FINAL REPORT
ORNL/Sub-7802/X05/4

INTERACTION OF ENERGETIC HYDROGEN WITH SURFACES

By
E. W. Thomas
K. O. Legg

Prepared for
OAK RIDGE NATIONAL LABORATORY
OAK RIDGE, TENNESSEE 37830

Operated by
UNION CARBIDE CORPORATION

For the
DEPARTMENT OF ENERGY

Contract No. W-7405-eng-26
Sub Contract No. -7802

30 September 1983

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF PHYSICS
ATLANTA, GEORGIA 30332
INTERACTION OF ENERGETIC HYDROGEN WITH SURFACES

Final Report
Covering the Period
November 1, 1982 to September 30, 1983

by

E. W. Thomas
K. O. Legg

Report Prepared by:
The Georgia Institute of Technology
School of Physics
Atlanta, Georgia 30332

Under subcontract number 7802 for
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830
operated by
Union Carbide Corporation
for the
Department of Energy
Contract No. W-7405-eng-26

30 September 1983
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the Department of Energy 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.
## Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>I. Title</td>
<td>1</td>
</tr>
<tr>
<td>II. Contract Number</td>
<td>1</td>
</tr>
<tr>
<td>III. Abstract</td>
<td>1</td>
</tr>
<tr>
<td>IV. Discussion of Results</td>
<td>1</td>
</tr>
<tr>
<td>A. Hydrogen Recycling in ISX-B</td>
<td>1</td>
</tr>
<tr>
<td>B. Laboratory Re-emission Studies</td>
<td>2</td>
</tr>
<tr>
<td>V. Conferences and Travel</td>
<td>2</td>
</tr>
<tr>
<td>VI. Publications</td>
<td>3</td>
</tr>
<tr>
<td>VII. Personnel</td>
<td>4</td>
</tr>
<tr>
<td>VIII. Appendix Measurement of H$_{\alpha}$ Emission on ISX-B</td>
<td>5</td>
</tr>
</tbody>
</table>
I. Title

Interaction of Energetic Hydrogen with Surfaces.

II. Contract Number

This report covers work performed on particle-surface interactions under a contract between Union Carbide Corp. with the Georgia Tech Research Institute. The work is covered by Project Authorization No. X05 under Basic ordering Agreement No. 7802 (under DOE Prime No. W-7405-eng-26).

This work covers the period 1 November 1982 to 30 September 1983. No continuation of this work is contemplated.

III. Abstract

During its final year the focus of this work has been on fuel recycling in the 1SX-B tokamak. New wide field detectors have been constructed and placed around the machine, together with the existing narrow field detectors, to monitor recycling behavior. All of the detectors were left in place throughout a large part of this period to monitor any long range changes in recycling.

Studies were made of toroidal variations, in-out slight correlations and pump limiter experiments. Theoretical analysis were made of detector expense and the recycling changes expected from variations in plasma position.

IV. Discussion of Results

Over the final project year we have put into operation a set of wide-angle H_d detectors and analyzed the performance of the existing ones. Recycling observations on 1SX-B have been made under a variety of operating conditions. Laboratory measurements related to recycling have been completed to form a Ph.D. thesis.

A. Hydrogen Recycling in 1SX-B

These have included analysis of detector optics and plasma recycling
geometry as well as observing recycling behavior in 1SX-B.

Geometrical analysis of detector optics has shown that a considerable fraction of the observed signal can emanate from the far side of the plasma. Analysis of plasma geometry shows that although the field of view of a detector may be narrow the radiation it observes can arise from neutrals recycled from a large wall area, including adjacent sectors.

Toroidal variations in recycling were studied for different plasma conditions and show strong variations depending on the plasma parameters. Observations were also made of recycling under conditions such as co-and counter-injection and pump limiter operation.

These data are discussed in detail in appendix A of this report.

B. Laboratory Re-emission Studies

Data taking and analysis have been completed on deuterium re-emission from the surfaces of ion bombarded steel and gold. It is clear that re-emission rates are very strongly influenced by surface cleanliness as well as temperature and dose. These results are being written up as a Ph.D. thesis by Mr. J. G. Chan of Georgia Tech.

V. Conferences and Travel

Drs. Legg and Thomas have made frequent units to ORNL during the year to perform studies on 1SX-B, to analyze data and to consult with Oak Ridge Personnel.
VI. Publications


VII. Personnel

Dr. Thomas has been Project Director and Principal Investigator devoting approximately 17% time to the project.

