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A FAST CCD DETECTOR FOR CHARGE EXCHANGE RECOMBINATION SPECTROSCOPY ON THE DIII–D TOKAMAK

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GENERAL ATOMICS

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ABSTRACT

Charge Exchange Recombination (CER) spectroscopy has become a standard diagnostic for tokamaks. CER measurements have been used to determine spatially and temporally resolved ion temperature, toroidal and poloidal ion rotation speed, impurity density and radial electric field. Knowledge of the spatial profile and temporal evolution of the electric field shear in the plasma edge is crucial to understanding the physics of the L to H transition. High speed CER measurements are also valuable for Edge Localized Mode (ELM) studies. Since the 0.52 ms minimum time resolution of our present system is barely adequate to study the time evolution of these phenomena, we have developed a new CCD detector system with about a factor of two better time resolution. In addition, our existing system detects sufficient photons to utilize the shortest time resolution only under exceptional conditions. The new CCD detector has a quantum efficiency of about 0.65, which is a factor of 7 better than our previous image intensifier-silicon photodiode detector systems. We have also equipped the new system with spectrometers of lower f/number. This combination should allow more routine operation at the minimum integration time, as well as improving data quality for measurements in the divertor-relevant region outside of the separatrix. Construction details, benchmark data and initial tokamak measurements for the new system will be presented.

I. INTRODUCTION

Charge exchange recombination (CER) spectroscopy is a standard diagnostic technique on magnetic fusion devices equipped with neutral hydrogen beam injection.[1–8] Utilizing the Doppler broadening and Doppler shift of various spectral lines, the ion temperature T_i, toroidal rotation speed V_ϕ and poloidal rotation speed V_θ have been measured. The intensity of the spectral line, combined with neutral beam deposition calculations, give the number density n_I of the species in question.[9] As is discussed in Ref. 10, combining these measurements with the radial force balance equation allows determination of the radial electric field E_r. Finally, measurements of the intensity of the D_α radiation from the neutrals in the beam allows one to check the beam deposition calculation.[11]

For the past decade, we have deployed on the DIII–D tokamak a multichord CER system,[3,12] resulting in substantial progress in understanding tokamak transport and confinement. In particular, the capability to determine E_r, coupled with a theoretical interpretation of sheared E×B suppression of turbulence, has played a key role in understanding the formation and maintenance of the various improved confinement regimes which have been discovered over the past several years.[10,13,14] The present system, which has 32 spatial channels spanning the tokamak minor radius, utilizes detectors based on a combination of microchannel plate image intensifier and silicon photodiode array coupled to fiber-fed spectrometers. The fiber views in the tokamak set the spatial resolution which is as small as 0.5 cm in the edge region. The minimum time resolution of the system is 0.52 ms which is, for example, barely adequate to address the evolution of E_r across the L-to H transition under most condition.[14] The decay time of the P-20 phosphor on the image intensifiers used in the present system may also be compromising the time resolution of that system.

It has been clear for some time that significant improvements in the signal, signal to noise and minimum integration time of the DIII–D CER system would require completely different technology than the intensified diode array technology that we have been using. CCD technology has been the choice of other groups;[4] however, until about 2 years ago, the readout speed of CCDs was too slow to meet our needs. With recent advancements, CCDs can now be superior to intensified diode arrays even when used at sub-millisecond integration time. This paper discusses the status of our development of a 16 chord CCD CER system to upgrade the edge CER system[3] on DIII–D.

