STATUS OF THE PNC HIGH POWER ELECTRON ACCELERATOR

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Design and construction of a high power CW(Continuous Wave) electron linac for studying feasibility of nuclear waste transmutation was started in 1989 at PNC. The PNC linac is the 10MeV, 20mA (average current, 20% duty) accelerator with eight normal conducting TWRR(Traveling Wave Resonant Ring) disk loaded accelerating tubes. Various methods have been proposed to transmute long-lived fission products using accelerators. The transmutation by photonuclear reaction using a electron accelerator has advantages of the small production for secondary radioactive waste and broad base of accelerator technology.

The PNC high power CW electron accelerator has been pre-commissioned with the injector and the first accelerating tube. By December 1995, the accelerator was partially built and the injector pre-commissioning began. Then 3.1 MeV beam had coasted though the beam dump. We have been very successful to produce 1 ms pulse width electron beam with 100 mA peak and energy about 3.1 MeV at present.

The whole facility will be completed in March 1997.

INTRODUCTION

Many research efforts have been spent in PNC to establish technologies for safety disposal of radioactive waste. The high level radioactive waste produced from the reprocessing of spent fuel is essential for the completion of nuclear fuel cycle. Current national policy in Japan is to solidify the high level radioactive waste into a stable form and to dispose it in a deep geological repository after 30 to 50 years of storage for decay heat reduction. However, the Japanese Atomic Energy Commission approved the long-term program for research and development on nuclide partitioning and transmutation in October 1988 beside solidification disposal mentioned above. The objective of the program (called OMEGA) is to explore a possibility to utilize the high level radioactive waste as useful resources and make the geological disposal more efficient.

The program is composed of two major area. One is the nuclear partitioning from the high level radioactive waste based on its potential value for utilization. The other is the transmutation of minor actinides and long-lived fission products into short-lived or stable nuclide. It is usually difficult to transmute long-lived fission products in reactors because of small neutron capture cross section. Various methods have been proposed to transmute long-lived fission products using accelerators. The transmutation by photonuclear reaction using a electron accelerator has advantages of the small production for secondary radioactive waste and broad base of accelerator technology. A high power electron accelerator will be required in future transmutation system.

Upon this projection, design and construction of a high power CW electron linac to study feasibility of nuclear waste transmutation was started in 1989 at PNC. Until now, a high power L-band klystron and a prototype high power TWRR accelerating tube were built and successfully validated many of design concepts until end of 1992. By December 1995, the accelerator was partially built and the injector pre-commissioning began. Then 3.1 MeV beam had coasted though the beam dump. The whole facility will be completed in March 1997.

THE LINAC DESIGN

The parameters of the beam produced by the linac are summarized in Table 1. These are very unique specifications for among the existing electron linear accelerators. The long pulse, 4 msec, is used for the beam stability studies of CW linac. The RF source parameters are summarized in Table 2.

Table 1 Beam parameters for the linac

Energy	10 MeV
Max. Beam Current	100 mA
Average Beam Current	20 mA
Pulse Length	0.1 ~ 4 ms
Pulse Repetition	0.1Hz ~ 50 Hz
Duty Factor	0.001 ~ 20 %
Norm. Emittance	50 π mm mrad*
Energy spread	0.5 %*

* estimated value by simulation

Table 2 Parameters of the RF source.

Accelerating Frequency	1249.135 MHz
Accelerating Mode	$2\pi/3$ mode
Number of Klystron	2
Klystron Power	1.2 MW

Injector

The injector consists of a 200kV DC gun, magnetic lens, a RF chopper, chopper slits, a prebuncher, and a buncher. Solenoid coils cover these elements from the exit of the gun to the first accelerating tube except between the RF chopper and chopper slits. Fig. 1 shows these injector components and schematic with the solenoid magnetic fields.

Electron Gun

The pulse characteristics of the accelerator beam are initially determined by the electron gun system. The accelerator requires a range of pulse widths from 100 μsec to 20 msec, rise and fall times of ~1 μsec.

