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APPLICABILITY OF A BONNER SHERE TECHNIQUE FOR PULSED NEUTRON IN 120 GeV PROTON FACILITY

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1. INTRODUCTION

The data on neutron spectra and intensity behind shielding are important for radiation safety design of high-energy accelerators since neutrons are capable of penetrating thick shielding and activating materials. Corresponding particle transport codes - that involve physics models of neutron and other particle production, transportation, and interaction - have been developed and used world-wide [1-8]. The results of these codes have been ensured through plenty of comparisons with experimental results taken in simple geometries. For neutron generation and transport, several related experiments have been performed to measure neutron spectra,

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attenuation length and reaction rates behind shielding walls of various thicknesses and materials in energy range up to several hundred of MeV [9-11]. The data have been used to benchmark – and modify if needed – the simulation modes and parameters in the codes, as well as the reference data for radiation safety design.

To obtain such kind of data above several hundred of MeV, Japan - Fermi National Accelerator Laboratory (FNAL) collaboration for shielding experiments has been started in 2007, based on suggestion from the specialist meeting of shielding, Shielding Aspects of Target, Irradiation Facilities (SATIF), because of very limited data available in high-energy region (see, for example, [12]). As a part of this shielding experiment, a set of Bonner sphere (BS) was tested at the antiproton production target facility (pbar target station) at FNAL to obtain neutron spectra induced by a 120-GeV proton beam in concrete and iron shielding.

Generally, utilization of an active detector around high-energy accelerators requires an improvement on its readout to overcome burst of secondary radiation since the accelerator delivers an intense beam to a target in a short period after relatively long acceleration period. In this paper, we employ BS for a spectrum measurement of neutrons that penetrate the shielding wall of the pbar target station in FNAL.

2. EXPERIMENTAL

1.1 Shielding structure of the pbar target station

Fig.1 shows geometry of the pbar target station shielding structure. The station consists of anti proton production target and graphite dump with iron and concrete shielding. The simple structure and material of the station is suitable to provide benchmark data of neutron penetration.

The target made of inconel and copper disks is irradiated with 120 GeV proton beam provided from a main injector ring of Tevatron to generate antiprotons. The time structure of the proton beam is 1.6 μs pulse width, more than a 2.2 s repetition period. The power of the beam reaches 75 kW during our experiment. Behind the target, a correction lens, collimator and pulsed magnet are placed to focus, collimate and bend antiprotons from the target. After these beam extraction devices, a dump made of graphite is placed to absorb remaining protons and secondary particles. These components are surrounded by shielding of 6 feet (183 cm) iron and 4 feet (122 cm) thick concrete. The area above these components is a restricted area during beam operation. At the boundary of the restricted area, concrete blocks of 3 feet sq. , (???) 7.5 feet height are placed to define boundary as well as trap the radiation.

1.2 A set of Bonner spheres

BS with unfolding technique is widely used to measure a neutron spectrum from thermal to

MeV range or more because of simplicity and its wide energy range [13]. As a first step, we employed it with the modification of signal readout to apply to neutron burst field, because readout time of typical electronics is approximately 10 μs per event however beam pulse duration is 1.6 μs.

BS consists of a thermal neutron detector placed at the center of different thickness of moderators to measure neutrons with changing energy responses. In this study, the thermal neutron detector of a 2 inch diameter sphere shaped proportional counter filled with 760 Torr ^{nat}BF3 gas (LND Inc.) was coupled with 81, 110, 150, 230 mm in diameter polyethylene moderators, as shown in Fig.2. The moderator set was originally designed by Uwamino et al to use with a 5 atm ^{3}He proportional counter [13]. The ^{3}He counter was replaced to ^{nat}BF3 counter for this study to reduce neutron sensitivity, which is important to apply it to burst field as seen in later.

The two modes of readout electronics for this counter were used for this counter, a pulse mode and a current mode. The pulse mode readout described in Fig.3 consisted of a pre-amplifier (PA; ORTEC 142PC), a timing filter amplifier (TFA; ORTEC474) and a digital storage oscilloscope (DSO; LeCroy LT584L). The TFA played important role to enhance counting rate with removing long time constant tail of the PA. The DSO recorded all output signals of TFA as a waveform after trigger signal taken from toroid (TORO105B) placed just before the antiproton production target. The TORO105B also provided proton beam intensity during this experiment.

