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Research into the advanced experimental methods for precision ion stopping range measurements in matter

I.E. BAKHMETJEV,[1] A.D. FERTMAN,[1] A.A. GOLUBEV,[1] A.V. KANTSYREV,[1] V.E. LUCKJASHIN,[1] B.Yu. SHARKOV,[1] V.I. TURTIKOV,[1] A.V. KUNIN,[2] V.V. VATULIN,[2] N.V. ZHIDKOV,[2] E.G. BALDINA,[3] U. NEUNER,[4] J. WIESER,[4] J. JACOBY,[4] AND D.H.H. HOFFMANN[5]

[1]Institute of Theoretical and Experimental Physics (ITEP), Moscow, Russia
[2]Russian Federal Nuclear Center—All-Russia Research Institute of Experimental Physics (RFNC-VNIIEF), Sarov, Russia
[3]Joint Institute for Nuclear Research (JINR), Moscow, Russia
[4]Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Germany
[5]Technische Universität Darmstadt, Darmstadt, Germany

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Abstract

The article presents the results of the experimental research on precision measurement of total stopping range and energy deposition function of intermediate and heavy ion beams in cold solid matter. The “thick target” method proves to be appropriate for this purpose. Two types of detectors were developed which provide an error of the total stopping range measurement of less than 3% and of the beam energy deposition function of about 7%. The experiments with $^{58}\mathrm{Ni}^{+26}$, $^{197}\mathrm{Au}^{+65}$, and $^{238}\mathrm{U}^{+72}$ ion beams in the energy range 100–300 MeV/u were performed on SIS-18 (Gesellschaft für Schwerionenforschung, Darmstadt) in 1999–2001. The measured data on the total stopping ranges for the above ion species in bulk and foiled Al and Cu targets are presented. The investigation showed that there is a noticeable discrepancy between the measured stopping ranges and the theoretically predicted ones. Also, it was shown that realistic ion energy deposition depends on the type of target (bulk or foiled). Further investigation is necessary to clarify the latter.

Keywords: Heavy ion; Stopping range; Stopping power; Solid matter

1. INTRODUCTION

For a variety of ion beam applications, precise knowledge of the fundamental parameters underlying their interaction with matter is required. These are such parameters as total ion stopping range and energy deposition.

This inspires a large number of experimental studies of stopping processes, such as differential energy losses in thin foils, stopping characteristics as functions of material density, temperature, and so forth. Up to now, most of the measurements of the stopping power of ion beams in solid and gas targets have been performed with thin targets, which allowed obtaining differential energy losses. A limited number of experiments on measurement of total stopping ranges of heavy ions for some ion beam parameters are available in literature. Most of the data on the total ion beam range in matter are reconstructed from the experiments with protons and α particles. This, however, does not solve the problem of projectile effective charge evolution inside the target, which may influence energy deposition function significantly. The available data on the stopping ranges of heavy ions in matter, however, show noticeable discrepancies, sometimes exceeding 20%. There exist a number of theoretical models of these processes, which also give different values of total ion stopping ranges in cold matter and different temperature- and density-dependent behavior. Verification and calibration of theoretical models using the values measured for protons and α particles is insufficient for prediction of beam–target interaction of fast intermediate and heavy ions. The recent studies showed that the available data on ion–material interactions are insufficient to form a reliable database for numerical modeling of the impact of intense ion beams on targets.

The deviation of realistic energy deposition function from the theoretically predicted ideal case may be caused by several reasons. First, experimental ion beams have certain pulse divergence $\Delta P/P$, as well as angular divergence, re-

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Address correspondence and reprint requests to: A.A. Golubev, Institute of Theoretical and Experimental Physics (ITEP), 117259 Moscow, Russia. E-mail: alexander.golubev@itep.ru

sulting in certain broadening of the Bragg peak as compared to the theoretical one. Second, there is lack of understanding of some processes of ion interaction with matter, such as the projectile charge evolution inside the target, the influence of target density, material structure, impurity content on ion energy loss, and deposition. Thus, there are certain indications that the equilibrium charge of the projectile is reached rather late, after the ion has traveled a long distance in the target. If so, more accurate determination of the effective charge of the projectile used to calculate stopping power should be required. It may also mean that the data on ion stopping powers from experiments with thin foils cannot be used to reconstruct the dE/dx function for solid targets due to the nonequilibrium character of the projectile charge evolution in the target made of foils. Also, the influence of low amounts of high-Z impurities (about 10^{-3} atoms per one target atom) may contribute the number of extra electrons sufficient to influence the projectile interaction with the target.

