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OPTIMIZATION OF T-SHAPED MAGNETIC SEPARATOR FILTERING ABILITIES

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Computer simulation was used to study influence of design parameters of T-shaped magnetic filter (separator) baffles on degree of plasma cleaning from macroparticles. Baffle system design for such filter was developed. Evaluation and development of highly effective conceptual baffle system was performed. Recommendations for designing of baffle systems of macroparticle filters were made.

1. INTRODUCTION

One of the promising and widely used methods for coatings deposition is vacuum arc method. The drawback of the method is presence of macroparticles in obtained coatings. It can significantly decrease characteristics of the films, deposited using this technique. Use of electromagnetic filters (separators) is an effective approach to remove macroparticles from plasma. These devices are constructed in such way, that there is no direct line-of-sight between cathode and workpiece. Inside filter, useful (ion) plasma component is transported by magnetic field along a curved path. Macroparticles are not influenced by magnetic field. They are moving along straight trajectories and thus are not able to reach the workpiece [1].

Practice of separators employment has shown that the absence of direct line-of-sight between cathode and substrate is insufficient for total plasma purification from macroparticles. They can bounce from plasma duct walls when collide them [1, 2]. If velocity of macroparticles is high enough, then after several collisions with walls they can reach system exit (substrate). To minimize the influence of bouncing phenomena on plasma filtering degree, walls of separators are equipped with transverse baffles. Presence of baffles in filtering system makes an additional barrier on macroparticles way thereby increasing the number of needed collisions to reach filter exit. Each time macroparticle collides a wall, it loses a part of its initial velocity. If macroparticles velocity is reduced to a level which is not sufficient to move further, it will be impossible for them to reach system exit.

Existing methods of plasma cleaning degree estimation are based on calculation of macrodefects density in deposited films that caused by macroparticles impacts. This calculation procedure is extremely time-consuming [3]. As for prediction of plasma filtering degree at separator development stage, a designer can rely on the only criterion: the system under design must provide absence of direct line-of-sight of substrate from cathode viewpoint. Macroparticles bouncing ability is greatly complicates system optimization problem in respect of its filtering capabilities: it is almost impossible to predict with sufficient reliability how design changes (including baffles) will affect plasma filtering degree.

Optimization task can be greatly simplified if computer simulation of macroparticle trajectories is used. In earlier work [1, 4] the task was solved in two-dimensional approximation for axisymmetric and plane-symmetric systems with a number of simplifying assumptions. Since errors introduced by these assumptions have a regular statistical nature, the method is quite useful for comparative evaluation of filtering capabilities of systems with different plasma guiding channel geometries. The computer program used has quite limited capabilities. More advanced one with much more features – Macroparticle Tracer (MPT) – have been developed and described later [5]. This program was used in current work for baffle system optimization of two-channel T-shaped magnetic filter.

2. BASIC APPROACHES

Since after each collision macroparticle loses some part of its initial velocity, the number of its bounces is limited. If initial velocity is V_0, then after N rebounds it will be decreased to V_N value, which is too low to continue movement: macroparticle sticks to plasma guide wall [1, 4]. So, filtering system should be constructed in such way that all (ideally) macroparticles will collide with system walls not less than N times before it can reach system exit.

From the common approaches to designing of filters baffle systems two basic ones can be separated: absorption and redirection. The first one is to provide maximum possible number of collisions of macroparticles with baffles. If a macroparticle is intercepted by such baffle system, it is unable to leave this system, i.e. the particle will collide with baffles walls until full loss of its velocity. The second approach is to reflect macroparticle in the "favorable" direction, for example, in the direction it came from. In practice, it is rather difficult to separate these two principles from each other. Any baffle system provides both of them simultaneously, but in different degree. Nevertheless, during design stage it is possible to vary their influence degree on macroparticles behavior. For example, two different baffle systems can be installed in a filter: one of them will take a role of macroparticle trap while another one will reflect macroparticles in the direction of this trap.

