Chapter 10

# Power Sources for Industrial DC Electron Accelerators

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Direct Current (DC) industrial electron accelerators ranging from 200 keV to 5 MeV and 10-500 kW power output are used for surface treatment of plastics & textile fabrics, colouring of diamonds, flue gas treatment and waste water treatment due to their large throughput, high electrical efficiency and smooth variation in energy as compared to RF Linacs.
Accelerator and Pulse Power Division (APPD), BARC has designed and developed three DC electron accelerators viz., 500 keV, 10 kW balanced Cockcroft-Walton type accelerator, 3 MeV, 30 kW parallel-fed voltage multiplier type accelerator and 1 MeV, 100 kW symmetrical Cockcroft-Walton type accelerator. The 500 keV machine is utilized for surface treatment whereas the 3 MeV and 1 MeV are utilized at Electron Beam Centre, Kharghar for water treatment.
High power industrial DC accelerators are based on Cockcroft-Walton type, parallel capacitive voltage multiplier (PCVM) and insulating-core transformer type. The voltage multipliers require HF source (few kHz to MHz) to reduce the regulation and ripple in output terminal voltage.Typically, a voltage gradient of 1 MV/m is the design criteria with gaseous insulating media. Apart from the main high voltage DC supply, these types of accelerators require auxiliary supplies floating at the high voltage terminal for its electron gun. Usually, the power is extracted from the ripple content of HV terminal and controlled remotely through fibre optic signals. Selection of proper scheme, components, and systematic design procedures, are very important factors for building a reliable and economical high voltage system. This chapter describes various challenges in the development of high-power DC accelerators.

## 10.1 HV Power Supplies for Industrial DC Accelerator

The basic building blocks of HV power supply for industrial DC accelerator are a variable dc supply powered from a 3-$\phi$ input, a power inverter, step-up transformer, HV multiplier and isolated gun power supplies for electron gun at HV terminal of accelerating column as shown in Fig. 10.1. The output of variable dc supply is inverted to desired high frequency

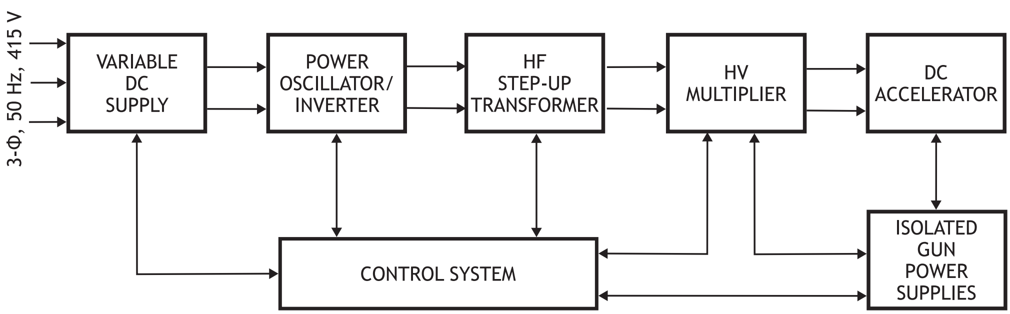


Figure 10.1: Building blocks of Industrial DC electron Accelerator.

and stepped-up to a stage voltage required for voltage multiplier circuit consisting capacitors and rectifier. The HV multiplier and DC accelerating column are oriented co-axially inside a pressure vessel to take advantage of pressurised insulating gas such as $SF_6$ or $N_2$ or mixture of these two in definite proportions.

## 10.2 Design Steps

Given the design parameters of output voltage, beam power, regulation and ripple, the design optimization is carried out as follows:

a) Selection of HV multiplier (Cockcroft-Walton/PCVM) and accelerating tubes

b) Optimization of the stage voltage, frequency based on the capacitor and diodes.

c) Selection of capacitors – type of dielectric, size, withstanding voltage for normal and surge conditions

d) Selection of diodes based on forward current, reverse bias voltage, leakage current, $t_{rr}$ (based on one tenth of forward conduction time) and series stack configuration

e) Estimation of electric fields (radial & vertical) and selection of insulation scheme

f) Design of corona guard for minimizing the electric stress to desired value & stray capacitance

g) Design of protection scheme for diode such as operating & surge voltages (passive & active)

h) Calculation of losses, thermal analysis and cooling scheme

i) Optimization of multiplier efficiency

j) Selection of HF oscillator & HF step-up transformer based on the stage voltage & power needed.

k) EMI protection for all stages of power supplies (both common mode & differential surge voltages)

l) Design of measurement & control system of accelerator potential and current.

## 10.3 Design Criteria for HF/HV Tuned circuits & Transformer

Given the operating frequency, stage voltage, power output and efficiency, the design procedure of HF/HV windings will follow the criteria given below:

a) Selection of core – Ferrite/amorphous/air-core depending on frequency & eddy currents

b) Selection of wire – depends on skin effect/proximity effect and current density to get high Q

c) Selection of number of turns & winding scheme to minimize the distributed capacitance

d) Selection of insulation scheme

e) Optimization of leakage inductance and HV insulation scheme for given core and window

f) Optimizing heat losses and cooling scheme

## 10.4 HV Power supplies of 500 keV, 20 mA DC Accelerator

The 500 keV, 20 mA DC accelerator has been designed and commissioned at BRIT, Vashi based on a balanced CW scheme with inductive compensation and surge protection [48, 49]. The output voltage of balanced CW multiplier in loaded condition is given by

$$V_o = V\left(2N + \frac{2}{\pi}\right) - \frac{I}{fC}\frac{N^3 - N}{6} \pm \left[\frac{I}{4fC}\left(N^2 + N\right) + \frac{V}{\pi}\right] \tag{10.1}$$

Where V is the peak input voltage, N is the number of stages, f is the frequency, I is the load current, and C is the stage capacitance. This accelerator has 10 stages with stage capacitance of 6.6 nF and compensating inductance of 35 mH. The design parameters are tabulated in table 10.1.