The processes of the projectile ionization and electron recombination may also appear significant for energy straggling, and, therefore, smoothing of the Bragg peak of energetic heavy ions.

2. THE "THICK TARGET" METHOD FOR PRECISION MEASUREMENT OF ION BEAM ENERGY DEPOSITION FUNCTION

All the above effects of ion beam energy deposition in solid matter require thorough experimental investigation with "thick targets."

The thick target method for precise measurement of the total ion energy deposition range in solids is promising for several reasons:

1. It provides direct measurement of the energy deposition function, rather than its reconstruction from the measured differential energy loss;
2. It eliminates the "edge effects," as compared to the "thin foil" approach;
3. It takes into account the beam straggling and fragmentation, secondary particles, and so forth.

This method consists of measuring energy deposited along the ion path in a target of variable thickness which is known with high precision and covers the total stopping range (Fig. 1). The energy deposited in the target material is measured by thin detectors, such as scintillators, calorimeters, semiconductor detectors, and so forth. The precision of the method is determined by the parameters of the detectors (energy resolution, efficiency of registration, detection threshold, etc., depending on the detector type) and the target parameters (precision with which the target thickness, density, and purity are known). To get accurate and reliable results, the ion beam parameters should also be well controlled.

It is reasonable to experiment with two target designs—the bulk material and foils—to evaluate edge and other effects on the whole picture of energy deposition on a scale of the target of total absorption.

The first design represents two wedges, the larger one sliding along the fixed smaller one to vary the target thickness. Such targets were manufactured of high purity Al and Cu (99.999) with precise control of the angle (22°) and surfaces of optical quality. The distance between the two wedges was $\sim 35\ \mu$m. The density of the target material was measured with an accuracy of 0.1% by two methods. The first method is based on measurement of the target volume and weighing the target. The second method is based on the Archimedes' principle. The step over the target thickness was determined by the step of a manipulator moving one of the wedges against the other. Axial resolution of the manipulator mounted at the HHT experimental area (SIS-18, Gesellschaft für Schwerionenforschung (GSI), Darmstadt), where the experiments were performed, was 20 μm. That allowed going through the bulk of the target with a minimum step of 8 μm.

The second design is an assembly of foils of different thickness. The thinnest foils were placed at the rear of the target (end of the stopping range) in order to provide higher spatial resolution near the Bragg peak.

3. THE DETECTORS FOR PRECISION MEASUREMENT OF ION BEAM ENERGY DEPOSITION FUNCTION

The existing experimental methods for precision measurement of total ion stopping range in matter were analyzed. Both the traditional methods for measuring energy losses (ΔE magnetic analysis, electrostatic analysis, time of flight method, Rutherford backward scattering, semiconductor detectors, and others) and the methods which allow measuring ion beam energy deposition profile in targets with high spatial resolution (calorimetric, acoustical methods, etc.) were considered.

Three types of detectors were used: (1) the calorimeter detector, (2) the detector on the basis of excitation of acoustic waves, and (3) radiochromic film MD-55-1(2) manufactured by National Institute of Standards and Technology. For precision measurement of the energy deposition profile, one of the calorimeters was placed in front of the target and used for calibration (Fig. 2). That provided absolute measurements of ion beam energy deposition in the target of varying thickness. The calorimeter measures the change of temperature in a thin layer of material due to its heating by the passing ion beam. The photo and the schematic diagram of the calorimeter are shown in Figure 3. The calorimeter is enclosed in a metal case and consists of a receiving platform made of a foil attached to thermomodules, which are fixed on a massive thermostat.

