Theory of Operation:

Beam Energy

A cyclotron operates under the principle of magnetic resonance. An ion can be accelerated in ever-increasing semicircular paths if magnetic and electric fields are properly applied.

As originally speculated by Ernest Lawrence, it is possible to use a uniform magnetic field to corral an ion along a circular path, returning it to the electric field gap where it was first accelerated. This can be continued, so long as the electric field oscillates at a resonant frequency, as determined by the charge-to-mass ratio of the ion and the magnetic field. This resonance is shown below, for an ion of charge q, mass m, velocity v perpendicular to uniform magnetic field B, traveling in a circular path of radius r:

$$\frac{mv^2}{r} = qvB$$

The frequency of revolution for this path is:

$$f = \frac{v}{2\pi r} = \frac{qB}{2\pi m}$$

So for a constant mass and uniform field, this frequency remains constant. This, the resonant frequency, is the frequency at which an oscillating electric field will optimally accelerate ions in a cyclotron. The frequency changes when the field is made nonuniform, or the ions begin to be relativistic, and thus effectively have varying masses; this latter concern gives the upper energy limit for cyclotrons.

The radius of path in the magnetic field increases with the increasing energy of the accelerated ions, and have therefore an outward spiralling trajectory; the maximum energy attainable in a particular cyclotron is therefore determined by the strength of the magnetic field, which determines the velocity (and thus energy) of particles at any particular radius, and by the radius at which particles are extracted from the cyclotron.

Beam Intensity

All cyclotrons have limits to beam intensity; two of the primary limits are due to the ions' long path length to the extraction point. One limit to path length is the mean free path of the ions, which is dependent on how hard a vacuum can be obtained in the acceleration chamber. When particle collisions are likely to occur before ions have reached the extraction radius, beam intensity is lost; if the acceleration chamber's vacuum is too soft, it's possible for no particles of maximum energy to be produced. How hard a vacuum is required depends on the path length of an ion from ion source to extraction radius. This is dependent on the electric potential between the D's, the operating magnetic field, and the extraction radius of the detector. Higher D voltages allow fewer passes through the D's before maximum energy is attained, lessening path length; higher magnetic field raises the maximum energy and thereby lengthens the path; and a greater extraction radius increases the path length, for each other constraint held constant. These relationships are shown in the equations below for the total path length:

$$E_i = \frac{mv_i^2}{2} = \sum_1^i qV_D \qquad r_i = \frac{\sqrt{2mE_i}}{qB} \qquad l = \sum_{r=0}^{r_{max}} (d + \pi r_i)$$

where q and m are the charge and mass of the ion, V_D is the voltage between dees, and E_i and v_i are the energy and velocity of the ion after the i^{th} pass through the D-gap of width d. B is the magnetic field strength; r_i is the radius of curvature for the i^{th} half-circle, and r_{max} the radius of extraction. These are derived under the assumptions of uniform magnetic field, nonrelativistic kinetic energy, and **a** centrally located ion source. Once these have been used to determine the path travelled by ions in the accelerating chamber, it is possible to compare with mean free path calculations for the appropriate gas and determine the maximum ideal pressure.

Vacuum Production

Achieving the ideal pressure, or approaching it, is done in this cyclotron using a system of three vacuum pumps. Two are mechanical, one for roughing out the chamber and the other for maintaining a low backing pressure for a diffusion pump. The diffusion pump is required to reach the low pressures needed for usable beam; these are on the order of 10^{-6} torr. Diffusion pumps operate by transferring kinetic energy out of a controlled gas (superheated oil compounds, typically) into the surrounding gas from the chamber being evacuated, with a net directional component directed towards the exit pipe. Most diffusion pumps use several jets to improve their best possible vacuum. Each jet compresses the ambient gas as it pushes it towards to the exit point. Gases in the evacuating chamber diffuse into the region of the pump and are then removed by the compression jets. Figure 1 shows the basic outline of a diffusion pump, similar to the one used in our cyclotron.

The types of fluids used in diffusion pumps have particular ideal traits: Low vapor pressure, chemical stability, low heat of vaporisation, and are safe to handle, use, and dispose. It shouldn't decompose, entrap gas, or react to its surroundings. The vapor jets can only be used in a low-pressure environment. If there is too great a pressure in the diffusion pump, the jets become turbulent, allowing backstreaming, a condition where gas from the surroundings stops the gas in the jets from reaching the walls of the pumping chamber, some of which then travels into the evacuating chamber. Any time the "backing pressure" at the exit pipe of the diffusion pump exceeds a certain value (the critical pressure), backstreaming will begin occurring, and the pump will not work. For this reason, our diffusion pump requires a mechanical pump to keep the downstream pressure low; for convenience reasons, we have a second such pump for roughing out the main cyclotron chamber while allowing the diffusion pump to remain active, as the startup time for such a pump is nontrivial.

