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Development of Power Electronics For a 0.2kW-Class Ion Thruster

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[1] DEVELOPMENT OF POWER ELECTRONICS FOR A 0.2KW-CLASS ION THRUSTER

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Abstract

Applications that might benefit from low power ion propulsion systems include Earth-orbit magnetospheric mapping satellite constellations, low Earth-orbit satellites, geosynchronous Earth-orbit satellite north-south stationkeeping, and asteroid orbiters. These spacecraft are likely to have masses on the order of 50 to 500 kg with up to 0.5 kW of electrical power available. A power processing unit for a 0.2 kW-class ion thruster is currently under development for these applications. The first step in this effort is the development and testing of a 0.24 kW beam power supply. The design incorporates a 20 kHz full bridge topology with multiple secondaries connected in series to obtain outputs of up to 1200 V_{DC}. A current-mode control pulse width modulation circuit built using discrete components was selected for this application. An input voltage of 28 ± 4 V_{DC} was assumed, since the small spacecraft for which this system is targeted are anticipated to have unregulated low voltage busses. Efficiencies in excess of 91 percent were obtained at maximum output power. The total mass of the breadboard was less than 1.0 kg and the component mass was 0.53 kg. It is anticipated that a complete flight power processor could weigh about 2.0 kg.

Introduction

Ion propulsion systems have the advantage of high specific impulse when compared to chemical and other electric propulsion systems. This can lead to reductions in launch vehicle class, increased payload mass fraction, and/or spacecraft life.[1] Currently, a throttleable 0.5 - 2.3 kW xenon ion propulsion system is being developed by the NASA Solar Electric Propulsion Technology Application Readiness (NSTAR) program for planetary spacecraft applications. This system includes a 30-cm thruster, xenon feed system (XFS), a power processing unit (PPU), and a data control and interface unit (DCIU) which will be used as primary propulsion on the New Millennium Deep-Space 1 mission to be launched in July 1998.[2]

There is also a potential need for high specific impulse propulsion for small spacecraft. Applications that might benefit from this technology include Earth-orbit magnetospheric mapping satellite constellations, low Earth-orbit satellites, geosynchronous Earth-orbit (GEO) satellite north-south stationkeeping, and asteroid orbiters using spacecraft of 50 to 500 kg and within the order of 0.5 kW.[1] Some inherent problems of using electric propulsion with small spacecraft include cost, limited power, volume, and thermal control capacity. This makes reduced parts count, simplicity, and high efficiency critical requirements for the implementation of this technology.

Technology for a 0.2 kW-class ion thruster is currently being evaluated under NASA's On-Board Propulsion Program. This design builds on the NSTAR 30-cm thruster, incorporating features such as a ring-cusp magnetic circuit, partial-conic discharge chamber, and nonferromagnetic materials.[3]

In addition to the thruster, a PPU is being developed for the low power ion propulsion system. Simplicity and minimum mass and volume with reasonable efficiency are the major design drivers. The breadboard will supply the six electrical outputs required by the ion thruster up to a total of 0.3 kW using a nominal input voltage of 28 ± 4 V_{DC}. The beam power supply processes 66 to 81 percent of the total thruster power, which ranges from 0.08 to 0.30 kW. It also supplies high voltage for ion acceleration making it the most critical component in the PPU.

This paper documents the design process and performance characteristics of the beam supply for the PPU. Also, it presents the results of resistive load tests and information on the design approach to be used for the other power supplies required for the system.

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Design Considerations

Spacecraft / PPU Interface

A number of assumptions regarding spacecraft interface requirements were made to initiate the design process. First, a nominal input voltage of 28 ± 4 V_{DC} was used because typical small spacecraft are anticipated to have unregulated low voltage power busses. Second, input-output isolation was desired for proper engine operation and to conform to anticipated single point grounding schemes. Finally, mass, volume, simplicity, and efficiency were chosen as design drivers.

