PN-ACD-233

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Neutron Transmission through Metal Capillary Tubes

(CHEN-MAYER -CAST 95)

A Final Report to CAST

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Date November 19, 1996

To USAID Center for Development, Information, Evaluation

From Sharon Vandivere

Subject CAST final reports

At the suggestion of John Daly of USAID's Bureau for Global Programs, I am sending the enclosed final reports of projects conducted under the Cooperation in Applied Science and Technology (CAST) program The CAST program is funded by USAID and administered by the National Academy of Sciences As I receive additional final reports, I will be sure to forward to you

If you have any questions regarding the reports or the program, please contact me at 202-334-2644 or <ocee@nas edu>

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1 Preliminary information

Host H Heather Chen-Mayer, Physicist, National Institute of Standards and Technology (NIST), USA*

Visiting Scientist Vladimir S Fokin, Senior Scientific Researcher, Institute of Physics and Technology of the Russian Academy of Sciences (FTIAN), Russia

Duration of Visit Nov 1, 1995 –Oct 31, 1996 Visitor returned to Russia on Dec 14, 1996 after a no-cost extension of the stay to finish the work

* Since the award of the grant, the host has switched affiliation from University of Missouri to NIST (as of May 1, 1995), which did not affect this project since the proposed work was to be performed at NIST

2 Scientific activities

2 1 Objectives proposed and research actually performed

We have proposed four objectives

- Devise neutron transmission measurement procedures for straight and bent metal capillaries,
- Determine neutron transmission properties of metal tubes from various sources,
- Identify potential applications,
- Design focusing devices

The research performed has touched each of these objectives, with emphasis on the first and second one These will be summarized in details in the following sections

2 2 Foundation of research performed on neutron transmission using metal capillaries

The guiding of neutrons through glass capillaries has become a useful technique for the focusing of cold neutrons, with gains in neutron current density of nearly two orders of magnitude under certain circumstances [1] Further gains in neutron current density using capillary optics can be achieved by increasing the acceptance volume of phase space for these focusing lenses The result is that the proportion of incident neutrons reaching the focus increases Since the phase space consists of real space and angular space, increasing either one is desirable We can increase the real space volume by maximizing the percentage of open channels through which neutrons travel, and the angular space by maximizing the critical angle of reflection to accept a neutron beam with a higher divergence The latter can be achieved by coating a glass capillary channel with a material such as nickel (or even better ^{58}Ni) which has a higher critical angle than glass In the case of nickel this increases the angular acceptance volume by $(1\ 73/1\ 10)^2 = 2\ 47$, the square of the ratio of the critical angles of nickel to glass Currently the technology to produce such a coating in a small channel (~ 0 05 mm ID) of useful length (~100 mm) is not available On the other hand, commercially available metal tubes (nickel and stainless steel), although with a higher ID, can be used as a good starting point to investigate whether the increase in critical angle can indeed increase neutron transmission, taking into account the surface quality, channel size, and bending behavior This is the focus of our research Since most of the previous experience has been with glass capillaries, it is necessary to make comparative studies between metal and glass capillaries of the similar dimensions and under the same experimental conditions

2 3 Experimental materials, equipment, conditions, and techniques

Neutron transmission measurements have been undertaken on capillaries of various materials These are nickel capillaries, of inner diameter (ID) of 0 44 mm, lead glass

capillaries, ID 0 53 mm, and non-lead glass capillaries, also ID 0 53 mm All measurements have been performed with capillaries of length 90 mm

In the past we have found that such transmission measurements are difficult to perform with accuracy Special care must be taken to reduce the background in the detector, and most importantly to avoid neutron leakage around the outer wall of the capillary Figure 1 is a schematic diagram of the holder used for these neutron transmission measurements A polymer incorporated with enriched ^{6}LiF (termed Li-poly), a most convenient and effective shielding material, is used as a tight shielding around the capillary and as a lining on the aluminum holder wherever the incident beam might scatter The capillary is threaded through a hole the size of the tube OD drilled in the Li-poly close to the entrance, and held by a clamp and oriented such that the length of the capillary lies along the axis of the incident beam The bending of the tube is achieved by combining the detector, shielding, and translation stages into one mechanism, described as follows

A neutron imaging detector, also termed a video radiation detector (VRD) [2], is held at the exit of the capillary (see Figure 2) with two layers of Li-poly as shielding, allowing only an aperture through which the tube is inserted This aperture can be translated together with the detector in the transverse direction by a motion controlled actuator (accuracy 0 001 mm), and therefore acts like a carriage for the end of the tube to create a dynamic bending geometry with three sections The farther the end of the tube is carried away from the straight position, the higher the transverse displacement (simply termed as "shift distance"), and therefore the smaller the bending radius created The entrance of the tube is clamped such that the first section of the capillary, 26 mm in length, is held straight, the following 57 mm section is curved, and the final 7 mm section of the capillary is assumed to be straight There is a space of about 3 mm between the exit end of the capillary and the sensor chip in the detector A helium-neon laser is used for alignment of the capillary along the axis of the incident beam

These measurements have been performed on the neutron guide NG-0 which views the cold neutron source at the 20 MW reactor at NIST The incident neutron beam is defined by two apertures upstream, a 25 4 mm Li-poly circular aperture and a rectangular Li-poly aperture of dimensions 25 4 mm x 19 1 mm The collimation of the beam entering a capillary is defined by the 25 4 mm aperture at a distance of 1757 mm Hence the half divergence angle determined by this geometry is θ_d = 7 2 mrad The spectral distribution of wavelengths for the beam is presented in Figure 3 and an average wavelength of 0 51 nm has been determined This means that an average critical angle of 8 8 mrad may be considered for the nickel capillaries (γ_c = 17 3 mrad nm–1) and 5 6 mrad for the glass capillaries (γ_c = 11 0 mrad nm–1)

The transmission is determined by measuring the neutron beam intensity exiting the capillary, which is achieved by integrating the transmitted signal over a certain amount of

time on the imaging detector, and comparing it with the incident beam intensity at the entrance of the tube obtained by the same method The transmission of the capillary is measured as a function of the transverse displacement of the exit end from its straight position As the displacement increases, or bending radius decreases, the transmission decreases Good neutron shielding in this experimental arrangement has made it possible to measure transmissions as low as 10^{3} - 10^{6} at smaller radii (shift distance up to 5 mm), with exposures up to 25 minutes, whereas for larger radii (shift distance of 0 to 1 mm) transmissions up to 0 87 are obtained with exposures of 5 – 10 seconds The statistical uncertainty in the measured transmission is estimated to be 5%

2 4 Results and discussions

We first discuss the results of the measurement on the Ni capillary The experimentally determined transmission of the Ni tube as a function of bending created by the end displacement (shift) is plotted in Figure 4 (open circles) The maximum transmission for the tube with inner diameter d = 0 44 mm is 0 86 when the tube is straight (shift = 0, see Table 1) At small displacements, the transmission can include the contribution from those trajectories that have no reflection from the tube wall When the displacement becomes large enough to block out the direct "line-of-sight", only those trajectories that undergo one or more reflections can be transmitted, delivering a real "guided" beam For capillaries of constant curvature, this threshold displacement is 4d, d being the inner diameter of tube However, in our case the under-illumination of the entrance in angular space (the incident beam divergence less than the critical angle of the tube) causes the line-of-sight to disappear earlier (< 4d) Using the 7 mrad half-divergence of the incident beam, the 57 mm curved plus the 7 mm straight sections cut off the most extreme line-of-sight trajectories when the end displacement is about 0 44 mm, or 1d However, since the incident beam has a wide range of wavelengths, and the 7 mrad is an average divergence perhaps corresponding to the average wavelength of 0 51 nm, there remain line-of-sight trajectories for neutrons of longer wavelengths entering at an angle higher than 7 mrad Experimentally this is signified by the flat response of the transmission as a function of bending initially and then the gradual decrease as the threshold is reached By stepping the motor that creates the bending at 0 05 mm increments, the onset of such a decrease can be examined At the cut-off, or when the shift equals d, the transmission remains quite high T = 0 63 Shifts that equal 2d and 3d give T = 0 25 and 0 11, respectively, and the greatest shift of 7d (about 3 mm) reduces the transmission to 0 014

Currently there is no analytic solution for the transmission through a curved circular guide A Monte Carlo program for neutron propagation through curved capillaries [3] has been used for computer simulation of the transmission The following are input parameters for the program the parameters of a polynomial fit to the neutron beam spectrum (neutron flux distribution as a function of wavelength, Fig 3), the geometry of the experiment (which determines the source divergence), the chemical composition and dimensions of capillaries (which determines the critical angle and acceptance of the tube),

and the geometry of the bent capillary which takes into account the three sections (straight-bent-straight) The Fresnel reflectivity equation is used in calculating the transmission, which is defined as the ratio of the number of neutron trajectories exiting the tube to that entering However, we first verify the results of simulation under a special case when the tube is not bent (shift = 0), the analytic calculation for both transmission and number of reflection is available [4] Since the incident beam has a broad wavelength distribution, the acceptance varies as a function of wavelength λ following $(\gamma_c\lambda/\theta_d)^2$, where λ is the wavelength, γ_c is the critical angle per unit λ, and θ_d is the averaged half divergence of the beam When $\gamma_c\lambda > \theta_d$, i e the acceptance is higher than the incident beam divergence, representing an under-illumination, unity is used in place of $(\gamma_c\lambda/\theta_d)^2$ This change-over occurs at $\lambda = 0\ 4$ nm for our experimental arrangement The transmission is determined by the integral of the acceptance factor modified by the wavelength distribution over the range of 0 2 to 1 0 nm which includes most of neutron wavelengths The calculated transmission of 0 94 compares well with that obtained from Monte-Carlo simulation, 0 97, as well as the average number of reflections, 1 22 vs 1 25, for zero shift The analytic calculation gives a slightly lower transmission, this may be attributed to the "step-function" cut-off treatment of the reflectivity which discards the possibility of non-zero reflectivity at $\theta > \theta_c$, but is included in the simulation which correctly uses the Fresnel equation The same argument can be made for the average number of reflections, which is proportional to the average reflection angle which is higher in the simulation

