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# MICROWAVE GENERATED PLASMA RAILWAY TRACK TREATMENT

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**Abstract**
Braking conditions are a fundamental issue for the railway and have been a limiting factor in network capacity & timetabling. This work was focused on taking high power microwave generated plasma out of the laboratory into a railway environment.
The Imagination Factory with no experience in microwave generated plasma has partnered with experts in this field to develop a mobile system which delivered 15kW 2.45GHz microwave generated plasma – Fig.1. The plasma was created within a dielectric tube placed in a monomode microwave cavity; the atmospheric plasma sustained in different inert gases (nitrogen, argon) as well as mixtures of inert gases with reactive molecules was jetted directly onto the railhead as to change the conditions for the wheel-rail interface. This technology is hoped to be a game changer in enabling predictable & optimized braking on the railway network. Challenges encountered during the demonstration phase will be discussed.


**Fig. 1.** Fullscale Demonstrator

## 1. Introduction

Effective railway acceleration and braking is reliant on the small contact patch between wheel and rail. This is roughly 1cm$^2$ and must support high loads under numerous different conditions. Traction in the contact is generated because of torque being applied through the driving wheelsets and low levels of traction, often known as low adhesion, between wheel and rail can occur under certain conditions and cause difficulties when accelerating or braking.
The wheel-rail contact is an open system and therefore exposed to several conditions and contaminants, 3$^{rd}$ layer, that may influence adhesion. This can include natural contaminants such as leaves and organic debris, iron oxides and wear particles, as well as artificial contaminants such as sand, oil and salt. Some of the causes of low adhesion in the wheel-

rail contact are well understood and can be predicted and mitigated, whilst others remain hard to prevent. Different environmental conditions such as temperature, precipitation and humidity change the properties of this third body layer and therefore change adhesion conditions on the railway. Low adhesion can lead to wheel slides and slips during acceleration and deceleration, which can cause large amounts of damage to the wheel and rail as well as causing safety issues and delays if a train cannot accelerate or decelerate when necessary.

The starting point of our project was work completed by British Rail in 1969-72 which had delivered 16kW DC Thermal Arc through a 5mm nozzle to improve the adhesion properties on the railhead [1]. The Imagination Factory has partnered with experts in the field to develop a mobile system using 15 kW, 2.45 GHz microwave generated plasma to treat the railway track as to remove the 3rd layer. The plasma can be tuned to deliver varying amounts of 'removal' by controlling its temperature & reactivity. Currently, it is not known which plasma "recipe" is the most effective and it is possible the solution is not one size fits all due to the complex composition of the 3rd layer.

Laboratory-based tests were designed to optimise the microwave power and the performance of the plasma-based cleaning system using a phantom layer. These tests are to be benchmarked against the final tests made in the actual railway track during the Autumn season to validate the closeness of the phantom layer to the actual 3rd layer and the effectiveness of the plasma treatment. Other tests such as the hardness testing and microstructure analysis are conducted to ensure that the plasma treatment does not damage the rail track to ascertain the application of the plasma treatment in the railway industry.

## 2. System Description

The atmospheric pressure plasma was created within a dielectric tube placed in a TE01 monomode microwave cavity; the atmospheric plasma sustained in different inert gases (nitrogen, argon) as well as mixtures of inert gases with reactive molecules was jetted directly onto the railhead as to change the conditions for the wheel-rail interface – Figs. 2 & 3. This technology is hoped to be a game changer in enabling predictable & optimized braking on the railway network. Challenges encountered during the demonstration phase will be discussed.