Different kinds of filters have their own, specific to this kind demands of baffle systems design. For filters of open architecture it is enough to redirect macroparticles off the volume of spiral plasma duct. Designing of straight filters one should avoid macroparticles redirection along plasma duct axis. Later interception of such particles will be difficult or not possible at all. In case of T-shaped magnetic filter, macroparticle movement along filter input axis is more preferable than athwart movement. Macroparticles having their trajectory angles small against this axis will mostly fly to the opposite filter arm, where they will be absorbed or redirected back (toward filter arm they came from) and only few of them will get to the output section. Meanwhile, if macroparticles are inside the output section of such filter, their movement along output axis is highly undesirable. As in case of straight filter type, interception of these particles will be impossible in most cases. It should be noted that macroparticles which made their way to plasma duct exit and have their trajectory angle near to 90º (relative to output axis) can be "filtered" by moving substrate away from system exit on some short distance.

Besides filtering capabilities, baffle system designer should take into account next factors. They are laboriousness, materials consumption and influence of baffle system on transport of useful plasma component.

3. BAFFLE SYSTEM SIMULATION

3.1. Anode area

T-shaped magnetic filter, which is being optimized in this work, is schematically shown in Fig. 1. It consists of cathodes 1, anodes 2, input 3 and output 4 plasma duct sections. Detailed description of the filter was given elsewhere [6]. Due to symmetrical arrangement of system input channels (arms), trajectories simulation was made considering macroparticle emission from the surface of only one of the cathodes.

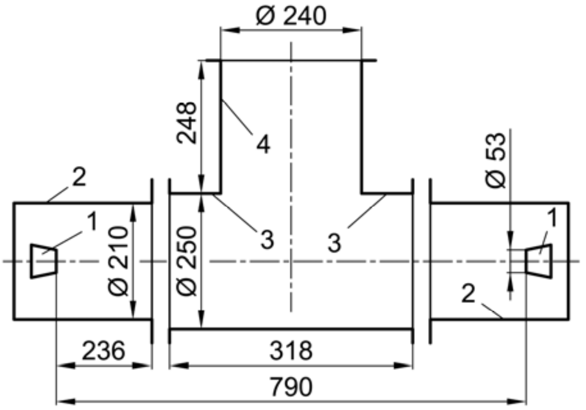

Fig. 1. Scheme of T-shaped magnetic filter

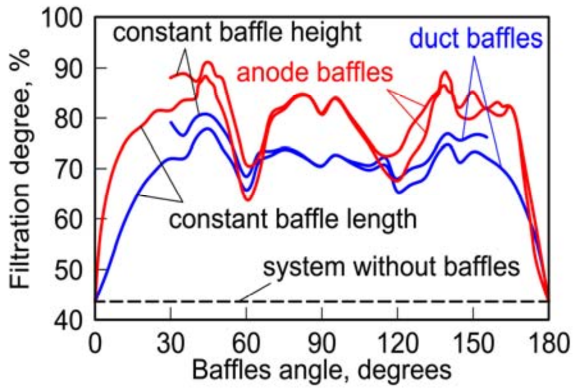

Fig. 2. Influence of baffles tilt angle on plasma filtering degree. Baffles step – 20 mm, macroparticle emission parameters: total number – 9900, distance between emission centers – 0.53 mm, angular step 1.8º

Fig. 2 shows dependencies of filtering degree on baffles tilt angle (hereafter "angle") with respect to anode/duct walls. Baffles were arranged with 20 mm offset. Angles range 0…90º is corresponding to baffles orientation towards system output and range 90…180º – towards system input (cathode). The figure demonstrates modeling results of two baffle systems. In first case baffles are present only at anodes walls, in second case – only at T-filter output section. Calculations were made in two variants. In the first variant baffles length kept constant (20 mm) while their angle was changing. In the second one baffles height (the distance between baffle end and anode/duct wall) kept unchanged, and it was equal to 20 mm. All curves were obtained for 9900 emitted macroparticles number. Amount of allowed macroparticle collisions N, when these particles are assumed to be absorbed by filter was 10. As it can be seen from the figure, baffles angle should be inside one of the ranges for reaching maximum filtering degree. These ranges are 30…50º, 70…100º and 135…165º. In such case baffle systems are demonstrating similar results. The only one can be stated unambiguously: baffles should not have angle close to 60 and 120º. That is why additional simulations are needed for optimal baffles angle selection. Results of these calculations will be provided below.

