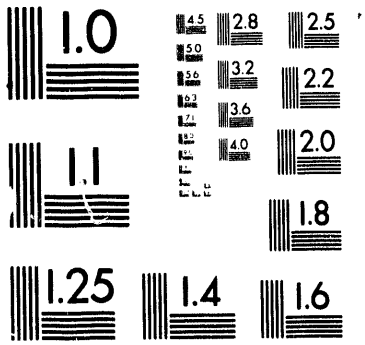
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WALL CONDITIONING EXPERIMENTS ON TFTR USING IMPURITY PELLET INJECTION

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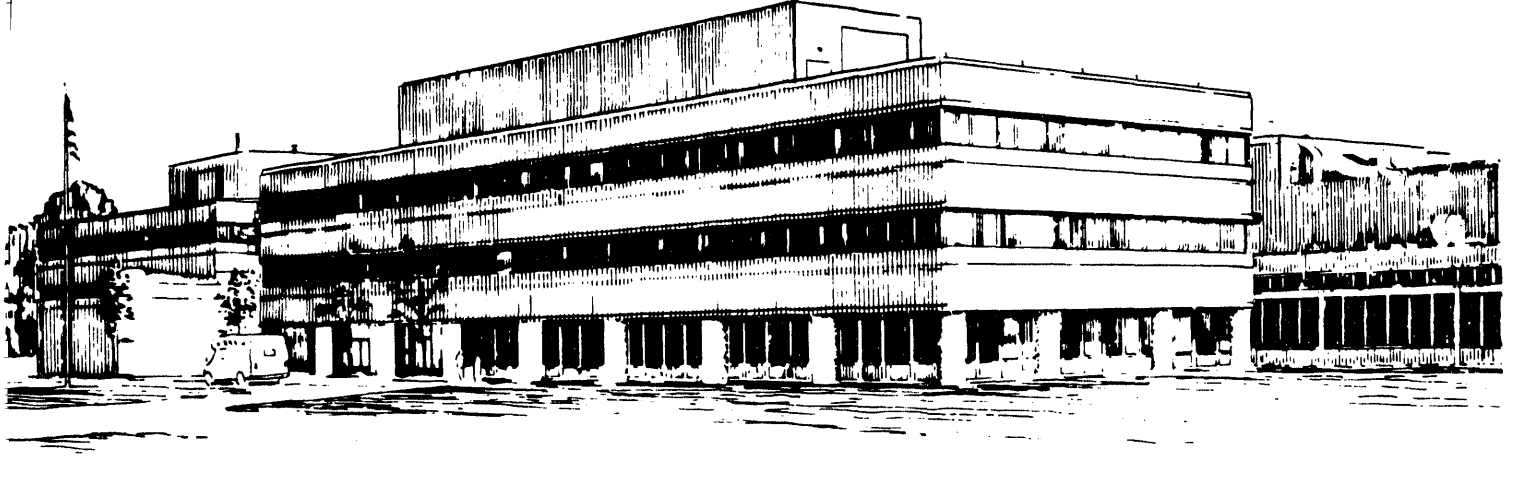

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WALL CONDITIONING EXPERIMENTS ON TFTR USING IMPURITY PELLET INJECTION

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ABSTRACT

This work describes experiments intended to optimize the limiter conditioning for TFTR supershots. It is shown that deposition of thin layers of lithium on the limiters by impurity pellet injection changes the plasma-wall interaction and improves supershot performance. Series of up to ten Ohmic plasmas each with two lithium pellets were useful in pre-conditioning the limiter. Generally, plasma performance increased with the amount of lithium deposited up to the maximal amount which could be deposited. Experiments were performed with different materials being deposited (carbon, boron and lithium) and with different methods of deposition.

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I. INTRODUCTION

TFTR supershot plasmas have confinement properties that are sensitive to the plasma-wall interaction and, therefore, to the condition or state of the limiter employed [1]. During the 1990 experimental run campaign, an effective technique for changing the plasma-wall interaction was found to be the deposition of thin, low-Z impurity films on the limiter by the ablation of injected impurity pellets [2,3,4]. This paper describes experimental efforts in the 1992 run campaign to enhance the energy confinement time of supershots by coating the carbon inner wall of TFTR with a sputter-deposited layer of boron or through the injection of lithium (Li), carbon (C) or boron (B) pellets into the plasma.