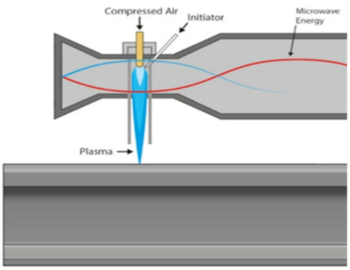



**Fig. 2.** Plasma Head Cross-section Schematic

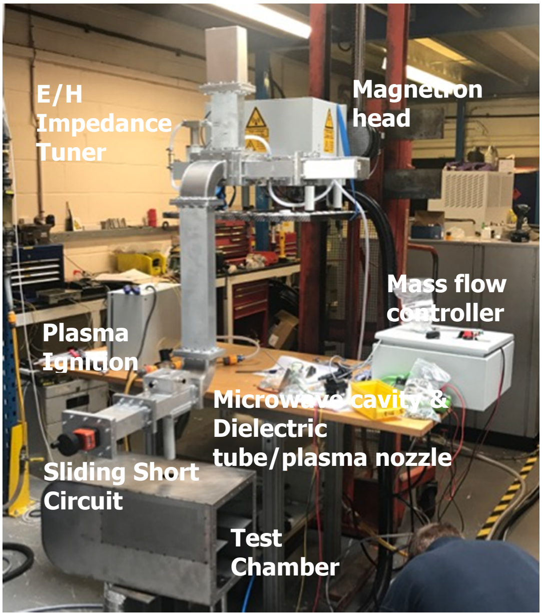



**Fig. 3.** Laboratory set-up

## 3. Laboratory Testing

### 3.1. Development & optimization of the microwave plasma system

The microwave system was commissioned, calibrated & tuned at low power levels (2kW). The initial plasma testing was completed with quartz glass tubes with an inside diameter ranging from 16 to 22 mm. The outside diameter of the dielectric tube was set to fit the fixed mechanical interface in the plasma chamber. The focus of this work was to understand the relationship between gas flow rate and power input. Initially we used a measure of the rate of increase in temperature of a target block of aluminium to evaluate the relationship between flowrate, vortex entrainment & microwave power input – Fig. 4.

The main objective of the work was to develop as high an intensity / concentration of the downstream plasma as possible. The quartz glass material had limitations with temperature and power input. It was therefore decided to embark on investigation into alternative 'microwave transparent dielectrics' which could support this goal. In addition to quartz, non-oxide ceramics as silicon carbide, aluminium nitride and boron nitride were investigated.

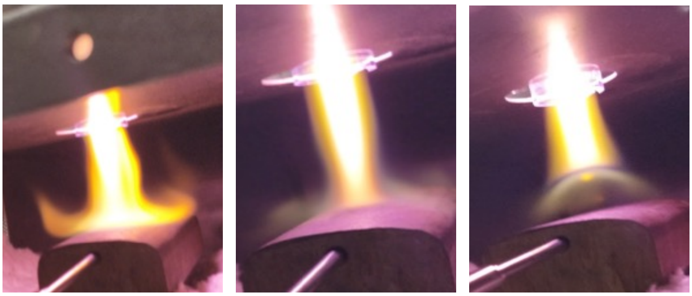


**Fig. 4.** Effect of gas flow on plasma afterglow delivery at 2kW

The silicon carbide (SiC) tube - SiC melting point $2830^{0}$C - was noted to absorb more microwave power than this setup can dissipate, which led to the melting of the tube. Aluminium nitride (AlN), Shapal$^{TM}$, in addition to being a very difficult to machine ceramic had a catastrophic failure on the first plasma test – Fig. 5. This material was discounted from further development.

**Fig. 5.** Thermal shock damage of the AlN tube

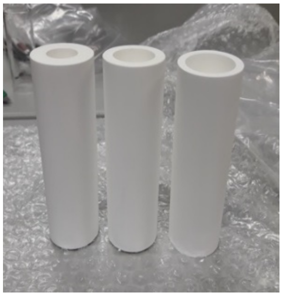


**Fig. 6.** BN machined tubes

The most successful material for our research – thermal shock & plasma efficiency - was found to be BN. Various BN blends were sourced. An unbound variant AX05 proved incredible flexibility for machining & good temperature resilience. This enabled the team to develop a range of tube ID and profiles.

### 3.2. Gas flow

The development of a vortex in the gas delivery is critical to creating a stable plasma. Computational Fluid Dynamic (CFD) analysis of the gas entrainment was completed to confirm vortex creation – Fig. 7. This included evaluation of the number of gas supply ports and pre-conditioning 'swirl' rings. These were then practically evaluated in the static testing section. A two-port solution with swirl ring was adopted for all testing.

