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The Development of the ISIS H- Surface Plasma Ion Source at RAL

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Abstract

ISIS H- Penning Surface Plasma Source (SPS) has been a world leading operational H- ion source for 20 years; it routinely produces 35 mA of H- ions during a 200 us pulse at 50 Hz for uninterrupted periods of up to 50 days. This paper details the development of the source that has occurred over the last 5 years. The pulse length has been increased from 200 µs to 1.5 ms and the output current doubled to 70 mA. These developments are required for the new Front End Test Stand (FETS) currently being built at RAL. Extensive three dimensional finite element modeling has allowed the thermal operation of the source to be understood in detail: the temperatures around the discharge region have been calculated and the transient thermal behavior of the pulsed source studied. This has allowed the source duty cycle to be significantly increased. Electromagnetic finite element analysis has allowed the source extraction and beam transport to be investigated. Different extraction geometries have been designed and successfully tested to give higher output currents. An energy analyzer and two emittance measurement systems (slit-slit and pepperpot) have been developed to allow the beam to be fully characterized. Several geometry and infrastructure modifications have been implemented and will be discussed.

1. Introduction

ISIS H^- Penning Surface Plasma Source (SPS) has been a world leading operational H^- ion source for 20 years; it routinely produces 35 mA of H- ions during a 200 us pulse at 50 Hz for uninterrupted periods of up to 50 days

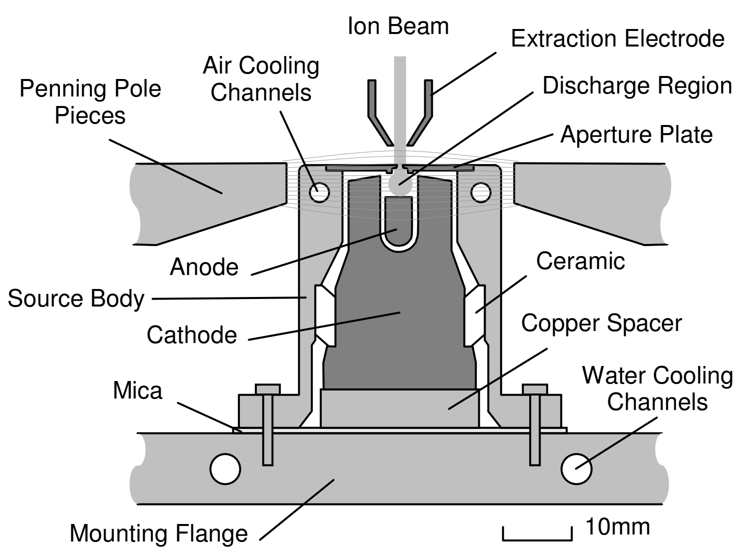

Figure 1: The ISIS H^- ion source. The figure shows a cross section through the source.

The source is of the Penning type, comprising a molybdenum anode and cathode between which a low pressure hydrogen discharge is struck. The basic construction is shown in figure 1. Hydrogen and cesium are fed into the discharge via holes in the anode. The anode and cathode are housed in the stainless steel source body. The anode is thermally and electrically connected to the body, whereas the cathode is isolated from the body by means of a ceramic spacer. The whole assembly is bolted to the ion source flange, separated by a thin layer of mica to provide electrical isolation for the cathode. The ions are extracted through the 0.6 x 10 mm extraction slit in the aperture plate.

1.1 Source Cooling Systems

Source cooling is provided by two systems illustrated in Figure 2: air cooling via two pipes in the source body nearest the electrodes and water cooling via a channel cut into the ion source flange. Air flows along one pipe and is then returned down the other. Air is used because of the safety hazards involved with having water close to the cesiated ion source.