As average beam current is very high (20 mA), a grid (intercepting wire mesh) cannot be used for current control because of exceeding electron beam energy deposit to the grid wire. A non-intercepting aperture grid is only capable of high beam current control. The two aperture grids configuration is necessary to control a greater range of beam current according to numerical simulation. The gun electrode configuration was designed using a computer code EGUN [2] calculated the electron trajectories through the gun in the presence of space charge.

RF Chopper

The RF chopper [4] consists of a RF chopping cavity and a slit. The RF chopping cavity is a rectangular cavity driven at f_0 (fundamental frequency: 1.249135MHz) with TM_{210} mode and $2f_0$ with TM_{410} mode. There are three field mixed together in the chopper cavity. First one is a fundamental (f_0) magnetic field, second one is second harmonic ($2f_0$) magnetic field, and third one is a DC magnetic field bias. Adjusting RF field amplitude and phase, a superposed magnetic field can be equal to zero on the beam center line in 120 degree phase length. The wave form from the chopper cavity is shown in Fig.2. This chopper provide small transverse emmitance and bigger acceptance for phase angle.

Buncher

The buncher is a TM_{010} room-temperature cavity at same frequency (1.249135 GHz) as the fundamental of the accelerating tubes. Bunching in the PNC injector occurs in two components: the prebuncher and the 1.2 m long, traveling-wave resonant ring buncher.

The beam current from the DC gun is 300 mA and one third of RF periodic (120 degree) beam passes through the chopper slits. In the buncher the wave phase velocity varies linearly from 0.695 to 1.0 of light velocity. The bunch width becomes about 10 degree at prebuncher exit and 5 degree at buncher exit. The injector has been modeled with the code PARMELA [5], which simulates the beam trajectory from the exit of the electron gun to the accelerating tube.

Accelerator Section

The accelerator proper is a traveling-wave accelerator with TWRR excited with microwave power at a frequency of 1249.135 MHz. The accelerating tube has a cylindrical, disk-loaded shape made by OFHC (Oxygen Free High-purity Copper). The structure is designed to produce a constant axial electric field over the length of each independently fed. The number of the accelerating sections is seven and one injector section. Each of the accelerating section whose length is 1.2 meters contains 13 of $2/3\pi$ mode cavities and two coupling cavities.

All accelerating sections are designed to have constant gradient structure under the condition of 100mA beam loading. The regenerative type and the cumulative type of BBU (Beam Break Up) will be suppressed partially in the constant accelerator structure because the one accelerator sections of each cavity are designed with the same frequencies of TM_{01} mode and with very different frequencies of TM_{11}-like mode. According to the progressive stop-band technique, the iris diameters in the initial region of the accelerator section are smaller than those in any preceding ones but larger than those in subsequently located ones. The choice of short accelerating section and low attenuation constant structures made possible increase the threshold BBU current and liberate the tolerance of the TWRR resonate frequency, temperature stability, and fabrication. A detail TWRR with accelerating section is described else where [6].

Beam Dump and Vacuum System

The conceptual design of the beam dump is based on the following design criteria: (1) to disperse the beam by magnet in front of the beam entry, (2) to stop the beam part by part in spatially separated blocks, (3) to minimize the induction of radioactivity.

The first criteria is for making the power density smaller by defocusing/spreading the beam. It is also assuring to avoid mishaps of the pin point beam hitting the component. The second criteria makes also a reduction of power deposition in a small region of the beam dump. The third criteria eliminates the use of water to stop the beam. Liquid target does increase the total inventory of the activated materials.

