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Initial Deuterium Pellet Experiments on FTU

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J. A. Snipes
MIT Plasma Fusion Center
Cambridge, MA, USA

Introduction Initial experiments have been performed with the Single Pellet INjector (SPIN) on FTU. SPIN[1] is a two-stage cryogenic deuterium pellet injector capable of injecting pellets with velocities up to 2.5 km/s. The nominal pellet mass for these experiments was approximately 1×10^{20} atoms. These initial pellet experiments concentrated on studying pellet penetration under a variety of plasma conditions to compare with code predictions[2] and to examine toroidal particle transport. The principal diagnostics used were two fast (~1 μsec) photomultiplier tubes at nearly opposite toroidal locations with H_α (D_α) interference filters ($\lambda = 656$ nm), a microwave cavity for pellet mass and velocity, a vertical array of soft x ray diodes without filters looking down onto the pellet, a DCN interferometer for electron density profiles, and a Michelson ECE system for electron temperature profiles. The time integral of the absolutely calibrated fast H_α signal appears to give reasonable agreement with the expected pellet mass. Toroidal transport of deuterium ions from the pellet to nearly the opposite side of the tokamak agrees with calculated thermal deuterium velocities near the plasma edge. Comparison of the experimental results with code calculations using the Neutral Gas Shielding model show good agreement for the post-pellet electron temperature and density profiles and the H_α profiles in some cases. Calculated penetration distances agree within 20%.

H_α Measurements The pellet H_α signals are measured using photomultiplier tubes that have fast time response (~1 μsec) to observe rapid changes in the ablation rate as the pellet traverses the plasma on a time scale of 100-200 μsec, typically. One signal, which views directly behind the pellet along its trajectory, was attenuated by an ND2 neutral density filter to eliminate stray light and prevent saturation of the photomultiplier tube. The other fast signal views the plasma radially in the midplane 210° away toroidally. The signals were absolutely calibrated including the fiber optics, interference and neutral density filters, and associated electronics.

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The distance penetrated into the plasma by the pellet is measured primarily by the duration of the H_α signal that views the pellet from behind times the measured pellet velocity. The pellet velocity is also measured using the H_α signal by taking the distance from the pellet microwave cavity to the plasma divided by the time difference between the pellet signal in the microwave cavity and the rise of the H_α signal. In addition, an array of soft x ray diodes without filters viewing the plasma from above at the pellet location has been used to follow the pellet trajectory within the plasma. The diode signals exhibit a short burst of light, lasting 20-50 μsec, typically, as the pellet passes their field of view. From the timing between bursts and the geometry of the diode views, the penetration distance and pellet velocity can also be determined. These data also indicate that the pellet velocity remains constant as it traverses the plasma. Good agreement is found between these two methods of determining the penetration distance and the pellet velocity.

By absolutely calibrating the H_α signal that views the pellet from behind, the integral in time and solid angle gives the total number of photons emitted by the pellet. This number should then be proportional to the number of deuterium atoms in the pellet assuming all atoms are ionized. Using the proportionality constant of $f = 0.03$ photons/atom found by McNeill,[3] reasonable agreement is found between the calculated number of atoms in the pellet and the measured density rise after the pellet. Figure 1 shows a typical H_α trace and its integral divided by 0.03 to give the total number of atoms in the pellet after it is completely ablated.

The time required for the toroidal transport of deuterium particles from the pellet can also be measured by the time delay between two fast H_α signals in the midplane, one looking directly at the pellet and the other 210° away toroidally. Figure 2 shows an example of the measured time delay between the two H_α signals of about 57 μsec. Similar particle transport effects from pellets have been observed with a fast interferometer on TFTR.[4] Assuming the rise in the second signal is due to increased recycling at the plasma edge when the deuterium particles from the pellet arrive at that location, the distance travelled by these particles is approximately 4.5 m, which yields a velocity of about 8×10^4 m/s. Comparing this to a thermal deuterium velocity leads to a temperature of about 130 eV. This may be interpreted as an average thermal speed of the arriving pellet particles.

Pellet Ablation Code Comparison A pellet ablation code employing Houlberg's Neutral Gas Shielding model[3] has been used to calculate the ablation and penetration of pellets in FTU to compare with the experimental results. Fits to the experimental electron density and temperature profiles just before pellet injection are input into the code along with the pellet mass and velocity. In some cases, the calculated temperature and density profiles just after complete ablation of the pellet agree reasonably well with experiment (Fig. 3). Note that the code calculation stops when the pellet is completely ablated and does not include radial energy transport that will lower the central electron temperature before the pellet reaches the plasma center.