Thruster / PPU Interface

Figure 1 shows a block diagram of the low power ion thruster system. The thruster requires six electrical outputs for proper operation. These outputs supply cathode heater, discharge, neutralizer heater, and neutralizer keeper currents and beam and accelerator voltages. The cathode and neutralizer heaters are used to raise the discharge and neutralizer cathode to emission temperature prior to ignition. The resistance of these heaters typically varies from 0.3 to 1.7 Ω as their temperature rises, therefore, a constant current source is necessary to control inrush currents. The main discharge and neutralizer cathodes emit electrons that maintain plasma discharges, therefore, constant current sources are used to avoid instabilities. Xenon gas is ionized inside the discharge chamber and two very closely spaced grids, known as screen and accelerator grids, accelerate them electrostatically. Constant voltage sources are required to provide grid potentials. Then, the neutralizer cathode provides an electrical path for the electrons created in the discharge chamber, so they can neutralize the ions outside the engine. The output specifications for all the power supplies in the PPU are shown in Table 1.

Grid-to-grid faults can occur due to the close proximity of the grids and the high potential between them. Therefore, both beam and accelerator supplies must include short circuit protection to prevent damage during these faults. A fault correction circuit is required to detect faults and immediately sequence the power supplies. The sequencing of power supplies, known as a "recycle", extinguishes the fault to avoid damage to the thruster, and then, restore steady-state conditions. The requirements to complete a recycle has been documented elsewhere (ref. 4).

PPU Design

Beam Supply

Topology

Topology selection for the beam supply is critical for the overall efficiency of the PPU. Table 1 shows that it processes 66 to 81 percent of the total power to the thruster. For this reason, a full bridge topology was chosen because it allows the use of lower voltage switching devices and requires a simpler transformer than other switching topologies. It also allows the use of soft switching techniques to maximize efficiency.[5,6] A switching scheme that alternately switches the two top transistors at 50 percent duty cycle and pulse width modulates the two bottom diagonal transistors was implemented. A low inductance power stage, using MOSFET switching devices, was build to reduce switching transients.[7,8] A switching frequency of 20 kHz was chosen to reduce switching losses, core losses, and the mass of the magnetic components. A photograph and a schematic of the breadboard beam supply are shown in Figures 2 and 3, respectively.

Transformer

The power transformer was wound on an EC-type core made of 3C85 material. Ferrite was chosen due to its high efficiency and lower density than tape wound cores. The primary winding consisted of multiple strands of 26 AWG wire sized to reduce skin effect losses and minimize conduction losses. A total step-up ratio of 51:1 was required to obtain an output voltage of 1200 V_{DC} at minimum input voltage. Therefore, the number of primary turns was minimized to reduce the total amount of turns. Also, winding techniques which reduce leakage inductance and interwinding capacitance were used. The secondary consists of four separate windings, each one producing up to 400 VDC for the beam output. This arrangement reduces the voltage rating required for the output rectifier diodes. The beam output is obtained by connecting the four secondaries in series.

PWM Control

Peak current-mode control was implemented with the beam supply because of its excellent regulation, current limit, and short circuit protection characteristics over voltage-mode control. The pulse width modulation (PWM) circuit was implemented using discrete components to avoid noise susceptibility problems associated with some current-mode PWM controller integrated circuits (ICs). This circuit includes cycle-by-cycle current limit on the primary current for short circuit protection and soft start capability.

Physical Characteristics
Minimizing the mass and size of the PPU is a critical design requirement. The beam supply has a component mass of 0.53 kg resulting in a component specific mass of 2.2 kg/kW. The heaviest component is the power transformer with a weight of 0.175 kg. The total weight of the breadboard is 1.1 kg. From these numbers it is anticipated that a flight version of a complete PPU could weigh as low as 2.0 kg.

Additional Circuitry

Command and Telemetry Circuit
Control and sequencing of the power supplies can be accomplished in several ways. These include state machines and software driven micro-controllers/micro-processors. To maintain simplicity, a state machine was chosen for this design. This state machine can be implemented using discrete components or field programmable gate arrays (FPGAs).

