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Review of Cockcroft-Walton High Voltage Low Current DC Power Supplies

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Abstract

High-voltage power supplies are key for developing particle accelerators, neutron generators, x-ray systems, ion implantation, etc. This paper reviews various developed voltage low current power supplies based on Cockcroft-Walton voltage multiplier circuits for accelerator-based neutron sources and other industrial and medical applications. The paper presents a detailed review of the topology of the power supply used for the high voltage generation, the key design parameters, key active and passive components used in the High Voltage (HV) system, key experimental results, protection and measurement circuit used in the power supply and about the system performance. The improvement that occurred in the size and performance of the power supplies due to the development in the technology of the magnetic components, semiconductors and energy storage devices in successive years is apparent in the discussion. Finally challenges and possible solutions for the compact design and system performance are concluded for the development of high voltage low current power supplies.

Keywords: Cockcroft-Walton Circuit, High Voltage Transformer, High Voltage Low Current Power Supply, Ion Implantation, Neutron Generator, Particle Accelerator, Voltage Multiplier

1. Introduction

Taking radiation safety and operational convenience into account, neutron generators stand out as the predominant form of accelerator-based neutron sources when compared to isotope and reactor-based alternatives[1]. Neutron generators find diverse applications in both industrial and biomedical fields, encompassing tasks such as nuclear data measurement, oil logging, neutron radiation-based tomography, neutron activation analysis, radiation hardening, radioactive breeding, and boron neutron capture therapy. These generators have gained significant traction for research purposes as well. Among the various methods of providing the required voltage, ranging from hundreds to thousands of kilovolts to the acceleration column of the neutron source, the Cockcroft-Walton-based high voltage low current power supply stands as the most favoured topology.

Accelerator The versatility and practicality of accelerator neutron sources have led to their extensive utilization. An accelerator neutron source primarily comprises components such as an ion source, ion source power supply, high voltage power supply, accelerator tube, vacuum system, and target[2]. In the context of neutron generators, the Cockcroft-Walton circuit is commonly adopted for developing high-voltage power supplies due to its proven reliability in terms of operational efficiency and performance.

The history of high voltage power supplies for accelerators can be traced from the year 1928 when Cock-Croft and Walton were suggested by Rutherford to design an 800 KV DC generator. They succeeded in developing high voltage DC generators up to 700 KV for accelerator application[3,4]. The requirement for radiation therapy in the medical world and similarly ion implantation in other industries is increasing day by day. Various Cockcroft-Walton power supplies developed and used for accelerators

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have been reviewed in this paper. Mainly the electrical circuit, number of multiplication stages, key active and passive components, measurement and protection circuits, insulation medium, system performance and stability, key results etc. are discussed and concluded in this paper. The list of power supplies mentioned in Table 1 has been considered for the discussion.

Table 1. Details of power supplies and their application[1,2,5-12]

S. No.	Description of power supply	Application
1.	500 kV, 2.5 mA DC power supply	For Linear Accelerator (Iowa Generator) at State University of Iowa
2.	200 kV DC power supply	Accelerator for neutron beam production from the exothermic reactions of D(d, n)He[3] and T(d, n) He[4] at Nuclear Research Laboratory, Ritsumeikan University, Kyoto
3.	600 kV, 10 mA DC power supply	For Ion source research at Lawrence Radiation Laboratory, University of California, Berkeley.
4.	200 kV, 200 mA DC power supply	To obtain high-intensity neutron flux by accelerating deuterium and tritium, at Hitachi Central Research Laboratory, Kukubunji, Tokyo.
5.	500 kV, 5 mA DC power supply	For ion implantation investigations encompassing range and energy loss measurements within silicon crystals, as well as the production of characteristic X-rays through the irradiation of heavy particles, at Nuclear Physics Division, Atomic Energy Research Establishment (AERE), Harwell, U.K.
6.	600 kV, 15 mA DC power supply	For 1.5 ns Compact Pulse Compact Neutron generator (CPNG-6) of China Institute of Atomic Energy (CIAE)
7.	1.2 MV, 50 mA DC power supply	For Industrial electron beam irradiator, at Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai.
8.	250 kV, 6 mA DC power supply	For compact neutron generator, at Lanzhou University, Lanzhou, People's Republic of China
9.	400 kV, 80 mA DC power supply	For an intense DD/DT neutron generator at, Lanzhou University, China.
10.	300 kV, 6 mA DC power supply	For compact neutron generator, Shanghai, China

2. Cockcroft-Walton HVDC Power Supplies

In those days when Cock-croft and Walton developed the first cock-croft Walton accelerator, hot filament X-ray tube rectifiers were used for the rectification. Condensers and filament rectifiers were required to develop a voltage multiplier circuit. They also required the batteries, generators or high voltage isolated step-up transformer to heat those rectifier filaments.