The other readout, current mode, was also adopted for the case of count rate exceeding the capability of the pulse mode even above mentioned readout. Fig. 4 shows schematic diagram of electronics for the current readout. In this mode, high voltage was applied to the outer case of the BF_3 counter to operate it under an ionization chamber mode with reading induced current on the central wire. The current was fed to an I/F converter (Laboratory Equipment Co.) to convert the current to the number of pulses that is easy to record. The conversion rate of the converter was 1 pC/pulse.

3. RESULT AND DISCUSSION

3.1 Output waveform from BS

BS was placed at the points shown in Fig.1, AboveTGT, AboveDUMP, IQ4, DUMPside, TGTside and TGTUS, for neutron measurement. Fig.5 shows the waveforms from Amplifier and TFA at TGTside point for the 5 types of the moderators. The shaping time of the amplifier was set to 3 μs. Both of the differential and integral parameters of TFA were 500. The circles and dots plotted on the waveforms denote peaks of pulses recognized by an off-line analysis program, automatically. The waveforms were recorded up to 50 ms from 5 ms before the beam trigger with 0.1 μs steps, which were determined with considering time distribution of the events and rise time of the counter, respectively. The events related to the proton beam were observed up to 40 ms, i.e. 35 ms after the beam pulse.

As observed in this figures, the number of slow events changes drastically with increasing moderator thickness. Since the response of BS for thermal neutrons decreases with increasing the moderator thickness, the slow events are identified to be thermal neutrons. In contrast to this fact, the number of event immediately after the beam trigger increases with moderator thickness. Since the thickness enhances the response of the detector for fast neutrons, the events immediately after the trigger correspond to relatively high energy neutron.

The time differences between nearby events are small, less than 1 μs for the worst case with thick moderator, as shown in extended figures in Fig.5. For such cases, the separation of these nearby events from the Amplifier output is impossible because the shaping time was 3 μs which was determined to cover entire rise time of the ^{nat}BF3 counter. These short interval pulses definitely cannot be counted by pulse height analyzer (PHA) without count loss. On the other hand, the TFA outputs separate such closed peaks because it consist of only rising portions of signals from pre-amplifier output by removing their tail using its differentiation function. In this case, the fact mitigates the signal pile-up efficiently.

The beginning part of the signals for 110 mm, 150 mm and 230 mm diameter moderators are saturated even for TFA output since a capacitor of the pre-amplifier would be saturated due to the high count rate. To compensate the effect, time profiles of the count rate are produced from the waveform data by offline analysis, as shown in Fig.6. Count rates for these cases are dropped during 100 ~ 300 μs after beam burst (t=5000 μs in this figure). The count loss of this time range was compensated using fitting curve of the time profiles with a polynomial. The compensation is performed only for TGTside point because the count rate of IQ4, dumpside and TGTUS cases are low enough to avoid this type of saturation.

For current mode readout data at Abovedump and AboveTGT points, normalization was done by using ratio of count rates between TFA and pC at AboveTGT point with the 230 mm moderator. The pC value would be converted to count rate by itself ideally, however, this conversion needs further development and calibration.

3.2 Comparison with simulation

To deduce neutron spectra based on the count rates of BS at each point, response functions and initial guess of neutron energy spectra were calculated using the Monte-Carlo codes. The response function for BS was calculated using the MCNPX code (version 25f), which is neutron and photon transportation code using the evaluated cross section library [8]. The library for neutron slowing down process and reaction rate calculation were LA150 (hydrogen, carbon and stainless steel) and ENDF/B-VI (boron and fluorine) [14]. For the energy region that is not covered by these libraries, MCNPX default physics models were used.

The neutron energy spectrum was calculated using the MARS15 code which can transport all secondary particles from 120 GeV proton induced reaction down to 0.2 MeV [1-4]. Furthermore, the code can transport neutrons down to thermal energy utilizing the MCNP neutron cross section library below 14 MeV. The shielding structure of antiproton production target vault was described using extended geometry file format. The description includes the shielding structure of iron and concrete, the devices after the antiproton production target (correction lens, collimator and pulsed magnet) and their magnetic field, the beam dump, etc. The description, however, still has ambiguities on density of material, target structure, density of the back fill and gaps/penetrations. Thus, the calculation results would have uncertainty from these ambiguities.

