Applications of accelerators for industries and medical uses at the Wakasa Wan Energy Research Center


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Abstract
At the Wakasa Wan Energy Research Center (WERC), we had constructed an accelerator system with a 5 MeV tandem accelerator and a 200 MeV proton synchrotron. The tandem machine has 5 beam lines for the MeV order beam experiments. Also the tandem beam is injected to the synchrotron. The beam accelerated by the synchrotron is used at three experimental beam lines. After the completion of the construction in 2000, we have been performing experiments using the system for the ion beam analyses (RBS, ERDA, PIXE) and irradiations for the material and biological sciences. In 2002, the study of the cancer therapy with a proton beam from the synchrotron was started. In this paper, the layout of the accelerator facility, recent development for the accelerators and experiments will be reported.

INTRODUCTION
Construction of the accelerator system at The Wakasa Wan Energy Research Center (WERC) was completed in July of 2000. It consists of a 5 MeV Schenckel type tandem accelerator and a 200 MeV proton synchrotron. After tuning and commissioning of whole the system, experimental researches using the accelerator beams started in August 2000.

The MeV-ion beam from the tandem accelerator is used for the irradiation for the improvement of the material and biological target and the ion-beam analyses such as “particle induced X ray Emission analysis (PIXE)”, “Rutherford Back Scattering analysis (RBS)”, “channeling RBS”, “Elastic Recoil Detection Analysis (ERDA)”, “Nuclear Reaction Analysis (NRA)” and so on.

The tandem accelerator works as not only a supplier for the experiments with MeV-energy beams but also an injector for the synchrotron. One of the applications of the beams from the synchrotron is the proton therapy. Although the application for the therapy requires much higher stability to the daily beam handling and certainty to the long term operation than other experiments, our combination of the tandem accelerator and synchrotron seems to be rather challenging. In any case, steady operation of the whole system is crucial.

In this report, an introduction of the experiments with the tandem accelerator beam will be given in the section of “ACCELERATOR AND EXPERIMENTAL BEAM LINES” first. The beam commissioning of the synchrotron and the medical beam line before the start of the cancer therapy in June of 2002 will be described at the viewpoint of operation of the accelerator and beam transport system.

ACCELERATOR AND EXPERIMENTAL BEAM LINES

Figure 1 shows the schematic layout of the accelerator complex at WERC. The system consists of two ion sources, a tandem accelerator, a synchrotron, two experimental rooms for the experiments using tandem beams and two rooms for the irradiation of the beams from the synchrotron.

Ion Source

One is a plasma sputter ion source called as "main ion source" and another a charge-exchange ion source. The former delivers highly intense pulsed H or C beams for injection into the synchrotron through the tandem accelerator. The maximum peak current of the pulsed hydrogen beam amounts to 18 mA by the pulse discharge with duration of 250 μs and repetition rate of 25 Hz. The current of around 8 mA is enough for usual operation, i.e., injection into the synchrotron through the tandem accelerator.

The tandem accelerator.

tron-adder with Li vapour supplies 36 bination of a high intensity hot cathode source and an elec-
ments with the beam from the tandem accelerator. A com-
 analyses of Japanese paper (washi) and shrimp have been
obtained by two micro-slits.

RBS measurement have been ap-
analyses of semiconductors. Another
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Tandem Accelerator

A beam from each ion source is pre-accelerated to 180 keV and injected to and accelerated by the tandem accelerator with a maximum terminal voltage of 5 MV. The voltage is generated by Schenkel rectifier. In order to enable transport and accelerate high intense beam from the ion sources, the conveyor current amounts to about 1 mA. By using large capacitance for the terminal condenser, the ripple of the voltage when injection of pulse beam is reduced to 2 kV at the terminal voltage of 5 MV. It corresponds to energy dispersion of 4×10⁻⁴ and less than one-tenth of that of the RFQ-DTL system.

Experimental Area With Tandem Beam

The beam accelerated by the tandem accelerator of the terminal voltage set at maximum 1.7 MV is transported to the irradiation room 1. The room has two beam lines. One is for the microanalysis experiments. The beam is focused to the size of a few μm by using a set of magnetic-quadrupole doublet. In the terminal chamber, PIXE, RBS, and ERDA experiments are available. The element analyses of Japanese paper (washi) and shrimp have been performed by PIXE⁴. RBS measurement have been applied to structural analyses of semiconductors. Another for the channeling-RBS experiment with a parallel beam obtained by two micro-slits.

