## *Раздел четвертый*

## ФИЗИКА РАДИАЦИОННЫХ И ИОННО-ПЛАЗМЕННЫХ ТЕХНОЛОГИЙ

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# ANGULAR TRAP FOR MACROPARTICLES

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Properties of angular macroparticle traps were investigated in this work. These properties are required to design vacuum arc plasma filters. The correlation between trap geometry parameters and its ability to absorb macroparticles were found. Calculations allow one to predict the behaviour of filtering abilities of separators which contain such traps in their design. Recommendations regarding the use of angular traps in filters of different builds are given.

## INTRODUCTION

In most cases, vacuum-arc film deposition needs applying of special devices – electromagnetic filters (separators). The necessity of their employment is caused by the fact that in addition to useful (electron and ion) components vacuum-arc plasma contains rather big cathode fragments – so-called macroparticles. Their contact with a coating can drastically degrade its quality. At their core, filters are utilizing the concept of spatial separation of plasma and macroparticle trajectories. They are designed in such way that there must not be a direct line-of-sight between the cathode and a workpiece. Magnetized plasma is being transported by curvilinear magnetic field from the cathode to deposition area. Macroparticles are not affected by transporting field due to their large mass. As a result, they are moving along straight trajectories and are not able to reach the substrate.

It is well known [1, 2] that macroparticles are capable to bounce off filter walls. Undergoing several rebounds they still can reach the substrate. Colliding with the walls, macroparticle loses some part of its initial velocity. After some number of collisions, macroparticle velocity is decreased so, that it can not proceed movement: macroparticle either sticks to the wall or falls due to gravity. It means that it is necessary to make such conditions, due to which macroparticle will undergo as much as possible number of collisions on its way to deposition area. To this end, plasma guiding channel is usually equipped with additional obstacles in the form of ribs (baffles).

The effectiveness of separator can be assessed after its manufacture by counting defects amount which was left on the coating due to macroparticle impacts. Such approach has two obvious drawbacks. Firstly, the counting process is rather time-consuming [3]. Secondly, separator has been already manufactured at that moment and making modifications of its initial design is problematic. Therefore filter evaluation should be made at the stage of its development. But there is a problem: it is almost impossible (until this work) to predict with sufficient accuracy an effect of a particular constructive change on plasma filtering degree.

Computer simulation of macroparticle movement paths significantly simplifies the problem of separator designing and assessment of already manufactured ones. Specialized software, named Macroparticle Tracer (MPT), was developed for these purposes. The model it uses and capabilities it possesses were described in detail earlier [4]. Later [5], basing on the MPT modelling results analysis, the highly effective baffle system for T-shaped magnetic filter was developed. It was found that the highest filtering degree is provided by baffles tilted on ~ 18° from anode wall and facing the cathode. At the same time, the location of these baffles with relation to emission centres (cathode working surface) is critical for their performance. It was shown that filtering degree is virtually independent from the step the baffles are shifted from each other (along the anode wall) in the range 1...70 mm (with baffles height equal to 20 mm). But most of the principles responsible for high filtration coefficient remain unclear.

The most practically valuable capability of baffle systems is to "absorb" macroparticles, i.e. to act as a "trap" for macroparticles. The analysis of the developed baffle systems for T-shaped separator [5] shown, that two baffle types are absorbing macroparticles most effectively. In the first case, the bunch from single baffle and plasma duct wall (generally, it can be a second baffle instead of wall) are involved in the absorption process and the baffle is tilted towards macroparticle emission centres – cathode. In the second one – the bunch from duct wall and two parallel baffles which are tilted away from the cathode. According to this constructive difference, the traps can be respectively separated into two conventional types: "angular" and "two-baffle". The scope of this work is to define properties of angular traps, which are responsible for their effectiveness and to make some recommendations regarding baffle systems engineering. All calculations were made in two-dimensional approximation and verified by MPT simulations. Macroparticles were considered as spheres having their radius tending to zero and therefore represented as points in calculations. Macroparticle angle of reflection from surfaces was considered equal to their fall angle [4, 6].

