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Direct Electron-Beam Injection Experiments for Validation of Air-Chemistry Models*

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Abstract (35 words or less):
Gas breakdown using direct electron beam injection provides an economical way of testing gas-chemistry models. Data obtained with a ~100 kV, ~200 A/cm^2, 50 ns electron beam is presented and compared with simulation and modeling.

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Direct Electron-Beam Injection Experiments for Validation of Air-Chemistry Models*

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Abstract: Gas breakdown using direct electron beam injection provides an economical way of testing gas-chemistry models. New data has been obtained using a ~100 kV, ~200 A/cm^2, 50 ns electron beam pulse. This work focuses on nitrogen and air with pressures between 0.02 and 20 Torr and extends previous work [D.D. Hinshelwood et al, 2008 ICOPS meeting]. As with the previous data, the measured line-integrated electron density increases as the pressures decreases for pressures between 0.1 and 1 Torr. The line-integrated density increases for pressures above 1 Torr. The experimental results are compared with results from a weakly-ionized gas model and a new strongly-ionized gas model [J.R. Angus, et. al, Phys. Plasmas **23**, 053510 (2016)].

An electromagnetic pulse (EMP) can be created by a man-made event such as a nuclear explosion or natural event such as an intense solar storm. These events can produce energetic beam-like electrons through the interaction of the radiation with the atmosphere. This transient current interacts with the atmosphere and the earth's magnetic field and acts like an antenna to radiate electromagnetic energy toward the earth with a frequency given by $\omega \sim 1/\tau$ where τ is the duration of the radiation event.

Systems-generated EMP effects (SGEMP) is another type of EMP which is caused by the lower-energy x-rays traveling through electronic equipment producing local photo-electron currents. This EMP pulse can couple to circuit boards, cables, and cases to produce spurious currents, potentially interrupting the normal operation of the device. The primary photo-electron beam interacts with the gas inside the equipment to form a plasma which can drift in a direction opposite to the primary beam and partially neutralize the beam current.

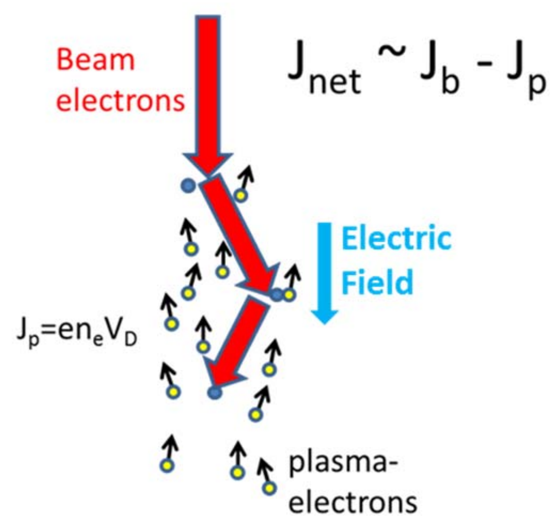

Figure 1. The interaction of an intense beam with gas generates a secondary plasma return current.

Regardless of the source of an EMP event it can have detrimental effects on electronics and other electrical equipment. The magnitude of the electric field is the key quantity for predicting the severity of the EMP event. Fortunately, not all of the energy in the primary electron beam is available to drive an EMP event. A portion of the primary beam energy is dissipated by collisions in the gas which gives rise to the creation and flow of secondary plasma electrons (see Fig. 1). These secondary electrons respond to the electric field and flow in a direction opposite to that of the primary electron beam. This reduces the net current density which is directly proportional to the size of the radiated electric field.

The generation of electrical conductivity through the interaction of a high-power electron beam with the air is a complicated process. The time-response of the secondary plasma to the electric field generated by an intense beam plays a major role in both the duration and magnitude of the EMP event. Therefore, a thorough understanding of how the secondary plasma forms and reacts to a beam-induced electric field is important for the understanding of the EMP.