In the irradiation room 2, we can perform the experiments setting the terminal voltage at maximum 5 MV. We have three beam lines in the room. One is for the modifi-
cations of the material by ion implantation or damage by irradiation. The irrad-
iation can be done under the circum-
stances of high (1000 K) or cold (100 - 300 K) temperature by using two stages. For instance, SiC, a kind of semiconductor is interesting in the application under the severe circumstances of high tempera-
ture and/or flux of radiation such as in the space and fusion reactor. By using of the beam line, the irradiation with β beam was carried out. The defect in SiC was observed by an electron microprobe.²

A second for the ion beam analysis. The line consists of a scattering chamber with a five-axis target goniometer, two turn tables and several detectors, a E×B velocity filter, a TOF counter and a gas counter for the particle identification. Transmission type ERDA have been applied to mass spectrometry of the hydrogen isotopes in the storing alloy by using the irradiation beam line. From now on, including such experiments, RBS, PIXE, ERDA, RBS-triggered TOF mass spectrometry and NRA experiments will be available. The beam line is now under development. AMS measurements will be able to be performed after future modification of the ion source, the injection system and beam current measurement. From the terminal window of a third line, the beam can be extracted to the air. By using three apertures, the beam size is reduced to 10 μm diameter. We can apply the beam to the bio-irra-
diation or archeological matter.³

Synchrotron

The proton beam from the tandem accelerator is in-
jected to the synchrotron and then accelerated to 200 MeV. The circumference of the synchrotron is 33.2 m. The superperiodicity is 4. Each lattice has QF-D-QD-D and it is operated in separate function style. Horizontal and vertical tunes are 1.75 and 0.85, respectively.

A period of the synchrotron consists of four modes, i.e., injection, acceleration, extraction and return to injec-
tion. Accelerated beams are slowly extracted out of stable region in the horizontal phase space by an RF knockout system in 0.5 s (RF driven extraction).³

Experiments With Synchrotron Beam

In the irradiation room 4, using 200 MeV proton beams from the synchrotron, we have performed measurements of the radiation effects on materials such as rare-earth magnets and electric devices with semiconductor. In this area, the beam is extracted in the air. The development of the dosimetry in the air is also done by comparison with the measurements of proton-proton inelastic scattering and gamma ray induced by 2⁷Al(p, 3pn)⁵⁵Na(β)²⁷Mg reaction and decay. Irradiation on biological targets are performed for the improvement of species and the measurement of the relative biological effectiveness (RBE) of the radia-
tion. Also, development of the technique of making and

Figure 1 Schematic layout of WERC accelerator system
Cancer Therapy Beam Lines

FIGURE 2 shows the concept of the cancer therapy beam lines in the irradiation room 3. The room has two beam ports so as to irradiate the diseased part of the patient set at a common isocenter in vertical and almost horizontal (9.5 degrees) directions. In both ports, the irradiation area transverse to the beam direction is made by scattering and periodically swinging proton beams by use of a scatterers and two wobbler magnets. Longitudinal area is obtained by of a ridge filter spreading the width of the Bragg peak in the human body (spread out Bragg peak; SOBP). Transverse and longitudinal area are limited by a collimator and a bolus, respectively. The diseased part of the patient is positioned at the isocenter by using of a X-ray CT and a bed. Relation of the position between the CT and the isocenter is known with an accuracy of a mm. Also, the spacial displacement of the bed can be measured accurately10.

SYNCHROTRON TUNING

The beam used for the cancer therapy requires high intensity, accurate control of the irradiation dose and the constant intensity during the extraction period. During the irradiation, the diseased part must be settled at the isocenter. Highly intense beam reduces the duration of the irradiation, i.e., the fixation of the patient. In our system, the irradiation field is made by swinging the beam by the wobbling magnets. The constant intensity during the irradiation is necessary for the homogeneous distribution of the dose in the irradiation field. The accurate control of the dose is yielded by the precise measurement of the dose, the homogeneous dose distribution and quickly switching beams off. The precise dosimetry and the beam switching depend on the statistical error in the beam current monitor and the time structure in the intensity variation. Therefore, the application of the synchrotron beam to the therapy strongly demands the highly intense beam with a good uniformity in the spill.

Improvement of The Intensity

As mentioned already, the 200 MeV proton beam from the synchrotron is obtained by repetition of injection, acceleration, extraction and deceleration in each 2 s. The extraction current is sensitive to the effective injection and acceleration. Pulsed beams from the ion source are deflected by the electric steerer at the injection line to the tandem accelerator. Only 1/40 fraction of the pulses is injected to the tandem. The steerer also regulates the duration of the pulse. Proton beams with 10 MeV from the tandem are injected to the synchrotron in the multi-turn method because the tandem beam is not so high to achieve single-turn injection. Pulsed beams with the peak current of 5 mA and duration of 20 μs are injected and stored up to 30 nC just before the start of the acceleration.

