On the Interaction Effects of Ionospheric Plasma with Dipole Magnetic Field of the Spectrometer AMS-02 Moving Onboard of International Space Station

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On the Interaction Effects of Ionospheric Plasma with Dipole Magnetic Field of the Spectrometer AMS-02 Moving Onboard of International Space Station

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***Abstract*—When the large-scale spectrometer AMS-02 with the super-conductive coils will be installed at ISS, their residual magnetic field could be effective dipole-like obstacle to form a so called “Magnisphere” in front of AMS due to its interaction with the plasma of ionosphere under conditions of super-sonic, but sub-alfvenic ISS velocity. The boundary (between magnetic field and plasma, at distance R_N ~ 5÷8 m from AMS) of such “Magnisphere” or other mini-magnetospheres, could essentially disturb the whole plasma and electromagnetic environments of ISS due to various small- and large-scale plasma instabilities or waves generation. Therefore we discuss a relevant actual problem and specific features of “Magnisphere” formation, structure and dynamics under essentially non-MHD conditions of the interaction between a dipole and plasma flow, when its directed ion Larmor is in a few times larger than R_N. Preliminary data of the laboratory and numerical simulations for such extremely non-MHD dipole-plasma interaction are presented.**

Keywords-ionosphere; plasma; magnetic dipole; AMS-02; International Space Station; laboratory and numerical simulations

I. INTRODUCTION

The idea to use a super-conductive magnet (with a moment $\mu \sim 10^8$ G•cm^3) on the board of satellite in ionosphere for the various active geophysical experiments and to simulate a magnetosphere-like phenomena, i.e. “Magnisphere” (MS), was proposed by V.P. Shabansky [1] more than 30 years ago and now is developed by ESA [2, 3] also. At that time a first attempt to simulate MS-formation [5, 6] at the large-scale facility KI-1 [4, 7, 8] of ILP was done. The main specific feature of MS as a region ~ R_N of disturbed density n in a plasma, overflowing dipole with velocity V (at presence of external magnetic field B_0) is determined by combined conditions on sonic Mach number $M_s = V/C_s >> 1$ and Alfven-Mach number $M_s = V/C_a << 1$. Here the velocity of satellite V is 8 km/s in the ionosphere with its ion-sound velocity $C_s = (T_e/m)^{1/2} \approx 1$ km/s and alfvenic one $C_a = B_0/(4\pi nm)^{1/2} \approx 270$ km/s for the typical electron temperature $T_e \sim 0.15$ eV and mass m of O$^+$ - ions with $n \approx 3•10^5$ 1/cm^3 in the Earth’ field $B_0 \approx 0.3$ G. So, from a general relation [9] for the scale $R_D \approx (\mu/M_aB_0)^{1/3}$ of boundary position ahead of dipole (viz R_D ~ between its field and undisturbed flow’ medium), we have a well-known magnetopause distance $R_{mp} \approx (\mu^2/4\pi nmV^2)^{1/6}$ for usual magnetospheric case of $M_a >> 1$, while for “ionospheric” case of MS at $M_a \leq 1$ this relation corresponds to scale $R_N \approx (\mu/B_0)^{1/3}$ of the problem on configuration of magnetic field when it is an addition of vacuum dipole field $B_d \sim \mu/r^3$ and quasi-uniform one B_0. This problem at presence of super-sonic plasma flow became very complicated and relevant plasma-field interaction processes were studied very poor up to now. For example, only recently first numerical modelling of similar to MS, but sub-sonic Ganymede’s interaction with the magnetospheric medium of Jupiter was done [10] by 3D/MHD-code, corresponding to well magnetized Jovian ions.

Real MS-problem would be even more difficult and obviously kinetic one since its expected scale of $R_N \leq 10$ m is in a few times smaller than any ion Larmor radius R_L of O$^+$-ions with their maximal, directed velocity $V = 8$ km/s. For the given problem, both of usually used approaches give the same result $R_L \sim 40$ m, based on the external field B_0 or on the dipole field at the MS-boundary $B_d(R_D) \sim B_0$. Such MS-configuration could be realized soon, when the Alfa Magnetic Spectrometer (AMS-02) with a super-conductive magnets [11] will be installed on the board of International Space Station (ISS) near the end of 2010. In spite of their special construction with a “racetrack” coils (to decrease a field outside of AMS and compensate its total magnetic moment) the AMS will have a non-compensate moment just at the level of proposed “Magnisphere”, i.e. $\mu \leq 10^8$ G•cm^3, as one could analyze NASA magnetic data [12] of AMS-02.

