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Measurement of a H^- Ion Beam with D-Pace's OWS-30 Wire Scanner

T. Bykov[1,2, a)], Ia. Kolesnikov[1,2], A. Makarov[1,2], I. Shchudlo[1,2], E. Sokolova[1,2], S. Taskaev[1,2, b)]

[1)]*Budker Institute of Nuclear Physics, Novosibirsk, Russia*
[2)]*Novosibirsk State University, Novosibirsk, Russia*

[a)] Corresponding author: timaisabrony@gmail.com
[b)] taskaev@inp.nsk.su

Abstract. A source of epithermal neutrons based on a vacuum-insulated tandem accelerator and a lithium target was proposed and developed for the technique of boron neutron capture therapy. A stationary proton beam of 2 MeV with a current of up to 5 mA was produced by the accelerator. To optimize the injection of a beam of negative hydrogen ions into the accelerator, a wire scanner OWS-30 (D-Pace, Canada) was installed [1]. The main problem is that using the wire scanner in the form in which it was provided does not allow us to determine the main beam parameters such as position and size. Also, the electron emission does not allow measurement of the total beam current and may lead to incorrect measurement of the beam profile. We have modernized the scanner by placing metal rings in front and behind the scanner with a negative potential to suppress the secondary emission of electrons from the scanner wires. We have developed software in which methods for calculating the position and size of the beam, methods for calculating the total current are implemented. Modernization of the scanner has made it possible to expand its capabilities. The suppression of the secondary electron emission made it possible to reconstruct the current profile of the ion beam and determine the value of the total current. The developed program allowed to display the coordinates of the beam, its dimensions and the total current. We are the first who proposed and implemented a new way of measurement of the beam emittance. A movable diaphragm was inserted in front of the wire scanner. Ion beams passing through the aperture of the diaphragm were measured by the wire scanner with a high level of detail when the diaphragm was moved along a radius. The use of a modernized scanner made it possible to detect the effect of space charge and the effect of the spherical aberrations of the focusing magnetic lenses on a beam of negative hydrogen ions. The use of the modernized scanner made it possible to optimize the injection of a beam of negative hydrogen ions into the accelerator, which led to an increase in the proton current and an improvement of the accelerator stability. The modernized scanner with an additional software for processing the results data and visualization has become a reliable device for beam diagnostics and for controlling beam entry into the accelerator.

AN OSCILLATING WIRE SCANNER - 30 DEVICE

The wire scanner (Fig. 1 a) has two tungsten wires 0.5 mm in diameter with a length of 49 mm (the angle between the wires is 103°) fixed on a common rod that is deflected from the axis crossing the center of the ion beam by an angle of 13.5°. When measuring, the rod rotates to an angle of −13.5° and returns back. The rod rotation axis is located at a distance of 190 mm from the center of the ion beam. When the wire intersects the center of the ion beam, it is inclined at an angle of 45° to the plane of the scanner flange. While the rod moves, the current and the angle of deflection of the rod are measured. The values obtained with a beam diameter less than 30 mm allow us to reconstruct the transverse profile of chord measurements with a spatial resolution of 0.1 mm.

Scanner control, data collection and data output is carried out by the Wire Scanner V 1.0 program. A typical graph of the current dependence on the rod angle is shown in Fig. 1 b. The scanner rod starts at the position of 13.5°, passes through 0, reaches an angle of −13.5° and returns back. The wires sequentially cross the beam, which leads to the appearance of two peaks. With reverse movement a signal shift possibly caused by the backlash of the rod is observed.

