Chapter 18

Megavolt DC Power Supplies for Industrial Electron Accelerators

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A DC Accelerator (DCA) is considered as a work-horse in the radiation processing industry for numerous radiation processing applications, viz. cross-linking of plastics, preservation of food articles, sterilization of medical products, environment cleanup etc. A DC accelerator comprises mainly a high-voltage generator, electron source, accelerating column and beam exit window, along-with several auxiliaries e.g. vacuum system, pressure vessel, beam-line, scan horn, magnets, cooling systems, control & safety-systems etc. Voltage generator provides acceleration potential for electron beam and provides required power for acceleration of electron beam. Voltage generator is usually a HV transformer or a voltage multiplier cascade. This chapter will give a brief description of cascaded voltage multipliers.

18.1 Cascaded Voltage Multipliers

A simple cascade voltage multiplier circuit was discovered by Cockcroft and Walton, hence, known as Cockcroft-Walton multiplier after them. A comparison of various forms of voltage multipliers i.e. simple, balanced, symmetric and parallel coupled multiplier is given in table 18.1 below. Here Voltage droop represents reduction in output voltage of generator from no load condition to full-load current (I_0). Ripple is the variation (peak to peak) in output voltage taking place due to input supply frequency (f). The main feature of all these voltage

Table 18.1: Comparison of main characteristics of Voltage multipliers

Description	**Conventional**	**Balanced**	**Symmetric**	**Parallel**
Output voltage V_0 (V)	2.N.V	N.V	N.V	N.V/ k, k = 1 + 4 (C_{AC}/ C_{SE})
Voltage droop V_D (V)	N.I_0/ [(3.f.C).(2N^2 + 1)]	N.I_0/[(6.f.C).(N^2 - 1)]	N.I_0/[(3.f.C).(N^2/2 + 1)]	N.I_0/ (k.f.C_{SE})
Ripple V_R (V)	N.I_0/ [(2.f.C).(N + 1)]	N.I_0/ [(4.f.C).(N + 1)]	N.I_0/ (2.f.C)	I_0/ (2.f.C_{SE})
Stage voltage (V_P)	V	V	V	V
Stage capacitance (F)	C	C	C	C_{SE}
Number of stages (N)	N	N	N	N
Frequency (Hz)	f	f	f	f

multipliers is that, input is high frequency AC voltage and output is high voltage DC. The first three circuits (i.e. conventional, balanced & symmetrical) utilize discrete capacitors and operate at moderate frequencies usually in 1-10 kHz range. The parallel circuit was mastered by Radiation Dynamics Inc. and marketed as ‘Dynamitron’ type generator. This generator operates at 30-300 kHz input and utilizes geometrical (i.e. stray) capacitances formed between metal components (i.e. corona guards and rectifiers) for development of High Voltage. Electrical scheme of the above voltage multipliers has been given in Fig. 18.1.

18.2 Selection Criteria for Type of Generator

In general, CW circuits are used when relatively lower output voltage is required. A conventional circuit is used for relatively lower voltage and current, whereas, symmetrical circuit is used when lower voltage but higher output current is desired. In this condition, the stored energy in the voltage generator is low and easy to handle during a HV discharge. Hence, conventional or symmetrical circuits are used in 0.2-2 MV range. Parallel circuit utilizes

