THE CLEARING FIELDS OF THE ISR

B. Angerth, E. Fischer and O. Gröbner
CERN, Geneva, Switzerland.

1. Introduction

Early studies of the space charge limits in the CERN Intersecting Storage Rings (ISR) for 28 GeV protons, showed that the design aim of $4 \cdot 10^{14}$ protons circulating in each ring might not be atainable if the beam space charge was neutralized[1,2,3].

Unless suitable counter measures are taken neutralization of the beams would rapidly occur due to ionization of the residual gas in the vacuum chamber by the beam protons. Of the ions and electrons produced the electrons get trapped in the beam space charge whereas the positive ions are immediately expelled. At a residual pressure of 10^{-9} torr nitrogen every beam proton produces on the average 1.4 electrons per second. Under these conditions an initially deneutralized beam would get neutralized in less than one second[4]. (The ISR design pressure was 10^{-9} torr.)

If neutralization is avoided, the beam potential with respect to the vacuum chamber walls will be about 80 V per ampere of circulating beam in oval ISR chambers ($160 \cdot 52$ mm^2) and about 120 V/A in the circular chambers (Ø 160 mm). The beam potential grows almost linearly with the beam intensity and will thus reach approximately 2 kV at an intensity of 20 A, corresponding to $4 \cdot 10^{14}$ stored protons[5].

Only few of the electrons liberated in the beam will have an initial energy permitting them to escape to the chamber wall immediately. The majority of electrons will get trapped. The energy of the trapped electrons will slowly increase, due to momentum transfer from beam protons by multiple Coulomb scattering, until they have acquired the escape energy. The rate of energy transfer to trapped electrons is proportional to the density of the beam, which for weak beams is approximately proportional to the beam current. For intense beams (exceeding 1 A) it is nearly independent of current. The estimated rate of transfer for intense beams is about 350 eV/s, which implies that a low energy electron would reach the escape energy in about 6 seconds, in a non-neutralized beam of 20 A intensity[2]. In strong beams trapped electrons gain rapidly in energy and produce secondary electrons but this becomes important only at higher degrees of neutralization.

Under steady state conditions the balance for electrons in the beam is given by the formula

$$N_P R_{P1} + N_e R_{P2} - N_e R_c = 0 , \qquad (1)$$

where N_P and N_e are the numbers of protons and electrons in the beam, R_{P1} the primary production rate (in trapped electrons per second per proton), R_{P2} the secondary production rate (in trapped electrons per second per trapped electron) and R_c is the clearing rate (per second).

For the average degree of neutralization, defined as $\eta = N_e/N_p$, we obtain

$$\eta = R_{P1}/(R_c - R_{P2}) . \qquad (2)$$

Equation (2) can be used for estimates. It must however be remembered that R_{P1} , R_{P2} and R_c depend implicitly on η . If the neutralization should not exceed 1% , one calculates from Eq.(2) a minimum clearing rate of 140 s^{-1} at 10^{-9} torr, that is a clearing time of $7 \cdot 10^{-3}$ s or less. For 10^{-10} torr the clearing time must be $7 \cdot 10^{-2}$ s or less. (Actual pressure $\sim 10^{-10}$ torr.)

Especially as, at an early stage of the project, there was no reason to believe that the actual pressure would be much better than the design pressure, it was decided to equip the ISR with a clearing facility. Studies on electron motion in the beams revealed that efficient clearing could most likely be achieved by short electrodes suitably spaced around the machine.

2. Electron motion in the beam

The circumference of each ISR ring is about 50% occupied by combined bending and focussing magnets. Within these magnets electrons will start drifting along the beam as they are subjected to crossed electric and magnetic fields, where the electric field consists of the radial component of the electric field from the beam space charge. The average drift velocity at 22 GeV/c is $3 \cdot 10^3$ m s^{-1} A^{-1}, except for very weak beams. This gives for the average drift length of 4 m a clearing rate of $R_c = 400$ I (in s^{-1}; I in A).

A second drift motion besides the crossed field drift, is caused by the gradient of the magnetic field across the beam. For the ISR, at maximum field, the gradient drift becomes

$$v_{grad} \approx 2.8 \, W \quad m/s , \qquad (3)$$

where W denotes the electron energy in eV.

