ISR-BWM/1s

15th July, 1971

ISR RUNNING IN

More about the dust wall model

This note advances a detailed hypothesis to explain the currently observed pressure bumps which accompany a rapid beam loss in the ISR. A qualitative description of the proposed process is given, followed by some numerical justification and proposed experiments to test the model.

1. Basic assumptions

   It is assumed that:

   i. There is present in the vacuum chamber a sufficient quantity of dust with a suitable range of grain sizes, roughly speaking below 1 micron.

   ii. There are some regions where the electron flux (from ionisation of the residual gas) hitting the wall is substantially higher than average. The location of these regions may change from one run to another.

   iii. The arguments about thermal motion presented in the running-in note ISR-MA/BWM/EEK, 8th June, 1971, are basically sound and are unlikely to be invalidated by the possiblity of refractory oxides like CaO and SiO$_2$ sticking to a stainless steel surface.

   iv. There are sufficiently few efficient dust traps at present in the ISR. An efficient dust trap is a slot or recess in which the gravitational potential, the probability of electrons arriving and the electric field from the beam or equipment are so small, that the smallest dust particle falling in has a very small probability of escaping again.

   v. Dust particles lying on the bottom of the vacuum chamber can absorb residual gas molecules up to at least a monolayer with a sticking coefficient near to unity.
2. **Description of the mechanism**

To illustrate the process I refer to the graph (Fig. 1) in K. Hübner's running-in report ISR-TH/KH/1s, 28th June, 1971.

i. Before stacking begins the dust particles have absorbed residual gas on to their surfaces.

ii. Stacking starts and continues up to about 1.5 A. Ionisation electrons escape from the beam, some attach themselves to dust particles and the smallest of these, helped by their thermal motion, are attracted into the beam. Here, they are rapidly heated by proton collisions and desorb their gas molecules. The pressure rises and remains constant during the plateau, suggesting that, at this stage, the rate of dust being drawn into the beam is limited by the electron flux available for charging the dust. The quantity of dust in the beam is small enough that no obvious beam loss occurs during the plateau. These particles are therefore small, with a large surface/volume ratio.

iii. Stacking is resumed to ~3.4 A. Larger electric fields from the stack lead to larger and more dust particles being pulled into the beam, more gas desorbed, more ionisation electrons, more charged dust particles and so on. The pressure is now rising during the current plateau.

iv. Stacking continues up to ~5.2 A without saturation. The dramatic rise in pressure now starts an avalanche of electrons, greatly increasing the number of particles that can collect electrons in a given time and probably permitting relatively large particles to be drawn into the beam through collecting multiple charges. The avalanche would be further increased due to spill-out if appreciable neutralisation of the beam started at this stage. The slope of the current plateau is now clearly evident and as the pressure rises to the peak value the beam loss rate increases to a maximum. At this moment there is the maximum quantity of dust in the beam, and the beam
loss is due mainly to multiple scattering by this
dust rather than by the gas in the pressure bump.

v. The avalanche can stop for one or both of two reasons:
a. the beam is now sufficiently neutralised that
the electric field is insufficient to pull in any but
the smallest particles,
b. all the dust in the region has now passed through
the beam, desorbed its gas and has had insufficient
time to accumulate a new layer of gas molecules to
sustain the pressure bump. Note that when the beam
has decayed into the 4 - 3.5 A region the pressure,
though high, is still decreasing, whereas during stacking
at 3.5 A the pressure was an order of magnitude less and
increasing. There is thus a clear hysteresis effect which
could partly be explained by a relative shortage of
absorbed gas on the dust after the avalanche ceases.
In fact it has once or twice happened on previous runs
that the pressure has reached a minimum and started to
rise again slightly, which is also consistent with
the hypothesis.

vi. It is interesting to consider the RF scans in Hübner's
Fig. 2. The beam loss between the scans appeared to
occur mainly in the high-density regions of the stack
nearest to the centre of the vacuum chamber, exactly
where one would expect charge dust particles to be
preferentially attracted.

vii The observations of B. Autin in running-in report
ISR-MA/BA/rh, 29th June, 1971, are generally consistent
with this model, though I have not yet had time to make
a detailed comparison.
3. Numerical justification for the hypothesis

