EMI-EMC Compliant APPT`s Power Processing Unit Integration

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Abstract

This work aims at describing design assembly and integration procedures of the Power Processing Unit (PPU) of an Ablative Pulsed Plasma Thruster (APPT), so as to minimize electromagnetic interference and electrostatic discharge on measurement channels .The basic concepts are: to avoid radiation generation, and in case some radiation is generated, to avoid coupling with other circuits.

All electronic circuits able to generate high voltage and rapid transient surges were installed into shielded compartments inside a unique container made of magnetic material.

The dividing panels were either welded or screwed on. Connections among compartments were done by means of feed-through capacitors acting as filters for the control and command signals. High voltage lines were implemented via coaxial wires. Batteries were placed in shielded and isolated compartments within the common container. A compact, closed system is thus achieved together with the filtering of induced fields due to the feeding wires.

Electronic circuit boards were fitted to the packaging at appropriate distances from conductive surfaces to avoid low frequency AC fields. Interconnecting wires were kept as short as possible to minimize emitted radiation and reactance[1].

Preliminary tests show that the design goals have been satisfactorily met; the S/N ratio was improved by 30 dB.

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Introduction

Final Box Design

An ideal enclosure should perform as a continuously closed conductive envelope in order to prevent outside fields from penetrating equipment and to prevent internally generated noises escaping the enclosure.

Such an envelope also protect from Electro-Static Discharge (ESD) and provides a conductive media to bind the internal cable screens or component shields. Unfortunately, an ideal box is never achieved because of ventilation openings, maintenance panels and doors, cover seams, cable through holes, and connectors.

However, for practical considerations in designing a box, note the following[1]:

-Try to keep the numbers and sizes of openings (side, top, bottom) to the minimum compatible with their functions.

-Cover ventilation openings or slots with perforated grids (1 mm thick, 2 mm diameter holes)

-Assure continuous electrical contact between grids and chassis (welding or fastener spacing   10 cm)

Theory of shielding and gasketing[2]

Fundamentals concepts

All electromagnetic waves consist of two essential components, a magnetic field, and an electric field. These two fields are perpendicular to each other, and the direction of wave propagation is at right angles to the plane containing these two components.

The relative magnitude between the magnetic (H) field and the electric (E) field components depends upon how far away the wave is from its source, and on the nature of the generating source itself.

The ratio of E to H is called the impedance Z_W. If the source contains a large current flow compared to its potential, such as may be generated by a loop, a transformer, or power lines, it is called a current, magnetic, or low impedance source.

The latter definition is derived from the fact that the ratio the E to H has a small value. Conversely, if the source operates at high voltage, and only a small amount of current flows, the source impedance is said to be high, and the wave is commonly referred to as an electric field. At very large distances from the source, the ratio of E to H is equal for either wave regardless of its origination. When its occurs, the wave is said to be plane wave, and the wave impedance is equal to 377 ohms, which is the intrinsic impedance of free space.

The importance of wave impedance can be illustrated by considering what happens when an electromagnetic wave encounters a discontinuity. If the magnitude of the wave impedance is greatly different from the intrinsic impedance of the discontinuity, most of the energy will be reflected, and very little will be transmitted across the boundary.

Most metals have an intrinsic impedance of only milliohms. For low impedance fields (H dominant) less energy is reflected and more is absorbed, because the metal is more closely matched to the impedance of the field. This is why it is so difficult to shield against magnetic fields. On the other hand, the wave impedance of electric fields is high, so most of the energy is reflected in this case.

Shielding effectiveness of metallic enclosures is not infinite, because the conductivity of all metals is finite. They can, however, approach very large values of shielding. Because metallic shields have less than infinite conductivity, part of the field is transmitted across the boundary and supports a current in the metal.

The amount of current flow at any depth in the shield, and the rate of decay is governed by the conductivity of the metal and its permeability. The residual current appearing on the opposite face is the one responsible for generating the field which exits on the other side. Our conclusion is that thickness plays an important role in shielding. When skin depth is considered, however, it turns out that thickness is only critical at low frequencies. At high frequencies even metal foils are effective shields.

