# MEASUREMENT OF THE PHASE PORTRAIT OF A 2 MeV PROTON BEAM ALONG BEAM TRANSFER LINE*

T. Bykov, Ia. Kolesnikov, S. Savinov, I. Shchudlo, S. Taskaev,
Budker Institute of Nuclear Physics, 11 Lavrentiev ave., 630090 Novosibirsk, Russia

*Abstract*

For the development of a promising technique for the treatment of malignant tumors - boron neutron capture therapy - an accelerator source of epithermal neutrons has been proposed and created at the Budker Institute of Nuclear Physics (Novosibirsk, Russia). For future therapy and radiation testing of materials for ITER and CERN with fast neutrons, it is necessary to ensure the transportation of a proton beam in a high-energy path at a distance of 10 meters.

For this purpose, a phase portrait of the proton beam was measured in the vertical and horizontal high-energy paths using a movable diaphragm with a diameter of 1 mm, mounted on a three-dimensional vacuum driver, and a wire scanner.

The software for remote control of the movable diaphragm and data processing of the wire scanner was developed. An algorithm for processing a series of measurements was also developed to reconstruct the image of the phase portrait of the beam and calculate the emittance. This work describes in detail the features of the measuring devices, control algorithms and data processing.

An experiment was carried out to measure the phase portrait and emittance of a proton beam with an energy of 2 MeV and a current of up to 3 mA. A beam of neutral particles was also measured. The effect of a bending magnet on the focusing and emittance of the beam is studied. The invariant normalized emittances calculated from the measured phase portraits make it possible to claim that the beam can be transported over distances of about 10 meters without changes in the current geometry of the high-energy beam line.

## INTRODUCTION

Epithermal neutrons source based on a vacuum-insulated tandem accelerator [1] with a lithium target and a neutron Beam Shaping Assembly (BSH) [2] is currently the only experimental facility of this class in the world. It is able to generate a stationary beam of protons or deuterons with an energy range of 0.6 to 2.2 MeV and a current range of 1 pA to 10 mA. Such a wide range of parameters opens up a whole range of applications, in addition to clinical trials and therapy.

For future therapy and radiation testing of materials with fast neutrons [3, 4], it is necessary to ensure the transportation of a proton beam in a high-energy path at a distance of 10 meters. For that purposes a beam phase portrait and emittance was measured.

* The study was supported by a grant from the Russian Science Foundation (project No. 19-72-30005) with the support of the Budker Institute of Nuclear Physics SB RAS.

## EXPERIMENTAL SETUP

To measure the phase portrait of the proton beam, the cooled diaphragm and the three-dimensional vacuum driver are placed in the diagnostic chamber in front of the bending magnet, the wire scanner is placed behind the bending magnet, and the luminescence effect of the lithium target is monitored by a video camera (Fig. 1). The wire scanner is placed so that one wire measures the current horizontally and the other vertically.

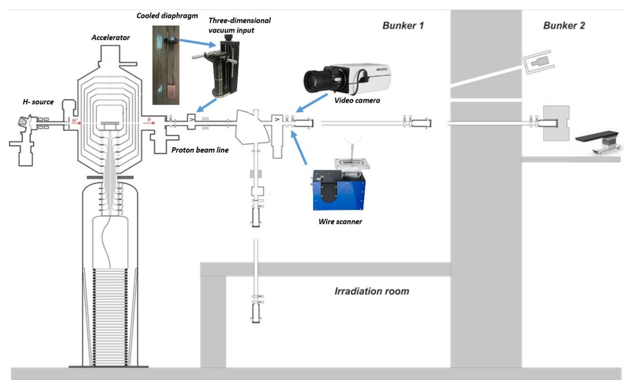


Figure 1: Experimental setup.

First, using a lithium target like a Faraday cup, the center of the beam is found. Further, by entering the motion, one coordinate is left fixed, and the other is moved and the current profile is measured. The same is repeated for the second coordinate.

