Vacuum Considerations for Planar W-Band Accelerator Structures

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In this note we review the basic theory of vacuum systems: (1) notions of pressure, conductance, pumping speed and throughput (2) analysis of transient pumpdown in the molecular flow regime (4) a review of the Monte Carlo method for conductance calculation and (5) analysis of conductance, following Roth, of various elements. We then make some simple estimates for a WR10 waveguide, and a planar accelerator structure, pumped from the ends, pumped from parallel ports, and pumped from a common manifold. In all cases, flow is conductance-limited, assuming an 8 l/s VacIon pump. With manifold pumping $5 \times 10^{-11}$ torr is achievable; with end-cell pumping on a 2" structure, 9-scale vacuum can still be reached. These numbers are based on the assumption of a specific outgassing rate of $1 \times 10^{-11}$ torr – l/s - cm$^2$, as for copper cleaned for vacuum and processed through high-temperature bakeout.

Introduction

It is not for nothing that vacuum is of great interest in industry and science research. Vacuum can be employed to: exert a mechanical force, to degas (steel, water, accelerators), to dehydrate (food, accelerators), to provide an inert atmosphere for a process (e.g., molten metal processing, accelerators), to provide thermal insulation (a thermos), to provide electrical insulation (circuit breaker, capacitor), to provide a long mean free path (TV tube, accelerators), to reduce the influence of extraneous gases for scientific studies (material science, accelerators). An excellent practical reference on the subject of vacuum is the text by Roth, and this note is in part just an elaboration on particulars mentioned there. A basic chemistry textbook may also be a helpful reference.

For the NLCTA experiment, as in most work involving accelerators, we will be covering about 12 orders of magnitude in the vacuum system, from a number density $3 \times 10^{19}$ cm$^{-3}$, as for atmospheric pressure when the system is opened up,

$$1.01 \times 10^5 \text{Pa} \approx 1.01 \text{bar} \approx 760 \text{mm Hg}(0^\circ \text{C}) \approx 760 \text{torr} \approx 14.7 \text{psi},$$

to $4 \times 10^7$ cm$^{-3}$ as for the minimum pressure we have set as a goal, $1 \times 10^{-9}$ torr. Over this range the composition of the gas will vary from air (78% N$_2$, 21% O$_2$, 1% Ar) or N$_2$ at 760 torr to water vapor and then carbon monoxide, as we pass through $10^3 - 10^7$ torr (high-vacuum), to hydrogen permeating from the material bulk as we pass into the range $10^7 - 10^{10}$ (ultra-high vacuum).

Let us review some basic features of gases. An ideal gas is one obeying Boyle’s Law, $PV = constant$, at constant temperature. Here $P$ is pressure, or force per unit area on the surrounding vessel, and $V$ is the interior volume of the vessel. Boyle’s Law is the basis for the first and simplest techniques for measuring pressure by comparison with a reference. For purposes of comparison it is customary to refer to standard temperature and pressure (STP), $0^\circ \text{C} \equiv 273.16^\circ \text{K}$ and 1 atm. To be fair we could also mention Charles’ Law, $V/T = constant$, at constant pressure, where $T$ is the absolute temperature. In general, one is interested in the variation of all variables and in this case one needs the ideal gas law

$$PV/T = N_m R_0,$$

A. Roth, *Vacuum Technology* (North-Holland, Amsterdam, 1982).

2 For example, Bruce H. Mahan, *University Chemistry* (Addison-Wesley, Reading, 1972).
where the universal gas constant is

\[ R_0 = \frac{1 \text{ atm} \times 22.414 \text{ liter}}{1 \text{ mole} \times 273.15 \text{ °K}} \approx 62.4 \text{ torr} - 1/°K = 8.315 \text{ J/mole} - °K. \]

The number of moles of gas or mole fraction is \( N_a \). A mole of gas corresponds to Avogadro’s number of unit constituents (be they atoms or molecules), \( N_A = 6.023 \times 10^{23} \). With the notion of mole in hand, we may state the ideal gas law in different terms as: one mole of gas at STP occupies a volume of 22.414 liters. With Avogadro’s help, we may express the universal gas constant as

\[ R_0 = N_A k_B, \]

where Boltzmann’s constant is

\[ k_B = 1.381 \times 10^{-23} \text{ J/°K}. \]

This constant is somewhat easier to remember after the units have been converted using \( e = 1.602 \times 10^{-19} \text{ C} \), to

\[ k_B \approx \frac{1/42 \text{ eV}}{273.15 \text{ °K}} \]

We may restate the ideal gas law in the form

\[ P = nk_BT, \]

where \( n \) is the number density of the gas particles, \( n = N_a/V \). In practical units this is

\[ n = 9.656 \times 10^{18} \text{ cm}^{-3} P(\text{torr})/T(°K). \]

At STP, \( n = n_L = 2.687 \times 10^{19} \text{ cm}^{-3} \), Lohschmidt’s number.

In theoretical terms, an ideal gas is an ensemble of a large number of non-interacting systems (particles), i.e., the complete Hamiltonian for the system is simply a sum of the individual Hamiltonians. The ideal gas law and other particulars can be derived in simple theoretical terms from an elementary treatment of the statistical mechanics of such systems. Real gases, on the other hand, consist of elements that, while electrically neutral, have polarizabilities, and thus are capable of short-range (Van der Waals) interactions, particularly at high densities. Aside from the non-ideal character of the gas, and related consequences (viscosity, condensation for example), one may be concerned also with the non-ideal character of the vacuum vessel. The ideal gas law is premised on a vessel that elastically reflects incident particles—energy is conserved, momentum is not, and the momentum imparted to the walls by the net flux of particles corresponds to the pressure on the walls of the vessel. On real vessel surfaces, particles may stick or may knock adsorbed particles loose.

In fact, it is important, in treating a vacuum system, to distinguish between the regime of viscous flow, where particles interact mainly with each other, and the regime of molecular flow, where particles interact mainly with the vessel, and don’t see each other. Viscous flow occurs at pressures in the range of \( 10^{-2} \) torr and higher. Molecular flow occurs, for typical vessel conditions, when...
dimensions, in the range of $10^{-3}$ torr and lower. In a high vacuum system such as is common in accelerator systems, one employs two stages of pumping. A rotary pump (or, functionally, a “roughing pump”) takes the system from 760 torr into rough vacuum of $10^{-2}$ torr, approaching a regime where a second pump (a turbomolecular pump for 6-7 scale vacuum and larger volumes, or an ion pump for 7-scale or better vacuum and the smaller volumes typical of rf work at SLAC) can function well and take the vacuum down at least to the $10^{-7}$ torr range, a typical minimal vacuum (on the high-side) for a working accelerator component (a linac section, for example). High-power components with elements sensitive to poisoning or ion-bombardment (a klystron gun for example) require better vacuum for long life, $10^{-9}$ torr (9-scale vacuum) or better.

In this note, we consider the particulars of the vacuum system for a planar W-Band accelerator, in the molecular flow regime. In the simplest picture, there are only two fundamental items of the microscopic dynamics to know in order to compute the macroscopic features of the vacuum circuit. The first is the Maxwell-Boltzmann distribution in velocities

$$f(\vec{v}) = n \left( \frac{m}{2 \pi k_B T} \right)^{3/2} \exp \left( -\frac{m\vec{v}^2}{2 k_B T} \right).$$

The other feature required is a rule for the interaction of particles from this distribution, with the geometry. In this connection, particulars of surface layers and sticking times cannot be ignored completely. The simplest approximation, that boundaries produce elastic particle reflection, is not very useful. Instead we will assume that particles arriving on boundaries are re-emitted, with a velocity vector randomly selected from the Maxwell-Boltzmann distribution. This “diffuse-reflection” condition is itself the subject of experimental and theoretical studies reported in the literature. We will ignore for now the circumstance that our vacuum will consist of several particle species, that ionization, recombination, and other processes may be present. The problem of interest is: given a pump and a geometry with a pumpout port, what pressure can we reach and how long to reach it? To come to grips with this problem, let us review the essentials of molecular flow from an elementary point of view.

