Development of battery-operated portable high-energy X-ray sources

— Innovation in X-ray nondestructive evaluation —

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We have developed a practical portable high-energy X-ray source, which can generate high energy X-rays with energies greater than 100 keV enabling the taking of high-definition X-ray transmission images using an R6 (AA) battery as a power source. This result is a consequence of the integration of the compact and energy-saving electron accelerator technologies of AIST and the carbon nanostructure technologies of private companies. In this paper, we discuss these elemental technologies and how to integrate them.

Keywords **:** X-ray, non-destructive evaluation, battery operated, electron accelerator, energy saving

1 Introduction

In Japan, there are many concrete structures and plant facilities that were built during the period of rapid economic growth, and aging of these structures has become an issue. To continue using the structures safely, it is necessary to deploy nondestructive evaluation in which the evaluation devices are carried onto the site to determine the deterioration condition without destroying the structure. There are various nondestructive evaluation methods using ultrasound, electromagnetic radiation, X-rays, or other radioactive rays. X-ray transmission allows imaging the inside of an object, just as in the roentgen exams of the human body. It is used in various fields since the test results can be seen and understood easily.

However, when using X-ray transmission such as for wastage evaluation of pipes in a plant, high-energy X-ray is necessary for steel pipes, and since the device for X-ray source necessary for such tests is bulky and heavy, testing in small spaces is difficult. Also, an X-ray device with large output has further disadvantages. It requires a long time for the heater or filament to warm up and cannot be used instantly when it is necessary, and its energy consumption is large. In many cases evaluation using X-ray transmission may be dismissed due to poor usability. If such issues are solved, inspections can be done more frequently, thus reducing the possibility for failures and accidents.

The author *et al.* set as an objective the development of a portable X-ray generation device that allows generation of high-energy high-output X-rays of 100 keV or over, and this device should be operable by power sources readily available such as dry cell batteries. As a result, we succeeded in the development of a high-energy X-ray generator operable by batteries using a carbon nanostructure as an electron source. This X-ray generator produces X-rays of 100 keV or over with only one AA battery. In some conditions, 100 or more shots of high-resolution X-ray transmission images can be photographed. This performance is practical for a portable X-ray source. When used, the X-ray transmission evaluation can be conducted by carrying the X-ray source onto the site without an AC source or heavy batteries, and it is hoped to be a new X-ray source for nondestructive evaluations.

In this paper, the development of the battery-operated high-energy X-ray generator is described, and consideration will be made of how the researches that we have been doing produced this result.

2 A battery-operated portable high-energy X-ray source

The X-ray can be generated by accelerating the electron beam emitted from the cathode and injecting the beam onto a metal target. A conventional X-ray tube uses the thermionic emission phenomenon of the filament or heater to obtain thermionic electron emission from the cathode. Because of its structure, one must wait until the cathode temperature becomes constant, electricity must be constantly supplied to the heater, and power is consumed even when the X-ray is not being generated. The usability of the device as a portable X-ray source is compromised due to such issues.

In the X-ray source using carbon nanostructure that was developed by the author *et al.*[1], X-rays at output equivalent or higher than the conventional X-ray source can be generated without the heater or the filament, and the issues of warm up

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and energy consumption can be solved.

The carbon nanostructure used in the newly created X-ray tube was developed by the companies engaging in joint research. The graphene sheet composed of carbon has a coniferous form, and the tip has a nanometer size tubular structure that becomes thicker on the substrate side. It is therefore mechanically stable and the electric field readily concentrates at the tip, and this allows electron emissions with high current density of 100 mA/cm^2 or higher at room temperature.

