THE CONCORDIA DUST ACCELERATOR
DESCRIPTION AND GENERAL MANUAL

PROLOGUE

This booklet is an outline of the configuration and operational procedures of the accelerator and its adjuncts. The discussion is fairly comprehensive but by no means complete in detail; you should consult the journals, files, manuals and drawings listed in the preliminary pages. We refer to them at intervals in the text. The system was first installed at the NASA Greenbelt Laboratory, where it was used by Otto Berg and his group. In 1975 it was moved to Concordia, under an agreement initiated by Mr. Berg, to our great benefit. Much thanks and credit go wholeheartedly to him for his consistently strong interest in us. We also owe large thanks and credit to Robert Brummond, then chairman of the physics department, for his vision and energy. He was sure that the facility would be valuable and that we were capable of handling it, and he pursued the acquisition vigorously and competently.

I OVERVIEW

See Figure 1. The assembly begins with a pressurized Van de Graaff accelerator by High Voltage Engineering, rated at positive 2 MV although we have seldom if ever run it that high. We have altered somewhat the original construction, principally with respect to the vacuum and control systems.

Where a VdG would usually have an ion source, there is a device –the "injector"—which inserts "dust" particles, made of iron and typically about one micron diameter, into the accelerating column. Emerging from the VdG, particles traverse a grounded drift tube—the "CV" tube—which is fitted with sensors allowing us to measure the charge and velocity of each particle.

After passing through the CV tube, particles enter a chamber in which we may place some desired experiment. A student dubbed this chamber "corn popper" and we still call it that.

Adjunct to those components are the systems for VdG vacuum; particle measurement and control and readout; operational control; corn popper vacuum; tank gas filling and releasing; tank evacuation preparatory to filling.

Near the ground end of the VdG is a junction box cabinet. In the corner is a filing cabinet, containing reference material. In drawers along the wall there are capacitors, diodes, transistors, and resistors. Under the workbench there are two sets of drawers containing miscellaneous components and special parts; and under the workbench also there is a supply of paper tape for the printer in the CV console.

Especially note the injector tool box, stored under the workbench near its center (Figure 1).

II THE VAN DE GRAAFF MACHINE

II-A VACUUM SYSTEM

See Figure 2. The system is essentially conventional; we need only to make a few special remarks.

The high-vacuum gauge is the Phillips (Penning) type, which cannot burn out. But it has low sensitivity at pressures below 10^{-6} torr, and it may acquire carbon contamination leading to erroneously high readings. The first of these factors is not serious, since our operating vacuums are amply good for VdG operation. The second factor is handled by occasional cleaning. We have two spare Phillips gauge tubes, stored in the large cabinet near the door of the laboratory.

Notice the VdG diffusion pump water valve **VW-6**, located inside the VdG vacuum console as indicated in Figure 2.

We need not describe the general procedures and cautions for VdG vacuum startup, since the system is conventional. One special remark—begin with the Phillips gauge switched to the low (10^{-5} torr) range. When the diffusion pump is first switched on, the Phillips gauge also comes on, and reads initially around 70 or 80 microamperes on the 10^{-5} scale.

Remember to start the refrigerator.

Of course you must have the valves VAC-1 and VCV-1 to the accelerating column and the CV tube open. **But the valve VCP-1 to the corn popper is closed.**

Protections

The sensitrol relay on the forevacuum thermocouople gauge shuts off the diffusion pump if the forepressure is too high. In any case you must reset the sensitrol relay before turning on the diffusion pump.

There is a thermal switch on the diffusion pump wall to guard against water supply failure.

A "good vacuum-poor vacuum" relay disables the VdG accelerating voltage belt spray if the Phillips gauge exceeds about 20 (μA) on the 10^{-5} scale. That feature is only for protection against sudden large leaks, since we never operate the VdG unless the vacuum reading is below (say) 10 μA on the 10^{-6} scale. When the vacuum is initially coming down from startup, with the Phillips gauge still on the 10^{-5} scale, you may hear that relay clatter as the system switches from the "poor vacuum" condition to the “good vacuum” condition. The clatter may be alarming until you understand what is happening; observe the change in the corresponding pilot lamps.

Filling the Accelerating Column

If you need to remove the injector (Section III) you must fill the accelerating column with air. We now suppose that you have high vacuum.

Close valve VAC-1 (Figure 2) between the accelerating column and the manifold.

See Figure 3. Fill the accelerating column through valves VR-1 and VR-2, with the roughing forepump not running. Of course valve VR-3 to the CV tube is **closed**, since you still have high vacuum in the CV tube.

Recycling the Vacuum

See Figure 3. To recover the accelerating column vacuum, use the roughing system. Pump out the column through valves VR-1 and VR-4, with valves VR-2 and VR-3 closed and VR-5 open. The "roughing" thermocouple gauge tells you when you may close VR-1 and **cautiously** open valve VAC-1 to complete the pump-down. You may allow the Phillips gauge to go into the 10^{-5} range.

But if the forepressure goes too high, the sensitrol relay (Figure 2) shuts off the diffusion pump; you must then let the forepressure recover, and reset the circuit.

Shut down the roughing system when it is not in use.

Injector Leaks

If you have worked with the injector (Section III) you may not have replaced its vacuum seals properly. Then you have a very serious VdG vacuum leak, aggravated by the tank pressurization. Check the injector seals **carefully** before closing the tank. In addition, **watch the VdG vacuum readings** while pressurizing the tank (see below), to see whether or not the VdG vacuum is affected by the tank pressure. If there is an effect, **you must redo the guilty seals at once**. That is expensive in time and labor, since it involves taking down the VdG vacuum again. Thus, if you take extreme care in making the injector seals, you will save yourself a great deal of grief.

II-B TANK PRESSURIZATION

The VdG operates at a tank pressure up to a maximum of 375 lbs/in^2 above atmospheric pressure, with a mixture of CO_2 and N_2. (We buy our gases from Acme Welding.) Observe the tank-filling and tank-dumping system, Figure 4, located as shown in Figure 1.

Dumping the Tank

To release the tank gas, remove the hose coupling at the tank gas valve VTF-1 (Figure 4) and open VTF-1 moderately. Go away; the tank gas is unbreathable, although not toxic. Come back after a time and open VTF-1 a little wider. Finally, when the tank pressure is atmospheric, you may remove the tank bolts.

Caution: Disconnect the cable on the top of the tank at the ground end. That cable goes along the top of the tank to the generating voltmeter and the corona needle assembly. **If you forget** this job, you will have the pleasant task of rebuilding the connector.

Now you can roll the tank back to expose the accelerating column and the VdG ball.

Pressurizing the Tank

First be confident that the injector and its electronics are in proper condition and that the VdG belt runs properly (Section III). Also be as confident as possible that the injector vacuum seals are proper—see above, and Section III—and that you have replaced the VdG ball if you removed it (Section III).

Gently roll the tank into place; a blow to the tank base may alter the assembly alignment. Install **all** the tank bolts, tightening them evenly and snugly by repeated small increments in sequence.

Reconnect the cable above the tank.

See Figures 4 and 5. Connect the flexible delivery hose which runs from the gas bottles to the tank, at VTF-1. You will now remove most of the air from inside the tank, using the Stokes vacuum pump, so that the CO_2-N_2 filling will be essentially pure. Open valve VTF-2 to the tank vacuum gauge, and VTF-1 to the hose so that its air will be removed.

Start the Stokes pump. Close its relief valve VS-1 and open its valve VS-2 to the tank. The pump brings the tank pressure down to a fair level after perhaps an hour, a process which the tank vacuum gauge monitors.

Watch the VdG vacuum for evidence of a pressure-sensitive vacuum leak (see Injector Leaks, above).

When appropriate, close the Stokes valve VS-2, turn off the Stokes pump, and open the Stokes relief valve VS-1.

In filling the tank with CO_2 and N_2 it does not matter (by the law of partial pressures) which gas is put in first. But by habit we usually insert CO_2 first. So, connect the delivery tee
to the CO_2 tank.

Now for the **filling** process, **the following sequence is critical:**

(1) Have VTF-1 **open**. If you do not, the gas bottle pressure fills the delivery hose when the delivery valves are opened, and the hose may burst. With a vacuum in the tank, VTF-2 should also be open.

(2) CO_2 tee valve VTF-4 **closed**.

(3) Open the $C0_2$ bottle valve VTF-5.

(4) Open VTF-4 a small amount. You hear $C0_2$ start to flow. In the bottle, the $C0_2$ is liquid; as it flows into the tank, it evaporates, so that the $C0_2$ gas is cold, and the tee and the delivery hose become frosted. Limit the flow of $C0_2$ so that the frost line stops short of the valve VTF-1.

The cold gas causes thermal stress on the accelerating column; we don't want it to crack. Inside the tank at the gas inlet, is a gas-deflecting baffle which prevents the gas from impinging directly on the accelerating column.

(5) Watch the tank vacuum gauge. When it comes to zero, the tank pressure is atmospheric. Now **close** VTF-2, since the gauge is not designed for pressures above atmospheric. (One time, that precaution was neglected; you will notice that the gauge zero is offset. The gauge works, but we have that vestige of a past error.)

From the atmospheric point and up, the "positive" pressure gauge is your monitor. The full complement of CO_2 is 75 PSIG. You may stop short of that, if not intending to fill the tank to its full rated pressure. But you should maintain about the proper ratio of $C0_2$ to N_2 about 1/3 by absolute pressure contribution. You can add more $C0_2$ later, if desired, according to the physics of partial pressure. Example: suppose you take the $C0_2$ pressure to 30 PSIG. You have put in three atmospheres of $C0_2$. Then you want to put in about nine atmospheres of N_2 that is about 135 lbs/in^2; the total tank pressure will then be about 155 PSIG. More or less.

(6) **Close** VTF-4 and VTF-5. Move the delivery tee to the N_2 bottle.

(7) Admit N_2 to the tank, opening VTF-7 and VTF-6 **in that order**. Experience indicates that we can run the VdG up to about 1.6 MV with a total tank pressure of around 180 to 200 PSIG. But of course it is all right to go to the full rated tank pressure.

(8) Close VTF-6 and VTF-7, then **close** VTF-1. **Caution:** if you forget to close VTF-1, you will slowly lose the tank gas through leaks in the delivery hose seals.

II-C THE VAN de GRAFF VOLTAGE

The VdG accelerating voltage is obtained in the usual way, by spraying charge onto the belt, which (running) conveys positive charge to the ball and deposits it there.

The VdG Control Console Panels 1D and 1K

See Figure 6, showing this console. Starting at the top of the console and going downwards, the important components are (referring to Figure 6):

- VdG DMM accelerating volts meter—AC. The meter is AC because the VdG voltage is measured by a generating voltmeter (see appendix) which produces an AC output proportional to the (DC) VdG voltage. Our calibration of the VdG voltage is discussed in the appendix.
- Focus monitor DMM voltmeter--DC. The particle beam focus voltage in the accelerating column (Section IV) is set by rotating a motor-driven control rod which goes to the VdG ball. The motor is inside the tank at the ground end, and the motor switch is in console 1K below, as we shall note. Rotating the control rod also turns a potentiometer which the monitor voltmeter reads, so that this reading indicates the rotary posture of the control rod and is therefore an index of the focus voltage. See Section IV.
- Corona tube current meter. This meter reads the plate current of a vacuum tube to which the corona needle (Figure 1) is connected. The VdG voltage is stabilized by controlling the corona needle current (see Figure 7). A DC voltage rectified from the generating voltmeter is applied to one input of a differential amplifier; the other input of that amplifier is a reference voltage. The output of the amplifier goes to the grid of the vacuum tube. If the VdG voltage rises (falls), the tube grid voltage rises (falls), thus increasing (decreasing) the corona current and tending to lower (raise) the VdG voltage.
- Phillips gauge meter. This meter repeats the reading of the corresponding meter on the VdG vacuum console.

- VdG voltage meter, panel. From the generating voltmeter. The meter approximately matches the VdG DMM voltmeter above, but we use the DMM for VdG voltage readings (see Appendix A-C for troubleshooting).
- VdG DMM meter terminals. Leading from the generating voltmeter to the DMM above.
- VdG control reference voltage adjust. Sets the reference voltage for the corona amplifier discussed above. To raise (lower) the VdG voltage, you raise (lower) the reference voltage. The grid of the corona tube changes accordingly. The terminals allow you to read the reference voltage in volts; but we never do that, because the number would not be helpful.
- Injector pulse height control activation and injector DC control activation. The injector parameters of pulse height and DC voltage (terms explained in Section III) are set by control rods driven by master-slave Selsyn motors. The same master drives either of two slaves, so you must select which of the two you wish to control. Press one switch or the other.

  Note carefully: if you turn an **un**activated control, it rotates helplessly and its zero point is lost. Normally the injector DC is activated; rarely if ever do we bother with the injector pulse height.
- Control power switch. Powers the elements in the console, **after** the circuit breaker CB-1DO1 (below) has been closed.
- Injector pulse height adjust. Turns the Selsyn motor for that function, **if** the corresponding activation switch (above) has been pressed. Rarely if ever used.
- VdG belt spray variac. Adjusts the voltage of the spray needles at the ground end of the VdG charging belt, thus adjusting the rate at which charge is carried to the VdG ball.
- Belt motor switch. Turns on the belt drive motor, **after** the circuit breaker CB-1DO2 (below) has been closed.
- CB-1DO1 circuit breaker. Cuts off power to the console.
- CB-1DO2 circuit breaker. Cuts off power to the belt motor.

- Focus voltmeter terminals. Leads from here go to the focus voltmeter on top of the console, as discussed above.
- Focus voltage switch. Momentary contact; runs the control rod motor discussed above. The motor coasts a bit, after it has been turned off; so the best technique for changing the focus setting slightly is to tap the switch briefly, while watching the voltmeter.
- Corona needle adjust. We can move the corona needle towards the VdG ball or away from it; the corona current changes accordingly. That adjustment helps in setting the VdG voltage, as discussed below.
- Corona tube grid voltmeter. This voltage is affected by the control reference voltage adjustment (above), and by the VdG voltage as discussed below. For best regulatory operation, the grid voltage should be in the neighborhood of **negative** six volts.
- Injector DC adjust. Turns the Selsyn motor for that function, **if** the corresponding activation switch (above) has been pressed. **Caution:** be very careful about the activation switch for this control. To reset the zero of the injector DC is something of a nuisance.

Turning on the VdG Voltage

Take the following steps **in order:**

(1) **Open the tank water valve** VW-1 located in the VdG vacuum console (Figure 2). The tank water runs through a radiator inside the tank, cooling the tank atmosphere and especially the belt motor.

(2) Turn on the VdG voltmeter and the focus monitor voltmeter on top of the console.

(3) Close CB-1DO1.

(4) Close the control power switch above CB-1DO1.

(5) Check that the injector DC control activation is **on**.

(6) Check that the injector DC adjustment is at zero (CCW). You can try gently to turn it CCW. If it resists fairly vigorously, it is at zero. The Selsyn motors do not give a solid zero feeling.

(7) **Carefully make sure** that the VdG belt spray variac is zero.

(8) Close CB-1DO2.

(9) Close the belt motor switch above CB-lDO2. The belt starts, as you can hear. The VdG voltmeters may now show a voltage, which is **negative**, although these AC meters do not say so. A frictional charging action, common with VdG machines, charges the VdG ball negatively.

(10) Turn up the VdG belt spray variac to about the 20 mark. The VdG voltmeters go to zero and then come up again, now indicating a positive VdG voltage. The VdG voltage now generally comes to some balance value determined by the existing in-out position of the corona needle and the existing control reference voltage. If it sparks repeatedly, not settling to an equilibrium, you need to reduce the VdG voltage as outlined below. Repeated sparking occurs when the tank gas pressure is too low for the voltage which the VdG is trying to reach.