The improvements in supershot performance through the conditioning of the inner wall of TFTR have generally been higher energy confinement times, higher neutron emission, and higher Q_{DD} values than have previously been observed in TFTR supershots. Also, because of the wall conditioning to be described below, plasma performance characteristic of supershots has been observed at higher plasma currents ($\approx$ 2.4 MA) than was previously the case ($\approx$1.9 MA for the 1990 campaign). The physics details of the salutary effects of improved wall conditioning on plasma performance will be described more completely elsewhere [5]. It is the purpose of this work to describe the several empirical techniques of wall conditioning employed during the 1992 experimental campaign. In that regard, and in the interest of simplicity, emphasis will be placed upon the energy confinement time (τ_E, measured magnetically at the time of peak neutron production) as an indicator of improved plasma performance because it has been previously established that the plasma density, temperature and neutron emission rate all improve as the gross energy confinement time increases in TFTR supershots [6]. Spectroscopic features of the edge plasma emission as measured by a poloidal array of detectors have been used to characterize the influx of some of the principal constituents of the plasma (D, C, and Li) and hence to draw

inferences about the condition of the limiter surface in the experiments to be described below [7,8].

The principal conclusions to be drawn from this work are that (1) wall conditioning with lithium improves supershot performance when increasing levels of lithium are introduced onto the limiter and (2) conditioning with combinations of Li and C pellets also shows promise. Several possibilities for further improvement of wall conditioning with injected impurities will be listed at the conclusion of this work.

II. 1992 IMPURITY WALL CONDITIONING EXPERIMENTS

During the 1992 TFTR campaign seven experiments aimed at conditioning the inner wall were attempted. The parameters associated with these experimental sequences are summarized in Table 1. In all cases neutral beam injection (NBI) lasting 1 s began at t = 3.0 s. An attempt to coat the inner wall of TFTR using three boron sputter sources comprised one of these experimental sequences and is discussed below. However, the principal device employed for wall conditioning was an impurity pellet injector [9]. This device was capable of injecting one or two impurity (Li, C or B) pellets into each TFTR discharge. Each cylindrical pellet could be as large as 2 mm dia x 2 mm long and each contained roughly enough impurity material ($\approx 2 \times 10^{20}$ atoms) to lay down one geometric monolayer in the TFTR vacuum vessel. Because the two pellets could be fired independently, the time interval between injected pellets could be easily adjusted and was chosen to be as small as 0.1 s. This minimum interval was dictated by the necessity for the plasma electrons to re-heat after the injection of the first pellet to a temperature high enough ($\approx$ 1 keV) to ensure that the second pellet injected would be completely ablated before reaching the TFTR inner wall. The pellet injector was relocated toroidally and underwent extensive modifications between the 1990 and the 1992 TFTR experimental run campaigns. The work reported below represents the initial attempt(s) to use the modified pellet injector.

Sequence 1. Comparison of plasmas conditioned by lithium pellets to those without pellets.

The main goal of sequence 1 (shots 68200 - 68244, See Figs. 1-3) was to ascertain the number of pellet-conditioned plasmas required to bring into equilibrium the effects of the lithium film deposited on the surface of the inner wall. This sequence constituted the first use of Li pellets in 1992. As shown in Table 1, there were forty-one useful plasma attempts (i.e.: discharges without neutral beam injector faults) each with plasma current (I_p) of 1.63 MA, injected beam power (P_b) of 20.8 MW, toroidal magnetic field (B_t) of 4.73 T, and major radius (R) of 2.45 m. The shot sequence began with fourteen beam-heated plasmas without Li pellets. There then followed a series of fifteen plasmas with two pellet injections attempted on each shot (at 2.2 s and 4.3 s, i.e.: both before and after NBI). Of these fifteen plasmas, four had some neutral beam source failures and are not represented in Figs. 1-3. Of the eleven remaining shots, three shots had no pellets and two shots had only one pellet due to failures of the pellet injector. Thus, this part of the sequence displayed some variability in the amount of deposited lithium but did have a series in which six out of seven shots achieved the desired pellet firing sequence. There next followed a series of six shots without Li pellets. These shots were performed to study the erosion of the lithium from the limiter. This series was followed by eight shots each with pellets again injected at 2.2 s and 4.3 s. This series reintroduced lithium onto the limiter in order to test the reproducibility of lithium conditioning. Finally, the sequence ended with three shots each with Li pellets injected at 2.0 s and 2.2 s (i.e.: both before NBI began). These particular shots (shots 68242-68244) featured more lithium injected into the beginning of the plasma and consequently had a higher lithium influx during the beam-heating phase of the discharge. This is demonstrated by the elevated LiII emission level seen in Fig 3. Two of these plasmas had exceptionally high supershot energy confinement. There was an accompanying improvement in plasma performance with shot 68244 being among the best supershots ever produced in TFTR. Moreover, it has been found that most of the improvement exhibited by 68244 occurred in the plasma core with about a

