LOI Progress Report

– First Experiment at the SP6 in November 2010 –

January 12, 2011

1. Introduction

The LOI was moved from the Hall 2 to the SP6 in the ISIS synchrotron to prepare for the beam test in early 2011 (fig.1). By the movement, a new breakout box was installed near the LOI which connects to the one in the Hall 2. Also, some modifications were made on the water interlock, and a new control line was laid between the LOI and the ISIS SP6 RF system to communicate their "Ready" status. All the RF signals on the cavity gap and triode grid were sent to the ISIS MCR (Main Control Room), while the anode voltages and currents were monitored at the mezzanine in the Hall 2 as before.

It took two weeks to prepare for the RF test. The first test was carried out on Saturday afternoon, November 20, 2010. Cavity gap voltage of 8.5kVpk was obtained quite easily at 2.28MHz with 52.5% duty, where no cavity bias current was applied. It ended with a current trip of the buck regulator (BR). In the following week, however, three damages were found on the triode feedback coil, grid switcher and toroidal current monitor at the final grid input. The feedback coil was installed across the final plate and grid with an higher-order-mode (HOM) damper, which was completely burnt due to overheating of the damping resistor. The power transistor of the grid switcher was dead. And, the spark traces were found between the current monitor and the current lead which threads through to the final grid.

After repair of all these damages, RF test was restarted. However, it barely produced 1.2kVpk at maximum due to BR current trip. Something should have been changed from the last Saturday: RF envelope contained a lot of spikes, and the BR output current showed an overshoot structure, which was never seen before. We have observed the RF waveforms in detail just before the BR current trip. However, we had no time to identify the reason(s) leading to the trip.

In the following sections are reported, new experimental setup in section 2, damages and repair in section 3, waveforms in section 4, other faults in section 5, to-do-list in section 6, and discussions & conclusions in section 7. Waveform data is summarized in the appendix, including the data taken by A Seville thereafter until January 12, 2011.

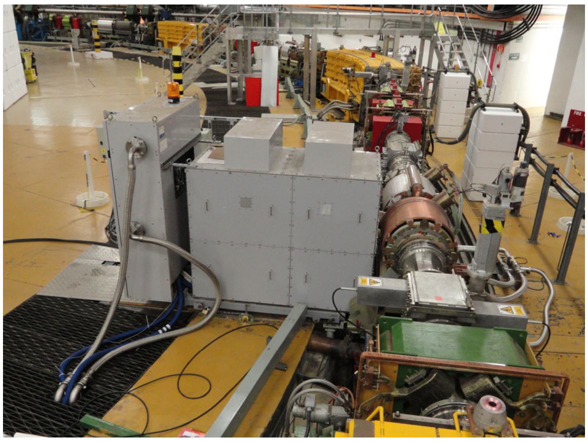


Fig. 1
LOI at the SP6. New breakout box is installed behind the LOI chassis.

2. New experimental setup

By the movement of LOI into the synchrotron room SP6, a new breakout box was installed near the LOI through which all the signals of LOI are sent to the LOI PLC except for the RF signals. RF signals on the cavity gap and triode grid were sent to the MCR through the original breakout box at the SP6. Anode voltages and currents were monitored at the mezzanine in the Hall 2 as before.

Water supplies were also changed. Water at SP6 was able to feed the LOI elements except for the Burle 4648 tetrode due to water shortage: tetrode was supplied by tapping the water duct for SP5. A 5kW(?) chiller was newly installed for water cooling of the grid switcher. Interlock signals on water flow of the cavity and liquid resistor had been checked directly by the LOI PLC. In the new system, they are incorporated into the “SP6 Ready” signal which is sent from the SP6 RF system to the LOI PLC through a new communication cable. Another condition included in the “SP6 Ready” is the vacuum of the 2nd harmonic cavity. The “LOI Ready” is sent in reverse to the SP6 RF system, which indicates all the anode supplies are switched “ON”.

In the experiment in January, 2010, FBC was burnt due to overheating of the damping resistor [1]. This comprised 4-turn secondary coil with a 250 ohms damping resistor. In this experiment, a new FBC was installed, where secondary winding turn was reduced to one-turn with a 100 ohms damping resistor, and the shorted turn number of the primary coil is 12. Power dissipation is then decreased to 2.5/16=0.13, compared to the one in January. The impedance across triode plate and grid, Zpg, with the new FBC is shown in fig. 2.

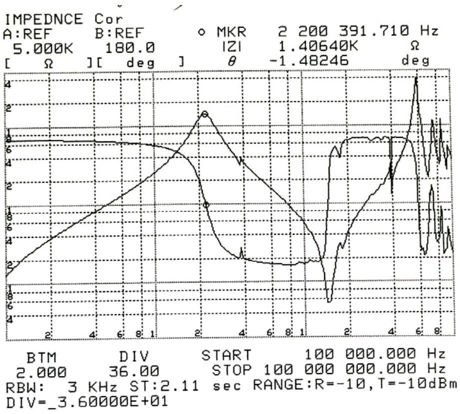


Fig. 2 Zpg.
Fundamental resonance peaks at 2.200MHz with 1.406kohms. First HOM valley locates at 14.206MHz.

3. Damages and repair

Damages were found after the BR trip in the last RF test with fixed frequency operation in November 20. These are listed below with repair works.

(1) Feedback coil (FBC)
Although power dissipation of the damping resistor is decreased to 0.13, the new FBC was burnt again (fig.3). The reason of overheating will be misuse of the resistor. The resistor is the type of W-500D, power rating of which is 350~500W with water cooling. However, it was used without water cooling: rating is reduced to 50W without cooling. The burnt FBC was replaced with a new one (fig. 4): one-turn secondary coil with a 164 ohms, 300W resistor which is provided with forced-air cooling. Shorted turn number of the primary coil is 6. The impedance of the coil itself is shown in fig. 5.

(2) Grid switcher
Switching power transistor, IRG4PH20K, at the output stage was dead, and then replaced with a new one. N Farthing suggested a surge absorber should be added between emitter and base (fig. 6).

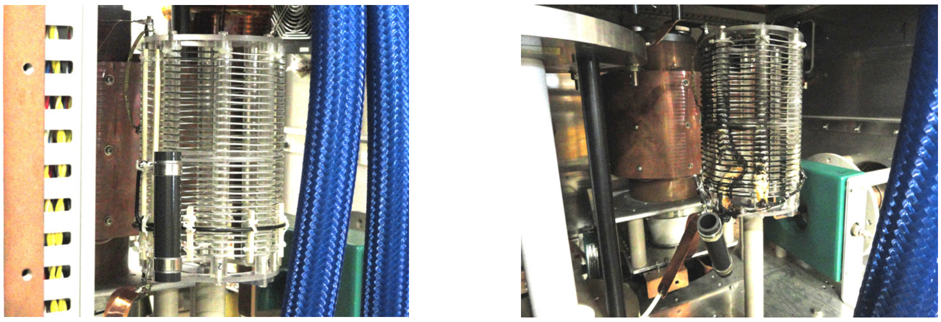


Fig. 3 New feedback coil before RF on (left), which was burnt after RF test in November 20, 2010 (right).

Fig. 4 Newest FBC with cooling fan.

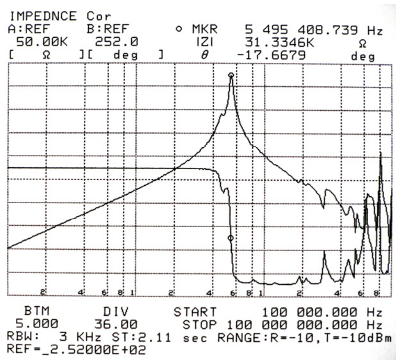


Fig. 5 Impedance of the newest FBC.

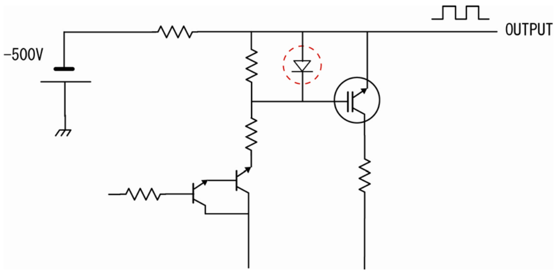


Fig. 6
Proposed surge absorber to the grid switcher in the dotted circle.

(3) Spark trace between grid-input current monitor and current lead

Distance between the current monitor and current lead threading through to the grid was very short. In the first day of this experiment, we unrolled the current monitor complex which includes Pearson model 110 and the current lead in order to check the polarity of the current monitor. This is because there was a discrepancy on the pulse polarity between the Spice simulation and the experiment for short pulse excitation in March 2010. We have then confirmed the current monitor has been set in the right direction: positive current toward the grid. After that, we restored the current monitor and lead complex to its original place. It is thought that the distance between them was insufficient, resulting in the spark (fig. 7). We then made more space between them by folding the edge of the current lead. The damaged current transformer was also reset at its original place by wrapping the damaged part with polyimide film. (The current monitor was replaced by A Seville with a new one in December 11, 2010.)

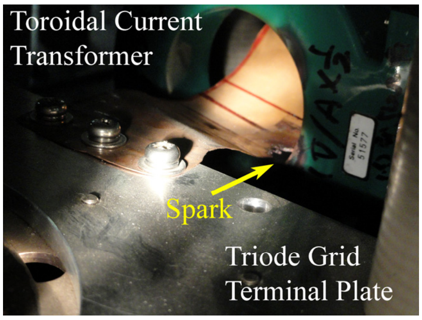


Fig. 7
Spark trace between the grid-input toroidal current monitor and the copper current lead which threads through to the grid.

4. Waveforms

4-1) Buck regulator (BR) output current

After the BR trip in the RF test in November 20, waveform of the BR output current has had an overshoot structure as shown in fig. 8. The same overshoot can be seen in the final grid voltage, although the peak to flat-top ratio is different from that seen in the BR current. Such voltage overshoot does not appear when the anode voltage is zero. It should be reminded, however, that the BR current overshoot did not show up in all the previous experiments (fig. 9).

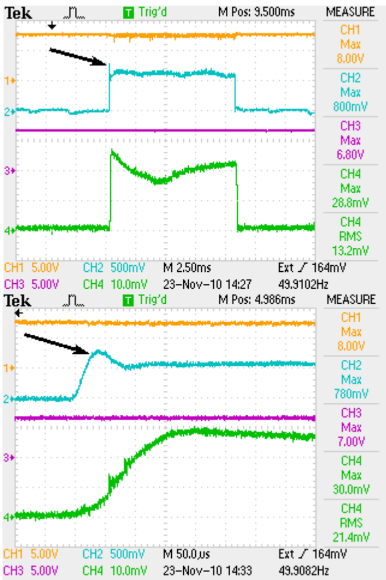


Fig. 8 From top trace, BR output voltage and current, tetrode supply output voltage and current after the RF test in November 20, 2010. Overshoot is shown with an arrow at the BR output current.

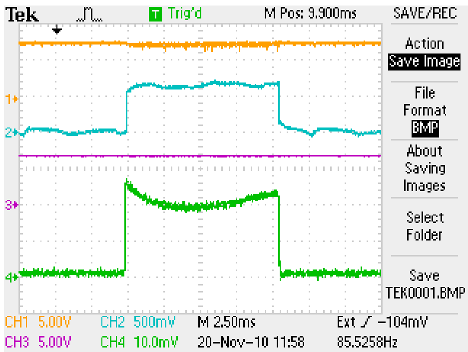


Fig. 9 From top trace, BR output voltage and current, tetrode supply output voltage and current before the RF test in November 20, 2010.

4-2) Timing of current rise-time for driver and final anode currents

Current spikes are pronounced for the tetrode anode current at the switching period as shown in fig. 10. In order to exclude possible instability in this period, BR switching was delayed after the tetrode current reached at its quiescent level: tetrode current spikes were moved out of the range where the triode is activated (November 24).

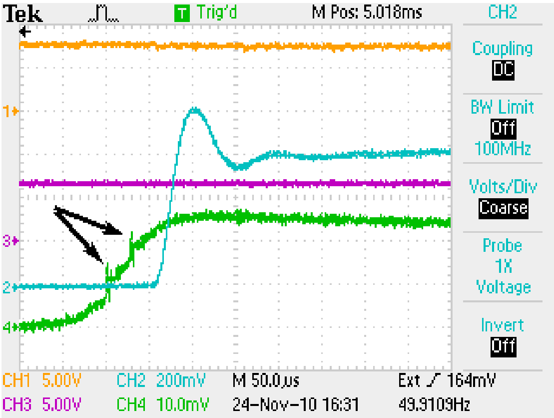


Fig. 10 From top trace, BR output voltage, tetrode supply output voltage, BR output current and tetrode supply output current. Tetrode current spikes are shown with arrows.

4-3) 66MHz component in the triode gridvolts and grid input current

Although the signal level is an order of 10mV, triode gridvolts and grid input current show 66MHz oscillation without an RF input, as shown in sections A-1 and A-2 of the appendix.

4-4) Waveforms at the onset of buck regulator current trip without 2.2 MHz RF input

In the last week of this experiment, LOI system became unstable that BR tripped at rather low output current without an RF input: BR tripped at 7Amps on November 22, and 3Amps on November 24 even without tetrode anode current. The trip was always accompanied by 130~160kHz oscillations in triode gridvolts as shown in sections A-3 and A-4. Such oscillations look the same with those generated at the anode current switching as shown in sections A-5, A-6 and A-9. It is seen, however, in section A-4 with a magnified scale that these oscillations are preceded by a burst of higher frequency components of 25~40MHz.

4-5) Spikes at the gridvolts and grid input current with 2.2MHz RF input

During RF ontime, an erratic jump of amplitude for all the RF signals appeared as shown in section A-7, A-9 and A-10. This step-function-like change is initiated by 169~182kHz oscillations.

4-6) Waveforms just before the onset of buck regulator current trip with 2.2MHz RF input

Figure in section A-8 was taken by triggering with gridvolts spike during RF ontime, where slight increase of an RF input causes the BR trip. It is seen that a burst of 25MHz component is created and damps over a cycle of 2.2MHz.

4-7) Buck regulator current waveform at the trip

A large oscillation at 27.1kHz was observed just before the BR current trip as shown in section A-11, where the BR current monitor is provided by the manufacturer DTI. It should be noted that the oscillation was preceded by the enhanced 9.6kHz oscillation, which is almost the switching frequency of the BR, 10kHz. Since 27.1kHz is higher than the switching frequency, the oscillation should be derived from external reason(s) other than inside of the BR: for example, there should be 27.1kHz oscillation at the triode grid input.

4-8) Triode gain

The triode gain was measured in November 25 without the bias current. The triode and tetrode anode currents were 10Amps average with 52.7% duty. The cavity voltage was less than 600Vpeak for the measurement, and the frequency was scanned between 2.206 and 2.28MHz around the cavity tuning point. The gain was 29~32, which agrees with that obtained previously [2]. However, in section A-12, comparison of grid and gap voltage envelopes shows a sudden change of the voltage gain. A large spike can be seen at $t = 0$sec, which is followed by an envelope with a slight increase of amplitude by 1.1. On the contrary, the gap volt changes by 3.5 after $t = 0$sec. We should think the circuit composition was essentially changed at $t = 0$sec by some reason(s).

As shown above, there are three frequency bands which seem related to the BR current trip: 9.6~27.1kHz, 130~180kHz and 25~40MHz. However, we have not succeeded yet to understand the correlation of them.

5. Other faults

(1) AC line in the 100V switch board was found to be burnt on November 11 (fig. 11). This was due to a poor contact of the cable end: repaired on the next day.

(2) With the rainfall, rain drops splashed onto the mezzanine. LOI modules are partly covered with sheets for protection on November 22.

