UCID - 16496

This is an informal report intended primarily for internal or limited external distribution. (The opinions and conclusions stated are those of the author and may or may not be those of the laboratory.) This report is not to be given additional external distribution or cited in external documents without the consent of the author or LLL Technical Information Department.

LAWRENCE LIVERMORE LABORATORY

University of California/Livermore, California

**ELECTRON TEMPERATURE IN THE BASEBALL
DISCHARGE - PRELIMINARY RESULTS AND ANALYSIS**

E. B. Hooper, Jr.

May 9, 1974

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Fig

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

ELECTRON TEMPERATURE IN THE BASEBALL
DISCHARGE - PRELIMINARY RESULTS AND ANALYSIS

E. B. Hooper, Jr.

Lawrence Radiation Laboratory, University of California
Livermore, California

ABSTRACT

First laser scattering results on the Baseball discharge target indicate $T_e = 5\text{eV}$. These results are discussed from the viewpoint of the discharge power balance.

ELECTRON TEMPERATURE IN THE BASEBALL
DISCHARGE - PRELIMINARY RESULTS AND ANALYSIS

E. B. Hooper, Jr.

Introduction

The first laser scattering results on the Baseball target discharge¹ are completed, yielding density measurements in agreement with the 3mm interferometer and electron temperatures of 5eV. This latter result is disappointing, so I wish to discuss briefly the experiment and some thoughts on the low temperature.

These are the first scattering results, and there is still some suggestion in the data of minor systematic errors related to the sensitivity of the apparatus at different wavelengths. The errors are small, however, and almost certainly will not change results by more than 20%.

One limitation to the present temperature measurements should be mentioned: The cathode filament was badly warped during these experiments so that perfect cathode-anode alignment could not be achieved. As a result, discharge currents in these data were unusually low (by 50% for given filament temperature) and the bombardment of surfaces with consequent impurity release was unusually high. As of this writing, the filament has been modified to prevent this problem and permit higher currents.

The electron temperature is in fair agreement with energy balance calculations. The model of Lee and McNamara² predicts $T_e = 10\text{eV}$ (typically) whereas Fowler's predicts 5eV.³

Experimental Results

I wish to summarize some of the pertinent results. Densities in the range of $10^{13} - 10^{14} \text{ cm}^{-3}$ are achieved at discharge currents 50-200 amperes and voltages ≤ 2000 volts. The total gas injected into the anode is in the range $5 \times 10^{17} - 2 \times 10^{18}$ molecules of deuterium, and $\sim 50\%$ of these actually enter the anode during the discharge period (≤ 1 msec). The vacuum tank is pumped with titanium gettering to base pressures in the range 10^{-9} to 10^{-8} torr. The filament electron emission was measured and was 40 amps total (from 12.5 cm^2) at its "standard" temperature. Higher temperatures were also used during the laser scattering experiments, but because of the misalignment problem the significance of the results is questionable.

We find that there are essentially two modes of operation - a "clean" mode in which the discharge behaves stably at the currents and voltages described above and a "noisy" mode in which the discharge voltage drops to a few hundred volts and the current increases to ~ 1 kAmp. The noisy mode is especially likely if the filament and anode are misaligned, the vacuum tank is freshly pumped from air, or the base pressure is $\geq 10^{-6}$ torr. Visual observations of this mode (including photographs) show that the plasma constricts to a narrow arc which contacts the metal wall of the tank. The path by which the electrical circuit is completed is not apparent; mechanisms similar to those in unipolar arcs⁴ are undoubtedly at work.

During the early phases of a "noisy" discharge, characteristics are similar to those of "quiet" discharges. As time progresses, the discharge becomes less well behaved; an abrupt transition then occurs (after $\sim 0.5 - 1$ msec) to the "noisy" mode.

Spectroscopic measurements in the visible have been made of both modes. In the "quiet" mode hydrogen (deuterium) light dominates. There is a hint

in the photographs of other lines but they are very weak. In the "noisy" mode, on the other hand, the total light emitted from the plasma increases enormously and many impurity lines are observed.

One tentative conclusion from these observations is that the plasma in the "quiet" mode contains only a low level of impurities. In the "noisy" mode, on the other hand, the plasma becomes filamentary, walls are bombarded, and impurities dominate.

