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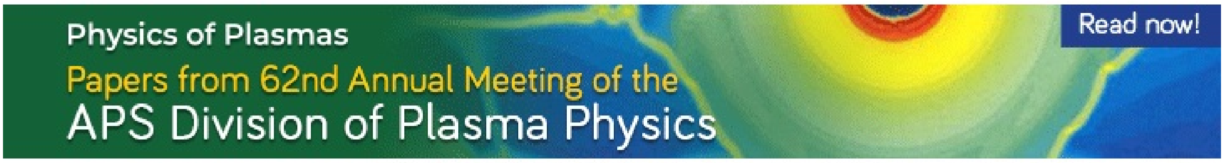

PHYSICS OF PLASMAS **24**, 063507 (2017)

Back diffusion of electrons in argon subjected to uniform time invariant orthogonal electric and magnetic fields

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In this study, the processes of back diffusion in Ar subjected to crossed fields are analyzed by using the Monte Carlo simulation method in the E/N range of 50 to 500 Td ($1\ \mathrm{Td} = 1 \times 10^{-17}\ \mathrm{V\ cm^2}$) for $0 < \mathrm{B/N} < 25 \times 10^{-19}\ \mathrm{T\ cm^3}$. At a given constant E/N, escape factors decrease with an increasing crossed, reduced magnetic field B/N. This reduction in the escape factor is more pronounced in the lower E/N range. Furthermore, the mean number of collisions of back scattered electrons is quite large, and at a given E/N, the mean number of collisions decreases as the crossed B/N increases. *Published by AIP Publishing*. [http://dx.doi.org/10.1063/1.4984989]

I. INTRODUCTION

In recent years, there has been renewed interest in the field of back diffusion of electrons to an emitting surface due to its importance in studies of electrical breakdown and in practical applications of plasma devices and radiation detectors.[1–4] Backscattering processes in argon have been reviewed[5] and using kinetic approaches, extensive analytical studies have been carried out in pure gases.[6–11] The back diffusion of electrons in Argon (Ar) was initially studied by a Monte Carlo Simulation Method.[12] In Ref. 12, it was shown that the back scattering electrons experienced many collisions rather than making one single collision before being absorbed by the cathode as suggested by the basic theories. The process of back diffusion is a non-equilibrium effect and largely occurs in the region where electrons in the swarm do not acquire the equilibrium energy. Back diffusion in nitrogen was also studied by means of Monte Carlo simulations.[1] In Ref. 1, it was also shown by Radmilovic-Radjenovic *et al.* that back scattering electrons experienced many collisions in nitrogen. The backscattering effects in Ar+ CH_4 mixtures were also analyzed.[13] In recent years, the back diffusion processes in Ar + SF_6, binary mixtures are analyzed using Monte Carlo Simulation methods by employing the realistic collision cross sections of the respective component gases by Dincer *et al.*[14]

Although crossed field discharge is an important subject in plasma and high voltage devices, to the best of our knowledge, the information on the analysis of the back diffusion under the crossed magnetic and electric fields in Argon is not available in the literature. Dujko *et al.* presented a systematic investigation of electron transport in CF_4 in crossed electric and magnetic dc fields analyzing temporal relaxation of electron energy distribution functions together with steady state transport data using a Monte Carlo simulation.[15] Furthermore, a comprehensive description of non-conservative electron transport in crossed fields for the most general case of arbitrary field directions was presented using a Monte Carlo simulation technique as an extension of the work in Ref. 15.[16] Non-conservative Boltzmann solution was also carried out by Ness and Makabe by including the effects of non-conservative collisions in Ar subjected to E × B fields.[17] Transport in combined electric and magnetic fields was discussed in detail in a review paper largely devoted to interpretation of transport data for proper use in plasma modelling.[18]

Dincer and Hiziroglu previously reported the crossed field response of back diffusion in N_2 in a limited study.[19] A review of plasma devices based on electron drift in crossed fields is presented.[20] The back diffusion of electrons to the cathode can be considerably effective in discharge simulation since the secondary electron emission coefficients can be altered in the presence of crossed fields. Phelps and Petrovic reported a detailed analysis of the breakdown in Ar and the model proposed explains measured breakdown and low-current discharge voltages for Ar over a wide range of electric field to gas density ratios in which the calculation of back diffusion coefficients is required.[5]

In this paper, we consider to provide information on backscattering of electrons to the cathode in crossed fields for Ar. The efficiency of electron transmission is analyzed in Ar subjected to the crossed time invariant, uniform electric and magnetic fields by using Monte Carlo Simulation methods.

