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Perspective

Restoration of Accelerator Facilities Damaged by Great East Japan Earthquake at Cyclotron and Radioisotope Center, Tohoku University

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The Cyclotron and Radioisotope Center (CYRIC) of Tohoku University is a joint-use institution for education and research in a wide variety of fields ranging from physics to medicine. Accelerator facilities at the CYRIC provide opportunities for implementing a broad research program, including medical research using positron emission tomography (PET), with accelerated ions and radioisotopes. At the Great East Japan Earthquake on March 11, 2011, no human injuries occurred and a smooth evacuation was made in the CYRIC, thanks to the anti-earthquake measures such as the renovation of the cyclotron building in 2009 mainly to provide seismic strengthening, fixation of shelves to prevent the falling of objects, and securement of the width of the evacuation route. The preparation of an emergency response manual was also helpful. However, the accelerator facilities were damaged because of strong shaking that continued for a few minutes. For example, two columns on which a 930 cyclotron was placed were damaged, and thereby the 930 cyclotron was inclined. All the elements of beam transport lines were deviated from the beam axis. Some peripheral devices in a HM12 cyclotron were broken. Two shielding doors fell from the carriage onto the floor and blocked the entrances to the rooms. The repair work on the accelerator facilities was started at the end of July 2011. During the repair work, the joint use of the accelerator facilities was suspended. After the repair work was completed, the joint use was re-started at October 2012, one and a half years after the earthquake.

Keywords: accelerator; cyclotron; Cyclotron and Radioisotope Center; earthquake; positron emission tomography
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Introduction

The Cyclotron and Radioisotope Center (CYRIC) of Tohoku University (CYRIC: http://www.cyric.tohoku.ac.jp/english/index.html) is a joint-use facility for education and research with a 930 cyclotron (K = 110 MeV) and a HM12 cyclotron. Fig. 1 schematically shows the cyclotron facilities of the CYRIC. In the 930 cyclotron, ion species from hydrogen to xenon are accelerated and supplied to nine beam lines situated in five target rooms. The beams are widely used not only in the fields of science and engineering but also in the fields of medicine and pharmacy, for the purposes of research, education, and university-industry collaboration. The beams are delivered to users for 4 days/week and 2,500 hours/year. The reliability measured according to the average operating time between failures is around 800 hours. The availability defined as the ratio of delivered beam time divided by the scheduled beam time is more than 95%. In contrast, the HM12 cyclotron, in which 12 MeV protons and 6 MeV deuterons are accelerated, is used exclusively for the production of positron-emitting radionuclides for positron emission tomography (PET) (Fukuda et al. 2013). The PET nuclides generated in the short-lived RI production system attached to the HM12 cyclotron are used for the development of PET radiopharmaceuticals, such as tau probes (Tago et al. 2014), and the clinical study of conditions such as Alzheimer's disease using a PET system (Tashiro et al. 2010). The beams are provided to users for 4 days/week and 300 hours/year. The reliability is around 200 hours. The availability reaches more than 99%.

A massive earthquake of magnitude 9.0 on the Richter scale struck eastern Japan at 14:46 on March 11, 2011, and the resulting tsunami devastated the coastal area of eastern

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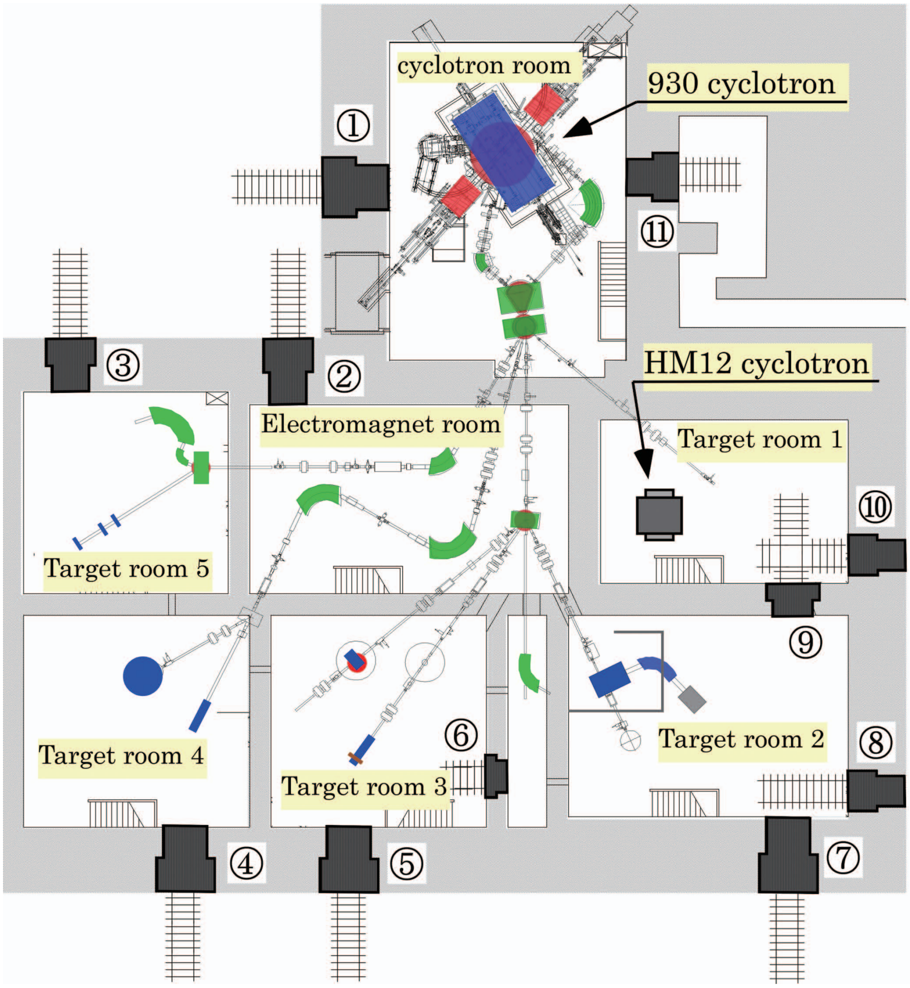

Fig. 1. Cyclotron facilities at CYRIC.
The 930 cyclotron is located at the cyclotron room, whereas the HM12 cyclotron is situated at the target room 1. Accelerated ions from the 930 cyclotron are transported to any one of nine beam lines in five target rooms. The numbers in a circle are a reference number for each shielding door.

