LOI Progress Report

– Considerations on the LOI Waveform Distortions and the beyond –

September 17, 2010

1. Introduction

It is found that large sub-harmonic waveform distortions in the LOI, which have really been a long-standing issue, can be well explained by the TopSpice [1] simulation with an assumption of 2.5% second sub-harmonic content in the frequency-law signal. Although the content is very small, it produces very large distortions in the grid voltage waveform due to the Miller effect upon grid-plate capacitance of the final triode when the load is a high Q cavity.

The cavity is tuned at resonance for the fundamental frequency, where the voltage gain of the final triode is high. The grid-plate capacitance is then increased by the same amount of gain (Miller effect), and is added across grid and ground. This effect considerably lowers the input impedance seen looking into the grid. This effect is small, on the contrary, to the sub-harmonic frequency because the cavity is off-resonant and the gain is lower. Then, the input impedance remains much higher than that for the fundamental frequency. Such difference of input impedance causes large difference of each component in the grid voltage, i.e. significant increase of the sub-harmonic component against the fundamental one.

In the TopSpice simulations, power tubes are treated as linear elements. In order to simulate the non-linear response of the power tubes, 7% second harmonic content is added at the driver-stage input over the whole frequency range of 5.2-12.4MHz. The simulation results then agreed very well with the experiments in January, 2010 [2]. In June 30, 2010, approximately 2.8% second sub-harmonic content was confirmed in the frequency-law signal by A. Seville, which also agrees our assumption.

As described above and will be discussed in details in section 4.1, large sub-harmonic distortion is the direct consequence of the high Q cavity as a load under the existence of a few % sub-harmonic content. If the load is a liquid resistor, it has no resonant structure and then the sub-harmonic distortion should not appear. Fortunately, we have a data to compare which was taken in August, 2008 with the liquid resistor [3]. It is conspicuous that there is no noticeable sub-harmonic distortion in the waveforms therein, although higher harmonic distortions can still be seen.

It is interesting to examine a finemet cavity on the waveform distortions, since it is a low Q cavity. The simulation was carried out for the J-PARC RCS RF cavity. The sub-harmonic distortions as well as harmonic distortions were quite small as expected.

In the following sections are reported, waveform distortions in section 2, LOI model in section 3, waveform analysis with sub-harmonic content in section 4, simulation with a finemet cavity in section 5, and conclusions in section 6.

2. Waveform distortions

Fig. 1 shows the waveforms taken in January 29, 2010 with 2^{nd} harmonic cavity as a load. The measuring points are specified in the LOI schematic (fig. 2). These waveforms have a remarkable feature that the grid voltage and gap-input current are largely distorted, although the grid-input current and the gap voltage show rather smooth sine waveform. Especially, from view point of ferrite bias tuning, grid voltage distortion should be improved because it gives an error to the phase comparison between grid and cavity voltages.

3. LOI model

In modelling the LOI, it is important to take into account any stray capacitances and to express an inductor as an element which has higher-order-mode resonances. Fig.3 shows an inductor model. Each coil element is expressed by an inductance L_1, L_2, etc which is assumed to couple the adjacent coil by the coupling coefficient K=0.5, and the next adjacent one by 0.3 and the third adjacent one by 0.1. Similarly, capacitive coupling is also assumed for the coil pairs to be inversely proportional to their distance as C=2.4pF, C/2, C/3 and so on. Shunt resistor R of 30kohms is attached across each coil element. The number of coil elements is 12 for anode chokes and 4 for grid-plate feedback coil. The inductance of the ferrite-loaded cavity (L_{cav}) was so changed that the cavity stays on tune, i.e. $L_{cav}(t)=1/(\omega^2(t)\ C_{cav})$, where C_{cav} is the cavity gap capacitance, 1,760pF. The cavity shunt impedance was chosen to be 538ohms [4].

The simulation model thus obtained was checked by comparing the measurements of grid-to-cathode impedance (Z_{gk}) in the driver stage and plate-to-grid impedance (Z_{pg}) at the triode. Good agreement was obtained up to ~60MHz [5]. However, this model could not explain the sub-harmonic distortions. We have then investigated every possibility to produce the distortions even by modifying the model parameters. However, no sub-harmonic distortions appeared. These difficulties led us to the assumption that the sub-harmonic component should be mixed intrinsically in the frequency-law signal to the LOI.

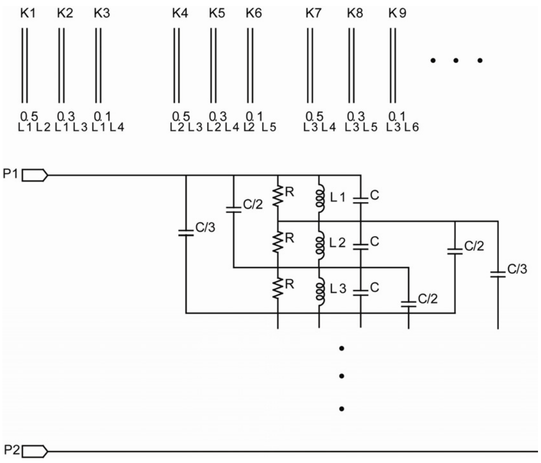


Fig. 3: Inductor model

4. Waveform analysis with sub-harmonic content

The 2nd sub-harmonic and 2nd harmonic contents in the voltage source of the simulation are assumed to be 0.025 and 0.072, respectively. Fig. 4 shows the simulation results. General trend agrees well with the experiments in fig. 1. The interpretation of sumilation is given below for the case of 5.15MHz fundamental frequency, where the distortion is very large.