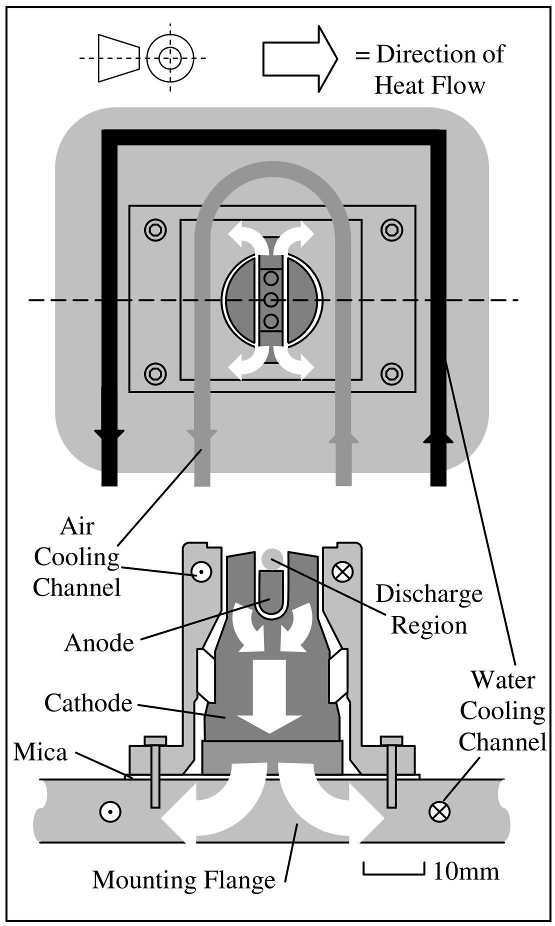

Figure 2: The two ISIS ion source cooling systems: Water is shown in black and air in grey.

1.2 Source Timing

The operational source runs in pulsed mode with a 1% duty cycle. The timing for the source runs as follows: First a piezoelectric valve in the base of the source opens for approximately 200 μs to inject Hydrogen gas. This takes about 600 μs to reach the discharge region through holes in the anode, after this time the 50 A discharge current is turned on. The discharge takes approximately 250 μs to stabilize before the +17 kV extraction voltage is turned on and negative ion are extracted. The discharge current and extraction voltage are turned off together at the end of the pulse.

1.3 Post Extraction

After extraction the beam is bent through 90°, then further accelerated to 35 keV as shown in figure 3. The 90° bend analyzes out all the electrons and negatively charged molecular Hydrogen leaving only H^- ions. The analyzing magnet sits in a refrigerated box, this serves as a Cesium trap to prevent Cesium vapor entering the next stage of the accelerator. The magnet also enlarges the beam in the horizontal direction, so that the slit extracted beam is expanded to have an equal aspect ratio after post acceleration.

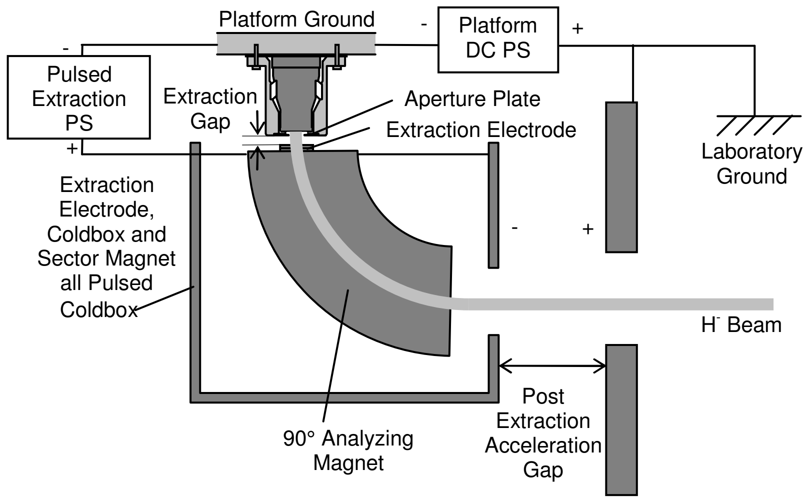

Figure 3: The 90° analyzing magnet and post acceleration system.

