HIGH CURRENT COMMISSIONING OF THE H^- ION ACCELERATING COLUMN OF THE ISIS INJECTOR

H Wroe and N D West
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon., England

Abstract

The preaccelerator of the ISIS linear accelerator injector consists of a 665 keV medium gradient dc accelerating column which, at full specification, is required to deliver an H^- beam of 650 μA mean. Although the initial operating experience with the column at low beam duty cycle was satisfactory, at high values of mean beam current the frequency of high voltage breakdown increased to an unacceptable level. An account is given of the experimental study of this phenomenon, of the mechanism thought to be responsible and of the modifications carried out to achieve the present improved performance.

Introduction

The accelerating column [1] of the ISIS injector was originally built in 1975 to provide a low duty cycle proton beam of pulsed current up to 200 mA [2]. In conversion to an H^- accelerator for ISIS, the column was essentially unmodified except for the reversal of gradient and the installation of a new ion source.

The column, illustrated in Fig.1, is in 16 sections constructed from titanium alloy electrodes and pyrex insulators, bonded with PVA adhesive. The column sits in an epoxy glass fibre vessel, pressurised with SF6 and operates at the relatively modest uniform gradient of 1.5 kV/mm, given by 665 kV over the 444 mm vacuum length.

The H^- ion source [3] is a Dudnikov type Penning source, which uses caesium vapour and a pulsed hydrogen supply, and a 90° gradient bending magnet after the extractor provides beam focusing. The magnet pole pieces, together with a surrounding refrigerated box on which excess caesium vapour is condensed, are held at the beam extraction potential. The source operates at 50 Hz, with a pulsed arc of 500 μs duration, and gives pulsed beam currents up to 30 mA. The average gas flow from the source of about 13 atmos.cc/min is handled by two 2000 l/s turbo pumps at the ground end of the column and by a further turbo pump at the ion source enclosure. A diaphragm plate, at extraction potential, separates the ion source enclosure from the accelerating structure and helps to limit the flow of gas down the column.

Voltage Breakdown At High Duty Cycle

No problem was found in high voltage conditioning the column, nor in its early operation at low beam duty cycle. When high duty cycle operation of ISIS started in early 1985, however, frequent voltage breakdown was experienced. Typically, with a pulsed beam current of 10 mA, at 200 μs pulse length and 12.5 Hz pulse frequency the time between breakdowns averaged about 4 mins.

It was found that the breakdowns only occured if beam was being accelerated down the column and that each breakdown followed the acceleration of a roughly fixed quantity of beam charge. This value of charge accelerated between breakdowns will be referred to as <Q> which, for the case above, is equal to 6 mC. Following a breakdown, there was no difficulty in quickly re-establishing full operating voltage, showing that there was no problem of voltage deconditioning.

A probable explanation for the breakdown time constant was thought to be the steady build-up of charge on the surfaces of the insulators due to bombardment by energetic particles, initiated somehow by the beam. It had been calculated [4] that some 3% of the H^- beam would be stripped by the hydrogen gas, mainly close to the column entrance, and produce a significant electron current, but a mechanism by which particles could reach the insulators was not immediately obvious, particularly in view of the large,