The calculated H_α profile also agrees well with the measured profile in some cases (Fig. 4a). Note that the calculated profile has been normalized to the measured profile by forcing the total number of photons emitted to be equal. In other cases, however, the calculated and measured profiles do not agree as well in that the calculated profile begins to rise much later in the plasma and then rises much more steeply than the experimental profile (Fig. 4b). It appears that the neutral gas shielding is too strong in the early stages of ablation in comparison with experiment.

The penetration distances were also calculated by the code and gave reasonable agreement with experiment to within ± 20%. The calculated versus measured penetration distances are shown in Figure 5 for the cases in which the pellet did not pass the center of the plasma. Since many of the higher velocity pellets do pass the plasma center, the code will need to be modified to include calculations of the penetration beyond the center.

Conclusions The initial deuterium pellet results on FTU show reasonable agreement with the Neutral Gas Shielding model for the final penetration distances of the pellets that do not pass the plasma center, though the shape of the calculated H_α profile disagrees with the measured profile. Integrals of the absolutely calibrated H_α signal viewing the pellet from behind provide a good measure of the pellet mass assuming 0.03 photons/atom. The delay between two toroidally displaced H_α signals indicates particle transport velocities on the order of the average thermal deuterium velocity in the post-pellet plasma.

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References

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[2] W. Houlberg, et al., Nuclear Fusion, **28** (1988) 595.

[3] D. H. McNeill, Journal of Nuclear Materials, **162-164** (1989) 476.

[4] D. K. Mansfield, A. Janos, D. K. Owens, G. L. Schmidt, M. G. Bell, et al., Phys. Rev. Lett., **66** (1991) 3140.

Figure Captions

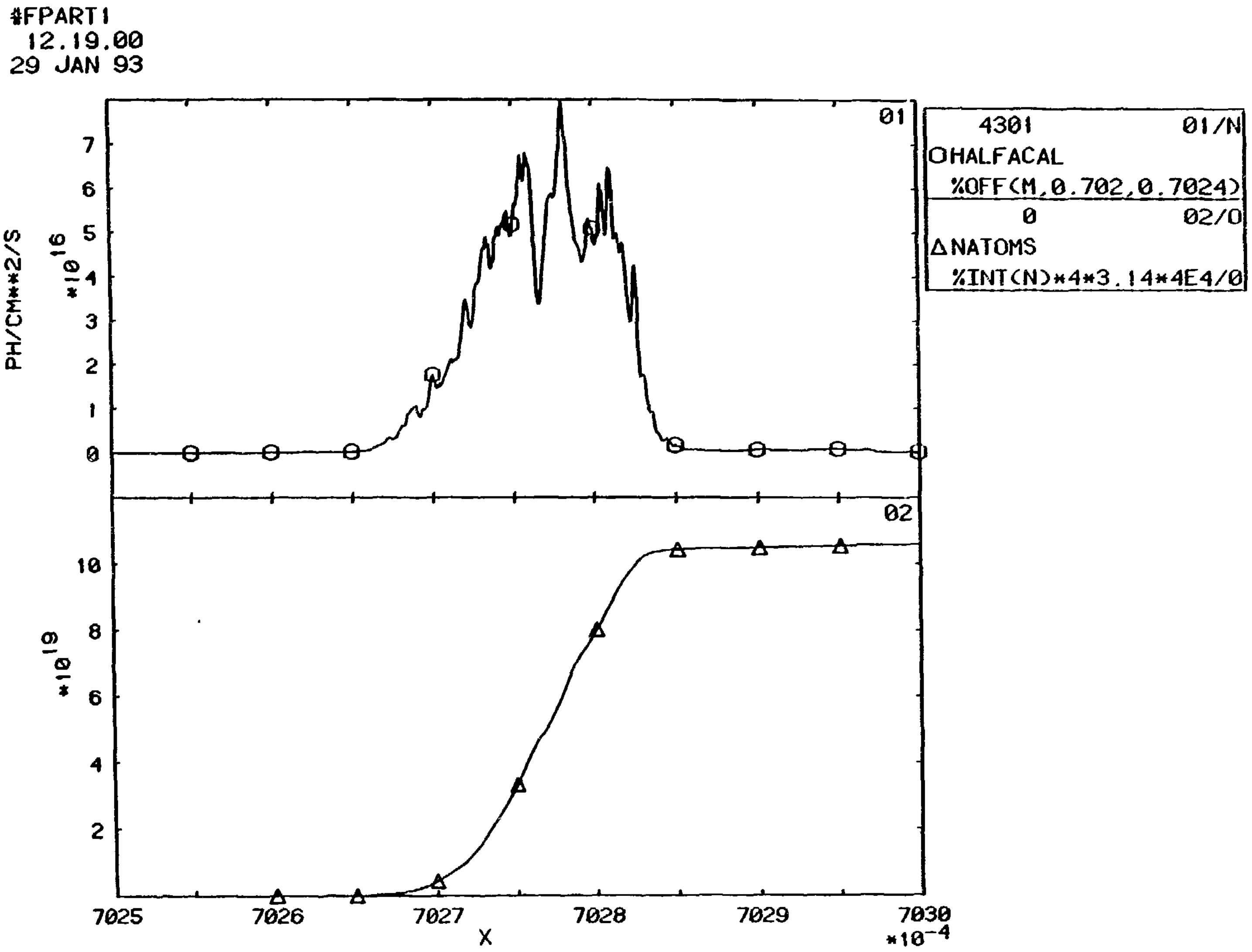
Fig.1. Calibrated H_α signal and its integral in time and solid angle. At the end of the pellet ablation, the integral is equal to the number of atoms in the pellet.