II. SIMULATION TECHNIQUE AND THE EMPLOYED MODEL

The technique that is used in this study is mainly the same technique in Ref. 4. The limiting orthogonal magnetic and electric fields in the Townsend discharges are evaluated.[4,21] A brief description is given here, with the implementation of back diffusion processes. An independent means of evaluating swarm parameters without any assumption with regard to the collision electrons frequencies under the orthogonal magnetic and electric fields is provided with the Monte Carlo simulation technique. Furthermore, back diffusion of electrons can be easily simulated and investigated with the

Monte Carlo simulation although the electron swarm is not in the equilibrium range. The technique is based on a free-flight time approach with fine time steps in which the motion of an electron between collisions is governed by Lorentz force. Special care is taken to select for a time-step because Ar has a large Ramsauer-Townsend effect. Hence, the energy change of an electron during one time step is not greater than 3%.

In crossed fields, the equation of motion of an electron with velocity v is governed by the equation

$$m\,\frac{dv}{dt} = e\,(E + v\,x\,B), \tag{1}$$

where e is the charge of the electron with mass m and E and B are the electric and magnetic fields, respectively.

In the present simulation, magnetic and electric fields are uniform in the gaseous medium, time-invariant, and applied along the negative z and positive x directions in Cartesian coordinates. Therefore, the acceleration along the applied magnetic field is zero and the velocity component along x will not be disturbed. The remaining related velocity components at the end of a time step are

$$v_{y1} = v_{y0} + \left(\frac{e}{m}\right) v_{z0}\,B_x\,(\Delta t), \tag{2}$$

$$v_{z1} = v_{z0} + \left(\frac{e}{m}\right) (E_z - v_{y0}\,B_x)\,(\Delta t), \tag{3}$$

where v_{y0} and v_{z0} are the respective initial velocity components and the subscript "0" denotes the velocity at the beginning of a time step Δt and the subscript "1" denotes the velocity at the end of Δt.

The position of the electron with the above defined velocity components will be updated at the end of the time step Δt. The presented cross-sectional data in Ref. 21 have been used as adopted in our recent work for Ar.[14] The cross section of the total collision is defined as the summation of the momentum transfer cross section with the integrated inelastic cross sections. For the elastic momentum transfer, curve-fit expressions given in Ref. 22 according to measurements of Hayashi[23] are used up to 20 eV. Above 20 eV, an expression is not defined for the elastic momentum cross section in Ref. 22. Hence, at higher energies, we have employed the tabulation for the elastic momentum transfer collision cross section as given in Ref. 23. The expressions for ionization and excitation collision cross sections defined in Ref. 22 are also adopted. In the absence of the magnetic field, evaluated escape factors in Ar with the adopted cross section agree well with those of the simulation results reported before.[4,12] The same cross section was employed for the evaluation of limiting fields in crossed discharges in $Ar + SF_6$ gas mixtures, and the limiting fields obtained by the simulation without the magnetic fields agreed with the experimental results in the literature.[4] The ionization cross section has a threshold energy of 15.8 eV and the excitation collision cross section has a composite level of 11.5 eV. In this study, the gas density is accepted as $3.32 \times 10^{16}\,\mathrm{cm}^{-3}$ (133.33 Pa at 20 °C). The scattering is assumed isotropic and such an assumption is due to the collision cross section set rather than being theoretical. We have employed the free flight time approach with fine time steps. The mean collision time is divided into time steps evaluated in the program in such a way that the energy change in the beginning and end of a time step is limited to less than 3%. The state of the electrons with their position and energy is updated at the end of each time step. At the end of a time step, the probability of collision is calculated and compared with a random number uniformly distributed between 0 and 1.0. The simulation of a collision process and deciding on the nature of collision have been reported previously by Dincer *et al.*[14,24] For an inelastic collision, the corresponding threshold energy is subtracted from electron energy and in the case of an ionization collision after subtracting the threshold energy, the remaining energy is shared equally between the two electrons. If the collision tests for inelastic collisions fail, then the collision is deemed to be an elastic one with an energy loss simply governed by $\frac{2m}{M}$ where m and M are the masses of an electron and Ar atom, respectively. Moreover, only the binary electron-molecule collisions are considered because the density of the gas is sufficiently low and the gas is weakly ionized.