At a satisfactory equilibrium, the corona tube current is perhaps about 10 μA, and the corona tube grid voltage is around six volts **negative**. If you want more corona tube current, you can raise the belt spray variac a bit.

Note: This is outlined in detail on a laminated sheet hanging from the VdG console.

Achieving a Good Equilibrium VdG Voltage

A satisfactory equilibrium requires a coordinated adjustment of spray variac, corona needle position, and control reference voltage. The following sequence of steps is perhaps best, although your experience will teach you your own technique.

Observe the corona tube current. If it is very small and the corona tube grid voltage is not too negative, increase the spray variac a little. The VdG voltage does not change much, if the corona tube is working.

If the tube grid bias is too **large** (like –10 volts), the control circuit is trying too hard to raise the VdG voltage, by shutting off the corona current. You can restore the grid bias to its normal value of around –6 volts, either by moving the corona needle **out** a little (punch OUT and STOP) or by turning the reference voltage **down** CCW.

If the tube grid bias is too small (like near zero), the control circuit is trying too hard to lower the VdG voltage, by increasing the corona current. Restore the grid bias to its normal range of around –6 volts, either by moving the corona needle **in** a little (punch IN and STOP) or by turning the reference voltage **up** CW.

But perhaps your achieved equilibrium is not at the desired VdG voltage.

Changing the VdG Voltage to a New Equilibrium

To raise the equilibrium VdG voltage, turn up the reference voltage a limited amount. If that makes the corona tube grid bias too negative, move the corona needle out a little. By judicious manipulation you achieve equilibrium at the desired VdG voltage.

To **lower** the equilibrium VdG voltage, turn the reference voltage down a limited amount. If that puts the grid bias too close to zero, move the corona needle in a little. Again by a judicious combination you achieve equilibrium at the desired VdG voltage.

With practice, you acquire the required skill.

Shutting off the VdG voltage

Turn the injector DC adjustment to zero; turn the belt spray variac to zero. Shut off the belt motor. Turn off CB-1DO2. Turn off the control power. Turn off CB-1DO1. Turn off the DMM voltmeters on top of the console.

III THE PARTICLE INJECTOR

III-A BASIC DESIGN

See Figure 8. This drawing is schematic; but it is good enough for you to recognize the parts of the device.

The supply of dust for injection into the accelerating column is in a cavity within the "body" of the injector.

Above the dust, and insulated from it, is a flat perforated plate called the "tongue."

Attached to the body, and insulated from it, is the "base," which is removably bolted to the accelerating column.

Leading from the body cavity to the base cavity (also called the needle cavity) is a small hole A, Figure 8.

Leading from the base to the acceleration region is a second small hole B.

In the needle cavity, positioned with its point centered on hole B, is a tungsten needle with a point which may be made very sharp or alternatively rounded.

There is in the VdG ball a local positive DC voltage source, the "injector DC," locally powered but remotely adjusted from the laboratory ground, as mentioned in Section II-C. Of course the local ground for the injector DC is the frame of the ball.

The injector body is connected to that voltage; call it V_o.

The tongue is connected to the plate of the 6BK4 vacuum tube labeled VT1.

The spare 6BK4's are stored in a drawer marked "special tubes" under the laboratory bench near the filing cabinet.

The grid of VT1 is connected to the output of a local one-shot multivibrator.

In the quiescent state, VT1 is cut off, so that the voltage V_T at the tongue (relative to local ground) is V_o.

To inject a particle, the grid of VT1 is given a positive pulse—see Figure 9—by triggering the multi-vibrator from the laboratory through the chain of devices sketched in Figure 9.

Now VT1 conducts; V_T falls because of the current through R_1 in Figure 8.

The resulting electric field between the tongue and the dust raises some particles, making a cloud inside the cavity.

One or more of the cloud particles may get through hole A into the needle cavity.

Now the needle is at V_o and the base is at local ground. So there is a strong field at the tip of the needle. If a particle hits the needle, the particle becomes positively charged; the needle then repels the particle, which may pass through hole B into the accelerating column. The particle subsequently emerges into the laboratory with a kinetic energy equal to the product of its charge and the VdG voltage.

Clearly this process is chancy. One injection pulse to YT1 is by no means certain to yield a particle to the laboratory. But if the injector and dust are in good condition, if V_o and V_T are appropriate, if the beam focus is good, and if the system from injector to corn popper is aligned, then the yield can be satisfactory.

The dust is in good condition if it is dry and out-gassed. But pumping to the dust space is only through holes A and B in series; thus, when the vacuum is "young," the dust may be gassy.

III-B THE DUST

Our injector dust is spheres of carbonyl iron, meaning that the particles are produced by the reduction of iron carbonyl $Fe(CO)_X$ in a mist process.

All of our reserve supplies are stored in the large cabinet near the door of the laboratory. Our supply categories are:

A "the original" particle diameter around 1 micron

B particle diameter around 5 microns

C particle diameter around 5 to 10 microns

D particle diameter around 10 to 30 microns

III-C INJECTOR PULSING

The injection pulses given to VT1 (Figure 8) are generated by the arrangement shown in Figure 9. In the VdG ball, a one-shot multi-vibrator delivers—on command—a positive pulse to the grid of VT1. The amplitude of that pulse, determining the voltage excursion V_T (Figure 8) is adjusted as sketched in Figure 9, through the injector pulse height controlof Figure 6.

Performance tests have convinced us that the present (1995) adjustment is good enough; so we do not ordinarily bother with it, although of course you may if you like.

Commands to the VT1 multivibrator are generated as shown in Figure 9. The command is a pulse, transmitted through the LED—fiber optics cable—LSD chain, triggering the multi-vibrator in the ball.

There are two command sources, one in the "CV console" (Figure 1) and one in a box (the JS pulser) on top of the CV console. Using a switch in that box, you select the desired command source.

As discussed in Section IV, we use the CV command source when we are measuring the charges and velocities of particles; we use the JS pulser when we are testing the performance of the system. The CV console command source has three modes: manual, automatic at an adjustable rate up to roughly one per second, and semi-automatic at the same adjustable rate. In the manual mode, the operator must produce an injection pulse by pressing a switch. In the automatic mode, commands occur at the chosen rate without ceasing. In the semi-automatic mode, commands occur automatically until a particle is received and measured as described in Section IV, when the commands stop until the operator resets the mode.

The JS command source gives commands at a relatively high adjustable rate up to about five per second, and the particle measurement system in the CV console is not activated. The relatively high particle yield of the JS source makes it convenient for testing purposes, although we then get only oscilloscope indications of the particle flux. ("JS" is for James Schlotterback, the student who developed the device in 1987.)

Testing the Command Circuitry

We can make tests at two points. The first is at the LED terminal on the **outside** of the tank base, as indicated in Figure 9, where one can see with an oscilloscope the command pulses given to the LED. The second is at the plate of VT1, where **with proper precautions** one can see with an oscilloscope the excursions there. See Section III-E, and also the VdG journals.

III-D VdG BALL POWER, AND THE CHARGING BELT

See Figure 9. Power to operate the instrumentation in the VdG ball is supplied by two 110 VAC 60 Hz alternators which are inside the belt pulley in the ball. If the belt turns the pulley without slipping, the alternators work properly. But we have had trouble with the belt slipping on the pulley; then the ball instrumentation power is erratically low in both voltage and frequency. With the tank open, this condition can be checked by measuring the alternators as described below; but when the tank is closed, the slippage can be detected only by seeing its effects, namely erratic behavior of the injector and the beam focus. If the alternator voltage is sufficiently low, for example, the VT1 multi-vibrator may oscillate spontaneously, generating particles in uncontrolled clusters. You can see those clusters in the manner described in Section IV.

Belt Dressing

We have a liquid belt dressing, which we have found to be effective in preventing the slippage just described. Dressing treatment may be needed at widely spaced intervals; with the belt stationary, apply the dressing to the inside of the belt at the ground end, using an old paint brush or similar applier.

III-E MAINTENANCE OF THE INJECTOR AND OTHER BALL INSTRUMENTATION

Of course you must first dump the tank gas and roll the tank back, as described in Section II.

Removing and Replacing the Ball

The ball, which is actually a cylinder, is held in place by two spring-loaded studs, one on top of the ball at its junction with the accelerating column, and one underneath. Press in the studs with fingers; then gently slide the ball back, making sure to avoid damaging anything inside. Set the ball aside.

In replacing the ball, it is probably wise to observe top and bottom, since the studs may not be exactly symmetrical. In any case, you gently slide the ball on, matching its stud holes with the studs. When you get a match, the studs pop out into the holes.

Checking Belt and Alternators

For that you must run the belt. But there are **dangers**:

(1) The belt develops a frictional VdG voltage. Therefore, **ground the HV end of the VdG to the laboratory before running the belt.**

(2) **Make sure that the injector DC is set to zero** (Section II-C), to avoid being killed by the voltage *V*, which may be 10 kV or more.

(3) **Disconnect the focus voltage supply from the focus electrode**, using the in-line disconnector in the cable which runs from the focus

supply to the electrode. The focus voltage is lethal. **That voltage is still present** at its own terminal. **Stay away from it.**

(4) **Make sure** that the belt charge variac on the VdG console **is at zero**.

Now you can run the belt safely. There is a **15 minute limit** to avoid overheating the motor, which now gets less cooling than it does in the pressurized tank.

Note: There is a cutoff switch on the side of the big junction box near the tank end (see Figure I), for disabling the belt motor. The switch can be used if there is danger that one person might start the belt inadvertently while another person is working at the ball.

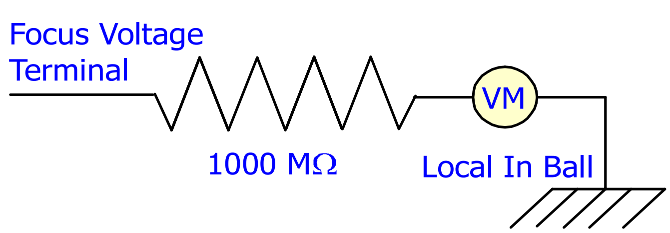
Find the output terminals for each alternator, on junction strips near each pulley support (Figure 9). Run the belt and measure each alternator voltage; you should find near 120 VAC for each, relative to the local ball frame ground.

Also observe the belt tracking.

If the alternators are low, and/or if the belt does not track well, it is time for a belt dressing treatment. If the dressing treatment (Section III-D) is not effective, you may need to adjust one or the other of the belt pulley blocks in the ball.

Checking Focus Voltage Supply

This has never failed. But you can check it, with a DC voltmeter and a series resistance—say 1000 MΩ or more—sufficient to extend the voltmeter range to at least 10 kV, as indicated in the sketch here. We have some special high-voltage resistors, stored in a drawer under the center of the laboratory workbench.



Checking the V_T Injection Pulses

The injector DC supply in the ball has never given any trouble. But you can check the V_T pulses. Follow the procedure outlined in VdG Journal III, pp 17-18, or VdG Journal IV, p. 89.

Adding or Replacing Dust

A dust filling of the injector can last a long time, like years, unless the injector **as a whole** has been dismounted (see below) or you wish to change the dust type.

To change or replenish the dust in the **injector without removing the injector as a whole,** proceed as follows.

1) Admit air to the accelerating column (Section II-A).
2) Remove the insulating tongue **holder** (Figure 8), which is held to the injector body by three Allen screws. The tongue comes along. **Do not loosen the screws** which hold the tongue to the insulator. You can now see the dust.
3) With a spatula tool from the injector tool box (Section I) remove or emplace dust as desired, filling the cavity to about one-third full, and gently smoothing the dust surface.
   The tongue when replaced **must not touch the dust**.
4) **Carefully clean** the insulator O-ring and its seating surfaces—a tissue wetted with alcohol is useful. **Carefully** replace the insulator with the tongue, **making sure** that the O-ring is properly seated. Tighten it **carefully** and uniformly. Note the connecting wire from the tongue to VT1; restore that connector. Restore the vacuum (Section II-A).

Needle Work

You should not remove the injector as a whole without good and solid reasons; if you cannot get particle yield (Section IV) every other possible explanation should be eliminated before you dismount the injector. In general, there are three justifications for that step: (a) there is something wrong with the needle; (b) the base-body space (Figure 8) is so packed with dust that the injector DC voltage breaks down from body to base, or (c) there is so much dust packed into crevices around the focus electrode that the focus voltage breaks down.

To remove the whole injector, first admit air to the accelerating column (Section II-A).

Study the leads from the injector to the VT1 pulsing system.

Remove those leads thoughtfully so that you know how to restore them.

Remove the injector carefully by taking out the bolts which hold its base to the accelerating column. (Now you can see the focus electrode; examine it for your information, but **do not try to remove it**.)

Carry the injector to the workbench; hold it upright to avoid spilling dust through hole A (Figure 8). At the workbench, mount the injector—still upright—in the special mounting jig which is stored on the shelf behind the workbench.

If you intend to lay the injector down, as is for instance needed for cleaning or for needle work, remove the tongue insulator as described above, and unload the dust.

For needle work or cleaning, lay the injector flat with its base up.

Begin by searching for the needle—Figure 10. Shine a good light into the injector side, and set a traveling microscope (like our Swift) in place as sketched. Try to see the point of the needle, which is just below hole B. It looks like a fuzzy star. This is difficult; but you can do it.

Now if you decide you need to work with the needle, or if you want to clean the injector, remove the base.

Caution—observe the orientation of the base relative to the body. You must preserve that orientation when you replace the base.

You can now inspect the needle easily, with the microscope. Judge **carefully** and **thoughtfully** before you remove the needle. See Section IV for further comments.

To remove the needle, use the special wrench sketched in Figure 11. The wrench is stored in the injector tool box (see Figure 1).

There are some spare needles in the injector tool box. But if it seems desirable to make a new needle, follow the procedure described in VdG Journal IV, page 88.

Caution: observe the screw threads on the needle mount (Figure II) and observe the diameter of the tungsten wire. There are two injectors, one of which is mounted on the 25-kV "auxiliary" accelerator. Some of the stored needle mounts fit one of those injectors, while some fit the other one. Likewise there are two diameters of tungsten wire in storage in the tool box; the VdG injector uses 0.010-inch wire.

Clean the injector (see below) before replacing the base.

Watch the orientation of the base when you put it back on. Tighten its screws some, but not all the way; set up the microscope and look for the needle through hole B. **The needle must be visible** (Figure 10). If it is not, you will get few if any particles. Finally tighten the base screws firmly, and uniformly, checking the needle visibility during that process.

The injector body has sideways adjustment screws which permit slight lateral movement of the body relative to the base. We have had very little (if any) need to use this feature. **Be very careful about the base-to-insulator O-ring.** A vacuum leak here would be very troublesome.

Cleaning the Injector and Focus Electrode

After long-extended operation, like years, considerable dust collects in the crevice between the injector body and its body-base insulator; likewise, dust collects in crevices around the mounting of the focus electrode. Since the dust is a conductor, it can engender small sparking which interferes with operations.

While the injector base is off, as described above, you can clear out the injector dust with a small alcohol-moistened absorbent probe. Likewise you can clean the crevices—or at least those which are accessible to a probe without moving the electrode—around the focus electrode.

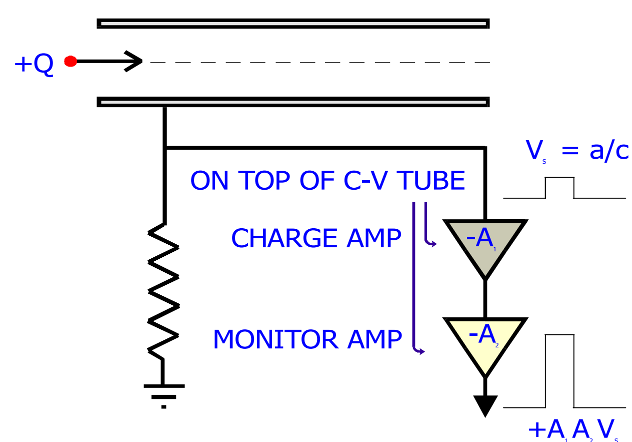
IV PARTICLE OBSERVATION AND PRODUCTION

First we describe the instrumentation of the CV tube, through which the particles pass after they emerge from the VdG. Then we discuss the process of getting particles.