Japan (Shibahara 2011). Detailed information on the earthquake, tsunami, and recovery can be found at the websites (JST, MFAJ, PMJHC). The city of Sendai, in which the CYRIC is located, was the nearest major city to the epicenter of the earthquake. Although the CYRIC was not affected by the tsunami, it experienced strong shaking with an intensity of 6-lower to 6-upper on the Japanese seven-stage seismic scale during the earthquake (JMA). There were, fortunately, no human casualties, but the cyclotrons, beam transport lines, power supplies, and shield doors were damaged. This paper reports our emergency response activity in the wake of the earthquake, the damage to the accelerator facilities, and the repair work.

Emergency Response Activities

Situation on the day of the disaster

On the day of the earthquake, joint use of the HM12 cyclotron was not in process because the operation schedule for fiscal year 2010 had ended. Regarding the 930 cyclotron, the joint use experiment finished in the morning as scheduled. A stability test of the main coil in the 930 cyclotron and test operation of an electron cyclotron resonance ion source were under way when the earthquake occurred. All the test operators (cyclotron operators and students) were in the cyclotron control room. Two people worked in the radiation controlled area of the cyclotron building.

As we started to feel slight shaking at 14:46, the Earthquake Early Warning sounded. The shaking grew stronger, and all the members in the control room went under the desks for protection. The electricity in the facility went out during the prolonged shaking. Two people who happened to be near the doorway of the radiation controlled area voluntarily evacuated themselves rather early while the earthquake grew stronger.

After the shaking ceased, people gathered, calling to each other, in the designated evacuation area in accordance with the emergency response manual. There were no great damage to the cyclotron building, which were renovated in 2009 mainly to provide seismic strengthening. The evacuation was smooth thanks to the thorough anti-earthquake measures, such as the fixation of shelves and securement of the width of the evacuation route in the office and radiation controlled area. In the evacuation area, earthquake aftershocks continued intermittently and snow occasionally blew, while public radio provided information about the situation. We took a head count and confirmed the safety of all members at work in the CYRIC that day.

If this had been a normal day of joint use, outside users, students working in the radiation controlled area, and patients and families involved in clinical studies using PET imaging might have been present. Fortunately, however, no joint use of the cyclotrons was scheduled on the day the earthquake occurred. Moreover, during the morning, the outside users who worked overnight for a joint use experiment had left from the CYRIC after the experiment was finished in the morning. There were thus no visitors in the CYRIC for whom assistance in emergency evacuation was necessary.

The students of the CYRIC were dismissed and returned home after the safety of all the members was confirmed. In accordance with the regulations, the staff in charge of radiological control checked for damage that could lead to radioactive leaks in the RI storehouse and the buildings and confirmed that everything was all right. To prevent secondary disasters such as fires, the accelerator group confirmed that the gas valves and gas cylinders (containing mainly flammable gases) were securely closed. Because earthquake aftershocks continued intermittently and the controlled area was dark because of the blackout, the inspection was made in a group setting. In addition, the breakers on the switchboard were left untouched so the inspection could be completed quickly. After the inspection was over, we took a head count of the people again, closed and locked the CYRIC, and dismissed ourselves. The staff was scheduled to reassemble on March 14 (the Monday of the following week).

Emergency response activities after the earthquake

On March 14, first, the facilities department assessed the CYRIC buildings. The building itself was found to be all right, and we were allowed to enter it. Then, we checked the entire area of the CYRIC and cyclotron facilities using hand-held flashlights. We found some critical locations inside the radiation controlled area and established off-limits areas where no one was allowed to stay alone, and the inspection was made in a group setting. In addition, the main breaker at the substation for the facilities was thrown open. On this day, knowing that the restoration rate of essential services was still low in the city and sunset would be early, we dismissed ourselves rather early in the afternoon after the inspection was over. Because most public transportation, including bases, was unavailable, except for some sections of the subway, and gasoline was very difficult to obtain, it was decided that we should stay home until March 17, except for the people who were able to come to the campus the next day and the day after.

On March 15, a special high-voltage power source for the CYRIC was made available in the substation, and we started restoring power to the facilities. We learned that the task force of Tohoku University for the Fukushima first nuclear power plant accidents was to be set up in the CYRIC. Thus, to restore the function of offices, we recovered power to these rooms in the cyclotron building. Because the earthquake shook the experimental apparatuses, we had to be careful in restoring the power to prevent secondary disasters, for example, in performing an insulation test of the distribution system. Then, we restored power to the radiation monitoring system to automatically evaluate the radiation dose in the air around the CYRIC. However, because the main device for processing the measured data was damaged after it fell from the rack, we could not restart the measurement. A signal was not successfully transmitted from each detector, demonstrating the total loss of the system. In addition, we started restoring the CYRIC's e-mail and web servers.

As of March 16, the water supply to the Aobayama campus, where the CYRIC was located, was not yet restored, but the pump for the water tank was restored so that we could use the restrooms. Meanwhile, we checked for water leaks in the water supply and sewerage system. The water supply was restored on March 17. However, commuting was still difficult, and there was no expectation of recovery; thus it was decided that we should stay home until March 23. The university headquarters requested us to submit the first disaster report on the properties by March 22; we managed to collect and submit the results of the visual inspection in the dark with hand-held flashlights.

On March 24, the furlough ended, but commuting was still difficult; nonetheless, we had more people and started to rearrange collapsed items and restore power in the radiation controlled area. As April began, the city bus restarted the service to the Aobayama campus, and gasoline became available. Around this time, when the power restoration was completed, we started examining the facilities for damage by, for example, current testing of the electromagnets and operation testing of the drive and vacuum systems. Group of visitors, including the University President, the Minister of Education, Culture, Sports, Science and Technology, and members of the Diet visited during the damage investigation and restoration.