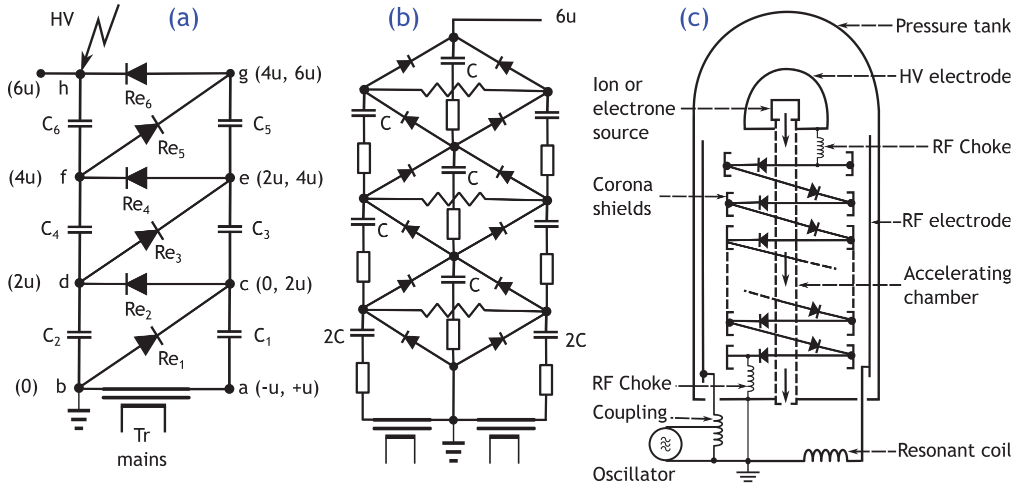

Figure 18.1: Electrical Scheme of the three types of voltage multiplier circuits: (a) conventional CW circuit, (b) symmetrical CW circuit, and (c) parallel (dynamitron) circuit.

geometric capacitances, which are of very low value (in pF), hence stored energy is low, even at much higher voltages. Therefore, parallel circuit is used for higher voltages usually in 2-6 MV range.

It can be seen from Table 18.1 that voltage droop and ripple are in cubic and square order of the number of stages (N) respectively in conventional as well as symmetrical circuits. The stage voltage is usually kept in 50-200 kV range, in view of HV source economics and commercial availability of HV Capacitors. Therefore, voltage droop and ripple are within desired limit for lower output voltages and current in conventional circuit. Droop in symmetrical circuit is approximately 1/4 times as compared to conventional circuit and also, ripple is of much lower value. Therefore, symmetrical circuit is preferred for moderately lower voltage and higher currents. In a Parallel circuit, Voltage droop is proportional to number of stages and ripple is independent of number of stages, hence, this circuit can have large number of stages i.e. very high output voltage and power (e.g. 5 MV, 300 kW).

In conventional and symmetrical circuits, frequency of operation is kept in 1-10 kHz range, which is restricted by dissipation and commercial availability of HV capacitors. Although, in extreme cases frequencies as low as 50 Hz and as high as 100 kHz are reported. In parallel circuit, since geometrical capacitances are utilized, capacitances are in pF and dissipation factor is in 10^{-7} range. Hence, frequencies as high as 100-300 kHz are used to maintain droop within permissible limits (10-50%), which is governed by source economics.

18.3 500 keV, 10 kW DC Accelerator at BRIT, Vashi

This is the first accelerator developed by APPD was commissioned at BRIT Vashi, Navi Mumbai in August 1998. High voltage generator of this accelerator is based on 10-stage balanced CW multiplier, which is sourced from a Ferrite-core based transformer of 10 kV_P/ 30 kV_P-0-30 kV_P, 10 kHz rating. Input to this transformer is supplied from a water cooled Triode-tube based oscillator. Schematic of the 500 keV DC accelerator is shown in Fig. 18.2. The 500 kV multiplier is housed in a vessel filled with high purity Nitrogen at 6 kg/cm^2 pressure. The 500 keV DC accelerator is operational at 200-500 keV energy, 3 kW beam power and tested at 5 kW for short time. HV generator specifications, HV supply characteristics and