The same problem of non-MHD conditions ($R_L \geq R_{mp}$) of mini-magnetosphere formation around small dipole obstacles in a solar wind plasma flow appears today in a lot of space physics situations: magnetized asteroids [13], magnetic anomalies at the Moon surface [14], probably Phobos [15] and finally magnetic sails [16] and shields [17] for spacecraft. But since in all these studies the flow has a high $M_a >> 1$, their results could be not applied easy to our MS-case. As a result, now are absent any opportunities to predict probable effects of AMS on ISS environments beside of laboratory simulations.

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Up to now only a few experiments [18-20] were done in the relevant region of plasma and dipole parameters, but unfortunately they had not enough data of measurements to conclude about a mechanism and intensity of plasma-dipole interaction and moreover, about probable secondary effects, most important for the given study of possible influence of AMS-magnet onto ISS environments (plasma and electromagnetic disturbances). In the extreme case, such kind of influence could affect onto radio-communications and its nature could be related with the various plasma wave and instabilities or particles acceleration, that we hope to reveal.

II. Simulative Approach, Facility and Tasks

A. *Dimensionless Criteria of Problem Based on π-Theorem*

Any simulative experiment should be based on similarity analysis that relates laboratory parameters to the natural phenomena. To determine the criteria of similarity we need to use an approach based on a set of Maxwell and Vlasov equations [21, 22] or to start more easily from the most general π-theorem [23] of dimensional analysis. In a latter case, if the problem is described by a total number $K = 10$ (here) of determining dimensional (and independent) parameters: μ, B_0, V, n, T_e, m, m_e and e (of electrons), light velocity C and R_p (radius of dipole surface), than according to π-theorem, in equations should appear $K - 3 = 7$ dimensionless (and independent) complexes, as criteria of the problem. Therefore, beside the introduced earlier most important criteria $M_s > 1$, $M_a < 1$ and $\varepsilon_N = R_{L0}/R_N$ (~ 4 for the ion Larmor $R_{L0} = VmC/zeB_0$, here), we could choose the following ones, as $R_N/C_{st} \sim 3 > 1$, $R_p/C_{st} \sim 0.3 < 1$, $m_e/m << 1$ and magnetic Reynolds number $Re_m = 4\pi\sigma R_N V/C^2 >> 1$ for the plasma Coulomb conductivity $\sigma(T_e)$.

It is important to note, that for usual definition of Stoermer length as $C_{st} = (e\mu/mVC)^{1/2}$, on the base of these 7 criteria we could obtain all another need criteria of the problem, such as plasma beta $\beta = 8\pi nT_e/B_0^2 = 2(M_a/M_s)^2 << 1$ and $\alpha = B_0^2/8\pi m_e C^2 = (C_s/C)^2/[\beta\bullet(m_e/m)] << 1$. As well as the ion Knudsen number $Kn_i = \lambda_i/R_N >> 1$, relative Debye length $r_d/R_N << 1$ and important ratio for collisionless skin depth $C/\omega_{pe}R_N = (R_N/C_{st})^2\bullet(m_e/m)^{1/2}/M_a \sim 1$, which corresponds to the limiting case for probable formation of Chapman-Ferraro current [24] at the boundary of our “Magnisphere” or Mini-Magnetospheres [14].

Another 2 additional criteria (to the 7 main ones) are two angles: θ for $\boldsymbol{V}$ and $\boldsymbol{\mu}$, as well as φ for $\boldsymbol{V}$ and $\boldsymbol{B_0}$. According to the data [12] about AMS-02 at ISS, we choose $\theta \approx 90^0$ and the full simulation should supply $\varphi \sim 45^0$. In laboratory only physically similar conditions, based on the method of limited simulation [25], could be realized in a sense that dimensionless parameters are either << 1, >> 1 or ~ 1, both in the laboratory and space, but without obligatory equalities of corresponding criteria.

