Chapter 22

E-gun Power supply for EBWWT Accelerator

– *Arka Mitra*

The objective of this chapter is to describe the design aspects of electron gun (E-gun) power supply for EBWWT accelerator situated at EBC, Kharghar. The design considerations and basic control philosophy of the power supply have been given in the following sections. The power supply floating at high voltage dome potential uses saturable reactors as variable impedance for controlling filament power. This magnetic component based design is robust and more suitable in HV and HF discharges often encountered during operating conditions (one dominant discharge frequency being 26 MHz at peak discharge current of 21 kA) than commonly used SMPS based alternatives. The detailed design methodologies of different aspects of the power supply and its controller are discussed in this chapter.

22.1 Description of the Power Supply

E-gun power supply is a floating power supply consisting of the filament and anode power supplies to power the electron gun. The outputs are referenced to the common dome terminal. Filament power supply can be controlled independently through fiber optic links. Health Signals of Filament Supply will be available through fiber optical links. Anode power supply has been realized by putting a 125 MΩ biasing resistor between dome and anode terminals.

22.1.1 Input Specifications

Input electrical parameters to the electron gun supply are specified in table 22.1.

Table 22.1: Input Specifications

Maximum input voltage	: 155 V_{rms}
Minimum input voltage	: 115 V_{rms}
Maximum input current	: 5 A_{rms}
Input frequency	: 10 kHz ± 10%
Efficiency	: greater than 85% at full load
Signal Protection	: Current Limiting

22.1.2 Filament Power Supply Specifications

Filament power supply parameters are specified in table 22.2.

Table 22.2: Filament power supply specifications

Type	: Current Controlled
Current	: 0-20 A_{rms} @10 kHz
Output voltage	: 0-15 V_{rms} @10 kHz
Minimum settable output current	: 2 A_{rms}
Maximum settable output	: 20 A_{rms}
Current setting	: Continuously Variable
Line regulation	: 5%
Load regulation	: 5%
Remote current control	: PWM Optical Signal
Current Feedback	: PWM Optical Signal

22.1.3 Block Schematic of the Filament Power Supply

A block schematic of the filament power supply is given in Fig. 22.1. The input to the Gun

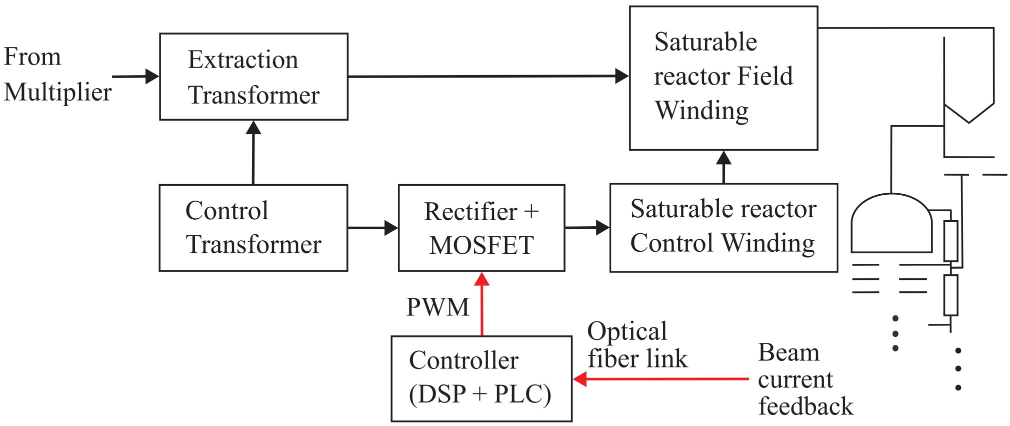

Figure 22.1: Block schematic of the GPS.