Directly injecting an electron beam into a gas to characterize the plasma response has a number of advantages over using laboratory radiation sources to produce the primary electron beam. First, present laboratory radiation sources tend to be very large and very expensive to operate compared to direct-injection sources. Furthermore, the shot rate at these radiation facilities is typically 2-4 shots a week while the shot rate for the direct-injection experiments can be up to ten shots a day. At this time, laboratory radiation sources are also only capable of producing a fraction of the flux required to simulate a real EMP event and the beam energies are limited by the available radiation spectrum. In direct-injection experiments, the electron beam current as well as the beam energy can be controlled to provide a wide range of relevant beam conditions. Furthermore, the primary electron beam can be well diagnosed so that the initial conditions can be well characterized. This allows for the isolation of the gas-chemistry physics from the physics of beam-generation by the radiation source, providing an excellent opportunity for the validation of the assumptions made in gas-chemistry models.

In this paper, the time response of the initially neutral gas in response to the direct injection of an intense electron beam into air and nitrogen (N_2) is measured using the experimental setup shown in Fig. 2. In this experiment, a modified Febetron pulser is used to inject ~100 kV, 50 ns, 4 kA beam into a 10.3-cm-long, 18-cm-diameter gas-filled transport region. In the experiments reported here, the pressure in the gas-cell is varied between 0.02 Torr and 20 Torr. A companion paper explores the interaction of a ~1 MV, 800-kA, 50-ns beam with nitrogen gas over a similar pressure range.[1] The gas-filled cylinder is separated from the vacuum electron-beam diode by two ½-mil-thick aluminized Kapton foils. One foil provides a flat equipotential surface which functions as the anode in an electron-beam diode. The other foil provides a barrier between the gas cell and the vacuum diode.

The beam energy is obtained from a voltage measurement in the vacuum pulsed-power section using standard techniques. The beam current is measured using b-dot loops on the vacuum side of the experiment. The beam energy and angular distribution as well as the current as it enters the gas cell are obtained from the voltage and current measurements by using the Integrated Tiger Series (ITS) to calculate the scattering and beam attenuation in the two foils. The spatial distribution of the injected beam is determined using contact radiography. This measurement is obtained by sliding the graphite collector all the way up the gas cell so that it is in contact with the pressure foil. The x-ray image produced by the electron beam as it strikes the graphite collector provides time-integrated information about the spatial distribution of the primary electron beam. Contact radiography at several different axial locations shows that the beam evolves from an approximately uniform radial distribution to a Gaussian distribution as it propagates across the gas cell.

The time-varying breakdown of the gas and the subsequent return-current flow are measured with a variety of diagnostics. A laser interferometer is used to measure the time-varying line-integrated electron density in the gas-cell. The scene beam of the interferometer can be moved in both the axial and radial directions to obtain a density measurement at a wide variety of locations in the gas cell. The net current that flows in the system is measured by b-dot loops positioned at the end of the gas cell as indicated in Fig. 2. The difference between the beam current and the net current provides an estimate of the plasma current. Framing photographs show that the light emission from the plasma is similar for similar gas pressures and beam conditions. Finally, a measurement of some important spectroscopic lines can provide some insights into the complicated chemistry which occurs as collisions in the gas create a wide variety of excited gas species.

The simplest gas-chemistry model is that of a weakly-ionized gas. This model assumes that the density of the reaction products remains small enough so that electrons always interact with unexcited gas. For N_2 gas the reaction products includes various rotational and vibration modes, numerous excited electronic states, as well as ionized states. A commonly used cross section data set for a number of gases is available from Ref. [2]. For weakly-ionized N_2 the dataset includes a single elastic cross section, an aggregate rotational cross section, cross sections for 10 vibrational modes, 12 electronic excitation cross sections, and an ionization cross section. These cross sections can be used in two ways. First, when the mean-free-path is short compared to the beam