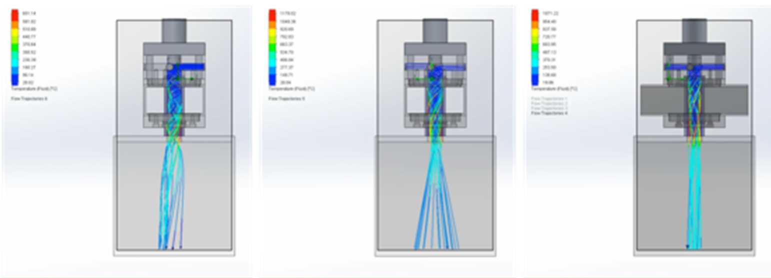


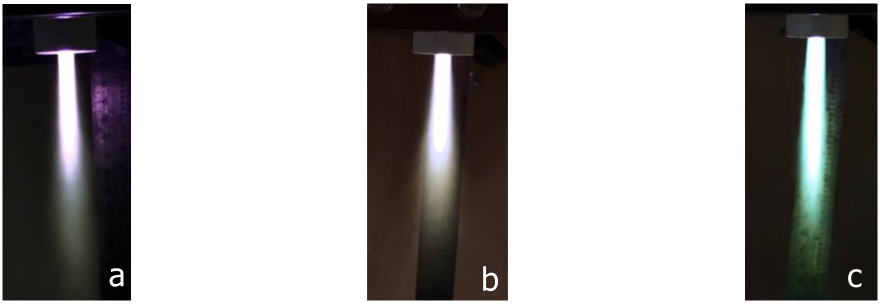
**Fig. 7.** CFD simulation of gas flow and gas inlet design

### 3.3. Gas type investigation

Plasma was successfully ignited and sustained in inert gases like argon and nitrogen and in mixed nitrogen & oxygen and nitrogen & water, Figs. 8 a-c.

*Neutral Plasma*
Initial tests were completed using bottled nitrogen. This was utilized mainly to reduce the likelihood of NOx creation. The performance of the nitrogen plasma is mostly related to a thermal ablation effect. Note: Purple colour indicates stable plasma, Fig. 8a.

*Reactive Plasma*
Two types of reactive plasmas were created by mixing nitrogen with different amounts of oxygen and water.
The addition of $O_2$ to the $N_2$ was done in order to promote oxidative reactions and hence, to create active species within the plasma which will oxidize the 3$^{rd}$ layer – Fig. 8b. Note: White colour indicates stable plasma.
By bubbling $N_2$ through a water scrubber (water at 20$^0$C), a dual reactivity (reductive & oxidative) was created. The water molecule splits into $H^+$ fueling reduction & $OH^-$ oxidative species in the plasma – Fig. 8c. Note: Greenish white colour indicates stable plasma




100% $N_2$ 5% $O_2$ $H_2O$

**Fig. 8.** Plasma afterglow in different gases

### 3.4. Development of infrared temperature measurement methodology
Test methodology was developed to enable the creation of stable plasma and replicate the dynamic movement of the railhead through the established afterglow, Fig. 9.
The microwave behavior of the plasma tube materials changes with temperature, which detrimentally affects the plasma stability. It has been established that there are 3 distinct phases of plasma within the test, ignition –> stability –> decay. The development of more exotic materials & cooling designs will be continued in the next phase to reduce this effect.
The evaluation of the performance of the plasma was achieved through a sample steel block being introduced through the plasma after ignition and during the stable period of testing; this was generally accepted as 2 seconds after ignition. The steel block speed can be adjusted using the pneumatic control circuit for slow, medium & fast test speeds representative of the DMU speeds at British Rail testing facility.
The use of FLIR infrared cameras enabled the recording of the surface temperature on the block. This system enabled rapid evaluation of thermal performance for each diameter/ power/ flowrate & gas type. The camera has limitations in frame rate & temperature range and in order to capture the full range of surface temperature multiple tests were completed with different electronic filters. An example of the measurement is shown in Fig. 10, dielectric tube internal diameter 4mm, 15kW, nitrogen flow rate 35L/min.