B. *KI-1 Facility of ILP and the Tasks of Planned Simulations*

A planned simulative experiments will be done at the up-grated KI-1 facility [4, 7, 8] of ILP (Fig. 1) consisting of a high-vacuum (up to 10^{-7} Torr) and large-scale chamber of ∅ 1.2 m and 5 m length made from stainless-steel and supplied by a source (8) of background plasma (1) flowing in a field $\boldsymbol{B_0}$.

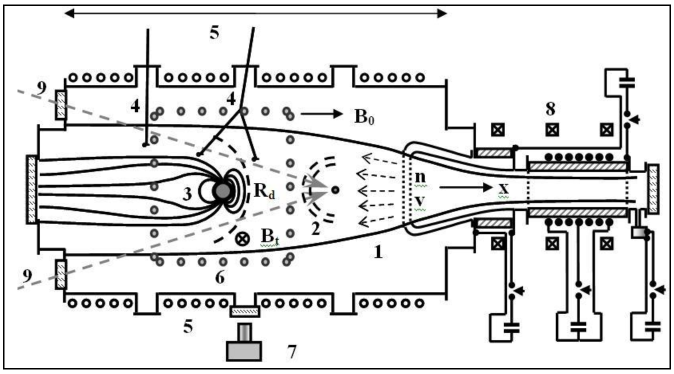

Fig. 1. A principle scheme of KI-1 facility: 1 – quasi-stationary plasma flow; 2 – pulsed plasma (from laser target); magnetic dipole; 4 – probes; 5 – external solenoid for $\boldsymbol{B_0}$-field; 6 – internal coils for transverse $\boldsymbol{B_t}$; 7 – Image Tube; 8 – θ-pinch source of plasma flow; 9 – windows for CO_2-laser beams.

Beside it, KI-1 facility consist of a high-energy laser system for other purposes (see in III A, B and Ref. [4, 7, 8, 26-28, 30-32]) and have a set of pulsed and compact magnetic dipoles with the moment up to $\mu \approx 10^7$ G•cm^3 as well as a systems of magnetic and various electric probes (including a double Langmuir ones). Its main up-grade should supply an additional quasi-uniform magnetic field of $\boldsymbol{B_t}$-component for which a new coils (6) will installed inside of chamber. Another one will be a models of both AMS-02 coils and some elements of ISS construction. So, a general program of planned simulations includes 3 main Tasks for the problems of interaction: T1 – plasma with a dipole; T2 – plasma with a model of AMS-02 and T3 – plasma with a model of AMS-02 at presence of ISS-model.

The laboratory simulative Task T1 (pure dipole source) will be performed under the following experimental parameters: $\mu \sim 10^5$ G•cm^3 (R_p = 3,75 cm), $n \sim 10^{10}$ 1/cm^3 (H^+), $V \sim 100$ km/s, $T_e \sim 15$ eV and $B_0 \sim 15$ G, with the criteria qualitatively close to ISS-case: $M_s \sim 3$, $M_a \sim 0.3$, $R_N/C_{st} \sim 2$, $R_p/C_{st} \sim 0.35$, $\varepsilon_N \sim 3$, $Re_m \sim 1000 >> 1$ and $m_e/m << 1$ (for the $R_N \approx 20$ cm, $C_{st} \approx 10$ cm and $R_L \approx 60$ cm). For the chosen plasma parameters an electron scale $C/\omega_{pe} \equiv C/(4\pi e^2 n/m_e) \approx 5$ cm $< R_N$ of MS-scale, so to achieve an extreme condition of $C/\omega_{pe} \sim R_N$ of problem, we plan further to decrease plasma density n in a few times with a special efforts to design a Langmuir probes of enhanced sensitivity.

III. Data of Preliminary Experiments and modelling

In the past and present a several types of preliminary experiments in the fields close to the “Magnisphere” problem (of large ion Larmor > R_D) were done at KI-1 facility in the various performances at $M_a > 1$ (at zero or weak field B_0) .