Dr. K. O. Legg, Senior Research Scientist, occupied the position of Co-Principal Investigator at 33% time.

Mr. Jin-Gor Chan, Ph.D. student at Georgia Tech was funded entirely by Georgia Tech to work on laboratory re-emission studies.
Appendix

Measurements of H$_d$ emission on ISX-B

Contents

Abstract

1. Construction of Detectors
2. Detector Placement
3. Analysis of Detector Optics
4. Recycling Dependence on Plasma Position
5. General Behaviour
   5.1 Toroidal Variations
   5.2 In/out Shift Correlations
   5.3 Dependence on Fueling Conditions Co-and Counter Injection
   5.4 Performance of Fan Detectors
   5.5 Comparison of H$_d$ Data with Neutral Flux Spectra
6. Pump Limiter Experiment
7. Summary
Abstract

The present status of work on the detection and analysis of $H\alpha$ emission in ISX-B is described. New wide field detectors have been built and the optics of the existing detectors has been analyzed. It is concluded that about 25% of the signal emanates from the far side of the plasma. The origin of the neutrals which give rise to the emission seems to be a very broad area of the wall in the vicinity of the detector. Comparisons with data on the energy spectra of neutrals entering the wall show that the predominant source of $H\alpha$ radiation is reflected slow neutrals with less than 100eV of energy.

I. Detector Construction

The construction of the standard small angle detectors was detailed in our third Progress Report (30th Sept. 1982).

For studying the overall $H\alpha$ radiation in single sectors three "fan-field" detectors were constructed. Electronically these are identical to the earlier detectors, using the same type of PIN diodes and amplifiers. Each has two filters, a narrow band (1nm bandwidth) $H\alpha$ filter and a broad band (10nm bandwidth) filter to provide adequate u.v. and i.r. blocking. The optical system employs a cylindrical lens and a plano-convex spherical lens to give a wide field of view in one direction (along the sector radius) with a restricted field of view in the other (around the torus)—see Fig. 1. The focal lengths of the cylindrical and spherical lenses are 5cm and 3.8cm respectively. As in the narrow field detectors, the PIN diode lies at the focal plane of the cylindrical lens. Thus the area sampled is approximately 2.3cm x 7.8cm at the top of the plasma and 3.5cm x 23cm at the bottom of the plasma (taking into account the geometric optical considerations detailed below). This is sufficient to sample a large poloidal area of the plasma with about equal weight given to signals from the top and the bottom. It covers
Fig. 1. Two views of "fan"-field detector optics.
the maximum area visible through the standard 1 1/2" windows.

The sensitivity factors for the different detectors are given in Table I. For the fan detectors (F1, F2 and F3) the factors are only relative and unrelated to the narrow field detectors since the geometry precludes any absolute measurements.
<table>
<thead>
<tr>
<th>Det #</th>
<th>Calibration</th>
<th>Phot s⁻¹ bit⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.4 x 10⁹</td>
<td>3.2 x 10⁹</td>
</tr>
<tr>
<td>2</td>
<td>3.2 x 10⁹</td>
<td>3.2 x 10⁹</td>
</tr>
<tr>
<td>3</td>
<td>2.0 x 10¹⁰</td>
<td>8.5 x 10⁹</td>
</tr>
<tr>
<td>4</td>
<td>7.1 x 10⁹</td>
<td>5.8 x 10⁹</td>
</tr>
<tr>
<td>5</td>
<td>4.6 x 10⁹</td>
<td>4.4 x 10⁹</td>
</tr>
<tr>
<td>6</td>
<td>2.9 x 10⁹</td>
<td>1.2 x 10⁹</td>
</tr>
<tr>
<td>F1</td>
<td>5.3</td>
<td>7.7 relative</td>
</tr>
<tr>
<td>F2</td>
<td>1.5</td>
<td>2.9 values only</td>
</tr>
<tr>
<td>F3</td>
<td>2.2</td>
<td>3.8</td>
</tr>
</tbody>
</table>
2. **Detector Location**

   Detectors have been placed around the machine as detailed in table II and fig. 2. From 12/22/82 onwards detector locations remained unchanged to permit long term monitoring of recycling. From 6/21/83 "fan field" detectors were installed to monitor radiation from large plasma edge areas in 3 sectors.
Table II

