ION - GAS COLLISIONS DURING BEAM ACCELERATION

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Summary

The following paper is an attempt to understand the effects which residual gas in an accelerator beam tube can have on the ion beam passing through it, and on certain other aspects of the accelerator's performance. The approach to the problem is felt to be the most fundamental. That is: all possible collision processes between injected beam and residual gas are examined (most of the cross-sections are quite well known experimentally[1]); a uniform axial electric field is assumed, together with a pressure gradient determined by kinetic theory equations for gas conductance assuming the source of gas to be the ion source. From this point on, it is in principle possible to calculate the resulting energy spectra of positive, neutral, and negative beam, as well as backstreaming electrons, evolved when only a positive ion beam is injected. In practice, only a numerical solution of the resulting equations can yield a solution. This solution is carried out, and the results are discussed.

General Discussion of Collisions Between Ions and Gas Atoms

Here we discuss the types of collisions which occur in the energy range up to the order of 1 mev between ion projectiles and gas atoms, the types of secondary particles produced, and the secondary processes which can occur. The discussion here will be limited to H_2^+ ions in hydrogen gas, for clarity.

Charge Exchange

Charge exchange is a collision in which the ion picks up and holds the target atom's electron, leaving behind a positive ion at rest, and becoming a fast neutral particle with essentially the same energy as the incident ion:

$$\underset{\text{(fast)}}{H_2^+} + \underset{\text{(at rest)}}{H_2} \longrightarrow \underset{\text{(fast)}}{H_2} + \underset{\text{(at rest)}}{H_2^+}$$

To a good approximation, the fast neutral produced has the same direction and magnitude of momentum as the incident ion. The cross-section is peaked at 4×10^{-16} cm^2 between 2 and 40 kev, and drops off rapidly with increasing ion energy[2].

Ionization

Ionization is a collision in which the incident ion converts the target atom into an ion-electron pair with very little momentum transfer. Thus, the ion continues on relatively undisturbed, and an ion-electron pair is left at rest:

$$\underset{\text{(fast)}}{H_2^+} + \underset{\text{(at rest)}}{H_2} \longrightarrow \underset{\text{(fast)}}{H_2^+} + \underset{\text{(at rest)}}{H_2^+} + \underset{\text{(slow)}}{e^-}$$

It is not strictly correct to say that the ion-electron pair are at rest, but for our purposes the approximation is good. The cross-section peaks at 3.5×10^{-16}cm^2 between 60 and 150 kev and drops off proportional to $(E)^{-1}$ with increasing energy.[1]

Rutherford Scattering

Rutherford Scattering is due to the electric repulsion between the proton in the ion and the proton in the target atom. For our purposes, only collisions of this type with high momentum transfer would be of concern, since they would cause beam diffusion and bombardment of the beam tube electrodes. The cross-section for scattering at angles greater than one degree is very small for the case treated here, ad= so this process is ignored.

Stripping

If any neutral beam is produced by charge exchange, it can then later be converted back to ion beam by stripping, for example:

$$\underset{\text{(fast)}}{H2} + \underset{\text{(at rest)}}{H_2} \longrightarrow \underset{\text{(fast)}}{H_2^+} + \underset{\text{(at rest)}}{H_2} + \underset{\text{(slow)}}{e^-}$$

This is a secondary process in our case, since the neutral beam must first be produced in a charge exchange collision. The cross-section is peaked between 60 and 150 kev at 1.8 x $10^{-16}cm^2$ and falls off proportional to $(E)^{-1}$ with increasing energy.[2]

Other Processes

Passing note is made of two-electron pickup which forms H_2^- from H_2^+ and higher-order processes. The cross-sections for these processes are not significant here.

Calculations of Beam Spectrum in the Beam Tube

Specifications of Beam Tube Conditions

The conditions in an accelerator beam tube which must be taken into account are the beam tube aperture, the beam tube length, the gas flow into the beam tube, and the total voltage across the beam tube. The aperture, length, and gas flow determine the residual gas pressure versus axial position in the beam tube (when proper consideration is given to the speed of the vacuum pump located at the base of the beam tube). The average axial electric field is just the ratio of the total voltage to the beam tube length. Thus, if the energy of a primary or secondary particle is known at one point in the beam tube, its energy at any other point is determined.

