Title

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Author

Olson, R.E.

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R. E. Olson, K. H. Berkner, W. G. Graham,
R. V. Pyle, A. S. Schlachter, and J. W. Stearns

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Design Data for Calculating Neutral Beam Penetration Into $Z_{eff} > 1$ Plasmas*

R.E. Olson, SRI International, Menlo Park, California
K.H. Berkner, W.G. Graham, R.V. Pyle, A.S.Schlachter, and J.W. Stearns,
Lawrence Berkeley Laboratory, Berkeley, Calif.

Impurities such as C, N, O, Fe, and Mo in a confined plasma reduce the penetration of the energetic neutral deuterium or hydrogen beam injected for heating or fueling the plasma, thus affecting the energy- and fuel-deposition profiles. New calculations, confirmed by recent experimental results, show that previous estimates of the reduction of neutral beam penetration due to impurities in the plasma were overly pessimistic. Until recently,[1] the cross sections used to calculate beam attenuation had been assumed to be q^2 times the cross section for $H^+ + H$ obtained from the Born approximation, where q is the charge state of the ion. This led to very large cross sections for large values of q, and thus to very stringent requirements on the acceptable level of impurity ions in the plasma.

Electron-loss collisions that lead to beam attenuation are of two kinds:

$H + A^{+q} \rightarrow H^+ + A^{+q-1}$ electron capture

$H + A^{+q} \rightarrow H^+ + A^{+q} + e^-$ impact ionization

where A is any atom and q is its charge state. The sum of the cross sections for these two processes is the electron-loss cross section.

Olson and Salop in 1977 calculated charge-transfer and impact-ionization cross sections for some fully and partially stripped ions colliding with atomic hydrogen.[2] They concluded that the sum, i.e. the electron-loss cross section, scaled roughly as $q^{1.3}$ at an energy of 50 keV/amu. At about the same time the Oak Ridge group reported electron-capture measurements for partially stripped light ions colliding with atomic hydrogen at low energies.[3] Their results are in excellent agreement with the theoretical calculations of electron capture.

To obtain an overall picture of electron-loss collisions for a large range of energies and charge states the following were needed:

1. experimental confirmation of the calculated impact ionization cross section;
2. extension of electron-capture measurements to higher energies and higher values of q, and
3. extension of the theoretical calculations to higher values of q and to partially-stripped heavy ions.

We have calculated cross sections for single-electron capture and for impact-ionization by A^{+q} (q= 5,10,25,50) ions incident on atomic hydrogen, where A is any atom, in the energy range 50-1200 keV/amu, using a classical trajectory Monte Carlo method.[2] We have also measured cross sections for the same processes for Fe^{+q} ions incident on molecular hydrogen for q = 11-22 at 1100 keV/amu, for q= 3-16 at 300 kev/amu, and for q= 3-13 at 100 keV/amu.[4] The experimental electron-loss cross sections for molecular hydrogen, divided by two, are in excellent agreement with the calculated atomic hydrogen cross sections.

Our calculations for the electron-loss cross section for an ion A in charge state q, can be put in the form

$$\sigma^{\text{loss}}_{A^{+q}+H}(q,E) = q^{\alpha(q,E)}\,\sigma^{\text{loss}}_{H^{+}+H}(E)$$

where $\sigma^{\text{loss}}_{H^{+}+H}$ is the electron-loss cross section for H^{+} + H, and where α is the scaling parameter. The results for α are dependent on q and on the energy per amu of the ion. For q in the range 5-50, α ranges from 1.1-1.3 at an energy of 50 keV/amu, and approaches the Born-approximation limit of $\alpha = 2$ at energies greater than 1000 keV/amu. Values of α for q=5-50 and for energies between 50 and 1200 keV/amu will be presented. Our experimental results for Fe ions, along with recent measurements of electron-capture cross sections for various heavy ions colliding with atomic hydrogen at low energies by the Oak Ridge group, are in excellent agreement with the calculated cross sections.

We can thus predict the electron-loss cross section for an ion in charge state q=5-50 colliding with atomic hydrogen in the energy range 50-1200 keV/amu; howver , the scaling for high charge states remains to be confirmed experimentally. The result is much less pessimistic than that predicted by q^2 scaling. For example, if one uses a q^2 dependence for q=26 at an energy of 120 keV per nucleon, we would predict that the electron-loss cross section will be overestimated by approximately a factor of seven.

1. See, for example, summary by C.F. Barnett, Atomic Physics 5, R. Marrus, M. Prior, and H. Shugart, Eds. (New York: Plenum Press (375) 1977)
2. R.E. Olson and A. Salop, Phys. Rev A 16, 531 (1977)
3. R.A. Phaneuf, F.W. Meyer, R.H. McKnight, R.E. Olson, and A. Salop, J. Phys. B 10, L 425 (1977)
4. K.H. Berkner, W.G. Graham, R.V. Pyle, A.S. Schlachter, J.W. Stearns and R.E. Olson, J. Phys. B (in press), Lawrence Berkeley Laboratory Report LBL-6344 (unpublished)

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