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Induced Charge of Spherical Dust Particle on Plasma-Facing Wall in Non-uniform Electric Field

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Abstract

Induced charge of a spherical dust particle on a plasma-facing wall is investigated analytically, where non-uniform electric field is applied externally. The one-dimensional non-uniform electrostatic potential is approximated by the polynomial of the normal coordinate toward the wall. The bipolar coordinate is introduced to solve the Laplace equation of the induced electrostatic potential. The boundary condition at the dust surface determines the unknown coefficients of the general solution of the Laplace equation for the induced potential. From the obtained potential the surface induced charge can be calculated. This result allows estimating the effect of the surrounding plasma, which shields the induced charge.

Keywords: dust particle, induced charge, non-uniform electric field

1. Introduction

As the duration of plasma confinement in fusion devices becomes longer, the dust particles can be important to the behavior as an impurity to the core plasma and potential formation near plasma-facing plates. The absorption of radioactive tritium to the dust causes the safety issue in fusion reactors. In several fusion devices (TEXTOR-94, ASDEX-U, LHD, DIIID, NSTX etc.), the dust particles have been collected and their characteristics analyzed [1, 2], where the radii are wide-ranging between a few nm and a few tens μm. These dusts are composed mainly of metals and hydro-carbons, which are used for most divertors and plasma-facing materials. The understanding of the characteristics of dust particles in plasma, such as charging, absorption current, and acting forces, can be quite important for suppressing and controlling their behavior in plasma. The dust density in fusion devices usually is too low to bring collective effects. The investigation of the behavior of a single dust particle in boundary plasma is important. In this study we theoretically investigate the induced charge of the conducting dust particle with a spherical shape on the plasma-facing wall in a non-uniform electric field.

2 Electrostatic potential

A spherical conducting dust particle with a radius R_d is attached on an infinitely extended conducting plane wall. The local electrostatic potential is composed of the sum of the external one ϕ_{ex} and the one ϕ_{in} due to induced charges on the conducting dust particle.

$$\phi(r,z)=\phi_{ex}(z)+\phi_{in}(r,z) \tag{1}$$

where (r,z) is the conventional cylindrical coordinate, where the origin is located at the contacting point of the spherical dust to the plane wall (Fig.1).

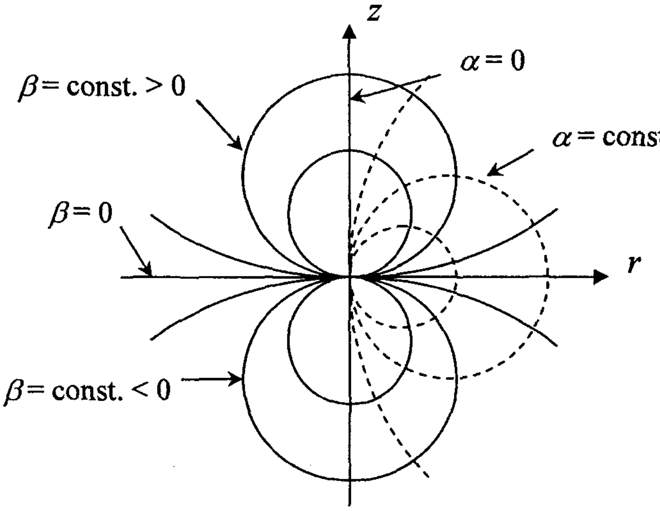

Fig.1 The cylindrical coordinate (r,z) and the bipolar coordinate (α,β). The infinitely extended conducting plane wall and the surface of the spherical dust are indicated by $\beta = 0$ and 1/2, respectively.

In this study the externally applied potential is approximated to be non-uniform toward the normal direction to the plane wall, i.e. z,

$$\phi_{ex}(z)=\sum_{k=0}^{k_{\max}} h_k z^k . \tag{2}$$

At the surface of the plane wall ($z = 0$) the external potential corresponds to the biased wall ϕ_w, $\phi_{ex}(z=0)=\phi_w$, which is the same as the surface of the conduction dust. The potential ϕ_{in} due to the induced charge satisfies the Laplace equation:

$$\frac{\partial}{\partial\alpha}\left(\frac{\alpha}{\alpha^2+\beta^2}\frac{\partial\phi_{in}}{\partial\alpha}\right)+\frac{\partial}{\partial\beta}\left(\frac{\alpha}{\alpha^2+\beta^2}\frac{\partial\phi_{in}}{\partial\beta}\right)=0 \tag{3}$$