Qualitative Effects of Beam Collisions

We have seen above that if a certain primary ion beam is injected into the beam tube, it produces various types of secondary particles as it travels along the axis. Specifically, ionization collisions produce additional positive ion beam with energy dependent on where the ionization occurs, and backstreaming electrons which are accelerated in the opposite direction, back towards the high voltage terminal. Charge exchange collisions produce neutral beam, which is not accelerated, rather, travels with the energy at which it was produced. Later, this neutral beam can be stripped, producing positive ion beam which is again accelerated, and electrons. Since the cross-sections for these processes are strong functions of the incident projectile energy, a calculation must find not just the current in each type of beam, but the energy spectrum.

The end results which are to be gotten are then the energy spectrum of the positive ion beam which emerges from the end of the beam tube, the energy spectrum of emerging neutral beam, and the energy spectrum of backstreaming electrons which strikes the high voltage terminal. The positive ion beam spectrum and the backstreaming electron beam spectrum are most useful results. The positive ion spectrum can be measured experimentally, by passing the beam through an analyzing magnet and performing a momentum analysis. The result, when compared with the calculations, can provide a means for measuring the gas pressure in the upper end of the beam tube, and thereby, for example, evaluating the effectiveness of terminal vacuum pumping. When the backstreaming electron spectrum is known, its effect in producing X-rays at the terminal can be estimated. This is important because it has been observed that transmission of ion beams of order 1 milliampere in a 3 mev accelerator causes very high X-ray intensity at the high voltage terminal. These X-rays ionize the pressurized insulating gas in the accelerator, thereby allowing large corona leakage currents to flow from the terminal, posing a limitation on ion beam current due to drain on the accelerator power supply. The calculated backstreaming spectrum serves as an aid in deciding whether these X-rays are in fact due to residual gas in the beam tube.

Differential Expressions for Beam Energy Spectra

Let the following functions be defined:

$P(x,E)$ = The number of H_2^+ ions at the axial position x in the beam tube which have an energy E,

$U(x,E)$ = The number of neutral beam molecules at x with energy E,

$B(x,E)$ = The number of backstreaming electrons at x with energy E.

$dP(x,E;x',E')dxdE$ = differential contribution to $P(x',E')$ from dx at x, dE at E;

$dU(x,E;x',E')dxdE$ = differential contribution to $U(x',E')$ from dx at x, dE at E:

$dB(x,E;x',E')$ = differential contribution to $B(x',E')$ from dx at x, dE at E.

When we take into account the dominant collision processes as discussed above, and the energies imparted to the particles produced, we see that the following expressions for dP, dU, and dB are obtained:

$$dP(x,E;x',E') = \delta(E'-Kx'+Kx)\ \frac{\partial^2 P_1(x,E)\ dxdE}{\partial x\,\partial E} + \delta(E'-Kx'+Kx)\ \frac{\partial^2 P_2(x,E)dxdE}{\partial x\partial E} - \delta(E'-E)\ \frac{\partial^2 P_2(x,E)}{\partial x\partial E}\ dxdE + \delta(E'-E-Kx'+Kx)\ \frac{\partial^2 P_3(x,E)}{\partial x\partial E}\ dxdE$$

where K is the axial electric field, and

$$\frac{\partial^2 P_j(x,E)dxdE}{\partial x\partial E} = \text{number of ions produced}$$

in dx, dE by the j-th process. These factors can be written as

$$\frac{\partial^2 P_1(x,e)}{\partial x\partial E} = P(x,E)\,\sigma_{01}^{i}(E)\quad n(x)$$

$$\frac{\partial^2 P_2(x,E)}{\partial x\partial E} = P(x,E)\,\sigma_{01}^{ic}(E)\quad n(x)$$

$$\frac{\partial^2 P_3(x,E)}{\partial x\partial E} = U(x,E)\,\sigma_{01}^{\iota}\ (E)\ n(x)$$

where $n(x)$ = number of molecules of H_2 gas per unit area.

$\sigma_{01}^{i}(E)$ = ionization cross-section

$\sigma_{01}^{ic}(E)$ = charge exchange cross-section

$\sigma_{01}^{\iota}(E)$ = stripping cross-section

The differential equation for production of H_2^+ ions is then

$$dP(x,E;x',E')dxdE = \{P(x,E)[\sigma_{01}^{i}(E)\,\delta(E'-Kx'+Kx) + \sigma_{01}^{ic}(E)\,\delta(E'-Kx'+Kx) - \delta(E'-E)\sigma_{01}^{ic}(E)] + U(x,E)\sigma_{01}^{\iota}(E)\,\delta(E'-E-Kx'+Kx)\}\,n(x)\,dxdE.$$

Similarly, we obtain

$$dU(x,E;x'E')dxdE = P(x,E)\delta(E'-E)\sigma_{01}^{\iota}(E)\,n(x)\,dxdE$$

$$dB(x,E;x'E')dxdE = [P(x,E)\sigma_{01}^{i}(E) + U(x,E)\sigma_{01}^{\iota}(E)]\delta(E'-Kx+Kx')\ n(x)\ dxdE.$$

We are now faced by a set of three coupled differential equations. We want to integrate over x and E to obtain $P(x',E')$, $U(x',E')$ and $B(x',E')$. There are several difficulties in trying a straightforward analytic solution, the most forbidding of which is that we intend to use experimental values for the cross-sections as functions of energy. The practical approach is to do a numerical integration.