Detector Locations

<table>
<thead>
<tr>
<th>Date</th>
<th>640</th>
<th>641</th>
<th>665</th>
<th>666</th>
<th>667</th>
<th>670</th>
<th>1375</th>
<th>1376</th>
<th>1377</th>
</tr>
</thead>
<tbody>
<tr>
<td>6/2/82</td>
<td>11,TC</td>
<td>-</td>
<td>14,BC</td>
<td>10,TO</td>
<td>15,TC</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/2/82</td>
<td>#2</td>
<td>#3</td>
<td>#4</td>
<td>#1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/2/82</td>
<td>11,TC</td>
<td>1,TC</td>
<td>14,BC</td>
<td>10,TO</td>
<td>15,TC</td>
<td>14,TO*</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8/31/82</td>
<td>#2</td>
<td>#5</td>
<td>#3</td>
<td>#4</td>
<td>#1</td>
<td>#6</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9/1/82-12/7/82</td>
<td>10,TO</td>
<td>14,BC</td>
<td>11,TO</td>
<td>1,TC</td>
<td>-</td>
<td>11,TC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/7/82</td>
<td>#4</td>
<td>#3</td>
<td>#2</td>
<td>#5</td>
<td>#1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/7/82-12/16/82</td>
<td>10,TO</td>
<td>-</td>
<td>11,TO</td>
<td>1,TC</td>
<td>-</td>
<td>11,TC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/16/82-12/22/82</td>
<td>#4</td>
<td>#2</td>
<td>#5</td>
<td>#1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/22/82</td>
<td>10,TO</td>
<td>14,BC</td>
<td>12,SC</td>
<td>1,TC</td>
<td>15,TC</td>
<td>11,TC</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>12/22/82</td>
<td>#4</td>
<td>#3</td>
<td>#2</td>
<td>#5</td>
<td>#6</td>
<td>#1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6/21/83</td>
<td>#4</td>
<td>#3</td>
<td>#2</td>
<td>#5</td>
<td>#6</td>
<td>#1</td>
<td>13,BO</td>
<td>1,TC</td>
<td>11,TI</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>#3</td>
<td>#1</td>
</tr>
</tbody>
</table>

*See Table I Progress Report #3

T=top, B=bottom, C=center, O=outer, I=inner, S=side.
Fig. 2 (a) Detector locations prior to 12.22.82
Fig. 2 (b) Detector locations after 12.22.82
3. **Analysis of Detector Optics**

The existing narrow field $H_\alpha$ detectors consist of a narrow band $H_\alpha$ filter, a lens with a photodiode at its focal point and a signal amplifier. These detectors mount on flanges above and below the torus. The source of $H_\alpha$ radiation is assumed to be neutral atoms from the wall which enter the plasma edge, where they are excited to the $n=3$ level. Because the detectors collect light from a cone in front of them emission can be detected from the top and bottom plasma sheaths. Over the small (<5 cm dia) areas observed by the detectors the plasma edges can be considered to be uniform plane emitters.

Consider a plane object emitting light homogeneously and isotropically. Assume that the detector is small, so that we only need consider rays at shallow angles to the axis. Then the fraction of emitted light from each elementary object area which falls on the lens is, from fig. 3,

$$\frac{\pi R^2 L}{4\pi L^2} = \left(\frac{R_L}{2L}\right)^2$$

Consider the detection of points about an elementary annulus radius $R$. Each point is imaged at the detector plane as a circle of radius

$$c = (1- \frac{a(L-f)}{L_L})R_L$$

centered at a radius

$$\frac{f}{L-f} R$$

The fraction of the light passing through the lens which is detected is given by the overlap of the image spot with the detector.

Several cases may be considered:
Fig 3 (a) Definition of optical parameters.

Fig 3 (b) Enlarged view of detector-image overlap.
1. Detector completely within image spot, i.e. $c > r$, $R \leq \frac{L-f}{f} (c-r)$