in the bipolar coordinate (α, β) [3]. The relation between the cylindrical coordinate (r,z) and the bipolar coordinate (α,β) is

$$z + i r = \frac{i R_d}{\alpha + i\beta}, \tag{4}$$

where i denotes the imaginary unit. Here the ranges of α and β are $0 \le \alpha \le \infty$ and $-\infty \le \beta \le \infty$, respectively (Fig.1). The plane $z = 0$, i.e. $\beta = 0$, corresponds to the wall surface and $\beta = 1/2$ ($\equiv \beta_0$) indicates the surface of the spherical dust particle. The general solution of the Laplace equation (3), which satisfies the condition $\phi_{in} = 0$ at $\beta = 0$, is given by

$$\phi_{in}(\alpha,\beta) = \sqrt{\alpha^2 + \beta^2} \sum_{n=1}^{\infty} c_n I_{\lambda n}(\alpha,\beta) , \tag{5}$$

and

$$I_{\lambda n}(\alpha,\beta) \equiv \int_0^{\infty} d\lambda \ \lambda^n e^{-\beta_0 \lambda} \frac{\sinh(\beta\lambda)}{\sinh(\beta_0 \lambda)} J_0(\lambda\alpha), \tag{6}$$

where J_0 is the first kind Bessel function of the 0-th order and the coefficients c_n's are determined by the boundary condition at the surface of the spherical dust. The external potential is also expressed in (α,β):

$$\phi_{ex}(\alpha,\beta) = \sum_{k=0}^{k_{\max}} h_k z^k = \sum_{k=0}^{k_{\max}} h_k \left(\frac{R_d \beta}{\alpha^2 + \beta^2} \right)^k , \tag{7}$$

where the coefficient h_0 corresponds to the biased wall potential ϕ_w. With the aid of the relation

$$(-1)^n \frac{d^n}{d\beta^n} \frac{1}{\sqrt{\alpha^2 + \beta^2}} = \int_0^{\infty} d\lambda \lambda^n e^{-\beta\lambda} J_0(\lambda\alpha) \equiv I_n(\alpha,\beta), \tag{8}$$

the external potential is expressed by the function $I_n(\alpha,\beta)$. The total electrostatic potential $\phi(\alpha,\beta)$ is obtained as a combination of the externally applied potential ϕ_{ex} and the induced potential ϕ_{in}. In the case of $k_{\max} = 4$,

$$\begin{aligned}
\phi(\alpha,\beta) &= \phi_{ex}(\alpha,\beta) + \phi_{in}(\alpha,\beta) \\
&= \phi_w + \sqrt{\alpha^2 + \beta^2} \ [(h_1 R_d + \frac{h_2 R_d^2}{3\beta} + \frac{h_3 R_d^3}{5\beta^2} + \frac{h_4 R_d^4}{7\beta^3}) \ I_1(\alpha,\beta) \\
&+ (\frac{h_2 R_d^2}{3} + \frac{h_3 R_d^3}{5\beta} + \frac{h_4 R_d^4}{7\beta^2}) \ I_2(\alpha,\beta) \\
&+ (\frac{h_3 R_d^3}{15} + \frac{2 h_4 R_d^4}{35\beta}) \ I_3(\alpha,\beta) + \frac{h_4 R_d^4}{105} \ I_4(\alpha,\beta) \ ] \\
&+ \sqrt{\alpha^2 + \beta^2} \sum_{k=1}^{\infty} c_k I_{\lambda k}(\alpha,\beta) ,
\end{aligned} \tag{9}$$

where the first and second terms of the RHS of eq.(9) are the external potential and the last term corresponds to the induced potential. From the boundary condition at the surface of the spherical dust $\beta = \beta_0 = 1/2$:

$$\phi_{ex}(\alpha,\beta_0)+\phi_{in}(\alpha,\beta_0)=\phi_w, \tag{10}$$

the coefficients c_n's are expressed by the known quantities,

$$c_1=-(h_1R_d+\frac{h_2R_d^2}{3\beta_0}+\frac{h_3R_d^3}{5\beta_0^2}+\frac{h_4R_d^4}{7\beta_0^3}),$$

$$c_2=-(\frac{h_2R_d^2}{3}+\frac{h_3R_d^3}{5\beta_0}+\frac{h_4R_d^4}{7\beta_0^2}),$$