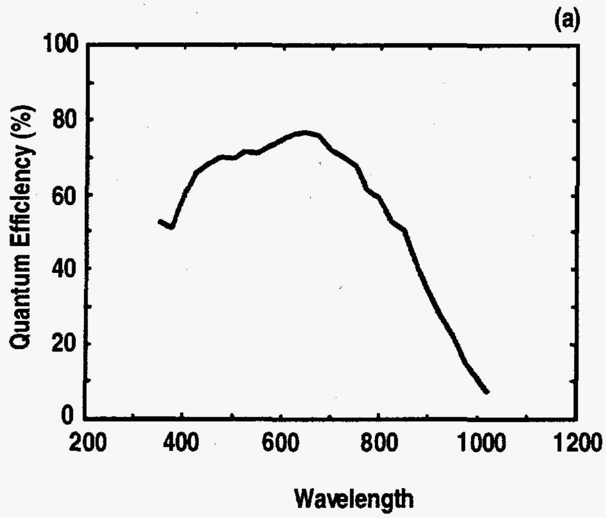
II. DESIGN PHILOSOPHY AND CHOICES

Our design choices were based on the philosophy that the new system should achieve significantly better signal and signal to noise than the present system in order to make it worth the development effort. The signal, based on photoelectrons in the detector, should be well above that achieved with the intensified diode array system; this requires that the quantum efficiency of the detector be well above the 10% than can be obtained with standard image intensifier. In addition, the minimum integration time should be well below the 0.52 ms already obtained. Furthermore, the detector should maintain good linearity at the high signal levels needed to utilize short integration times. Finally, the detector should still have many pixels across the 5 to 6 nm wavelength range needed for the measurement in order to be able to accurately measure the complex spectra which usually are seen. (The idealized case of a single, isolated spectral line is essentially never seen in practice on DIII–D.) Indeed, we wanted to increase the dispersion (in pixels/nm) in order to improve the accuracy of our rotation speed measurements.

The new spectrometer and detector system had to work with constraints provided by the existing tokamak optics and the optical fibers which bring the signal to the spectrometers. The existing tokamak optics and fiber optics have an effective f/number below f/4. In addition, the fibers have a 1.5 mm core diameter. Furthermore, since this system will be the main ion temperature diagnostic on DIII–D, the CCD readout and data acquisition had to be flexible enough to allow coverage of shots up to 10 s long. The previous system could take data at multiple times during the shot and we needed to maintain this option.

In order to push the signal levels as high as possible, the detector should have good quantum efficiency and its coupling to the spectrometer should minimize light loss. The best quantum efficiency is available with a back-illuminated, thinned CCD chip. The quantum efficiency of these chips is two to three times that of the front illuminated chips. Furthermore, to minimize losses, one of the design goals was to allow no optical elements between the CCD detector and the spectrometer. Fiber optic image transformers, which were used in our previous design,[3] were ruled out by this criterion. Finally, image intensifiers were ruled out of the design because of the linearity criterion and the low quantum efficiency. We have seen significant nonlinearity at high light levels with our two-stage MCP intensifiers which has limited the gains we can use, thus making it harder to utilize short integration times. In addition, the most efficient phosphors for image intensifiers, P20, has a multiexponential time decay which makes it difficult to assess whether the phosphor is limiting the time resolution under a given set of conditions. Eliminating the image intensifier had an additional advantage, since the electron amplification process in an intensifier adds noise, effectively multiplying the photon statistics standard deviation by a factor of 1.8.

After considerable research, the CCD detector chosen was the VCCD 512.[15] The active area of this chip is 9.2 by 9.2 mm; this is divided into an array of 512 by 512 pixels, each 18 microns on a side. The quantum efficiency of this back-illuminated, thinned chip is shown in Fig. 1(a). It