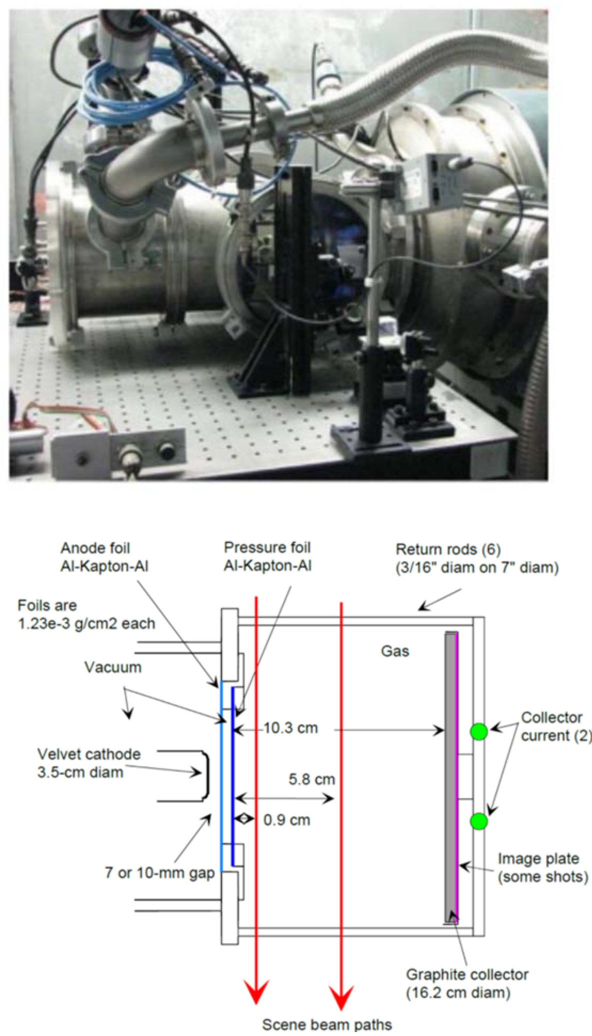

Figure 2. The experimental setup used to directly inject an intense electron beam into a gas.

diameter (i.e. high pressure), they can be used to compute transport coefficients that can be used as constitutive relations in a fluid model of the plasma. Alternatively, when the mean free path is large (i.e. low pressure) the cross sections can be used to implement a fully kinetic Monte-Carlo treatment.

The underlying assumptions of a weakly-ionized gas break down when the electron-electron collision frequency becomes comparable to the electron-neutral collision frequency. Because of the long-range nature of the Coulomb force, failure of the weakly-ionized gas model occurs when the ionization fraction $f=n_e/n_{gas}$ is just a few percent. When this happens the electron energy distribution is no longer dominated by electron-neutral collisions but rather driven towards a Maxwellian by electron-electron collisions. However, the chemistry becomes significantly more complicated. For example, stepwise ionization can reduce the energy barrier for ionization resulting in significantly higher ionization rates. In addition, dissociative recombination reactions can produce a source of atomic nitrogen which has a totally distinct set of reactions from N_2. A new gas chemistry model has been developed to handle strongly ionized N_2 gas.[3] In this model, the nitrogen gas transitions from a weakly ionized molecular state to a strongly ionized atomic state and momentum transfer is no longer dominated by electron-neutral collisions but by electron-ion collisions. Weakly-ionized and strongly-ionized gas models are tested by comparing results from these two models to the data obtained from the experiments described above. The results of this comparison will be presented as well as the directions for future research aimed at improving gas-chemistry models.

[1] I.M. Rittersdorf, et. al, this conference.
[2] http://fr.lxcat.net/home/
[3] J.R. Angus, D. Mosher, S.B. Swanekamp, P.F. Ottinger, J. W. Schumer and D.D. Hinshelwood, *Modeling nitrogen plasmas produced by intense electron beams*, Phys. Plasmas **23**, 053510 (2016).

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