2.1 500 KV, 2.5 MA DC Power Supply for Linear Accelerator

Wayne used dry selenium disc rectifiers so the need for filament heating can be avoided. This has opened the door to using more multiplication stages for high-voltage generation. Certainly, the maximum number of multiplication stages has limitations and it is limited by the load current requirements. This limitation can be overcome by the proper selection of input voltage and frequency. By increasing the number of stages, the voltage stress on the rectifier and the capacitor or condenser can be reduced. Wayne developed a 500 kV DC generator for linear accelerator using 22 stages of Cock-Croft Walton half wave doubler circuit[5]. A 1 µF condenser rated for 25 kV was used for the development of this complete 500 kV circuit. All condensers used were identical in all 22 stages. Five selenium dry disc type rectifiers were connected in series to develop a rectifier rated for 25 kV and 2.5 mA load current. A 250 V/10 kV, 750 Hz transformer was used to feed the multiply circuit in which secondary winding was insulated for 50 kV. This transformer was supplied through a variac by 750 Hz, 10 kVA alternator. The 500 kV DC generator was tested using a water load. The peak-to-peak output ripple voltage was 1200 V per mA of the load current. The overall efficiency was measured at 350 kV and a 0.5 mA load current was 70 per cent. The measured ripple was 3.5 times the theoretical expected value if all condensers and rectifiers were considered to be identical.

2.2 200 kV DC Power Supply for Neutron Beam Production

Ryuhei Kato and Toshihiko Kono developed a 200 kV Cock-Croft Walton single-stage accelerator for neutron beam production from the exothermic reactions of D(d, n)He[3] and T(d, n)He[4,6]. A total of eighteen selenium rectifiers rated for 20 mA were connected in series to develop a 200 kV rectifier. The input voltage frequency was 60 Hz. The measured percentage voltage ripple was 0.15% for approximately 66 mA load current. During the experiments, the voltage stabilization was found much better compared to the use of rectifier tubes in earlier cases.

2.3 600kV, 10 mA DC Power Supply for Heavy Ion Linear Accelerator

In the early days of development, selenium diodes operating at power frequencies or vacuum tubes operating at higher frequencies were used to construct high-voltage power supplies of the order of 500 kV. The development of these types of power supplies requires huge and complex mechanical shop floor facilities in the laboratory. The use of silicon diodes and ceramic capacitors helped in developing similar types of power supplies with the modest and simpler facilities available at laboratories. A 600 kV, 10 mA DC power supply was built for heavy ion linear accelerator for ion source research at Lawrence Radiation Laboratory using minimum facilities[7]. A total of 18 stages of the Cockcroft-Walton rectifier circuit are used to build this power supply. The rectifier circuit was driven by a 40 kV AC, 100 kHz, and 10 kW oscillator to produce 600 kV DC at a load current of 10 mA. To protect the power supply from damage during a short circuit due to sparking a thyratron crowbar circuit was used. 350 silicon diodes rated for 0.75 A, average DC and 600 V Peak Inverse Voltage (PIV) were connected in series to develop a rectifier for each stage. A 200 pF, 500 V ceramic capacitor was connected across each single diode for voltage equalisation. The diodes were mounted on an etched circuit board in a specific pattern which helps to reduce the voltage gradient. Two 2500 pF, 40kV capacitors were connected in series to achieve the stage capacitance and its voltage rating. The assembly of diode boards and capacitors was placed in the polyvinyl acetate cylinder. After assembly, this cylinder was filled with SF_6 gas at atmospheric pressure for insulation. A Low Conductivity Water (LCW) was used to test the power supply at various load conditions. A good agreement was found between experimental measurement and theoretical calculation through the test results. The experience of this 600kV rectifier circuit gave confidence to the developers to extend this technique up to several million volts.