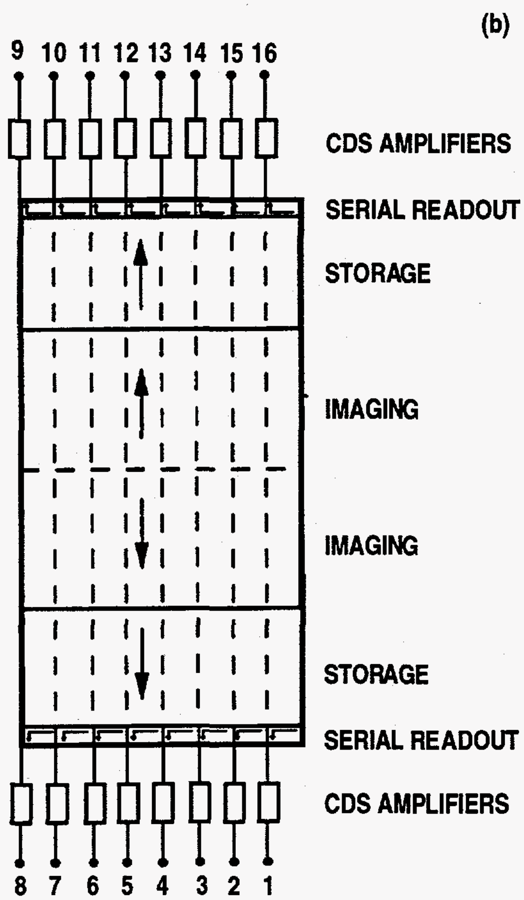


Fig. 1. (a) Quantum efficiency as a function of wavelength for the VCCD 512 imager. (b) Diagram of the VCCD imager showing how the chip is read out. The upper and lower halves of the 9.2 x 9.2 mm chip are readout through separate paths; each horizontal shift register is divided into 8 subregisters to increase the speed. Both halves of this figure were provided by David Sarnoff Research Center.

exceeds the quantum efficiency of the S20 photocathodes in our intensifiers by a factor of 6 to 8 in the wavelength range of interest. As is shown in Fig. 1(b), high readout speed is achieved by utilizing 16 parallel channels to readout the chip. Utilizing on chip summing, we have achieved a minimum integration time of 0.3 ms in a configuration where four spectra are spread across the vertical extent of the chip. The horizontal shift register of the chip saturates when each well contains approximately 600,000 electrons. Since the rms readout noise at the readout speed we use is about 45 electrons, the chip has about a 14 bit dynamic range.

The physical size of the chip, the desire for fast readout and cost considerations require trade-offs in the choice of spectrometers and in how the light is coupled to the spectrometer. Cost can be reduced if more spectra are imaged onto one chip; however, readout time is increased. A reasonable cost compromise was to image four spectra onto one chip, thus requiring four spectrometers for the 16 chords. Once that choice was made, it was clear that the CCD chip was big enough that it could be located directly at the exit focal plane of the spectrometer, without the need for intervening optics to reduce the image size. Each of the four 1.5 mm tall spectra is separated from the next by a 0.8 mm guard band. Since the f/number of the light coming through the fibers from the tokamak was smaller than that of most commercially available Czerny-Turner spectrometers, we could completely fill the spectrometer grating by locating the tips of the fibers at the entrance slit without any need for coupling optics at the entrance slit. Under these conditions, where the grating is always filled, the effective f/number of the spectrometer, based on the size of the grating, determines the system throughput. In addition, given the 1.5 mm core diameter of the fibers and the constraint of image sizes at the exit plane no taller than 1.5 mm, no combination of entrance and exit slit optics will result in greater photon throughput.

The spectrometer characteristics required some compromise between signal level and dispersion. Given the constraints discussed in the last paragraph, the highest signal would require a short focal length instrument with low f/number; however, the best dispersion is available at long focal lengths. The best compromise was the ACTON model 506 spectrometer.[16] This has a 0.66 m focal length and, with the 120 by 140 mm grating, an f/number of f/4.7. For additional dispersion, we utilized a 1200 g/mm grating blazed for 1000 nm, which is near the second order of the wavelength of the lines of interest. The dispersion in pixels/nm has increased about a factor of 1.6 over that of our present system. The lower f/number results in an increase in light collection by a factor of 2.1 relative to the spectrometers used with the intensifier-based detectors.

Each of the 16 output lines from the chip is digitized using an individual channel of a 14-bit digitizer (DSP Model 2840).[17] The maximum digitizing rate of the 2840 is 1.1 MHz; this limits the minimum integration time of the system to 0.3 ms, roughly a factor of two better than the old system. (The CCD chip itself can be read out at least another factor of two faster; however, utilizing this capability would require developing a 7 MHz, 14-bit digitizer.) The digitizers are controlled by General Atomics CDC-1 digitizer controllers.[18] Once digitized, the data is transferred to General Atomics DAD-1 FIFO buffer[19] interfaced with a CSPI SuperCARD[20] containing an Intel i860 processor with 16 MByte memory. One CDC-1/DAD-1 pair can acquire data simultaneously from two

CCD chips. The entire system is controlled by a FORCE SparcStation II[21] computer. We have developed IDL-based modules for data viewing and processing as well as remote control of the experimental parameters such as wavelength and integration time.