Table 10.1: Design parameters of 500 keV DC Accelerator.

| **Parameter** | **Value** |
|---|---|
| Electron beam Energy | 200-500 keV |
| Average beam current | 0-20 mA |
| Ripple | 1% |
| Input Stage voltage to multiplier | 30 $kV_p$-0-30 $kV_p$ |
| HF Transformer primary voltage | 0-10 $kV_p$ |
| Power oscillator frequency | 10 kHz $\pm$ 0.5 kHz |
| Tank Inductor, LT (@10 kHz) | 5 mH (Q = 500) |
| Tank Capacitor, CT (@10 kHz) | 50 nF (Q = 4000) |
| HVDC source | 0-10 kVdc, 0-2 A dc |
| Oscillator Efficiency | $\sim$75% |

The balanced CW multiplier and accelerating tubes are kept in a pressure vessel insulated with 6 kg/cm$^2$ pressure of $N_2$ gas. Figure 10.2 shows the 10 kV/10 kHz power oscillator, high-Q tank circuit and step-up transformer. Figure 10.3 shows the 10 stages compensated CW multiplier and isolated gun power supplies for powering the anode, grid and filament.

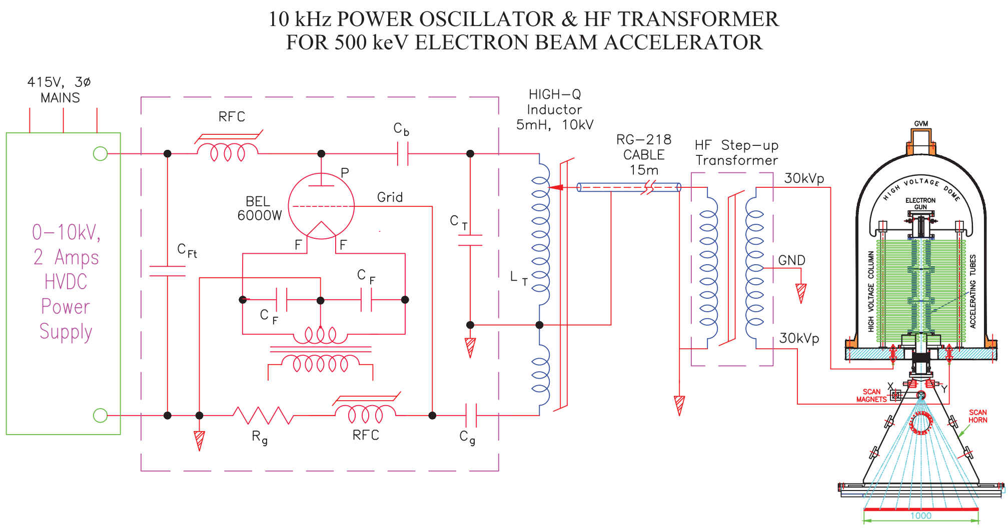


Figure 10.2: 10 kHz Power oscillator & HF transformer.

## 10.5 10 kHz Power Oscillator with High-Q Tuned Circuit and HF Transformer

The power oscillator is based on BEL6000W, water-cooled triode delivering a max. power output of 15 kW in the class-C Hartley circuit mode. The circuit diagram of oscillator is