**Microscopic Features of Gas Flow**

To appreciate the particulars of the ideal gas law, and the Maxwell-Boltzmann distribution, let us consider first a few numbers. We can better appreciate the number density by means of a length-scale characterizing particle separation. If we assign to each particle a cube of dimension $\rho$, then $n = \rho^{-3}$. At 760 torr, $\rho \approx 3$ nm. At $10^{-4}$ torr, $\rho \approx 3 \mu$m. These dimensions are large compared to particle sizes (of order Angstroms), and small compared to the mean free-path. As a point of reference, in N$_2$ at 1 torr and 273°K, the mean free-path is $\lambda \approx 64 \mu$m. The mean free-path is 1 mm at $6 \times 10^{-2}$ torr. In general,

$$\lambda(\text{cm}) = 1.7 \times 10^{-5} \frac{T(\circ\text{K})}{P(\text{torr})},$$
for air. Below the mtorr range, particles whizz about oblivious to all but the vessel surface. Our
intention is to operate mm-scale volumes at or below 10^{-9} \text{ torr}, and this corresponds to
n \approx 3.6 \times 10^7 \text{ cm}^{-3} \approx 4 \times 10^4 \text{ mm}^{-3}, or 40,000 particles per unit cell.

Let’s consider the kinematics of such particles. One can check that the average speed
associated with the Maxwell-Bolztmann distribution is
\begin{align*}
V_{\text{avg}} &= \frac{\int dV_x \int dV_y \int dV_z |\vec{V}| f(\vec{V})}{\int dV_x \int dV_y \int dV_z f(\vec{V})} = \frac{2^{3/2}}{\pi^{1/2}} \left( \frac{k_B T}{M} \right)^{1/2} \approx 1.45 \times 10^4 \text{cm s}^{-1} \left( \frac{T(\circ K)}{M(\text{amu})} \right)^{1/2}.
\end{align*}

The root-mean square velocity associated with the Maxwell-Boltzmann distribution is
\( V_{\text{rms}} = \left( 3k_B T / M \right)^{1/2}, \) where \( M \) is the particle mass, for example,
molecular hydrogen (H\(_2\)) \( M \approx 2.016 \text{ amu} \)
molecular nitrogen (N\(_2\)) \( M \approx 28.02 \text{ amu} \)
“air” \( M \approx 29 \text{ amu} \)
argon (Ar) \( M \approx 39.944 \text{ amu} \)

The third line should be regarded as rule of thumb. Recall that the atomic mass unit corresponds to
the mass in grams of one mole, and can be converted to the constituent mass via Avogadro’s
number. Thus for a nitrogen molecule, the mass is \( 4.65 \times 10^{-26} \text{ kg} \), the average kinetic energy
\( \bar{E} = 3k_B T / 2 \) is \( k_B = 3.71 \times 10^{-21} \text{ J} \) at 273.15\(^{\circ}\text{K} \), and the rms velocity is
\( V_{\text{rms}} = \left( 2\bar{E} / M \right)^{1/2} \approx 4 \times 10^4 \text{ cm/s} \). The time-scale for transit of a 1mm length is on the order of 0.3
\( \mu\text{s} \). The thermal energy in one mm cube is 0.1 fJ.

Also of interest is the \textit{molecular incidence rate}, the number of particles per unit time striking
a surface of unit area. One can show that this is
\[ \phi = \int dV_x \int dV_y \int dV_z f(\vec{V}) = \frac{1}{4} n V_{\text{avg}}, \]
or, explicitly,
\[ \int V^2 e^{-\beta V^2} dV = -\frac{\partial}{\partial \beta} \int e^{-\beta V^2} dV = -\frac{\partial}{\partial \beta} \frac{\pi^{1/2}}{2^{1/2} \beta^{3/2}} = \frac{\pi^{1/2}}{2 \beta^{3/2}}, \]
to compute the normalization for the distribution,
\[ \int dV_x \int dV_y \int dV_z f(\vec{V}) = \int \sin \theta d\theta \int d\phi \int V^2 dV f = n, \]
and the integral
\[ \int V^3 e^{-\beta V^2} dV = \frac{1}{2} \int e^{-\beta V^2} V^2 dV^2 = -\frac{\partial}{\partial \beta} \frac{1}{2} \int e^{-\beta V^2} dV^2 = -\frac{\partial}{\partial \beta} \frac{1}{2 \beta} = \frac{1}{2 \beta^2}, \]
to compute the numerator.
\[ \phi = \frac{n}{2\pi^{1/2}} \left( \frac{2k_B T}{M} \right)^{1/2} = \frac{1}{\sqrt{2\pi}} \left( \frac{P}{(k_B T)^{1/2}} \right) \approx 3.513 \times 10^{22} \text{ cm}^{-2} \text{s}^{-1} \frac{P(\text{tor})}{[M(\text{amu})T(\circ\text{K})]^{1/2}}. \]

In general, if we have a gas flowing through a surface of area \( A \), with mean speed normal to the area of \( V \), the number of particles crossing the surface per unit time will be \( N' = nAV \), where \( n \) is the number density at the surface. In this connection we may define the pumping speed at the surface such that \( N' = nS \), so that \( S = AV \). Notice that pumping speed has units of volume per unit time, corresponding to an imaginary volume \( N'/n \), enclosing \( N' \) particles. With this definition, in mind let us now consider the different situation of a surface of area \( A \), subject to a gas of molecular mass \( M \), at temperature \( T \). Let us suppose that the system is in equilibrium, so that the pressure \( P \) is the same on each side of the surface. In this case, the one may think of the surface as being subject to equal and opposite fluxes of particles, each of magnitude, measured in volume per unit time,

\[ S = \frac{1}{4} V_{\text{avg}}A \approx 3.63 \times 10^3 \text{ cm}^3 \text{s}^{-1} A\left(\text{cm}^2\right) \left( \frac{T(\circ\text{K})}{M(\text{amu})} \right)^{1/2} \approx 3.6 \text{ liter sec} \text{cm}^2 \left( \frac{T(\circ\text{K})}{M(\text{amu})} \right)^{1/2}, \]

where 1 liter = \( 10^3 \) cm\(^3\). For \( N_2 \) at 273.15\(^\circ\)K, this is \( S = 11.2 \) \( l \text{s}^{-1} A\left(\text{cm}^2\right) \). In this example, our (imaginary) surface, sees no net flux of particles across it; it is not a pump.

**Fundamentals of Vacuum Circuits**

If our interest is to reach a high-vacuum in a geometry, we may expect that some means of extracting particles from the geometry will be required. We need a pump. In addition, our geometry requires a pump-out port, an aperture across which net particle flow occurs. Note that the distinction between the pump and the geometry is somewhat artificial. The combined system is itself a geometry of some kind, and could well be completely sealed. For now, however, the distinction is helpful, for it permits us to lump the features of the pump into a single number, the pumping speed, \( S \), measured in units of volume per second.

