Power Supply Simulation and Optimization for the Three-Dimensional Ionization Profile Monitor

DESY Summer Student Programme, 2014

Dian Ahmad Hapidin

Institut Teknologi Bandung, Indonesia

Supervisor

Martin Sachwitz
Heiko Breede

31th of August 2014

Abstract

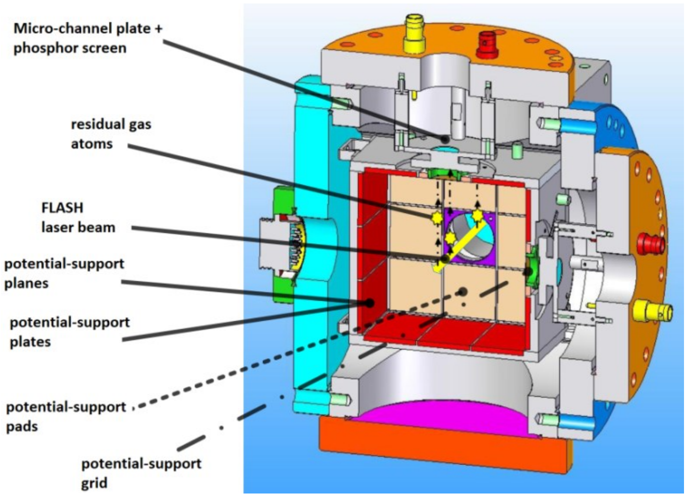
The performance of 3D-IPM depends on the accuracy and stability of power supply unit. The power supply has been designed to create alternating electric field at high frequency inside the 3D-IPM. Because of high frequency operation, the parasitic components of power supply should be considered. This paper discusses the effect of parasitic components to power supply performance. The simulation was done using Mentor Graphic-System Vision. The results shown that the accuracy of power supply tend to decrease at higher frequency and compensator circuit can improve the accuracy up to 94.8%. Optimum operating frequency and delay time of the power supply circuit was obtained.

Contents

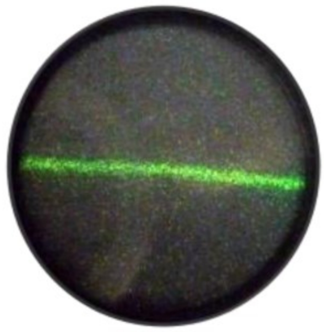
1 Introduction

1.1 Three-dimensional Ionization Profile Monitor (3D-IPM)

Ionization Profile Monitor (IPM) is an undisturbed determination of the position and intensity distribution of the laser beam. The three-dimensional Ionization Profile Monitor (3D-IPM) shown on figure 1.a designed to visualized the beam at two direction, X and Y. The FLASH laser beam with a variable wavelength from 4.1 to 45 nm is located in an Ultra High Vacuum (UHV) beam pipe. Despite the vacuum a certain amount of residual gases still exist. If the laser beam hits a residual gas atom, it becomes ionized and charged electrons and ions are created. By means of a homogeneous electric field, these electrons and ions can be deflected in a rectilinear way towards the microchannel plate (MCP). Here, the impacting particles create an avalanche of secondary electrons in the micro tubes of the MCP and are being visualized on the phosphor-screen. These results in an image of the intensity-dependent laser (see figure 1.b)[1]. The electric field of this design alternated at high frequency to the direction where the two MCP plates placed. In this way, the laser beam can be visualized in two directions simultaneously.