2.4 200 kV, 200 mA DC Power Supply to Obtain High-Intensity Neutron Flux

A three-stage high power symmetrical Cock-croft Walton circuit was constructed using small silicon rectifiers by Hara, for the development of 200 kV, 200 mA DC power supply[8]. This power supply was developed to obtain high-intensity neutron flux by accelerating a mixture of deuterium and tritium ions. Previously selenium rectifiers were used before the invention of silicon diodes. However, those rectifiers were not suitable for high-power rectification due to their high-power loss. The maximum available peak inverse voltage rating of the selenium diode was 20 V and its potential drop in the forward direction was 1 V. So due to this a considerable power drop and heat generation was occurring in rectifiers. The development of silicon diodes helped to overcome this issue for building high-power accelerators. A total of three stages of voltage multiplication were used for the development of this symmetrical voltage multiplier circuit. The rating of the single silicon diode used in the circuit was 500 V for 500 mA Forward DC. The reverse leakage current was less than 1 μA. Type A of a total of 320 silicon diodes was connected in series to build one rectifier column. Each diode was shunted by a 1 MΩ resistor and a small condenser for voltage equalisation and to avoid the voltage surge across the rectifier. A total of 12 such rectifier columns have been used in three stages of a symmetrical voltage multiplier circuit. All these rectifiers were cooled by dry air of 5 atm pressure. The capacity of condensers used in these three stages was 0.2 μF and the lowest condenser of the charge transporting column has twice the capacity that of others. This multiplier was fed by a symmetrically constructed transformer which had having output voltage of 35 kV for both windings and an input voltage frequency of 1 kHz. The output voltage efficiency found for this symmetrical voltage multiplier circuit was 95%. The most important asymmetry found in the voltage multiply circuit was due to asymmetry in the driving transformer's two secondary windings. The voltage drop in the rectifier circuit was only 7.7 kV at 200 mA load current and the ripple voltage was 5 V/mA load current. The transformer's primary current was found to double compared to the conventional Cock-Croft Walton circuit rated for the same output voltage and load current.

2.5 500 kV, 5 mA DC Power Supply for Ion Implantation

A three-stage Cockcroft-Walton voltage multiplier with a maximum output voltage of 500 kV for an output current capacity of 5 mA was built by Goode and used at Harwell, for ion implantation application[9]. The voltage multiplier circuit was fed by a 250 Hz, 100 kV supply. RC filters were provided for voltage soothing and oil cooled resistive divider was used for the output voltage measurement. This Cockcroft-Walton accelerator provides a variety of beams and facilities for a wide range of experimental work and the range can be still extended.

2.6 600 kV, 15 mA DC Power Supply for Compact Pulse Neutron Generator

A 600 kV, 15 mA Cockcroft-Walton high voltage power supply was engineered to support the 1.5 ns compact pulse neutron generator (CPNG-6) at the China Institute of Atomic Energy[10]. The power supply's design included a maximum no-load voltage capability of 600kV, while its highest operational voltage was set at 550kV to accommodate a load current of 15 mA. The main speciality of this power supply was high stability and low output voltage ripple. The power supply was made using 6 stages of symmetric Cockcroft-Walton voltage multiplier circuit. This rectifier circuit was driven by a thyristor inverter source at an intermediate frequency of 2.5 kHz. Over-current protection system was incorporated into the system for the fast turn-off of the system within 1 ns. To improve the voltage stability of the power supply, a dual voltage stabilizing circuit was used. The peak-to-peak output voltage ripple was reduced by the use of two stages of RC filters which were connected at the output terminal of the voltage multiplier circuit. As per the test results, the peak-to-peak output voltage ripple was 6.2 V at 300 kV and 6.8-8.3 mA of load current. The ratio of the peak-to-peak ripple voltage to the output voltage was 2.1 x 10^{-5}. A regulating triode was used in the 600kV, 15 mA power supply to provide a dual voltage stabilizing system and to improve the voltage stability of the power supply. An ohmic capacitive potentiometer was used for the measurement and sampling to provide the response time of the voltage stabilisation in nanoseconds. The complete rectifier rack of this power supply including its first filtering capacitor and protective resistors was housed in a glass fibre-reinforced plastic cylinder. For heat dissipation and insulation, this cylinder was filled with transformer oil. The targeted parameters of peak-to-peak output voltage ripple and voltage stability were established through the test results.