Consider a single pressure-bump region

i. Total gas evolved in 1 fast-decay incident

For a rough estimate we take:

Pressure \( P \approx 10^{-6} \) torr

Length of one pressure bump region \( L = 10 \) m

Cross-section of chamber \( A = 2 \times 10^{-2} \) m\(^2\)

Volume of region \( AL = V = 0.2 \) m\(^3\)

Then \( PV = 2 \times 10^{-7} \) torr m\(^3\) and since 1 torr m\(^3\) contains \( \approx 3 \times 10^{22} \) molecules there would be, during the time of the pressure bump, around \( 6 \times 10^{15} \) molecules in the region.

The pressure bump lasts about 50 seconds, the average speed in the region is \( 0.2 \) m s\(^{-1}\) and so \( V \) is "emptied" about once a second. The total number of molecules removed during one fast-decay incident is therefore about \( 3 \times 10^{17} \), or \( 10^{-2} \) torr % of gas.

One has to show that this quantity of gas could be stored by the dust particles.

ii. Quantity of dust required

It seems reasonable to assume that a baked-out refractory oxide surface can absorb at least one monolayer of gas molecules with a sticking coefficient near to unity. One monolayer is about \( 10^{19} \) molecules m\(^{-2}\) for hydrogen, somewhat less for other gases.

Total surface for \( 3 \times 10^{17} \) molecules in a monolayer is then \( 3 \times 10^{-2} \) m\(^2\). If we assume that about half the surface area of a (cubic) dust particle of side 'a' is available for absorption one would need:
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\[ N_d(a) = \frac{10^{-2}}{a^2} \quad (a \text{ in metre}) \]

dust particles available. For example:

\[ N_d(1 \mu) = 10^{10} \]

\[ N_d(0.1 \mu) = 10^{12} \]

For a density \( \rho = 2.5 \times 10^3 \text{ kg m}^{-3} \), the mass of dust required per region would be:

25 milligram of 1-micron particles

or 2.5 milligram of 0.1-micron particles.

iii. Absorption rate

The clean surface of the dust particles would act as a sorbtion pump. A rough estimate of its speed can be made as follows.

A vacuum chamber of length 10 m and circumference 0.5 m has a surface of 5 m\(^2\). A total dust surface of 3 \times 10^{-2} m^2 would then give an average surface efficiency for absorption of 6 \times 10^{-3}.

For hydrogen, with a molecular velocity of around 1.8 \times 10^3 m s\(^{-1}\), an absorbing surface of 3 \times 10^{-2} m\(^2\) would then have an effective pumping speed of 324 \( s^{-1}\) if a gas molecule had only one impact on the chamber wall before leaving the region. However, with a long pipe the number of wall impacts will be approximately the ratio of length to diameter, say about 60, so the effective pumping speed for hydrogen could approach 2 \times 10^4 \( s^{-1}\) during the formation of the first monolayer. For other typical gases the pumping speed would be a factor of 4 or 5 less.

The time required for the dust to absorb \( 10^{-2} \) torr \( \ell \) of hydrogen (\( \equiv 3 \times 10^{17} \) molecules) would then be:

500 seconds at \( P = 10^{-9} \) torr

0.5 seconds at \( P = 10^{-6} \) torr
and correspondingly longer for other gases.

So, according to this model, it would take some tens of minutes for the required quantity of gas to accumulate on the dust particles under normal pressure conditions. With a pressure bump of $10^{-6}$ torr however, the time would be quite short and the same dust particles could desorb and re-absorb gas a number of times during the "avalanche" process until a substantial fraction of the gas had been pumped away from the region.

iv. **Multiple Coulomb scattering on gas and dust**

During Run 74 (K. Hübler, 28.6.1971), the maximum decay rate during the "avalanche" was $7 \times 10^{-3}$ sec$^{-1}$, corresponding to an average pressure around the ring of about $7 \times 10^{-7}$ torr $N_2$ equivalent for multiple scattering with a half aperture of 14 mm. Four pressure bumps of $9 \times 10^{-7}$ torr, each 10 m long would only account for 5% of the $7 \times 10^{-7}$ torr average. Though the real pressure peak may be appreciably greater than the value at the gauges, I find it difficult to believe in a factor of 20. If the beam loss is mainly due to dust one can as well attribute all of it to dust within the errors of the present numbers.