Power Supply (henceforth abbreviated as GPS) is extracted from the last stage of the CW multiplier using an extraction transformer. The input power is divided between the control supply and the power supply. The control supply, consisting of control transformer and rectifier is fed to control winding of the saturable reactor through a MOSFET switch. The PWM of the Switching device is controlled by a controller based on beam current set point and feedback. The output of the switching circuit is a variable DC which is fed to control winding of the saturable reactor. Another part of the input power to the GPS directly feeds the field winding of the saturable reactor.

22.1.4 Principle of a Saturable Reactor

A saturable reactor works as current controlled variable impedance. It is an inductor with two windings on the same core. One winding carries the alternating current of the power line and called field winding and the other winding carries DC current and is called control winding. The current flowing through the control winding changes permeability of the core and hence the inductance of the reactor also changes (Fig. 22.2). To ensure that both the cycles of the alternating field current see same impedance two sets of control and field windings are used in quadrature.

22.1.5 Design of the Saturable Reactor for Filament Supply

A saturable reactor is designed based on the limiting conditions of the power supply. It ensures that the power supply is capable of delivering maximum current in the minimum input power and minimum current in the maximum input power condition. The design calculations are as follows:

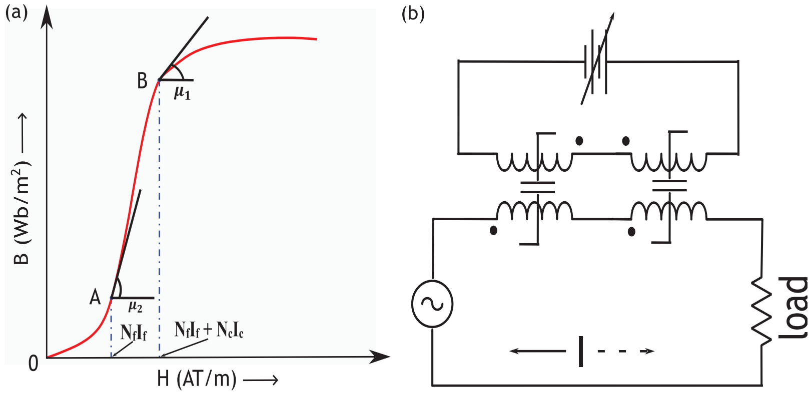

Figure 22.2: A Saturable Reactor: (a) Variation of permeability of saturable reactor with current in control winding, and (b) Control and field winding direction in saturable reactor core pair.

Set value for extraction transformer output	: 135 V_{rms} = 191 V_{peak}
Considering ±15% variation	
Maximum input	: 155 V_{rms} = 215 V_{peak}
Minimum input	: 115 V_{rms} = 162 V_{peak}
Operating frequency	: 10 kHz
Filament inductance	: 1×10^{-6} H
Inductive reactance	: 0.0628 Ω
Filament resistance at 20 A current	: 0.75 Ω
Maximum filament voltage	: 15 V
Maximum filament power	: 300 W
Minimum filament current	: 2 A
Filament resistance at 2A	: 0.15 Ω
Minimum filament voltage	: $0.15 \times 2 = 0.3$ V
Reactive drop across filament	:
Maximum	: $0.0628 \times 20 = 1.256$ V
Minimum	: $0.0628 \times 2 = 0.1256$ V
Taking filament primary voltage Maximum	: $15 \times 6 = 90$ V
Minimum	: $0.3 \times 6 = 1.8$ V
Secondary impedance referred to primary at maximum current	: $6^2 \times (0.75+j0.0628) = (27+j2.2608)\ \Omega$
Secondary impedance referred to primary at minimum current	: $6^2 \times (0.15+j0.0628) = (5.4+j2.2608)\ \Omega$
Primary side maximum current	: $90/\sqrt{27^2 + 2.2608^2} = 3.32$ A
Primary side minimum current	: $1.8/\sqrt{5.4^2 + 2.2608^2} = 0.307$ A
Maximum Z at primary side	: $155/0.307 = 505\ \Omega$
Maximum limiting inductive Reactance value	: $\sqrt{505^2 - 5.4^2}$-2.2608 = 503 Ω
Maximum limiting inductor value	: $\frac{503}{2\times\pi\times10\times10^3} = 8$ mH
Minimum Z at primary side	: $115/3.32 = 34.63\ \Omega$
Minimum limiting inductive Reactance value	: $\sqrt{34.63^2 - 27^2}$-2.2608 = 19.42 Ω
Minimum limiting inductor value	: $\frac{19.42}{2\times\pi\times10\times10^3} = 309\ \mu$H