IV-A PARTICLE SENSORS

In the CV tube there is a series of sensors. In the order in which a particle encounters them, they are (1) "coarse" alignment ensemble; (2) "start"; (3) "stop"; (4) "final." See Figure 12. (Some file material mentions a "fine" alignment sensor, but we ignore that, never using it.)

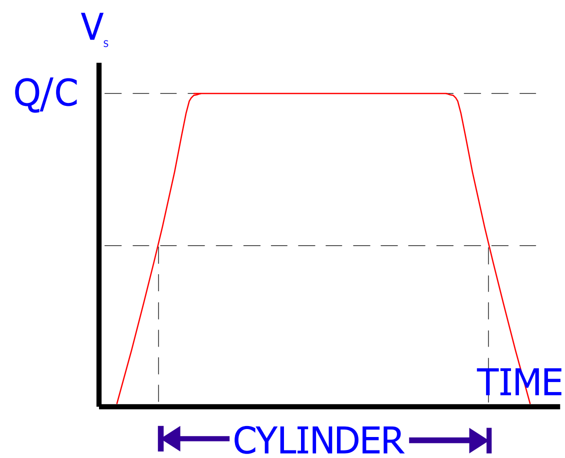
We shall explain the roles which the sensors perform; but first we explain the construction of the sensors, and how they detect the passage of particles.



At the locations called "start," "stop," and "final," the sensors are hollow cylinders as sketched here. Now let a particle with charge $+Q$ enter the cylinder as shown. It begins to induce a charge on the inner surface of the cylinder. Positive current thus flows to ground through R, generating a positive pulse voltage V_S at the input to the charge amplifier and a corresponding monitor amplifier output.

The cylinder and its connections have a capacitance *C*, which is made as small as possible but cannot be zero.

If *RC* is long compared to the transit time of the particle through the cylinder, the current through *R* remains essentially constant for that time; it then turns out that V_s is very nearly equal to *Q/C* when the particle is inside, provided that the cylinder makes a solid angle of essentially 4π around the particle. The dimensions (length 40 mm, inside diameter 6 mm) satisfy that provision to about 0.5%.



Considering the changes in solid angle as the particle enters and leaves the cylinder, V_s in detail looks like the drawing here, with rise time and fall time depending on the velocity of the particle.

For example consider a particle with $Q = 1 \times 10^{-15}$ Cb and velocity v = 1km/sec (1 mm/psec). The capacitance *C* is perhaps 2 pF, so that

$$V_s = \frac{1x10^{-15}}{2x10^{-12}} = 0.5 \text{ mV}$$

Also, $R = 2.5 \times 10^{10}$ ohms at each location, giving RC = 0.05 sec while the transit time in the cylinder is 40 psec, thus satisfying the time constant requirement.

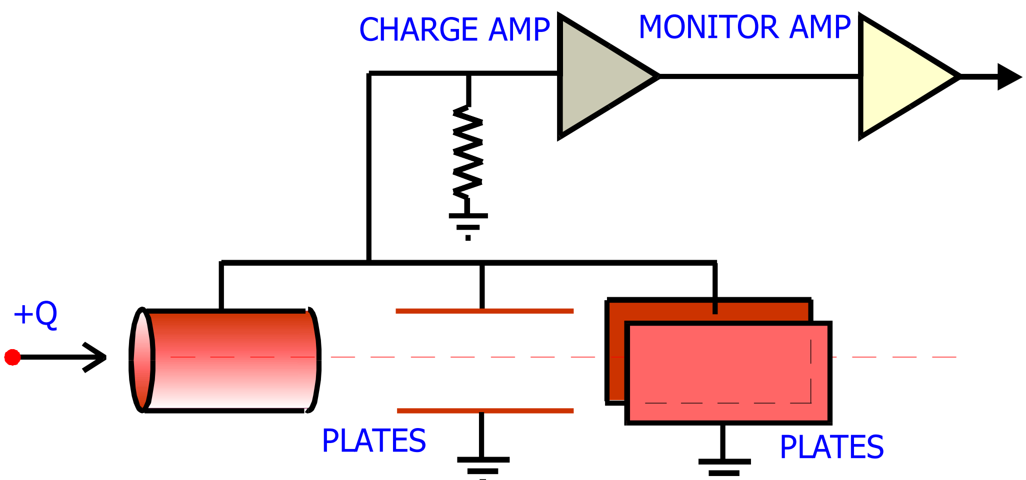
The charge $1x10^{-15}$ Cb is close to the smallest we observe; we see Qs as large, on the other hand, as $100x10^{-15}$ Cb and more. The velocity 1 km/sec is about the lowest we deal with; we may occasionally see velocities approaching 20 km/sec, with the dust ("A") which we commonly use. As we shall see below, particle charge and velocity depend strongly on the particle diameter; our dust "A" is roughly one micron in particle diameter on the average.

Charge unit **berg**

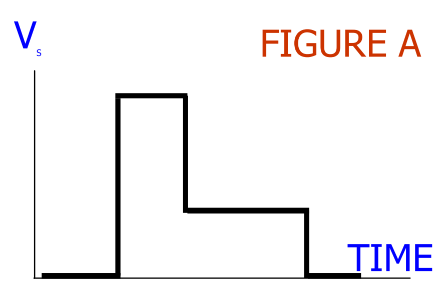
We commonly measure Q in the charge unit **berg**, which is 1×10^{-15} Cb. Thus for example a charge of 1×10^{-13} Cb is 100 bergs.

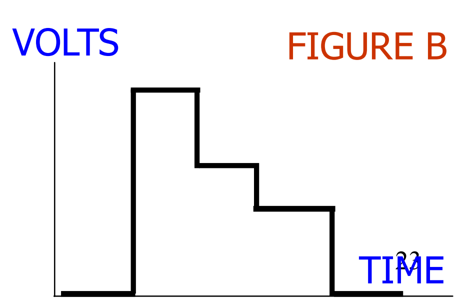
Coarse Alignment Ensemble

That group consists of three sensors in parallel, as sketched on following page.



Whereas the cylinder makes nearly a 4π solid angle around the entering particle, a pair of flat plates makes just about half that, and the ensemble is symmetrical about the central axis of the CV tube. Thus, if a particle travels along the central axis, its signature V_s is like the accompanying figure A. But if the particle passes, say, too close to the grounded plate of the vertically mounted pair while being on-axis with respect to the horizontally-mounted pair, its signature looks like B. Now suppose that every particle shows the B signature (except for pulse height, which varies





with *Q*; and pulse width, which depends on particle velocity). Since the particles ideally travel down the true axis of the accelerator, we infer from B **that the CV tube is off-line sideways**. You can sketch the particle signatures for other cases. We use these signals to adjust the alignment of the CV tube **at the upstream end**. See Section IV-C.

Amplifiers

At each location the output pulse height of the monitor amplifier is

$$\frac{A_1 A_2 Q}{C}$$

Thus *Q* is proportional to pulse height. The manufacturer's calibration figure for the "start," "stop," and "final" systems is 25.4 bergs/volt. We accept that figure because, although we can measure the gains A_1 and A_2, we have no good way of measuring *C*. Working backwards, with $A_1 = -2$ and $A_2 = -40$ and with the given calibration of 25.4 bergs/volt, we calculate *C* = 2 pF, which is reasonable for a well-designed cylinder mounting.

For the "coarse" ensemble, calibration is not important, because it is used only for alignment of the upstream end of the CV tube. In fact, the original coarse monitor amplifier failed. We built a replacement which works well enough and has a bit more gain than the original.

All of the charge amplifiers have been free of trouble. But we have had difficulties with the monitor amplifiers, particularly "start" and "stop." One troublesome feature is the "drift correction" circuit on each amplifier, designed (we suppose) to keep the output at zero between events; the circuit can lock in some way, and shut the amplifier off. We reset the circuit by momentarily removing its 9-volt supply, using a switch mounted on the C-V console.

IV-B GETTING PARTICLES

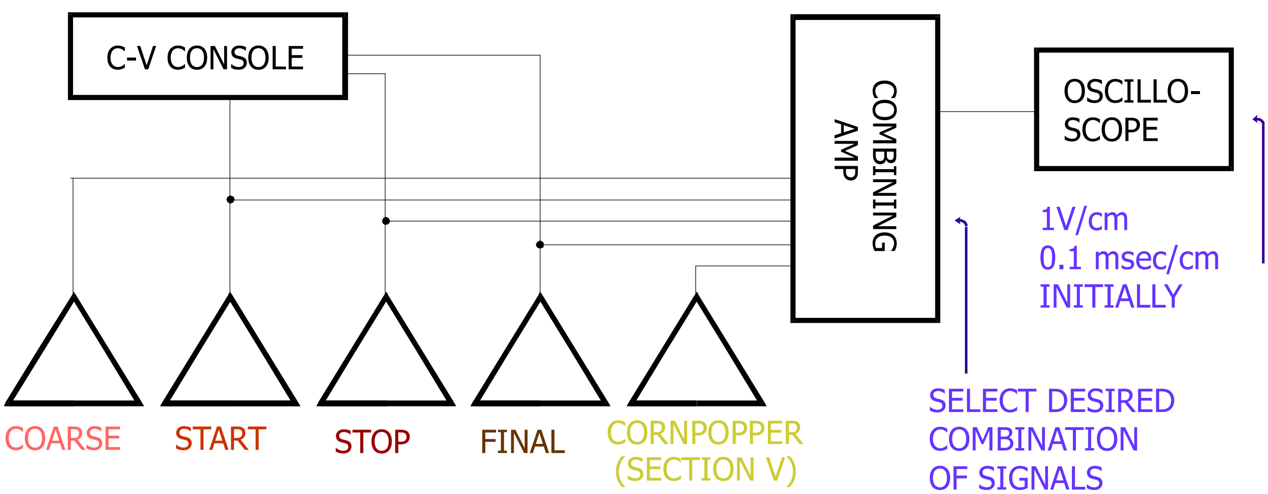
You want to obtain a flux of particles. Proceed as follows:

(1) Establish a VdG voltage (Section II-C). The value 1.45 MV is a good setting if there is no circumstance dictating another.

(2) Establish a focus voltage. A good setting is a monitor reading of between 2.00 volts and 2.50 volts. **Note:** the focus voltage setting system (Figure 9) may have backlash. To avoid ambiguity when we reduce the focus monitor setting, we run it all the way down to zero and come back up to the desired point. Your choice of focus setting will influence your choice of injector DC—see Section IV-C.

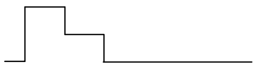
(3) Connect an oscilloscope to the combining amplifier, with which you can select up to five sensor signals for simultaneous display, as shown in the sketch below.

Note that the start, stop, and final outputs go to the CV console as well as to the combining amplifier.



The oscilloscope triggering is positive-going, and its vertical gain setting should be 1 volt/cm initially. The desired sweep speed depends on the signal combination.

Since particles are by and large produced one at a time, this oscilloscope arrangement allows you to follow the history of one particle as it travels down the CV tube. The oscilloscope is triggered by whichever signal in your combination is temporarily first.

For example, if your combination is coarse-final, then the oscilloscope signature  shows that the particle passed the coarse sensor and also passed successfully through the final sensor; the signature  shows that the  particle passed the coarse sensor but never arrived at final, having struck some structure along the way (exception: if a particle is very slow, it may not arrive at final until after the oscilloscope sweep is completed). A good sweep speed for the coarse-final combination is 0.1 msec/cm. Now if a particle strikes a sensor, it produces a very long pulse, since it deposits all of its charge on the body of the sensor, and the charge leaks off with a time constant of about 0.1 second. Thus the coarse-final signature shows that the particle reached the final sensor but struck it instead of passing through it.

Choose a signal combination for initial observations, and set the combining amplifier switches according to your choice. Perhaps the most useful initial combination is coarse-final or coarse-stop-final.

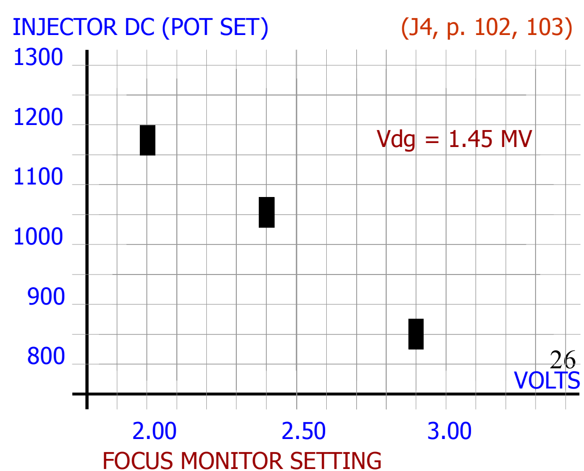
(4) **Check** that the deflection voltage supply on the CV console is **off**. See Section IV-D for the uses of that supply.

(5) Set the charge-velocity selection on the CV console to **NEITHER**, which means (Section IV-D) that the console system does not discriminate against any particle.

(6) Turn on the power to the CV console. The amplifiers coarse, start, stop, and final are now also powered. (The corn popper amplifier is not connected to the CV console in any way.)

(7) Punch the **–9.2 VDC** switch on the CV console to reset the drift correction circuits on the CV monitor amplifiers. You may need to do that again, later on.

(8) Set the injector command (Section III-C) to **JS** for preliminary



observations, because it gives relatively high flux with which you can study the system behavior most quickly. Later you can switch to the CV console injector command (Section III-C and IV-D) for particle measurements.

(9) Turn up the "injector DC" control (Sections II-C, III-C) and watch the oscilloscope for particle signatures. The graph here indicates our experience with respect to injector DC and focus monitor for best-focused particle flux. The numbers in the graph are at a VdG voltage of 1.45 MV; at other VdG voltages the numbers are somewhat different (Section IV-C).

Note: For any start-stop-final combination of signals, the pulse heights should be the same (in fact that is a measurement criterion, Section IV-D). If they are not the same, there is a "drift correction" error; punch the **–9.2 VDC** switch on the CV console.

Note: Pulse heights, and time intervals between sensor responses, vary drastically from event to event; particles come randomly over a wide range of charge—from about one berg to over 100 bergs—and with a wide range of velocities—from, say, one km/sec to (rarely) 15 or 20 km/sec, with Dust "A".

Now having a particle flux, you can proceed farther, looking first at the factors of alignment and focus, Section IV-C.

Turning off the Particles

For a temporary stop of the flux, shut off the injection pulsing by going to the CV pulsing mode and pressing "manual." To stop altogether, (1) turn the injector DC to zero, for startup safety in your next run; (2) turn off the deflection voltage in the CV console if you had it on; (3) shut down everything else. **Leave the focus setting alone**; there is no need to turn that control down.

IV-C ALIGNMENT AND FOCUS

Now that you have a particle flux, what are the particles doing? Do they come nicely down the CV tube through the final sensor, or do they go astray? Their fate is governed by the alignment of the CV tube and by the beam focusing. Ideally every particle passes all the way through. We never achieve that, but we can come close.

One might think that if the system is once aligned, it will stay aligned. But tiny shifts in the location of the beam origin, for example, caused perhaps by work on the injector, may generate noticeable alignment faults; and the CV tube might get bumped.

As for beam focus, there are three governing factors: VdG accelerating voltage, focus voltage (Figure 8), and injector DC voltage (Figure 8). The injector DC voltage influences focus because it affects the velocity with which a particle leaves the injector; that is analogous to the focusing effect of the extraction voltage in an ordinary ion source.