Much of this material is adapted from Livingston, Ch. **6;** diffusion pump information is adapted from "A User's Guide to Vacuum Technology", John O'Hanlon.

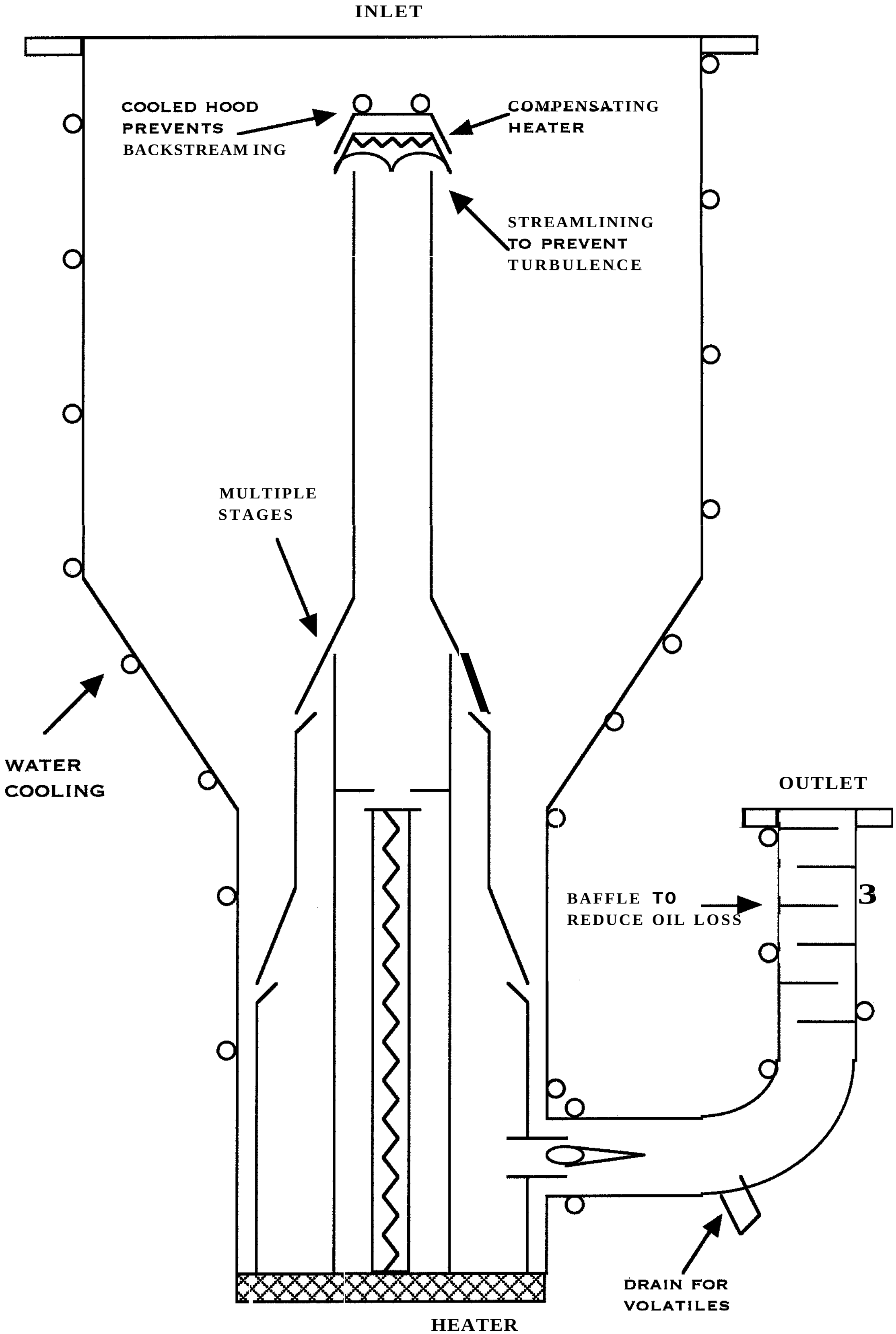

Figure 1: Diagram of a Diffusion Pump