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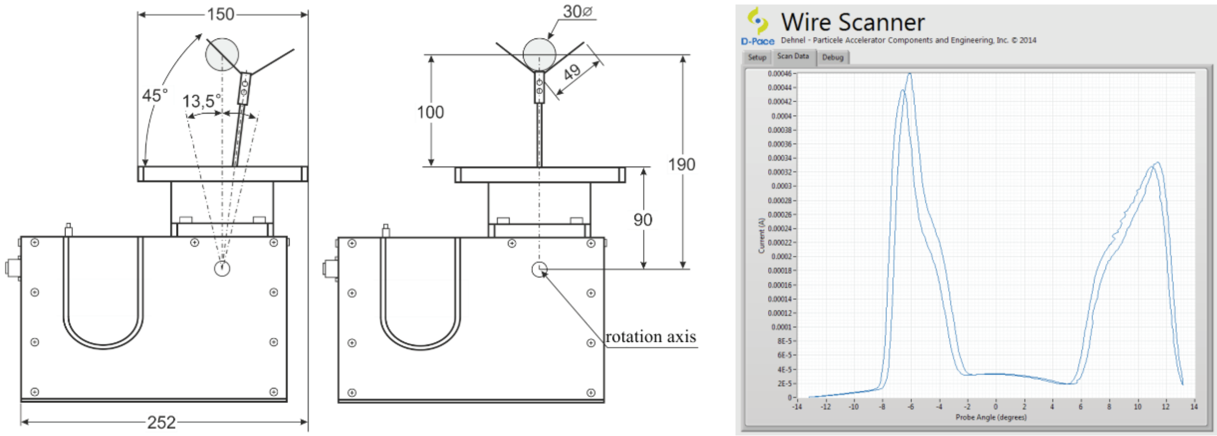


(a) (b)

FIGURE 1. (a) Scheme of the OWS-30 Wire scanner, (b) Scanner control software with the measurement results.

LOW-ENERGY TRACT OF THE TANDEM ACCELERATOR

The wire scanner is used for research on a vacuum-insulated tandem accelerator [2], the scheme of the low-energy tract is shown in Fig. 2.

The beam of negative hydrogen ions leaving the source 1 with an energy of 21 keV rotates in the magnetic field of the source by an angle of 15°, passes through the aperture of the conical diaphragm 2 with a diameter of 28 mm, is focused by a pair of magnetic lenses 4 and injected into the tandem accelerator with vacuum insulation.

The first thing noticed was that normally the signal detected by the scanner was positive (see Fig. 1 b), although a beam of negative hydrogen ions was measured. This might be in case of the current of electrons emitted from the wire exceed the current of negative hydrogen ions falling on the wire of the scanner.

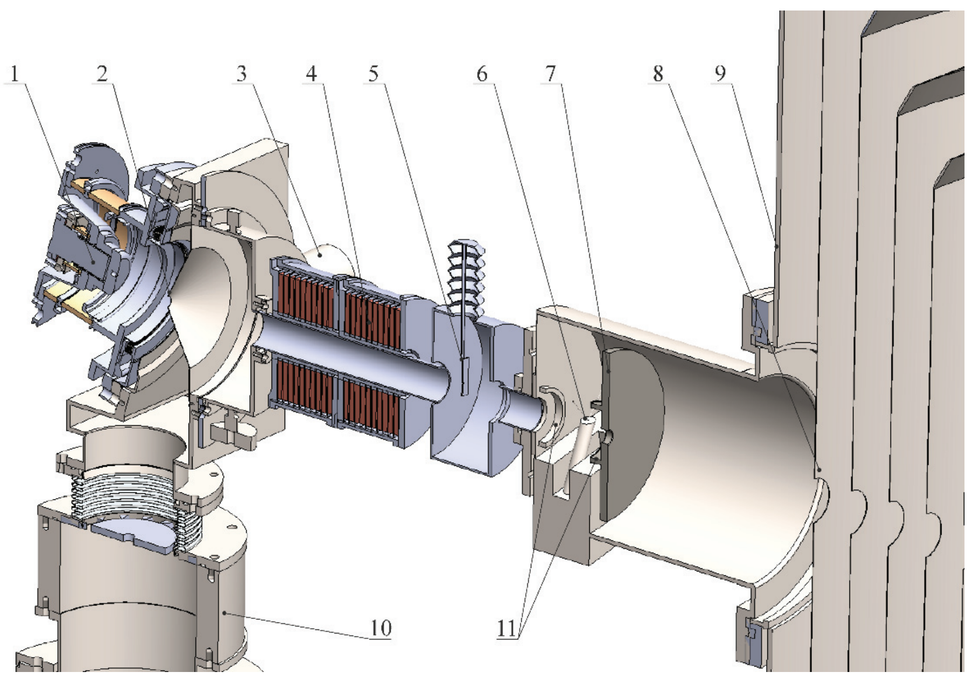


FIGURE 2. Scheme of low-energy tract. 1 - source of negative hydrogen ions; 2 - cone diaphragm; 3 and 10 - turbomolecular pumps; 4 - magnetic lenses; 5 - movable diaphragm; 6 - OWS-30 wire scanner; 7 - cooled diaphragm; 8 - first accelerator electrode; 9 - vacuum tank of the accelerator; 11 - metal rings.