Of those factors, the injector DC is the most sensitive and the most easily adjustable. Thus, once you have the accelerator running with some desired VdG voltage and some reasonable focus monitor voltage (Section IV-B), the best procedure is to adjust the injector DC for best beam behavior.

Preliminary Observations with an Oscilloscope

We now suppose that you have progressed through step 9 (Section IV-B). Adjust the injector DC until you maximize (at least approximately) the percentage of successful coarse-final signatures  leaving the VdG voltage and the focus voltage fixed. See Section IV-B.

Alignment of the CV Tube at the Upstream End

Study the coarse signals in detail, expanding the oscilloscope time base to perhaps 20 or 50 psec/cm. See Section IV-A, and VdG Journal III pages 84-85, for interpretation of the coarse sensor signals. If the upstream end of the CV tube is aligned, particles come through the coarse sensors randomly high-low and randomly left-right. Watch a series of signals to see if there is a **predominance** of vertically and/or horizontally off-line signals indicating the corresponding alignment error(s). If you convince yourself that there is such a predominance, adjust the position of the upstream end of the CV tube, using the alignment jacks at that end (Figure 12). Move the tube only a little at a time, say one or two millimeters in the indicated direction, until the predominance disappears.

Note: The upstream adjustment is sticky, because the end of the CV support scrapes on the end of the tank. Besides turning the jackscrew, you need to tap the support lightly to make it move. Notice the pencilled marks on the end of the tank; use them to see if you have actually moved the tube.

Alignment of the CV Tube at the Downstream End

At the downstream end of the CV tube, we test the alignment by bombarding a thin film of carbon.

A glass plate, like a microscope slide, can be given an opaque film coat of carbon soot. Now if the filmed plate is placed in the accelerator and struck by a particle, the impact makes a little hole in the film; the hole is many times larger than the particle. One can easily see the hole, by using an ordinary magnifying glass with a strong light behind the plate.

We have a supply of glass microscope slides, 5 cm by 7.5 cm. Coat one of these with candle soot, heavily enough so that the candle flame is at most faintly visible through the plate.

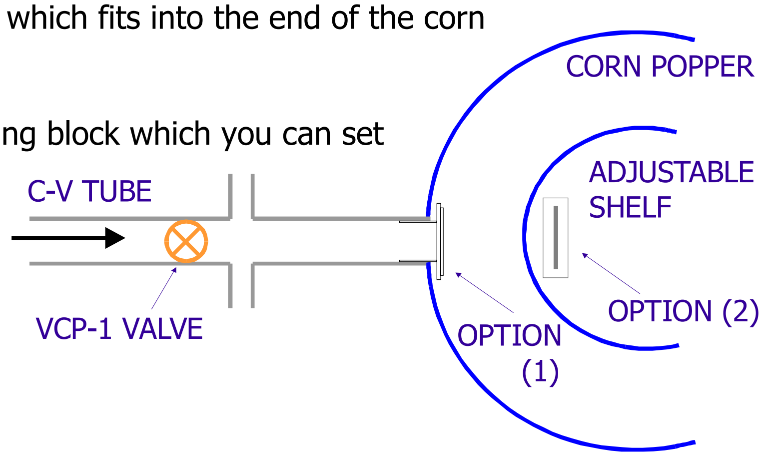
Mount the plate in the corn popper (Section V) intercepting the beam line as sketched here.

You have two options for mounting the plate:

(1) on a light clamping holder which fits into the end of the corn popper entrance pipe;

(2) On a free-standing mounting block which you can set on the adjustable shelf of the corn popper.

Use option (1) to test the CV tube down-stream alignment.



We will discuss option (2) in Section V.

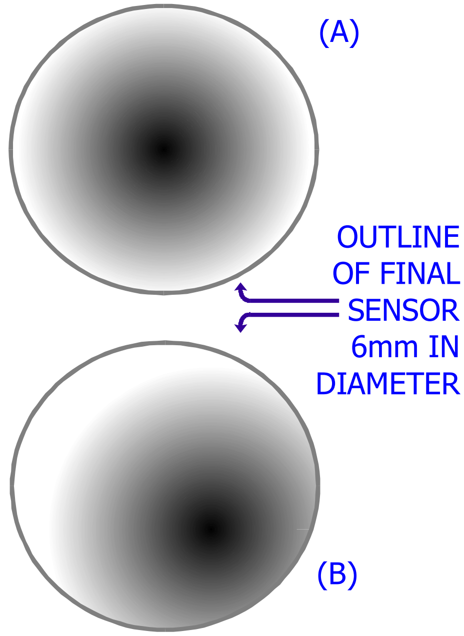
Of course, in order to insert the plate you need to take down the vacuum in the corn popper chamber and raise the dome. See Section V. **Valve VCP-1 is closed,** of course.

After inserting the plate at option I, get a vacuum again in the chamber (Section V), good enough so that you can open valve VCP-1 without fear, when the time comes for that. Usually the chamber vacuum is around 1×10^{-5} torr, which is quite good enough for these purposes.

With valve VCP-1 closed so that particles cannot strike the carbon plate, obtain a particle beam, as well-focused as possible, by the coarse-final criterion discussed above. When you are ready, **open** valve VCP-1, thus allowing particles to bombard the plate. Let perhaps several hundred particles strike the plate; you can judge that by watching the oscilloscope. The JS injection pulsing mode gives a good particle rate for this purpose, but the CV pulser in automatic mode may also be satisfactory.

Then **close valve VCP-1**, shut off the accelerator, take down the chamber vacuum (Section V), remove the carbon plate, and inspect it.

Examining the Carbon Plate



Set the plate in front of a good light and look at it through a magnifying glass. If you had a good focus during the bombardment, you see a pattern like the sketch here—a rather dense core of specks with scattered specks around it, and a faint "halo" which outlines the inside diameter of the final sensor cylinder.

If the core is centered (A) then of course the downstream end of the CV tube is aligned. If not, (B), we see how to move the tube; in (B) **the CV tube** is a trifle high and needs a little lowering, and is off to **the left as seen looking downstream** and needs to be moved a bit to the right (looking downstream).

Focus

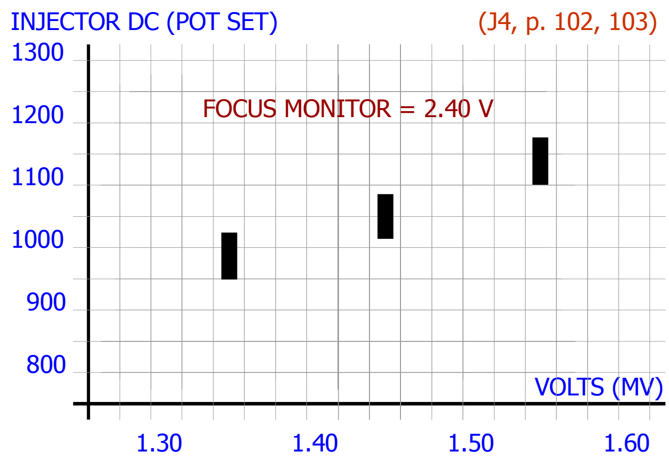
Focus of the particle beam is tested in two ways, already mentioned: the percentage of particle impacts on the CV tube sensors, and the carbon-plate display. The impact test is of course the most convenient, because it involves only watching oscilloscope traces; but it is credible only if the system is aligned, since a well-focused but poorly aligned beam can make many sensor impacts. We now suppose that you have good alignment.

Using either coarse-final or stop-final as your signal combination, and with a given VdG voltage and a given focus monitor voltage, adjust the injector DC to maximize the percentage of successful signatures  or  The graph on page 27 shows you approximately what to expect for example at a VdG voltage of 1.45 MV and a focus monitor setting of 2.40 volts; your experience may be a bit different from the graph.

If the VdG voltage is changed, the focusing conditions change also. The graph below is a sample of the effect of the VdG voltage, at one value of focus monitor voltage.

If you obtain a transmission-through-final rate of 95% or more, then you have at least a fair focus. If the percentage falls much below that, the focus is poor at best.

From the diagrams on page 31, it is obvious that a carbon-plate pattern indicates the quality of focus; if the pattern shows no dense core, or if the core is weakly defined, then the focus is poor. See Figure 17 for a typical beam profile with fair focus.



As long as the local voltages in the VdG ball—namely the injector DC and the focus voltage—are consistent with their corresponding control panel indicators, the focusing conditions should remain about like those indicated in this text. A substantial departure from these focusing conditions is an indicator that the in-the-ball voltages have changed or that those voltages are erratic; and that, in turn, indi-cates that the VdG belt may be slipping as discussed in Section III-E. Thus, if you find it difficult or impossible to achieve or maintain a consistent focus, it is time to open the tank and check the belt operation; see Sections III-D and III-E.

IV-D MEASURING PARTICLE CHARGE *Q* AND VELOCITY *v*

As stated in Section IV-B, the CV monitor amplifiers (except for coarse) are connected to the CV console.

Action in the C-V Console

Note: this action occurs if you use the CV console injection command; the JS injection command is **not** connected to the console.

See Figure 13.

(1) Circuitry in the console reads the pulse heights from the start, stop, and final monitor amplifiers. If they are **all** the same, an internal computer calculates the particle charge *Q* according to the calibration constant 25.4 bergs/volt. The result is delivered to a printer which (if you turn it on) puts *Q* on a paper tape and displays *Q* on a meter above the printer; the meter reading is in units $1x10^{-14}$ coulombs.

(2) The start pulse begins a timing circuit in the console, and the stop pulse ends that timing. (That is why those two sensors are called start and stop.) Now the console knows the distance between those two sensors; and it computes the start-stop time of flight and the particle velocity ν. That time of flight, and the computed ν, are printed along with *Q*.

If anyone of the three start-stop-final pulses is different in height from the others, or if the particle does not pass through final, the system rejects the event. Thus, a printout testifies that the particle emerged at the end of the CV tube.

An example (from an actual event) of the readings from the printer lines:

4	045.65	*Q* in bergs
3	000.50	*Q* in hundreds of bergs
2	40.39	TOF for 100 mm, in µsec
1	2.51	velocity in km/sec (mm/µsec)

The small discrepancy between TOF and velocity is an artifact of the system. But you can use the TOF print as a check on the velocity print if the latter is hard to read. As for *Q*, we use line 4 as a rule.

If *Q* is much over 100 bergs, the computer seems to go off scale. Then line 4 usually prints zero, and line 1 prints 109.99.

Restricted Selection of Particles by *Q* and ν

If we wish particles only within some restricted range of Q or ν or both, the CV console can make the selection. For example we might want only particles between 2 and 6 km/sec and between 2 and 10 bergs; or particles with ν less than 5 km/sec and any *Q*; and so on. **Warning:** see Figure 14, showing the *Q*-ν region in which we get particles (with dust "A"). If your selection is in a non-populated region of Figure 14, **it is in vain**.

The selection is by electrostatic deflection. In brief, a particle is shunted away from the beam axis, by the **downstream** deflection plates (Figure 1) **unless** it satisfies the established criteria. The plates are charged by the (optional) deflection voltage supply (Figure 13). If an acceptable particle comes, as measured by the signals at the start and stop detectors, the plates are rapidly discharged, allowing the particle to pass.

This description is incomplete, particularly with respect to the role played by the **upstream** deflection plates. See the manufacturer's manual M8 for a better account.

In our experience, a voltage of 1.5 kV across the deflection plates is sufficient. (The deflection is **independent of *Q*** and inversely proportional to the VdG voltage; see Appendix.)

To use this arrangement:

(1) Find the selection controls on the CV console (Figure 13), and select your desired *Q* and ν ranges. Your setting is displayed above the selection switches.

(2) Find the deflecting voltage supply (Figure 13) and turn it on, to at least 1.5 kV.

(3) Inject particles **with the CV console control**. (The JS injection system is **not connected** to the console electronics; if you are using JS injection, the deflection voltage must be turned off.)

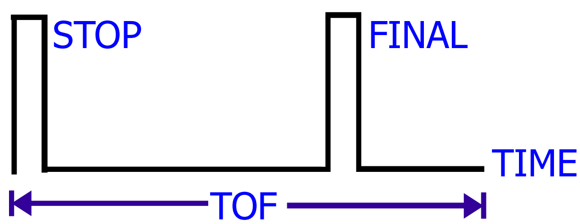
If you **do not want any restriction** on *Q* and/or ν, switch the selection setting to **NEITHER**, and leave the deflection voltage **off**.

Measurements with an Oscilloscope

An oscilloscope trace, at start or stop or final, can give you *Q*; use the displayed pulse voltage and the calibration figure 25.4 bergs/volt.

For this purpose, as well as for velocity measurements discussed below, the on-screen storage oscilloscope is suitable because you can examine its traces at leisure.

We observe that oscilloscope-measured *Q*'s are consistent with console-print *Q*'s. Thus you can get *Q* confidently from an oscilloscope in cases for example when the printer gives you no reading.



A stop-final combination trace, like the sketch here, can give you the particle velocity, from the displayed time of flight and the stop-final distance. By examining the construction drawings furnished by the manufacturer of the CV tube, we determined that the stop-final distance (from the leading edge of the stop sensor to that of the final sensor) is 1186 mm. However, when we determine that distance by using stop-final time of flight combined with **printed** velocity from the CV console, we find (on the basis of about 80 trials) that the distance is 1128 mm, with a statistical variance of about 1%. The discrepancy, about 5%, appears to mean either that the construction drawings are in error or that the CV-computed velocities are in error. Since a precise knowledge of particle velocity is not in general important, we usually call the distance 1150 mm for convenience when we need to enter it into some calculation.

(Of course the oscilloscope measurements are subject to error in the oscilloscope timing, but that factor was carefully checked.)

Incidentally we note that no pulse from start or stop or final is ever larger than about 6 volts; we suppose that the corresponding amplifiers saturate at about that value, that is at a *Q* of about 150 bergs or so.

Finding the Mass and Diameter of a Particle

If we know the *Q* and v for a particle, and the VdG accelerating voltage *V*, we can calculate the mass of the particle; and, by assuming a value for the density of the material, we can get the particle diameter.

Write the kinetic energy

$$QV = \frac{mv^2}{2} \tag{1}$$

so that

$$m = \frac{2QV}{v^2} \tag{2}$$

Also

$$m = \frac{\rho \pi D^3}{6} \tag{3}$$

where *D* is the sphere diameter and ρ the density. (Electron microscope photographs show that these particles are spherical.)

Thus

$$D = \left(\frac{6m}{\rho\pi}\right)^{\frac{1}{3}} \tag{4}$$

For the density we use 4 gm/cm^3, that is 4x10^3 kg/m^3, although the nominal density of solid iron is about 8 gm/cm^3; photographs suggest that the particles are spongy, and a water-immersion measurement we once made gave the lower figure. However, the diameter is not very sensitive to the density—a factor of 2 in density changes the diameter by only about 25%, which in this context is trivial.

In the units we commonly employ, convenient forms for calculations are

$$D = \left[\frac{Q_B V_{MV}}{(v_{km/s})^2}\right]^{\frac{1}{3}} \text{ microns} \qquad (5)$$

$$m = \frac{2Q_B V_{MV}}{(v_{km/s})^2} \text{ picograms} \qquad (6)$$

where Q_B is the particle charge in bergs, V_{MV} is the VdG voltage in millions of volts, and $\nu_{km/sec}$ is the velocity in km/sec. In the diameter expression, we have taken a density of 4 gm/cm^3. Also, in (5) we have said π=3, good enough for this purpose. An example, from an actual event:

Q_B = 8 bergs V_{MV} = 1.45 MV $v_{km/sec}$ = 4.4 km/sec

and we find

D = 0.84 micron m = 1.2 picograms

IV-E OBSERVED PARTICLE CHARACTERISTICS

We have recorded charge and velocity for a great many particles, and have made graphs which are in the files. For such work the data are taken with no Q-ν restrictions, so that we see the distributions as the accelerator produces them.