2.7 1.2 MV, 50 mA DC Power Supply for Industrial Beam Irradiator

For an Industrial electron beam irradiator, a 1.2 MV, 50 mA power supply was developed using 3 stages of symmetric Cockcroft-Walton voltage multiplier circuit[11]. Sulphur hexafluoride (SF_6) at 6.5 atm was used as an insulating medium in this high-voltage power supply. The power supply was driven by a 50 Hz power frequency source and had 83% power efficiency. The capacitance values of the coupling or oscillating columns were 45 nF and 28.13 nF respectively. The power supply was tested up to 1.32 MV in no-load conditions and up to 1.2 MV at a load current of 50 mA. During the testing, the ratio of ripple voltage to output voltage was found as 9.4%. This value was found two times the theoretically calculated value. The difference between the measurement values and theoretically calculated values was found mainly due to asymmetry in the circuit. The asymmetry in the circuit was found to be the main reason for the odd harmonics and the asymmetry in the charging and discharging of the capacitors was found to be the reason for the even harmonics. The load current measurement was also found to be affected by the asymmetry in the charging and discharging of the capacitors which was eliminated by adding a parallel capacitor in the measuring circuit.

2.8 250 kV, 6 mA DC Power Supply for Compact Neutron Generator

A compact 4-stage symmetrical Cockcroft-Walton power supply was developed for a compact neutron generator by Zhan-Wen Ma *et al*. The power supply was rated for 250 kV DC output voltage for 6 mA load current[12]. The Cockcroft-Walton circuit was driven by a 1 kHz intermediate frequency power supply. A total of twelve equipotential rings were used to balance the electric field in the power supply. The complete voltage multiplier circuit along with its measurement circuit, the input high voltage step-up transformer and equipotential rings were assembled in a glass fibre-reinforced plastic cylinder. The cylinder was filled with transformer oil for proper heat dissipation and insulation. The cylinder had four wheels at its base for ease of movement. The capacitance values for the first stage of the voltage multiplier was 16 nF for all 3 capacitors of oscillating and smoothening columns. The capacitance value for all the capacitors of the 2nd, 3rd and 4th stages for smoothening and oscillating columns was 8 nF. The total leakage current of the power supply was 1 mA. This leakage current was summing a total of current through the measurement circuit, protection circuit and other components. The voltage drop measured 250 kV output voltage for 1 mA and 6 mA load current were 1.35% and 0.53% respectively. The ripple voltages measured at 250 kV output voltage for a load current of 1 mA and 6 mA were 0.08% and 0.53% respectively. Protective resistors have been provided at the output of the voltage multiplier circuit for short-circuit protection. The test results showed that the protective resistors provided at output were enough for the short circuit protection. The complete power supply system was stabilized by the voltage stabilization circuit using an ohmic-resistive potentiometer circuit. The test result showed that the maximum instability of the system was less than 0.63% for 250 kV output voltage at 6.9 mA load current for input voltage variation of ±10%.

2.9 400 kV, 80 mA DC Power Supply for Intense Neutron Generator

At Lanzhou University, a 400 kV, 80 mA Cockcroft-Walton power supply was developed for an intense neutron generator[1]. The power supply was made of 6 stages of symmetric Cockcroft-Walton voltage multiplier circuit and driven by an intermediate power supply at 2.5 kHz frequency. The capacitance value of all the oscillating (AC) columns accept the first stage (the immediate stage after the high voltage step-up transformer) was 24 nF, whereas the value for the first stages was 48 nF. The capacitance values of all the smoothing column capacitors were 48 nF. The calculated voltage drop and output voltage ripple were 7.85% and 0.25% respectively. All the components of the power supply such as oscillating capacitors, smoothing capacitors, rectifiers, measurement and protection circuits, equipotential rings etc. were assembled in a glass fiber-reinforced plastic cylinder. This cylinder was filled with transformer oil. Four wheels were provided at the bottom of the cylinder for ease of the movement of power supply. The step-up transformer was made of two stages for stepping up the voltages. The rated value of the primary winding was 380 V, 2.5 kHz. The first secondary coil will step the voltage up to 5 kV, at 2.5 kHz and the second stage of the secondary coil will step the voltage up to 30 kV at 2.5 kHz. The transformer was designed for a power rating of 80 kW. Transformer oil was used for the high voltage isolation and heat dissipation in the transformer. A 600 kΩ current limiting resistor was provided at the output of the voltage multiplier circuit to protect the power supply during the short circuit. The voltage measurement was carried out using a high-value resistor in series with a microammeter.