The neutron spectra were deduced based on the count rates of BS using an unfolding code, SANDII [15], with the calculation results of response function and neutron spectrum as an initial guess. Fig. 7 shows neutron energy spectra for each point in comparison with one obtained with MARS15. One can see that the calculations are in a reasonable agreement with experimental results. For instance, calculation well describes the difference in magnitudes between AboveTGT and Abovedump points. For all points, the C/E values for the case without moderator are ranging from 0.6 to 0.7 instead of around 1.0 for the other moderators. It indicates that determination of thermal neutron contribution - drastically affected by surroundings and gaps in shielding - should be improved.

For high-energy component, the experimental results for TGTUS and TGTside cases show difference from calculation above 10 MeV. This energy region is mainly determined by the counting rate of the 230-mm moderator case. The tendency is interesting because these two points are in similar shielding situation except for angle from the target. The reason of the difference should be studied in more detail because the 230 mm moderator has its peak sensitivity only around 10 MeV.

4. CONCLUSION

The energy spectra of burst neutrons from 120 GeV proton induced reactions were measured using a set of Bonner spheres (BS) with readout system consisting of a timing filter amplifier and digital storage oscilloscope. The experimental results support order of magnitude of calculation results based on theoretical models except for some cases that should be investigated from both experiment and geometrical input error in the calclulation. The current readout of BS shows capability to operate it under the intense burst field that is impossible to use pulse mode counting. The dynamic range of this mode overlaps to one of activation technique which is also a reliable way to determine neutron flux. The technique would also be adopted to a radiation monitor placed in an intense pulsed field. We would like to continue this study to determine absolute intensity of neutron field using the detector itself. The lack of sensitivity for over 10 MeV neutrons should also be improved in further experiment. Since the behavior of the neutrons is key feature for radiation safety design of this high energy accelerator, the results would be helpful to develop a counter system to measure neutrons for an intense burst field.

Acknowledgment

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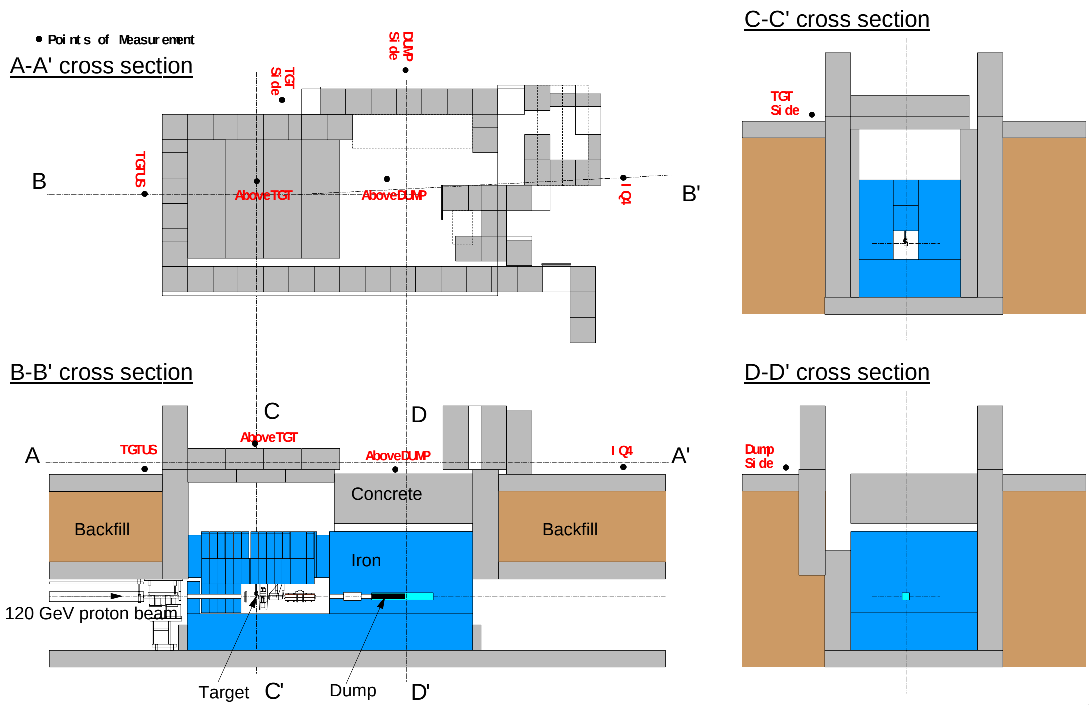

