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MICROWAVE DRIVEN SPACE-CHARGE COMPENSATION WITH OPTICAL DIAGNOSTICS AND FEEDBACK

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Abstract

A system is being developed for the maintenance of a space-charge neutralising plasma from the residual gas within the LEBT of the Front End Test Stand (FETS) at UKRI-STFC Rutherford Appleton Laboratory. Space-charge compensation of a H^- beam will occur when an ion beam is allowed to collide with and ionise a background gas. Appropriate space charge compensation can improve the beam transport and mitigate excess beam loss. The time required to reach the equilibrium space charge compensation of the pulsed H^- beam is experimentally found to be 50 µs – 100 µs at a hydrogen pressure of 10^-5 mbar. Thus, the beam pulse is initially mismatched into the subsequent accelerator in our case this is the RFQ in FETS. This paper shows the development of an optical diagnostics approach to measure the space charge compensation time and the first attempts to maintain a low density plasma in the low energy beam transport to ideally reduce the space charge compensation time to zero. This has been done by injecting S-Band (3.4 GHz) microwaves that have been amplified to 75 W into a LEBT cavity situated between two solenoids. The optical diagnostics has been designed for detecting the weak light emission from this low density plasma.

SPACE CHARGE COMPENSATION OF PULSED H- ION BEAMS

When no space charge compensation is occurring the particles within the beam will repel each other, thus complicating the beam transport. The beam potential of an uncompensated beam can can be in the region of several hundred volts (negative for H^-) [1]. Space charge compensation occurs through the interaction of the beam particles, in our case H^- ions, and the background gas, in our case H_2 molecules. The following reactions are relevant:

$$H^- + H_2 \rightarrow H^- + H_2^+ + e \tag{1}$$

$$H^- + H_2 \rightarrow H_{fast} + H_2 + e \tag{2}$$

$$H^- + e \rightarrow H_{fast} + 2e \tag{3}$$

$$H_2 + e \rightarrow H_2^+ + 2e \tag{4}$$

The first reaction is ionisation of the background gas by the H^- beam, the second and third reactions create electrons by stripping the H^- ions and the fourth is ionisation of the background gas by electrons created in the previous reactions. In addition, there are reactions in which the hydrogen molecules are dissociated and subsequently ionised but these are less important for the space charge compensation. The positive ions created in the ionisation reactions (1) and (4) can be trapped by the negative beam potential. Eventually when/if the density of positive ions equals the density of H^- ions in the beam, the beam becomes space charge compensated, resulting in a very low beam potential. The time for the space charge compensation, if assuming only the primary H^- ions will ionise the background gas in reaction (1) can be expressed as

$$\tau = \frac{\eta}{n_{H_2}\sigma(E)v_{H^-}}, \tag{5}$$

where n_{H_2} is the background gas density, $\sigma(E)$ the ionisation cross section at the energy of the incident H^- ions and v_{H^-} their velocity. Here η is the final space charge compensation degree (0...1), which depends on the production rate of compensating particles and their confinement time. If we take the contribution from the electrons into account then this will depend upon the electrons energy distribution and reduce the compensation time from what is given by the above equation.

The interaction of the beam with the background gas also results in light emission as both the H^- ions and electrons cause excitations of the H_2 gas and hydrogen atoms, producing Balmer-series and Fulcher-band light emission in visible light range. The light emission intensity depends on the background gas density (pressure), the H^- beam energy and the energy distribution of the electrons released in reactions (1)-(4). In particular, as the beam potential changes drastically during the space charge compensation process, it is expected that the electron energy distribution also evolves during that time and affects the light emission. Both these emissions in visible light range can be detected and thus we can probe the space charge compensation process by measuring the time-resolved light emission. Any further interpretations will be reported in the following section.

The primary aim of this experiment is to shorten the space charge compensation time by maintaining a low density plasma in the low energy beam transport matching the density of the ion beam. This paper sets out the development of the optical diagnostics and the first attempts to ignite and maintain the plasma.

EXPERIMENT SETUP AND RESULTS

The Front End Test Stand (FETS) is designed to operate with a 65 keV 60 mA H^- beam (from a Penning ion source [2]), injected into a 3 MeV 4-vane 324 MHz radio frequency quadrupole (RFQ) and medium energy beam transport (MEBT) running at a 10% duty cycle [3]. The low energy beam transport consists of three solenoids and a ”diagnostics vessel” where the optical measurement is taken as shown in figure 1.