Numerical Integration

Since $P(x,E)$ and $U(x,E)$ do not depend on $B(x,E)$ in this approximation, we solve first for P and U, and then use those results to calculate B. We start with initial conditions of a monoenergetic ion beam injected at $x = 0$, with energy E_o, and of total current unity; no injected neutral beam:

$$P(0,E) = \delta(E-E_o)$$

$$U(0,E) = 0,$$

with $\delta(a)$ the Dirac delta function of argument a . These values are inserted into the expressions for dP and dU at $x = 0$. Then

$$P(dx,E') = \int_0^{dx}\int_0^{\infty} dxdE[dP(0,E;dx,E')]$$
$$U(dx,E') = \int_0^{dx}\int_0^{\infty} dxdE[dU(0,E;dx,E')] \ .$$

Now repeat at x = 0+dx, inserting the values obtained above for P(dx,E), U(dx,E) into the expressions for dP and dU at x = 0+dx. This process is reiterated until x = L, the end of the beam tube.

In the numerical solution, finite steps Δx replace dx, ΔE replace dE, and the integrals are replaced by sums.

The following parameters are used: beam tube diameter, 7.6 cm(D); beam tube length, 244 cm (L); initial beam energy, 10 kev; final beam energy, 3.0 mev. The residual gas concentration is

$$n(M)=n(x)=\{5.4 \times 10^{12} \ (L/TD^2)\} \{1 + (3/4)(L/D)[1-(M/T)]\}$$

The expression used for n(x) corresponds to a pressure at the base of the beam tube of 3 x 10^{-6} mmHg, where the pump speed is about 1500 liter/sec. This is a gas flow of about 20 std cc/hr.

The calculation was performed with the beam tube divided into 60 subintervals. Four values of pressure were used - a normal operating pressure of 1.5x10^{-6} mmHg (ion gauge reading), 4.5, 7.5, and 45 x 10^{-6} mmHg.

Results and Discussion

The calculated positive ion energy spectrum emerging from the accelerator at a nominal beam energy of 3.0 mev is shown in Figure 1, for the four values of pressure at the beam tube base. About 99.6% of the injected beam is transmitted in the main peak at 3.0 mev for a pressure of 1.5x10^{-6} mmHg. The low energy tail formed by the various processes discussed above comprises about 2% of the injected beam. These figures change to 88% and 180% respectively for a pressure of 4.5 x 10^{-5} mmHg. This spectrum should be able to be directly measured by passing the beam through an analyzing magnet, thereby making a momentum analysis. Of course, in an actual experimental situation, several ionic species would be present, each with its own tail. The measured height of the tail, and its shape, would provide an experimental check on the assumed linear variation of pressure in the beam tube.

Figure 2 shows the calculated backstreaming electron spectrum striking the high voltage terminal. The integrated electron current at an operating pressure of 1.5x10^{-6} mmHg is about 3% of the ion beam. When the pressure is increased by a factor of 30, the electron current goes up by a factor of 61, to 180%.

Consider the effects of this backstreaming current on accelerator operation. When it strikes the terminal it deposits the energy it acquired during back-acceleration. This causes heating and outgassing of the exposed surfaces, adding to the gas load in the beam tube. That is not a severe problem, since cooling can be provided on the exposed parts. A much more severe problem is the X-rays created by the electron bombardment of the terminal.

This problem has been investigated by C. M. Turner.[3] His main emphasis was on limitation to operating voltage imposed by other sources of X-rays. At the high beam currents used today as in the Dynamitron, we see X-rays as a limit to beam current too. The process is: the backstreaming electrons create X-rays in the terminal, which ionize the insulating gas, and cause radiation damage in the terminal. The ionization causes high corona drain current in the insulating gas.