Damage to the Accelerator Facilities

Miyagiken-oki earthquakes of magnitude around 7.4 occur approximately once per 37 years in and around Miyagi Prefecture. The last earthquake occurred in 1978, the year after the CYRIC was established, and the probability of an earthquake within 20 years of January 2010 was predicted to be more than 90% in a long-term evaluation by the Headquarters for Earthquake Research Promotion (HERP). Fortunately, the earlier repair work in 2009, which was done mainly to provide seismic strengthening of the cyclotron building, prevented heavy damage to the building. In addition, inspection tours by industrial physicians and safety and health supervisors were regularly made in the office and radiation controlled areas to enforce the measures for preventing the falling of cabinets and shelves, avoiding the storage of objects on top of them, and keeping the width of the evacuation route clear. Although some books and PCs fell, no human injuries occurred, and a smooth evacuation was made, thanks to these daily efforts. On the other hand, damage occurred in the cyclotron facilities because of the shaking, which continued for a long time. The damage to the cyclotron facilities is summarized as follows.

The 930 cyclotron

The 930 cyclotron was installed on two columns (4 m in height and 1.7 × 0.8 m^2 each in cross section) made of steel-reinforced concrete (Fig. 2). The columns were driven deeply into the bedrock of Aobayama, independently from the foundation of the cyclotron building, to support the 930 cyclotron, which weights 250 t. In addition, when the 930 cyclotron was updated in 1999, beams were added to the upper part of the columns to suppress horizontal movement in preparation for the next possible Miyagiken-oki earthquake. In this earthquake, the columns were greatly damaged above the beam level (Fig. 3). Damage not only appeared in the mortar of the column surface but also reached the internal concrete, so we could even see the reinforcing bars. As a result, the 930 cyclotron was inclined by about 5 mm.

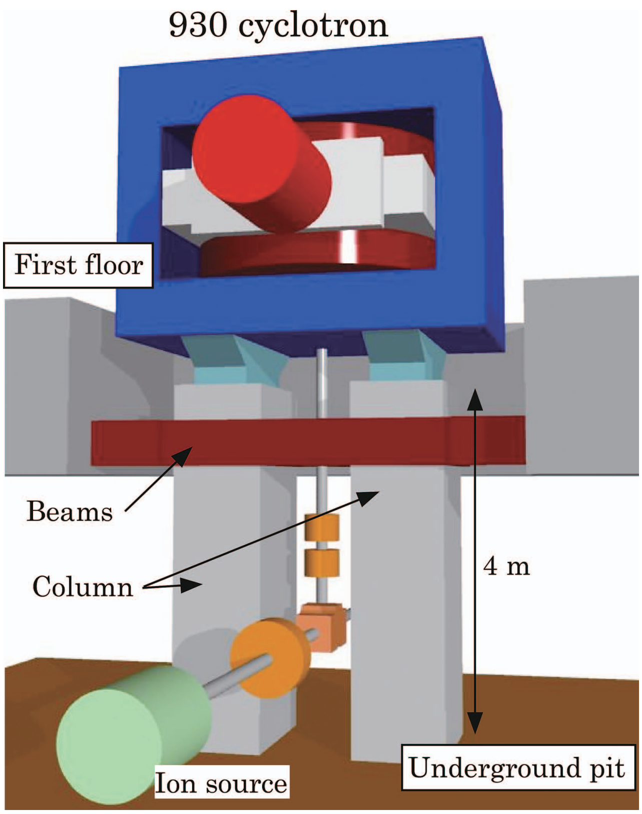

Fig. 2. 930 cyclotron with columns.
The 930 cyclotron is placed on two columns made of steel-reinforced concrete. The columns are held by the beams, which embedded in the first floor, to suppress horizontal movement in earthquakes.

In the 930 cyclotron, some traces of burning in the main coil were found. Fractures in the bolts that fix the acceleration chamber on the yoke and cracks in the welding areas of the bolt mounting base were also found. Moreover, the knock pins in the acceleration chamber were deformed by a strong force. Fortunately, however, the dee electrodes and earth plates were not greatly damaged.

Fig. 4 shows the damage in the areas surrounding the 930 cyclotron. Damage was obvious in the devices connecting the 930 cyclotron and the room floor: the puller system, deflector mount, and RF resonator. The vacuum junction came off of the puller system, and the locking mechanism was damaged. The mortar of the support base collapsed, and the drive unit also came off. In the deflector, the floor that fixes the support base was damaged, and the guides for the deflector mount were deformed. In the RF-related components, the rail attachment parts for the resonator were fractured, and the axle of the resonator support was deformed. In the RF amplifier, most of the bolts connecting the amplifier housing to the resonator were damaged and fell out, and the copper sheet for wiring in the housing was torn. The damage indicated that the 930 cyclotron on the columns was shaken differently from the peripheral devices fixed to both the cyclotron and the room floor.

Beam transport lines and target rooms

The effects of the different shaking of the 930 cyclotron were also observed in the connections between the 930 cyclotron and the beam lines. In the beam extraction line

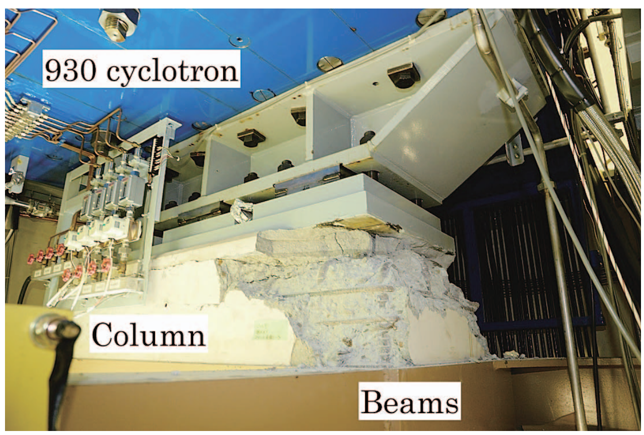

Fig. 3. Damaged cyclotron column.
The columns on which the 930 cyclotron was placed were partly damaged. A part of the mortar of the column surface peeled off and the internal concrete were also damaged. The damage of the columns appeared only above the beams. This indicated that the columns were shaken with the building, while the 930 cyclotron were shaken differently from the building.

