Dujko, Sasa (2009) ***The multi-term Boltzmann equation analysis and Monte Carlo study of hydrodynamic and non-hydrodynamic charged particle swarms.*** **PhD thesis, James Cook University.**

Appendix A

Benchmark Calculations: The ionization model of Lucas and Saelee

In this appendix the results of benchmark calculations for the ionization model of Lucas and Saelee are presented. The definition of this model is given by Eq. (6.2). We consider the reduced electric field of 30 Td, the reduced magnetic field range: 100-500 Hx and the angles of 0°, 30°, 60° and 90°. The utility of the ionization model of Lucas and Saelee lies in the fact that all variations associated with the effects of ionization processes can be controlled through the variation of the parameter F. Both the bulk and flux values of transport properties are presented. In Monte Carlo simulations, a large number of electrons (typically $1 \times 10^5 - 1 \times 10^6$) were followed through a neutral gas. At time $t = 0$, electrons were initially released from the origin according to Maxwellian velocity distribution with the mean starting energy of 1 eV. All calculations were performed at zero gas temperature. Monte Carlo simulations that were performed usually lasted between 24 hours and several days on the fastest personal computers.

From tables shown below, it is evident that, over the range of B/n_0 and ψ there is an excellent agreement among these two independent techniques. Agreement to at least 1.5% exist between results obtained by a multi term theory and Monte Carlo simulation for all transport coefficients except for the bulk value of $n_0 D_{xx}$ for $F = 1$ at B/n_0 of 500 Hx and ψ of 60°. The discrepancies in the results are attributable to the statistical uncertainties associated with the Monte Carlo method. These 'benchmarks' support the numerical integrity of the present theory and code.

Table A.1: A comparison of the mean energy and drift velocity components for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 100 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^4 ms^{-1}$)	W_x^* ($10^4 ms^{-1}$)	W_y ($10^4 ms^{-1}$)	W_y^* ($10^4 ms^{-1}$)	W_z ($10^4 ms^{-1}$)	W_z^* ($10^4 ms^{-1}$)
	MC	7.348	—	—	—	—	—	2.053	—
0	Δ(%)	0.1	—	—	—	—	—	0.1	—
	BE	7.359	—	—	—	—	—	2.055	—
	MC	7.264	—	0.482	—	0.288	—	1.896	—
30	Δ(%)	0.1	—	0.2	—	0.3	—	0.4	—
	BE	7.272	—	0.483	—	0.289	—	1.889	—
	MC	7.067	—	0.847	—	0.296	—	1.573	—
60	Δ(%)	0.1	—	0.1	—	0.1	—	0.1	—
	BE	7.068	—	0.848	—	0.297	—	1.574	—
	MC	6.947	—	0.986	—	—	—	1.406	—
90	Δ(%)	0.1	—	0.1	—	—	—	0.1	—
	BE	6.946	—	0.987	—	—	—	1.405	—

(a) $F = 0.5$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^4 ms^{-1}$)	W_x^* ($10^4 ms^{-1}$)	W_y ($10^4 ms^{-1}$)	W_y^* ($10^4 ms^{-1}$)	W_z ($10^4 ms^{-1}$)	W_z^* ($10^4 ms^{-1}$)
	MC	6.667	1.550	—	—	—	—	2.057	2.500
0	Δ(%)	0.1	0.6	—	—	—	—	0.6	0.2
	BE	6.672	1.560	—	—	—	—	2.069	2.505
	MC	6.604	1.432	0.484	0.484	0.291	0.353	1.900	2.303
30	Δ(%)	0.0	0.3	0.6	0.0	0.7	0.8	0.5	0.2
	BE	6.604	1.437	0.487	0.484	0.293	0.356	1.910	2.308
	MC	6.442	1.178	0.849	0.846	0.299	0.364	1.572	1.906
60	Δ(%)	0.1	0.2	0.6	0.1	0.3	0.5	0.4	0.1
	BE	6.438	1.181	0.854	0.845	0.300	0.362	1.579	1.907
	MC	6.336	1.043	0.987	0.980	—	—	1.400	1.700
90	Δ(%)	0.1	0.5	0.6	0.1	—	—	0.6	0.0
	BE	6.335	1.048	0.993	0.981	—	—	1.408	1.700