The design of the command and telemetry circuit is in progress. Commands will be simplified to a two bit command word, which allows up to four possible states. These states are standby, cathode conditioning, and run with up to two setpoints for the thruster operation. The cathode conditioning command is used the first time the thruster is operated after being exposed to atmosphere. This command initiates a process that removes water and other contaminants from the cathode inserts. The run command will perform the complete startup sequence for the thruster. This consists of heating the cathodes, starting their discharges, and applying high voltage. If necessary, states for additional setpoints could be implemented by adding bits to the command word. Telemetry consists of only one bit of information that will indicate that a particular parameter is within normal, pre-defined limits. For thrust calculation purposes, the beam current telemetry has a 12 bit resolution.

Recycle Circuit
An independent circuit monitors and detects recycle events. The same design used for the NSTAR breadboard power processors was implemented in the low power design.[9,10,11] After an overcurrent is detected on the beam supply, the beam and accelerator supplies are turned off to extinguish the fault. Also, the discharge current is reduced to minimize the ion density inside the discharge chamber and avoid starting another recycle when high voltage is reapplied. Then, the beam and accelerator supplies are turned on. Finally, the discharge current is restored to nominal value.

Power Supplies
The accelerator, discharge, neutralizer keeper, and heater supplies required for this application process a small fraction of the total power to the engine. As shown in Table 1, their respective maximum outputs are 0.3, 56, 2, and 27 W. A commercially available switching voltage regulator will be used for this application. This IC includes the control and power functions for an isolated or non-isolated single transistor topology. With the addition of a power transformer, an output filter, and a minimum number of external components, a complete power supply can be built with current-mode control, current limit, soft start, undervoltage lockout, and thermal shutdown features. Since isolation is required for this application, a flyback topology was chosen for the accelerator supply because of its advantages at higher output voltages. A forward topology was chosen for the other supplies because of its advantages at higher output currents.[5,6]

Test Procedure

The beam supply was characterized using a resistive load at power levels between 0.05 and 0.24 kW. Digital multimeters were used to measure input and output voltages and currents. Efficiency was defined as the output power divided by the input power, including any housekeeping power. At each setpoint, line regulation was tested by sweeping the input voltage from 24 to 32 V_{DC} and load regulation was tested by sweeping the load resistance over the operating range of the power supply. Regulation was defined as the maximum minus the minimum output divided by the setpoint. Finally, the output of the power supply was mechanically shorted at each power level to demonstrate short circuit fault survivability.

Results and Discussion

Overall Output Characteristics

The beam supply operated stably across the complete output voltage and power envelope and through the complete input voltage range. Output voltage ripple was found to be less than 5 percent for all operating conditions. Short circuit survivability tests demonstrated stable operation during the fault while the cycle-by-cycle current limit function of the PWM circuit properly controlled the maximum input current, by limiting the duty cycle of the MOSFETs.

Efficiency

Because the beam supply processes 66 to 81 percent of the power across the 0.08 to 0.30 kW total thruster power range, efficiency is critical in this design to obtain reasonable overall efficiency. At lower power levels it is difficult to obtain high efficiency because housekeeping power is a larger fraction of the total power processed by the power supply. For this reason, core, conduction, and switching losses were minimized and transients were controlled to avoid the need for energy consuming snubbers. The result was a beam supply efficiency comparable to that in other existing ion propulsion power processors. Figure 4 shows a plot of efficiency versus power at minimum, nominal, and maximum input voltage obtained from preliminary resistive load tests on the beam supply. The efficiency was above 0.91 at full power (1200 V_{DC} @ 0.204 A_{DC}) and a nominal input voltage of 28 V_{DC}. It decreased to 0.86 at minimum power (640 V_{DC} @ 0.088 A_{DC}). These reported efficiencies include all housekeeping power including PWM control, gate drives, telemetry, and losses.

Table 2 shows how losses are distributed in the power supply. The components with the highest losses in this design are the MOSFETs. The sum of their conduction and switching losses comprise almost 48 percent of the total losses.

Some options that will be explored for possible efficiency improvements in the beam supply include the use of optimized magnetic cores to reduce core losses, soft switching techniques to reduce switching losses, and paralleling additional MOSFETs in the power stage to reduce conduction losses.

Regulation

The line/load regulation specification for this design was less or equal to 5 percent, as shown on Table 1. Figures 5 and 6 show the results of the regulation tests. Line regulation was better than 2 percent for any output voltage setpoint and load regulation was better than 1.5 percent at nominal input voltage.

