JP0150526

JAERI-Conf 2001-002

ICANS-XV
15th Meeting of the International Collaboration on Advanced
Neutron Sources
November 6-9, 2000
Tsukuba, Japan

7.4
A Study on 3-GeV Proton Beam Transport Line for JSNS

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Abstract

For the neutron science and the muon science, experimental facilities are to be built in the JAERI/KEK joint project on multi purpose high intensity proton accelerator. In the first phase of the project the proton beam power is 1 MW which will be up graded to 5 MW in the second phase. In the first phase both neutron and muon facilities utilize a common proton beam from the 3-GeV rapid cycling synchrotron. The muon science facility is located at upper stream of neutron facility. This configuration creates various technical problems. As in the first phase the intensity is high up to 333 μA, optimization of beam optics is stringently requires to provide adequate beam profile on the targets and minimize the beam loss. Beam optics, profile and spill of 3-GeV proton beam are thoughtfully studied. At the initial stage a 2-cm thick carbon target for the muon experiment will be placed in the beam line. This scheme, so called cascade targets, shares the beam efficiently. The beam optics and beam spill were calculated with the TRANSPORT and DECAY-TURTLE codes. A reference beam line was established, which had about 70 m in length. The profile and spill of the beam were calculated by taking into account of the coulomb and nuclear elastic scattering. The beam can be shaped at 13 and 5 cm in full width and height, respectively, on the neutron target, these dimensions satisfy the requirement from the neutron target.

1 Introduction

Science driven by a neutron, muon, exotic nuclei, kaon and neutrino has been rapidly growing in many research fields such as life science, material science and nuclear physics. For the research of the forefront science, it is required to use high intensity source. Especially for the neutron science, the source with intense pulse at the level several MW is requested. On the other hand, many accelerators and nuclear reactors had been and are going to be terminated in all the world due to the ruined facility and cut out of the budget. Without building new facility, it can be anticipated the famine of the particles sources. In order to supply deficiency, new facilities are to be built at the JAERI Tokai site under the join project between JAERI and KEK.

As for a new spallation neutron source, mercury target will be employed, which is irradiated by 3-GeV protons with the average current of 333 mA and the repetition rate of 25 Hz in the first stage. The incident power of the protons is 1 MW, which is the $\sim$ 6 times higher than the highest power of the existing facility of ISIS. In the second phase of this plan, it is expected that power will be increased up to 5 MW. Due to the high power beam, the high pressure wave is caused in the mercury target. It is known that the pressure wave is well characterized by the peak current density of protons. Therefore, in order to reduce the pressure wave, the distribution of the proton beam should be kept as possible as flatter.

In this project, not only one facility for the neutron science, but also the other facilities for the muon science, physics of the exotic short-lives nuclei, kaon, pion and neutrino will be constructed. Furthermore, an experimental facility for the development of the accelerator-driven nuclear waste transmutation system (ADS) will be planned to built. This is quite different scheme from others project for the spallation neutrons source, and the total cost will be high. In order to cut down a construction cost, some facilities will be combined in the same experimental hall using a common beam. For example, there was an idea that thin targets for the muon and short-live nuclei production were placed at upstream of the neutron target. This scheme, so called cascade targets, shares the beam efficiently if the interaction between thin targets and beam is insignificant. However, it can be easily anticipated that the proton spill is high due to the scattering of the primary protons at the thin targets. Losses of $\sim$15% and 0.5% of primary 1 MW beam are equivalent to the incident powers of ISIS and KENS, respectively. The total amount of the beam loss should be kept as lower as possible. For the maintenance of the beam line components such as magnets, it is required to localize the position where protons are lost. By the localization it becomes easy to shield the beam line without using massive material and makes drastically cost saving.

As for a preliminary report, this paper is described general information of 3-GeV proton beam transport line for JSNS. Beam optics and the beam loss are studies for the design of the beam lines.