The foil thickness is selected not more than 1% of the total stopping range of the ions of interest in the considered target material. The thermostat is isolated from the calorimeter

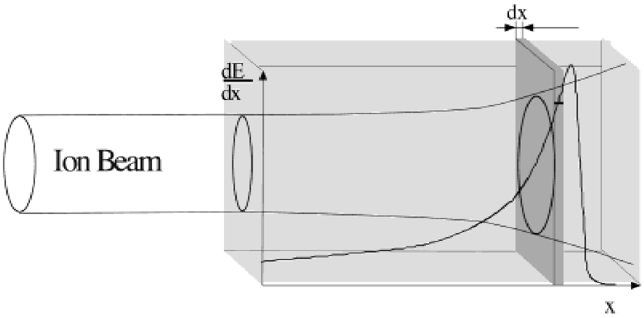

Fig. 1. The thick target method.

body. The ions passing through the foil deposit part of their energy in it. The increment of the foil temperature is directly proportional to the deposited energy. Two thermoelements measure the increment of the foil temperature and transform it to the electrical signal. Two thin-film resistances (thickness 0.05 mm) are glued to the surface of the foil out of direct exposure to the beam for absolute calibration. The error of the specific deposited energy measurement is 7%. The size of the device is ∅50 × 11 mm. The aperture of the calorimeter is ∅15 mm. The detector sensitivity is 5 mV/J. The amplifier with $K = 10^4$ and the oscilloscope are used to record the signal. Figure 4 shows the typical electrical signal from the calorimeter (right curve) for a typical ion beam pulse (left curve) depositing its energy in the calorimeter. The time of the signal amplitude growth is ~1 s. This time is determined by the rate of dissipation of the absorbed thermal energy in the volume of the receiving plate. After that, the temperature of the receiving plate starts to decrease exponentially. The parameters of the exponent are determined by heat conductivity of thermoelements. Since the measurements are carried out in vacuum and the temperature increment of the receiving plate is a hundredth of a grad, radiation heat transfer and exchange with residual gas may be neglected. The time constant of the calorimeter (the time during which the signal decreases *e* times) is ~10 s.

The acoustic detector is based on the piezoelectric effect and records an acoustic wave generated by interaction of ion beam with a thin foil. The view and the schematic diagram of the acoustic detector are show in Figure 5. The detector is enclosed in a metal case and consists of a receiving plate in the form of an ellipse made of a foil attached to a piezoelectric sensor mounted in the focus of the ellipse. The ion beam strikes the detector in the second focus of the ellipse. The receiving plate is isolated from the acoustic body by thin wires. Such a configuration allows us to decrease the noise level of the detector to 10 mV, at the maximum linear target signal of 10 V. The dynamic range of the preamplifier is 1000. The acoustic detector was calibrated on the proton beam with ion energies between 70 MeV and 200 MeV produced by the proton accelerator U-10 (Institute of Theoretical and Experimental Physics, Moscow). The accuracy of calibration on the absorbed dose was 5%; the particle current was measured with an error of 3.4%. The beam intensity varied between 10^8 and 10^{10} particles per pulse with a pulse duration of 100 ns. The calibrated curve of the output signal from the acoustic detector as a function of the absorbed energy is shown in Figure 6 (left curve). The sensitivity of the acoustic detector is ~77 V/J. Figure 6 demonstrates the linear character of the detector response in the described conditions, with the absorbed energy of the proton