The simulated transmission as a function of bending is compared in Figure 4 (line) with the experimentally measured values (open circles) For small bendings (shift < d), the measured values tend to be lower than the simulated values, but then have excellent agreement for shift distances up to 0 7 mm (1 7d) But when the shift distance becomes more than 2d the experimental transmission falls more rapidly than simulated transmission These differences can be interpreted as follows at very small bendings, or when the tube is nearly straight, the natural form of the tube may deviate from the perfect linearity and therefore cause the transmission to decrease compared with the simulation As the bending increases to the intermediate distances, the tension in the tube may actually cause it to conform to a more ideal shape, and thus the good agreement with simulation As the bending continues to increase, however, the number of reflections along the tube increases (Fig 4, right vertical scale) to an extent that the reflectivity loss which is not included in the Fresnel equation can no longer be neglected In other words, although the Fresnel reflectivity is calculated based on the index of refraction for the chemical compositions of the material comprising the capillary, it does not consider the roughness and the waviness of the walls, or the non-specular losses, which may also depend on the degree of bending This is amplified at higher bendings where R^N (R is the reflectivity, N is the average number of reflections) decreases as N increases for $R < 1$, resulting in the rapid decrease in the neutron transmission

The experimental and simulated transmissions for glass capillaries are presented in Figures 5 (lead glass), and 6 (non-lead glass) We can see that for both types of glass tubes the main features are common to the Ni capillary transmission For small bending shifts the measured transmission is lower, in the intermediate region where the shift is comparable to the tube diameter, the agreement is better, and at higher shifts the measured values are consistently lower than the simulated ones, though the differences vary The ratio of the experimental transmission to the simulated value is listed at selected regions of bending (shift values) in Table 1 The more the ratio deviates from 1, the worse the agreement There is a general trend of worse agreement at higher shifts for all three cases, signifying the increased number of reflections and the increased loss associated with it, as argued earlier

Table 1 Ratio of experimental transmission to simulated transmission for the three types of capillaries at selected bending points γ_c is the critical angle per unit wavelength calculated based on the composition of the capillary material

shift (mm)	Ni (γ_c = 17 3 mrad/nm)	Pb glass (γ_c = 10 6 mrad/nm)	non Pb glass (γ_c = 9 8 mrad/nm)
0 0	0 89	0 85	0 71
0 5	1 0	0 84	1 0
1 0	0 72	0 27	0 34
2 0	0 34	0 21	0 22
3 0	0 17	0 16	0 17

For the Pb glass capillary, the attempt to increase the bending shift up to 4 mm has led to the breaking of the capillary at the point of maximum curvature near the clamp However, the non-Pb glass capillary has survived At 4 mm shift (7 5d) (not shown in the figure) the ratio is even lower, 0 08 It is important to note that the chemical composition of this non-lead glass is not known exactly, and in the simulation program the composition of soda-lime glass has been used which may lead to the worse agreement between the experiment and simulation Nevertheless, the program quite correctly describes (for Ni and lead glass - very precisely) the trend of transmission of all three samples From these results we can obtain the measured reflectivity compared to the ideal values at each point of bending, if all sources of errors are taken into account This will be our future effort Figure 7 summarizes all three transmission curves, and it is obvious that the Ni capillary transmits neutrons better than the glass ones not only for small shifts but for the whole bending range

Other common factors that can be the cause of the difference between the experimental and simulated transmissions for both types of tubes are discussed as follows

1 The actual shape of the bent tube may differ from its approximation as a cubic curve in the simulation model [3], $y(x) = 3y_{max}(L_b x^2 - x^3/3)/(2L_b^3)$ where x is the distance along the tube, y_{max} is the shift distance in the experiment, and L_b is the length of the curved

section, and in our case L_b = 57 mm Unless the capillary is traced over such a theoretically generated curve, which is impractical to do in our dynamic bending arrangement, the cubic shape is only an approximation It would be interesting to assess how much the transmission is affected if the model assumes shapes that deviate from the cubic

2 There may be some unintended movement of the entrance or, especially, of the exit end of the tube in the direction transverse to that of bending, Experimentally, special attention has been paid to fix the entrance part of the capillary securely In addition, the position of the spot projected by the transmitted beam on the imaging detector is recorded for each shift Ideally this position should not vary, since the detector is displaced along with the end of the tube Several series of the position monitoring have been performed, and the result of one series is presented in Figure 8, where the (x, y) coordinates of the exit spot are plotted as a function of shift distance There is a slight movement in the x-coordinate (perpendicular to the shift direction) of 9 pixels (0 135 mm) - about 0 3d, such a small change is not expected to cause a significant drop in the transmission Movement of the spot in the direction of the shift (y-coordinate, 36 pixels - 0 48 mm) is somewhat higher, which can have some effect in the transmission This effect will be studied in more details in the future After returning to the zero shift position, repetitive measurements have shown that the transmission values are reproducible

3 The actual neutron spectrum may be different from that calculated and used in the simulation Time-of-flight measurements will be performed in the future to verify the spectrum An additional series of experiments has been undertaken with a monochromatic neutron beam of 0 4 nm wavelength and they will be discussed next

Monochromatic neutron transmission measurements have been performed with the experimental arrangement shown in Figure 9 Neutrons diffracted from the 002 planes of a pyrolitic graphite crystal give an incident beam of wavelength 0 4 nm The experimentally measured divergence (FWHM) determined by measuring the beam transmitted through a Cd slit with a width of 0 29 mm is 23 0 mrad in horizontal direction, and 16 5 mrad in the vertical Since the simulation program only accepts one divergence value, the geometric mean (square root of the product) is used as the average divergence, 19 5 mrad A separate measurement gives 21 9 mrad and 15 4 mrad for the horizontal and vertical directions, respectively, yielding the average divergence of 18 4 mrad, which can be used to estimate the error margin in the divergence

Figures 10 represents results of experimental and simulated transmission results for 0 4 nm wavelength neutrons for Ni and lead glass capillaries with 0 44 and 0 53 mm internal diameters, respectively Figure 11 summarizes the experimental transmissions for these tubes and additional Ni capillaries with d = 0 5 and 0 54 mm We find that the Ni (0 44 mm) tube, as in the measurements performed with a white neutron beam, has a higher transmission than the glass and other nickel tubes, despite the larger diameters of these other tubes Past studies show that capillaries from the same material demonstrate a

greater transmission when the inner diameter is higher [6] Among these other tubes, Ni (0 50 mm) and Ni (0 54 mm) tubes have similar values of the transmission, and both values are higher than that of Pb-glass (0 53 mm) in the entire range of bending shifts, except for the straight position where the value of the glass tube is about 6% higher

Comparison of experimental and simulation transmissions shows somewhat different behavior from that of white beam measurements For the glass tube, the region of small bending shows poor agreement, but very good agreement beyond that Although the values for the Ni tube are in reasonable agreement, the dependence seems different from the white beam results Overall, the shape of the these curves are better followed in the glass tube results than in the Ni tube results, for both the monochromatic beam and the white beam By eliminating the uncertainties in the wavelength distribution, we can suggest that perhaps the mechanical properties of the two types of tubes result in slightly different curved profiles when bent by the same nominal amount

In all experiments the Ni capillaries showed better performance than glass monocapillaries We have tried to assemble a neutron focusing device (FD) from Ni capillaries 0 44 mm inner diameter and length 90 mm We have used 9 tubes positioning them in such a way that the 8 tubes surrounding the center one form a ring, which subtends an angle at the desired focus equal to the twice the critical angle of Ni (Fig 12), with the help of two Li-poly frames (Fig 13) From Fig 14 and 15 we can see that at short distances from the exit end of this device (about 14 - 30 mm) the bright spots from every tube is distinct At longer distances all these spots come together In the range 50 - 60 mm the intensity of the transmitted beam is approximately constant and reaches a maximum at 54 mm, which is 2 3 times higher than that at 14 mm However, this maximum intensity is about 8% less than the intensity of the direct beam (over a diameter of 1 12 mm) For distances 70 - 96 mm the spot is becoming more and more homogeneous and its intensity decreases This device demonstrates the possibility of using Ni capillaries to focus neutrons To achieve a real gain, it is necessary to bend the capillaries with the help of a couple of intermediate supports and increase the number of capillaries Using tubes of smaller diameter would be preferable in that case

2 5 Summary

We have studied the transmission properties of metal and glass capillaries, straight and bent, using a white and a monochromatic neutron beam The results are compared with those produced by a Monte-Carlo simulation program, and with analytic calculations when applicable A prototype Ni capillary lens has also been constructed and measured These studies provide useful information for the future design of neutron lenses using metal capillaries

References

[1] Q F Xiao, H Chen, V A Sharov, D F R Mildner, R G Downing, N Gao and D M Gibson Rev Sci Instrum , 65, 3399 (1994)

[2] R G Downing, C J Zeissler and H Chen SPIE Conf Proc 1737, 308-321 (1993)

[3] Q -F Xiao, I Yu Ponomarev, A I Kolomitsev and J C Kimball SPIE Conf Proc 1736, 20-31 (1993)

[4] D F R Mildner, V A Sharov and H Chen J Appl Cryst , 28, 69 (1995)

[5] D F R Mildner, H H Chen-Mayer, V A Sharov, V S Fokin and P L Reader J Appl Cryst , accepted for publication (1996)

[6] P L Reeder, A J Peurrung, D S Sunberg, J J Stoffel(s), H H Chen-Mayer, D F R Mildner, V A Sharov and V S Fokin Nucl Instrum Meth , submitted (1997)

3 Specific Benefits of the Visit

During the course of this visit we have had intensive exchange of ideas in the field of capillary optics and its applications We expect a number of these ideas will be explored collaboratively in the future The work that has been performed by Dr Fokin has been the first extensive research on both the transmission through curved capillaries and the use of metal capillaries for the transmission of cold neutrons During the course of this visit he has also collaborated with Dr Paul Reeder of Pacific Northwest Laboratory of Richland WA, and Vasily Sharov of X-Ray Optical Systems, Inc of Albany, NY on the transmission of cold neutrons through steel stainless steel capillaries Corrections required for this work resulted in a method for the determination of the reflection coefficient for neutron transmission though capillaries when the reflectivity is not close to unity In addition, this collaboration was extended to some research on scintillating fibers for neutron imaging These research activities have resulted in two publications that have been submitted for publication, and another already accepted

"The Number of Reflections for Neutron transmission through Cylindrical Channels", D F R Mildner, H H Chen-Mayer, V A Sharov, V S Fokin and P L Reeder, accepted for publication, Journal of Applied Crystallography, 1997
"Metal Capillaries for Neutron Lenses", P L Reeder, A J Peurrung, D S Sunberg J J Stoffel(s), H H Chen-Mayer, D F R Mildner, V A Sharov and V S Fokin, submitted to Nuclear Instruments & Methods A, 1997
"Imaging Neutron Beams with Scintillating Fiber Faceplates", P L Reeder, A J Peurrung, W C Richey, H H Chen-Mayer, V A Sharov, V S Fokin and D F R Mildner, submitted to Nuclear Instruments & Methods A, 1997