2 Beam line on the 3-GeV proton transport line in JSNS

The accelerator complex in the JAERI/KEK joint project is shown in Fig. 1. Protons accelerated up to 400 MeV by the Linac will be injected in the 3-GeV rapid cycling synchrotron. For the particles and nuclear physics, the 3-GeV protons are injected to the 50-GeV synchrotron will be established to deliver beams in experimental hall. Using the superconducting Linac, 600 MeV beam will be deliberated to the experimental facility of ADS.

The facilities for neutrons (N), muons (M) and exotic nuclei (E) had originally been planned to be build in the same experimental hole using the same beam line. As production target, carbon (1 and 2 cm in thickness) and tantrum (5 mm in thickness) will be used in M and E facilities, respectively. It should be note that the construction of E-facility is postponed due to the higher cost of the initial construction. The facilities for the muon and the neutron is shown in Fig. 2. M-facility has two target stations. The establishment of the ultra-high intensity muon channel using carbon with 1 cm in thickness is, however, postponed to the second phase.

From the 3-GeV synchrotron, protons are transported in a distance of approximately 300 m to the neutron target. This beam transport line is mainly composed of the two sections of the low beam spill line, so called a quiet line, and the high beam spill line in the M-N facilities.

2.1 Characteristics of lower beam spill line

In this transport line, the beam loss is regulated smaller than 1 W/m, determined from the hands on maintenance requirement. The beam from the 3-GeV ring is shared with the beam transport to the 50-GeV synchrotron. The beam line to N-facility crosses the tunnel of 50-GeV synchrotron. In order to avoid an interference, the 3-GeV beam line is raised 3 m to provide a clearance for the tunnel of 50-GeV synchrotron.

In the 3-GeV synchrotron, a painting technique is utilized to inject the protons with the emittance of 144 π mm·mrad. If the protons can be accelerated without blow up, the emittance of the beam will be shrink to 54 π mm·mrad due to the adiabatic damping. However, it can be said the emittance will not be shrunk ideally because of the space charge effect. It makes difficult to predict of the distribution in the real and the phase space of beam at the exit channel of the 3-GeV synchrotron. In order to define the maximum emittance, the beam scraper should be located around at the exit of the synchrotron. However, without knowledge of the distribution of the phase space, the beam loss at the scraper can not be obtained quantitatively. In the 3-GeV synchrotron, the dynamical aperture is located at near the entrance of the synchrotron. The maximum emittance of 216 π mm·mrad is determined by this aperture. We decided that the acceptance of the beam line is enlarged more than 216 π mm·mrad instead of the utilization of the scraper.

In order to avoid the beam enlargement due to the momentum spread of the beam, FODO cells with dispersion free will be used in the straight section except for the matching section. For the long straight line located at just upstream of the M and N facilities, the FODO cells having phase advance of 74° is designed. Since the beam radius in the FODO cell with this phase advance is the smallest in the same length of beam direction, it reduces the number of the magnets.

2.2 Characteristics of beam line in the M and N facilities

In the M-N facility, at first the proton penetrate the muon production target made of carbon. In the first phase of the facility, a carbon of 2 cm in thickness will be used. Both targets having 1 and 2 cm in thickness are planned to be used in the next phase. Each target is cooled by the water flowing at the edge of the target and placed in the vacuum chamber. From view of beam optics design of the muon extraction channel, it is required to focused on the target in order to increase the luminosity of the source.

When protons penetrate the carbon target, some fractions of the protons are scattered around the target. Collimators made of copper are inserted between the target and the magnet located at the downstream to protect the magnet from the scattered protons. Therefore collimators are also cooled by the circulating water because protons of several 10 KW order magnitude could be lost.

For the safety reason, a beam window is placed at 1.3 m upstream of the mercury target. It is composed of 2 pieces of INCONEL alloy in 3 mm thickness and cooling water in of a 5 mm thick layer. After passing the window, beams finally reach the neutron target.

