A PULSED MULTIDIPOLE ION SOURCE

M.A. Hone

CERN, Geneva, Switzerland.

GENEVA
1979
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Summary</td>
<td>1</td>
</tr>
<tr>
<td>2. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>3. Design and Construction</td>
<td>3</td>
</tr>
<tr>
<td>4. Operating Principles and Results</td>
<td>8</td>
</tr>
<tr>
<td>5. MDS Magnet Fields</td>
<td>27</td>
</tr>
<tr>
<td>6. Langmuir Probe Measurements</td>
<td>38</td>
</tr>
<tr>
<td>6.1 Electron temperatures</td>
<td>46</td>
</tr>
<tr>
<td>7. Filaments and Cathodes</td>
<td>52</td>
</tr>
<tr>
<td>8. Extracted Beam Measurements</td>
<td>63</td>
</tr>
<tr>
<td>9. Beam Emittances and Profiles</td>
<td>77</td>
</tr>
<tr>
<td>10. Conclusion</td>
<td>85</td>
</tr>
</tbody>
</table>

Acknowledgements

References
A Pulsed Multidipole Ion Source

M.A. Hone

1. SUMMARY

With the aim of improving certain characteristics of the proton beam, at present produced by the CERN duoplasmatron, two prototype pulsed multidipole ion sources have been built. They are in effect miniature versions of the large d.c. ones being intensively developed as neutral beam injectors for some of the larger Tokamak and Mirror fusion devices now under construction in several countries.

Preliminary results are encouraging and it appears possible to produce a source of protons with much less noise on the beam pulse, simpler to operate and of our duoplasmatron dimensions. It remains now to be seen if the M.D. source will operate satisfactorily in our 500KV and 750KV preinjector columns and tests are currently under way. Deuteron and alpha particle tests are envisaged at a later date.

2. INTRODUCTION

Following on from the earlier work by R. Limpaecher, K.R. Mackenzie¹) and R.J. Taylor²) on the production of large volume quiescent uniform plasmas, high current multipole ion sources are being developed in several fusion research centres. Such sources are being increasingly favoured for use in intense neutral beam injectors due to their high gas and electrical efficiencies together with very low emittance and divergence properties, noise free beams and simple construction and operation.
The inherent characteristics of low noise together with low emittance and high intensity raises the interesting possibility of replacing the long-standing CERN Linac duoplasmatron\(^3\)\(^4\) with a pulsed scaled down multidipole ion source. Requests have been made to reduce, if possible, the noise (or 'grass') on the duoplasmatron proton beam by 'users' such as the 800MeV Booster Synchrotron. Unfortunately, adjusting the source for minimum noise produces in general an inferior beam and an alternative device would seem necessary. When it was learned that there can be virtually no noise on beams from multipole, quiescent plasma sources using full line cusps generated by powerful permanent magnets, it prompted us to investigate these devices further.

Following discussions with E. Thompson\(^\dagger\) on a visit to CERN, and a later visit to the U.K.A.E.A. Culham Laboratory, it was found that a small, single extraction aperture multidipole d.c. proton source built there\(^5\) could possibly be adapted to our needs.

The main question to be answered was could the source arc be turned on within our required 20 µs or so and, by pre-setting their d.c. power supply and switching it on rapidly, it appeared possible. Noise on the beam compared to the duoplasmatron was essentially zero. Extrapolating their measured beam values, positive ion current densities of \(\sim 265 \text{ mA.cm}^{-2}\) at the 12 mm diameter extraction hole could be obtained for values of arc current less than our duoplasmatron uses. Hydrogen flow was similar at \(\sim 5 \text{ std. cm}^3\text{ min.}^{-1}\). Thus, theoretically, a beam intensity of \(\sim 300\text{ mA}\) at \(\sim 5 \text{ std.cm}^3\text{ min.}^{-1}\) of hydrogen was possible which compares favourably with the duoplasmatron values of \(\sim 100\text{ mA.cm}^{-2}\) positive ion density at the 20 mm diameter expansion cup exit hole, giving \(\sim 340\text{ mA}\) beam current, at \(\sim 7 \text{ std.cm}^3\text{ min.}^{-1}\) of hydrogen.

Emittance values at that time had not been fully measured but were estimated at \(\sim \pi \times 0.25 \text{ mm mrad} \) normalized, for the full beam. (This has recently been confirmed at the SIN Laboratory\(^6\) who have purchased a similar source from Culham.)

\(^\dagger\) Present address: The JET Project, Culham, Nr. Abingdon, Oxon, England.
The ion beam was extracted using a single aperture, three electrode system \(^7\)\(^8\) but it was intended in our case to use the electrostatic field of our accelerating column directly for extraction, as is done with the duoplasmatron.

In order that tests with an MD source be done as quickly as possible at CERN, the possibility of purchasing a complete device from Culham was investigated. This was possible but since we also required a circular mounting flange small enough to allow mounting of the source in our new 750kV preinjector column, some redesign was necessary. (It should be mentioned here that the Thompson/Holmes source had a cubical copper arc chamber mounted on a square vacuum flange). It soon became clear that the design change would become a major one leading to a long delivery time, unless we accepted a version suitable only for mounting in the 500kV columns of the '3MeV' experimental area and old Linac preinjectors. These columns are equipped with larger diameter anodes and ion source mounting tubes than the 750kV one.

Fortunately, the MDS source is of a much simpler construction than a duoplasmatron and it was decided to try and build a cylindrical version (interchangeable with the source used in the 750kV preinjector) in the CERN workshops.

3. Design and Construction

For the first prototype, (hereafter referred to as MDS1), it was decided to use an air cooled, cylindrical, 12 continuous line cusp configuration, with a single oxide cathode (filament) directly heated by 50Hz current (Fig 1 & Fig. 2). For our relatively modest power dissipation, due to the \(^{10^{-6}}\) arc duty cycle (\(\sim 100\ \mu\)s pulse length at 1 Hz rep. rate) and about 150 watts continuous oxide cathode power, extensive water cooling channels are not obligatory in the source. Hence a simple construction, quickly fabricated, was possible. If a temperature limited bright emitter filament type cathode such as tungsten was used, dissipating \(\sim 1\ \text{kW}\), better cooling becomes necessary - mainly to avoid destroying the special permanent magnets around the arc chamber. Such a source, using water cooling was built and is described later.
Referring to Fig. 2 and Fig. 3 the arc chamber was made of 316L vacuum grade stainless steel machined to a wall thickness (at the magnets) of 1.3 mm. Four reinforcing ribs were added to reduce distortion by atmospheric pressure. The permanent magnets, made from a Cobalt-Samarium polymer, are arranged in 12 equally spaced rows running longitudinally and continued over the back plate down to the cathode orifice. Due to the thin wall, a magnetic field strength of ~1.5 kG is obtained at the inside surface. The magnet rows are held and separated by aluminium alloy wedges and are pressed into firm contact with the arc chamber by means of a system of split cones and a pressure plate at the rear. The assembly of chamber and magnets is contained in the one piece aluminium alloy source body, all vacuum seals being viton 'o'-rings. Fig. 4 shows the main parts before assembly. The front of the arc chamber is closed off with a stainless steel 'exit plate' comprising a central titanium 'exit cup' (similar in appearance to the duoplasmatron expansion cup but not functioning in the same way). This 'cup'/plate assembly is insulated
from the source arc chamber and body by means of an $\text{Al}_2\text{O}_3$ flat ring (Fig. 5).

