

## **Advances in the Understanding of DC Plasma Arc Behaviour – Insights from Photography**

QG Reynolds and RT Jones  
*Pyrometallurgy Division, Mintek (South Africa)*

The development of photography as a tool for the study of direct current plasma arcs as applied to DC arc furnace technology is followed over the course of more than a decade of research on metallurgical pilot plants at Mintek. The scale of the facilities available has permitted the study of arcs from 0.5 to 8kA current, generated by DC power supplies between 300kVA and 5.6MVA in size.

Early studies made use of primitive digital cameras and consumer video equipment to produce images of arcs under a variety of conditions, and to capture arc interaction with liquid slag surfaces inside operating furnaces. Both single- and multiple-electrode furnace arrangements were examined.

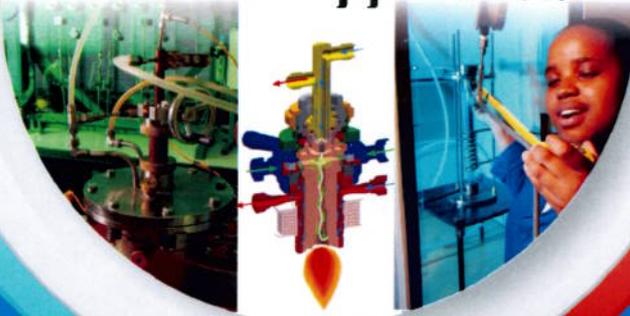
More recent work has seen the application of specialised digital high-speed video camera equipment to the study of the evolution and motion of arcs at extremely short time scales (milliseconds or less). Dynamic numerical models of simple arc systems were initially used to predict a variety of qualitative phenomena - including transition effects with increasing current and arc length, and the formation of spontaneous arcs at the flat anode surface - which were subsequently confirmed by observation in high-speed photography experiments.

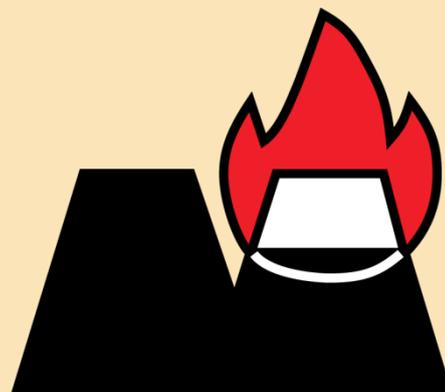
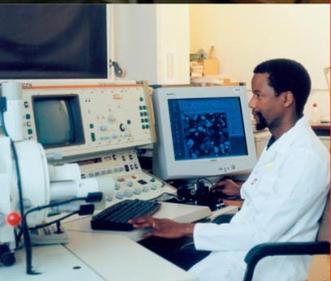
High-speed imaging results from a variety of electrode arrangements are presented, including single and multiple cathodes, reverse-polarity arcs, and effects of electrode composition on arc behaviour.

3<sup>rd</sup> International Round Table on Thermal Plasmas for Industrial Applications, Glenburn Lodge, Muldersdrift, South Africa, 31 October – 4 November 2011, p 35

# Programme and Abstract Book

## 3rd International Round Table 2011 Thermal Plasmas for Industrial Applications





# MINTEK

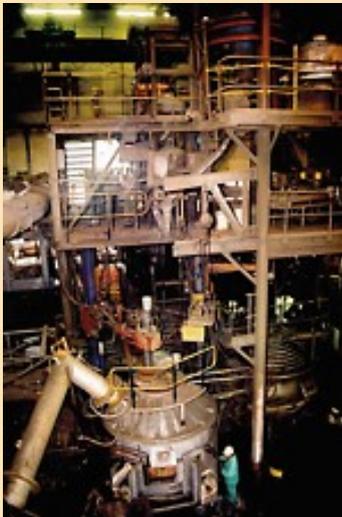
## Advances in the Understanding of DC Plasma Arc Behaviour – Insights from High Speed Photography