Initially, an X-ray tube was created as a prototype with this carbon nanostructure as an electron source, molybdenum mesh as an extraction electrode, and a metal plate as a target. However, in this structure, the mesh electrode became hot and emitted gas, and abnormal electrical discharge occurred. The carbon nanostructure had a critical problem where the nanostructure was damaged by discharge and the emission property deteriorated, and this caused frequent abnormal discharges. To overcome this flaw, we designed and fabricated an X-ray tube, using the simulation code used in accelerator development, with a structure in which the electron beam focused on the target efficiently without using mesh electrodes. This X-ray tube is a bipolar X-ray tube where the electron source of the cathode is charged with a negative high voltage and the target of the anode is charged with a positive high voltage (Fig. 1).

The fabrication process of the X-ray tube using carbon nanostructure involved the stabilization treatment of the emission current called aging. Since the abnormal discharge in this phase damaged the electron source, we searched by trial-and-error the processing condition that allowed stabilization of the emission current without discharge. As a result, we obtained a cold cathode X-ray tube that could generate high-output X-rays of almost the equivalent to that of the thermionic electron emission X-ray tube.

Since this X-ray tube did not have the heater or filament and this characteristic could be utilized in a portable X-ray evaluation, we created a battery-operated portable X-ray generator as shown in Fig. 2. This X-ray generator produces X-rays by storing power temporarily in the power storage circuit using one AA battery as the power source. X-rays are produced as the X-ray tube is activated by high voltage generated in the high-voltage generating circuit when power necessary to generate X-rays is accumulated. The high-voltage generating circuit can generate voltages of ±50 kV or more and X-rays of 100 keV or more. This X-ray tube has extremely high energy efficiency since the energy consumption falls to almost zero when it is not generating X-rays. Also, it is convenient as a portable X-ray source since it does not require warming up and can generate X-rays immediately. It is also portable since the total weight is 5 kg or less including the power source.

Figure 3 shows the X-ray transmission image of a table tap shot using the X-ray tube activated on 2 J power from the power storage circuit in Fig. 2 supplied to the high voltage generating circuit. The openness of the electrodes in the outlet can be visualized. However, the resolution is insufficient at 2 J, as noises stand out in the fine structures when the irradiated area is large.

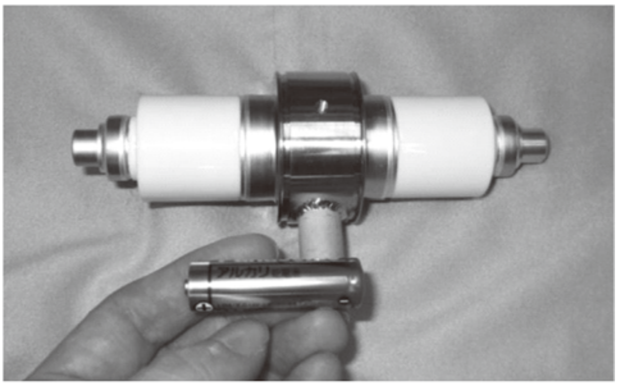

Fig. 1 X-ray tube using the carbon nanostructure electron source.

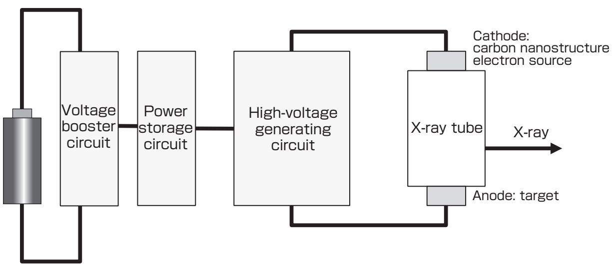

Fig. 2 Diagram of battery-operated X-ray generator.