Energy Input into the Discharge

The total discharge power, measured as input electrical energy, is as high as 400 kW into a plasma ($n = 5 \times 10^{13} \text{ cm}^{-3}$) with volume less than 1 liter. Unfortunately, about 75% of the energy is in ion bombardment of the cathode because of acceleration across the cathode sheath.

The remaining power, ~ 100 kW, is in the form of energetic electrons. The fraction of this power which is deposited in the plasma is uncertain. The energy balance model of Lee and McNamara² has as an input density and discharge voltage and current. One output of the model is the electron current from the cathode, which is calculated to be $\sim 10\%$ of that measured experimentally.

We can look at this conclusion from the opposite viewpoint: if the energy deposited is indeed low, the energy loss mechanisms may be classical, and additional power input - e.g. from a neutral beam - may heat the electrons very efficiently.

Electrical Energy Losses

We make several assumptions to calculate the electrical energy flow from the plasma, not including acceleration across the sheath:

- 1) The ions are cold.
- 2) Electron thermal losses across the sheaths are classical.
- 3) Secondary electron emission from the anode is small.

In that case, the ions entering the sheath have a directed velocity

$v_i \geq \sqrt{kT_e/m_i}$. Lee and McNamara² also argue that the density at the sheath edge is 1/2 that in the plasma center, so with A the area of one electrode:

$$P_i = nA(kT_e)^{3/2}/(m_i)^{1/2} \text{ for ions}$$

$$P_e = \frac{kT_e}{e} I_{e, \text{ anode}} \text{ for electrons.}$$

The electron current at the anode is $I_{e, \text{ anode}} = I_{\text{DISC}} + 1/2enA(kT_e/m_i)^{1/2}$.

Combining these, one finds for $A = 12.5 \text{ cm}$: $P_{\text{out}} = 1.7 \times 10^{-13} nAT_e^{3/2} + T_e I_{\text{DISC}}$ watts. We take $A = 12.5 \text{ cm}$; "standard" plasma conditions are $n = 5 \times 10^{13} \text{ cm}^{-3}$, $T_e = 5\text{eV}$, and $I_{\text{DISC}} = 200\text{A}$. Then $P_{\text{out}} = 2.2 \times 10^3$ watts far below the maximum possible input power of 100 kW.

Hobbs and Wesson⁵ have calculated energy loss through sheaths in the presence of secondary emission from the surface. They find a maximum enhancement of 3.1 for infinite secondary emission coefficient. As the effect is not important at the cathode we find

$$\begin{aligned} P_{\text{out}, s} &= 4.1 \times 10^{-13} nAT_e^{3/2} + 3.1 T_e I_{\text{DISC}} \text{ watts} \\ &= 6.0 \text{ kWatt at standard conditions.} \end{aligned}$$

Finally, they point out that a maximum enhancement of 8.3 would occur for free effusion of electron to the wall. This would presumably correspond to the maximum possible anomalous transport of energy, and yields

$$\begin{aligned} P_{\text{out}, \text{ max}} &= 1.0 \times 10^{-12} nAT_e^{3/2} + 8.3 T_e I_{\text{DISC}} \text{ watts} \\ &= 15 \text{ kWatt at standard conditions} \end{aligned}$$

Energy Lost to Deuterium

Because of the pulsed nature of the discharge, the fairly large vacuum tank, and the gettering system the gas pressure in the body of the plasma is less than 10^{-4} torr; in 1 liter this corresponds to 3×10^{15} molecules, a number too low to be significant for energy loss. On the other hand, the

gas injected into the anode forms a reservoir at high pressure which is in contact with the plasma and which may cause significant energy loss.

We estimate the losses three ways: At high T_e ($\geq 20\text{eV}$) each ion pair produced in deuterium costs 32eV; the energy needed increases at low T_e .

A lower limit on the loss is thus

$$\begin{aligned} P_D^{(\text{Min})} &= 32 \cdot neA \sqrt{\frac{eT_e}{m_i}} \\ &= 6.1 \times 10^{-11} n \sqrt{T_e} \text{ watts} \\ &= 6.8 \text{ kWatts at } 5 \times 10^{13} \text{ cm}^{-3} \text{ and } 5\text{eV} \end{aligned}$$

Englehardt and Phelps⁶ have calculated the energy losses of electrons drifting in hydrogen under the influence of a d.c. electric field. At 5eV, ionization takes about 0.15 of the input power, so the energy per ionization is about $13.6/0.15 = 91\text{eV}$. Thus we predict the energy loss to be $P_D = 19.3 \text{ kWatts}$.