The current density in thick shields is the same as for thin shields. A secondary reflection occurs at the far side of the shield for all thickness. The only difference with thin shields is that a large part of the reflected wave may appear on the front surface.

A gap or slot in a shield will allow electromagnetic fields to radiate through the shield, unless the current continuity can be preserved across the gaps. The function of an Electromagnetic Interference (EMI) gasket is to preserve continuity of current flow in the shield. If the gasket is made of a material identical to the walls of the shielded enclosure, the current distribution in the gasket will also be the same. (This assumes it could perfectly fill the slot, which is not possible due to mechanical considerations.)

Shielding Equations

It was shown that electromagnetic waves incident upon a discontinuity will be partially reflected, and partly transmitted across the boundary and into the material. The effectiveness of the shield is the sum total of these two effects, plus a correction factor to account for reflections from the back surfaces of the shield. The overall expression for shielding effectiveness is written as:

$$SE = R + A + B \qquad (1)$$

Where:
SE is the shielding effectiveness
R is the reflection factor
A is the absorption term , and
B is the connection factor due to reflections from the far boundary.
All values are expressed in dB (decibels).

The equations for the three principal fields are given by de expression:

E-Field

$$R_E = 353.6 + 10\log_{10}\frac{G}{f^3 \boldsymbol{m} r_1^2} \qquad (2)$$

H-Field (equation 3)

$$R_H = 20\log_{10}\left(\frac{0.462}{r_1}\sqrt{\frac{\boldsymbol{m}}{Gf}} + 0.136 r_1\sqrt{\frac{fG}{\boldsymbol{m}}} + 0.354\right)$$

Plane Wave Field

$$R_P = 108.2 + 10\log_{10}\frac{G \times 10^6}{\boldsymbol{m}\,f} \qquad (4)$$

Where $R_E, R_H, y\, R_p$ are the reflection terms for the electric, magnetic and plane wave fields expressed in dB.

G is the conductivity referred to copper

f is the frequency

$\boldsymbol{m}$ is the relative permeability referred to the free space

r_1 is the distance from the source to the shield in inches.

The absorption term A is the same for all three waves and is given by the expression:

$$A = 3.338 \times 10^{-3} \times t \times \sqrt{\boldsymbol{m}\,f\,G} \qquad (5)$$

Where A is the absorption penetration loss expressed in dB, and t is the thickness of the shield in mils.

The factor B (equation 6) can be mathematically positive or negative (in practice it is always negative), and becomes insignificant when $A \rangle 6dB$ It is usually only important when metal shields are thin, and at low frequency (i.e. below approximately 20 kHz).

$$B = 20 \times \log_{10}\left| 1 - \left(\frac{(k-1)^2}{(k+1)^2}\right)\left(10^{-A/10}\right)\left(e^{-j227 \times A}\right)\right|$$

Where

B is expressed in dB

A is the absorption loss in dB

$$|k| = \left|Z_S\Big/Z_H\right| = 1.3 \times \left(\boldsymbol{m}\Big/fr^2 G\right)^{1/2} \qquad (7)$$

Z_S = shield impedance

Z_H = Impedance of the incident magnetic field

If magnetic shielding is required, particularly at frequencies below 14 kHz, it is customary to neglect all terms in equation (1) except the absorption term A.
Conversely, if only electric field or plane wave protection is required then reflection is the important factor to consider in the design.

The following results are based on the equations described in the previous section and will aid the designer in determining Absorption and Magnetic Field Reflection Losses.

We are considering:

$G = 0.0545$

$\boldsymbol{m} = 64.17$

$F = 0.1$

$t = 40$

By applying equation (5), one gets.

$A = 78.96\ [dB]$

These shielding numbers are theoretical, hence they are very high (and unrealistic) practical values[2]

By applying equation (3), one gets.

