Some lessons from long pulse operation of negative ion sources and accelerators

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Abstract
Operation of the neutral beam system of ITER for the entire ITER pulse is foreseen, with pulse lengths extending up to 1 hour. Operation for such pulse length is entirely new for neutral beam systems and the associated sub systems. This paper reviews some of the experience gained so far in the operation of the MANTIS test bed where long pulse operation of the ITER reference type of negative ion source is being studied. The three identified adverse effects of long pulse operation - reduced negative ion yield, reduced plasma grid temperature effect (see below) and increased caesium consumption – are still being studied, but some tentative explanations for each effect are given. In addition to the aforementioned effects, some operational difficulties associated with long pulses will be discussed, and some areas where caution will be needed in the future long pulse, high power operation of the ITER injectors are indicated.

1 Background and acknowledgements

Before going further with this subject it is a necessary pleasure to acknowledge that the vast majority of the work that is reported below was carried out by my co-workers, D Boilson, H P L de Esch, C Jacquot, A Krylov, D Riz, L Svensson, and R Trainham. I wish to acknowledge also the many fruitful discussions held on many of the topics discussed below with the aforementioned colleagues.

In 1996 the DRFC, Cadarache, France started testing the Kamaboko III negative ion source with deuterium. This ion source was designed and built by JAERI, Naka, Japan, can be regarded as a model of the reference design of ion source for the ITER neutral beam injectors. The ion source is a magnetic multi-pole arc discharge source with twelve 1.5 mm diameter, 17.5 cm long tungsten filaments. To achieve the required negative ion yield caesium has to added to the discharge to enhance the negative ion yield. The source was first tested in Japan, where it reached the nominal performance of an extracted and accelerated current density of 280 A/m^2 of H$^-$ during short pulse operation (<5 s).

Accelerated D$^-$ beams produce neutrons on impact with a target via D-D reactions. For this reason the safety rules associated with ionising radiation apply to the ion source test facilities at the Japanese laboratories and testing of the ion source(s) in deuterium is not allowed. It was therefore agreed to test the source at the MANTIS test bed in the DRFC, Cadarache, France, where operation with accelerated D$^-$ beams is authorised (with some limitations, see section 3).

It is very important to note that as electrons and negative ions have the same negative charge, both can be (and are) extracted from the ion source and accelerated. Consequently it is not possible to determine electrically the negative ion fraction of the accelerated beam. Therefore the only accepted measure of the negative ion current is that derived from the known beam energy and the power deposited on a remote target that is inaccessible to any accelerated electrons. Usually electrons are prevented from reaching the target by transverse magnetic fields between the accelerator and the target that are sufficiently strong to deflect the electrons away from the target, but weak enough to have little effect on the accelerated negative ions. This is the situation on the MANTIS test bed.

Once the Kamaboko III ion source was brought into operation on the MANTIS test bed, it was confirmed that the source did indeed, in short pulse operation (<5 s) produce 280 A/m^2 of

H^-, measured calorimetrically ≈1.6 m from the accelerator. However deuterium operation immediately presented a difficulty due to the high co-extracted electron currents.

In all negative ion accelerators the co-extracted electrons are deflected by the magnetic fields from the magnetic filter in the ion source and from permanent magnets embedded in the extraction grid onto the extraction grid which is typically at a potential difference from the plasma grid of between 7 and 10 kV. The trajectories of the negative ions are little affected by these fields because of their much higher mass, and they continue through the apertures in the extraction grid to the subsequent acceleration stage(s). This arrangement prevents the waste of power in accelerating the electrons and the consequent degradation in the overall accelerator efficiency. An obvious result of the deflection of the electrons onto the extraction grid is the power load to the grid from the electrons. A well designed accelerator can accept co-extracted electron currents that are less than or equal to the extracted negative ion current. The co-extracted electron current from the original Kamaboko III ion source in deuterium operation was >10 times the extracted D^- current, obviously well above acceptable levels. Increasing the strength of the magnetic filter of the ion source was from about 400 Gauss.cm to 900 Gauss.cm was found to reduce the co-extracted electron current by approximately a factor 10 with little effect of the extracted negative ion current. Subsequently 216 A/m^2 of D^- was accelerated onto the beam target at close to the parameters needed for the ITER negative ion source, i.e. with a source pressure of 0.35 Pa (0.3 Pa is specified for ITER) and <1 electron extracted per accelerated D^- for a pulse length of 5 s (see figure 1). Unfortunately it was necessary to have an arc discharge power of almost 80 kW, almost twice that anticipated.

Taking advantage of this "PG temperature effect" (see section 2) would reduce the required power to produce the >200 A/m^2 of D^- required for ITER, so it was decided to test the Kamaboko III ion source (with the high magnetic filter strength) in long pulse operation with a hot plasma grid.

2 Long pulse plasma grids

As noted in section 1, caesium is added to the discharge to enhance the negative ion yield. Typically the extracted and accelerated negative ion current increases by a factor 4 when the source is "caesiated". In short pulse (typically <5 s), increasing the plasma grid (PG) temperature to ≈300 °C causes the negative ion yield to increase significantly, often by >100%. In a caesiated source the main negative ion production is thought to be the back scattering of H (or D) atoms from the PG surface as H^- (or D^-). The action of the caesium is to reduce the work function of the PG surface, which enhances the probability of an electron in the metal escaping and attaching to the incoming atom. The work function of the surface is a strong function of the Cs coverage of the surface, falling to a minimum at ≈0.7 monolayers. The actual coverage of the surface must be a dynamic equilibrium between the incoming and outgoing fluxes. It is conjectured that increasing the PG temperature increases the Cs evaporation rate and the Cs coverage decreases towards the optimum.

