https://doi.org/10.46813/2022-139-070

EMITTANCE MEASUREMENT OF THE ACCELERATED BEAMS (A REVIEW)

A.F. Dyachenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: dyachenkoa@kipt.kharkov.ua

A review of emittance measurement methods of the accelerated (ionic or electronic) beams on various accelerating facilities both foreign, and Ukrainian is presented. There are some ways of emittance measurements in their various modifications: a slit method ("two slits", "four slits", Allison scanner), pepperpot method, and also gradient method (quadrupole scanning). The most high-speed and exact enough way of emittance measurement what is pepperpot method in detail considered on example UNILAC GSI (Darmstadt, Germany). Possibility of a field angular distribution use in a distant zone of an optical diffraction radiation made electronic bunch, passing through rectangular apertures in screens (DESY, Hamburg, Germany) is shown.

PACS: 29.17.w, 29.27.Bd

INTRODUCTION

For successful carrying out of the experimental nuclear physical researches connected with use of charged particles accelerated beams, as much as possible exact knowledge of their parameters is necessary. Effectively working systems of beams diagnostics on accelerating facilities are necessary for this purpose. Research of the processes take place during acceleration, conditions measuring of beams coordination with transport lines elements, a choice of an optimum configuration of focusing elements without knowledge of emittance parameters are complicated.

The work purpose is a review of the emittance measurement methods of an accelerated beam (ionic or electronic) on various accelerating facilities. Thus the basic attention is given modern methods of an emittance measurement of ionic beams and their adaptation to easy ions and the protons accelerators working in NSC KIPT.

1. ACCELERATED BEAM EMITTANCE

Each beam particle is characterized by position (x, y, z) and an impulse (p_x, p_y, p_z) during of each moment time. According to Liouville's theorem the volume of all particles in six-measured phase space of coordinates and impulses is invariant. Such six-measured volume which in phase space a beam occupies, name an emittance. Assuming that ions move under small corners to axis Z, i. e. $p_z >> p_{x,y}$, and pass an equal potential difference conveniently, firstly, to replace impulses p_x and p_y values their corners values concerning direction Z: $x' = p_x/p_z$, $y' = p_y/p_z$; secondly, to consider velocity dispersion V_z minimum so invariant that will allow to take on the invariance of the four-dimensional phase volume named a transverse emittance. Besides, counting movements on X and Y coordinates independent, it is possible to consider in addition also phase subspaces {x, x'} and {y, y'}. Geometrically two-dimensional volume will be in this case the area in corresponding coordinates and emittance values will be defined under formulas [1]:

$$\epsilon_x = \frac{1}{\pi}\int\int_{area}^{x} dx dx', \quad \epsilon_y = \frac{1}{\pi}\int\int_{area}^{x} dy dy'.$$

2. BASIC APPROACH TO EMITTANCE MEASUREMENT

Experimental techniques of emittance measurement have some distinctions, but are reduced to that the small part of an accelerated beam "is cut out" on known distance by means of a mask which can have different configurations, and then is scanned on the distance defined by particles energy. A measurement result is the curve of the split beam current distribution in a direction of one of transverse coordinates. This information has enough to calculate of particles angular distribution. The simplest realization of this technique is use of the slit distributor and wire scanner (Fig. 1) [1].

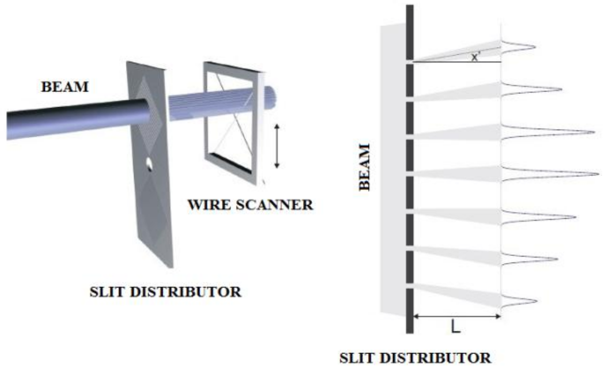


Fig. 1. Slit distributor and wire scanner for beam emittance measurement

There are some basic ways of emittance measurement in their various modifications: slit method ("two slits", "four slits", Allison scanner), pepperpot method, and also gradient method (quadrupole scanning).