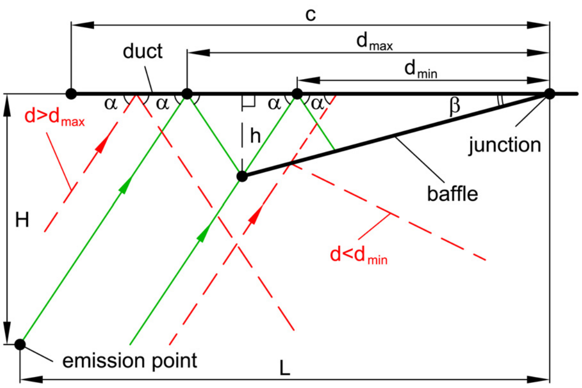

*Fig. 1. Schematic view of the angular trap*

## COMMON PROPERTIES

Angular trap is schematically shown in Fig. 1. It is made up of junction of baffle and plasma duct wall (hereinafter the "junction"). Free end of the baffle is directed toward macroparticle emission centre. The angle $\beta$ formed between the trap baffle and the wall can take values in the range $0<\beta\leq 90^{\circ}$. Macroparticle is considered to be intercepted if it collided with the trap walls not less than two times.

This requires to satisfy the following conditions:

$$0<d_{min}<d\leq d_{max}\leq c\,, \tag{1}$$

$$0<\alpha<90^{\circ}\,, \tag{2}$$

where $d$ – is the distance between points of trap junction and macroparticle impact; $c$ – length of the baffle, which macroparticle collided first; $\alpha$ – the angle between wall or baffle (whichever collided first) and macroparticle trajectory (hereinafter the "glancing" or "grazing" angle); $d_{min}$ and $d_{max}$ – minimum and maximum possible values of the distance $d$, which are defined as:

$$d_{min}=h\frac{\sin(\alpha-\beta)}{\sin(\alpha)\sin(\beta)}\,, \tag{3}$$

$$d_{max}=h\frac{\sin(\alpha+\beta)}{\sin(\alpha)\sin(\beta)}\,, \tag{4}$$

where $h$ – the height of the baffle relative to the wall. If $d>d_{max}$, then macroparticle, being reflected from the wall, will fly past the baffle of the trap (see Fig. 1). In condition of $d<d_{min}$, macroparticle will hit the outer side of the baffle instead of colliding the wall and therefore will not get inside the trap.

After each macroparticle rebound inside the trap, the grazing angle of the particle ($\alpha$) will be increased by the value of trap angle ($\beta$). Until $\alpha<90^{\circ}$ macroparticle will move deeper inside the trap, i.e. toward the trap junction. Hence, the number of macroparticle collisions with the walls of angular trap on the way inwards can be defined as:

$$n=\left\lfloor\frac{90^{\circ}-\alpha+\beta}{\beta}\right\rfloor. \tag{5}$$

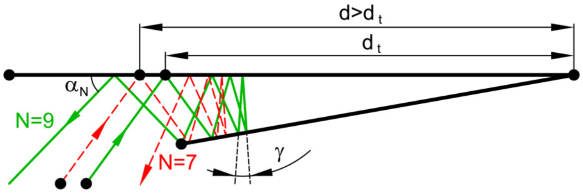

*Fig. 2. Trajectory of macroparticle inside angular trap for $d\leq d_t$ (solid line) and $d>d_t$ (dashed line) cases*

Hereinafter, $\lfloor X\rfloor$ means rounding of value $X$ to the nearest integer towards zero (floor function).

After $n$ collisions macroparticle will change its direction to "opposite" one – it will move out of the trap (away from the junction). After each rebound from the trap wall, macroparticle glancing angle ($\alpha$) will decrease by the trap angle value ($\beta$) until $\alpha$ angle become equal to (or less than) zero. Therefore total number of macroparticle collisions ($N$) with the trap can be obtained from expression (5) if value 180º is used instead of 90º. However, in most cases, the result will be valid only for macroparticles with emission point inside the trap (otherwise, macroparticle will leave the space between trap baffles earlier than the glancing angle becomes equal to zero), which is impossible in considered case.

As it can be seen from (5), the number of collisions during the movement of intercepted macroparticle inwards the trap does not depend on the trap size (baffle and plasma duct wall lengths). The number of macroparticle rebounds on its way out of angular trap, as it was mentioned above, depends on lengths of the trap walls and on the point of the first impact $d$ (Fig. 2). There is some threshold value $d_t$ of the distance $d$ between trap junction and the first collision point. The number of collisions will be two more (in general) if $d\leq d_t$ is true.