Range of inductance 26.66 times

Set value for extraction transformer output	: 135 V_{rms} = 191 V_{peak}
Considering ±15% variation Maximum input	: 155 V_{rms} = 215 V_{peak}
Minimum input	: 115V_{rms} = 162 V_{peak}
Operating frequency	: 10 kHz

Hence, it is required to have a saturable reactor with inductance variation ranging from 8 mH to 300 μH. Hence six core pairs of EE6450P are used in series with control windings of 50 turns each of 1 mm^2 Teflon wire and field winding of seven turns each of Litz wire. The experimental variation of inductance with control current variation is given Fig. 22.3.

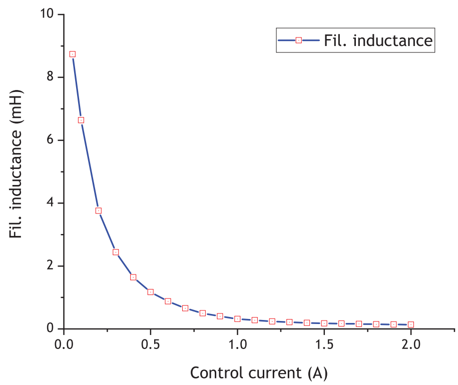

Figure 22.3: Control current vs. saturable inductance of Filament Supply.

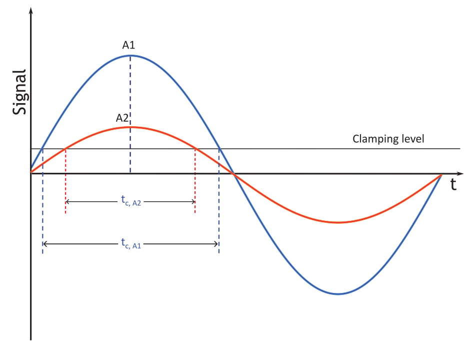

Figure 22.4: Filament current to variable pulse width optical signal.

22.1.6 Control Supply

The control power supply (Fig. 22.5) consists of a control transformer and a rectifier which converts the 10 kHz Supply voltage to DC voltage of 12 volts in the secondary and 10 volts in the tertiary winding. The tertiary winding is used to drive the MOSFET. The secondary voltage is chopped by the MOSFET and variable DC voltage after filtering is fed to the control winding. Maximum control current supply is 2 A. The Pulse width of the gate drive signal of MOSFET is generated by the PLC and DSP based controller situated at the ground side based on beam current feedback and beam set point. This electrical signal is converted to optical pulse and sent to the GPS through fiber optic link. The optical signal is then converted back to electrical signal and fed to the gate of the MOSFET switch to control the voltage across the control winding of the saturable reactor. This mode of control signal transmission ensures isolation between the controller, which is at ground side and the GPS, which is floating at dome potential.

22.1.7 Feedback/Health Signal

The filament current feedback is taken from a CT at the primary of the filament transformer. A Zener and photo diode based electrical to optical signal conversion circuit is in use. It generates an optical signal whose pulse width changes based on the amplitude of the filament current (as shown in Fig. 22.4) and the signal is sent to the controller via optical fiber. The major components of the e-gun power supply have been enumerated above. Figure 22.6 shows the photograph of assembled Gun power supply in an EMI shielded cabinet.