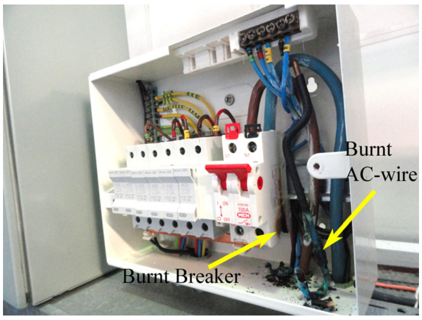


Fig. 11
Burnt AC100volts circuit breaker and the AC wire.

6. To-do-list

(1) Change “LOI Ready” to include “Buck Regulator Trip” status.

(2) Put a surge absorber at the output stage of the grid switcher.

(3) Extend bandwidth of the “OFFSET” input of the CAVTUN module to cover 50Hz.

(4) Replace G2 cable (RG58c/u) with RG8U between breakout boxes at SP6 and Hall 2.

(5) Make the LOI side panel thick with 6mm aluminium plate rather than the present 3mm thick.

7. Discussions and conclusions

This is the first experiment after the LOI was moved from the Hall 2 to the SP6 in the ISIS synchrotron. In the first day with an RF input, the LOI could produce 8.5kVpk across the cavity gap at 2.28MHz without a ferrite bias current, and it ended with the buck regulator (BR) current trip. Damages were found on the LOI modules in the following days. After repairs, however, only 1.2kVpk could be achieved at the cavity gap due to the BR trip. Apparently, burst of

25~40MHz components observed in the gridvolts and grid input current trigger the BR trip. Also, an erratic jump of amplitude is always seen for all the RF signals, which is initiated by 169~182kHz oscillations with a short period. The erratic jump accompanies the change of triode voltage gain, which is indicating the circuit composition is changed at this point. At the BR output current monitor, 27kHz oscillations could be seen just before the current trip. Since 27.1kHz is higher than the switching frequency, the oscillation should be derived from external reason(s) other than inside of the BR.

There seem to be three frequency bands which are related to the BR current trip. The correlation of these frequencies is yet to be understood. We are also thinking if there are any other damages in the LOI HPD, or in the BR, or in the final triode tube itself. It should be noted, however, that characteristics of the triode anode voltage and current is the same as before, ie 15kV with 10Amps with 50% duty.

Following subjects are also to be studied before the beam test, such as improvement of the waveform distortions, fine cavity-tuning and phase-locked operation with fundamental cavity. As for the waveform distortion at grid voltage, it is essential to remove the subharmonic component in the RF law signal [3].

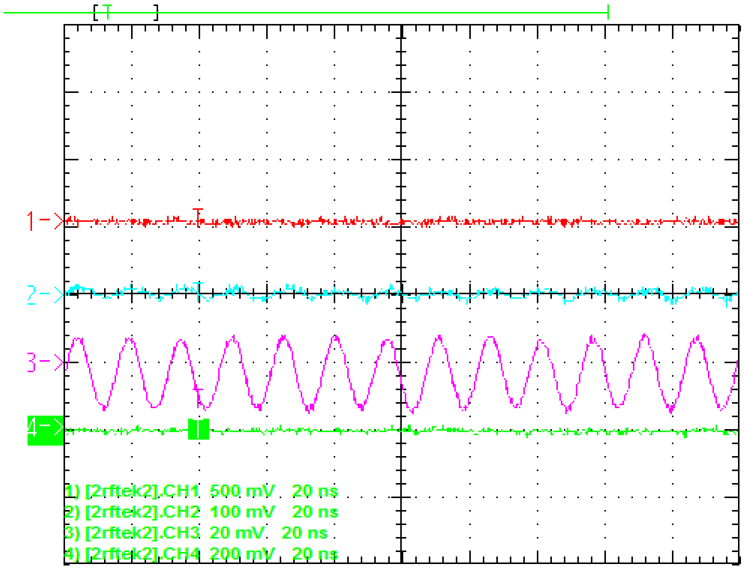
References:

[1] LOI Progress Report LOI-7, http://www-accps.kek.jp/Low-Impedance_Cavity/LOI-7.pdf
[2] T Oki et al, Nuclear Instruments and Methods in Physics Research, A565, pp.358-369, 2006.
[3] LOI Progress Report LOI-8, http://www-accps.kek.jp/Low-Impedance_Cavity/LOI-8.pdf

RF waveforms

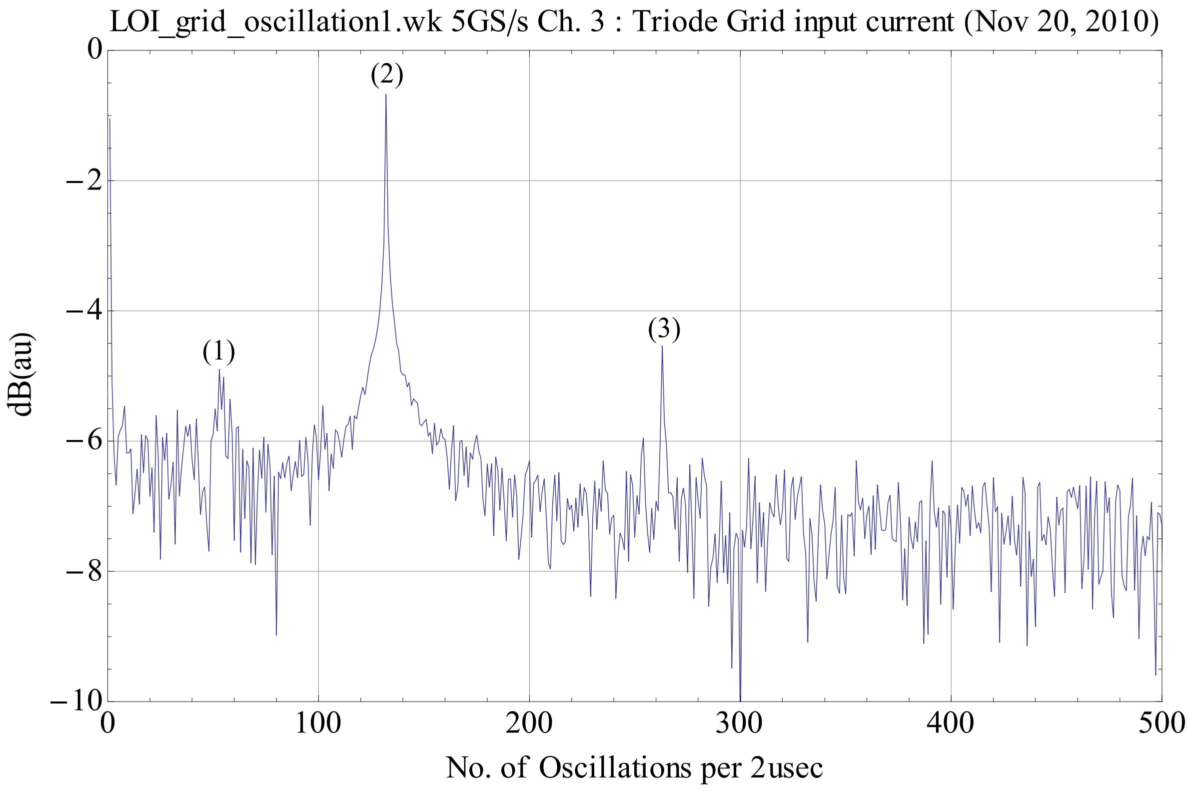
(A-1) LOI_grid_oscillation1.wk 5GS/s (Nov 20, 2010)
No RF input to LOI system.
(A-2) LOI_grid_oscillation2.wk 5GS/s (Nov 20, 2010)
No RF input to LOI system.
(A-3) LOI_buckreg_trip.wk 10MS/s (Nov 22, 2010)
Conditions triggered on buck regulator trip,
No RF input to LOI system.
(A-4) LOI_buckreg_trip_10us.wk 100MS/s (Nov 22, 2010)
Conditions triggered on buck regulator trip,
No RF input to LOI system.
(A-5) LOI_600gapvolts_spikes.wk 500KS/s (Nov 26, 2010)
RF input to LOI system through ISIS AVC.
(A-6) LOI_600gapvolts_spikes-env-20MHz.wk 500KS/s (Nov 26, 2010)
RF input to LOI system through ISIS AVC,
AVC gain not on full - stopped on envelope mains ripple.
:poor resolution to see the spikes in detail. See (A-10)
(A-7) LOI_600gapvolts_spikes-fast.wk 250MS/s (Nov 26, 2010)
RF input to LOI system through ISIS AVC & RF at 2.206 MHz,
Triggered on Gridvolts spike during RF ontime.
(A-8) LOI_600gapvolts_spikes-fast-20MHz.wk 250MS/s (Nov 26, 2010)
RF input to LOI system through ISIS AVC & RF at 2.206 MHz,
Triggered on Gridvolts spike during RF ontime – nearer to trip.
(A-9) LOI_Dec21_2010_20ms.wk 500kHz (Dec 21, 2010)
LOI operation @ 700V
(A-10) LOI_Dec21_2010_1ms_steptrigger.wk 10MHz (Dec 21, 2010)
LOI operation @ 700V
(A-11) LOI_Dec21_2010_100us_steptrigger.wk 100MHz (Dec 21, 2010)
LOI operation @ 700V
Scope 1 Ch3: Buck Regulator current triggered on trip as winding up RF.
(A-12) JanRunning3.wk 500KS/s (Jan 12, 2011)
LOI tests with reduced standing current

(A-1) LOI_grid_oscillation1.wk 5GS/s (Nov 20, 2010)



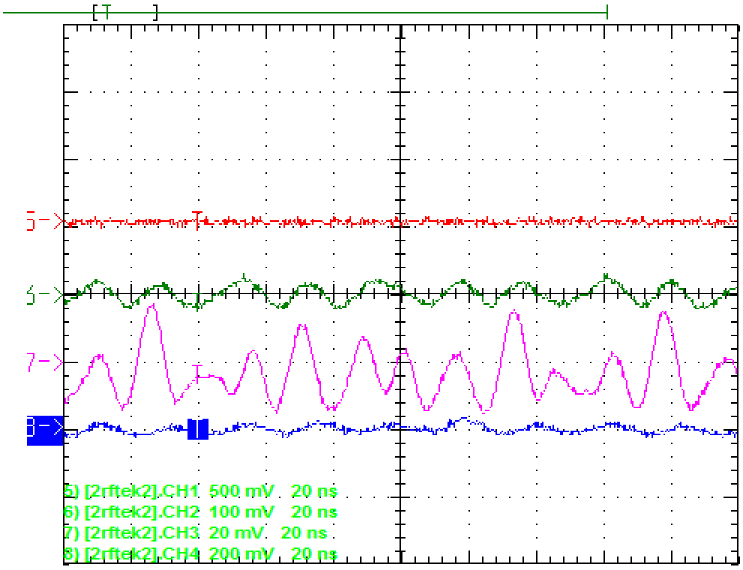
LOI test Nov 20, 2010
No RF input to LOI system

Ch1: Gapvolts Envelope (1V=1.2kV pk)
Ch2: Triode Gridvolts
Ch3: Triode Grid input current
Ch4: Cavity input current



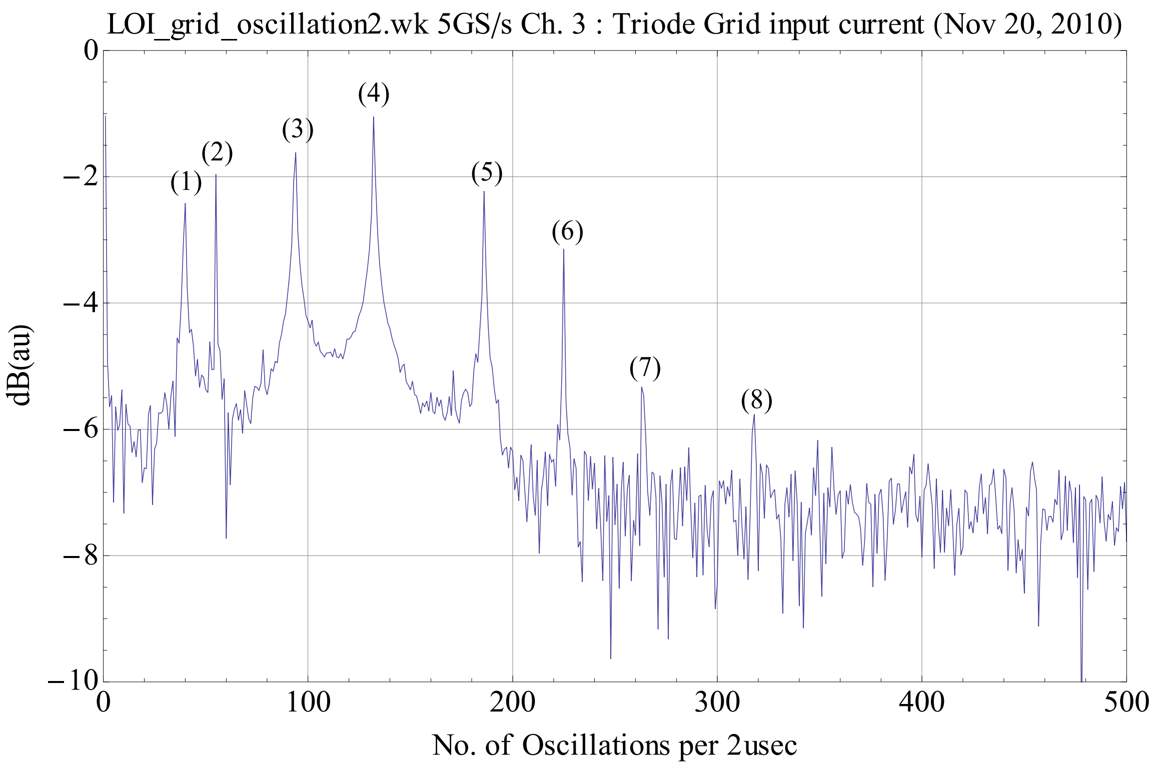
FFT: (1) 26.8MHz, (2) 66MHz, (3) 131.2MHz.

(A-2) LOI_grid_oscillation2.wk 5GS/s (Nov 20, 2010)



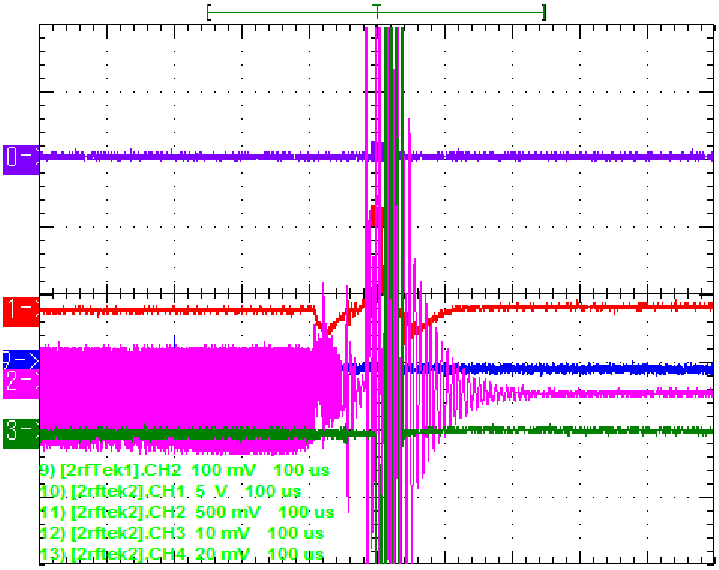
LOI test Nov 20, 2010
No RF input to LOI system

Ch1: Gapvolts Envelope (1V=1.2kV pk)
Ch2: Triode Gridvolts
Ch3: Triode Grid input current
Ch4: Cavity input current



FFT: (1) 20.0MHz, (2) 27.4MHz, (3) 46.8MHz, (4) 66.1MHz, (5) 93.2MHz, (6) 112.5MHz, (7) 131.9MHz, (8) 159.0MHz.