Maintaining a constant PG temperature during operation requires the removal of the power arriving at the PG from the plasma. Unfortunately the optimum operating temperature of the PG is around 300 °C, which cannot be easily maintained with conventional water cooling as a water pressure of >8 MPa would be required to avoid boiling of the water. Therefore 2 grids have been designed by JAERI on the basis of having a relatively high thermal resistance connection (a thermal bridge) between the PG and the water cooling. The principle is quite straightforward: Power flows from the discharge to the PG at about 10 W/cm^2 at the anticipated arc discharge power. In steady state the total power to the grid will flow to the cooling water, and if the thermal resistance of the bridge is large compared to that across the grid itself, the temperature drop across the grid will be small compared to that across the bridge. For example a ΔT of ≈50°C is allowable on the grid, and the maximum absolute temperature is ≈350 °C, so the ΔT across the bridge must be 300 °C. These parameters along with the properties of the grid material and geometry determine the allowable distance across the grid to the thermal resistance. Two grids have been designed on this principle by JAERI and delivered for testing with the Kamaboko III ion source at the MANTIS test bed. The first is made of 6 mm thick CuCrZr alloy with cooling channels along each edge of the grid. The thermal resistance is created by reducing the thickness of the grid between the cooling channel and the main part of the grid. This section is also machined to form an 'S' shape in section, to have the required length of the resistance in the shortest distance along the grid surface. A photograph of the grid is shown as figure 2. This grid is known as the "frame cooled grid" (FCG). The second grid is made of molybdenum is also 6 mm thick. The relatively low thermal conductivity of molybdenum (compared with the CuCrZr alloy) means that the allowable distance to the edge of the thermal bridge is only a few centimetres. In this case small cooling tubes run across the surface of the grid and small stainless steel discs are brazed at appropriate intervals to both the tubes and the grid to provide the thermal bridges. A photograph of the grid is shown as figure 3. This grid is known as the "actively cooled grid" (ACG).

3 Experience with long pulse operation of the negative ion source

It is of some interest to list the changes that were made for long pulse operation of MANTIS and the subsequent modifications once long pulse operation started. The main, planned, and implemented changes to the system were:

- *New data acquisition system.*
- *New timing system.*
- *Arc series resistances:* The 1 Ω air cooled resistance installed in series with each of the 12 filaments, were replaced with 0.3 Ω water cooled resistances (coiled stainless steel tube embedded in epoxy).
- *Source cooling water:* The water cooling of the source and filaments has had to be rearranged to have parallel paths instead of series in order to produce higher flows.
- *Remote operation:* As MANTIS is not a shielded test bed, the radiation dose to the operators from the neutron production during deuterium operation limits the total D^- beam on time. This was estimated to be 5.5 x 10^4 s at 30 keV. Considering the amount of experimental time needed to get the system operating at the desired parameters, 200 A/m^2, D^-, 1000 s, this was considered too short, and therefore remote operation of the test bed would be required. The system developed, which operates over the Internet, allows long pulse operation from a distant PC. This remote operation can include:
    - Video monitoring of the MANTIS enclosure
    - Set up or modification of the shot timing and data acquisition
    - The ability to abort the shot
    - Real time monitoring of the electrical and thermal signals via a "virtual oscilloscope"
    - Access to the acquired data

Once these changes were made long pulse operation started and several unforeseen, unplanned, changes had to be made in order to establish reliable long pulse operation. The major changes were:

- *Source flanges:* The KAMABOKO III source was constructed with a large number of diagnostic flanges, with Viton O-rings making the vacuum seals. Many of these consist of a stainless steel rectangular flange bolted to the copper source body with a stainless steel extension tube incorporating a second Viton O-ring seal to a second flange, which then connects to a blank flange or a diagnostic. Radiation from the source heats these components, and, as stainless steel has a low thermal conductivity, the conduction cooling to the water cooled source body is low and the temperature of the second seal rises continuously throughout the pulse for the pulse lengths of interest. This has been measured via a thermocouple brazed into a blank flange installed on a typical extension tube (see figure 4). The temperature rises linearly to >120 °C after 300 s of arc with an arc power of about 50 kW. As this is approximately the maximum acceptable temperature for a Viton O-ring, flanges of this type had to be replaced with blank flanges bolted directly to the source body.
- *Breakdown protection system*: The protection systems in the high voltage (HV) feed for both the extraction and acceleration grids consisted of an R-C-L-diode circuit, which was sent into oscillation by breakdowns, these being extinguished as the voltage reversed. Although this worked quite well with a single gap system, it was not so with the double gap negative ion extraction/acceleration system. It is believed that the unreliable operation arose from the different oscillation periods for the two HV circuits. This was tolerable during short pulse operation as the number of breakdowns was smaller and the cut off at the end of the short pulse limited the damage. The protection system was changed to be simple resistances of ≈1 kΩ in series with each grid in each HV circuit. This is further backed up by computer surveillance of the HV currents: if either exceeds some threshold value for >20 ms, the computer commands the system off.
- *Extraction grid supports and feedthrough*: The extraction grid was supported from the plasma grid by small unshielded ceramic insulators inside the accelerator. These became coated with copper sputtered from the grids by breakdowns between the extraction grid and the plasma grid. The extraction grid voltage was supplied via a small insulated feedthrough on the plasma grid support flange. A breakdown from the extraction grid to the acceleration grid put the full acceleration voltage across the extraction gap and therefore across the extraction grid feedthrough until a breakdown occurred across the extraction gap. The extraction grid support had to be completely rebuilt so that it is supported from the acceleration grid support and the HV and water cooling were re-arranged so that they come through a ceramic feedthrough located on the vacuum tank, which is capable of withstanding more than the acceleration voltage.

3.1 Experimental results

An immediate benefit of long pulse operation is that parameters can be varied within a single shot, eliminating any shot to shot variation. An example is shown as figure 5. Here the Cs has been added to the source and during the shot the pressure in the source was changed by more than a factor 4, from 0.2 to 0.8 Pa. It can be seen that increasing the pressure has a small effect on the arc power at the very highest pressure, but almost no effect on the accelerated negative ion current (Idrain) over the pressure range covered. This clearly demonstrates that with a caesiated source the extracted negative ion current is independent of the source pressure in the range of interest.

Unfortunately three adverse effects are found with long pulse operation, as described below.

3.1.1 Plasma grid temperature effect

Both the types of long pulse grid have been tested on MANTIS, and they both reach the required temperature (approximately) at the anticipated arc power (see figure 5). Unfortunately the expected increase in the extracted and accelerated negative ion current was found to be much less than expected, varying from zero to a maximum of 40% (measured with the ACG), with typical values being around 20% (see curve c) of figure 6). Many experiments have been carried out to try to explain the lack of PG temperature effect in long pulses.

