High Power RF/Microwave Systems and Components Design for Particle Accelerators: Tutorials

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Time for one cycle = T
Pulse duration = \( \tau \)
Pulse repetition rate or frequency of the pulse signal = \( 1/T \)
Duty ratio = \( \tau/T \)
Average power = Peak power x duty ratio
T.1 If the ON time for the pulse modulated signal is 10 microsecs which repeats at every 1 msecs let us calculate the duty ratio?

ON time 10 microsecs, OFF time 1msecs
Duty ratio= ON time divided by total time duration of the signal.
Hence Duty ratio is 0.01

Pulse Modulated Signal

A klystron amplifier is energised with an anode power supply of 100kV,100Amp. If the klystron has an overall efficiency of 50%. Calculate the output power delivered by the klystron at its catcher cavity. If the klystron is operated at a pulse duration of 10microsecs at 100Hz what is the average microwave power output of the klystron.
RF & Microwave Systems for Particle Accelerators
Tutorial Exercises

Choose the most appropriate option:

A. Wavelength range most appropriate for Microwaves
   a) fm to pm
   b) nm to µm
   c) mm to cm
   d) m to km

B. Circulator is used between RF amplifier and RF cavity
   a) To increases RF power
   b) To match load with RF amplifier
   c) To protect amplifier from reflection
   d) To measure forward and reflected power

C. 10 dBm is equal to
   a) 1 mW
   b) 10 mW
   c) 1 W
   d) 10 W
Why the DC is placed between the circulator and cavity and why not after the RF amplifier.
Match the statements in column A to the appropriate statements in column B

<table>
<thead>
<tr>
<th>Column A</th>
<th>Column B</th>
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<tbody>
<tr>
<td>1 Directional Coupler</td>
<td>A Indus Accelerators</td>
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<tr>
<td>2 Super conducting RF cavity</td>
<td>B Protection against reflection</td>
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<td>3 Circulator</td>
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<td>4 S parameter measurement</td>
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<td>5 RF Signal Characterization</td>
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</table>
RF System for a Particle Accelerator

- A stabilised signal generator
- An LLRF system for stabilising amplitude and phase
- An RF amplifier to amplify the RF signal for correct field in cavity
- DC Power supply/Pulse Modulator for the Amplifier
- A transmission system to carry power from the Amplifier to the cavity
- An accelerating cavity to transfer the RF power to the beam
- Feedback from the cavity to the LLRF system to correct errors in Amplitude and Phase.

Gain (dB) = 10 \log_{10} (Gain)

dB = 10 \log(Po/Pin)

1W = 30 dBm

\begin{align*}
10 dBm & \quad 56 dBm \quad 100 dBm \quad 98.5 dBm \\
\text{DC Power} & \quad \text{Supply or} \\
\text{Modulator} & \\
\end{align*}
In a typical microwave system following components with their characteristics are installed in series

<table>
<thead>
<tr>
<th>Component</th>
<th>Characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microwave generator output</td>
<td>10dBm</td>
</tr>
<tr>
<td>Driver amplifier, Gain</td>
<td>51 dB</td>
</tr>
<tr>
<td>Circulator insertion loss</td>
<td>1 dB</td>
</tr>
<tr>
<td>Klystron amplifier Gain</td>
<td>61.5dB</td>
</tr>
<tr>
<td>Waveguide line insertion loss</td>
<td>1.5dB</td>
</tr>
<tr>
<td>Microwave cavity</td>
<td></td>
</tr>
</tbody>
</table>

Calculate the output power in Watts delivered by the microwave system to the cavity when the microwave system is fed with input of 10dBm from the generator.
Basic Calculation

If \( C_t \) = total PFN capacitance
\( V_c \) = voltage across PFN capacitors
\( V_p \) = pulse voltage across the load
\( I_p \) = current through the load
\( \tau \) = duration of pulse

\[
\frac{1}{2} C_t (V_c)^2 = \int V_p \, I_p \, dt
\]

or

\[
C_t = \frac{2 \times V_p \times I_p \tau}{(V_c)}
\]

And the total inductance is found from the PFN characteristic impedance

\[
Z_0 = \sqrt{\frac{L_t}{C_t}}
\]

So that

\[
C_t = \frac{\tau}{2Z_0} \quad \text{and} \quad L_t = \frac{\tau Z_0}{2}
\]
T2. Creating a Pulse / Pulse Modulated Carrier

Simple circuit concept to produce RF burst

T3. Hard Tube Pulse Modulator configuration.