$R_H = 14.61\ [dB]$

Schelkunoff´s formulas are excellent for calculating near-field SE of metal sheets, provided the transverse near-field wave impedance is used[5]

$$SE = A + R_H = 78.96 + 14.61 = 93.57\ [dB]$$

PPU Description

An EMI shield box for the Power Processing Unit (PPU) was constructed and validated to be used in a Development Model (DM) thruster.
The high power is a 12VDC to 4000V supply regulated source devoted to deliver the high energy pulse to the thruster main electrodes connected to a high voltage electrolytic capacitor bank or non electrolytic capacitor (shown in Fig 1).

The PPU has two discharge circuits that contribute to the radiated emissions: the main capacitor circuit and the spark plug circuit. The high emissions at the 100KHz frequencies have been observed in previous PPU without a special box. According to above considerations all electronic circuits able to generate high voltage and rapid transient surges were installed into shielded compartments inside a unique container made of magnetic material.

The dimensions of the box are 17 cm high, 44 cm width and 36 cm length.
A photograph of the completed PPU breadboard is shown in Fig 2.

PPU Shield Box

The Shielding Effectiveness (SE) of metal barriers in low frequencies is:

$$E = 20 \times \log_{10}\left(\frac{e\boldsymbol{m}_r}{D}\right) \quad [dB] \qquad (8)$$

e = thickness all lenght
D = the longest dimensions of box in the same units as e dimensions.

For example, if we use 1 mm metal sheet iron the SE is:

$\mu_r = 64.17 \quad D = 20\,\text{mm}$

Replacing in equation (8), we obtain

$$E = 10.12 [dB]$$
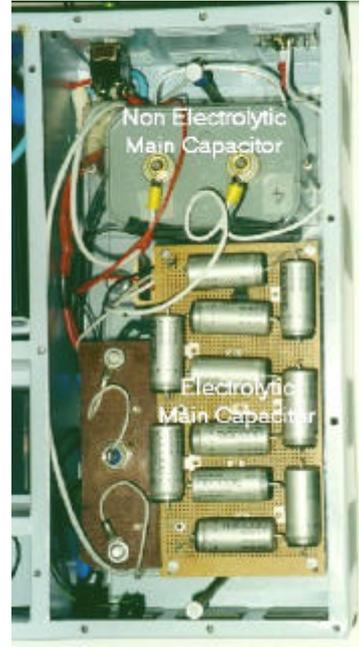
Figure 1: Breadboard Switching Power Supply.

Shielding Impedance[3]

The metal surface impedance is defined as field ratio E/H. The surface impedance of metal shielding is called R_S

$$R_S = \frac{17 \times 10^{-6}}{\boldsymbol{s}_r \times e} \quad [\Omega] \qquad (9)$$

$\boldsymbol{s}_r$ is the conductivity of deposited metal relative to copper.

e is the thickness of metal in millimeters

$\boldsymbol{s}_r \,(\text{iron}) = 0.0545$

Replacing in equation (8), we obtain

$$R_S = 31.2 \quad [\Omega]$$

At high frequencies, the skin depth makes the surface impedance shielding increase as the square root of the frequencies :

$$Z_i = 370 \times 10^{-6} \times \sqrt{f\boldsymbol{m}_r / \boldsymbol{s}_r} \qquad (10)$$

f = frequencies in MHz

$\boldsymbol{m}_r$ = magnetic permeability

$\boldsymbol{s}_r$ = relative conductivity

As an example, we analyze switching power frequency (100kHz) because it is the most important source of noise for impulse sensing devices, consisting of a resonant mechanical fixture which is tuned to the thruster working frequency in order to maximize one axis displacements. These are measured by means of Piezoceramic Transducers (PZT), whose output signals are digitally processed allowing for the determination of the average impulse bit, i.e., the average thrust. Functional testing involved, instead, the full integration of the test stand with the thruster and with a data acquisition system based on a TDS 220 Tektronix Oscilloscope with data acquisition board and signal conditioning circuitry.