2. Modeling

2.1 Thermal Modeling

A thorough understanding of the thermal characteristics of the ion source is essential if operation is to be extended to higher duty factors, whilst maintaining an optimal regime for H– ion production and source lifetime. This can be achieved by producing a comprehensive thermal model of the source. ALGOR FEA software has been used for thermal modeling, beginning with a simple model of the ion source to understand its thermal operation.

In typical operation the ISIS ion source operates with a 4 kW, 500 μs, 50 Hz discharge. The assumption is made that all the electrical power as measured in the external circuit goes into heating the electrode surfaces exposed to the discharge. The discharge is bounded on all sides by sections of the cathode, anode and aperture plate. The total surface area of these exposed regions is found and the total power divided proportionally between them.

Initial 2D transient modeling has shown that the 19.5 ms off period of the 50 Hz cycle is long enough to allow the surface energy applied during the discharge pulse to conduct into the thermal mass of the electrodes before the start of the next pulse. The temperature at the electrode surfaces varies by about 50ºC during the 20 ms cycle, and this temperature increase only penetrates a few millimeters from the electrode surface. This localized effect means that the pulsed power in the discharge can be modeled as an average DC equivalent when modeling the entire ion source, thus reducing the complexity of the model and allowing steady state calculations.

In addition to the amount of heating and cooling the thermal resistivity of the ceramic insulator and mica sheet are important factors in determining the source temperatures. In the real world thermal contact resistance between materials plays an important role. To progress further with the thermal FEA a number of coefficients are required that can only be determined by experiment.

2.1.1. Thermal Test Rig

A thermal test rig was built to study the convection and radiation from the ion source surfaces and the thermal contact resistances at each interface between materials. The component dimensions were chosen to be the same as those of the ISIS ion source, with blocks of material representing the cathode, copper spacer, mica and ion source flange. The block of molybdenum representing the cathode was heated and held at a specific temperature while the temperatures of the different materials were monitored using thermocouples.

A series of experiments was run at a range of pressures from 10^{-6} mbar to 10^{1} mbar in atmospheres of N_2 and H_2. The mechanical loading on the components was varied by setting the torque on the four threaded rods which held the components together. The effect of the number of layers into which the mica was cleaved was also studied.

Using an FEA model of the thermal test rig the required parameters were estimated. The thermal contact resistance was modeled as a 0.01 mm thick layer at each material interface. The thermal resistivities of the interface layers were adjusted in the model until the calculated heat-up curves matched those obtained by experiment. This was when the steel/mica and mica/molybdenum interface layers had a thermal resistivity between 30,000 and 40,000 times that of copper (significant contact resistance) and the copper/molybdenum interface had the same resistivity as copper (negligible contact resistance). Different surface radiation functions were tested in the model until the measured low pressure ($<10^{-4}$ mbar) cool-down curves were matched. Convective cooling in a pure H_2 atmosphere begins between 10^{-3} and 10^{-2} mbar whereas in pure N_2 it does not become significant until pressures of 1 mbar and above. The convective heat transfer coefficients (HTC) were found by curve fitting the measured cooling curves.

2.1.2 Cooling

The two cooling systems are modeled using HTCs applied to the pipe surfaces. The units of HTC are $Wm^{-2}K^{-1}$, where K is the temperature difference (ΔK) between the coolant and the surface. Values of HTC can be calculated empirically using the Nusselt number, which depends upon the specific heat capacity, dynamic viscosity, thermal conductivity, mass density and velocity (v) of the coolant and the diameter of the cooling pipe.

The range of coolant flow rates used in normal operation on ISIS (30-80 ms^{-1} for air and 0.02-0.04 ms^{-1} for water) provides a range of HTC values to be applied to the model. The thermal model also requires the coolant temperature as an input. Both air and water are fed into the source at 20ºC, however, as the coolant travels along the cooling channels it heats up, thus reducing the amount of heat it can remove from the source (because ΔK decreases).