The schematic of this type of pulse modulator or *pulser* is shown in Figure-3.

Switch $S_1$ charges the capacitor (and opens). Then $S_2$ discharges the capacitor into the load and a pulse is produced. In this type of modulator, only a small fraction of the energy stored in the capacitor is transferred to the load.
T 4. Basic building blocks of a Line-Type Pulse Modulator. Examples where these are used? Functioning for each part with technical considerations?

**Schematic of a Line-Type Pulse Modulator**

**Elements and Functioning of Line-Type Pulse Modulator**

**DC power supply:** This is a (variable output) high voltage supply. While a simple three phase rectifier based or an SCR based regulated power supply could be used, these days with great advancement in switch mode power supplies (SMPS), we could go for an SMPS. SMPS are compact, efficient and still have good regulation. In a three phase rectifier supply, regulation may still be done by controlling the primary voltage with a three phase motorised auto-transformer.

**Isolating element** to prevent excessive current from the dc supply during the pulse when the switch is ON. But it should still allow current to charge the transmission line at a sufficient rate. The inductor is non-dissipative and we can gain double voltage on charging due to resonant charging.

‘resonant charging’. This type of charging is an **LC resonant charging** that allows us to charge the transmission line to **two times** of the voltage that it would have otherwise got charged to. In other words, the use of inductor helps us charge the transmission line to **double of dc supply voltage**.
We know that a transmission line can be considered as having distributed L (inductance) and C (capacitance) parameters. If dc voltage is applied between the two conductors of the transmission line, the line’s (distributed) capacitance will get charged to that voltage. Now consider a circuit in which a charged transmission line is discharged by a switch through a ‘load’. The load is resistive. This is shown in Figure-5(a).

Discharge of a transmission line

Our knowledge of distributed circuit analysis reveals that under ideal conditions constant current will flow through the load for the time duration equal to twice the delay of the length of the transmission line for an electromagnetic wave. If \( l \) is the length of the line and \( v \) is the speed of the electromagnetic wave, then delay \( \tau \) is given by

\[
\tau = \frac{l}{v}
\]  
(1)
Since current will flow through the load resistance for a time $2.\tau$, therefore, it is clear that the width of the pulse produced across the load would be $2.\tau$. The direction of current flow would obviously be into that terminal of the load connected to the switch and also usually at ground so that the pulse at the load would be \textit{negative} with respect to ground. The transmission line also has a characteristic impedance $Z_0$ (purely real for a lossless line). This causes the entire circuit to behave like a resistor $Z_L$ (load impedance) driven by a voltage source with source impedance $Z_0$. Figure-5(b) illustrates this. Pulse thus has an amplitude $V_0$. $Z_L/(Z_L + Z_0)$, $V_0$ being the voltage to which the line was charged.

The pulse transformer transforms the impedance of the load to a value which is close to the characteristic impedance $Z_0$ of the transmission line for maximum power transfer. In most cases the impedances of devices like klystrons and magnetrons (that are our loads) are nowhere close to $Z_0$. One may ask that the transmission line and its $Z_0$ is our choice but there are limitations to our choice and due other factors $Z_0$ is generally restricted to few tens of ohms. Then, for maximum power transfer and to provide the requisite voltage to the device, we have to use a transformer between the transmission line and the load.

The high voltage switch requires a trigger circuit that has to be designed dependent on the application.
From the Transmission Line to the Pulse Forming Network (PFN)

With a cable as our transmission line, we get a delay of about 3.333 ns per meter of the cable length. Even if the speed of electromagnetic wave were considered half of \( 3 \times 10^8 \) m/s due to any dielectric filled in the cable, we would get a delay of only 6.666 ns per meter. With practical cable lengths of few meters, we could at best produce pulse widths of few tens of nanoseconds, and at most, a little over 100 ns. Thus with a cable we cannot produce pulse widths of the order of microseconds. To overcome this, we create a structure or a network using lumped L and C components which act (to some extent) like a transmission line having a very slow speed of the electromagnetic wave. Such an LC ladder network forms the pulse across the load hence it is known as the Pulse Forming Network or the PFN.

The Pulse Forming Network

The PFN is a lumped parameter LC network but it cannot produce ideal rectangular pulses (Guillemin’s theory of networks). However if we deliberately consider non-ideal pulses that have non-zero rise and fall times then it is possible in principle to produce such pulse shapes by using LC networks. Ideal rectangular pulses and the realizable non-ideal pulse shapes are shown in Figure-6. Different types of Guillemin’s LC networks are shown in Figure-7. Their detailed discussion is beyond the scope of this paper.
The type D network has equal capacitances in each section. With some modification, we derive the type E network which is the common type of configuration for the pulse forming network (PFN) used. Nominally all the capacitances and inductances in this PFN are of the same value. To obtain a good pulse shape however, we have to adjust the inductances.