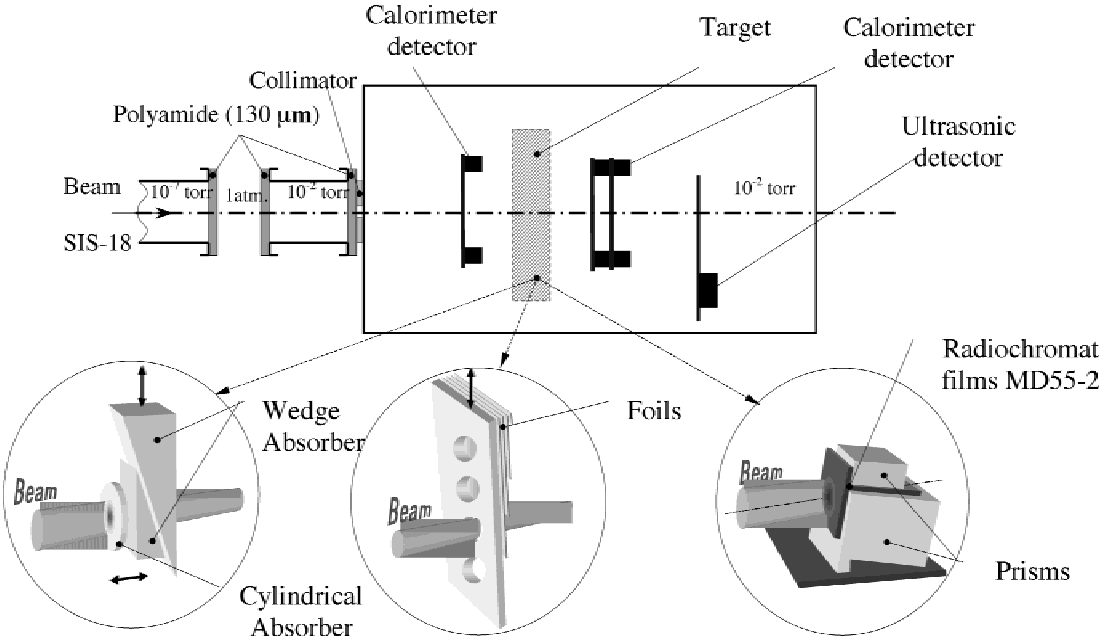

Fig. 2. The experimental setup.

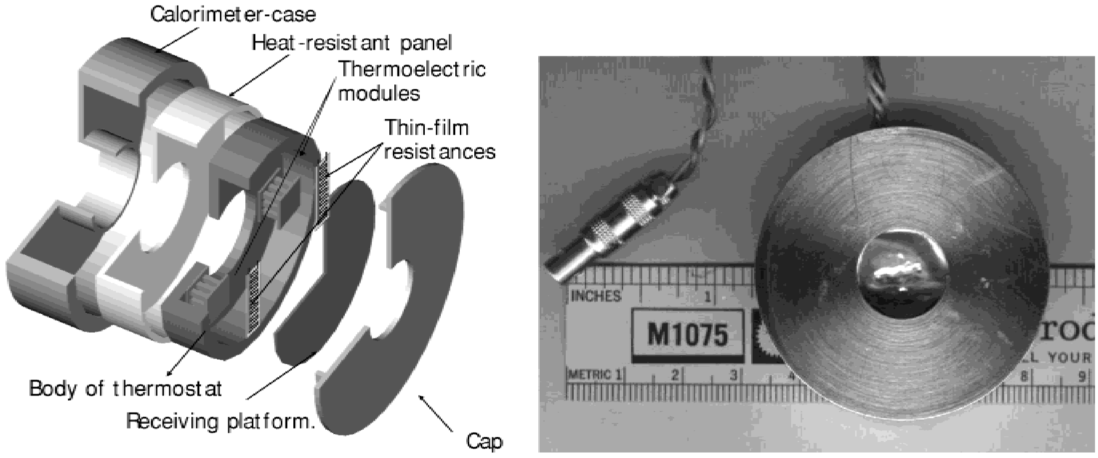

Fig. 3. Calorimeter detector.

beam changing 30 times. The typical signal from the acoustic detector at the impact of an ion beam pulse (see Fig. 4, left curve) is shown in Figure 6 (right curve). The period of the signal oscillation and the time delay between the beam pulse and the acoustic wave are determined by the geometry of the receiving plate and the sound speed in the material of the plate.

The third type of detector used for on-line control of the quality of ion beam adjustment on the target and for measurement of the total stopping range is the radiochromic film RCF-MD55-1(2). Two radiochromic films were used in the experiment (see Fig. 2, the right target scheme). The first was positioned before the target and the second mounted between two massive plates turned at a small angle to the beam axis. Figure 7 illustrates the typical images from these films. Developing of the second film on a microdensitometer allows us to get the information on the energy deposition and stopping range of the ion beam in the target.