The front exit plate assembly can be biased at a few hundred volts via a vacuum feedthrough and the cable seen in the photographs. The ion beam is extracted from the central hole in the titanium cup. Hydrogen gas (for protons) is fed into the arc chamber around the cathode supports as shown in Fig. 2. Externally the MDS has the same dimensions as the new linac duoplasmatron. Thus the same adaptors used for changing the source position relative to the accelerating column anode can be used. To remove the heat generated by the oxide cathode air is simply blown over the rear surface of the source. The magnets become hot in operation but it is estimated that the least cooled ones do not exceed 100°C (the maximum recommended for continuous use) since the rear ones reach $\sim 60°C$. The design could be improved in this respect but it was decided that any operational source would be water cooled with the capability
to run with a tungsten or tantalum filament. Once it was seen that
the MDS1 worked, a second water cooled version was designed and built
(Fig. 6), and designated MDS2. A third design, using a heat pipe cooled
copper arc chamber has been completed and constructed but not yet tested,
(Fig. 7). Since surface effects may be present the three models of
the MDS with their arc chambers made of stainless steel, aluminium alloy
and OFHC copper should prove useful for cross-checking results. The
water cooled MDS2 arc chamber, being a "cleaner" simpler design, makes the
assembly of the 36 magnets and pressure pads much easier to install in
the source body, there being no spacers for positioning the magnets. As
seen in Fig. 8, the chamber has twelve slots across the back and down the
sides for holding the magnets. Fig. 9 shows the chamber fitted with the
interconnecting water pipes and the cable for the front exit plate biasing.
The major components associated with the arc chamber are shown together
in Fig. 10. Finally, Figs. 11 and 12 show the air and water cooled
assembled sources together, front and rear views.

4. OPERATING PRINCIPLES AND RESULTS

The basic achievement of the multidipole ion source is that it
creates a large volume quiescent plasma of very uniform density. By
extracting from such a region a low noise, low divergence ion beam can
in principle be obtained. High arc efficiencies (that is, the ratio of
extracted beam to arc power) can be attained, (which is more important for
those people operating d.c. or long pulse, high duty cycle, high beam current
sources). In our case, our duty cycle of $10^{-4}$ together with our modest
requirement of $\sim350$ mA proton current, produces a low figure for arc
efficiency when compared to other values reported 9). Referring to
Fig. 2, hydrogen gas introduced into the arc chamber is ionised when an
arc is struck between the cathode and anode (chamber walls). As mentioned
earlier, if a sufficient number of magnetic cusps are present around the
anode wall, the primary electron containment time is greatly increased as
the electrons are reflected at the field between the cusps. Thus the sur-
face area seen by the electrons (and ions) is greatly reduced and to
further reduce the primary electron loss, the front extraction exit plate
FIG. 6  CROSS SECTION OF THE WATER-COOLED VERSION OF THE MULTIDIPOLE ION-SOURCE.
(FITTED WITH MINIATURE SCANNING LANGMUIR PROBE IN SPECIAL EXIT 'CUP'.)
FIG: 7
HEAT-PIPE COOLED
VERSION OF MDS 2
and 'cup' are either connected to the cathode or biased separately at or below the arc voltage level. The primary electrons arriving at the plate are repelled, adding to the total containment time and increasing the positive and negative plasma current density values ($J_{i+}$ and $J_{e-}$). The cathode is situated in the central magnetic field-free region and the ion beam is extracted also from the field-free central plasma volume. Since the plasma is very quiet and the positive ion density very constant over the area of the beam exit hole, in theory a low emittance, low divergence bright beam of protons should be possible, assuming the extraction system is correctly matched and the species yield of $H^+$ high. Calculations have been done\textsuperscript{9} showing that the arc or discharge current ($I_d$) can be written as

\[ I_d = n_i C_s \epsilon (S+F+\alpha A)/n_0 \sigma_i \lambda_p. \]

where:

\[ n_i = \text{ion density, (cm}^{-3}\text{)} \]

\[ C_s = \text{ion acoustic velocity} \ (C_s = (kT_e/m_i)^{\frac{1}{2}}) \]

* i.e. more negative than
S = approximate loss area for a single line-cusp
(S ≈ cusp length L times the ion gyroradius,
S ∝ L (m_i ν_i/eB))

F = surface area of the cathode supports

α = fraction of the exit plate (or grid) actually
illuminated by the plasma

A = total area of the plate or grid

n_o = neutral gas density (cm⁻³)

σ_i = total ionization cross-section for electrons in hydrogen

λ_p = primary electron mean free path.

A 1% ionization efficiency and a plasma density near the exit plate that is \( \sim e^{-1} \) of the bulk plasma density were assumed. They found that to obtain about \( 10^{12} \) cm⁻³ plasma density at the extraction region, a volume plasma density of about \( 2.7 \times 10^{12} \) cm⁻³ and a neutral density of \( 2.7 \times 10^{14} \) cm⁻³ (7.5 milliTorr) was needed. As shown in Fig. 13 in the results, we have measured a plasma density, at the extraction aperture, of about \( 0.45 \times 10^{12} \) cm⁻³ for a neutral density of \( 7.2 \times 10^{14} \) cm⁻³ (20 milliTorr). The electron plasma density was found to be about \( 0.165 \times 10^{12} \) cm⁻³. If we apply the \( e^{-1} \) criterion it means the volume plasma density (in the MDS2) was about \( 0.95 \times 10^{12} \) cm⁻³.

It should be pointed out that these values from our MDS2 source were obtained with the exit plate probably (in the light of later experience) insufficiently negatively biased. This was due to a defective arc voltage measuring probe which in turn caused the wrong voltage to be applied to the exit plate. Thus it was probably drawing electron current and the plasma density was depressed. Unfortunately, the exit plate was biased separately and not connected to the cathode (auto bias). This plus some of the assumptions made in ref. 9 not being fully applicable to our actual source geometry and volume, and the fact, as shown in Fig. 14, that we measure lower \( J_i^+ \) values when using an oxide cathode as opposed to a tungsten filament, could explain our lower plasma density values for a
higher neutral density. Also, the Langmuir probe used (described later) was biased so that it gave a 'pessimistic' value for $J^+$. Measurements made keeping the 'exit' at $-150V$ and correctly measured arc voltages of less than 100 V together with a value of $J^+_1$ obtained from a fully saturated Langmuir probe, gave values of $\sim 1.5 \times 10^{12} \text{cm}^{-3}$ for $n_1$, with $n_0 = 1.08 \times 10^{15} \text{cm}^{-3}$, (30 milliTorr of $H_2$). These two different results are shown together in Fig. 13. Also shown are the higher values obtained of $n_1$ and hence $J^+_1$ when a tungsten temperature limited filament is used (in MDS2), all other conditions being equal, the $J^+_1$ increases by about 1.5 times. Fig 14 shows the results obtained with the Langmuir probe in MDS2 as shown in Fig. 6. The results of a brief set of measurements done with Helium (prompted by the current interest in alpha particle beams), are shown also in both Figs. 13 and 14. Since the later results were obtained with an 'optimistic' setting on the Langmuir probe, true values are probably somewhat less. Some of the problems found in interpreting the probe signals are discussed later. The importance of maintaining the front exit plate more negative than the cathode during the arc is shown in Fig. 15, which shows the saturating of plasma current density ($J^+_1$) when the exit plate voltage is near to the arc voltage. Unless otherwise stated, all other results quoted have been obtained with the plate biased at $-150V$. The exit plate floating potential, $V_F$, is indicated also in Fig. 15. At this point the plate draws zero current and the value of $V_F$ varies from about $-32V$ at 40A arc current to $-34V$ at 120A I (arc). This is best seen in Fig. 16 which shows the front plate characteristics. The variation in $J^+_1$ with exit bias for a tungsten filament is shown in Fig. 17, however, the values of $J^+_1$ are too low due to the Langmuir probe not measuring the full positive ion saturation current. The useful gain in $J^+_1$ (and hence any extracted beam in theory) obtained by biasing the front exit plate separately at $\sim -150V$ instead of connecting it to the cathode (or filament) is shown in Fig. 18. Also the arc voltage, and hence impedance, is more stable and constant, over the 100 $\mu$s pulse length used in all these measurements, when the exit plate is biased separately. The fact that the plate draws quite a heavy
FIG 13  POSITIVE ION DENSITY VALUES IN MDS2 AGAINST ARC CURRENT

- TUNGSTEN FIL. WITH HYDROGEN
- TUNGSTEN FIL. WITH HELIUM
- OXIDE FIL. WITH HYDROGEN

EXIT PLATE AT -150v
H₂: 10, He FLOW: 14 cc · min⁻¹
L/PROBE AT -250v
L/P AREA: 0.47 mm²

EXIT PLATE AT -100v
L/PROBE AT -100v
(other data as above)
FIG 14  PLASMA POSITIVE ION CURRENT DENSITY AGAINST ARC CURRENT FOR THE OXIDE FILAMENT AND A TUNGSTEN FILAMENT IN MDS2 FOR HYDROGEN AND HELIUM