The practical PFN is shown in Figure-8. It consists of n sections each of which is an LC circuit. Thus, a PFN clearly simulates a transmission line.

Figure-6: Ideal and non-ideal pulses

(a) Ideal (b) Non-ideal trapezoidal (c) Non-ideal parabolic rise/fall

Figure-7: Different Guillemin network configurations for pulse formation
Design aspects of Line-Type Pulse Modulator

To start designing a line-type pulse modulator, it is a good approach to start with the load. In the systems designed and developed at RRCAT, the loads are either magnetrons or klystrons. Both these are high voltage vacuum tubes. While magnetron is a microwave oscillator, the klystron is an amplifier that needs a microwave input signal. Typical maximum ratings for magnetrons are 50 kV, 115A and for klystrons they are 55 kV, 270 A.
Transformer ratio: Consider for example a 3 MW, S-band magnetron which operates with a 5 μs pulse of 49.8 kV voltage and 115 A current. Then the impedance of magnetron is ~433Ω. To provide power to this magnetron, we should have a transmission line with characteristic impedance close to 433Ω. Secondly the dc charging power supply has to have a voltage rating of two times of 49.8 kV, that is ~100 kV or, if we were to consider resonant charging using an inductor, dc supply should be of the same voltage (49.8 kV) as the pulse voltage. Both the requirements are difficult to meet. The diameter of the hollow outer conductor of the (coaxial) cable has to be large as compared to the diameter of the inner conductor for the required characteristic impedance and even if we were to have such a cable, we still have the problem of high voltage rating of dc supply. Interestingly, both the problems have one solution – using a (pulse) transformer. A step-up pulse transformer would not only bring down the impedance as seen on its primary side (by the transmission line) but also bring down the voltage requirement of the dc supply. The line would need to be charged to a much less voltage and produce a much lower amplitude pulse across the reflected load from the secondary to the primary of the pulse transformer. It must be remembered that the power does not change by the use of a transformer. Therefore a decrease in voltage also causes an increase in current on the primary side of the transformer.
The transformer ratio and the transmission line impedance now need to be decided. The guideline is that transmission line or, more appropriately, the PFN that acts as our transmission line has a characteristic impedance from few ohms to about 100Ω. PFN can be conveniently designed for impedance values below 25Ω.

**The PFN:** To consider the design of an n-section PFN, we first take $L_1 = L_2 = L_3 = \ldots = L_n = L$ and $C_1 = C_2 = C_3 = \ldots = C_n = C$. Then, we have the relations for the characteristic impedance $Z_0$ and the pulse width $T_p$ as

$$Z_0 = \sqrt{\frac{L}{C}} \quad (2),$$

$$T_p = 2n \sqrt{LC} \quad (3).$$

The equations come from considerations similar to that of a distributed parameter transmission line.

We have a limited choice for the capacitance C dependent on the manufacturer, though of course we could always order for custom values. The pulse width $T_p$ is also fixed within some limits. This leaves us with $Z_0$, $L$ and $n$. Since we have two equations but three varying quantities, we have some flexibility in our design.
The waveforms across the pulse transformer primary load in case of matched load, positive mis-match and negative mis-match are shown in Figure-9. In essence, we shall fix $Z_0$ and decide $L$ and $n$ from equations (2) and (3).

Figure-9: Voltage and current pulses under different load conditions
Isolating Element, the charging inductor: It was mentioned earlier that the inductor as an isolating element (for the dc supply) serves two purposes – 1. It serves to isolate the dc power supply from the closed high voltage switch during the discharge of the PFN. 2. The inductor of a suitable value forms an LC circuit with the PFN capacitors. When the PFN capacitors are being charged by the dc supply, the charging is relatively much slower than the short discharge time of the PFN. The PFN inductors of few microhenrys do not have much role to play during the PFN charging except to act like shorted connectors. Therefore, all the capacitors behave as if they are in parallel and the PFN has a total capacitance of \( nC \). When this PFN capacitance is charged by another inductor, this is known as LC resonant charging