QG Reynolds and RT Jones

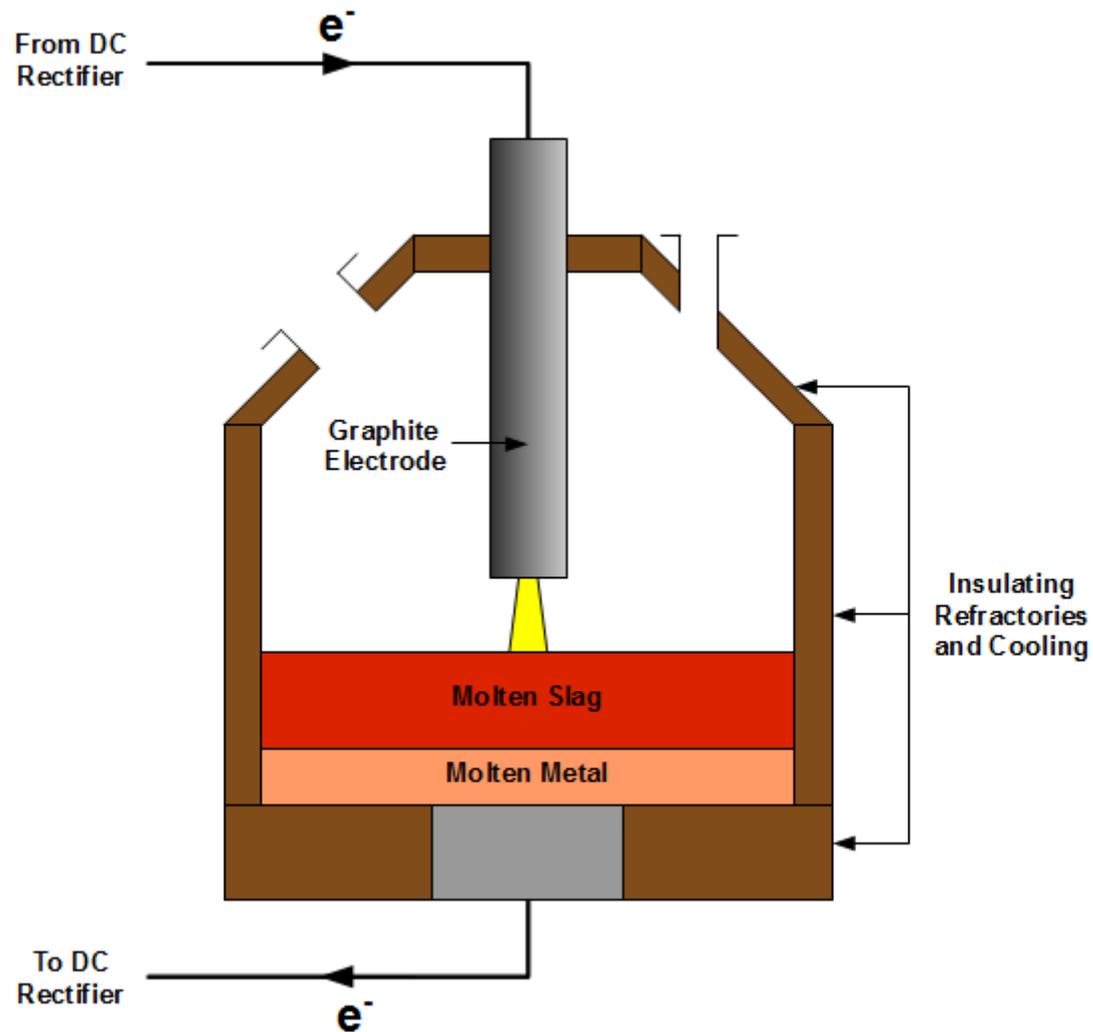
*Pyrometallurgy Division, Mintek*

# Introduction

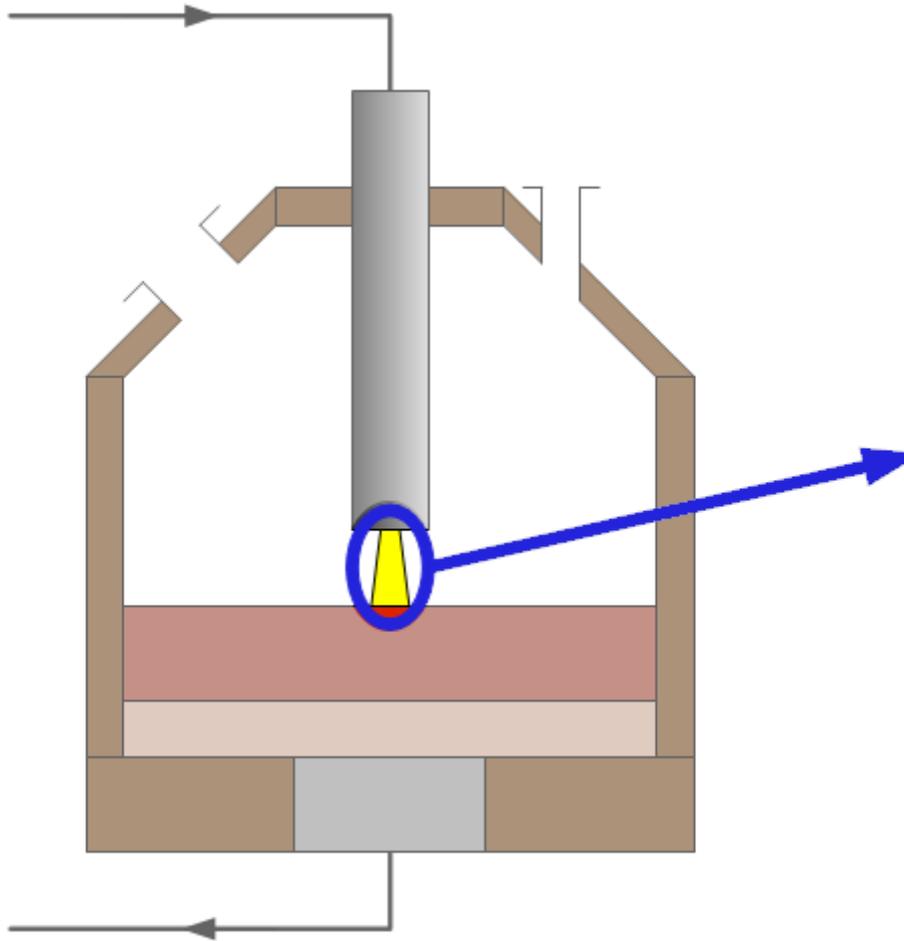
- DC plasma arc furnaces are seeing increased use in metallurgical industry
- Advantages over AC electric and fossil-fuel furnaces for some processes and applications
- Mintek has been at the forefront of DC arc furnace technology for many years
  - Ilmenite, FeCr, Pb/Zn, FeNi, PGM, Mg...



# Introduction



# Introduction



# Understanding the arc

- The DC plasma arc is a high-temperature, high-velocity jet of ionised gas
- The arc is a multi-physics phenomenon, sustained by interactions between electromagnetic, temperature, and velocity fields within the furnace
- The arc at moderate to high current is unsteady, with time scales characteristic of arc motion typically very short (milliseconds or less)



# Why photograph arcs?

- The arc is usually the principal heating and stirring element in DC furnaces
- Understanding the nature and behaviour of the arc is important for furnace operations
  - Process control
  - Feed system design
  - Power supply interactions
- The furnace environment is harsh, hot, and dusty - photography is ideal as a direct, non-contact form of measurement

# Why photograph arcs?

- Can compare against arc models which suggest that the arc is a highly dynamic system
  - Transition effects (with current, arc length)
  - Transient phenomena, eg. anode arc formation
- Can directly study effect of electrical design changes, eg. changing power supply polarity
- Can show behaviour before and during arc extinguishment or “blow-out”

# How to photograph arcs?

- Big problem #1 – too much action!
  - Arc column can move and evolve very rapidly
  - Transient phenomena last for very short time periods
- Big problem #2 – too much light!
  - 15,000x visible light intensity of typical well-lit office
  - Can over-expose and even damage film or digital sensors very easily
- Solution? Use high-speed video cameras
  - Fast recording speeds slow or freeze rapid motion
  - Extremely short shutter speeds reduce light intensity without filters