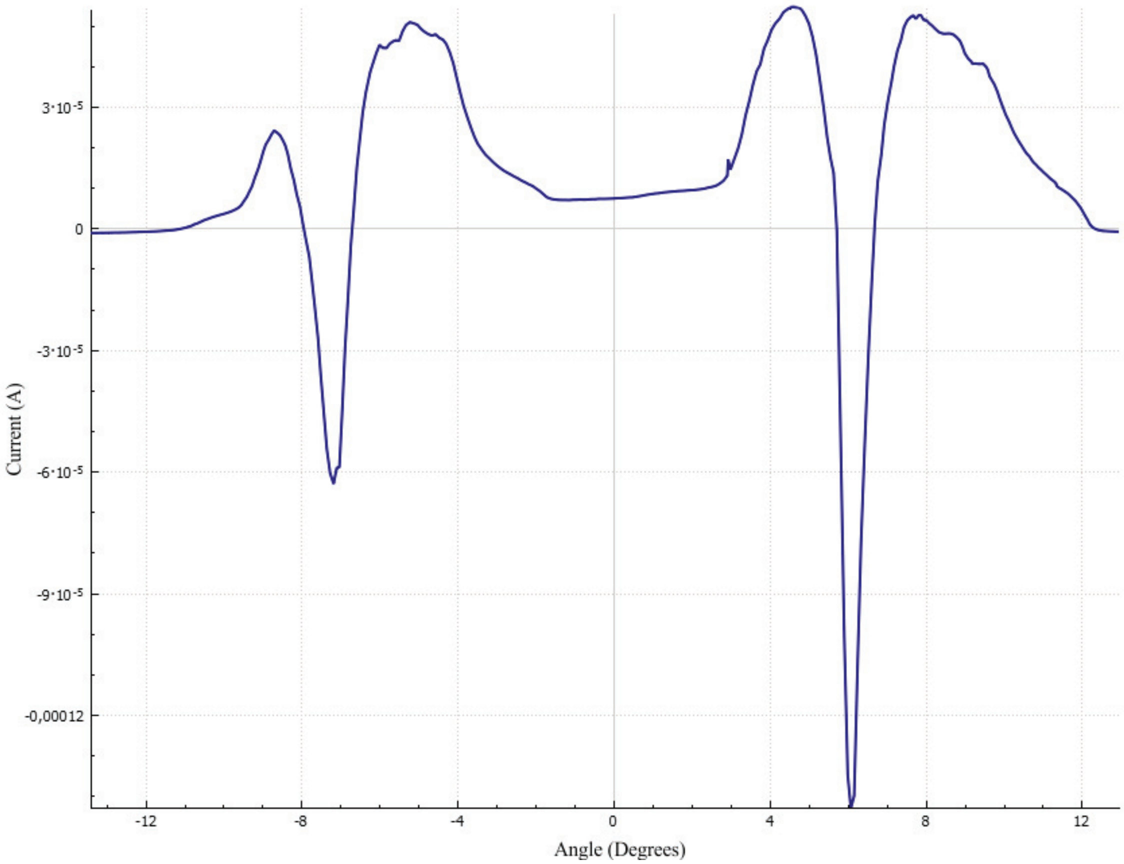


FIGURE 3. The current dependence on the angle of deflection of the scanner rod.

The second thing noticed was that in the large current beam mode (up to 6 mA), the measured signal change polarity: from positive to negative, in case the wire passes through the center of the ion beam (Fig. 3). It should be noted that this effect was obtained at a power density of 1.6 W/cm^2, which is greater than the maximum intensity of 1 W/cm^2 in the scanner specification.