3. SLIT METHODS

Historically the first methods of emittance measurement were slit methods which were embodied in various constructive decisions.

"Two slits" method. The facility scheme for phase volume measurement by the "two slits" method is resulted in Fig. 2. The first slit allocates all particles with the given coordinate x_0. The second slit allows to establish of the allocated particles current distribution on trajectories inclinations dx/dz. Behind the second diaphragm the current collector – Faraday cup is established. As both

slits pass particles with all values *y*, *dy/dz*, available for particles with the fixed coordinate x_0, after all values *x* detour we receive phase volume to a plane *x*, *dx/dz* projection (beam emittance) [2].

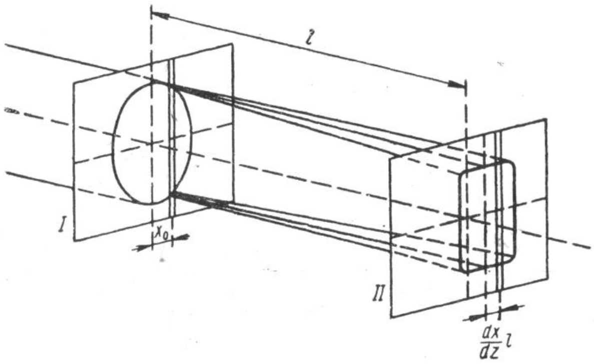


Fig. 2. Facility scheme for emittance measurement by "two slits" method

"Four slits" method is schematically shown in Fig. 3. The slits pair in the first plane allocates particles with a given value of coordinates x_0, y_0. The second slits pair allows to measure of the allocated particles current distribution on trajectories inclinations *dx/dz*, *dy/dz.* If to place a horizontal slit in the first plane in position $y_0 = 0$, and a horizontal slit in the second plane in position $dx/dz = 0$ this method allows to define section of four-dimensional phase volume a plane $y = 0$, $dy/dz = 0$ [2].

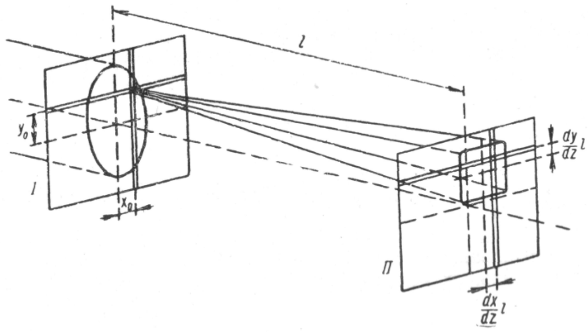


Fig. 3. Facility scheme for emittance measurement by "four slits" method

Allison emittance-scanner is schematically presented in Fig. 4. A beam of current *i* impinges on the narrow front slit of the scanner pod. The emerging missing beam passes between a pair of electric deflection plates driven by a linear ramp generator. The ramp voltage changes slowly compared to the ion transit time; thus, for ions passing through the rear slit, there is a simple relationship between the initial angle *x'* and the instantaneous ramp voltage. The scanner current as a function of time during the ramp then is proportional to the phase space density *d2i/dxdx'* as a function of *x'*. The scanner pod is stepped across the beam to complete the measurement as a function of *x, x'*. The computer program can calculate and display phase-space contours, rms emittance, emittance versus beam fraction, and Courant-Snyder (Tviss) beam-envelope parameters [3].

Emittance measurement of H^+ ions beams on the electrostatic accelerator ("Sokol", Institute of Applied Physics, Sumy). A facility scheme for emittance measurement on this accelerator is presented in Fig. 5. A part of the ionic beam which has passed through the moved diaphragm (1) is measured by wire probe (2).