Replacing in equation (10) to obtain

$$Z_i = 4 \times 10^{-3} \ [\Omega]$$

Now consider the high value of R_s or Z_i, in this case $Z_i = 4 \times 10^{-3} \ [\Omega]$

The importance of the wave impedance is shown by an electromagnetic wave encountering an obstacle such as a metal shield . If the impedance of wave Z_W differs greatly from the natural impedance of shield Z_i, much of the energy is reflected and the rest is transmitted across the surface boundary, where absorption in the shield further attenuates it. Because most metals have an intrinsic impedance of only milliohms, less low impedance H-field energy is reflected and more is absorbed. This is because metal is more closely matched to the impedance of the field. This is also why it is difficult to shield against magnetic fields[4]. On the other hand, the wave impedance of electric fields is high, so most of the energy is reflected in this case.
At higher frequencies, typically over 10 MHz, EMI shielding is governed mostly by absorption.

Basic Equations to determine Absorption and Magnetic Field Reflection Losses[3]

The effectiveness of the shield representing the primary reflection at the air-metal interface is:

$$R = \frac{(K+1)^2}{4 \times K} \qquad (11)$$

Where

$$k = \frac{Z_w}{Z_i} \qquad (12)$$

Expressed R in dB

$$R = 20 \times \log(R) \quad [dB] \qquad (13)$$

The wave impedance is given by

$$Z_{max} = \frac{18000}{F \times D} \quad [\Omega] \qquad (14)$$

$$Z_{min} = 7.9 \times F \times D \ [\Omega] \qquad (15)$$

Where

F = frequencies in MHz
D = distance in meters

We consider $F = 0.1$ MHz and $D = 0.1$ meters

Replacing in equations 14 and 15 to obtain

$$Z_{W\,max} = 1.8 \ [G\Omega]$$

$$Z_{W\,min} = 0.079 \ [\Omega]$$

So the following relationship results

$$K_H = 19.7$$

To determine magnetic field reflection loss R_H.

$$R_H = 5.438$$

Expressed R_H in $[dB]$

$$R_H \ [dB] = 14.7 \ [dB]$$

The Skin effect thickness is obtained using the next formula

$$d = \frac{66 \times 10^{-6}}{\sqrt{s_r \times m_r \times F}} \quad [m] \qquad (16)$$

This relationship results in Absorption loss

$$A = \frac{8.7 \times e}{d} \qquad [dB] \qquad (17)$$

Where

d = skin thickness in meters

s_r = relative conductivity referred to copper

m_r = magnetic permeability

F = frequencies in MHz

e = the thickness of metal in the same unit as d

We consider

$$s_r = 0.0545 \qquad m_r = 64.168 \qquad F = 0.1$$

Replacing in equations (16)

$$d = 1.116 \times 10^{-4} [m]$$

We used iron metal sheet where $e = 1mm$

Determine Absorption Loss by equations (17)

$$A = 77.95 [dB]$$

These shielding numbers are theoretical, hence they are very high (and unrealistic) practical values[2]

$$SE = A + R_H = 77.95 + 14.7 = 92.65 \ [dB]$$

Finally, we met the same results, but were using two different ways.

Testing for EMI[6]

The requirements for Electromagnetic Interference (EMI) compatibility and susceptibility for all spacecraft subsystem were tailored from MIL-STD-461B.

The purpose of this test was to check that emission from the PPU, would not cause any problem measurement channels. The PPU was located on the PPT as physically possible and was connected to it through an extension harness, and the firing commands were issued from the PPU command subsystem. The reason to perform this test early in DM was to allow time for possible changes in the shielding design of the PPU Flight Model.

The main capacitor discharge circuit was modeled as a magnetic dipole and the electromagnetic field was estimated using Schelkunoff´s solution to Maxwell's Equations. For the main discharge the radiated magnetic field was the primary concern. The spark plug discharge circuit was modeled as a Hertzian dipole. For the spark plug circuit, the radiated electric field was the primary concern[7].

Acceptance Test Results

The PPU has two discharge circuits that contribute to the radiated emissions: the main capacitor circuit and the spark plug circuit. Besides the high emissions at the 100KHz frequency have been observed in previous PPU without a special box.

The test receiver was manually tuned to selected frequencies across the 14kHz to 1MHz range. Measurement at these selected frequencies were taken by firing the PPT numerous times in order to account for shot to shot variations.

