APPLICATIONS OF TANDEM/SYNCHROTRON ACCELERATOR TO PHYSICS, ENGINEERING, BIOTECHNOLOGY AND PROTON CANCER THERAPY

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Abstract

A multi-purpose accelerator facility, based on two negative ion sources, tandem accelerator and synchrotron is under construction at Tsuruga. The ion beams extracted from the tandem accelerator are introduced into two experimental rooms (room 1 & 2) and the beams from the synchrotron into a treatment room (room 3) and an experimental room (room 4).

1 NEGATIVE ION SOURCES

In this facility, proton cancer therapy has been planned, using 200MeV proton beam with an averaged current of 10nA. The pulse width of the beam extracted from tandem is 200μs and the repetition rare of synchrotron is 0.5Hz. On the assumption of beam transparencies of 30$\%$ in tandem and 25$\%$ in synchrotron, beam current of more than 1.3mA negative hydrogen ion is needed for the beam injected into the tandem. A plasma sputter type negative ion source is chosen, in which the hydrogen beam current more than 10mA can be extracted with pulse mode using the TiH target electrode. Various kinds of negative ion beam can be also extracted from this ion source by changing the electrode composed of materials with positive electron affinity. For example, ion species such as BO, BO_2, C, Al, Si, P, Ti, V, Cr, Fe, Co, Ni, Cu, As, As_2, Ag, In, Sn, Ta, W, Pt, Au, Pb, Bi, etc. are available.

Negative helium beam is extracted from a charge exchange type ion source. The positive helium ions extracted from a duoplasmatron is injected into the alkali vapor gas cell, where negative helium is produced after the formation of the neutral helium in a metastable state. The negative helium beam with the current of 100μA in pulse mode of pulse width 200μs and of repetition rate 50Hz will be developed.

The negative ion beam extracted from the ion source is accelerated up to 150keV, analyzed and injected into the tandem accelerator. The beam emittance of hydrogen, helium and carbon is about 25 mmEmradEMeV$^{1/2}$.

2 TANDEM ACCELERATOR

The negative ion beam injected into the tandem is accelerated to the terminal voltage V and is converted into the positive ion beam with q charge sate in the Ar gas cell or by a carbon foil. Maximum charging voltage of the terminal electrode is 5MV in use of the Schenkel circuit, where stability voltage is $\pm$ 2kV. The voltage V for the room 2 is (0.5 - 5.0)MV, but it is limited to (0.5 - 1.7)MV for the room 1. Average ion charge q after passing through the Ar gas cell is calculated as a function of atomic number Z in cases of V = 1.7MeV and 5.0MV, where the charge equilibrium is assumed. The value q is 2 in V = 1.7MV and 3-4 in V = 5.0MV. The energy of the ions at the exit electrode is (20-25)MeV in V = 5.0MV. The carbon foil can be installed on the beam line just outside the tandem accelerator. At V = 5.0MV, value of q after passing the foil increases linearly from 9 to 12 in $10 < Z < 25$ and q is almost constant to be 13-15 in $Z > 30$.

The ion beam is transported to room 1, room 2 or synchrotron accelerator using switching magnets. For the beam to room 1, the radius of curvature R is 0.5m, the deflection angle θ is 106deg. and the magnetic field in maximum $B_{\max}$ is 0.65T and, for the beam to room 2 and, R = 0.5m, θ = 18deg. and $B_{\max}$ = 0.35T. This performance limits the ion species available in rooms 1 and 2 , as the ions of $Z < 20$ (H, He, B, C, Al, Si, P) in room 1 and the ions of $Z < 60$ in room 2.

Ion species available for initial phase experiments are proton, helium and carbon. The ion charge q, the energy range E[MeV] and the maximum dc ion current $I[\mu$A] in each ion introduced into rooms 1 and 2 are summarized as follows.

	room1			room2		
	q	E	I	q	E	I
H	1	$1.0 - 3.4$	5.0	1	$1.0 - 10$	100
He	2	$1.5 - 5.0$	1.0	2	$1.5 - 15$	50
C	3	$2.6 - 6.8$	2.5	$4 - 6$	$2.5 - 25$	50

3 ROOM 1

The following beam lines are planned.
1) Element analysis beam line
2) Atomic collision study beam line
3) Material surface analysis beam line

Multi MeV ion beams will be used for element analysis of the materials by means of Particle Induced X-ray Emission (PIXE)ARutherford Back Scattering (RBS)A and Elastic Recoil Detection Analysis (ERDA). Local analysis will be also possible by scanning the focussed ion beam, where two quadrupole magnets and movable slits with the step width of $\sim$10μm are used. The space resolution on the samples is expected less than 2μm.