$$c_3=-(\frac{h_3R_d^3}{15}+\frac{2h_4R_d^4}{35\beta_0}),$$

$$c_4=-\frac{h_4R_d^4}{105}, \text{ and}$$

$$c_k=0: k>5. \tag{11}$$

Note that the relation $I_n(\alpha,\beta_0) = I_{\lambda n}(\alpha,\beta_0)$ at the dust surface is used to derive the relations (11). Finally we obtain the total local potential consisting of the external and induced ones for the case of $k_{\max} = 4$:

$$\phi(\alpha,\beta)=\phi_{ex}(\alpha,\beta)+\phi_{in}(\alpha,\beta)$$

$$=\phi_w+\sqrt{\alpha^2+\beta^2}\ \{\ h_1R\,I_{s1}+\frac{h_2R^2}{3}(\frac{\beta_0-\beta}{\beta_0\beta}I_1+\frac{I_{s1}}{\beta_0}+I_{s2})$$

$$+\frac{h_3R^3}{5}(\frac{\beta_0^2-\beta^2}{\beta_0^2\beta^2}I_1+\frac{I_{s1}}{\beta_0^2}+\frac{\beta_0-\beta}{\beta_0\beta}I_2+\frac{I_{s2}}{\beta_0}+\frac{I_{s3}}{3})$$

$$+\frac{h_4R^4}{7}[\frac{\beta_0^3-\beta^3}{\beta_0^3\beta^3}I_1+\frac{I_{s1}}{\beta_0^3}+\frac{\beta_0^2-\beta^2}{\beta_0^2\beta^2}I_2+\frac{I_{s2}}{\beta_0^2}+\frac{2(\beta_0-\beta)}{5\beta_0\beta}I_3+\frac{2I_{s3}}{5\beta_0}+\frac{I_{s4}}{15}]\} \tag{12}$$

Here the function I_{sn} is defined as

$$I_{sn}(\alpha,\beta)\equiv\int_0^\infty d\lambda\ \lambda^n\frac{\sinh[(\beta_0-\beta)\lambda]}{\sinh(\beta_0\lambda)}J_0(\lambda\alpha). \tag{13}$$

3. Induced charge

The electric field of the normal direction to the spherical dust surface gives the charge density $\sigma_s(\alpha)$ at the spherical dust surface ($\beta=\beta_0=1/2$):

$$\sigma_s(\alpha)=\varepsilon_0E_n\big|_{\beta=\beta_0=1/2}=\varepsilon_0\frac{\alpha^2+\beta_0^2}{R_d}\frac{\partial\phi}{\partial\beta}\bigg|_{\beta=\beta_0=1/2}$$

$$=-\varepsilon_0\frac{(\alpha^2+\beta_0^2)^{3/2}}{R_d}\{\ h_1R_d\,I_{c20}(\alpha)$$

$$+\frac{h_2 R_d^2}{3}[\frac{I_{10}(\alpha)}{\beta_0^2}+\frac{I_{c20}(\alpha)}{\beta_0}+I_{c30}(\alpha)]$$

$$+\frac{h_3 R_d^3}{5}[\frac{2I_{10}(\alpha)}{\beta_0^3}+\frac{I_{c20}(\alpha)}{\beta_0^2}+\frac{I_{20}(\alpha)}{\beta_0^2}+\frac{I_{c30}(\alpha)}{\beta_0}+\frac{I_{c40}(\alpha)}{3}]$$

$$+\frac{h_4 R_d^4}{7}[\frac{3I_{10}(\alpha)}{\beta_0^4}+\frac{I_{c20}(\alpha)}{\beta_0^3}+\frac{2I_{20}(\alpha)}{\beta_0^3}+\frac{I_{c30}(\alpha)}{\beta_0^2}+\frac{2I_{30}(\alpha)}{5\beta_0^2}$$
$$+\frac{2I_{c40}(\alpha)}{5\beta_0}+\frac{I_{c50}(\alpha)}{15}], \tag{14}$$

where $I_{n0}(\alpha)\equiv\int_0^\infty d\lambda\ \lambda^n e^{-\beta_0\lambda}J_0(\lambda\alpha)$ and

$$I_{cn0}(\alpha)\equiv\int_0^\infty d\lambda\ \lambda^n\frac{J_0(\lambda\alpha)}{\sinh(\beta_0\lambda)}. \tag{15}$$