The coefficient of back diffusion is defined as

$$f_{bd} = \frac{J_{eb}}{J_{et}}, \tag{4}$$

where f_{bd} is the back diffusion coefficient, J_{eb} is the number density of backscattered electrons to the cathode, and J_{et} is the number density of total electrons emitted by the cathode. The escape factor f_{es} is defined as

$$f_{es} = 1 - f_{bd}, \tag{5}$$

where the density of the net electron flux value is normalized at the totally absorbing cathode surface.[14]

In the presented simulation, the initial electrons are injected from the cathode with constant energies. The angle of entry with respect to the applied electric field direction on the z-axis is assumed as a cosine distribution. The number of initial electrons injected into the drift space is on the order of 10^4 in the E/N and B/N range investigated. All the electrons in the swarm are traced until the termination time (50 or 100 ns) or until they reach the cathode due to the back diffusion. The termination time of the simulation depends on the number of initial electrons and, also, on the value of E/N and B/N for a given electron emission energy. In the E/N range of 50–500 Td, the escape factors are evaluated at various B/N values ranging from 0 to $25 \times 10^{-19}\,\mathrm{T\ cm}^3$ in crossed fields for a given constant electron emission energy employing Eqs. (4) and (5).

III. RESULTS AND DISCUSSION

The simulation results of the escape factors with negligible B/N are compared with the recent data in Ar, and very good agreement is observed with our previous results in the absence of the magnetic field.[14] Then, the analysis is carried out in crossed electric and magnetic fields.

In Fig. 1, the open squares give the obtained results in this study with a negligible magnetic field of $B/N = 3.3 \times 10^{-23}\,\mathrm{T}$ cm^3. Open triangles represent previous results of Dincer *et al.*[14]

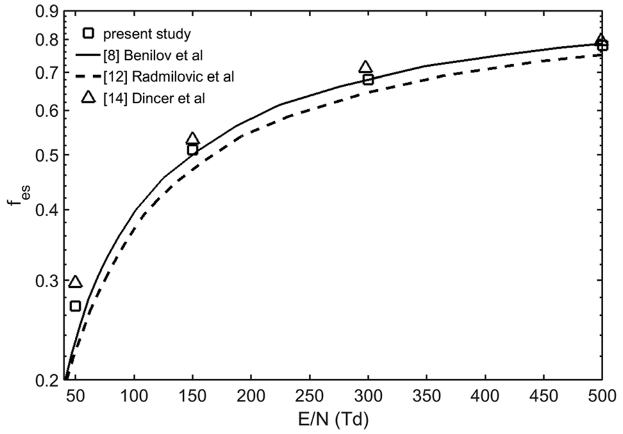

FIG. 1. The monoenergetic emitted electron escape factors in Ar with the 1 eV initial energy for a totally absorbing cathode.

with the applied electric field only. The results of Radmilovic and Petrovic[12] and Benilov and Naidis[8] are also shown for a totally absorbing cathode.

Figure 1 compares the escape factors evaluated in the absence of the magnetic field of various researchers with those of the present paper results in crossed magnetic field of negligible magnitude for various E/N values with very good agreement in the E/N range investigated. In Fig. 2, escape factors in crossed fields are shown at a given B/N for various E/N values. As shown in Fig. 2, the escape factors are obtained as a function of reduced electric fields under the constant B/N value. The electron emission energy initially is 1.0 eV. At a given B/N, escape factors increase as E/N increases. However, at a given E/N escape factors decrease as the applied magnetic field B/N increases.

Figure 3 gives the escape factors for an initial electron emission energy of 0.6 eV in the crossed fields. It can be seen from this figure that a similar response of reduction in escape factors is observed at a constant E/N as the crossed B/N values increase. The escape factor increases as the initial emission energy is reduced to 0.6 eV at a given E/N and given B/N. Furthermore, for a constant initial electron energy, and at a given E/N value, escape factors decrease with increasing magnitudes of crossed number density reduced magnetic fields.