4.1 Grid voltage and grid-input current

The input impedance seen from the driver tube (tetrode) looking into the final triode is very low compared to the output impedance of the tetrode, 5kohms. The tetrode, then, acts as a constant current source and the waveform of the output current is proportional to that of the input voltage.

Simulation shows that, at 5.15MHz, each harmonic content in the grid-input current is 0.0241 : 1 : 0.0878 for 2nd sub-harmonic : fundamental : 2nd harmonic, respectively. This ratio is quite close to the harmonic content assumed in the frequency-law signal.

However, in the voltage waveform, the situation changes drastically. Due to the Miller effect upon grid-plate capacitance of the final triode, the input impedance seen looking into the triode grid is greatly depressed for the fundamental frequency. Fig. 5 shows the calculated input impedance (Z_{in}) where the cavity is tuned at 5.15MHz. In order to help understand the 'depression', simple model calculations are also shown. The model expresses the driver stage with a parallel resonant circuit having a static grid-plate capacitance (120pF) and the increased capacitance (120pF × voltage gain) by the Miller effect. The latter resonant curve is then shifted to lower frequency side. The Z_{in} is 312, 11.7 and 40.6 ohms for 2nd sub-harmonic, fundamental and 2nd harmonic frequencies, respectively. Therefore, the sub-harmonic component in the grid voltage is increased by 27 times against the fundamental one. In another words, only 2.5% sub-harmonic content in current produces 67% content in voltage. The FFT analysis of the grid voltage in fig. 4 shows 84% content, which almost agrees this expectation.

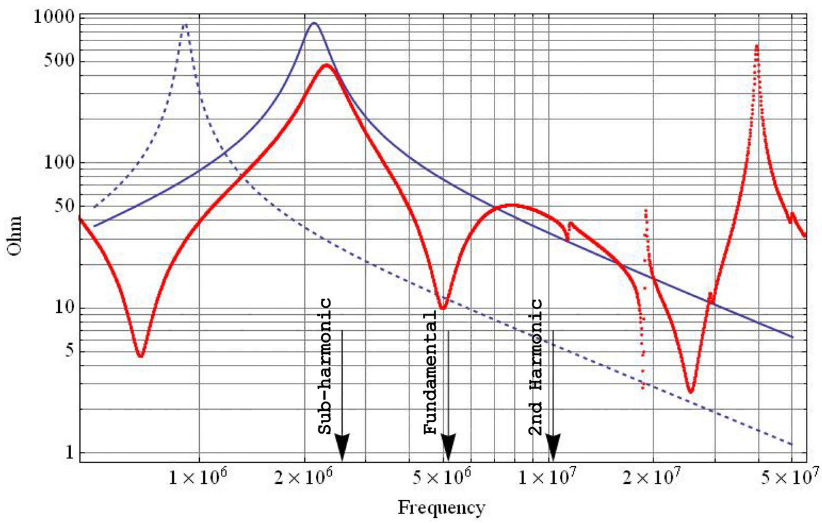


Fig. 5: Input impedance, Z_{in}, by the simulation (red). Driver stage impedance is simply expressed as a parallel resonant circuit with (blue dot) and without (blue solid) Miller effect, where voltage gain is 20.

As for other resonant peaks in fig. 5, see in reference [5].

4.2 Cavity gap voltage and gap-input current

The waveform can be analysed using the equivalent circuit shown in fig. 6. Here, the voltage source (V_s) has a magnitude of the open-end voltage, Z_{out} the output impedance of the LOI, and Z_{cav} the shunt impedance of the ISIS 2nd harmonic cavity which is tuned at 5.15MHz. The gap voltage and gap-input current are given by $V_s \cdot Z_{cav}/(Z_{out}+Z_{cav})$ and $V_s/(Z_{out}+Z_{cav})$, respectively. These expectations are compared with simulations in Table 1. Due to low output impedance nature of the LOI with a high Q cavity, $Z_{out}+Z_{cav}$ is small for the frequencies other than fundamental one. The sub-harmonic and higher harmonic currents are then enhanced.

4.3 Observation of sub-harmonic content in the frequency-law signal

A. Seville measured the sub-harmonic and harmonic contents in the frequency-law signal as is shown in fig. 7. Approximately 2.8% sub-harmonic content was observed, which agrees our assumption (2.5%).

4.4 Simulation with reduced sub-harmonic content

Assuming sub-harmonic content to be one order of magnitude smaller, i.e. 0.25%, TopSpice simulation was carried out as shown in fig. 8. The waveform distortion is greatly improved, and the problem on the zero-crossing of the grid voltage for phase comparison will be solved.