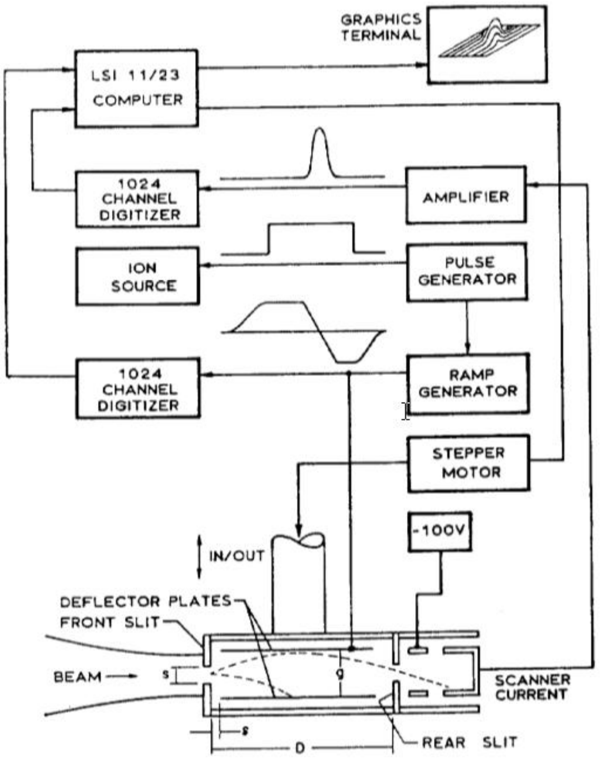


Fig. 4. Schematic of electric-sweep emittance scanner

The emittance is calculated by positions of a diaphragm slit and a probe which define angular and spatial coordinates of ions beam. In front of the chamber with a diaphragm there is an axial ball-bearing (3). Moving of a diaphragm and a wire probe is provided with step motors (4) by means of rods with a thread (5). A diaphragm slit which allocates an ionic beam part, is established for the width of 0.2 mm. Behind the chamber with a wire probe Faraday cup (6), used for measurement of ions beam current (H^+ ions energy of 1 MeV, a beam current of 25 μA) is established [4].

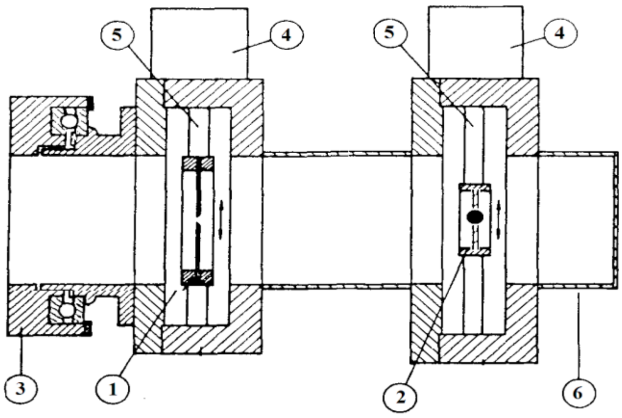


Fig. 5. Facility scheme for ions beam emittance measurement of the electrostatic accelerator

U-240 *cyclotron beam diagnostics system* (INR, Kiev). Distribution of a beam particles density in transverse phase planes is measured serially by two mobile diaphragms (cooled deionize water) with mutually perpendicular slits. The range of particles angular deviations in the beam which has passed through this or that slit, is measured by profilometer with horizontal and vertical molybdenum wire strings (diameter of 0.1 mm), established on a distance L = 1091 mm from slits.

Such method does not demand scanning of the second slit at each fixed deviation of the first slit. Scanning of slits is made independently. It allows more operatively than in a diaphragming method with partial integration to define parameters of a beam [5].

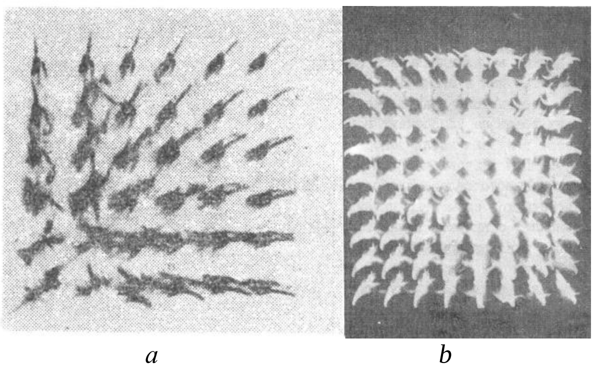
Emittance measurements of a beam in the injection channel of the linear accelerator H^- ions (INR, Moscow). In the injection channel of H^- ions (I = 10 mA, W = 400 keV) adjustment for a maximum particles current passage on the channel to an input in low aperture booster resonator RFQ is carried out. Emittance measurements of an along the channel by three measuring instruments (slit – multiwire collector type) are realized. The channel adjustment algorithm for maintenance of beam coordination with RFQ is offered. Reasons analysis of particles losses in the channel, connected with deviation of the beam gravity center from channel axis is carried out [6].