4. THE EXPERIMENTAL RESULTS

The series of experiments on measurement of ion stopping range and energy deposition in cold solid targets was conducted at the HHT experimental area of the SIS-18 accelerator facility (GSI, Darmstadt) during three runs in 1999–2001. ^{58}Ni, ^{197}Au, and ^{238}U ion beams with the energies 100, 200, and 300 MeV/u interacted with Al and Cu (solid and made of foils) targets. Typically a 1-μs ion beam pulse consists of four 50-ns bunches (see Fig. 4, left curve). The pulse shape was controlled on-line during the experiments by a fast current transformer. The ion beam was focused in a $\varnothing$5 mm spot on the target surface by magnetic quadrupole lenses. The area of effective registration was $\sim\varnothing$15 mm with both the acoustic and calorimeter detectors, thus overlapping the beam spot on the target.

The typical experimental curves of the beam energy deposition profiles in the target measured by three different detectors are shown in Figure 8. The deviation of the experimental data from different detectors is not more than the experimental errors. The experimental error is about 3–3.2% and consists of the uncertainty of the ion energy (1%) and the error of the method itself (2.8–3.0%). The latter includes the target thickness error 0.5% and the energy resolution of the detectors 2.75–2.9%, depending on the detector type.

All the experimental data on total stopping ranges R_p of ^{58}Ni^{+26}, ^{197}Au^{+65}, and ^{238}U^{+72} ion beams in Al and Cu

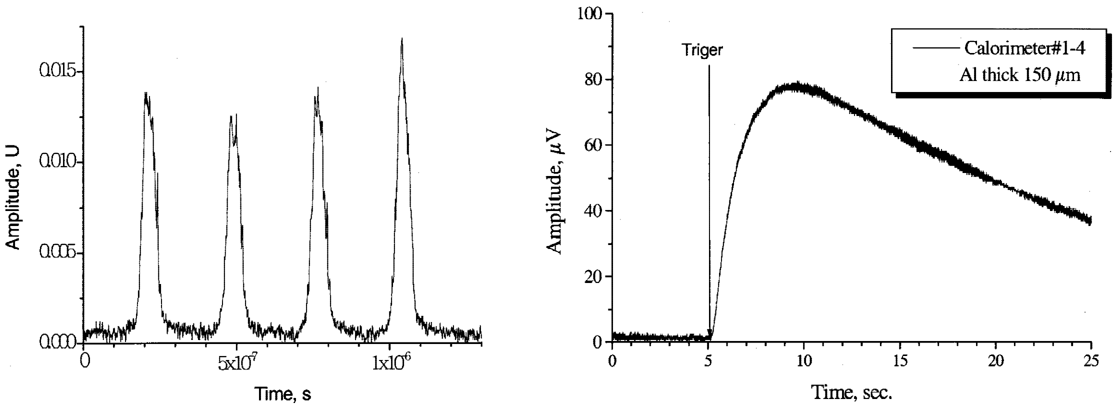

Fig. 4. The typical ion beam pulse (left curve) and typical signal from the calorimeter (right curve).

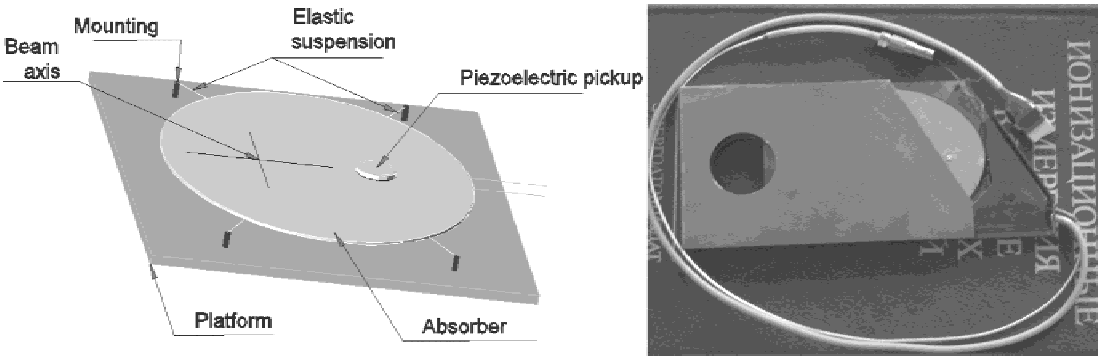

Fig. 5. Acoustic detector.

targets are presented in Table 1 in comparison with the numerical simulation by the code SRIM. Maximum deviation between the experimental and the calculated data is 15%. The investigations showed that it is important to take into account the realistic beam parameters (energy and angular divergence) and target parameters (density variations, impurities). The above factors, however, are insufficient for adequate theoretical description of the process of ion–matter interaction. It is understood that certain theoretical concepts should be improved. In particular, the notion of an effective charge of an ion penetrating matter needs thorough reconsideration. The influence of secondary particles on ion energy deposition is also one of the processes requiring more detailed investigation.