As electrons must be cleared before they have had the time to accumulate much energy the gradient drift will generally be small compared with the crossed field drift.

With the primary production rate $R_{P1} = 1.4 \cdot 10^9$ P (in s^{-1}; P in torr) and the clearing rate of $R_c = 400$ I as given above one finds, neglecting R_{P2} and the gradient drift, a degree of neutralization of

$$\eta = 3.5 \cdot 10^6 \frac{P}{I} \quad . \qquad (4)$$

This means - in this approximation - that at a given beam current the neutralization increases linearily with pressure and reaches 35% for an 1 A beam at 10^{-7} torr. The linear dependence of η on P/I is a fair approximation up to at least $\eta = 0.5$. R_c (see Eq. (2)) decreases (at least within the magnet units) and R_{P2} increases with increasing neutralization. At the same time R_{P1} decreases since with increasing neutralization the escape energy decreases.

Because of the small drift velocity required for clearing electrons, even very low energy electrons are likely to migrate through most straight sections in times short compared to what is required for clearing. It was therefore decided not to cover the straight sections entirely with clearing electrodes but to mount short electrodes in all the coil-overhangs of the main magnets. Electrodes placed at these positions should be able to collect all electrons, both those swept out of the magnet units and those migrating randomly through the straight sections.

3. The clearing electrodes

The electrodes finally adopted are 243-250 mm long (depending on mounting position) and 130 mm wide. They are slightly curved around the beam at a distance from the beam exceeding by a few millimeters the minimum required aperture. The electrodes are fitted in pairs on opposite sides of the beam.

Each of the two ISR rings contains 132 main magnets. As a pair clearing electrodes is mounted at both ends of every magnet, the total number of clearing electrodes amounts to 1056 for the whole machine. In this number is not included some special electrodes fitted in certain long straight sections (see below).

The main parts of the electrodes are constructed from 1 mm thick sheet of austenitic stainless steel. A complete electrode can be fully assembled and tested in the laboratory. The final mounting in the vacuum chamber requires only a few minutes. The high voltage is fed to the electrodes individually through connections of approximately 50 Ω characteristic impedance.

Special precautions had to be taken to reduce the risk of RF interaction between the beam and the clearing electrodes which might cause beam instabilities. On the outside of the vacuum chamber the electrode is therefore connected to a box terminating the electrode by a matched 50 Ω impedance for the frequency range from below 10 to 500 MHz. The effects of resonances in the GHz range are reduced by not giving all electrodes the same length.

4. Clearing voltage controls

The electrodes along 1/8th of an ISR ring are fed from common positive and negative high voltage power supplies in adjacent equipment buildings. The voltage can be adjusted continuously from 0 up to 10 kV. An interlock against vacuum failures is provided.

All power supplies are remotely adjustable from the ISR control room. Checking of the correct clearing voltage can be done by the controls computer. If the output of any power supply deviates by more than a given amount from the requested clearing voltage a fault message appears on the alarm printer in the control room.

5. Experimental results

The purpose of the tests so far made was mainly to establish optimum clearing voltage settings, to estimate the clearing efficiency and, in particular, to find out whether there are uncleared regions around the ISR circumference and finally to observe beam decay rates as function of the applied clearing voltage.

5.1 Clearing efficiency

In one series of measurements the voltage difference between the electrodes has been varied. It was found that the electron current drawn by the positive electrode saturated for voltages between 300 and 400 V for 1 A of beam current. This is in rough agreement with what one should expect from the calculated beam potential. The clearing current could be furthermore increased by applying asymmetric voltages, that is by giving the median plane between the two electrodes in a pair a positive potential, with respect to the chamber sections without clearing electrodes. In Figure 1 the clearing

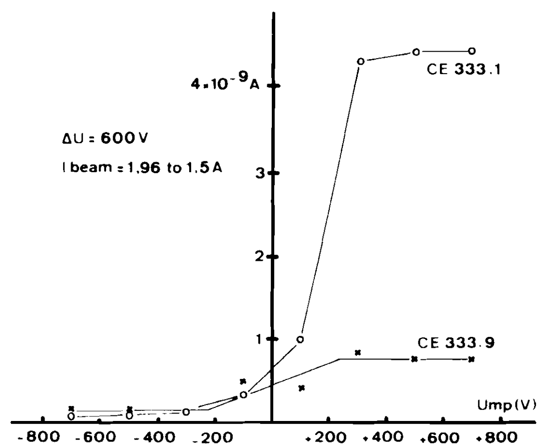

Fig. 1 Clearing current of two electrodes in straight section 333 versus median plane potential U_{mp}.