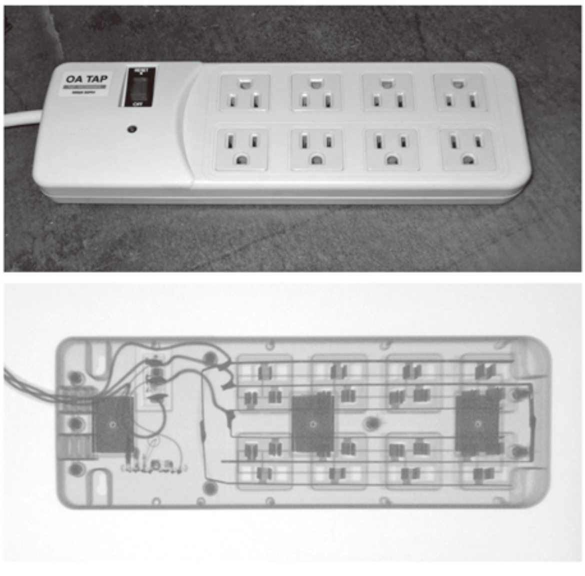

Fig. 3 (Top) Device under test: table tap. (Bottom) X-ray transmission image photographed using the battery-operated X-ray source. Input power 2 J.

Figure 4 is an X-ray transmission image shot by supplying 20 J power to the high voltage generating circuit. The LSI chips in the laptop PC can be photographed at resolutions of 0.2 mm or less. Also, the electrodes in the ceramic insulator about 10 cm in diameter can be seen clearly. With energy of about 20 J, high-resolution X-ray transmission images of various objects can be photographed well for practical purposes. It was confirmed that when X-ray transmission images were photographed at energy of 20 J per shot, over 100 shots could be taken using one AA size nickel metal hydride battery (capacity: 2000 mAh), or over 300 shots with two batteries. The X-ray tube did not show deterioration after X-ray generation for 10^6 shots at 50 J energy per shot. It was confirmed that it can be used as a portable X-ray source without problem.

Moreover, the maximum emission current of this X-ray tube was 50 mA or higher, and X-rays with high output could be generated in a short time. This allows short-time exposure of 1 millisecond or less. Using this high output property, it can be used as an X-ray tube for computer tomography (CT) that requires high output X-rays, as well as for ordinary X-ray transmission image photography.

If the X-ray source technology is likened to a radio, the conventional X-ray source is a vacuum tube radio where one has to mind the battery all the time when carrying it around, while the carbon nanostructure X-ray source is equivalent to a transistor radio, and the portability of the X-ray source increases dramatically. This will allow nondestructive evaluation and diagnosis by X-rays to be done easily on site, and new innovations in X-ray evaluation can be expected.

3 Circumstances leading to achievement of the results

The author *et al.* have been involved in the development and practical application of the electron accelerators,

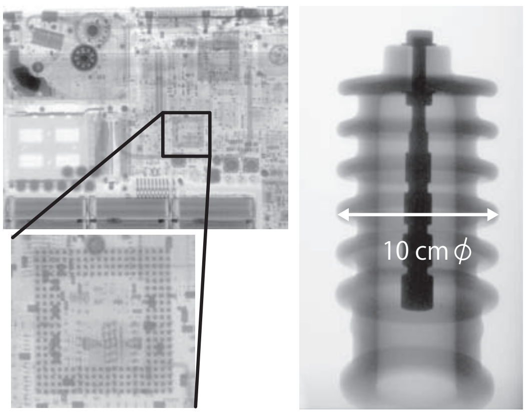

Fig. 4 X-ray transmission image with input power 20 J. (Left) X-ray transmission image of laptop PC. (Right) X-ray transmission image of alumina insulator with test electrode.

and the development of the new X-ray source described in chapter 2 was realized by fusing the portable ultra-small accelerator and X-ray source technology of AIST and the carbon nanostructure electron source technology developed by companies. Moreover, the technologies for ultra-small accelerators and X-ray sources were based on the technologies for energy saving and downsizing of the electron accelerator. The elemental technologies that became the basis of the development of a new X-ray source are described as follows.

3.1 Energy saving in electron accelerator facility

The author *et al.* have been involved in the management, operation, and research using the S-band electron linac (linear accelerator) with maximum energy 400 MeV at AIST. This accelerator was completed in 1979, and has been used as the electron storage ring TERAS for synchrotron radiation, the electron storage ring NIJI-IV for free electron laser, the high-intensity slow positron beam source for material evaluation experiments, and others[2]. Energy-saving measures were conducted for the entire accelerator facility when the aged air conditioning system was renovated in FY 2005.