(a)



(b)

Figure 1: (a) the set-up of 3D-IPM (b) image of FLASH laser beam[1]

Table 1: The output voltage of each power supply connector[1]

Reference voltage = 0 V					
Input Voltage (V_{in}) = 600 V					
first half period			second half period		
Connector	Ratio (V_{out} / V_{in})	$V_{connector}$ (V)	Connector	Ratio (V_{out} / V_{in})	$V_{connector}$ (V)
X*i*0	0	0	X0*i*	0	0
X*i*1	19/120	95	X1*i*	19/120	95
X*i*2	½	300	X2*i*	½	300
X*i*3	101/120	505	X3*i*	101/120	505
X*i*4	1	600	X4*i*	1	600

* *i = 0,1,2,3,4*

The alternated electric field inside 3D-IPM is provided by power supply unit which is able to feed 3D-IPM plate with high frequency square voltage up to 1000V. Based on FEM analysis, the homogeneous electric field inside 3D-IPM design will be achieved if the each connector voltage in one period satisfying the values shown in table 1.

1.2 IPM Power Supply Design

Figure 2 is the simplified circuit of power supply that will be used to generate alternating electric field inside the IPM. The circuit divided into two parts, first is matrix circuit (figure 2.a) and second is driver circuit (figure 2.b).

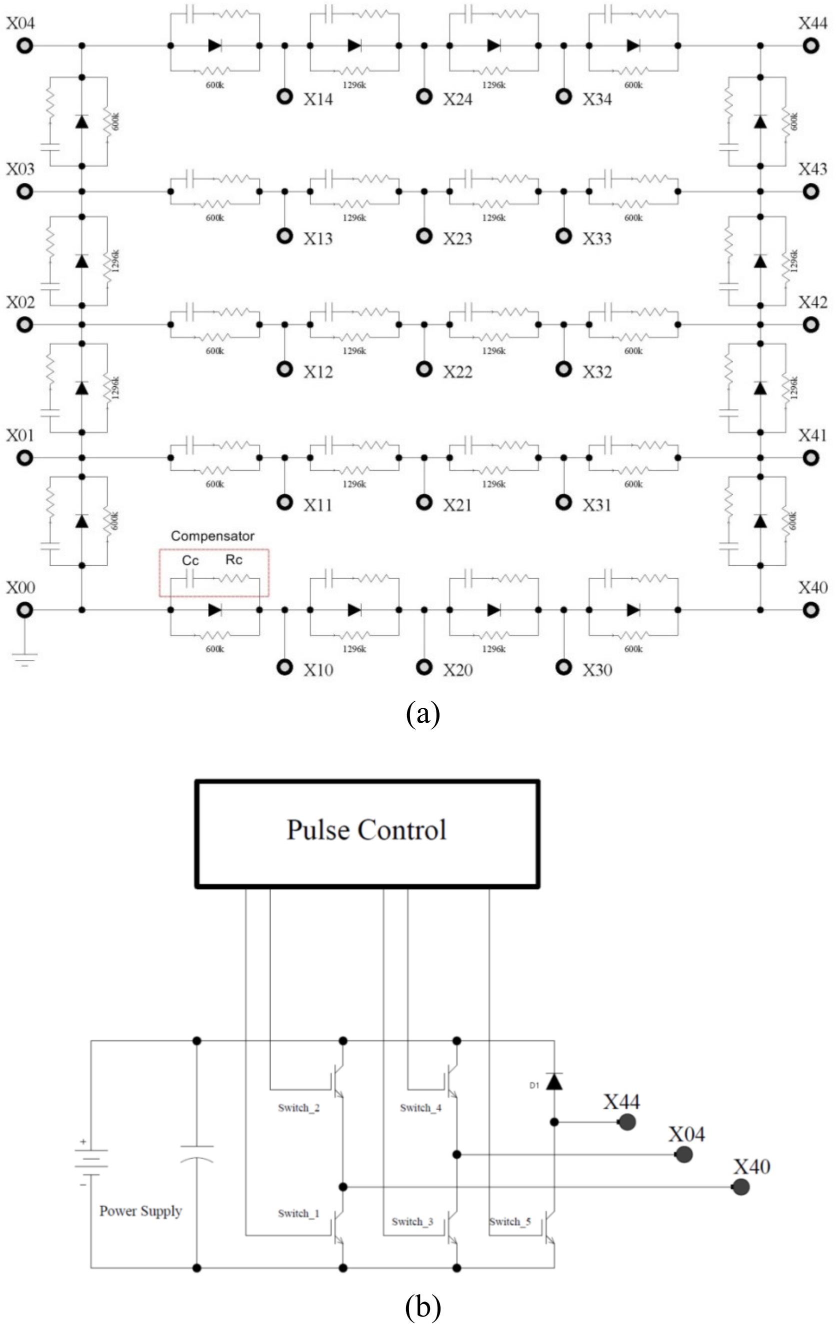


Figure 2: The circuit of (a) matrix and (b) driver[3]