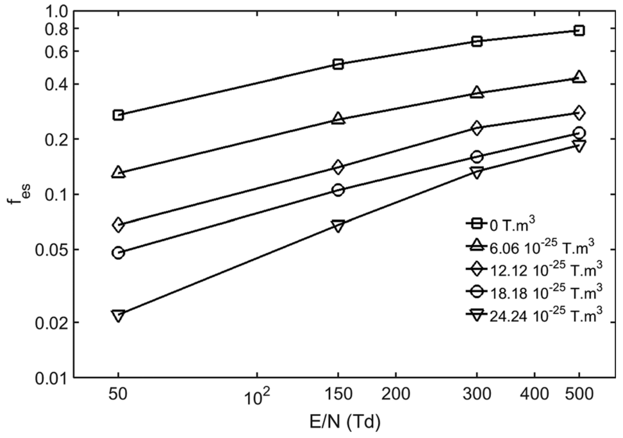

FIG. 2. The monoenergetic emitted electron escape factors in Ar with 1 eV initial energy.

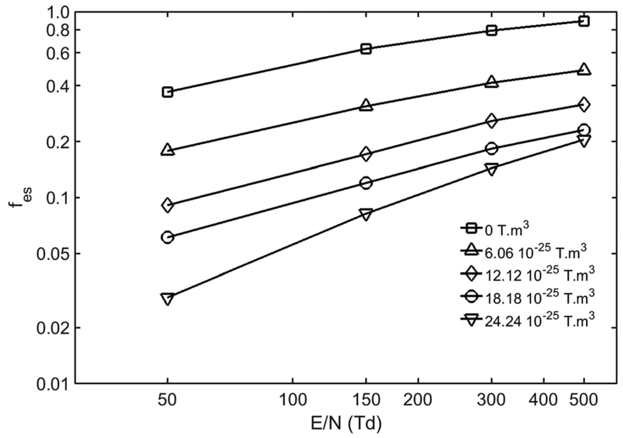

FIG. 3. The monoenergetic emitted electron escape factors in Ar with 0.6 eV initial energy.

Table I gives the variation in the ratio of the escape factors to E/N at a constant B/N. In this table, $f_{es(E\times B)}$ is the escape factor calculated in crossed fields and $f_{es(0)}$ is the escape factor with the applied electric field only. In the simulations carried out, the standard errors are given as $MCE_{(0)}$ and $MCE_{(E\times B)}$ for the applied electrical field only and for crossed magnetic fields, respectively, with the corresponding number of initial electrons used shown as I_0 and $I_{0(E\times B)}$. At 500 Td with B/N = 0, the error is less than 2% and is obtained with 1000 initial electrons. However, it is necessary to use 2.5×10^4 electrons at E/N = 50 Td with the crossed magnetic field of 24.24×10^{-25} Tm^3 in order to obtain an error of about 4%.

Table II is similar to Table I except that the initial electron energy is 0.6 eV. The same response of reduction in escape factors observed in Table I is also valid for Table II, that is, in crossed fields, at a given E/N, escape factors decrease as B/N increases. The ratio of escape factors $f_{es(E\times B)}/f_{es(0)}$ is the numerical value of a factor M at a given E/N and B/N if the escape factor in crossed fields is defined as

$$f_{es(E\times B)} = M f_{es(0)}. \tag{6}$$

The factor M also decreases at a given E/N as B/N increases in crossed fields.

Figure 4 shows the mean number of collisions at the fixed B/N value as a function of E/N value in the crossed fields. It can be observed from Fig. 4 that, for the back scattering electrons, the mean number of collisions before they are back scattered and absorbed is quite large. Hence, their ranges are longer than a single mean free path.

Similar behavior in Ar has been observed before.[13,14] In Fig. 4, curve 1 corresponds to the case in the absence of the crossed magnetic field and curves 2 and 3 give the variation as a function of E/N for 12.12×10^{-25} T m^3 and 24.24×10^{-25} T m^3. The mean number of collisions becomes smaller as B/N increases at a given E/N. This study shows that the back scattered electron staying time decreases in the discharge as at a fixed E/N while the crossed number density reduced magnetic field increases.