It turns out that in this case the coefficient of secondary emission of electrons from the wire depends on the position of the wire relative to the beam: more than 1 at the periphery of the beam and can be less than 1 at the center. The possible explanation is the effect of space charge on the secondary electrons collection. The dependence of the secondary emission coefficient on the position of the scanner detected by us indicates a systematic error of the scanner when measuring the profile of the ion beam: the profile measured by the scanner does not correspond to the profile of the ion beam.

To eliminate this effect, secondary electron emission was suppressed by placing metal rings with an internal diameter of 60 mm (11 in Fig. 2) at a distance of 50 mm in front of the scanner and behind it, to which a negative potential was applied. The calculated potential distribution along the path axis at a potential of rings −300 V is given in these proceedings [3], from which it can be seen that a potential barrier with a height of at least 160 eV is created for electrons emitted from the wire. In this case, the measured signal became negative - it began to correspond to the current of negative hydrogen ions (Fig. 4).

The suppression of the secondary emission made it possible to make a device for measuring the beam current from the current measuring device to the wires.

An analysis of signals waveform shows that additional information can be obtained about its position and the value of the total current. Determination of the beam position, its dimensions, and also the total current was realized in the software described in the next section.

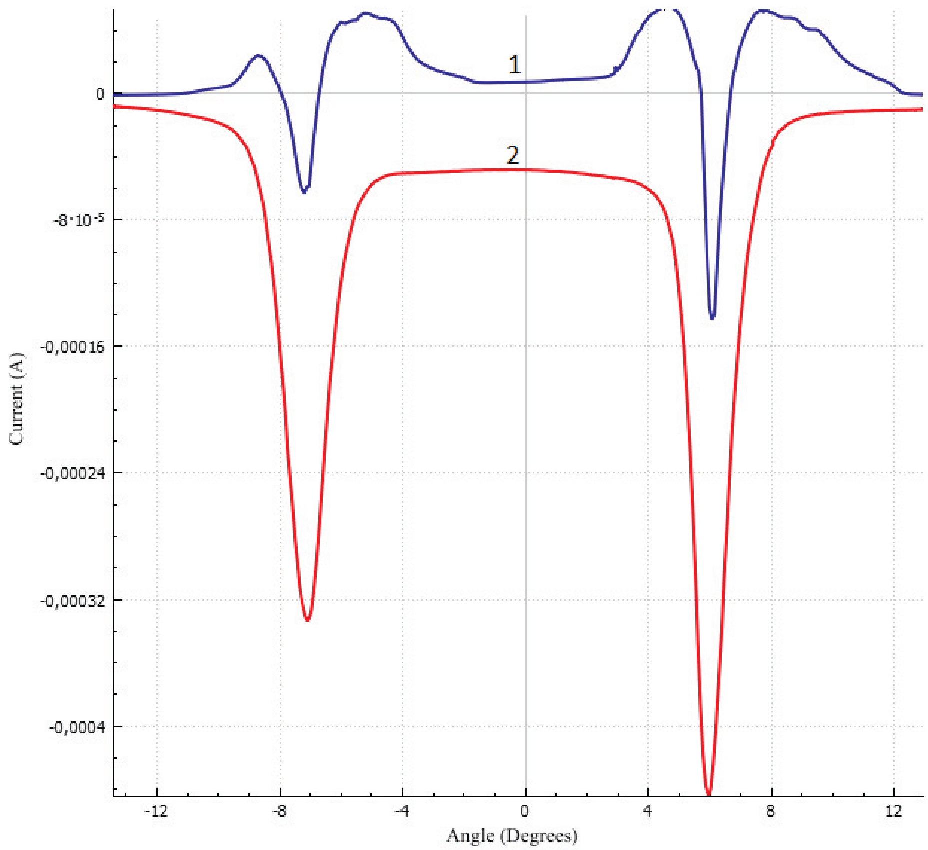


FIGURE 4. The current dependence on the angle of deflection of the scanner rod (graph 1 – no suppression, graph 2 - the secondary electron emission suppressed).

DESCRIPTION OF THE DEVELOPED SOFTWARE

The program V1.0 originally supplied with the wire scanner displays only the measured current by the angle of the rod, and stores the results in a file. Since the necessary initial data for calculating the beam parameters are available, a program has been developed that produces additional data processing. Fig. 5 presents the user interface of this program, which allows you to display several measurements in one window which is convenient for comparison, and on separate tabs gives the calculated values of the total beam current, its size and position.