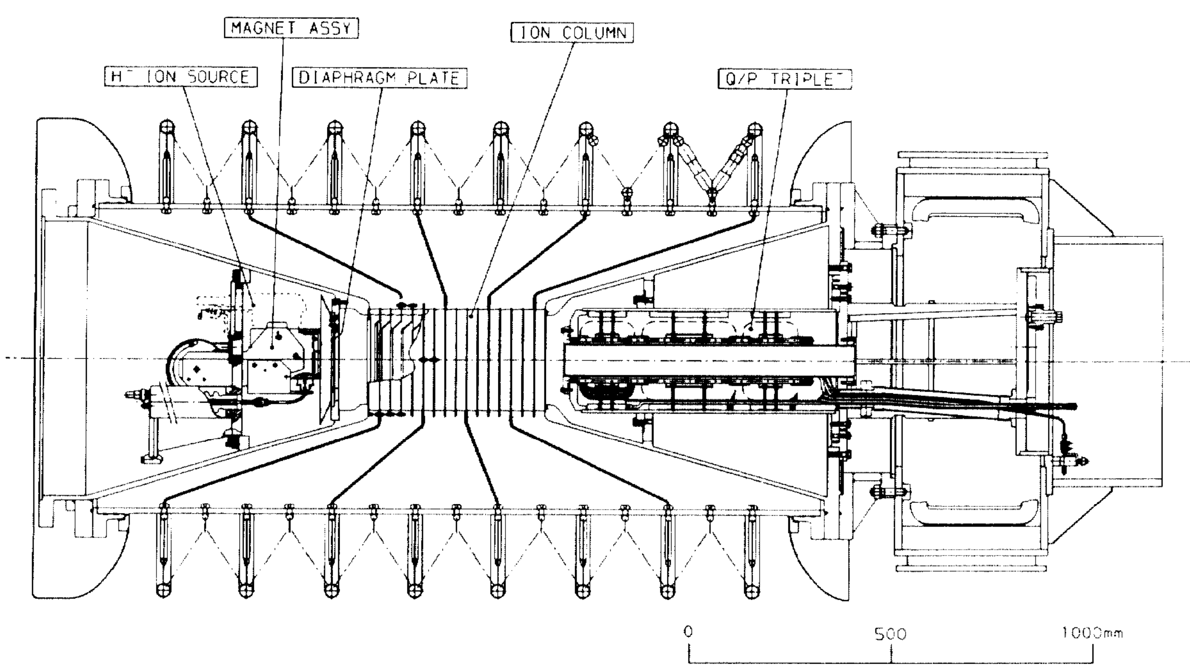


Fig.1 665 keV Preaccelerator - with original 140 mm aperture electrodes.

140 mm, aperture in the column electrodes and the strong axial field.

The frequency of breakdowns was found to increase with pressure in the column. For example, with the extracted beam pulse rate fixed at 12.5 Hz and ion source arc pulse rates, and hence gas pulse rates, of 12.5, 25 and 50 Hz, average values for <Q> were 10.7, 7.4 and 4.0 mC respectively, showing a clear dependency on the gas flow from the source.

Reducing the voltage on the column from 665 kV produced no significant increase in <Q> until it was below 500 kV. Also, progressively shorting out the accelerating gaps from the ground end, while keeping a constant gradient over the remaining gaps, gave no increase in <Q> until only 6 gaps remained. Both these experiments show a high voltage breakdown behaviour very different from that commonly experienced.

Effect On Breakdown Of Modifications To Column

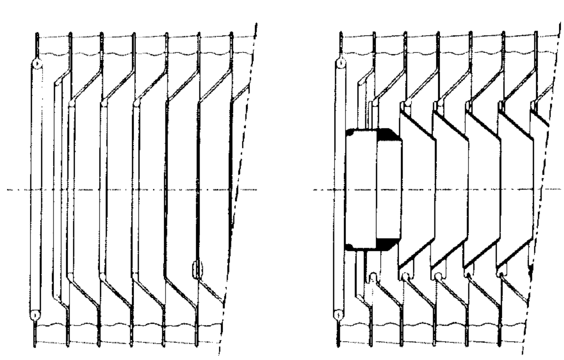
In an attempt to reduce the frequency of breakdowns various modifications to the column were explored.

Several arrangements of beam collimation were tried to prevent particles entering the column at large angles, such as energetic H° particles originating in the magnet gap and able to reach the electrodes, but without improvement. The number of gas scattered particles able to reach the electrodes was calculated to be too small to be of significance.

An electrode was installed downstream from the diaphragm plate and biassed at up to -5 kV relative to the extraction potential, to prevent negative particles created at the extraction potential from entering the column, but with no improvement.