Conclusions

A breadboard beam supply for a low power ion propulsion system was fabricated and tested. This power supply processes up to 0.24 kW of output power by converting the input voltage of 28 ± 4 V_{DC} into a maximum of 1200 V_{DC}. A 20 KHz, full bridge topology was used to minimize switching and core losses and the mass of magnetic components. A total of four secondaries were connected in series to reduce the voltage rating requirements on the rectifier diodes. Current-mode control was implemented using a PWM circuit built from discrete components. Ferrite cores were used for the major magnetic components to take advantage of its weight and efficiency characteristics.

The beam supply was tested on a resistive load and demonstrated load and line regulations better than 2 percent, output ripple less than 5 percent, and efficiencies in between 0.86 and 0.91 over the power range of 0.05 to 0.24 kW. It also demonstrated immunity to a short circuits. The total component and breadboard mass of this design was 0.53 and 1.1 kg, respectively.

The accelerator, discharge, neutralizer keeper, and two heater supplies designs utilize commercially available switching regulator ICs that incorporate all the control and switching functions required by a flyback or forward topology. These will be integrated with the beam supply, recycle, and command and telemetry circuits into a complete PPU.

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Table 1. Low power ion PPU output specifications

	Beam	Accelerator	Discharge	Neutraliz	Heaters	Thruster
Input Voltage (V)	24 - 32	24 - 32	24 - 32	24 - 32	24 - 32	
Output Voltage	640 - 1200	-160 - -300	28	20	7	
Output Current	0.088 - 0.204	0.3 - 1.0 mA	0.94 - 1.94	0.1	4.0	
Output Power (W)	56 - 245	0.048 - 0.3	26.3 - 54.3	2	28	
Total Power (W)						84.3 - 301.6
Regulation Mode	Voltage	Voltage	Current	Current	Current	
Output Ripple (%)	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	
Regulation (± %)	≤ 5	≤ 5	≤ 5	≤ 5	≤ 5	

Table 2. Measured and calculated power losses at nominal input voltage and maximum output power

	Power (W)
Conduction Losses - Transformer	1.5
Output	0.35
MOSFETs	8.5
Diodes	1.3
Input Inductor	0.5
Core Losses - Transformer	1.9
Output Inductor	0.75
Switching Losses	2.5
Housekeeping	3.9
Other	1.9
Total	23.1