TUNGSTEN FIL. WITH H₂

V(ARC) = 50v

V(ARC) = 65v

V(ARC) = 100v

TUNGSTEN FIL. WITH He (V(ARC) = 100v)

OXIDE FILAMENT WITH H₂
(V(ARC) = 45v)

EXIT (AND CUP) AT -150V
H₂:10cc, He FLOW = 14 cc.min⁻¹
L/PROBE AT -250V

NOTE: AVERAGE RATIO OF TUNGSTEN J⁺ TO OXIDE J⁺ = 146% (FOR H₂)
FIG 15  VARIATION OF POSITIVE ION CURRENT PLASMA DENSITY WITH EXIT PLATE BIAS, AT DIFFERENT ARC CURRENTS IN MDS 2, USING AN OXIDE CATHODE

$J_i^*(\text{mA} \cdot \text{cm}^{-2})$ 300

$V_f$

$H_2 = 10 \text{ cc} \cdot \text{min}^{-1}$

L/PROBE BIASED AT -250V and 6 mm ABOVE AXIS

EXIT PLATE VOLTAGE
H₂ = 10. cc.min⁻¹
OXIDE CATHODE

ARC VOLTAGES AT MINIMUM
VALUES FOR STABILITY AND NOISE

I(arc)  V(arc)
- 120A (50V)
- 100A (49V)
- 80A (50V)
- 60A (50V)
- 40A (50V)

Vf = -32V at 40A
to -34V at 120A

FIG16 CURRENT COLLECTED (ions or electrons) ON MDS2 FRONT EXIT PLATE
(FOR DIFFERENT ARC CURRENTS) AS A FUNCTION OF EXIT BIAS
FIG 17 VARIATION OF POSITIVE ION CURRENT PLASMA DENSITY WITH EXIT PLATE BIAS AT DIFFERENT ARC CURRENTS (IN MDS2, WITH A TUNGSTEN FILAMENT)

$H_2 = 10 \text{ cc.min}^{-1}$ L/PROBE AT-100V AND AT 6 mm ABOVE AXIS
NB: SIGNAL NOT SATURATED FOR $I_+^+$

$J_+^+(\text{mA.cm}^{-2})$

- 120A $(I_{(arc)} - (V_{(arc)} = 50V)$
- 100A $(V_{(arc)} = 50V)$
- 80A $(V_{(arc)} = 38V)$
- 60A $(V_{(arc)} = 100V)$

AVERAGE VARIATION IN $J_+^+ \pm 6 \text{ mA.cm}^{-2}$

EXIT PLATE VOLTAGE
FIG 18  EFFECT ON $J_i^c$ OF CONNECTING MDS 2 FRONT EXIT PLATE TO THE SOURCE OXIDE CATHODE

$H_2 = 10 \text{ cc.min}^{-1}$  L/PROBE AT -250 V

EXIT BIASED AT -150V

FRONT EXIT PLATE CONNECTED TO CATHODE (AUTO BIAS)

ARC VOLTAGES IN BRACKETS

$J_i^c$ (mA.cm$^{-2}$) vs. $l$ (arc)$\AA$
current of positive ions when at -150V tends to damp down any oscillations on the arc originating in the power supply. Fig. 19 shows the effect on the arc voltages if the exit plate is allowed to draw negative (electron) current. At zero or anode potential the effect on $J^+$ is severe as would be expected since the electron containment time is now not only governed by the magnetic cusps and the exit plate receives a large fraction of the primary electron drift current to the anode. Thus the arc impedance increases and $J^+$ falls as seen in Figs. 15 and 17.

Fig. 20a shows how the exit plate floating potential increases under high arc voltage conditions. This can arise only with the oxide cathode it seems, if its emissivity falls, usually due to contamination. (Fig. 20b is the low arc voltage condition). Although a higher $J^+$ may be obtained, since the ionisation power of electrons in hydrogen peaks at $\sim 80eV$, (Fig.21), the plasma noise increases enormously and presumably damage, from ionic bombardment, of the oxide cathode would increase. Thanks to our low duty cycle this probably would not be serious, but the noise on the plasma and hence on the ion beam would not be acceptable. The variation of $J^+$ with arc power was calculated and is shown in Fig. 22 for hydrogen and an oxide cathode, and in Fig. 23 for a tungsten filament in helium.

The arc efficiency, defined as the ratio of extracted beam to arc power has been plotted, (Fig. 24), as a function of arc current, for two different situations. The theoretical beam current, calculated from integrating the $J^+$ values, in the exit 'cup', over the beam exit aperture, was used. The source is notably less efficient with He, but that measurement has not yet been repeated nor done with the oxide cathode.

With the oxide cathode current fixed, the arc efficiency drops as the arc voltage is increased (Fig.25). This agrees with the results of Stirling and Ryan et al 9) and also with Leung10). The plasma density did not noticeably saturate at about 80 to 90V arc voltage "due to the fall in ionizing electron power with energy above 70eV (Fig. 21), plus the loss of ions to the cathode and its supports with increasing arc voltage", as reported in refs. 9 and 10, but not many different arc voltages were obtained for a given arc current in the course of the measurements.
FIG 19 CURRENT (+ve IONS OR ELECTRONS) COLLECTED ON MDS 2 FRONT EXIT PLATE (AT DIFFERENT EXIT BIAS VOLTAGES) AS A FUNCTION OF THE ARC CURRENT. (arc voltages shown in brackets)

H₂ FLOW = 10 cc.min⁻¹
OXIDE CATHODE

(50v) (50v) (50v) (49v) (50v) -200v EXIT BIAS
(60v) (57v) (50v) (50v) -50v
(80v) (106v) (80v) (80v) -32 -34v (Vₑ)
(95v) - ZERO

I(arc)A ————>
FIG 20A CURRENT COLLECTED (+Ve IONS OR ELECTRONS) ON MDS2 FRONT EXIT PLATE AT A CONSTANT ARC CURRENT, AND VARIATION OF ARC VOLTAGE AND ARC IMPEDANCE WITH EXIT BIAS.

HIGH ARC VOLTAGE CONDITIONS

I(arc) = 100 A (at 80 us from trigger)

I(fil) = 62 A r.m.s. ≅ 285 W (OXIDE FIL)

H₂ = 10 cc. min⁻¹

| V(arc) - Vₑ | = 50 V

EXIT PLATE BIAS VOLTAGE
LOW ARC VOLTAGE CONDITIONS

\[ I_{\text{arc}} = 100 \text{ A} \]

\[ I_{\text{fil}} = 54 \text{ A} \text{ r.m.s} \quad 205 \text{ W (OXIDE FIL)} \]

\[ H_2 = 10 \text{ cc} \cdot \text{min}^{-1} \]

**FIG 20b** CURRENT COLLECTED (+ve ions or electrons) ON MDS 2 FRONT EXIT PLATE AT CONSTANT ARC CURRENT AND VARIATION OF ARC VOLTAGE AND ARC IMPEDANCE WITH EXIT BIAS
FIG 21  IONISING POWER OF ELECTRONS AS A FUNCTION OF THEIR KINETIC ENERGY (SINGLY AND MULTIPLY CHARGED IONS TAKEN TOGETHER)

\[ \text{Energy (electron-volts) vs. } \alpha \text{ ions per centimetre} \]

\[ \text{\(2^\circ \text{C}, \rho \cdot 1 \text{mm Hg}\)} \]
The electrical schematic of the source during these measurements is shown in Fig. 26. A pulse forming network (delay line), charged between pulses, discharges into the arc chamber and the required discharge time (∼100 μs) is set by the value of the delay line length used (P.F.N.).

The line has a characteristic impedance of 10 Ω and, since the arc impedance is about 1 to 2 Ω, the arc current remains constant during the pulse. To ensure reliable firing of the arc, the line is charged to ∼1 or 2 kV, depending on the arc current desired, by means of the charging unit.

Thus a spike of about this value appears on the leading edge of the discharge voltage, then the arc voltage rapidly falls and stabilizes at the discharge value, determined by the filament/gas conditions prevailing. This circuit is virtually identical to that used with the duo-plasmatron except that the latter now has a thyristor arc 'tail-clipper' to provide variable arc pulse lengths easily and on demand. In Fig. 26, some typical arc and beam waveforms are shown.

