A Method to Estimate Electron Density in a High-Voltage Fuse' Arc

Muhammad A. Saqib, Anthony D. Stokes, Brian W. James, and Ian S. Falconer

***Abstract*—Stark broadening of the Si II doublet at 504.1 nm and 505.6 nm has been used to estimate the electron density in two model silica-sand-filled high-voltage, high breaking capacity fuses. For a 240 mm long fuse which successfully interrupted a test circuit set up to deliver a 4.5 kA prospective current, the electron density fell from ~ 2×10^{18} cm^{-3} shortly after arc initiation to ~ 1×10^{18} cm^{-3} just before current zero; for a 112 mm long fuse and a prospective current of 1.25 kA the electron density was $\leq 1\times 10^{17}$ cm^{-3} for the duration of the arc.**

***Index Terms*—High breaking capacity fuse, spectral lines, Stark broadening, the fuse' arc.**

I. Introduction

A HIGH-VOLTAGE, high breaking capacity (HBC) fuse is an important component of modern electrical energy distribution system. It is considered superior to the equivalent circuit-breaker for interrupting short-circuit currents because of its short operating time, cost-effectiveness, and self-fault-sensing characteristics [1], [2]. The pre-arcing behavior of these fuses is now well-understood, but a lack of information as to the characteristics of the fuse arc has prevented researchers developing a model which will quantify the behavior of this phase of the operation of the fuses. Although empirical models of the arc have been developed [3] and have been used for some calculations, it is necessary to know the arc temperature and electrical conductivity, which depend on the electron density and temperature of the arc, to model the arc [4]. The lack of knowledge of the arc parameters such as electron density and temperature is particularly acute in the case of HBC fuses which are packed with sand - usually silica sand - to absorb the arc energy.

Although there have been a number of studies to determine plasma temperatures during fuse arcing, there have been few measurements of electron density in the arc. Chikata et al. [5] replaced an opaque fuse holder with a Pyrex glass tube in order to observe the visible radiation from the sand-filled fuse arc, and from Stark broadening of silicon lines obtained electron densities of the order of 10^{18} cm^{-3}. Cao [6] used an arc in ice to provide access to the radiation emitted, and measured densities of the order of 10^{18} cm^{-3} from the Stark broadening of the hydrogen Balmer lines. The drawback of this already reported work is that it does not reflect the actual situation in sand-filled high-voltage fuses in which the burning arcs are constricted by the surrounding silica sand and enclosed by opaque fuse cartridges. The reported measurements [5], [6] are also integrated over the duration of the arc, and do not provide any indication about their variation in the arcing period. This study reports the investigation of the arc, which is produced inside the model fuses and is surrounded by SiO_2 in opaque fuse cartridges just like in actual fuses. The light from the arc is carried to a monochromator by an optical fibre which is then analysed to make an estimate of the electron density using the Stark-broadening parameters of Si II spectral lines. The model fuses are tested at 6 kV (50 Hz) for 1.25 and 4.5 kA prospective fault currents, conditions likely to be encountered in power distribution networks. The study reports the time-resolved measurements of electron density during the evolution of the arc.

II. Stark Broadening of Spectral Lines

As a consequence of the long range of the Coulomb force the collisional broadening of spectral lines from moderately ionized plasmas such as the fuse arc is dominated by the collisions of charged particles with the emitting atoms. This Stark broadening is given for singly ionized atoms by [7, 8]

$$\Delta\lambda = 0.2\left[1+1.75\times10^{-4} n_e^{1/4}\alpha\left(1-0.11 n_e^{1/6} T^{1/2}\right)\right]\times10^{-16} w n_e \quad (1)$$

where $\Delta\lambda$ half width of the Stark broadened line in nm

$n_e =$ electron density in cm^{-3}

$T =$ plasma temperature in Kelvin.

The constants α and w are characteristic of the transition of interest, and depend weakly on the plasma temperature. They are tabulated by Griem [9].