# How to photograph arcs?

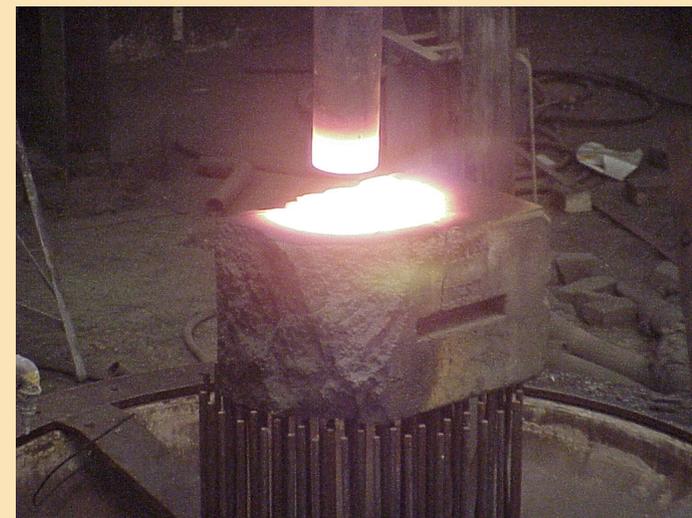


- Olympus iSpeed 3 camera
- Up to 2000 frames per second at 1280 x 1024
- Up to 150,000 frames per second at reduced resolution
- Shutter speeds down to  $1\mu\text{s}$

# How to photograph arcs?

- Access to existing furnaces can be difficult – not designed with photography in mind
  - View ports, feed ports, tapholes may all provide useful lines of sight
  - Dust and fume generally obscures arc though
- For studying the arc in isolation, a more controlled environment can be set up
  - No furnace containment vessel
  - No molten bath
  - Arc struck in air between graphite electrode and graphite block anode

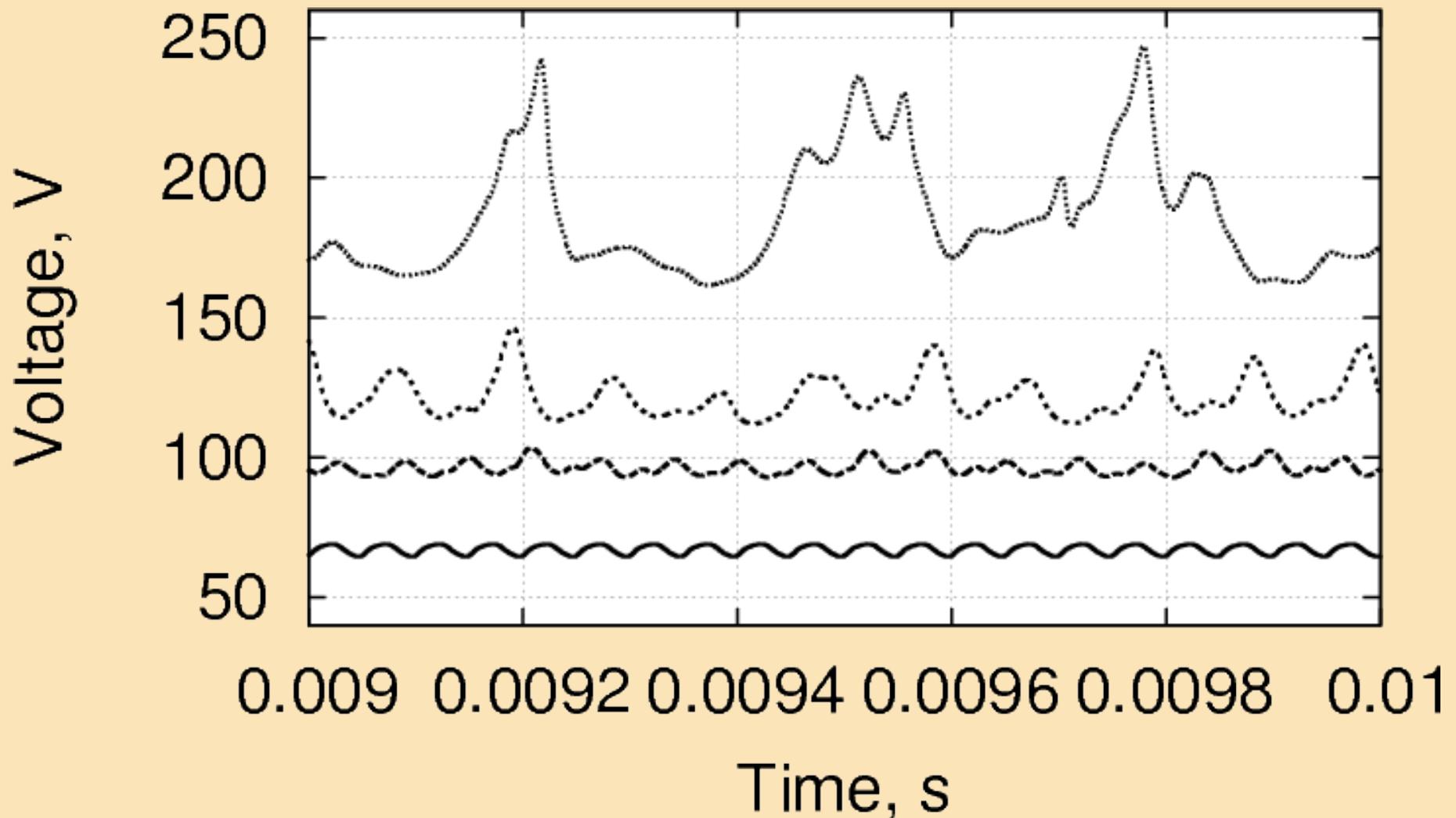
# How to photograph arcs?