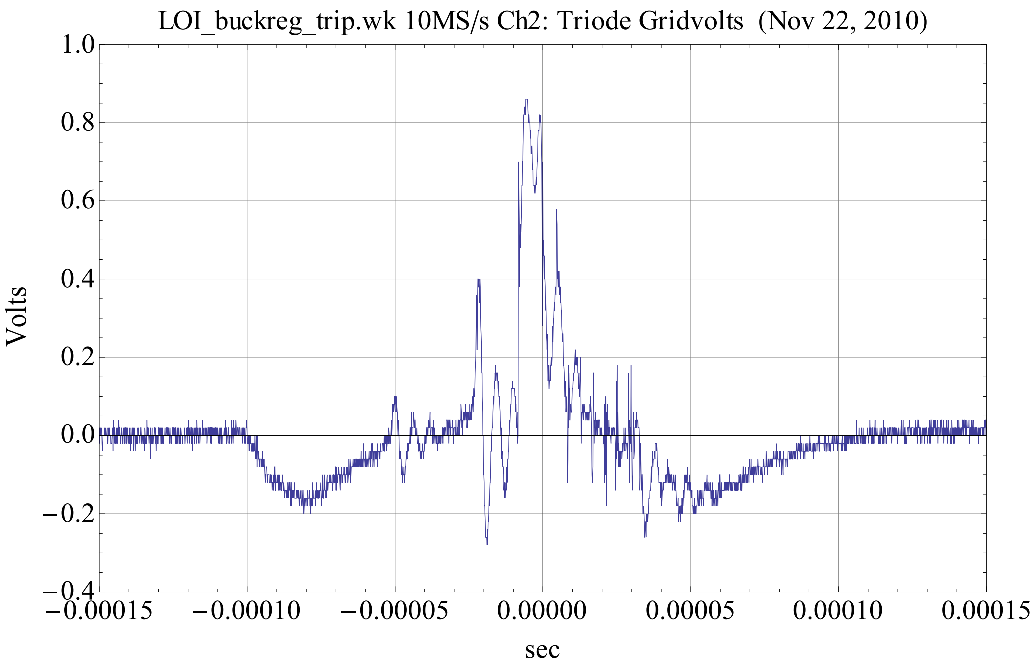
(A-3) LOI_buckreg_trip.wk 10MS/s (Nov 22, 2010)



LOI test Nov 22, 2010

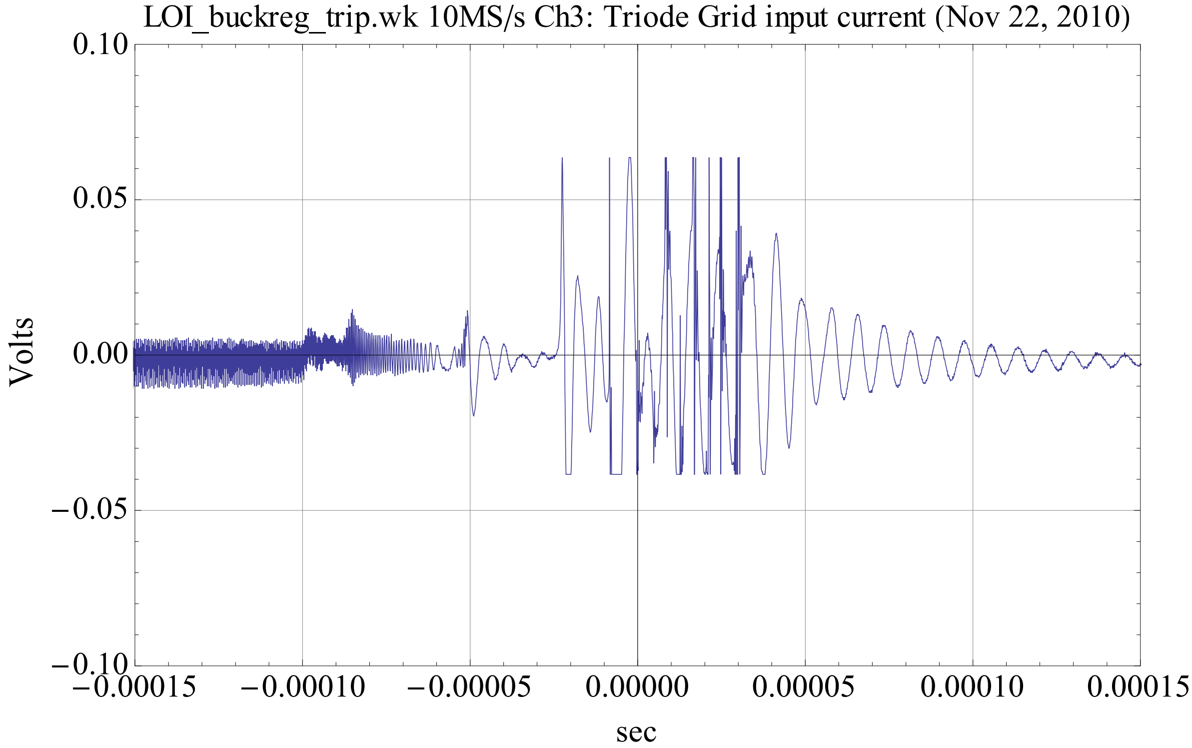
Conditions triggered on buck regulator trip
No RF input to LOI system
Scope 1 Ch2: Cavity Gapvolts monitor

Ch1: Gapvolts Envelope (1V=1.2kV pk)
Ch2: Triode Gridvolts
Ch3: Triode Grid input current
Ch4: Cavity input current



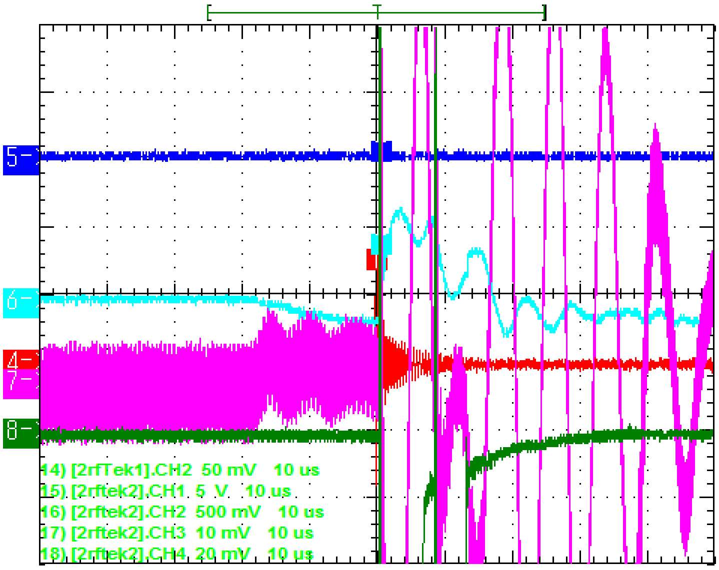
1/peak distance = 158.5KHz.

(A-3)



Ringing frequency: ~3.3MHz (left part) and 158 ~ 127kHz(right part).

(A-4) LOI_buckreg_trip_10us.wk 100MS/s (Nov 22, 2010)

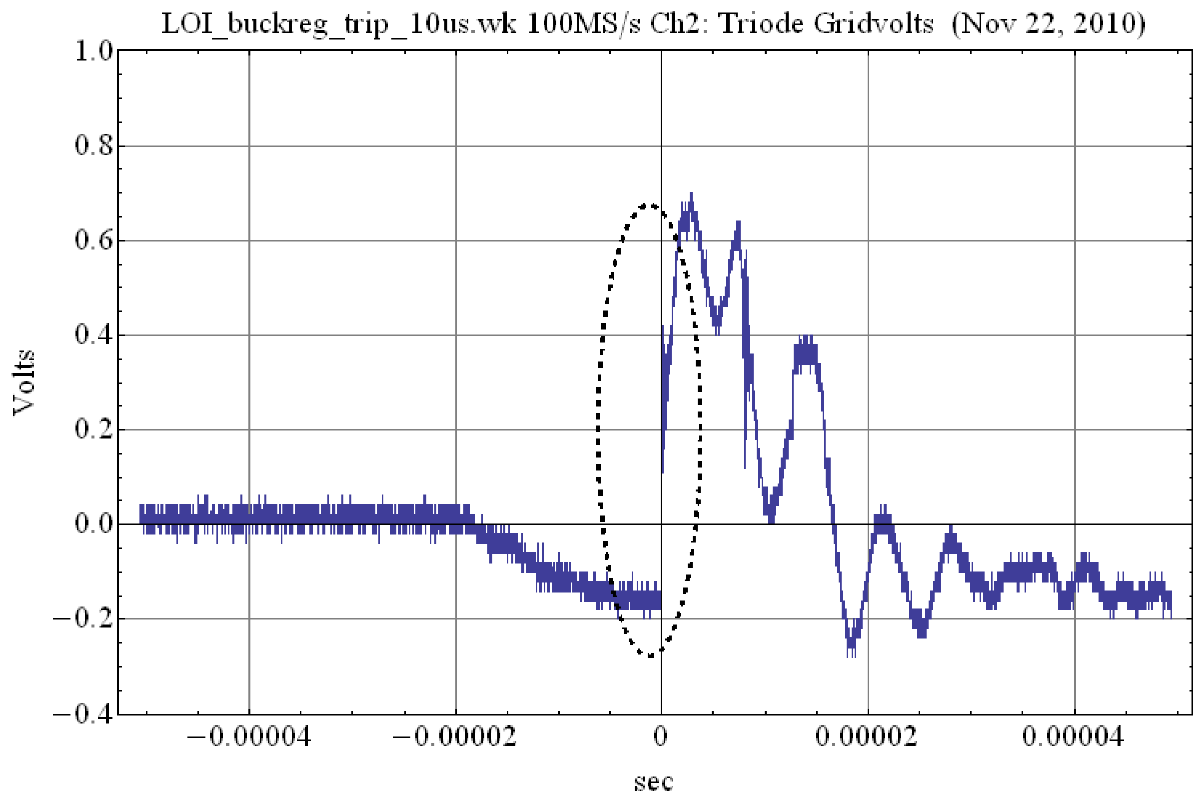


LOI test Nov 22, 2010

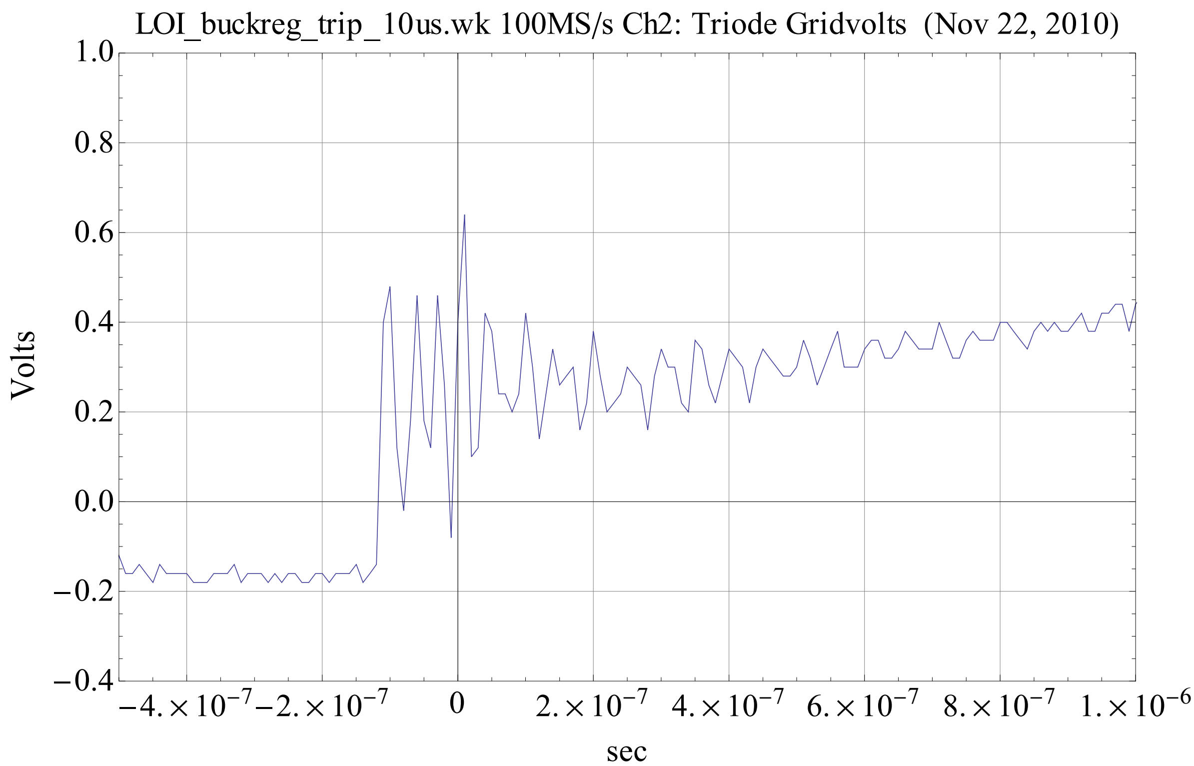
Conditions triggered on buck regulator trip
No RF input to LOI system
Scope 1 Ch2: Cavity Gapvolts monitor

Ch1: Gapvolts Envelope (1V=1.2kV pk)
Ch2: Triode Gridvolts
Ch3: Triode Grid input current
Ch4: Cavity input current

(A-4)



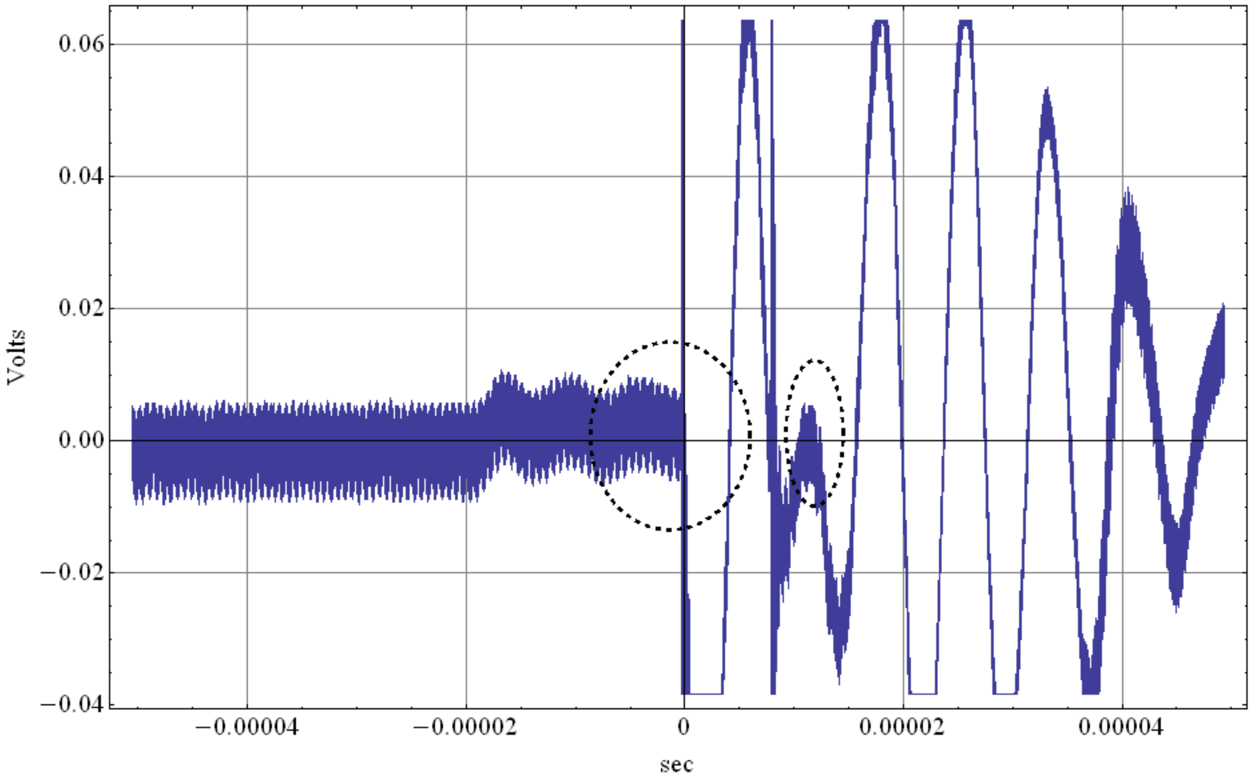
1/peak distance = 133kHz.