Grid material: It can be hypothesised that the work function of the surface of the grid with a coverage of Cs depends on the grid material. In fact this was not expected as the normal operation procedure is to operate the source in "volume", i.e. without Cs, for a number of pulses before adding Cs. This is done to make sure that everything is working correctly and the source is performing as expected, and because the source is cleaned by plasma and H (or D) atom bombardment during this phase. However a consequence of this is that the PG surface is always covered with tungsten evaporated from the filaments before Cs is added to the source. A careful comparison has been made between the two long pulse grids, the FCG made of CuCrZr, and the FCG made of Mo, as shown by figure 7. It is clear that in general the two grids have approximately the same efficiency.

Source wall temperature: In long pulses the source walls reach thermal equilibrium. The equilibrium temperature varies slightly around the source, being between 70 and 90 °C for an arc discharge power of 50 kW. As mentioned in section 1, it is conjectured that the Cs coverage of the PG is a dynamic equilibrium between the arrival of Cs from the plasma and the evaporation from the PG. Now the flux from the plasma to the PG must depend on the flux of Cs into the plasma, which, in the absence of any Cs injection into the source, must come from the source walls. Were Cs present on the source walls as a simple layer of Cs many monolayers thick, then the rate of evaporation of Cs towards the plasma would depend strongly on the wall temperature: a change from 20 °C to 70 °C would cause the Cs vapour pressure to increase 100 fold. This would be expected to perturb the abovementioned dynamic balance, and a higher PG temperature would be needed to get the hoped for enhancement in negative ion yield. Unfortunately the only way to increase the PG temperature, with the long pulse grids being used, is to increase the arc power, but that also increases the source wall temperature, increasing the Cs flux and so on. Therefore to test this hypothesis an attempt was made to change the source wall temperature whilst keeping the PG temperature high. The initial idea was to interrupt the discharge, to allow the source walls to cool and then to restart the discharge. The cooling channels are located every ≈5 cm around the source. The walls are 12 mm thick, and we "knew" that heat would flow through the copper rapidly, taking ≈1.5 s to travel the <2.5 cm to the cooling tube. Thus we expected that the flow of heat through the copper walls would be such that they would cool down in <10 s. This was a mistake. The average power flow to the source walls is a gentle 10 W/cm^2, and the cooling system is arranged to remove the total power arriving at the source walls (≈50 kW). However it had been overlooked that the walls are thermally massive and that it takes >30 s for the power to heat the walls to their equilibrium temperature (≥60 °C). Obviously the cooling takes about the same time to cool the walls back to 20 °C. Unfortunately in this time the PG cooled also, so nullifying the sought after result.

De-coupling of the PG temperature and the source wall temperature was achieved by removing the cooling from the PG and running a series of 20 s arc pulses. In this situation the PG temperature ratcheted up each shot whilst the source walls remained at <36 °C during the pulse, and they were cooled down to ≈20 °C between pulses. It was found that the extracted negative ion current increased almost linearly with the PG temperature until the limit in PG temperature was reached, i.e. when the inter-pulse cooling equalled the temperature rise during the arc discharge, see curve b) of figure 6. It is to be noted that the increase in the negative ion yield was greater than has been seen in any long pulses with the Kamaboko III ion source on MANTIS, but it was significantly below that achieved in short pulse operation (see curve a) of figure 6).

To date there is no definite explanation for the lack of plasma grid temperature effect in long pulses and the results discussed here shed some doubt on the standard model of negative ion production on the PG surface enhanced through a reduced work function with Cs on the surface. It is hypothesised that the standard model may be correct if the lack of PG temperature effect in long pulses is related to the co-deposition of Cs and tungsten on the PG. Since the PG temperature can only be increased to the range of interest (>200 °C) by operating the discharge for long pulses it is not possible to test this hypothesis with the tungsten filaments currently being used.

3.1.2 Negative ion yield

As has been carefully noted in section 1, the negative ion current density extracted from a negative ion source is derived from the beam energy and the power deposited on a remote target. With the Kamaboko III ion source on MANTIS during long pulse operation the current arriving at the target is typically only 50 – 60% of the current taken from the high voltage acceleration power supply. The difference between the calorimetrically determined current and the electrically measured current from the power supply (the “lost” current) is too large to be explained by experimental error. The lost current could be due to accelerated electrons that are deflected out of the beam path before they reach the target; ‘backstreaming’ positive ions created by energetic electrons, negative ions or energetic neutral atoms; or it could be that the accelerated ion beam is so divergent that only 50 – 60% is intercepted by the target.

There are two potential sources of accelerated electrons: Electrons extracted from the ion source are largely dumped on the extraction grid, but some are reflected and some of those escape to the acceleration gap. Electrons are also directly created in the acceleration gap by stripping.

To test if the lost current could be due to extracted and accelerated electrons the ion source was operated in pure argon. No negative ions are produced in Ar discharges (except from impurities) but the electron density is, in the Kamaboko III source, quite high. It was found that although very high electron currents were extracted from the ion source (the current to the extraction grid is interpreted as an electron current), <3% of the extracted current was found on the acceleration grid, and no power was intercepted by the calorimeter (within the experimental error).

To test if accelerated stripped electrons or backstreaming positive ions created the lost current the pressure in the ion source was varied by a factor 4. To a first approximation, the backstreaming positive ion current and the number of electrons created by stripping are proportional to the source pressure. As the fraction of the current drain from the power supply that was measured at the target did not change within the experimental error, neither stripping nor positive ions can explain the lost current.

We have been left with the hypothesis that the “lost” current is due to extremely bad beam optics. A new diagnostic drift duct is now installed on MANTIS, which is designed to determine if this is correct. Results from this diagnostic duct are the subject of ongoing experiments, which are reported elsewhere in detail at this meeting. Here it suffices to report that the measurements support the hypothesis. However the reason for the bad beam optics is an important subject for future experimental and theoretical investigations.

3.1.3 Caesium consumption

For experiments on the development test beds the Cs consumption is not a significant consideration. This is not the case for the ITER injectors which must operate for pulse lengths of >1 h, and it must be anticipated that from time to time it will be necessary to refill the Cs oven and to clean the ion source and/or accelerator due to Cs contamination. Such operations will have to be carried out by remote means as the injectors will be highly activated. Therefore it is important to minimise the intervention frequency, hence the Cs consumption should be as low as possible.