Scaling $7 \times 10^{-7}$ torr $N_2$ equivalent for multiple scattering to hydrogen by the $Z^2$ law and using E. Fischer's (3.6.1971) equivalence between hydrogen and CaO particles (which I don't quite understand), gives a mass of $\sim 10^{-9}$ kg CaO in the beam to account for the loss rate. The corresponding number of particles in the beam are:

- for 1 micron particles: $4 \times 10^5$
- for 0.1 micron particles: $4 \times 10^8$

which are rather small fractions of the numbers of dust particles required to account for gas desorption, estimated in (ii). This is not surprising, since the particles spend only a small fraction of their time in the beam.
v. Charging rate of dust particles

If

\[ N_e \quad = \quad \text{electron flux on vacuum chamber (m}^{-2}\text{s}^{-1}) \]
\[ N_{d}(a) \quad = \quad \text{no. of dust particles in pressure bump region} \]
\[ 3a^2 \quad = \quad \text{effective surface of dust particle} \]

then the number of dust particles charged per second, assuming single charges only, is roughly:

\[ \frac{N_e N_{d}(a)}{3a^2} \]

\( N \) is difficult to estimate. About 1 electron per second at \( 10^{-6} \text{ torr} \) \( N_2 \) is produced in the ISR per circulating proton. If one assumes that 10\% escapes to the walls of the vacuum chamber, the electron flux on a chamber of 0.5 m circumference for \( 10^{14} \) protons (5 A) circulating is about \( 2 \times 10^{10} \text{ m}^{-2}\text{s}^{-1} \), and is independent of \( 'a' \). At \( 10^{-6} \text{ torr} \) around \( 6 \times 10^{11} \text{ sec}^{-1} \) charged dust particles would be produced under these assumptions, which is certainly enough to sustain the avalanche.

vi. Electric field from beam

In the note B.W. Montague, 8.6.1971, it was stated that a field of 2.7 V m\(^{-1}\) is sufficient to pull into the beam a singly-charged dust particle of size \(-56 \text{ millimicron} \). It was also stated, incorrectly, that a slot of depth/width ratio \( 10 : 1 \) was necessary to attenuate a field of 20 kV m\(^{-1}\) to 2.7 V m\(^{-1}\); the correct ratio is about \( 3 : 1 \) in fact.

Fields from an unneutralised ISR beam of \( 10^{14} \) protons (5 A) lie typically in the range 5 - 25 kV m\(^{-1}\) at the vacuum chamber wall. This leaves a considerable reserve for dust particles in the sub-micron range to be pulled into the beam even at lower currents or under conditions of appreciable neutralisation.
vii. Heating of particles in the beam

The initial rate of temperature rise of a particle in the beam is independent of particle size and amounts to about 4000°K per millisecond for the parameters we have used in this note. Thus in 100 μs or so the particles have completely desorbed their gas.

The equilibrium temperature from radiation goes only as the 1/4 power of particle size and is about 1500°K for 1-micron particles. Hence even very small particles in the 50 millimicron range are rapidly baked out.

viii Transport of dust particles by collisions from protons

By considering the energy and momentum balance in a single collision one can rather easily show that the average acceleration of a dust particle in the direction of the protons due to multiple collisions is:

\[
\frac{dv}{dt} = \frac{N_p}{V} \frac{dE}{dx}
\]

where \( N_p \) = no. of protons in ISR beam

\( V \) = volume of ISR beam

\( \frac{dE}{dx} \) = specific energy loss of protons in a massive target.

With \( N_p = 10^{14} \) (5 A)

\( V = 0.4 \text{ m}^3 \)

\( \frac{dE}{dx} = 4 \times 10^{-14} \text{ J kg}^{-1} \text{ m}^{-2} \)

we find

\[ \frac{dv}{dt} = 10 \text{ m sec}^{-2}, \text{ about 1 g.} \]

One can also note that a 1-micron particle undergoes about 8 \( \times 10^{10} \) collisions per second whilst in the beam.