Fig.1 Plan and cross sectional views of the antiproton production target station

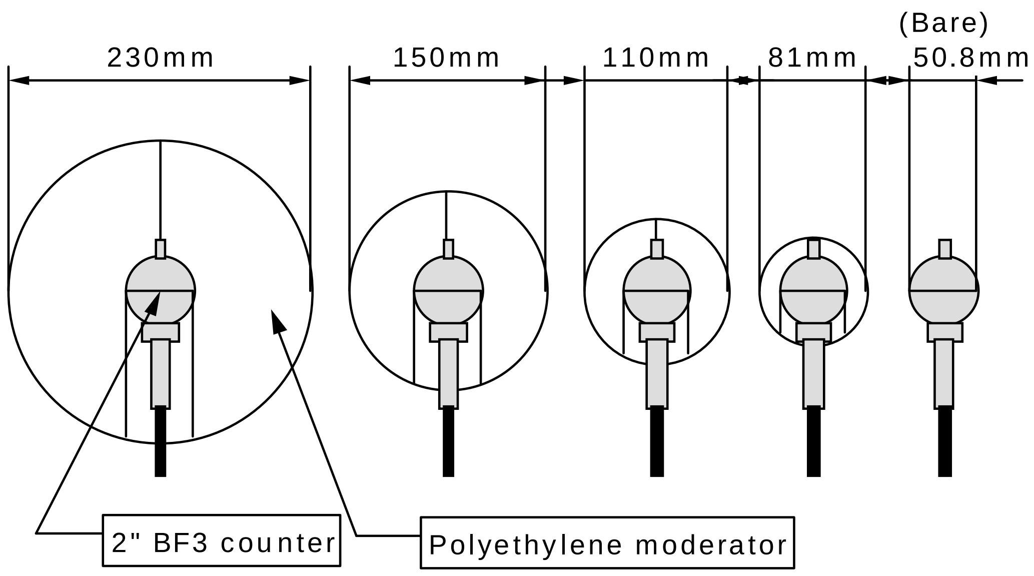

Fig.2 Setup of a BF3 counter and moderators for the set of Bonner spheres in this experiment