Before going further it is necessary to consider what is meant by “consumption”. The effect of Cs injection into the source is to increase the extracted negative ion current density and to reduce the co-extracted electron current. Typically Cs is injected into the ion source until stable, repeatable operation is achieved and the Cs injection is then stopped. More Cs is injected when either the extracted negative ion current decreases or the extracted electron current increases, i.e. Cs is injected into the ion source as and when necessary to maintain the negative ion production rate and the co-extracted electron current. The Cs consumption rate is defined as the rate of injection of Cs averaged over the entire operational time of the ion source.

During the experiments with long pulses on MANTIS it was noted that significantly more Cs was being injected into the ion source than had been anticipated. The rate of “consumption” of Cs was calculated to be $\approx 4.6*10^{-6}$ g/s/aperture. This is >1600 times the rate estimated for the ITER ion source ($2.8*10^{-9}$ g/s/aperture) from previous short pulse experiments.

To establish what was happening to the “consumed” Cs, following an experimental campaign in which 5 g of Cs had been injected into the ion source, the source was cleaned with water and the resulting “polluted” water was chemically analysed. Surprisingly it was found that ≈4.5 g ±20% of Cs had been on the walls of the ion source and the plasma grid. It was also found that the polluted water contained a substantial amount of tungsten. This has led to the suggestion that the Cs effect disappears not because the Cs has left the ion source, but because the Cs is somehow “blocked” on the walls and the PG surface in loosely bound tungsten – caesium mixture, the tungsten being evaporated from the filaments during the arc operation.

4 Long pulse beam acceleration

In general all the effects of long pulse operation of the Kamaboko III ion source reveal themselves within 100 s, so MANTIS is usually operated for pulse lengths of <300 s, although occasional longer shots are produced to ensure there are no unforeseen problems in operating for longer pulses. Figure 8 shows one such shot. In this pulse the current to the extraction grid (IG2) started to run away after about 450 s, for no obvious reason, and the shot was aborted. In that case it was thought that the extraction grid voltage was slightly high, possibly causing excessive power loading of some region of the grid. When the voltage was lowered by 2 kV (from 8 kV) there was no runaway, and the pulse was continued until it reached the preset limit of 1000 s, see figure 9. This example indicates that a power to a grid only slightly above the tolerable limit could lead to a long operating time, but that it eventually leads to a runaway situation.

5 Other and future long pulse problems

Very high powers are present in a neutral beam injector, and it is necessary to ensure that any component receiving power is adequately cooled. It is recalled that cooling components in vacuum poses particular problems as convection is, of course, absent and thermal conduction is, in general, inefficient. On a microscopic scale essentially all surfaces are rough, and any mechanical connection between two surfaces is poor. As there is no gas to fill the interspaces, the conduction paths are limited to the high points on the surfaces, and the thermal conduction is poor between the two surfaces. This means that during long pulses essentially every component receiving power, even low levels of power, must be actively cooled. This is, of course, well known. However it is difficult to be certain that no power arrives on any given component, especially as there are known sources of "devious power". Devious power is power that is marginal to the main aspects of the injector. Examples are the power from the partial energy neutrals created in the accelerator by stripping, from secondary electrons, and that from X-rays. A couple of examples are given below in order to indicate that this potential problem has to be taken seriously.

The first example comes from the 1 MV test bed at Cadarache. This test bed is used for the development of the SINGAP 1 MeV D^- accelerator for ITER. It has the source at ground potential and the D^- ions are accelerated up to a positive high potential, then transported through a metal walled duct to a target. Both the duct and the target are at the high positive potential, and the walls of the vacuum chamber are at ground potential. It is found that when high voltage is applied to this set-up, without any source operation (the voltage is simply applied between two metal surfaces) a "dark current" flows between ground potential to high voltage. The dark current is a strong function of the applied voltage, being initially zero below about 250 kV, then increasing strongly with the voltage until, within a few 10's of kV it becomes significant compared to the available current from the 1 MV power supply, 100 mA. However the level of dark current can be reduced by "conditioning" the system, which consists simply of applying high voltage, waiting until the dark current reduces, then increasing the voltage and so on. The power associated with the dark current heats the components at high voltage, which are not actively cooled. However, this is not normally a problem with the duty cycle used on the test bed. During conditioning after modifying one of the electrostatic stress shields at the accelerator the power from the dark current heated the new uncooled stress ring. This doughnut shaped stainless steel ring had been manufactured without any holes to allow the gas trapped inside the ring to escape into the vacuum. The result was a rather spectacular shower of sparks and a sudden increase of pressure in the test bed when the internal pressure blew a hole through a small region that had been heated locally to the melting pointed stainless steel due to electric fields focussing of some of the dark current onto a small region of the ring, see figure 10. This focussing onto the rings was not foreseen.

The second example is associated with the use of the SINGAP type accelerator in the ITER neutral beam injector. A particularity of the SINGAP accelerator is that any electrons created by stripping in the main acceleration gap are accelerated along with the negative ions until they reach the exit of the accelerator. In fact the majority of these electrons exit the accelerators through the large apertures in the last grid of this type of accelerator. The power and energy of these electrons has been carefully calculated: when the accelerator is operating at full performance, 1 MeV, 40 A of D^-, the average electron energy is ≈720 keV, and the power carried by the electrons is ≈3 MW. Of course care is being taken in the design of the injector to deposit this power onto water cooled components. However there are two forms of devious power resulting from these electrons: X-rays and back scattered electrons. The former was recognised as a potential problem if the X-rays were to deposit too much power in the 4.5 K surfaces of the injector cryopumps. Therefore a study was undertaken by the UKAEA using the MCNP package to calculate where these X-rays would deposit their energy. (These calculations are still ongoing.) Fortuitously the MCNP package includes back scattering of the electrons, which had been completely overlooked. Although only ≈3% of the electron energy is back scattered, the calculations showed that up to 40 kW of power could be deposited in on part of the 80 K chevron shields of the cryopumps (see figure 11). Although such a power level could be acceptable for a short pulse due to the thermal inertia of the 80 K panels, it is well above the acceptable level for long pulse operation. Changes to the injector design are now being considered to avoid this situation.