# Modelling vs. observations

- Testwork performed in 2009 to investigate certain qualitative results seen in arc modelling
- Models used high spatial and temporal resolution to generate time-dependent velocity, temperature and electromagnetic fields
- Transient, dynamic behaviour in models resulted in some interesting predictions
  - Transition effect with arc length, from steady-state through regular oscillations to chaotic behaviour
  - Small, temporary arcs spontaneously form at the anode surface

# Modelling – Arc Length (500A)



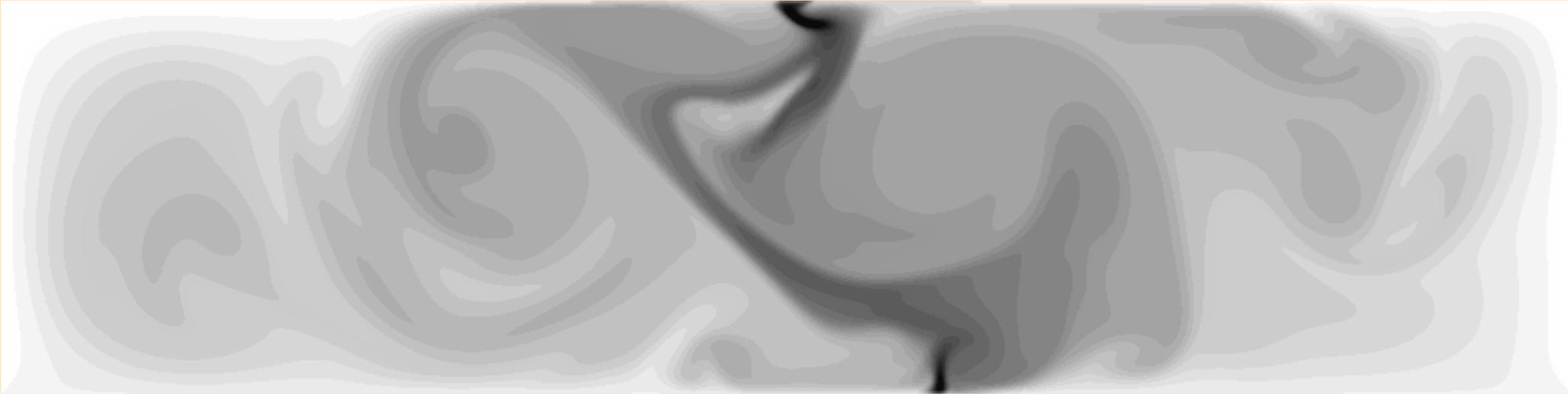
1.25 cm ——— 2.5 cm .....  
1.875 cm - - - - - 3.75 cm .....

## Observations – Arc Length (1kA)



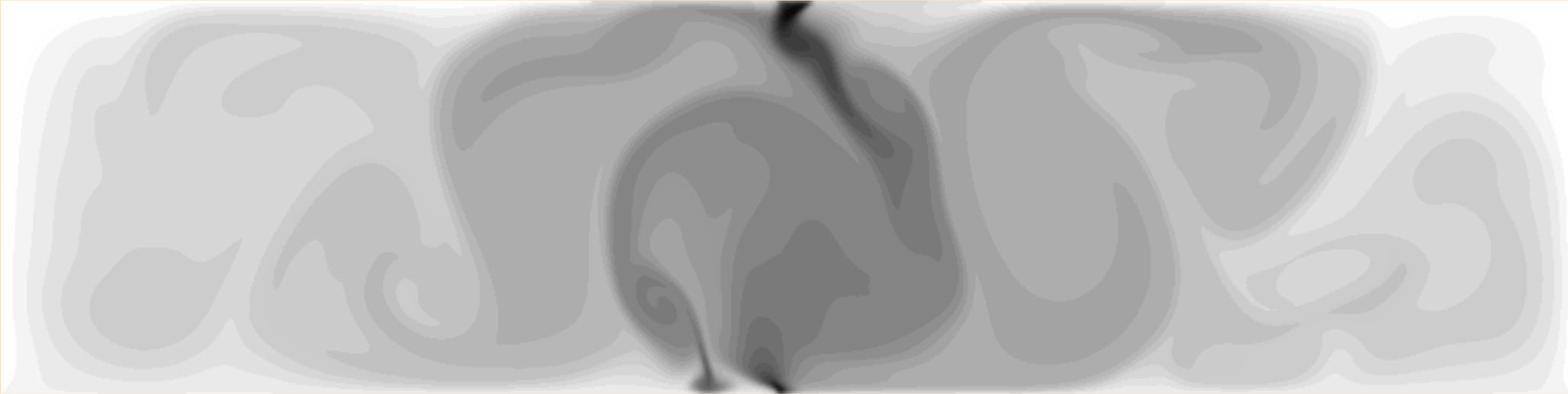
- High speed imaging of arcs at 5000 frames/s, 5 cm (left) and 10 cm (right) arc length
- Qualitative agreement between model and reality
- Arc dynamics can change from *regular oscillations* to more *unpredictable, chaotic behaviour* as arc length increases

## Modelling – Anode Arcs



- Temperature plot, scale 2000 (white) to 15000 K
- Time 7.80 ms from ignition
- Temporary arcs are an emergent phenomenon and form spontaneously at anode (lower surface)

## Modelling – Anode Arcs



- Temperature plot, scale 2000 (white) to 15000 K
- Time 9.98 ms from ignition
- These “anode arcs” are highly mobile and transient in nature

