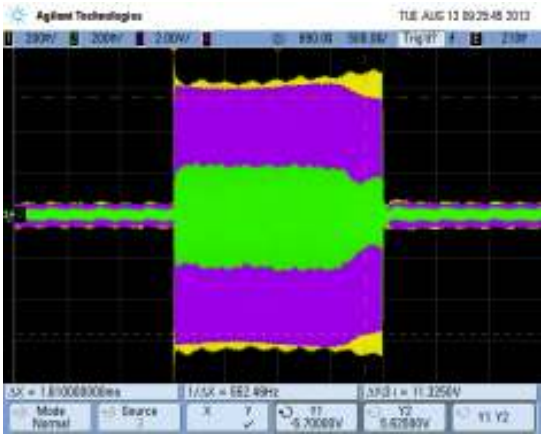


Picture 27



Picture 28



Picture 29

005-M3-2013 (after biasing)			
Q measurement			
Bias Current (A)	0, before	10000	0, after
SG setting (dBm)	4.0		4.0
Max Cavity Voltage (V)	5.02		5.55
Resonant frequency (MHz)	39.748		40.521
f1	39.707		40.474
f2	39.868		40.632
Q	**246.9**		**256.5**

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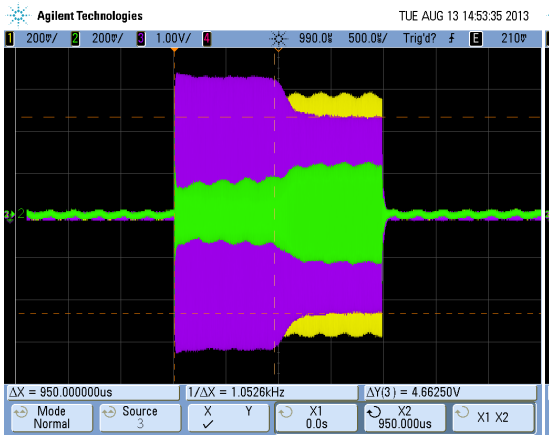
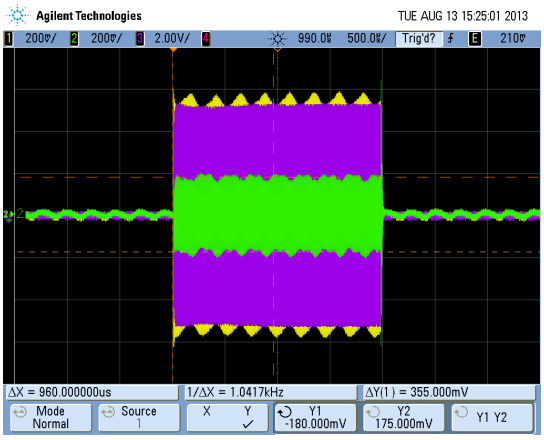
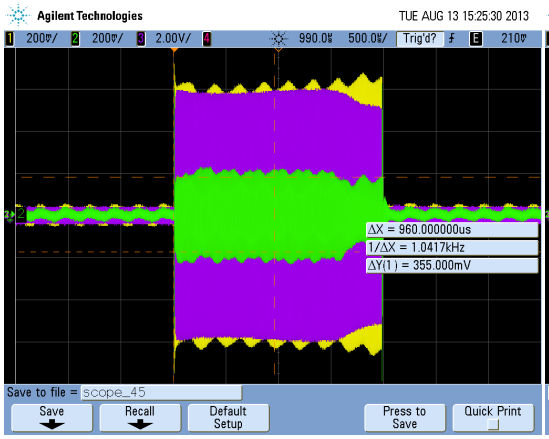
Bias Current (A)	Setting (dBm)	Res. Freq. (MHz)	Forward Power (V)	Reverse Power (V)	Forward Power (kW)	Reverse Power (W)	Cav. V before HLE	Cav. V after HLE	Time @ start of HLE (ms)	Loop position (in.)	Picture #
0	3.0	38.487	1.00	0.54	2.499	729	3.3	NO HLE		3-1/4	
0	7.0	38.487	1.20	0.72	3.599	1296	3.7	NO HLE		3-1/4	
1000	4.0	41.190	1.10	0.40	3.024	400	6.5	4.6	0.98	1-1/2	30
3000	4.0	42.240	1.20	0.32	3.599	256	9.5	6.4	0.94	1-1/2	
3000	7.0	42.240	1.40	0.46	4.899	529	10.3	6.6	0.75	1-1/2	
8000	4.0	42.802	1.10	0.35	3.024	306	10.5	NO HLE		1-1/2	31
8000	7.0	42.802	1.20	0.40	3.599	400	11.8	10.5	1.6	1-1/2	32
10000	4.0	42.890	1.10	0.39	3.024	380	10.5	NO HLE		1-1/2	33
10000	7.0	42.890	1.30	0.45	4.224	506	12.0	NO HLE		1-1/2	34
(using 500ms current pulse)											
1000	4.0	40.922	1.01	0.38	2.549	361	4.7	NO HLE		1-1/2	
3000	4.0	42.154	1.10	0.25	3.024	156	8.3	6.3	1.2	1-1/2	
8000	7.0	42.776	1.20	0.37	3.599	342	11.3	NO HLE		1-1/2	
10000	7.0	42.874	1.20	0.34	3.599	289	11.7	NO HLE		1-1/2	