50% reduction in the central particle diffusivity and a reduction in the ion thermal conductivity by a factor of 2-3. This shot is discussed in more detail elsewhere [5].

Sequence 1 documented the approach to equilibrium of the wall-conditioning without the presence of lithium and demonstrated the approach to a new wall-conditioning equilibrium achieved by injecting a Li pellet both before and after beam-heating. The energy confinement time sporadically displayed an improvement of up to 40% with Li pellet conditioning (Fig. 1). As seen in Fig 1, in the initial conditioning sequence, at the beginning of NBI, ten to fifteen shots were required before the measured confinement times assumed a reproducible (± 5%) level. As seen in Fig. 2, the CII emission in the target plasma was reduced in the initial conditioning sequence as if the beam-heating, by itself, performed a conditioning process which reduced the influx of carbon from the limiter during the Ohmic phase of subsequent discharges. However, the CII emission measured in the beam-heated phase was not influenced by this initial beam conditioning. The effects of conditioning the inner wall with lithium could be seen clearly during both the Ohmic/target and beam-heated phases and were characterized by a generally decreased level of CII emission indicating a reduction in carbon influx. In addition, the Dα emission measured during beam-heating was reduced while the LiII emission level increased as a result of lithium conditioning.

Sequence 2. Evaluation of Ohmic pre-conditioning discharges

Sequence 2 (shots 68407-68426, See Fig. 4) was an attempt to observe the approach to equilibrium of the effects of Li pellets in Ohmic plasmas. This sequence was also used to pre-condition the limiter surface for the beam-heated experiments of sequence 3 which followed. In sequence 2, the first four discharges had no pellet injected, there then followed twelve discharges with two Li pellets injected and two discharges with only one pellet due to injector failures. The plasma current and discharge conditions were the same as for sequence 1 with the exception that these were Ohmic discharges. (I_p = 1.63 MA, B_t = 4.73 T, R = 2.45 m, See Table 1).

After about ten discharges with pellet injection, the CII and Dα emission reached their equilibrium values (Fig. 4) with the CII emission being about 30% lower than before the lithium injection began. Lower levels of CII emission in Ohmic target plasmas have been previously associated with better limiter conditioning and better plasma performance [1]. The tendency for the Ohmic plasmas (i.e.: those shots at the beginning of the sequence without Li pellet injection) to increase slightly in CII emission is commonly seen after beam-heating sequences. It is probably the inverse effect to that seen at the beginning of the beam-heating in sequence 1, in which the CII emission decreased.

Also seen in the insert to Fig. 4 are two density traces, one taken during the Ohmic phase before conditioning began and one taken near the end of the pellet sequence. All discharges were initiated with an identical pre-fill of deuterium gas. The reduced density level obtained after pellet conditioning is taken as a direct demonstration of the reduced effective recycling coefficient of the inner wall as a result of the deposited lithium layer.

Sequence 3. Comparison of boron pellet conditioning to lithium pellet conditioning.

This sequence (shots 68427-68488, See Figs. 5 and 6) contained fifty-five useful plasmas all having I_p = 1.63 MA, P_b = 17.8 MW, B_t = 4.73 T and R = 2.45 m (Table 1). The machine parameters were the same as in sequence 1 except that the beam power was lowered from 20.8 MW to 17.8 MW to ensure that MHD events at the β limit were avoided. There were another six plasmas in this sequence which experienced beam faults. These plasmas were dropped from consideration and are not represented in the data displayed.