Before the energy-saving measures were executed, the power consumed when the electron linac was in operation momentarily reached 600 kW, and the annual amount of power used was about 2.5 GWh or more. Estimating the electron linac beam power truly needed during electron injection to the storage ring, it was only 0.01 % of the power consumed when the accelerator was actually in operation, at 320 (MeV) × 100 (mA) × 1 (μs) × 2(pps) = 64 (W). In case of the positron experiment, it was 70 (MeV) × 100 (mA) × 1 (μs) × 100 (pps) = 700 (W) or several hundredth of the actual power consumed.

There were several factors for this extremely low efficiency. The major factor was because originally, the air conditioning and water heating/cooling systems for this electron linac and the accompanying facilities were designed for generation of high-output electron beams of several 10 kW in order to handle various experiments. Therefore, they were not optimized for low-energy modes such as the positron experiment or low pulse rate modes such as injection to electron storage rings.

To solve this issue, total measures were necessary for the electron linac itself as well as its air conditioning and water cooling/heating systems. Therefore, energy-saving measures were considered by combining the accelerator technology accumulated over time and the latest technology for air conditioning, water cooling/heating, and power source systems. In executing these energy-saving measures, the following basic principles were set.

1. Energy is used only for the amount it is needed.

2. Energy is used only during the time when it is needed.
3. Energy is used only at the place where it is needed.
4. Latest technology with high energy efficiency is used.

To determine the specifications of the devices that would be renovated or newly acquired based on the above principles, it was necessary to see when, where, and how much energy (electrical power) was consumed. Therefore, the power consumed in each section was surveyed, and measures were taken within the budget allotted for renovations[3].

The main measures were decentralization of the water cooling/heating and air conditioning systems and the renewal of the high-power microwave generator of the electron linac. By estimating and considering the consumed power under various experimental conditions for the water cooling/heating and air conditioning systems, it was found that drastic reduction in power consumption could be achieved in a decentralized system rather than a centralized one. Therefore, a decentralized system was introduced that allowed ON/OFF of the water cooling/heating and air conditioning of different parts according to the type of experiment.

The S-band electron linac used eight 22 MW klystron devices, which were state-of-the-art at the time of construction, to generate high-power microwaves for electron acceleration. Currently, 80 MW klystron with about four times the output has been developed, and three to four old devices were replaced with one newest device. Since the power consumption of the conventional klystron did not stabilize at low pulse rate, pulse rate of 50 pps or over had to be used even when it was for injecting electrons to the storage ring, and therefore, the power consumption became high at about 30 kW per device or about 100 kW for three devices. The newly installed 80 MW klystron could be operated at 2 pps that was more optimal for electron injection to the storage ring, and the average power consumption was reduced to 10 kW or less. In this section alone, the renovation brought about the decrease of energy consumption to 1/10. This allowed reduction in the capacity of water cooling/heating and air conditioning systems, and large-scale energy savings became possible.

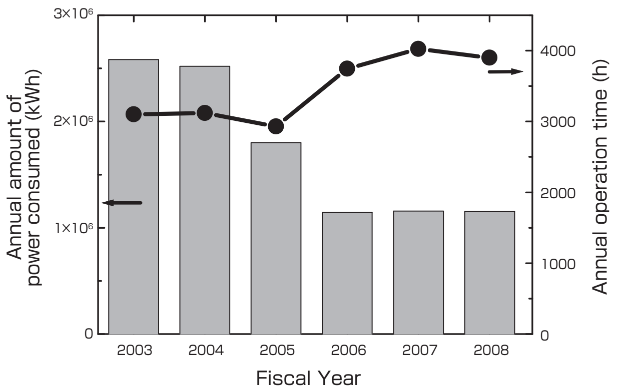

Fig. 5 Annual amount of power used at the electron linac building (Tsukuba Central 2-4 Bldg., AIST) (bar graph) and annual operation time of the electron linac (line graph).