The induced charge Q_{din} on the conducting spherical dust is obtained

$$Q_{din}=\int_{S_d}\sigma_s dS=-2\pi\varepsilon_0 R_d^2\int_0^\infty\frac{\alpha}{(\alpha^2+\beta^2)^2}\frac{\partial}{\partial\beta}(\phi_{ex}+\phi_{in})\Big|_{\beta=\beta_0=1/2}d\alpha$$

$$=-2\pi\varepsilon_0 R_d^2(d_1h_1+d_2h_2R_d+d_3h_3R_d^2+\cdots) \tag{16}$$

where σ_s and S_d are the surface charge density (eq.(14)) and the dust surface area, respectively. In the case of $k_{\max}=4$, the numerical coefficients d_k's are

$$d_1=I_{qc2}$$
$$d_2=\frac{1}{3}(\frac{I_{q1}}{\beta_0^2}+\frac{I_{qc2}}{\beta_0}+I_{qc3})$$
$$d_3=\frac{1}{15}[\frac{6I_{q1}}{\beta_0^3}+\frac{6(I_{q2}+I_{qc2})}{\beta_0^2}+\frac{3I_{qc3}}{\beta_0}+I_{qc4}]$$
$$d_4=\frac{1}{105}[\frac{45I_{q1}}{\beta_0^4}+\frac{15(I_{qc2}+2I_{q2})}{\beta_0^3}+\frac{3(5I_{qc3}+2I_{q3})}{\beta_0^2}+\frac{6I_{qc4}}{\beta_0}+I_{qc5}], \tag{17}$$

where $I_{qn}\equiv\int_0^\infty d\alpha\frac{\alpha I_{n0}(\alpha)}{\sqrt{\alpha^2+\beta_0^2}}=\int_0^\infty d\alpha\frac{\alpha}{\sqrt{\alpha^2+\beta_0^2}}\int_0^\infty d\lambda\ \lambda^n e^{-\beta_0\lambda}J_0(\lambda\alpha)$

$$=\int_0^\infty d\lambda\,\lambda^{n-1}e^{-2\beta_0\lambda}=\Gamma(n)/(2\beta_0)^n \tag{18}$$

and $$I_{qcn}\equiv\int_0^\infty d\alpha\frac{\alpha I_{cn0}(\alpha)}{\sqrt{\alpha^2+\beta_0^2}}=\int_0^\infty d\alpha\frac{\alpha}{\sqrt{\alpha^2+\beta_0^2}}\int_0^\infty d\lambda\ \lambda^n\frac{J_0(\lambda\alpha)}{\sinh(\beta_0\lambda)}$$

$$= \int_0^\infty d\lambda \frac{\lambda^{n-1} e^{-\beta_0 \lambda}}{\sinh(\beta_0 \lambda)} = 2\Gamma(n)\,\varsigma(n)/(2\beta_0)^n \qquad (19)$$

Here $\Gamma(n)$ and $\zeta(n)$ are the Gamma and Rieman's Zeta functions, respectively. The first term of the RHS corresponds to the charge in the uniform electric field.

4. Conclusion

The induced charge of the conducting spherical dust particle on the conducting wall in the non-uniform electric field is calculated theoretically as well as the local electrostatic potential. The non-uniform electrostatic potential is approximated by the polynomial of the normal coordinate toward the wall. These results can be compared to the results from the particle computer simulation [4], where the total charge includes both the effects of the induced charges and plasma shielding. This theoretical analysis is useful to understanding the dust behavior in the boundary plasma [5].

Acknowledgement

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References

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Agenda

JSPS-CAS Core University Program Seminar on Production and Steady State Confinement of High Performance Plasmas in Magnetic Confinement Systems

27--29 July, 2005, Hefei, China

(each one with 25 min durations including 5 min. for discussion)