The concept of the present design is, as shown in Fig. 3, Ring and Disk (RD) system. The part where energy is deposited consists of 17 rings and 5 disks (thickness of 5 cm). Each plate is made from OFHC (Oxygen Free High-purity Copper). All the rings have different inside diameters (the beam runs inside this ring.). The frontmost ring has the inside diameter of 19.6 cm and other rings have smaller diameter with increment of 1.2 cm from upstream to downstream. In a module a cooling water flows in series from ring to ring. In order to reduce radiolysis of cooling water and to eliminate the vacuum window between the beam dump (target) and the accelerating tube, cooling water is not exposed to direct incident electron beam. These modules form a total target block and it also electrically insulated from the main body of the beam dump. The problem of connecting between the beam dump and the accelerator (the pressure difference between 1×10^{-5} torr and 1×10^{-7} torr in the accelerating tube) was solved by using a differential pumping stations and a low conductance beam transport tube.

RF modulator and Klystron

The klystron is able to operate complete CW (1.2MW CW). But the facility power station could not supply such large power(~5MW), which made the klystron operate 20% duty. Modulation of the klystron pulse voltage is accomplished by controlling the anode voltage for 90kV operation. For 147kV, the beam voltage modulation is employed, using pulse transformers and solid-state switch.

The klystrons used on the PNC accelerator were developed specifically to operate in CW and pulse with good efficiency(> 65%). Extensive window development was necessary to achieve continuous power of 1.2MW at L-band. The output window was designed and tested for pill-box type windows with using TWRR unit replaced the accelerating tube. The test results agree the characteristic of field decrease and reduction of VSWR in the pill-box by the design and suggests that the klystron will be able to produce more than 1.2MW RF with this new window [9].

Control and Data Acquisition Systems

A control system consists of two major parts: (1) computer control and monitor system, (2) an interlock system for use of the machine protection that shuts off the accelerator equipment and to protect personnel.

The computer control and monitor system is consisted of three network layers, which are Ethernet layer, VME-bus layer (SCRAM-net), and high speed communication layer. The beam control contains controls and status displays for each individual linac equipment . These systems are connected Ethernet layer (Ethernet with TCP/IP protocol). The communication network is supervised by the system control work stations which also manage the whole linac operation. These processors are not responsible for crucial operations such as interlock system.

The VME-bus layer (served as the beam control and some of them contained PIOP (Parallel Input/Output Processor) system) is interfaced with the linac equipment and each VME-bus systems connected with Ethernet and SCRAM-net(15MB/sec). Each PIOP node is connected with high speed communication lines as horizontally(or hypercube shape connection), which makes each node communicate with another node a short time as compared with shared bus system. A combination with high speed communication layer and DSP (Digital Signal Processor as node processor) makes fast data processing for large number input events simultaneously. This concept of data processing could not be achieved in conventional system.

The interlock system employs hard wire programmable sequencer system connected crucial equipments, which is completely independent from computer assist system because of more redundancy for safety aspect.

COMMISSIONING

Pre-Commissioning

The commissioning was carried out with partially build accelerator. The injector, the first accelerator section, the beam dump, and RF source was completed in December 1995. The RF conditioning was made in site using own RF source. Within a few days after the RF conditioning, the buncher and accelerating section was able to store about 1 MW RF peak power in the resonant ring. The unique aspect of this power RF conditioning is burst-pulse operation, which is nine short pulse(100μsec) within 4 msec period. The 4 msec pulse power and the CW klystron allow to this kind operation.

Beam-Commissioning

Beam commissioning began and 3.1MeV beam had coasted though the linac to the beam dump. By March 22, 50mA of 1 msec beam was achieved. The resonant ring of the buncher and first accelerating section were tuned to the maximum resonated RF power. The RF chopper and the chopper slits were adjusted by the RF power to apply the cavity with a fundamental (f_0) RF power, then DC magnetic baias, finally second harmonic ($2f_0$) RF power. Fig. 4 shows the beam current in each beam current monitor. The beam current after the chopper shows one third current from the electron gun exit. The energy spectrum measured by bending magnet are shown in Fig. 5. After using the RF chopper, the energy resolution ($\Delta E/E$) is about 5%. This is rough adjustment because the bunch monitors have not been prepared and all phase and bunch length have not be tuned yet. Until now ~100 mA beam with pulse width 1 msec repetition 0.5 Hz has been accelerated. Studies continued at design goal of 100 mA beam with 4 msec and repetition 50Hz, including the resonant rings control with high power operation. The temperature control of resonant rings and accelerating tubes is getting critical with high duty operations.