6 Summary

Long pulse operation of the reference design of negative ion source for ITER has thrown up unexpected problems. Whilst the problem of poor beam optics may be unique to the Kamaboko III source on MANTIS, the same cannot be assumed for the high Cs consumption. Thus the results clearly show that more work is needed to reduce in the Cs consumption in long pulse operation if this type of source is to be used on ITER. If the reason for the high Cs consumption is eventually shown to be related to the tungsten evaporated from the filaments, using different filaments (e.g. thoriated tungsten) or the RF driven source could solve this problem. However Cs will always escape from the source via the apertures in the accelerator, and the rate of loss could be proportional to the temperature of the source walls. The Cs loss rate at ≈20°C (as in short pulse operation) results in an acceptable Cs consumption rate, so keeping the source walls as close as is reasonable to 20 °C should be a design objective for the ITER source.

Long pulse operation will pose problems related to devious (or stray) power. Because this power will fall on components in vacuum, the temperature of the components could increase until the component fails. Three sources of devious power, dark current, X-rays and back scattered accelerated electrons created by stripping in the accelerator, have been identified. It is suggested that some time, and possibly R&D should be devoted to examining and researching other forms of devious power.

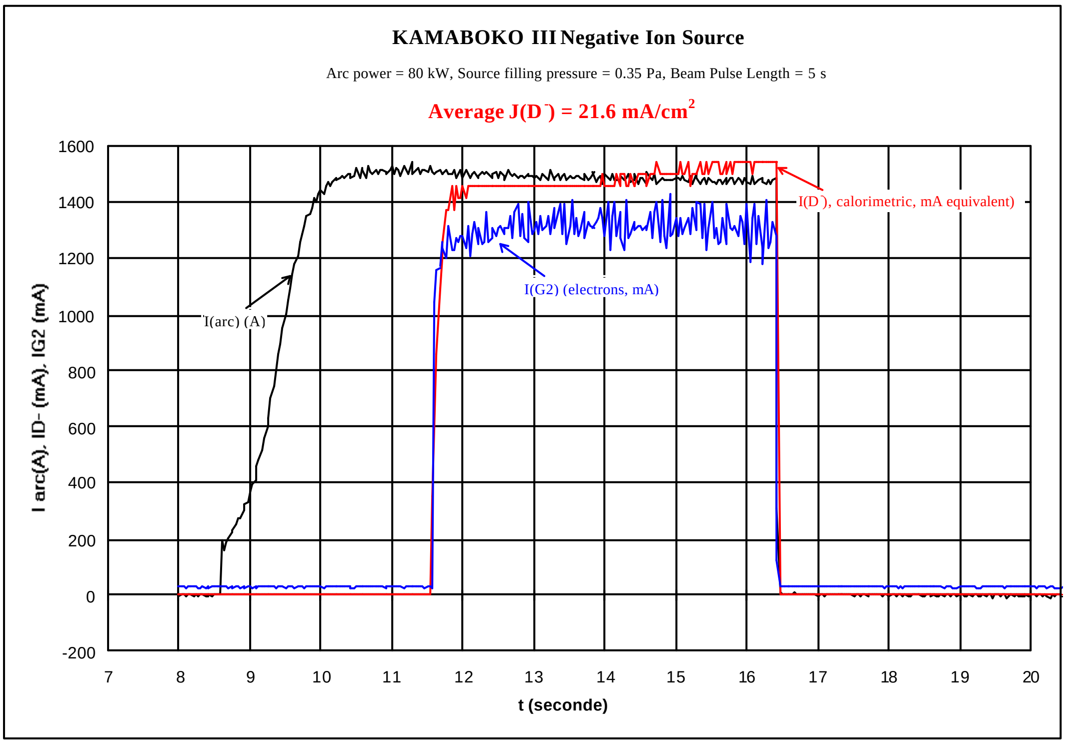

Figure 1 Kamaboko III ion source: 216 A/m^2 D^- for a pulse length of 5 s.

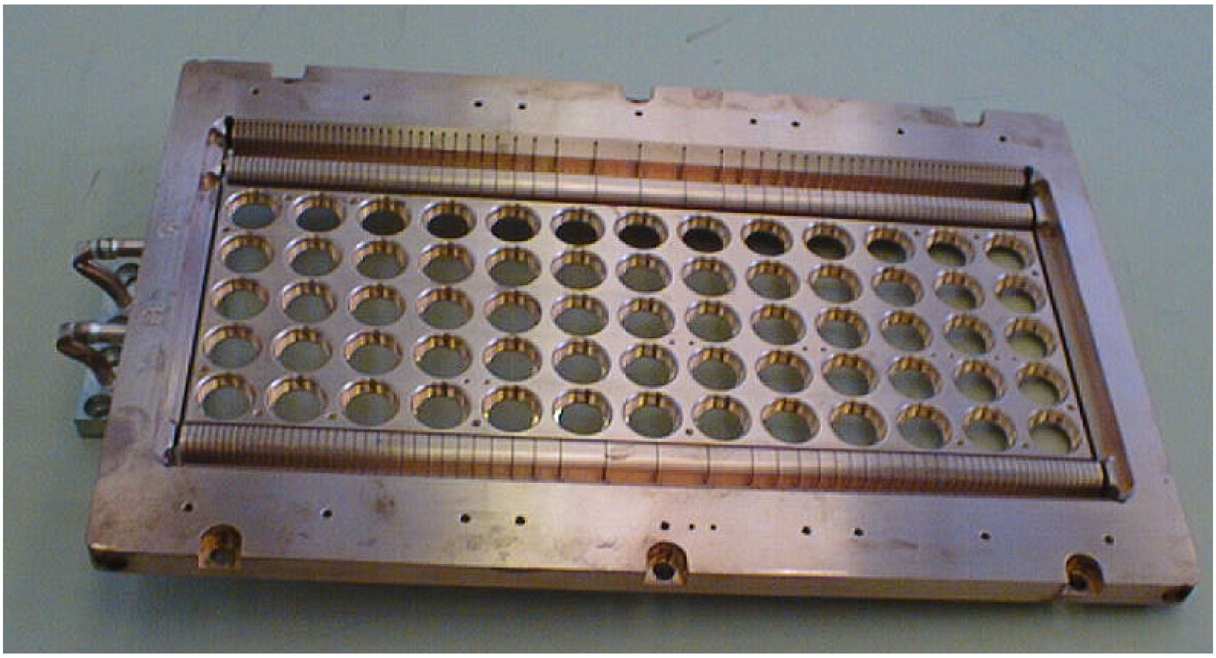

Figure 2 “Frame cooled” long pulse grid made from copper, chrome zirconium alloy.