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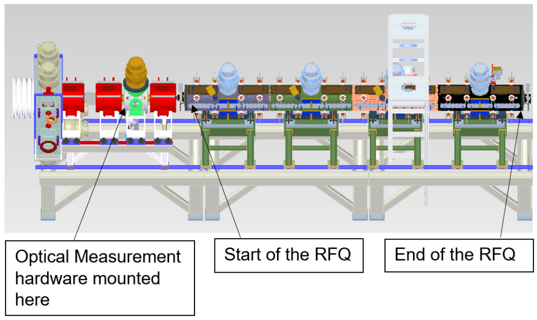

Figure 1: FETS functional overview

Setup for Optical Emission Measurement

The experimental setup consists of an MPPC photo-diode from Hamamatsu (part number S14420-1550MG). These devices are a packaged array of avalanche photodiodes where the optimum photon detection efficiency is centered at 600 nm with a maximum quantum efficiency of 40% and a wavelength range of 300 nm – 1000 nm. To bias the MPPC we used an adjustable 50 V power supply set to 47 V, to provide the bias which increases the gain for the MPPC by 3.6×10^6, this was needed along with other gain stages on the PCB for the MPPC due to the low light environment (see figure 2 for the circuit).

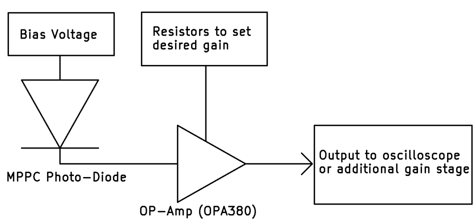

Figure 2: Optical Diagnostic PCB Block Diagram,

The experiments were carried out with, the MPPC mounted inside a container that doesn't allow any light in. To achieve this it was mounted in a metal container, with 2 BNC connectors 1 to carry the signal to the oscilloscope and the other to carry the 47 V bias for the MPPC.

Figure 3 shows the results from the main experiment, the LEBT beam current is produced by a Penning ion source, with a 200 µs beam pulse from a 700 µs discharge pulse, where the beam is extracted by pulsing the extract voltage. What can also be seen in the figure is that the RFQ beam current (measured with a transformer toroid after the RFQ), does not follow a square pulse. This first 70 µs transient is attributed to poor space charge compensation. The loss of beam occurs because of the LEBT solenoid magnets are optimised for beam transmission for the space charge compensated part of the pulse, this results in poor transmission in the first 70 µs when the beam in not compensated. In addition, the LEBT light signal exhibits a transient with its duration matching the transient of the RFQ beam current. The higher level of light in the transient is presumably due to incomplete space charge compensation resulting in high beam potential propelling repelled electrons to higher energies, and then tapers off to a baseline level, which corresponds to the equilibrium space charge compensation degree and lower beam potential (thus the lower light level). The above reasoning relies on the probability for light emission caused by electron impacts increasing with the energy of the electrons accelerated by the beam potential. When at lower beam potential the electrons gain less energy, which is seen as a reduction in the light emission. The saturation level of light emission is thought to be caused by the H^- beam itself if the beam is fully space charge compensated in the end.

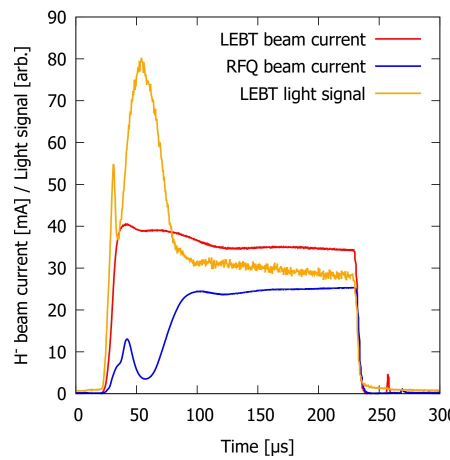

Figure 3: Example of beam current and (total) optical emission signals.

Optical Emission Measurement with Bandpass Filters

After this experiment measuring the total emitted light, an optical band-pass filter was added which was centered at 660 nm with a range of ±5 nm, this was also repeated with a separate band-pass filter centered at 600 nm with a range of ±20 nm. These two filters measure the Balmer-alpha and Fulcher band emissions of hydrogen atoms and molecules, respectively. This was done to test the accuracy and sensitivity of the hardware, as the optical filters attenuate the signal significantly. Also, the filters allow the study of the space charge compensation process in greater detail as the signals are proportional to the atomic molecular hydrogen densities. In the measurement, shown in figure 4 the penning source had a partially blocked aperture resulting in 10 mA – 15 mA less current than usual, which further proves the sensitivity of the hardware.