III. The Experiment

The experimental set-up for these measurements was identical to that used for the fuse arc electron temperature measurements discussed in [10]. Indeed, the data from which the electron density was deduced were obtained from the spectra which had been taken primarily for these electron temperature measurements. It must be clarified here that reference [10] discusses about the time-resolved measurements of arc temperature for a model fuse when it was tested at 1.25 kA fault current whereas the temporal estimation of electron density for two model fuses – of different dimensions – at two fault currents – 1.25 kA and 4.5 kA – is the subject of this paper.

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Fig. 1. The long fuse; 240 mm long with inside diameter of 43.7 mm.

Fig. 2. The short fuse, 112 mm long with inside diameter of 59.5 mm.

Two experimental versions of a silica-sand-filled fuse, cylindrical in shape with a 0.55 mm diameter uniform silver wire stretched inside the middle of the fuse barrel along its axis, were constructed for these measurements. One was 240 mm long with an inside diameter of 43.7 mm (the long fuse, Fig. 1), the other 112 mm long with an inside diameter of 59.5 mm (the short fuse, Fig. 2). (Commercial fuses use a somewhat different design to ensure the current goes to zero well before reaching its maximum value and that reignition does not occur.) A 6 kV, 50 Hz waveform was applied to the fuse by closing the pneumatically-driven mechanical make switch MS1 in the synthetic test circuit shown in Fig. 3, the values of L and C in this circuit were set to give a prospective current of 1.25 kA for the short fuse, and 4.5 kA for the long fuse. The make switch MS2 in this circuit is switched to crowbar the fuse in the test circuit at current zero in case the fuse malfunctions. The voltage across the fuse was measured with a Tektronix P6015, 20 kV, 1,000× attenuation high-voltage probe; the current with a 190.8 A/V shunt. A Nicolet Pro 42C digital oscilloscope [11] was used to record these signals, as well as a reference pulse to indicate the time at which the arc spectra were recorded.

The arc spectra were recorded with a Princeton Applied Research Model 1460 Optical Multichannel Analyzer (OMA), a spectroscopic system in which the spectrum is recorded by a linear photodiode detector array which is coupled to the exit plane of the monochromator by an image intensifier which can be gated "on" by a high-voltage pulse. An optical fiber, inserted in the fuse body to touch the fuse element, was used to transfer light from the arc to the OMA [12]. A 62.5 μm core diameter multimode silica fiber was used as this material should have negligible effect on the arc characteristics. The other end of the fiber was located at the centre of the 25 μm entrance slit of a Jarrell-Ash MonoSpec 27 Monochromator [13], which spectrally dispersed the arc radiation.

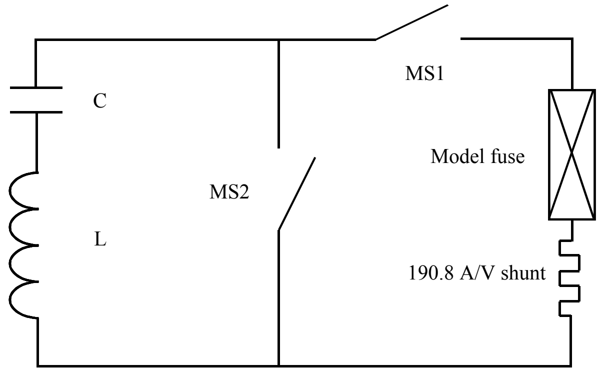

Fig. 3. Synthetic test circuit.