The data acquisition system is based on that used on the real time plasma control system on DIII–D.[18,19] Since the data are in computer memory during the shot, there is considerable flexibility in the data acquisition system. For bright lines, data can be sampled at shorter integration times and then summed before final storage to increase the dynamic range. In addition, a future possibility is real time feedback control of ion temperature or rotation, based on neural net analysis of the spectra.[22]

III. INITIAL TOKAMAK DATA

The first two spectrometers equipped with CCD detectors took data during the 1995 run campaign on DIII–D. These were coupled to the tokamak using extra fiber optics which were located between the fibers used for the intensifier-based system.

As an initial check of the time response of the system, we examined the Doppler-shifted D_α radiation from the neutral beams when the beams are periodically modulated. Previous measurements with a fast photodiode digitized at 1 MHz shows that the beams turn on in about 100 μs and turn off in about 60 μs. The turn off looks particularly sharp, since it is effected by turning off the high voltage; the turn on is more gradual since switching on the high voltage also alters conditions somewhat in the ion source. By scanning the start time of the CCD data acquisition system in 100 μs increments from shot to shot, we found the start time which showed the sharpest modulation in the Doppler-shifted D_α signal. This modulation of the signal on one pixel on the CCD detector is shown in Fig. 2. The delay of the start time is 100 μs from the nominal trigger time for beam turn off, consistent with the previously measured turn off time. Since there is no smearing of the detected signal from the CCD system across the beam turn off, the data in Fig. 2 indicate that the intrinsic time resolution of the CCD system is well below the 0.3 ms minimum integration time.

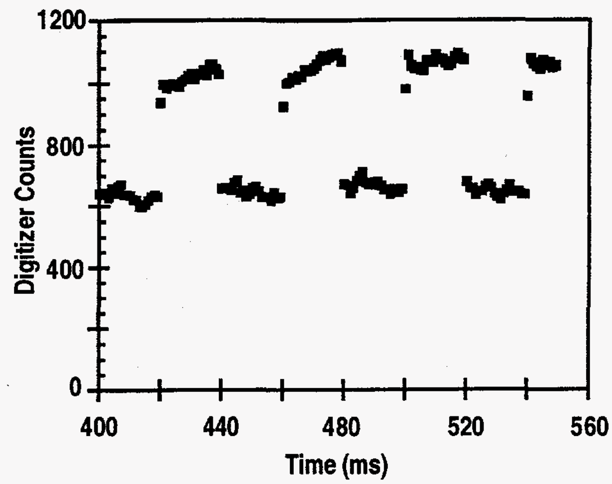


Fig. 2. Detected signal in a single pixel at a wavelength near the peak of the Doppler-shifted D_α signal from the 30 LT neutral beam on DIII–D when the beam was modulated 20 ms on, 20 ms off. The modulation triggers occurred at integer multiples of 20 ms after the start of the tokamak shot. The start trigger for the CCD system timing was at 400.1 ms. The 0.1 ms delay allows for the time it takes for the beam to turn off after receiving the trigger. The integration time of the CCD system was 1.0 ms for these data.

The rapid time response of the CCD system is also shown in Fig. 3(a), where we have plotted the signal in a single pixel as a function of time during the ELMing phase of an H–mode discharge. As can be seen by comparing with the D_α signal in Fig. 3(b), the edge plasma variation during the ELM modulated both the D_α and the C VI signal. The signal level from the CCD system is sufficient to begin resolving changes in T_i and V_{rot} across the lifetime of one of these transient structures. The prospect of interpreting the evolution of the associated electric field structure on this timescale is exciting and such measurements will help further our understanding of tokamak confinement and transport.

The fibers coupling the CCD system to the tokamak at present do not include any which see the very edge of the plasma. Accordingly, we have yet to do L to H transition studies with the CCD system. We have looked at the change in C VI toroidal and vertical rotation speeds across