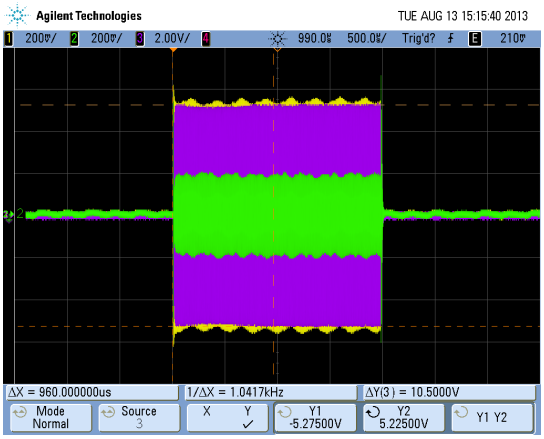
Picture 30



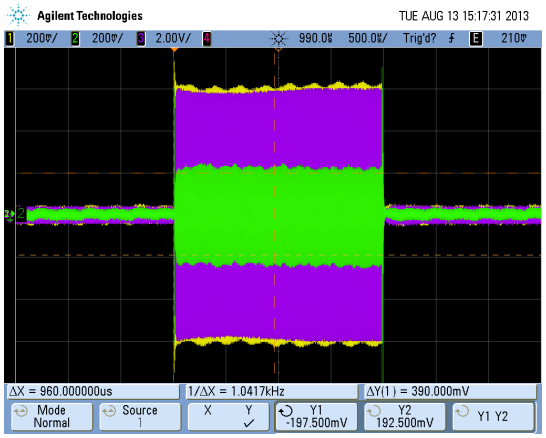
Picture 31



Picture 32



Picture 33



Picture 34

M4D21A 310			
Q measurement			
Bias Current (A)	0, before	10000	0, after
SG setting (dBm)	4.0	4.0	
Max Cavity Voltage (V)	3.83	10.5	
Resonant frequency (MHz)	38.997	42.890	
f1	38.969	42.859	
f2	39.085	42.915	
Q	**336.2**	**765.9**	

Appendix - A

Low Power Test Description:

The low power test fixture is used to measure the quality factor, Q, and the permeability, μ, of the ferrite core, both unbiased and then again after the toroids have been subjected to a 10,000A bias. Before testing any ferrite cores, an aluminum "dummy" core is placed in the fixture and measurements are made to calculate the inductance and capacitance of the fixture itself. The following figure shows the components that are used for the low power test.