The matrix circuit consists of 25 connectors, compensator capacitor, diode, and voltage-divider circuit. Each connector of this circuit has square output voltage and connected to IPM plates to create homogenous alternated electric field. The compensator circuit has a role to optimize the accuracy of the output voltage. It is able to decrease or increase the output voltage by adjusting the capacitor (Cc) value. The matrix circuit basically constructed from several voltage divider circuit. We can easily analyze the output voltage from one row by applying kirchoff law or voltage divider formula. Assume 600 V given to X40 pin, then the output voltage of X10, X20, X30 could be calculated as follows ;

$$V_{out} = \frac{R_G}{R_{total}} V_{in} = \frac{R_G}{3792\ \Omega} 600\ V$$

$$V_{X30} = \frac{R_1}{3792\ \Omega} 600\ V = \frac{600\ \Omega}{3792\ \Omega} 600\ V = 94.93\ \mathrm{V}$$

$$V_{X20} = \frac{R_1 R_2}{3792\ \Omega} 600\ V = \frac{1896\ \Omega}{3792\ \Omega} 600\ V = 300\ V$$

$$V_{X10} = \frac{R_1 R_2 R_3}{3792\ \Omega} 600\ V = \frac{3192\ \Omega}{3792\ \Omega} 600\ V = 505.06\ V$$

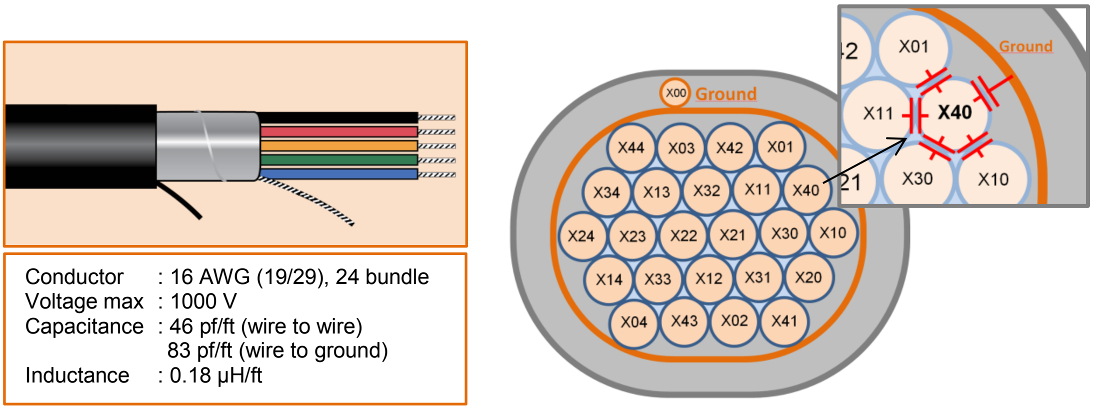
The matrix driver circuit consists of switching component (IGBT IKW08T120), pulse control, and external power source (see figure 2.b). This circuit has a role to switch voltage from external power source with certain pulse profile and feed it to X04, X40, and X44 of matrix circuit. The pulse profile of this circuit e.g. frequency, pulse width, and delay will be controlled by the pulse control. This pulse control is an external module which can be provided by signal generator or other devices.