A. *Small-Scale Experiment “Magnet” with a Laser Plasma*

It was done in the 1987 during preliminary studies for preparation of the first MS-simulation [5, 6] and was shortly described [26] within a general frame of the MHD-approach to exploding plasma’ dynamics in the dipole field. It dictates that if a spherical cloud of such diamagnetic plasma with energy E_0

is ejected without B_0 at distance X_0 from dipole μ, than the cloud's deceleration boundary is determined by main energetic criteria $\text{æ} = 3E_0 X_0^3/\mu^2$. In particular, when a line X lies in the equatorial plane (i. e. $\theta = 90^0$), a plasma should be stopped [26, 27] by magnetic pressure at distance $R_m^* \approx 0.75X_0/\text{æ}^{1/6}$ ($<< X_0$) of such non-stationary magnetopause (that is analog of the usual expression for its position at R_{mp}). So, for the conditions of "Magnet" with a permanent $\mu \approx 4{\bullet}10^3$ G•cm^3, X_0 = 40 cm and the effective $E_0 \approx 160$ J, we should have $R_m^* \approx 2$ cm and the field' exclusion at large distances X > 2 cm, while in "Magnet" (see Fig. 2a) we had registered of dipole field' decrease ($B/H_d < 1$) only at distances X > 3 cm. Therefore we can conclude that probably due to effects of large ion Larmor (or some others non-MHD processes, see in III D), the outward shift of diamagnetic boundary could occur with opposite inward (to dipole) enhanced penetration of plasma stopping front, according to observation of reduced plasma luminosity at and near dipole surface of radius $R_p \sim 1$ cm (see 1 at Fig. 2b). Here the Larmor radius $R_L = V_0mC/zeB_d$, ≈ 8 cm (determined by dipole field B_{dm} at calculated point of $R_m^* \approx 2$ cm) gives a value of low ions magnetization $\varepsilon_m = R_L/R_{mp}^* \approx 4$ for their $<m/z> \approx 2.5$ a.e.m. and velocity $V_0 \approx 160$ km/s.

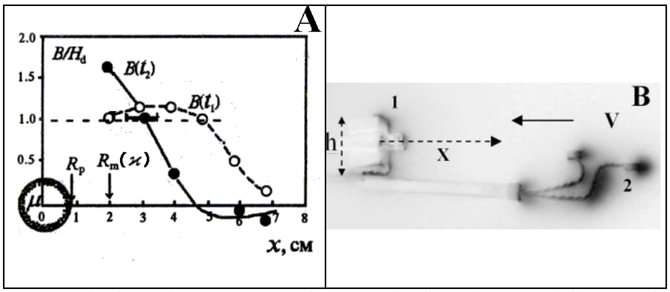

Fig. 2. The data of "Magnet" experiment on the formation (A) of diamagnetic boundary at minimal $X_2 \approx 3$ cm ($t_1 \approx 2.1$ μs and $t_2 \approx 2.6$ μs) by laser-produced plasma, overflowing a permanent magnet (1) of a height h = 1.7 cm, shown at the time-integrated photo (B) with magnetic probes (2) shining in the plasma.

One of the most obvious effect of the large Larmor influence onto intensity of plasma – dipole interaction is a non-MHD flute instability [28], observed for the first time in a pioneering work of Bostick with a plasma gun [29]. We could observe clear and study such kinds of plasma flutes near dipole only during our recent large-scale laser experiments AMEX (see in III B and Fig. 3), while in the "Magnet" – a strong lower-hybrid activity only near boundary at X ~ 3 cm.