In current separator design, anode baffles having their angles lower then 162º and positioned on its far (from the cathode) end are decreasing amount of macroparticles got into output section directly from cathode (i.e. not reflected from walls). It happens because some part of T-filter output section is in direct line-of-sight from cathode surface. However, such angle of anode baffles also worsens conditions of useful plasma component transport when it corners from input to output section of T-filter. Dependencies shown in Fig. 2 for baffles inside anode and plasma duct have common nature. The only difference is that in case of duct baffles the dependency is weaker.

In order to choose an optimal anode baffles angle, additional simulation was made. Baffles length was changing while their offset kept constant. Baffles angles selection was based on simulation results shown in Fig. 2. These angles are 44, 90 and 139º. Additional calculations were made for 162º angle. This angle is of interest due to minimum plasma losses during its

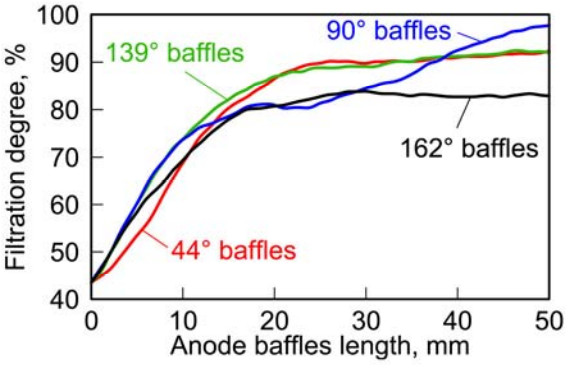

Fig. 3. Influence of anode baffles length on plasma filtering degree for differently angled baffles with the same height. Baffles step and height are 20 mm, macroparticle emission parameters: total number – 9900, distance between emission centers – 0.53 mm, angular step 1.8°

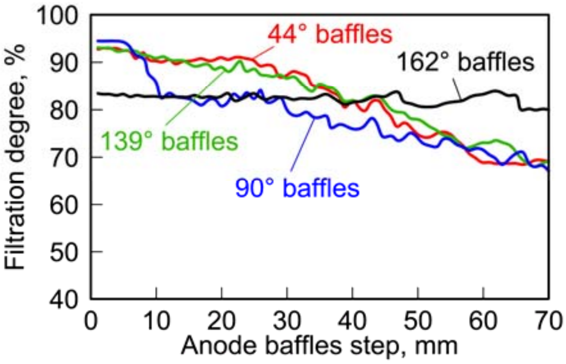

Fig. 4. Influence of anode baffles offset on plasma filtering degree for differently angled baffles with the same height. Baffles step and height are 20 mm, macroparticle emission parameters: total number – 9900, distance between emission centers – 0.53 mm, angular step 1.8°

cornering (see above) if baffles are tilted such way. Calculation results are given in Fig. 3. It can be seen, that filtering degree rises along with baffles lengthening. When 20…30 mm level is reached, rise of filtering degree nearly stops. (The only exception is curve for 90º baffles.) Filtering degree growth stoppage can be explained next way. Any macroparticle got into baffle system needs certain number of collisions before it can leave the system.

Allowed number of macroparticles collisions N was limited to 10 in calculations made. Therefore, if baffles length is enough for macroparticles to collide 10 times, further baffles lengthening will have no effect until allowed number of collisions N will not be increased. In the same time there are some macroparticles which have trajectories making them able to leave baffle system after only few collisions. For example, hitting a baffle and then anode. In this case baffles lengthening can slightly influence on such macroparticles interception and therefore is responsible for not complete stoppage of filtering degree growth after 20…30 mm baffle length level.