(a) $F = 1$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^4 ms^{-1}$)	W_x^* ($10^4 ms^{-1}$)	W_y ($10^4 ms^{-1}$)	W_y^* ($10^4 ms^{-1}$)	W_z ($10^4 ms^{-1}$)	W_z^* ($10^4 ms^{-1}$)
	MC	6.219	2.718	—	—	—	—	2.067	2.781
0	Δ(%)	0.1	0.1	—	—	—	—	0.4	0.1
	BE	6.221	2.719	—	—	—	—	2.076	2.780
	MC	6.164	2.502	0.484	0.484	0.293	0.394	1.905	2.553
30	Δ(%)	0.0	0.1	1.0	0.2	0.7	1.2	0.5	0.2
	BE	6.164	2.506	0.489	0.485	0.295	0.399	1.915	2.559
	MC	6.026	2.062	0.852	0.845	0.303	0.405	1.574	2.113
60	Δ(%)	0.1	0.1	0.6	0.1	0.0	0.7	0.5	0.1
	BE	6.022	2.063	0.857	0.844	0.303	0.402	1.582	2.111
	MC	5.932	1.831	0.991	0.976	—	—	1.402	1.885
90	Δ(%)	0.1	0.2	0.6	0.2	—	—	0.6	0.1
	BE	5.930	1.834	0.997	0.978	—	—	1.410	1.883

Table A.2: A comparison of the diagonal diffusion tensor elements for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 100 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ ($\circ$)		n_0D_{xx} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{yy} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{zz} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$
	MC	2.261	—	2.258	—	3.088	—
0	Δ(%)	0.0	—	0.1	—	0.2	—
	BE	2.261	—	2.261	—	3.093	—
	MC	2.249	—	2.509	—	2.835	—
30	Δ(%)	0.1	—	0.6	—	0.1	—
	BE	2.252	—	2.524	—	2.836	—
	MC	2.229	—	3.030	—	2.324	—
60	Δ(%)	0.1	—	0.1	—	0.0	—
	BE	2.228	—	3.034	—	2.327	—
	MC	2.208	—	3.282	—	2.070	—
90	Δ(%)	0.2	—	0.1	—	0.2	—
	BE	2.213	—	3.278	—	2.075	—

(a) $F = 0.5$

ψ ($\circ$)		n_0D_{xx} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{yy} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{zz} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$
	MC	2.026	2.194	2.027	2.195	2.819	3.221
0	Δ(%)	0.6	0.1	0.5	0.1	1.0	0.1
	BE	2.038	2.192	2.038	2.192	2.847	3.226
	MC	2.022	2.188	2.281	2.476	2.586	2.931
30	Δ(%)	0.7	0.1	0.2	0.2	0.7	0.4
	BE	2.036	2.189	2.286	2.472	2.604	2.944
	MC	2.020	2.178	2.750	2.991	2.114	2.398
60	Δ(%)	0.3	0.1	0.2	0.4	0.7	0.2
	BE	2.026	2.176	2.756	2.980	2.129	2.403
	MC	2.007	2.161	2.954	3.191	1.898	2.164
90	Δ(%)	0.5	0.2	0.7	0.2	0.1	0.8
	BE	2.017	2.165	2.974	3.198	1.897	2.146

(a) $F = 1$

ψ ($\circ$)		n_0D_{xx} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{yy} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	n_0D_{zz} $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\mathrm{m}^{-1}\mathrm{s}^{-1}$
	MC	1.889	2.147	1.881	2.147	2.664	3.236
0	Δ(%)	0.1	0.1	0.6	0.1	0.3	0.5
	BE	1.892	2.149	1.892	2.149	2.671	3.221
	MC	1.888	2.156	2.115	2.432	2.403	2.903
30	Δ(%)	0.0	-0.1	0.4	0.1	-0.2	0.1
	BE	1.894	2.149	2.128	2.438	2.441	2.930
	MC	1.885	2.143	2.570	2.965	1.987	2.391
60	Δ(%)	0.4	0.1	0.1	0.8	0.3	0.3
	BE	1.893	2.140	2.571	2.942	1.993	2.383
	MC	1.887	2.130	2.761	3.158	1.770	2.148
90	Δ(%)	0.6	0.1	0.4	0.4	0.4	0.8
	BE	1.888	2.131	2.773	3.145	1.777	2.130