In addition, the application allows to display a two-dimensional beam distribution (Fig. 6). Since each measurement of the profilometer is the sum of the currents arriving at the wire, we can form a system of linear equations. If we take n and m for the number of measurements from the first and second wire, respectively, then the number of equations will be $n + m$. And the number of unknown variables will be $n \times m$. There are infinitely many solutions of such a system, so the restoration of the internal distribution of the beam belongs to the class of ill-posed problems.

In the first approximation, the solution of such a system can be the normalized multiplication of profiles from two wires. In most cases, the image constructed by this method looks like a rectangle. This allows you to define a rectangular area on the plane with the beam inside. This method is implemented in software (Fig. 6 a).

In addition, a method for constructing an image using a neural network is proposed and implemented. The inputs for the neural network are profiles with two wires, the number of inputs is $n + m$. And the output is the pixels brightness of the image $n \times m$. The neural network was trained by the back propagation method on a pre-prepared set of images with different internal forms of the beam (hollow, Gaussian, homogeneous, offsets of maximum) (Fig. 6 b).

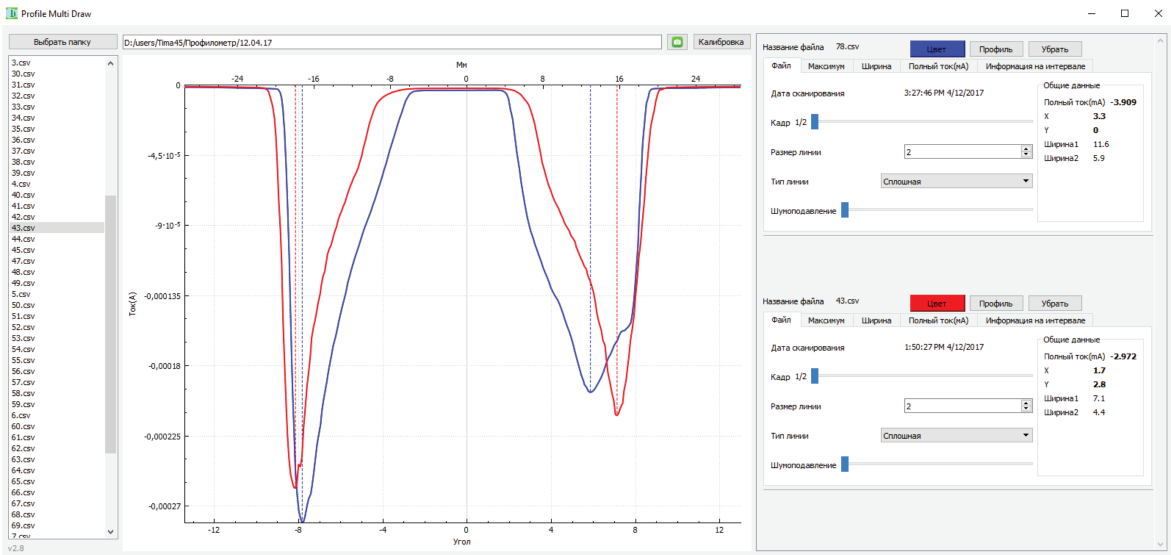
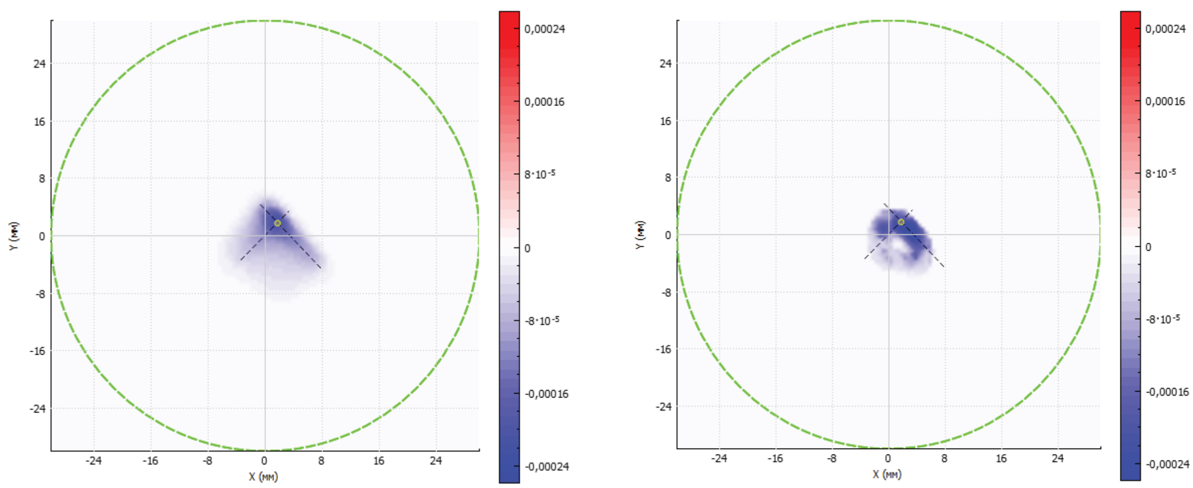