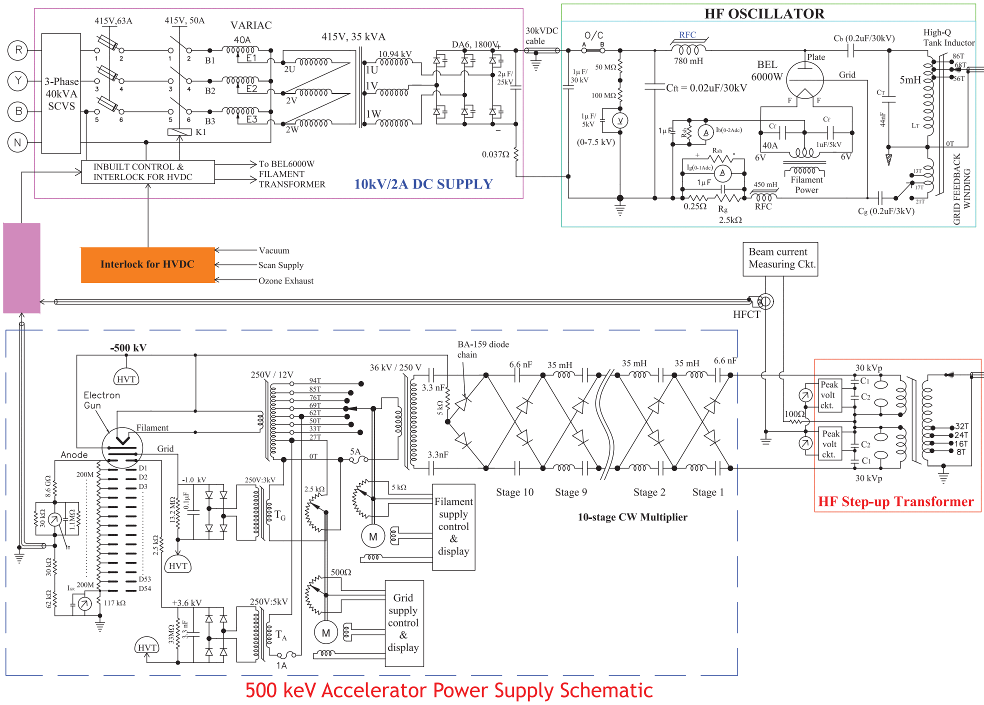


Figure 10.3: Balanced CW multiplier & Gun supplies.

shown in Fig. 10.2. The construction details of high-Q tank inductor rated for 5 mH, 175 kVA, 10 kHz are shown in Fig. 10.4. Litz wire construction (60 Nos. of SWG-26 enamelled copper wire transposed) is adopted for to minimize the eddy current losses at 10 kHz and sectionalized winding is used to minimize the distributed capacitance. The tank capacitor bank (50 nF) is made up of high-Q ceramic capacitors each rated for 15 kV & 50 A rms. The HF transformer step-ups 10 $kV_p$, 10 kHz to 30 $kV_p$-0-30 $kV_p$. The HF transformer is designed to have minimum distributed capacitance & losses and best voltage regulation at 10 kHz. Ferrite cores of HP3P type offer minimum core loss at 10 kHz and large power density. U-100 & I-100 cores are stacked in E-E shapes to get a core cross section of 75 $cm^2$ and window area of 130 $cm^2$. The winding scheme and ferrite core details (10 kHz Ferrite Core, 7 kV: 30 kV-0-30 kV, 15 kVA) are given in Fig. 10.5. To minimize the winding capacitance, the secondary winding is sectionalized into 10 sections. Nomex paper insulation is incorporated between windings and transformer oil is used for heat removal and HV insulation. The self-resonant frequency has been made greater than 40 kHz in this design. The efficiency and regulation of this HF transformer are: 96% and 97% respectively. This transformer is located near the accelerator for safe and convenient transmission of HF power using co-axial cable at a moderate voltage less than 10 $kV_p$.

## 10.6 HV Power Supplies of 3 MeV, 30 kW DC Electron Accelerator

The 3 MeV DC accelerator is based on parallel coupled Voltage Multiplier similar to the Dynamitron type of HV generator [50]. The output voltage of the multiplier is given by:

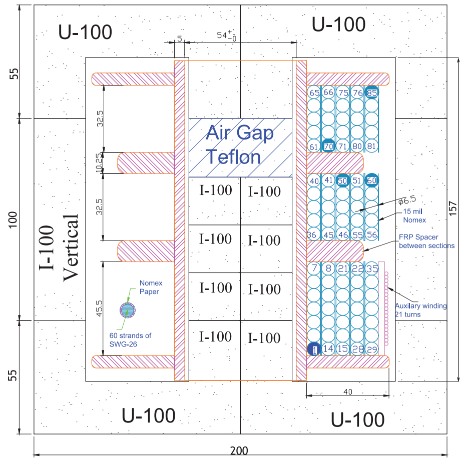


Figure 10.4: Cross section view of high-Q inductor.

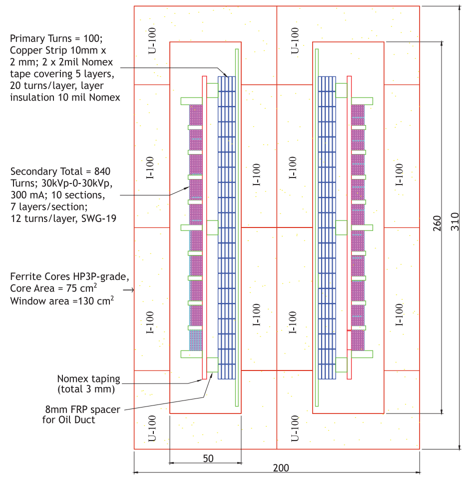


Figure 10.5: Cross section of HF Transformer.

$$V_o = \frac{N.V_i}{k} - \frac{N.I}{k.f.C_{se}} \pm \frac{I}{2.f.C_{se}} \tag{10.2}$$

Where, capacitive coupling factor

$$k = 1 + \frac{4.C_{ac}}{C_{se}} \tag{10.3}$$

N - no. of stages, $V_i$ - Peak RF input to the RF Electrodes, $C_{ac}$ - rectifier (anode to cathode) capacitance, $C_{se}$ - corona guard to RF Electrode, I - current, f - input frequency. The design parameters of the 3 MV voltage multiplier are tabulated in table 10.2. The H.V. multiplier

Table 10.2: Design parameters of 3 MV Voltage multiplier.

| **Parameter** | **Value** |
|---|---|
| RF Input | 150 kV-0-150 $kV_p$ |
| Output Voltage | 3 MV |
| Output Current | 10 mA |
| Source Frequency | 100-120 kHz |
| Number of stages | 74 |
| Capacitive Coupling Factor, k | 6 |
| Capacitance (Cse) | $\geq$ 3.6 pF |
| Capacitance (Cac) | $\leq$ 4.5 pF |
| Ripple | $<$ 2% |

has a cylindrical shape of 97 cm OD and 3.3 m height. The voltage multiplier receives its input from the RF Electrodes through capacitive coupling. The electrical circuit is shown in Fig. 10.6.