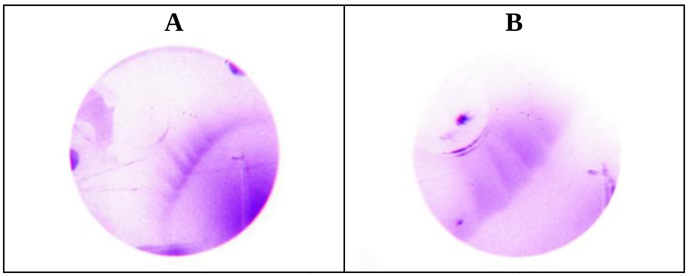

Fig. 3. Development of non-MHD flutes at the boundary of laser-plasma blob, expanding from the right-bottom corner inward to dipole (∅20 cm at the left-top) with a moment $\mu \approx 2.5{\cdot}10^6$ G•cm^3, directed into the paper: at **a** – early stage of almost free expansion at the moment t = 2.1 μs; at **b** (in larger scale) – a final stage of magnetopause formation at the moment t = 3.5 μs. At the back sides some elements of probe diagnostics are seeing and both given Image Tube' photos were obtained with the 30 ns exposition at presence of 0.1 mTorr H_2-gas to enhance a plasma luminosity.

B. *Large-Scale AMEX Experiments with a Laser Plasma*

These series of simulative experiments [27, 30, 31] were done last times for the study of probable dangerous world-wide effects during extreme cases of strong compression of the Earth magnetosphere (up to ~ $3R_E$) by giant Coronal Mass Ejections with the effective energy up to 10^{34} ergs. As a result, a non-stationary, so called "artificial" magnetosphere (in a flow of exploding-like plasma) could occur, with the scaling described in III*A* and verified [31] in AMEX (Artificial Magnetosphere EXperiment). It was realized like a "Magnet", but with the pulsed dipole of moment up to $\mu \approx 10^7$ G•cm^3, $E_0 \sim 300\div600$ J and large distance X_0 up to 75 cm. As result a record level of ion magnetization $\varepsilon_m = R_L/R_{mp}^* \approx 0.3\div0.4 < 1$ was achieved, but additionally a some range of $\varepsilon_m \sim 1$ was explored and the result of its influence onto dimensionless minimal distances of the plasma front-boundary $\Gamma_p = R_n/R_m^*$ and diamagnetic boundary $\Gamma_B = R_B/R_m^*$ are presented in Fig. 4 together with corresponding data of 3D/PIC Hybrid code [32].

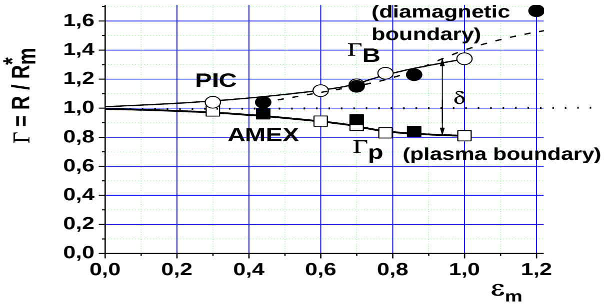

Fig. 4. Combined dimensionless data of the minimal distances of the plasma front-boundary $\Gamma_p = R_n/R_m^*$ and diamagnetic boundary $\Gamma_B = R_B/R_m^*$, obtained in the AMEX experiments (solid symbols) and by PIC-calculations (open ones) for various levels of ion magnetization $\varepsilon_m = R_L/R_{mp}^*$. A dimensionless gap $\delta = (\Gamma_B - \Gamma_p) \sim 1$ means that a distance of plasma penetration into dipole field without its diamagnetic exclusion could achieve a size of ion Larmor R_L.

C. *Disturbance of Ar-Plasma Stream by Small Pulsed Dipole*

During a set of KI-1 experiments [4] on the simulation of non-stationary phenomena in the Earth magnetosphere, a separate study with a quasi-steady Argon plasma was done to test an influence of the low ions magnetization onto position and structure of magnetopause (see curves n_i and ΔB at Fig. 5). This experiment "KEVL" (Space Experiment In Laboratory) was done in 2003 according to described principle scheme of KI-1 experiments (see Fig. 1) in variant, including plasma flow (1) of ~ 100 μs duration, dipole (3) of 10^5 G•cm^3 during ~ 1 ms, probe diagnostics (4) and uniform field B_0. Taking into account a registered high speed $V_0 \sim 30\div50$ km/s of plasma stream we can conclude, that the ions could have z up to 4. So if their $m/z \sim 10$, than the ions Larmor radius $R_L = V_0mC/zeB_{dm}$, ≈ 25 cm for the expected $R_m^* \approx 8$ cm and consequently, the criterion ε_m had a value ~ 3 rather close to "Magnet" one. Therefore we could expect (and had registered indeed, see Fig. 5) a similar to "Magnet" effect of essential difference between a calculated position $R_{mp} \approx 8$ cm of diamagnetic boundary R_B and its real location at $R_B \approx 17$ cm. Furthermore, a KEVL-measurements of the ion density distribution $n(x)$ give a quantitative data on the intensity and boundary $R_n \leq 4$ cm of plasma penetration inside of calculated MHD-boundary $R_{mp} \approx 8$ cm, if a streaming ions are not enough magnetized.