FIGURE 5. The user interface of the program that performs additional processing of the scanner data.



(a) (b)

FIGURE 6. (a) Internal beam distribution constructed by the multiplication method, (b) Internal beam distribution constructed by the neural network.

The algorithm of recalculation of angles into coordinates calculates the position of each pixel. The origin corresponds to the center of the input diaphragm of the accelerator and is set during calibration.

Calibration by position is carried out as follows. Inside the vacuum chamber made in the form of a tube and located to the left of the scanner (Fig. 2), a cylinder with a hole 3 mm in diameter is inserted. It is verified that the hole in the cylinder is coaxial with the hole of the cooled diaphragm of the accelerator (8 in Fig. 2). Then a rod with a fixed wire is inserted into the hole of the cylinder in such a way that during measurement the scanner lightly touches the wire. The wire is energized and the scanner measures the current. The obtained data allow determining coordinate shifts relative to the center of the inlet of the accelerator and taking into account the backlash of the scanners rod.

METHODS OF CALCULATION OF POSITION, SIZE AND TOTAL CURRENT OF ION BEAM

Next, there will be the descriptions of the algorithm for recalculating angles into coordinates and methods for calculating the beam size and the total current.

Method for Calculating the Position of the Beam in a Plane

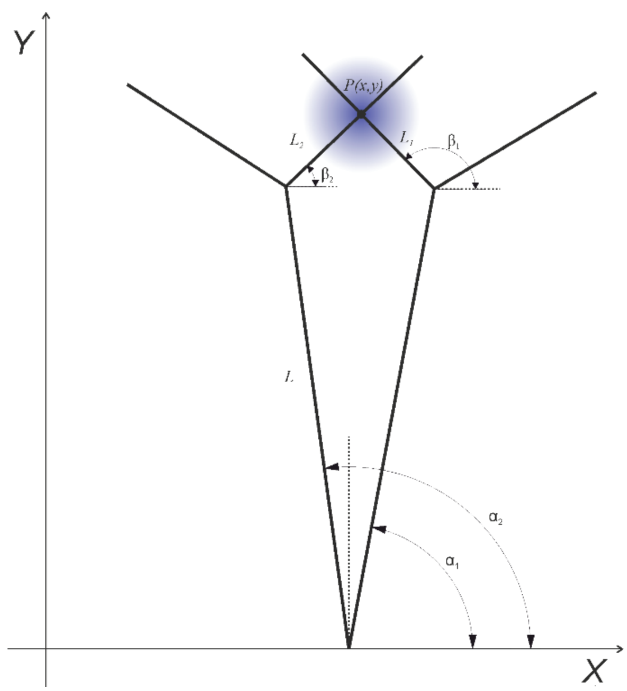


FIGURE 7. The positions of the scanner for α_1 and α_2 angles

Figure 7 shows two positions of the scanner, in which the wires of the scanner cross a given point on the plane. Here α_1 and α_2 – are the angles of the scanner's rod recorded in a file, γ – angle between wires, β_1 и β_2 – angles of wires to the abscissa axis ($\beta_1 = \alpha_1 + \gamma/2$, $\beta_2 = \alpha_2 - \gamma/2$), L – rod length, L_1 and L_2 – unknown lengths from the rod to the point of intersection point P with unknown coordinates *(x,y)*. Knowing the angles α_1, α_2, γ and the length L is computable coordinates of intersection *P(x,y)*. Equating the coordinates *(x,y)* of the intersection of the wires, we obtain a system of equations with two unknowns:

$$\begin{cases} L\cos\alpha_1 + L_1\cos\beta_1 = L\cos\alpha_2 + L_2\cos\beta_2 \\ L\sin\alpha_1 + L_1\sin\beta_1 = L\sin\alpha_2 + L_2\sin\beta_2 \end{cases} \quad (1)$$

The system of equations is solvable, its solution is:

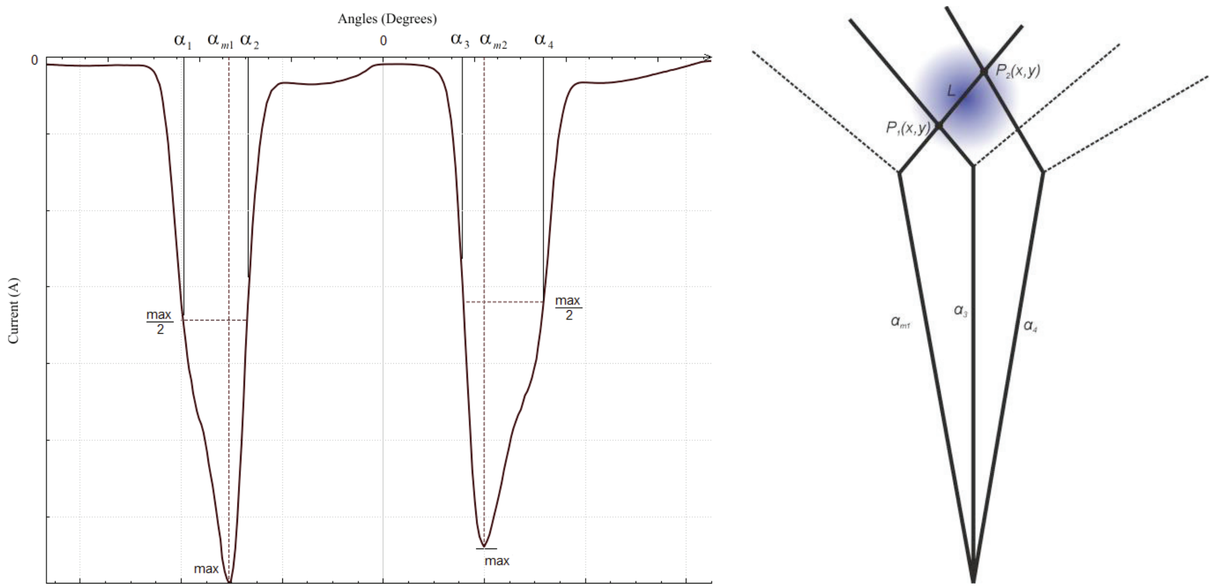
$$L_1 = L\frac{\sin\alpha_2 - \sin\alpha_1 + \mathrm{tg}\beta_2(\cos\alpha_1 - \cos\alpha_2)}{\sin\beta_2 - \cos\beta_1\,\mathrm{tg}\beta_2} \quad (2)$$

$$L_2 = L\frac{\sin\alpha_1 - \sin\alpha_2 + \mathrm{tg}\beta_1(\cos\alpha_2 - \cos\alpha_1)}{\sin\beta_1 - \cos\beta_2\,\mathrm{tg}\beta_1} \quad (3)$$

The intersection coordinate is ($L\cos\alpha_1 + L_1\cos\beta_1$, $L\sin\alpha_1 + L_1\sin\beta_1$).

Method for Determining the Beam Size

To calculate the beam size, the angles are determined at which the current reaches a maximum and at values that are half the maximum current (Fig. 8 a). The search intervals of angles for the first and second wires are separated by zero. This means that the first wire crosses the beam in the angular interval from 13,5° to 0°, and the second one from 0° to –13,5°.



(a) (b)

FIGURE 8. (a) The dependence of the current on the angle, (b) The position of the scanner at which points are determined for calculating the width.