Table A.3: A comparison of the mean energy and drift velocity components for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 200 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ (∘)		ε (eV)	R_i m^3s^{-1}	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	7.349	—	—	—	—	—	2.054	—
0	Δ(%)	0.1	—	—	—	—	—	0.1	—
	BE	7.359	—	—	—	—	—	2.055	—
	MC	7.167	—	0.491	—	0.590	—	1.734	—
30	Δ(%)	0.1	—	0.1	—	0.1	—	0.1	—
	BE	7.173	—	0.492	—	0.592	—	1.735	—
	MC	6.687	—	0.864	—	0.614	—	1.061	—
60	Δ(%)	0.1	—	0.1	—	0.1	—	0.0	—
	BE	6.689	—	0.865	—	0.615	—	1.061	—
	MC	6.332	—	1.008	—	—	—	7.023	—
90	Δ(%)	0.1	—	0.0	—	—	—	0.1	—
	BE	6.333	—	1.008	—	—	—	7.022	—

(a) $F = 0.5$

ψ (∘)		ε (eV)	R_i m^3s^{-1}	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	6.667	1.554	—	—	—	—	2.063	2.502
0	Δ(%)	0.1	0.4	—	—	—	—	0.3	0.1
	BE	6.672	1.560	—	—	—	—	2.069	2.505
	MC	6.521	1.306	0.491	0.490	0.594	0.723	1.738	2.106
30	Δ(%)	0.1	0.2	0.6	0.2	0.5	0.0	0.3	0.1
	BE	6.520	1.309	0.494	0.491	0.597	0.723	1.744	2.107
	MC	6.126	0.775	0.863	0.861	0.617	0.741	1.058	1.275
60	Δ(%)	0.1	0.4	0.5	0.1	0.3	0.4	0.4	0.2
	BE	6.120	0.778	0.867	0.862	0.619	0.774	1.062	1.278
	MC	5.819	0.494	1.007	1.004	—	—	0.699	0.844
90	Δ(%)	0.1	0.4	0.3	0.0	—	—	0.3	0.0
	BE	5.821	0.496	1.010	1.004	—	—	0.701	0.844

(a) $F = 1$

ψ (∘)		ε (eV)	R_i m^3s^{-1}	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	6.218	2.717	—	—	—	—	2.070	2.781
0	Δ(%)	0.1	0.1	—	—	—	—	0.3	0.1
	BE	6.221	2.719	—	—	—	—	2.076	2.780
	MC	6.091	2.286	0.493	0.490	0.599	0.807	1.744	2.340
30	Δ(%)	0.1	0.1	0.4	0.2	0.2	0.2	0.2	0.2
	BE	6.089	2.285	0.495	0.491	0.600	0.805	1.748	2.336
	MC	5.738	1.367	0.866	0.861	0.619	0.825	1.060	1.416
60	Δ(%)	0.0	0.0	0.3	0.0	0.3	0.1	0.3	0.1
	BE	5.738	1.367	0.869	0.861	0.621	0.824	1.063	1.415
	MC	5.474	0.876	1.008	1.003	—	—	0.699	0.936
90	Δ(%)	0.1	0.1	0.3	0.1	—	—	0.3	0.1
	BE	5.473	0.875	1.011	1.002	—	—	0.701	0.935