In order to reduce the flow of hydrogen gas down the column, the 40 mm diameter aperture in the diaphragm plate was replaced by a 10 x 20 mm slot. This reduced the vacuum pressure at the ground end of the column by a factor of about three and increased the average value of <Q> by about 50%.

Improved shielding of the column insulators was explored by installing insert electrodes in the apertures of the existing electrodes. The first arrangement tried, shown in Fig.2(a), was a set of flat disks, with 50 mm apertures, supported by an arrangement of locating buttons. In spite of the reduced column pumping speed, and hence higher vacuum pressure, the value of <Q> was increased by a factor of about five.



(a) Flat disk (b) Conical disk

Fig.2 Column insert electrodes

Improving the pumping speed at the ion source enclosure, by increasing the size of pump and pumping manifold, increased <Q> by a factor of nearly two.

Using the improved design of insert electrode shown in Fig.2(b), with a 30 mm aperture in the diaphragm plate, produced a further gain, with the time to a breakdown averaging about 15 mins for a mean beam current of 320 µA, ie a <Q> of 288 mC.

For reasons discussed in the next section, it was decided to explore the effect of non-linear gradient distributions in the column. An arrangement which appeared to be close to an optimum used a voltage gradient over the first four gaps at 75% of the gradient over the rest of the column, with the total voltage maintained at 665 kV. This increased the time between breakdowns to an average of about 140 mins, for a beam of 15 mA, 400 µs, at 50 Hz, giving a <Q> of 2,500 mC.

The situation above represents the present state of preaccelerator development and, although the performance may sometimes be a little worse, the breakdown rate is generally acceptable. During recent operation, for example, with a mean preaccelerator beam current of 160 µA, the breakdown rate has averaged about one per two hours. The ability to re-establish full operating voltage, immediately after a breakdown, results in negligible lost beam time.

Diagnostic Investigation Of Breakdown Phenomenon

At a late stage in the above modification work, an intensive investigation of the breakdown phenomenon was instigated in the hope of uncovering its basic mechanism. Some of the diagnostic methods which produced negative results will be mentioned briefly first.

Light emitted by the column was studied, externally using a television camera and internally using fibre optics and a photomultiplier, but no data of significance were obtained.

A multi-wire beam position detector was set up in the 665 kV beam line to look for beam steering effects immediately preceding a breakdown, but no movement of any relevance was found.

A high speed tape recorder was used to study possible changes in the column voltage just before a breakdown, but no evidence for this was found. It was revealed, however, that the breakdowns occured both during and between beam pulses, with about equal frequency.

A scanning mass spectrometer, also capable of recording fast pressure changes for a given mass, showed no significant vacuum changes preceding a breakdown.

One of the original, flat, insert electrodes was tested for surface contamination. No caesium was found, the only significant contaminants being from hydrocarbons.

The X-ray emission from the column was monitored and showed a strong signal coincident with the beam pulse, but no unusual emission between pulses.

The first significant results were obtained using diagnostics which allowed the voltage across each of the 16 accelerating gaps to be continuously monitored during beam acceleration. This employed a small capacitor, with a neon bulb in parallel, placed in series with a high voltage resistor to form a relaxation oscillator. Such an assembly was placed in parallel with each column grading resistor and an optical fibre carried the light pulses from the neon bulb to a photo detector located at ground potential. Each oscillator was individually calibrated and gave a working pulse rate of about 1 kHz, which was adequate to study voltage changes during the interval between beam pulses.

With this equipment it was found during beam acceleration that the voltage across the early gaps fell, displaying a saw-tooth waveform and showing that column electrodes, Nos 2, 3 & 4, were receiving a pulse of negative charge during each beam pulse, which was calculated to be equal to about 22%, 16% and 2%, respectively, of the value of beam charge. No additional change in voltage was found immediately before a breakdown, whether the breakdown occured during or between beam pulses.