2.10 300 kV, 6 mA DC Power Supply for Compact Neutron Generator

A 300 kV, 6 mA integrated Cockcroft-Walton high voltage power supply was developed by Zaho *et al.* for a compact neutron generator[2]. To make the power supply compact, all electrical components such as the voltage multiplier circuit, step-up transformer, measurement and protection circuits, equipotential rings etc. along with the isolation transformer were assembled in the glass fiber reinforced plastic cylinder. Their newly designed high-voltage power supply was more compact than the traditional power supplies for neutron generators. The voltage multiplier circuit was driven by a 1 kHz intermediate frequency power supply. A total of four stages of a symmetric voltage multiplier circuit was used to achieve the output voltage of 300 kV. A resistive-capacitive divider circuit was used for the voltage measurement. The low voltage signal of the divider circuit was given to the control circuit of the input intermediate power supply for output voltage stabilization. To enhance the distribution of the electric field, a total of 12 equipotential rings were integrated into the power supply system. These rings were interlinked using voltage equipotential resistors, each with a resistance of 160 MΩ. The entirety of the components was housed within a cylinder constructed from glass fibre-reinforced plastic, which was then filled with transformer oil. The step-up transformer employed in the system had a power rating of 3 kW. The silicon steel core was used for the construction of the transformer. A design flux density of 1.2 T was considered for it. As per the test results the power loss of the transformer was only 60 W when the output power was 2 kW. 8 nF capacitors were used for the AC and DC column of the first stage of the voltage multiplier circuit. The measured value of voltage drop in the power supply at 300kV/6 mA was 2.21%. To protect against overcurrent, a configuration involving two 5 kΩ resistors was implemented in series with rectifiers positioned at both the highest and lowest potentials within the voltage doubler circuit. Additionally, a 600 kΩ resistor was linked to the output of the voltage multiplier circuit. Notably, no overvoltage protection device was incorporated into the power supply design. Experimental findings underscore that the power supply exhibited an output voltage variation of under 0.5% when operating at 300 kV/6 mA, even when the input voltage fluctuated within a range of ±8%.

3. Conclusion

An evolved designer of Cockcroft-Walton power supply should always consider the aspects of modularity, compactness, cost, longevity etc. along with the performance parameters such as voltage drop, output voltage ripple stability etc. When the output current of the Cockcroft-Walton power supply was constant, the voltage drop in the system depends on the driving frequency of the input voltage source, the capacitance values of the oscillating (AC) and smoothing (DC) column capacitors and the number of the voltage multiplication stages. The same parameters affect the output voltage ripple except the capacitance values of the AC column capacitors. This was true for both symmetric and conventional voltage multiplier circuits. The voltage drop and output voltage ripple can be reduced by decreasing the number of stages of voltage multiplication. But by decreasing the number of stages the voltage stress on each stage will increase and that will put a factor of difficulty in the design and development of the power supply. Similarly, the value of the voltage ripple or voltage drop can be reduced by increasing the value of driving frequency and/or by increasing the value of stage capacitance. However, the driving frequency was limited by the resonance frequency of the transformer whereas the increase in value of stage capacitance will make the system bulky. So an optimum approach should be applied in the selection of driving frequency, stage capacitance value and the number of multiplication stages. Mostly all researchers have adopted a symmetric voltage multiplier circuit to develop of power supply to reduce the voltage drop and output voltage ripple for the same number of stages and other design parameters compared to conventional Cockcroft-Walton voltage multiplier circuits. It was observed that various specific key parameters have been focused on by the designer such as stability, output voltage ripple, voltage drop, compactness etc., while designing the power supply. After a study and review of protection circuits for various power supplies, it can be said that one current limiting resistor was enough at the output of the voltage multiplier circuit for the over-current protection during the short circuit and there was no need for individual series resistor with each rectifier. In the worst case, the current limiting resistor should be connected in series with the rectifiers connected at the lowest and highest potential of the voltage multiplier circuit. The stability of the power supply can be achieved by the appropriate selection of the measurement circuit and control topology of the input driving power supply. The compactness of the power supply can be achieved by using a reasonably high-frequency input driving power supply and a good insulating medium having a high dielectric constant. By an optimum design of a step-up transformer having a higher resonance frequency, a limitation on the use of a higher frequency driving source can be mitigated. But it may increase the percentage impedance of the transformer. The use of equipotential rings was commonly observed in power supply for the improvement of the electric field distribution. By optimization of various key design parameters such as driving frequency, number of stages and values of stage capacitance and by use of modular architecture, more novel and compact stable designs of power supplies can be achieved for the design of compact neutron generators and other applications which can have ease of maintenance and flexibility.