Table A.4: A comparison of the diagonal diffusion tensor elements for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 200 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ ($\circ$)		n_0D_{xx} 10^{25}m^{-1}s^{-1}	$n_0D^*_{xx}$ 10^{25}m^{-1}s^{-1}	n_0D_{yy} 10^{25}m^{-1}s^{-1}	$n_0D^*_{yy}$ 10^{25}m^{-1}s^{-1}	n_0D_{zz} 10^{25}m^{-1}s^{-1}	$n_0D^*_{zz}$ 10^{25}m^{-1}s^{-1}
	MC	1.119	—	1.117	—	3.077	—
0	Δ(%)	0.0	—	0.2	—	0.5	—
	BE	1.119	—	1.119	—	3.093	—
	MC	1.092	—	1.625	—	2.579	—
30	Δ(%)	0.3	—	0.1	—	0.2	—
	BE	1.095	—	1.623	—	2.573	—
	MC	1.031	—	2.596	—	1.518	—
60	Δ(%)	0.1	—	0.5	—	0.3	—
	BE	1.032	—	2.609	—	1.522	—
	MC	0.987	—	3.053	—	0.994	—
90	Δ(%)	0.3	—	0.2	—	0.1	—
	BE	0.984	—	3.058	—	0.995	—

(a) $F = 0.5$

ψ ($\circ$)		n_0D_{xx} 10^{25}m^{-1}s^{-1}	$n_0D^*_{xx}$ 10^{25}m^{-1}s^{-1}	n_0D_{yy} 10^{25}m^{-1}s^{-1}	$n_0D^*_{yy}$ 10^{25}m^{-1}s^{-1}	n_0D_{zz} 10^{25}m^{-1}s^{-1}	$n_0D^*_{zz}$ 10^{25}m^{-1}s^{-1}
	MC	1.007	1.081	1.007	1.077	2.831	3.223
0	Δ(%)	0.4	0.1	0.4	0.5	0.6	0.1
	BE	1.011	1.082	1.011	1.082	2.847	3.226
	MC	0.989	1.065	1.466	1.602	2.359	2.682
30	Δ(%)	0.4	0.6	1.1	1.2	0.3	0.2
	BE	0.993	1.071	1.483	1.621	2.366	2.676
	MC	0.943	1.017	2.383	2.592	1.384	1.572
60	Δ(%)	0.1	0.4	0.4	0.8	0.8	0.4
	BE	0.944	1.021	2.393	2.613	1.396	1.578
	MC	0.901	0.972	2.791	3.019	0.910	1.040
90	Δ(%)	0.3	0.0	0.5	0.3	0.2	0.0
	BE	0.904	0.972	2.804	3.009	0.912	1.040

(a) $F = 1$

ψ ($\circ$)		n_0D_{xx} 10^{25}m^{-1}s^{-1}	$n_0D^*_{xx}$ 10^{25}m^{-1}s^{-1}	n_0D_{yy} 10^{25}m^{-1}s^{-1}	$n_0D^*_{yy}$ 10^{25}m^{-1}s^{-1}	n_0D_{zz} 10^{25}m^{-1}s^{-1}	$n_0D^*_{zz}$ 10^{25}m^{-1}s^{-1}
	MC	0.940	1.070	0.936	1.061	2.660	3.225
0	Δ(%)	0.1	0.9	0.5	0.1	0.4	0.1
	BE	0.941	1.060	0.941	1.060	2.671	3.221
	MC	0.922	1.046	1.382	1.603	2.213	2.663
30	Δ(%)	0.4	0.6	0.4	0.2	0.3	0.1
	BE	0.926	1.052	1.388	1.607	2.220	2.664
	MC	0.883	1.000	2.247	2.622	1.309	1.584
60	Δ(%)	0.1	0.8	0.1	1.0	0.1	1.0
	BE	0.884	1.008	2.246	2.597	1.310	1.568
	MC	0.853	0.973	2.621	2.969	0.859	1.050
90	Δ(%)	0.3	1.0	0.3	0.1	0.2	0.8
	BE	0.850	0.963	2.630	2.971	0.857	1.042