5. MDS MAGNETIC FIELDS

Before discussing the Langmuir probe measurements of J⊥ and electron temperature (T_e) some details of the MDS magnet field will now be given. The values of the field in certain parts of the arc chamber must be known if the correct interpretation of the Langmuir probe results is to be done. As mentioned earlier, the longitudinal and rear radial cusp lines are created by rows of permanent magnets.
FIG 22  PLASMA POSITIVE ION CURRENT DENSITY AGAINST ARC POWER FOR
THE OXIDE FILAMENT IN MDS 2 WITH HYDROGEN

EXIT PLATE (AND CUP) AT -150v
ARC VOLTAGE CONSTANT AT 45v
H₂ = 10 cc. min⁻¹
L/P AT -250v

FIG 23  PLASMA POSITIVE ION CURRENT DENSITY AGAINST ARC POWER FOR
A TUNGSTEN FILAMENT IN MDS 2 WITH HELIUM

EXIT PLATE AND CUP
AT -150v (L/PROBE: -250v)
ARC VOLTAGE CONSTANT AT -100v
He = 14 cc. min⁻¹
FIG 24 VARIATION IN ARC EFFICIENCY WITH ARC CURRENT AT CONSTANT ARC VOLTAGE, FOR HYDROGEN AND HELIUM IN MDS 2

\[ H_2 \ (10 \text{cc.min}^{-1}) \ V(\text{arc}) = 45 - 47 \text{v} \]

OXIDE CATHODE

\[ \text{He} \ (14 \text{cc.min}^{-1}) \]

TUNGSTEN FILAMENT

\[ V(\text{arc}) = 100 \text{v} \]

\[ \mathcal{E}(A/\text{kw}) \]

\[ I(\text{arc}) \ A \]
Fig 25: Drop in arc efficiency with increased arc voltage in MDS2

\[ \varepsilon(A/kV) \]

\[ I(\text{arc}) = 40A \]

\[ 60A \]

\[ 0 - 10 - 20 - 30 - 40 - 50 - 60 - 70 - 80 - 90 - 100V \]

\[ \text{ARC VOLTAGE} \]
FIG 27(a) CROSS-SECTION OF MDS 2 ARC CHAMBER SHOWING RADIAL MAGNETIC FIELD VALUES (PEAK) ON CUSPS AXIS
North and south poles alternate around the chamber circumference and Fig. 27(a) shows the effect produced, in cross section. Fig. 27(b) confirms the cusp lines by using iron filings in a simulated chamber/magnet arrangement. The cathode (or filament) sits in a region with negligible magnet field and the normal double sheath criteria may be applied to it\textsuperscript{11). The self-generated field of the oxide cathode was measured at $\sim 0.03 G$ at 4cm distance, for $\sim 58A$ r.m.s. cathode current, and was $\sim 2G$ at 5 mm. Fig. 26 shows the result of a Hall probe field measurement across the diameter of the chamber, at the cathode position, and on the cusp’s axis.
FIG 28  MAGNETIC FIELD ACROSS MDS 2 ARC CHAMBER AT FILAMENT (CATHODE)
A central region of \( \sim 45 \) mm diameter lies in a field of \( < 10G \) and the actual field at the oxide cathode surface is \( \sim 2 \) to \( 3 G \) at the tip area. Fig. 29 confirms the same rapid fall off in field at the rear of the arc chamber and, importantly, the virtual zero field at the beam exit aperture and Langmuir probe. In fact the exit 'cup' lies completely in a field free region as intended. Thus the theory\(^{12}\) for an electric probe in a non-magnetised plasma volume may be used. In view of the results so far obtained, it would not appear necessary to modify the fringe fields at the front end of the arc chamber wall, where
6mm to ends of magnet rows

Magnet rows end abruptly. The polymer type magnets were chosen with this in mind since they are easily machined without deterioration. In the rectangular source at Culham 5), where the magnet rows run across the chamber at right angles to the beam axis, such a modification was reportedly done. In our design, the distance between the effective ends of the magnet rows and the inner

Fig. 30 Relative positions of Langmuir probe exit cup, filament shield, and oxide filament
surface of the exit plate was kept to a practical minimum. Thus, since the plate (due to its bias) repels electrons, the surface area of the anode unprotected by a strong cusp field (and hence a 'loss area' for particles) is relatively small. The dimensions of this area are shown in Fig. 30.

The 'cup' housing the Langmuir probe is deeper than the actual 'cup' used in the source during accelerating column tests for practical reasons, involving the accommodation of the linear motion feedthrough supporting the probe (Fig. 6). It is assumed that axial and radial values of plasma current density as measured in the deeper cup will not be worse in the 'normal' one (and probably will be better).

A typical curve of the variation in $J_1^T$ across the cup is shown superimposed on a linear plot of the radial magnetic field in Fig. 31. Across the central 10 mm diameter beam exit hole the variation in $J_1^T$ is only a few percent. The variation is given in more detail later. Fig. 32 shows the "normal" cup (type 2) dimensions and gives details of the floating titanium shield which was in place for all the measurements. Since, in the past, there has been evidence of bombardment of the duoplasmatron anode and/or expansion cup by backstreaming electrons in the pre-injector column, it was decided to operate and investigate the MDS prototypes with a cathode protecting shield. Otherwise, judging from the extent of previous damage to the duoplasmatron, the oxide cathode would be rapidly destroyed. It should be pointed out that such a column condition is abnormal and is normally not allowed. In an early test of the MDS1 source in the 500 kV "3MeV" column without such a shield, voltage holding of the column was poor, indicating, perhaps, the presence of a weak electron backstreaming axial "beam" which then liberated material from the cathode. Since the cathode is well inside the arc chamber it is hard to imagine the column extracting field playing any direct part. Subsequent runs with the TA6V shield (same material as used for the column anode and the MDS exit cup), were achieved with good voltage holding, both in the 500 kV and 750 kV preinjectors. The shield apparently does not noticeably interfere with the MDS arc properties.
FIG 31 Magnetic field across arc chamber and plasma density at \( I_{\text{arc}} = 80 \text{A} \) across 'deep' Langmuir 'cup'.

6. LANGMUIR PROBE MEASUREMENTS

For all the plasma density and temperature measurements a miniature Langmuir probe \(^{12},^{13}\) was used, (Fig. 33). Only the main area of interest i.e. in the 'exit cup', was explored so that a practical working ion source suitable for the preinjector could be designed as quickly as possible. Thus the probe scanned across the whole of the
Fig. 32 Relative positions of type 2 'cup' shield and oxide filament
cup on a diameter. Unless otherwise stated, the previously described results of the plasma properties were made at the 10 mm diameter exit hole, either on the axis or at the hole edge. Fig. 34 shows the theoretical current characteristic when such a probe is immersed in a field-free plasma and biased positive and negatively. When negative it collects the saturated positive ion current which is then used, knowing the area of the probe tip, to calculate the plasma positive ion current density \( J^+ \). The point \( V_f \) is the floating potential where the probe receives equal currents of ions and electrons and the net resulting probe current is zero. The plasma potential \( V_{p2} \) is obtained at the intersection of the \( I_e \) slope and the saturated electron current slope at \( I_{es} \). The slope at \( I_e \) gives the electron temperature (as shown later). Therefore, in order to measure the variation in \( J^+ \) across the MDS exit cup, the probe was biased well into the ion saturation region and the current obtained recorded during the scan across the cup.
FIG 34 THE IDEAL LANGMUIR PROBE CHARACTERISTIC

FIG 35 SCHEMATIC OF TYPICAL PROBE-CURRENT VOLTAGE CHARACTERISTIC.