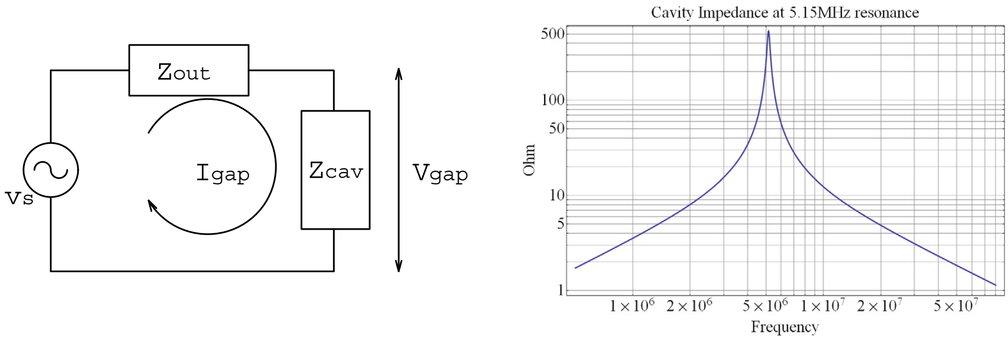


Fig. 6: Equivalent circuit to estimate the gap voltage and gap-input current (left), and 2nd harmonic cavity impedance (Z_{cav}) tuned at 5.15MHz (right).

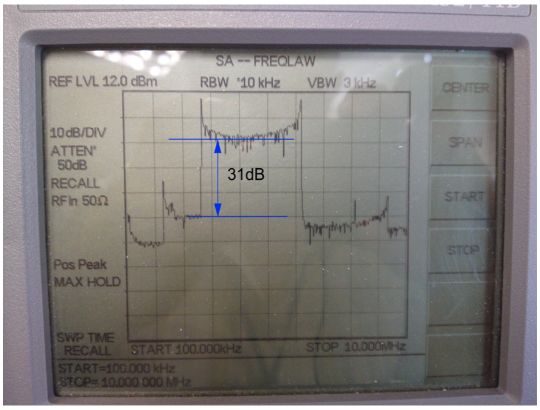


Fig. 7: FFT result of the frequency-law signal. 2nd sub-harmonic component is ~31dB lower than fundamental one. (photo by A. Seville)

Table 1: Comparison of simulated results with expected values by a circuit in fig. 6. The numbers are normalized so that fundamental component has a unit magnitude.

		Sub-harmonic 2.60MHz	Fundamental 5.15MHz	2nd Harmonic 10.35MHz
Vs (Open-end Voltage)		4.24	43.53	1.51
Zout (Ω∠deg.)		16.79∠-10.47	20.95∠16.03	28.34∠28.83
Zcav (Ω∠deg.)		11.9∠88.7	538∠0.1	11.6∠-88.8
|Vs/(Zout + Zcav)|		0.224	0.0779	0.06
	Expectation	(2.87)	(1)	(0.770)
	simulation	3.64	1	1.01
|Vs Zcav/(Zout + Zcav)|		2.66	41.93	0.696
	Expectation	(0.0634)	(1)	(0.0166)
	simulation	0.0694	1	0.0257

5. Simulation with a finemet cavity

It is interesting to examine a finemet cavity on the waveform distortions, since it is a low Q cavity. The simulation was carried out for the J-PARC RCS RF cavity, where the parameters are shunt impedance 725ohms, gap capacitance 199pF, cavity inductance 44uH, and the resonant frequency is 1.7MHz [6]. Initially, the system encountered a vigorous oscillation at 47.95kHz, which is a resonance with the triode blocking capacitor (96nF), the anode choke (101.9uH) and the cavity inductance (44uH). However, this oscillation was stopped when the blocking capacitor is increased to 192nF. The result is shown in fig. 9. The sub-harmonic distortions as well as harmonic distortions were quite small as expected: *ironical enough*! Finemet cavity does not require smooth sine-waveform of the grid voltage because it does not need bias tuning.

6. Conclusions

The long-standing issue, i.e. large sub-harmonic distortion of the grid voltage, has been analysed successfully by the TopSpice simulation. The distortion is the direct consequence of the high Q cavity as a load under the existence of a few% sub-harmonic contents in the frequency-law signal. In order to eliminate the distortion, two measures should be effective: one is to reduce the sub-harmonic content down to one order of magnitude smaller, i.e. less than 0.25%, and the other to use a broadband cavity instead of the high Q cavity.

References:

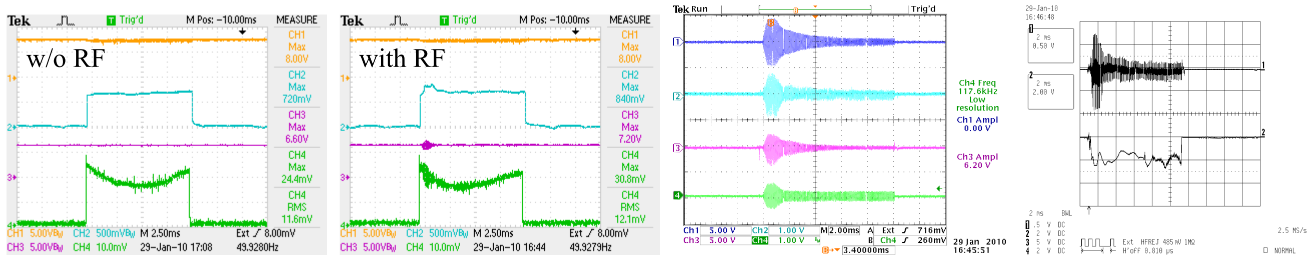
[1] Penzar Development P.O. Box 10358 Canoga Park, CA 91309 U.S.A.
[2] LOI Progress Report LOI-7, February 18, 2010.
[3] LOI Progress Report LOI-5, November 10, 2008.
[4] Y. Irie et al, EPAC'06, MOPCH118.
[5] Y. Irie, 'Comparison of TopSpice Simulations and Measurements upon Zgk and Zpg' (in Japanese), Internal memo, May 6, 2010.
[6] F. Tamura, private communication, June, 2010.