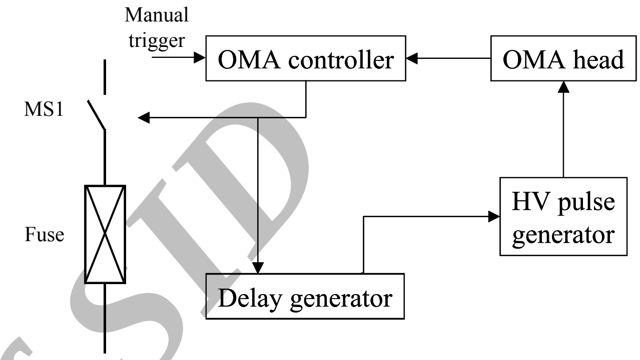

Fig. 4. Triggering circuit for time-resolved spectroscopy.

The OMA was run in the gated mode, synchronized to the triggering of the fuse test circuit. The experiment is initiated by a pulse provided by the OMA, which triggers the closing of the pneumatically operated make switch MS1 (Fig. 3). This pulse is delayed to trigger the high-voltage pulser which gates "on" the image intensifier for a few microseconds at an appropriate time during the arc. This procedure is necessary to synchronize the "read" cycle of the OMA with the operation of the test circuit. The timing circuitry for this experiment is shown in Fig 4. (The switch MS1 closes around 65 ms after activation, and there is a further delay of 1-6 ms before the arc is initiated, depending on the fuse used and the prospective current.)

IV. An Estimate of the Electron Density

The width of the spectral lines recorded in the course of the electron temperature measurements which we are reporting in another paper [10] is such that we should be able to estimate an upper limit to the contribution of Stark broadening to the line width. This should, in turn permit the estimation of an upper limit to the electron density in the plasma. Observation of the width of the individual spectral lines acquired at earlier times during the arcing of the long fuse, which were significantly broader than those observed for the short fuse, confirm that the line width is, at least in some cases, broader than the instrumental resolution of the monochromator used. The Doppler broadening corresponding to the electron temperatures we have measured from the relative intensity of Si II spectral lines [10] is < 0.01 nm, and will not contribute significantly to the line width. Thus a deconvolution of the instrumental width of the monochromator used from the measured line width should enable the contribution of Stark broadening to be determined and an estimate made of the electron density.

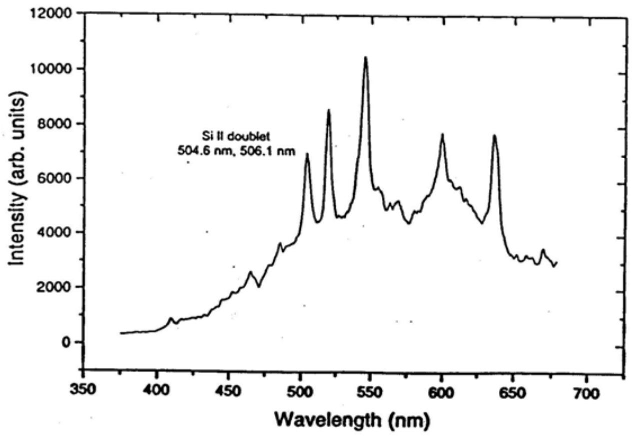

Fig. 5. Spectrum of the arc of a silica-sand-filled HBC fuse 1.2 ms after arc initiation.

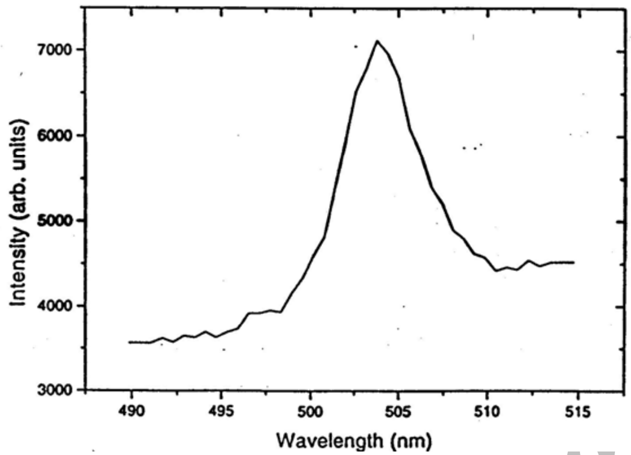

Fig. 6. Expanded view of the region of the spectrum shown in Fig. 5 around the Si II doublet at 504.6 and 506.1 nm.