## Observations – Anode Arcs



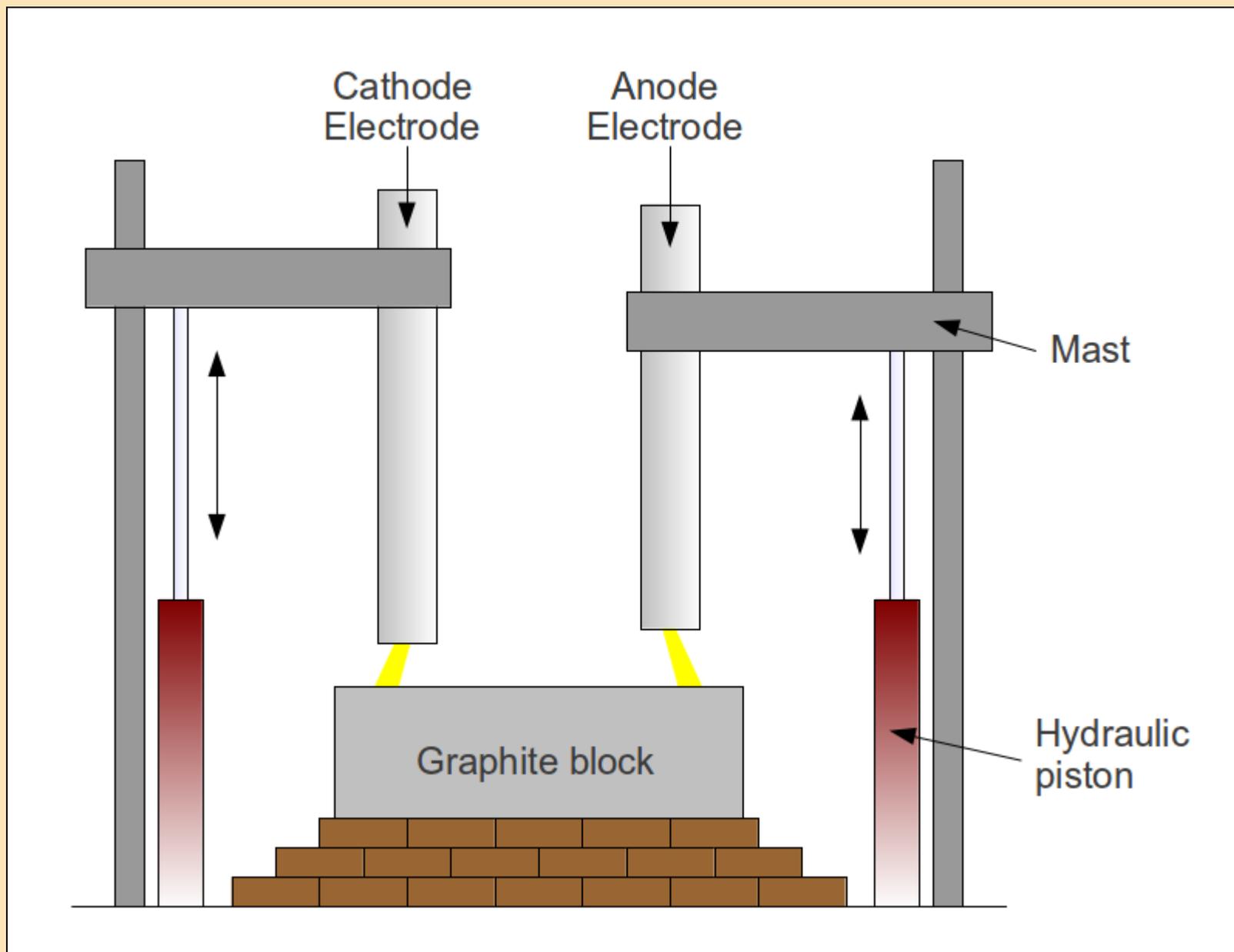
- Above: Anode arc formation sequence at 1kA, successive frames at 5000 frames/s
- Below: Arcs on anode surface at 3kA with near-IR filter, 5000 frames/s



# Polarity Effects

- Much misunderstanding around the direction of electric current and how it affects plasma arcs
- Traditionally, polarity of power supplies for DC furnaces results in electron flow from electrode (cathode) to furnace hearth (anode)
- Recent theoretical designs propose a *dual-electrode* DC furnace
  - No hearth anode
  - Two electrodes connected as anode and cathode
- ...but what happens to the arc when the polarity is reversed?

# Polarity Effects



# Polarity Effects

Anode (reverse polarity)

Cathode (normal polarity)



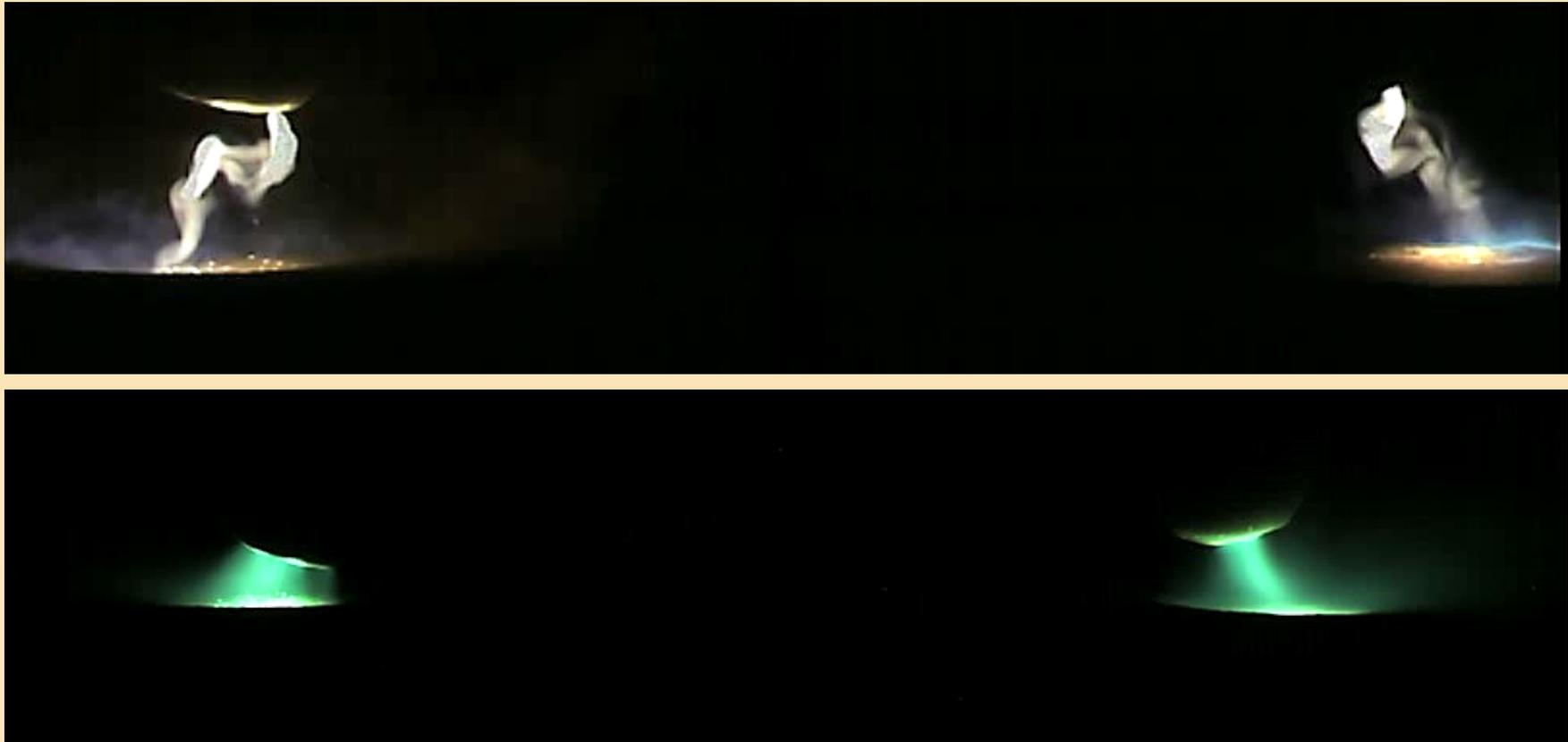
- High speed video, 5000 frames/s, dual-electrode test at 3kA and 10cm arc lengths
- Similar behaviour and dynamics
- Heating of electrode more pronounced for reverse polarity arc – electron condensation