As for 90º baffles curve, filtering degree growth is caused by narrowing of anode effective passage (lowering of cross-section diameter): along with lengthening, baffles height raises more rapidly for 90º baffles then for other ones. More precisely, height and length for 90º baffles is the same. Baffles with 90º angle and 50 mm length are narrowing anode effective passage nearly twice. The higher baffles height is, the lower the number of macroparticles got into output section bypassing anode baffles. Since output section of the filter has no baffles (yet), such macroparticles are not filtered (almost). From data given in Fig. 3 one can conclude that more preferable angles for anode baffles are 44 and 139º.

Apart from baffles angle and length, filtering capabilities of baffle system are affected by their offset, i.e. the distance between bases of baffles. The offset along with baffles angle define distance between baffles. The lower this distance, the shorter the path macroparticle can make between collisions. Therefore, macroparticle have to collide more times to get to baffles base. The same applies to macroparticle flight in opposite direction, i.e. from baffles base. Thus, the lower the distance between baffles, the higher macroparticle filtering degree can be expected. It follows from above, that filtering degree should be more strongly dependant from the offset for baffles having their angle close to 90º (distance between baffles is proportional to sine of their angle). These conclusions are confirmed by simulation results shown in Fig. 4. Filtering degree for 162º angled baffles remains virtually unchanged when baffles offset grows from 1 mm to 70 mm. Such behavior makes 162º baffles interesting from practical point of view because baffles number is directly dependent from their offset (while the wall length they are placed on remains constant). This makes it possible to use smaller number of baffles without loosing filtering properties of designed baffle system.

As mentioned above, macroparticle movement athwart anode axis is highly undesirable in case of T-shaped filter. Macroparticles with such trajectory angles should be intercepted or redirected (in opposite direction or along the axis) before they managed to reach output section of plasma duct, i.e. this must be made inside anode. Therefore, baffles need to be placed with an offset making macroparticles unable to bounce from anode without colliding with one of the baffles, i.e. anode walls must be "shielded" by baffles. It is evident that the offset value to make shielding possible depends on the angle between baffles and anode. This fact along with influence of distance between baffles also explains behavior of curve for 162º angled baffles in Fig. 4. It should be noted, that baffles having their angle equal to 90º are incapable of shielding. As a result, such baffle design is nearly useless in intercepting macroparticles that are moving athwart to anode (plasma duct) axis.

In order to determine the angle of macroparticles injection into filter output section volume after they interacted with anode baffles, a series of additional calculations were made. Results of the calculations are shown in Fig. 5. For clarity, the figure shows traces of only those macroparticles that made their way inside output section of T-filter. It can be seen, that only 162º