3 Beam optics calculation

The beam optics were calculated with TRANSPORT[1] code. In this study, the PSI-version[2] of the TRANSPORT was used. In order to calculate the beam spill due to the interaction between proton and the muon production target, DECAY-TURTLE[3] modified in PSI[2]was used. DECAY-TURTLE calculates the tracking particles by Monte-Carlo technique. In the calculation 1 million protons were created. DECAY-TURTLE can treat the coulomb and proton-nuclei interaction by using supplemental program of MUSCAT, which is extracted from REVMOC[4]. By using MUSCAT, the cross section for the total and elastic scattering of the proton-nuclei can be obtained. The angular spread of the coulomb and the elastic scattering is also obtained with MUSCAT.

3.1 Low beam spill line

The beam envelope in the low beam spill line obtained by the calculation with TRANSPORT is shown in the Fig. 3. The total number of the quadrupole and the dipole magnets are 63 and 8, respectively. The magnets with a bore diameter of 200 mm are operated, which have the field gradient of less than 8 T/m except at vertical bending section. At this vertical bending section, the quadrupole magnet has the maximum field gradient of $\sim$10 T/m. To erase the dispersion in the short length, the gradient in this section is relatively larger. Therefore magnets having smaller diameter of 150 mm will applied to obtain high gradient. By using double bend module, the dispersion is erased in the straight section right after the bending section.

3.2 Beam line in the M and N facilities

The beam envelope inside the M-N facility is shown in Fig. 4. On the muon targets, denoting as M1T and M2T in this figure, there are waist in the beam envelope. The effective beam radius on the muon target is 10 mm. By making the waist, it can be efficiently reduce the beam halo due to the interaction between proton and carbon.

In order to sustain both the high neutronics performance with a technically feasible density, the beam is expand to be shaped at 13 and 5 cm in full width and height. Between the carbon target and the mercury target, the expansion section is necessary. In this part, 6 of quadrupole magnets are used to fit the profile on the neutron target. Proton is focused at the final quadrupole so as to fit the beam line in the shielding at the entrance of the mercury target. After passing this magnet, the beam radius is gradually increased.

In this figure, the radius of the beam with emittance of 54 π mm·mrad is shown. For the beam having 216 π mm·mrad emittance, the radius is double of the value shown in Fig. 4.

4 Result and discussions

4.1 Beam loss in the M-N facility

Calculations including the interaction between carbon and proton were made to obtained the beam loss. In this calculation, the collimator was ignored. Calculation were made for the beam, which was uniformly distributed in the phase space with the maximum emittance of 54 π mm·mrad. The loss was also calculated for the beam which was distributed in the phase space as Gaussian shape having 54π mm·mrad in 2 σ.

The amount of the loss is shown in Table 1. It is found that total amount of the beam spill is $\sim$ 14 %, which is equivalent to the incident power of the ISIS target for the primary beam of 1 MW. By the comparison of results between the uniform and Gaussian distributions, it is recognized that the total beam loss is irrespectively of the initial conditions. The table shows that $\sim$ 10% beam is lost by the interaction between carbon and proton targets. Approximately 1/3 of the whole beam loss is cause in the beam window.

In order to understand the dominant process on the beam spill, the spatial distribution of the loss was calculated. The distribution is shown in Fig. 5. It is found the almost loss is caused in the magnet (QM1 and QN1) located at the neat of the target. For QN1, beam of $\sim$ 20 kW beam irradiate the magnet. The result by using collimator with 65×65 mm^2 hole is also shown in Fig. 5. By the collimator, the beam loss can be localized at the collimator, because most beam loss is caused by the nuclear interaction, which is described below. The beam loss at the magnet can drastically decrease by the collimator, whereas the maximum loss is $\sim$ 1 kW at QN3. The whole beam loss with the collimator is the same as the without collimator.