## 10.7 HF Power Oscillator for 3 MeV DC Accelerator

The power oscillator is rated for 10kV, 50 kW and 120 kHz operating frequency. The Power oscillator design is based on water cooled triodes EEV make BW1121J2 in push-pull Col-

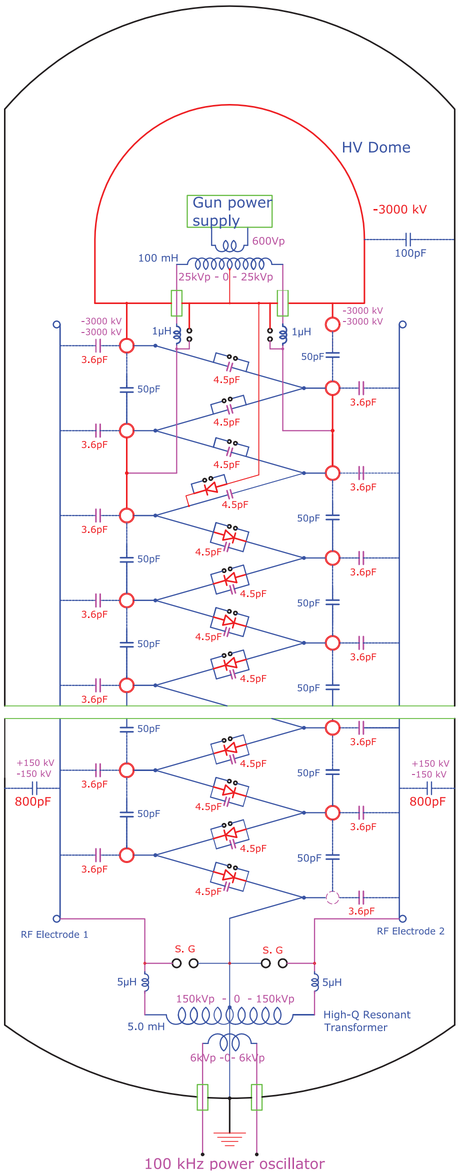


Figure 10.6: Electrical Circuit of HV Generator.

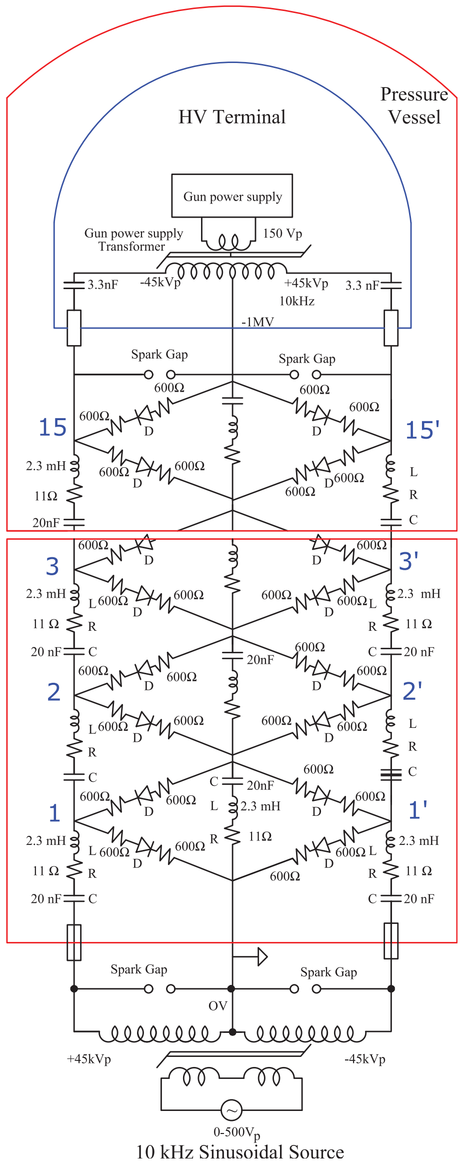


Figure 10.7: Electrical Schematic of the 1 MV, 100 mA CW multiplier.

pitts configuration. The tank circuit for the oscillator is formed by the secondary winding inductance ($L_T$) of the RF transformer and capacitance ($C_T$) formed by RF electrodes of the voltage multiplier column. The frequency is determined by $L_T$, $C_T$ and stray capacitances of HV multiplier. The Grid feedback for the oscillator is derived by arranging a set of electrodes in the RF electrode assembly in a capacitive divider configuration. (Fig. 10.8). The oscillator is operated in class-C mode for 75% plate efficiency with grid leak bias which also has the advantages of self-adjustment with varying load conditions. A fast-acting trip circuit has been incorporated in the grid biasing circuit to pull down the oscillator output in case of HV sparking in the HV multiplier inside accelerator tank. This prevents the damage to the HV rectifiers in the multiplier. The plate voltage, plate current, grid feedback voltage and current are monitored and controlled by PLC. The power oscillator is installed in an RF shielded cabinet. The triode tubes are cooled using Low Conductivity Water.