Next, the coordinates of two points *(P_1,P_2)* are calculated from the angles α_1, α_{m2} and α_2, α_{m2}, the distance between these points is calculated and this value is displayed on the application tab in the width field. Similarly, the width at angles α_3, α_{m1} and α_4, α_{m1} for the other wire is calculated. Figure 8 b shows the points *(P_1,P_2)* and the corresponding positions of the scanner.

In the developed program, where is an additional opportunity to choose at which height from the maximum to calculate the beam size.

Method for Calculating the Total Current

The calculation of the total current is carried out by summing the measured current values (formula 4) multiplied by a coefficient equal to the ratio of the area swept out by the wire when moving S to the cross-sectional area of the wire S_{wire}. This coefficient depends on the speed of the scanner rod and is calculated for all intervals of the angle measurement.

$$I = \sum_{i=0}^{n} I_i \frac{S(\Delta\alpha_i)}{S_{wire}}. \tag{4}$$

The area S swept out by the wire is calculated as the difference of the circle sector areas described by the end of the wire and the sector of the circle described by the end of the rod, according to the following formula.

$$S = \pi \frac{\Delta\alpha}{360}(R^2 - Lw^2), \tag{5}$$

where $\Delta\alpha$ – the difference between the angles of two measurements, Lw – rod length. R – radius of the circle described by the end of the scanner's wire, is calculated by the following formula 6.

$$R = \sqrt{Lw^2 + l^2 - 2 \times Lw \times l \times \cos(\beta)}\ , \tag{6}$$

where l is the length of the wire, β – the angle between the rod and the wire.

APPLICATION OF THE WIRE SCANNER

The upgraded OWS-30 wire scanner together with the developed software was used to measure milliampere level 21 keV H^- beams injected into a vacuum-insulated tandem accelerator. Its use made it possible to detect the effect of space charge and spherical aberration of focusing magnetic lenses on the beam of negative hydrogen ions injected into the accelerator. It is established that the profile of the injected beam has the form close to the torus, and the maximum beam density is realized at an intermediate pressure of the residual gas in the transport channel of 7.5 mPa. With the use of a movable diaphragm, the phase portrait of the beam is measured and the value of its normalized emittance – 1.7 ± 0.1 mm mrad measured on 2/3 of beam current. The results of the study are described in detail in the published article [3].

The scanner became a reliable diagnostic for measuring the current of the injected ion beam and monitoring the position of its injection into the accelerator. The use of the scanner made it possible to accurately align the magnetic focusing lens and in real time to monitor the position of the ion beam, which was one of the components of success in increasing the proton current from 5 to 6.7 mA.

CONCLUSION

The vacuum-insulated tandem accelerator was equipped with the OWS-30 wire scanner (D-Pace, Canada, under TRIUMF license) designed to measure the beam profile. When using the scanner it is established that it does not allow to reliably measure the beam profile due to the effect of the space charge of the ion beam on the secondary emission of electrons from its wires for the case of milliampere levels of 21 keV H^- ions. Also, the beam related information provided to the user by the V1.0 software required significant improvement.

To carry out reliable studies, the scanner and its software have been modernized. To suppress the secondary electrons emission, metal rings with a negative potential were installed in front and behind the scanner. The software is supplemented with a program that processes data and provides real-time information about the position, size and total current of the ion beam.

The use of a modernized wire scanner made it possible to detect the effect of space charge and the effect of spherical aberration of the focusing magnetic lenses on a beam of 21 keV negative hydrogen ions, to measure its phase portrait and controlling the position of the beam, to ensure reliable operation of the accelerator at high proton beam currents up to 6.7 mA.

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REFERENCES

1. D-Pace Specification Document 2120009.
2. S. Taskaev, "Accelerator based epithermal neutron source", Phys. Part. Nucl. **46**, no. 6, 956-990, (2015). doi:10.1134/S1063779615060064.
3. T. Bykov, D. Kasatov, Ia. Kolesnikov, A. Koshkarev, A. Makarov, Y. Ostreinov, I. Shchudlo, E. Sokolova, I. Sorokin, S. Taskaev, "Measurement of the space charge effect of a negative hydrogen ion beam", *these proceedings.*