Figure 14 is a sample, with respect to Q and ν, from a run made in February 1995. It is fairly representative, although we sometimes have seen velocities exceeding 10 km/sec on other occasions. The figure exhibits a fairly definite relation between Q and ν, with of course many variations.

We calculated the diameter of each particle in the sample, using Eq(5), page 37, and constructed Figure 15, showing charge and diameter. The graph shows that Q tends to go as D^2. Thus, as might well be expected, the particles tend to have roughly the same charge per unit surface area. From Figure 15, that comes out roughly 0.005 or 0.004 coulombs/meter^2.

No doubt the charge which a particle receives when it hits the injector needle depends on whether the particle touches the needle near its point, where the needle-to-base field is strongest, or farther back. We observe that a sharp-pointed needle yields larger *Q*'s, for the same particle size, than does a balled needle.

To get a handle on the shape of the ν-*Q* curve, Figure 14, write

$$QV = \frac{mv^2}{2}$$

Now we have $m \propto D^3$; suppose for the moment that we can also strictly say $Q \propto D^2$, from Figure 15. From those statements we obtain Dv^2 = constant (at a given *V*); that is D^2v^4 = constant, so Qv^4 = constant, matching Figure 15.

Looking again at Figure 15, it is tempting to speculate that the curve $Q = 16D^2$ represents something like a maximum surface charge per unit area of a particle, under the conditions then present in the injector. That translates to a maximum surface charge of about 0.016 coulomb/meter^2.

Because of $Q \propto D^2$ and $m \propto D^3$, it turns out that the slowest particles, in general, have the largest kinetic energy and momentum. As an example consider three particles from the sample used for Figures 14 and 15:

Q in bergs ($1x10^{-15}$ Cb)	**Velocity (km/s)**	**Mass (picograms)**	**Diameter (microns)**	**Kinetic energy (nano-joules)**	**Momentum (kg•m/s)**
4.36	6.0	0.35	0.56	6.3	$2.1x10^{-12}$
28.5	3.3	7.6	1.6	41	25
86.9	1.9	70	3.2	126	133

One must bear this point in mind, if kinetic energy and momentum are factors in some experiment. But if kinetic energy **per unit mass** is the critical factor, then the velocity is the important quantity.

Statements Tv^4 = constant and Qv^4 = constant

Suppose it is strictly true that *Q* is proportional to the square of the particle diameter *D*:

$$Q = AD^2 \qquad \text{(a)}$$

Also the mass *M* is proportional to the cube of *D*:

$$M = BD^3 \qquad \text{(b)}$$

where A and B are constants.

Now for the kinetic energy we can write

$$T = QV = \frac{Mv^2}{2} = \frac{BD^3v^2}{2} = AD^2V \quad \text{(c)}$$

These expressions yield

$$BDv^2 = 2AV \quad \text{(d)}$$

Now cube (d):

$$(BD^3\, v^2)(B^2u^4) = 8A^3V^3 \quad \text{(e)}$$

so that (using (c))

$$Tv^4 = \frac{4A^3V^2}{B^2} \quad \text{(f)}$$

This makes intelligible the remark at the bottom of page 38, where we note that the slowest particles typically have the largest kinetic energy. Of course (f) depends on (a), which reflects only a tendency.

Now $T = QV$. So from (f) we get

$$Qv^4 = \frac{4A^3V^2}{B^2} \quad \text{(g)}$$

reflecting a tendency which is seen in Figure 14.

It is amusing to compare these expressions—say (g)—with the numbers of our experience.

From Figure 15, say A = 12 bergs/μm^2 = 0.012 Cb/m^2.

Also we write $B = \pi\rho/6$= 2.1x10^3 kg/m^3 if ρ = 4 gm/cm^3 (p. **??**).

Then at V = 1.45 MV, the constant term in (g) is

$$\frac{4A^3V^2}{B^2} = \frac{4(1.012)^3(1.45\times10^6)^2}{(2.1\times10^3)^2}(Cb/m^2)^3(J/Cb)^2(m^3/kg)^2$$
$$= 3.3Cb(m/s)^4 \quad \text{(h)}$$

Now from Figure 14 let us take for example

Qv^4 = **[**3500 (bergs)(km/s)**]** ^{4}**[**(1x10^{-15} Cb/berg)**][**(1x10^3 m/km)**]** ^{4}
= 3.5 Cb (m/s)^4. (i)

But we might have used different numbers from Figures 14 and 15.

V THE CORN POPPER

The corn popper, as a student dubbed it, is the arrangement for experimental studies associated with particle passage or impact. It has essentially two components: a chamber, designed to accept experimental apparatus, and a vacuum system—entirely separate from the VdG vacuum system—for servicing the chamber.

V-A CHAMBER

See Figure 1. In the chamber we can place any desired device, within size limits. The device can be connected to the laboratory through a multi-terminal receptacle mounted on the chamber wall. Leads from the receptacle go either to a banana-jack board located outside the chamber on the CV tube side or to several cables with BNC terminations. A diagram on the inner chamber wall permits identification of the respective leads, but you may wish to use an ohmmeter to verify any connections you have made.

In the chamber is a shelf, adjustable in position either vertically or horizontally by means of motor drives which are controlled by the up-down and left-right switches on the blue panel. Two scales, inside the chamber and visible through the transparent bubble cover, monitor the positions of the shelf.

V-B VACUUM SYSTEM

The corn popper vacuum system is separate from that of the VdG; the only link between the vacuums is valve VCP-1 (Figure 1). If there is a good vacuum on both sides of that valve, as for example around 1×10^{-5} torr on the corn popper side and a reading of 5 to 10 μamp on the VdG Phillips gauge meter, then valve VCP-1 may be opened or closed as you choose. For instance (as we have remarked) you can use valve VCP-l as a beam stopper, when you have a beam but do not want it to strike anything in the corn popper.

Water: **Note** the corn popper water valve located in the VdG vacuum console (Figure 1).

Vacuum system switches on the big blue panel are master switch, forepump switch, and diffusion pump enabling switch. On the smaller panel at the lower left are the diffusion pump safety and relay switches, and a thermocouple circuit which reads both the forepressure and the experiment chamber pressure. To start the diffusion pump you must reset the safety switches in the lower left panel. The thermocouple on the forepressure side furnishes the signal for the safety relay.

Note the ionization gauge circuit, located also in the lower left panel. The forepump serves both for backing the diffusion pump and for pumping down the experiment chamber. Originally there was a second forepump, used to take the diffusion pump discharge while the big forepump was working on the chamber; but we found it **not** necessary, and removed it (it is now the VdG forepump). When valves VCP-2 and VCP-6 are closed to isolate the diffusion pump, its discharge pressure does not rise unduly. Valve VCP-7 is **thus never used, and is always closed**.

The procedure for recycling the chamber vacuum is not unusual. If there is no gassy apparatus in the chamber, it attains a vacuum approaching 1×10^{-5} torr.

V-C CORN POPPER ALIGNMENT

The corn popper alignment is important only to the extent (1) that there must of course be for particles a free path all the way through; (2) that the corn popper structure itself <u>may</u> be used as a guide in the proper placement of apparatus within the experiment chamber, relative to the line of the particle beam; however, there is an alternative to that policy, as discussed below.

Alignment at the C-V Tube End

To check the position of that end of the corn popper assembly, use a carbon-plate test (page 30), using option (1). Put a carbon plate into the holder which fits into the corn popper entrance tube; but before emplacing the holder, use a sharp point to scribe a circle in the carbon at the inside edge of the holder, which is concentric with the entrance tube. Examining the plate after bombardment (Section IV-C), you can see the position of the beam relative to that outline, thus judging the corn popper alignment at its input end.

If necessary, this end of the corn popper can be nudged side ways a bit, and can be moved up or down a bit by using (or removing) shim plates under its legs. But a slight misalignment is of no great moment, as we say on the following page.

Alignment at the Far End

There are marks on the floor which help in judging the lineup of the assembly. Usually it can be seen well enough by eye. Precise alignment of the assembly is not critical **unless the structure itself is to be used itself to establish the proper location of instruments in the experiment chamber**. But, on the other hand, a carbon-plate test, with a plate mounted on the vertical backing of the chamber shelf, can be used to establish the point where particles strike that surface. Combining that information with the carbon-plate test at the entrance, described above, you know the line of the particle beam through the chamber.

V-D CORN POPPER INSTRUMENTATION

We have the following pieces of apparatus, developed here for use in the corn popper experiment chamber.

Calibration Instrument for VdG Volatge

This instrumentation consists of two deflection plates (the "Colby plates") and a detector mount. This is described in the calibration discussion in the appendix.

Carbon-plate Mounts

One of these is made for insertion into the pipe which leads from the corn popper to the CV tube; a second mount is made to sit freely on the chamber shelf. See Section IV-C.

Sample-Bombardment Assembly

This assembly consists of a particle-passage sensor—with associated amplifiers—and a sample mount, with a movable shutter, behind the sensor. See Figure 16. The system is intended for studies of particle impact on surfaces; the sample holder takes whatever material one wishes to bombard.

We need to be quite sure that a particle which passed through the final sensor in the CV tube did in fact impinge upon the sample at a well-known location. Thus the passage sensor in Figure 16 is only a few centimeters in front of the sample; if the sensor shows that a particle passed through, the particle must surely strike the sample.

With the best beam focus, the aiming-point tolerance of the sample mount adjustment is probably about two millimeters.

There is a magnetic shutter between the sample and the end of the sensor. With the shutter blocking the beam, establish a well-focused particle flux. When ready, withdraw the shutter and allow particles to hit the sample as desired. Observe particles with an oscilloscope, using a signal combination which includes the corn popper sensor, so that you have visual confirmation of each impact.

To **raise** the shutter, apply about 18 VDC—of the proper polarity—from a portable source; the current will be about 350 mA—**momentarily**. If the polarity is right, the permanent magnet above the shutter coil grasps and holds the shutter armature, so that the coil can be turned off. To make the shutter fall so that it is closed to the particle beam, reverse the polarity of the current source and again apply it momentarily. The shutter armature becomes magnetized in the repelling polarity with respect to the permanent magnet, so that the magnet releases its grip and the shutter falls.

This arrangement is needed because the coil power, about 6 or 7 watts, would heat the coil unduly in the vacuum, if the coil were left on while the shutter was up.

Delayed Trigger Source

Suppose that a particle has just passed the final sensor in the CV tube. The delayed trigger source delivers a robust 4-volt positive pulse when the particle reaches a certain distance beyond the final sensor **regardless of the velocity of the particle**.

The purpose of the device is to assist in oscilloscope observations of signals from experimental apparatus in the corn popper chamber. Suppose that some instrument there is designed to give a signal when a particle strikes it; it is most desirable that the oscilloscope reading that signal should be triggered **just as** (or very shortly before) the particle reaches the instrument. The pulse from the delayed trigger source can be used to start the instrument-reading oscilloscope. So if the instrument is placed in the corn popper just beyond the **triggering distance** of the delayed trigger source, then the oscilloscope can be made to capture every detail of the signal from the instrument.

The source is called "delayed" because its pulse is delivered after the particle has passed the final CV-tube sensor.

The **triggering distance** is adjustable, so that it can be matched to the size of any instrument placed in the corn popper.

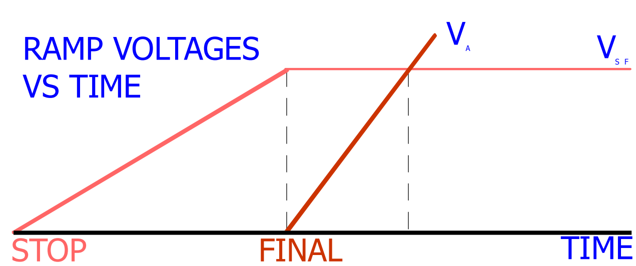
To **measure** the triggering distance, connect the **interval timer** discussed below to the "end" and "trigger out" terminals of the delayed trigger source. Using the manual injection mode, get one particle through the system, with a printed-out velocity on the printer in the CV console. Thus you obtain the "delay" time t_D, namely the time elapsed between the passage of the particle through the CV-tube final sensor and the trigger pulse; and you obtain the particle velocity v. **The triggering distance is the product of vt_D.** It is advisable to make several trials.

The device works as follows. When a particle passes the stop sensor in the CV-tube, its pulse turns on a linear ramp generator; when it passes the final sensor, its pulse stops the ramp generator, and the ramp voltage is held. So we get a ramp voltage $V_{sf} = K_1 t_{sf}$, where K_1 is an adjustable constant and t_{sf} is the time of flight of the particle from stop to final. But $t_{sf} = L/v$, where L is the stop-final distance (Section IV-D). Thus

$$V_{sf} = \frac{K_1 L}{v}$$

The particle pulse at final also turns on a second ramp generator, producing a ramp voltage $V_a = K_2 t_a$, where K_2 is a constant and t_a is the elapsed time after the particle passes final.

The two ramp voltages are fed to a comparator. When $V_a = V_{sf}$, we write



$$K_2 t_D = \frac{K_1 L}{v}$$

where t_D is the time elapsed between the particle passing final and the equality of the voltages. At that instant the comparator fires, driving a one-shot multivibrator which delivers the output trigger pulse. Thus we have

$$vt_D = \frac{K_1 L}{K_2}$$

We adjust νt_D by adjusting K_1.

A good focus is critical for satisfactory usage of the device; if particles impact the stop sensor or the final sensor, false signals occur.

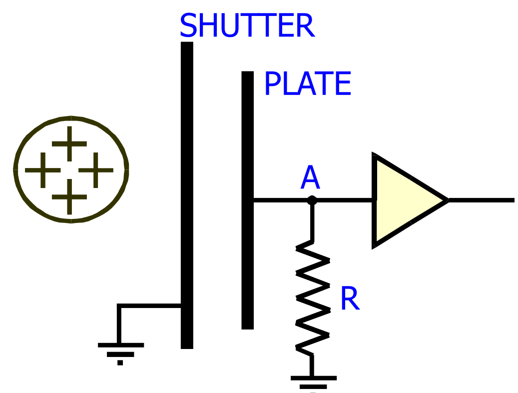
Interval Timer

There is an electronic times, which counts microseconds up to 9999. Its inputs require positive logic pulses of about 2.5 volts or more.

APPENDIX

A-A THE GENERATING VOLTMETER

To understand this instrument, which measures the VdG voltage, imagine the arrangement in the sketch. A metal plate, connected to ground through a resistor *R*, looks at a positively charged ball. A grounded shutter can be placed in front of the plate, or taken away. Initially the shutter is in place; the voltage at point A is zero. But now the shutter is removed, and the plate acquires an induction charge. While the corresponding current is flowing through *R*, a positive voltage occurs at A. Now the shutter is replaced; the induction charge flows away, and a corresponding negative voltage occurs at A. If we move the shutter in and out, we generate a kind of alternating voltage at A.