Fraction of photons emitted from each point which are detected is

$$\delta F = \left( \frac{R}{2L} \right)^2 \left( \frac{r}{c} \right)^2$$

Thus for an annulus

$$F_{an} = 2\pi R \left( \frac{rR}{2Lc} \right)^2 \delta R$$

The total fraction of light measured from all points on the object circle satisfying $R \leq \frac{L-f}{f} (c-r)$ is

$$F_1 = 2\pi \left( \frac{rR}{2Lc} \right)^2 \int_0^{\frac{L-f}{f} (c-r)} R \, dR$$

$$= \pi \left( \frac{rR}{2Lc} \right)^2 \left( \frac{L-f}{f} \right)^2 (c-r)^2$$

2. Partial overlap of image spot with detector, i.e. $c > r$, $\frac{L-f}{f} (c-r) < R \leq \frac{L-f}{f} (c+r)$

In this case the fraction of light falling on the lens which is detected is given by the overlap of the two circles radius $r$ and $c$ whose centers are separated by a distance

$$d = \left( \frac{f}{L-f} \right) R$$

This area is

$$c^2 (\alpha_1 - \sin \alpha_1 \cos \alpha_1) + r^2 (\alpha_2 - \sin \alpha_2 \cos \alpha_2)$$

where

$$\alpha_1 = \cos^{-1} \left[ \frac{c^2 + d^2 - r^2}{2dc} \right]$$

$$\alpha_2 = \cos^{-1} \left[ \frac{r^2 + d^2 - c^2}{2dc} \right]$$
Thus the total fraction of emitted light from all \( \frac{L-f}{f} (c-r) < R \leq \frac{L-f}{f} (c+r) \) which falls on the detector is

\[
F_2 = \left( \frac{R_L}{2L} \right)^2 2\pi \int \frac{L-f}{f} (c+r) R \left( c^2 (a_1 - \sin a_1 \cos \alpha_1) + r^2 (a_2 - \sin a_2 \cos \alpha_2) \right) dR
\]

This must be integrated numerically. For \( c < r \) the lower limit becomes \( \frac{L-f}{f} (r-c) \).

3. Image spot completely within detector, i.e. \( r < c, R \leq (r-c) \frac{L-f}{f} \)

In this case all light entering the lens falls on the detector

\[
F_1 = \left( \frac{R_L}{2L} \right)^2 2\pi \int_0^{(r-c)(L-f)/f} R dR
\]

\[
= \pi \left( \frac{R_L}{2L} \right)^2 (r-c)^2 \left( \frac{L-f}{f} \right)^2
\]

4. No overlap of image with detector, i.e. \( R > \frac{L-f}{f} (c+r) \)

No light is detected. This sets an upper limit to the size of the area contributing to the measured signal.

**Special Cases**

1. Detector on image plane, i.e. \( a = p, c = 0 \)

Then \( F_2 = 0 \) and from section 3 above

\[
F_1 = \pi \left( \frac{R_L}{2L} \right)^2 (r-c)^2 (L-f)^2
\]

\[
= \pi \left( \frac{R_L}{2L} \right)^2 (r-c)^2 (1 - \frac{f}{L})^2
\]

Thus the signal detected rises with \( L \) until, for \( L \gg f \), the signal is independent of distance, \( L \).
2. **Ha detectors**

These are arranged with a small area photodiode detector at the focal point of a lens with the intention that they should sample a column through the plasma. Their dimensions are:

\[
\begin{align*}
R_L &= 1.0 \text{ cm} \\
r &= 0.1 \text{ cm} \\
f &= 12.7 \text{ cm} \\
a &= 12.7 \text{ cm} \\
L &= 30 \text{ cm (plasma top)} \\
 &= 93 \text{ cm (plasma top)}
\end{align*}
\]

Numerical evaluation shows the following:

For \(L=30 \text{ cm}\): \(c=0.423 \text{ cm, } F_1=9.45 \times 10^{-6}, F=1.29 \times 10^{-5}\), while \(R_{\text{max}} = \frac{L-f}{f} (c+r) = 0.576 \text{ cm}\).

For \(L=93 \text{ cm}\): \(c=0.137 \text{ cm, } F_1=2.60 \times 10^{-6}, F=3.92 \times 10^{-6}, R_{\text{max}} = 0.863 \text{ cm}\).

Thus about 25% of the observed signal is from the farther plasma edge. This is the result of sampling a larger area at the bottom of the plasma (\(R_{\text{max}} = 0.863 \text{ cm}\)).

Adjustment of the photodiode position, \(a\), shows that the focal point position does indeed yield the largest ratio of plasma top to plasma bottom signals. Away from this point the increase in \(R_{\text{max}}\) for \(L=93 \text{ cm}\) tends to boost the unwanted signal from the far side of the plasma. Indeed, if the detector position is such that the top of the plasma is in focus, the spread of \(R_{\text{max}}\) at 93 cm is sufficient to produce an overwhelming signal from the bottom of the plasma with only a 25% increase in total top plasma signal (although from a very small area). Focusing the bottom of the plasma on the detector, however, yields \(F=3.6 \times 10^{-5}\) over a radius of 0.63 cm, while the signal from the plasma top is \(F=1.03 \times 10^{-5}\).