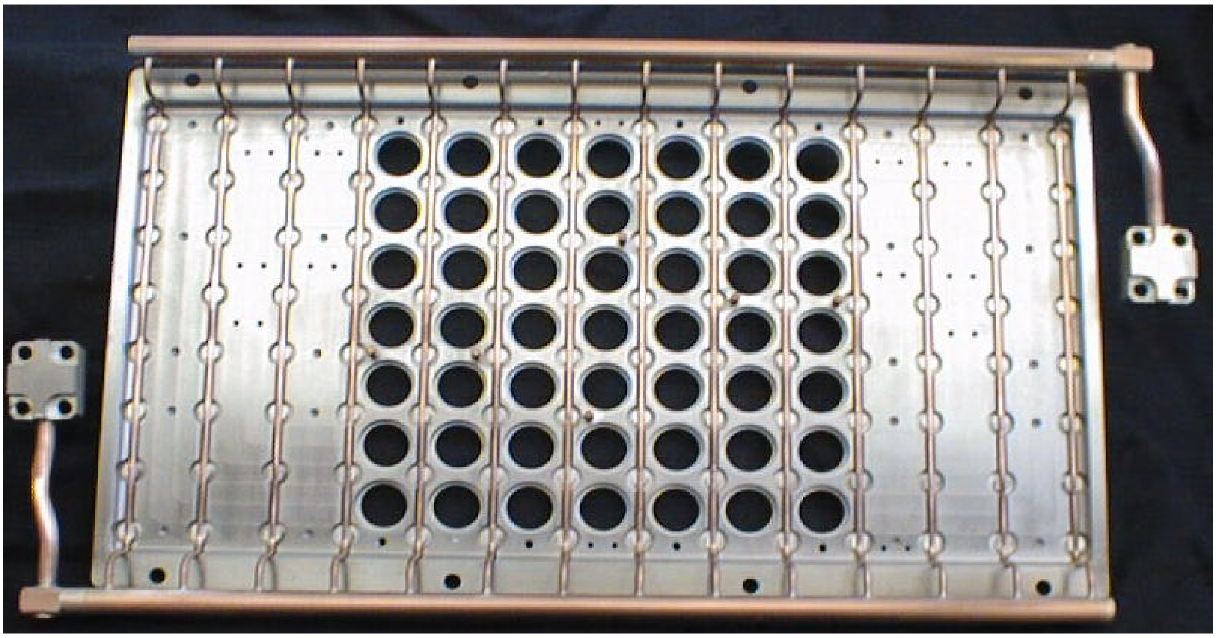

Figure 3 "Actively cooled" long pulse grid made from molybdenum. The cooling tubes are copper, and the small cylindrical thermal bridges are of stainless steel..

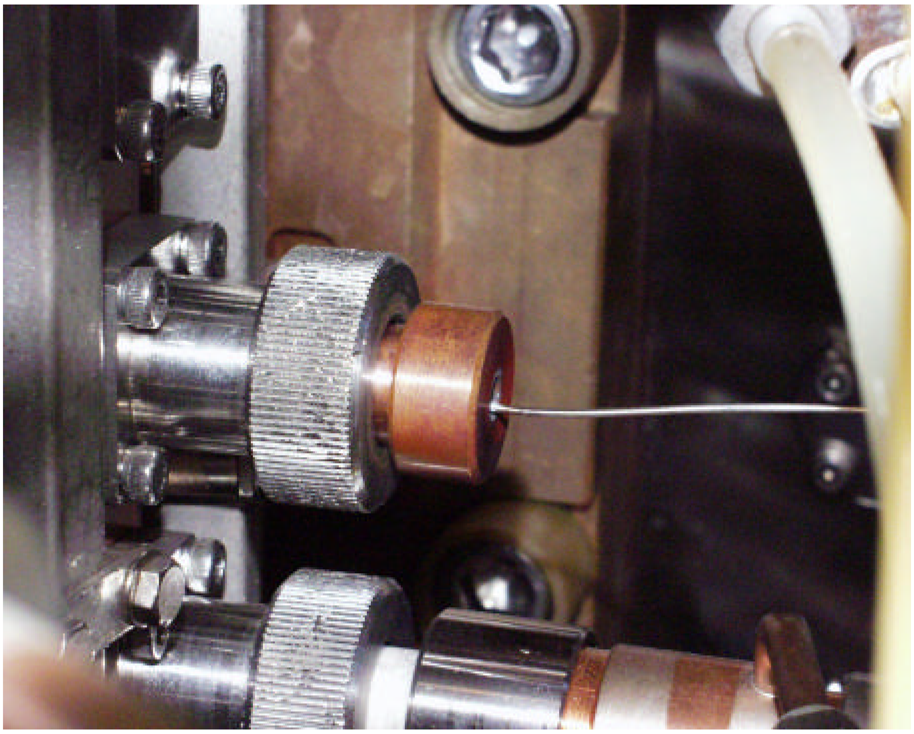

Figure 4 Typical diagnostic flange on the Kamaboko III ion source. The source body (to the left of the picture) is water cooled copper. The stainless steel adaptor flange is bolted to the source, but this thermally insulates the diagnostiic (in this case the copper cylinder with the thermocouple attached) from the source body.

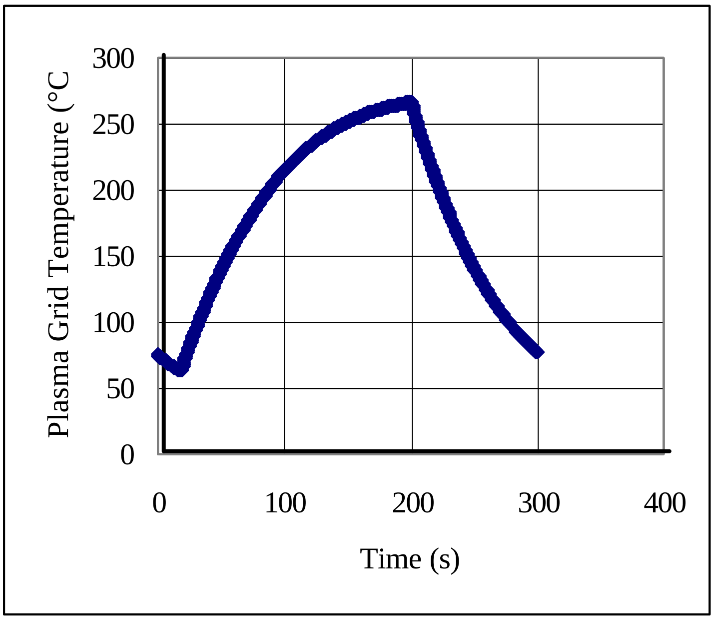

Figure 5 Temperature of the "frame cooled" long pulse grids during a long pulse with an arc power of ≈45 kW.