FIG 36 THEORETICAL SHAPE OF THE SATURATION CURRENT PORTION OF THE PROBE CHARACTERISTIC FOR VARIOUS PROBE SHAPES WHEN THE PROBE CURRENT IS LIMITED BY ORBITAL MOTIONS.
In practice the probe characteristic is more like that in Fig. 35 where the curve does not flatten off in the saturation regions due to sheath effects. The (Fig. 33) probe showed the effect in Fig. 36 of behaving like a cylinder rather than a plane, due to the significant thickness of the positive ion sheath around the tip compared to the probe radius. From the Child Langmuir law for space-charge limited current the thickness of such a sheath \( d \) cm is given by

\[
d = (5.45 \times 10^{-5} \cdot V_s^{3/2} / J_i^+)^{1/4}
\]

where \( V_s \) = probe bias potential with respect to the arc chamber containing the plasma (in volts).

and \( J_i^+ \) = saturated ion current density (mA.cm\(^{-2}\))

Thus for a \( V_s \) of -250 V and \( J_i^+ \) of \( \sim 500 \) mA.cm\(^{-2}\), \( d = 1.65 \times 10^{-2} \) or 0.165 mm. This is significant compared to the probe diameter of 0.6 mm. If we take lower values such as a \( V_s \) of -100 V and \( J_i^+ \) of 250 mA.cm\(^{-2}\),

\[
d = 0.145 \text{ mm} \quad \text{i.e. still significant.}
\]

Such a sheath increases considerably the effective gathering area of the probe and can lead to too large a value of \( J_i^+ \) when using the saturation current method. It is probably better to estimate \( J_i^+ \) from actual ion beam current measurements, working backwards. A larger probe would of course lower the error due to a sheath but would then influence the plasma over a larger volume than the present case. However, to measure the electron temperature the Langmuir characteristic is valid and the results are given later. With an ion saturation slope as in Fig. 35, the value of \( I_{is} \) can also be in error significantly. Thus without doing further investigations the values of \( n_i \) (Fig. 13) should be taken as approximate. They appear to agree with other results however and are useful (due to the stability and low noise of the plasma) for comparing different source conditions.
The Fig. 13 values were obtained from the relationship\(^{12),13} \)
\[
\eta_i (\text{cm}^{-1}) = \frac{10^{12} \times I_{is} (\text{mA})}{S (\text{mm}^2) \times T_e ^{1/2} (\text{eV})}
\]

where \(S = \) the probe area

For protons in the hydrogen plasma the mean free path, \(\lambda_i\) is given by:

\[
\lambda_i = 14.2 \times 10^{-3}/P (\text{Torr}) \quad (\text{cm})
\]

this gives \(\lambda_i = 4.7 \text{ mm at } 30 \times 10^{-3} \text{Torr ( } \equiv 10 \text{ cc.min}^{-1} \text{ of } \text{H}_2\)

which is equal to only eight times the probe diameter. However, there is apparently little probe shadowing effect\(^{12}\), as the distribution of the electron energies as calculated from the Langmuir curve slopes was found to be Maxwellian\(^{12),14}\). The electron mean free path at 30 milliTorr = 20.4 mm which is comparable to the distance between cusps at the arc chamber wall. The source would be more efficient with a lower neutral gas density and hence a longer electron-mean-free path so that the primary electrons can make many bounces off the chamber walls.\(^9\) As shown later, the \(J_i^+\) value increases with lower hydrogen flow and pressure but eventually plasma noise becomes significant. A compromise between required proton beam, optimum extraction hole (to match the column anode field) and noise will need to be found for preinjector operation. The species yield of \(\text{H}^+\&\text{H}_2^+\text{ etc.}, which has not yet been measured will also influence the final source design. To obtain high proton yield it may be necessary to create a more intense arc discharge with a related rise in the neutral gas density required. It is hoped that the prediction of > 90% proton yield mentioned by Stirling and Leung et al\(^9\) will eventually prove possible.

Before looking at the electron temperature results the \(J_i^+\) scans across the MDS2 deep cup are shown in Fig. 37. Even at high arc currents the \(J_i^+\) variation across the beam exit hole is low. It is interesting to note that the plasma current density falls off steeply only right at the cup wall which is biased at -100 V in this case. Fig. 38 shows the effect
Fig. 37 Plasma +VE ion current $I_s$ and current density ($J_i^+$) variation across 'cup' with $I_{(arc)}$

$I_s$ (mA) MDS 2 fitted with special Langmuir probe exit 'cup' ($\theta 10$ mm exit hole) and TA6V shield between oxide filament (cathode), probe and exit hole. Source conditions: $I_{(fil)} = 32.5$ A (Metrix) ($\pm 133$ W) Hy flow $= 8.2$ cc min$^{-1}$ Probe at $-200$ V Exit 'cup' at $-100$ V Rep. rate $= 0.83$ Hz Arc chamber pressure $= 20 \times 10^{-3}$ torr

$J_i^+$ (mA cm$^{-2}$) Probe active area $\geq 1.2$ mm$^2$

Source axis

$I_{(arc)}$ at $140$ A \  $120$ A \  $100$ A \  $80$ A \  $60$ A

1.2 sec sample and hold readout time between $\sim 100 \mu$s arc pulses

Note 1: $I_{(arc)}$ synchronised with 50 Hz $I_{(fil)}$ current

2: 3 scans at each $I_{(arc)}$ scan time $= 62$ sec

Cup radius in mm

(1.D = 60 mm)
Fig. 38 Effect of synchronising $I_{(arc)}$ with the 50Hz filament current

Source conditions: $I_{(arc)} \approx 120 \text{ A}$, pulse length $\approx 100 \mu\text{s}$
$V_{(arc)} \approx 160 \text{ V}$, repetition rate $\approx 1 \text{ Hz}$
$I_{(fil)} \approx 32.5 \text{ A (Metrix)} (\approx 133 \text{ W})$

Hy flow = 8.2 std. cc. min$^{-1}$
Probe at $-200 \text{ V}$
Source exit 'cup' at $-100 \text{ V}$
Arc chamber pressure $\approx 20 \times 10^{-3} \text{ torr}$

$I_S = (400 \mu\text{A/div}) = \text{Langmuir probe + VE ion current}$
or $J^+ = (100 \text{mA.cm}^{-2}/3\text{div})$

3 scans with $I_{(arc)}$ synch. with $I_{(fil)}$

$\sim 1 \text{ sec. sample and hold}$
readout time between arc pulses

3 scans with $I_{(arc)}$ unsyn. with $I_{(fil)}$

position of 10 mm diameter beam exit hole

MDS 2 with $\phi 10 \text{mm}$ beam exit hole in special Langmuir probe 'cup', and TA6V titanium shield plate between filament, probe and exit hole

'cup' radius in mm

51.5 mm scan (scanning speed = 0.83 mm sec$^{-1}$ = 62 sec/scan)
of synchronising the arc pulse with the 50 Hz mains on the cathode. A significant reduction in the pulse to pulse probe current variations is seen. This is because the arc power supply is connected to one side of the cathode and if the two are not synchronised, the cathode voltage can add or subtract to the arc voltage depending when the arc pulse occurs in the 50Hz cycle. This slightly varying arc voltage shows up as a variation in probe current (or $J^+$). All the measurements reported here were done with the arc fired at constant mains phase. Such an arrangement cannot however be used in the New Linac preinjector due to the nature of the Linac/PS/SPS timing system. However, it was found later that the unsynchronised state did not appear as a noticeable variation in the proton beam obtained during some tests with the MDS1 source. The same is found to be true with the duoplasmatron in the Linac. Finally, the variation of $J^+$ with hydrogen flow is shown in Fig. 39.

6.1 **Electron temperatures**

To measure the temperature of the electrons in the MDS2 exit cup, a large number of Langmuir probe characteristics were obtained using the miniature probe in Fig. 33. Typical examples are shown in Fig. 40 and Fig. 41. The circuit used for reading out the Langmuir probe signal is shown in Fig. 42, the probe being connected across a 100 Ω 1% resistor and the resulting signal read by the sample and hold, at every arc pulse, as used in ref. 13). From the theory of the Langmuir characteristic, in the electron collecting region,

$$\ln I_e = \ln I_{es} + \frac{e}{kT_e} (V_p - V_p^0)$$

where $I_{es}$ is the electron saturation value and $V_p^0$ is the plasma potential, $V_p$ being the bias voltage applied to the probe, and $I_e$ the probe current.