Knowing the length of macroparticle trajectory on its way inward the trap (see Fig. 2), the angle formed by trajectory parts during macroparticle movement inside and outside the trap ($\gamma$) and macroparticle glazing angle at the final rebound ($\alpha_N$), one can obtain the value of threshold distance $d_t$ from the following:

$$d_t=h\frac{\sin(\alpha_N+\beta)}{\sin(\alpha_N)\sin(\beta)}\left[1+\frac{\sin(\beta)\sin(\gamma)}{\sin(\alpha+\beta)\sin(\alpha_N)}\times\right.$$
$$\left.\times\left(1+\sum_{i=2}^{n}\prod_{k=2}^{i}\frac{\sin(\alpha+(k-2)\beta)}{\sin(\alpha+k\beta)}\right)\right]^{-1}, \tag{6}$$

where $\alpha_N=180^{\circ}-\alpha-2n\beta$, $\gamma=2(\alpha+n\beta-90^{\circ})$.

Fig. 3 demonstrates the nature of dependencies (3), (4) and (6). It is clear from the figure that function $d_t(\alpha)$ can be approximated by a series of straight lines without any substantial loss of result accuracy that will

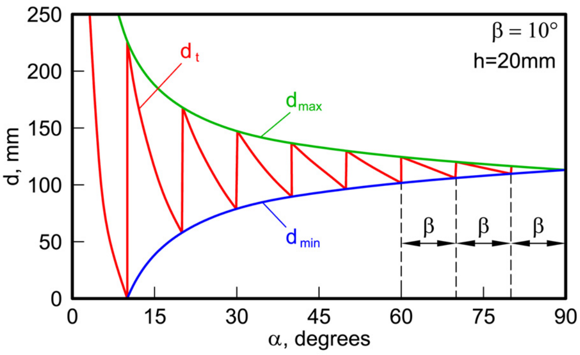

*Fig. 3. Dependency graph of $d_t$, $d_{max}$ and $d_{min}$ from macroparticle grazing angle*

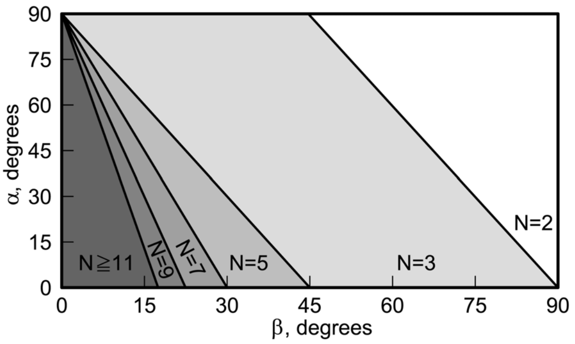

*Fig. 4. Minimum number of macroparticle collisions N with angular trap walls for different values of macroparticle grazing angle α and trap angle β*

significantly simplify calculations. It should be mentioned that distance $d$ will be always less (or equal) than $d_t$ value for glancing angles $\alpha \geq 90 - \beta$, because $d_t = d_{max}$ in this instance.

In most cases maximum value of $N$ does not represent practically meaningful interest. It is connected to the fact that besides trap geometry and macroparticle glancing angle, maximum of $N$ depends on relative location of the trap itself and macroparticle emission point. So, for the same values of $\alpha$, $\beta$, and $h$ the distance $d$ can be both lower than threshold value $d_t$ and higher than it depending on $H$ and $L$ values (see Fig. 2). It means that estimation of filtering capabilities based on minimum $N$ value is more reliable. In case $c >> d$ total minimum number of impacts can be written as follows:

$$\begin{cases} N = 2\left\lfloor (90° - \alpha)\beta^{-1} \right\rfloor + 1 \text{ for } \alpha < (90° - \beta) \\ N = 3 \text{ for } (90° - \beta) \leq \alpha < 2(90° - \beta) \\ N = 2 \text{ for } 2(90° - \beta) \leq \alpha \end{cases} . \qquad (7)$$

Here, $N$ possesses the values 3 and 2 because the minimum of $N$, as it was said above, does not exist in the range of angles $\alpha \geq (90° - \beta)$, since $d_t$ is always equal to $d_{max}$ in this case (Fig. 3).

Since $N = f(\alpha)$, for every angular trap having angle $\beta$, there is a certain critical angle $\alpha_{cr}$, above which the number of macroparticle rebounds $N$ will be less than desired. That is, a trap with angle $\beta$ will ensure necessary filtering degree only if condition $\alpha < \alpha_{cr}$ is true. For values $N = \left\{2k+1; k \in \mathbb{N}^*\right\}$, critical angle value can be derived from (7):

$$\alpha_{cr} = 90° - 0.5(N-1)\beta . \qquad (8)$$

Diagram on Fig. 4 shows the dependency (7) of macroparticle-trap collisions number $N$ on macroparticle glancing angle $\alpha$ for different values of trap angle $\beta$. Region interfaces in the figure are corresponding to $\alpha_{cr}$ values for different values of $N$. As it can be seen from the figure, angular trap is most effective for low values of $\alpha$ and $\beta$ angles. Low values of glancing angle mean that macroparticle flow is directed along one of the trap baffle. Growth of trap efficiency in this case confirms earlier results of modelling [5].