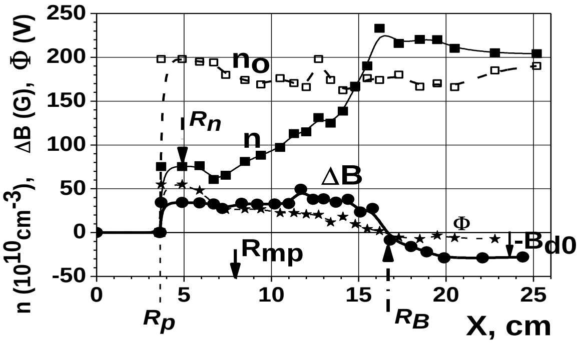

Fig. 5. Structure of the plasma (at $R_n \approx 5$ cm) and magnetic field (at $R_B \approx 17$ cm) boundaries in front of dipole ($\mu \approx 10^5$ G•cm^3) overflowing by Ar-plasma stream with velocity V ≈ 47 km/s in a field $B_0 = 26$ G ($\theta = 90^0$ and $\varphi = 0$).

D. PIC/Hybrid Modelling of "Magnet"-like Experiment and Probable Hall-Effects in a Plasma-Field Interaction.

To understand a nature of non-MHD interaction processes between a rarefied plasma streams and magnetic dipole, leading to outward shift of diamagnetic boundary and enhanced plasma penetration to near-dipole space (deep inside of MHD stop-distance at R_m^* or R_{mp}, see Fig. 2, 4 and 5), we had conducted a series of "Test" runs by 3D/PIC Hybrid model developed at Kyushu University [32]. They were done under the same level of ion magnetization criterion $\varepsilon_m = R_L/R_{mp}^* \approx 4$ (and smaller) as in a "Magnet" experiment, but with a different value of energetic criteria *æ* = $3E_0 X_0^3/\mu^2 \sim 3000 >> 1$ (instead of *æ* ~ 10^7 in "Magnet"), that is not so important for the explored basic problem of plasma-dipole interaction.

For the chosen parameters of runs with $\mu \approx 4•10^3$ G•cm^3, $E_0 \approx 1.5$ J and distance $X_0 = 10$ cm we had a fixed scale $R_m^* = 2$ cm and varied in runs a charge $z = 2.5 \div 13$ of ions only, with their both constant mass $m = 6.25$ a.m.u. and front velocity $V_0 \approx 160$ km/s (of spherical cloud). It allows us to change only a level of ions magnetization or the ratio $D = R_m^*\omega_{pi}/C$, more suitable for using in their unmagnetized case. This criterion D is the ratio of magnetopause scale R_m^* to the ion skin-depth C/ω_{pi}, i.e. a well studied parameter [13] for solar wind case, which determines an opportunity to form a Earth-like magnetosphere at $D >> 1$ or to have a very small plasma disturbances at $D \leq 0.5$. The equivalence of these criteria in a form $\varepsilon_m \approx 1/D$ (for our plasma-dipole problem) is based on a general relation of equality between a scales R_L and C/ω_{pi}, when a plasma kinetic pressure nmV_0^2 should be equal to magnetic field' pressure $B_{dm}^2/8\pi$ at calculated distance R_m^* (or R_{mp}) of plasma stopping at magnetopause. But since indeed a plasma with unmagnetized ions would not stop at this distance, it could be more preferably to use more natural (and not so local) scale C/ω_{pi} in such case. For example, in the presented at Fig. 6a data of "Magnet" modeling we had a calculated ion Larmor $R_L \approx 8$ cm for $z = 2.5$ and a similar scale $C/\omega_{pi} \approx 8$ cm, according to local ion density $n \approx 6•10^{12}$ cm^{-3} of non-uniform plasma (at $R_m^* = 2$ cm), as was in the experiment.