Blocking diodes: From circuit theory we know that due to the resonant LC circuit, the PFN capacitors will keep getting charged to twice the dc voltage value and then discharge back to zero. To charge the capacitors to \( 2V_{DC} \) and hold them there, we use blocking diodes in series with the inductor. The diodes allow capacitor charging but do not allow discharging since they do not allow reverse current. Generally one diode may have a voltage rating much lower than \( 2V_{DC} \). Therefore peak inverse voltage rating is increased to the desired value by stacking them in series.
10. Design Example and Selection of Components/Sub-systems

We mentioned the example of a magnetron in section 9. We now consider the broad design of the pulse modulator for the same magnetron. Main specifications of the magnetron are 49.8 kV, 115A, 5 µs pulse width and a maximum pulse repetition rate (PRR) of 325 Hz. (Since magnetron efficiency is about 45% to 50% it shall produce 3 MW microwave power.)

10.1 Transformer ratio: If the transformer ratio (secondary : primary) \( k = 2 \), then primary side load, \( Z_p = \frac{433 \Omega}{k^2} = \frac{433 \Omega}{4} = 108.25 \Omega \) and the primary voltage \( V_p = \frac{49.8 \text{ kV}}{k} = \frac{49.8 \text{ kV}}{2} = 24.9 \text{ kV} \).

For \( k = 3 \), \( Z_p = \frac{433 \Omega}{9} \approx 48 \Omega \), \( V_p = \frac{49.8 \text{ kV}}{k} = \frac{49.8 \text{ kV}}{3} = 16.6 \text{ kV} \).
For \( k = 4 \), \( Z_p = \frac{433 \Omega}{16} \approx 27 \Omega \), \( V_p = \frac{49.8 \text{ kV}}{k} = \frac{49.8 \text{ kV}}{4} = \approx 12.4 \text{ kV} \).
For \( k = 5 \), \( Z_p = \frac{433 \Omega}{25} \approx 17 \Omega \), \( V_p = \frac{49.8 \text{ kV}}{k} = \frac{49.8 \text{ kV}}{5} = \approx 9.9 \text{ kV} \).
For \( k = 6 \), \( Z_p = \frac{433 \Omega}{36} \approx 12 \Omega \), \( V_p = \frac{49.8 \text{ kV}}{k} = \frac{49.8 \text{ kV}}{6} = 8.3 \text{ kV} \).
For convenience of PFN design, \( k = 5 \) and \( k = 6 \) are suitable. Since the resonant charging scheme is a very convenient, then, for any \( V_p \) value as calculated above, we need dc power supply of the same value depending on \( k \). Generally, a low dc power supply rating is convenient. Of course, it has to be compensated for by the higher current ratings of the dc supply, the switch and other components. The switch still has to have a double voltage rating.
Suppose we were to choose $k = 6$, so that $Z_p \approx 12\Omega$ and $V_p = 8.3$ kV. Then, considering some loss of power due to non-ideal inductors and capacitors and keeping slightly negative mis-match between the PFN/line and the load at the pulse transformer primary, it should be appropriate to choose a dc power supply of 10 kV for PFN/line resonant charging. The current rating of this supply is yet to be found.

**10.2 The PFN:** In our example, if we take $C = 12\text{nF}$. (High voltage capacitors of 12nF, 40nF, etc. are readily available in India.) We may choose $Z_0 \approx Z_p = 12\Omega$. Cable impedance is almost always 50Ω or 75Ω. Then we should choose $Z_0 = 12.5\Omega$, a sub-multiple of 50Ω. But the choice of value $Z_0 = 12.5\Omega$ is better since in that case $Z_p$ is slightly less than $Z_0$ and we have the desired slight negative mis-match.

Using the values in (2),

\[
L = Z_0^2 C = 12.5^2 \times 12 \times 10^{-9} \text{H} = 1.875 \times 10^{-6} \text{H} = 1.875 \mu\text{H}
\]

Equation (3) gives with $T_p = 5 \mu\text{s}$,

\[
n = \frac{T_p}{2\sqrt{LC}} = \frac{5 \times 10^{-6}}{2\sqrt{1.875 \times 10^{-6} \times 12 \times 10^{-9}}} = 16.667
\]

Since $n$ is an integer, we may choose $n = 17$ (or 16). We may want to reduce $n$ and calculate back $L$. $n = 16$ would give $L \approx 2\mu\text{H}$.
We have to confirm if inductors of the order of few microhenrys could be fabricated or not. Using the formula for an inductor $L = \frac{\mu N^2 A}{\ell}$, where $\mu$ is the permeability, $N$ is the number of turns, $A$ is the area of cross section and $\ell$ is the length of the inductor, we find that for an air core inductor ($\mu = \mu_0$), we are able to get practically useful values for $N$, $A$ and $\ell$. (For example, if $L = 2\mu H$, we may choose $A = \pi (0.04)^2 m^2 \approx 5.03 \times 10^{-3} m^2$ and $\ell = 0.08 m$ so that $N \approx 5$ and the inductor could be conveniently fabricated.)