Fine structure at the onset. 1/peak distance = 24.6MHz.

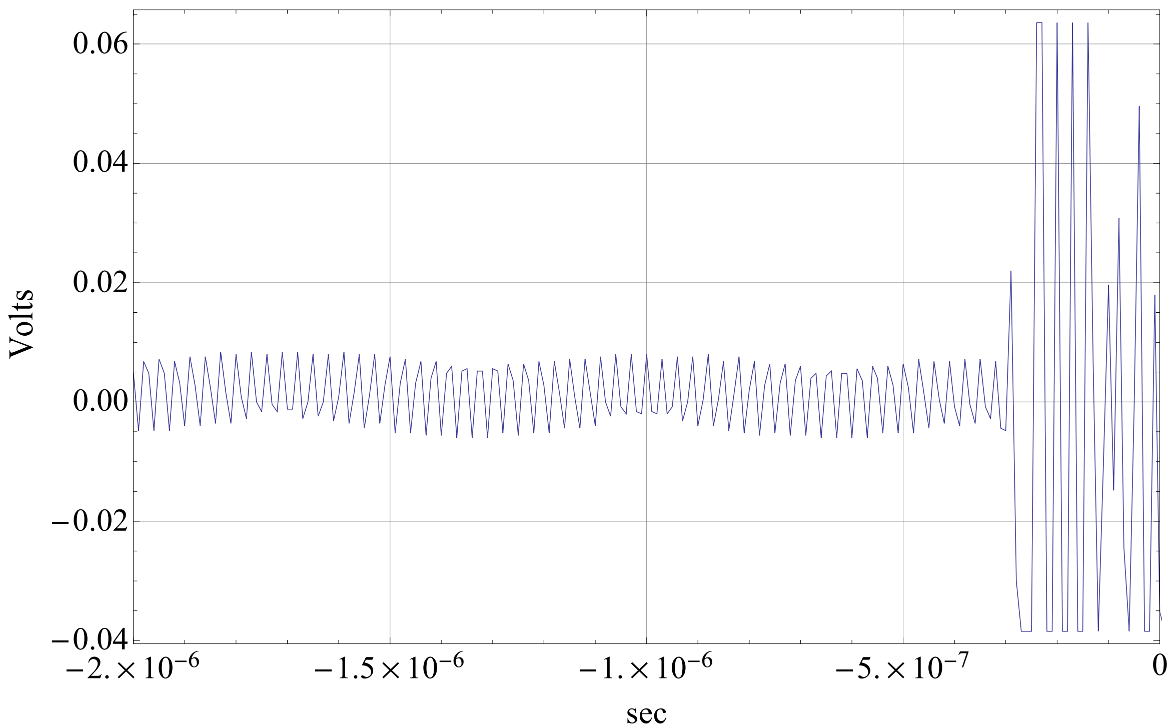
(A-4)

LOI_buckreg_trip_10us.wk 100MS/s Ch3: Triode Grid input current (Nov 22, 2010)



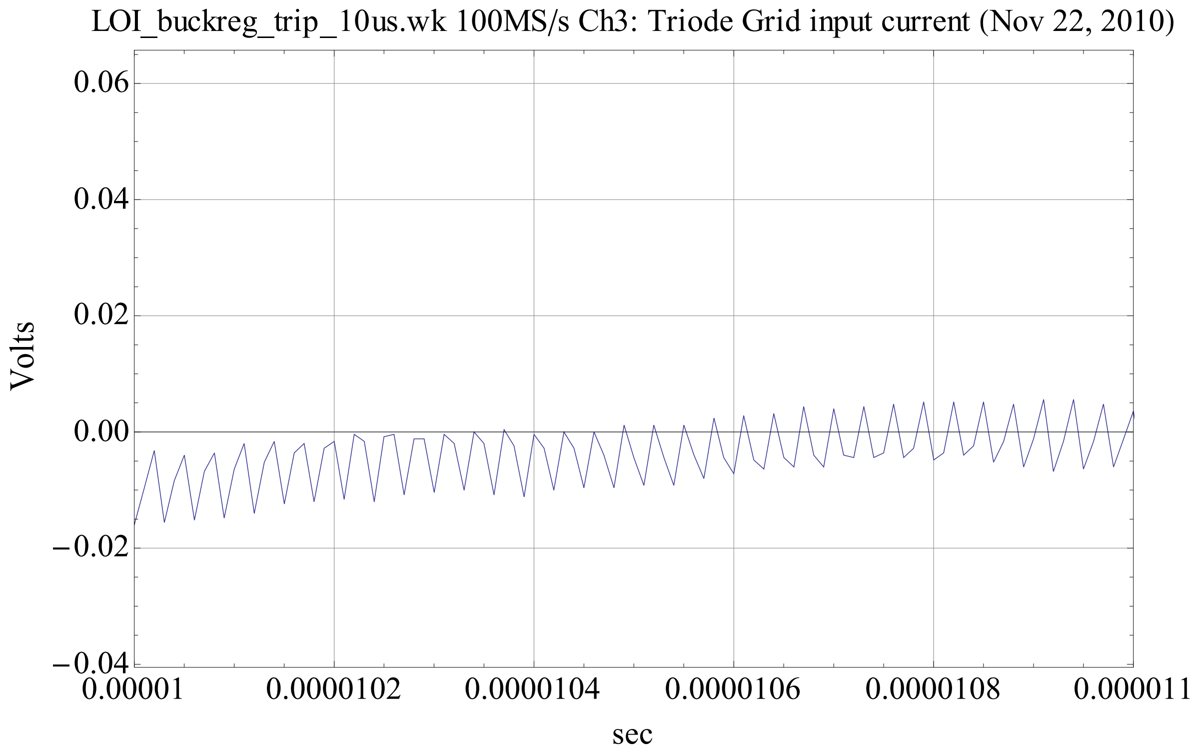
1/peak distance = 134kHz.

LOI_buckreg_trip_10us.wk 100MS/s Ch3: Triode Grid input current (Nov 22, 2010)



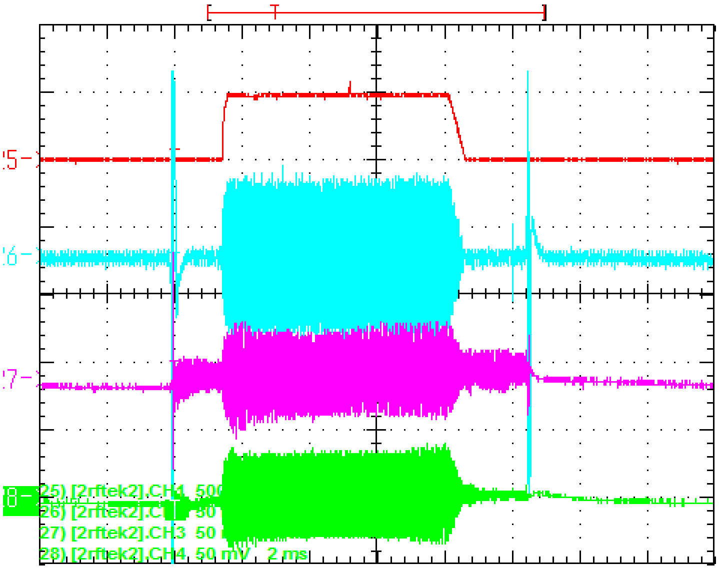
Fine structure at the onset. 1/peak distance = 34 ~ 39MHz.

(A-4)



1/peak distance = 33MHz.

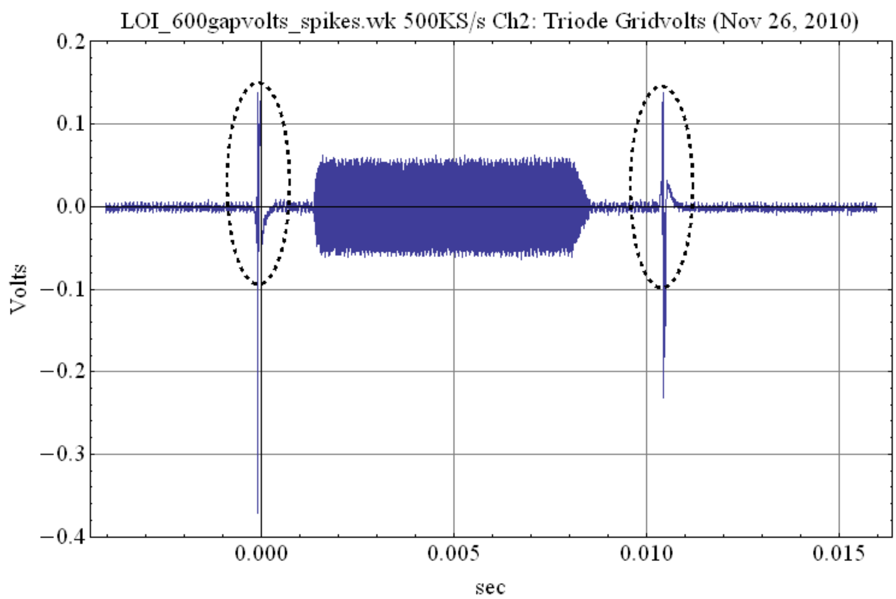
(A-5) LOI_600gapvolts_spikes.wk 500KS/s (Nov 26, 2010)



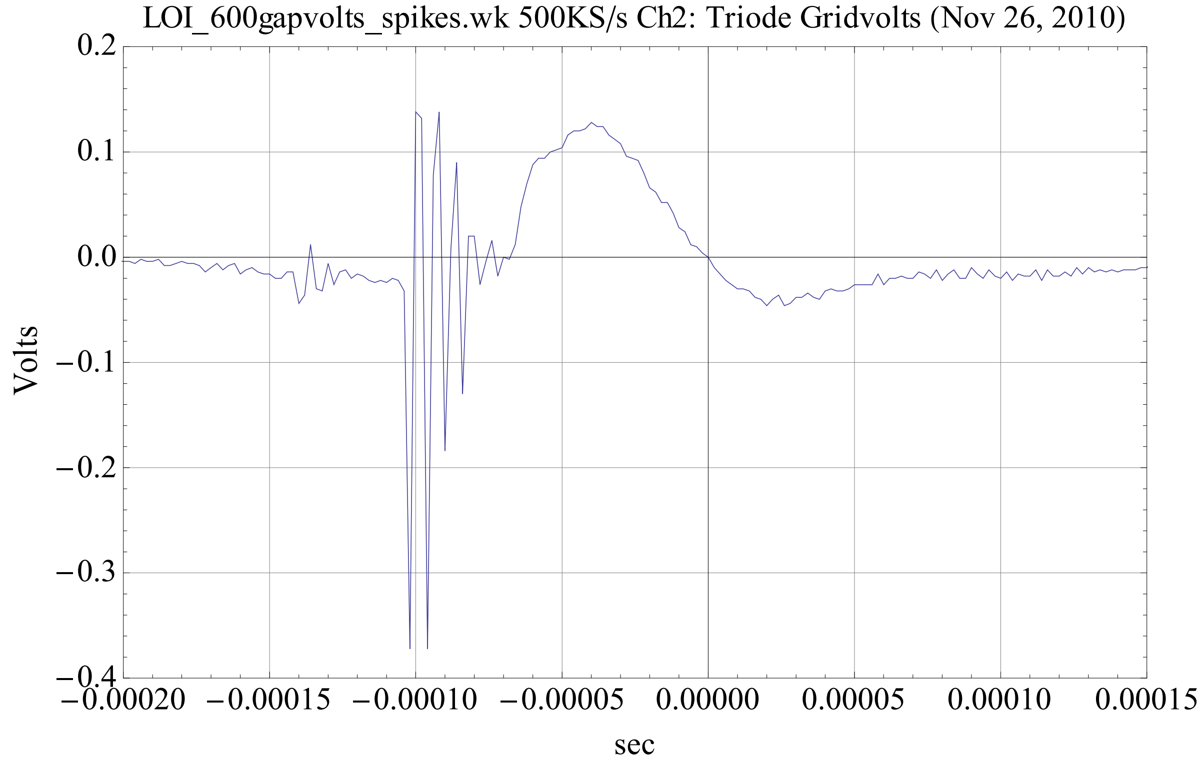
LOI test Nov 26, 2010
RF input to LOI system through ISIS AVC (envelope demand: 1ms,0.0V, 1.5ms, 0.5V, 8ms, 0.5V, 8.5ms, 0V) & RF at 2.206 MHz

Ch1: Gapvolts Envelope (1Vpk = 1.2kV pk)
Ch2: Triode Gridvolts (1Vpk = 309 Vpk)
Ch3: Triode Grid input current (0.1V= 2A into 50Ohms)
Ch4: Cavity input current (0.1V= 2A into 50Ohms)

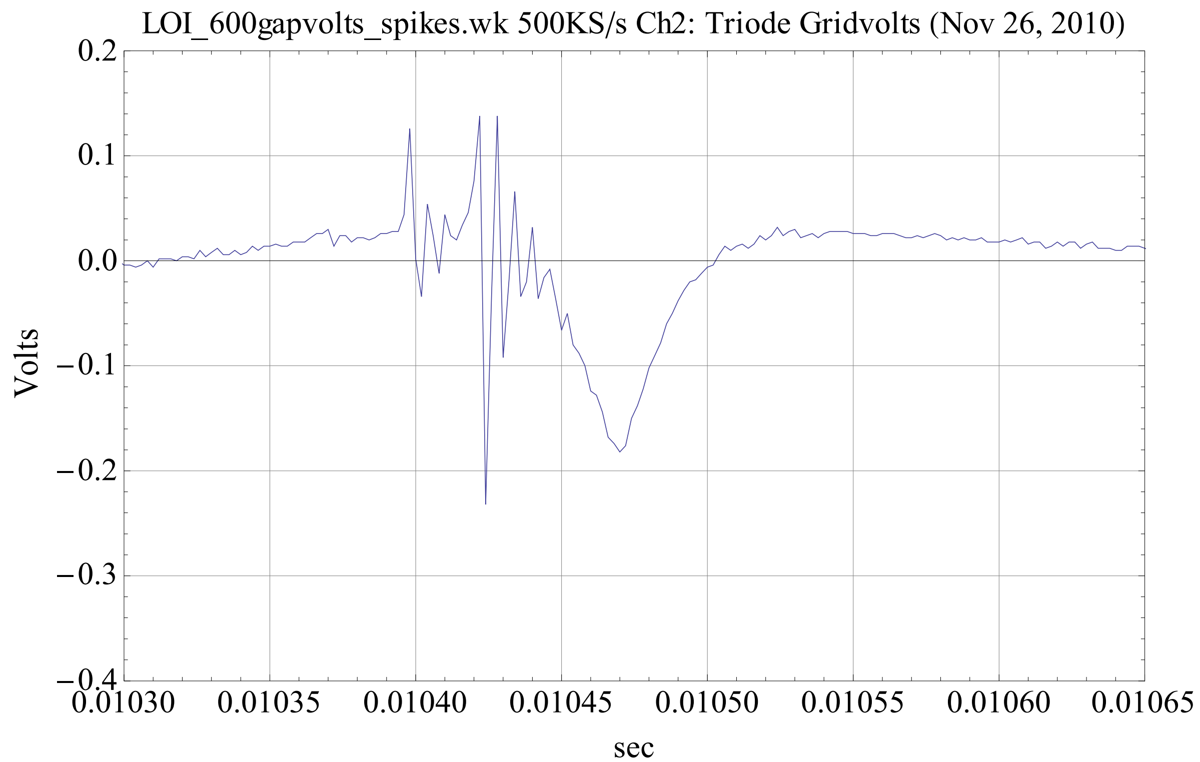
NB 2RF6 PD output is showing -7V during RF ontime => 70degrees



(A-5)

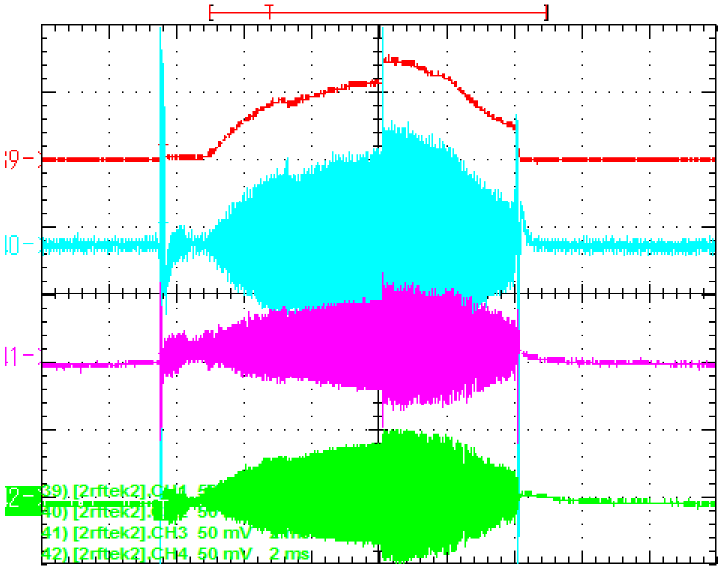


Triode gridvolts at the beginning of anode switching: ringing frequency is 156kHz, width of broad peak is ~80usec.