Thus the plot of $\ln I_e$ against $V_p$ should start as a straight line of slope $\frac{e}{kT_e}$, and change sharply to the horizontal at $V_p = V_p^0$. (The fact that the early part of the graph is straight shows that the electron energy distribution is Maxwellian.13,14)
FIG 39 VARIATION OF POSITIVE LANGMUIR PROBE CURRENT \( \propto J^+ \) WITH HYDROGEN FLOW IN MDS 2 (OXIDE CATHODE)

1 arc = 60 A
EXIT APERTURE = \( \phi \) 10 mm

INCREASING INSTABILITY and/or PLASMA NOISE

APPROXIMATE RANGE FOR MINIMUM NOISE ON \( I_p \)
$H_2 = 10 \text{ cc. min}^{-1}$
EXIT AT -150v
PROBE ACTIVE AREA = 0.47 mm$^2$

**FIG 40**  LANGMUIR PROBE CHARACTERISTICS FOR DIFFERENT ARC CURRENTS IN MDS 2 WITH AN OXIDE FILAMENT
\[
Te = \frac{0.43}{d \frac{d}{dVp} \log i_e}
\]

~\(0.1\) mA peak (max pulse topulse variation)

Vf \(\sim 18\) V

\(I_e(mA)\) electron current

\(I(I) = 60\) A

V(\(arc\)) = 143.5 V

\(H_2 = 8\) std.cc.min\(^{-1}\)

\(I(f) = 476\) A / 50 Hz \(= 137\) W

EXIT PLATE AT \(-100\) V

FIG 41 TYPICAL LANGMUIR PROBE SIGNAL IN MDS 2
A typical example of such a plot is shown in Fig. 43, with the derived data. The slope does not become sharply horizontal due to the sheath effects mentioned earlier. That is, when the probe is positive with respect to the plasma, the thickness of the double layer increases with increasing potential difference between probe and plasma. Thus the effective measuring area of the probe increases with $V_p$.

By using the formulae mentioned for $n_i$ and the values of $T_e$ obtained from the curves the plasma density was calculated for $n_i$ and $n_e$, $n_e$ being given by

$$n_e = \frac{I_{es} \times 4 \times 10^{10}}{S \times T_e^2} \text{ (cm}^{-3}\text{)}$$

where $I_{es}$ is in (mA), $S$ in (mm$^2$), and $T_e$ in (eV).
neutral gas density \( = 7.2 \times 10^{14} \text{ cm}^{-3} \)

\[ I_{es} = 1 \text{ mA} \]

\[ S \text{(probe area)} = 1 \text{ mm}^2 \]

\[ \frac{I_{is}}{S} = 1 \text{ mA} \]

\[ n_i = \frac{I_{is} \times 10^{12}}{S \times T_e} \]

\[ n_i \approx 4.2 \times 10^{11} \text{ cm}^{-3} \]

\[ I \text{(arc)} = 60 \text{ A} \quad \text{EXIT AT} \cdot 100 \text{ v} \]

\[ V \text{(arc)} = 139-8 \text{ v (arc power} \geq 8.4 \text{ kW)} \]

\[ H_2 = 8 \text{ cc} \cdot \text{min}^{-1} \quad (P = 20 \times 10^{-3} \text{ Torr}) \]

\[ I \text{(fil)} = 46.5 \text{A}_\text{rms} = 145 \text{ W} \]

\[ T \text{(fil)} = 850 \text{ °C (OXIDE FILAMENT)} \]

\[ n_e = \frac{I_{es} \times 4 \times 10^{10}}{S \times T_e} \cdot \] 

\[ n_e = 1.7 \times 10^{11} \text{ cm}^{-3} \]

\[ \text{SLOPE} = \frac{e}{kT_e} \cdot \therefore T_e = 58 \text{ eV} \]

\[ V_{pl} \text{ (plasma potential)} = 1.5 \text{ v} \]

\[ V_f = -18 \text{ v} \]

**Fig 43** EXAMPLE OF LANGMUIR PROBE CHARACTERISTIC IN MDS 2 (AND DERIVED DATA)
The variation of electron temperature with arc current is shown in Fig. 44 for different filaments in hydrogen and helium.

These values are about half those found in the expansion cup of the duoplasmatron\(^{13}\). The oxide cathode always gave a more varying value of \(T_e\) with \(I_{\text{arc}}\) compared to the tungsten filament results. This was also often found in the values of \(J_i^+\) with arc current. In general, the results are much easier to reproduce with a tungsten filament but, as discussed later, there are serious problems to be overcome before such a filament could be operational in the MDS source. Fig. 45 is included to show the effect, mainly at higher arc currents, on the electron temperature when the exit plate/cup was not sufficiently negatively biased, using an oxide cathode. The increase in \(T_e\) (to about duoplasmatron values) was, as might be expected accompanied with an increase in noise on the probe signal. The actual signal from the probe, at 100A arc, is seen in Fig. 46 and should be compared with Fig. 47 which shows a 'normal' probe signal. Fig. 46 is very similar in noise level to a probe signal from the duoplasmatron expansion cup. Fig. 48 is the probe signal with a tungsten filament in \(\text{H}_2\) (= 10 cc.min\(^{-1}\)) at 40A arc. Fig. 49 shows the same but with a tantalum filament (described later). Fig. 50 shows a resulting Langmuir probe signal with the tungsten filament in helium gas at 14cc.min\(^{-1}\). The plasma noise levels with the temperature limited 'bright emitter' filaments are clearly very low and less than that with the oxide cathode, (except perhaps the tantalum one). Fig. 49 (tantalum filament in \(\text{H}_2\)) was taken at a lower arc density than Figs. 48 and 50. The filament L-probe signals are also more constant during the pulse, which is also seen on the arc voltage. Finally, Fig. 51 gives the variation of \(T_e\) with \(\text{H}_2\) flow in MDS2 using an oxide cathode. The MDS2 source fitted with the Langmuir probe is shown in Fig. 52 and Fig. 53.

7. FILAMENTS AND CATHODES

The form and relative positions of the tungsten and tantalum filaments used are shown in Fig 54 and Fig. 55. Fig. 30 showed the oxide cathode position. In contrast to the oxide cathode, the tungsten filament required about 1.1 kW and the longest lifetime recorded was 67 hours of continuous running in MDS2.
FIG 44  ELECTRON TEMPERATURE VARIATION WITH ARC CURRENT IN MDS2 FOR OXIDE AND TUNGSTEN FILAMENTS IN HYDROGEN AND HELIUM

(MEASURED AT EDGE OF Ø 10mm EXIT HOLE)

EXIT AT 150v  H₂ = 10 cc
and  He FLOW = 14 cc.min⁻¹
FIG 45  ELECTRON TEMPERATURE AGAINST ARC CURRENT IN MDS2

H₂ FLOW: 8 STD. CC.MIN⁻¹
I (FIL): 45A (≈ 148W)rms
-200 V ON PROBE
-100 V ON EXIT 'CUP'

Tₑ MEASURED ON AXIS, AT ø 10 EXIT HOLE
FIG 46 - CURRENT SIGNAL $I_s$ FROM LANGMUIR PROBE

(lower trace = sample and hold gate)

$I_s = 1.2$ mA/div, $T/B = 20$ $\mu$s/div (scope in chopped mode.)

$I(\text{arc}) = 100$ A, $V(\text{arc}) = 151$ V

$I(\text{fil}) = 35$ A rms \hspace{1cm} $H_2 = 8.1$ $\text{cm}^3\cdot\text{min}^{-1}$

Exit = $-100$ V. MDS 2, oxide cathode.