10.3 The charging inductor: We could find its value by considering the equivalent series RLC circuit at the time of charging. The voltage across the capacitor rises as a cosine function, when the diode blocks and holds it to $2V_{DC}$. At that instant the current falls to zero. It is obvious that the charging time is half the sinusoidal cycle whose time period and frequency depends on $L$ and $C$ values as

$$T_{CH} = \frac{T_R}{2} = \frac{\pi}{\sqrt{L_{CH} C_{PFN}}}$$

where $C_{PFN} = nC =$ total PFN capacitance, $T_R =$ time period of resonant charging cycle and $T_{CH} =$ charging time. We could neglect the effect of resistances in the circuit without much error. Now the charging time is almost equal to the pulse repetition time neglecting the small microsecond pulse width during discharging. For the present magnetron, a maximum pulse repetition rate of 325 Hz has been specified. Let us assume that our limit is 300 Hz.

We then have

$$L_{CH} = \frac{T_{CH}^2}{\pi^2 C_{PFN}} = \frac{(1/300)^2}{\pi^2 \times 16 \times 12 \times 10^{-9}} = 5.86 H$$

A Value $L_{CH} = 5H$ or so will charge the PFN faster. Only the peak (maximum) current rating of the dc supply has to be higher.
10.4 High voltage switch, the thyatron: If we consider the PFN to charge to about 10 kV, the thyatron should have an anode (blocking) voltage rating of at least 25 kV. Maximum current through the thyatron is the pulse current through the pulse transformer primary. In the secondary the pulse current is 115 A. Therefore the primary current is $115 \, \text{A} \times 6 = 690 \, \text{A}$. Thyatron of 1.4 kA peak current is suitable. A lower value may be chosen if we do not expect the short circuiting of load. The average current is simply the pulse current $\times$ duty cycle. Therefore, average current $= 690 \, \text{A} \times 5\,\mu\text{s} \times 300 \, \text{Hz} \approx 1\, \text{A}$.
10.5 The high voltage charging dc power supply: We have already calculated the approximate value of dc supply voltage $V_{DC}$ to be 10 kV. We now confirm this.

The practical charging inductor has its own resistance and it has been found convenient to talk of the quality factor $Q$ of such an inductor. From our RLC circuit theory, we can derive that PFN gets charged to a voltage slightly lower than $2V_{DC}$ given by

$$V_{PFN} = V_{DC}[1 + e^{-\pi/(2Q)}]$$

which clearly equals $2V_{DC}$ for ideal inductor of infinite $Q$.

In this case

$$V_{PFN} = V_{DC}[1 + e^{-\pi/(2Q)}] = 1.855V_{DC}$$

showing that for $Q$ as low as 10, the charging efficiency is still as good as 93%.

Since our $V_{PFN}$ was 2 x 8.3 kV = 16.6 kV, we have,

$$V_{DC} = V_{PFN}/1.855 = 16.6\text{ kV}/1.855 \approx 9\text{ kV}.$$ 

Considering drop in voltage in secondary of our non-ideal high voltage pulse transformer, we must choose a $V_{DC}$ still higher. Here, a 10 kV value seems ok for $V_{DC}$.

Mathematically, the effective value of the (sinusoidal) current drawn from the dc supply in this case is just the average value of the charging current which is $2I_m/\pi$, $I_m$ being the maximum value of the current. From circuit theory we know that

$$I_m = \frac{V_{DC}}{\sqrt{L_{CH}/C_{PFN}}} = \frac{10 \times 10^3}{\sqrt{5/(16 \times 12 \times 10^{-9})}} \approx 2\text{ A}$$

And

$$I_{eff} = \frac{2I_m}{\pi} = \frac{4}{\pi} \approx 1.27\text{ A} \approx 1.3\text{ A}$$
Therefore our dc power supply has ratings 10 kV and 1.3 A, respectively. At this stage we have obtained design values of the components and sub-systems. The overall pulse modulator circuit is shown in Figure-10.
Exercises – Line Type Pulse Modulators to be solved in tutorial

Q. 1 Why is slight negative impedance mismatch used for PFN and load (pulse transformer primary)?
Ans: The slight negative mismatch is helpful for easy recovery of the thyatron switch.