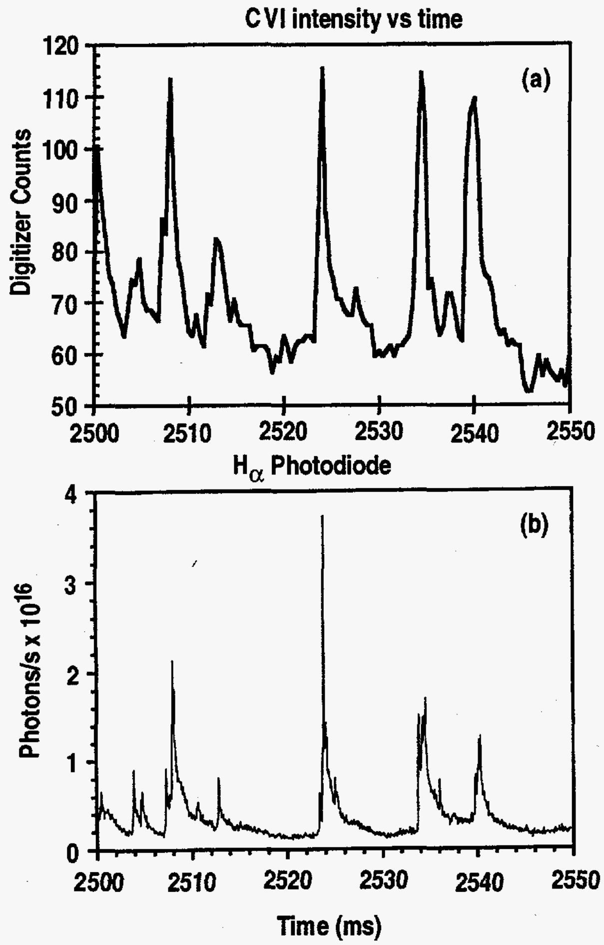


Fig. 3. (a) Signal intensity at a wavelength near the peak of the C VI line during the ELMing phase of an H–mode discharge in DIII–D. The integration time of the CCD system is 0.40 ms. (b) Signal intensity from a D_α photodiode showing the ELM-induced modulation.

the L to H transition at a point about 5 cm inside the separatrix. The change in the toroidal rotation speed is illustrated in Fig. 4.

Comparison of the signal on the CCD system with that on the intensifier based system shows that the number of photoelectrons per pixel has increased by about a factor 10. The increase in dispersion in pixels/nm of a factor of 1.6 indicates that the increase in signal per unit wavelength interval is about a factor of 16. Under conditions where photoelectron statistics dominate the signal to noise, the CCD system has a better signal

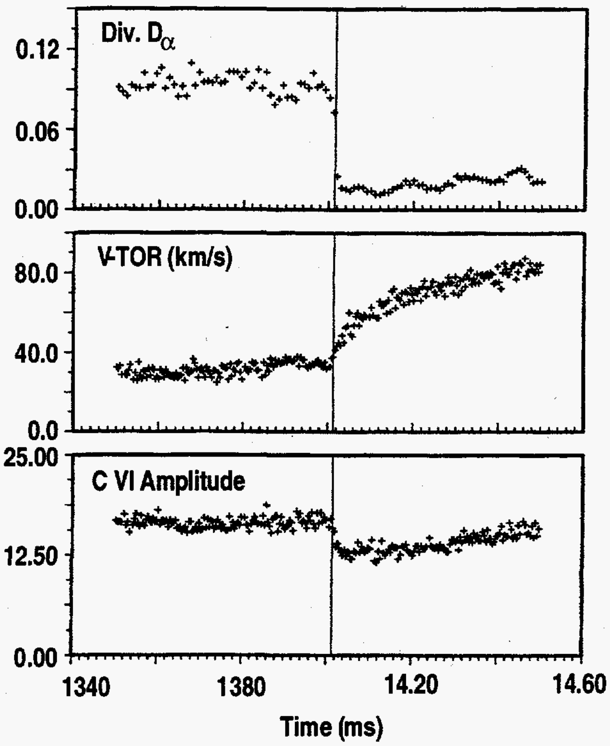


Fig. 4. The C VI rotation and signal intensity measured along a tangential viewing chord located about 5 cm from the plasma edge showing the change in rotation across the L to H transition. Also shown is the D_α signal from the plasma edge; the drop in this signal indicates the time of the L to H transition. The integration time for the CCD system was 0.4 ms for these data.

to noise ratio by a factor of about 6 than the intensifier-based system. (The difference in signal to noise is not just the square root of the signal ratio because, as mentioned previously, the amplification process in an image intensifier increases the noise.)