A measurement of the stray magnetic field from the ion source magnet showed an exponentially decreasing field along the exit beam axis, of about 17 mT at the position of the diaphragm plate, falling to 4.5 mT at the centre of the first insert electrode. Although this field is unimportant to the beam dynamics, the crossed electric and magnetic fields provide a mechanism for stripped electrons, starting at rest, to move vertically on cycloidal orbits to reach the column electrodes. This was confirmed by detailed dynamics computations, for which typical electron orbits are shown in Fig.3. At the input to the column, stripped electrons arrive at the nearby electrodes with relatively modest energies but sufficient, apparently, to generate secondaries and initiate a cascade process. Electrons stripped further down the column reach the downstream electrodes with considerably higher impact energies.

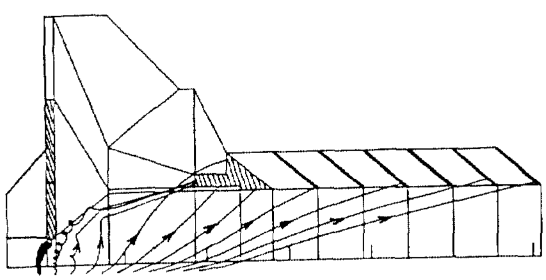


Fig 3. Computed trajectories of stripped electrons.

Replacing the stainless steel diaphragm plate by one of mild steel reduced the stray field, the maximum value being reduced to only 1.3 mT some 100 mm down-stream from the diaphragm. The result of this change, however, was an unexpected increase in the rate of breakdowns, the value of <Q> falling to about 60 mC. The measured gap voltages showed that the discharge current was no longer centred on the early electrodes, but was distributed more evenly down the column and was of much smaller total current. It can be assumed that the greater energy reached by the primary, stripped electrons, before hitting the electrodes, was reponsible for a higher rate of deposition of charge on the insulators.

A further diagnostic tool used to explore the behaviour of the column, during beam acceleration, was an X-ray camera which employed a pin-hole in a sheet of lead and a well shielded X-ray film holder. With the stainless steel diaphragm installed, and taking an exposure over several weeks operation, the camera revealed X-ray sources at the positions of the six conical insert electrodes nearest to the ground end of the column. Each source formed a line image, corresponding to the inner edge of the electrode aperture, and clearly showed the source to be brightest at the top, thus supporting the idea that vertically deflected electrons were the primary source of the activity.

An X-ray telescope was next constructed, using lead collimators and an NaI crystal viewed by a photomultiplier. With the use of horizontal slit collimators, this showed that the X-ray emission strongly peaked at some 30 mm above the column axis, corresponding to the position of the top edge of the insert electrode apertures.

Another attempt to eliminate the stray magnetic field was made by setting up a large window frame magnet coil at one side of the column and 3 m away, which could almost cancel the maximum stray field when the mild steel diaphragm plate was fitted. The output of the X-ray telescope, directed at the position 30 mm above the column axis, was measured as a function of magnet coil current and showed an initial increase, presumably due to the electrons reaching a higher energy as they were progressively lost further down the column. The intensity then fell but just failed to reach a minimum value at the maximum coil current available. It is not known whether column breakdown might have been reduced at such a point, but further investigation was curtailed by the ISIS operations schedule.

Conclusions

The breakdown phenomenon is thought to be initiated by electrons stripped from the accelerated H^- beam. These are able to reach the column electrodes due to the presence of a stray magnetic field from the ion source magnet. The time constant associated with the breakdown is believed to result from the slow build-up of charge on the column insulators.

The frequency of breakdown has been reduced to an acceptable level, typically one breakdown per two hours for a mean value of accelerated current of 160 μA, by the introduction of modified column electrodes, together with increased pumping speed at the ion source and a reduced field gradient over the first four accelerating gaps. The contribution from the latter change is thought to be due to the focusing effect produced in the column, which helps to prevent a cascade discharge taking place between the edges of the column electrode apertures.

Acknowledgements

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