Injected Microwaves Setup and Results

The experiment was repeated without the optical filters, and and with 3.4GHz microwaves being injected into the vessel, the reason why 3.4GHz was chosen for the microwave frequency is because of the physical size of the wave guide fitting the diagnostics vessel flange, and availability of amplifiers. Another factor for the 3.4GHz is because the experiment was designed to exploit the fringe field from the LEBT solenoids for electron cyclotron resonance with

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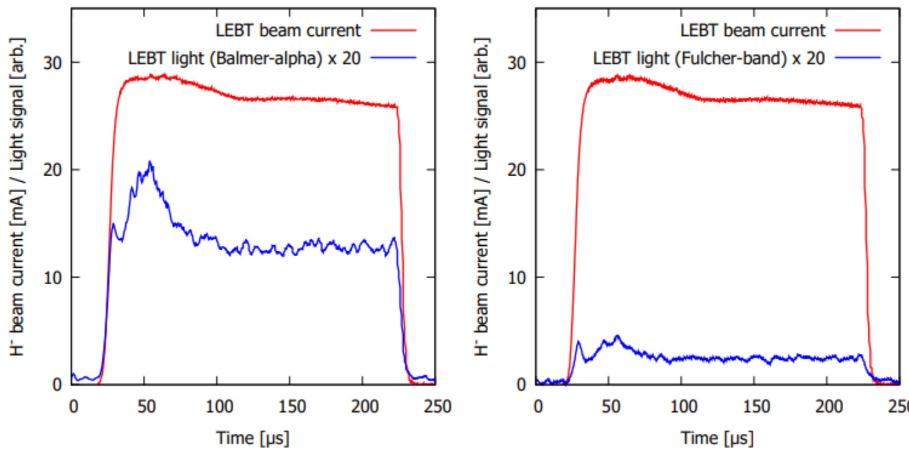

Figure 4: Light emission signals measured with Balmer-alpha and Fulcher-band optical filters.

$B = \frac{2\pi f_{RF} m_e}{e}$. To set this up an RF signal generator was connected to a 2-stage RF amplifier to amplify the microwaves to 75 W. This experiment did not produce the results expected for a couple of reasons. Firstly, the resonant electron heating by the microwaves requires a certain magnetic field from the solenoid, however the solenoids current, and thus the fringe field, for optimum beam transport was not as expected from simulations. This results in resonance only being on the solenoid on one side of the vessel, causing low coupling and thus a large proportion of reflected microwave power. Secondly, FETS is currently running at a 1 Hz repetition rate for commissioning, which makes sustaining the plasma with microwaves between pulses more difficult than at higher beam pulse repetition rate.

FUTURE EXPERIMENTS AND IMPROVEMENTS

Future improvements primarily consist of addressing the issues with the incorrect fringe field for the required microwave frequency, one potential method to achieve this is through the use of permanent magnets around the wave guide, to provide the magnetic field strength. In addition, to being able to increase the repetition rate, radiation surveys need to be carried out for each change in repetition rate which would allow FETS to run at a maximum of 50 Hz, which would significantly reduce the amount of time that the microwaves need to be able to sustain the plasma for between each pulse. Another potential experiment would be to use a monochromator to provide a more accurate reading of the light emission spectrum than using fixed wavelength optical filters. In addition to this a retarding field analyzer (see figure 5) could be used, as we have measured the light emission with a matching transient to the RFQ beam current, and thus believe that this is due to evolving space charge compensation degree. However, to be certain about this we need to measure the beam potential which would be done with the retarding field analyser measuring the maximum energy of the electrons repelled by the H^- beam. The retarding field analyser works by detecting the electron current repelled by the H^- beam and tuning the negative bias voltage connected to the retarding grids until no current is measured on the output pin. The negative voltage required to stop the electron flow equals the beam potential maximum.

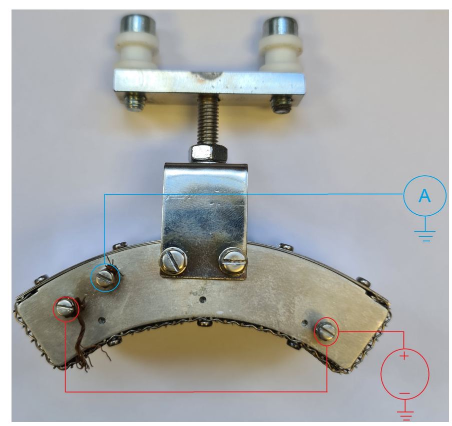

Figure 5: Retarding Field Analyzer

CONCLUSION

In conclusion, measuring the light emission appears to be a straightforward diagnostic to measure the space charge compensation time. With benefits of being non invasive and thus can be done ”parasitically” when operating the ion source LEBT.

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