Fig. 2. Comparison of two H_α signals separated by 210° toroidally showing a delay of about 57 μsec before the arrival of the pellet particles.

Fig. 3. Comparison of the measured and calculated a) electron temperature and b) electron density profiles before and after pellet injection.

Fig. 4. Comparison of the measured and calculated H_α profiles during pellet ablation. Case a) shows good agreement with experiment, while case b) shows disagreement.

Fig. 5. Comparison of the calculated and measured penetration distances for discharges in which the pellet did not pass the plasma center.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*10^19
7
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5
4
3
2
1
0
10
8
6
4
2
7025
7026
7027
7028
7029
7030
*10^-4
X
4301 01/N
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△NATOMS
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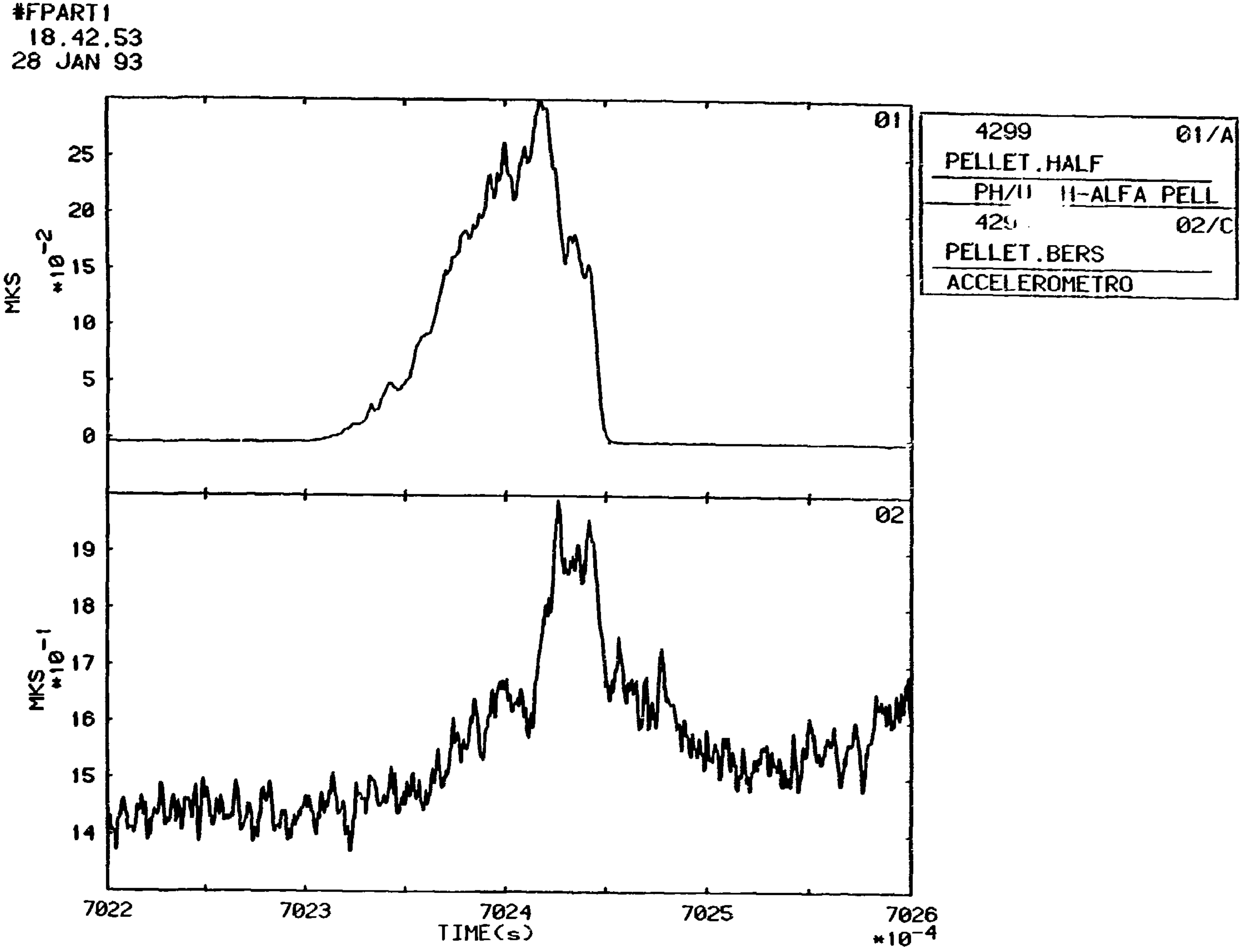
Fig.1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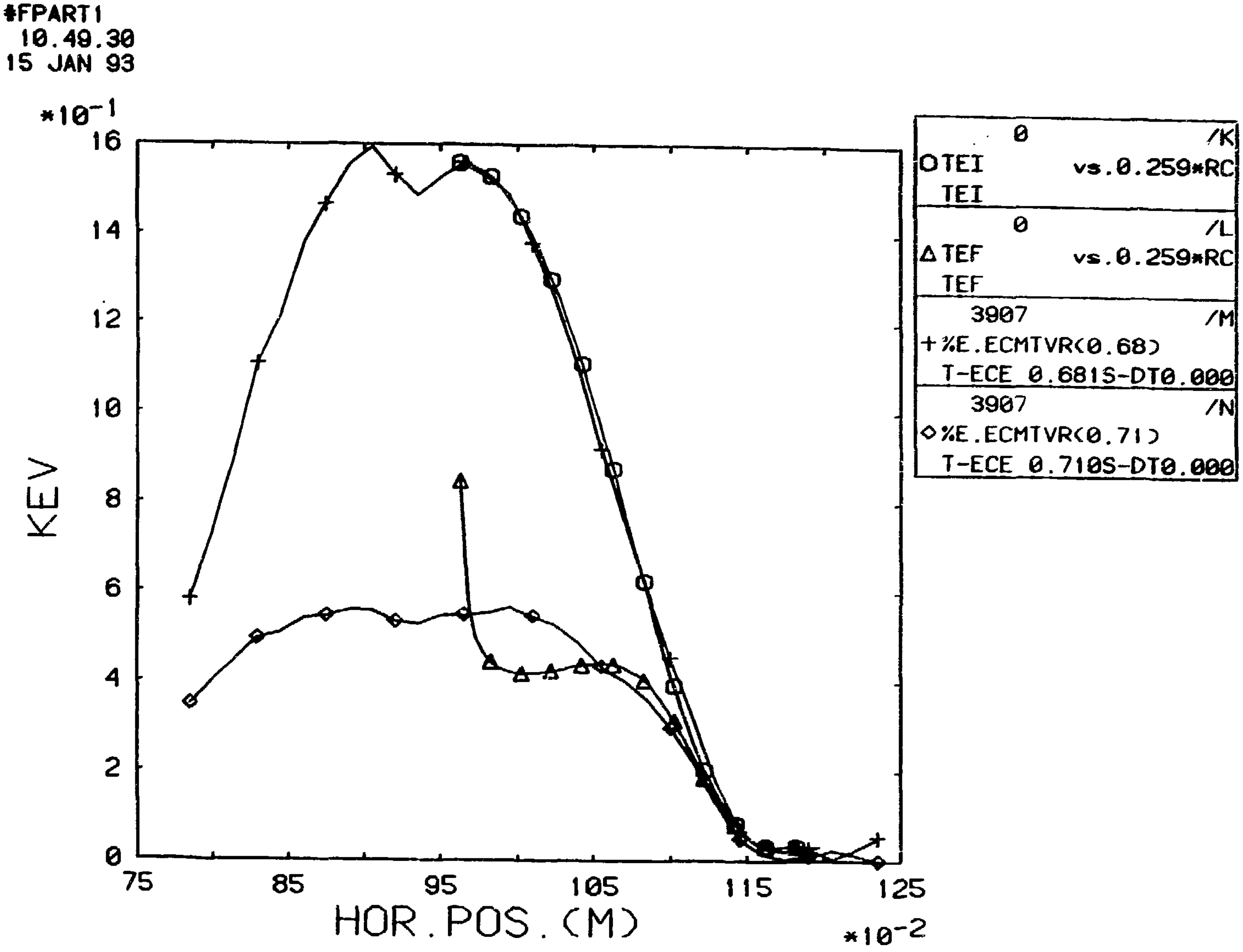
01
MKS
*10^-1
19
18
17
16
15
14
02
7022
7023
7024
7025
7026
TIME(s)
*10^-4
4299
01/A
PELLET.HALF
PH/II
II-ALFA PELL
429
02/C
PELLET.BERS
ACCELEROMETRO