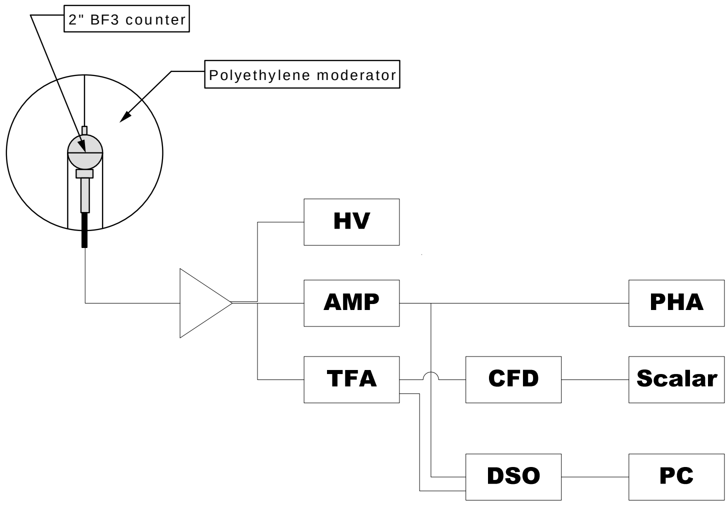

Fig.3 Electronics of pulse mode read out for BS in the field of neutron burst

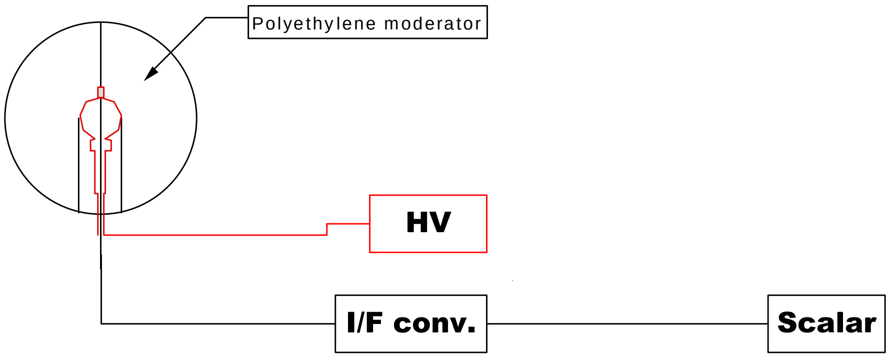

Fig.4 Electronics of current mode read out for BS. High voltage is applied to the shell of the BF3 counter to operate it as ionization chamber.

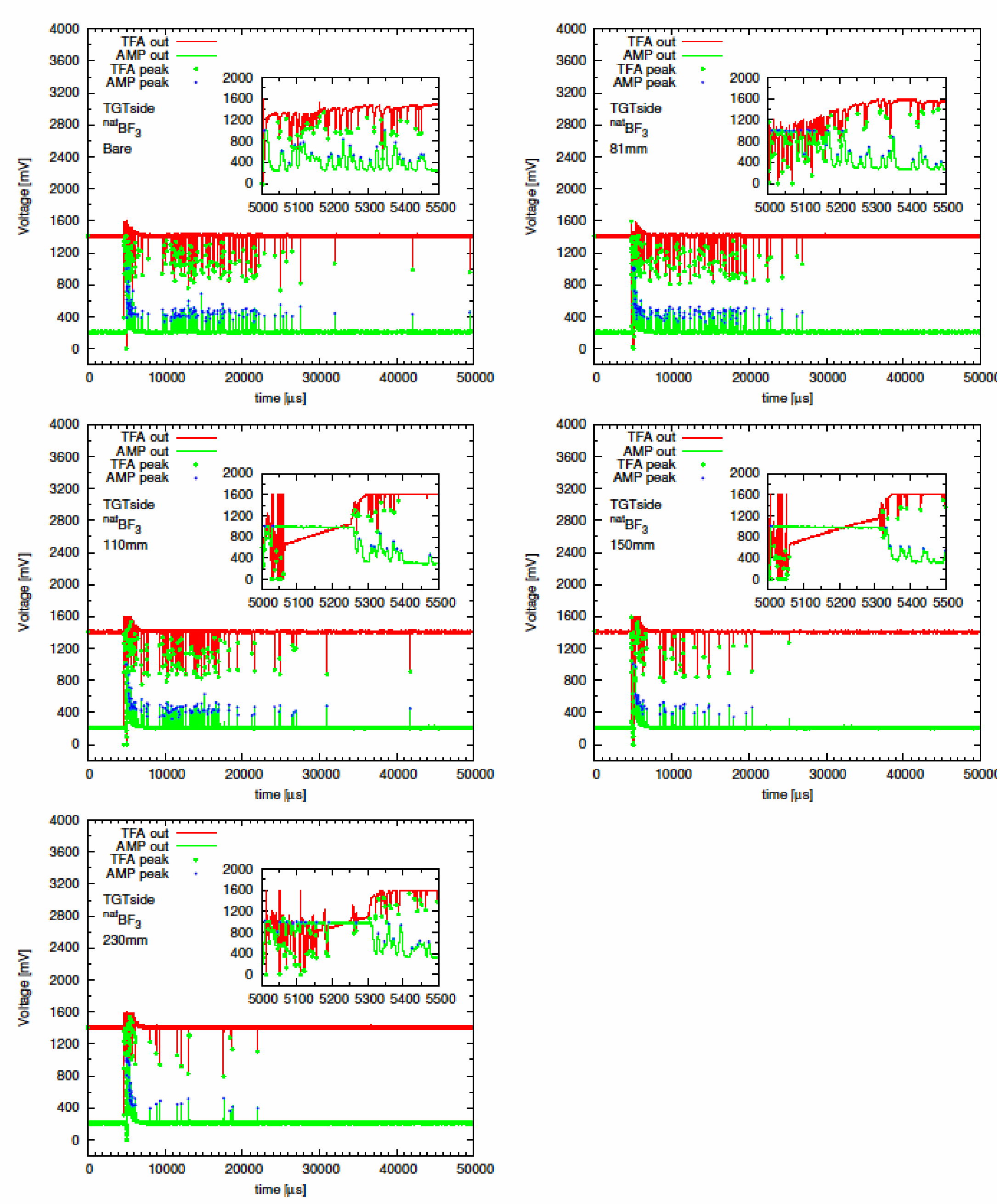

Fig. 5.: Waveforms of BS with different thickness moderators through an shaping amplifier (AMP) and timing filter amplifier (TFA) at TGTSide position. The points and circles denote peak position recognized by offline analysis.