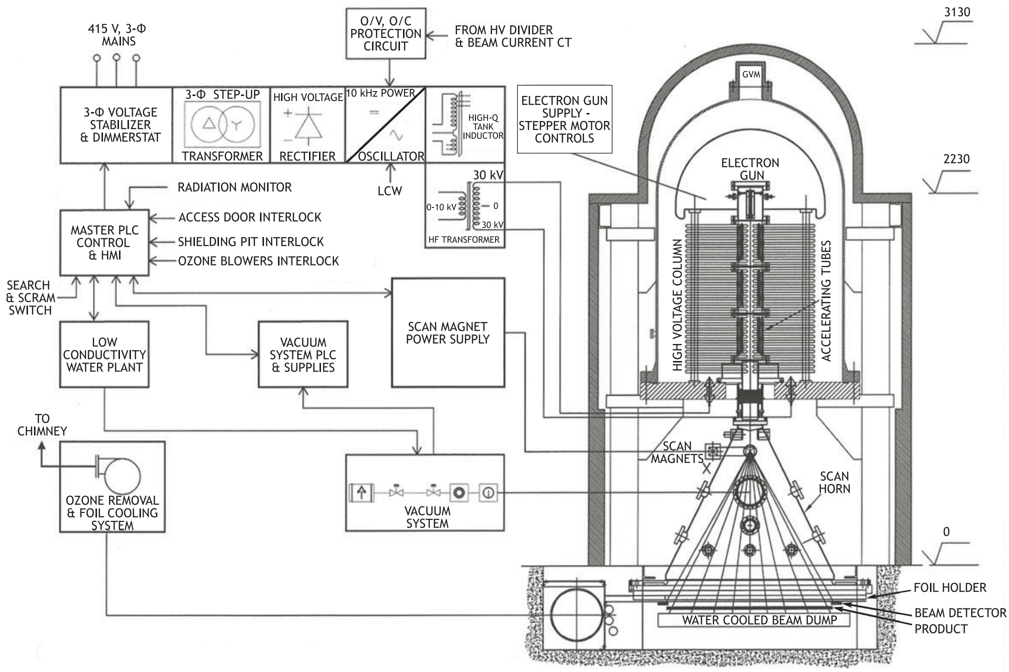

Figure 18.2: Schematic of 500 keV, 10 kW DC Accelerator.

photograph of the generator are shown in Fig. 18.3. This accelerator is suitable for radiation processing aimed at surface modification with beam penetration depth up to 1.4 mm in unit density materials. Accelerator has been utilized for various applications i.e. cross-linking of polythelene, graft-polymerization of rubber tiles, silver nano-particle grafting on fabric, radiation damage studies on solar panel materials etc.

H.V. Generator scheme:	Balanced CW Multiplier
Output Voltage:	200-500 kV
Output current:	0-20 mA
Voltage regulation:	10 %
Ripple:	< 2 %
Input voltage:	30kV$_p$-0- 30kV$_p$
Frequency:	10 ± 0.5 kHz
No. of stages:	10
Stage capacitors:	6.6nF, 80kVdc, tanδ 0.02
Stage rectifiers:	1kV, 1A, 300ns (176 Nos. in series)

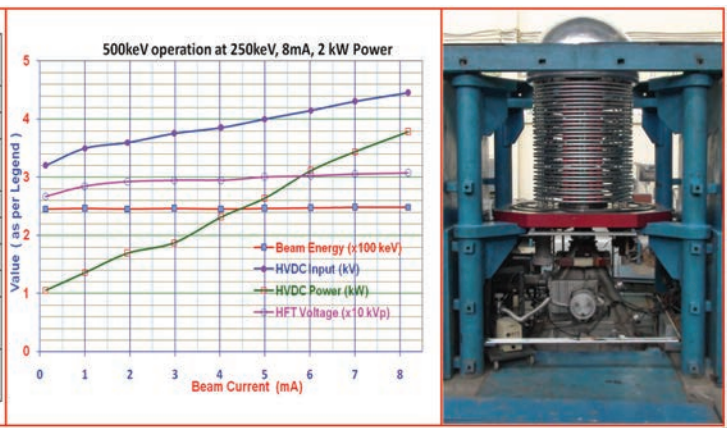

Figure 18.3: (Left) specifications, (middle) characteristics, (right) photograph of 500 keV DCA.

18.4 3 MeV, 30 kW DC Accelerator at EBC, Kharghar

The 3 MeV DCA is the second accelerator designed and developed by APPD in 2009. High voltage generator of this accelerator is based on Parallel Coupled Voltage Multiplier scheme. The 415 V, 3-phase mains power is converted to variable 0-10 kV DC, which is inverted at 100-120 kHz frequency using a water-cooled triode tube based push-pull oscillator, which is, in turn stepped-up at 150 kV$_P$-0-150 kV$_P$ using a high Q-factor resonant type transformer. Voltage multiplier is a 74 stages parallel-fed multiplier, which receives input power via capacitive-coupling between semi-cylindrical RF Electrodes and the corona-guards. Electrical schematic and salient details of the HV generator are shown in Fig. 18.4.