4.2 Interaction of proton with carbon target and beam window

An additional calculation was performed by taking account of the energy struggling but ignoring the scattering with carbon. In the comparison of result by this calculation and the calculation without the target and window, it is recognized that energy struggling does not effect on the beam loss. This is ascribed to the fact that due to the free of dispersion in the M-N facility.

In order to recognize the growth of the emittance of the beam, changes of the angular distributions at the target and window were calculated. In Fig. 6, the distributions are shown. By the carbon, the distribution is not drastically changed in the forward angular region smaller than 8 mrad. This is ascribed to the lower coulomb force, because the coulomb force dominates scattering at the most forward region. and carbon has lower atomic number. In the larger angular region, the distribution is, however, significantly changed due to the nuclear interaction. On the other hand, the distribution is significantly changed by the INCONEL window. Therefore it is better to use thinner window which gives the lower effect. By this fact, the window was recently changed to thinner one in the design study.

4.3 Beam profile at the targets

Figure 7 shows beam profile, in other word the current density distribution. In this calculation, the initial beam condition is given by the uniform and Gaussian distribution in the phase space. The results show that the peak current for the uniform and Gaussian distribution is 7.95 and 10.39 μA/cm^2, respectively. This different is caused by the initial condition of the proton beam. It can be thought that the peak current has $\sim$ 30 % ambiguity for the assumption of the initial condition. However, the difference of the initial conditions makes the beam loss in front of the mercury target smaller than $\sim$100 W.

In the point of view to suppress the pressure wave in the mercury target, it is better to be irradiated by the proton beam with flat distribution than the present result. In Ref. [5], it is reported that the flat distribution can be obtained by using octapole magnet. Therefore, the additional calculation was performed for the beam line using octapole magnet. The beam profile distribution using by the octapole was calculated by using a uniform distribution in the phase space. The result is shown in Fig. 8. By using the octapole magnet, it can be achieved the flatter beam. Also in Fig. 8, the distribution is shown in case of the center position of the beam is moved 1cm in the horizontal axis. The vibration of the beam position in the horizontal axis is happened in the present accelerators, because of the instability of kicker of 3-GeV synchrotron. Therefore, it is inevitable the peaking at the edge by using the octapole magnet, so that we decided not to utilize of the octapole magnet in the beam line.

Without the knowledge of the distribution in the phase space, it is quite difficult to predict the current density on the mercury target. In the early stage after established the accelerator facility, the power is quite lower. By studying of the phase space, the shock wave and the life time of the target material in the future the best optics can be found. In order to have the capability of changing the optics in the future, it is thought reasonable to placed 6 and more magnets between the carbon and the mercury target.

4.4 Estimation of the air-activation surrounding the beam line in the N-M facility

In the calculation of DECAY-TURTLE, the transport of the secondary particles such as neutrons is ignored. The author had been developed the calculation code of NMTC/JAM[6, 7, 8] for the neutronics calculation based on the intra-nuclear cascade and evaporation model. Therefore, the NMTC/JAM was developed to take into account of the charged particle transport in magnetic field.

By using simplified beam line in the M-N tunnel, the activation of the air surrounding the beam line was calculated with NMTC/JAM and DCHAIN-SP[9]. It was recognized that ^{41}Ar dominated the activation of the air except short lives nuclei. The activities of short-lived nuclei can be reduced by the cooling at decay tank in short time. On the other hand, ^{41}Ar has long the half-life time of 1.8 h. It is necessary to dilute the air by a plenty of not activated one for the emission to the atmosphere.

It should be note the activity of the air is a preliminary results. By the certain optimizations such as utilizing boron implanted concrete surrounding the beam line, the activity will be reduced by a factor of ten.