In general, if we have a pressure difference maintained across an area \( A \), we expect to find a net flux of particles through the aperture proportional to this difference. Relating pressures to number densities using the ideal gas law, we may write this as \( N' = C(n_1 - n_2) \). The quantity \( C \) is referred to as conductance, and is a constant associated with the aperture (and the temperature \( T \), and the molecular mass \( M \)). Actually, such a relation need not be confined to a single thin area, but could be applied to any system with two identifiable ports. Labelling the ports 1 and 2, we may express the net flux from 1 to 2 as \( N' = C(n_1 - n_2) \). The quantity \( C \) is then the conductance for pumping port 1 from port 2 or vice versa. Occasionally one refers also to the inverse of conductance as the resistance.

Associated with conductance and pumping speed is the notion of throughput. Throughput at a pumping port is given by

\[ Q = SP, \]

where \( S \) is the pumping speed at the port, and \( P \) is the pressure at the port. Expressing this in terms of the number of particles per second crossing the plane of the pumping port, \( N' \),

\[ Q = \frac{N'}{n} P = N' k_B T, \]
one can see that throughput is the rate of thermal energy flow multiplied by $2/3$. In an isothermal system, with no internal sources of particles, net throughput is zero. So for example, for a two-port system, throughput at the inlet equals throughput at the outlet, and is equal to throughput at any plane splitting the system into two parts.

Considering a two-port system, and using the definition of conductance one may express the throughput according to

$$Q = N' k_B T = C (n_i - n_2) k_B T = C (P_1 - P_2).$$

Notice that the pumping speeds associated with each port may be different, $S_i = N'/n_i$, $S_2 = N'/n_2$, and we may express

$$\frac{1}{C} = \frac{1}{S_i} - \frac{1}{S_2}.$$

With these results it is straightforward to show that conductance adds for paths in parallel, and reciprocal conductances add for paths in series. In passing we note that one may also see throughput expressed as “$Q = \Delta (PV)/\Delta t$”.

**Transient Pumpdown**

As for electrical circuits there are two kinds of problems one may be interested in solving for a vacuum circuit: (1) calculation of circuit behavior for known circuit parameters (2) calculation of circuit parameters. Let us consider first (1) with attention to the system depicted in Fig.1.

![Diagram of a pump system](image)

**FIGURE 1.** A pump employed to pump evacuate a volume $V$, attached by means of a geometry with finite conductance $C$.

We may express the throughput at the plane of the inlet valve to the pump according to

$$Q = S_{p0} P_p - Q_p,$$

where $S_{p0}$ is the *theoretical pumping speed*, $P_p$ is the pressure at the inlet and $Q_p$ is the gas load internal to the pump, *i.e.*, the throughput generated from particles leaving the interior surface of the pump. The *actual pumping speed* at the pump inlet is

$$S_p = \frac{Q}{P_p} = S_{p0} - \frac{Q_p}{P_p},$$
and the pumping speed at the outlet of the device to be pumped, $S_v$, is given by

$$\frac{1}{S_v} = \frac{1}{S_p} + \frac{1}{C}.$$ 

The notation is clarified somewhat by Fig. 2.

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![Diagram of pumping problem](image)

**FIGURE 2.** Notation for the pumping problem.

To close this system of relations, we note that throughput at the outlet of the device to be pumped (equal to the throughput everywhere else) is given by

$$Q = S_v P_V = Q_V - V \frac{dP_v}{dt},$$

where $Q_v$ is the gas load from the device. With some algebra we may set down a simple description of the dynamic behavior of the system. First we express

$$P_p = P_V - \frac{Q}{C},$$

and eliminate $P_p$, writing,

$$Q = S_{p0} P_V - Q_p = S_{p0} P_V - \frac{S_{p0}}{C} Q - Q_p \quad \Rightarrow \quad Q = \frac{S_{p0} P_V - Q_p}{1 + S_{p0} / C}.$$ 

Finally we make use of our result for throughput in terms of time rate of change of pressure to obtain,

$$V \frac{dP_v}{dt} + \frac{S_{p0} P_V - Q_p}{1 + S_{p0} / C} = Q_v \quad \Rightarrow \quad \frac{dP_v}{dt} + \frac{1}{T_v} P_v = \frac{Q_v}{V},$$

where the pumpdown timescale is
\[ T_v = V \left( \frac{1}{S_{p0}} + \frac{1}{C} \right) \]

and the effective outgassing throughput referred to the device chamber is

\[ Q'_v = Q_v + \frac{Q_p}{1 + S_{p0}/C} \]

This system of equations is easily solved when the circuit parameters are constant (as after the molecular flow regime has been entered). Multiplying by \( e^{t/T_v} \) and integrating we have

\[ P_v(t) e^{t/T_v} = \frac{Q'_v}{V} T_v(e^{t/T_v} - 1) \]

assuming constant outgassing rate for simplicity. The result is

\[ P_v(t) = P_v(0) e^{-t/T_v} + P_v(\infty)(1 - e^{-t/T_v}) \]

with asymptotic pressure

\[ P_v(\infty) = \frac{Q'_v}{V} T_v = Q_v\left( \frac{1}{S_{p0}} + \frac{1}{C} \right) = Q_v\left( \frac{1}{S_{p0}} + \frac{1}{C} \right) + \frac{Q_p}{S_{p0}} \]

For pressure to drop from \( 10^{-2} \) torr to \( 10^{-9} \) torr one requires a time \( 16T_v \), and one requires that \( P_v(\infty) \leq 10^{-6} \) torr. The asymptotic throughput is \( Q(\infty) = Q_v \), the asymptotic pressure at the pump inlet is

\[ P_p(\infty) = P_v(\infty) - \frac{Q_v}{C} = \frac{Q_v + Q_p}{S_{p0}} \]

and the asymptotic actual pumping speed is

\[ S_p(\infty) = S_{p0} \frac{Q_v}{(Q_v + Q_p)} \]

Notice that in the limit of zero outgassing within the device to be pumped we have asymptotic pressure

\[ \lim_{Q_p \to 0} P_v(\infty) = \frac{Q_p}{S_{p0}} \]

This is the ultimate pressure for this pump.

Let us consider an example corresponding to a chamber of dimension 5 cm × 0.46 cm × 0.46 cm (volume \( 1.1 \times 10^{-3} \) l). We suppose that our pump has a theoretical pumping speed of 8 l/s and is connected to the chamber by a lumped conductance of \( C = 0.3 \) l/s. The pumpdown time is then 3.7 msec, and the system will pump down in a fraction of a second.

To compute the asymptotic pressure we require a figure for the wall surface area, \( A_w \) and
the specific outgassing rate, \( \hat{Q}_v \). Outgassing throughput is then \( Q_v = A_v \hat{Q}_v \). The correct figure for specific outgassing rate depends on the material and the material preparation. We are interested in copper, and depending on the history of the copper, this figure could be as high as \( \hat{Q}_v \approx 1 \times 10^{-7} \text{torr} \cdot \text{l/s} \cdot \text{cm}^2 \).\(^6\) However, at SLAC it is common practice, particularly for high-power microwave parts, to clean for vacuum, and to perform a high-temperature (450\(^\circ\)C) bakeout; with such preparation, the specific outgassing rate for copper is typically \( \hat{Q}_v \approx 0.5 \times 1.0 \times 10^{-11} \text{torr} \cdot \text{l/s} \cdot \text{cm}^2.\(^7\) We will employ the higher figure \( \hat{Q}_v = 1 \times 10^{-11} \text{ l/s} \cdot \text{cm}^2 \) for estimates here. If the interior surface area is 9 \( \text{cm}^2 \) then the gasload throughput from the volume is \( Q_v \approx 10^{-10} \text{ torr} \cdot \text{l/s}. \) Neglecting the pumping speed compared to the very low conductance (we are “conductance limited”), and neglecting also the outgassing internal to the pump, the asymptotic pressure is \( P_v(\infty) = Q_v / C \approx 3 \times 10^{-10} \text{ torr}. \) If by means of parallel ports, a conductance much higher than the pumping speed were arranged, then at best the asymptotic pressure would reach \( P_v(\infty) = 4 \times 10^{-11} \text{ torr} \) with this 8 l/s pump. These numbers assume negligible ultimate pressure for the pump employed.