1.3 Parasitic components of wire

Parasitic component always exist in every circuit because of non-ideal system. It is a circuit element (resistance, inductance or capacitance) that is possessed by an electrical component but which it is not desirable for it to have for its intended purpose. For instance, a resistor is designed to possess resistance, but will also possess unwanted parasitic capacitance. Parasitic elements are unavoidable. All conductors possess resistance and inductance and the principles of duality ensure that where there is inductance, there will also be capacitance.

For low frequency systems the parasitic component usually neglected, but at high frequency it can be serious problem. The parasitic components can create resonant circuit which is able to generate self oscillation (ringing), attenuation, and decrease the accuracy of the device. The power supply designed to operate at high frequency, thus the parasitic components should be considered. This paper will discuss the effect of parasitic component inside the connector wires to the power supply performance.

In basic circuit theory, the wires always assumed ideal and the voltage at all points on the wires is exactly the same. In reality, this situation is never quite true. Any wire has series resistance and inductance. Also, a capacitance exits between any pair of wires. The parasitic component value of the wire depends on its quality, figure 3.a shows the wire specification used in simulation. The stray capacitance may exist between wire to ground and among the wires. Figure 3.b shows the connector configuration inside the 24 bundles of wires and the stray capacitance illustration.



(a) (b)

Figure 3: (a) wire specification (b) the wire cross section with connector configuration and the stray capacitance illustration among the wires

2 Method

The power supply design simulated by Mentor Graphic-System Vision. The simulation was done in three steps. First step simulate the circuit at ideal condition and the results will be the reference for the next steps. Then the parasitic components such as stray capacitance and parasitic inductance of the wires added into the simulation. The wire equivalent model created based on real wire specification. The frequency is changed to observe how much the parasitic components affect the device accuracy. This procedure was taken to determine the optimum operating frequency of power supply. The wire parasitic components predicted to be able to decrease the power supply accuracy, in this case the compensator circuit will be applied to improve the power supply performance.

3 Simulations Results and Discussion

3.1 Driver Circuit

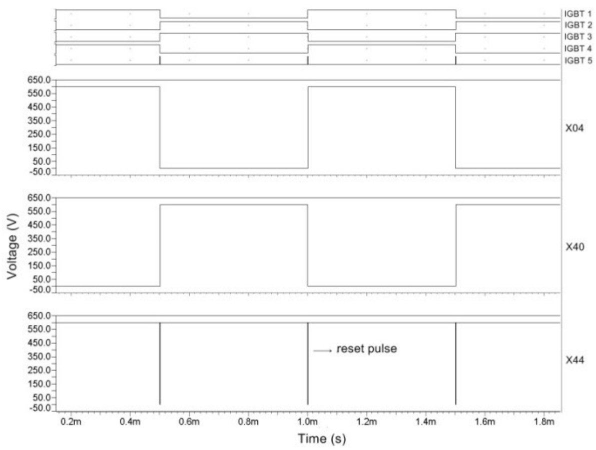
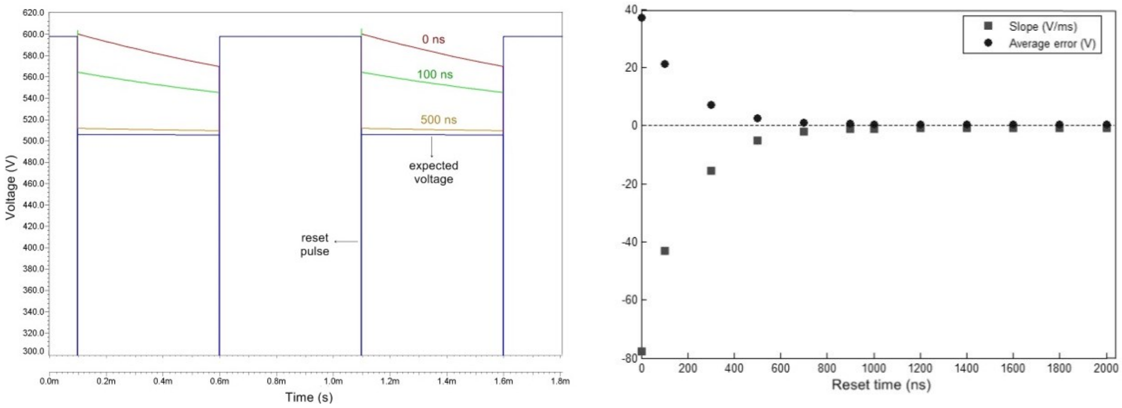