4. PEPPERPOT METHOD

This method versions at all similarity of type "pepperpot" masks essentially differ registering devices execution. So the slits in the second plane can replace photosensitive emulsion with the subsequent exhibited places photometric measurements. On two facilities in NSC KIPT has been carried out as much: *the small-sized linear accelerator of deutons* (SLAD) [7] and *the protons linear accelerator* U-12 [8].

The target with apertures (mask) made of a copper foil in the thickness of 20 μm for elementary beams allocation from an analyzed particles stream on SLAD was used. Apertures in diameter of 170 μm placed in points of a rectangular two-dimensional grid with the period of 2×2 mm. The mask apertures system blocked only the fourth part of an investigated stream with axially-symmetrical density distribution.

On U-12 the similar mask was used, but blocking all beam and with smaller apertures (120 μm). The diverged elementary beams registration was carried out by means of photographic plates for nuclear researches of type MP. Nuclear plates choice as the detector has been caused by necessity of the high spatial resolution. Besides, the used registration method possesses high sensitivity to accelerated ions beams in the absence of electromagnetic fields influence on measurements results. Protons elementary beams profiles are presented in Fig. 6,a,b.



a *b*

Fig. 6. Structure of elementary beams with protons energy: 1.5 MeV (SLAD) (a); 3 MeV (U-12) (b)

Modern most high-speed and enough exact emittance measurement way of a single impulse of high-current heavy ions beams is *pepperpot method used on UNILAC* GSI (Darmstadt, Germany) [9].

This pepperpot system which can move on a beam axis by means of the pneumatic motor is shown in Fig. 7. The laser beam rejected by a mirror is used with the calibration aim.

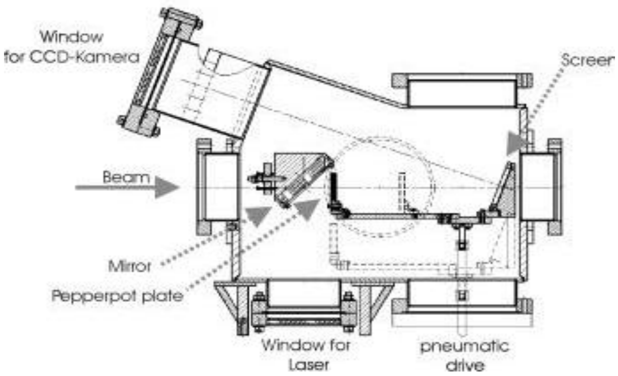


Fig. 7. Pepperpot system on UNILAC scheme

The thin plate with a considerable quantity of very small apertures (pepperpot plate) which is established perpendicularly to a beam axis is used at carrying out of measurements (Fig. 8).

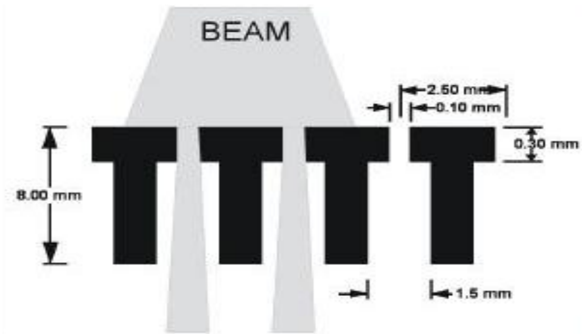


Fig. 8. Pepperpot plate scheme

The used pepperpot plate is made of a copper. The constant grid template has located 15×15 apertures which are drilled in a plate on the area 45×45 mm. Passing through this plate, the beam creates light spots on the fixing screen established behind it. The phase dependence of angular deviations on coordinates is find and parameters of the accelerated beam phase figures are calculated on these spots sizes and intensity distribution in them.