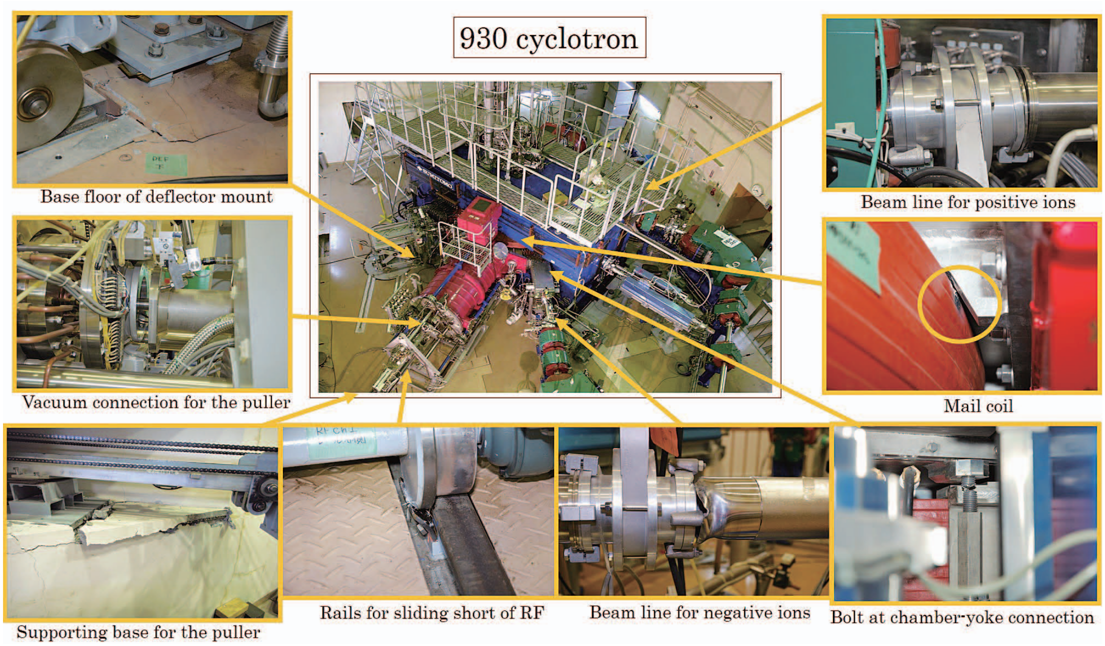

Fig. 4. Damage around 930 cyclotron.
The base floor of deflector mount, which was fixed both the 930 cyclotron and the base floor, was damaged. The connecting devices of the puller system came off. The mortar of the support base for the puller system collapsed. Rails for the shielding short of RF resonator were fractured. Beam ducts for both negative and positive ions were disconnected and deformed. A bolt connecting the acceleration chamber and yoke was broken. Some parts of the main coil were burned.

for positive ions, the claw clamps for the beam duct were fractured, and the flange of the gate valve was deformed. In the beam extraction line for negative ions, the beam duct came away, fell, and struck the flange of the gate valve; as a result, both the flange and the beam duct were damaged.

The damage to the beam transport lines was similar to that to the beam extraction lines; seven beam ducts came off and were damaged. When the ducts fell off, the atmosphere instantaneously flowed into the beam line, and some vacuum pumps were damaged. In some electromagnets, the coils were damaged by striking the claw clamps for connecting the beam ducts in the shaking of the earthquake or partially damaged by a falling body (Fig. 5).

Regarding the beam line alignment, the quadrupole magnets and bending magnets deviated by about ± 1 mm. The south side of the cyclotron building seemed to have sunk by about 1 mm, affecting the horizontal level. In addition to the need to readjust the position of the 930 cyclotron, it was also necessary to adjust the alignment and level of the beam lines.

In the electromagnet room where the beams are transported to target rooms, the hanging columns of the ventilation duct fell, and the ducts dropped (Fig. 6). Fortunately, the duct stopped on the beam of the overhead traveling crane and did not fall further onto the beam line, which therefore remained in place.

The shielding doors showed the heaviest damage in the target rooms. Shielding doors, numbered 8, 10, and 11 in Fig. 1, were open when the earthquake occurred. The

Fig. 5. Electromagnet damaged by falling object.
Some electromagnets were partly damaged by a falling object. In this figure, the distortion of the top hollow conductor is obvious. The falling object was stored on top of a shielding blocks without fall-prevention measures.

drive components for two shielding doors (8 and 10 for target rooms 2 and 1) were severely damaged by lateral vibration, and the doors, each weighing 15-20 t, fell from the carriage onto the floor (Fig. 7). The two doors blocked the entrances to the target rooms and made it impossible to bring in heavy machinery and materials needed for the restoration work. In the shielding doors in two other places, the drive chains were torn, indicating that the shielding doors rocked on the rails during the earthquake. In the six

Fig. 6. Ventilation duct that fell onto the ceiling crane.
In the electromagnet room, the hanging columns of the ventilation duct fell, and the duct dropped. The duct stopped on the ceiling crane and did not fall onto the beam line. Consequently, further damage of the beam line was prevented.

shielding doors (1-5 and 7) leading to outside of the building, the rails were tilted toward the opening direction; thus, if they were closed, they would automatically open. The slope was especially obvious in the three shielding doors on the south side, coinciding with the sinking of the cyclotron building mentioned above. It was necessary to readjust the horizontal level of the rails in these shielding doors. In addition, most of the shielding doors moved perpendicular to the rails and were positioned such that they rubbed the opening section of the wall. In particular, we could open shielding door 11 during the opening and closing test several days after the earthquake, but later it became difficult to close the door owing to interference with the door section of the wall (it became possible to close the door after the largest aftershock of April 7). The damaged doors in the target rooms did not cause problems; however, we were concerned that, for the shielding doors leading to outside of the building, raindrops and dust might enter the target room, or the radiation controlled area might become open to the outdoors. Therefore, testing of the shielding doors leading