Next we consider how to determine the conductance parameter for a given geometry; for example, how the 0.3 l/s figure was arrived at in the foregoing example.

**Conductance of Various Geometries in the Molecular Flow Regime or A Short Guide to Roth’s Text**

The most accurate means of calculating conductance, particularly in an articulate geometry, is the Monte Carlo technique.\(^4\) This technique is not only practically useful, but is instructive in illustrating the meaning of conductance. We review this technique first, and then go on to consider some simple geometries where the conductance calculation is analytically tractable, and provides helpful results for quick, “zeroth-order” estimates.

**Monte Carlo Calculation of Conductance**

Consider a geometry with two ports, an inlet and an outlet. The geometry we suppose connects two large chambers at prescribed pressures. The most fundamental way of computing the conductance of the geometry is as follows. We randomly select a collection of particle velocities \( V \) from the Maxwell-Boltzmann distribution, and randomly select a position \( R \) on one port aperture, from a uniform distribution. For each value \( (R, V) \) we launch a particle (numerically) into the aperture. When the particle hits a boundary, we select a new \( V \) again from the Maxwell-Boltzmann distribution. We continue tracking the particle until it exits one of the apertures and we make a note of which aperture this particle exited through. After we have finished this procedure for all values \( (R, V) \) at this port, we have arrived at a value for the probability of transmission from this port to the other port, just the ratio of the number of transmitted particles, to the number of particles employed in the sampling. We may compute the conductance of the geometry in terms of these probabilities \( P_{i \rightarrow o}, \ P_{o \rightarrow i} \). In steady state, we may enumerate the fluxes of particles in various directions.

\(^6\) In general, for materials in “as-received” condition, particularly for rusty, cast or anodized materials, this figure could be as high as \( \hat{Q}_v = 1 \times 10^{-6} \text{torr} \cdot \text{l/s} \cdot \text{cm}^2 \). See, for example, D. J. Santeler, D. W. Jones, D. H. Holkeboer, and R. Pagano, “Vacuum Technology and Space Simulation”, National Aeronautics and Space Administration (1966) NASA SP-105. Chapter 9, “Outgassing of Materials” (pp. 197-222).

\(^7\) Richard S. Callin (private communication).
The net flux of particles is given by
\[ N' = N'_{i\rightarrow o} - N'_{o\rightarrow i} = A_i \phi_i p_{i\rightarrow o} - A_o \phi_o p_{o\rightarrow i}. \]

Making use of \( \phi_i = V_{avg} n_i / 4, \phi_o = V_{avg} n_o / 4 \) we have
\[ N' = \frac{1}{4} V_{avg} (n_i A_i p_{i\rightarrow o} - n_o A_o p_{o\rightarrow i}). \]

On the other hand, when \( n_o = n_i \) the system is in equilibrium, and we should have no net particle flow. This implies \( A_i p_{i\rightarrow o} = A_o p_{o\rightarrow i} \), and permits us to express
\[ N' = \frac{1}{4} V_{avg} A_i p_{i\rightarrow o} (n_i - n_o). \]

Making use of the definition of conductance we see that
\[ C = \frac{1}{4} V_{avg} A_i p_{i\rightarrow o} = C_A p_{i\rightarrow o}, \]
where \( C_A = V_{avg} A_i / 4 \) is just the conductance an the aperture of area \( A_i \) (more on this shortly). In this way the conductance of an arbitrary two-port geometry may be computed by (1) numerically computing the probability of transmission from inlet to outlet \( p_{i\rightarrow o} \) and (2) multiplying that probability by the conductance of the inlet aperture.

In order to check the results of a Monte Carlo calculation, and just as a matter of convenience, one would like, however to have some analytic results for various common geometries. We consider six examples, following Roth. Two are elementary: an aperture and a tube. The others are compound elements constructed from apertures and tubes.

**Aperture**

First we consider an aperture of area \( A \) in a plane separating two volumes at pressure \( P_i \) and \( P_o \) as depicted in Fig. 3. The number of particles crossing per unit time from volume 1 to volume 2 is
\[ N'_{i\rightarrow o} = A \phi_{i\rightarrow o} = A \frac{1}{4} n_i V_{avg}, \]
and the number crossing per unit time in the other direction is
\[ N'_{o\rightarrow i} = A \phi_{o\rightarrow i} = A \frac{1}{4} n_o V_{avg}. \]
Thus the net flux of particles per unit time between the two volumes is
\[ N' = A \frac{1}{4} (n_i - n_o) V_{avg}. \]
From the definition of conductance, \( N' = C (n_i - n_o) \), and thus the conductance of the aperture is
\[ C = \frac{1}{4} AV_{avg} \approx 3.63 \text{ liter sec}^{-1} A \text{(cm}^{-2}\) \( \left( \frac{T(\text{K})}{M(\text{amu})} \right)^{1/2}. \) (thin aperture, area \( A \).)
For air at 293.15 K (20°C) this is $C = 11.5 l/s A (cm^2)$.

**FIGURE 3.** The simplest geometry consists of simply an aperture as depicted on the left. A somewhat less abstract version of the application is shown on the right.

**Long Tube**

Next we consider a long thin tube of constant cross-section and compute the conductance between two imaginary planes cutting the tube, separated by a length $L$, as shown in Fig. 4.

**FIGURE 4.** We consider conductance between two imaginary planes a length $L$ apart in a tube of constant cross-section.

First we compute the variation in number density between the two planes. Our model of the surface-interaction consists of the assumption that particles hitting the wall are re-emitted in random directions with a velocity distribution consistent with the isothermal assumption. In a length $dz$, the rate of longitudinal momentum transfer to the vessel walls is

$$dp' = MV_{avg} \phi W dz,$$

where $W$ is the wall circumference. Meanwhile, the longitudinal force applied to the ensemble of particles streaming through the tube is

$$dF = AdP = Ak_BT dn,$$

where $A$ is the tube cross-section, and $dP$ is the incremental drop in pressure corresponding to the drop in particle number $dn$, as we proceed down the tube a distance $dz$. Conservation of momentum dictates that $dp' = -dF$, and thus
− \frac{dn}{dz} = \frac{MV_{avg} \phi W}{Ak_bT} = \frac{MV_{avg}}{Ak_bT} (\frac{1}{2}nV_{avg}) W = \frac{2}{\pi} \frac{W}{A} n.