Scintillating fluorescent screen is made from Al_2O_3. The distance between a pepperpot plate and the screen can be variously: from 150 to 250 mm to change the resolution in a case overlap spots. For errors reduction caused by a light refraction, the chamber internal part completely blackens.

For program processing of the experimental data, measured on UNILAC the advanced technique [10-13] is offered. Algorithm of this technique the following:

- the light picture turns to the numerical matrix presented in bmp format by the digital chamber;

- at first it's necessary smoothing procedure of experimental data carry out as a during acceleration secondary processes which lead to noise induction and some background take place. The least squares method with use of Legendre standard polynoms is applied for this purpose;

- further program cyclic procedures for separate spots extraction are carried out. After that their intensity distribution matrixes are processed. Such distributions in horizontal and vertical directions approximate Gauss functions taking into account that experimental projections have the asymmetrical form. Therefore on two Gaussian for the left and right peak parts (concerning of a maximum) pick up for each of them;

- after approximation by Gauss functions of intensity projections the sizes of all spots are defined. At the same time angular deviations according to inside of the beam coordinates are calculated that allows to construct corresponding phase planes figures which characterize emittance and Tviss parameters;

- the transverse emittance parameters are defined by means of new numerical graphic algorithm. On the area and a slope angle of a phase figure approach by its ellipse is carry out. It gives the chance to calculate emittance value and Tviss parameters analytically [10].

With the help a pepperpot method *the ionic beam transverse emittance was measured and in the cyclotron* DC-72 *injection channel* [14]. At that such pepperpot advantages method have been noted:

- at emittance measurement of powerful electronic and ionic beams by advantage pepperpot techniques that slits or apertures sizes (100…500 µm), made in a mask, cut out from a beam such part in which already there is no influence of its charge, and beam scattering behind a mask is defined only by emittance;

- the second advantage of this technique is that with its help, unlike other methods, it is possible to measure separate bunches emittance and to receive beam distribution in phase space;

- the third advantage of this technique is that it, in principle, allows to receive independently beam distributions in $\{x, x'\}$- and $\{y, y'\}$-planes of phase space [14].

The original diagnostic device is developed at Peking University for H^+ beam single impulse (current 0.1…10 A at 20…150 keV with the impulse length of 4 µs) which is *a combination of Faraday cup and pepperpot measurement facility* [15]. It consists of the main Faraday cup with a pepperpot mask in its bottom and Faraday cup array which are on a distance of 3 mm from a mask. The pepperpot mask contains 25 identical apertures (diameter is of 0.5 mm), and its thickness makes 2 mm, but actually the apertures wall thickness is approximately 0.5 mm to prevent any smearing effects due to beam scattering (Fig. 9).

An overall view of the pepperpot device is shown in Fig. 10. Signals of the main Faraday cup and Faraday cup array are delivered outside the vacuum chamber by the special multi-core cable protected wires.

Although this pepperpot device has the ability to measure the total current and beam distribution of a single microsecond pulse simultaneously, it cannot provide the beam emittance information so far. In order to solve this problem the upgrade plan was proposed with replacing the Faraday cup array disk with a fluorescent screen and CCD camera (UNILAC variant) [14].