Table A.5: A comparison of the mean energy and drift velocity components for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 500 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^5 ms^{-1}$)	W_x^* ($10^5 ms^{-1}$)	W_y ($10^5 ms^{-1}$)	W_y^* ($10^5 ms^{-1}$)	W_z ($10^5 ms^{-1}$)	W_z^* ($10^5 ms^{-1}$)
	MC	7.348	—	—	—	—	—	2.055	—
0	Δ(%)	0.1	—	—	—	—	—	0.0	—
	BE	7.359	—	—	—	—	—	2.055	—
	MC	6.304	—	0.482	—	0.832	—	0.654	—
30	Δ(%)	0.1	—	0.0	—	0.1	—	0.1	—
	BE	6.312	—	0.482	—	0.833	—	0.655	—
	MC	6.304	—	0.482	—	0.865	—	0.654	—
60	Δ(%)	0.1	—	0.0	—	0.0	—	0.1	—
	BE	6.312	—	0.482	—	0.866	—	0.655	—
	MC	5.092	—	0.559	—	—	—	0.152	—
90	Δ(%)	0.1	—	0.0	—	—	—	0.0	—
	BE	5.096	—	0.559	—	—	—	0.152	—

(b) $F = 0.5$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^4 ms^{-1}$)	W_x^* ($10^4 ms^{-1}$)	W_y ($10^4 ms^{-1}$)	W_y^* ($10^4 ms^{-1}$)	W_z ($10^4 ms^{-1}$)	W_z^* ($10^4 ms^{-1}$)
	MC	6.668	1.554	—	—	—	—	2.066	2.504
0	Δ(%)	0.1	0.4	—	—	—	—	0.1	—
	BE	6.672	1.560	—	—	—	—	2.069	2.505
	MC	6.457	1.202	0.276	0.276	0.837	1.011	1.608	1.943
30	Δ(%)	0.1	0.3	0.4	0.0	0.1	0.2	0.2	0.1
	BE	6.458	1.206	0.277	0.276	0.838	1.013	1.611	1.946
	MC	5.817	0.457	0.481	0.482	0.868	1.035	0.656	0.784
60	Δ(%)	0.1	0.6	0.2	0.0	0.1	0.3	0.0	0.1
	BE	5.809	0.460	0.482	0.482	0.869	1.038	0.656	0.785
	MC	4.846	0.062	0.558	0.559	—	—	0.151	0.175
90	Δ(%)	0.1	1.6	0.2	0.0	—	—	0.6	0.
	BE	4.853	0.063	0.559	0.559	—	—	0.152	0.175

(c) $F = 1$

ψ ($\circ$)		ε (eV)	R_i m^3s^{-1}	W_x ($10^4 ms^{-1}$)	W_x^* ($10^4 ms^{-1}$)	W_y ($10^4 ms^{-1}$)	W_y^* ($10^4 ms^{-1}$)	W_z ($10^4 ms^{-1}$)	W_z^* ($10^4 ms^{-1}$)
	MC	6.221	2.716	—	—	—	—	2.073	2.775
0	Δ(%)	0.0	0.1	—	—	—	—	0.1	0.2
	BE	6.221	2.719	—	—	—	—	2.076	2.780
	MC	6.032	2.106	0.277	0.276	0.840	1.123	1.614	2.156
30	Δ(%)	0.1	0.1	0.0	0.0	0.1	0.1	0.1	0.1
	BE	6.033	2.109	0.277	0.276	0.841	1.124	1.616	2.159
	MC	5.462	0.814	0.482	0.481	0.869	1.150	0.657	0.870
60	Δ(%)	0.1	0.1	0.0	0.0	0.1	0.0	0.0	0.1
	BE	5.463	0.813	0.482	0.481	0.870	1.150	0.657	0.869
	MC	4.663	0.116	0.558	0.559	—	—	0.152	0.193
90	Δ(%)	0.1	0.0	0.2	0.2	—	—	0.0	0.0
	BE	4.664	0.115	0.559	0.558	—	—	0.152	0.193

Table A.6: A comparison of the diagonal diffusion tensor elements for the ionization model of Lucas and Saelee as a function of ψ at E/n_0 of 30 Td and B/n_0 of 500 Hx using the Monte Carlo code (MC) and multi-term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $F = 0$