It is obvious that the glancing angle range at which macroparticles are able to get into the trap is dependent on its position relative to macroparticle emission centre. (This range is always less than 0...90°). As a result, the trap effectiveness and therefore expediency of its application in a particular place depends on the place itself. Knowing the coordinates of emission point, relative to angular trap, one can determine the angle range making it possible for macroparticles to travel inside the trap:

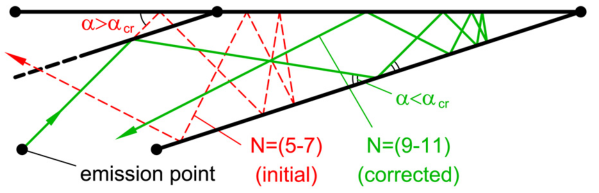

*Fig. 5. Trajectories of macroparticle with grazing angle higher than critical before (dashed line) installation of adjacent trap and after (solid line)*

$$\begin{cases} \alpha_1 < \alpha \leq \alpha_2 \text{ for } \beta < \beta_t \\ \beta_t < \alpha \leq \alpha_2 \text{ and } (\beta - \beta_t) < \alpha \leq (\beta - \alpha_1) \text{ for } \beta > \beta_t \end{cases} , \qquad (9)$$

where

$$\alpha_1 = \arctan\left((H-h)/\left(L - h\cot(\beta)\right)\right),$$

$$\alpha_2 = \arctan\left((H+h)/\left(L - h\cot(\beta)\right)\right),$$

$$\beta_t = \arctan(H/L),$$

where $L, H$ – values that define distance from the emission point to the trap junction (see Fig. 1). Condition $\beta > \beta_t$ means that the first macroparticle collision can occur with both the baffle and duct wall. Thus if every angle inside the range calculated from (9) satisfies condition $\alpha < \alpha_{cr}$, then all macroparticles leaving given emission point will be absorbed by the angular trap.

In practice, it is hardly probable to design a baffle system which totally meets $\alpha < \alpha_{cr}$ requirement. Consequently, there will always be some number of macroparticles that angular trap can not absorb. But due to the fact that baffle system consists of a set of traps, using (3) and (8) one can determine the distance between neighbouring angular baffles (baffle step) at which macroparticles with grazing angles $\alpha > \alpha_{cr}$ will hit the baffle of adjacent trap instead of colliding plasma duct wall (Fig. 5). In such case macroparticle will change its glancing angle on more acute one, i.e. its glancing angle will become lesser than critical. As a corollary such macroparticle will be absorbed by the trap. However, for trap angles $\beta \geq \alpha_{cr}$ (for example, when $h = 20$ mm and $N = 7$ – $\beta \geq 22.5°$) selection of the step is not possible because it will have zero or negative value.

## ANGULAR TRAP IN T-SHAPED PLASMA DUCT

If angular trap is installed inside the anode (or input section) of T-shaped separator [5], macroparticle which leaves trap needs to collide filter walls not less than two-three times to reach system output. The number of macroparticle rebounds after it is considered absorbed by filter (completely loses its initial velocity) is considered equal to 10 [6]. Thus $N = 7$ is enough for macroparticle absorption. According to diagram in

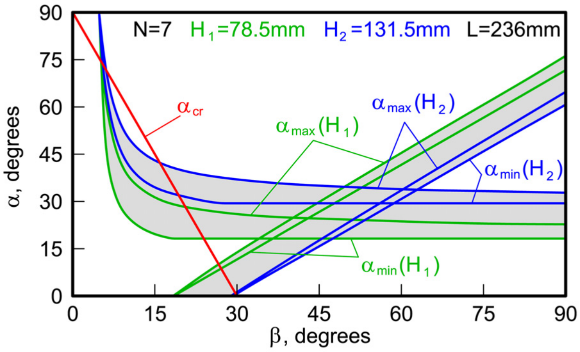

*Fig. 6. Dependence of critical glancing angle and the range of possible glancing angles (greyed) of macroparticles on the value of trap angle. The trap is placed at far from cathode side of T-shaped filter anode. Calculation was made for two utmost points ($H_1$ and $H_2$) on cathode working surface*