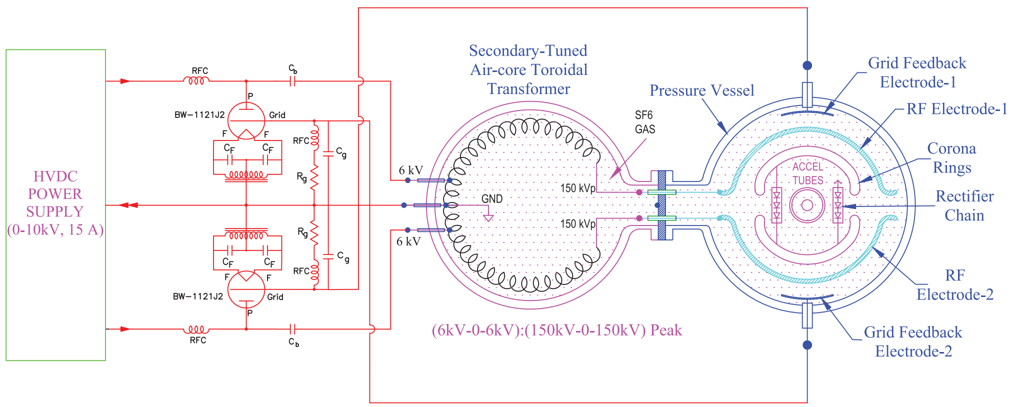


Figure 10.8: Typical driving circuit for 3 MeV, 30 kW DC accelerator.

## 10.8 Design Aspects of HF Transformer for Parallel Coupled Voltage Multiplier

The parallel coupled voltage multiplier takes advantage of the distributed capacitance formed between corona guards and RF electrodes (RFE). It is driven by a parallel resonant tank circuit consisting air-core transformer and RFE. At resonance condition, the secondary voltage is Q times the induced voltage. The induced voltage is proportional to $\omega$M.IP and is maximized when critical coupling, $k_c$ is achieved. The design parameters of the RF transformer are tabulated in table 10.3:

Table 10.3: Design Parameters of the 120 kHz RF Transformer.

| **Parameter** | **Value** |
|---|---|
| Primary voltage | 6 $kV_p$-0-6 $kV_p$ |
| Secondary Voltage | 150-0-150 $kV_p$ |
| Operating Frequency | 100-120 kHz |
| Secondary inductance | 5 mH |
| Q-factor of secondary (unloaded) | >1000 |
| Q-factor of secondary (loaded) | 200 |
| Source impedance | 1 kΩ |
| Load impedance | 1 MΩ |
| Power Output (resistive) | 40 kW |
| Losses in RF transformer windings | 6 kW |
| Self-resonant frequency | > 360 kHz |
| Distributed capacitance | < 20 pF |
| Operating environment | $SF_6$ gas at 6 kg/cm$^2$ |

### 10.8.1 Design Criteria

- Selection of $L_T$ & $C_T$ and circulating current $I_T$ of tank circuit
- Selection of transformer scheme (air-core, toridal)
- Selection of wire & dimensions (Litz wire to minimize skin effect & proximity effect)
- Optimization of $L_T$, Q-factor, CD, coupling factor, k to get the desired output voltage & $\eta$
- Design of HV insulation (turn-turn primary-secondary and between output terminals)
- Minimization of Heat dissipation & cooling system
- Protection fom HV surges

The equivalent circuit of the secondary tuned RF transformer is shown in Fig. 10.9 and cross section of toroidal transformer is shown in Fig. 10.10. The output voltage,

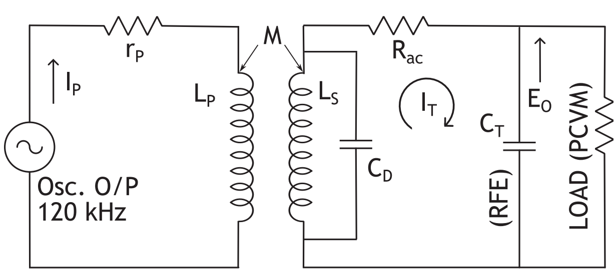


Figure 10.9: Equivalent circuit of the Oscillator & RF transformer.

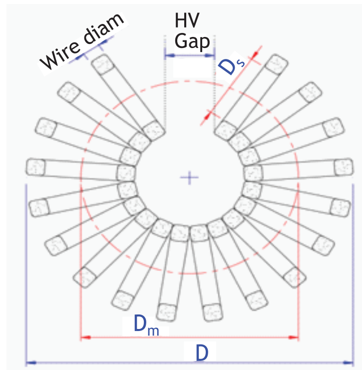


Figure 10.10: CSview of RFT.