To find out how much the coolant temperature increases a Computational Fluid Dynamics (CFD) model using ANSYS CFX modeling software has been produced. Figure 4 shows the results from the CFD calculation for air flow in the pipe at 75 ms^{-1} with the source body head held at 450ºC. The air temperature increases to ≈300°C by the time it exits. To allow this increase in coolant temperature to be modeled in the ALGOR FEA, the air cooling pipe in the source head was divided into 6 sections, with the coolant set to different temperatures as calculated using CFD.

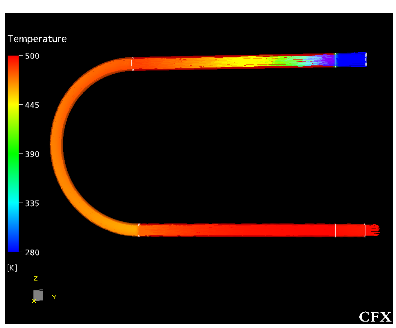

Figure 4: Results from the Computational Fluid Dynamics model of the air cooling system.

CFD was also used to find the temperature increase of the cooling water in the flange. There is only a few degree difference between inlet and outlet temperature because water has a much higher specific heat capacity and density than air. This allows the water cooling pipe in the ALGOR FEA to be modeled in one section all with the same coolant temperature.

The empirical equations for HTC were tested using CFD and found to be correct for flow rates up to 150 ms^{-1} for air and 70 ms^{-1} for water, allowing for the onset of turbulence in the cooling pipes.

When all the parameters that correspond to normal operation of the ISIS source are applied in the model the temperatures obtained are very close to those measured in the actual source. This provides validation that the model is realistic.

In normal operation the source temperatures are monitored using thermocouples for the cathode, anode and source body. All three thermocouples are positioned some distance from the electrode surfaces exposed to the discharge plasma so they do not give actual surface temperatures. A realistic model of the source allows surface temperatures to be inferred for the first time.

Using the steady sate solution as a starting point it is possible to run a transient study. This allows the peak surface temperatures reached during the cycle to be calculated. The initial 2D transient thermal modeling indicated that the surface heating during the discharge on period only has time to penetrate a few millimeters into the electrode mass. To ensure accurate results the elements near the electrode surfaces are made very thin (10^{-5}m) in the direction of heat flux.

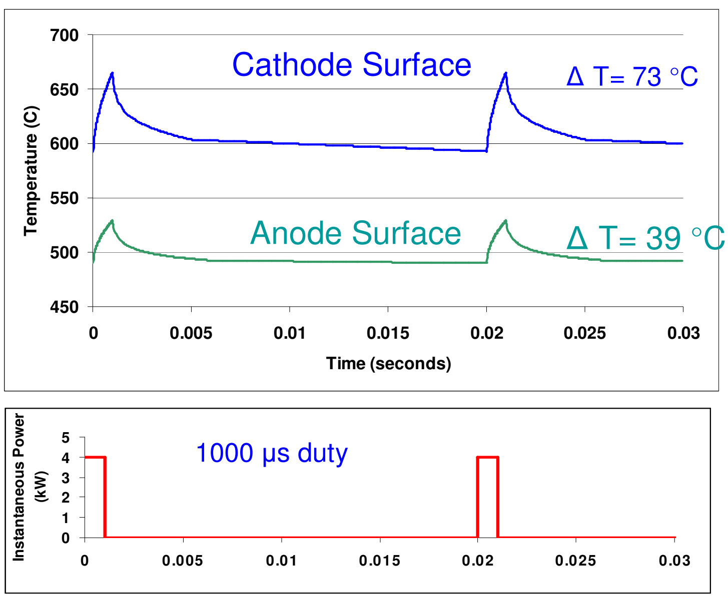

Figure 5: Transient Temperature results showing how the anode and cathode surface temperature increase during a 1000 μs pulse at 50 Hz.

Figure 5 shows how the peak temperatures vary through the cycle. During the on period there is a rapid increase in the surface temperature of the materials directly exposed to the plasma. This temperature then decays away as the discharge energy dissipates into the thermal mass of the material. The peak source body temperature does not vary because it is not directly in contact with the plasma. In a similar way there is no detectable change in temperature at the thermocouple measurement points.