Figure 4: The pulse profile of driver circuit

The matrix circuit must be fed by certain square voltage pulse to generate alternating electric field. The voltage pulse provided and controlled by driver circuit. The driver circuit simulated in ideal condition (IGBT parasitic components were neglected). Pulse control will switch the IGBTs in order to feed X44, X04, and X40 connector by pulsed voltage from power supply. Figure 4 shows the pulse given to each IGBT gate pin and the output voltage at X40, X04, and X44. Switch_1 and Switch_2, also Switch_3 and Switch_4 are switched alternately to get square wave at X04 and X40. Switch_5 serves as reset to definitely have all outputs at 0V in respect to X00.

The reset pulse is necessary to obtain accurate output voltage. Exact reset timing adjustment is delicate, as we want unnecessary delay as small as possible, but overlaps must be avoided as they would cause fatal short circuits. Figure 5.a shows the output waveform of X43 connector at different reset time. Lower reset time tend to result poor accuracy, thus finding optimum reset time is important. Figure 5.b shows the relation of reset time to the average error voltage and voltage slope. We want the stable and accurate voltage, therefore the error and the slope must be as small as possible. From the figure, optimum reset time obtained at 1000ns, this value will be used for further simulation.

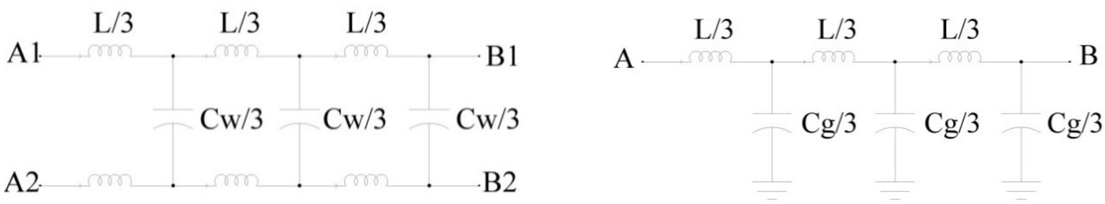


(a) (b)

Figure 5: (a) comparation of output voltage at different reset time (b) reset time effect to voltage slope and average error

3.2 Matrix Circuit

The matrix circuit (figure 2.a) is the main part of power supply. The matrix performance will affect the homogeneity of electric field and overall performance of 3D-IPM. The matrix circuit simulated to know the behavior of the power supply at different frequency, thus we can determine the optimal operation frequency and provide appropriate action in order to improve its performance.