5. CONCLUSION

The experimental results may be summarized as follows:

1. Two types of absolutely calibrated detectors (calorimeter and acoustic) for precise measurement of the total stopping range (with the accuracy better than 3%) and energy deposition function of heavy ion beams in solid cold matter using the thick target method were developed and their adequacy proved experimentally. The measurement techniques using these detectors were established.
2. The total stopping ranges and energy deposition functions of the beams of intermediate and heavy ions $^{58}Ni^{+26}$, $^{197}Au^{+65}$, and $^{238}U^{+72}$ in the energy range 100–300 MeV/u were measured in the solid and foiled Al and Cu targets.

The investigation of the stopping of ion beams in cold matter carried out in 1999–2001 at GSI (Darmstadt, Germany) corroborated that the new direct data on the stopping powers and ranges of ions in solid matter is indispensable for further research in many fields of fundamental and applied science where intense ion beams are applied as an instrument for investigation of material properties. The available data obtained mainly from the experiments with thin foils and reconstructed from the data for light ions (basically protons and α particles) cannot provide the required accuracy, as data obtained in this way does not account for some impor-

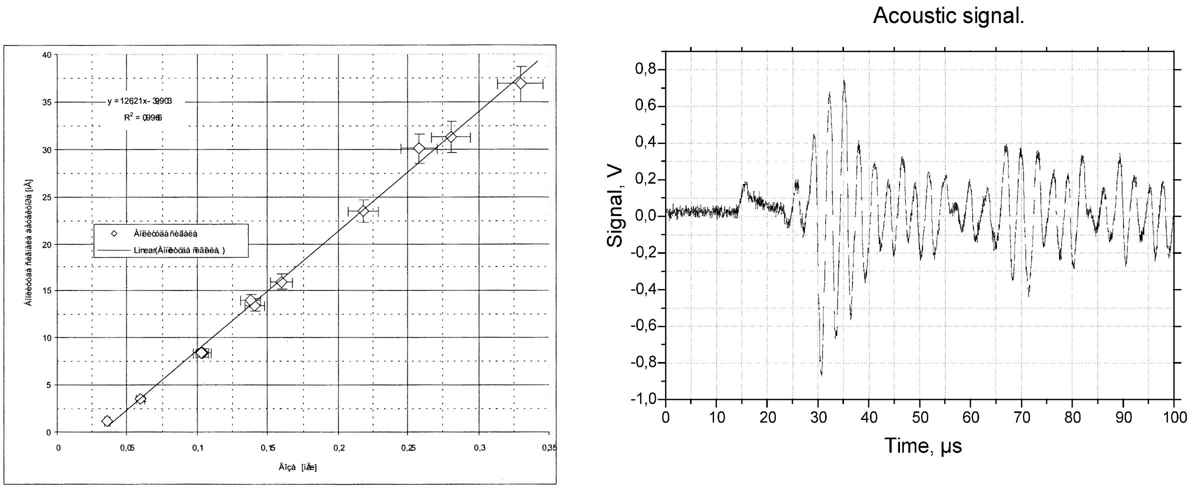

Fig. 6. The calibration curve (left curve) and typical signal from the acoustic detector (right curve).

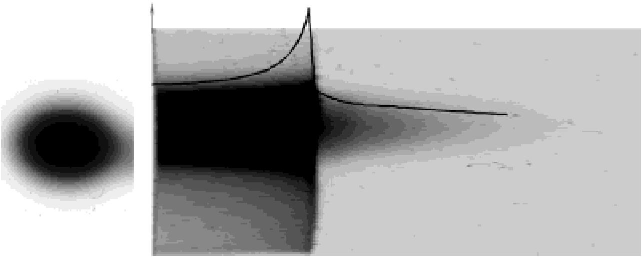

Fig. 7. The ion beam images on the radiochromic film before and in the target.

tant effects, such as evolution of the charge of an ion passing through the bulk matter, collective effects in condensed matter, secondary particles, and radiations.