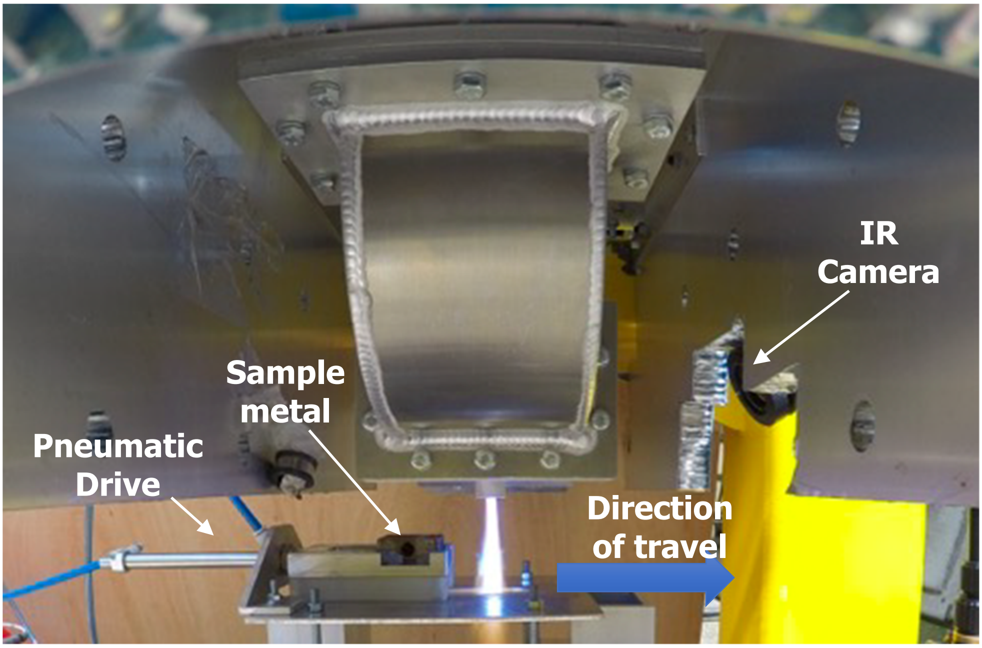



**Fig. 9.** Sliding shuttle & metal block

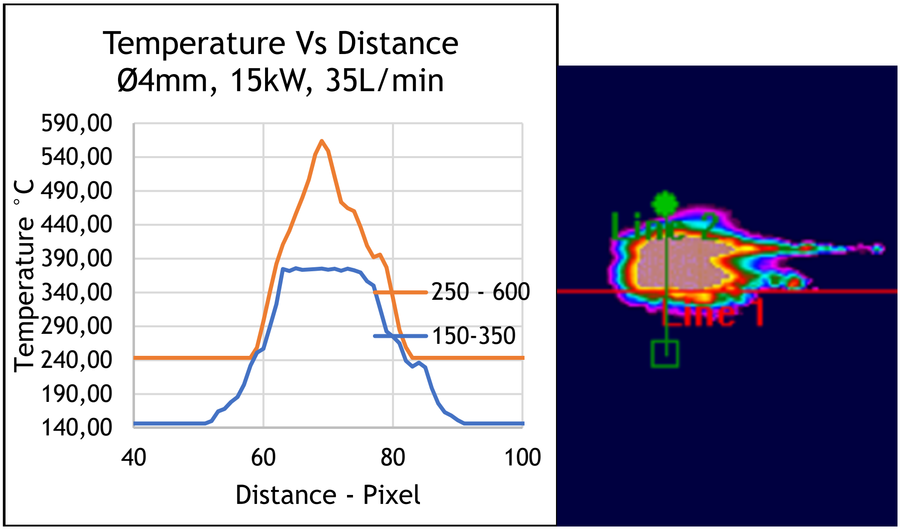



**Fig. 10.** Thermal images of the rail surface

## 4. Mobile Testing, Results & discussion

The mobile test equipment, Fig. 11, was satisfactorily protected from shock damage using sprung AV mounts. Limitations of DMU speed control & repeatability of braking cycle led to the exclusion of brake deceleration testing from the evaluation methodology for on-track testing. The track lateral movement & relative vertical movement limited the test site to the straight and testing within a 20m zone with vertical movement less than 8mm. The plasma nozzle was pre-set to a maximum height of 25mm from the railhead, Fig. 12. During the testing, the track has been temporarily marked at meter increments to aid in analysis.