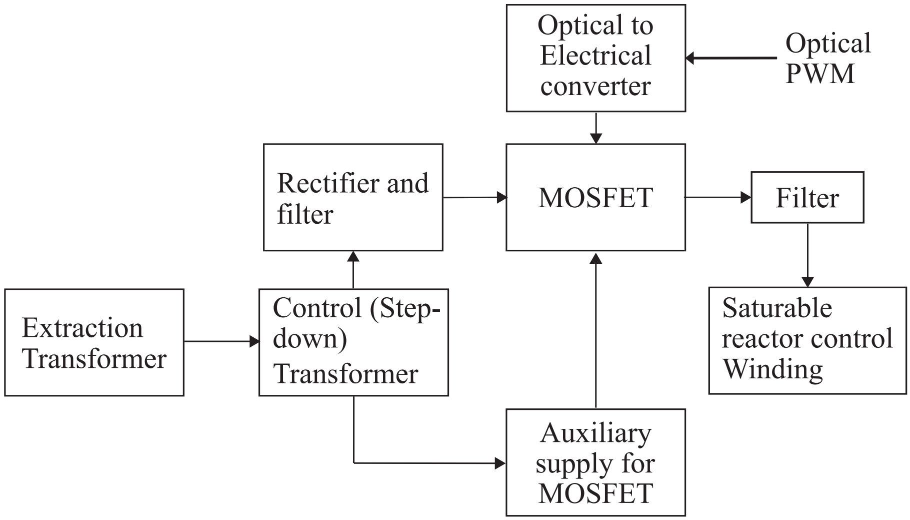

Figure 22.5: Control Supply Schematic.

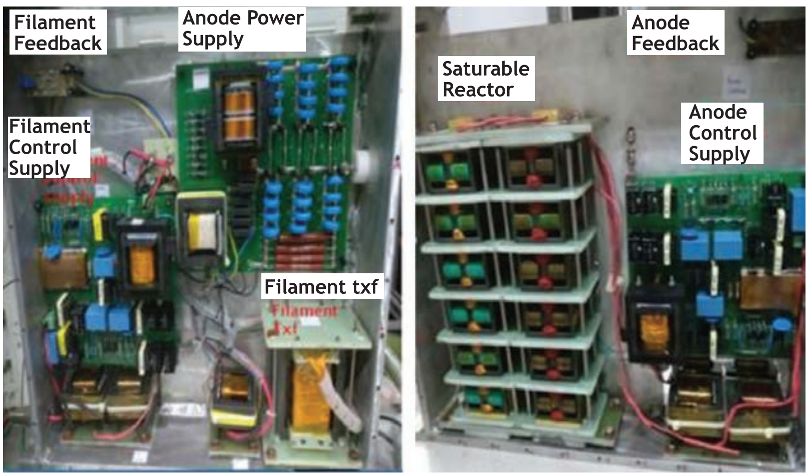

Figure 22.6: Photograph of assembly of e-gun power supply.

22.2 Design of the Controller

The controller for the GPS is designed to keep the beam current around a given set point. The supervisory control has been implemented on PLC. Beam current feedback is fed to the PLC which determines the duty cycle of the MOSFET switch which feeds the control supply of the saturable reactor and hence controls the series impedance and current of the filament power supply. The supervisory controller is of PI topology which feeds the PWM to a C2000 DSP based local controller. This local controller generates optical signal which is fed to the GPS via optical fibre link. To determine the controller parameters, first the dynamic behaviour of the electron gun is modelled. The simplified schematic of the filament cathode assembly is given in Fig. 22.7.