ψ ($\circ$)		n_0D_{xx} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{yy} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{zz} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$
	MC	2.469	—	2.461	—	3.067	—
0	Δ(%)	0.1	—	0.3	—	0.8	—
	BE	2.468	—	2.468	—	3.093	—
	MC	0.238	—	0.942	—	2.345	—
30	Δ(%)	0.0	—	0.7	—	0.7	—
	BE	0.238	—	0.949	—	2.361	—
	MC	0.238	—	0.942	—	0.884	—
60	Δ(%)	0.0	—	0.7	—	0.8	—
	BE	0.238	—	0.949	—	0.891	—
	MC	0.171	—	2.491	—	0.174	—
90	Δ(%)	0.0	—	0.6	—	0.0	—
	BE	0.171	—	2.507	—	0.174	—

(a) $F = 0.5$

ψ ($\circ$)		n_0D_{xx} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{yy} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{zz} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$
	MC	0.224	0.239	0.224	0.240	2.837	3.231
0	Δ(%)	0.4	0.0	0.4	0.4	0.3	0.1
	BE	0.223	0.239	0.223	0.239	2.847	3.226
	MC	0.216	0.232	0.866	0.964	2.163	2.452
30	Δ(%)	0.0	4.9	0.9	2.2	0.6	0.4
	BE	0.216	0.244	0.874	0.986	2.177	2.463
	MC	0.194	0.209	2.087	2.322	0.821	0.928
60	Δ(%)	0.0	7.9	0.2	1.0	0.5	0.4
	BE	0.194	0.227	2.091	2.346	0.825	0.932
	MC	0.162	0.172	2.389	2.522	0.165	0.195
90	Δ(%)	0.6	0.0	0.0	0.1	0.6	0.5
	BE	0.163	0.172	2.389	2.521	0.166	0.196

(a) $F = 1$

ψ ($\circ$)		n_0D_{xx} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{xx}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{yy} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{yy}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$	n_0D_{zz} $10^{25}\text{m}^{-1}\text{s}^{-1}$	$n_0D^*_{zz}$ $10^{25}\text{m}^{-1}\text{s}^{-1}$
	MC	2.084	2.361	2.074	2.335	2.649	3.213
0	Δ(%)	0.1	0.7	0.4	0.4	0.8	0.2
	BE	2.082	2.344	2.082	2.344	2.671	3.221
	MC	0.202	0.228	0.820	0.972	2.040	2.463
30	Δ(%)	0.0	-0.1	0.4	0.1	-0.2	0.1
	BE	0.202	0.241	0.821	0.984	2.046	2.456
	MC	0.182	0.205	1.958	2.325	0.774	0.934
60	Δ(%)	0.5	8.0	0.8	1.1	0.5	1.4
	BE	0.183	0.223	1.974	2.351	0.778	0.921
	MC	0.156	0.173	2.250	2.494	0.160	2.069
90	Δ(%)	0.0	0.0	1.8	0.4	0.6	0.8
	BE	0.156	0.173	2.292	2.505	0.159	2.053

Appendix B

Benchmark Calculations: The modified attachment model of Ness and Robson

In this appendix the results of benchmark calculations for the modified attachment model of Ness and Robson are presented. The definition of this model is given by Eq. (6.4). For illustrative purposes, we employ the so-called attachment cooling model with the attachment amplitude of 0.5. We consider the reduced electric field of 30 Td, the reduced magnetic field range: 100-500 Hx and the angles of 0°, 30°, 60° and 90°. Both the bulk and flux values of transport properties are presented. As for the ionization model of Lucas and Saelee, we have followed a large number of electrons (typically $1 \times 10^5 - 1 \times 10^6$) between collisions through a neutral gas. Whenever electron is lost due to attachment another electron is randomly selected in its place from the ensemble of remaining electrons. This procedure was tested and found to be correct (Petrović *et. al.* (2002)). The initial conditions for electron are chosen as for the ionization model of Lucas and Saelee and Reid ramp model: at time $t = 0$ electrons are released from the origin according to Maxwellian velocity distribution with the mean starting energy of 1 eV. All calculations were performed at zero gas temperature. Typical CPU time for our simulations was in the range from 24 hours to several days.

From tables shown below, it is evident that, over the range of B/n_0 and ψ there is an excellent agreement among these two independent techniques. Agreement to at least 1.5% exist between results obtained by a multi term theory and Monte Carlo simulation for all transport coefficients. The discrepancies in the results are attributable to the statistical uncertainties associated with the Monte Carlo method. These 'benchmarks' support the numerical integrity of the present theory and code.