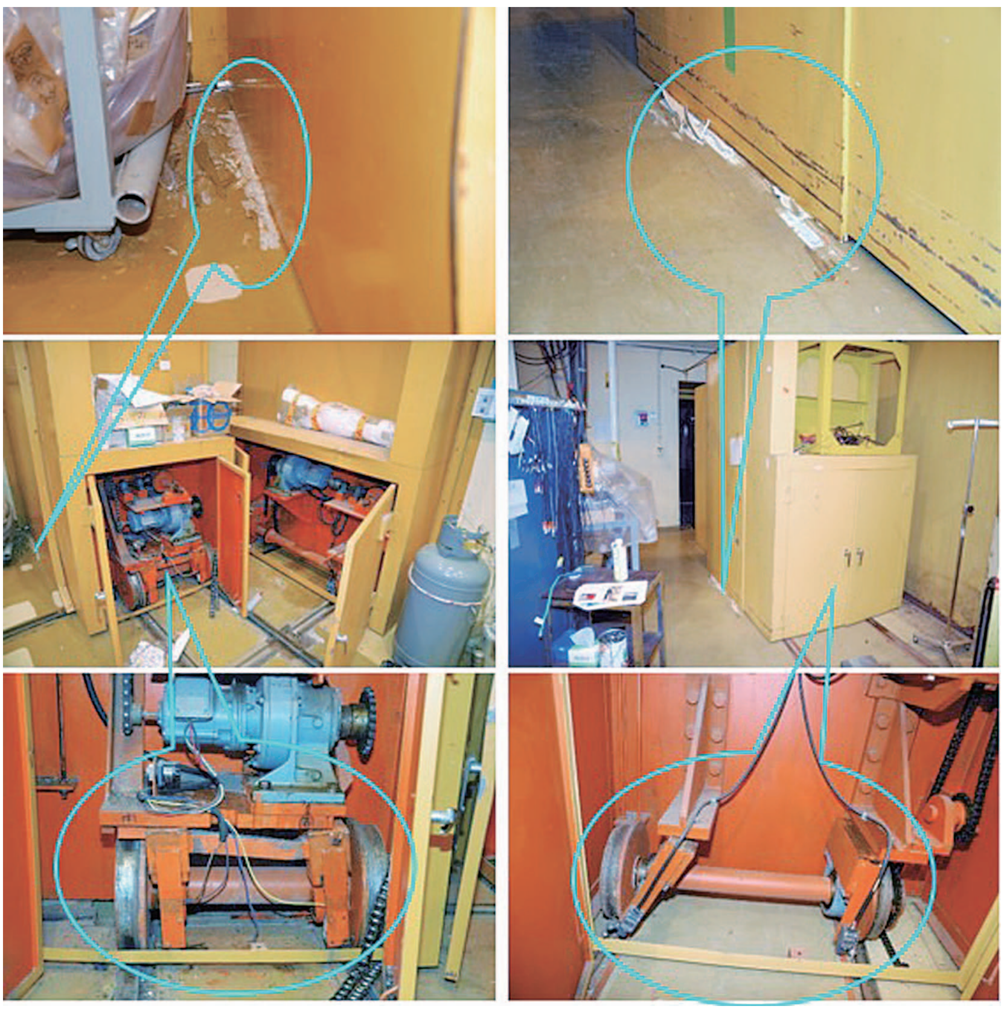

Fig. 7. Damaged shielding door.
Drive component was completely destroyed, and main body of the door fell onto the floor. The doors blocked the entrances to the target rooms and made it impossible to bring in heavy machinery needed for the restoration work.

to outside of the building was limited to a drive test with a short stroke, and we decided to postpone the full-scale opening and closing test until the repair work was complete.

In each target room, concrete blocks (100 × 50 × 50 cm^3) are bound together and piled up to strengthen the radiation shielding. Additional measures were taken to prepare male-female rods or frames to bind these shielding blocks at intervals, in anticipation of a Miyagiken-oki earthquake. Although the blocks did not fall thanks to these measures, ten blocks that had no frames slipped out of place (Fig. 8). The deviation was probably caused by the loose tolerance of the holes in which the rods were fitted.

In addition, in one case, the power supplies of electromagnets fell to one side together with the rack and were damaged, and in another case, a vacuum chamber fell from the support, together with the vacuum pump. Further, a lathe turned over in the machine shop.

The HM12 cyclotron

In the HM12 cyclotron, the yoke, which is vertically oriented to save space, is situated entirely on the rails and is easily partitioned, creating a structure that allows for easy maintenance in the acceleration chamber.

In this earthquake, great shaking continued for a long time, and the entire yoke rocked on the rails; as a result, the lock pins that fix the yoke and their attachment parts were broken. In addition, damage occurred in the connections with the peripheral devices fixed to the floor and the HM12 cyclotron, which rocked on the rails because of the damage to the lock pins. Specifically, the coolant pipe was deformed and came out of the header, and the pipe support fixings were fractured. In the RF devices, the waveguides were partly damaged, and the cable bearer for pipes and

Fig. 8. Mismatch between shielding blocks.
In each target room, concrete blocks (100 × 50 × 50 cm^3) are piled up to strengthen the radiation shielding. The shielding blocks are bound together with male-female rods. Thanks to the measure, the shielding blocks did not fall but slipped out of place within the tolerance of the rods.