Evidently then the density variation takes the form

\[ n_2 = n_1 \exp\left(-\frac{2}{\pi} \frac{W}{A} L\right), \]

for plane \#2 a length \( L \) downstream of plane \#1. The net flux of particles rightward out of plane \#2 corresponds to

\[ N' = \eta AV_{avg} n_2 / 4, \]

where \( \eta \) is a correction for the geometry that Roth puts at \( \eta \approx 32/3\pi \). (We can check such factors with a Monte Carlo calculation.) From the definition of the conductance we have then

\[
C = \frac{N'}{(n_1 - n_2)} = \frac{8}{3\pi} \frac{AV_{avg} n_1 \exp\left(-\frac{2}{\pi} \frac{W}{A} L\right)}{n_1 - n_2},
\]

\[
= \frac{2^{9/2}}{3\pi^{3/2}} A \left(\frac{k_bT}{M}\right)^{1/2} \left[\exp\left(\frac{2}{\pi} \frac{W}{A} L\right) - 1\right]^{-1}.
\]

In practical units this is

\[
C \approx 12.3 \text{ls}^{-1} A \left(\frac{\text{cm}^2}{\text{cm}^4}\right) \left(\frac{T^{(\circ K)}}{M(\text{amu})}\right)^{1/2} \left[\exp\left(\frac{2}{\pi} \frac{W}{A} L\right) - 1\right]^{-1}
\]

\[
= 19.4 \text{ls}^{-1} \frac{A^2 \left(\text{cm}^4\right)}{W(\text{cm})L(\text{cm})} \left(\frac{T^{(\circ K)}}{M(\text{amu})}\right)^{1/2},
\]

with the last approximate equality corresponding to the limit \( WL/A \ll 1 \). For air at 293.15\(^\circ\)K (20\(^\circ\)C) this is

\[
C \approx 61.6 \text{ls}^{-1} \frac{A^2 \left(\text{cm}^4\right)}{W(\text{cm})L(\text{cm})},
\]

For a rectangular cross-section of dimensions \( a \times b \), this is

\[
C \approx 30.8 \text{ls}^{-1} \frac{a^2 b^2 \left(\text{cm}^4\right)}{(a + b)(\text{cm})L(\text{cm})}.
\]

This result should be multiplied by a correction factor, \( K \), that varies from \( K \approx 1.11 \) for \( b=a \), to \( K \approx 1.44 \) for \( b=0.1a \).

From this analysis one can see why the vacuum pump literature suggests using the largest diameter, shortest tubing possible in making the pump connection. Of course, one doesn’t need a formula to appreciate this, in view of the interpretation of conductance in terms of inlet aperture.
area and transmission probability.

**Short Tube**

The last result applies to conductance between two imaginary planes in a tube. In general, and particularly in the case of a short tube connecting two chambers, one would like to account also for the conductance of the entrance aperture. This is accomplished by computing the conductance of the aperture and the tube separately, and adding the reciprocals as for elements in series. The picture is that of Fig. 5. The result is

\[
\frac{1}{C} = \frac{1}{C_A} + \frac{1}{C_t},
\]

with \(C_A\), the conductance of the aperture, and \(C_t\), the conductance of the tube as computed from the previous formulae.

\[ \text{FIGURE 5. We consider a short tube between two chambers. The assumption is made that the chambers are of infinite cross-section.} \]

**Diaphragm**

Next consider the geometry depicted in Fig. 6, consisting of an aperture of area \(A\), a tube of uniform cross-section, and a smaller aperture of area \(A'\). We may add reciprocals as for elements in series. The conductance \(C\) may be computed as

\[
\frac{1}{C} = \frac{1}{C_t} + \frac{1}{C_A'},
\]

with \(C_t\), the conductance of the tube, and \(C_A'\), the conductance of an aperture of area \(A'\). Equivalently we may proceed along the tube in the opposite direction, and compute \(C\) as

\[
\frac{1}{C} = \frac{1}{C_A} + \frac{1}{C_t} + \frac{1}{C_D},
\]

where \(C_D\) is the conductance of the aperture \(A'\) taking account of its situation as a diaphragm in a tube (as opposed to an aperture in a plane). Equating these two results, we obtain the conductance associated with the diaphragm,

\[
\frac{1}{C_D} = \frac{1}{C_A'} - \frac{1}{C_A} \quad \Rightarrow \quad C_D = \frac{C_A'}{1 - A'/A},
\]
We consider a short tube between two chambers, with a *diaphragm* on one port, i.e., a constriction of aperture $A'$ smaller than the tube cross-section $A$. The assumption is made that the chambers are of infinite cross-section.

**Two Tubes**

Next consider the geometry depicted in Fig. 7, consisting of two tubes of uniform and similar geometry, the larger with aperture of area $A$, the smaller with area $A'$. We distinguish the joining aperture by referring to it as a flange, and wish to account for the conductance of this flange in series, $C_F$. The conductance $C$ of the assembled geometry may be computed as for elements in series. From left to right we have

$$
\frac{1}{C} = \frac{1}{C_A} + \frac{1}{C_1} + \frac{1}{C_F} + \frac{1}{C_2},
$$

and from right to left we have

$$
\frac{1}{C} = \frac{1}{C_{A'}} + \frac{1}{C_2} + \frac{1}{C_1}.
$$

and equating these two results, we obtain the conductance associated with the flange,

$$
\frac{1}{C_F} = \frac{1}{C_{A'}} - \frac{1}{C_A} \quad \Rightarrow \quad C_F = \frac{C_{A'}}{1 - A'/A}.
$$
We consider two tubes of similar, uniform geometry, one with cross-section $A$, the other with cross-section $A'$. Elbow

Finally we note Roth’s result for an elbow between two tubes of identical geometry, as depicted in Fig. 8. Such an element may be treated as a tube of the same geometry, albeit with the length extended by an amount depending on the tube width. For tube of circular cross-section and diameter $D$, Roth puts the tube equivalent length $L_e$ at $L_o < L_e < L_o + 1.33D$, where $L = L_1 + L_2$.

Distributed Gas Load

After pumpdown, when the system has reached a steady-state between outgassing and pumping, one is often interested to know the pressure profile within the device. In the example illustrated in Fig. 1, the gas load was lumped at the end of a prescribed conductance. It is not uncommon however to be faced with a gas load distributed through an extended geometry. In this connection let us consider a simple example, corresponding to a linear element of a vacuum system, with distributed gas load per unit length $Q'$ (just the specific gas load per unit area multiplied by the circumference). Let us denote the inverse conductance per unit length (resistance per unit length) by $R$. Then, in a length $dz$ of the linear element, proceeding away from the pumping port, we have an increment to the gas load throughput given by $dQ = -Q' dz$, and we have an increment in pressure $dP = QR dz$. Putting these two relations together we have
\[ \frac{dQ}{dz} = -Q', \quad \frac{dP}{dz} = QR, \quad \Rightarrow \quad \frac{d^2P}{dz^2} = -RQ', \]

and we suppose the resistance per unit length is constant for simplicity. This relation is easily solved once we know the boundary condition to be applied. At a closed end, throughput must vanish, and thus \( \frac{dP}{dz} \propto Q = 0 \). The solution for the pressure profile takes the general form

\[ P(z) = P(0) + zP' - \frac{1}{2} z^2 RQ', \]

where the constant \( P' \) is to be determined from the boundary condition. For a tube extending from a pump inlet at \( z=0 \), to a closed end at \( z=L \), we have

\[ \left. \frac{dP}{dz} \right|_{z=L} = P' - LRQ' = 0 \quad \Rightarrow \quad P' = LRQ'. \]

The pressure profile then takes the form

\[ P(z) = P(0) + L^2 RQ' \left( \frac{z}{L} \right) \left( 1 - \frac{z}{2L} \right) = P(0) + \frac{Q_v}{C} \left( \frac{z}{L} \right) \left( 1 - \frac{z}{2L} \right), \]

where \( C = 1/RL \) is the conductance of the tube, and \( Q_v = Q'L \) is the net outgassing throughput, computed as the product of area-specific outgassing throughput multiplied by the interior wall area. The pressure at the pump inlet has been determined from our transient analysis, \( P(0) = Q_v / S_{p0} \), where we neglect the outgassing intrinsic to the pump (i.e., zero ultimate pressure for the pump alone). Thus we have

\[ P(z) = Q_v \left[ \frac{1}{S_{p0}} + \frac{1}{C} \left( \frac{z}{L} \right) \left( 1 - \frac{z}{2L} \right) \right]. \]

Maximum pressure occurs at the closed end at \( z=L \), and is given by \( P(L) = Q_v / 2C \), in the limit of conductance-limited flow (\( S_{p0} \gg C \)). This is one-half the value one would compute by naively lumping the load at one end of the device.