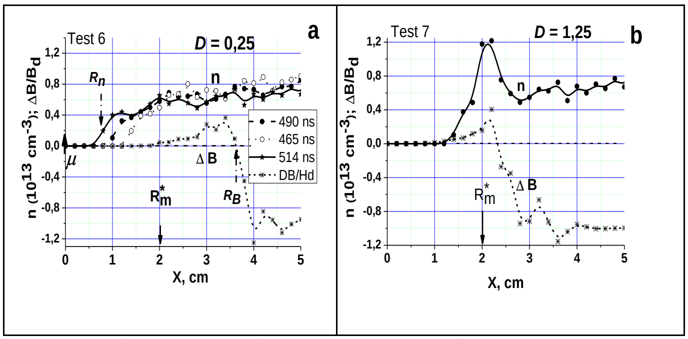

Fig. 6. Data of "Magnet" modeling (a) at low level of ion magnetization $\varepsilon_m \approx 4$ (where a data of ΔB at t = 490 ns are approximately the same as in other numbered times) and comparative data for modeling of close to MHD-case (b) at $\varepsilon_m \approx 0.8$ and time t = 514 ns of plasma stopping.

These data of Fig. 6a clear show that under the given experimental conditions of small $D \sim 0.25$, plasma propagates with initial velocity up to the dipole surface' place (at X ~ 1 cm in "Magnet", see Fig. 2b) or even to the radius of Stoermer forbidden zone at $0.4C_{st} \sim 0.5$ cm. While a magnetic field' exclusion occurs only up to X ≈ 3.7 cm instead of MHD magnetopause' location at $R_m^* = 2$ cm (and experimental $R_B \approx 3$ cm). In contrary, at $D > 1$ (Fig. 6b for hypothetical $z = 13$) plasma stopping at $R_n \approx 1.7$ cm and diamagnetic boundary at $R_B \approx 2.3$ cm are realized, rather close to the same $R_m^* = 2$ cm.

The data of all "Test" runs on plasma deceleration at X-axis are presented in Fig. 7 in a form of ratio $\eta = \Delta V_x/V_0$, where ΔV_x is a velocity decrease (near R_m^*) after passage of R_B-boundary.

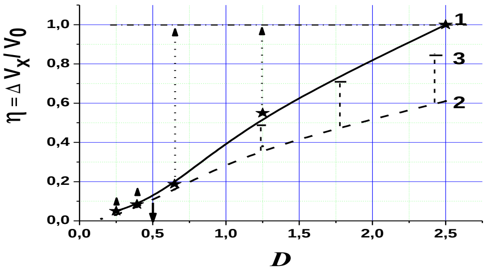

Fig. 7. The dependence of plasma velocity loss upon the value of criterion $D = R_m^*\omega_{pi}/C$ (inversely proportional to ion magnetization criterion ε_m) for all "Test" runs (1) in comparison with a simplest estimation for $\eta = 1 - 1/(1+D^2)^{1/2}$ of a new Hall-currents model (2) for penetration of collisionless plasma across a dipole field [34]. Upward arrows show a level of additional deceleration of fast plasma front, propagating up to the X ≈ 1÷1.5 cm, while a downward one – a critical value of $D \approx 0.5$ need to transition into MHD-range [13]. A levels (3) denote a model data of $\eta(D)$ relation for more sophisticated estimations.

A very small $\eta \leq 0.1$ were registered at the non-MHD regime of $D < 0.5$ and analysis of 2D-distribution of ion density n did not reveal any flute-type disturbances in the equatorial plane of dipole (align to Z), but its essential local compression and transverse velocity V_y were registered here (inside of R_B) in the direction of ion Larmor rotation. In these regime and plane an asymmetry of diamagnetic boundary were revealed on Y-direction (closer to dipole in the same direction), while in the meridian plane a large (~ B_d), a non-dipole B_y-field components were registered with opposite directions at different sides of equatorial plane. A level of these B_y-fields approximately corresponds to the ion current density ~ nzV_{0x}. It is important to note, that a simplest estimations of a new Hall-current model of ILP [34] give a qualitatively reasonable relation for diamagnetic boundary' shift as $R_B/R_{mp}=(1+1/D^2)^{1/6}$, which was observed and is presented at Fig. 2, 4-6.