January 29, 2010

Experimental Conditions: 2nd Harmonic Cavity without Liquid Resistor, AC bias with Feedback Loop, trimming bias demand, phase detector offset=~0 volts.

DRIVER New Choke	N2=0	Damper 1	1st peak (3.200 MHz),	1st valley (~9.0 MHz)	; 1/23/2010, isolated measurements in-situ
		Zgk	1st peak (2.359MHz),	1st valley (~9.2MHz)	; 1/25/2010
FINAL Old Choke	N2=0	Damper 1	1st peak (~3.1 MHz),	1st valley (~9.8 MHz)	; 1/21/2010, isolated measurements in-situ
FEEDBACK COIL	N2=12	Zpg	1st peak (2.035 MHz)	1st valley (11.391 MHz)	; 10/23/2010

DC setup: Triode HV (2kV/V), Output Current (35A/V), Tetrode HV (1kV/V) and Output Current (10A/10mV).



Upper: Gap- Input Current (20A/V)
Lower: Δϕ Output (10deg/V, gap volt & grid volt) with "CAV TUNE"

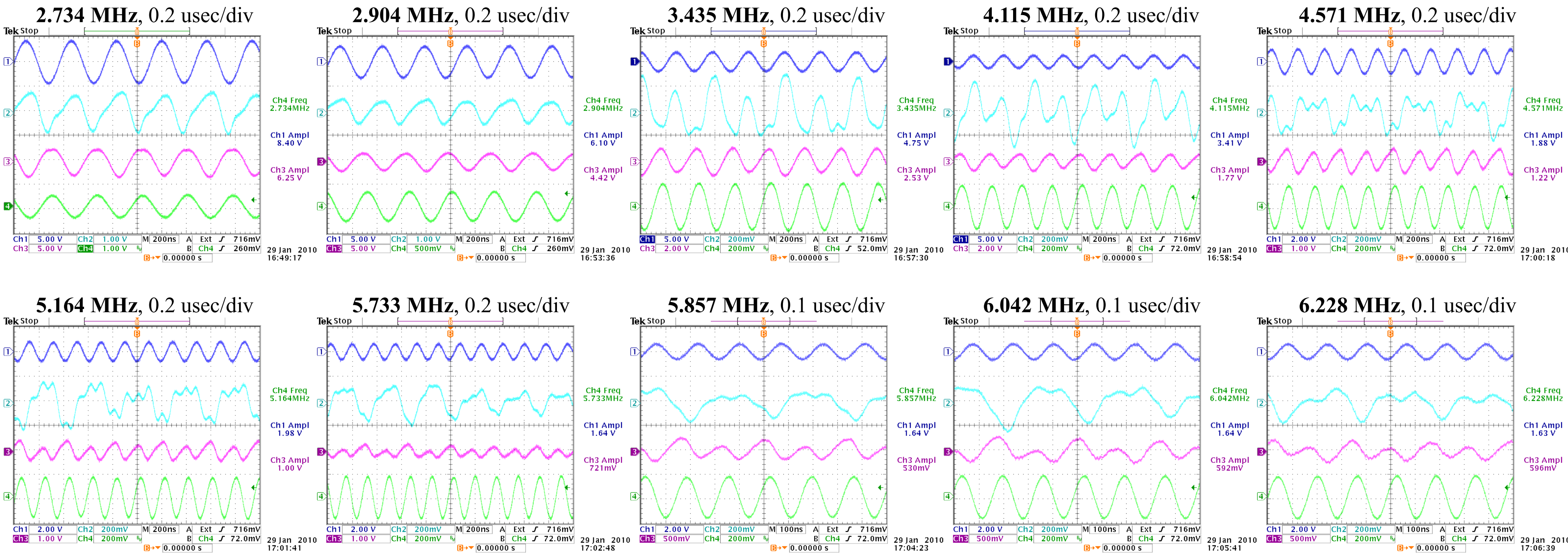


Fig. 1: (taken from fig.5 in LOI-7) RF envelopes (above) and waveforms with 2nd Harmonic Cavity at full cycle operation. From top to bottom line in each screen, cavity gap voltage (╳1,590), gap-input current (20A/1V), grid voltage (╳143) and grid-input current (20A/1V).