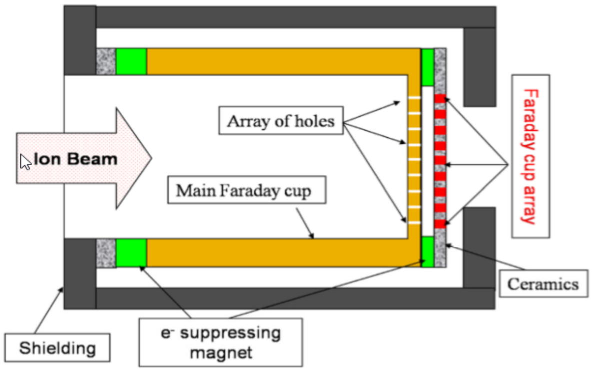


Fig. 9. Schematic diagram of the pepperpot beam profile measuring device

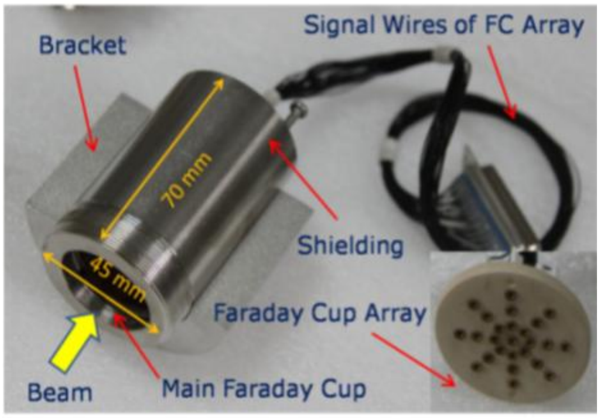


Fig. 10. Photo of the pepperpot beam distribution measuring device

The similar device was developed and in NSC KIPT, but, unfortunately, this engineering design has not been finished. We consider possibility to use pezo- or ultrasonic gauges as registering devices.

In principle it is possible to consider pepperpot technique as the slit method version. An each method distinctive feature is the way of a beam splitting on elements: in slit method this is a slit scanning, and the mask itself forms separate beams.

5. GRADIENT METHOD

For emittance measurement of easy elements ions beam (H^-, $^2H^{1+}$) *in the cyclotron* DC-72 *injection channel* [14] a gradient method (quadrupole scanning) was provided use also. Usually such measurements are spent in beam transport lines where are available quadrupole lenses. Emittance measurement variant of ions $^2H^{1+}$ beam by means of the scanner C, located on distance L from the lens Q_3 edge is considered (Fig. 11).

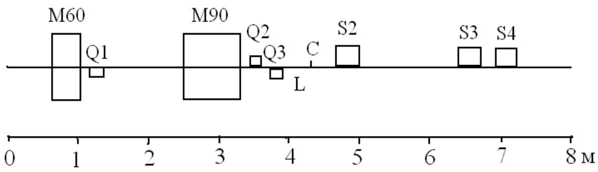


Fig. 11. Scheme of hydrogen ions axial injection channel, where M60 and M90 – rotary magnets; S2, S3 and S4 – solenoids

The beam current changes from 0 to 700 µA. At carrying out of measurements it must be reconstructed Q_1, Q_2 lenses gradients for necessary character ensuring of beam envelope change (the beam after Q_2 lens should not diverge strongly). Emittance measurement procedure consists in beam size definition for several values of the Q_3 quadrupole gradient, and the gradient change area should contain a beam size minimum point.

Such way of emittance beam measurement is inapplicable, when a beam owns field influence becomes essential (the relative error reaches 70% at a current 700 μA). This method is seldom applicable because of measurements big error.

6. DIFFRACTION INTERFERENCE METHOD

In case of the beams high brightness having the small transverse sizes (as a rule lower of 100 μm) or high frequency of impulses repetition (an order of MHz) the energy allocated in interrupting devices (screens, masks) does their use difficult.

It is offered (DESY, Hamburg, Germany) to use field angular distribution in a distant zone optical diffraction radiation (ODR), made electronic bunch, passing through rectangular apertures in screens (Fig. 12) [16].

Optical diffraction radiation which is emitted forward in the first slit (FDR) interferes with the return radiation made in the second slit (BDR). Slits various apertures are necessary to signal suppression avoid because of a destructive interference between emitted fields. The ODR interference pattern contains valuable information about beam parameters: transverse size, angular divergence and relative position inside the slits can be retrieved from it.

The experimental setup consists of in-vacuum actuator used to insert an aluminum coated silicon screen into a precise position with respect to the electron beam axis. The screen holder is shown in Fig. 13. The 0.5 mm slit aperture on the screen is made by means of a lithographic technique using anisotropic etching in a KOH solution, allowing the creation of clean and very sharp edges.