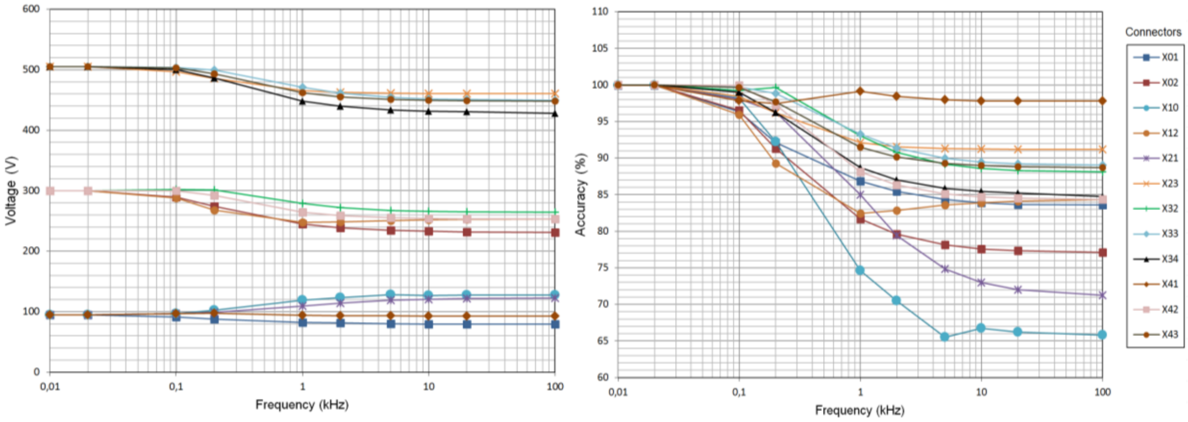


(a) (b)

Figure 6: Wire equivalent model for stray capacitance between wire to (a) ground (b) wire

The connecting wires between power supply and 3D-IPM will be considered. A wire can be modeled using a basic circuit that consists of an infinite series of infinitesimal R, L, and C components. In order to simplify the discussion, the equivalent wire model ignore the resistances, in this case the model called lossless wire model (see figure 6). The wire was modeled with a series of three L-C sections. In reality, a real wire is an infinite series of infinitesimal inductors and capacitors. The wire length is 1 meter with point A and point B are the initial and the end of wire. C_g and C_w are the capacitance of wire to ground and wire to wire.

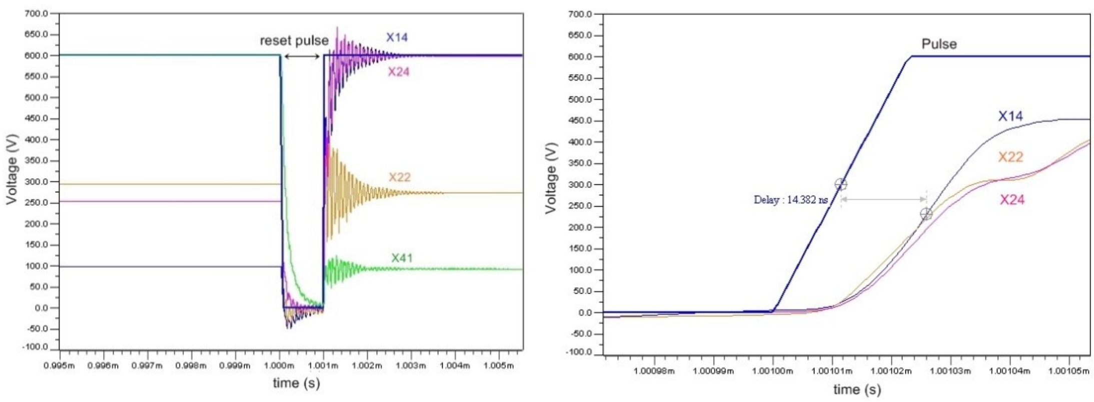
Figure 7 shows the voltage and accuracy of the connectors at different frequency, swept from 10 Hz – 100 kHz. Almost all connector voltage decrease at higher frequency, especially the connectors closest to the shield (ground). This behavior occurs because of the low pass filter circuit created by ground capacitance (C_g) and matrix circuit resistance. The accuracy also tend to decrease at higher frequency (figure 7.b).



(a) (b)

Figure 7: The (a) voltage and (b) accuracy of connector voltage at different frequency

The impedance at points A and B (figure 6) and each node in between depends not just on the source and load resistance, but also on the LC values of the wire. The inductive and capacitive reactance of wire parasitic components depends on frequency. At low frequencies, the LC pairs introduce negligible delay and impedance, reducing the model to a simple pair. But at higher frequency the the inductive and capacitive reactances may equal in magnitude, resulting resonance effect.