**Application of Standard Formulae to a W-Band Linac Section**

In this section, we apply formulae noted in the previous sections, for air at 293.15 K (20°C). In the following, and for simplicity, we neglect the outgassing intrinsic to the pump. For the sake of reference, however, note that the specification for the Varian VafIon 8 l/s (the pump of choice at SLAC) lists an ultimate pressure below \( 10^{-11} \) torr. This corresponds to an intrinsic outgassing throughput somewhere below \( Q_p = 8 \times 10^{-11} \) torr l/s cm². This ultimate pressure is sufficiently far below the nominal \( 10^{-9} \) torr requirement typical of linacs that we ignore it. We also neglect the distributed character of the outgassing, recognizing that the correction factor for maximum pressure is a factor of 1/2. We are persuaded to simplify our estimates to this degree based on the experience that formulaic conductance values tend to deviate at the few 10% level from the more rigorous Monte Carlo results for the assembled geometry.

**Waveguide Network**
The simplest conductance to calculate for a W-Band accelerator is that of the connecting guide. For a rectangular tube we have

\[ C = \frac{30.8 \text{ l/s}^{-1} \frac{a^2 b^2 (\text{cm}^4)}{(a + b)(\text{cm}) L(\text{cm})^3}} \]

and for the smaller standard waveguide sizes, \( b = a/2 \). Multiplying by a correction factor \( K \approx 1.15 \) for this aspect ratio, we have

\[ C = \frac{5.90 \text{ l/s}^{-1} \frac{a^3 (\text{cm}^3)}{L(\text{cm})}}{(b = a/2)} \]

and using \( a = 0.254 \text{ cm} \) as for WR10, and taking \( L = 30.48 \text{ cm} \) as for a length of 1 foot, we have \( C \approx 3.2 \times 10^{-3} \text{ l/s}^{-1} \). We may compare this to the series conductance presented by a matching iris, using \( C = 11.5 \text{ l/s} A (\text{cm}^2) \) for an aperture. We estimate the area as \( A = ab/2 = a^2/4 \), and for \( a = 0.254 \text{ cm} \), this gives \( C = 0.19 \text{ l/s} \), much larger than the conductance of the guide, and thus a small correction. The two become equal for a guide length of 0.53 cm.

This value for conductance is quite small. We assume a gas load looking into the structure of \( Q_v \approx 10^{-10} \text{ torr l/s} \); this corresponds to a specific outgassing rate of \( \hat{Q}_v = 10^{-11} \text{ torr l/s - cm}^2 \) as discussed further below. Assuming a theoretical pumping speed of 8 l/s, the asymptotic pressure is \( P_v(\infty) = Q_v / C = 3 \times 10^{-8} \text{ torr} \). While these considerations suggest that end-pumping might be acceptable, if one were willing to relax the requirement to a few on the 9-scale, they also suggest that one consider pumping closer to, or integral to the structure. If the pump inlet is located closer the structure, say 0.5 cm down the guide from the end-cell, conductance of the guide and coupling iris in series would be 0.1 l/s, corresponding to \( 10^{-9} \text{ torr} \).

In passing let us note that pumpdown time-scale depends on the volume, and is conductance limited, \( T_v \approx V/C \). The volume of the guide itself is 0.98 cm\(^3\) or \( 10^{-3} \text{ l} \), so that \( T_v \approx 0.3 \text{ sec} \). Generally, one may expect that W-Band structures will reach steady-state much more quickly than the longer wavelength accelerator structures. While this sounds good, we shouldn’t forget that the reverse side of the coin is that they are much less tolerant of outgassing; rf induced outgassing will be a big concern.\(^9\)

**Structure Version 0.1**

The simplest estimate of the conductance for a W-Band planar structure would consider rectangular guide and ignore the periodic roof indentations. The length would be \( L = 50 \lambda/3 \approx 5 \text{ cm} \), with \( \lambda \) the free-space wavelength. The aperture, as a first estimate, would be symmetric with \( a \approx b = \lambda/\sqrt{2} \approx 0.23 \text{ cm} \). In this case

\[ C \approx 15.4 \text{ l/s}^{-1} \frac{a^3 (\text{cm}^3)}{L(\text{cm})} = 4 \times 10^{-2} \text{ l/s}^{-1}. \]

This value for conductance is quite small. Assuming a specific outgassing rate of \( \hat{Q}_v \approx 10^{-11} \text{ torr l/s - cm}^2 \), the wall area of \( A_w = 2a(a+2L) \approx 4.7 \text{ cm}^2 \) corresponds to an outgassing rate of \( \hat{Q}_v \approx 10^{-11} \text{ torr l/s - cm}^2 \).\(^9\)

\(^8\) See Roth, p. 85.

\(^9\) As a reminder, we note that depending on the preparation, the value for copper outgassing can be 4 orders of magnitude larger than that used here for vacuum-prepped copper.
outgassing throughput of $Q_v = A_w \dot{Q}_w \approx 5 \times 10^{-11}$ torr l/s. With a theoretical pumping speed of 8 l/s, with the pump connected directly to the structure, the asymptotic pressure is $P_v(\infty) = Q_v / C \approx 1 \times 10^{-9}$ torr. After the correction of 1/2 for the distributed load, one is left with a safety factor of 2. This vacuum would be considered an acceptable vacuum for high-power rf work. Pumpdown time-scale depends on the volume, and is conductance limited, $T_v \approx V / C$. The volume of the structure is 0.98 cm$^3$ or $3 \times 10^{-4}$ l, so that $T_v \approx 7$ sec.

**Structure Version 0.2**

Concerned with possible difficulties in pumping the structures from the end, P. J. Chou incorporated vacuum manifolds in his design. Let us consider first a simpler geometry consisting of a pumping port on each cell, as seen in Fig. 9.

![Figure 9. Model of pumping manifolds in the W-Band structure.](image)

We consider a working volume corresponding to one W-Band cell, with transverse dimensions on the order of $a = b = \lambda / \sqrt{2} \approx 0.23$ cm, and length $L = \lambda / 3 \approx 0.11$ cm, so that $V = abL \approx 6 \times 10^{-6}$ l, and the wall surface area is $A_w = 2a(a + 2L) \approx 2.1 \times 10^{-1}$ cm$^2$. Assuming a specific outgassing rate of $\dot{Q}_w \approx 10^{-11}$ torr l/s cm$^2$, the outgassing throughput is $Q_v = A_w \dot{Q}_w = 2 \times 10^{-12}$ torr l/s. The pumping manifold we suppose is a rectangular tube with height and width 1/2 that of the full cell. We assume the length of the cell is held to 2 cm. The conductance is then

$$C = 15.4 \text{ l}s^{-1} \frac{(0.23/2)^3}{2} \approx 1 \times 10^{-2} \text{l}s^{-1}.$$  

The asymptotic pressure is then $P_v(\infty) = Q_v / C = 2 \times 10^{-10}$ torr assuming conductance limited pumping. This is an improvement by an order of magnitude over pumping from the ends of a 2” structure. After the correction of 1/2 for the distributed load, one is left with a safety factor of 10.