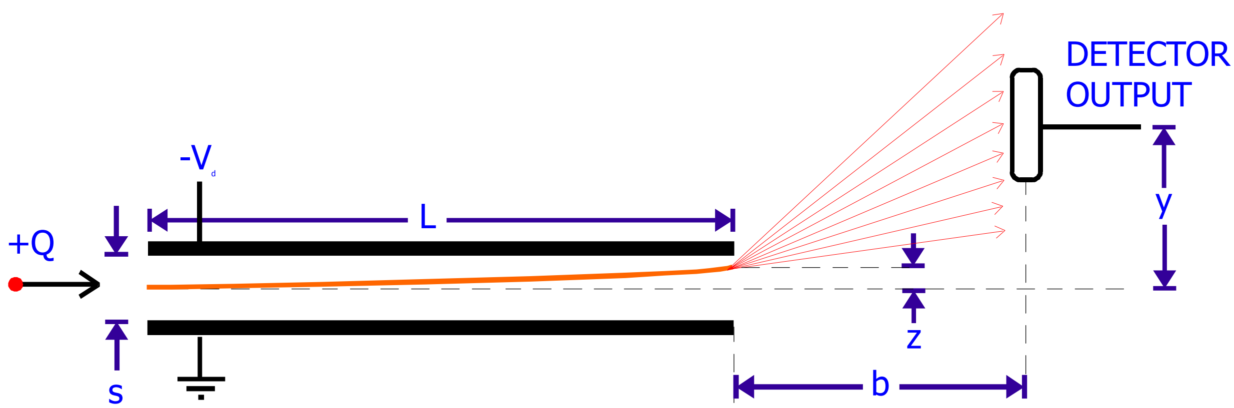


In the generating voltmeter, the sensitive plate is a set of pie-shaped segments concentrically arranged around a central transverse shaft. The shutter is a similarly segmented disk, rotated by a motor concentrically with the stationary plates, and the charged ball is of course the VdG ball. There is an alternating voltage at A, proportional to the VdG voltage; our voltmeter reads an adjustable fraction of the generating voltmeter voltage.

A-B CALIBRATION OF THE VdG

The accelerator came with a calibration, to the extent that the panel VdG voltmeter on the console (Section II-C) is marked in MV. But we did our own calibration in 1988, with results close to the manufacturer's statement. The work was done by then-student Brent Colby.

Our method was the electrostatic deflection of particles from the accelerator. As sketched here, two parallel metal plates of length *L* and



separation *s* were mounted in the corn popper, in such a way that undeflected particles passed straight between them. A detector with a narrow entrance aperture was mounted a distance *b* beyond the downstream end of the plates. The detector could be moved transversely, by a motor-driven screw. A voltage-divider arrangement measured the distance *y* from the detector to the beam axis.

To make an observation, we first short-circuited the plates, and placed the detector where it saw the undeflected particles, thus establishing the zero point for deflection measurements. Then we connected one plate to a voltage $-V_d$; the other plate was at ground. Now the particles were deflected; we moved the detector to see them.

If a particle with mass *m*, charge *Q*, and velocity ν passes between the plates, its deflection at the downstream end is

$$z = \frac{QV_d L^2}{2smv^2} \qquad \text{(AB-1)}$$

But, with VdG voltage *V*, we have

$$QV = \frac{mv^2}{2} \qquad \text{(AB-2)}$$

Thus

$$z = \frac{L^2 V_d}{4sV} \qquad \text{(AB-3)}$$

Note that *z* is independent of *Q* and *m*; that is, every particle is deflected the same amount. That is a great convenience for the experiment; we needed only one detector position to see the deflected particles.

(The arrangement changed the particle kinetic energy slightly, but not appreciably, since V_d was a few kV while *V* was more than one MV. We thus gained engineering simplicity, needing only one high-voltage lead for V_d.)

Leaving the plates, the particle travels a straight line to the detector. Now the particle path between the plates is a parabola with origin at the plate entrance. Also, the subsequent straight path is tangent to the parabola at the plate exit, and the slope of the parabola at that point is

$$\frac{V_d L}{2sV}$$

from (AB-3). From these considerations we finally have

$$V = \frac{(L^2 + 2bL)V_d}{4sy} \qquad \text{(AB-4)}$$

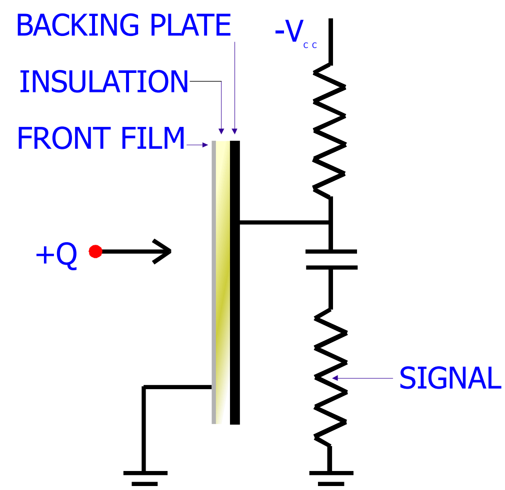
Knowing *L*, *b*, V_d, and *s*, we find *V* from the measured value of *y*. We made a series of trials at various values of *V* and V_d.

There was an average ratio between the voltage-divided generating voltmeter output (read with the same DMM which is now in place on top of the VdG control console) and our measured *V*'s.

Having a satisfactory value for that ratio in terms of consistency, we adjusted the voltage divider from the generating voltmeter accordingly, to make our DMM reading of *V* correspond to our measured *V*. So we now use the DMM for all readings of *V*.

The estimated precision of our result is 3%, which amounts to a possible error of about 0.05 MV if V is 1.5 MV. We are satisfied with that precision, for dust particle work. (If the accelerator were changed into a proton machine, one might want a better voltage calibration; that might be achieved through electrostatic deflection of protons or through some nuclear reaction.

The detector in this experiment was one of a pair left behind by visitors from the Langley laboratory in 1981. Its design is sketched at the right. In front of a backing plate there is a thin layer of malleable insulation; in front of that, there is a thin grounded metallic film. The backing plate is connected through a resistor to a low voltage negative source, say –40 volts DC. Particles are fired at the front film. If a particle penetrates the film and punctures the insulation, plasma material from the front film momentarily short-circuits the backing plate to the film, producing a voltage excursion at "signal." The insulation then flows to seal the hole, so that the device becomes ready for another particle.



A-C ANOMALOUS BEHAVIOR OF THE VdG VOLTAGE METER

One may sometime notice the VdG voltage panel meter in VdG Console (1D) going off-scale, reading over 2.5 MV while the VdG DMM meter on top of the console reads properly. If that occurs, pull out panel 1D—it is on a sliding rack—and find the battery which is in the circuit of the panel meter. (See Drawing 12 in the VdG mechanical-electrical file.) Check that battery; it should be three volts. If the battery is good and its connections are good, the panel meter should read normally.

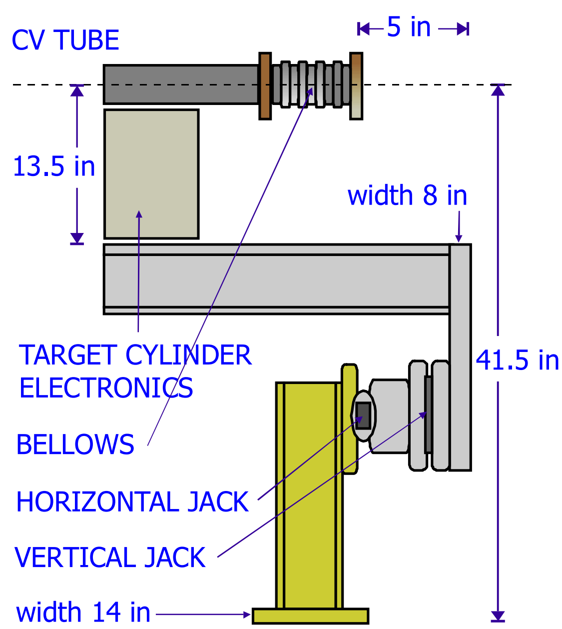
A-D NOTES FOR APPARATI REPLACING THE CORN POPPER

The corn popper can be removed and replaced with a detector or whatnot. However there are physical limitations to the device being attached.

The flange connecting the CV tube to the new device is a 5-inch ASA flange. **Note:** it has no O-ring groove.

The beam axis is 41.5 inches above the floor.

A 4-inch wide I-beam below the CV tube runs about 5 inches past the end of the ASA flange. This obstruction is something to consider when one is building a platform for a device. This I-beam has a support on this end that is 8 inches wide (used to mount the corn popper body to the CV tube) and is mounted to the floor with a 14-inch wide base.



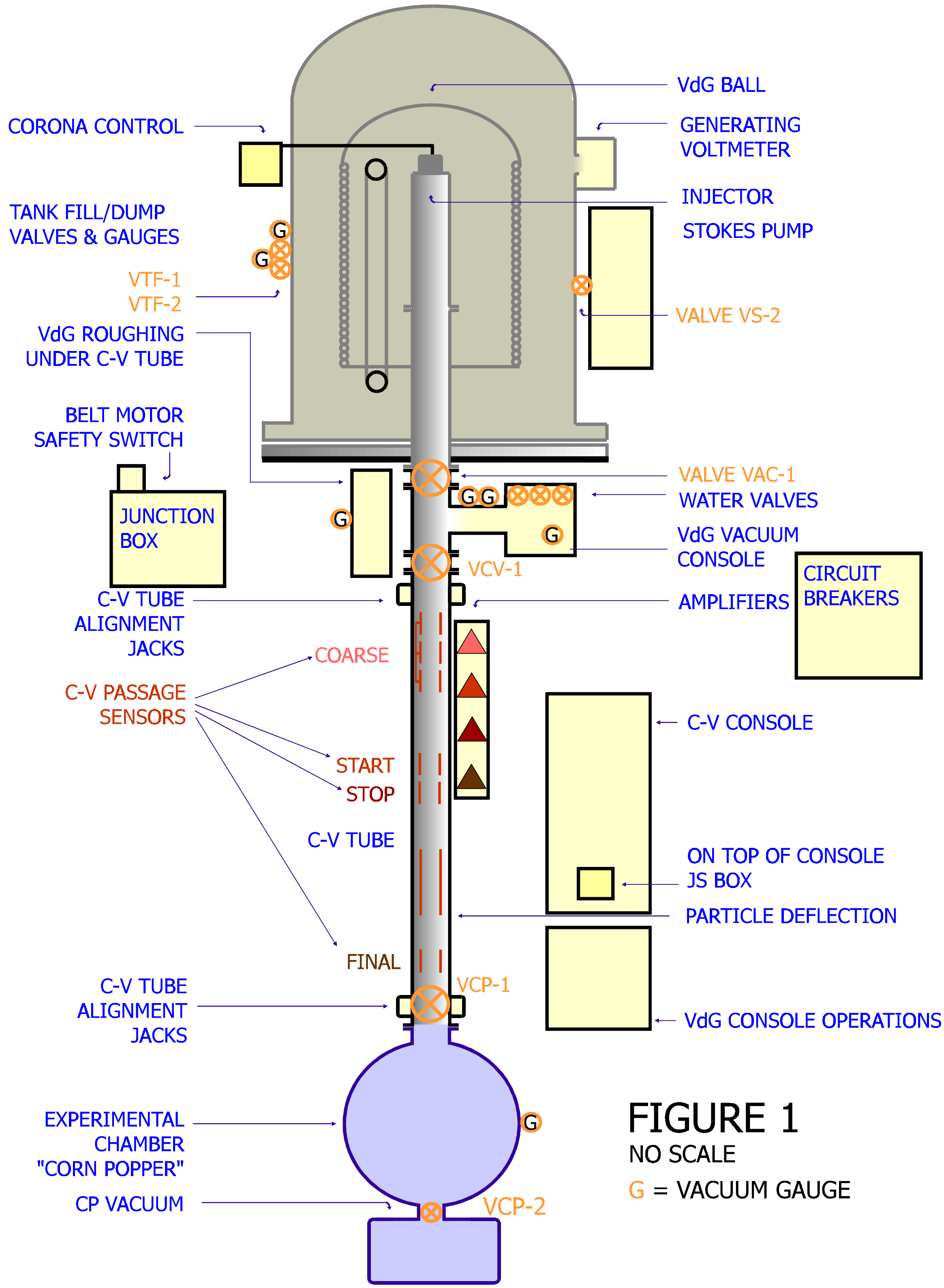


FIGURE 1

NO SCALE

G = VACUUM GAUGE

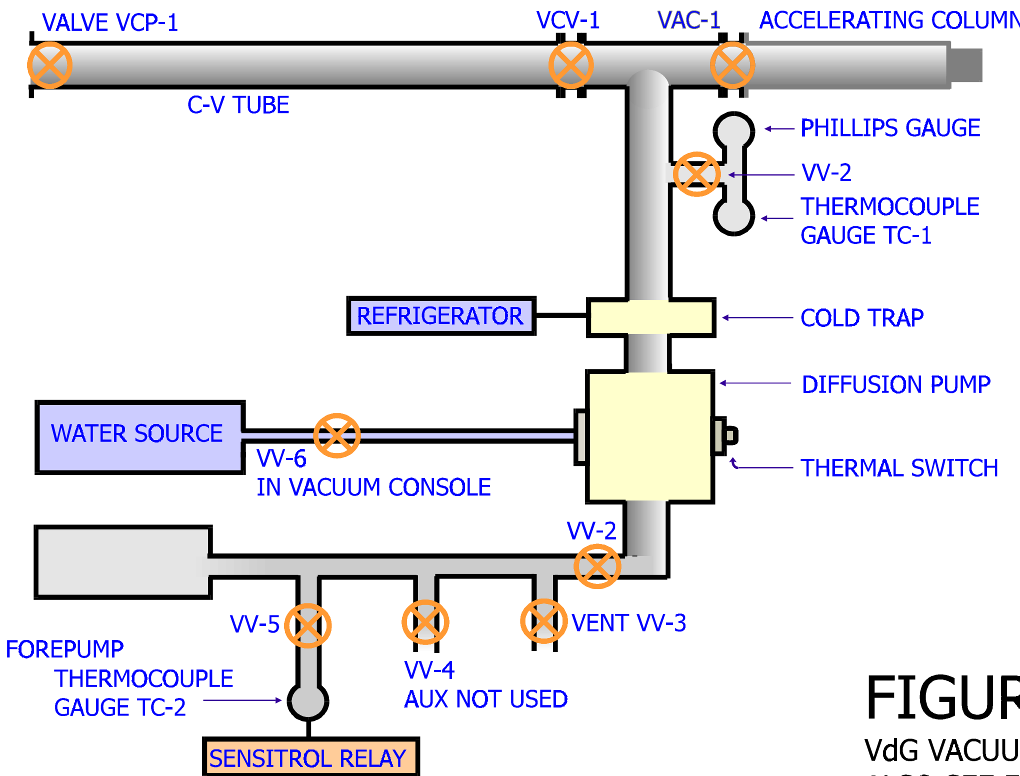


FIGURE 2
VdG VACUUM SYSTEM
ALSO SEE FIG. 3

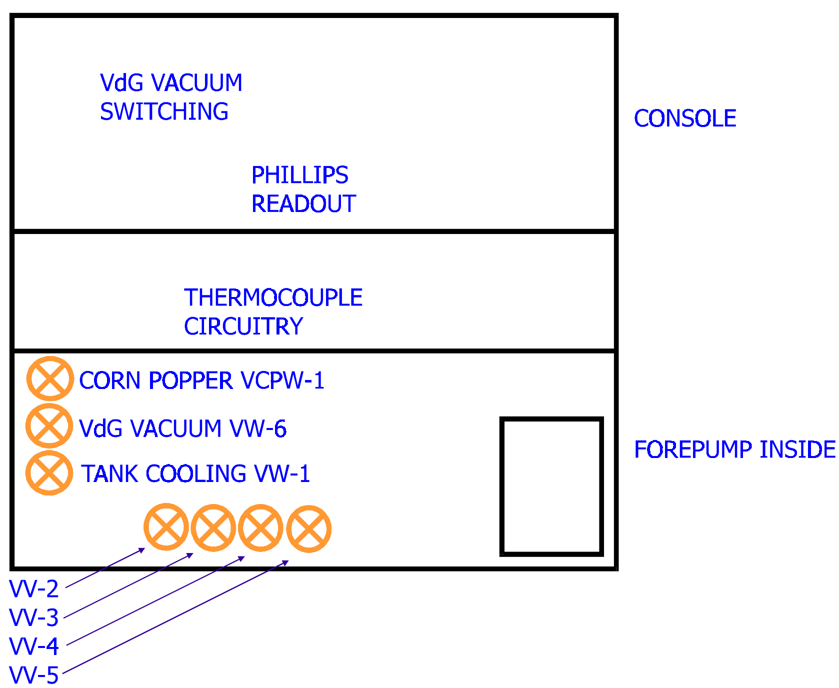
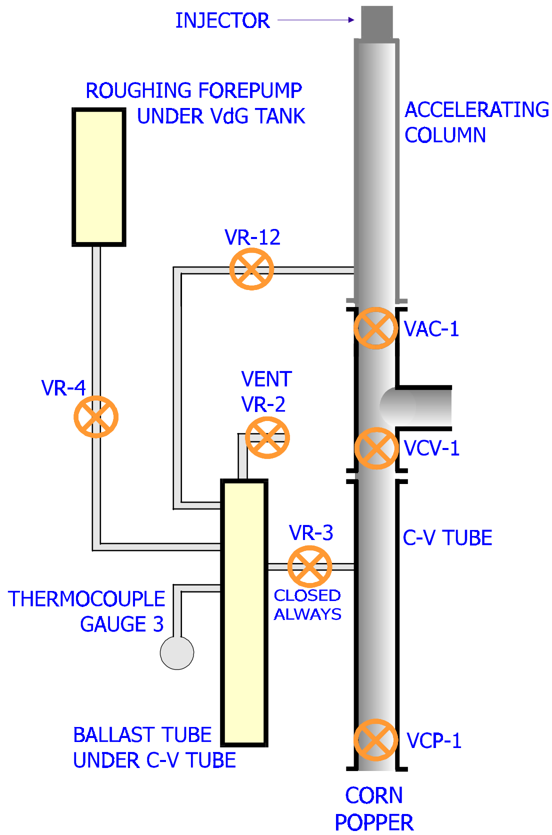