4 Possibilities of Future Collaboration

In September 1994 the NIST capillary optics team visited Russia at the invitation of colleagues at the Kurchatov Institute During this visit we were introduced to Dr Vladimir S Fokin From this visit, the idea of an extended visit to NIST by Dr Fokin was hatched The CAST grant has enabled his stay from Nov 95 to Oct 96 Upon his return to FTIAN, Fokin has talked to Academician Valiev and Prof Afanas'ev regarding his work at NIST on neutron optics and his ideas for multilayer structures which could be used for neutron focusing and steering Valiev has proposed to use the facilities which are available in one of the laboratories where similar work is already underway They are depositing multilayer x-ray mirrors and it is possible for them to make Si-Ni (and other) structures with layer thicknesses up to 2 nm, and up to perhaps several hundred layers Another laboratory is making superlattices The idea is to make model structures what might be tested at the Kurchatov Institute

Two members of the NIST team, H H Chen-Mayer and D F R Mildner are planning to visit Moscow again for two weeks in September, 1997 Included in the itinerary will be a

visit to the Institute of Physics and Technology of the Russian Academy of Sciences We intend to hold discussions not only with Dr Fokin, but also Profs Valiev and Afanas'ev regarding future joint collaboration between FTIAN and NIST Evidently the Russian scientists intend to have some formal type of collaboration that will enable them to obtain some financing from Russian sources for the work There is already a memorandum of understanding between NIST and the Russian Academy of Sciences for cooperation in the physical, chemical and engineering sciences signed on in July, 1996 in Moscow by Dr Jack H Gibbons, Assistant to the President for Science and Technology During this visit we will also complete the writing on a joint paper with Dr Fokin based on the research that he has performed during his visit to NIST

5 CAST Program Goals

i Benefits to Russia and to the US

Experimental work on the focusing of radiation using capillary optics has virtually stopped in Russia during the critical situation when finances are so poor The CAST program has enabled some of their experimental work to be carried out in the US, and may lead to further research being performed at the Kurchatov Institute by FTIAN scientists A continued collaboration will be an additional insurance that these benefits are not lost This research can also be viewed as a continuation of the collaboration between NIST and Russia, which had been started with the Kurchatov Institute

The benefit to the US has been the rapid development of neutron focusing for neutron absorption measurements in materials, in particular the development of the use of metal capillaries which allow an increased transmission of neutrons This work may have an impact in the design of future instrumentation at research reactors, particularly neutron-based analytical techniques (prompt gamma activation analysis and neutron depth profiling) These instruments have the capability for measuring both nondestructively and quantitatively high spatial resolution elemental profiles in materials of key technological importance Such technologies include the research and development of semiconductors, optical waveguides, polymer science, metallic alloys, coatings and superconductors With the production of intense, steady sate , finely focused neutron beams, the most intense such neutron fields outside a nuclear reactor, the possibility of real time neutron tomography and useful neutron microscope has been advanced

ii Improved Scientific and Technological Linkages

During the course of this collaboration, Dr Fokin was able to see and understand the methods and way of life of US research institutes He was able to return with a better appreciation of how science is performed in the west He has maintained contact with the research team at NIST via the internet Consequently he is now in a position to

appreciate better how to advise others at FTIAN and in Russia to link up with other scientific groups We expect at least a couple of publications based on the results that Fokin has obtained during the course of his investigations

iii Defense Conversion Aspects

The origin of the neutron transport work using capillary optics was within the former Kurchatov Institute of Atomic Energy in Moscow, the umbrella for much of the fundamental research in nuclear and defense related fields in Russia, with the expectation of future defense related applications The research we have conducted has great commercial applications This project has led to a switch of Dr Fokin's primary research interest from laser optics which has definite defense applications to a field benefiting the civilian sector

iv Commercial Applications from Collaborative Research

The concept of capillary optics for the transport, guiding and focusing of radiation (x-rays and neutrons) has already been commercialized through the company X-Ray Optical Systems, Inc of Albany, NY This company is very much interested in the results of the research which can improve on the transmission characteristics of glass capillary optics, whether it is nickel coated glass capillaries or metal capillaries Consequently significant results of our future collaboration will be closely followed by this company

6 FINANCIAL REPORT

Amount received from NRC		$14,000
Expenditures		
living allowance November 1, 1995 - October 31, 1996 12 months, $1500/month	$18,000	
Travel all travel done at government rates through NIST Moscow-Washington return air fare (11/01/95 - 12/14/96) 572 + 532	$ 1,104	
Supplies nickel tubing stainless steel tubing	$ 358 $ 113	
Total expenditure		$19,575
balance		–$5,575
further amount to be received from NRC upon submission of scientific report		$ 1,000
other sources of support supplement paid to increase living allowance to $1500/month, paid from NATO travel grant		$ 4,575

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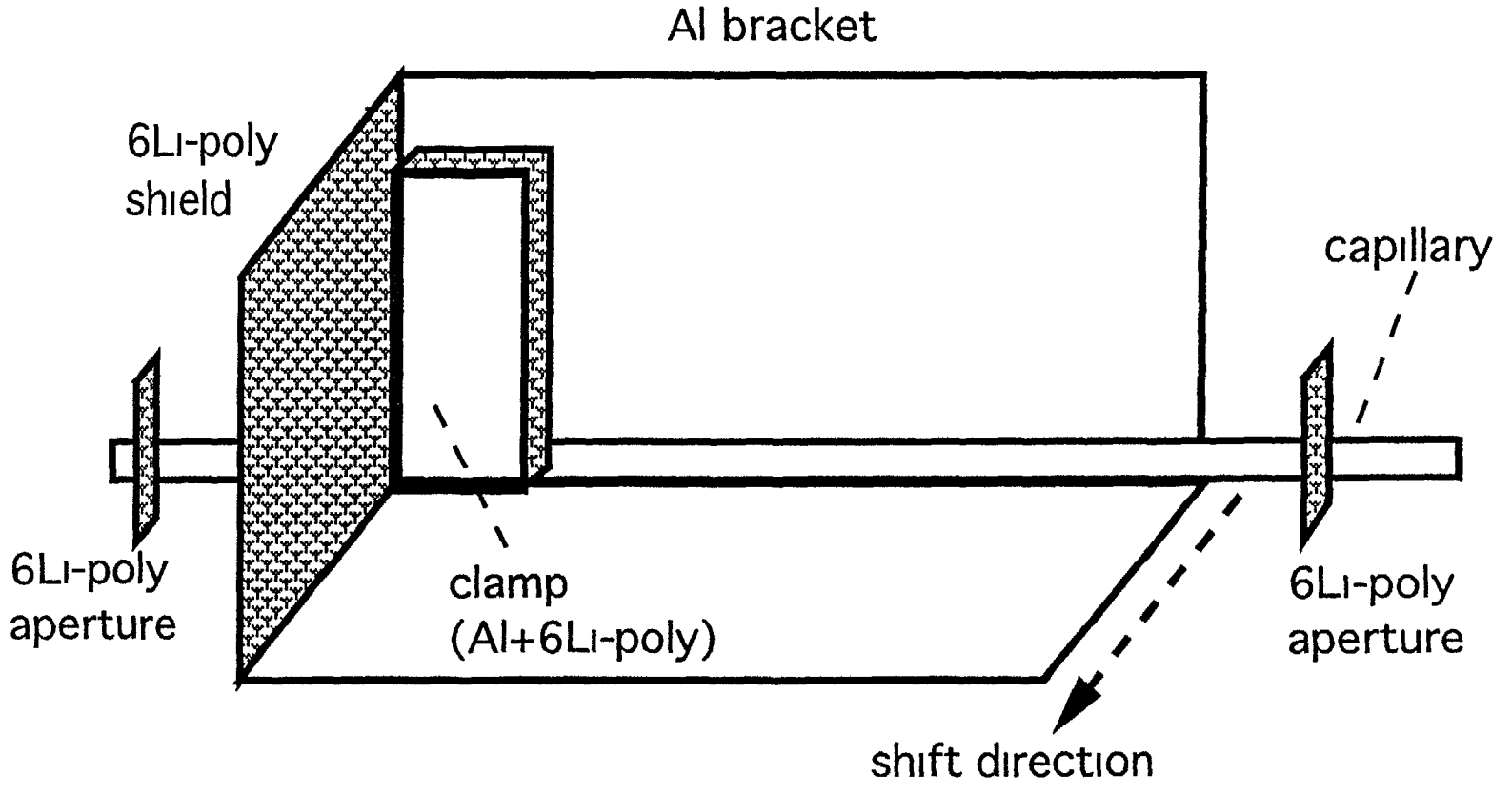
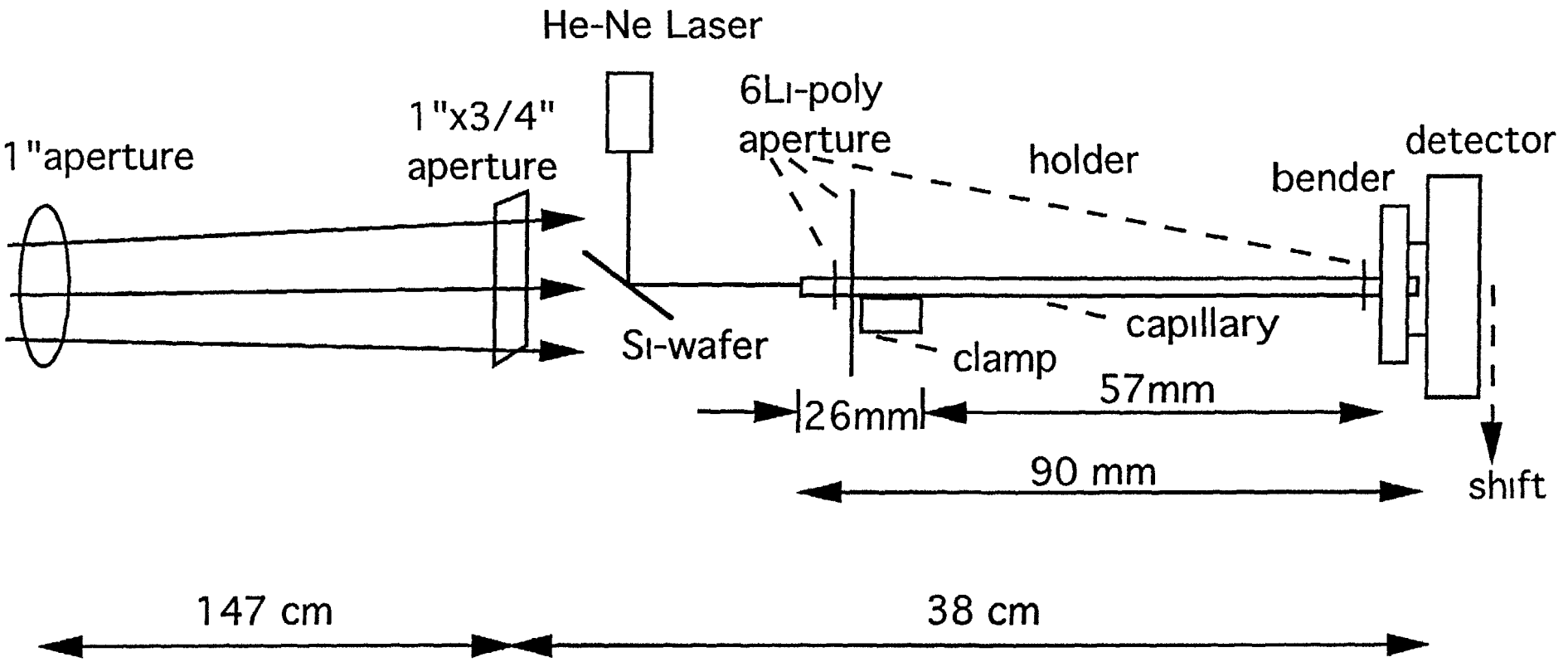


