Building a Compact and Easy-to-Operate High-Voltage Power Supply for High-Speed Ion Generation

Bunsaku Arakatsu, Kiichi Kimura, Yoshiaki Uemura*
Faculty of Science and Agriculture, Imperial University

Since Cockcroft and Walton succeeded in the method of artificial atomic transmutation by high-velocity ion bombardment using their ingeniously designed high-voltage power supply in Cambridge, England, similar research has been conducted in various locations in Europe and America, including Professor Lorence's laboratory at the University of California.

We believed this research would find application not only within pure atomic physics but inevitably across a broad spectrum of scientific fields, opening new realms of applied physics. We anticipated that laboratories worldwide would require this type of research, demanding individuals proficient in their techniques and solid knowledge. We therefore felt it imperative to ensure that even on this isolated island in the tropics, we should engage in this research and master its techniques, preparing for the future.

However, replicating the equipment necessary for the original research exactly as found in Europe and America would have required enormous expenses. Therefore, I sought to assemble it within the scope of a typical laboratory's space, equipment, and budget, aiming for something as compact as possible, relatively inexpensive, and not overly complicated to operate. After much deliberation, I obtained sympathetic assistance from the Japan Society for the Promotion of Science, enabling me to acquire a high-voltage power supply essentially as described below.

This enables easy observation of artificial nuclear transmutation phenomena involving light elements such as H, Li, Be, and B. At present, we have completed a series of preliminary observations and have become quite proficient with technology. Consequently, we are now finally in a position to conduct substantive research.

Taking the opportunity of the invitation from Applied Physics, we would like to describe the power supply we constructed, hoping it may serve as a reference for those in laboratories with relatively limited funds and facilities who wish to attempt such experiments. Of course, this assembly is not our ideal design. We gathered whatever were available in the lab, adapted to the inconvenient conditions of this island, and also harbored the desire to use this equipment for other research purposes. Consequently, it has many aspects that are disproportionate for this specific purpose alone. We wish to make this point clear in advance.

Our laboratory possesses three 60kV X-ray transformers (manufactured by Shimadzu Corporation) whose one end is grounded. These are identical in construction, each featuring an independent autotransformer that allows arbitrary adjustment of the primary voltage. As shown in Figure (1), they are connected to rectifier tubes and capacitors for use. We used rectifier tubes manufactured by Tokyo Electric Company with a breakdown voltage of 220,000 volts. The capacitors were

Sumitomo-manufactured O.F. type high-voltage capacitors with a test voltage of 200,000 volts, a working voltage of 150,000 volts, and a capacitance of 0.016μF.
Now, if transformers T1 and T2 are operated い such that their phases are exactly opposite, as the earth-fault side of capacitor C1 oscillates between -V2 and +V2, the voltage on the high-voltage side of C1 will fluctuate between V1 and V1 + 2*V2.
This is sent to capacitor C2 via rectifier tube K2. If we set the transformer T3 connected to the ground-fault side of C2 to operate with a phase exactly opposite to T2, i.e., in phase with T1, the high-voltage side of C2 will oscillate between V1+2V2 and V1+2V2 +2V3. This is stored in capacitors C3 and C4 via rectifier tubes K3 and K4.

Commercially available rectifier tubes typically have a maximum withstand voltage of around 200,000 volts. Therefore, the transformer voltage V1, etc., is limited to about 60,000 volts at most. As long as the voltage stored on the high-voltage side of C3 and C4 does not exceed 250,000 volts, all rectifier tubes will be safe. Now, assuming V1 = V2 = V3 = 50,000 volts, the voltage across K1 and K2 would be approximately 200,000 volts. This would be within the scope of their insulation strength, allowing C3 and C4 to obtain 250,000 volts. In practice, operating with this configuration made it easy to achieve the desired voltage.
Now, to facilitate the generation of high-speed ions for use in atomic artificial transmutation research, the ground side of C4 is directly connected to one terminal of a transformer T4 rated at approximately 40 kV. The insulated side of C4 connects to the rectifier tube K5 and as needed, to the tip II of the Wien-type cathode ray tube (we used a modified Oliphant-Rutherford type tube) via a milliampere meter mA. The high-voltage side of C3 is directly connected to the intermediate electrode I, which serves as the cathode for the ion generation tube and as the anode for the ion acceleration tube.
When T4 is now operated, although voltage fluctuation occurs between II and I, II always functions as the anode, creating a voltage difference. This generates current in the circuit C4 - K5→II→I→C3→K4→C4 circuit, driving a large number of ions through the ion source tube P1. A portion of these ions is then fed into the ion accelerator tube P2, where they attain high velocity due to the electric field drop between I and O. The key feature of this apparatus is the convenience of operating this entire ion current circuit solely from the grounding end by driving T4. Unlike Cockcroft's design, which placed the motor and transformer at the highest voltage point, this compact system employs the capacitor C4 for insulation.
The benefits of this approach extend beyond operational safety and ease; it significantly reduces unnecessary corona discharge at high-voltage points, enabling efficient voltage generation even in humid environment of this island. In practice, when attempting these experiments, we encounter limitations caused by insufficient rectifier tube capacity, transformer output fluctuations, and capacitor characteristics irregularities. Excessive tip discharges make it difficult to actually apply high voltage to the ions. Though a minor point, this method proved truly effective for conducting such high-voltage experiments. Admittedly, there is a drawback: the acceleration voltage of C3 fluctuates within a small range, resulting in uneven ion velocities within a certain range. However,