**Structure Version 0.3**

The geometry actually developed by P. J. Chou has a wide manifold covering the full length of the structure. Let us consider this employing the picture of Fig. 8, but now appreciating that the volume to be pumped has length $L \approx 50 \lambda / 3 \approx 5$ cm, and wall area

---

\[ A = 2a(a + 2L) \approx 5\text{cm}^2, \] corresponding to outgassing throughput \( Q_V \approx 5 \times 10^{-11} \text{torr} - \text{l/s}. \)

Conductance of the manifold in this geometry is

\[
C \approx 30.8 \text{ls}^{-1} \frac{(a/2)^2 L}{(a/2 + L)L_m} \approx 30.8 \text{ls}^{-1} \frac{(a/2)^2 L}{L_m} \approx 30.8 \text{ls}^{-1} \frac{(0.23/2)^2 5}{2} \approx 1 \text{ls}^{-1},
\]

with lengths in units of cm, and where we assume that the manifold height \( a/2 \) is one-half that of the accelerating cell. The manifold width is the structure length \( L \), and the manifold length is \( L_m \approx 2\text{cm} \). Notice that since \( Q_V = A \dot{Q}_V = 2aL \dot{Q}_V \), \( P_V(\infty) \approx Q_V / C \propto L_m / a \) and is independent of structure length as one would expect for distributed pumping.

Asymptotic pressure in this case is \( P_V(\infty) \approx 5 \times 10^{-11} \text{torr} \), assuming conductance limited pumping (i.e., theoretical pumping speed much larger than 1 l/s), representing a factor of four improvement over the parallel manifolds, and a factor of 40 improvement over end pumping. After the correction of 1/2 for the distributed load, one is left with a safety factor of 40.

**Structure Version 0.4**

Finally, let us consider a somewhat more realistic geometry, as a check of the foregoing estimates, made for simplified geometries. We assume end-pumping, with pumps of theoretical speed \( S \), and negligible ultimate pressure for the sake of illustration. We take up the geometry illustrated in Fig. 9. Splitting this structure in the middle, we see that throughput at the midplane is zero, from symmetry. In this case we may we may view the geometry as two lines in parallel, closed off at one end and pumped from a common port, at speed 2\( S \). Thus if the structure conductance from one port to the other is \( C \), the equivalent conductance is \( 2C \), and the ultimate maximum pressure (at the midplane, neglecting outgassing from the pump, and assuming conductance-limited flow) is \( P_V(\infty) = Q_V / 4C \), where an additional factor of 1/2 arises from the distributed character of the outgassing. Let us then compute the conductance, \( C \). As indicated in Fig. 10, we must account for the guide conductance \( C_w \), the conductance of the iris \( C_i \), the cell conductance \( C_C \), the conductance of the aperture to the beam tube \( C_A \), the conductance of the tube itself, \( C_T \), and, at the other end of the structure, the conductance of the aperture to the coupling iris tube, \( C_{WA} \). Total conductance for these series elements is then determined from

\[
\frac{1}{C} = \frac{1}{C_w} + \frac{1}{C_i} + \left( \frac{1}{C_C} + \frac{1}{C_A} + \frac{1}{C_T} \right) \times N + \frac{1}{C_{WA}} + \frac{1}{C_i} + \frac{1}{C_w}.
\]

We evaluate each of these terms. The waveguide is a rectangular pipe,

\[
C_w \approx 5.90 \text{ls}^{-1} \frac{(0.254)^3}{1} \approx 9.7 \times 10^{-2} \text{ls}^{-1} \quad (1 \text{cm of WR10}),
\]

the coupling iris we treat as an aperture,

\[
C_i \approx 11.5 l/s (0.254/2)^2 = 0.19 \text{ls}^{-1} \quad \text{(coupling iris)},
\]

the accelerating cell is a rectangular pipe,

\[
C_C \approx 15.4 \text{ls}^{-1} \frac{(0.23)^3}{0.11 \times 0.9} = 1.89 \text{ls}^{-1} \quad \text{(one 2\pi/3 W – Band Cell)}.
\]
Next we have the aperture to the beam tube and this we treat taking into account the “flange” effect, and an area ratio of 1/4,

\[ C_A \approx 11.5 \, l/s \, \frac{(0.23/2)^2}{1 - 1/4} = 0.20 \, l/s^{-1} \]  (flange between tubes),

The beam tube itself, coupling cells together, corresponds to

\[ C_T \approx 15.4 \, l/s^{-1} \, \frac{(0.23/2)^3}{0.11 \times 0.1} = 2.13 \, l/s^{-1} \]  (coupling tube).

\[ \text{FIGURE 10. Approaching a realistic model of an accelerator section. Here 5 cells are shown; we consider } N \text{ cells, with } N=50. \]

Since we are treating the iris as an aperture, we needn’t separately enumerate \( C_{WA} \). We have

\[
\frac{1}{C} = 2\left( \frac{1}{C_W} + \frac{1}{C_I} \right) + \frac{1}{C_C} + \frac{1}{C_A} + \frac{1}{C_T} \times N
\]

\[
\approx 2\left( \frac{1}{9.7 \times 10^{-2}} + \frac{1}{0.19} \right) + \left( \frac{1}{1.89} + \frac{1}{0.20} + \frac{1}{2.13} \right) \times 50.
\]

or \( C \approx 3.0 \times 10^{-3} \, l/s^{-1} \), this is approximately (75% of) just the conductance of 50 tube-apertures.

With \( Q_v \approx 5 \times 10^{-11} \, l/s \), ultimate pressure is \( P_v(\infty) = Q_v / 4C \approx 4 \times 10^{-9} \) torr. For this example, we have taken coupling tubes to have 1/4 the area of the cells themselves, and to occupy 10% of the length. Actual mileage may vary.

**Practical Pumps & Gauges**

Roth provides an extensive discussion of pumps and gauges, and an abundance of helpful literature may be found elsewhere, particularly in the training literature for vacuum technicians and
service representatives.\textsuperscript{11,12} Here we offer just a word or two.

To produce a vacuum one employs a pump; there are three general classes of pumps: positive displacement pumps (rotary pump, for rough vacuum), momentum exchange pump (turbomolecular pump, diffusion pump), capture & hold pump (sorption pump, cryopump, getter, ion-pump). These classes correspond roughly to: displacing a volume of molecules from the system, knocking individual molecules out of the system, or capturing molecules to a surface. Many pumping systems are actually a hybrid of these.

It is common practice at SLAC to employ \textit{sputter ion pumps}, and to employ pump current as the vacuum readout. A cartoon of such a pump is shown in Fig. 11. Generically, ion-pumps employ a stream of electrons flowing through a working volume ionizing the working gas that is to be removed. Efficiency of ionization is improved by extending the electron path length through the gas, and this requires an applied magnetic field of order kG. Ions are guided out of the volume bulk by means of an applied electric field derived from voltages on the order of kV. Sputter ion pumps fall into the class of “cold-cathode ion-sorption” pumps. \textit{Cold-cathode} refers to the cathode producing the electrons. Generically, “sorption” refers to either adsorption or absorption; in an ion-sorption pump, ions produced by the electron stream land on the cathode, and are \textit{adsorbed}. The adsorption process can be either physical adsorption, or chemical adsorption, as when an oxide is formed with the ion and the trapping material (typically, titanium). The “sputter” qualifier refers to the circumstance that the cathode trapping material is continuously sputtered (knocked off by impinging ions) depositing fresh trapping material (e.g., titanium) on the surface. Current collected in this manner provides a measure of the ambient density of the working gas, with a calibration factor depending on the ionization rate, itself a function of the electron voltage and the cross-section appropriate for the gas constituents. Notice that some gases are less easily ionized and less reactive than others (less prone to oxide or nitride formation as required for chemisorption); for example, noble gases have relatively high ionization potentials, and for this reason, argon is not easily pumped by ion-pumps, and the ion-pump current does not accurately reflect the density of argon, if the calibration factor for, say, nitrogen is used.