holderbender

Fig 1



bendingsetup

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Fig 2

NEUTRON SPECTRUM AT THE EXIT OF NG0 GUIDE

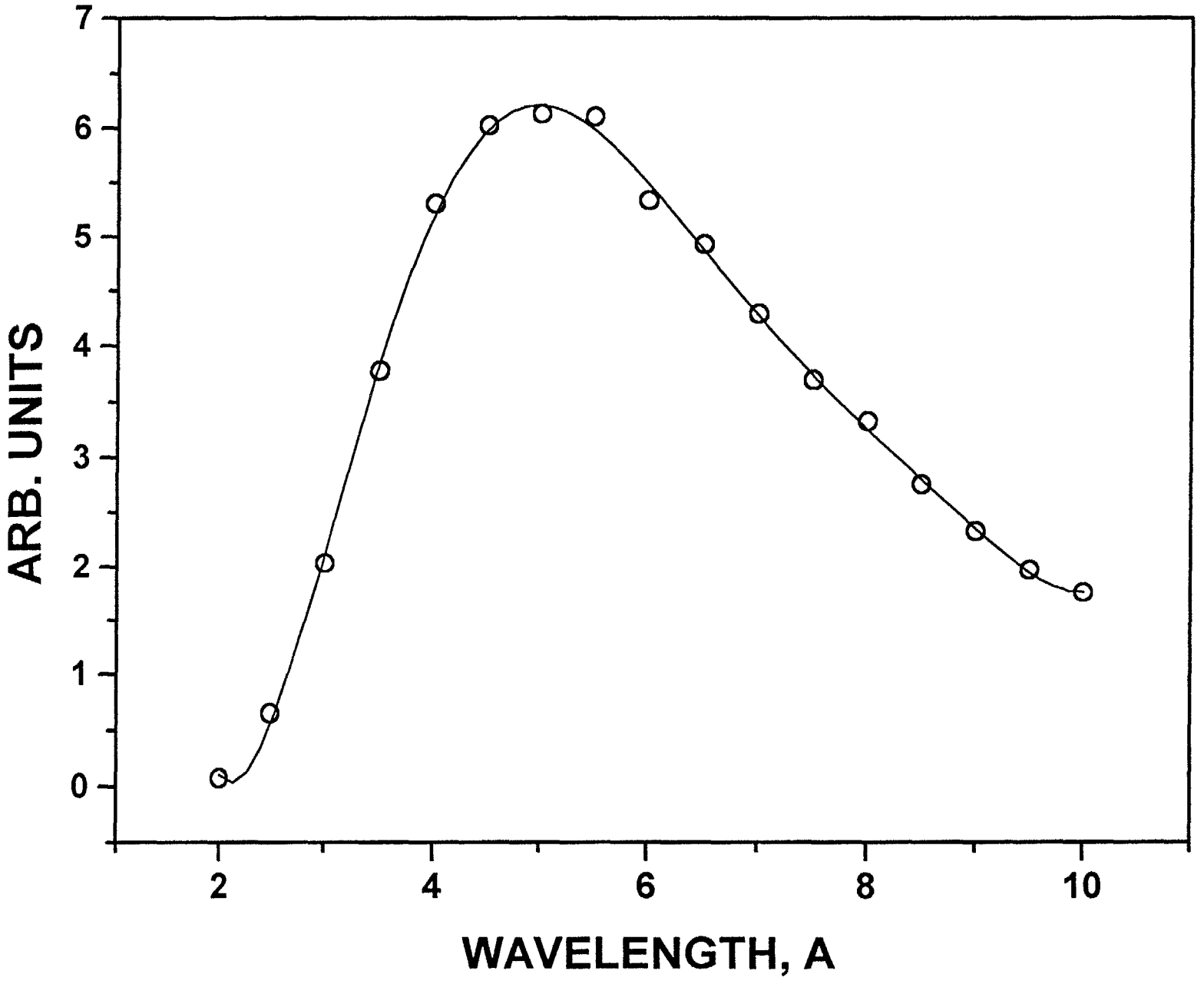

Fig 3

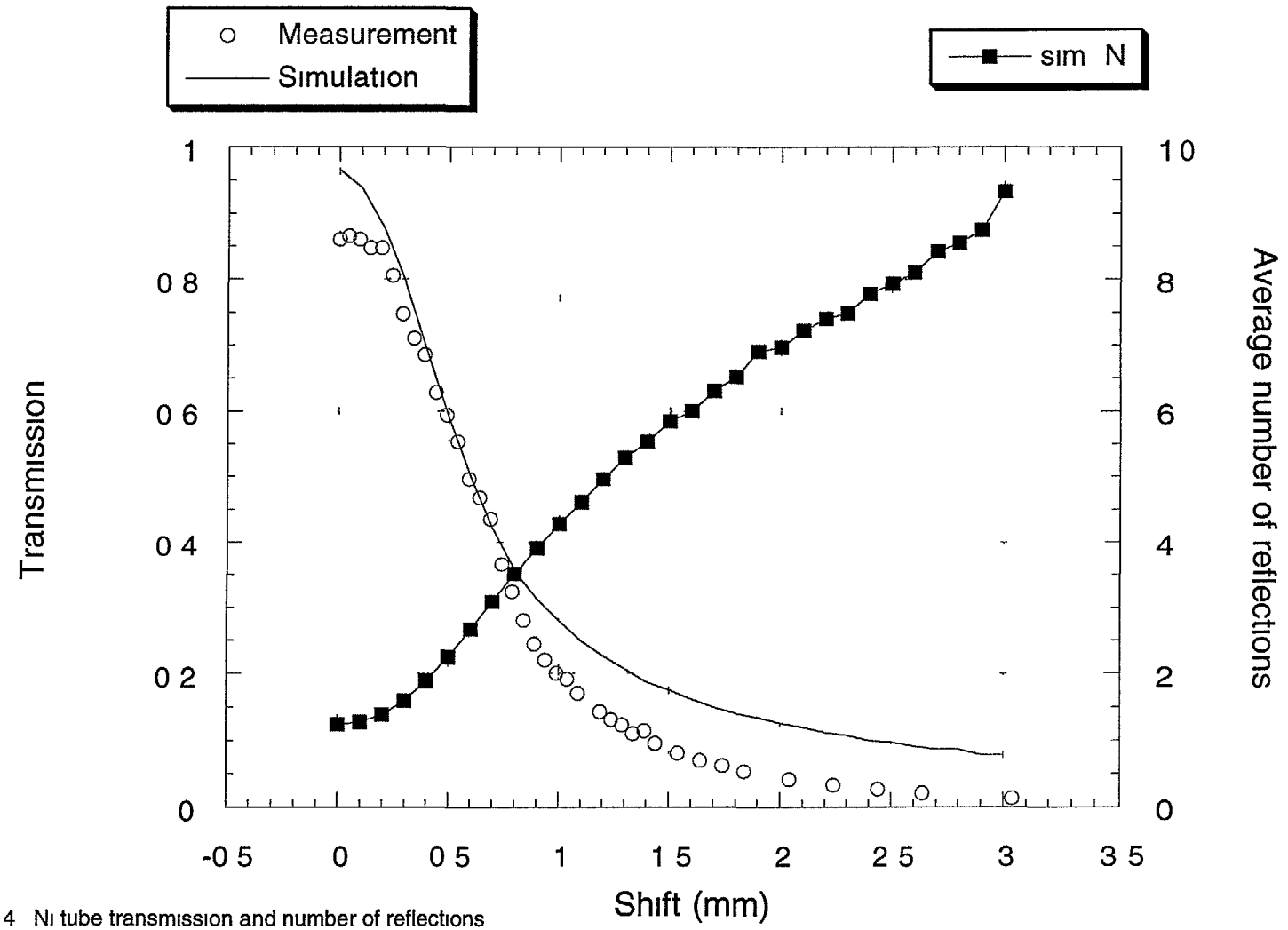

Fig 4 Ni tube transmission and number of reflections

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Fig 4