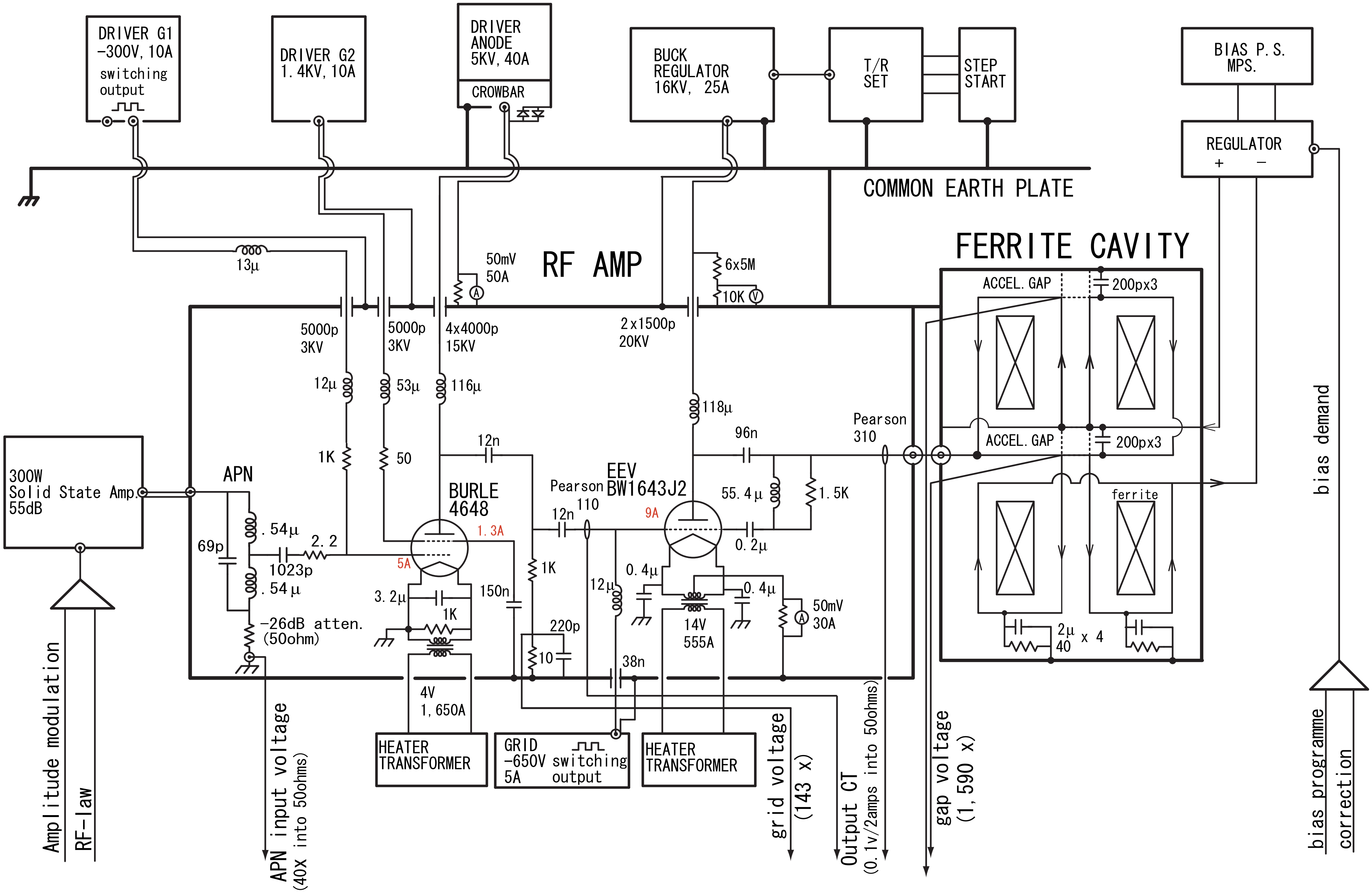


Fig. 2: LOI schematic

May 19, 2010 (YI)

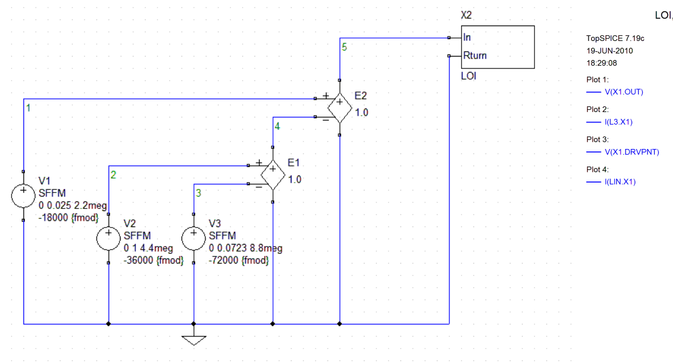
Generator contents:

Fundamental (1.0),

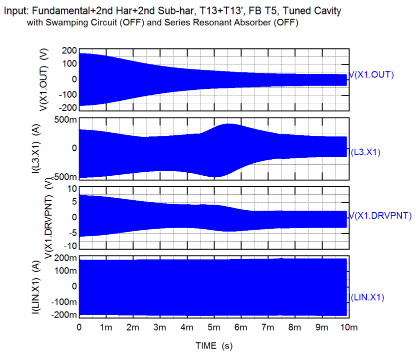
2nd Sub-harmonic (2.5%),

2nd Harmonic (7.23%).