E. Short Description of Basic Equations for Simplest Version of a New Model for Plasma non-Diamagnetic Propagation across a Dipole Field due to Hall-Current

We propose that described peculiarities could be explained by the so called Hall-term $\boldsymbol{J}\times\boldsymbol{B}/zenC$. Due to main Chapman-Ferraro current at magnetopause it generates field B_y

$$\frac{\partial}{\partial t}B_y=-\frac{\partial}{\partial Z}\frac{J_yB_z}{zne} \qquad (1)$$

This field is maximal in the meridian plane (but = 0 at X-axis) and positive above the equator (negative below it). Current associated with B_y field flows toward dipole along the interaction axis X and back in the cusp regions. To estimate J_x at the interaction axis we retain in the stationary induction equation only the convection and generation terms

$$\frac{\partial}{\partial X}V_xJ_x\approx\frac{C}{4\pi}\frac{\partial^2}{\partial Z^2}\frac{J_yB_z}{zne} \qquad (2)$$

The Hall-term could be replaced by plasma deceleration term $nmV_x\,\partial V_x/\partial X\approx J_yB_z/C$ and derivative along Z by the scale of magnetosphere R_{mp} (or R_m^*), as $\partial^2/\partial Z^2\approx-1/R_{mp}^2$. This gives

$$\frac{J_x}{zne}\approx\frac{1}{D^2}\cdot\frac{V_o^2-V_x^2}{V_x} \qquad (3)$$

We note that the main field B_z is convected by a sum of plasma and current velocities $\partial B_z/\partial t\approx-\partial/\partial x\left(V_x-J_x/zne\right)B_z$. In a stationary case the sum should be zero and we can derive velocity of plasma penetration across magnetic barrier or velocity change

$$\Delta V_x/V_o=1-1/\sqrt{1+D^2} \qquad (4)$$

The jump of magnetic field is derived from the velocity change as $\Delta B_z\approx\sqrt{4\pi nm(V_o^2-V_x^2)}\sim D/\sqrt{1+D^2}$. The radius, where dipole field is equal to this value is magnetopause position and the shift is given by

$$\frac{\Delta R_{mp}}{R_{mp}}=\left(\frac{D^2}{1+D^2}\right)^{1/6}-1 \qquad (5)$$

or $R_B/R_{mp}=(1+1/D^2)^{1/6}$. Thus, Hall-term leads to plasma penetration inside of magnetosphere and outward shifting of the magnetopause.

IV. DISCUSSION AND CONCLUSIONS

A presented data of all 3 kinds of simulative experiments of parts *A*, *B* and *C* at given Section III and modeling of part *D* clear show, that an essential affect of the finite ion Larmor radius R_L (or Hall-scale C/ω_{pi}) onto plasma-dipole interaction exists, at least in a explored before a super-alfvenic regime. As a result the diamagnetic boundary shifts outward from its MHD-distance R_{mp} near dipole, while the plasma front-boundary could penetrate inside it up to the dipole, if R_L (or C/ω_{pi}) is in a few times larger than R_{mp}. Almost all observed non-MHD features of plasma-dipole interaction (described just above in part *D*) correspond rather well to a previous similar PIC-modeling [33] and a new type of Hall-currents model [34], shortly presented in part *E*. But they contradict to some recent experiments [17] or PIC-simulations [35] and allows us to predict, that the interaction of planned AMS-magnet at ISS with the ionosphere would have essentially non-MHD and kinetic nature, characterized by development of plasma waves and instabilities at "free" propagation region ($C_{st}\le X\le R_B$) of plasma. In the prepared now at KI-1 facility of ILP, a new class of plasma-dipole experiments, we plan to simulate all these processes in sub-alfvenic regime and up to scales C_{st} or C/ω_{pe}.

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