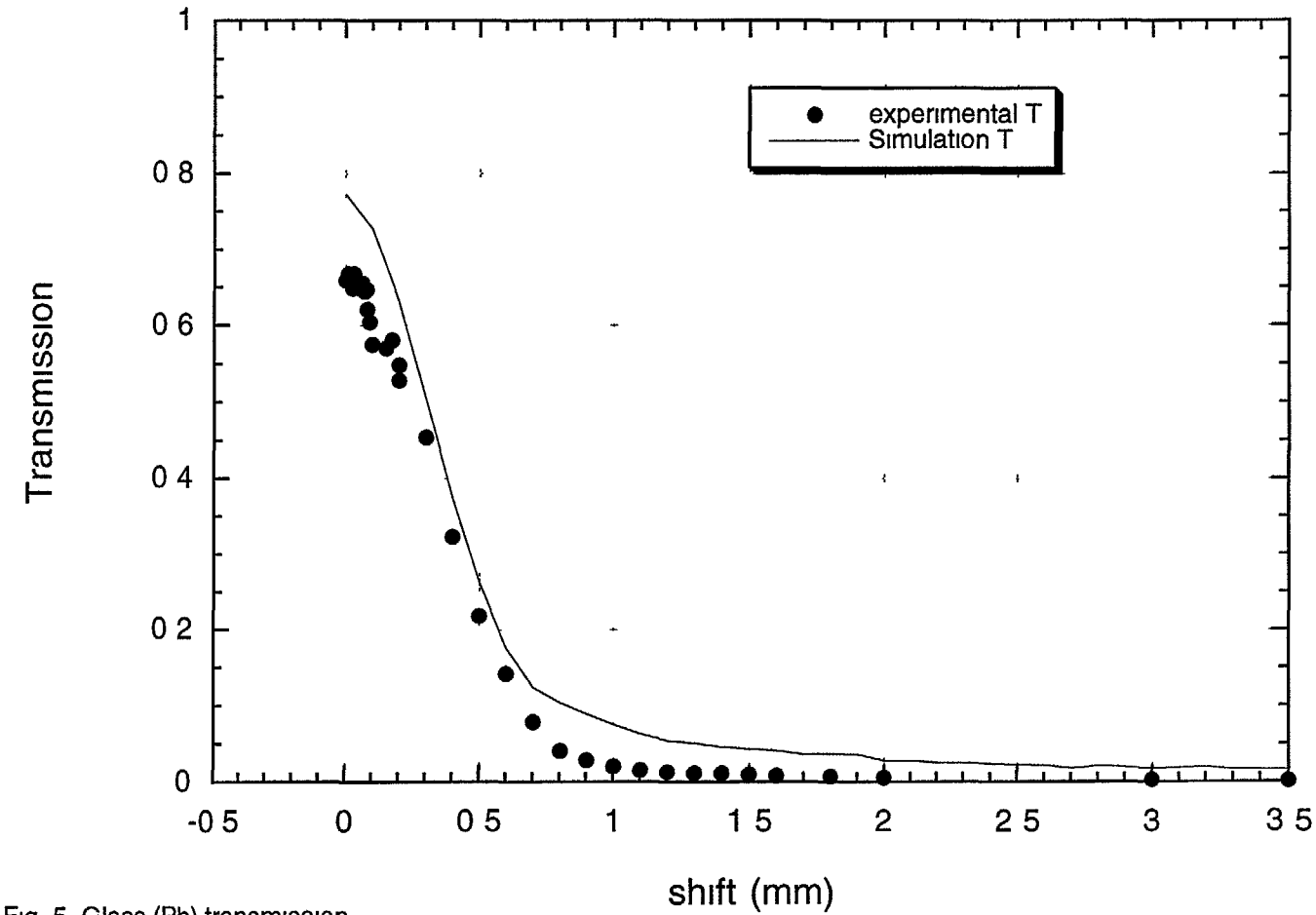

Fig 5 Glass (Pb) transmission

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Fig 5

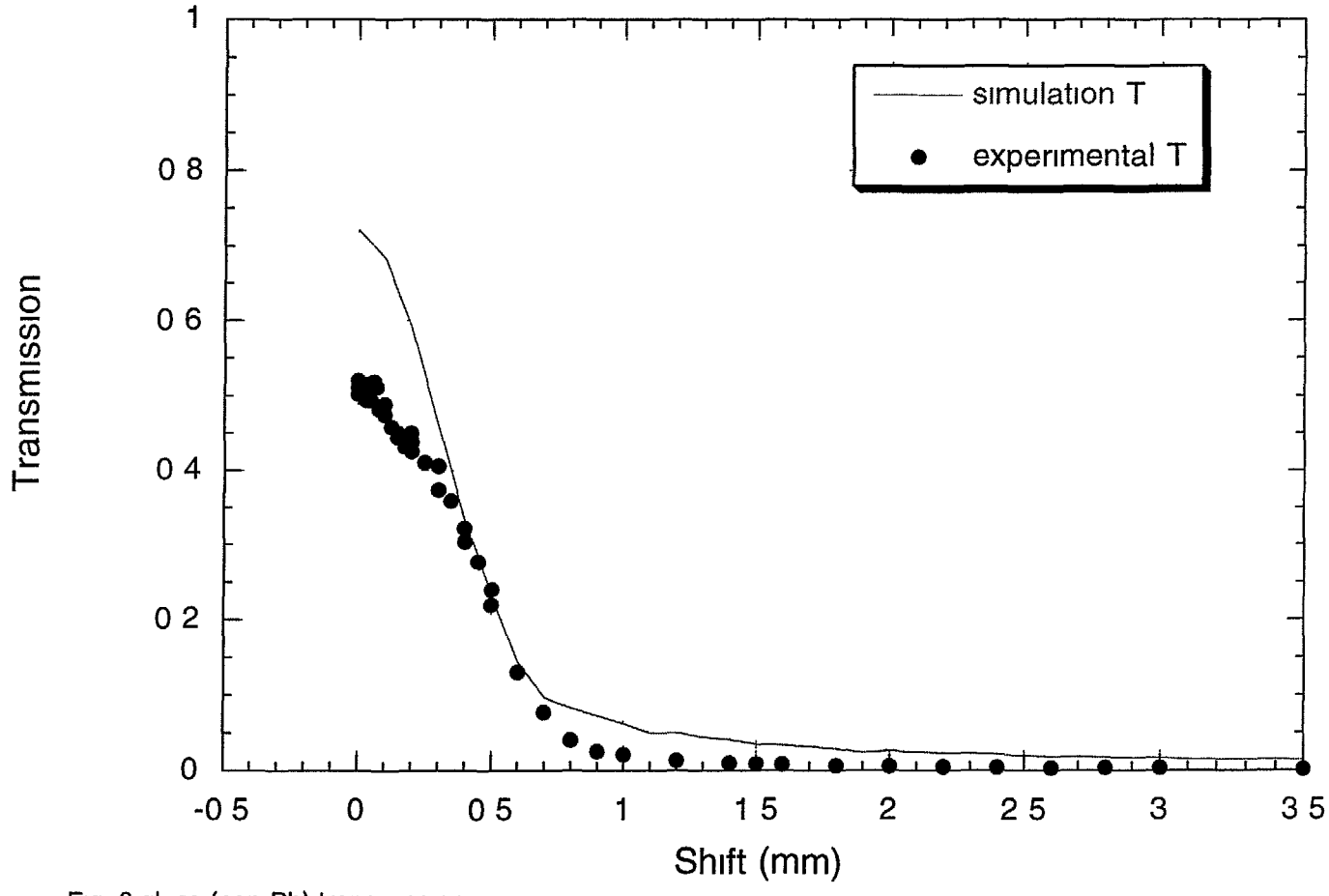

Fig 6 glass (non-Pb) transmission

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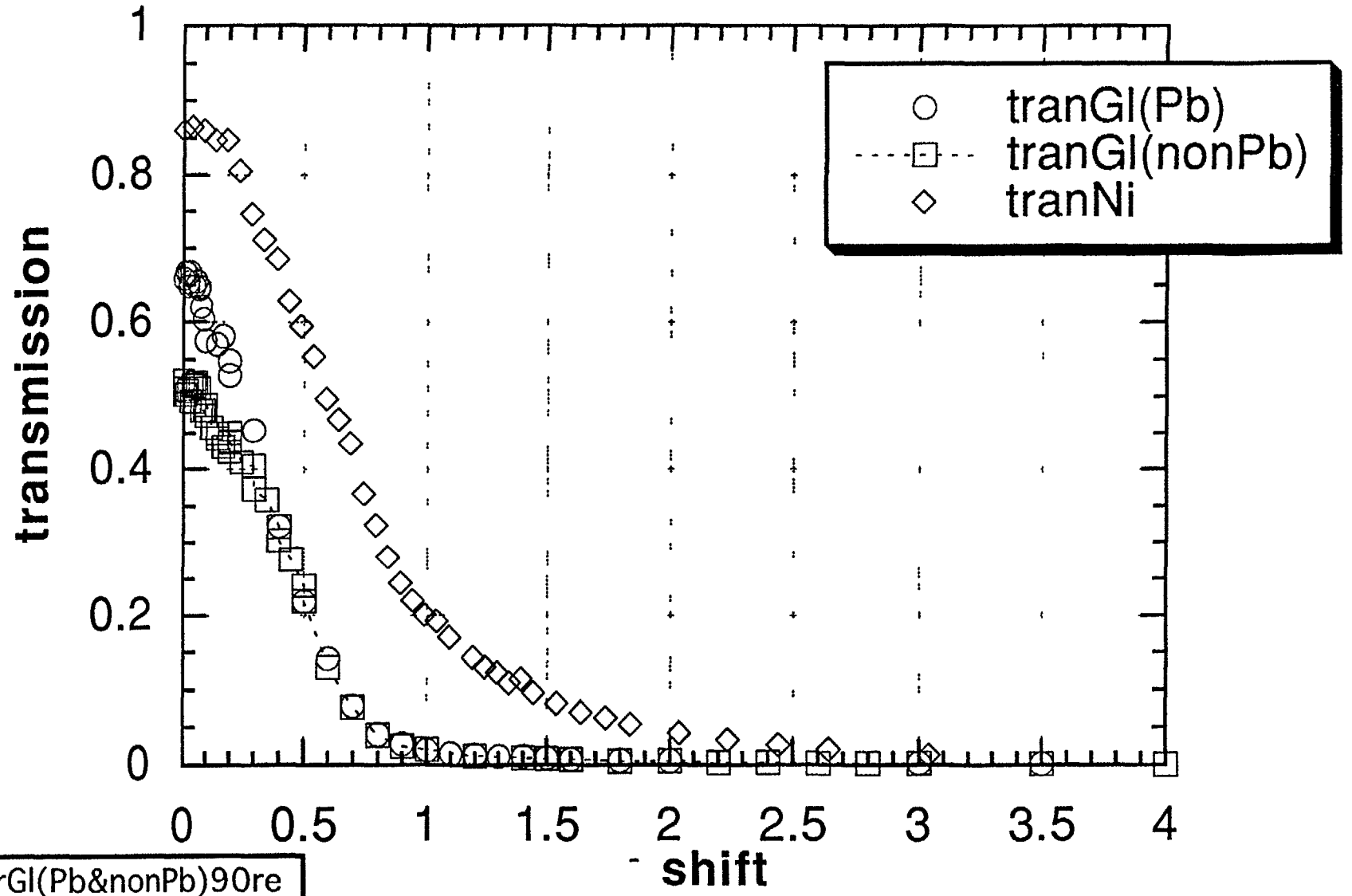
Fig 6.