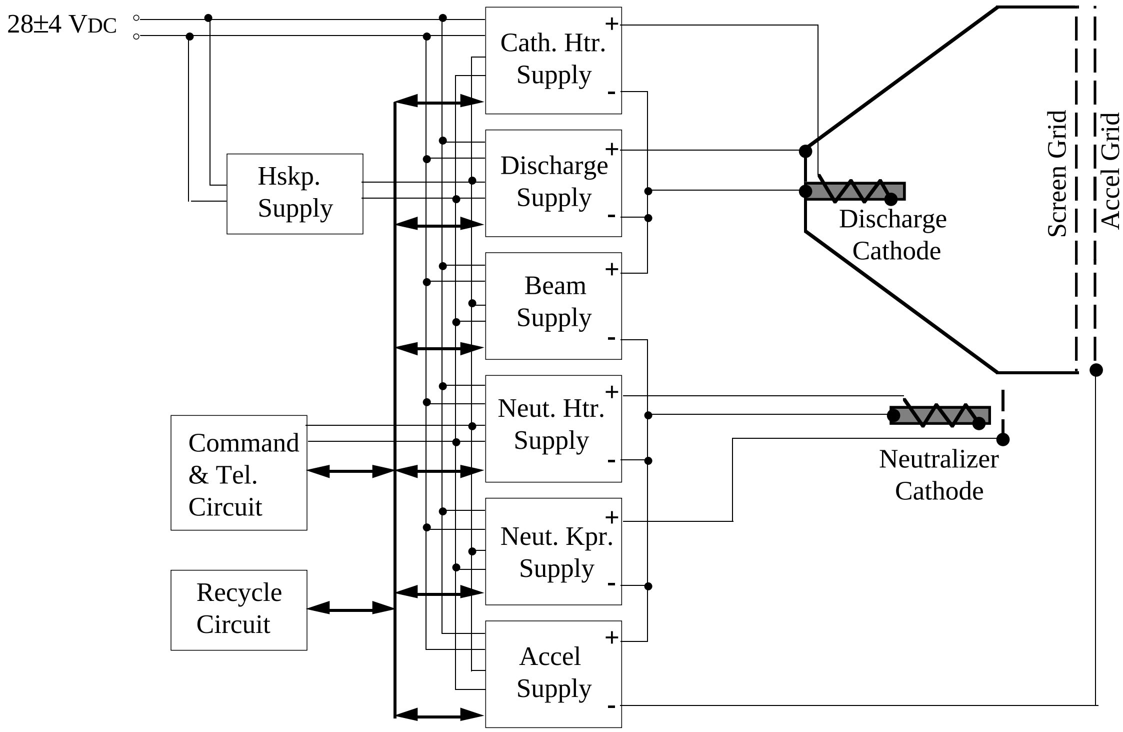

Figure 1. Low power ion propulsion system block diagram

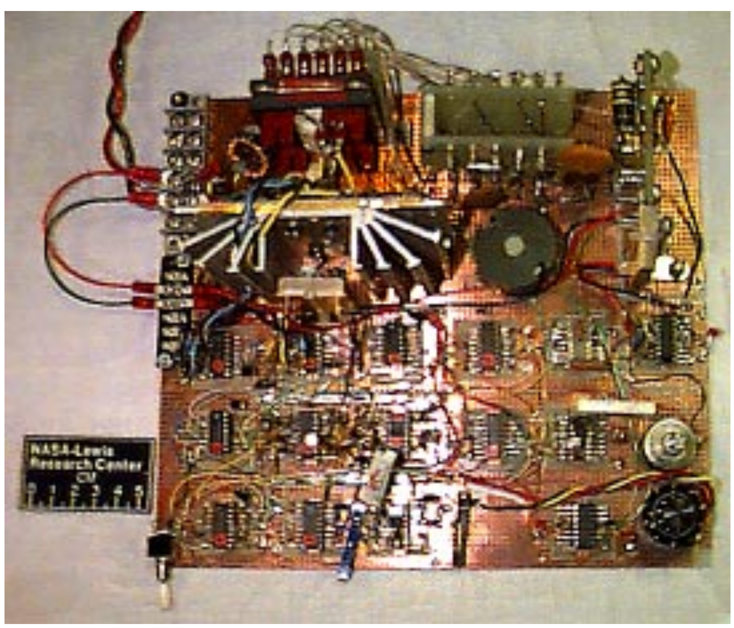

Figure 2. Low power ion breadboard beam supply

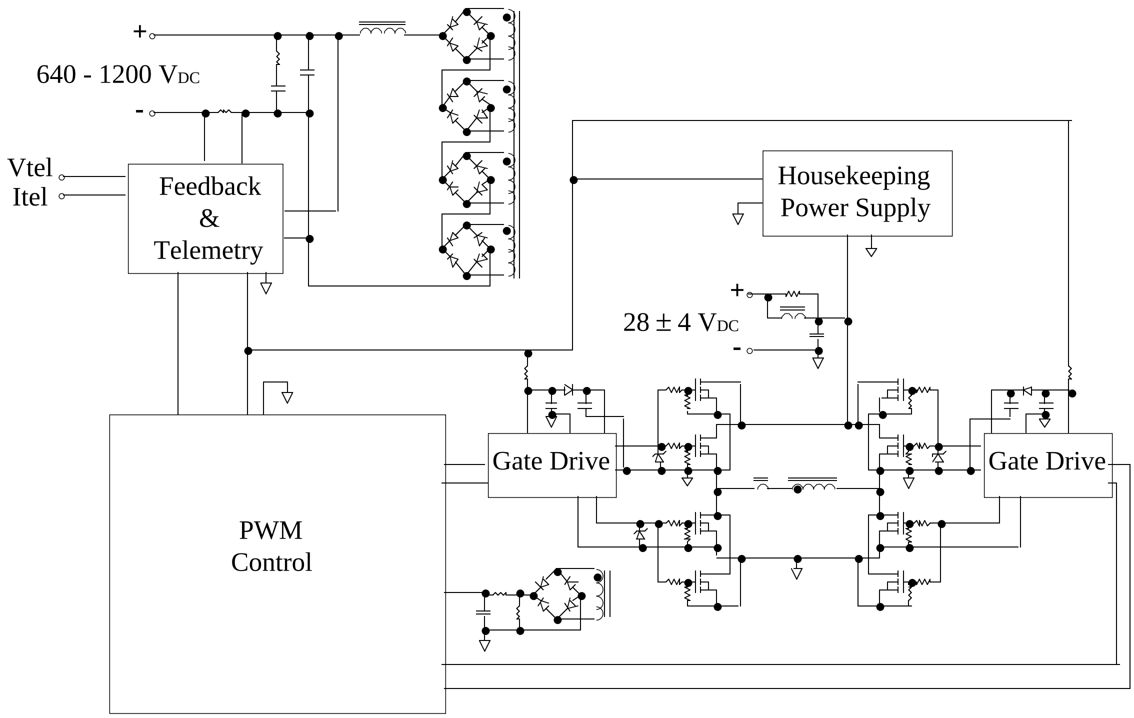