There were three main purposes for this particular experimental sequence: (1) to observe the effects of an Ohmic pre-conditioning campaign (sequence 2) upon subsequent neutral beam-heated discharges (2) to compare the efficacy of Li pellets to that of B pellets and (3) to attempt to have the plasma benefit from four pellets injected before NBI rather than from merely two pellets. Toward these ends, the scenarios described below were carried out during sequence 3.

The initial beam-heated plasmas (shots 68427-68443) each had two Li pellets before NBI (at 2 0 s and 2.2 s) although pellet injector failures occurred on four of these plasmas. This series of discharges was preceded by a series of Ohmic plasmas each having two injected Li pellets (sequence 2 as discussed). This Ohmic pre-conditioning was done in an attempt to influence the subsequent neutral beam-heated plasmas (sequence 3) by increasing the pre-deposited lithium layer. This scheme seemed to be effective because, despite some sporadic behavior, the beam-heated discharges immediately following the Ohmic pre-conditioning sequence exhibited both high confinement times and high neutron emission rates (shots 68427-68443, Fig. 5). Further, the LiII emission in the Ohmic target plasma (just prior to beam-heating) and during the beam-heating phase were at their highest levels near the beginning of this sequence while the CII emission (measured during beam-heating) was at its lowest level (Fig. 6). It thus appears as if this conditioning sequence was most effective within five to ten shots of the end of Ohmic pre-conditioning and the start of neutral beam injection (≈ shots 68427-68432). The initial set of fifteen lithium-assisted beam-heated plasmas was followed by nineteen beam-heated plasmas without Li pellets (shots 68444-68464). These plasmas were used to erode lithium from the TFTR limiter so as to allow a comparison of Li and B pellets. After roughly ten discharges, the lithium was removed (as indicated spectroscopically in Fig. 6) and the plasma confinement had stopped deteriorating (Fig. 5). This erosion rate was consistent with the erosion rate observed during sequence 1.

After the lithium was removed from the limiter, there followed a series of plasmas into which B pellets were injected (shots 68467-68478). The B pellets were similar in size to the Li pellets employed. There were ten plasmas with B pellet injection attempted at 2.0 s and 2.2 s (as was done for the preceding lithium-assisted plasmas). For five of these plasmas, only one pellet fired successfully. However, on the last three shots (shots 68476-68478) of this part of the sequence, both B pellets were fired successfully. As can be seen in Fig. 5, the influence of the boron on τ_E was a marginal improvement over the no-pellet shots and considerably less improvement compared to the lithium-assisted plasmas. Because there was a correspondingly small improvement in the neutron

emission rate for these discharges, it is concluded that Li pellets are more effective than B pellets at conditioning supershots.

Immediately following the boron experiments, a different scenario of Li pellet injection was employed (shots 68479-68486) wherein pellets were injected at 2.0 s and 2.2 s (i.e.: before NBI) but only for discharges which had been preceded by a discharge in which pellets were injected at 3.9 s and 4.1 s (i.e.: after NBI). This was done in an attempt to make every other plasma experience the benefit of four Li pellets - the two pellets from the tail end of the previous discharge and the two injected immediately before NBI. This tactic thus dictated that alternating discharges experience a reduced effect from Li pellets (i.e.: obviously, in those discharges with injection taking place at 3.9 s and 4.1 s, no lithium could be deposited just before NBI). During this sequence, there were four plasmas which experienced the benefit from four pellets in the manner just described; however, the first of these had reduced neutral beam power. The plasmas assisted by four pellets were observed to be improving but were just beginning to reach the confinement, neutron emission, and lithium emission levels of the initial plasmas of the sequence when this particular experiment was terminated due to limitations on machine time. Evidently, the four-pellet approach has some promise but needs also to be preceded by about ten Ohmic pre-conditioning discharges. Also, there was considerable difference in performance between the plasmas assisted by four pellets and those that were not (i.e.: alternating discharges in the sequence 68482-68486, Fig. 5). This result strongly suggests that it is desirable to put as much lithium as possible into the plasma immediately before neutral beam injection.