Fig. 2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4
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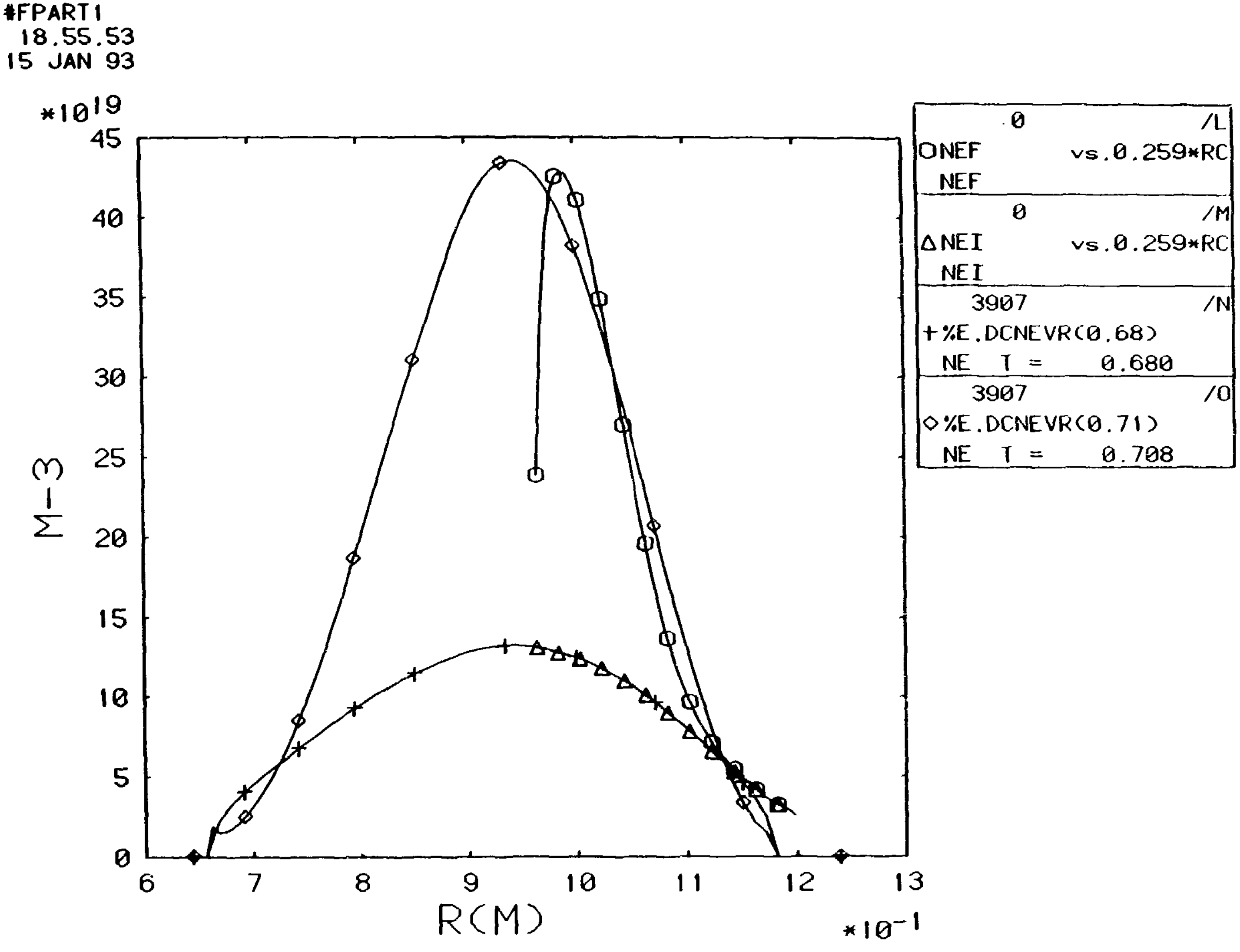
85
95
105
115
125
HOR.POS.(M)
*10^-2
0 /K
○TEI vs.0.259*RC
TEI
0 /L
△TEF vs.0.259*RC
TEF
3907 /M
+%E.ECMTVR(0.68)
T-ECE 0.681S-DT0.000
3907 /N
◇%E.ECMTVR(0.71)
T-ECE 0.710S-DT0.000