With the detector at the focal point of the lens a shift of the plasma from \(L=25\) to \(L=35 \text{ cm}\) causes a rise in signal from \(F=1.10 \times 10^{-5}\) to \(F=1.38 \times 10^{-5}\).
This multiplied by the expected change in recycling (see next section) yields

\[
\frac{I}{2AN_o R_o} F = 4.6 \times 10^{-7} \text{ at 25 cm.}
\]

\[
= 5.1 \times 10^{-7} \text{ at 35 cm.}
\]

Thus the measured Hα signal actually increases slowly with distance, going roughly as \(3/\sqrt{L}\) around this plasma position.
4. Recycling Dependence on Plasma Position

Approximate the top of the plasma as a long cylinder of radius $R_0$. Fig. 4 shows a plane section through the plasma along a torus radius. The problem then reduces to an essentially two dimensional situation. For simplicity, in order to obtain a qualitative idea of how the recycled flux depends on the geometry, we shall assume that the emission of neutrals from the plasma edge and the wall is essentially isotropic in the x-y plane. Then the particle density emitted from the plasma edge at any radius $R$ is

$$\frac{\pi R^2}{\pi R} N_0$$

Thus at any point $X$ on the upper wall the density is

$$\frac{N_0 R_0}{\sqrt{(X^2+L^2)}}$$

At any point on the side wall the density is

$$\frac{N_0 R_0}{\sqrt{[(L-y)^2+D^2]}}$$

If reemission of neutrals is proportional to the local neutral flux to the wall then the reemitted flux (which is also cylindically symmetric) into any point on the top of the plasma at $x$ from the point $X$ on the upper wall is

$$\pi R_0 \int \frac{dx}{\sqrt{(X^2+L^2)} \sqrt{[(L-\sqrt{(R_0^2-x^2)} + (X-x)^2}]}$$
Fig 4. Definition of plasma - containment vessel geometry.
From a point \( y \) on the outer wall, the reemitted flux into \( x \) will be

\[
\frac{\frac{\mathcal{A} \mathcal{N}_R \, dy}{\sqrt{(L-y)^2+D^2}}}{\sqrt{\left(\frac{1}{(D+x)^2+(L-y-\sqrt{(R_o-x)^2})^2}\right)^2}}
\]

Thus the total flux reemitted into the plasma at point \( x \) is

\[
I(x) = \frac{\mathcal{A} \mathcal{N}_R}{\sqrt{(L^2+x^2)}} \int_{-D}^{D} \frac{dx}{\sqrt{(L+x)^2+\left(\frac{1}{\sqrt{(L-y)^2+\left(\frac{1}{(R_o-x)^2}\right)}+\left(\frac{1}{(D+x)^2}\right)^2}\right)^2}} + \mathcal{A} \mathcal{N}_R \int_{0}^{L-R_o} \frac{dy}{\sqrt{D^2+(L-y)^2}\sqrt{\left(\frac{1}{\sqrt{(L-y)^2+\left(\frac{1}{(R_o-x)^2}\right)}+\left(\frac{1}{(D+x)^2}\right)^2}\right)^2}}
\]

Let us simplify by taking the case of a centrally located detector (which is most common for H\( \alpha \) studies) i.e. \( x=0 \).

The equations then become

\[
I(0) = \frac{2\mathcal{A} \mathcal{N}_R}{\sqrt{(L^2+x^2)}} \int_{0}^{D} \frac{dx}{\sqrt{(L+x)^2+\left(\frac{1}{(L-R_o)^2+x^2}\right)^2}} + \mathcal{A} \mathcal{N}_R \int_{0}^{L-R_o} \frac{dy}{\sqrt{D^2+(L-y)^2}\sqrt{\left(\frac{1}{\sqrt{(L-R_o-y)^2+D^2}}\right)^2+\left(\frac{1}{(D-x)^2}\right)^2}}
\]