Finally, the last shot of Sequence 3 (shot 68487) had one boron and one Li pellet injected at 2.0 s and 2.2 s, respectively. This was done in an attempt to observe any synergistic effect which might be present when both materials were deposited on the limiter. This synergy might occur if any chemical compounds involving C, D, Li or B which formed on the limiter were playing a role in the enhanced supershot performance. However, the performance of this plasma was not noticeably enhanced over that of nearby plasmas. It is thus tentatively concluded that no strong synergistic effect was present.

Sequence 4. Conditioning experiments at higher currents

This sequence (shots 69018-69044, See Fig. 7) was run at increased plasma current (I_p = 2.2 MA) in order that the enhanced-confinement plasmas might have an extra margin of stability. Sequence 4 consisted of twenty-five plasmas. However, seven discharges suffered neutral beam faults and were dropped from consideration. Each of the remaining eighteen useful plasmas had parameters Pb = 25.7 MW, B_p = 5 T, and R = 2.50 m (Table 1). The larger major radius was chosen to avoid an integral q value at the limiter. The salient feature of sequence 4 is that a comparison was made between high-current plasmas influenced by two Li pellets injected immediately before beam-heating with those plasmas additionally influenced by two Li pellets injected at the end of the preceding plasma (shots 69035-69043, Fig. 7). This is the same comparison accomplished at lower current in a subsection of sequence 3 (shots 68479-6846, Fig. 5). Because alternating discharges in this section of sequence 4 are seen to have significantly different confinement times it is taken as strong reinforcement of the conclusion from sequence 3 that it is desirable to put as much lithium as possible into the plasma before NBI.

Sequence 4 was preceded by thirteen Ohmic pre-conditioning discharges (shots 69004-69017, Fig. 7) each with one or two Li pellets injected; this was done in an attempt to reproduce the beneficial interaction that took place between sequences 2 and 3. However, the pre-conditioning series run just before sequence 4 was complicated by the fact that it was part of an accelerated campaign to recover from a major disruption. On TFTR, such disruptions have the effect of reducing supershot performance by increasing the particle recycling coefficient of the limiter. Low recycling conditions are recovered only after extended (>30 shots) plasma operation. Thus, because the pre-conditioning campaign was abbreviated due to limitations on machine time, there can be no assurance that the limiter was optimally pre-conditioned prior to the start of sequence 4. However, because the lithium layer was not removed between pellet injection scenarios in sequence 4, it is expected that the lithium built up in the preceding Ohmic plasmas allowed a equilibrium level of lithium to be established for both pellet injection scenarios.

Even with these uncertainties, it can be seen in Fig. 7 that regardless of the details of pellet injection, so long as Li pellet conditioning was used, supershot-like confinement times ($\approx$ 0.10 - 0.15 s) as well as supershot plasma performance were obtained at I_p = 2.2 MA. This represents a significant increase in the plasma current at which supershots have been observed in TFTR. During the 1990 run, supershot performance could not be obtained above currents of $\approx$ 1.9 MA. In 1992, as a result of lithium conditioning, this upper limit was eventually extended to about 2.45 MA in experiments that are more completely described elsewhere [5].

Sequence 5. Comparison of carbon and lithium conditioning

During this sequence (shots 69102-69128, See Fig. 8) conditioning with C pellets was investigated and compared to conditioning with Li pellets. This sequence contained twenty-one useful plasmas and another seven plasmas with lower beam power due to source faults. The plasma conditions were I_p = 1.98 MA, Pb = 25.5 MW, B_t = 4.95 T and R = 2.52 m (Table 1). The major radius was again chosen to avoid integral q(a) values. Alternative C injection was accomplished by either injection of the C pellet late into the beam-heated phase of the plasma or by embedding a small C pellet in a larger Li pellet (thus forming a Li/C or composite pellet). These tactics were employed because previous experiments had shown that the injection of C pellets before NBI severely perturbed the plasma and therefore risked causing a disruption. In sequence 5, the experiments essentially compared Li pellets to the combined injection of Li and C. The rationale for performing these C pellet experiments was to simulate the beneficial effects of a carbon bloom. In 1990, it was observed that discharges which suffered a carbon bloom often caused improved plasma performance in the discharge immediately following the bloom [1].