# Polarity Effects



- High speed video, 5000 frames/s, dual-electrode test at 1kA, 5cm arc length
- Arc at anode (reverse polarity) electrode
- Arc root is highly mobile, but jet shape and direction are familiar from normal polarity tests

# Polarity Effects



- Increased arc mobility at anode electrode can make real-time observations look very different!
- Top: both arcs at 5000 frames/s, 3kA
- Below: both arcs at 60 frames/s, 3kA

# Arc Extinguishment

- Failure or loss of the arc in a DC furnace can be highly disruptive to the operation
  - Downtime due to laborious arc re-strike procedure
  - Surges can potentially damage fuses, power supply
- Investigation of behaviour during arc loss involves high speed measurement of electrical data together with high speed camera
  - Synchronised triggering system to ensure visual and electrical data are matched
  - Electrical measuring equipment still at prototype stage



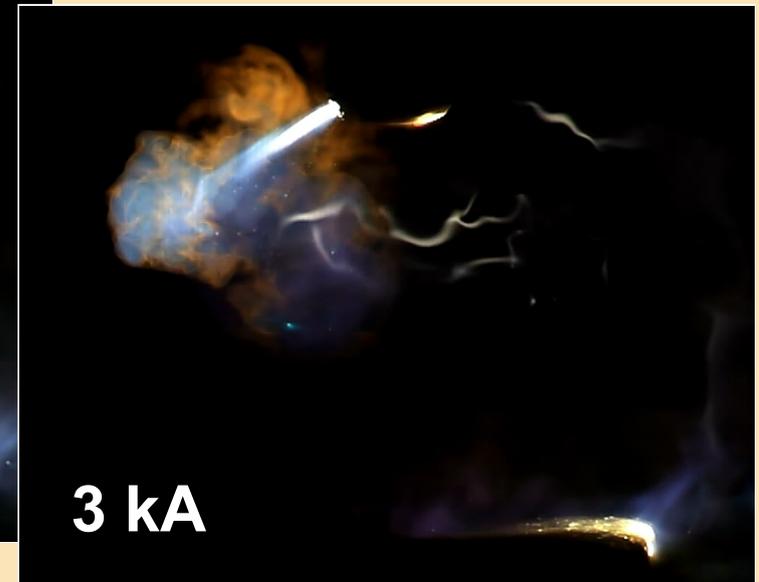
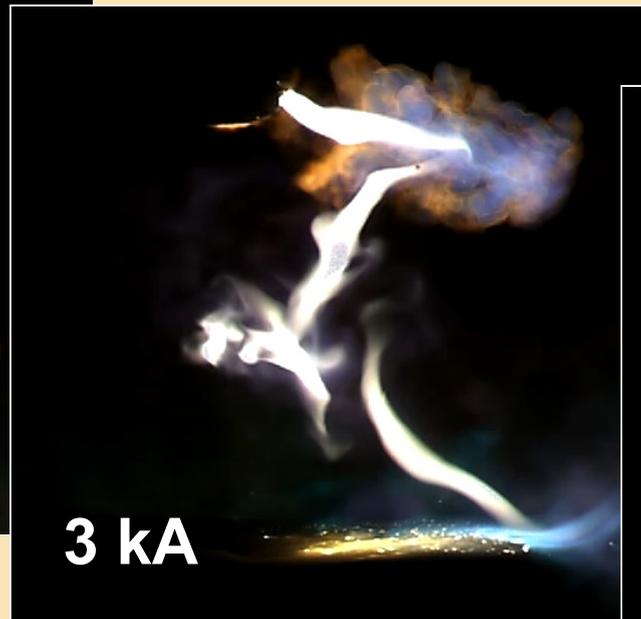
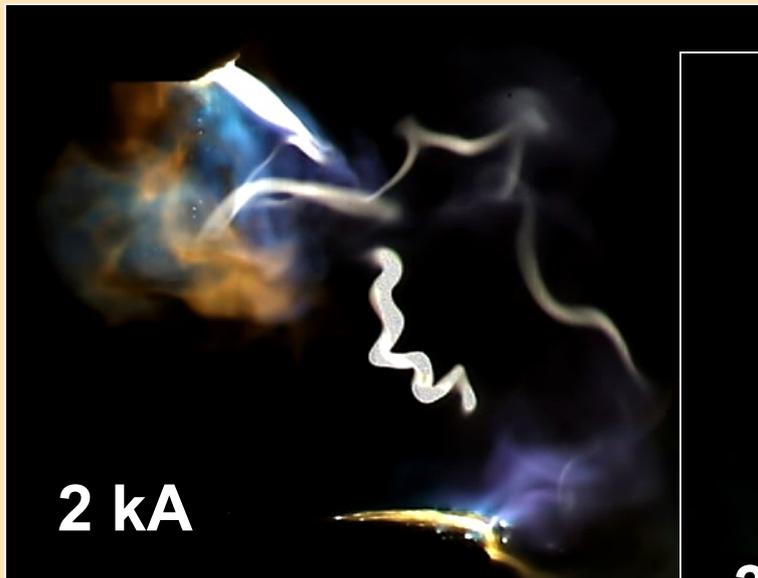
# Arc Extinguishment