Nickel tube 0.44mm ID, L 90mm, L_b 57mm
Glass (Pb&non Pb) tubes 0.53mm ID, L 90mm, L_b 57mm
July 1996



NicorGl(Pb&nonPb)90re

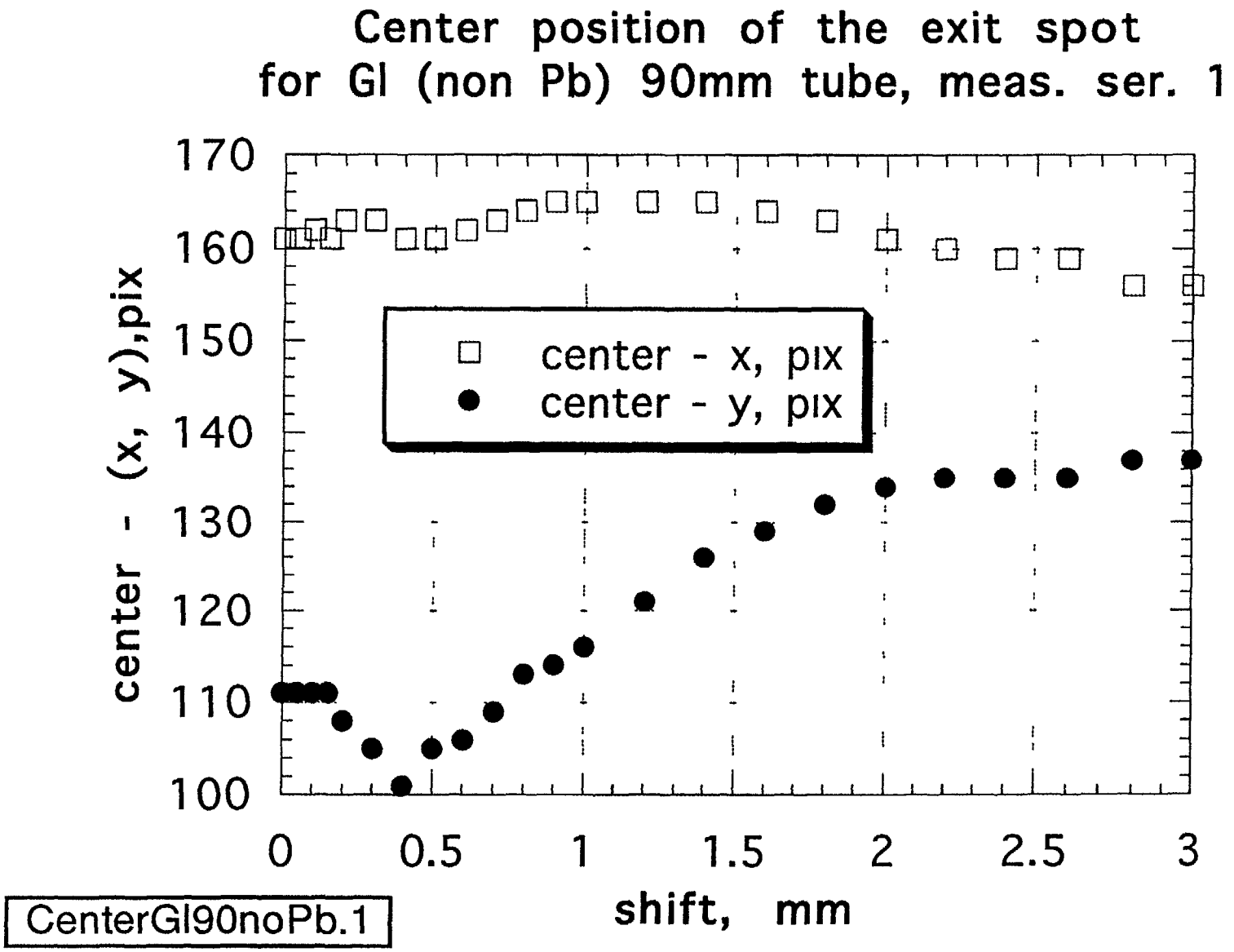

Center position of the exit spot
for Gl (non Pb) 90mm tube, meas. ser. 1
center - (x, y),pix
170
160
150
140
130
120
110
100
0
0.5
1
1.5
2
2.5
3
shift, mm
center - x, pix
center - y, pix
CenterGl90noPb.1

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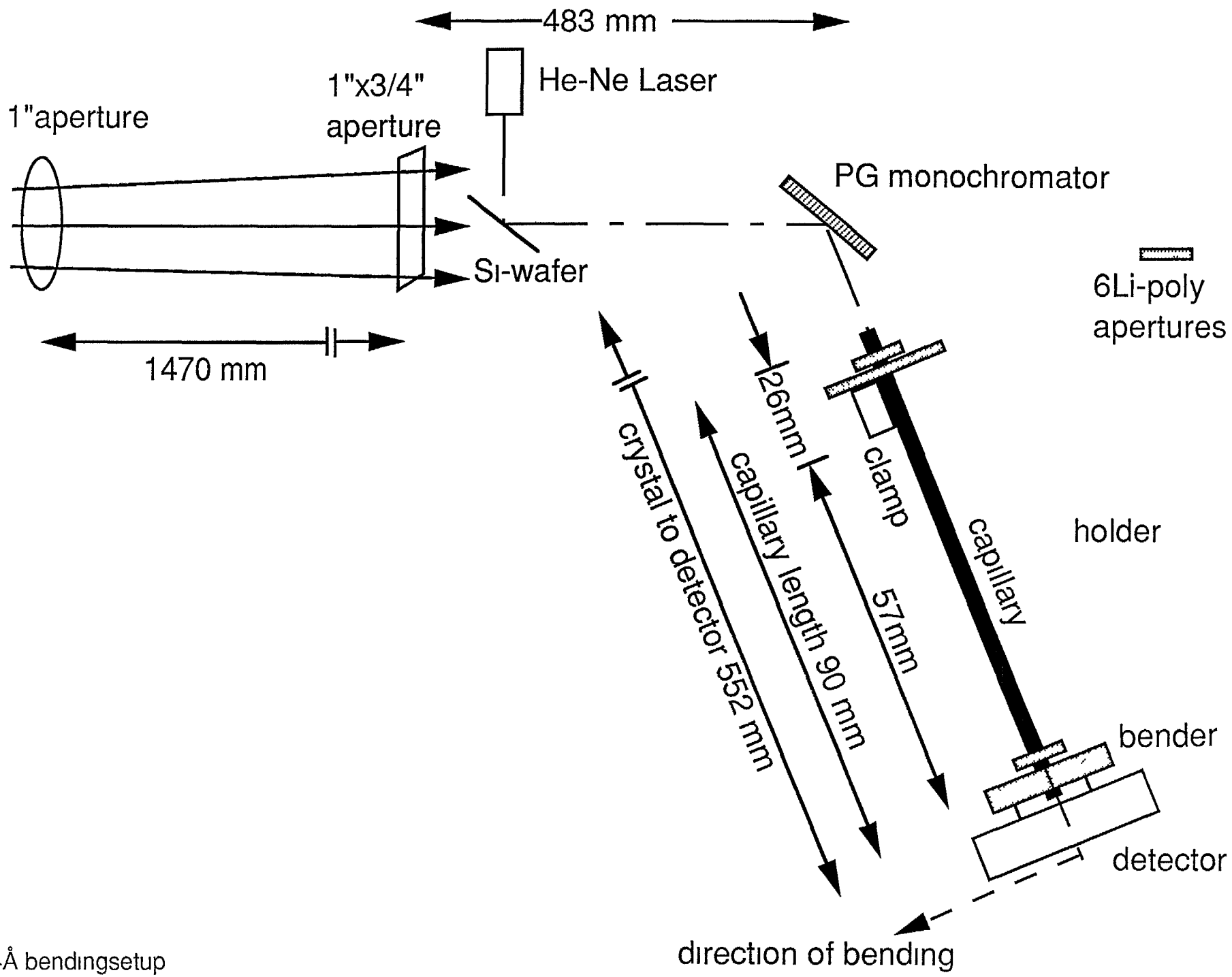
Fig 8