The dominant radiation event of the PPT firing is a broadband pulse that lasts for a relative short time (see Table 1). The event repeats at the relatively low 3Hz. PPT frequency.

In addition, testing showed a large 10-30 dB shot to shot variation in measured signal amplitude. A Loop antenna was used to cover the frequency range and was located 1 meter away from the location of the main capacitor.

Table 1: PPU Discharge Circuits Characteristics	
Parameter	Main Capacitor
Discharge Voltage	4000V
Max. Currents	30KA
Pulse Length	10μs
Cap. Energy	50 J

Most data were collected on a Personal Computer (PC) Notebook based Data Acquisition System (DAS) and high frequency data were collected on a TDS 220 Tektronix storage oscilloscope. This 100MHz scope is capable of storing the data in its own memory (for post test to the PC) and also performs data analysis such as fast Fourier transform on the stored data. The Fourier transform results are then displayed on the scope screen and/or transferred to the PC.

The oscilloscope was used to record the radiated emissions in two cases first from PPU without special shield box and second from a Shield box PPU. And performed fast Fourier analysis on both signals. The results are shown in Figs. 3&4 over a range from DC to 1MHz.

The discharge current spectrum in Figs. 3&4 contains much more white noise with some current peaks (labeled 100KHz in Fig. 3). This 100KHZ peak however, may also originate in the converter which switches at 100KHz.

Above 200KHz there are no peaks in the discharge current spectrum.

The emissions were significantly reduced across the entire frequency range (see Fig. 4) when an iron tape was used to cover the main capacitor. The tests show that the design goals have been satisfactorily met.

During these tests, the PPU was powered on but no anomalies attributable to the PPU were observed in other systems.

Conclusions

A conservative approach was taken to assure that the radiated emission from the Power Processing Unit (PPU) did not adversely affect the measurement channels or the other systems.

The EMI shield was successfully implemented; allowing the PPU to be tested in a Development Model (DM) firing test in the vacuum facility belongs to Lockheed Martin Aircraft Argentina S.A (shown in Fig.5)

 The PPU test was taken in order to verify PPU compatibility with Data Acquisition Systems on Piezoceramic Transducer (PZT) output measurement channels at the activation frequency.

The lessons learned from these tasks on reducing emission effects were incorporated in the design of the Ablative Pulsed Plasma Thruster (APPT,P4S-1) which is being developed by Instituto Universitario Aeronáutico IUA, as a low cost-mass-power, simple and highly efficient propulsion option for microsatellites orbit and/or attitude control.

These include isolation, grounding, power and signal filtering, and shielding schemes.

List of Acronyms

EMI   Electromagnetic Interference
EMC   Electromagnetic Compatibility
APPT Ablative Pulsed Plasma Thruster
PPT   Pulsed Plasma Thruster
PPU   Power Processing Unit

ESD   Electro-Static Discharge
SE   Shielding Effectiveness
DM   Development Model
PZT   Piezoceramic Transducer
DAS   Data Acquisition System
PC   Personal Computer

Acknowledgements

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[7] AIAA 2001-3641 Addressing EO-1 Spacecraft Pulsed Plasma Thruster EMI Concerns.