- Many possible reasons for arc failure
  - Voltage too high, exceeding power supply limitations
  - Arc length too long for a given current, plasma loses too much energy to sustain conduction
  - Sudden alteration in process chemistry, change in gas environment
  - Disruption of attachment surfaces, eg. electrode breakage, material floating on molten pool
- Present work focuses on the arc length failure mode



# Arc Extinguishment

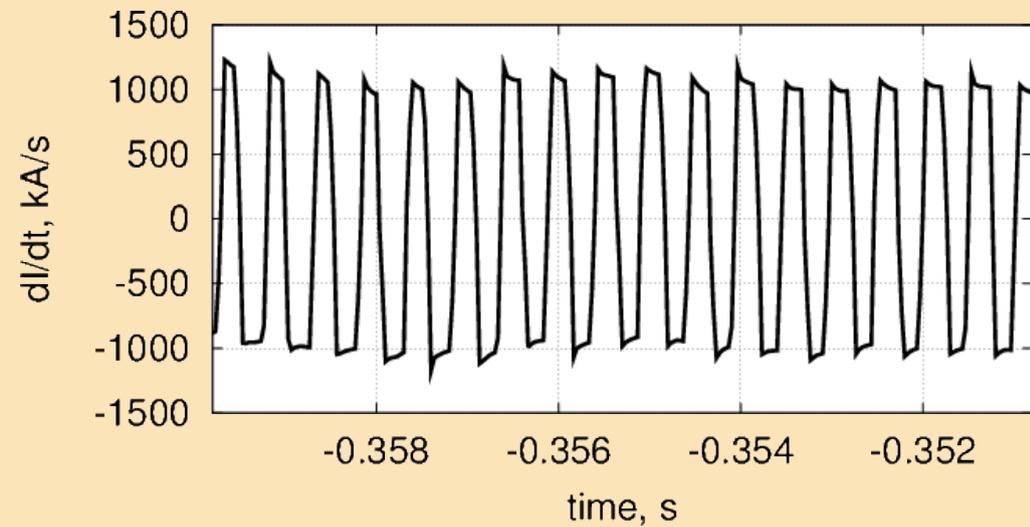
- Arc failure initiated by formation of a fireball at electrode surface, flooding space between electrode and anode with plasma
- More common at higher currents tested (2-3kA)



# Arc Extinguishment

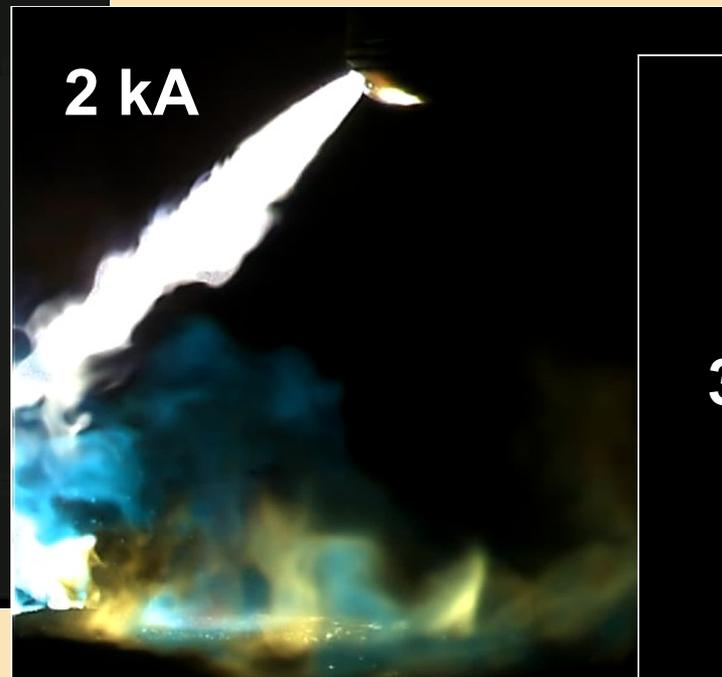
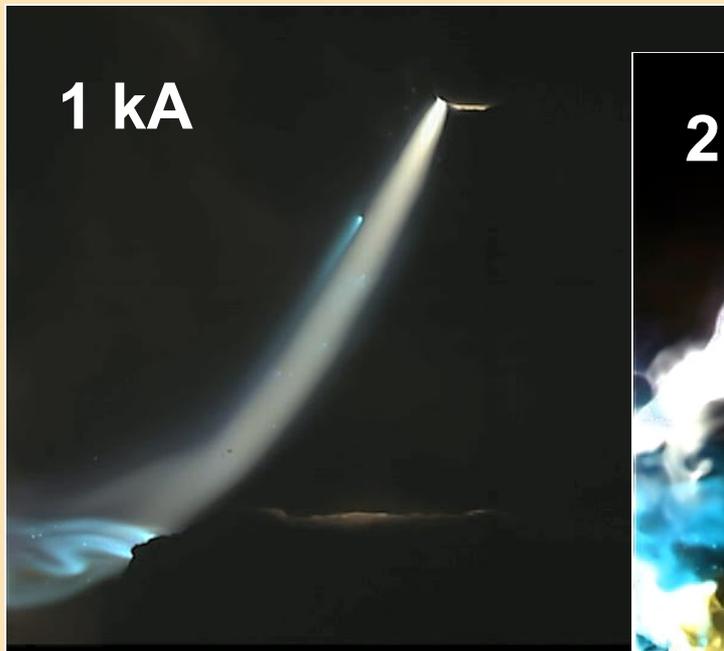