2.2 Magnetic Modeling

One critical aspect of this design is the optics of beam transport from the ion source aperture through the 17 kV extraction region and then a 90° sector magnet with a bending radius of 80 mm and a field index of n=1. The extraction electrode and sector magnet are housed inside a cold box which is held at the extraction potential. The sector magnet is intended to remove any electrons from the H- beam, and also focus the beam profile from 0.6×10 mm at the ion source aperture to ≈10×10 mm at the cold box exit. However, it has been suspected for some time that steering and focusing are compromised by inadequate termination of sector magnet fringe fields, and sub-optimal extraction geometry.

To allow a better understanding of the factors affecting the beam optics in this region a MAFIA FEA model has been developed.

2.2.1 Finite Element Analysis

MAFIA employs a finite integration technique to solve for electromagnetic fields. This has an advantage over finite difference techniques in that the time taken to calculate the fields increases linearly (rather than as a power) with the number of elements. The downside of the finite integration technique is that the model must be discretized onto a regular mesh, unlike finite difference techniques which can have an irregular tetrahedral mesh. This has important consequences when trying to model a problem with both large and small features. The accuracy of the result from any FEA is dependent upon the element size local to the result.

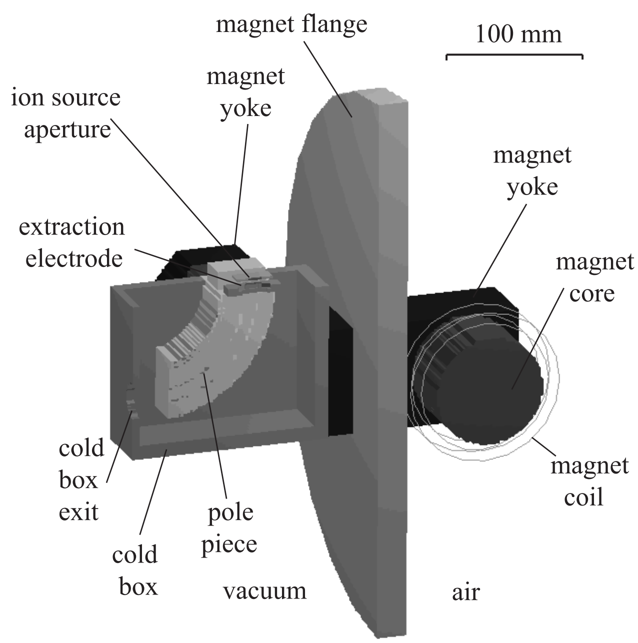

Figure. 6. MAFIA model of the ISIS ion source extraction region and 90° sector magnet.

In the FEA model in Figure 6 the extract electrode is very small compared to the rest of the model. It is essential that the fields in this region are calculated accurately and hence a high mesh density is required. Available computing resources prevent a high mesh density being used throughout the model, so great care is taken to optimize the regular grid, whist keeping the elements small enough around the extract regions and pole pieces. The mesh density is increased until the results converge and a 1GB problem size (limited by the computer RAM available) is reached. In the present model the density of mesh elements varies from 1×10^3 to 2×10^{13} m^{-3}.

After the electromagnetic fields have been calculated particles representing the H^- ions are run through the model. 10,000 particles are emitted from the ion source aperture plate with uniform thermal energy, orthogonal to the aperture plate and with a random uniform spatial distribution. MAFIA uses time stepping particle in cell (PIC) code to calculate the particle positions after one time step. The time step is reduced until the particle trajectories converge to a solution. 20,000 5 ps time steps are used to ensure accurate results. Horizontal and vertical emittance monitors are setup in MAFIA at the cold box exit to monitor the particles.

2.2.2 Analyzing Magnet

In the standard ISIS design the only attempt to deal with fringe effects at the end of the sector magnet is to cut off the pole pieces 14 mm back from the full 90° bend. It is obvious that the beam profile is asymmetric, the beam is strongly divergent in the horizontal plane and there is severe aberration in the focusing in vertical plane.