Various other measures were taken based on the above principles, and, as shown in Fig. 5, 60 % reduction in the amount of power used was achieved for the total facility compared to before renovations. Through these measures, the operation time of the electron linac increased and the researches could be conducted more efficiently.

The energy-saving know-hows obtained by being directly involved in these measures led to the development of a low-power driven circuit for an ultra-small electron accelerator and a new X-ray source.

3.2 Development of C-band small electron accelerators

The research using high-intensity slow positron beam was conducted using the aforementioned S-band electron linac. However, since this was a time-shared accelerator, the positron experiment had to be interrupted when the storage ring injection was done, and the time for experiments was limited. Also, since the accelerator was not built for the purpose of positron generation, the generation efficiency of positrons was poor. To solve these issues, an exclusive electron linac was needed, and it was necessary to install a small electron linac with good positron generation efficiency within the limited shielded space.

Moreover, in experiments using the positron beam, high pulse rate of the accelerator was desirable to prevent the detector from becoming saturated. Therefore, we selected the C-band electron accelerator which has a short microwave filling time in the accelerating tube and with which the pulse rate could be set high, and developed the components for this system (Fig. 6)[4]. This C-band electron accelerator, because it had a smaller resonator, had the advantage over the conventional S-band electron linac since the sizes of accelerating tube and waveguide could be downsized.

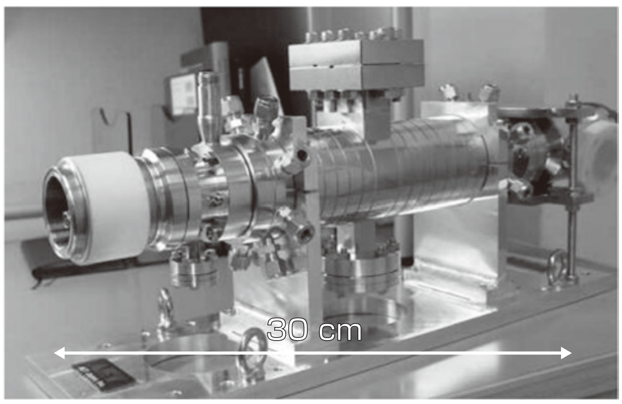

Fig. 6 First part of C-band electron accelerator.

For this accelerator, new circuit using a high-voltage high-current semiconductor switch was developed for the generation circuit of the high-voltage pulses to be supplied to the microwave amplifying tube (klystron). High-power microwaves of about 2 MW were generated by running the C-band klystron with small semiconductor switches of about 18 cm × 7 cm × 7 cm, and the electron beam was successfully accelerated.

The attainment, in the process of R&D of this C-band accelerator, of higher frequency of microwaves, the high-voltage semiconductor switch, and the high-voltage pulse generation was the technological base for realizing the new X-ray source.

3.3 Battery-operated ultra-small electron accelerators

In the 2000s, there was an increase in accidents due to aging of pipes in plants as well as leakage of steam from the pipes in nuclear power plants, and the social demand for on-site evaluation increased. Pipes with covering materials such as heat insulations were extremely troublesome to inspect since the covering had to be removed, and an inspection method without removing the covering material was desired. At that time, the author *et al.* were conducting research on downsizing and energy savings in electron accelerators as described in sections 3.1 and 3.2. As mentioned in chapter 1, thinking that the findings from our research could fulfill the social demands, we did a conceptual design for an electron accelerator and an X-ray source system that pursued ultimate downsizing and energy savings. Here, we returned to the basics to redesign the conventional accelerator technologies such as efficient high-voltage pulse generation, microwave generation, electron generation, and control technology. We developed and fabricated prototypes based on the details obtained, and succeeded in generating high-energy X-rays by operating an ultra-small electron accelerator with AA batteries.