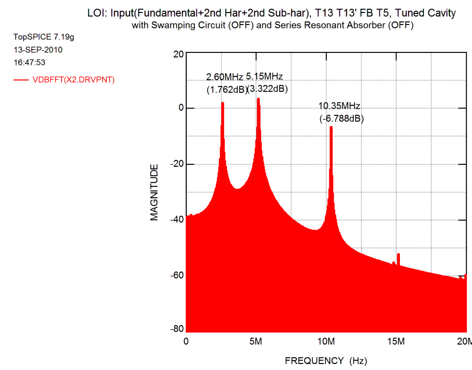
TopSpice Schematic



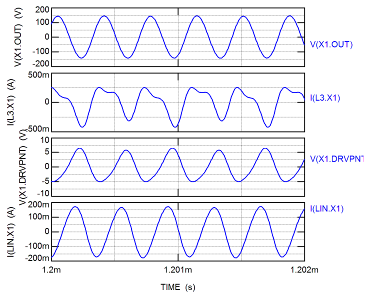
RF envelope



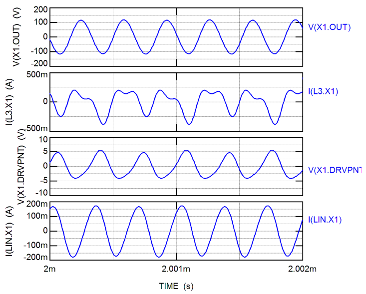
FFT grid voltage (6.4, 6.42)msec



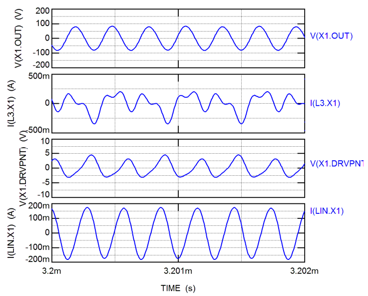
(1.2, 1.202)ms, 2.726MHz



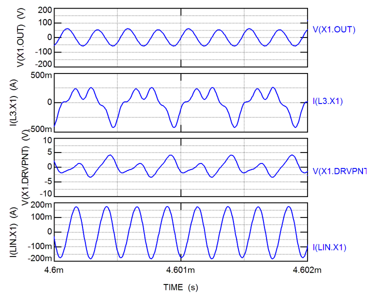
(2.0, 2.002)ms, 2.944MHz



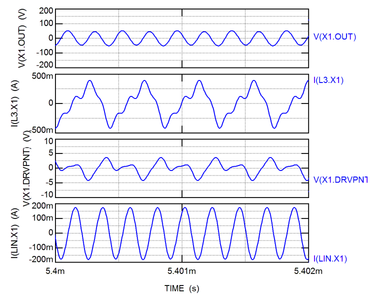
(3.2, 3.202)ms, 3.436MHz



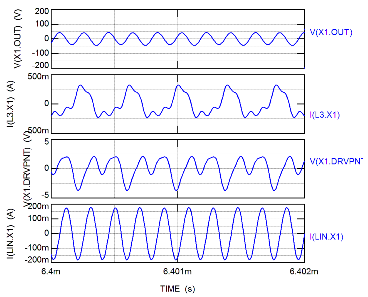
(4.6, 4.602)ms, 4.174MHz



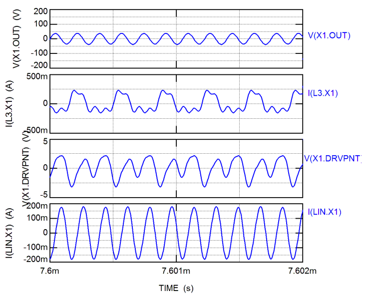
(5.4, 5.402)ms,4.626MHz



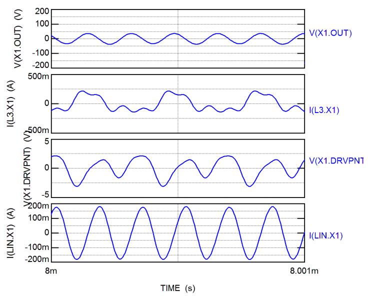
(6.4, 6.402)ms, 5.166MHz



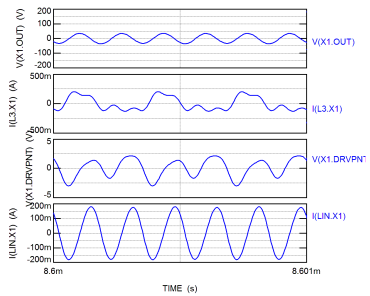
(7.6, 7.602)ms, 5.712MHz



(8.0, 8.001)ms,5.856MHz



(8.6, 8.601)ms, 6.029MHz



(9.89, 9.891)ms, 6.199MHz

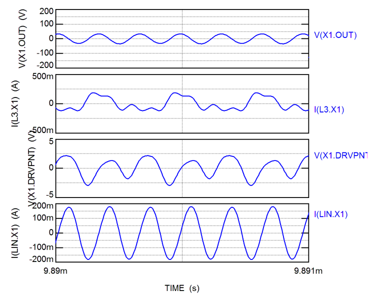


Fig. 4: LOI with 2.5% sub-harmonic content. From top trace, cavity gap voltage, gap-input current, grid voltage and grid-input current [a.u.]