FIGURE 3

VdG ROUGHING
SCHEMATIC
NO SCALE



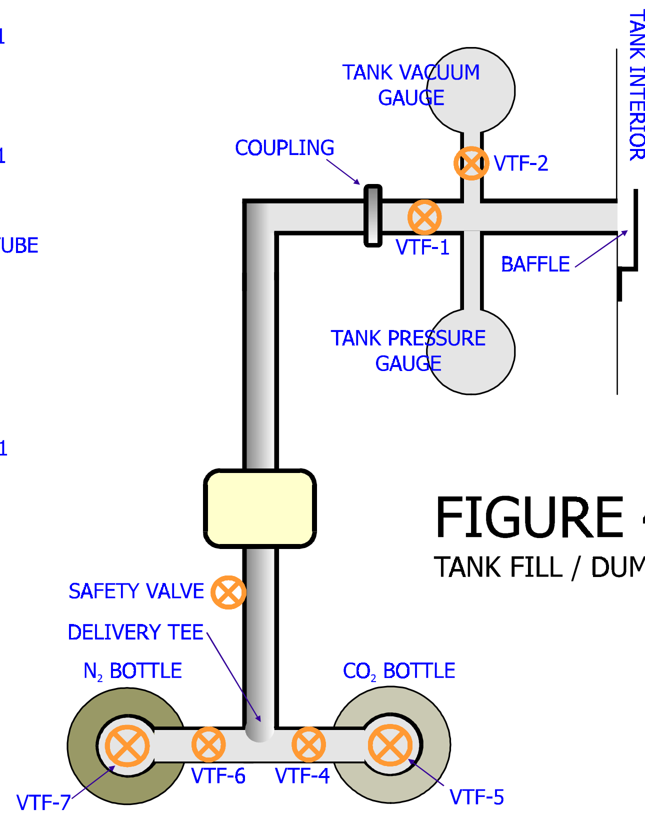


FIGURE 4

TANK FILL / DUMP

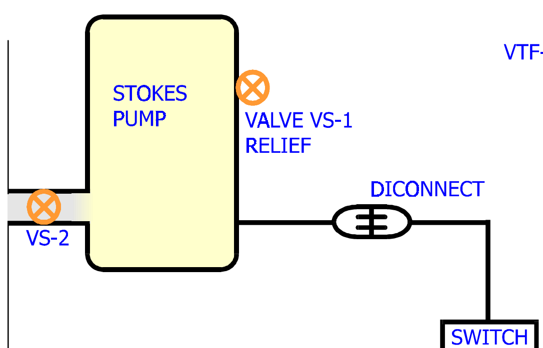


FIGURE 5

STOKES PUMP

0

FIGURE 6

VdG CONTROL CONSOLE

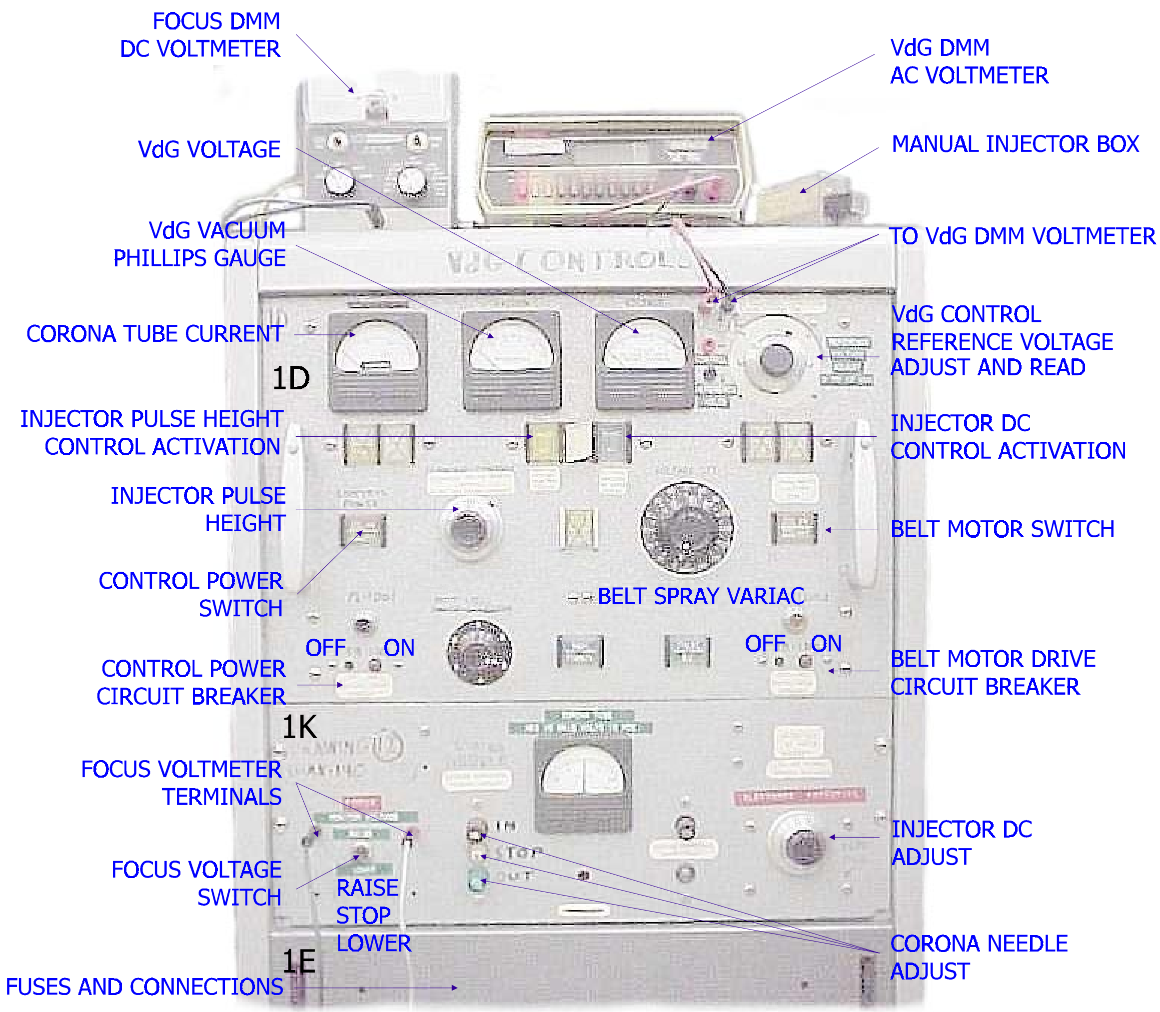


FIGURE 7

VdG VOLTAGE STABLIZER BLOCK DIAGRAM

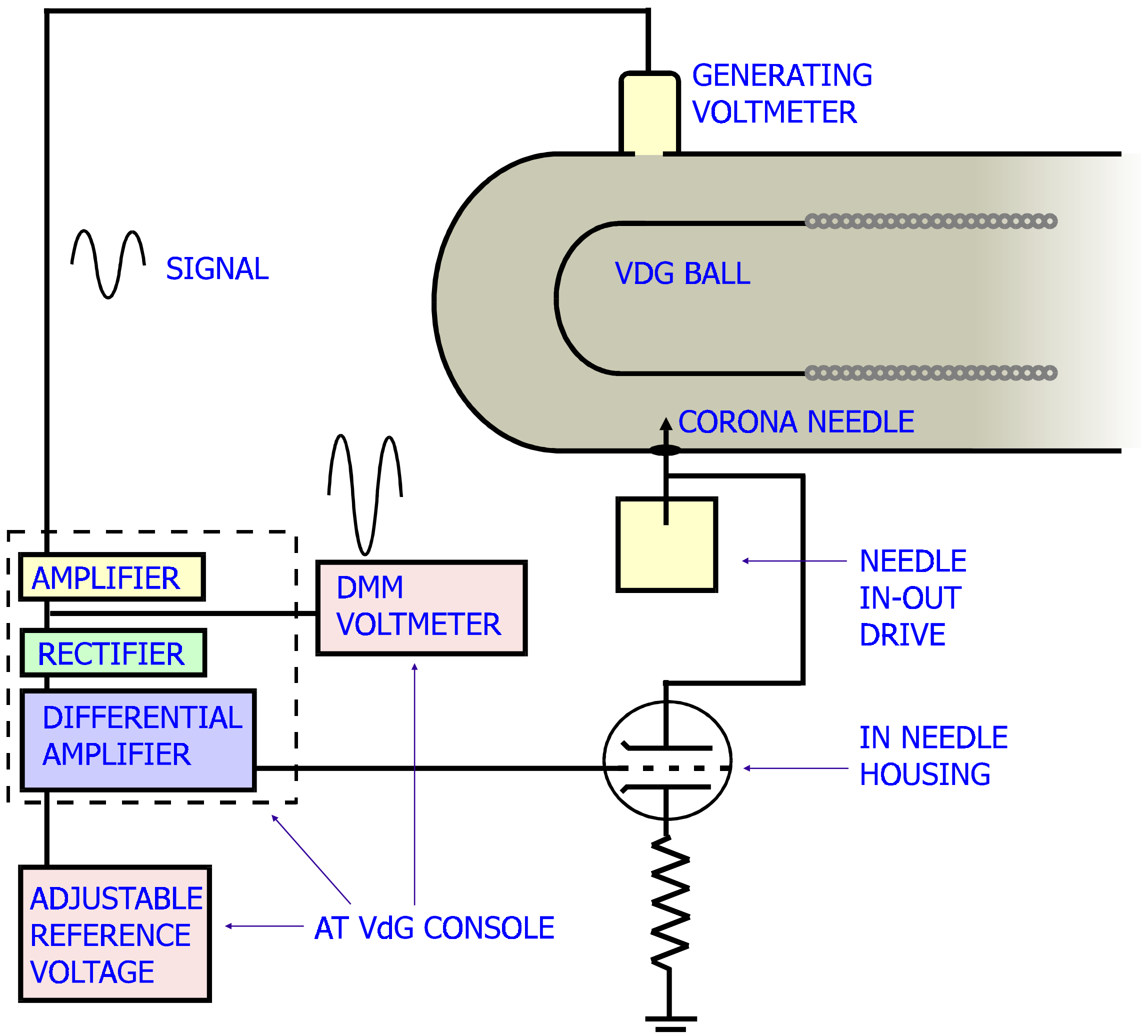


FIGURE 8

INJECTOR SCHEMATIC REPRESENTATION

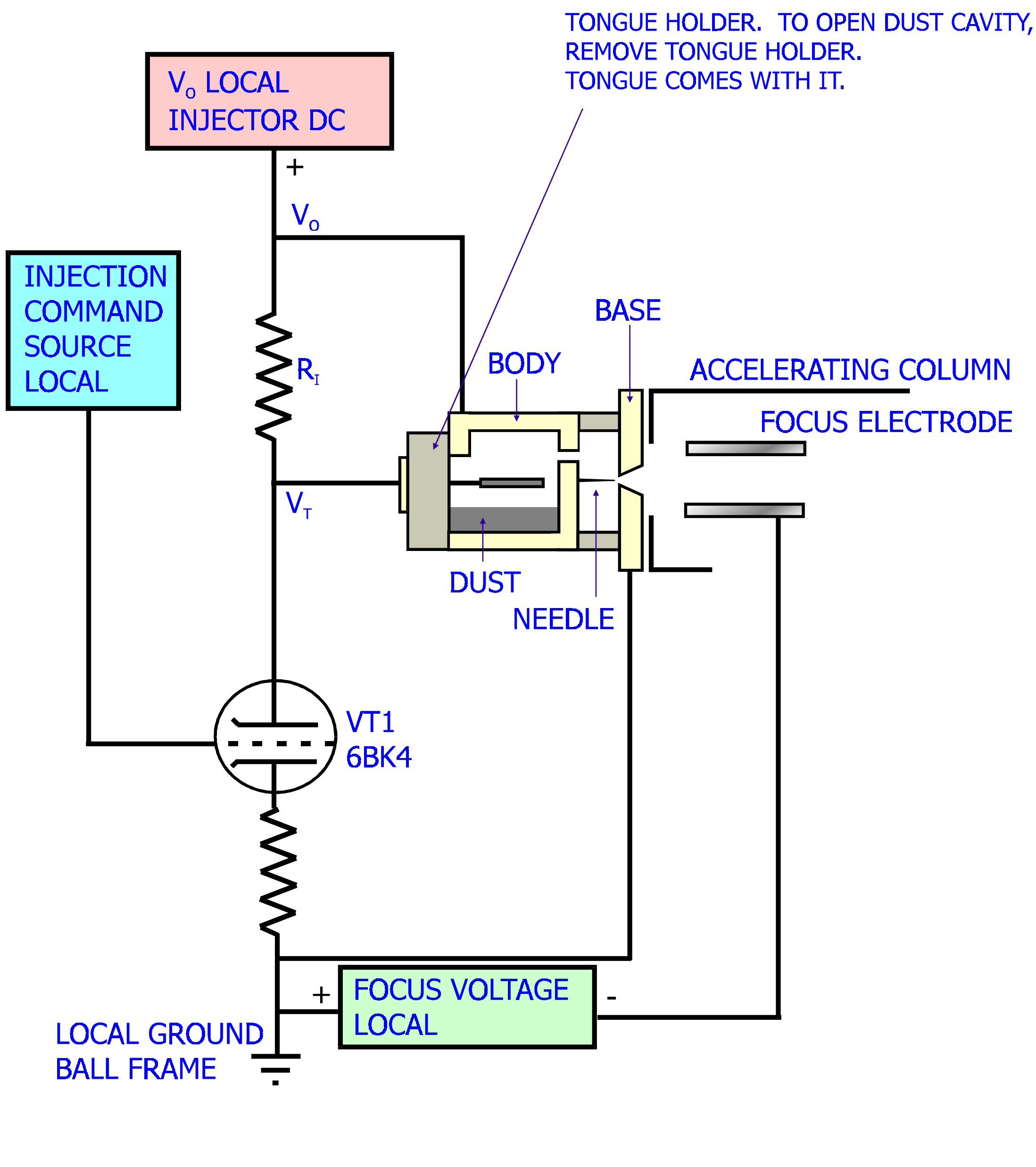


FIGURE 9

BALL POWER
AND INJECTION COMMAND ARRANGEMENT BLOCK DIAGRAM

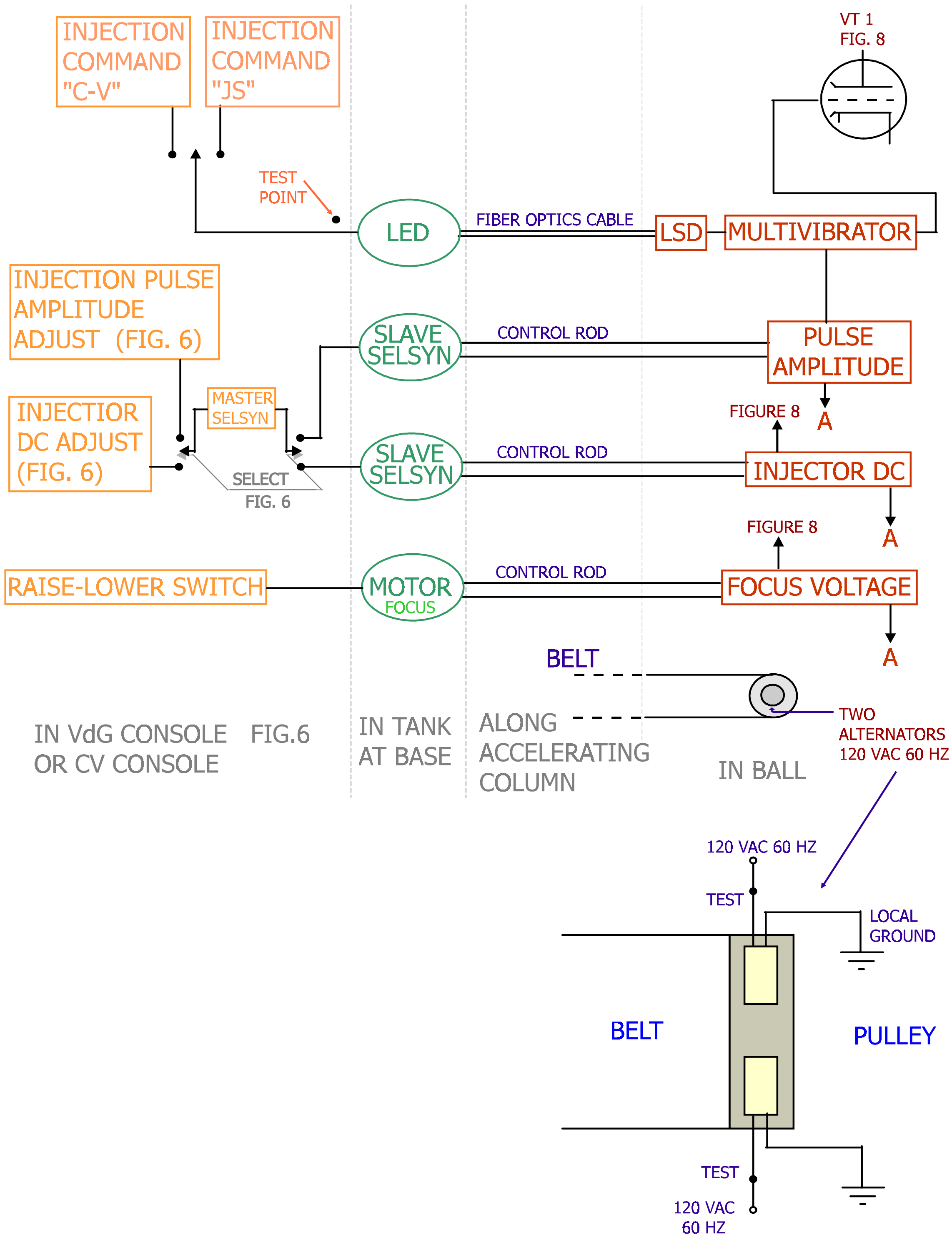
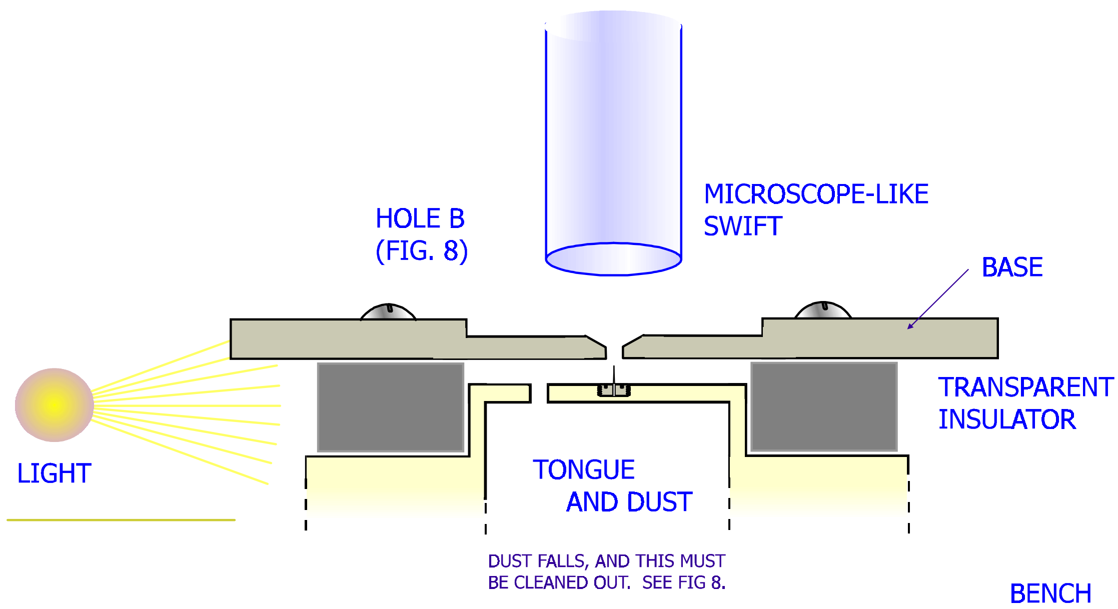


FIGURE 10