Alternatively we take the plasma to be in contact inside the anode with a total number, N , of deuterium molecules. The power loss is then:

$$P_D^{(M)} = \left(\frac{3}{2} kT_e \right) neN \langle \sigma v \rangle_e,$$

Calculations⁶ show that $\langle \sigma v \rangle_e$, the energy loss rate, is a rapidly increasing function of T_e in the range about 5eV; $\langle \sigma v \rangle_e = 10^{-9} \text{ cm}^3/\text{sec}$ at $T_e = 1.7\text{eV}$ and $10^{-8} \text{ cm}^3/\text{sec}$ at 5eV. Using the latter value and taking $N = 10^{17}$ molecules (probably an over estimate)

$$\begin{aligned} P_D^{(\text{Max})} &= 2.4 \times 10^{-10} T_e n_e \text{ watts} \\ &= 60 \text{ k watts at } 5 \times 10^{13} \text{ cm}^{-3} \text{ and } 5\text{eV}. \end{aligned}$$

This latter approximates an upper limit and is close to the maximum possible energy input. It thus appears that energy losses to the injected deuterium may be adequate to explain the low electron temperature, especially if the net input energy is low.

Energy Loss to Impurities

Radiation losses by impurities can be extremely high.⁷ Possible sources of impurities are:

- 1) Insulators - oxygen, silicon, aluminum
- 2) Cathode filament - tungsten
- 3) Anode - copper

The spectroscopic information indicates that the impurity level is low in the "quiet" mode. We examine here "how low is low enough."

Oxygen is a probable impurity, and as considerable information exists about it, we use it as an example. The ionization rates at 5eV and corresponding ionization times at $n = 5 \times 10^{13} \text{ cm}^{-3}$ are⁸

<u>transition</u>	<u>$\langle \sigma v \rangle$</u>	<u>ionization time</u>
$0 \rightarrow 0^+$	$1.73 \times 10^{-9} \text{ cm}^3/\text{sec}$	$1.5 \times 10^{-5} \text{ sec}$
$0^+ \rightarrow 0^{++}$	$8.06 \times 10^{-12} \text{ cm}^3/\text{sec}$	$2.5 \times 10^{-3} \text{ sec}$
$0^{++} \rightarrow 0^{+++}$	$6.71 \times 10^{-14} \text{ cm}^3/\text{sec}$	0.15 sec

We thus have exclusively 0^+ . It is interesting to note, however, that at 7-10eV the rate of ionization is large enough to yield predominately 0^{++} .

The dominant transitions in 0^+ at low T_e are the resonance multiplet at 834 Å. We also know for these lines that $gf = 1.5$ with g the degeneracy and f the oscillator strength.¹⁰

We assume that all excited ions radiate. Post¹¹ has derived an expression (independent of species) for the power lost, which for a 1 liter plasma is

$$P_{im}^{(P)} = 1.9 \times 10^{-21} (gf) n_e n_i \frac{E_1(x)}{T_e^{1/2}} \text{ watts}$$

with $x = \text{excitation energy} / kT_e$, n_i the impurity density, and $E_1(x) =$

$\int_x^\infty (e^{-z}/z) dz$. A similar expression was derived by Gibson and Mason¹² for work on Zeta:

$$P_{im}^{(GM)} = 2.5 \times 10^{-21} (gf) n_e n_i \frac{e^{-x} [1 - x e^x E_1(x)]}{T_e^{1/2}} \text{ watts}$$

These results are compared in Table 1. In addition we present results from dense pinch work using different assumptions than above. Kogan¹¹ using results by Knorr.¹⁴ Calculates for $T_e = 10\text{eV}$

$$P_{im}^{(k)} = 2 \times 10^{-24} n_e n_i \text{ watts}$$

Knorr's analysis yields approximately the same result at 5eV. Note however, that this result assumes an equilibrium between ionization and recombination. Even in that case the result is a lower limit.⁷ We present it here as a lower limit estimate.