5 Concluding remarks

For the design of the proton beam line in JSNS, calculations were made for the beam optics and beam spill with the TRANSPORT and DECAY-TURTLE codes. A candidate beam line was obtained, which had about 70 m in length. The profile and spill of the beam were calculated by taking into account of the coulomb and nuclear elastic scattering. By the calculation results with DECAY-TURTLE, it is found that the beam emittance growth by the coulomb interaction between the carbon target and protons is not significantly larger than the heavy target. Protons are lost $\sim$ 10 %. mainly by the nuclear reaction on the carbon target. By focusing at carbon target to have the waist in the beam envelope, the growth of the emittance can be kept smaller. At the beam window of the neutron target, 5 % of the beam are disappeared. The beam can be shaped at 13 and 5 cm in full width and height, respectively, on the neutron target, these dimensions satisfy the requirement from the neutron target.

In order to estimate the activation of the air surrounding beam line, whereas the radiation level is too high, calculation was made with NMTC/JAM. It is found that dilution by a plenty amount of fresh air is necessary. In such circumstance, high density of the NO_x is also great issue. The density of NO_x should be suppressed at a lower level in order to protect the magnet from the nitric acid produced by the chemical reaction of $NO_x + H_2O$. In the beam line of M-N facility, some specialized techniques are required for the maintenance of the magnets, because the total amount of the lost beam in this area is equivalent of the beam induced in the target of ISIS. The radiation level at the magnet will be too too high for the ordinary cables to endure the exposure. A Mineral Insulation Cable (MIC)[10], which has high radiation resistance, will be used as the magnet cable. Also the residual activity of the magnet is expected too high to handle by hands. For the repairing of the magnet, the remote handling technique will be necessary. These studies are now under progress.

Acknowledgments

The authors would like to thank to Prof. Y. Irie of KEK for his useful discussions of the beam optics.

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Table 1: Lost beam (%) in M-N facility

Phase space distribution	Uniform	Gaussian
Carbon and window	14.24	14.91
Carbon	9.26	10.32
Window	5.14	5.34

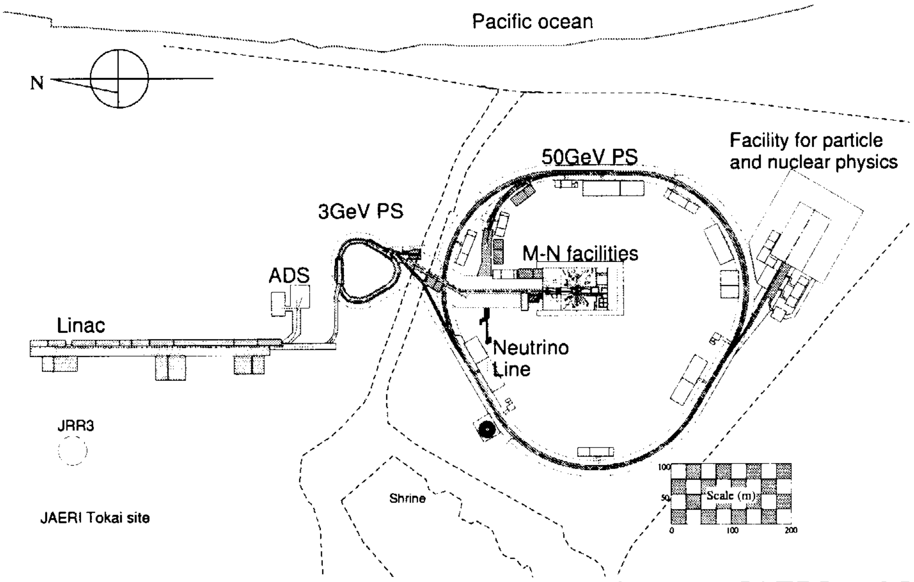

Fig. 1: Accelerator complex in the joint project between JAERI and KEK.