Table 2. Summary of high voltage power supplies

S. No.	Rating of power supply	Driving frequency	No. of Stages	Remarks
1.	500 kV, 2.5 mA DC	750 Hz using alternator	22	(a) Use of selenium rectifiers and condenser and (b) use of conventional Cockcroft-Walton Circuit (c) air insulation
2.	200 kV DC	60 Hz, power source	1	(a) Use of selenium rectifiers conventional Cockcroft-Walton Circuit (b) Special features of output voltage stabilization and low output voltage ripple (c) air insulation
3.	600 kV, 10 mA DC	100 kHz from 10 kW oscillator	18	(a) Use of silicon rectifiers, ceramic capacitors and conventional Cockcroft-Walton Circuit (b) SF_6 insulation
4.	200 kV, 200 mA DC	1 kHz AC power source	3	(a) Use of silicon rectifiers, ceramic capacitors and symmetric Cockcroft-Walton Circuit (b) Cooling and insulation by dry air at 5 atm. (c) low output voltage ripple and voltage drop

Table 2. Continued...

S. No.	Rating of power supply	Driving frequency	No. of Stages	Remarks
5.	500 kV, 5 mA DC	250 Hz, 100 kV power source	3	RC filters were provided for voltage soothing and oil cooled resistive divider was used for the output voltage measurement
6.	600 kV, 15 mA DC	2.5 kHz by Thyristor inverter source	6	(a) speciality of high stability and low output voltage ripple (b) Symmetric Cockcroft-Walton circuit (c) Use of transformer oil as insulation
7.	1.2 MV, 50 mA DC	50 Hz power source	3	(a) Use of Symmetric Cockcroft-Walton circuit (b) SF_6 at 6.5 atm for insulation (c) Use of current limiting resistor at output to protect the power supply during short circuit
8.	250 kV, 6 mA DC	1 kHz power source	4	(a) Use of Symmetric Cockcroft-Walton circuit (b) Use of transformer oil as insulation (c) Output voltage stabilization, low voltage drop and output voltage ripple (d) Use of protective resistors at output for over-current limiting during short circuit
9.	400 kV, 80 mA DC	2.5 kHz power source	6	(a) Use of Symmetric Cockcroft-Walton circuit (b) Use of transformer oil as insulation (c) Use of current limiting resistor at output to protect the power supply during the short circuit
10.	300 kV, 6 mA DC	1 kHz power source	4	(a) compact power supply for neutron generator (b) Output Voltage stability (c) Use of transformer oil as insulation (d) Use of Symmetric Cockcroft-Walton circuit

The summary of various high-voltage power supplies discussed in this paper is given in Table 2. The driving frequency, no of multiplication stages, insulation medium, special features of power supply etc. are provided in the summary table.

In light of both present conditions and prospects, developers may contemplate the adoption of a higher operating frequency within the 40-50 kHz range. This strategic choice will enable the utilization of smaller passive components, contributing to system miniaturization. To augment the built-in current, a parallel Cockcroft circuit emerges as a favourable option. Additionally, it will be possible to offer a variety of overcurrent tripping ranges, tailored to the specific requirements of the application, thus enhancing the adaptability of the power supply. A critical consideration lies in the selection of the insulating medium. Opting for a green insulating medium having higher pressures within the 5-6 bar range can significantly enhance system compactness and efficiency.

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