(a) (b)

Figure 8: The wire parasitic components generate (a) ringing at high speed switching time (b) delay of the output voltage to switching pulse

The parasitic components also can generate ringing as shown in figure 8.a. Ringing occurs at the edge of reset pulse because of fast changes of voltage value. The rise and fall time of the reset pulse are 23 ns and 70 ns. The ringing frequency is about 15.7 MHz. Ringing is undesirable because it causes extra current to flow, thereby wasting energy and causing extra heating of the components, moreover the electric field inside 3D-IPM at ringing region will be unstable. It is also found that the voltage transmitted from the initial point (point A) charges and discharges the wire's inductance and capacitance. Therefore, the voltage signal does not arrive instantly at the end of wire (point B) but is delayed. Figure 8.b shows the delay between voltage at the end of wires and reset pulse.

The ringing exists at every half cycle of the output voltage waveform. It takes about 4µs untill the voltage relatively stable, then if we take reset time (1µs) into account, there will be about 5µs of unstable region each half cycle. Figure 9.a shows this unstable region. This is a problem because the bunch distance of FLASH is 1µs. It means there will be ten bunches that will meet the unstable region each cycle. On this region, the voltage fluctuate as well as the electric field, so the ionized gases created by bunches will move to unpredictable direction. In this case, the ten bunches on unstable region may not be displayed on 3D-IPM screen. But the effects of this unstable region for 3D-IPM performance has not been observed or simulated yet.

Although the unstable region can not be eliminated, but there is some way that can be applied to minimize the effect. First, we can add the snubber circuit to damp the ringing[2]. The snubber circuit will dissipate some energy of ringing so the unstable region will be shorter. Second, we can use the wires that has lower parasitic components value. The ringing frequency depends on the value of stray capacitance and parasitic inductance, therefore using better wires will lead to better device performance. The last, we can ignore this unstable region if we have the trains with bunch distance more than 5µs. Because, in this case, we can set the output voltage pulse in such way so that the bunches will never meet the unstable region. The illustration of this case given on figure 9.b.

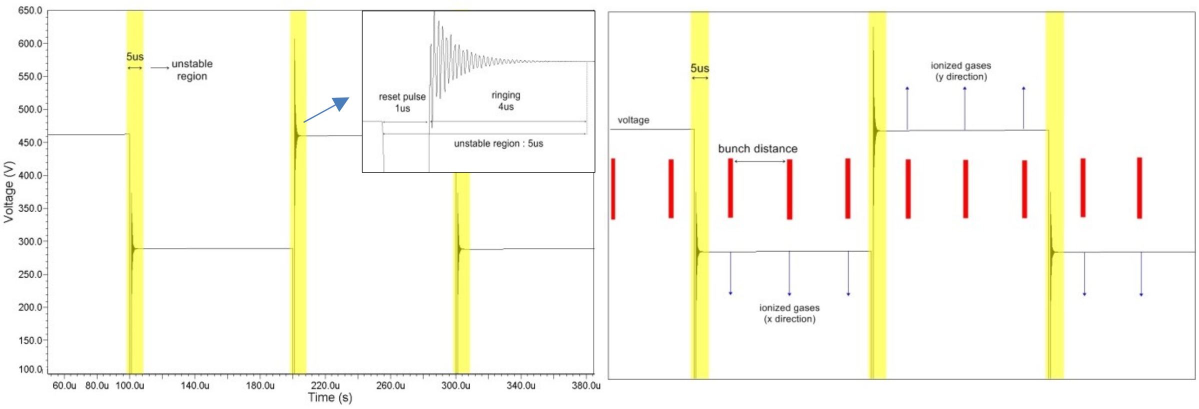


Figure 9 : (a) The output voltage at X43 connector (b) the illustration of bunches passing through the electric field region inside 3D-IPM

Finding the optimal operating frequency is the next important parameter to be determined. The FLASH can generate the trains with length up to 800µs and 3D-IPM design must be able to display it to two directions. Considering this aspect, the power supply should provide alternating voltage with period less than 800µs. Thus the operating frequency of power supply should be more than 1.25 kHz. The unstable region should be taken into account because we want this region as small as possible compare to overall voltage output. At 100 kHz the ringing almost dominate the output voltage, so operating the power supply at frequency more than 100 kHz is not possible. Then the operating frequency range of this device supposed to be from 1.25 kHz to 100 kHz.