$$E_o = Q(2.\pi.f_r.M.I_P) \tag{10.4}$$

where

$$M = k\sqrt{L_P.L_S} \tag{10.5}$$

The resonance frequency of tank circuit is

$$f_r = \frac{1}{2\pi\sqrt{L_S C_T}} \tag{10.6}$$

The secondary self-inductance of toroidal resonant transformer is given by

$$L_S = 2\pi N_2 \frac{D_m - (D_m^2 - D_s^2)^{\frac{1}{2}}}{1000} \tag{10.7}$$

where $L_S$ is the inductance in µH, $D_m$ (= D - $D_s$) is the mean dia. of toroid and $D_s$ is the dia. of winding section. After calculating the number of turns in secondary, the the primary inductance and number of turns are fixed by solving the Eq. (10.7). The unloaded quality factor of secondary inductance is given by

$$Q = \frac{2\pi f L}{R_{ac}} \tag{10.8}$$

Where $R_{ac}$ is the total ac resistance accounting skin effect and proximity effect. For single layer loosely wound toroid, $R_{ac}$ is given by [51]

$$R_{ac} = R_{dc}\left\{1 + F + \left(\frac{k}{d_o^2} + \frac{1}{4}\frac{K^2N^2}{D^2}\right) n^2 d^2 G\right\} \tag{10.9}$$

where N = No. of tums, n = No. of strands, d = dia. of one strand, do overall dia. of Litz wire and D = overall dia. of coil. The circulating current in the wire is given by

$$I_T = \frac{E_o}{2\pi f L} \tag{10.10}$$

The power dissipation in the secondary winding at resonance is

$$P = I_T^2 R_{ac} = \left(\frac{E_o}{2\pi f L}\right)^2 R_{ac} = \frac{E_o^2}{QX_{L_T}^2} \tag{10.11}$$

The tank circuit efficiency is given by

$$\eta = \frac{Q_{unloaded} - Q_{loaded}}{Q_{unloaded}} \tag{10.12}$$

By simultaneously solving the above equations, the desired specifications were achieved.

1. The Litz wire wire made of AWG-40 strands is chosen for 120 kHz and for 60 A current and forced cooling in $SF_6$ gas, current density of 5 A/mm$^2$ is chosen. Copper area of 12.4 mm$^2$ works out to 2464 strands of AWG-40 copper with each strand enamelled and twisted uniformly.
2. Single layer toroidal winding scheme is chosen to achieve Q-factor > 1000. The dimensions are optimized and the required inductance of 5 mH and Q ∼1500 are achieved at 120 kHz.
3. The RF transformer OD was set at 1500 mm considering a separation of 250 mm from winding to shield to minimize the distributed capacitance to 20 pF. An optimization was done for the dimensions of former to get maximum Q-factor. This has resulted at $D_s/D = 0.3$. For this ratio, the number of tums is 280 and $R_{ac} = 1.5\ \Omega$ at 120 kHz. The primary winding has been made with 14 turns of Litz wire over the secondary winding near to the ground potential.
4. For 300 kV insulation across secondary output, a gap of 200 mm is provided across the toroidal former in $SF_6$ gas. The maximum electric field of 51 kV/cm was calculated across corona rings in between +150 kV and -150 kV output terminals.
5. $SF_6$ gas at 6 kg/cm$^2$ pressure is used as the bulk insulation and G-11 grade fibre reinforced epoxy (HY557) is chosen for toroidal bobbin for the RF transformer.
6. Two layers of polyimide (Kapton) tape of 1mil thick is wound over the entire Litz cable. This has provided a tum-to-turn insulation of 10 kV.
7. Plate type heat exchanger is provided to remove the heat from windings and maintain the winding temperature < 50 ℃.
8. The winding scheme with the optimized dimensions is shown in Fig. 10.11.

The 3 MeV DC accelerator and RF transformer pressure vessels are shown in Fig. 10.12(a) and the RF transformer winding is shown in Fig. 10.12(b). This accelerator at no load has been tested up to 3 MVdc along with this RF Transformer.

### 10.8.2 Protection Circuits

The RF transformer is protected against the common mode HV surges due to dome discharges with the help of the high frequency inductors and spark gaps designed to absorb and bypass them to ground. For the ±150 $kV_p$ transformer a simplified circuit is shown in Fig. 10.13.