CONCLUSION

The PNC high power CW linac injector and first accelerating section was installed and pre-commissioned during the beginning of 1996. This pre-commissioning shows important results that the accelerator with the traveling wave resonant ring under 100 mA beam loading is easily handled and verified the acceleration of long pulse beam such as 1 msec. Studies continued at design goal of 100 mA beam with 4 msec repetition 50Hz. The rest of accelerating section will be installed by March 1997, then 10MeV high power CW(average 20mA 20%duty) electron linac commissioning will be ready.

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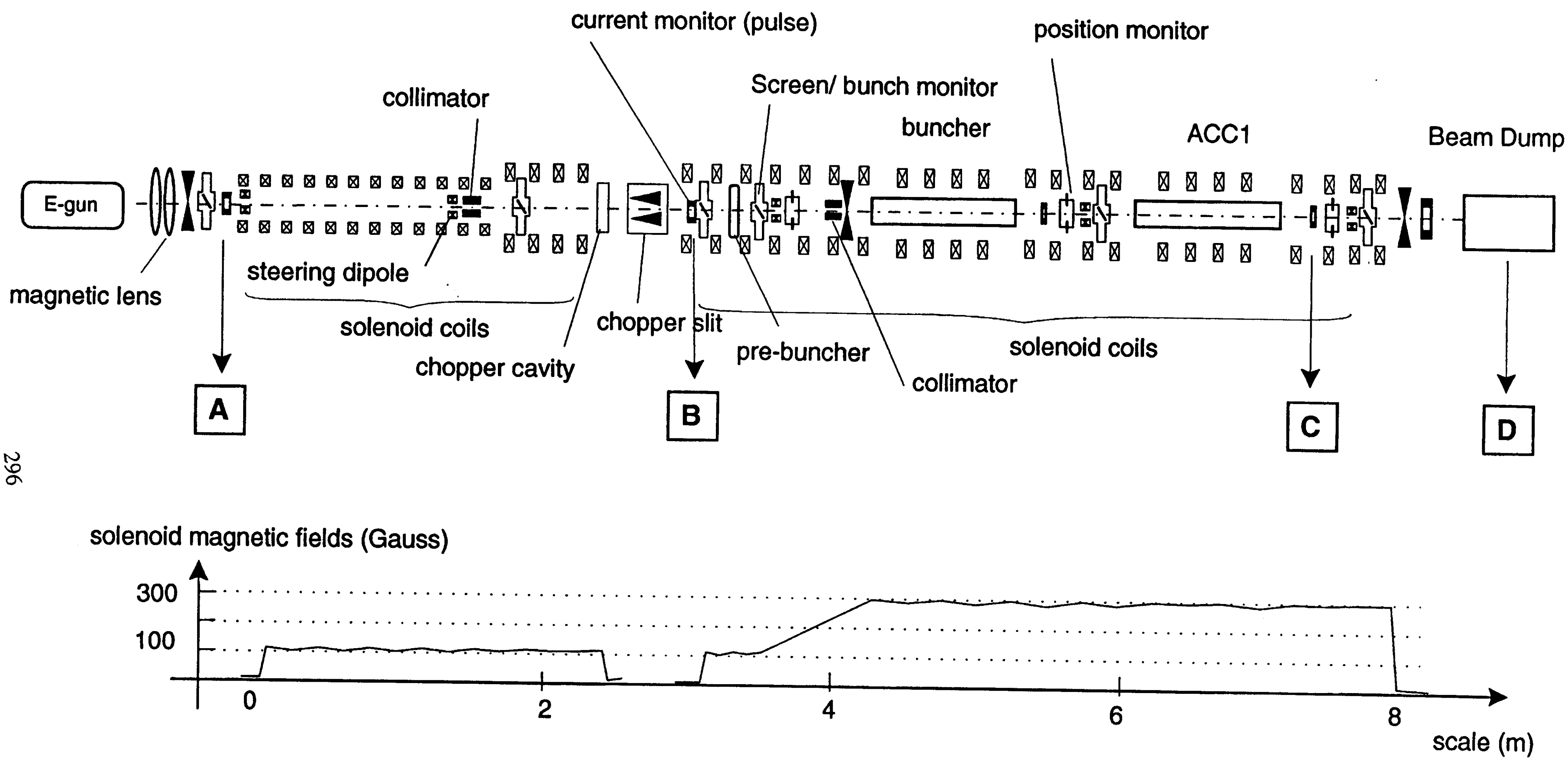