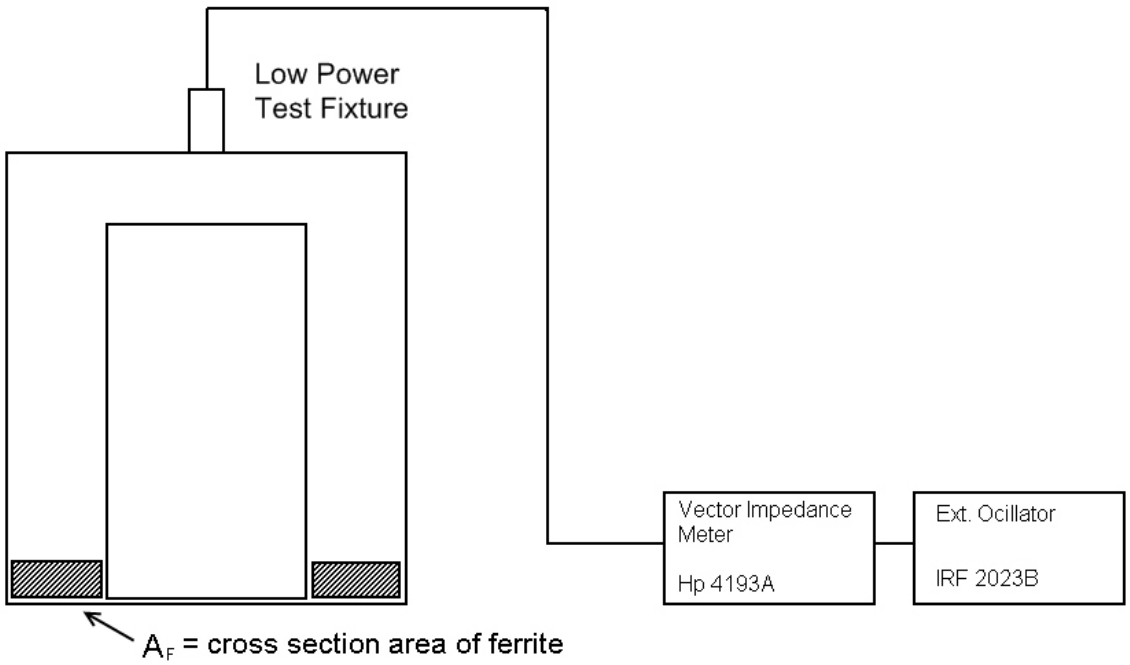


Figure 1: Low power test equipment

Low power test procedure:

1. Load the fixture with:
    a. No core (unloaded)
    b. "dummy" Al core
    c. Ferrite core to be tested
2. Connect the signal generator to the external oscillator plug of the HP vector impedance meter, and connect the probe of the vector impedance meter to the low power fixture.
3. Find the resonant frequency, f_0. The impedance phase will be 0 degrees at f_0.
4. Find the 3-dB frequencies, which will have an impedance phase of -45 degrees and +45 degrees. These can be called f_{low} and f_{high}.

The inductance and capacitance of the unloaded fixture are calculated by using equations 1-2:

$$L = \frac{\mu_0 l}{2\pi} \ln\left(\frac{r_o}{r_i}\right) \qquad (1)$$

$$C = \frac{1}{(2\pi f_0)^2 L} \qquad (2)$$

where μ_0 is the permeability of free space, l is the length of the fixture, r_o is the outer radius of the fixture, and r_i is the inner radius.

The capacitance of the fixture will not change when the fixture is loaded with a core, so we will use equation 2 to calculate the inductance of the loaded fixture. The fixture is then loaded with a "dummy" Aluminum core and the resonant frequency measured. The corrected inductance of the fixture is now calculated using equation 3.

$$L_{fixture} = \frac{1}{(2\pi f_0)^2 C} \qquad (3)$$

We can then calculate the Q, L, and μ of the ferrite using equations 4-6:

$$Q = \frac{f_0}{f_{high} - f_{low}} \qquad (4)$$

$$L_{ferrite} = \frac{1}{(2\pi f_0)^2 C} - L_{fixture} \qquad (5)$$

$$\mu = \frac{L_{ferrite} l_{ferrite}}{\mu_0 A_{ferrite}} \qquad (6)$$

where $l_{ferrite}$ is the average circumference of the toroid and $A_{ferrite}$ is the cross sectional area of the toroid.