The power supplied to the filament causes temperature rise in the filament and indirectly

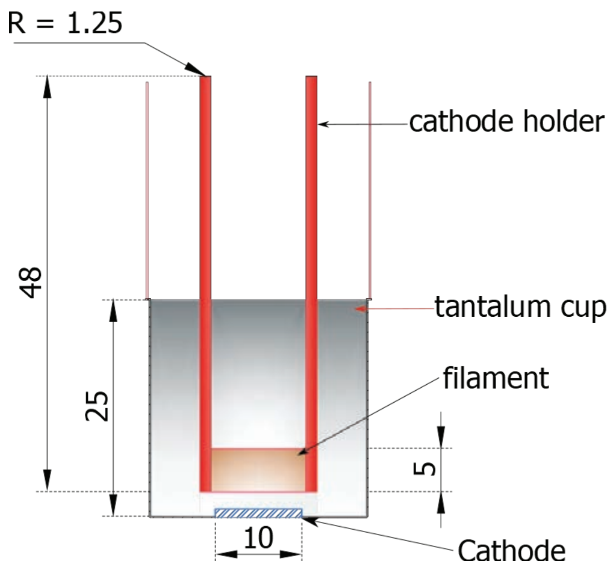

Figure 22.7: Filament Cathode assembly.

heats the LaB_6 cathode. The governing equations for the heat transfer are:
Input power = increase in filament thermal power due to its heat capacity + conductive heat loss through the lead + radiative heat loss.

$$P = m_f C_{pf} \frac{\mathrm{d}T_f}{\mathrm{d}t} + \frac{(T_f - T_b)}{R_{thf}} + Q_{rf} \tag{22.1}$$

Where,
P = input power to the filament
m_f = mass of the filament
C_{pf} = specific heat of tungsten in J/kg-K
T_f = temperature of the filament
T_b = background temperature for conduction
R_{thf} = thermal resistance from filament to background temperature comprising two leads = $\frac{l_{flead}}{kA_{flead}}$
Q_{rf} = radiated heat output from filament.
In the same way, we can write the equation for the cathode:
Net radiative heat input to the cathode = increase in cathode thermal power due to its heat capacity + conductive heat loss.

$$Q_{rc} = m_c C_{pc} \frac{dT_c}{dt} + \frac{T_c - T_b}{R_{thc}} \tag{22.2}$$

Where,
T_c = temperature of the cathode
V_{fc} = view factor of the filament to cathode (calculated later in details)
m_c = mass of the cathode
C_{pc} = specific heat of LaB_6 in J/kg-K
R_{thc} = thermal resistance from cathode to background temperature comprising the cathode holder cup and two strips in parallel to its vertical wall and three strips above it connecting the cup to background temperature.

This resistance is equal to resistance of horizontal portion of the cup+ resistance of vertical portion of the cup in parallel to two strips+ resistance of three strips in parallel.
With k = thermal conductivity of tantalum,
Horizontal portion resistance = $\ln\left(\frac{\text{Radius of Cathode}}{\text{Radius of cup}}\right)/(2\pi k \times \text{ Thickness of Cup})$
Vertical portion resistance = $\frac{l_{cup}}{(k\times\text{annular area perpendicular to the heat flow having width 0.15 mm})}$,
Strip resistance = $\frac{l_{strip}}{k\times A_{strip}}$, and
Q_{rc} = radiated heat input to cathode.
When we know the temperature of the filament, we can calculate the current density (J_c) by famous Richardson-Dushman equation:

$$J_c = RT_c^2 exp\left(-\frac{qW}{k_b T_c}\right) \tag{22.3}$$

where, R is the Richardson constant, which is 29 $A/cm^2/K^2$ for LaB_6, q is the charge of an electron, T_c is the filament surface temperature in K, W is the work function of LaB_6 (= 2.7 eV), and k_b is the Boltzmann constant (= 1.38×10^{-23} in SI unit).
The radiation heat transfer model is obtained by considering filament, cathode and environment as a three-body radiation system.
The solutions of the above equations give a time evolution of cathode and filament temper-

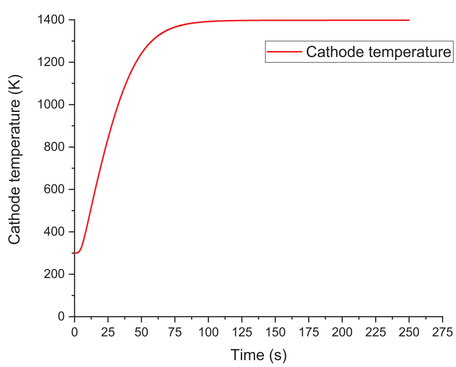

Figure 22.8: Cathode temperature vs. time for 66 W filament input.