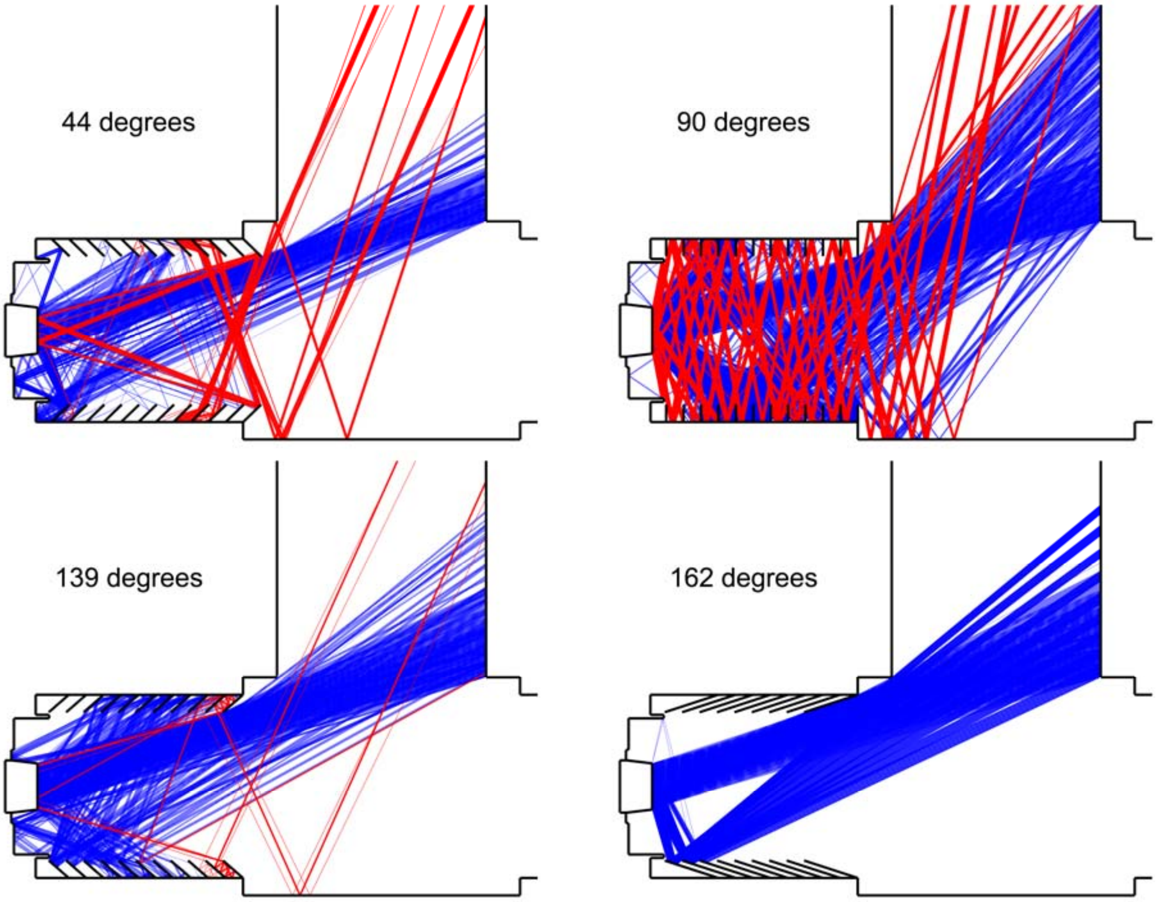

Fig. 5. Trajectories of macroparticle traveled to output plasma duct section for anode baffles with different tilt angles. Baffles step and height are 20 mm, macroparticle emission parameters: total number – 9900, distance between emission centers – 0.53 mm, angular step 1.8°

angled baffles are not reflecting macroparticles in the way making them impossible (or difficult) to intercept (shown in red) inside output section. Baffles with other angles are "generating" macroparticles that cannot be intercepted. It means that whatever the baffles in output section will be, these macroparticles will definitely reach the substrate.

It can be noticed in Fig. 5, that there are no macroparticles that left 162° anode baffles in the direction of output section after they got into space between baffles. That is, either macroparticles intercepted by such baffle system are absorbed by them, or redirected toward opposite arm of T-shaped filter. Moreover, it is clearly visible that all macroparticles arrived inside filter output section after colliding anode baffles were reflected from the first three ones (nearest to cathode). Hence none of macroparticles trapped by the baffles will leave anode volume in the direction of output section if these three baffles are changed in the right way. Thus only macroparticles traveled to T-filter output section directly from cathode (not reflected) are left to be filtered. Trajectories of such macroparticles have relatively narrow angle values range. This significantly simplifies plasma duct baffles design problem.

Baffles with 162° angle value were selected as anode baffles, and first three baffles were changed. Reasons for selection of this angle are followed. As it shown in Fig. 2 and Fig. 3, 162° angled anode baffles are capable of intercepting most of macroparticles. Filtering degree they provide is virtually not affected by their offset (see Fig. 4), i.e. it allows installation of only several baffles without any noticeable filtration fall off. Use of only several baffles significantly lowers designed system complexity and cost. More than that, such baffles design makes least difficult for plasma to get through T-shaped duct bending (where input and output sections are meet each other). Installation of these baffles along with changing of first three baffles minimizes the number of macroparticles that managed to get to output section (Fig. 5): macroparticles trapped by these baffles are either absorbed by them, or redirected to opposite filter arm.