This ultra-small electron accelerator is composed of the electron gun, the accelerating tube, the microwave source, the vacuum pump, the pulse generator, and the control system, just as in large electron accelerators. Since the conventional accelerator had several accelerating tubes, temperature controlled water was necessary to synchronize their resonance frequencies. Since the new accelerator has only one accelerating tube, no cooling is necessary as the heat load is low when operated on dry cell batteries. This accelerator employs a method of synchronizing the resonance frequency by varying the frequencies rather than keeping the resonance frequency constant by controlling the temperature of the accelerating tube. It is a system without a water cooling/heating system that required large amounts of power consumption like in the conventional accelerator. The vacuum pump is an ion pump that uses a little amount of power in high vacuum.

In this accelerator, a 9.4 GHz X-band pulse magnetron tube that has higher frequency than the aforementioned C-band is used as a microwave source. To operate this magnetron and the electron gun of the accelerator, the battery power source is boosted to 12 kV or higher, the electric energy is stored in the storage circuit, and the high-voltage pulses of about 100 kW are generated at intervals of about 1 microsecond using the semiconductor switch. By supplying to the accelerating tube the 9.4 GHz microwaves generated in the magnetron tube with the high voltage pulses, the electron beam is accelerated and a high-energy electron beam of 100 keV or over is generated. X-rays are generated by injecting this electron beam onto the heavy metal target.

Figure 7 shows a photograph of the prototype of the main body of the accelerating tube composed of the electron gun, the accelerating tube, the vacuum pump (ion pump), the X-ray target (gold film), and the X-ray emission window. It is about palm size (the accelerating tube is about 3 cm) and the weight is about 1.5 kg. The flange and valve in the photograph are necessary only in the prototype, and the weight will be reduced to half when they are removed. This main body and the components for microwave and power sources can be fit in a small camera case and carried easily with one hand.

This ultra-small accelerator has a peak electric consumption of 100 kW order, but since the pulse width is 1 microsecond, the average power consumption can be 20 W or less by lowering the pulse rate, and X-rays can be generated with 10 to 12 AA batteries. X-ray transmission imaging is possible by combining this X-ray source with the X-ray imaging system[5][6]. To complete this system, we created the technology to generate high-voltage high-power pulses from dry cell batteries by trial-and-error. This could be applied to the electron emission property tests for carbon nanostructures and X-ray generators mentioned below, and

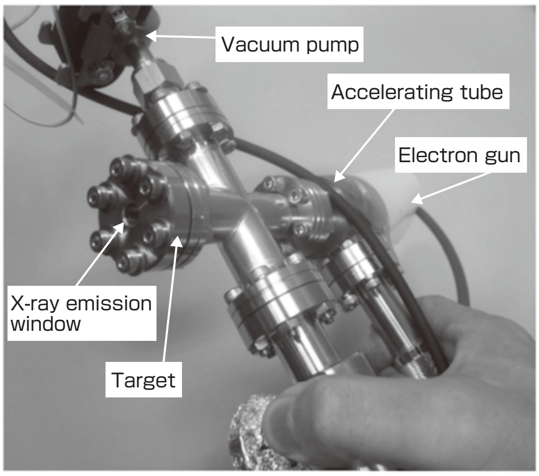

Fig. 7 Main body of the X-band ultra-small electron accelerator.

led to the advancement of the device development in a short time period.

3.4 Application of the carbon nanostructure electron source to the X-ray source

The electron source of the aforementioned ultra-small electron accelerator must have the heater power source ON at all times including when X-rays are not being generated, since it employs the principle of thermionic electron emission, and can operate for only about four hours on 10 AA batteries. Therefore, dry cell batteries tend to be used as emergency power source, and this is not an X-ray source that could be truly used any time, anywhere. This problem of thermionic electron emission electron sources does not only apply to high-frequency electron acceleration but also applies to general portable X-ray sources.