The sequence of beam-heated plasmas was preceded by five Ohmic pre-conditioning plasmas (shots 69096-69101, Fig. 8) each having two injected Li pellets. There then followed a sequence of seven discharges with two Li pellets injected before NBI (shots 69102-69110, Fig. 8). These initial plasmas of sequence 5 had slightly higher LiII emission than

did subsequent plasmas. There next followed a discharge into which one C and one Li pellet were injected at 2.0 s and 2.4 s, respectively. Carbon pellets were injected into the post-NBI phase of the next three discharges (shots 69113-69118, Fig. 8). Finally, four discharges were taken into which two Li/C composite pellets were injected just before NBI and these discharges were compared to four discharges into which two Li pellets were injected (shots 69121-69124 and 69125-69128 respectively, Fig. 8). The four discharges with composite pellets were seen to have significantly higher confinement times than subsequent discharges with only Li injected. However, the reproducibility of this result was not tested due to limitations on machine time. It should also be pointed out the confinement times obtained with the composite pellets were shorter than the confinement times obtained with lithium conditioning in the beginning of sequence 8 (shots 69102 - 69110). However a direct comparison is difficult to make in this case because the initial discharges in this sequence were preceded by Ohmic pre-conditioning with Li pellets.

The plasmas conditioned with combinations of lithium and carbon had high τ_E, high neutron emission rates, and high central density. On the basis of this brief comparison, it is thus concluded that further experiments should be undertaken to find the optimum combination of Li and C pellet injection. In particular, the efficacy of composite pellets should be investigated in future experiments.

Sequence 6. Movement of the plasma column

This was another Ohmic sequence (shots 69129-69149, See Fig. 9) of fourteen useful 1.4 MA plasmas each having two Li pellets injected per plasma. In addition, this sequence featured the movement of the plasma column from the outboard limiter onto the inner wall limiter. During this series of discharges, the plasmas began and ended at R = 2.75 interacting with the TFTR outboard limiter. At t = 2.0 s these plasmas were moved onto the inner wall limiter for 1.2 s during which time two Li pellets were injected (Fig. 9). This in-and-out movement (from R = 2.75 m to R = 2.45 m to R = 2.75 m) was done in an attempt to minimize the erosion of the freshly-deposited lithium by minimizing the duration of the plasma-inner-wall interaction. As a result of this tactic, the CII emission from

the plasma decreased well below levels attained using other methods of Li pellet conditioning (Fig. 9). This decrease was observed after about ten Ohmic plasmas and, because of constraints on machine time, it is not clear that equilibrium was attained. Thus, this technique seems to hold promise and should be optimized in future experiments.

After completing a conditioning series in the manner described, the LiII emission level measured immediately before NBI in the next target plasma (shot 69152, Fig. 10) was among the highest obtained in the 1992 campaign while the CII emission was among the lowest. Although the plasma performance following this type of conditioning was good, it was not at the best level of performance which had been attained. The best 1992 supershot also occurred at R = 2.52 m, I_p = 2.0 MA, but had 30.8 MW of beam power as compared to the 26 MW injected into shot 69152.

It is interesting to note that immediately following this conditioning effort involving plasma movement, both the CII and LiII emission levels in the Ohmic target plasma were at the respective magnitude associated with the best plasma performance (highest τ_E) attained by TFTR. However, because the plasmas associated with these emission/influx levels did not attain the highest plasma performance, it is concluded that a reduction of carbon influx is necessary but not sufficient for the attainment of peak plasma performance.

Comparison of the time evolution of the plasma immediately after the initial Li pellet conditioning with the best TFTR supershot indicates that movement of the plasma during lithium deposition did attain the low edge density and CII emission of the best TFTR plasmas but did not attain the same high central density [5].

Sequence 7. Conditioning using boron sputter sources.

In order to lay down a thicker layer of boron than could be achieved with the injection of B pellets, deposition with RF sputter sources was attempted [10]. Three sputter sources with pure boron targets were inserted into the TFTR vacuum vessel and each was operated at 1 kW of RF power for eight hours in a 5 mTorr atmosphere of Helium. A total of ≈ 0.3 g of boron was eroded from the targets which is larger than the ≈ 0.03 g typically deposited by a pair of B pellets but is smaller than the ≈ 10 g

typical of plasma-vapor deposition of boron from diborane gas [11]. The potential advantage of the boron sputter deposition over boronization with diborane vapor is that, when the latter technique has been employed in the past, the TFTR limiters have been observed to retain large amounts of both hydrogen and deuterium (up to 40%) making them incompatible with supershot operation. Also, while it has been found that the retained hydrogenic species can be removed by conditioning discharges, such discharges also remove the deposited boron [11]. As a result of the alternative method of boronization employed in sequence 7, the limiters were not loaded with either hydrogen or deuterium so that the effects of a boron layer on supershot performance could potentially be assessed in a clearer fashion than was previously possible.