Initial operation of the CCD system revealed one major drawback relative to the intensifier-based system; the CCD is much more sensitive to neutron/γ radiation produced by D-D fusion reactions and the subsequent production of γ rays by neutron capture. The CER spectrometers for both systems are located just outside the DIII–D neutron shield. While the intensifier-based system had no significant problems with n/γ radiation, we have had to equip the CCD system with a significant amount of neutron shielding. Our present shield has shielding material on five sides, with the spectrometer being on the sixth side. We use 6.5 cm of lead and 15 cm of borated polyethylene as a shield. This had provided about a factor of 40 reduction in the n/γ hits on the detector. Since the lead shield alone produced a factor of 20 reduction, the CCD hits are clearly due primarily to γ rays. This is interesting, since the neutron dose in milliREM in the CER room is a factor of 100 greater than the γ dose. These results indicate that adding as much lead as possible on the sixth side of the shield would result in greater reduction in the n/γhits.

IV. FUTURE PLANS

Our ultimate goal is to replace the intensifier-based system for the 16 edge chords of the DIII–D CER system. In order to reach that goal, we still have several jobs left. First, the post amplifier which couples the Sarnoff electronics to the DSP 2840 digitizers needs improvement. We have yet to achieve the 45 electron rms readout noise because the amplifier is adding about a factor of two to the electronic noise. Second, although the factor 40 reduction in the n/γ hits is significant, we really need another factor of 3 to 5 reduction. This will require rebuilding the mounting structure for the CCD to include more lead between the CCD and the spectrometer. Third, since each spectrometer is coupled to 4 spatial chords, we need to finish building the final two detector systems.

V. REFERENCES

[1]R. C. Isler, Phys. Rev. Lett. **30**, 1359 (1977).

[2]R. J. Fonck, D. S. Darrow, and K. P. Jaehnig, Phys. Rev. A **29**, 3288 (1984).

[3]P. Gohil, K. H. Burrell, R. J. Groebner, J. Kim, W. C. Martin, E. L. McKee, and R. P. Seraydarian, in the Proceedings of the Fourteenth IEEE/NPSS Symposium on Fusion Technology, (IEEE, Princeton, 1992) Vol. II, p. 1199.

[4]M. von Hellermann, W. Mandl, H. P. Summers, H. Weisen, A. Boileau, P. D. Morgan, H. Morsi, R. Konig, M. F. Stampf, and R. Wolf, Rev. Sci. Instrum. **61**, 3479 (1990).

[5]R .J. Fonck, R. J. Goldston, R. Kaita, and D. Post, Appl. Phys. Lett. **42** (1983) 239

[6]Y. Koide, et al., Phys. Rev. Lett. **72**, 3662 (1994).

[7]K. Ida and S. Hidekuma, Rev. Sci. Instrum **60**, 867 (1989).

8K. Ida, H. Yamada, H. Iguchi, K. Itoh, and CHS Group, Phys. Rev. Lett. **67**, 58 (1991).

[9]A. Boileau, M. von Hellermann, L. D. Horton, H. P. Summers, Plasma Physics and Controlled Fusion **31**, 779 (1989).

[10]K. H. Burrell et al., Phys. Plasmas **1**, 1536 (1994).

[11]R. P. Seraydarian, K. H. Burrell, et al., Rev. Sci. Instrum **59**, 1530 (1988).

[12]R. P. Seraydarian and K. H. Burrell, Rev. Sci. Instrum. **57**, 2012

(1986).

[13]K. H. Burrell Plasma Phys. Controlled Fusion **36**, A291 (1994).

[14]K. H. Burrell, M. E. Austin, T. N. Carlstrom, S. Coda, et al., Plasma Physics and Controlled Nuclear Fusion Research 1994 (IAEA, Vienna, 1995) Vol I, p. 221.

[15]David Sarnoff Research Center, Princeton, NJ 08543.

[16]ACTON Research Corporation, Acton, MA 01720.

[17]DSP Technologies, 48500 Kato Road, Fremont, CA 94538.

[18]J. R. Ferron, Rev. Sci. Instrum. **63** (1992) 5464.

[19]J. R. Ferron and E.J. Strait, Rev. Sci. Instrum. **63** (1992) 4799.

[20]CSP, Inc., 40 Linnell Circle, Billerica, Massachusetts 01821.

[21]FORCE Computers, San Jose, California 95124.

[22]D. R. Baker, R. J. Groebner, and K. H. Burrell, Plasma Phys. Control. Fusion **36** (1994) 109.

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