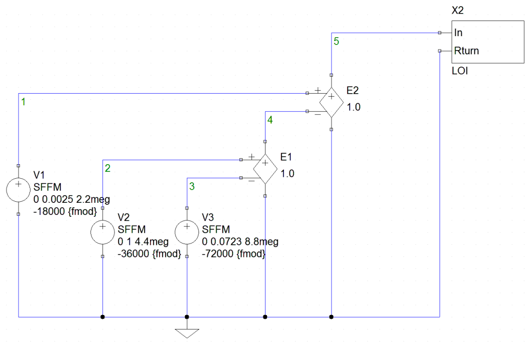
TopSpice Schematic

Generator contents:

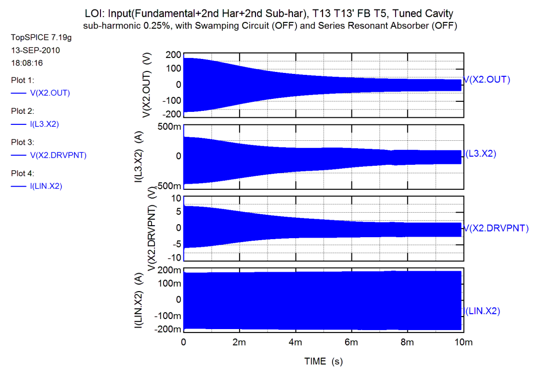
Fundamental (1.0),

2^{nd} Sub-harmonic (0.25%),

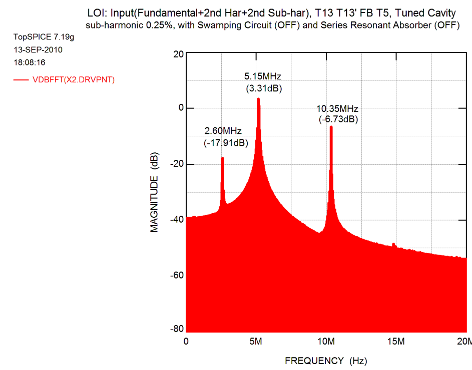
2^{nd} Harmonic (7.23%).