Appendix B

High Power Test Description:

The high power testing fixture consists of a half-wave coaxial cavity with the ferrite test core at one end and an adjustable drive loop (for impedance matching) at the other end. A high-current bias power supply generates a pulse up to 10,000 Amps through a conductor in the center of the coaxial fixture. This allows for controllable bias of the test core. A 5 kW solid state RF amplifier excites the coaxial cavity at a frequency of 35-45 MHz, depending on the ferrite core.

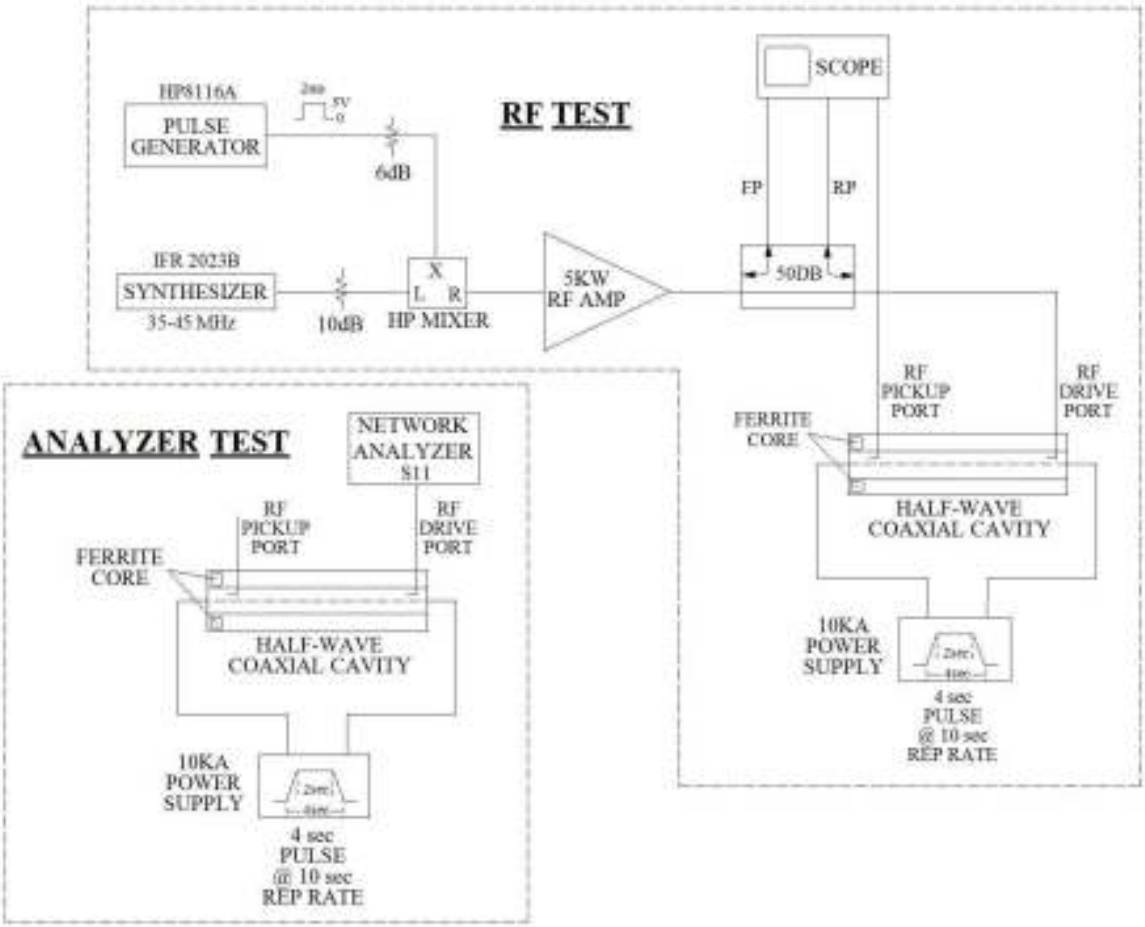


Figure 2: Block diagram of high power test equipment

The short-circuit (SC) RF current is measured at the end of the coaxial cavity that contains the ferrite core. The cavity end that houses the ferrite core also has a hydraulic clamp that facilitates changing cores and preserving good electrical contact. Figure 2 is a block diagram containing the equipment used for the high power test.