Turner has estimated the efficiency of a backstreaming electron in creating corona current. He takes into account the materials present in the terminal and the variation of efficiency with electron energy. An interpolation of his results for the 3 mev Dynamitron gives

$$dI(corona) = B(0,E)E^2dE \qquad (1)$$

where E is the electron energy in mev. When the spectra of Figure 2 are integrated with equation (1), we obtain the following results:

Ratio of Corona to Ion Beam	Pressure at Base of Accelerator
6.5%	$1.5x10^{-6}$ mmHg
21 %	$4.5x10^{-6}$
38 %	$7.5x10^{-6}$

It is now clear that the beam tube pressure must be limited in order to prevent undue drain on the high voltage power supply due to corona leakage currents in the pressurized insulating gas.

References

1. N.V. Fedorenko, Soviet Physics Uspekhi 2(68), 526 (1959)
2. S.K. Allison, Rev. Mod. Phys. 30 1137 (1958)
3. C.M. Turner, "The Effects on Pressure Insulated Electrostatic Accelerators of Ionization Currents in the High Pressure Insulating Gas", unpublished report, Brookhaven National Laboratory, 1955

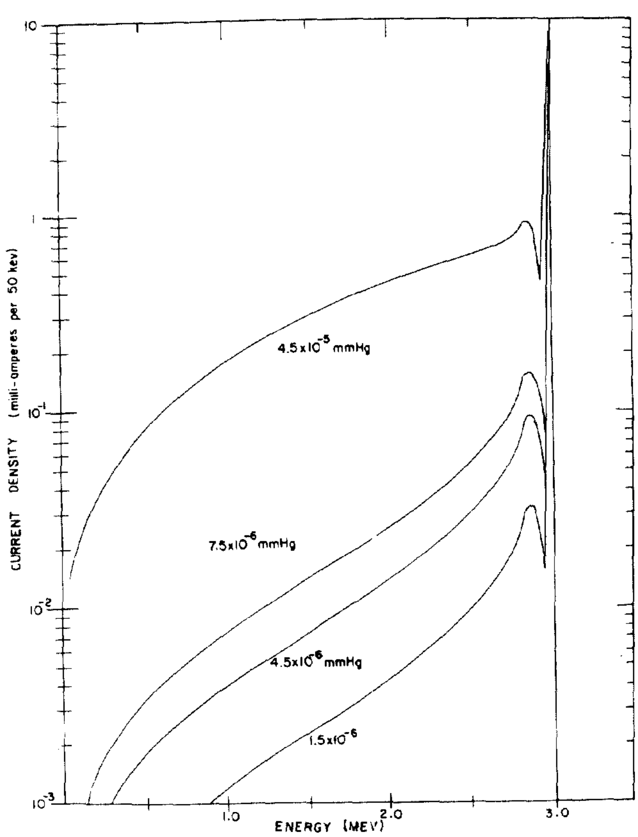

Fig. 1. Positive ion energy spectrum emerging from accelerator for a nominal 10 ma ion beam.

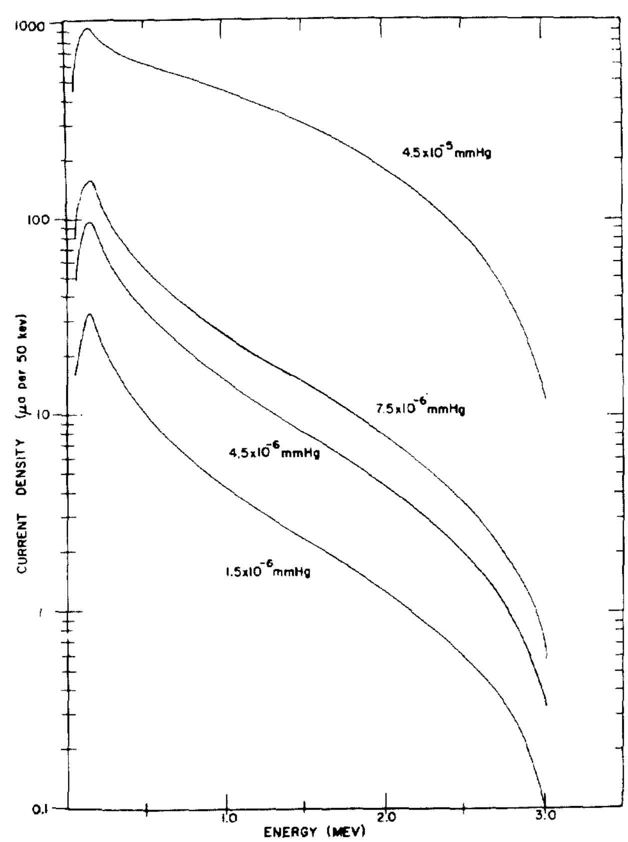

Fig. 2. Backstreaming electron energy spectrum for a 10 ma ion beam.