current of two electrodes is plotted against the median plane potential U_{mp}. The potential difference between the plates was kept constant at 600 V. Only when $U_{mp} \geq 300$ V, are the clearing currents saturated, indicating that at $U_{mp} = 0$ a large fraction of the electrons do not reach the electrode. The reason for this is most likely the difference in beam potential between round chamber sections and oval chamber sections. A pair of clearing electrodes can be considered as an extension of the oval magnet chamber to which it is attached.

It was also observed that low decay rates could only be obtained for optimum clearing conditions. In Figure 2 the beam loss $\dot{I}/I$ per minute of a 2 A stack is plotted against the median plane potential with a constant potential difference of 600 V between the plates.

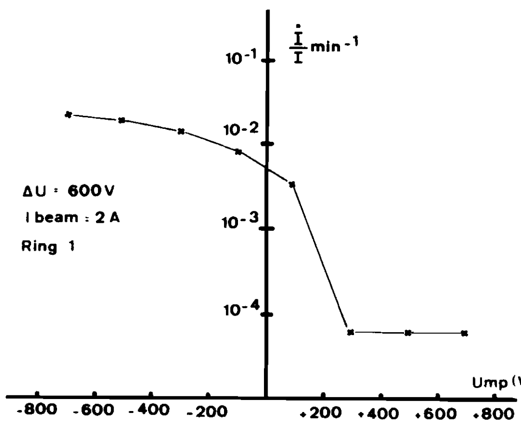

Fig. 2 Beam decay rate versus median plane potential U_{mp} for a 2 A stack.

The "natural" decay rate of the given stack is obtained for $U_{mp} \geq +300$ V. Below this value the decay rate increases steeply the more U_{mp} is made negative. Under these conditions the electrons seem to be efficiently trapped in the chamber sections between the clearing fields, causing a high degree of beam neutralization.

5.2 Neutralization pockets

Experiments have shown that electrons created by the beam are able to migrate over rather long distances, passing through several magnet sections before they reach the next clearing electrode. Indeed, by switching electrodes off over a part of the circumference the clearing current of a test electrode is roughly inversely proportional to the number of collecting electrodes. This result would indicate that a smaller number of electrodes may be sufficient to give adequate clearing of the beam. As was already pointed out, however, variations in the cross-section of the vacuum chamber give rise to longitudinal beam potential variations. These may lead to electrons being trapped in potential wells thus partly neutralizing the beam. As an example, an ISR standard round vacuum chamber, fitted between two pieces of oval chamber, creates a potential well of about 160 V in presence of a 4 A beam[5] (see also the Introduction).

It was possible to create artificially electron traps by switching off the clearing electrodes in one of the long straight sections with enlarged cross-section and measure the accumulated negative charge on a biased test electrode.

The degree of neutralization reached in these experiments was between 17 and 30% for a 4 A beam. Varying the charge accumulation time, that is the interval during which the test electrode is at zero potential, permits the neutralization time to be determined. The extrapolated values for 100% neutralization are of the order of 10 seconds, in rough agreement with expectation for a vacuum pressure of 10^{-10} torr.

Some of the long straight sections and intersecting regions have cross-section variations of the vacuum chamber where the beam is very likely to be partly neutralized. Since this might be the cause of increased beam decay rates, all these locations are now being equipped with additional clearing electrodes.

References

1) CERN Study Group (1964), Report on the design study of intersecting storage rings (ISR) for the CERN proton synchrotron, CERN/542, chapter IV.8.

2) B. Angerth (1965), Review of studies on beam neutralization in storage rings, AR/Int. SG/65-1.

3) E. Fischer (1966), Clearing fields for the ISR, ISR-VAC/66-15.

4) K. Symon (1964), Private communication.

5) L. Thorndahl (1971), Space charge potentials inside three different ISR chambers, CERN-ISR/RF/71-20.