This investigation proves that the direct experimental data on ion beam interaction with cold matter are not described with sufficient accuracy by the existing theoretical models and, therefore, further experimental and theoretical research in this direction is required. More experimental data for a variety of ion and target species would be of great help both for theoretical and numerical research. The proposed thick target method, rather than using thin targets, proved its applicability and adequacy in the context of the considered problem. The proposed method and developed detectors allow us to obtain accurate enough experimental data on the total stopping range of ions in cold matter. Measuring the energy deposition function, however, is a more complicated task, and its accuracy should be increased. Moreover, it would be desirable to get more detailed experimental information on the processes accompanying ion penetration through matter, such as the evolution of the ion charge, electron fields waken in the bulk of the target, fragmentation of the projectile and the target nuclei, and so on. These issues may require other experimental approaches, and will be complementary to the presented research.

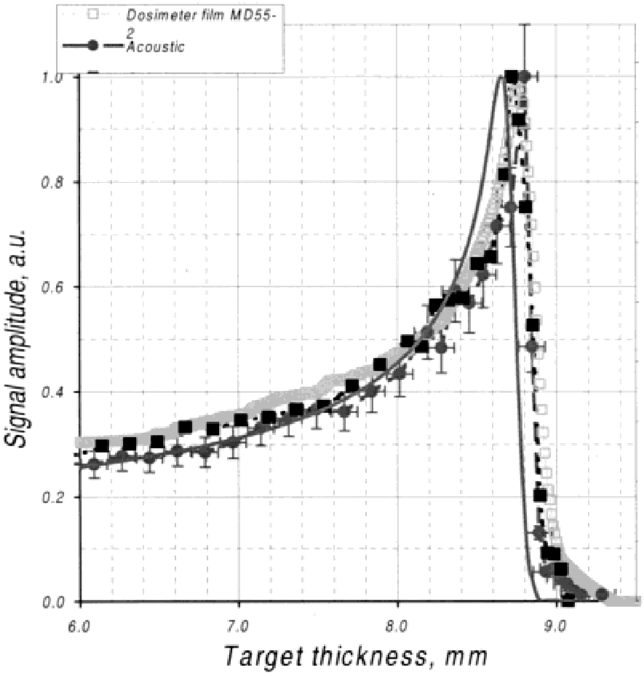

Fig. 8. The Ni 200-MeV/u ion beam energy deposition profiles.

Table 1. *Total stopping ranges*

Ion	Target		Energy (MeV/u)	Range (mm)		Deviation (%)
				Numerical (TRIM)	Experiment	
^{58}Ni^{+26}	Al	Wedge	100	2.87	2.77 ± 0.08	3.6
			200	8.99	9.10 ± 0.08	−1.1
			300	17.99	17.95 ± 0.08	0.2
		Foils	100	2.87	2.95 ± 0.08	−3.1
			200	8.99	9.60 ± 0.08	−6.8
	Cu	Wedge	100	3.19	3.20 ± 0.06	−0.9
		Foils	200	3.19	3.45 ± 0.06	−8.8
			300	4.09	4.05 ± 0.08	1.2
^{97}Au^{+65}	Al	Wedge	180	1.33	1.13 ± 0.08	15.0
			290	7.77	7.53 ± 0.08	3.1
	Cu	Wedge	180	1.33	1.41 ± 0.08	6.0
		Foils	284	2.68	2.45 ± 0.07	8.6
^{238}U^{+72}	Al	Wedge	200	4.09	4.05 ± 0.08	1.2
			300	7.33	7.10 ± 0.08	3.3
		Foils	200	1.45	1.40 ± 0.08	4.8
			300	7.33	7.45 ± 0.06	−1.9
	Cu	Wedge	200	1.45	1.45 ± 0.06	0.7
			300	2.67	2.55 ± 0.06	3.7
		Foils	300	2.67	2.60 ± 0.06	2.6