Fig. 3a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M-3
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*10^-1
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○NEF vs.0.259*RC
NEF
0 /M
△NEI vs.0.259*RC
NEI
3907 /N
+%E.DCNEVR(0.68)
NE T = 0.680
3907 /O
◇%E.DCNEVR(0.71)
NE T = 0.708
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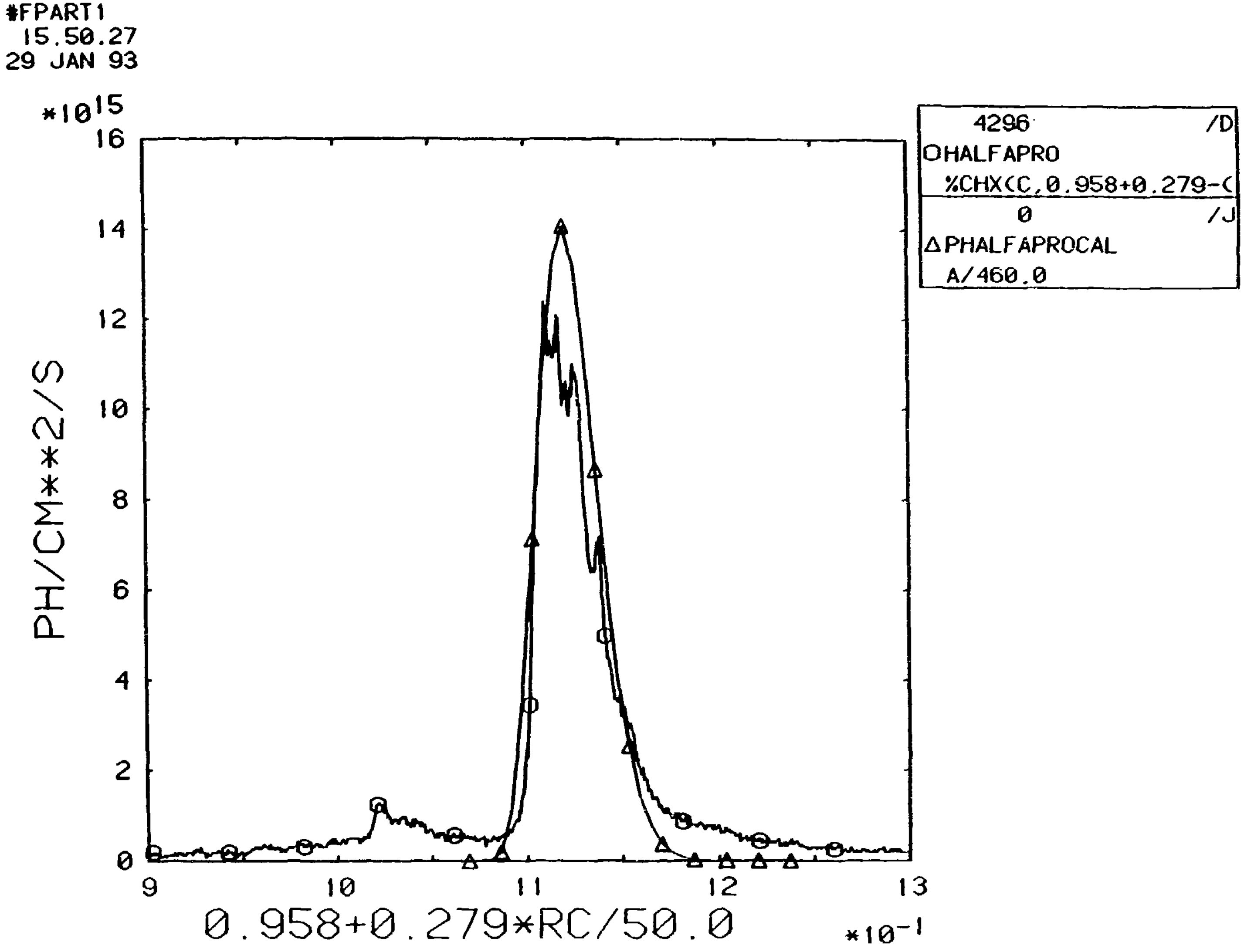
9
10
11
12
13