This issue can be solved if there is a high-performance electron source that does not require a heater or a filament, but carbon nanotubes (CNT) that produce electron emission at room temperature have a disadvantage in that the structure is destroyed and deteriorates readily under a strong electric field like X-ray tubes[7]. Therefore we looked for a cold cathode electron source with high stability under high electric field, and focused on a carbon nanostructure (CNX) electron source developed by certain companies. This electron source had a coniferous form that became thicker on the substrate side, and the tip was a nanometer structure as in CNT and the electric field concentrated at the tip. Since it was considered to be more stable in high electric fields than CNT, we expected it to be a hopeful X-ray source.

Therefore, we started the product development in July 2008, after checking its function in a preliminary experiment using the CNX electron source. Other carbon-based cold cathode electron sources were commercially available, but we selected the CNX electron source because the company brought the manufacturing machine for the electron source to AIST, so an environment that allowed free trial-and-error became available for the development of the X-ray source. Experiments under various conditions were possible, and the new X-ray generator described in chapter 2 was realized.

4 Discussion

Here, the findings from the development of the battery-operated high-energy X-ray generator are discussed.

The development of the battery-operated high-energy X-ray generator using carbon nanostructures was realized through the combination of the researches for energy saving and downsizing of the electron accelerator and the technology for a battery-operated ultra-small electron accelerator that were being conducted at AIST, and the technology for the carbon nanostructure electron source of private sector companies. The motivation for the downsizing research of electron accelerators was from the necessity that arose in the course of research, to solve the issues of the large electron accelerator that was owned by AIST. We became aware that the energy saving and downsizing of the accelerator might find wide industrial applications in nondestructive evaluation, medicine, and sterilization, and set them as new development topics. The development of the components for small C-band accelerators led to the development of the energy saving technology and of ultra-small accelerators. In the C-band small electron accelerators and the X-band ultra-small electron accelerators, the human resources and facilities including those for the conventional S-band electron accelerators, radiation detection technology, and radiation-controlled area were greatly useful. This result would not have been achieved without the large electron accelerator facility.

For energy savings in accelerators, we were able to execute various energy saving measures, rather than leave them as mere desk plans, because we ran into an opportunity of renovating the aged air conditioning and water cooling/heating systems. The measures included experimental ones that would not have been employed in an ordinary electron accelerator system. We were able to accumulate the technologies and know-hows for energy savings in accelerators by observing the effectiveness of the various measures.

The development of the X-band ultra-small electron accelerator was the result of the combination of the social demand for a portable high-energy X-ray source and the necessity for downsizing and energy savings in the electron accelerator at AIST. Although this accelerator had a heater for thermionic electron emissions, and could not be called a truly practical portable X-ray source, by presenting our technological level by publishing our result to the outside world, we were able to find a new technology called the carbon nanostructure electron source. Moreover, the companies worked on this development with passion, brought the manufacturing machines for the electron source to AIST, and through repeated trial-and-error and concentrated effort, we were able to develop a truly practical X-ray generator in just half a year.

The results of this research is the result of the integration of various factors in addition to individual technologies, including facilities, people, change in the research environment, accumulation of technology, social demands, and the publication of the results. However, the factors do not lead to new results if they are simply collected. For example, if the linac was in operation without any problem, one would not think actively about energy savings or downsizing or employing an electron source with carbon nanostructure, and the developments that followed might not have occurred.

Actively looking for incompleteness or problems in elemental technologies and solving problems one at a time by incorporating different elemental technologies, may lead to new results because the linkages with other elemental technologies become clearer and stronger.

5 Summary and future issues

This paper described how the elemental technologies linked together toward the development of an X-ray source that operates on one AA battery and that can photograph high-resolution X-ray transmission images. The developed X-ray source not only can replace the conventional X-ray source as a single X-ray source, but it can be carried anywhere without warm-up, and progress of new X-ray nondestructive evaluations can be expected. To realize this, it is necessary to create a total system including a detector and a safety device as well as the X-ray source. Also, development of higher energy X-ray source using microwave acceleration techniques is necessary to handle inspections of large-scale structures.