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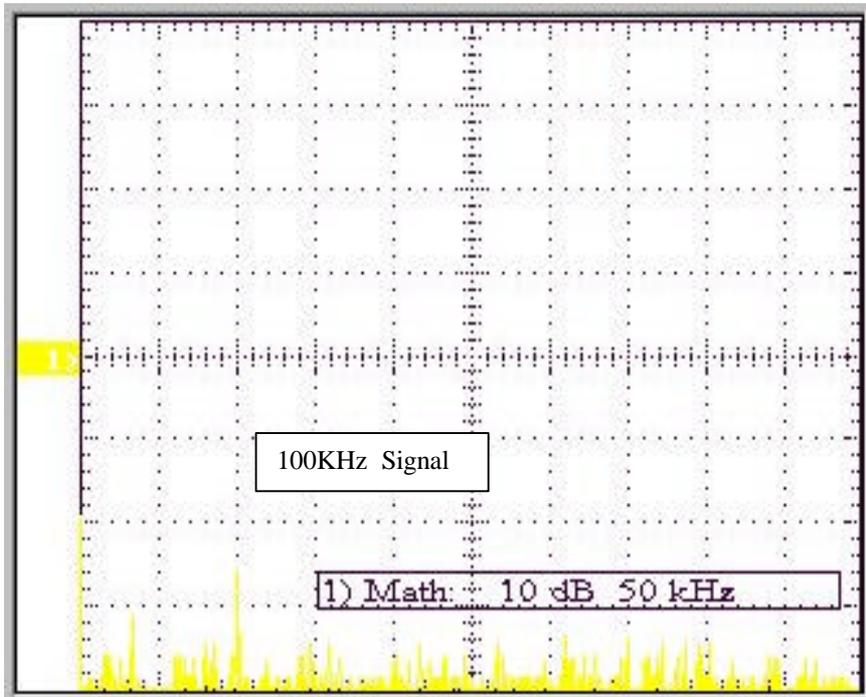
Figure 3: Fourier analysis of the radiated emission from a PPU without shield box.
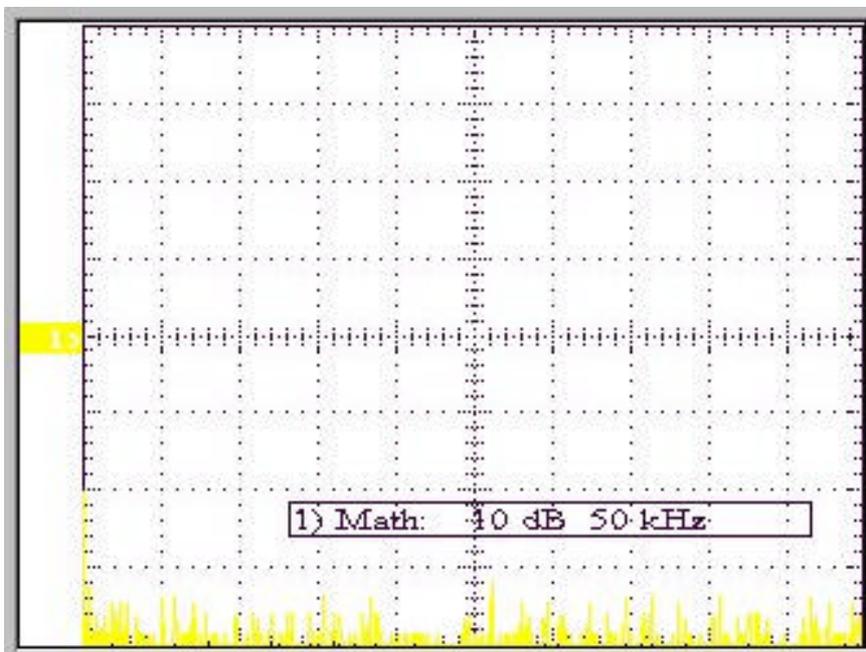