3.2. Plasma duct area

Selection of baffles angle inside T-filter input

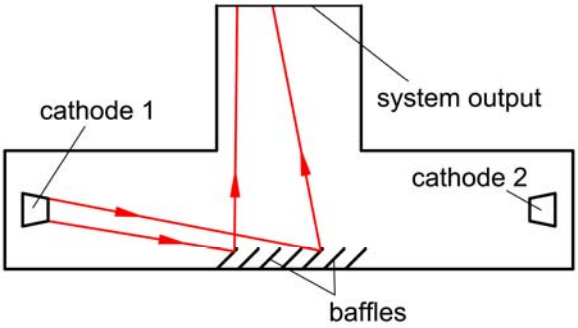

Fig. 6. Scheme of input duct baffles, which "generates" macroparticles that cannot be intercepted

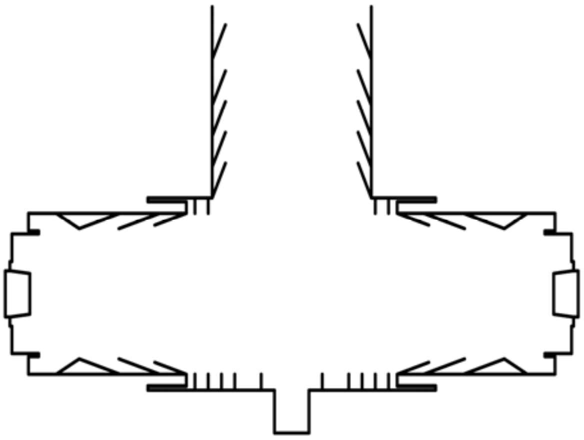

Fig. 7. Scheme of T-shaped magnetic filter equipped with developed (optimized) baffle systems.

sections needs no simulation due to the following reasons. If the baffles are tilted in the direction opposite to cathode of current arm, many macroparticles will be reflected by such baffles directly to the substrate (Fig. 6). Most of them will be traveling near plasma duct output axis and therefore will bypass output section baffles.

If the baffles will be tilted towards cathode (of current arm), they will reflect macroparticles from cathode of the opposite arm in the same way. Thereby, because both channels (arms) of system with T-shaped filter under study are active, tilting baffles inside input section will lead to reflection of macroparticles in the way they cannot be intercepted by other baffles. As a result, there are only two choices: either baffles are placed at right angle to input duct section, or not placed at all. The first one is preferable. According to simulation results shown in Fig. 5, significant amount of macroparticles is arriving to input section walls with incidence angle not greater then 30º. As shown above, 90º angled baffles are good at interception of such macroparticles. It should be noted, that unambiguity of baffles angle selection inside input sections of T-filter additionally confirms optimality of anode baffles angle selection (162º). These are the baffles "generating" minimal number of macroparticles, which are impossible to intercept by 90º input section baffles.

As for plasma duct output section, baffle system design task is reduced to interception of macroparticles making their way there directly from emission centers, i.e. from cathode. Angle spectrum of such macroparticles trajectories is rather narrow and is about 61…72º with respect to walls of plasma duct output section. If the baffles will be oriented in the way their angle to incident macroparticles will be near 90º, then macroparticles will be redirected backwards. If so, reflected macroparticles most likely will be absorbed when trapped by anode baffles. Baffles with 156º angle to output section walls satisfy this condition. According to the curves in Fig. 2, such tilt angle is inside preferable angles range from the plasma filtering degree point of view and it also affects plasma cornering the least way. In addition, baffles inside duct output section having their angle higher then 90º will not reflect macroparticles directly to filter exit (substrate).

3.3. Entire plasma guide

According to outlined above principles, T-shaped magnetic filter was "equipped" with three baffle systems as shown in Fig. 7. Modeling of this system shown, that macroparticle filtering degree is 99.56% if maximum allowed number of macroparticle collisions N is not exceeding 10. For comparison, calculated earlier [5] at the same conditions classical toroidal filter [1] provides close filtering degree, which is equal to 99.59%. However, T-shaped filter being studied has effective passage diameter of plasma guide two times larger then toroidal one, what is known to have an adverse influence on filtering degree and positive effect on system coefficient of effectiveness [1].