July 27, Wednesday, 2005

No	Start	End	Dura. min.	Title	Chairman	Speaker	Affiliation
	9:00	9:10	10	Opening ceremony	B. N. Wan	Coordinators	Japan China
1	9:10	9:35	25	Long pulse operation of high performance plasmas in JT-60U	B. N. Wan	S. Ide	JAERI
2	9:35	10:00	25	HT-7 long pulse experiments		Junyu Zhao	ASIPP
3	10:00	10:25	25	Long pulse ICRF discharges in LHD		R. Kumazawa	NIFS
4	10:25	10:50	25	IBW and ICRF experiment in HT-7 tokamak		Yanping Zhao	ASIPP
	10:50	11:05	15	Coffee break			
5	11:05	11:30	25	High Power Neutral Beam Injection in LHD	T. Watari	K. Tsumori	NIFS
6	11:30	11:55	25	Experiment observation of the pulse high pressure gas puffing on HL-2A		X. T. Ding	SWIP
7	11:55	12:20	25	Formation of edge transport barrier by LH transition and large reversed plasma current on LHD		K. Toi	NIFS
8	12:20	12:45	25	Dynamics of secondary large-scale structures in ETG turbulence simulation		Jiquan Li	SWIP
	12:45	14:00	75	Lunch break			
9	14:00	14:25	25	Formation of low aspect ratio torus equilibria by ECH	K. Toi	T. Maekawa	Kyoto Univ.
10	14:25	14:50	25	Preliminary experiment of plasma current startup by ECR wave on SUNIST spherical tokamak		Yexi He	Tsinghua Univ.
11	14:50	15:15	25	Density modulation experiments on HT-7 and LHD		K. Tanaka	NIFS
12	15:15	15:40	25	Dual-electrode Biasing Experiment in A Toroidal Plasma		Yi YU	USTC
	15:40	15:55	15	Coffee break			
13	15:55	16:20	25	ICRF Experiments and Potential Formation on the GAMMA 10 Tandem Mirror	Yexi He	M. Ichimura	Tsukuba Univ.
14	16:20	16:45	25	MHD flow layer formation at boundaries of magnetic islands in tokamak plasmas		Jiaqi Dong	SWIP
15	16:45	17:10	25	Magnetic islands observed by a fast-framing tangentially viewing soft X-ray camera on LHD and TEXTOR		S. Ohdachi	NIFS
16	17:10	17:35	25	Tomographic analysis of central MHD activities and radiation losses on the HL-2A and LHD		Yi Liu	SWIP
	19:00	21:00		Reception party			

July 28, Thursday, 2005

No	Start	End	Dura. Min.	Title	Chairman	Speaker	Affiliation
1	9:00	9:25	25	Divertor study in JT-60U	S. Ide	H. Kubo	JAERI
2	9:25	9:50	25	Poloidal divertor experiment in HL-2A		X. R. Duan	SWIP

3	9:50	10:15	25	Review of divertor study on LHD		T. Morisaki	NIFS
4	10:15	10:40	25	Divertor design for EAST		Shizeng Zhu	ASIPP
	10:40	10:55	15	Coffee break			
5	10:55	11:20	25	Theory of zonal flow in tokamak and helical plasmas	Shaojie Wang	T. Watari	NIFS
6	11:20	11:45	25	Measurement of zonal flow in HT-7 tokamak		Guosheng Xu	ASIPP
7	11:45	12:10	25	Suppression of neoclassical tearing modes towards stationary high-beta plasmas in JT-60U		A. Isayama	JAERI
8	12:10	12:35	25	Overall feature of EAST operation space by using simple Core-SOL-Divertor model		Y. Hiwatari	CRIEPI
	12:35	14:00	85	Lunch break			
9	14:00	14:25	25	Assessments of flow drive by use of Ion Bernstein Wave on Heliotron-J and HT-7 devices	Jiaqi Dong	Y. Torii	Kyoto Univ.
10	14:25	14:50	25	Advanced Tokamak Equilirium Theory		Shaojie Wang	ASIPP
11	14:50	15:15	25	Magnetic sensorless control of plasma position and shape in a tokamak		K. Nakamura	Kyushu Univ.
12	15:15	15:40	25	Low Frequency Instability in Magnetized Plasma Column		Jin-lin XIE	USTC
	15:40	15:55	15	Coffee break			
13	15:55	16:20	25	Spectroscopic study on impurity transport of core and edge plasmas in LHD	K. Nakamura	S. Morita	NIFS
14	16:20	16:45	25	Impurity Measurement and Study on HL-2A divertor tokamak		Z. Y. Cui	SWIP
15	16:45	17:10	25	Development of A New ECE Imaging System for Core		Jun WANG	USTC
16	17:10	17:35	25	Dust particle behaviors in boundary plasma of a fusion device		Y. Tomita	NIFS
	17:35	18:00	25	Closing acticity			
	18:10			Bus departure for hotel			
				July 29, Friday, 2005			
				Discussion of CUP working group			

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