Figure 4: Fourier analysis of the radiated emission from a PPU with special shield box.
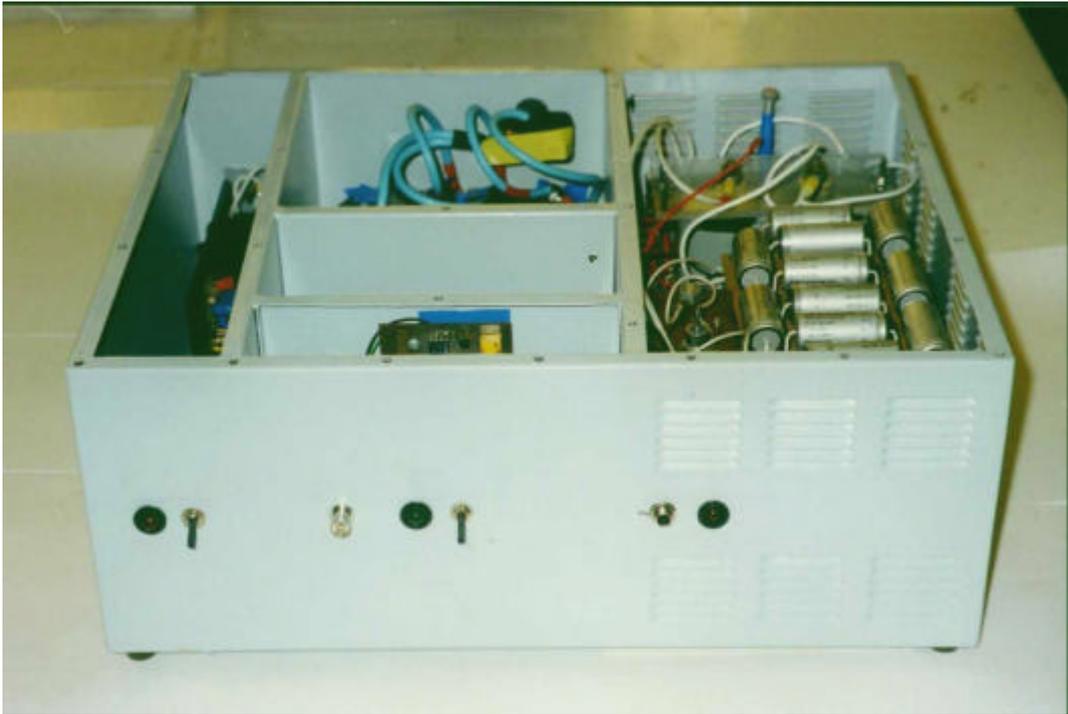
Figure 2: Breadboard Power Processing Unit
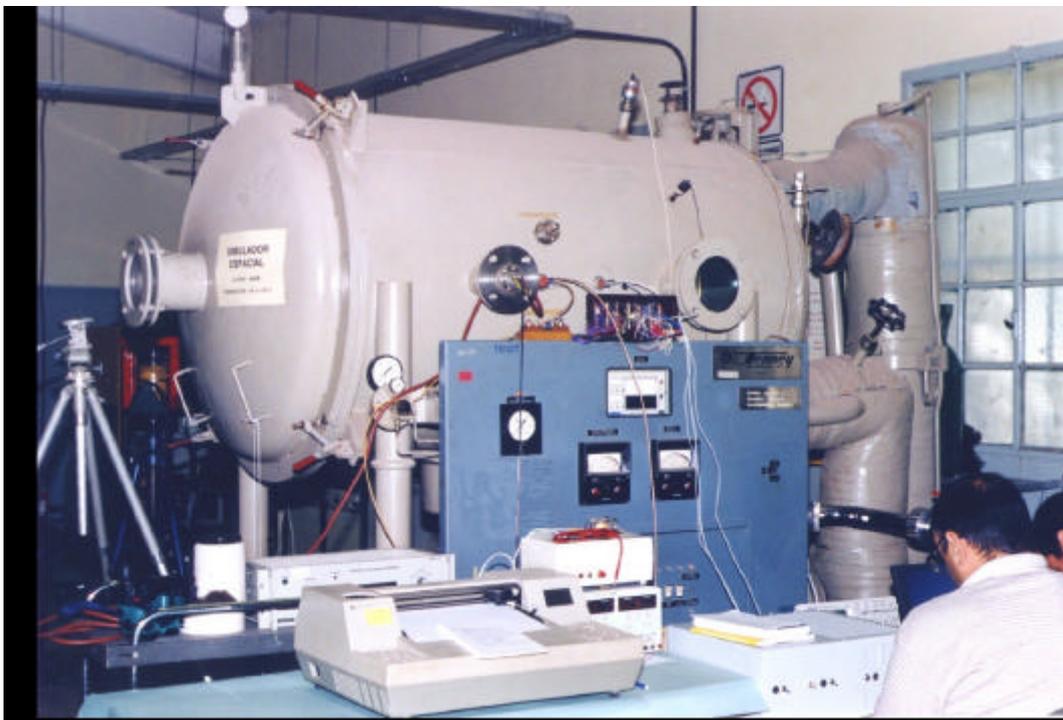
Figure 5: PPU&DM firing test in the vacuum facility