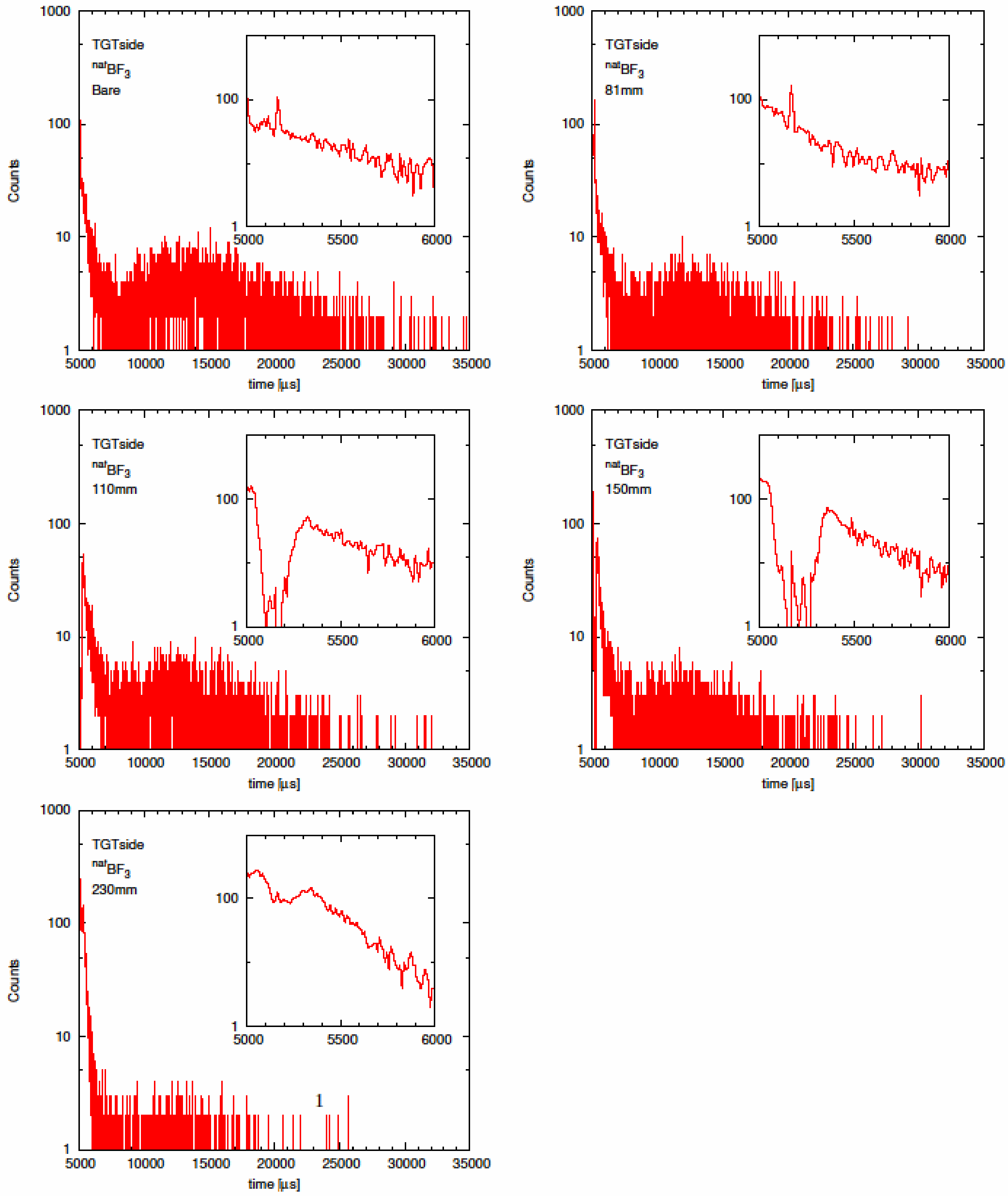

Fig. 6: Count rate distribution as a function of time for BSwith different thickness moderators at TGTside point.