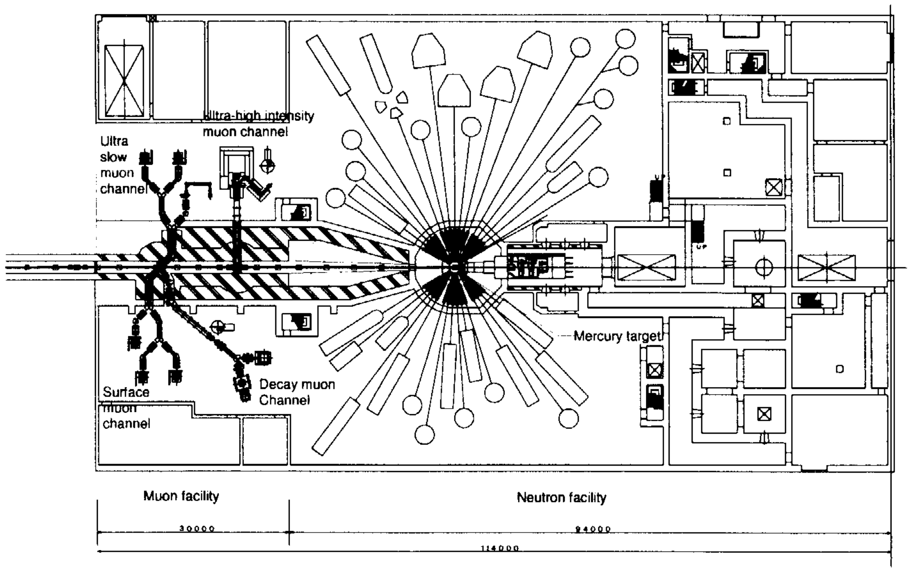

Fig. 2: Neutron facility in the JSNS and the muon facility.

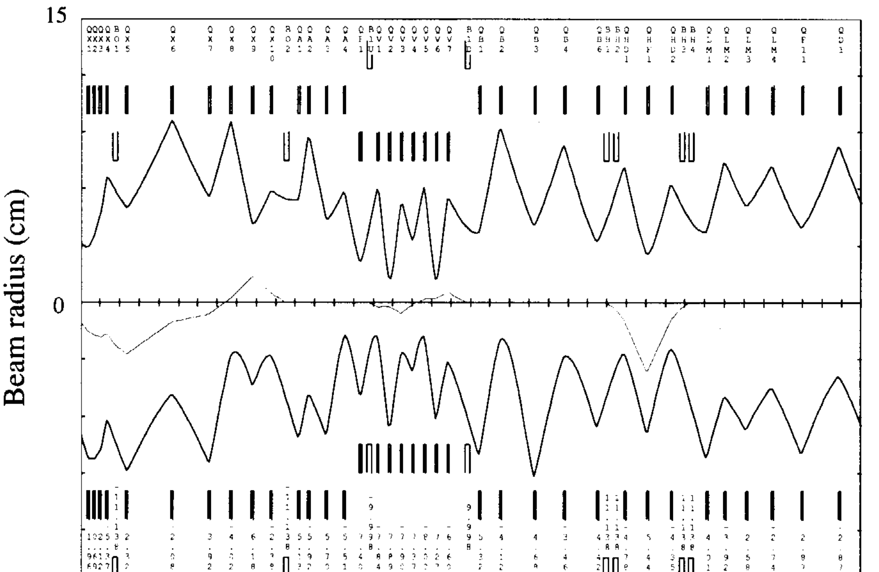

Fig. 3: Envelope for the beam emittance of 216 π mm · mrad from the exit of the 3-GeV synchrotron to the entrance of N-M facilities. Above and below graph to the center line shows beam radius for vertical and horizontal direction, respectively.