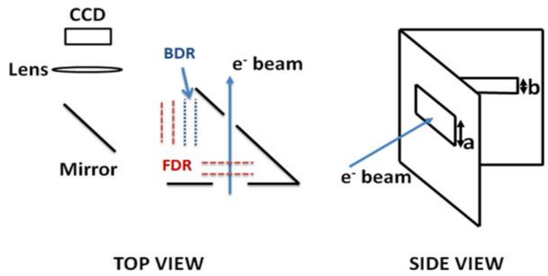


Fig. 12. Two slits setup sketch

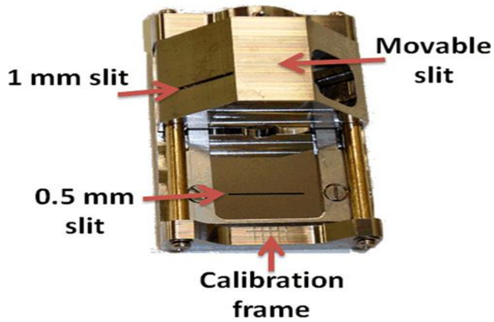


Fig. 13. Screens holder image

CONCLUSIONS

Emittance measurement existing methods of the accelerated beam (both ionic, and electronic), their constructive decisions used on various foreign and Ukrainian accelerating facilities are considered. Historically the first emittance measurement methods were slit technique ("two slits", "four slits" methods) which were realized in various designs (Allison scanner). Masks method versions which now is most widely used, at all masks similarity (pepperpot type) running of the registering devices (photographic plate, CCD-chamber, Faraday cup) differ essentially. The gradient method is seldom applicable because of measurements big error. The direction of optical diffraction radiation interference use is perspective. The considered methods are tabulated (Table). The emittance measurement method choice, in each specific case, is defined by the accelerated beam parameters and possibilities of the constructive decision realization.

Summary list of measurement emittance methods

Measurement method	Version	Realization
Slit method	"Two slits" method [2]	Allison emittance-scanner [3]; EA "Sokol" (IAP, Sumy) [4]; U-240 cyclotron (INR, Kiev) [5]; Linac (INR, Moscow) [6]
	"Four slits" method [2]	
Pepperpot method	Photographic plate; CCD camera; Faraday cup array	Linacs SLAD [7], U-12 [8] (NSC KIPT, Kharkov); UNILAC GSI (Darmstadt, Germany) [9]; HIT (Heidelberg, Germany) [17]; Peking University [15]
Gradient method		DC-72 cyclotron (JINR, Dubna) [14]
Diffraction interference method		DESY (Hamburg, Germany) [16]

REFERENCES

1. A. Muller, M.Ye. Smirnova, D. Feily, et al. Use of emittance measurement system for ionic engine diagnostics // *Electronic magazine "Works MAI"*. Is. 73. URL: www.mai.ru/science/trudy/.
2. I.M. Kapchinskiy. *Particles dynamics in linear resonant accelerators*. M.: "Atomizdat", 1966, p. 234-236 (in Russian).
3. P.W. Allison, J.D. Sherman, D.B. Holtkamp. An emittance scanner for intense low-energy ion beams

// *IEEE Transactions on Nuclear Science*. 1983, v. NS-30, № 4, p. 2204-2206.