Table B.1: A comparison of the mean energy and drift velocity components for the modified attachment model of Ness and Robson as a function of ψ at E/n_0 of 10 Td and B/n_0 of (a) 100 Hx; (b) 200 Hx and (c) 500 Hx using the Monte Carlo code (MC) and multi term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $B/n_0 = 100$ Hx

ψ ($\circ$)		ϵ (eV)	R_i (10^{-17}m^{3}s^{-1})	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	5.445	1.606	—	—	—	—	7.299	7.015
0	Δ(%)	-0.1	0.4	—	—	—	—	0.4	0.1
	BE	5.444	1.613	—	—	—	—	7.326	7.022
	MC	5.359	1.578	-1.743	-1.754	1.106	1.060	6.660	6.392
30	Δ(%)	0.1	0.6	0.4	-0.2	0.5	0.1	0.5	-0.1
	BE	5.355	1.587	-1.750	-1.749	1.112	1.061	6.694	6.387
	MC	5.131	1.514	-3.026	-3.047	1.115	1.054	5.388	5.091
60	Δ(%)	-0.1	0.5	0.5	-0.3	0.3	-0.1	0.6	-0.2
	BE	5.130	1.521	-3.041	-3.039	1.119	1.053	5.419	5.100
	MC	4.982	1.471	-3.498	-3.512	—	—	4.753	4.448
90	Δ(%)	-0.1	0.3	0.6	0.1	—	—	0.4	-0.1
	BE	4.981	1.476	-3.518	-3.517	—	—	4.774	4.447

(b) $B/n_0 = 200$ Hx

ψ ($\circ$)		ϵ (eV)	R_i (10^{-17}m^{3}s^{-1})	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	5.444	1.612	—	—	—	—	7.305	7.028
0	Δ(%)	0.0	0.1	—	—	—	—	0.3	-0.1
	BE	5.444	1.613	—	—	—	—	7.326	7.022
	MC	5.262	1.555	-1.705	-1.706	2.164	2.059	6.062	5.775
30	Δ(%)	-0.1	0.3	0.2	0.1	0.5	0.1	0.4	0.1
	BE	5.259	1.559	-1.708	-1.708	2.174	2.062	6.090	5.778
	MC	4.592	1.358	-2.960	-2.970	2.188	1.988	3.576	3.240
60	Δ(%)	-0.1	0.2	0.3	-0.1	0.3	-0.4	0.3	-0.1
	BE	4.591	1.361	-2.969	-2.969	2.194	1.980	3.587	3.239
	MC	3.792	1.118	-3.424	-3.431	—	—	2.313	1.971
90	Δ(%)	-0.2	0.3	0.3	0.1	—	—	0.3	-0.1
	BE	3.784	1.122	-3.435	-3.434	—	—	2.319	1.968

(c) $B/n_0 = 500$ Hx

ψ ($\circ$)		ϵ (eV)	R_i (10^{-17}m^{3}s^{-1})	W_x (10^4ms^{-1})	W_x^* (10^4ms^{-1})	W_y (10^4ms^{-1})	W_y^* (10^4ms^{-1})	W_z (10^4ms^{-1})	W_z^* (10^4ms^{-1})
	MC	5.440	1.614	—	—	—	—	7.307	7.007
0	Δ(%)	0.1	-0.1	—	—	—	—	0.3	0.2
	BE	5.444	1.613	—	—	—	—	7.326	7.022
	MC	5.180	1.533	-0.931	- 0.931	2.958	2.795	5.627	5.321
30	Δ(%)	0.1	0.2	0.0	0.0	0.2	0.1	0.2	0.1
	BE	5.184	1.536	-0.931	-0.931	2.964	2.797	5.641	5.323
	MC	3.700	1.096	-1.611	-1.614	2.983	2.525	2.224	1.882
60	Δ(%)	0.0	0.1	0.2	0.0	0.2	-0.1	0.2	0.0
	BE	3.700	1.097	-1.614	-1.614	2.990	2.524	2.229	1.882
	MC	1.018	0.300	-1.861	-1.864	—	—	0.503	0.463
90	Δ(%)	-0.1	0.3	0.2	0.0	—	—	0.0	0.0
	BE	1.017	0.301	-1.864	-1.864	—	—	0.503	0.463