Fig. 1 Injector components and schematic.

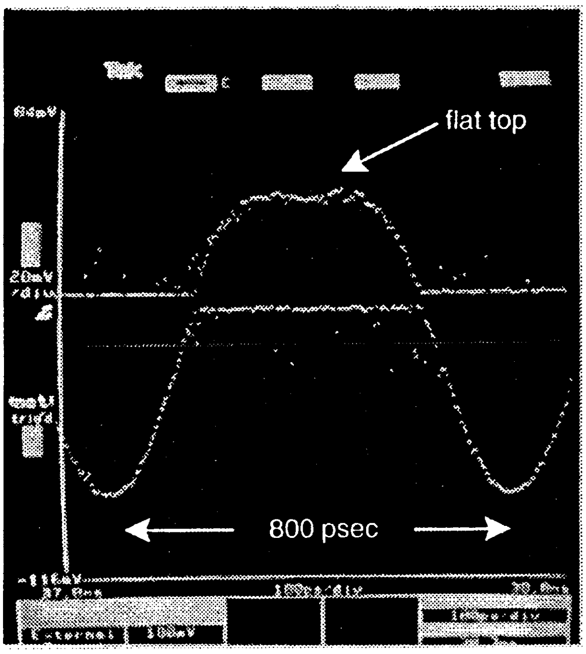

Fig. 2 Waveform in chopper cavity.

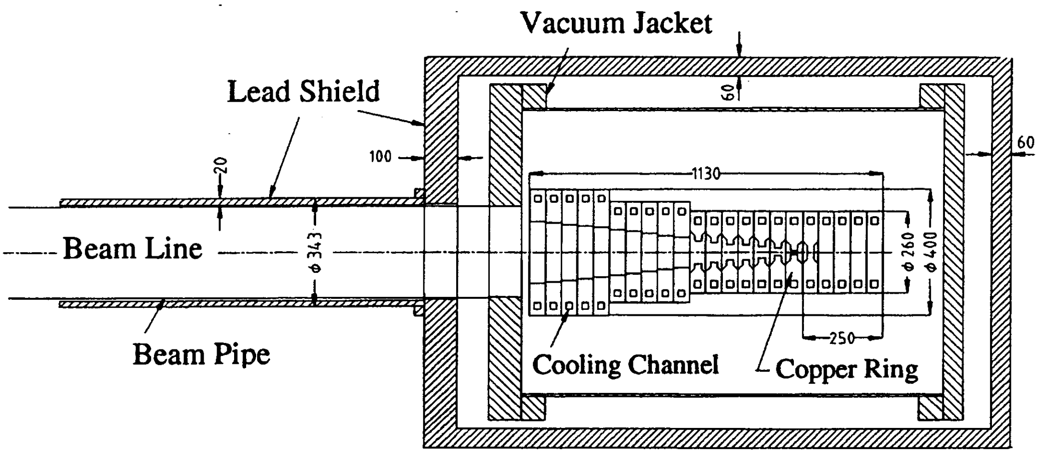

Fig. 3. A cross section view of the beamdump.