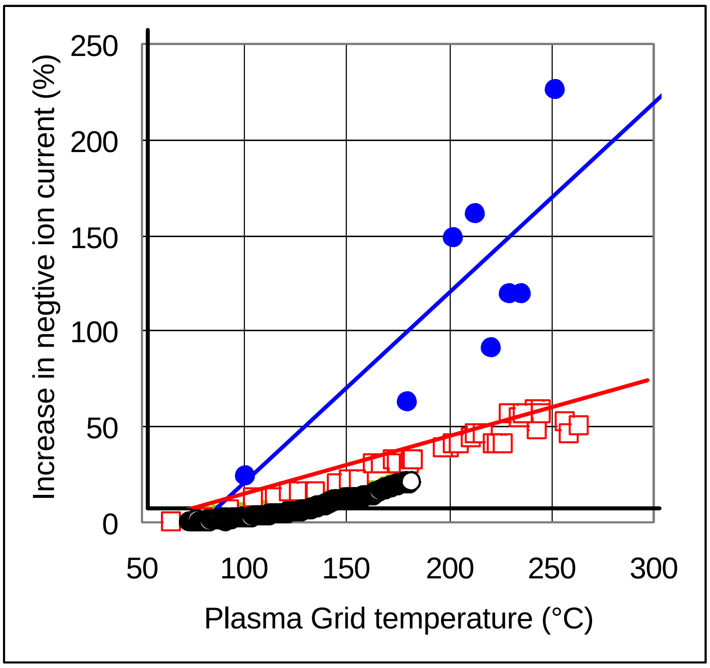

Figure 6 Increase in negative ion yield from the KAMABOKO III ion source with the plasma grid temperature, arc power ≈50 kW, source filling pressure ≈0.3 Pa, H_2 in all cases.

a) During short pulse (<5 s) operation with an uncooled Mo grid.
b) With 20 s pulses, and the uncooled FCG (CuCrZr) grid, with the source walls at <36 °C
c) 150 s pulse with the FCG, 150 s pulse.

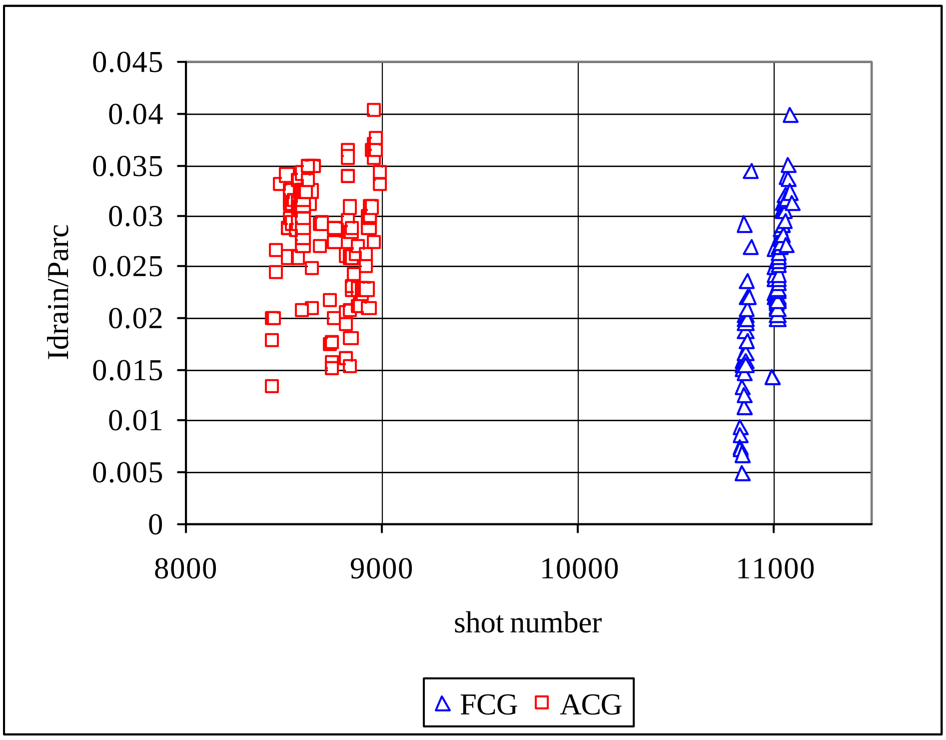

Figure 7 Comparison of the negative in production efficiency for the Kamaboko III ion source with the two long pulse grids.