Fig. 3b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PH/CM**2/S
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11
12
13
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*10^-1
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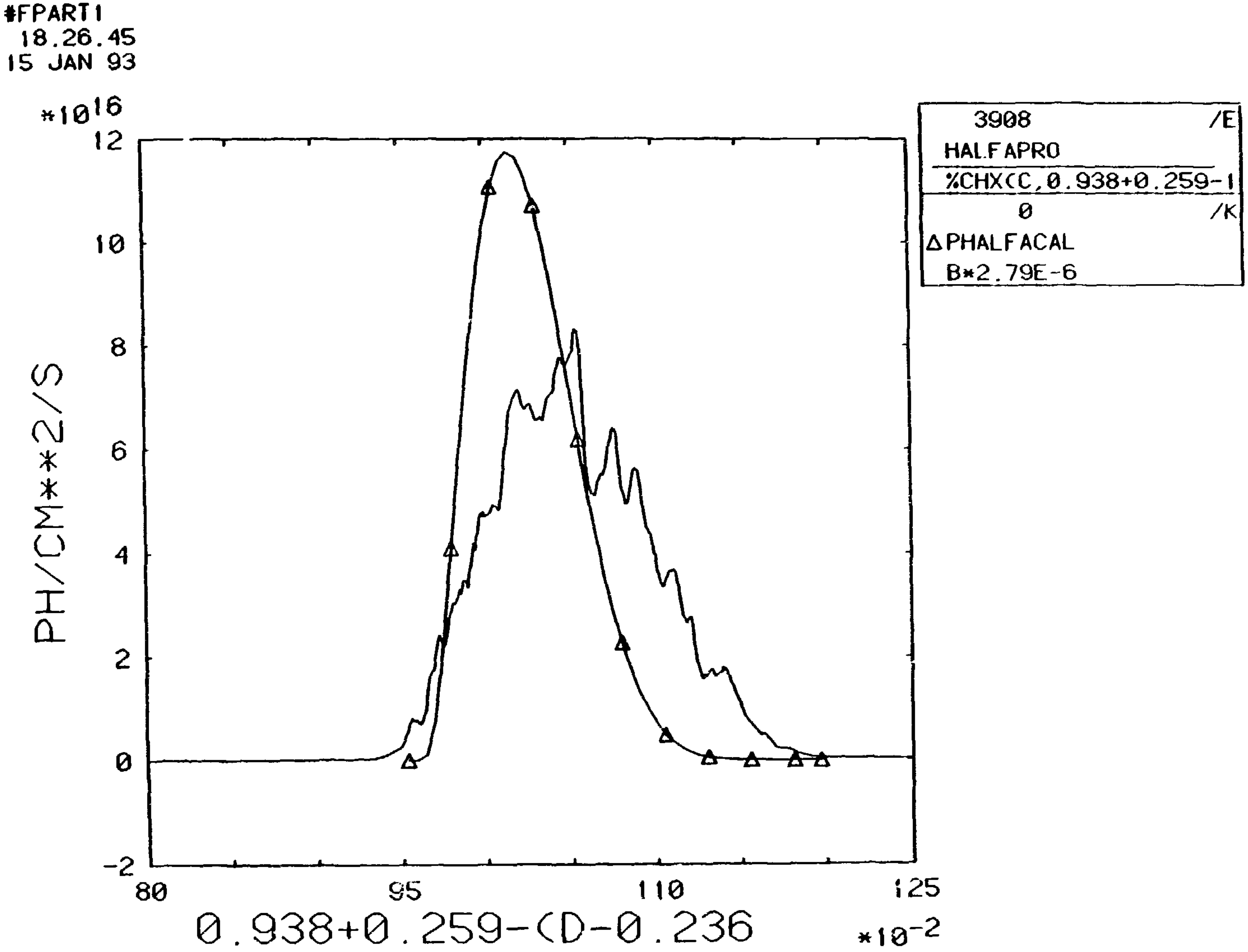
○HALFAPRO
%CHX(C,0.958+0.279-(
0 /J
△PHALFAPROCAL
A/460.0