H.V. Generator scheme:	Parallel Coupled Voltage Multiplier
Output Voltage:	1- 3 MV
Output current:	0 - 10 mA
Voltage regulation:	10 %
Ripple:	< 1 %
Input voltage:	150kV$_P$-0- 150kV$_P$
Frequency:	100- 120 kHz
No. of stages:	74
Stage capacitors:	C_{SE} = 3.9 pF, C_{AC} = 4.5 pF
Stage rectifiers:	8kV, 0.35mA, 50ns (21 Nos. in series)

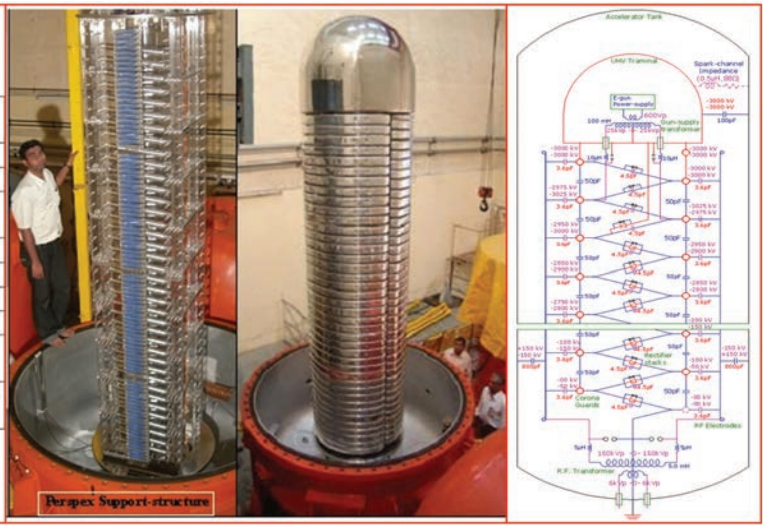

Figure 18.4: Specifications, 3MV multiplier photo & Electrical schematic of 3 MV generator.

18.5 1 MeV, 100 kW DC Accelerator for Waste Water Treatment

This is the third DC Accelerator designed and developed by APPD in 2018. The high voltage generator of this accelerator is based on 15 stages symmetrical CW multiplier. The 415 V, 3-phase, 50 Hz mains power is converted to variable 0-500 V, 250 A DC and subsequently inverted at 10 kHz using an IGBT based solid-state inverter. This 500 V$_P$, 350 A, 10 kHz power is stepped-up at 45 kV_P-0-45 kV_P using a high step-up ratio, ferrite-core based transformer. A block schematic of 1 MeV, 100 kW DC Accelerator is shown in Fig. 18.5.

The 1 MeV, 100 kW DC accelerator is among highest power rating accelerators ever realized using Cockcroft-Walton multiplier scheme. Also, it is the highest efficiency HV generator which is 90-92%. This supply is housed in a vessel filled with high purity Nitrogen gas at 6 kg/cm^2 pressure. Main specifications and electrical schematic are shown in Fig. 18.6. The 1 MV generator has been tested at 1000 kV at no load and up to 50 mA of electron beam loading. Power supply efficiency of DC input to Beam power output is 90%. The no load and load characteristics of 1 MV supply are shown in Fig. 18.7 below.