Since \( 0<y<\frac{1}{2}(L-R_o) \) the second integral can be approximated as

\[
2\mathcal{A} \mathcal{N}_R \int_{0}^{\frac{L-R_o}{2}} \frac{dy}{\sqrt{\left(\frac{1}{\sqrt{D^2+(L-\frac{L-R_o}{2})^2}}\right)^2+\left(\frac{1}{y+D^2}\right)^2}}
\]
where \( Y = L - R_o - y \)

\[
2AN_o \frac{R_o}{L} \left( \frac{1}{\sqrt{\left[ D^2 + \left( \frac{L - R_o}{2} \right)^2 \right]}} \right) \left[ \frac{dY}{\sqrt{(D^2+Y^2)}} \right]^{L-R_o}_{0}
\]

\[
= 2AN_o \frac{R_o}{L} \ln \left[ \frac{L - R_o + \sqrt{D^2 + (L - R_o)^2}}{D} \right]^{L-R_o}_{0} - \left[ \frac{L - R_o}{2} \right]^2 \frac{D}{D^2 + \left( \frac{L - R_o}{2} \right)^2}
\]

The first integral is an elliptic integral of the first kind whose value is

\[
2AN_o \frac{R_o}{L} \frac{1}{L} F(a, q)
\]

where \( a = \tan^{-1} \frac{D}{L - R_o} \), \( q = \frac{\sqrt{L^2 -(L - R_o)^2}}{L} \)

The elliptic integral is obtainable from tables.

Thus

\[
\frac{I(0)}{2AN_o R_o} = \frac{1}{L} F(a, q) + \frac{\ln \left[ \frac{L - R_o + \sqrt{D^2 + (L - R_o)^2}}{D} \right]}{\sqrt{D^2 + \left( \frac{L - R_o}{2} \right)^2}}
\]

For our case \( R_o \approx 25\text{cm}, L \approx 50\text{cm} \) and \( D \approx 35\text{cm} \).

Hence

\[
\frac{I_o}{2AN_o R_o} = \frac{1}{50} F(54.4^\circ, 0.866) + 0.018 = 0.039
\]

For \( L=45 \),

\[
\frac{I_o}{2AN_o R_o} = \frac{1}{45} F(60.2^\circ, 0.896) + 0.015 = 0.042
\]

For \( L=55 \),

\[
\frac{I_o}{2AN_o R_o} = \frac{1}{55} F(49.4^\circ, 0.838) + 0.020 = 0.037
\]
From the above numbers we can deduce a rough power law dependence of recycling in the form

\[ I \sim 1/L^{0.63} \]

Thus as the plasma moves up and down, wall bombardment and consequent recycling do change.

From this we can see that while reemission from the top wall tends to dominate, reemission from the top of the side walls can also be a significant factor. Furthermore, while the detectors may sense only a limited region in the plasma edge, the recycling signal which is measured, in the absence of a strong recycling source results from wall emission over a wide area.
5. General Behaviour

5.1 Toroidal variations

In general the behaviour of the H_a signals was similar to that described in Progress Report #3. As before, toroidal variations were large, with peaks near the gas puff and limiter sectors. Two typical cases are shown in fig. 5. In fig. 5a a low gas puff, low electron density plasma is shown. At low \( \bar{n}(e) \) the incoming gas is confined in the gas puff sector, but spreads as \( \bar{n}(e) \) increases. At the same time the limiter sector H_a signal rises proportionally to \( \bar{n}(e) \) until it is comparable to the sector 10 signal. The H_a signals in sectors 11 and 15 also rise roughly proportionally to \( \bar{n}(e) \). The sector 10 signal shows little dependence on \( \bar{n}(e) \). For a high density plasma (fig. 5b) the signal is dominated by the limiter recycling. It no longer peaks sharply around the gas puff region. The gas puff region signal does rise markedly with \( \bar{n}(e) \) (although not proportionally to it) showing that the fueling gas signal is not dominant for high density plasmas. The spreading of the gas puff signal around the machine at higher \( \bar{n}(e) \) may be the result of more rapid sputtering and the recycling mechanisms as the wall bombardment increases.

The sector 15 signal should be treated with reserve since the field of view of this detector is restricted by the upper rail limiter.

5.2 In/out shift correlations

Correlations of H_a signals with in/out plasma shifts have been observed frequently. In some cases the effect is quite striking. For example in shot# 46589 (see fig. 6) most of the fine structure in the H_a signal from channel 640 (sector 10 at 1.17 in radius) is identical to that in channel 665 (sector 11 at 1.11 in radius), peaks in whose H_a spectra correspond to positive (outward) displacements of the plasma. Simultaneously, channels 670 and 641 (sectors 11 and 14 at 0.92 radius) show sharp dips at these points.
Fig. 5 (a) $\text{H}_\alpha$ signals at various times around ISX-B.