Fundamental study on the interactions between ion beams and solid (or gas) will be done. Fine structure measurements of PIXE spectra are also planned using a crystal spectrometer. This will yields informations about the states of the chemical bond between the elements in the solids. The ion beam probe analysis about the surface state on the materials is planned in vacuum with ultra low pressure less than 10^{-10} Torr.

In the room 1, the ion implantation will be carried out, where intense ion beams with the energy of 200keV and with the current of order of 100mA are generated by a μ-wave ion source. Available ion species are N^+, O^+, Ar^+, Kr^+, and etc. The system of the beam transport and the beam focusing are under construction together with the vacuum vessel for the implantation experiments. The dynamic process of the implantation may be examined in situ using the MeV ion beam probe.

4 ROOM 2

Four beam lines are planned.
1) Ion implantation beam line
2) Beam line for extraction to the atmosphere
3) Positron production beam line
4) Neutron production beam line

The 10MeV proton beams with the maximum current 100μA (dc) are introduced from the tandem accelerator. When the boron ions with energy of 10MeV are implanted into Si, the boron atoms are deposited at the position $\sim$12μm from the surface with the layer of full half width of $\sim$0.2μm. Implantation of the metal beam into the insulator may yield the material of the insulator within the thin conductive layer. Research on such materials useful for technological device will be done.

The range of 10MeV proton in air is $\sim$1 m (the range of 10MeV He^{2+}; $\sim$1 cm), and so the beams extracted are available for the experiment at the atmosphere. Biotechnological research on various plants is planned (the range in H_2O is 1.2mm). The element analysis using PIXE in the atmosphere will be also done. The beam focusing will be tried, where the diameter is expected to be a few μm.

Proton beam irradiation on target materials such as B and Al yields β^+ decay radioisotopes due to the nuclear reactions of $^{11}B(p,n)^{11}C$ and $^{27}Al(p,n)^{27}Si$. The positrons emitted from the radioisotopes can be converted into slow-positrons with sharp energy width using the metals with negative work potential against the positron as W or Ni. The conversion efficiency of the slow-positron is of order of 10^{-4}. Since backgrounds due to neutrons and γ-rays will be high in the production area, good signal to noise ratio is not expected when the material analysis is done in room 2. The slow-positron beam accelerated are transported through the longitudinal uniform magnetic fields from the production region to the room 1, in which various kinds of material analysis will be carried out. The intensity of the slow-positron available for the analysis is estimated to be $\sim 10^{+7}$ per second, which is higher than 10^{+3} of that obtained from the usual radioisotope ^{22}Na. The production of the spin polarized positron beam will be also tried.

The neutrons produced by the ion beam irradiation will be tried to be thermalized. The material analysis using the neutron will be also planned. The cold neutron production will be studied.

5 SYNCHROTRON ACCELERATOR

Proton, helium or carbon beams with pulse width of 200μs is injected into a synchrotron accelerator by multi-turn injection with the energy of 10MeV, 8.3MeV and 25MeV, respectively. The lattice of the synchrotron is the separated function type using 8 bending magnets and 8 quadrupole magnets. The bending magnet has the radius of curvature of 1.91m with the maximum bending field of 1.12T. The circumference of the ring is 33.2m. The synchrotron accelerates the beam up to $B\rho$ = 2.15Tm, that is 200MeV for proton, 55MeV/u for helium and carbon (q/m = 1/2), in repetition frequency of 0.5Hz. For the other heavy ions , acceleration energy are 25MeV/u at q/m = 1/3, 14MeV/u at q/m = 1/4 and 8.8MeV/u at q/m = 1/5. The beam is accelerated by a FINEMET core loaded untuned cavity with 0.61MHz to 5.1MHz. A low emittance beam can be extracted with a high efficiency by diffusion-resonant extraction scheme with keeping the separatrix constant. The transverse radio frequency perturbation with a certain frequency band width is applied to the beam to make it diffuse and exceed the separatrix of the resonance. The time-averaged beam current is 10nA for proton, 0.5nA for helium and 0.2nA for carbon.

6 ROOM 3 (TREATMENT ROOM)

The range of 200MeV proton in H_2O is $\sim$25cm and the injected beams lose most of its energy near the region of beam stopping which is called as the Bragg peak. One vertical and one horizontal beam lines will be installed for cancer therapy using 200MeV proton beam. The irradiation field of 10cm $\times$ 10cm will be produced by use of a scatterer made of Pb and of a pair of Wobbler magnets. The distribution of the beam energy deposition profile will be adjusted so as to fit a tumor using fine degrader, ridge filter, collimators , bolus, etc. 50 persons per year are planned to be treated.

7 ROOM 4

A beam line will be settled for studies on physics, engineering and biotechnology. The biological effect of the ion beam irradiation on plants will be researched from the point of view of the mutation and the cell surgery induced by ion beams. The beam optics study will be done in order to improve the system of proton cancer therapy. The experiments of the beam irradiation on the materials are also planned.