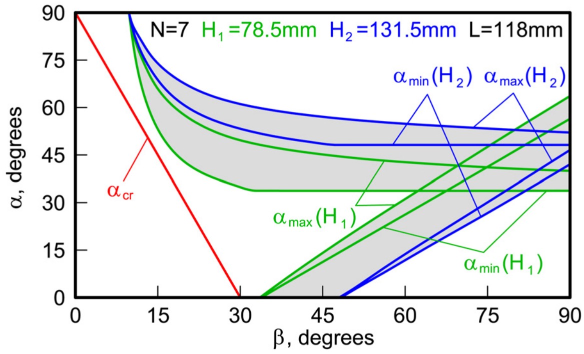

*Fig. 7. Dependence of critical glancing angle and the range of possible glancing angles (greyed) of macroparticles on the value of trap angle. The trap is placed at the middle of T-shaped filter anode. Calculation was made for two utmost points ($H_1$ and $H_2$) on cathode working surface*

Fig. 4, a trap having angle $\beta = 18^o$ will absorb all macroparticles with glancing angle inside range $0 < \alpha \leq 36^o$.

Dependencies of critical angle and macroparticle glancing angle range on trap angle are shown in Fig. 6. Calculations were made for a single trap having its height $h = 20$ mm and placed on far (from cathode) side of anode. In the calculation of grazing angle range only two utmost points of cathode working surface were taken into account. It is easy to show that macroparticle glancing angles for emission centres which are between said ones will be within calculated range. It can be seen from the figure that condition $N \geq 7$ can be provided by the trap having its angle in range $6^o \leq \beta \leq 15^o$. At this rate all emitted from cathode surface macroparticles have grazing angle below critical one. As long as the angle of the trap grows, the number of intercepted by it macroparticles with angle above critical value will be rising. When angle $\beta$ exceeds the value of 30º, all macroparticles will have grazing angle higher than critical (inasmuch as $\alpha_{cr} = 0$) and requirement $N \geq 7$ become unrealizable in principle.

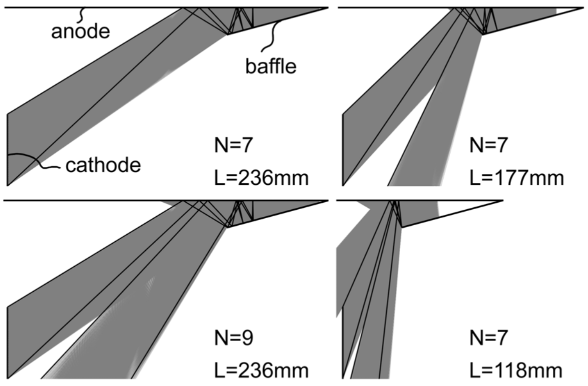

*Fig. 8. Simulation results of macroparticle trajectories intercepted by angular trap which is placed at different distances from cathode and for different efficiency factors. The trap angle is $\beta = 15^o$ and number of emitted macroparticles is ~ $10^4$. Trajectories of macroparticles leaving utmost points of cathode working surface at maximum grazing angle are highlighted by a thicker line*

Additional calculations were made to investigate the influence of angular trap placement on its efficiency. Currently, the trap was located at the centre of anode instead of its far from cathode side. Calculations results are given in Fig. 7. One can see that condition $N \geq 7$ is not feasible for angular trap placed in such a way. It is explained by shift of macroparticle grazing angle range towards higher values at constant $\alpha_{cr}$. Increase of value $H$ will obviously lead to similar result. However it should be kept in mind that a real baffle system will consist from multiple traps. Therefore, the efficiency criterion used ($N \geq 7$) is overestimated if a whole baffle system is being considered.

Fig. 8 shows simulation results of macroparticle collisions with angular trap ($\beta = 15^o$) for different values of $L$. The figure also shows the influence of effectiveness factor – value $N$ was increased from 7 to 9. Modelling of macroparticle trajectories was performed using MPT software. It can be seen from the figure that in conditions where $N = 7$ and $L = 236$ mm, as it was assumed, the trap absorbs all intercepted macroparticles. At the same time it can not fulfil $N \geq 9$ requirement – notable number of macroparticles is leaving the trap. A similar result is obtained by reducing distance $L$. Simulation results are fully confirming the above calculations (see Figs. 6 and 7).