when strict control of ion velocity is necessary, the ion flow can be aligned by applying a magnetic field. We found this method generally acceptable as a standard power supply. (Initially, we inserted capacitor C3 to reduce this fluctuation in the accelerating voltage, but this only increased the likelihood of overall equipment failure with relatively little effect, so we later removed it entirely.) Now, when we actually began experiments on artificial atomic transmutation, various troublesome minor incidents arose.
Since the cathode ray tube used must bear considerable (mechanical) load, its electrodes are made of iron weighing up to 100 kg. Consequently, after the initial vacuum operation, expelling the gas contained within requires a rather troublesome painstaking procedure. Even after achieving a reasonably stable state by applying high voltage to I and II, the vacuum in tube P2 occasionally deteriorates abruptly, causing sudden discharges between 1 and 0. This results in rapid fluctuations in the voltage of each capacitor.

For example, the voltage difference between C4 and C3 may suddenly increase, destroying the glass disc used for P1's insulation. Alternatively, the grounding terminals of C3, C4, etc., may experience a sudden voltage rise (negative), causing undesirable discharges at various points along the grounding line. Consequently, it also tends to cause various adverse effects and inconvenience to other laboratories. While it may seem trivial, for those actually conducting experiments, this fault carries considerable significance.
To prevent this, the following procedure was adopted: First, all capacitors were individually placed atop insulator stands approximately 150 cm high. This was done even for those intended for direct grounding. Then, instead of direct grounding, water resistors with a diameter of 3 cm and a length of about 100 cm were used as R1 and R2. (To prevent boiling, we attached flasks of about 1 liter capacity at two points.) This arrangement allows the resistors to function as good conductors for the 60-cycle AC supplied by transformer T4. However, during the sudden voltage changes described earlier, they act as instantaneous good insulators, gradually grounding the voltage spike over time. This nearly eliminates the aforementioned failure. Indeed, it actively mitigates the abrupt changes occurring in P2, effectively reducing the voltage drop that is the fundamental obstacle in the experiment. Needless to say, placing this resistor at the grounding point also offers considerable convenience for the experimenter. Furthermore, we performed four independent grounding operations within this single room, grounding each part of the apparatus separately. Furthermore, the laboratory was enclosed with wire mesh to prevent the propagation of sudden electromagnetic changes occurring inside to the outside. The heating of the rectifier tubes was entirely powered by rechargeable batteries. These were also placed atop insulating porcelain insulators 150 cm high and housed in metal containers with round corners.

Through this assembly and these precautions, we conducted experiments for approximately one year without a single destructive failure or complaint from others, enabling us to continue the experiments. With this apparatus, we achieved a current of 20 milliamps in the ion generation tube, and an accelerated ion current of 10 microamperes. It has withstood approximately two hours of

measurement experiments each time without failure. It has enabled relatively detailed, long-term observation of deuterium transmutations (1) caused by deuterium ion impacts, as well as Li atom transmutations and has also withstood experiments causing extremely strong destruction in a short time.
Although the voltage of this apparatus is still low, the inadequacy of the vacuum pump used for vacuum work (currently employing a Leybold oil pump with a suction capacity of 25 L/sec) is far more significant than any dissatisfaction with the voltage for this type of research.
This limitation becomes even more acutely apparent when we try to use a 100cm discharge tube P2. Many of our various designs and plans depend on the pump's capacity, and we observe that the current power supply achieves reasonable level of harmony. For a laboratory with limited resources conducting this type of research, our power supply seems to be the practical limit and perhaps the best achievable outcome. We are currently planning (an upgrade: translator's insertion) for the pump, and once that is achieved, we intend to give renewed consideration to the improvement of this power source.

April 29, 1935, on the occasion of the Emperor's Birthday.

(1) The details of the observations concerning deuterium have already been published in part in the journal ‘Science (科学)’, Volume 5, Issue 4.