4Å bendingsetup

Fig 9

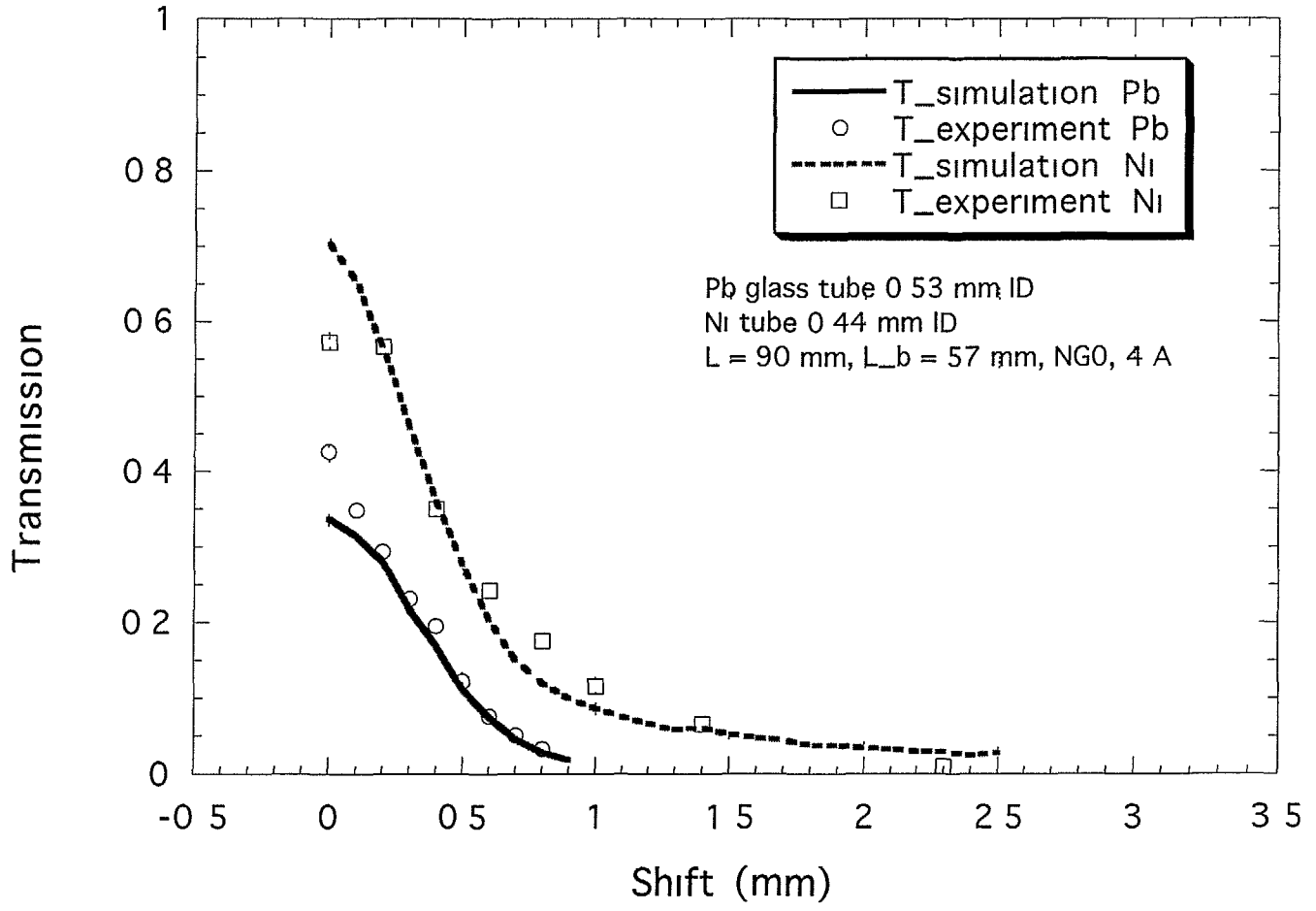
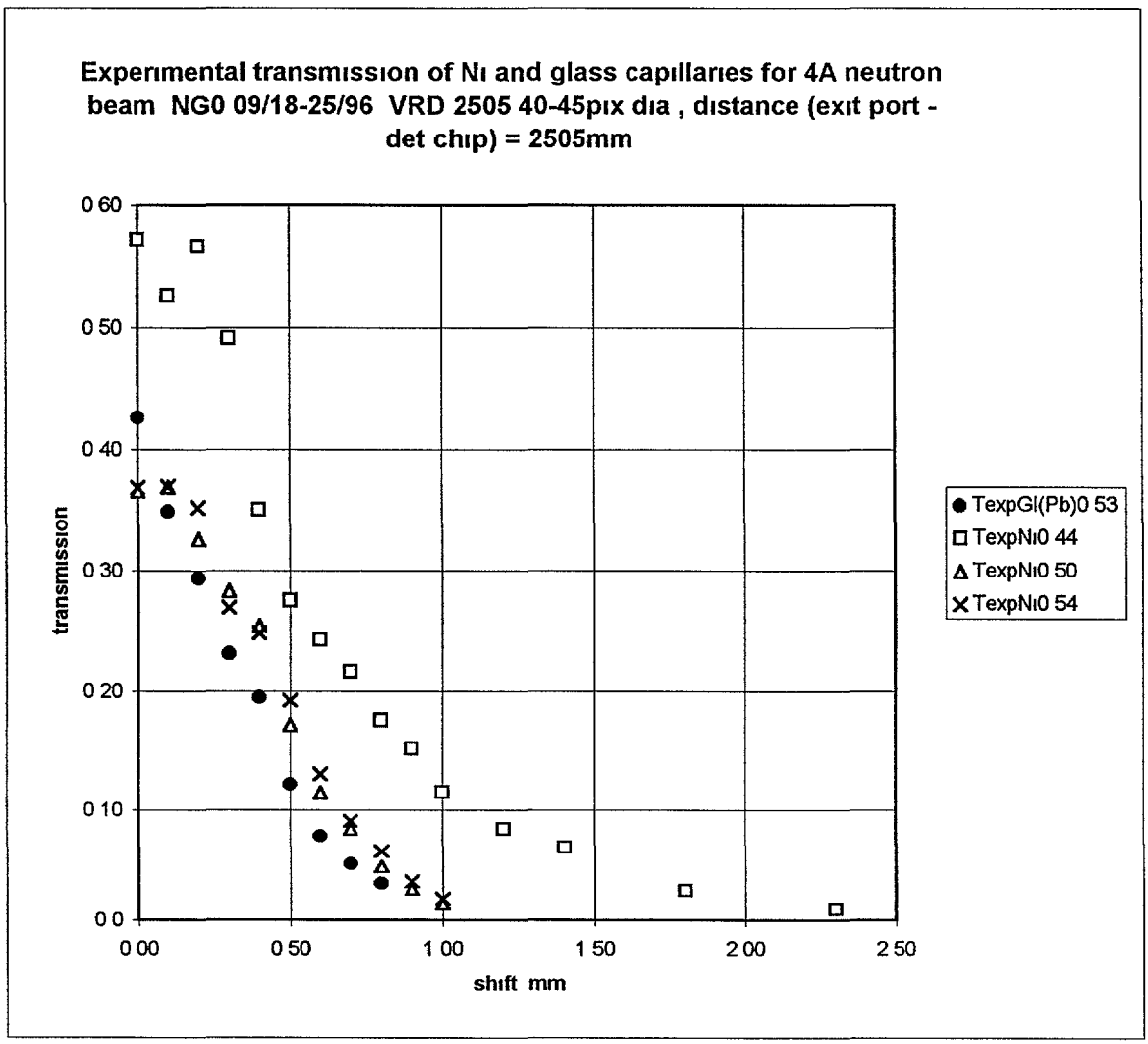


Fig 10 Pb glass tube + Ni tube bent wl = 4A

Fig 10

shift	TexpGl(Pb)0 53	TexpNi0 44	TexpNi0 50	TexpNi0 54
0 00	0 4264	0 5722	0 3650	0 3675
0 10	0 3484	0 5260	0 3679	0 3688
0 20	0 2938	0 5662	0 3256	0 3513
0 30	0 2314	0 4917	0 2832	0 270
0 40	0 1950	0 3502	0 2540	0 2488
0 50	0 1221	0 2757	0 1723	0 1925
0 60	0 0764	0 2429	0 1150	0 1313
0 70	0 0511	0 2161	0 0829	0 0901
0 80	0 0332	0 1758	0 0482	0 0623
0 90		0 1520	0 0282	0 0346
1 00		0 1155	0 0146	0 0191
1 20		0 0827		
1 40		0 0662		
1 80		0 0264		
2 30		0 010		



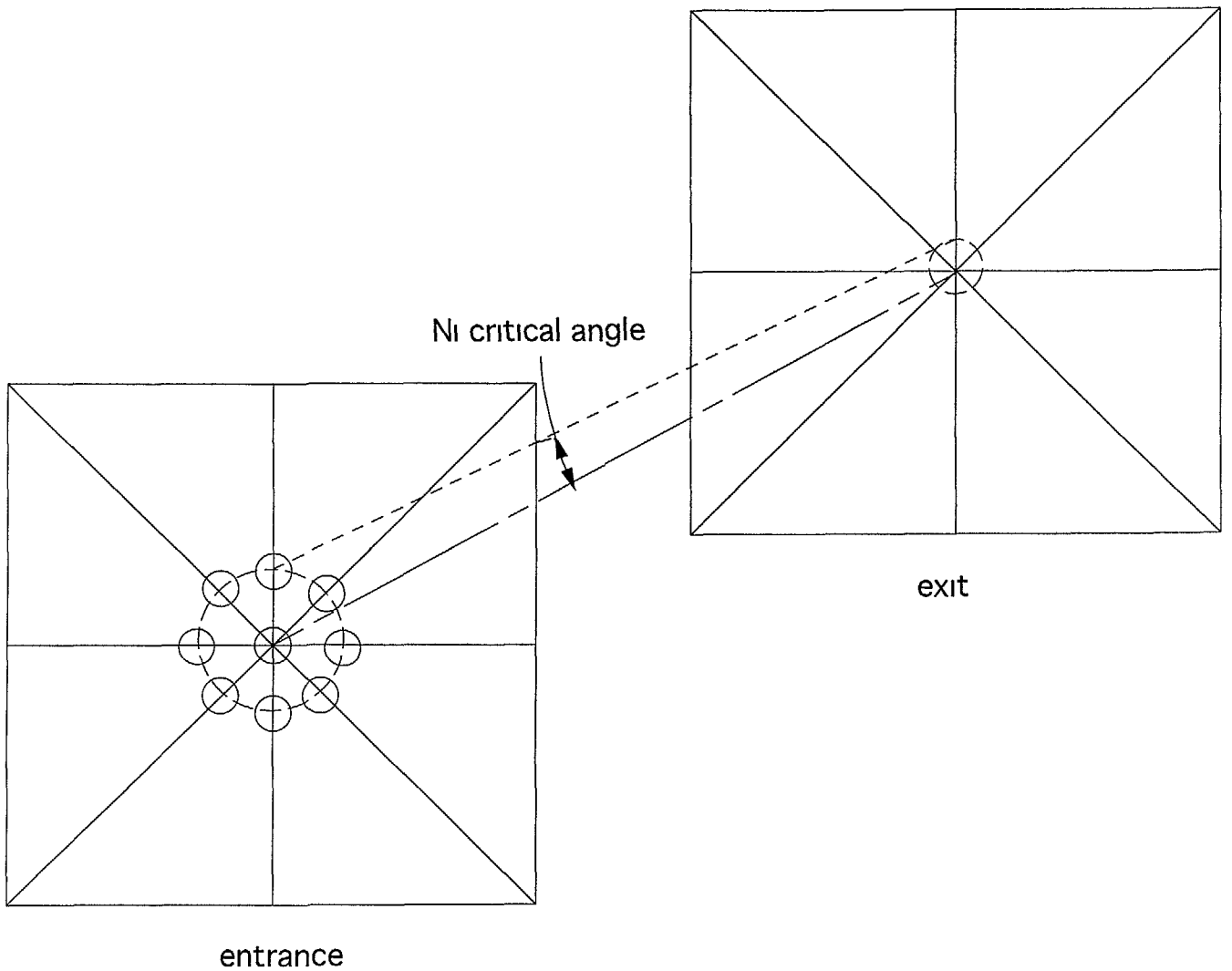


Fig 12 Schematics of Ni capillary focusing device design

Fig 12

Fig 13.