**Fig. 11.** Mobile test rig at British Rail testing facility

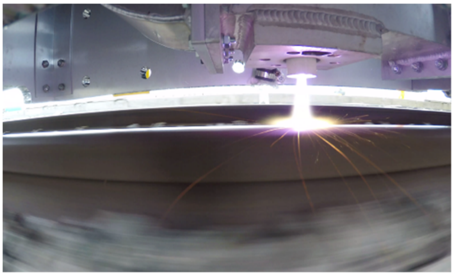


**Fig. 12.** Go-Pro image of plasma on the rail during mobile testing

Testing was completed for 3mm, 5mm, 7.5mm ID plasma tubes at slow (5km/h), medium (10km/h) & fast (15km/h) speeds with power ranging from 9-15kW. The test area was marked with cones to aid the driver in getting to speed, maintaining speed during plasma delivery and braking to a safe stopping point.
Evidence shows a rust removal effect on the railhead with the application of plasma, Fig. 13. This is most markedly seen with the 3mm ID plasma tube for all types: neutral, $O_2$ & $H_2O$ plasmas.


**Fig. 13.** Effect on railhead oxidation

As in the dynamic test protocol, FLIR infrared thermal analysis has been used to understand an indication of microwave power to speed relationship. IR & video cameras have been side mounted on the waveguide. The video camera also enables evaluation of plasma distance to the railhead. Every test configuration has been analysed for peak temperature, width & length of the plasma thermal area of influence for any given power input & speed – see Fig. 14.

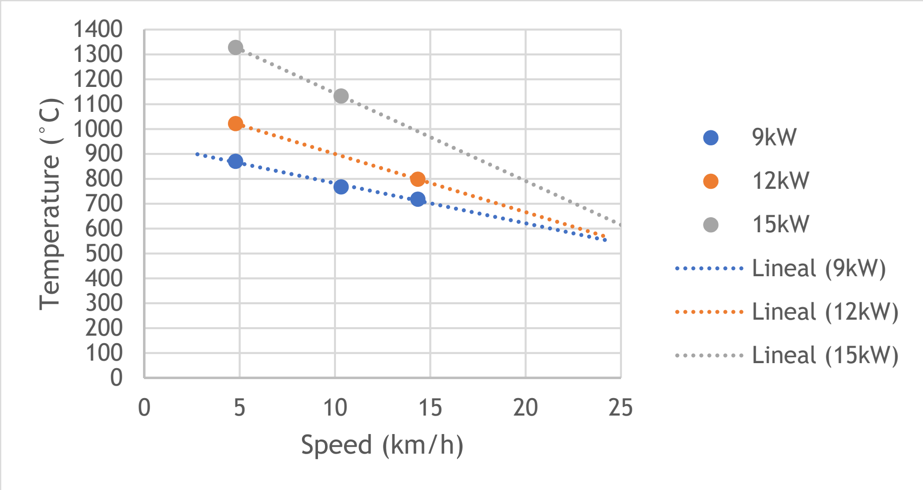



**Fig. 14.** Microwave power/peak temperature vs. Speed dependence, dielectric tube 3 mm

The results clearly show a higher performance for the smaller diameter, enabling higher temperature delivery with lower power input at speed.

The peak temperature effect is believed to be most relevant for Predictable & Optimised Braking for the on passenger mounted embodiment. This measure is indicative of energy which would be delivered onto the 3rd layer and which would create a disturbance along the running contact patch, enabling drying and removal of contaminants to give 'summer braking' conditions. The predicted energy levels are still well within the theoretical maximum proposed. This is partly due to the plasma density/energy concentration that can be achieved with the 2.45GHz microwave frequency.

## 5. Conclusion

An understanding & optimization of 2.45GHz microwave generated atmospheric plasma in the context of track treatment has been demonstrated. The effect on 3rd layer contamination has been demonstrated in the laboratory and on the track.

Currently, 15kW is the maximum power magnetron available at 2.45GHz. In order to achieve a higher power microwave source, 896MHz is to be considered. When transitioning from 2.45GHz to 896MHz, the plasma electron energy concentration is believed to reduce proportionally with the frequency. This, therefore, shows that there is capacity within the energy equation to accommodate available 896MHz magnetrons and maintain realistic electrical energy supply for onboard train systems.

## References

1. Balwanz W.W., 1979, Plasma Cleaning of Surfaces. In: Mittal K.L. (eds) *Surface Contamination*. Springer, Boston, MA, 255-269.