In the future, we wish to work on these topics and continue research that may bring true innovation to the field of X-ray evaluation.

Acknowledgement

The development of the X-ray source using the carbon nanostructure was a joint research with Dialight Japan Co., Ltd. and Life Technology Research Institute Inc., under the 2008 R&D Project (to support small and medium businesses), AIST. Part of the development for the C-band electron accelerator was supported by the Budget for Nuclear Research of the Ministry of Education, Culture, Sports, Science and Technology of Japan, based on screening and counseling by the Atomic Energy Commission. We obtained cooperation of the Electron Accelerator Group, AIST. For energy saving renovation of the electron accelerator, we obtained cooperation of the Research Facilities Department, AIST and the Monitoring Room. Shingo Ichimura, Director, AIST introduced us to the companies manufacturing the carbon nanostructure. I am grateful to all the people who cooperated.

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Discussion with Reviewers

1 Original technological development for downsizing the electron accelerator

Question and comment (Hisao Ichijo, Evaluation Division, AIST)

In the description about downsizing the electron accelerator, it cannot be readily understood that it was your original technological development. I think you should cite your papers and patents and emphasize the fact that this was an original research result.

Answer (Ryoichi Suzuki)

In the electron accelerator research field, it has been widely known that downsizing could be accomplished by raising the acceleration frequency, and that itself is not original. However, we were the first to develop a small electron accelerator for generating positrons. I cited the paper that reported this technology at an academic society. Also, since this result is not the main theme of the paper, I added it to the section on the circumstances surrounding this research.

2 Effort on the conceptual design of the battery-operated ultra-small electron accelerator

Question and comment (Hisao Ichijo)

You wrote the "conceptual design" in the description for the development of the battery-operated ultra-small electron accelerator. I think you should include how you utilized the already accomplished energy saving measures in this conceptual design, focusing on the technological aspect.

Answer (Ryoichi Suzuki)

Although I cannot write the details since it is an intellectual property, I added some descriptions on the technologies we considered in the conceptual design.

3 Application to nondestructive evaluation and issues

Question and comment (Hisao Ichijo)

In the manuscript, I think the originality will become clearer if the author adds his innovative and ingenious undertakings in the last paragraph. Also I think you should describe the possibility of application to nondestructive evaluation and the issues that must be solved.

Answer (Ryoichi Suzuki)

I integrated the wordings in the figures and the text. I added an explanation for the system without cold/hot water in the ultra-small accelerator. In this paragraph and the following one, I added how the topics of ultra-small accelerators and the development of the carbon nanostructure X-ray source linked together.

4 Components of the research

Question and comment (Mitsuru Tanaka, Research Coordinator, AIST)

I believe the components of this research are energy saving, downsizing, and the introduction of electron source. Wide-ranging technologies to support those components were nurtured in the research using the accelerator facility, and the actual measures to meet the powerful demands for energy saving and downsizing spurred the practical application, and the employment of important technology for high-performance electron source from exterior institutes also played the role in spurring the development. I think those were the syntheses of the *Full Research*.

Answer (Ryoichi Suzuki)

It was exactly as you pointed out. I rearranged the paper for better reading.

5 The efficacy of the carbon nanostructure as the X-ray electron source

Question and comment (Hisao Ichijo)

In the manuscript, pertaining to the carbon nanostructure electron source and the X-ray source, you only describe that it is hopeful as an electron source for X-rays, but can you add descriptions and figures that explain how it is effective. Also, if you describe the various methods considered to solve the technological issues, the improvements that were expected by incorporating the carbon nanostructure electron source, and the process that led to this technological integration, I think the selection and integration of the elemental technologies will become clearer.

Answer (Ryoichi Suzuki)

Also considering the comments of Reviewer Tanaka, since this paragraph is the main theme of this paper, I summarized the points and placed them before the development process. I added the experimental results including the figures and provided detailed explanations. For the integration of carbon nanostructure technology, some explanations were added in the section on the circumstances.