TABLE I. Ratio of escape factors in crossed fields with 1.0 eV initial electron emission ($N = 3.32 \times 10^{22}$ m^{-3}).

B/N (T m^3)	E/N (Td)	50	150	300	500
6.06×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.13/0.27	0.255/0.51	0.355/0.68	0.43/0.78
	$MCE_{(E \times B)}$	3.36×10^{-3}	4.36×10^{-3}	6.77×10^{-3}	7.04×10^{-3}
	$I_{0(E \times B)}$	1×10^4	1×10^4	5×10^3	5×10^3
	$MCE_{(0)}$	4.44×10^{-3}	7.06×10^{-3}	1.04×10^{-2}	1.31×10^{-2}
	I_0	1×10^4	5×10^3	2×10^3	1×10^3
12.12×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.068/0.27	.14/0.51	0.23/0.68	0.278/0.78
	$MCE_{(E \times B)}$	2.05×10^{-3}	3.47×10^{-3}	4.21×10^{-3}	6.33×10^{-3}
	$I_{0(E \times B)}$	1.5×10^4	1×10^4	1×10^4	5×10^3
18.18×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.048/0.27	0.105/0.51	0.16/0.68	0.215/0.78
	$MCE_{(E \times B)}$	1.51×10^{-3}	2.50×10^{-3}	3.67×10^{-3}	5.80×10^{-3}
	$I_{0(E \times B)}$	2×10^4	1.5×10^4	1×10^4	5×10^3
24.24×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.022/0.27	0.068/0.51	0.133/0.68	0.185/0.78
	$MCE_{(E \times B)}$	9.27×10^{-4}	1.78×10^{-3}	2.77×10^{-3}	3.88×10^{-3}
	$I_{0(E \times B)}$	2.5×10^4	2×10^4	1.5×10^4	1×10^4

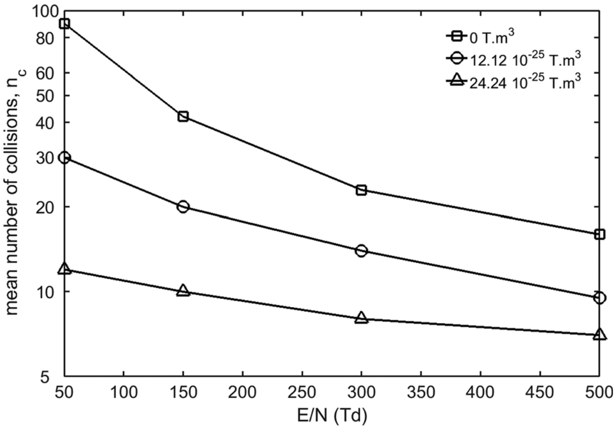

FIG. 4. Mean number of collisions at the fixed B/N value as a function of E/N value in the crossed fields.

Figure 5 gives the maximum range of the back scattered electrons at fixed E/N values of 50 Td and 150 Td as a function of B/N. The simulation results reveal that the range of electrons returning to the cathode position decreases at a fixed E/N as B/N increases. Hence with shortened ranges, the back scattering electrons experience a decreased collision number as B/N increases at a given E/N.

IV. CONCLUSION

In the present simulation conditions, it is observed that the application of reduced magnetic fields at a given E/N reduces the mean energy of electrons and increases the relaxation time for the swarm to achieve equilibrium. A similar response of the swarm in crossed fields in Monte Carlo studies of electron transport has been observed before by Dujko *et al.*[15] In Ref. 15, the authors have shown that the application of the magnetic fields depopulates higher energy electrons in the tail of electron energy distribution functions reducing the mean energy and changing the speed of relaxation. Furthermore, the back diffusion process takes place largely in the non-equilibrium region and in order to eliminate the effect pressure dependence and geometry, the swarm development should be carried out for multiples of maximum range of electrons which are going to be back scattered as reported by Radmilovic and Petrovic.[12]

In the simulations carried out, care is taken for the swarm to develop for multiples of the maximum ranges depending

TABLE II. Ratio of escape factors in crossed fields with 0.6 eV initial electron emission energy ($N = 3.32 \times 10^{22}$ m^{-3}).