Let us elaborate a bit on the function of the trapping material. This material is referred to as a “getter” and in fact ion-sorption pumps are also referred to as getter-ion pumps. The gettering or trapping action takes advantage of the fact that the gaseous constituents common to air (with the exception of argon) will react with a metal surface; titanium, meanwhile, easily forms \textit{stable, low vapor-pressure} nitrides and oxides. When ions react with the surface forming nitrides or oxides, they are removed from the system, never to return unless there is some gross disturbance to or heating of the gettering surface. This is referred to as chemisorption. While titanium is most commonly employed, the first getter used was barium; in addition zirconium-aluminium compound, magnesium, niobium, and vanadium have been used. As a layer of chemisorbed compounds develops on the surface, the getter needs to be refreshed; in situ, the solution for this is to deposit a new layer of getter material, and this can be accomplished with either a sublimating source (one sufficiently hot for atoms to go from the solid state directly to vapor), an evaporating source (liquid to vapor), or a sputtering source (where atoms are knocked off). Other getter removal mechanisms are physical adsorption (trapping of a molecule) or diffusion into the bulk, as for hydrogen on titanium. In passing we note that titanium sublimes (solid-vapor transition) at 1110°C.

\textsuperscript{12} \textit{Fundamentals of Vacuum Technology}, Purdue University, Genesys Systems Inc., 1180 East Meadow Drive, Palo Alto, CA 94303, Tel: 415-494-3701
For the sake of illustration let us note some particulars of the pump most commonly employed for rf work at SLAC, the Varian 8 l/s VacIon Pump, employed as illustrated in Fig. 12. The pump consists of two parts, the pump body and a magnet assembly consisting of a magnet and a magnet bracket. Other parts and accessories consist of two cables; one is a 13' HV cable (Teflon insulated, stainless steel wrapped, bakeable to 250°C), the other is a 10' cable with right angle connector. Specifications are: 8 l/s for nitrogen, 40,000 hr (≈4 yr) lifetime at 10⁻⁶ torr, maximum operating voltage 3.3 kVdc±10%, maximum starting pressure 10⁻² torr, ultimate pressure 10⁻¹¹ torr, maximum baking temperature 400°C for the pump and 300°C for the magnet. The ambient temperature during operation should be 32°F to 105°F (0°C to 40°C). Pump interior volume is 0.4 l. The pump flange is 2.75" OD ConFlat. The maximum confined magnetic field is 1400 G, and the magnet fringe field at the flange is 200 G. Calibration factor for nitrogen corresponds to 1 μA at 10⁻⁸ torr. For operation of the controller it is helpful to know that this is a diode-type pump, so that the “+” setting should be used for output polarity on the controller back panel. System should be roughed to 10⁻² torr (10⁻³ torr is recommended) prior to start of the ion pump. Once the voltage has reached 2 kV, the front panel START-PROTECT switch may be placed in the PROTECT setting, and any subsequent rise above 5×10⁻⁴ torr will result in shutoff of the pump. While the open-circuit voltage is 3.3 kV, peak voltage in operation is about 1.8 kV, occuring at 50 mA, corresponding to about 90 W. Protect circuit shutoff current is 65mA±20%. The manufacturer states that “the accuracy obtained is comparable to that of a good ionization gauge.” Taking this to be the case, and given various studies of, for example, Granville-Phillips ionization gauges, we may expect the pump current to provide an accurate measure of pressure (assuming nitrogen) at the level of a factor of two. Pump current reading is not considered accurate below 10⁻⁸ torr, where

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an ionization gauge is more properly employed—- if it is really necessary to know the pressure in
that limit. For rf applications, one is typically happy to know that the vacuum is below the 8-scale,
and leave it at that.

![Vacuum System Diagram](Varian_87-900-002-01)

**FIGURE 12.** Example of a schematic for a vacuum system employing an ion pump, based on Varian 87-
900-002-01.

The manufacturer states achievable pressure below $10^{-11}$ torr. This figure and the theoretical
pumping speed permit us to estimate the intrinsic outgassing, using $P_r(\infty) = Q_p / S_p$. Thus
$Q_p \approx 8 \times 10^{-11}$ l/s $\cdot$ cm$^2$. This is in fact comparable to the outgassing expected from a 2”
structure; however, we know from our analysis that since we are operating in the regime of
conductance-limited flow, it has negligible effect on the ultimate pressure attainable in the structure.

By the way, in connection with roughing, let us observe that we have given short-shrift to
the viscous flow regime; this is not unreasonable, since, for typical geometries, conductance is
higher there than in the molecular flow regime.

**Future Work**

It seems clear that with any of the pumping schemes mentioned we can reach 9-scale
vacuum. The worst case is end-cell pumping corresponding to $5 \times 10^{-9}$ torr, or lower, depending
on the beam tube aperture. For distributed inlet pumping, one per cell, we obtain $2 \times 10^{-10}$ torr and
common-manifold pumping gives $5 \times 10^{-11}$ torr. Note that neither of these schemes suffers so
severely from the requirement of pumping through the cell-to-cell coupling tube. More precise
figures would be useful and so Monte Carlo calculation of actual conductance could be performed.
A code for this purpose exists (written some years ago for a different application) and can be
modified. The numerical calculation however is not too complicated and would could just as easily
write a new code. Convenient specification of the geometry is the only tricky part, and the code
thus written would require modification for any changes to the boundary layout.

Clearly one would like to see some demonstration of these numbers, particularly as a check
of the actual outgassing rate of EDM’d copper structures, after vacuum preparation (clean for
vacuum followed by 450° C bakeout). It would be quite helpful to have a high-power W-Band
source to gain practical vacuum experience with an operating structure, and future prototype
vacuum circuits. This will be an interesting aspect of the subharmonic drive experiment on the
NLCTA.
For a large-scale system, consideration of getter coatings for the connecting guide would be worthwhile. A distributed getter, combined with a common roughing manifold could greatly simplify the vacuum circuit for a 1 m W-Band linac. It would be very interesting to consider specially coated connecting waveguide and components for purposes of in situ auto-pumping of these miniature devices. A strategy for occasional in situ bakeout remains to be devised. The idea of structure as getter raises a number of questions. Would a Ti-coated structure have favorable vacuum features and acceptable electrical and pulsed-heating features? What degradation of wall $Q$ results from employment of a getter as both an electrical boundary and a pump? Does this degradation worsen over time? Would W-Band accelerator structures be routinely refurbished or replaced?

Also, one additional note on a slightly different subject. It seems interesting to observe that all of SLAC’s experience with breakdown studies has been situated in a vacuum chamber pumped by ion-sorption pumps, and that the primary indicator of breakdown in practical terms, has been the vacuum burst registered by the pump current (together with reflected power and X-ray burst registered by scintillator). Roth mentions that ion-pumps historically have been subject to vacuum bursts corresponding to disturbance of the sorption surface. One wonders if there could be some interaction between evanescent rf and the pumps, if perhaps our breakdown experience is to some degree influenced by our choice of pump and pumping geometry.