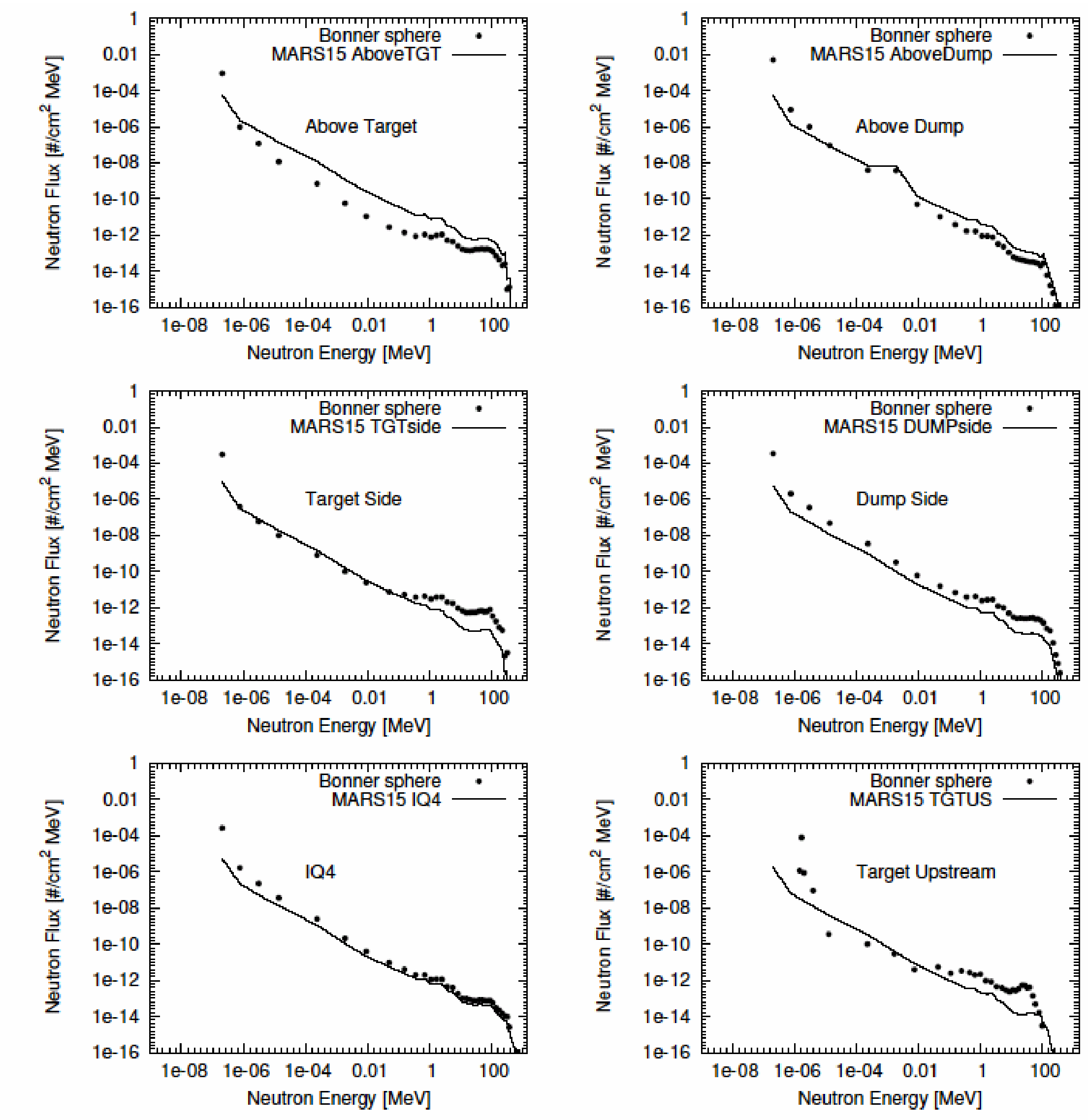

Fig. 7: Neutron energy spectrum estimated from BS count rate and unfolding method in comparison with MARS 15 calculation at each point.