- High speed video, 5000 frames/s, 2kA
- Fireball formation sequence



# Arc Extinguishment

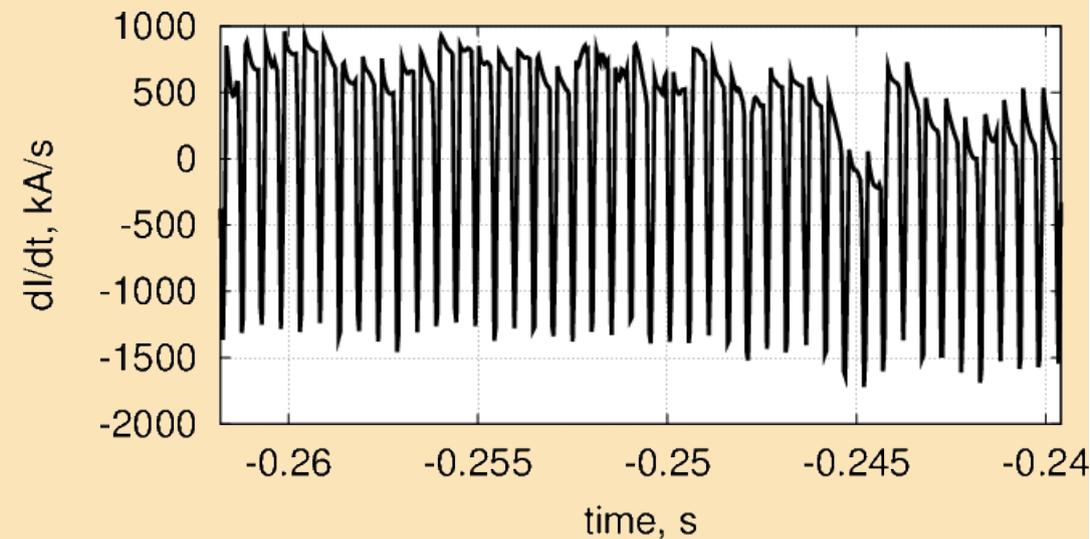
- Between 0 and 100ms after the fireball, a pseudo-steady state arc jet forms in the plasma cloud
- Arc extinguishes shortly after



# Arc Extinguishment



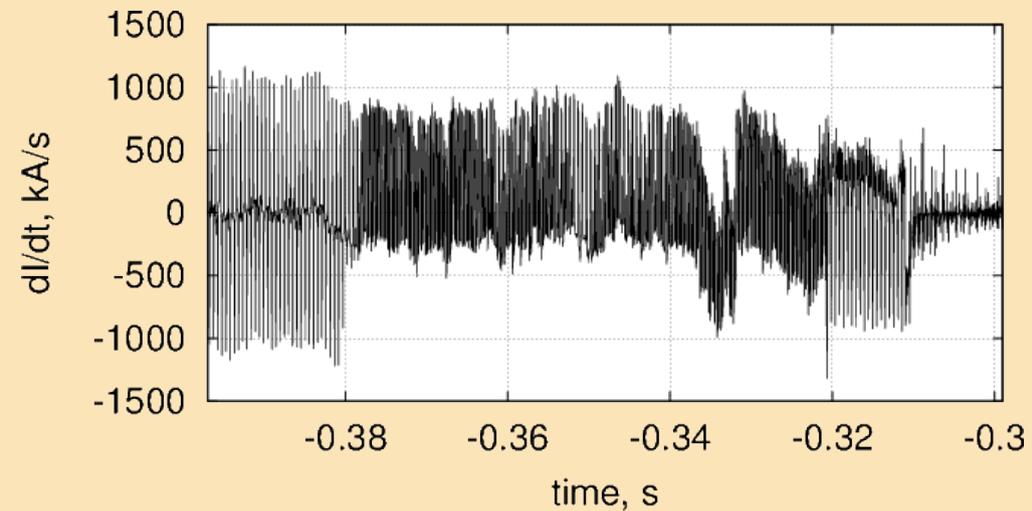
- High speed video, 5000 frames/s, 2kA
- Establishment of pseudo-stable jet



# Arc Extinguishment



- High speed video, 5000 frames/s, 3kA
- Complete sequence to arc failure



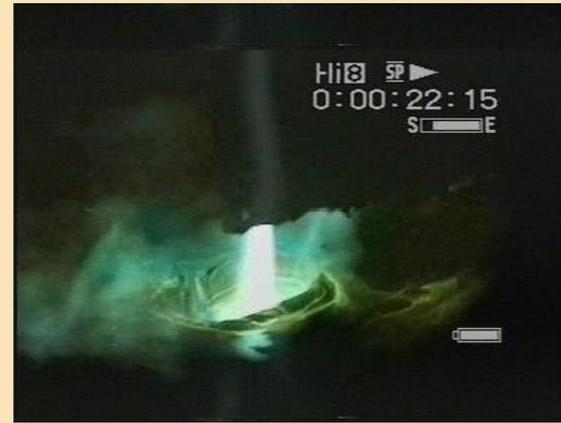
# Conclusions

- High speed photography has proved to be a valuable tool in understanding DC plasma arcs
- Experimental confirmation of many qualitative phenomena first seen in modelling work
- Versatile test facilities can be used to study arc behaviour in various furnace configurations
- Future work planned
  - Further development of synchronised high speed electrical measurements
  - Extension of testwork to include interactions with liquid surfaces such as slag, metal, etc

# Acknowledgements



# Thank you



- Jones et al, *DC Arc Photography and Modelling*, J. Min. Eng. **15** 11S1, 2002
- Reynolds et al, *Twin-electrode DC smelting furnaces – Theory and photographic testwork*, J. Min. Eng. **19** 3, 2006
- Reynolds et al, *Mathematical and computational modelling of the dynamic behaviour of DC plasma arcs*, INFACON XII, June 6-9 2010, Helsinki Finland
- Reynolds et al, *High-speed photography and modelling of DC plasma arcs*, ICHSIP 29, Sep 20-24 2010, Morioka Japan

<http://www.mintek.co.za/Pyromet>