It should be said that the wire scanner was used not in a standard way. Normally it should be used to measure low-energy charged-particle beam profiles (< 1 MeV) [5]. The use of cooled diaphragm with a hole of 1 mm allows to reduce the heat power generated on the wire probes so that it allows to measure the proton beam current with energy of 2 MeV and current up to 3 mA. During the experiments this constraint were found. A further increasing in current leads to overheating of the tungsten scanner probes and to the ignition of a plasma discharge.

## DATA PROCESSING

An example of a measurements made by wire scanner is shown on Fig. 2. Each graph corresponds to the measurement of the beam at a given position of the cooled diaphragm. In this case it can be seen that the beam distribution is measured along the X axis, and the Y axis is fixed. Then the graphs are shifted taking into account the coordinates of the cooled diaphragm.

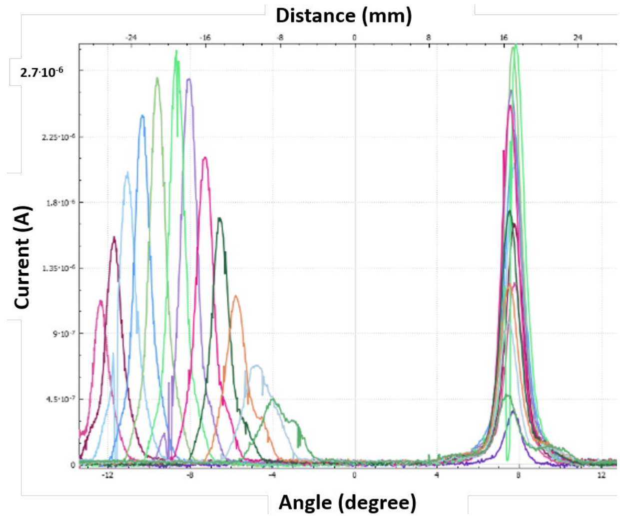


Figure 2: Beam measurements along one coordinate made by wire scanner.

Then all graphs as a whole are shifted to the origin. A mean graph is built between two adjacent graphs, with the values that are the average values between the two values of the corresponding graphs. This operation is repeated several times. As a result, a more continuous, smoother distribution is obtained from a discrete set of curves.

Then a 3D phase portrait is constructed. The examples of phase portrait obtained in this way is shown in Fig. 3.

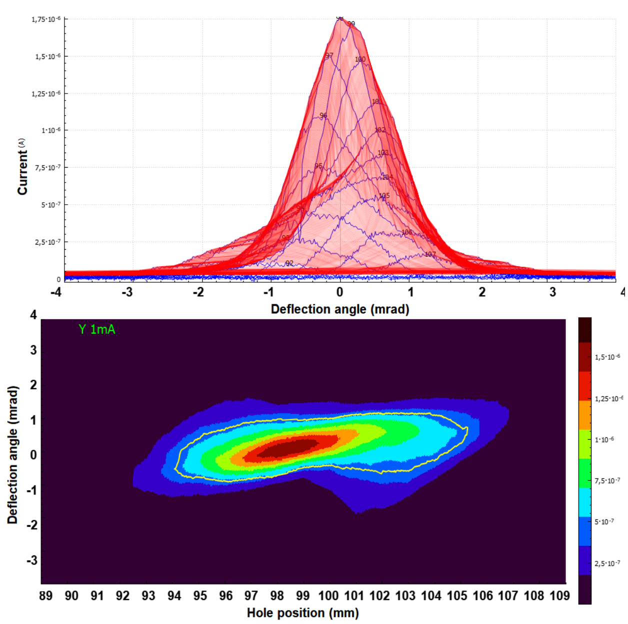


Figure 3: Shifted and augmented graphs and the 3D phase portrait is a result of data processing.

The coordinate of the cooled diaphragm is plotted along the X axis, the deflection angle of a beam is shown along the Y axis, and the current value is indicated by color.

In order to calculate the emittance, the following steps were taken. The area is determined, the total current in which is 2/3 of the total current throughout the portrait, and the area value will be denoted as $\varepsilon_{2/3}$. This area was then multiplied by the relativistic coefficients $\beta$ and $\gamma$, for a proton beam with an energy of 2 MeV they are $\beta = \sqrt{\frac{2T}{E}} =$ 0,065 and $\gamma = \frac{1}{\sqrt{1-\beta^2}} =$ 1,002, respectively. Thus, the invariant emittance is $\varepsilon_{\text{inv}} = \varepsilon_{2/3}\beta\gamma$. Note that the X axis in most cases lacked the scanning range, so the emittance will be indicated with an inequality sign.