In addition, when it is steered to be on centre in the vertical plane, the beam is angled upwards by ≈15 mrad as a result of bending in the magnet fringe field. It has previously been suggested that this effect can be overcome by the insertion of a tube of high permeability material into the fringe field region. This approach has been investigated further to include the effects of extraction and optimized to produce a new design, where 'maximag' magnet steel has been used for the insert. The optimal design has the pole pieces cut off 3 mm back from the full 90° bend, and a 'maximag' tube (internal diameter 30 mm, wall thickness 5 mm) extending from 3 mm in front of the 90°plane to flush with the cold box exit. The results show a large reduction in divergence in the horizontal plane, and the vertical emittance now shows the beam to be both on centre and parallel to the axis. However, there is still an asymmetric beam profile and evidence of aberration in the focusing in the vertical plane.

3. Ion Source Development Rig

A crucial part of the ion source development program is the ability to test sources off-line. The Ion Source Development Rig (ISDR) allows development to continue without compromising the operation of ISIS. The ISDR is basically a copy of the ISIS source but with two important modifications: the Penning field is provided by a separate magnetic circuit to allow the source to operate at different extraction voltages and Penning fields; and the source mounting has been modified to allow sources of different sizes to be tested.

The key to understanding beam behavior is a comprehensive set of diagnostics. The ISDR is equipped with a diagnostic vessel onto which various measurement devices can be mounted:

- A pair of X and Y slit-slit emittance scanners are permanently mounted on the sides of the diagnostic vessel and can be retracted without stopping the source.
- A pepperpot emittance device can be mounted on the rear of the vessel. The pepperpot can be moved along the axis of the beam and can be moved onto the same measurement plane as the slit-slit scanners whilst the beam is running.
- The head of the pepperpot can be replaced by a scintillator profile measurement head, allowing profile measurements along the axis of the beam.
- A retarding potential energy analyzer can be mounted on the rear of the vessel in the place of the moveable pepperpot/profile device.
- Beam current is measured via a torriod permanently mounted on the entrance to the diagnostics vessel.
- A buffer gas delivery system mounted directly after the beam current torriod allows for the controlled and measured introduction of various gasses to study the effect of space charge.
- A dipole magnet can be installed in the vessel to study the degree of stripping in the beam.

In addition there is pressure monitoring and a full set of ion source parameter monitoring; source temperatures, power supply voltage and current monitoring.

3.1 Current Work

3.1.1 Extended Duty Cycle

Thermal modeling has shown that longer duty cycles can be achieved by reducing the thickness of the mica insulation shown in figure 1. The discharge duty cycle has now been increased to the maximum allowable by the power supplies. Figure 7 shows a 1.8 ms discharge at 50 Hz.

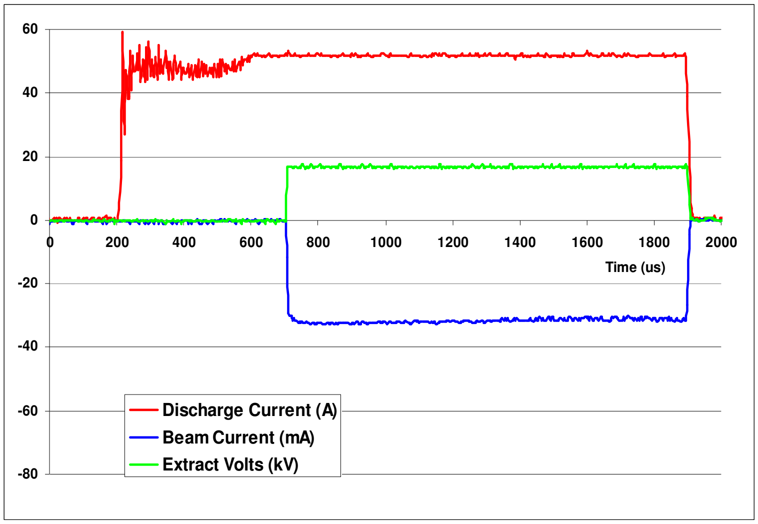

Figure. 7. A 1.8 ms discharge pulse length at 50 Hz.