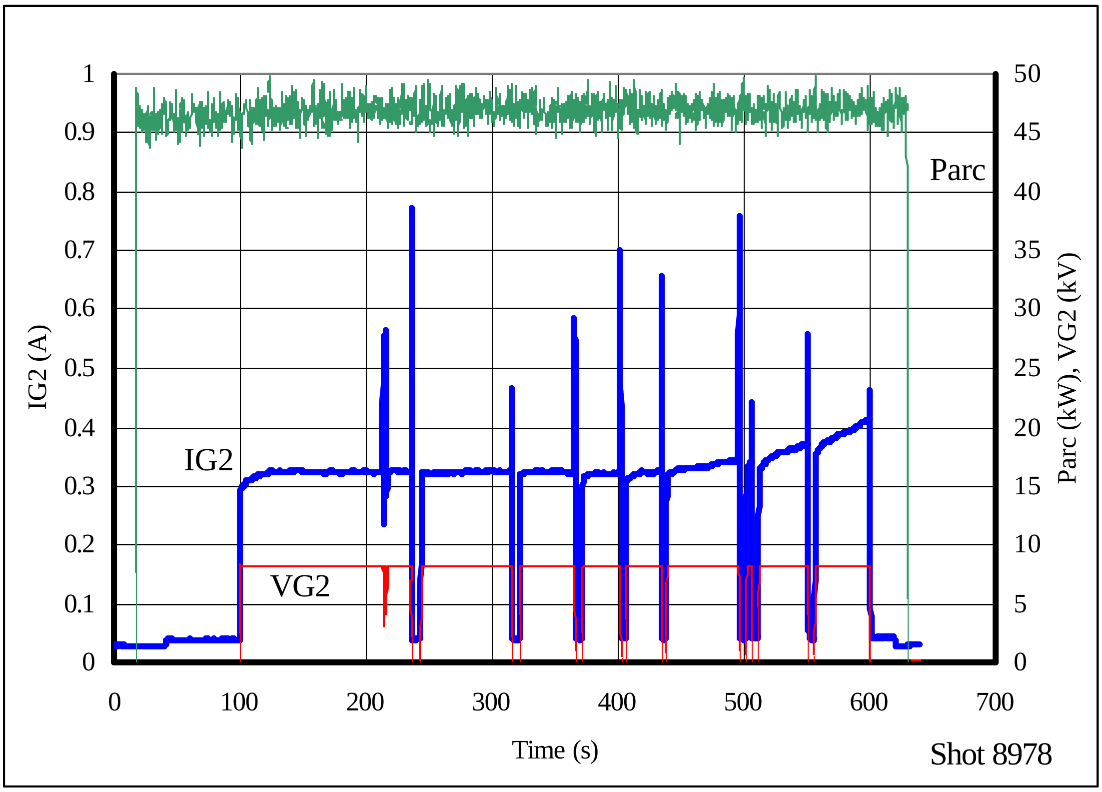

Figure 8 Example of a pulse of >300 s where the current to the extraction grid (IG2) was seen to run away after ≈450 s.

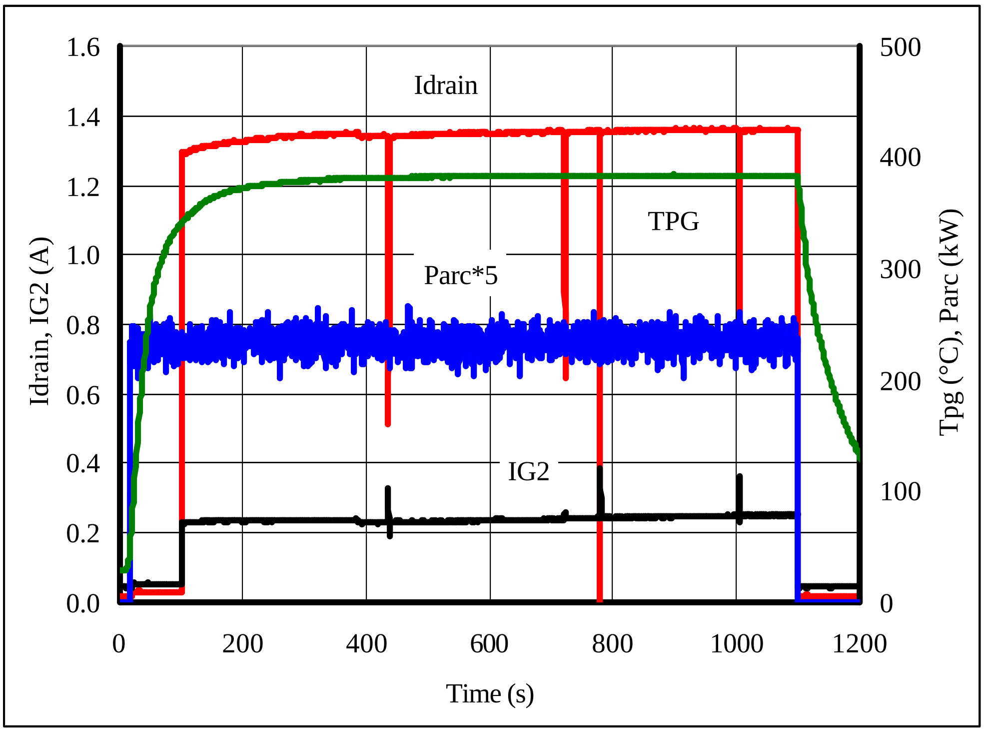

Figure 9 1000 s H- pulse

Figure 10 Photograph of the electrostatic shield damaged by long exposure to the dark current. The arrow indicated the small hole formed by the combination of electron heating and the internal pressure of the ring.

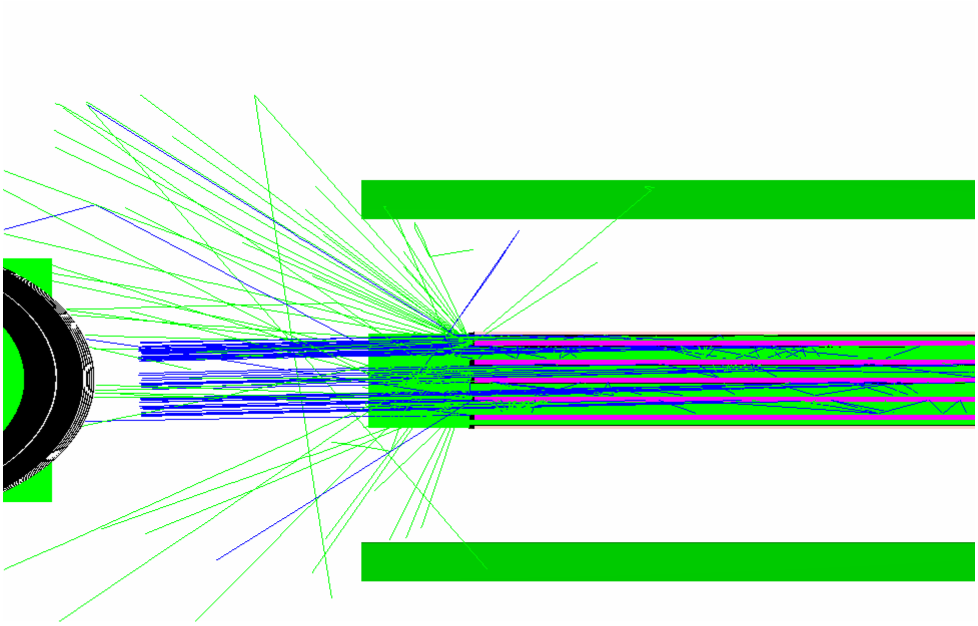

Figure 11 Calculated tracks of backscattered electrons in the ITER injector.