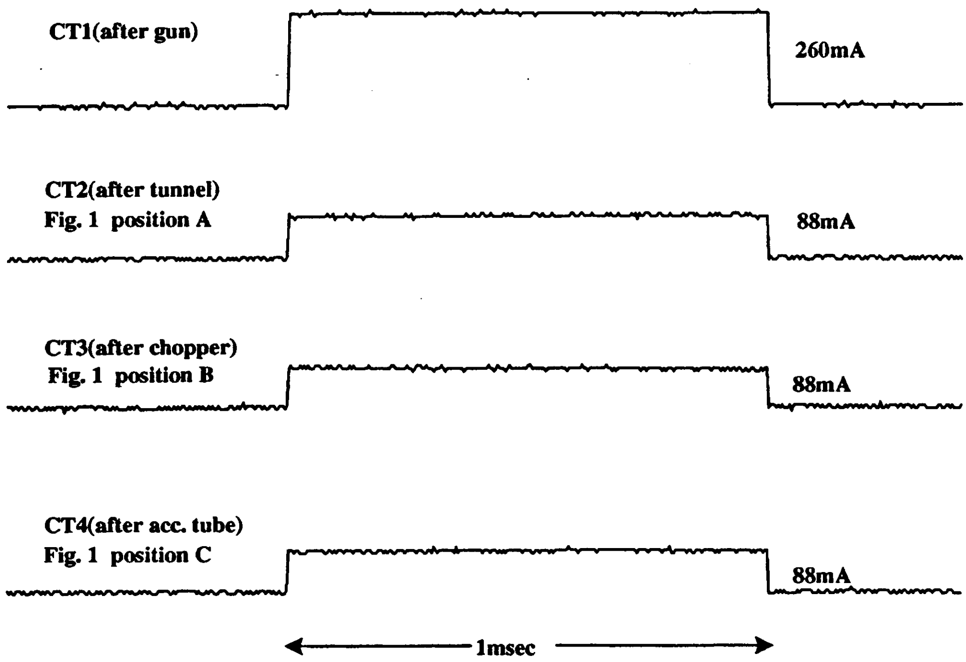

Fig. 4 The beam current in each current monitor.

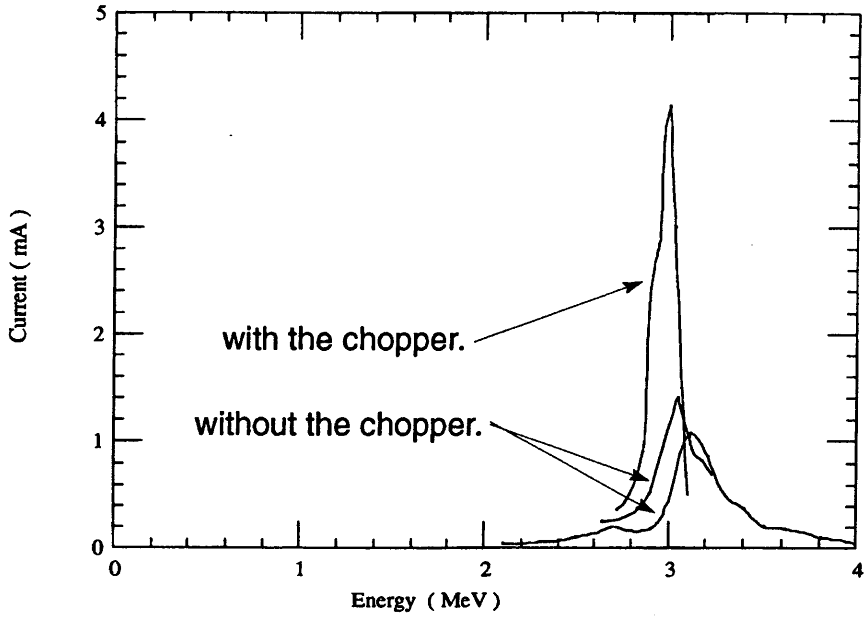

Fig. 5 Energy spectrum.