Shot #47450
signal at 150 ms
\[ n(e) = 2.2 \times 10^{13}, \text{ 4 Torr 1/s} \]

signal at 280 ms
\[ n(e) = 5.1 \times 10^{13}, \text{ 51 Torr 1/s} \]

signal at gas puff peak
\[ n(e) = 1.8 \times 10^{13}, \text{ 18 Torr 1/s} \]

Fig 5 (b) H signals at various times around ISX-B.

Shot #51291
sector 10
channel 640
1.17 m radius

sector 11
channel 670
0.92 m radius

sector 11
channel 665
1.11 m radius

sector 14
channel 641
0.92 m radius

in/out shift

Fig. 6. $H_\alpha$ and in/out shift data for shot #46589.
These variations in the Hα signals could reflect either changes in
gallery (i.e. the position of the plasma edges with respect to the detector)
or true changes in recycling. Calculations of the measured Hα intensity from
the top and bottom of the plasma after the methods of section 3 (above) show
that, for a reasonable plasma shape the Hα signal of the outer detector
(channel 666) should decrease about 6% for a 5cm outward plasma shift and
should increase about the same amount when the plasma shifts in 5cm. For the
inner detector (channel 670) the signal goes up on an outward plasma shift and
down on an inward shift. These changes are opposite in sign to what is
actually observed. Thus the signal changes cannot be due to geometrical
factors.

We can see from section 4 that as the plasma shifts outwards the outer
wall will be more heavily bombarded, leading to an increase in recycled flux
to the plasma edge beneath the outer detector and a decrease beneath the inner
one as we have observed experimentally. The analysis of this situation is
quite complicated and will not be attempted here. Nevertheless inspection of
the general form taken by the equations of section 4 suggests that the effect
will in general be quite substantial. If a local recycling source is present
near the inner or outer wall the effect will be more marked.

5.3 Dependence on fueling condition - co-and counter-injection

In our progress report #3 we described how the Hα signals are affected by
various types of fueling gas puffing, neutral beam injection and pellet
injection. ISX-B now has co-and counter-injection beam lines installed. It
is of interest to determine whether recycling behaviour changes with the type
of injection used. Because of differences in gas puffing, n(e) and other
parameters it is difficult to compare the data. However, there are no obvious
differences in the way the recycling behaves between the two types of neutral
beam injection.

5.4 Performance of fan detectors

The spectra produced by the fan detectors are very similar in shape to those of the narrow field detectors, see fig. 7. This is to be expected, especially in sectors 1 and 11 where the narrow field and fan field detectors are adjacent. We have already shown that the narrow field detectors measure particle emission from a broad wall area. The fan field detectors also integrate this signal over a larger plasma edge area. Thus differences would be expected only if the plasma was very inhomogeneous or there was a strong recycling centre abutting the plasma in the field of view of one detector but not of the other.

The fan field detectors were calibrated with respect to each other. If we compare their signals for a typical shot (52323) we find that the ratios of the corrected \( \frac{N}{N_a} \) signals of the fan detectors with those of their closest narrow field detectors are as follows:

- **Sector 13,14**
  \[
  \frac{\text{ch 641 (phot/s)}}{\text{ch 1375 (bits)}} = 7 \times 10^8
  \]

- **Sector 11**
  \[
  \frac{\text{ch 670}}{\text{ch 1377}} = 4 \times 10^8
  \]

- **Sector 1**
  \[
  \frac{\text{ch 666}}{\text{ch 1376}} = 4 \times 10^7
  \]

It is clear that in sector 1 the fan detector shows a relatively far higher signal than its narrow field counterpart on the adjacent flange. This suggests either a strong recycling centre at the plasma edge visible only to the fan detector or unusually strong \( H_\alpha \) emission from the plasma bottom (which is sampled to a greater extent by the fan detector) or, probably more likely, a partially obscured window beneath the narrow field detector. A recent check
Fig. 7. Narrow- and wide-field $H_\alpha$ signals around ISX-B. Shot#52323.
of the window shows that this indeed seems to be the case.