It can be seen that proposed baffle system does not provide total plasma filtering of macroparticles. In the first place it is related to obvious restrictions imposed on baffles design. Such as maximum simplicity and minimum cost without significant loses of filtration capability. If these restrictions can be ignored, one may raise next question. Is it possible to filter out all macroparticles and if not, then how much filtering capabilities can be increased? Availability of high-performance computational systems and MPT software make it possible to try to create a highly effective filter on conceptual level. Such baffle system was developed, however design, list of principles it incorporates and their study are out of the scope of this work.

A series of calculations were made in order to determine filtering abilities of developed conceptual system. These calculations are also including modeling of baffle system given in Fig. 7 to compare filtering abilities of both baffle systems. Is it shown earlier [5], comparison of highly effective filtering systems should be made with maximally possible number of emitted macroparticles. Maximum allowable number of macroparticle collisions N is also should be raised. Calculation results are shown in Fig. 8. It can be seen that conceptual baffle system design possesses greatly higher filtering properties. It should be noted, that said conceptual baffle system is only one of the possible variants. Detailed study of this system may lead to understanding of baffles design principles it incorporates. The use of these principles during baffles

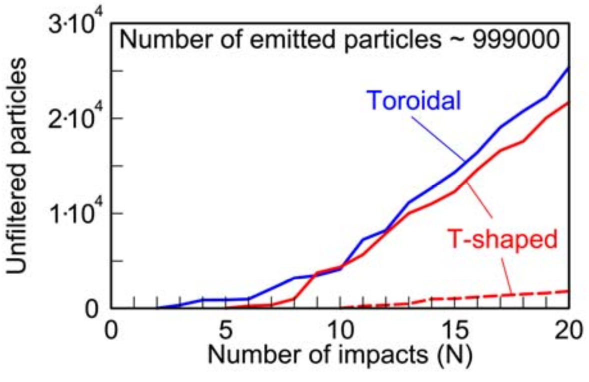

Fig. 8. Dependence of unfiltered macroparticles number on maximum allowed number of macroparticles collisions N at the system exit. Solid line – for baffle system shown in Fig. 7, dashed – for conceptual one. Macroparticle emission parameters: distance between emission centers – 53 μm, angular step 0.18º

designing may lead to creation of fundamentally new types of plasma filters.

Modeling results given in this work are not bounded to absolute dimensions of the system (see Fig. 1) and baffles. It was found that proportional change of all dimensions will lead to the same results.

4. CONCLUSION

On example of two-channel T-shaped magnetic filter this work demonstrated ability to optimize filtering properties of separators using MPT software computer modeling. Dependency between filtering abilities of investigated system and such anode and plasma duct baffles design parameters as tilt angle, length and offset has been established. Complex estimation of found relationships allowed to offer baffle design suitable for both single- and two-channeled embodiments of studied filter. Proposed calculation method allowed to develop filtering system with high filtering degree, which is 99.56%, without complicating design as compared to previously known variants. Examination of developed conceptual baffle system design has shown its ability to absorb nearly all macroparticles at the price of its complexity and cost value.

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ОПТИМИЗАЦИЯ ФИЛЬТРУЮЩИХ СВОЙСТВ Т-ОБРАЗНОГО МАГНИТНОГО СЕПАРАТОРА

Д.С. Аксёнов

При помощи компьютерного моделирования исследовано влияние конструктивных параметров рёбер Т-образного магнитного фильтра (сепаратора) на степень очистки плазмы от макрочастиц. Разработана конструкция рёберной системы для такого фильтра. Произведена оценка и разработка высокоэффективной концептуальной рёберной системы. Выработаны рекомендации касательно проектирования рёберных систем фильтров.

ОПТИМІЗАЦІЯ ФІЛЬТРУЮЧИХ ВЛАСТИВОСТЕЙ Т-ПОДІБНОГО МАГНІТНОГО СЕПАРАТОРА

Д.С. Аксьонов

За допомогою комп'ютерного моделювання досліджено вплив конструктивних параметрів ребер Т-подібного магнітного фільтра (сепаратора) на ступінь очищення плазми від макрочастинок. Розроблено конструкцію реберної системи для такого фільтра. Проведені оцінка та розробка високоефективної концептуальної системи ребер. Разроблені рекомендації щодо проектування реберних систем фільтрів.