Figure 3. Breadboard beam supply schematic diagram

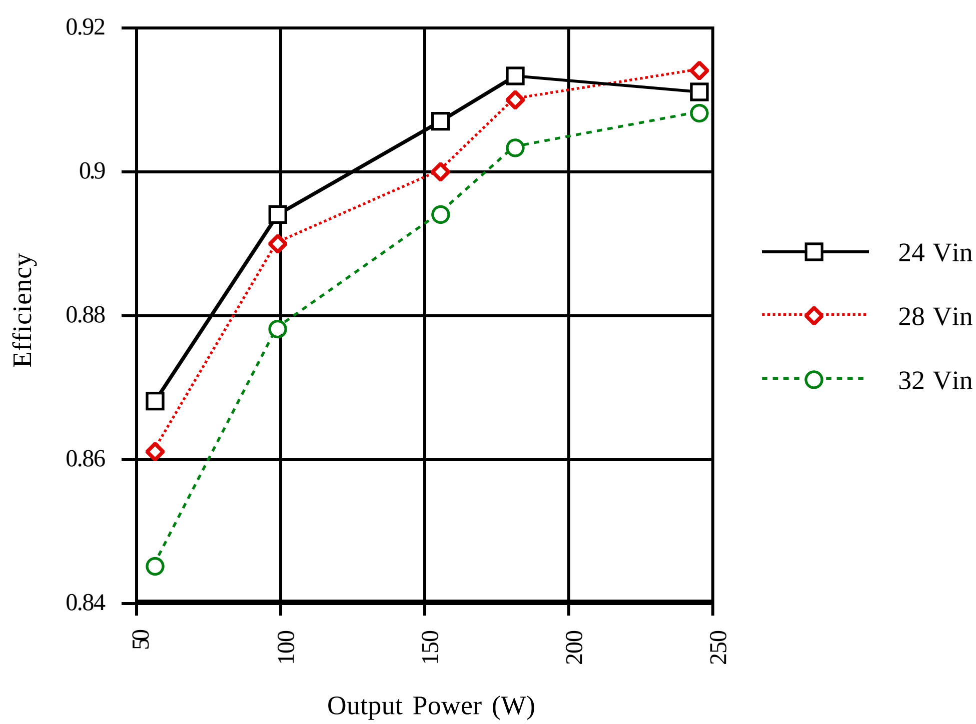

Figure 4. Beam supply efficiency at various output power levels

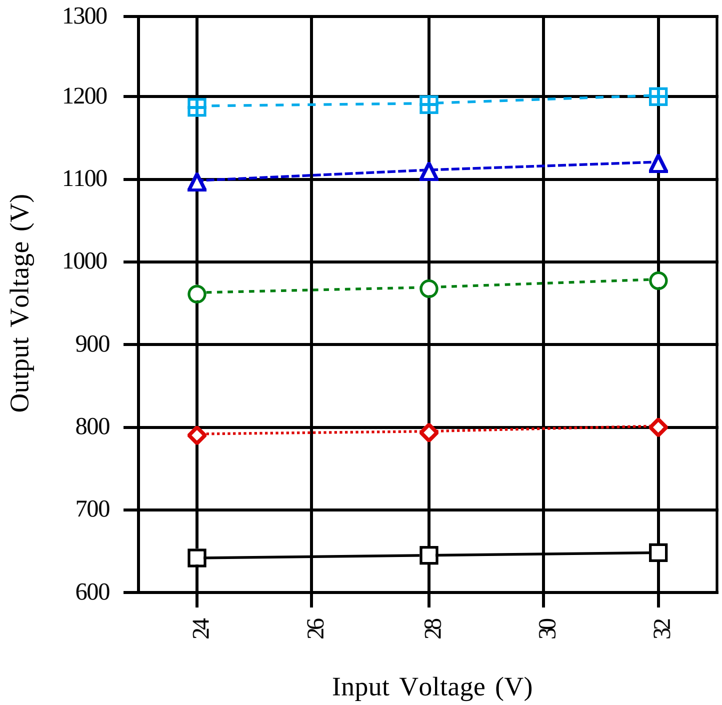

Figure 5. Beam supply line regulation test results