Triode gridvolts at the end of anode switching: ringing frequency is 167kHz, width of broad peak is ~60usec.

(A-6) LOI_600gapvolts_spikes-env-20MHz.wk 500KS/s (Nov 26, 2010)



LOI test Nov 26, 2010

RF input to LOI system through ISIS AVC (envelope demand: 1ms,0.0V, 1.5ms, 1.0V, 8ms, 1.0V, 8.5ms, 0V) & RF at 2.206 MHz

AVC gain not on full - stopped on envelope mains ripple

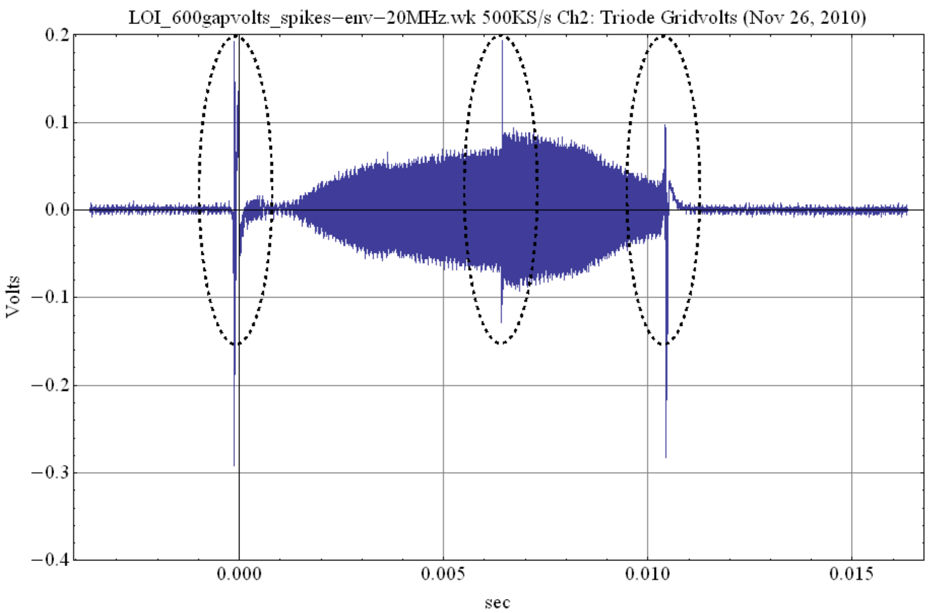
Ch1: Gapvolts Envelope (1Vpk = 1.2kV pk)

Ch2: Triode Gridvolts (1Vpk = 309 Vpk)

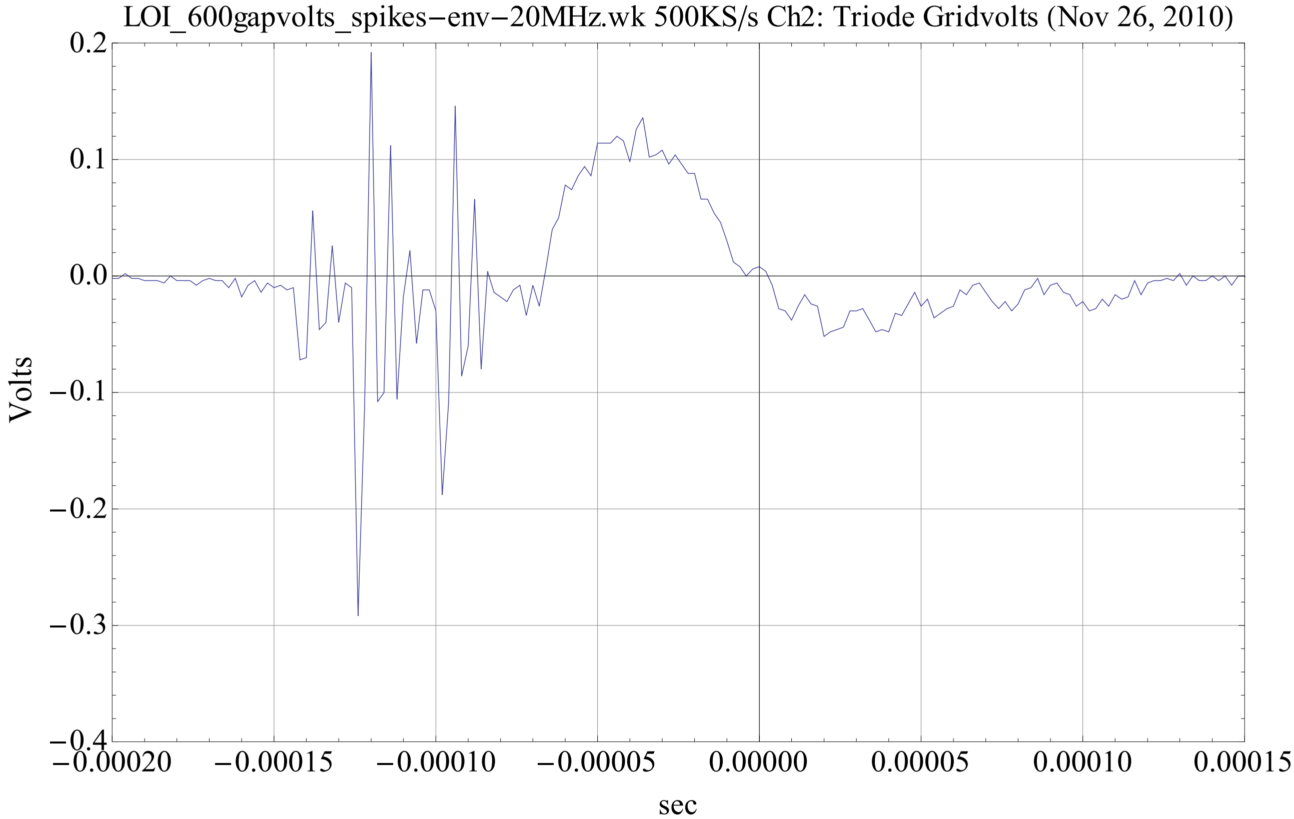
Ch3: Triode Grid input current (0.1V= 2A into 50Ohms)

Ch4: Cavity input current (0.1V= 2A into 50Ohms)

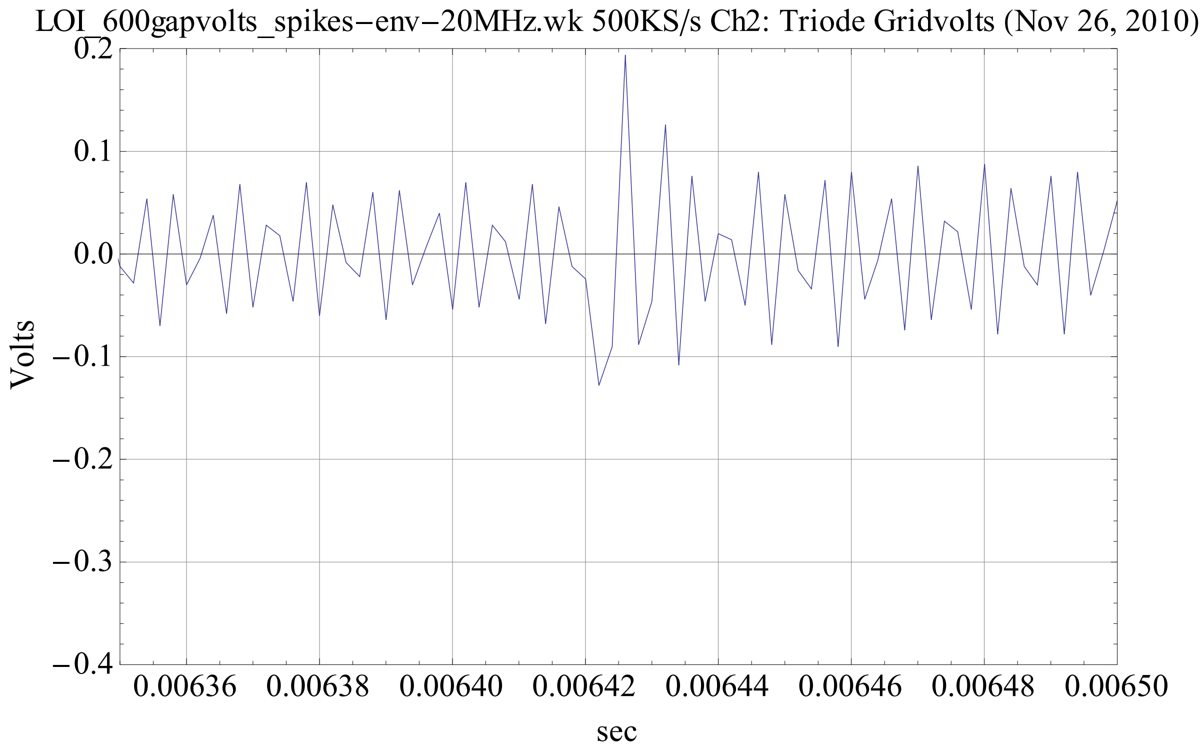
Triggered on Gridvolts spike during RF on time showing 40ns period ~ 25MHz same as oscillation after grid switching



(A-6)

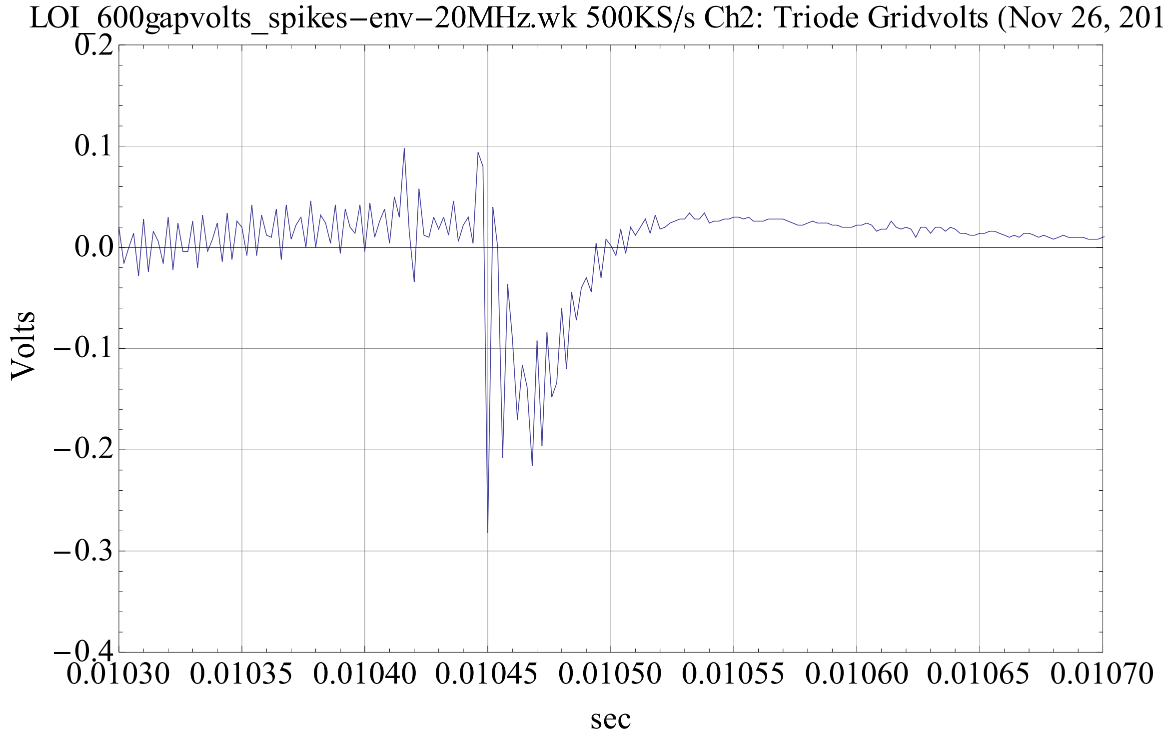


At the beginning of anode switching: ringing frequency is 170kHz, width of broad peak is ~70usec.



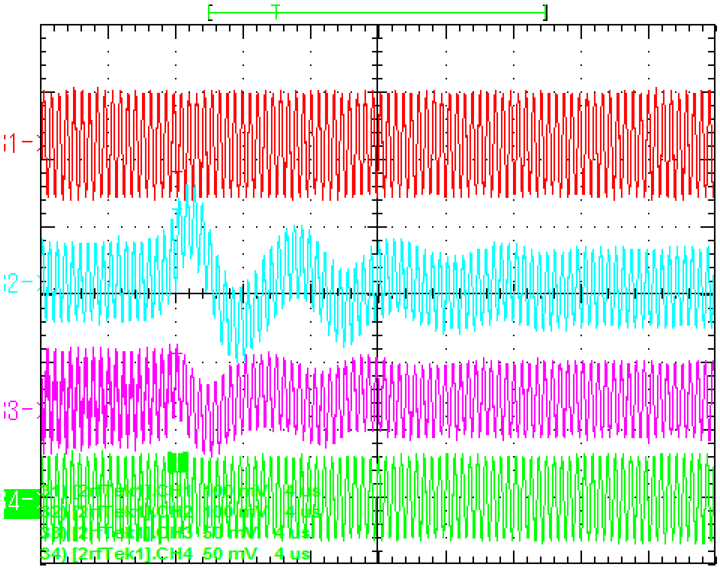
In the middle of RF period/near at the erratic jump of envelope.
1/peak distance = 167kHz: poor resolution!! (should be around 2.2MHz)

(A-6)



At the end of anode switching: ringing frequency is 100.0kHz, width of broad peak is ~50usec.