4. I.G. Ignat'ev, M.I. Zakharets, S.V. Kolinko, D.P. Shulha. Emittance measurement of electrostatic accelerator ions beam // *Journal of nano- and electronic physics*. 2014, v. 6, № 1.
5. O.E. Valkov, O.V. Dubinin, O.K. Zaichenko. Measuring method of entering beam parameters of the cyclotron U-240 stable isotope separator // *Technics and Methods of an Experiment. Nuclear Physics and Atomic Energy*. 2011, v. 12, № 1, p. 94-97.
6. S.E. Bragin, O.M. Volodkevich, V.A. Gaidash, et al. H^- beam emittance measurements in trasport channel of INR linac // *Problems of Atomic Science and Technology*. 2012, № 3(79), p. 58-62 (in Russian).
7. Ye.V. Gussev, P.A. Demchenko, I.K. Kovalchuk, et al. Emittance measurement of proton beams on accelerator with alternating-phase focusing // *Problems of Atomic Science and Technology*. *Series "Technics of Physical Experiment"*. 1979, № 2(4), p. 91-93.
8. P.A. Demchenko, I.K. Kovalchuk, V.V. Mitrochenko, et al. Experimental researches of protons dynamics in accelerator with alternating-phase focusing // *Problems of Atomic Science and Technology*. *Series "Technics of Physical Experiment"*. 1985, № 3(24), p. 28-31.
9. T. Hoffmann, W. Barth, P. Forck, et al. Emittance measurements of high current heavy ion beams using a single shot pepperpot system. URL: http://www.hep.ph.ic.ac.uk/fets/pepperpot/docs+papers/hoffmann_biw00_pepperpot.pdf.
10. M.E. Dolinska. Modeling of inner beam processes and their account at carrying out of diagnostics on accelerators of the charged particles: abstract of a thesis … candidate of technical sciences: 01.04.16. INR, NAS of Ukraine, Kyiv, 2003.
11. M. Dolinska, M. Domke, P. Forck, et al. Emittance measurements at the new UNILAC pre-stripper using a pepper-pot with a PC-controlled CCD-camera // *Proceedings DIPAC*. Chester, UK. 1999, p. 171-173.
12. M.E. Dolinska, N.L. Doroshko. Pepper-pot diagnostic method to define emittance and twiss parameters on low energies accelerators // *Problems of Atomic Science and Technology*. *Series "Nuclear Physics Investigations"*. 2002, № 2(40), p. 107-111.
13. M.E. Dolinska, N.L. Doroshko, A.K. Zaichenko. *Beam diagnostic by pepperpot method*: Preprint KINR-02-3, Kyiv, 2002, 12 p.
14. N.Yu. Kazarinov, V.I. Kazacha, I.V. Kalagin, A. Gall. *Measuring methods of the ion beam transversal emittance in the injection channel of the cyclotron DC-72*: Preprint JINR P9-2002-120, Dubna, 2002, 15 p. (in Russian).
15. H.T. Ren, S.X. Peng, J. Zhao, et al. A pepper-pot based device for diagnostics of the single-shot beam // *Proceedings of* IPAC2013, Shanghai, China. P. 3093-3095.
16. A.Cianchi, V.Balandin, M. Castellano, et al. First non-intercepting emittance measurement by means of optical diffraction radiation interference // *New Journal of Physics*. 2014, № 16, p. 1-12.
17. M. Ripert, A. Buechel, A. Peters, et al. A low energy ion beam pepper pot emittance device // *Proceedings of BIW2010*, Santa Fe, New Mexico, US. P. 297-301.

Article received 17.01.2022

ВИМІРЮВАННЯ ЕМІТТАНСА ПРИСКОРЕНОГО ПУЧКА (ОГЛЯД)

О.Ф. Дьяченко

Подано огляд методів вимірювання еміттанса прискореного (іонного або електронного) пучка на різних прискорювальних установках як зарубіжних, так і українських. Існує декілька способів вимірювання еміттанса в різній їх модифікації: щілинний (методи «двох щілин», «чотирьох щілин», сканер Аллісона), рeppеrpot-(«перечниця») метод, а також градієнтний (квадрупольне сканування). Докладно розглянуто найбільш швидкісний і досить точний спосіб вимірювання еміттанса, яким є рeppеrpot-метод, на прикладі UNILAC GSI (Дармштадт, Німеччина). Показано можливість використання кутового розподілу поля в дальній зоні оптичного дифракційного випромінювання, створеного електронним банчем, що проходить через прямокутні апертури в екранах (DESY, Гамбург, Німеччина).

ИЗМЕРЕНИЕ ЭМИТТАНСА УСКОРЕННОГО ПУЧКА (ОБЗОР)

А.Ф. Дьяченко

Представлен обзор методов измерения эмиттанса ускоренного (ионного или электронного) пучка на различных ускорительных установках как зарубежных, так и украинских. Существуют несколько способов измерения эмиттанса в различной их модификации: щелевой (методы «двух щелей», «четырех щелей», сканер Аллисона), рeppеrpot («перечница») метод, а также градиентный (квадрупольное сканирование). Подробно рассмотрен наиболее скоростной и достаточно точный способ измерения эмиттанса, каким является рeppеrpot-метод, на примере UNILAC GSI (Дармштадт, Германия). Показана возможность использования углового распределения поля в дальней зоне оптического дифракционного излучения, произведенного электронным банчем, проходящим через прямоугольные апертуры в экранах (DESY, Гамбург, Германия).