Fig. 5 shows the arc spectrum recorded 1.2 ms after arc initiation for the long fuse, and Fig. 6 an expanded view of the region of the spectrum around the Si II doublet at 504.1 nm and 505.6 nm for which the line width measurements were made. (This doublet was chosen for the line width measurements as its components had the minimum separation of the Si II doublets in the spectrum shown in Fig. 5.) Note the intense continuum emission in Fig. 5, which is presumably due to thermal emission from the heated fulgurite surrounding the fuse arc. Calculating the contribution of the Stark broadening to the measured line width is complicated as we observe not a single line, but two Si lines separated by 1.5 nm which were not resolved. The following procedure was adopted to estimate the Stark broadening: the sum of the instrumental half width and the separation of the lines was subtracted from the measured width of the Si II doublet. The instrumental profile of the OMA was determined from the spectrum of a low-pressure Hg discharge lamp. This conservative approach is valid when deconvolving lines which exhibit a Lorentzian line profile [14], which is a good approximation for Stark broadening [7]. The noisy signals, the strong continuum emission and the broad effective instrumental profile for these measurements justify this simple approximation.

TABLE I
ESTIMATED ELECTRON DENSITY AT VARIOUS TIMES FOR THE LONG FUSE AT 4.5 KA PROSPECTIVE CURRENT

Arcing time (ms)	Half width (nm)	Corrected half width (nm)	Electron density×10^{18} cm^{-3}
0.83	6.7	2.8	2.0
0.99	5.7	1.8	1.3
1.20	5.0	1.1	0.7
1.44	5.3	1.4	0.9

V. RESULTS AND CONCLUSION

Electron densities estimated using the above procedure on our data for the long fuse at 4.5 kA prospective current are shown in Table I. These results demonstrate that, shortly after arc ignition the density is greater than 10^{18} cm^{-3}, and decreases during the arc to ~ 10^{18} cm^{-3}. The density was so low for the short fuse at 1.25 kA prospective current that it was possible only to show that the electron density was $\leq 10^{17}$ cm^{-3}.

These results confirm that it should be possible to make reliable measurements of the electron density of the arc in a silica-filled HBC fuse from the Stark broadening of Si II spectral lines provided a grating of higher resolution is installed in the monochromator for the line width measurements.

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In 1974 he spent a year at Culham Laboratory, where he gained expertise in laser diagnostics. On his return he played a leading role in the design and construction of TORTUS (Toroid of the University of Sydney), a medium-sized tokamak specifically designed for the study of plasma waves and the development of diagnostics which went into operation in 1981. Although he continued to contribute to the TORTUS program, in the 1980s he expanded his interests to the study of processing plasmas.

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In 1966 Dr. Falconer accepted a position as Lecturer in the School of Physics at the University of Sydney, where he worked on laser diagnostics of plasmas, using lasers operating at wavelengths from the ultraviolet to the submillimetre regions. He has extended his interests from laser diagnostics to plasma spectroscopy, and from fusion-related plasma to gaseous electronics. He retired in 1997, but continues his association with the University of Sydney's School of Physics as an Honorary Senior Lecturer.

During his tenure at the University of Sydney, Dr, Falconer has traveled overseas to continue his researches at the University of Hull (UK), the MIT Plasma Fusion Center, the JET Joint Undertaking at Culham (UK), and the Laboratoire de Spectrometrie Physique in Grenoble. He has also worked for a period of several months at the CSIRO's Division of Applied Physics in Sydney.

Dr. Falconer's research interests are based around the application of laser and spectroscopic techniques to the measurement of the characteristics of plasmas ranging from fusion plasma to the dielectric barrier discharges that form the pixels of plasma screen TVs.