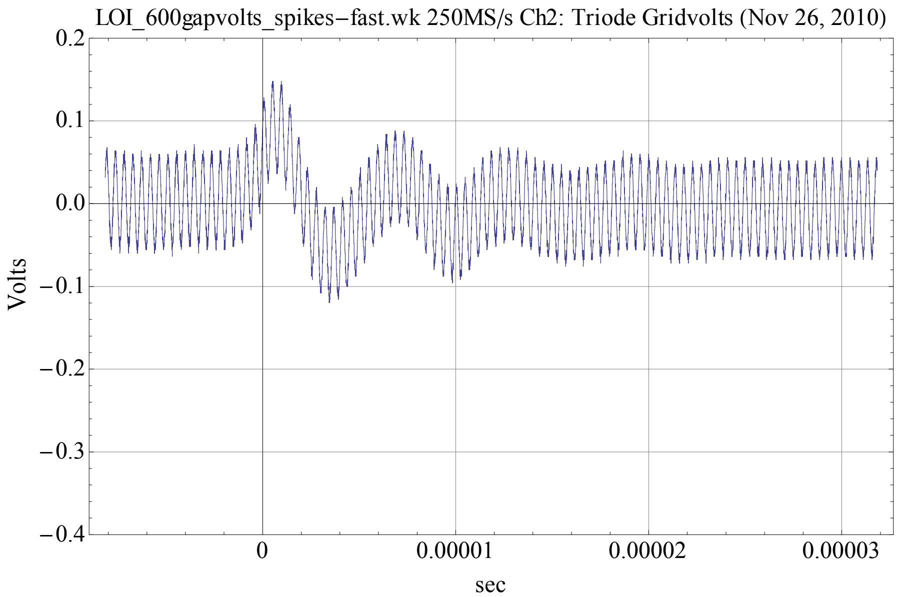
(A-7) LOI_600gapvolts_spikes-fast.wk 250MS/s (Nov 26, 2010)



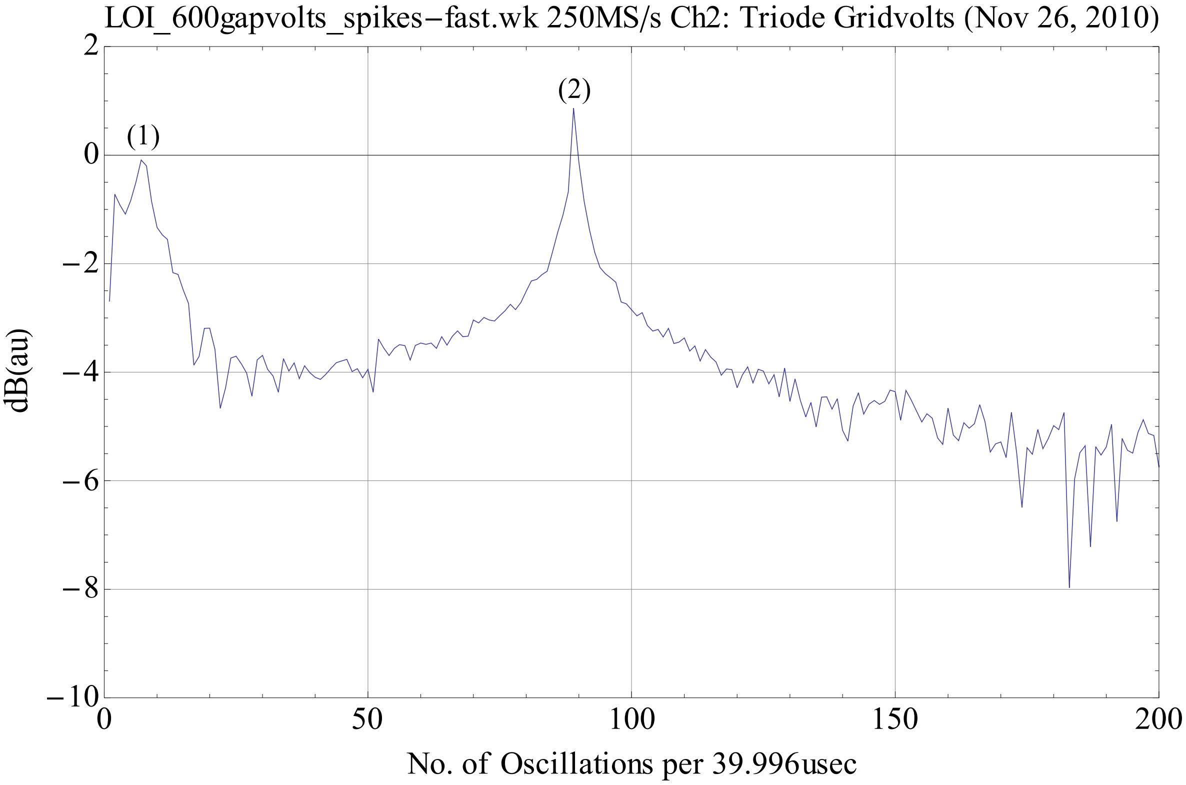
LOI test Nov 26, 2010
RF input to LOI system through ISIS AVC (envelope demand: 1ms,0.0V, 1.5ms, 0.5V, 8ms, 0.5V, 8.5ms, 0V) & RF at 2.206 MHz

Ch1: Gapvolts Envelope (1Vpk = 1.2kV pk)
Ch2: Triode Gridvolts (1Vpk = 309 Vpk)
Ch3: Triode Grid input current (0.1V= 2A into 50Ohms)
Ch4: Cavity input current (0.1V= 2A into 50Ohms)

Triggered on Gridvolts spike during RF ontime showing 6.64us period ~ 150KHz same as oscillation after grid switching

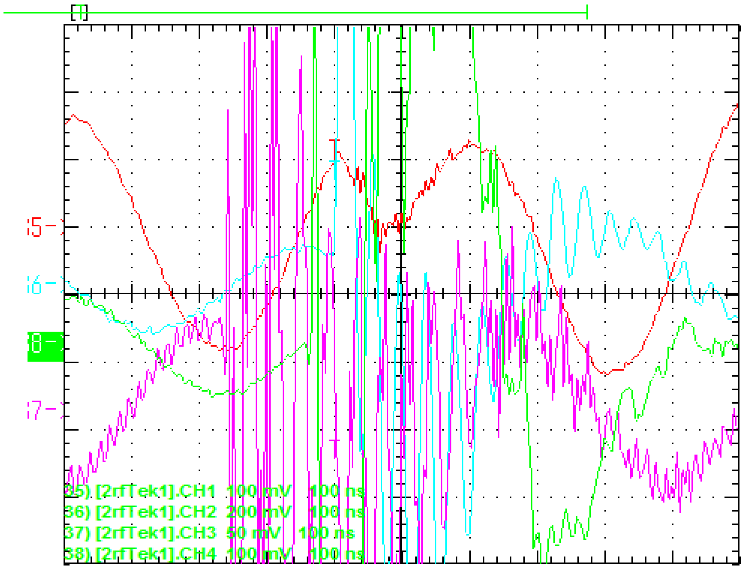


(A-7)



FFT: (1) 182kHz, (2) 2.219MHz.

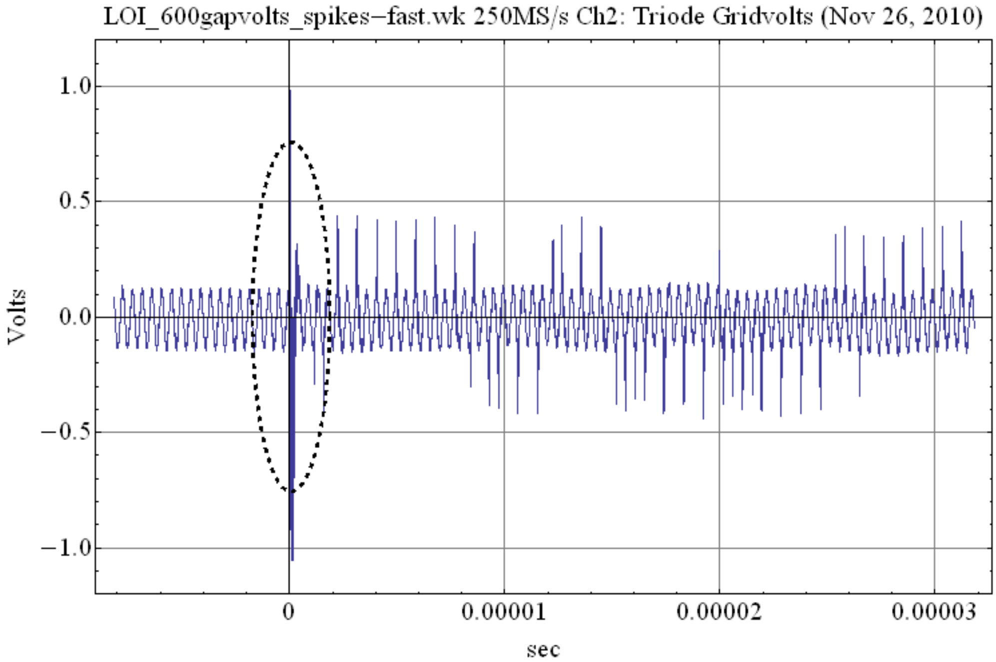
(A-8) LOI_600gapvolts_spikes-fast-20MHz.wk 250MS/s (Nov 26, 2010)



LOI test Nov 26, 2010
RF input to LOI system through ISIS AVC (envelope demand: 1ms,0.0V, 1.5ms, 1.0V, 8ms, 1.0V, 8.5ms, 0V) & RF at 2.206 MHz

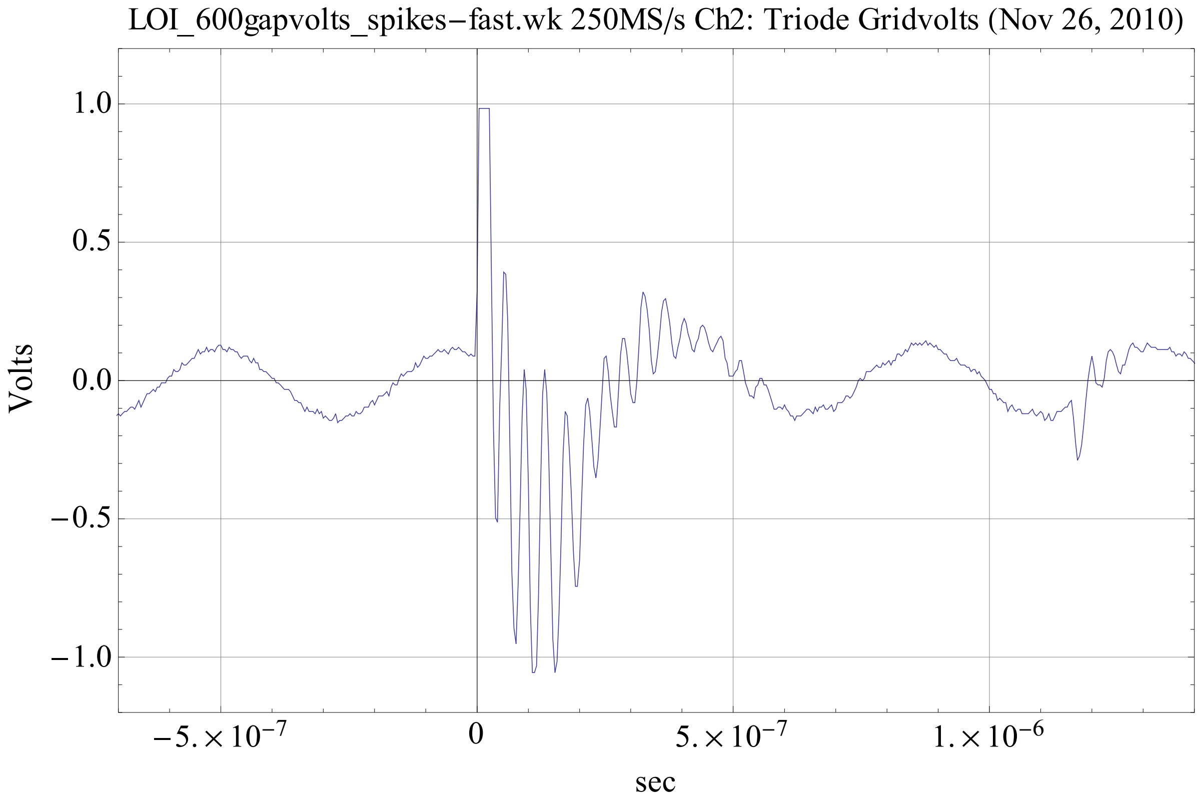
Ch1: Gapvolts Envelope (1Vpk = 1.2kV pk)
Ch2: Triode Gridvolts (1Vpk = 309 Vpk)
Ch3: Triode Grid input current (0.1V= 2A into 50Ohms)
Ch4: Cavity input current (0.1V= 2A into 50Ohms)

Triggered on Gridvolts spike during RF ontime showing 40ns period ~ 25MHz same as oscillation after grid switching – nearer to trip.

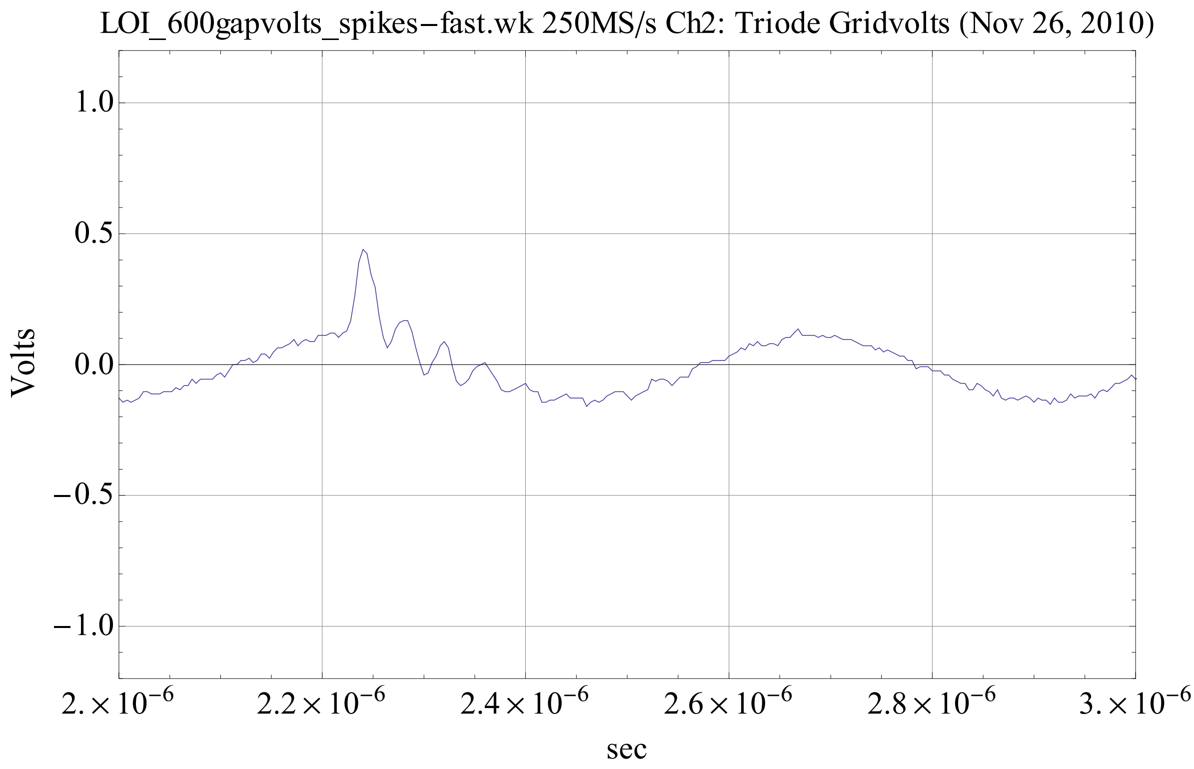


Frequency of the continuous wave is 2.207MHz.