In order to improve the accuracy of the device, the compensator circuit can be added. This circuit is able to decrease or increase the connector voltage by adjusting the compensating capacitor (C_c) value (figure 2.a). The simulation of the matrix circuit was done at three different conditions. The first was the simulation of circuit at ideal condition, it means the wire parasitic components are not considered. The second was the simulation at unideal condition, considering the wire parasitic components. The last was the simulation at unideal condition and applying the compensator circuit in order to improve performances. For this simulation, 5kHz operating frequency was choosen. Figure 10 shows the simulation results of connector voltage accuracy at the conditions. The circuit at ideal condition has average accuracy up to 99.7 %, and this is decreased for non-ideal condition to 90 %. After applying the compensator circuit, the average accuracy rise up to 94.8 %.

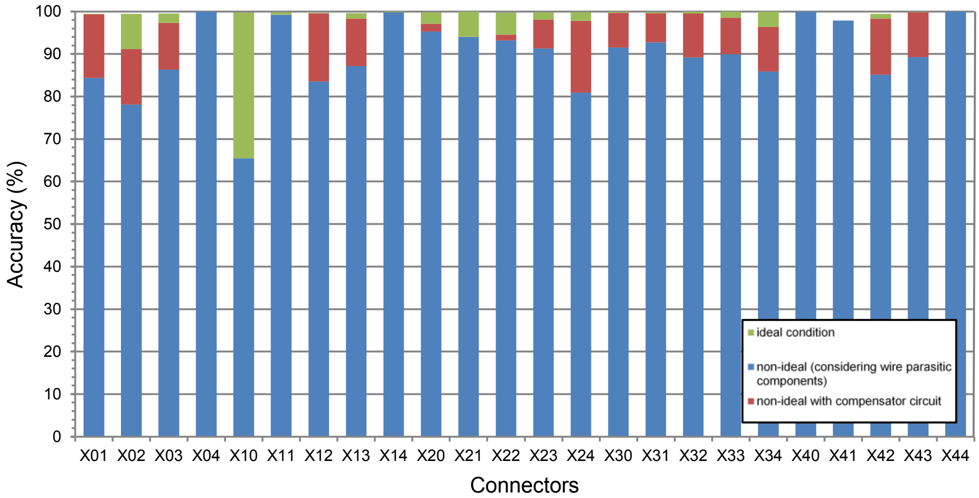


Figure 10: Comparison of connector voltage accuracy from the simulation at three conditions ; ideal condition, non-ideal condition, non-ideal condition with compensator circuit

4 Conclusion

The simulation of 3D-IPM power supply was done. The optimum reset time achieved at 1µs with operating frequency range from 1.25 kHz to 100 kHz. The results show that parasitic components of wires decrease device performances. It also was found that these components generate high frequency ringing each half cycle of output voltage. The ringing may lead unstable electric field and decrease 3D-IPM performance, but the effects of the ringing need to be observed further. The average accuracy of the power supply at 5kHz for non-ideal condition is 90% and the compensator circuit can improve it to 94.8 %.

References

[1] H. Breede, H.-J.Grabosch, L. V. Vu, M. Sachwitz, *New Compact Design of a Three-Dimensional Ionization Profile Monitor (IPM)*, Proc. SPIE 8778 (2013).

[2] D. A. Hapidin, M. M. Munir, Khairurrijal, *Designing of High Voltage Power Supply for Nanofiber Synthesis using High Voltage Flyback Transformer (HVFBT).* ISIMM (2014).

[3] Matrix 1x25 circuit, GBS ELEKTRONIK GmbH, http://www.gbs-elektronik.de/