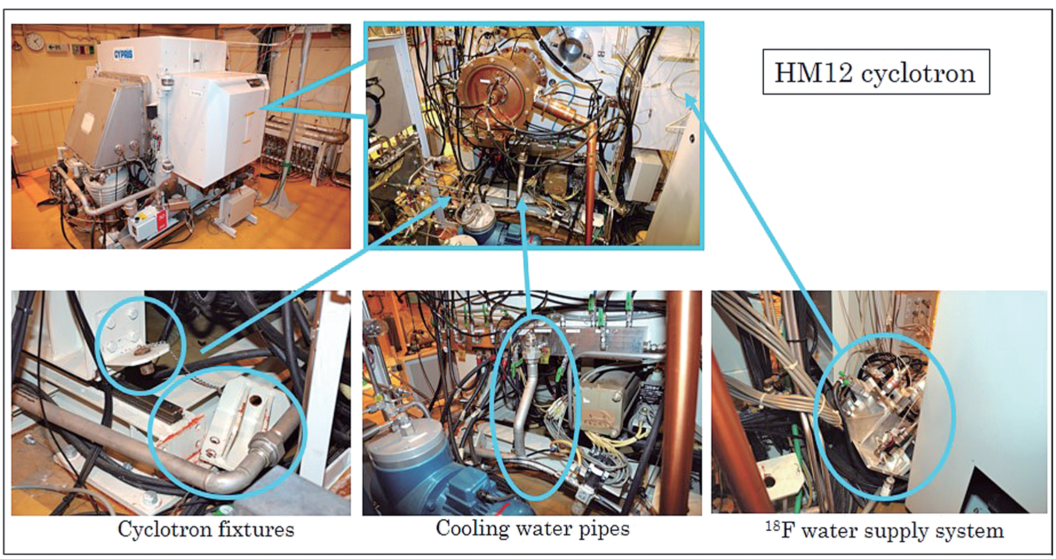

Fig. 9. Damaged HM12 cyclotron.
The HM12 cyclotron is placed on the rails to allow for easy maintenance. In this earthquake, the HM12 cyclotron rocked on the rails, and consequently the cyclotron fixtures were damaged. Pipes of the cooling water was deformed and came out. The water supply system for ^{18}F fell off of the stand.

wiring was damaged. Further, the water supply device for ^{18}F fell off of the support, and the drive system and solenoid valves were damaged. Defects were also found in the compensator drive system. Fig. 9 illustrates the damage to the HM12 cyclotron.

Repair Work on Accelerator Facilities

Drawing restoration plans

We submitted the second to fourth disaster reports describing the findings on the damage as described in the previous sections. The implementation of the first supplemental budget was enabled at about the end of May.

The most important restoration activity was the repair of the columns on which the 930 cyclotron was placed. Depending on the repair method, we had to dismantle and remove the 930 cyclotron. Owing to the structural limitations of the building, we could neither leave the dismantled yoke and other components on the floor of the cyclotron room nor bring them out through the somewhat small opening of the shielding door. To dismantle and remove the cyclotron, we needed to reopen the carry-in entrance of the cyclotron room (which was filled with concrete 5 m in thickness after the cyclotron was installed). This also made it necessary to temporarily change the radiation controlled area. Therefore, before the repair work, we examined the strength of the columns. Fortunately, there was no problem with their strength, and it was not necessary to considerably elevate the 930 cyclotron while repairing the columns.

Having learned that dismantling of the 930 cyclotron was unnecessary, we prepared an outline process flow. We planned to start by removing the injection and extraction beam lines and related devices from the cyclotron room, and then support the 930 cyclotron with jacks. Then, we could repair the columns.

After the columns were repaired, we planned to remove the peripheral devices such as the RF resonators, and adjust the position and horizontal level of the 930 cyclotron. Then, we planned to reassemble the peripheral devices and perform a water flow test, a current test, a vacuum test, and finally an accelerated test. Although the damage to the 930 cyclotron was not clear at this point, we decided to conduct the acceleration test on March 2012, assuming that the 930 cyclotron had experienced neither a water leak nor an insulation failure.

We decided that, in parallel to the repair of the columns, our priority was to restore the shielding doors of the target rooms. After the earthquake, many shielding doors were difficult to open and close, so it was difficult to bring machinery in and out for restoration. In particular, in the shielding door of the target room 1, which contained the HM12 cyclotron, the drive component was completely destroyed, and it was impossible to open and close the door. Thus, we decided to start the repair of the HM12 cyclotron after the shielding door of the target room 1 was repaired. We planned to realign the elements of beam transport line in each target room with reference to the position and horizontal level of the 930 cyclotron, which was to be adjusted earlier.

We decided to complete the restoration of the accelerator facilities by July 2012 and restart joint use in September 2012.

Repair of the shielding doors

The repair work on the shielding doors began at the end of July 2011. Our goal was to repair the two shielding doors for which the drive components were completely destroyed and fell onto the floor of the respective rooms. Each shielding door was situated at the entrance of the target room, where the concrete door, 2 m long and 15 t in weight, slides perpendicularly along the wall surface, leaving only a small gap of 5 mm between the wall and the door. It was possible that opening and closing the door might become impossible unless its central axis was very well aligned with the opening area in the wall. Since the load capacity of the crane in the target room is only 2.8 t and there was no way to bring in large machinery through the narrow stairway, it was impossible to lift the shielding door blocking the entrance. In this situation, the first idea was to dismantle the shielding door on the spot, remove it, and make a new one. However, this method would produce a large amount of waste and powder dust in the radiation controlled area. Therefore, we looked for a way to somehow lift the shielding door on the spot without dismantling it, exchange the destroyed drive component, and fine-tune the position. To lift the door, we made full use of chain blocks, jacks, and, when needed, the beam of the crane. Shielding doors (8) and (10) indicated in Fig. 1, were repaired by this method, and the position of each door was adjusted precisely by millimeter increments.

It was necessary to adjust the flatness of the rails for the shielding doors leading to outside of the buildings, as discussed earlier. To do so, the rails were temporarily removed after the part of the concrete floor in which they were buried was removed. Therefore, the rails were divided into an entrance area section and an outside area section so that we could perform the task while keeping the shielding door on the rails (Fig. 10). Further, because the entrance area was in the radiation controlled area, we had to take care, for example, by preventing the scattering of powder dust and establishing a procedure for testing the waste for contamination. After removing the rails, we performed horizontal leveling by adjusting the height of the baseplate, re-laid the rails, and then recast the concrete. All the shielding doors were repaired by November 2011.