Table B.2: A comparison of the diagonal diffusion tensor elements for the modified attachment model of Ness and Robson as a function of ψ at E/n_0 of 10 Td and B/n_0 of 100 Hx using the Monte Carlo code (MC) and multi term code for solving Boltzmann equation (BE). Δ represents the percentage deviation between these two sets of the results.

(a) $B/n_0 = 100$ Hx

ψ ($\circ$)		n_0D_{xx} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{xx}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{yy} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{yy}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{zz} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{zz}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)
	MC	1.712	1.686	1.716	1.682	2.594	2.637
0	Δ(%)	0.9	0.2	0.6	0.4	0.3	0.2
	BE	1.727	1.689	1.727	1.689	2.603	2.643
	MC	1.692	1.659	1.917	1.878	2.331	2.391
30	Δ(%)	0.5	-0.1	0.7	0.4	0.5	-0.3
	BE	1.701	1.658	1.931	1.885	2.344	2.383
	MC	1.628	1.584	2.272	2.224	1.819	1.862
60	Δ(%)	0.4	-0.1	1.1	0.2	0.5	0.1
	BE	1.635	1.583	2.298	2.229	1.829	1.864
	MC	1.584	1.536	2.417	2.357	1.565	1.600
90	Δ(%)	0.4	-0.1	1.3	0.1	0.4	0.1
	BE	1.590	1.534	2.450	2.360	1.572	1.602

(b) $B/n_0 = 200$ Hx

ψ ($\circ$)		n_0D_{xx} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{xx}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{yy} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{yy}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{zz} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{zz}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)
	MC	0.834	0.817	0.834	0.818	2.607	2.653
0	Δ(%)	0.5	0.4	0.5	0.2	-0.1	-0.4
	BE	0.838	0.820	0.838	0.820	2.603	2.643
	MC	0.806	0.785	1.241	1.228	2.081	2.129
30	Δ(%)	0.6	-0.4	0.4	-0.8	0.8	0.3
	BE	0.811	0.782	1.246	1.218	2.098	2.136
	MC	0.706	0.674	1.863	1.801	1.085	1.097
60	Δ(%)	0.4	-1.2	0.2	-1.1	0.5	0.1
	BE	0.709	0.666	1.867	1.780	1.091	1.098
	MC	0.586	0.545	1.853	1.727	0.588	0.535
90	Δ(%)	-0.2	-0.5	0.7	1.3	-0.3	-0.7
	BE	0.585	0.542	1.866	1.750	0.586	0.531

(c) $B/n_0 = 500$ Hx

ψ ($\circ$)		n_0D_{xx} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{xx}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{yy} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{yy}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	n_0D_{zz} ($10^{25}\text{m}^{-1}\text{s}^{-1}$)	$n_0D^*_{zz}$ ($10^{25}\text{m}^{-1}\text{s}^{-1}$)
	MC	0.182	0.179	0.181	0.176	2.600	2.645
0	Δ(%)	0.0	-0.6	0.5	0.1	0.1	-0.1
	BE	0.182	0.178	0.182	0.178	2.603	2.643
	MC	0.172	0.168	0.748	0.751	1.900	1.934
30	Δ(%)	0.6	-2.4	0.8	-1.1	0.7	0.8
	BE	0.173	0.164	0.754	0.743	1.914	1.950
	MC	0.124	0.114	1.397	1.256	0.545	0.486
60	Δ(%)	0.0	N.A.	-0.1	-0.4	0.4	0.0
	BE	0.124	N.A.	1.395	1.251	0.547	0.486
	MC	0.342	0.329	5.010	4.792	0.337	0.275
90	Δ(%)	-0.3	-0.6	0.2	0.7	1.2	1.1
	BE	0.341	0.327	5.019	4.824	0.341	0.278

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