High noise conditions

FIG 47 - L/ PROBE SIGNAL WITH EXIT AT $-150$ V

oxide cathode, low noise conditions.
FIG 51 VARIATION OF ELECTRON TEMPERATURE WITH $H_2$ FLOW IN MDS2 AT CONSTANT ARC CURRENT OF 60A

(OXIDE CATHODE)

$T_e (eV)$

$H_2$ FLOW (std.cc.min$^{-1}$)

maximum noise on L/probe $I_j$ signal

minimum noise on L/probe $I_j$ signal

noisy L/probe $I_e$ signal
The oxide cathode requires about 180 watts and has run under similar arc conditions in the duoplasmatron for $\sim 6540$ hours, spread over 1 year (1975) ($= \sim 20 \times 10^6$ pulses). The tantalum filament has not yet been tested to destruction. Thus the useful gain in plasma density and perhaps beam (these filaments have not yet been tested in an accelerating column), obtained with tungsten, plus even lower noise levels, is offset by the short lifetime. Thanks to the low duty cycle for the arc the main cause of failure is evaporation.
Fig. 55 Relative positions of Langmuir probe exit 'cup', filament shield, and Ta filament

at the hottest part of the filament. Fig. 56 taken from the extensive data available on tungsten\(^{14}\),\(^{15}\) shows the problem concisely. W.L. Stirling et al report longer lifetimes with tungsten wire of ± 1.5\% diameter tolerance and short lifetimes with ± 3\% tolerance wire\(^9\)). It is not yet known what the tolerance is on the commercial filaments we used in these tests, each filament consisting of three spirally wrapped together wires. Damage due to ion bombardment is negligible but during the arc the emission current is greater
FIG 56 EMISSION AND LIFE OF A TUNGSTEN FILAMENT AS FUNCTIONS OF THE VOLTAGE ACROSS IT.

THE HEAVY RECTANGLE SHOWS THE EFFECT OF 5% CHANGE IN VOLTAGE.

than the heating current\(^9\). Since, (if we want to fit a multidipole source in the restricted space now occupied by the duoplasmatron), we are limited to one filament or cathode entry port on the axis of the arc chamber, a solution may be to increase greatly the emitting area of the filament and run at as low a temperature as possible. At the minimum arc setting of 40A (for stable firing) with a 10 std. cc. min\(^{-1}\) hydrogen gas flow, a type BD 482-034 tungsten filament was set at a 1.068 kW power level (53.63A r.m.s./19.89V), and ran for 67 hours.
Tantalum has ~ten times the emission of tungsten at the same temperature (2500°K), but evaporates faster and can be poisoned\(^1\). If a tungsten (or perhaps tantalum) filament can be developed with a sufficient lifetime, it would be preferable to the oxide cathode in terms of reproducibility, lower noise, automatic clean-up after exposure to any contaminants and simpler more robust construction. For the moment the operating experience with the oxide filament in the CERN duoplasmatrons is, together with its long life (if not disturbed), a strong incentive to continue using it in the MDS.
Fig 57 shows the dimensions and orientation (to avoid sagging when hot) of the oxide cathode used. Fig. 58 gives the current/power relationship and Fig. 59 the temperature/current plot. The temperatures are derived from uncorrected optical pyrometer readings and should be taken as approximate. There was no observable gas cooling effect with flows of $\sim 10$ std. cc min.$^{-1}$ in the MDS sources ($p = 30$ milliTorr) (unlike in the duoplasmatron which has $\sim 500$ milliTorr H$_2$ arc chamber pressure at about the same flow rate).

Fig. 60 shows examples of the arc current and voltage for the tungsten filament and oxide cathode at 80A/100V and 100A/65V respectively. If the oxide cathode is in good condition the arc produced appears very similar to that with the tungsten. However, often the oxide cathode exhibits a narrow operating temperature band and must be frequently re-adjusted for good arc conditions. Such a situation can sometimes be improved by over-running the cathode at a higher temperature for several minutes. This can remove contaminants and re-form the oxide. In general such problems arise when frequently venting the source to the atmosphere during modifications. The tungsten filament does not have this problem due to its high operating temperature and chemistry. If the gas flow is too low, the rise time of the arc becomes very long in MDS2 (aluminium alloy arc chamber) and in the case of MDS1 (stainless steel arc chamber) a true delay in the firing of the arc is seen. These differences may be due to surface effects as Thompson et al have observed temporary gas starvation effects in a larger MDS source of stainless steel, during arc turn on.

8. EXTRACTED BEAM MEASUREMENTS

Before the Langmuir probe measurements were done, a rough idea of the plasma positive ion current densities, and hence possible ion beams obtainable from the MDS source, was found using the apparatus in Fig. 61. A disc surrounded behind by a ring, both mounted on insulators, was presented close to the pulsing MDS2 source. The distance was adjusted until no measured current was falling on the ring and hence only on the disc. The disc and ring were biased at the same voltage with respect to the source and
FIG 58  POWER VERSUS CURRENT FOR THE OXIDE CATHODE
FIG 59 OXIDE FILAMENT TEMPERATURE VARIATION WITH FILAMENT CURRENT IN MDS 2

$H_2$ FLOW: 8 cc.min$^{-1}$
PRESSURE: $20 \times 10^{-3}$ torr.
FIG 61 SCHEMA OF SIMPLE BEAM EXTRACTOR
this tension was varied over a few hundred volts. The currents collected on disc and ring were measured as shown. Fig. 62 shows a typical scan result with an oscilloscope photo of the signals on disc (target 1) and ring (target 2). In effect, the disc behaves like a plane Langmuir probe as it is biased more and more negatively since it is immersed in the plasma escaping from the source cup. By applying simply the total ion saturation current collected on the disc to the area of the 'cup' exit hole (10 mm diameter) a value of \( J^+ \) in mA.cm\(^{-2} \) was obtained for different arc values. This result is shown in Fig. 63, and gave low values for \( I^+_D \) \( (J^+_i) \), mainly due to the source exit plate not being biased negatively enough for the reasons stated earlier. Using this system the extracted ion current, normalised for the 10 mm aperture, was calculated from measurements with different hydrogen flow rates for each arc current setting. Fig. 64 shows the results, together with Fig. 65. Fig. 66 shows the disc/ring assembly.

In parallel with these 'laboratory measurements' the MDS1 (stainless steel, air cooled) source was tested both in the 500 kV and 750 kV pre-injectors, and some preliminary results are given here.

In Fig. 67a the lower trace shows the beam current in the IM1 beam transformer situated just after the accelerating gap of the 500 kV (3 MeV facility) column\(^17 \). The upper trace shows the signal from the IM2 monitor situated about 30 cm downstream. Clearly the beam was transmitted with high efficiency in this region. The noise appearing at the beginning of the IM2 signal was probably due to secondary electrons produced by the edge of the beam in the housing and not trapped. Fig. 67b gives the variation of beam current with arc current for another source position and first triplet settings. The corresponding signal in IM2 was highest at the lower arc values (up to 60A) in this case. The optimum values of relative source position in the column anode plus exit cup geometry, arc settings, etc. have yet to be established. Fig. 68 shows the result in Fig. 67b compared to theoretical beam calculated from the \( J^+_i \) values measured in MDS2 with two different filament types, (assuming perfect extraction from the plasma boundary at the cup exit aperture.
FIG 62 POSITIVE ION CURRENT COLLECTED ON TARGET N°1

(MDS1 WITH Φ 10mm EXIT AT -100V I(arc)=80A V(arc)=89V
I(fill)=46.5 A_RMS H2 = 8 cc.min⁻¹)
ARC NOT SYNC. WITH I(fill)
T1 AT 3mm FROM EXIT CUP

PHOTO: V₁ = V₂ = -250V
UPPER TRACE —> TARGET1 SIGNAL
LOWER TRACE —> TARGET2 SIGNAL
Vert. = 100mA/Div

V(polar) —> POLARISATION OF TARGET N°1 'DISC' AND N°2 'RING'
Hy flow = 8 std. cc. min$^{-1}$
Oxide filament temp. $\sim 875^\circ$C
EXIT PLATE AT $-100\,\text{v}$

MDS 2 with 10mm diameter beam exit hole
(Type 2 'cup')

---

**Fig. 63** Variation of positive ion current density at beam exit with arc current
FIG 64 Variation of extracted +VE ion current with gas flow and arc current
Oxide cathode temp. \( \sim 875^\circ C \)

Extractor plate at -200V

Extractor ring at -200V

Source front exit plate at -100V

Extractor plate at 3mm from exit hole

**FIG 65** Variation of extracted \( +\)VE ion current with arc current and gas flow
Fig. 69 shows the effect on the arc, and ion beam at 500 keV, of too cool and too hot oxide cathode temperatures, the range being about 50°C for that particular cathode.

Fig. 70 is an example of a typical duoplasmatron beam in similar beam monitors. Note the difference in noise levels between the two types of ion-source. The noise on the duoplasmatron beam can be much reduced at a certain position of the source in the column anode, but the emittance then becomes unacceptable.