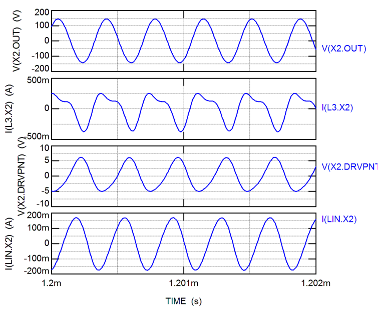
RF envelope



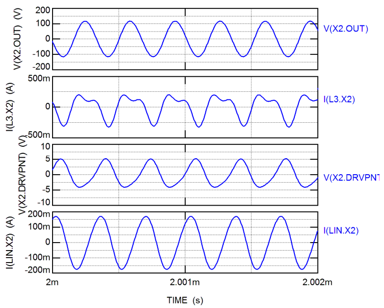
FFT grid voltage (6.4, 6.42)msec



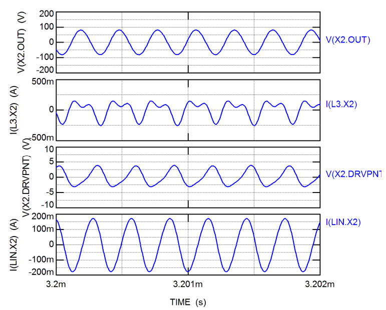
(1.2, 1.202)ms, 2.726MHz



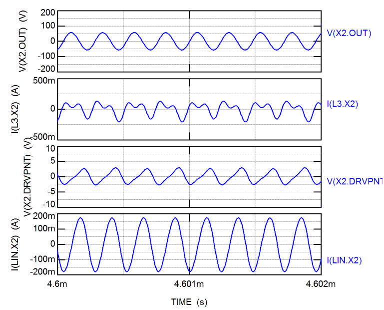
(2.0, 2.002)ms, 2.944MHz



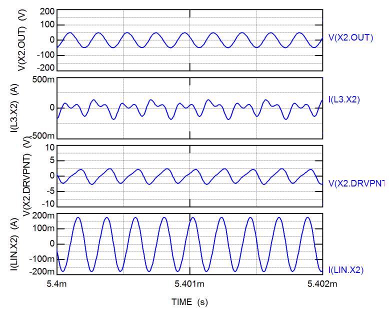
(3.2, 3.202)ms, 3.436MHz



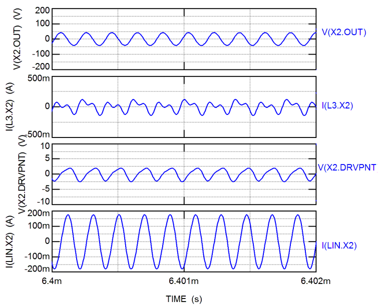
(4.6, 4.602)ms, 4.174MHz



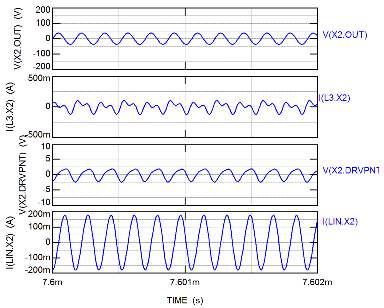
(5.4, 5.402)ms,4.626MHz



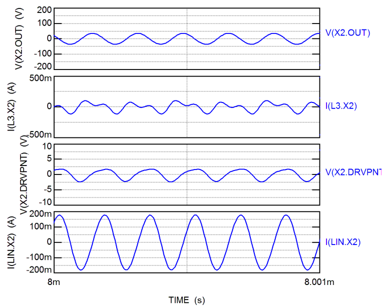
(6.4, 6.402)ms, 5.166MHz



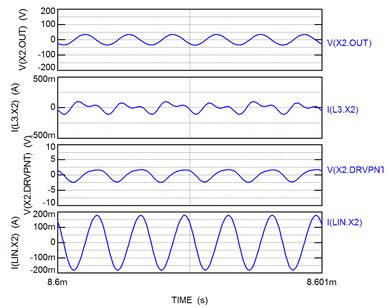
(7.6, 7.602)ms, 5.712MHz



(8.0, 8.001)ms,5.856MHz



(8.6, 8.601)ms, 6.029MHz



(9.89, 9.891)ms, 6.199MHz

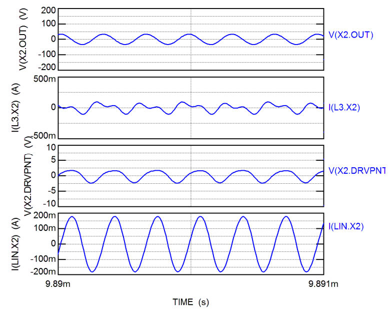


Fig. 8: LOI with 0.25% sub-harmonic content. From top trace, cavity gap voltage, gap-input current, grid voltage and grid-input current [a.u.]

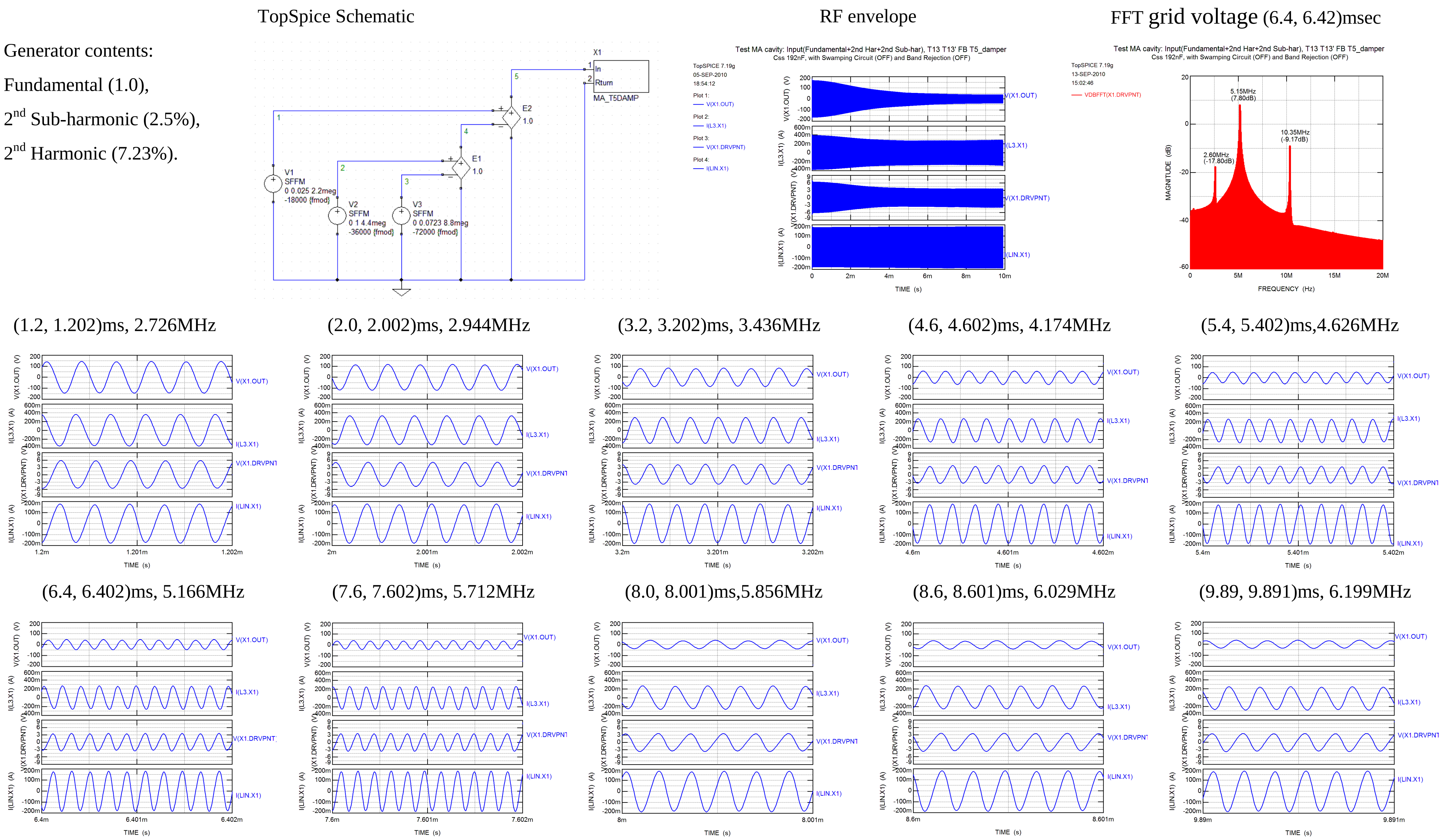


Fig. 9: Finemet Cavity with 2.5% sub-harmonic content. From top trace, cavity gap voltage, gap-input current, grid voltage and grid-input current [a.u.]