Residual helium embedded in the limiter is also incompatible with supershot plasma performance, thus plasma operation was suspended for several days after the boronization to allow helium to pump out of the TFTR vacuum vessel. This tactic seemed to succeed because, within seventy-two hours after boronization, the partial pressure of helium was as low as it was prior to the operation of the boron sputter probes. In addition, helium was not detected in the first plasmas after the boronization. Conversely, the water peak as measured by a residual gas analyzer was reduced by a factor of 3 due to boron sputtering but had risen to its initial value by the time of the resumption of plasma operation. This recovery in water vapor partial pressure was attributed to two small air leaks which occurred during the period of vessel inactivity following boronization. These leaks probably saturated the ability of the boron layer to adsorb oxygen. However, because oxygen is not an important impurity during TFTR supershot operation, these leaks were not considered serious enough to affect the assessment of boron sputtering on supershot performance.

After boronization and the subsequent helium pumpout period, the first two plasma attempts suffered hardware failures. This unfortunate circumstance made an unambiguous comparison with previous supershots problematic. However, eight of the next ten plasmas were supershot attempts with I_p = 2.0 MA, P_b = 21.5 MW, B_t = 4.8 T and R = 2.45 m (Table 1). These plasmas exhibited performance characteristics similar to 1990 supershot plasma attempts at the same machine settings (Fig. 11).

Hence, as opposed to the immediate and profoundly beneficial effects of wall-conditioning with Li pellets, no such clear effects were observed when boron was deposited by either B pellets (sequence 3) or with RF sputter deposition (sequence 7). It thus appears that boron may not be as effective as lithium at improving supershot performance. The apparent ineffectiveness of boron sputtering as compared to Li pellet injection is not completely understood at present. It is possible that even though the amount of boron sputtered inside the vacuum vessel was large ($\approx$ 0.3 g), the amount of boron actually deposited onto the limiter may have been much less. It is also possible that the method of impurity deposition by the plasma for pellets may play a role in the enhancement of plasma performance.

III. DISCUSSION

Empirical optimization of the Li pellet conditioning of TFTR supershots represented a significant effort in the 1992 campaign. It was found that boron sputtering and boron pellets were not as successful as Li pellets at conditioning the limiters to enhance supershot performance.

Results of the 1992 run suggest that a near-optimal conditioning sequence on TFTR might be:

(a) ten Ohmic plasmas each with two Li pellets and contacting the inner wall limiter only while the lithium is being deposited on the limiter ($\approx$ 1 s).

(b) five pairs of plasmas with NBI, alternating two pellets before the beams with two pellets after NBI. In this manner every other plasma would have the conditioning benefit of four pellets.

Further efforts at improving the pellet conditioning could still incorporate:

(a) the use of C and Li pellets in combination,

(b) more and larger Li pellets,

(c) more extensive use of plasma motion to decrease the erosion of lithium from the limiter.

The plasma performance (neutron emission, confinement time, and energy content) increases steadily with the lithium content on the limiter

(Fig. 12). The improvement in the plasma performance associated with the Li pellet injection is correlated to changes in the same parameters that correlate with τ_E in supershots without Li pellets. The lithium seems associated with decreased hydrogen and carbon recycling both before and during the beam-heating (Fig. 13) [1,12]. There is also a strong correlation of τ_E at the time of peak neutron emission with the peakedness of the neutral beam deposition (Fig. 14) [13]. In this regard, the effect of the Li pellets seems more like an extension of the supershot plasma rather than a fundamentally new confinement regime.

The very best 1992 supershot plasma was preceded by a bloom-like event on the preceding plasma as had occurred in 1990 [5]. Since the C pellets give spectroscopic signals which are similar to the bloom events, further investigation of possible synergistic Li + C pellet experiments are desirable. It may be possible to inject a C pellet into the beam-heated phase of a preceding discharge to avoid the large perturbations which occurs when these pellets are injected into Ohmic discharges.