(A-8)

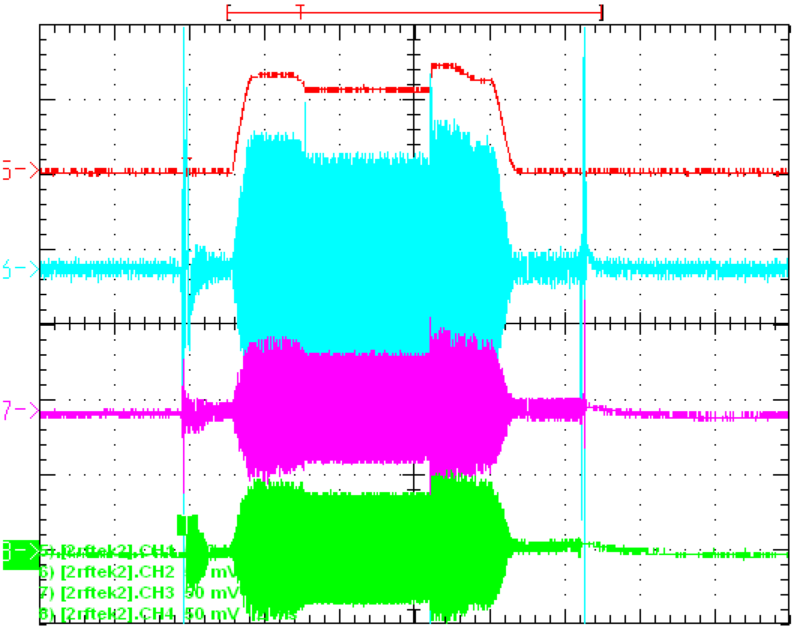


Spike frequency = 25MHz.



Spike frequency = 25MHz.

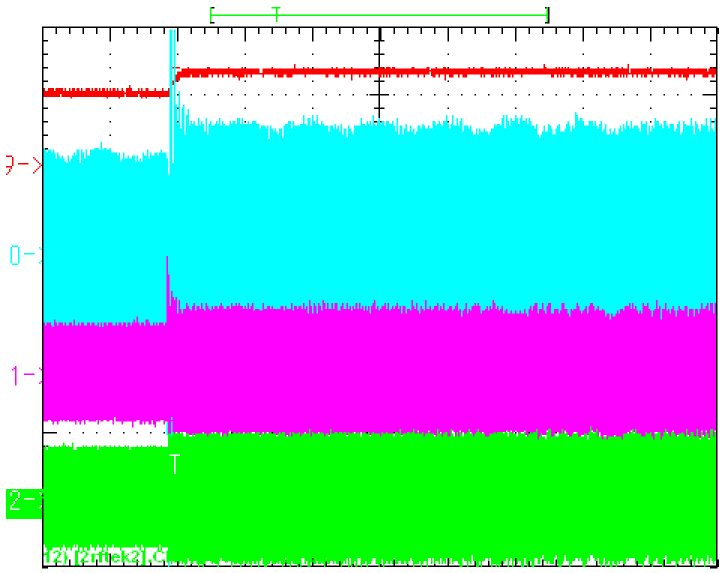
(A-9) LOI_Dec21_2010_20ms.wk 500kHz (Dec 21, 2010)



LOI operation @ 700V

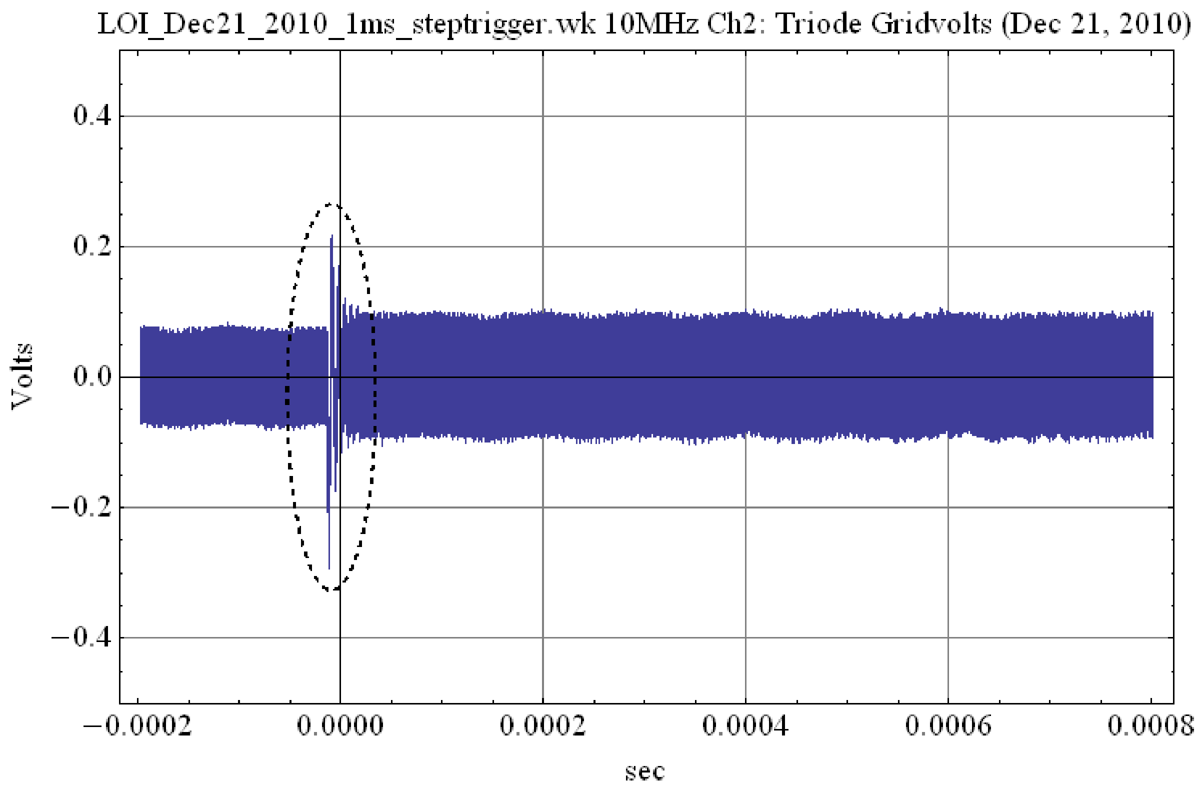
Ch1 Gapvolts envelope
Ch2 Triode Gridvolts
Ch3 Triode grid input current (.1V = 2A into 50ohms)
Ch4 Cavity input current (.1V = 2A into 50ohms)

(A-10) LOI_Dec21_2010_1ms_steptrigger.wk 10MHz   (Dec 21, 2010)

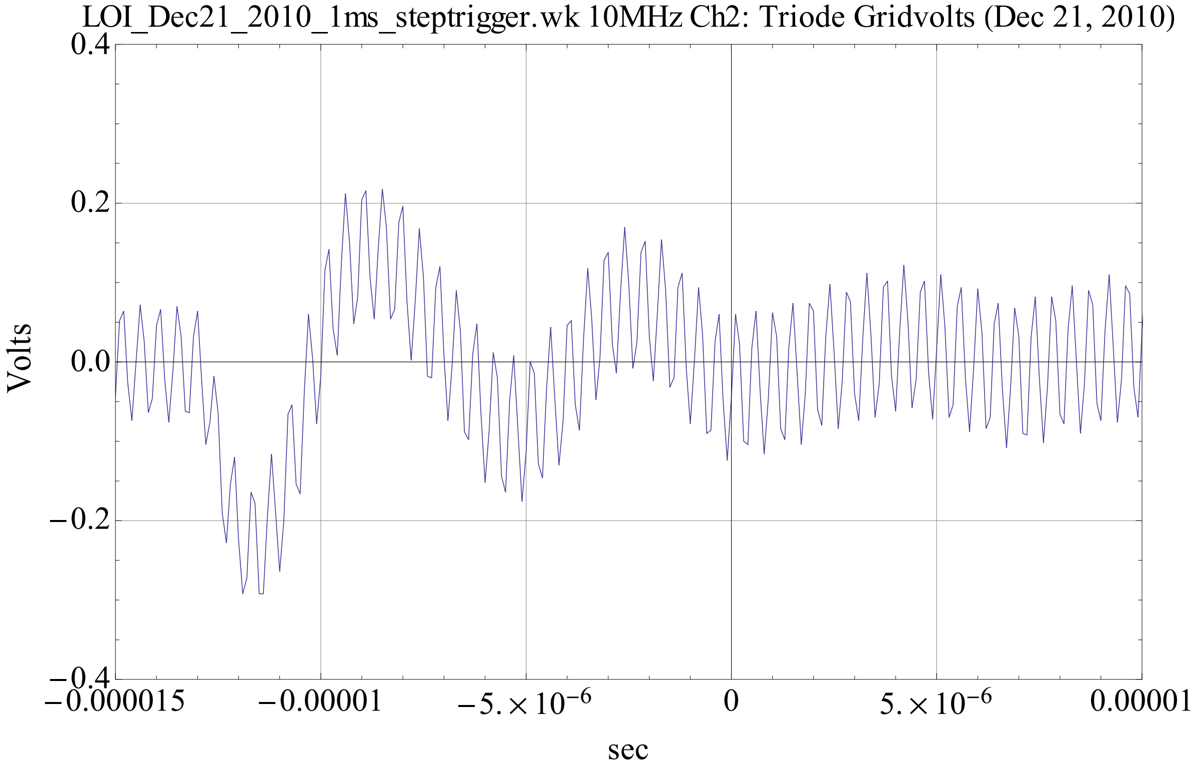


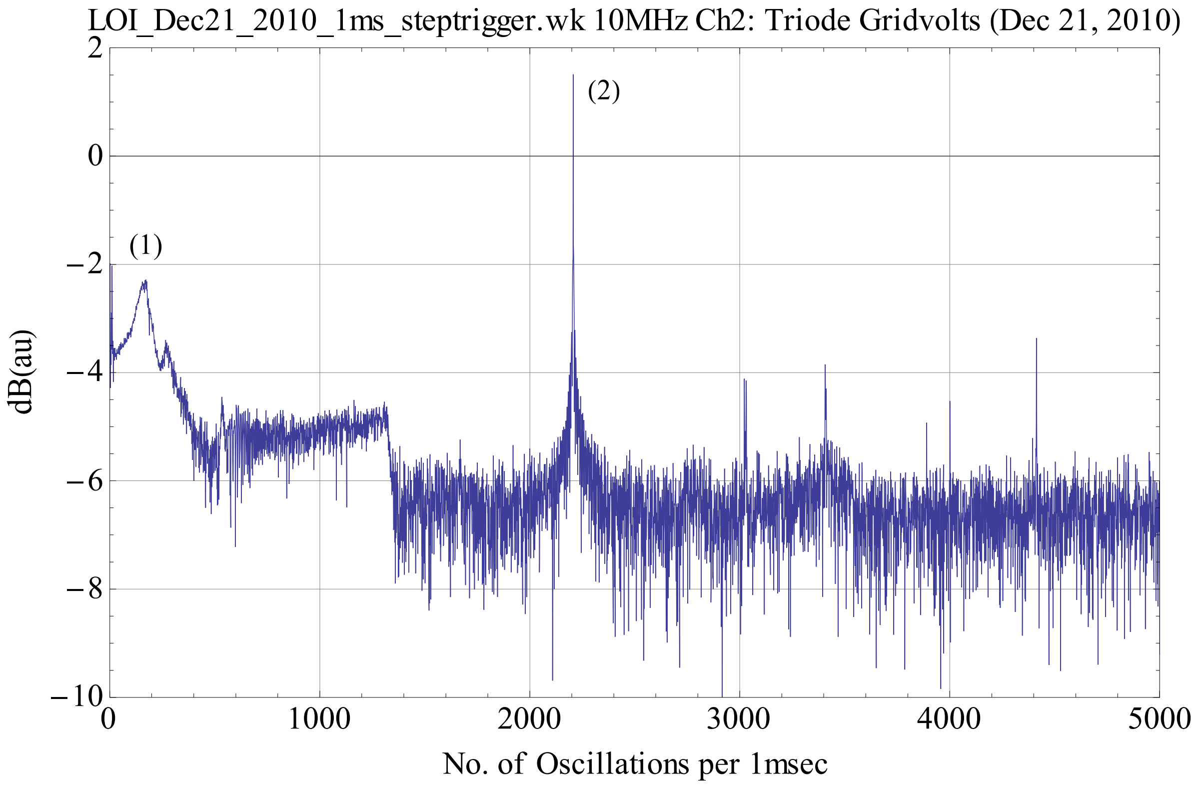
LOI operation @ 700V

Ch1 Gapvolts envelope
Ch2 Triode Gridvolts
Ch3 Triode grid input current (.1V = 2A into 50ohms)
Ch4 Cavity input current (.1V = 2A into 50ohms)



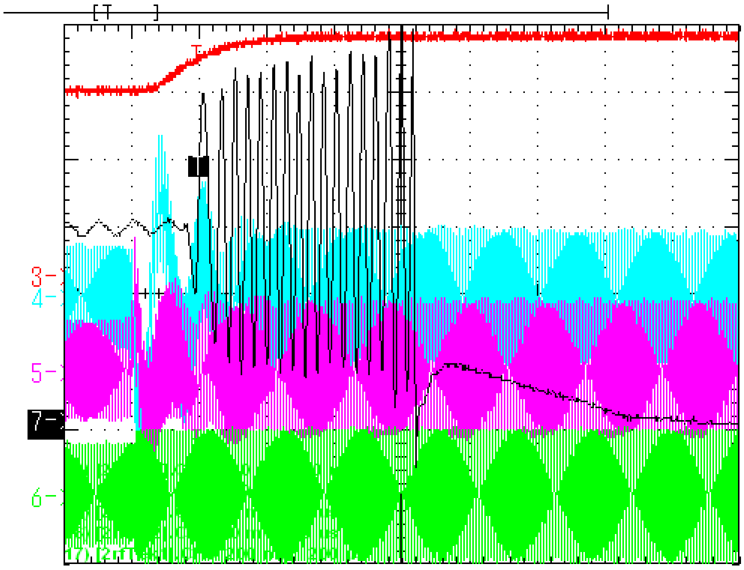
(A-10)





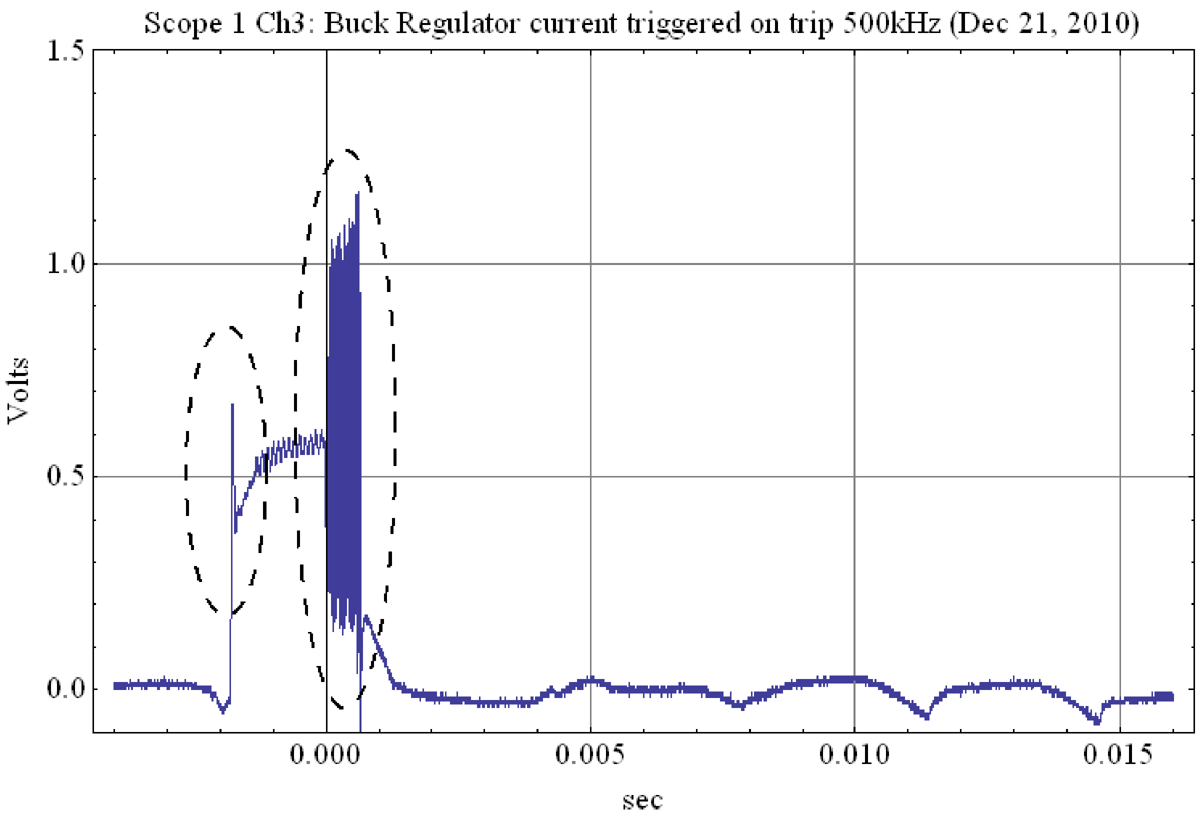
FFT: (1) 168.5kHz, (2) 2.205MHz.