The long pulse extraction voltage power supply failed shortly after this, so we are now waiting for a new power supply to be constructed. We can presently only extract 500 µs long pulses.

3.1.2. Increased Output Current

By increasing the aperture slit width and decreasing the extraction electrode jaw gap spacing, beam currents up to 78 mA have been achieved as shown in figure 8.

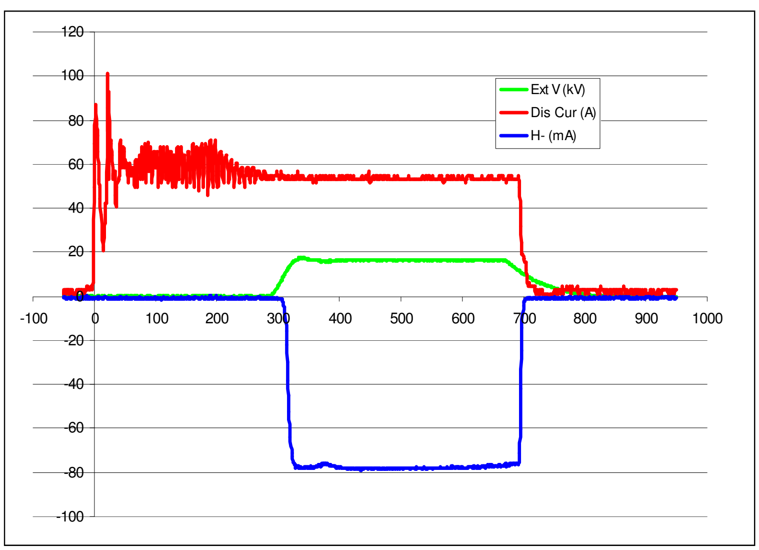

Figure. 8. 78 mA H^- beam current at 50 Hz.

3.1.3 Variation of Extraction Voltage

It is clear that the present extraction and transport arrangement on ISIS is sub-optimal and improvements will yield higher output currents and lower emittances. A detailed investigation is currently underway.

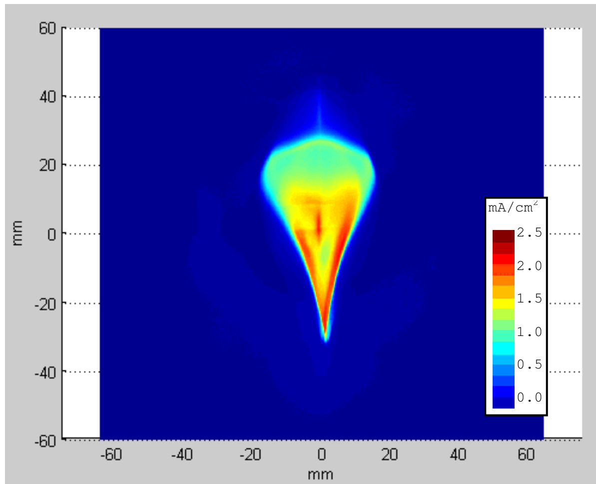

Figure. 9. A beam profile measurement at 9 kV Extraction Voltage.

3.1.4 Electrode Erosion

A database containing operational data and microscope images of electrode erosion is currently being built. This will provide a basis for a detailed study into electrode ware and source lifetime.

4. Future Work

The new scanning peperpot and profile measurement system will allow detailed study of beam transport. Space charge studies with Krypton buffer gas will be investigated. Different extraction geometries and post acceleration gaps will be studied. Plasma meniscus modeling will provide a deeper understanding of H^- production in the discharge. More detailed beam transport modeling using updated software. Different materials will be investigated for extended lifetime studies.

5. References

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