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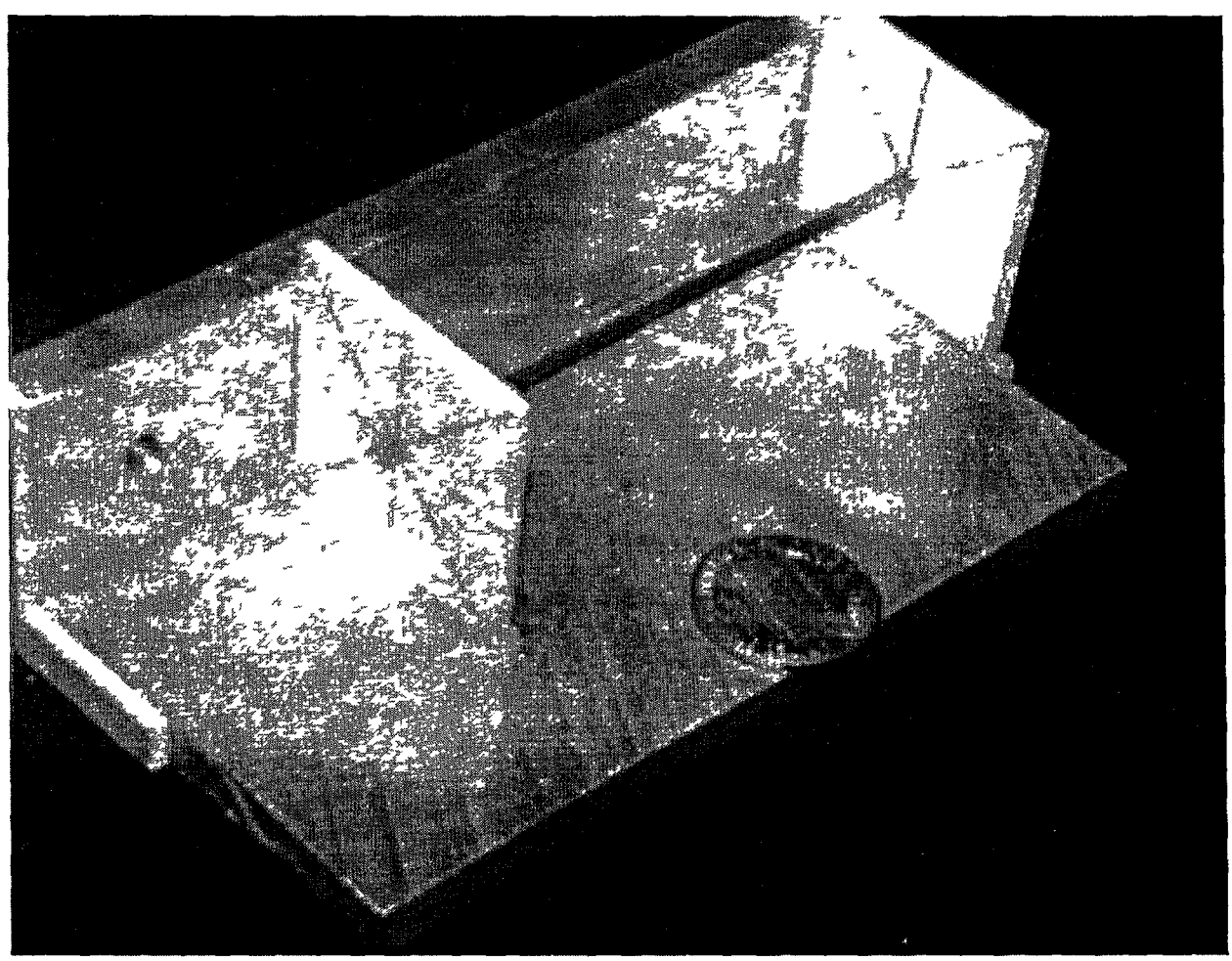

Fig 14

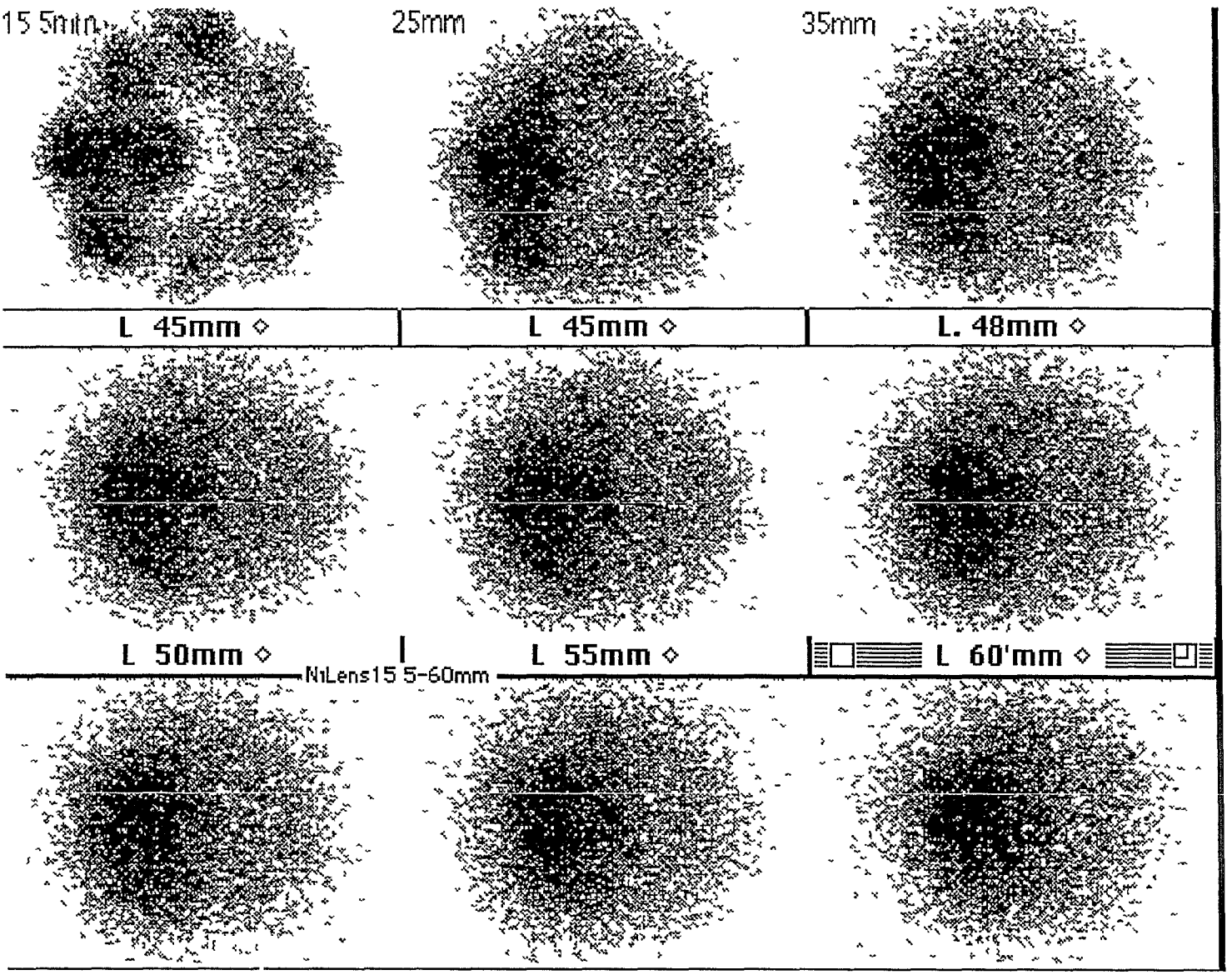

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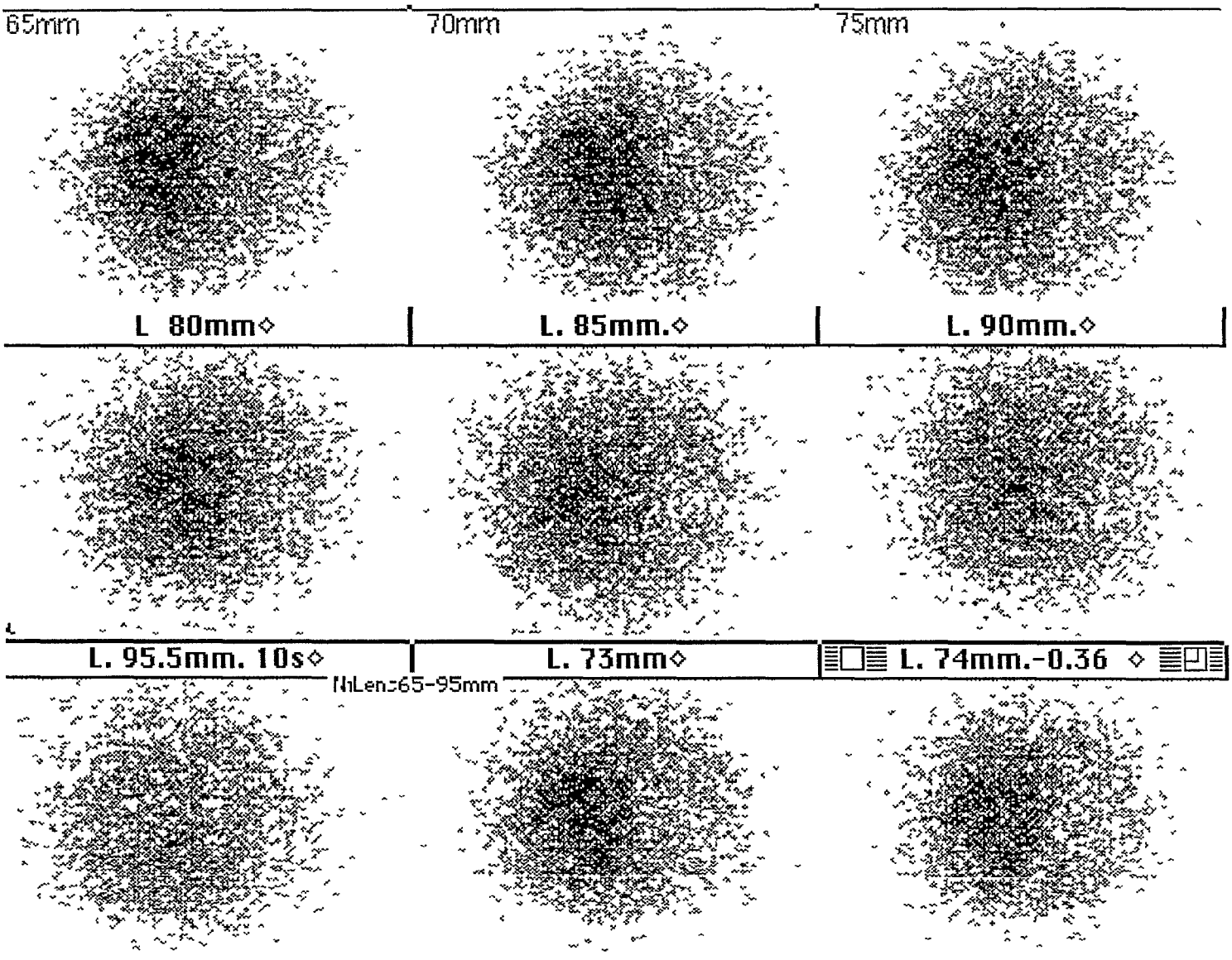
Fig 15



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