B/N (T m^3)	E/N (Td)	50	150	300	500
6.06×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.178/0.37	0.31/0.63	0.415/0.79	0.485/0.89
	$MCE_{(E \times B)}$	3.83×10^{-3}	6.84×10^{-3}	6.97×10^{-3}	7.07×10^{-3}
	$I_{0(E \times B)}$	1×10^4	5×10^3	5×10^3	5×10^3
	$MCE_{(0)}$	6.82×10^{-3}	1.08×10^{-2}	1.29×10^{-2}	9.89×10^{-3}
	I_0	5×10^3	2×10^3	1×10^3	1×10^3
12.12×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.091/0.37	0.171/0.63	0.258/0.79	0.317/0.89
	$MCE_{(E \times B)}$	2.34×10^{-3}	3.76×10^{-3}	4.37×10^{-3}	6.58×10^{-3}
	$I_{0(E \times B)}$	1.5×10^4	1×10^4	1×10^4	5×10^3
18.18×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.061/0.37	0.12/0.63	0.183/0.79	0.231/0.89
	$MCE_{(E \times B)}$	1.85×10^{-3}	2.65×10^{-3}	3.87×10^{-3}	4.21×10^{-3}
	$I_{0(E \times B)}$	1.5×10^4	1.5×10^4	1×10^4	1×10^4
24.24×10^{-25}	$f_{es(E \times B)}/f_{es(0)}$	0.029/0.37	0.082/0.63	0.144/0.79	0.205/0.89
	$MCE_{(E \times B)}$	1.18×10^{-3}	2.24×10^{-3}	2.87×10^{-3}	4.04×10^{-3}
	$I_{0(E \times B)}$	2×10^4	1.5×10^4	1.5×10^4	1×10^4

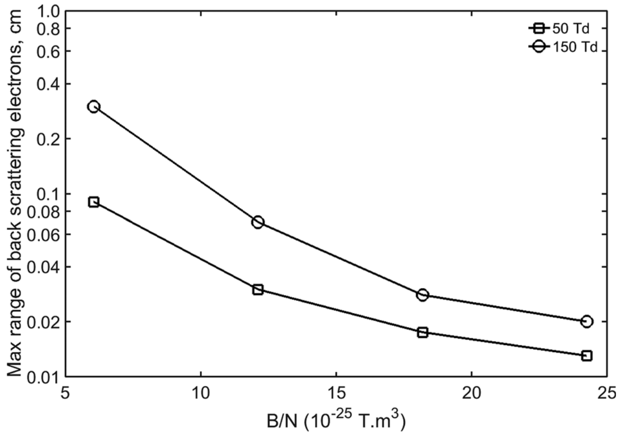

FIG. 5. Maximum range of the back scattered electrons at fixed E/N values of 50 Td and 150 Td as a function of E/N.

on B/N and E/N. Since the swarm development is governed by combined effects of reduced electric and magnetic fields, at a constant E/N of 50 Td and B/N of 18.18×10^{-25} T m^3 for number densities corresponding to 0.5, 1, and 3 Torr, the simulation is carried out with an initial energy of 1.0 eV to test the pressure dependence of the escape factors. The escape factors found do not show pressure dependence as they are evaluated as 0.0493, 0.048, and 0.0487, respectively, for 0.5, 1, and 3 Torr of pressure.

In the E/N and B/N range of the present study, the simulation results show that the electron escape factors in crossed fields decrease at a fixed E/N as B/N increases. At a given B/N value, the escape factors increase as E/N increases. The mean number of collisions of back scattered electrons is quite large, and at a given E/N, the mean number of collisions decreases as the crossed B/N increases. In crossed fields, the mean collision number of electrons before being back scattered and absorbed also decreases as E/N increases at a fixed B/N value. The maximum range of the back scattered electrons is shortened if the applied magnetic field is increased.

The simulations carried out correspond to the right side of the Paschen minimum where the application of the magnetic field reduces the mean energy of electrons and acts as reduced electric field is decreased.[3,4] However, on the left side of the minimum with a low Nd (d is the gap distance) product, the response to crossed fields can be reversed where the application of the magnetic field can increase the mean energy acting as the reduced electric field is increased as noticed in Ref. 17.

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