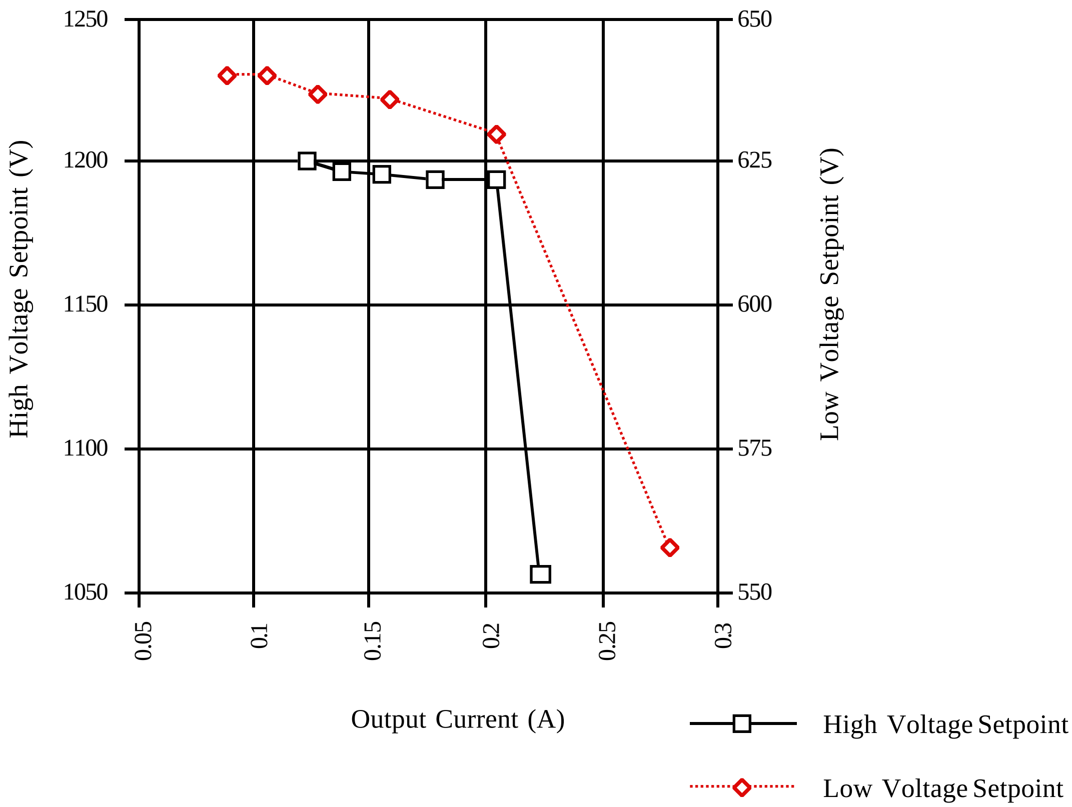

Figure 6. Beam supply load regulation test results

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13. ABSTRACT ***(Maximum 200 words)***

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