Repair of the 930 cyclotron

The restoration of the 930 cyclotron started at the end of June 2011, beginning with the removal of the injection and extraction beam lines and related devices from the cyclotron room. Next, we placed four 200-t jacks (Fig. 11), and lifted the 930 cyclotron without applying weight to the columns. After iron plates were wrapped around the upper

Fig. 10. Repair work on shielding door.
It was necessary to adjust the horizontal level of the rails for shielding door. The repair work was conducted in the following steps: removing the concrete and rails, adjusting the height of the baseplate, re-laying the rails, and recasting the concrete. The repair work was performed by dividing into an entrance area section and an outside area section. In the picture, rails are re-installed on the entrance area section, and the door is pulled to the outside area section.

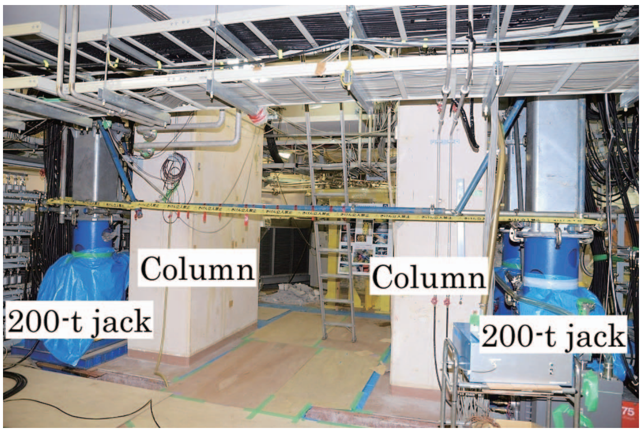

Fig. 11. Columns and temporary placed 200-t jacks for the 930 cyclotron.
During the repair work on the damaged columns, the 200-t jacks were used to lift the 930 cyclotron without applying weight to the columns. After the columns were repaired and the horizontal level of the 930 cyclotron was adjusted, the 200-t jacks were removed.

part of the columns, grout was injected to repair them. Here, we attempted to apply the weight of the cyclotron to the columns; as a result, the base plate on top of the column deformed, and gaps appeared between the plate and the column at both ends of the plate. The degree of deformation changed when we put the load back on, and the horizontal level of the 930 cyclotron changed. Therefore, to eliminate the bending deformation, holes of about 5 mm were bored at 20-cm intervals around the column in the absence of the weight of the cyclotron; epoxy resin was injected to glue and fix the plate and the columns. At the same time, the

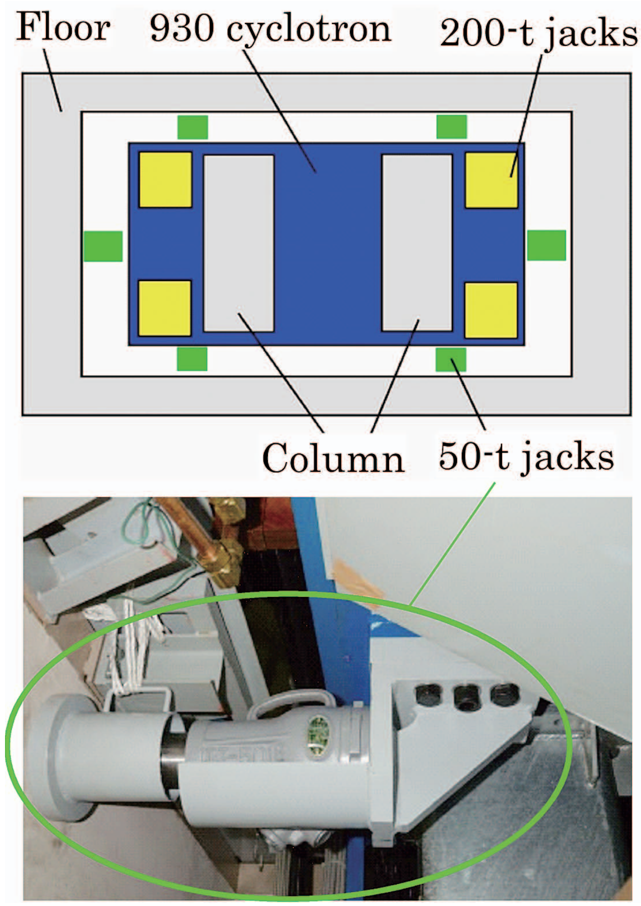

Fig. 12. Horizontal anti-vibration jack.
The 50-t jacks were used to suppress the horizontal movement of the 930 cyclotron by earthquakes. The 50-t jacks were also used to adjust the position of the 930 cyclotron by applying a stretching force between the 930 cyclotron and the room floor. After the restoration, the 50-t jacks remains at the place as the earthquake measures.

floor was repaired around the base of the puller system and the deflector mount.

After the columns were repaired, the horizontal level of the 930 cyclotron was temporarily adjusted, and the RF resonator, deflector, and main probe were carefully removed. Two types of earthquake measures were taken because we had to perform the final centering while aftershocks were still frequent. The first is the use of a 50-t jack to suppress the horizontal movement of the 930 cyclotron (Fig. 12). We could reduce the burden on the column by placing six jacks so as to apply a stretching force between the 930 cyclotron and the room floor so that the 930 cyclotron could swing together with the building. The jacks were also used to adjust the position of the 930 cyclotron. The second measure is the use of a bracket to keep the top yoke from falling when it is lifted. Like the 50-t jacks, six brackets connect the top and bottom yokes to suppress the horizontal movement of the top yoke while it is lifted.

The position, horizontal level, and levelness of the 930 cyclotron were adjusted while the acceleration chamber was temporarily removed. The target precision was 0.2 mm, and the adjustment was made within the target range. Then, we performed a vacuum leak test and repaired the low-vacuum area between the earth plate and the pole, reinstalled and centered the acceleration chamber, and finished the work for 2011.