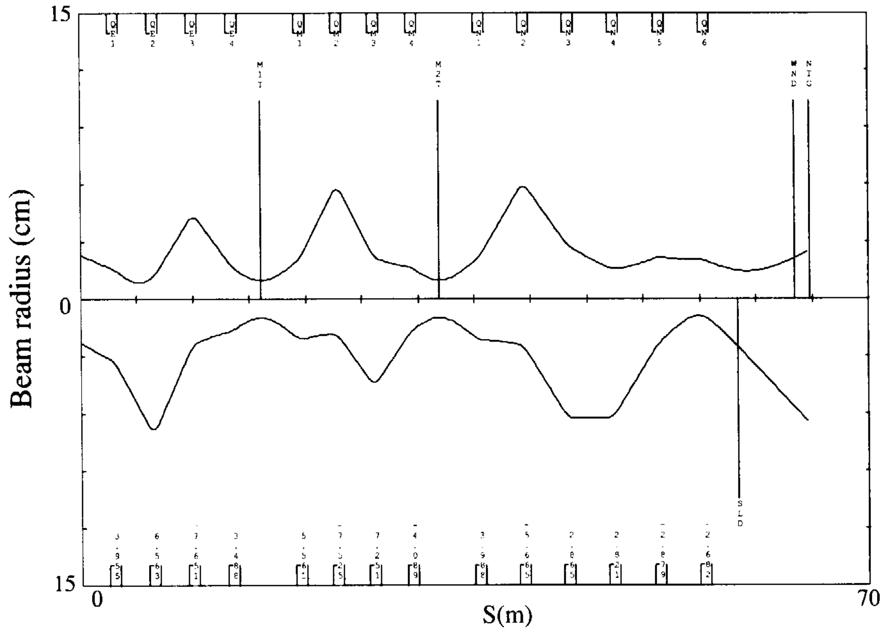

Fig. 4: Envelope for the beam emittance of 54 π mm · mrad in the N-M facilities.