## RESULTS AND DISCUSSION

The influence of the proton current on the phase portrait of the beam was studied. The emittance coincides with an accuracy of 10% for proton beam currents from 0.5 mA to 3 mA. The phase portrait depends on the current since the space charge of the beam affects the beam, and a 1.5% change in the magnetic lens current significantly affects the beam transport. The normalized emittance was defined as 0.23 mm mrad.

The effect of the focusing magnetic lenses, which are located in the entrance to the accelerator, on the proton beam after passing through the accelerator was also studied. The current 66 A and 56 A in magnetic lenses is the optimal mode used when conducting a beam with parameters standard for BNCT. In the weak focusing mode (65 A and 55 A), the beam has a large angular divergence in comparison with other modes. In the strong focusing mode (67 A and 57 A), it would seem that the beam size is small and the angular divergence is acceptable. However, with such focusing, the ion beam heats up the entrance diaphragm of the accelerator strongly, which makes this mode unacceptable during long-term operation.

The estimated beam sizes were obtained for the positions of the lithium target. That is 30 mm at position (Fig. 4 A) after going down through the bending magnet. Beam is expanded further down into irradiation room (Fig. 4 B) with the size 55 mm. Beam has the size 20 mm (Fig. 4 C) after the bending magnet going straight through and expand up to 28 mm at the position D (Fig. 4) and 38mm at Bunker 2 at the BSH (Fig. 4 E).

A beam of this size can be delivered to Bunker 2 for clinical trials and in the radiation testing room.

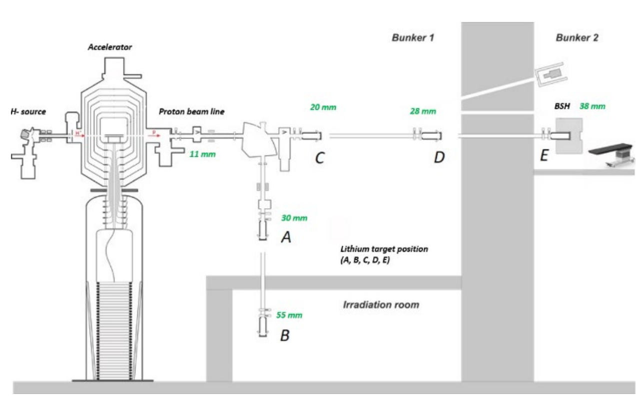


Figure 4: Estimated beam size at different positions of the lithium target.

## CONCLUSION

The phase portrait of a proton beam obtained in the vacuum insulated tandem accelerator was measured using a movable diaphragm and a wire scanner. The result obtained made it possible to determine the size of the proton beam in lithium target placement positions.

## REFERENCES

[1] S. Taskaev, "Development of an accelerator-based epithermal neutron source for boron neutron capture therapy", *Phys. Part. Nucl.* vol. 50 no. 5, pp. 569–575, 2019. `doi:10.1134/S1063779619050228`

[2] L. Zaidi *et al.*, "Beam Shaping Assembly Design of $^{7}$Li(p,n)$^{7}$Be Neutron Source for Boron Neutron Capture Therapy of Deep-seated Tumor", *Appl. Radiat. Isot.,* vol. 139, p. 316, 2018. `doi:10.1016/j.apradiso.2018.05.029`

[3] A. Shoshin *et al.*, "Test results of boron carbide ceramics for ITER port protection", *Fusion Eng. Des.*, vol. 168, 112426, March 2021. `doi:10.1016/j.fusengdes.2021.112426`

[4] D. Kasatov *et al.*, "Fast-neutron source based on a vacuum-insulated tandem accelerator and a lithium target", *Instrum. Exp. Tech.*, vol. 63, no. 5, pp. 611–615, 2020. `doi:10.1134/S0020441220050152`

[5] D-Pace Oscillating Wire Scanner Probe, `https://www.d-pace.com/?e=70`