Fig. 4a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110
125
0.938+0.259-(D-0.236
*10^-2
3908 /E
HALFAPRO
%CHX(C,0.938+0.259-1
0 /K
△PHALFACAL
B*2.79E-6

Fig. 4b

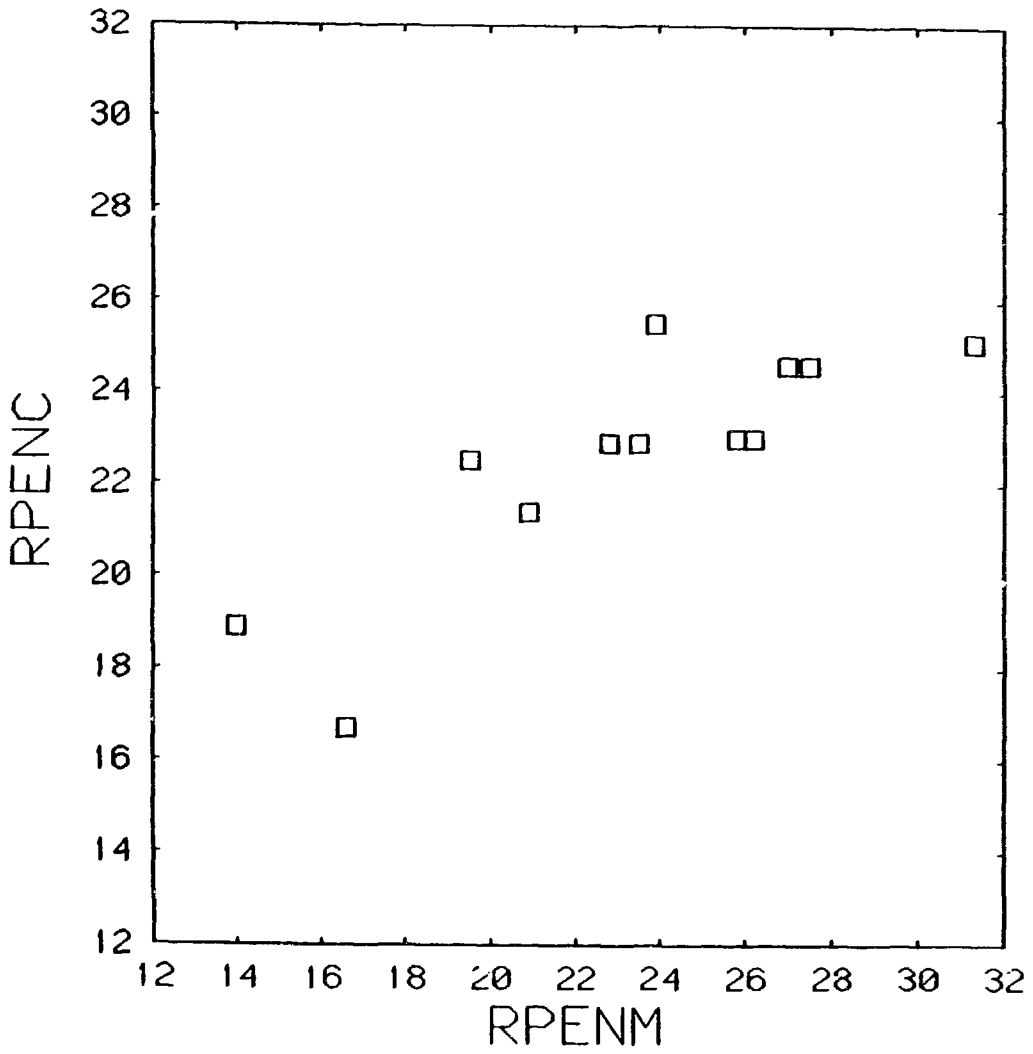

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Fig 5