To estimate how long a particle takes to cross the beam we assume that, at the peak of its thermal motion, it is just
lifted by the field of the beam against gravitational and image forces. Thereafter the part of the beam field (assumed constant) necessary to overcome the image force becomes available to accelerate the particle. A field of 20 kV m\(^{-1}\) is just sufficient to lift a particle of 0.5 \(\mu\) under these assumptions. The equation of the motion is then:

\[
\frac{d^2z}{dt^2} = \frac{e^2}{4\pi\varepsilon_0 \rho a^3} \left[ \left( \frac{g\rho a}{kT} \right)^2 - \frac{1}{z^2} \right]
\]

where \(z\) is the height of the particle above the bottom of the vacuum chamber. This integrates to

\[
\frac{dz}{dt} = \frac{2e^2}{4\pi\varepsilon_0 \rho a^3} \frac{1}{z} \left[ \frac{1}{z} + \left( \frac{g\rho a}{kT} \right)^2 \right]^{\frac{1}{2}}
\]

for zero initial velocity, and with \(z\) a few centimetres the second term dominates leading to

\[
\frac{dz}{dt} \approx \frac{2e^2 g^2 \rho a^3}{4\pi\varepsilon_0 (kT)^2} \cdot z^{\frac{1}{2}}
\]

when the particle enters the beam.

With \(z = 0.1 \, \text{m}\) and \(a = 0.5 \, \mu\),

\[
\frac{dz}{dt} \approx 0.4 \, \text{m sec}^{-1}
\]

so a 0.5\(\mu\) particle would cross a 2 cm beam in about 50 millisecond. With 1 g acceleration due to proton impacts it would gain an azimuthal velocity of 0.5 m sec\(^{-1}\) in a single traversal. Particles smaller than 0.5\(\mu\) will stay longer in the beam and acquire large azimuthal velocities. (H. Koziol has made a similar calculation using slightly different assumptions and reaches an essentially equivalent result.)

4. Possible experiments

It is not obvious how to devise an experiment which distinguishes unambiguously between dust particle effects and other phenomena. For
example, electron or ion bombardment of the vacuum chamber could liberate gas and create a sort of avalanche effect. The only clear distinction between this and a dust effect depends on whether or not the beam loss rate can be accounted for by multiple scattering on the gas alone in the pressure bump regions. We do not know the numbers well enough yet to exclude the pressure bumps as being solely responsible.

Detection of visible light might be helpful, but it may not be easy to distinguish between that produced by many fine dust particles and that of the equivalent mass (for multiple scattering) of gas.

There are, however, some simple experiments which could give useful indications. Stacking up in stages of, say, 1 A and waiting some time (5 - 10 minutes) on each plateau to look for anomalous pressure changes. Making several adjacent separated stacks, moving these radially and looking for correlations between beam loss and radial position or stack density. Switching off clearing fields in the pressure bump regions and observing pressures and beam loss rates. Stacking repeatedly into saturation for some time to look for evidence of dust transport around the ring. Examination of the foils of the dump block SEMs at the next shut-down for indications of damage by heavy particles, (as observed in the transfer channels last year).

Some of the above experiments have been proposed for the next period. More draconian methods such as dust traps, should await further experimental evidence of dust particles.

5. Some points, purely for uninhibited speculation

i. There must exist natural dust traps in the ISR where some particles could land. The maximum current increases steadily with time. Is this a coincidence?

ii. Mass spectrometer analyses show a strong peak at mass 28, corresponding to CO, N₂ but also to Si. SiO₂ is a component of building dust but silicon has a rather low vapour pressure at the temperatures involved.
iii. If the dust started off in large lumps, say between 0.3 and 1 micron, it would required multiple charges to pull it into the beam, but once in might cause abrupt beam loss. Could some of the early "brick-wall" observations result from this? Could these particles be gradually fragmentated into the millimicron size by proton collisions, giving them the possibility of absorbing larger quantities of gas and permitting them to be pulled into the beam more gradually and at lower field levels?

All constructive comments are welcome.

B.W. Montague

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