Q. 2 What could be the ways to compensate for pulse transformer droop?
Ans: In PFN based modulators the droop can be compensated by adjusting the impedances of the individual sections. Initial sections are tuned with the help of inductors such that the impedance from first section to last section decreases and the resultant pulse delivered at the output of pulse transformer is droop compensated.

Q. 3 How do we minimize pulse transformer rise and fall times?
Ans: Pulse transformer rise and fall times depend on the leakage inductances. The leakage inductances have to be minimised for achieving the desired rise/fall times.

Q. 4 How much energy taken from HV supply is delivered to the load? (Full in ideal conditions, loss-less PFN, matched impedances.)
Ans: In practical case the losses in the energy storage capacitors, PFN inductance and the circuit resistance, loss in the closing switch and mismatches etc reduce the energy delivered to load. Practical upto 95 % energy is delivered to the load.

Q. 5 What is command charging? What are the benefits? How is this implemented?
Ans: Command charging is the process of charging the PFN capacitors after command charge trigger. This way the losses in the capacitors can be reduced and also a better stability of the output pulse is achieved for varying pulse repetition rates. Also the life of the capacitors increases.
Q. 6 What are the instrumentation / different measurements involved in pulse modulators? What are the safety equipments?
Ans: High voltage probes, fast current transformers, Digital Storage Oscilloscopes with adequate probes. The safety devices are grounding rods, discharge rods, automatic safety relays, door switches etc.

Q. 7 How to protect the microwave tube / other devices from damage?
Ans: Interlock and protection circuits are designed to protect the devices from damage in case of overvoltage or short circuits. Shunt diode network is used across the PFN to discharge the unused energy in a load in case of the arcing of the microwave tube. Also in case of filament supply failure the high voltage supply is switched off by means of a fast acting protection circuits. Overvoltage protection is provided to limit the voltage across the microwave tube.

Q. 8. How do we do ‘PFN tuning’?
Ans: PFN tuning is done by adjusting the inductance value of each section of the PFN. There are various ways to achieve this. One of the popular way is to introduce the tuning slug (a copper continuous cylinder) inside the inductors so that the value of the inductance decreases as the insertion in the inductor is increased.

Q. 9 Why ferrites are not used for pulse transformers in high power pulse modulators? (Bsat is too less.)
Ans: Ferrites have low saturation induction. For high power pulse modulators the commonly used cores are made of thin laminations of CRGO. Bias is also used to bias the cores in negative direction of the pulse such that a large flux swing can be achieved.
Q. 10 What are the ways of cooling thyatron?
Ans: The thyatrons are cooled by forced air cooling, oil cooling.

Q. 11 Discuss the new technologies (HV SMPS, command charging, etc.)
Ans: Lot of progress has taken place in the advancement of the pulse modulators to make them more reliable, compact, efficient and robust. Particularly in the case of high mean power modulators the charging supply has now been replaced by means of High voltage Switched Mode power supplies. A very high stability from pulse to pulse can be achieved. The power conversion efficiency is high. Command charging is introduced by introducing a high voltage switch in place of a charging diode in the line type pulse modulator configuration. The charging switch or thyatron is first trigger to charge the PFN to desired voltage. Once the charging voltage is stably achieved and the charging switch achieves OFF state, the discharge switch or thyatron is trigged. This makes the pulse modulator more reliable, stable and increases the life of the high voltage components.
Hard switch type Pulse Modulators

Q1). What are the techniques for output droop compensation in hard switch type Modulators?
• Output voltage droop can be compensated using passive bouncer network or active compensation using fast programmable power supply or controlling switching devices (Marx Modulator).

Q2). In bouncer compensated Modulator how the bouncer capacitor charges to the same voltage again after the pulse?
• The bouncer network is L-C type tank circuit and due to losses in practical capacitor, inductor and bouncer switch element, the bouncer capacitor should charge to lesser voltage after going through its complete cycle. But the main pulse current also flowing through bouncer network can cause the bouncer capacitor voltage to be less, more or equal than its previous value depending upon time delay between bouncer switch and main switch.

Q3). Why arcing condition might be more hazardous in hard switch type Modulators?
A. Because the energy storage capacitor is very big in comparison to line type modulators so if the switch fails to open the arcing may continue for a long time and damage the microwave device. Normally crowbar protection is used to avoid this condition.