The angle of the exit cup of either source can have an influence on the ion trajectories down the column. As a starting point the angle for the MDS source was set at a standard Pierce value (67.5°). Using the SLAC 166\(^{18}\) code, and assuming a given plasma boundary shape and position, the ion trajectories were calculated for a 67° and 45° angle exit cup.
FIG 67(a) upper trace = IM₂
lower trace = IM₁
 calibration pulses ≥ 500 mA
MDS₁ at Iₐrc = 135 A, H₂ = 11.1 cc·min⁻¹
EHT = 500 kV, exit at -50 V
I멸 = 53.8 A digital
source position -41 mm
wide band tuning for triplet quads

FIG 67(b)

EXIT AT -100 V
14 mm Ø HOLE
H₂ 975—11.8 cc·min⁻¹

FIG 67b BEAM CURRENT IN IM₁ AS A FUNCTION OF Iₐrc WITH MDS₁ IN 500 kV PRE-INJECTOR
FIG 68 THEORETICAL ION BEAM CURRENTS (CALCULATED FROM J⁺ VALUES) AVAILABLE FROM Ø 10 mm EXIT APERTURE IN MDS 2 AND AN ACTUAL BEAM MEASURED IN A 500kV PRE-INJECTOR
Figs. 71 and 72 show the computer plots obtained. More importantly, the position of the plasma boundary, with respect to the extraction field of the column anode, has a significant effect on the theoretical ion trajectories; this is shown in Fig. 73 for the MDS source in the 750 kV column. Also the shape of the plasma surface would have a large effect if it was outside the exit cup aperture and two hypothetical cases are examined in Fig. 74 and Fig. 75 (using the duoplasmotron cup geometry).

It should be stressed that these trajectories are hypothetical since the actual position and shape of the plasma boundary is not known, and different for each source arc/\textit{J}_i and position setting. However, they serve to show the main influencing factors involved.

9. BEAM EMITTANCES AND PROFILES

This final section deals briefly with the few measurements so far made on the MDS beam in the two preinjectors. Fig. 76 was the first emittance measurement, done manually, on the 500 keV beam. It should be treated as a rough guide only since the apparatus and method used was very simple. The beam was scanned by a slit and the amplitude of the current collected on a single collector wire downstream noted by hand for each position.
FIG 71  CALCULATED ION TRAJECTORIES IN 500 KV COLUMN FOR MDS SOURCE (AT D=15 MM, EXIT φ=14 MM, I=250 μA)

FIG 72  CALCULATED ION TRAJECTORIES IN 500 KV COLUMN FOR MDS SOURCE WITH 45° ANGLE AT EXIT CUP
FIG 73. Calculated ion trajectories in 750 KV column for two different MDS source positions (1*175 mA, exit φ 14 mm).
FIG 74. PLASMA BOUNDARY EXTERNAL AND CONVEX

FIG 75. PLASMA BOUNDARY EXTERNAL AND CONCAVE
Normalised emittance for whole beam (including $H_2^+, H_3^+$ and possibly heavier masses) estimated at $< 11 \pi \text{mm mrad}$

Central area (relative intensity $> 20$)
Emittance estimated at $< 4.5 \pi \text{mm mrad normalised}$

Relative intensity $\sim 20$

Total ion current $= 220 \text{mA}$

Source fitted with type 1 cup, exit beam hole $\varnothing 14$

Fig. 76 Emittance of MDS1 +ve ion beam at 500keV
Nevertheless, the values obtained are quite encouraging when compared to the duoplasmatron value of about $40 \pi$ mm mrad at 750 keV for 90% of a 250 mA beam.

Fig. 77 (a & b) shows the results obtained during the first brief tests in the 750 kV preinjector for the new linac. These were obtained with the sophisticated computerised slit system. Values of $\varepsilon_{r.m.s.} = 20.41 \pi$ mm mrad and $22.76 \pi$ mm mrad in the vertical plane, before and after passing through the buncher are indicated, for a beam of $\sim 300$ mA before, and $\sim 160$ mA after, the buncher\(^{19}\). The emittance in EM2 before the buncher probably indicates considerable contamination from $H_2^+$, $H_3^+$ and maybe $O^+$ or $N^+$ ions. This is further supported by the considerable losses in the beam transformer readings between IM4 and IM5. For an arc of 102A and 10.2 cc min$^{-1}$ hydrogen the following beam current readings were obtained:

<table>
<thead>
<tr>
<th>Station</th>
<th>Current (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IM2 (after column)</td>
<td>325</td>
</tr>
<tr>
<td>IM4 (before buncher)</td>
<td>301</td>
</tr>
<tr>
<td>IM5 (after buncher)</td>
<td>163</td>
</tr>
<tr>
<td>IM6 (into linac Tank 1)</td>
<td>163</td>
</tr>
<tr>
<td>IM9 (out of Tank 3)</td>
<td>140</td>
</tr>
</tbody>
</table>

As seen in Fig. 77(b), the emittance was cleaned up after passing through the buncher and appeared quite reasonable.

The maximum current obtained at 50 MeV was 140 mA compared to a maximum of 160 mA obtained with the standard duoplasmatron\(^4\).

Emittance measurements at 50 MeV indicated that the beam quality was at least as good as that from the duoplasmatron and probably better.

The linac operating settings, including the transport line from preinjector to Tank 1, were not fully optimised for the MDS beam in the brief time available for the tests. Fig. 78 shows the difference in beam profile stability between the MDS1 and duoplasmatron ion beams at 750 keV. The profiles were made with a moveable slit and a beam transformer behind it, and the MDS1 profile showed no variation over several scans whereas the duoplasmatron one always displays the variations shown here.
FIG 77a

FIG 77b

MDS 1
750 keV EMITTANCE: BEFORE AND AFTER BUNCHER
DUOPLASMATRON HORIZONTAL BEAM PROFILE

FIG 78

MULTIDIPOLE ION SOURCE HORIZONTAL BEAM PROFILE
In general, the MDS beam was very stable and showed, as before, very low noise levels compared to the duoplasmatron one. Species analysis of the ion beam was not performed in these tests.

10. CONCLUSION

The results so far obtained with the two prototype pulsed multidipole ion sources are encouraging. No inherent problems have been found when pulsing them with hydrogen or helium at the short (100 μs) pulse time required for the CERN linacs. Ion beams of very low noise and high stability have been transported efficiently in both the 500 kV and 750 kV preinjectors and in the new 50 MeV Linac, and reasonable emittances measured. It is certain that optimum conditions, position inside the column, and exit geometry, etc. for the MDS have not yet been found, leaving room for more improvements in beam quality. It is hoped that the preliminary work reported here will lead eventually to an improved ion source for the CERN high energy accelerator complex.

ACKNOWLEDGEMENTS

The author wishes to thank the many people who have assisted in the realisation of the contents of this report. Special thanks are due to the local divisional workshop's staff: in particular to W. MacDonald, W. Burkhalter, N. Mezin, G. Schraner and J.C. Gervais for the rapid production of the mechanical items involved. The essential measurements assistance, advice and ideas by and from H. Haseroth, C. Hill and J. Grando is recognised, together with the help received from fellow section members, H. Charmot, J.P. Romero and J.L. Vallet. Lastly, but not least, the very useful discussions with and information obtained from E. Thompson and A. Holmes of Culham Laboratory is acknowledged.
REFERENCES

5) A.J.T. Holmes, E. Thompson et al., UKAEA, Culham Lab. Exp. Div. B.
7) E. Thompson, "Further measurements of the ion optics of a single aperture three electrode extraction system, 1976 " Symposium on Ion Sources, II-3-1.
12) "Plasma diagnostic techniques", Ch. 4, p. 125, Electric probes, by F.F. Chen (Ed. by Huddlestone) (1965).
14) "Electronics" by P. Parker, (pub. E. Arnold Ltd.) (1960).
16) "Procedure for making the oxide coated cathode for the Linac Duoplasmatron ion source", H. Charmot, M.A. Hone, J.L. Vallet, MPS/LIN/Note 74-7 (1974).
17) J. Knott, P. Tête and M. Weiss, MPS/LIN/Note 75-1, Fig. 1 (1975).