After the new year began, the restoration started with reinstallation of the peripheral devices such as the RF resonator and deflector, which had been temporarily removed. During this operation, we found new problems, such as deformation of the puller electrodes, scratches on the dee electrode tip, and a malfunction of the drive component of the deflector.

Despite some delays, the work went on according to the operation schedule until January 2012. Then, however, we started to be plagued with leaks from the cooling water joints. For example, water leaked from the beam tuning devices and from a gradient collector and a magnetic channel, both of which were located in the acceleration chamber; the leak points amounted to about 500, including those found in valve stands and coils. The direct cause was a very small deformation of pipes and hardening of the O-rings. Identification and repair of these leak points took time, and the acceleration test of the 930 cyclotron, originally scheduled for March 2012, became impracticable.

After the leaks were repaired, the vacuum test, current test of the coils, and operation test of the drive component were conducted sequentially. Meanwhile, a malfunction was newly found in the cryopump, and the interference of the apparatus in the RF resonator damaged the inner cylinder. After dealing with the malfunction, we completed the following steps: the impression of high voltages to the inflector and deflector, the RF test, and seasoning operations. Then, on July 2, 2012, the beam acceleration test was begun. In the acceleration test, we used 30-MeV proton beam so that the voltages of the high-voltage system and RF circuit could be set relatively low. At 20:25 on July 3, the following day, we succeeded in beam acceleration and extraction for the first time after the earthquake.

Repair of the beam transport lines and target rooms

All the elements of beam transport lines, such as dipole and quadrupole magnets, beam viewers, and so on, needed adjustment of the horizontal level and alignment with reference to the 930 cyclotron. Therefore, in all the target rooms involved, we re-marked the beam axis on the floor and reinstalled the benchmarks. The beam ducts, electromagnets, cooling water pipes, and cables were temporarily removed for this work.

As we removed the beam lines, we pushed forward the fabrication of beam ducts and the repair of the electromagnets, which were found to be damaged in the early stage of the survey. In addition, during the removal work, the soundness of the components was confirmed, for example, by insulation test of the electromagnets. As a result, bad insulation was newly found in an analyzer magnet. The insulation failure occurred between the yoke and coil and was attributed to the polyethylene terephthalate film, although it was difficult to identify the location by visual inspection. It was likely that the coil, shaken in the earthquake, hit the yoke. The insulation was restored simply by changing the films, and we changed the thickness of the films from 25 μm to 125 μm when changing the films. We also changed the film thickness to 125 μm in the other analyzer magnet with a similar structure as a precaution.

After the position and horizontal level of the 930 cyclotron were successfully fixed, we began surveying the injection and extraction beam lines. After a sequential survey, we reinstalled the beam lines and rebuilt the cooling water system, compressed air pipes, and electrical cables. Then, in the partitions separable by gate valves, we sequentially performed leak tests of the compressed air pipes and vacuum systems, and evaluated the electrical systems. These operations were completed by the end of September 2012.

Anti-earthquake measures were then applied in each target room to improve the performance of the shielding concrete blocks that showed displacement due to the shaking of the earthquake. Because no displacement occurred in the blocks piled in an integrated manner using frames and beams, it was decided to adopt the use of frames and beams to bind all of the blocks in the target rooms.

After the repair work was finished, we finally started to accelerate and supply beams at 19:50 on October 25, 2012 to restart joint use, 595 days after the earthquake. Before restarting the joint use, we were concerned that the beam parameters such as the beam current, the beam losses in the 930 cyclotron and in the beam transport lines, and the beam spot size on target might change owing to the re-installation of devices in the 930 cyclotron and to the re-alignment of the beam transport lines. The beam parameters, however, were almost the same as before the earthquake. The reliability and availability were also returned, though there were some minor troubles for a month after restarting the joint use.

Repair of the HM12 cyclotron

As discussed earlier, the shielding doors in the target room 1, where the HM12 cyclotron was located, were severely damaged. Because difficulties were expected, the repair work on the HM12 cyclotron started in December 2011 after the shielding doors were repaired. By then, the earlier repair work on other parts and the fabrication of replacement parts had finished, and the acceleration test was awaiting the completion of the parts replacement. However, because the beam line from the 930 cyclotron was in the target room 1 and the shielding rotary shutter was not installed at this time, the radiation control conditions would not be satisfied if we did the work only in the target room 1. Thus, the acceleration test had to be performed by closing all the target rooms during the night while other repair works were suspended. This test confirmed only the possibility of acceleration, putting aside the beam quantity and other considerations.

A full-scale acceleration test was conducted after the rotary shutter was installed. Meanwhile, both an insulation failure in the correction coils and a malfunction of the circuit for reading the beam current were newly found. Fortunately, the points of insulation failure in the correction coils were outside the yoke, and the repair was easy. The problem with the circuit for reading the beam current was resolved using a spare port.

On May 2012, the repair work on the HM12 cyclotron was completed, and the beam was supplied for production tests of radiopharmaceuticals for PET. After the test, joint use re-started at 11:00 on October 16, 2012, 586 days after the earthquake. We successfully accelerated the beams with the current of around 28 μA for protons and of 7 μA for deuterons on targets. The beam currents were almost the same as before the earthquake. The beams consequently yielded the required amount of radioisotopes for producing the PET radiopharmaceuticals. The reliability and availability of the HM12 cyclotron were completely recovered to the level before the earthquake.

Conclusion

The earthquake told us that everyday preparation is important. Thanks to the fall-prevention measures, items such as shelves, gas cylinders, and shielding blocks were not damaged, and the evacuation was quick. The preparation of an emergency response manual also contributed. It is still regretted that some temporarily placed items fell. On another front, it may be said that there were no human injuries because of the accumulated good fortune in this earthquake. We will use this experience to improve the manual and emergency procedures.

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We are sorry for the suffering of the people who are living as refugees and pray for the victims of the Great East Japan Earthquake.

Conflict of Interest

The authors declare no conflict of interest.

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