LOOKING AT NEEDLE IN PLACE IN INJECTOR
NOT SCALED



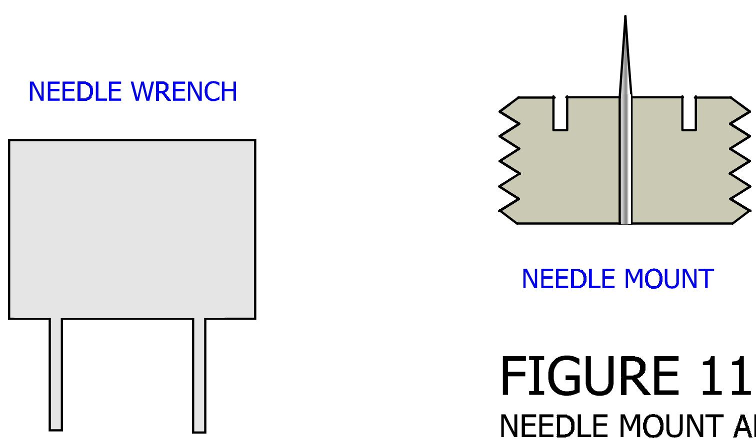


FIGURE 11

NEEDLE MOUNT AND WRENCH
NO SCALE

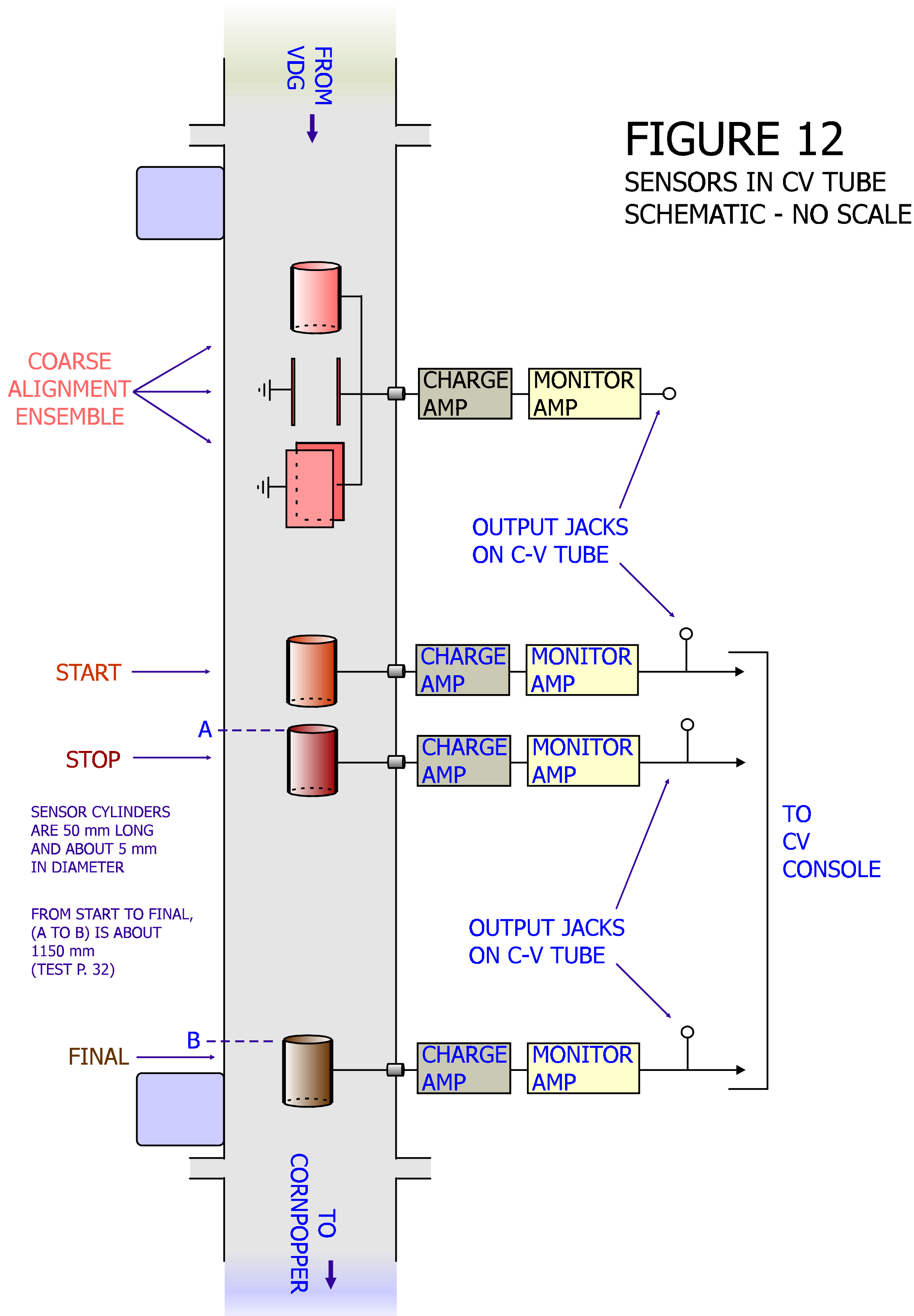


FIGURE 12
SENSORS IN CV TUBE
SCHEMATIC - NO SCALE
FROM VDG
COARSE
ALIGNMENT
ENSEMBLE
CHARGE AMP
MONITOR AMP
OUTPUT JACKS
ON C-V TUBE
START
A
STOP
SENSOR CYLINDERS
ARE 50 mm LONG
AND ABOUT 5 mm
IN DIAMETER
FROM START TO FINAL,
(A TO B) IS ABOUT
1150 mm
(TEST P. 32)
TO
CV
CONSOLE
B
FINAL
TO CORNPOPPER

FIGURE 13

C-V CONSOLE
PRINCIPAL OPERATIONAL ELEMENTS

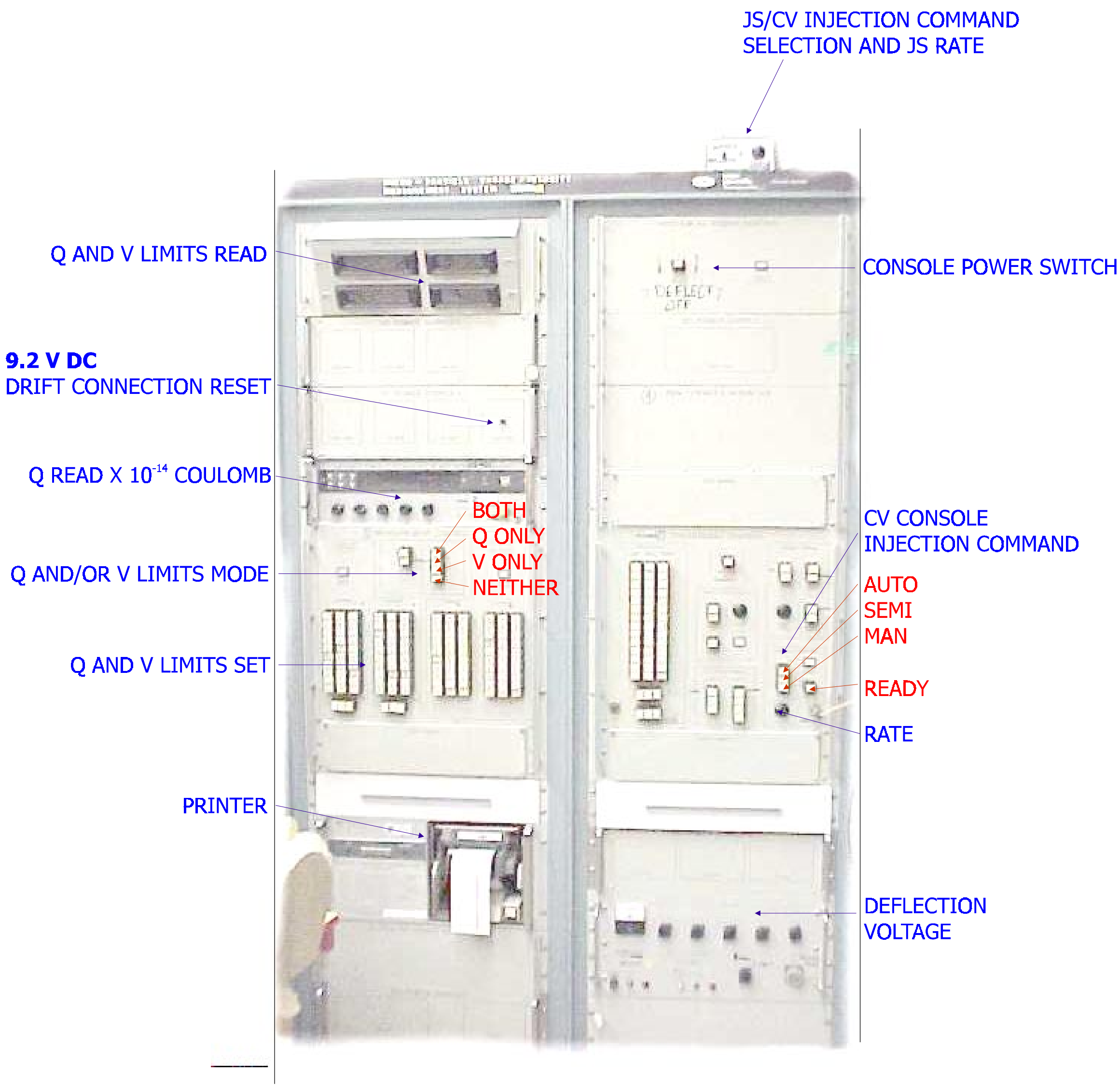


FIGURE 16

SENSOR AND SAMPLE MOUNT IN CORN POPPER