(A-11) LOI_Dec21_2010_100us_steptrigger.wk 100MHz (Dec 21, 2010)

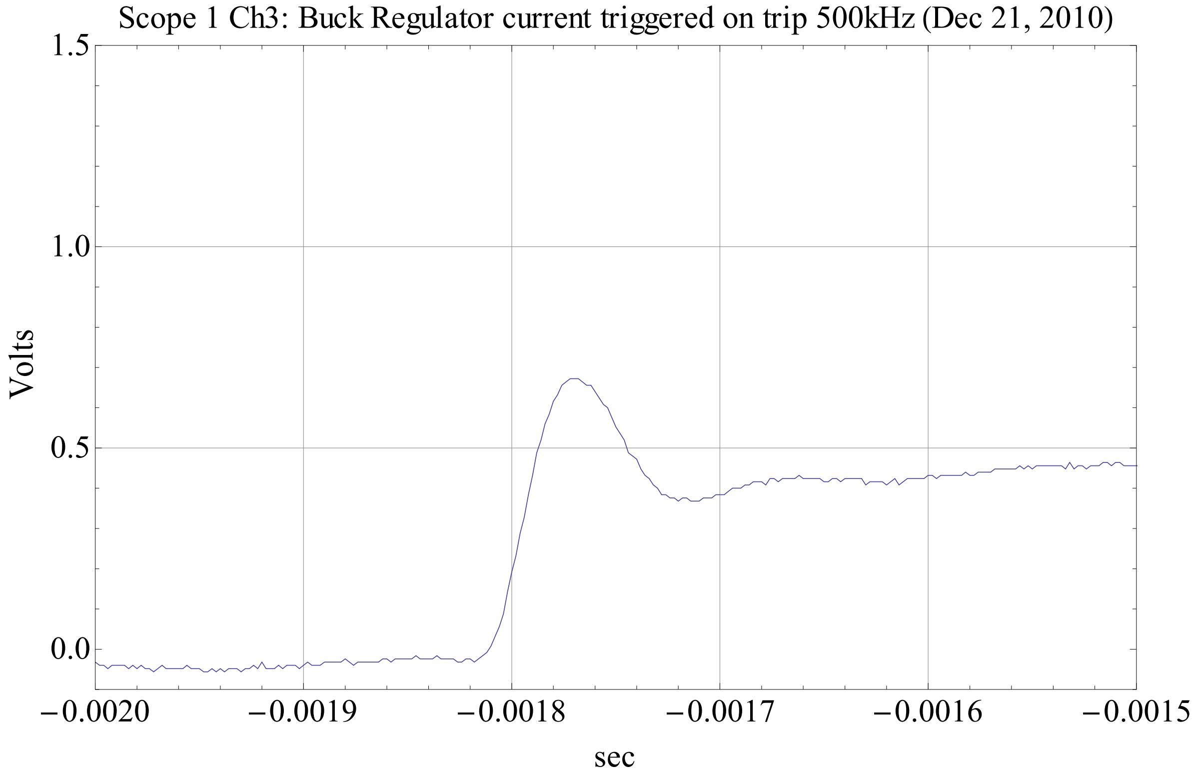


LOI operation @ 700V

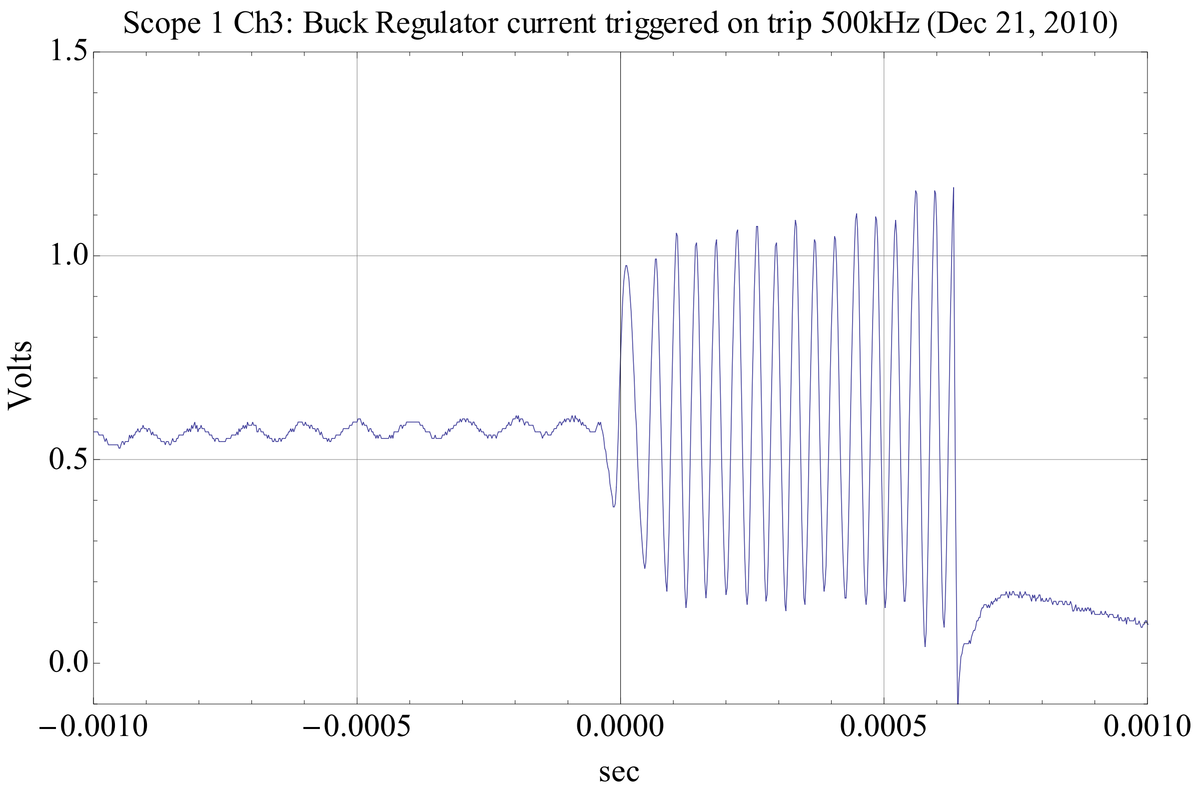
Ch1 Gapvolts envelope
Ch2 Triode Gridvolts
Ch3 Triode grid input current (.1V = 2A into 50ohms)
Ch4 Cavity input current (.1V = 2A into 50ohms)
Scope 1 Ch3: Buck Regulator current triggered on trip as winding up RF.



(A-11)

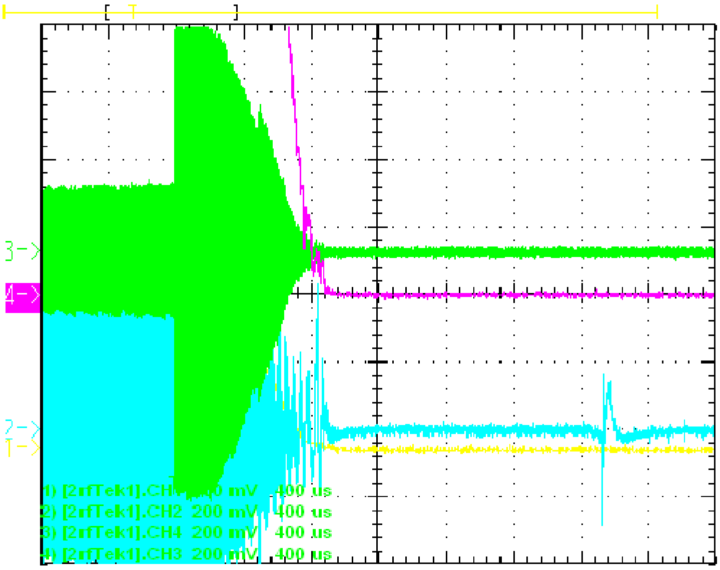


Overshoot width ~ 70usec.



Ringing frequency: 9.6kHz followed by 27.1kHz.

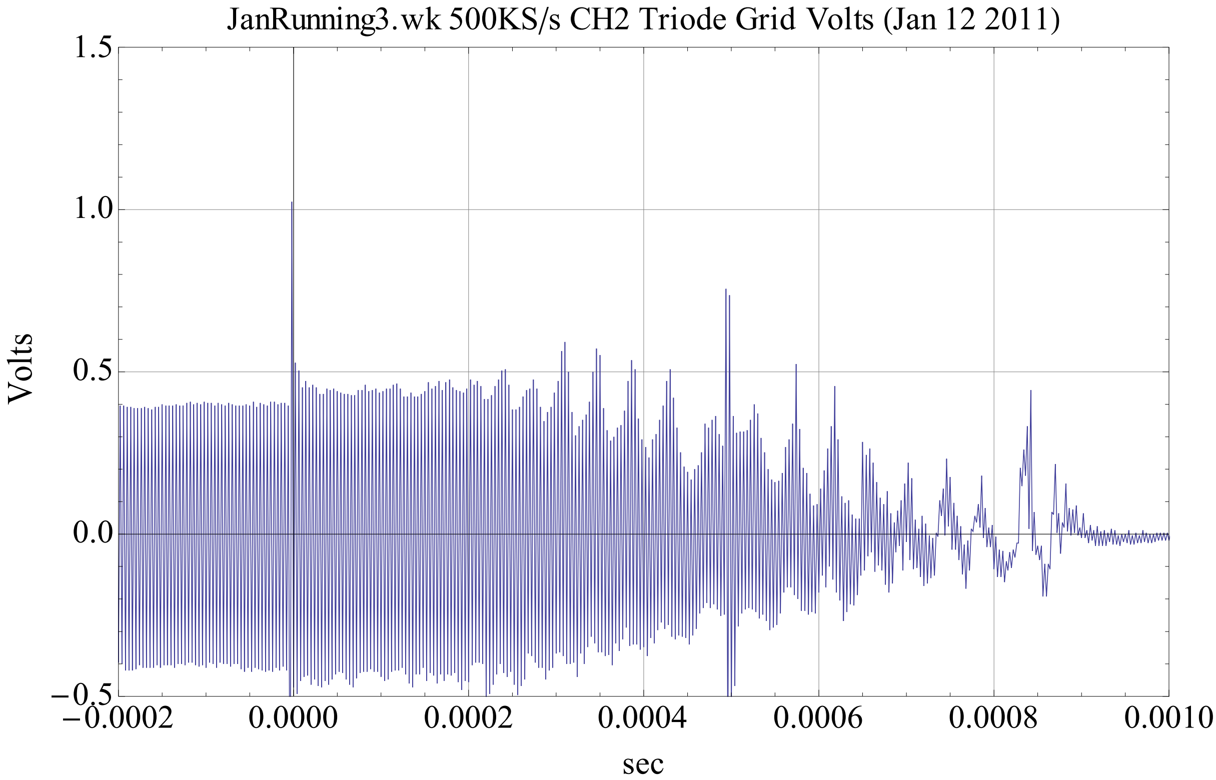
(A-12) JanRunning3.wk 500KS/s (Jan 12, 2011)



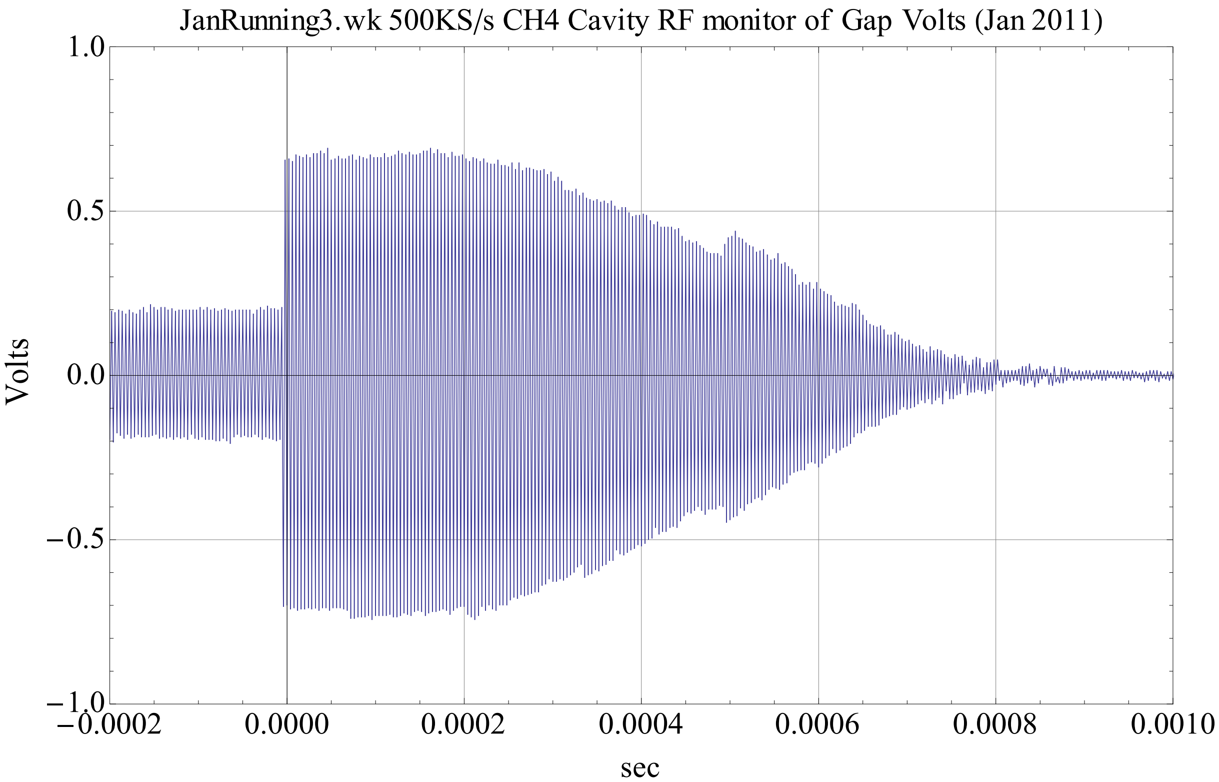
LOI tests with reduced standing current
Tetrode 5 A on meter
Triode 6A on meter.
Scope triggered on transient prior to trip

Ch1 Envelope of drive to AR:
CH2 Triode Grid Volts:
CH3 Gap volts envelope
CH4 Cavity RF monitor of Gap Volts:

(A-12)



Large spike (× 2.5) at 0sec, followed by a bit larger amplitude (×1.1) with 25.4kHz modulatio. Possible 180kHz modulation at the onset can not be seen due to poor resolution.



Step-function increase at 0sec (× 3.5). This increase does not correspond to that of grid volts!!