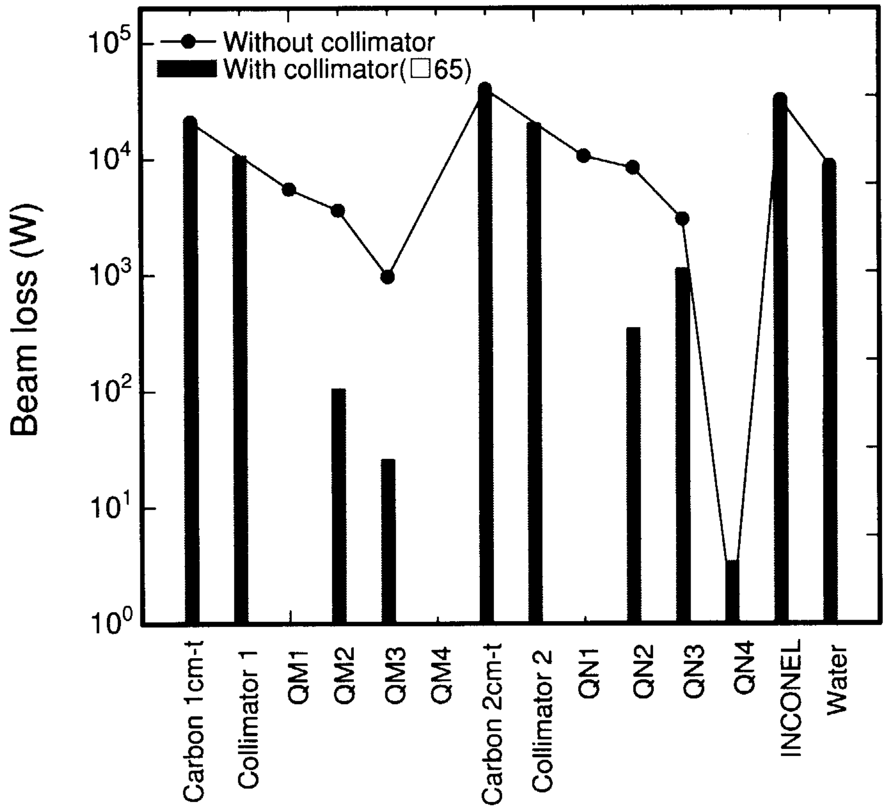

Fig. 5: Spatial distribution of the beam loss

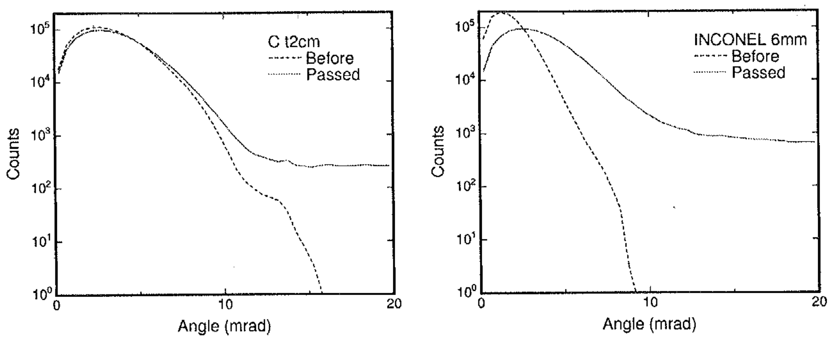

Fig. 6: Proton beam angular distribution along progressing axis before and after passed carbon target and beam window. Left and right shows the result for carbon and INCONEL, respectively.

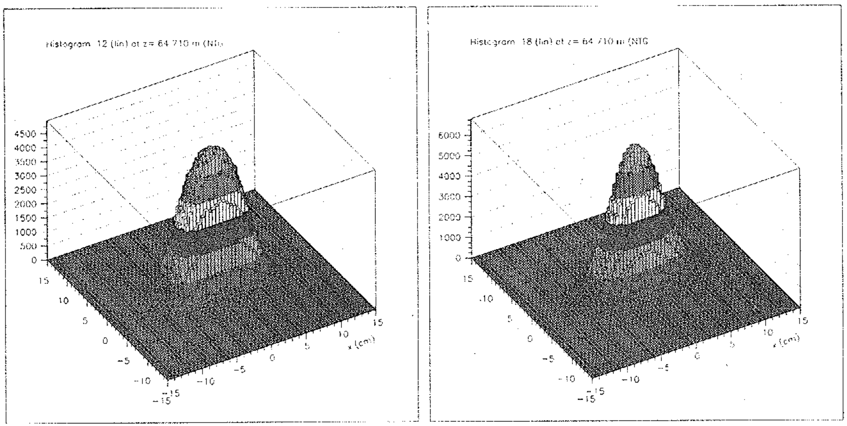

Fig. 7: Beam profile distribution on the mercury target. Left and right graphs show the result for the phase space having uniform and Gaussian distribution, respectively.

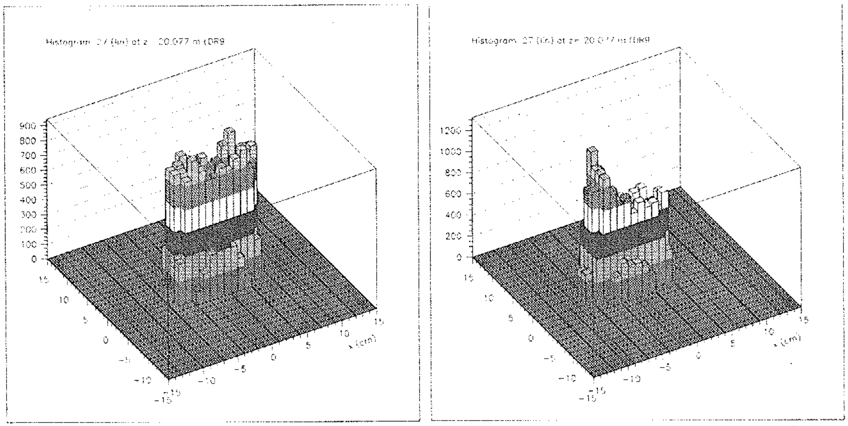

Fig. 8: Beam profile distribution on the mercury target using the octapole magnet. Left and right graphs show the result