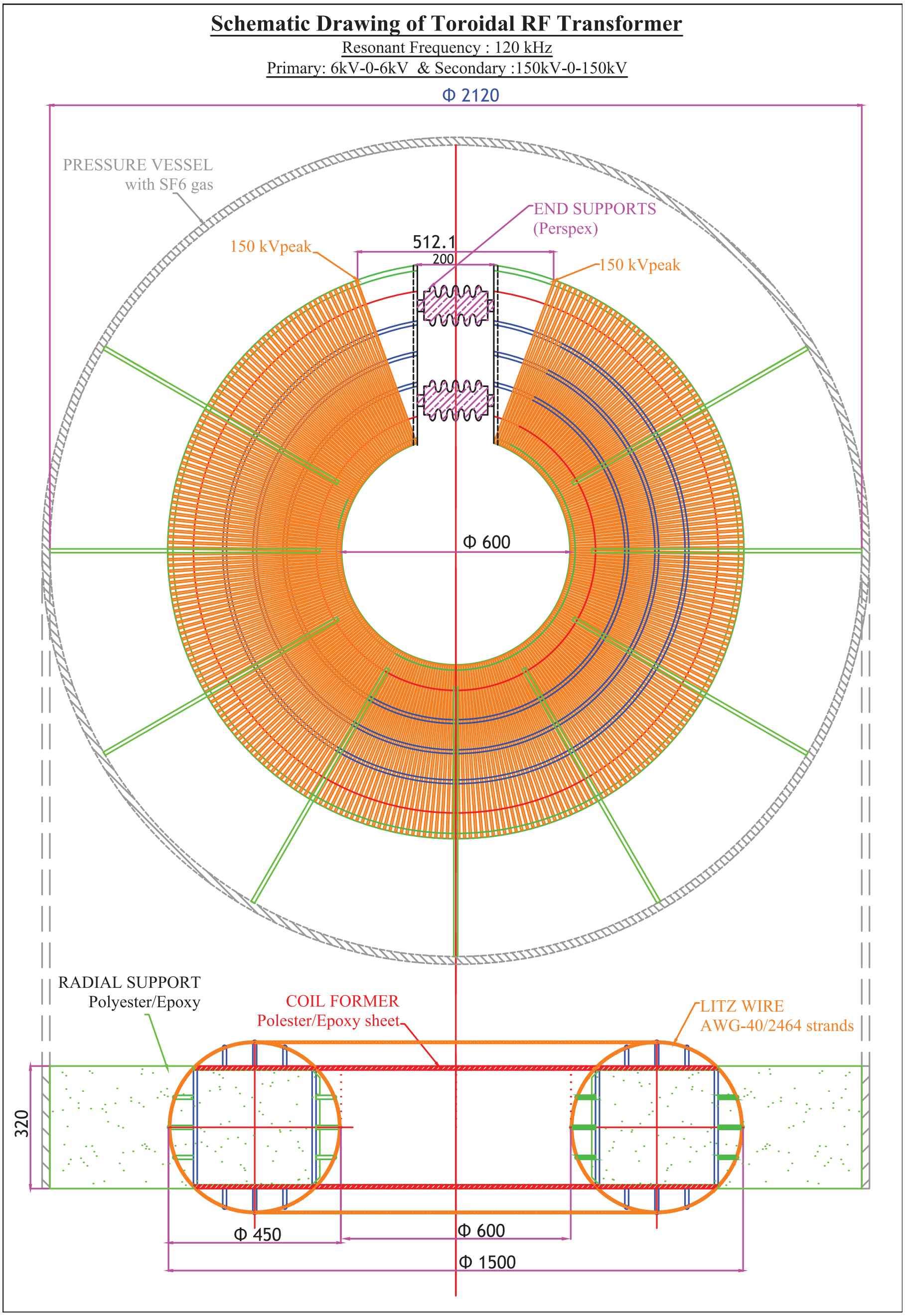


Figure 10.11: Winding scheme of 300 kV RF Transformer.

## 10.9 1 MeV, 100 kW DC Electron Accelerator

1 MeV, 100 mA DC accelerator has been designed and developed based on symmetrical CW Multiplier. The output voltage is defined by

$$V_o = 2NV - \frac{I}{fC}\left(\frac{N^3}{6} + \frac{N^2}{4} + \frac{N}{3}\right) \pm \frac{NI}{2fC} \tag{10.13}$$

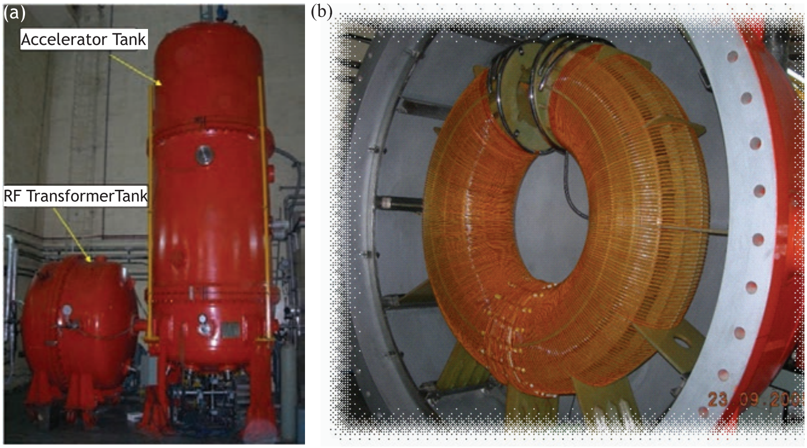


Figure 10.12: a) 3 MeV Accelerator Tank, and b) 300 kV RF Transformer.

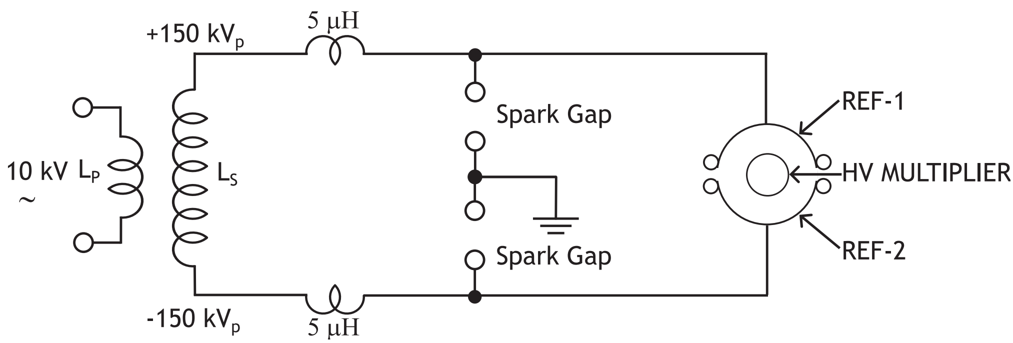


Figure 10.13: Protection circuit for 300 kV RF Transformer.