Injected and stored protons are lost during the acceleration period, especially early in the period. One of the reason of the loss is the betatron oscillation from the collective motion such as coupling by space charge effect. The variations of the tunes were measured carefully and the focusing and defocusing parameters were searched not so as for the beam to be lost as possible. Also, in order to expand the bunch and reduce the coupled motion caused by the space charge effect, the second harmonic voltage is added to the acceleration RF field. By these tuning, the maximum beam current of 8 nA is achieved.

FIGURE 3 The time variation of the intensity (a) is obtained by only knock-out RF sweep with constant gain. In the case (b), the duration of the injected beam was reduced to 12 μs and RF is amplitude-modulated and gain is adjusted as a function of time. (a) shows the average intensity of 20 pulses. In (b), upper shows the variation in one pulse. Lower the average of the 64 pulses.
Adjustment of Beam Spill

Although so far the proton beam of 8 nA has been achieved from the synchrotron, a limitation on the intensity is set at 3 - 4 nA for easy control of the beam spill. Figure 3 shows the intensities of the beams as a function of the lapse from the start of knockout-RF in action. After the ions are accelerated to the final energy, a separatrix, which is a boundary between stable and unstable regions in the transverse phase space, is formed by the excitation of two sextupole magnets. Then the knockout-RF is excited for slow extraction. In the Figure 3 (a), which is for the case that the frequency of RF is swept with a period of 1 ms during the extraction period as keeping its gain constant, you can find a “leak” before the extraction and ununiform time structure. The leak may be caused by the lack of matching between the emittance of the beam and separatrix size. The present system can adjust the beam emittance in the injection by changing duration of the beam pulse. Adjustment of the duration reduces the intensity, however, no “leak” can be found in Figure 3 (b). Duration is reduce to 12 µs from 25 µs. Also, the amplitude of the RF carrier is modulated so as to have a band width of 50 kHz and modulation gain is adjusted as a function of time in case of (b). Further tuning seems to be needed for the beam spill to become better for higher intensity.

IRRADIATION FIELD

The distribution of the dose in the irradiation field made by the scatterers of tungsten and a couple of wobbling magnets was measured by scanning a solid state detector in two transverse directions in a water phantom. The medical irradiation requires the irradiation diameter of up to 100 mm. The measurement confirmed the uniformity of the distribution within 2.5 % in the area for the 200 MeV proton from the horizontal beam port. The longitudinal distribution is adjusted by the range modulator of a combination of a ridge filter, polyethylene fine degraders and a bolus. The performance of the ridge filter was checked by longitudinally scanning in the water phantom. The measurement verified the control of the width of uniform SOBP up to 60 mm. Figure 4 shows the dose distribution in the irradiation field.

CLINICAL TRIAL

The first treatment started in June of 2002. In this fiscal year, Health, Labor and Welfare Ministry suggests us to check the availability and the safety for the treat-ments of six patients. Clinical application for two pa-tients with prostate cancer had been finished by the end of July. The treatments were done with 200 MeV proton from the horizontal port. Next four patients will be treated in early three months of 2003. Our medical team has a plan of application to the tumors in other part, for example, head and neck cancer by using another port and/or various energy beams.

PROBLEMS IN USE OF SYSTEM

The application of the accelerator system is in so wide region that it is difficult to share the system between the experimental groups. The limitation of the available ma-chine time yields being behind to the others in progress of the research and/or reduction of the number of clinical treatment. One of the solution may be the introduction of another injector dedicated to the synchrotron.

SUMMARY

The accelerator system with a tandem accelerator and a synchrotron was constructed and has been operated for the various experiments at the Wakasa Wan Energy Research Center. The tandem accelerator is used for irradiation for the material and biological science. Also the beam is applied for the ion beam analyses. The tandem accelerator does not only supply MeV-ions for above ex-periments but also work as an injector of the synchrotron. One of the purpose of the use of the tandem and synchro-tron system is medical application. The application re-quires the highly intense beam with uniformity in the time structure and under the accurate dose control. Careful tuning of the beam operation by the system had been per-formed before the start of the cancer therapy in June of 2002. Two patients had already been treated and other four cases will be scheduled in early three months of 2003.
ACKNOWLEDGEMENT

Authors would like to appreciate careful, exact and devoting machine operation of the accelerator operating staff Mr. Y. Hayashi, Mr. M. Yamada, Mr. H. Yamada, Mr. M. Dote, Mr. J. Mori, Mr. H. Hamaji and Mr. S. Kimura.

REFERENCE