5.5 Comparison of H α data with neutral flux spectra

Thomas¹ has reported measurements of the low energy neutral flux (up to 700eV) to the wall as a function of time in ISX-B. His analyser was attached to the outer wall of sector 10, where gas puffing takes place. He notes strong similarities between the neutral flux and the H α signal, indicating that the recycled flux measured by the H α detectors is caused by wall bombardment with low energy charge exchange neutrals.

Unfortunately, although the presence of gas puffing in sector 10 provides a large neutral flux to the wall, it also confuses the H α data. The data of shot 40319 (fig. 8), for example shows the H α signal in sector 10 rising in concordance with the gas puff. The neutral flux to the wall, however, shows a clear 20-30ms delay, as does the H α data taken in sector 14. Thus, as we have observed before, the principal H α signal in sector 10 results from direct impingement of the incoming gas on the plasma edge. Only its slow subsequent rise is due to recycling. The correspondence of the delay time in the neutral flux to the wall, with that observed in the H α signals away from the gas puff shows that signals do indeed result from slow neutral bombardment of the wall. Furthermore, the recycling follows immediately on wall bombardment, requiring no particle residence time at the wall. The recycling times found in the H α data are therefore the confinement times.

The neutral flux data show that almost all the neutral flux is below 100eV. Also, only the lowest energy neutral channel (200eV) tends to show a monotonic rise with time during steady gas puffing as do the H α signals. This again shows that the H α signals emanate from fuel recycled as a result of wall bombardment with low energy neutrals (<100eV). Since the reflection coefficient of such low energy neutrals is close to 100%, it follows that most

Fig. 62. Neutral flux measured by spectrometer for shot nos. 40319 and 40355. Energies for the four channels are 200, 300, 400, and 500 eV, respectively. Flux behavior in this energy range is identical to that of $D_a$ emission when the gas puff is turned off and on late in the shot.

Fig. 63. Gas puff and $D_a$ signals for shot nos. 40319 (solid line) and 40335 (dotted line). Gas is turned off at 145 ms at the latter shot, and the $D_a$ intensity drops rapidly during this time to essentially zero. As gas is turned back on at 190 ms, $D_a$ intensity rises rapidly.

Fig. 8. Comparison of $H_\alpha$ and slow neutral fluxes in sector 10.

(From ORNL/TM-8671 report, D. M. Thomas, 1983.)
of the \( H_\alpha \) signal, at least in the region of the gas puff, is given by particles reflected from the walls with only a small contribution from gas released from the walls. If a similar neutral energy spectrum exists elsewhere around the machine we should expect the source of \( H_\alpha \) signal to be the same.

6. **Pump Limiter Experiment** 7/18/83

The fan field detector in channel 1375 was set up so that it pointed towards the pump limiter installed in sector 13. Several sequences of shots were run with different gas puff settings and \( \bar{n}(e) \) values with the limiter pumps not activated. The pumps were then activated and the sequences repeated.

In most cases the \( H_\alpha \) data taken with the pumps activated were virtually indistinguishable from the equivalent shots taken before activation (see fig.9). Deviations of any significance were due to variations in the gas puff rate or \( \bar{n}(e) \). This was even true for channel 1375 whose detector was pointed at the upper pump limiter.

7. **Summary**

Recent \( H_\alpha \) data are in general agreement with those reported earlier. The narrow field detectors gather about a quarter of their signal from the opposite side of the plasma. Because of the separation of the plasma from the walls the flux entering the plasma edge at the measuring point can come from a broad wall area, including adjacent sectors. We should therefore expect that in the absence of strong recycling centers, \( H_\alpha \) measurements would be characteristic of the general recycling in that area of the machine. The \( H_\alpha \) signals seem to result principally from reflected charge exchange neutrals with energies less than 100eV, except near the gas puff, where the primary signal arises from the fueling gas entering the plasma edge directly. The delay times seen in \( H_\alpha \) data appear to be measures of the confinement time.
Fig. 9. $H_\alpha$ signals for equivalent shots, before pump limiter activation (solid, shot #51978) and after activation (dotted, shot #52002).
Anything which increases the charge exchange neutral flux, such as neutral beam injection, gas puffing and pellet injection tends to raise the $H_d$ signal. However there appears to be little difference between co-and counter-injection. The operation of pump limiters has no apparent effect on the $H_d$ signal. This is to be expected if the signal principally comes from reflected slow neutrals, since their reflection coefficient near the pump entrance is unchanged merely by activation.

Fan field detectors have been installed in several places around the machine. Their behaviour is similar to that of the narrow field detectors as we should expect.