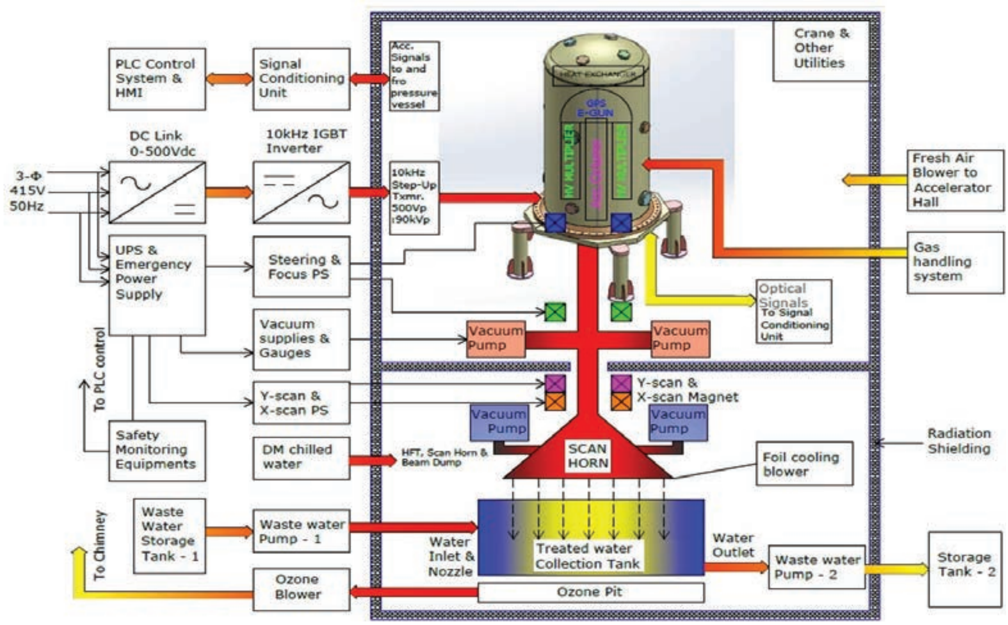

Figure 18.5: Block schematic of 1 MeV, 100 kW DC Accelerator for EB Waste Water Treatment (EBWWT).

H.V. Generator scheme:	Symmetrical CW Multiplier
Output Voltage:	0.8 - 1.0 MV
Output current:	0 - 100 mA
Voltage regulation:	284 kV
Ripple:	2.8 kV
Input voltage:	$45kV_P$-0- $45kV_P$
Frequency:	10 ± 1.0 kHz
No. of stages:	15
Stage capacitors:	20nF, 120kVdc, tanδ 0.02
Stage rectifiers:	4.0kV, 1.0A, 180ns (36 Nos. in series)

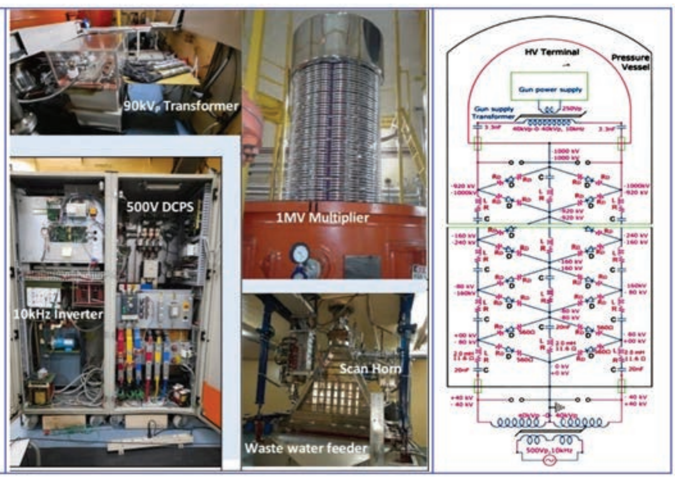

Figure 18.6: (Left) specifications, (middle) characteristics, (right) schematic of 1 MV DC supply.

18.6 Major Design Challenges in Megavolt DC Power Supplies

One of the main concerns of megavolt DC supplies is to protect the high voltage components from HV transients which are generated during a HV discharge. In order to limit the risk of damage, the stored energy in the supply should be kept minimum and a compromise on

Figure 18.7: (Left) No Load, (center) HMI display, and (right) Load characteristics of 1 MV supply.

ripple and regulation are important consideration.
In order to improve reliability, all the capacitors are tested at some margin, usually 50% of the working voltage which increases stored energy and makes power supply bulky. Also, the semiconductor diodes are vulnerable to transient over-voltages. Use of voltage snubbers or equalization circuits provides HV protection against these transients, but introduces stray-capacitances in the circuit, which puts adverse effects on voltage multiplication efficiency. These problems are overcome by using tightly close characteristics (PIV, t_{rr} & leakage current) in a rectifier stack. Hence, the reliability of supply depends on the careful testing of HV components. Stray-capacitances present in the power supply reduce voltage multiplication efficiency, which can be overcome by use of compensation inductors across the stages.

Suggestions for Further Reading

a) [48, 93–96]