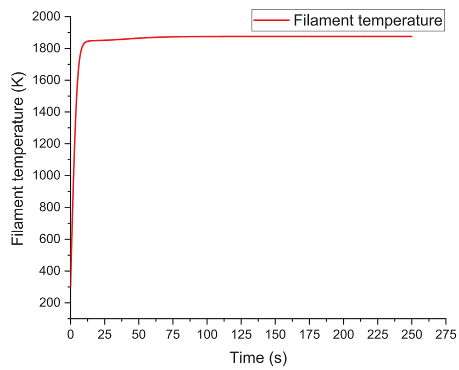

Figure 22.9: Filament temperature vs. time for 66 W filament input.

ature as shown in Figs. 22.8 and 22.9. So the equations are linearized around the operating point. The step response of the model linearized around an input of 66 W is shown in Fig. 22.10. For a specific filament power input, the filament and cathode steady-state temperature is obtained from the continuous equations and then the linearized equations are obtained around the operating temperature to obtain a workable transfer function. So in summary, for a specific filament power input the filament and cathode steady state temperature is obtained from the continuous equations and then the linearized equations are obtained around these operating temperature points. For designing the controller, maximum and minimum available power levels of 60 W and 150 W have been considered. In each case the PWM vs. beam current gain is calculated. It is worth pointing out that at higher power level the gain of the saturable reactor control current vs. inductance change will reduce as the reactor will move towards saturation while the filament power vs. beam current gain will increase as the cathode filament assembly gets hotter. Hence total gain is computed for both highest and lowest filament inputs and worst case gain of 300mA/PWM corresponding to 150W filament power is considered. The time constant is taken as 7s from the results of the linearized model. The feedback path comprises two isolators having bandwidth of 1 kHz, a measurement circuit of bandwidth 330 Hz and PLC scan delay of 3 ms. From the aforementioned considerations,

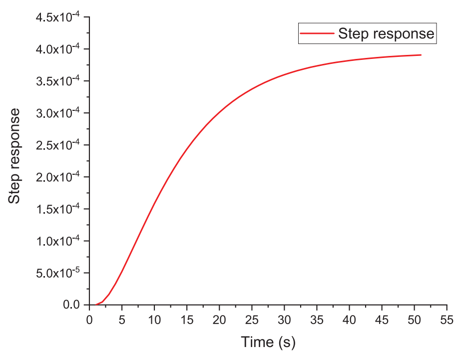

Figure 22.10: Step response of the linearized model.

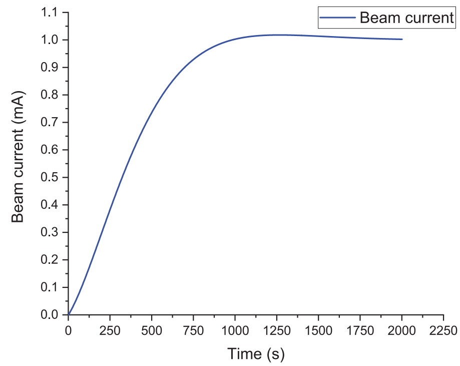

Figure 22.11: Closed loop block diagram of E-Beam Current.

the block diagram of the beam control system obtained is shown in Fig. 22.12. The PI con-