Obtained dependences along with performed calculations allow making recommendations regarding the application of angular traps in designing baffle systems for separators. Firstly, application of angular traps is preferred in places where angle between plasma duct wall and macroparticle trajectory ($\alpha$) has minimum value. These places usually are most distant from cathode (along duct axis) regions like, for example, "opposite" arm of T-shaped plasma duct or, as shown above, anode exit. Secondly, one should avoid trap angle ($\beta$) values higher than 30º due to very low effectiveness of such traps. Generally, the angle of the trap should be as low as admissible. Thirdly, it is not recommended to use angular traps in regions of a filter, where macroparticle movement along plasma duct axis in unacceptable. Such directions of macroparticle movement are the result of their rebounds from outer side of angular trap baffle. This applies to the so-called "straight" filters and output sections of curvilinear filters, such as, for example, L- and T-shaped ones. At the same time, installation of angular traps inside the input sections of said curvilinear separators will greatly enhance their filtering abilities if such installation does not contradict selection of the distance (see above).

Implementation of mentioned recommendations in published earlier work [5] related to optimization of filtering abilities of T-shaped separator partially explains high efficiency of developed baffle system. For a complete understanding of its functioning it is necessary to additionally perform analysis of "two-baffle" trap which was also used in filter design. However this is beyond the scope of current study and is the subject of further research.

## CONCLUSIONS

In this paper, the dependences which are characterizing effectiveness of macroparticle filtering by angular trap were established. Growth of filtering abilities is promoted by decreasing of trap angle, increasing of distance between the trap and the cathode along the axis of plasma duct and by decreasing of this distance transverse to the axis. The effectiveness of angular trap was calculated and results are confirmed by simulation in MPT on the example of T-shaped magnetic separator. Calculation results are explaining high filtering capabilities of baffle system containing investigated traps with small angles in its design, as it was found earlier [5] during optimization of T-shaped separator. Obtained dependences allow prediction of efficiency of angular traps application in the process of baffle systems designing which are used in magnetic separators.

## REFERENCES

1. I.I. Aksenov, A.A. Andreev, V.A. Belous, V.E. Strel'nitskij, V.M. Khoroshikh. *Vacuum arc. Plasma sources, coatings deposition, surface modification.* Kyiv: “Naukova dumka”, 2012, 728 p. (in Russian)
2. A. Anders. *Cathodic Arcs: From Fractal Spots to Energetic Condensation.* New York, Springer, 2008, 542 p.
3. R.L. Boxman. Recent developments in vacuum arc deposition // *IEEE Trans. Plasma Sci.* 2001, v. 29, p. 762-767.
4. D.S. Aksyonov. Calculation of Macroparticle Flow in Filtered Vacuum Arc Plasma Systems // *PAST.* 2012, N2, p. 108-113.
5. D.S. Aksyonov. Optimization of T-Shaped Magnetic Separator Filtering Abilities // *PAST.* 2012, N2, p.102-107.
6. I.I. Aksenov, V.E. Strel’nitskij, V.V. Vasilyev, D.Yu. Zaleskij. Efficiency of magnetic plasma filters. // *Surf. Coat. Technol.* 2003, v. 163-164, p. 118-127.

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## УГЛОВАЯ ЛОВУШКА ДЛЯ МАКРОЧАСТИЦ

***Д.С. Аксёнов***

Исследованы свойства угловых ловушек макрочастиц, необходимые для проектирования рёберных систем фильтров (сепараторов) вакуумно-дуговой плазмы. Установлены зависимости между геометрическими параметрами ловушки и эффективностью поглощения макрочастиц. Выполнены расчёты, результаты которых позволяют прогнозировать поведение фильтрующих качеств сепараторов, содержащих в своей конструкции такие ловушки. Даны рекомендации относительно применения угловых ловушек в фильтрах различных конструкций.

## КУТОВА ПАСТКА ДЛЯ МАКРОЧАСТИНОК

***Д.С. Аксьонов***

Досліджено властивості кутових пасток макрочастинок, які необхідні при проектуванні реберних систем фільтрів (сепараторів) вакуумно-дугової плазми. Встановлено залежності між геометричними параметрами пастки та ефективністю поглинання макрочастинок. Виконано розрахунки, результати яких дозволяють прогнозувати поведінку фільтруючих якостей сепараторів, які мають у своєму складі такі пастки. Наведені рекомендації щодо використання кутових пасток у фільтрах різних конструкцій.