Where V is the input voltage, N - number of stages, f – frequency, I – the load current, and C - stage capacitance. A 15-stage symmetrical Cockcroft-Walton scheme has been selected

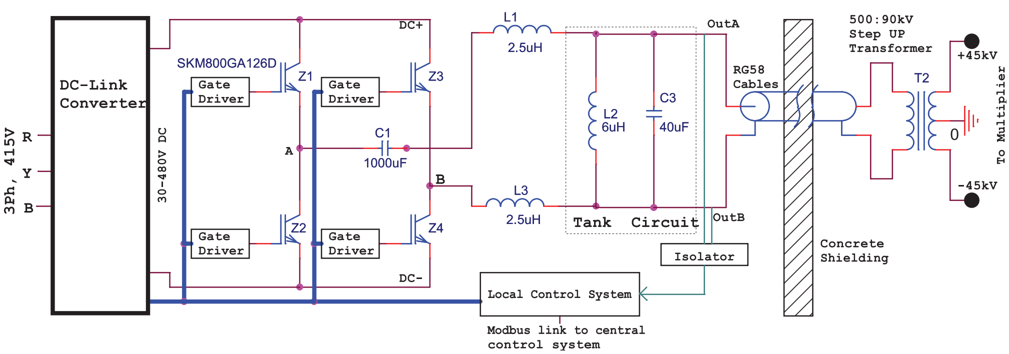


Figure 10.14: Scheme of 10 kHz Inverter & Ferrite core step-up transformer.

for generating 1 MV DC from a stage voltage of 45 kV$_p$-0-45 kV$_p$, 10 kHz. A solid-state power inverter connected to a variable dc supply (0-500 V) is powered by 3-$\phi$, 415 V, 50 Hz source. A ferrite cored transformer steps up the voltage from 500 $V_p$, 10 kHz to 45 kV-0-45 $kV_p$. The HV multiplier and accelerating column are kept inside a pressure vessel with $N_2$ + $SF_6$ gas mixture (95% $N_2$ + 5% $SF_6$ ) at 6 kg/cm$^2$ to provide the bulk HV insulation.

Table 10.4: Comparison of HV Power supplies developed by APPD, BARC.

| | **500 keV, 20 mA DCA** | **1 MeV, 100 mA** | **3 MeV, 10 mA** |
|---|---|---|---|
| Type | Balanced CW multiplier | Symmetrical CW multiplier | Parallel coupled multiplier |
| Unloaded output voltage ($V_o$) | $V_o$ = 630 kV; $V_i$ = 30 kV; N = 10 stages | $V_o$ = 1350 kV; 45 kV; N = 15 stages | $V_o$ = 3.5 MV ( k = ∼6); $V_i$ = 300 kV; N = 74 |
| Droop | 50 kV (f = 10 kHz) | 312 kV (f = 10 kHz) | 342.6 kV (f = 103 kHz) |
| Ripple | 17.8 kV | 37.5 kV | 13.888 kV |
| Capacitor Modules | 3.3 nF/ 40 kV (4 parallel | 2 series) → 6.6 nF/ 80 kV, total 20 modules | 3.3 nF/ 40 kV (18 parallel & 3 series) → 19.8 nF/120 kV, total 45 modules & Distributed gas insulated capacitors: 3.6 nF & 4.5 nF, rated for 300 kV operation |
| Rectifier Stacks | 22 × 4 nos. of BA159 diodes each rated for 1 kV, 1 A, total 22 rectifier stacks | 36 nos. of HVRW4 diodes each rated for 4 kV, 1 Adc, total 40 rectifier stacks | 8 nos. of UXFOB diodes each rated for 8 kV, 0.5 A, total 68 rectifier stacks |
| Compensation & Protection | 35 mH with 420 Ω for capacitor compensation and 1 GΩ across 22 diodes | 2.3 mH with 11 Ω for capacitor compensation and 0.5 mH with 100 Ω in both sides of rectifier stack | Surge protection for rectifiers (450 $\mu$H, 2.1 kΩ) and spark gap across rectifier for HV sparks |
| Energy Stored | 160 J | 2.4 kJ | 1 kJ |

### 10.9.1 Specifications of Power Inverter for 1 MeV Accelerator

The circuit scheme of power inverter is shown in Fig. 10.14 and the electrical schematic circuit of 1 MV, 100 mA symmetrical CW multiplier is shown in Fig. 10.7. A comparison of HV Power supplies developed by APPD, BARC for 500 keV, 1 MeV and 3 MeV DC Accelerators are given in table 10.4.

Input power: 3-Φ, 415 V, 50 Hz
Frequency: 10 kHz ±10%
Output voltage: 45 $kV_p$–0–45 $kV_p$
Efficiency: better than 90%
Power: 125 kW

## 10.10 Conclusion and Future Outlook

The design challenges and techniques for development of HV power sources of industrial DC electron accelerators (both Cockcroft-Walton & PCVM types) were explained. For accelerators up to 1 MeV, CW multipliers are comparatively simple to construct and modular. For energies 1-5 MeV, the PCVM type multipliers are more rugged against HV surges and are reliable. With simple modifications (replacement of HV diodes and power oscillator triodes) to the existing 3 MeV, 30 kW DC accelerator, the beam power of the accelerator can be enhanced up to 100 kW.

### Acknowledgement

The author sincerely thanks the vision of our senior mentors in making indigenous electronaccelerators. The contribution of the DC accelerator team in the successful development anddemonstration of the above high power electron accelerators in India is acknowledged.