Finally, we scale results from the Perhapsatron.¹⁵ Their toroidal plasma at 50eV and 10^{16} cm^{-3} radiated 10^9 watts at a 5% impurity level. The volume was 8.4 liters, so neglecting effects due to the temperature difference:

$$\begin{aligned} P_{im}^{Pr} &= 10^9 (n_e n_i V)_{\text{target}} / (n_e n_i V)_{Pr} \\ &= 2.3 \times 10^{-23} n_e n_i \text{ watts} \end{aligned}$$

This is probably a maximum radiation loss as at 50eV many levels of the radiating ions are excited.

These various energy losses are summarized in Table I for $n_e = 5 \times 10^{13}$:

TABLE I

Radiation Power (kWatts) From Impurities

(See text for various approximations)

Percent Impurity	$P(P)$	$P(GN)$	$P(k)$	$P(Pr)$
.1%	.04	.045	.005	.06
1%	.41	.45	.05	.58
10%	4.1	4.5	.5	5.8
100%	41.	45.	5.	58.

With the exception of the Kogan result, $p^{(k)}$, these numbers are in surprisingly good agreement. Note further that several other cross-section models are considered in Ref. (7); at $x = 3$ they are all about equal.

We see that an impurity level of $> 10\%$ is required to significantly effect the power balance in the discharge. At these levels, the presence of the impurity would be obvious in the visible spectroscopy described earlier.

Conclusions

We summarize these results as follows:

Power In

Maximum	100kW
Minimum	?

Electrical Power Out

Minimum	2.2 kW
Maximum with secondary electrons from anode	6.8
Maximum anomalous	15.0 kW

Power Loss to Hydrogen

Minimum	6.8 kW
Probable	19.3 kW
Maximum	60.0 kW

Power Loss to Impurities

1 % impurity	0.5 kW
10%	4.5 kW

It follows from these calculations that unless there is a violently anomalous energy loss mechanism not considered above, we are coupling only a fraction of the input energy into the body of electrons, perhaps 10% of that

in the primary electrons. It is furthermore apparent that at these low input energies the dominant energy loss is to the deuterium in the hollow anode.

References

1. E. B. Hooper, Jr. and O. A. Anderson, Bul. American Phys. Soc. 18, 1318 (1973).
2. E. P. Lee and B. McNamara, UCID 16445 (1974).
3. T. K. Fowler, Private Communication.
4. A. E. Robson and P. C. Thonenmann, Proc. Phys. Soc. 73, 508 (1959).
5. G. D. Hobbs and J. A. Wesson, Culham Report CLM-R61 (1966).
6. A. G. Engelhardt, and A. V. Phelps, Phys. Rev. 131, 2115 (1963).
7. Vasilev, A. P., Dolgov,--Savelev, G. G., Kogan, V. K., Nucl. Fusion Suppl., Part 2, 655 (1962).
8. W. Lotz, Astrophys. J., Suppl. Series XIV, No. 128, 207 (1967).
9. A. N. Zaidel, et. al., Tables of Spectral Lines (IFI/Plenum, NY, 1970).
10. C. W. Allen, Astrophysical Quantities, (Athlone, London, 1955), p. 68.
11. R. F. Post, Plasma Phys, 3, 273 (1961). (The numerical factor in Eq. 30 should be 6.0×10^{-26})
12. A. Gibson and D. W. Mason, Proc. Phys. Soc. 79, 326 (1962).
13. V. I. Kogan, Sov. Phys. Doklady 4, 1057 (1960).
14. G. Knorr, Z. Naturfosch 13a, 941 (1958).
15. H. J. Karr, E. A. Knapp, and J. E. Osher, Phys, Fluids, 4, 424 (1961).

Distribution List

Internal

O. A. Anderson	L-387
D. H. Birdsall	L-387
T. K. Fowler	L-382
R. F. Post	L-386
C. C. Damm	L-386
J. E. Osher	L-386
A. L. Hunt	L-386
A. H. Futch	L-386
J. H. Foote	L-386
G. W. Hamilton	L-386
R. A. Goodman	L-121
G. D. Porter	L-386
F. Coensgen	L-386
B. McNamara	L-388
E. P. Lee	L-388
J. A. Byers	L-388
R. W. Moir	L-386
J. R. Hiskes	L-388
R. V. Pyle (LBL)	9230 5-117

External

Dr. R. F. Scott
Division of Controlled
Thermonuclear Research
U. S. Atomic Energy Commission
Washington, D. C. 20545

NOTICE

"This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately-owned rights."