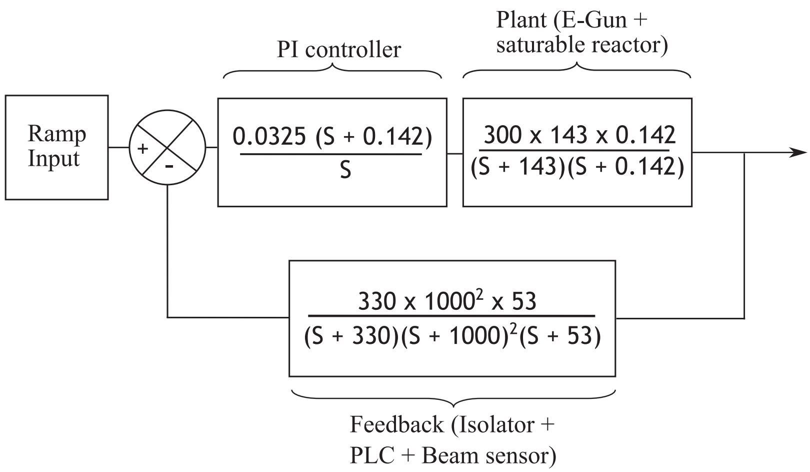

Figure 22.12: Closed loop block diagram of E-Beam Current.

troller is designed using the dominant pole compensation technique. The gain is determined using bode plot conforming to absolute stability criteria. The close-loop response to a step change in set point around 1 mA current is shown in Fig. 22.11.

Hence, the final controller transfer function is:

$$f_C(S) = \frac{0.0325(S + 0.142)}{S} \tag{22.4}$$

Suggestions for Further Reading

a) [115–120]

TUTORIAL

Q: Why is saturable reactor used to control the filament transformer input instead of an SMPS supply?
A: The GPS is a floating power supply with its reference at dome potential and is often subjected to HV and HF electrical discharges. If SMPS based power supply had been used, there would have been more probability of its failure due to the harsh operating conditions. The magnetic saturable reactor is much more immune to such transients and is expected to excel in the aforementioned operating environment.

Q: What is the principle of operation of Saturable reactor?
A: A saturable reactor has two windings wound on the same core. One among them carries the power and is referred to as 'Field Winding' and the other carries DC current and is called 'Control Winding'. The current in the control winding changes the permeability of the inductor core and hence its inductance changes and it offers variable impedance to the current through the field winding.

Q: What are the design challenges for gun power supply? How are they overcome?
A: 1) The GPS is floating at 1MV dome voltage and may be subjected to HV, HF discharges. Hence minimum possible amount of integrated circuit components are used and more preference has been given to magnetic components or components having higher tolerance towards transient surges.
2) It is subjected to 6 kg/cm^2 pressure of insulating gas (N_2 and SF_6) mixture which causes few design constraints such as electrolytic capacitors cannot be used in this environment.
3) The controller to the power supply is maintained at ground potential. Hence there has to be galvanic isolation between the two. Hence optical fibre has been used for signal communication between the power supply and the controller.
4) The optical fibre passes through the wall of pressure vessel which separates high pressure insulating gas medium and atmospheric air. To ensure no leakage fro the pressure vessel proper optical feed through has been designed.

Q: Enumerate the steps to determine transfer function of the beam current w.r.t. the MOSFET PWM.
A: The thermal behaviour of the electron gun is determined from the heat balance equation. Solving these equations we get the steady state temperatures of the cathode and filament surfaces for the given input power. The beam current vs. input power equations are linearized around these temperature points yielding beam current vs. filament input power transfer function for that particular operating point. It is noteworthy that the thermal behaviour of electron gun is highly non linear and hence it would yield a different transfer function if the operating point is changed.
The GPS filament power vs. the MOSFET PWM transfer function can be obtained using the saturable reactor inductance vs. control winding current and the dynamics of the MOSFET switch with its output filter (essentially a buck converter). The inductance vs. controller current curve has to be linearized around the required inductance value.
Combination of these tow transfer functions (beam current vs. filament input and filament input vs. MOSFET PWM) would give the final transfer function. But this transfer function will heavily depend on the chosen operating point as the underlying equations are non linear. Hence for designing the controller, worst case transfer function (the one with minimum phase and gain margins) has to be considered.