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Table 1

Sequence	#Shots	Ip(MA)	P_b(MW)	B(T)	R(m)	Comments
1	41	1.63	20.8	4.73	2.45	Compare Li /no Li
2	18	1.63	0	4.73	2.45	Ohmic
3	55	1.63	17.8	4.73	2.45	Compare Li/B
4	18	2.20	25.7	5.00	2.50	Higher Ip
5	21	1.98	25.5	4.95	2.52	Li+C pellets
6	14	1.4	0	4.70	2.7 to 2.45	Movement of Plasma
7	8	2.0	21.5	4.80	2.45	B probe

FIGURE CAPTIONS

Fig. 1. The energy confinement time measured during NBI at the time of peak neutron emission for sequence 1 supershots. The various operating regimes described in the text are separated by vertical lines as well as by different symbols. Density traces used to indicate relative pellet and NBI times are shown as inserts. In these inserts, pellet injection is indicated by arrows while NBI is characterized by a one second rise in density with a roughly rectangular shape. Each insert is also associated with a particular symbol.

Fig. 2. The level of CII emission (a. u.) in sequence 1 target plasmas measured 0.1 s before the beginning of NBI. The inserts, symbols and vertical lines are the same as for Fig. 1.

Fig. 3 The level of LiII emission (a. u.) in sequence 1 target plasmas. The inserts, symbols and vertical lines are the same as for Fig. 1.

Fig. 4 The levels of CII (left scale) and Dα (right scale) emission (a. u.) measured during Ohmic discharges and during Ohmic discharges after the injection of two Li pellets (sequence 2). Shown in the insert is a density trace from one of the initial Ohmic discharges and from one of the last discharges in the pellet-injection series. The carbon emission is represented with (O)'s while the Dα emission is represented with (X)'s.

Fig. 5 The energy confinement times for sequence 3 supershots. This sequence was run immediately following the Ohmic pre-conditioning carried out in sequence 2. The various operating regimes described in the text are separated by vertical lines as well as by different symbols. Density traces used to indicate relative pellet and NBI times are shown as inserts. The last discharge had a B and a Li pellet injected before NBI and is represented by an (O).

Fig. 6 The measured LiII emission associated with sequence 3. The inserts, symbols and vertical lines are the same as for Fig. 5.

Fig. 7 The energy confinement times for sequence 4 discharges. As a result of pellet conditioning, these discharges exhibited supershot-like confinement even at the high current level (2.2 MA) used in this sequence. The various operating regimes described in the text are separated by vertical lines as well as by different symbols. Density traces used to indicate relative pellet and NBI times are shown as inserts.

Fig. 8. The energy confinement time measured at the time of peak neutron emission for sequence 5 supershots. The various operating regimes described in the text are separated by vertical lines as well as by different symbols. Density traces used to indicate relative pellet and NBI times are shown as inserts. The types of pellets injected are also indicated.

Fig. 9. The (a) Dα light, (b) CII light, (c) plasma current, and (d) major radii for three Ohmic conditioning plasmas. The solid line is data taken after a sequence in which no pellets were injected and the CII emission had evolved to a low level. The short dashed line is data taken after a sequence in which two Li pellets per discharge were injected at 2.0 s and 2.2 s (also the conditioning plasma just before the start of sequence 5). The long dashed line is data taken after a sequence in which the plasma was moved onto the inner wall limiter only for the deposition of the lithium (sequence 6).

Fig. 10. The time evolution of the LiIII emission for three plasmas. The solid line is associated with the beginning of sequence 5. The long dashed line is the first plasma after sequence 6, and the short dashed line is the best TFTR supershot. It should be noted that NBI began at t =3.0 s.

Fig. 11. The energy confinement times for 1990 Supershots and 1992 post-boron-sputtering supershots plotted against beam power. Each plasma had R = 2.45 m, Ip = 2.0 MA, Bt = 4.8 T. The calculated L-mode scaling is also shown for reference.

Fig. 12. The gross energy confinement time at the time of peak neutron emission plotted against the LiIII emission in the target plasma. The data is from sequence 1. The symbols are the same as those in Fig. 1.

Fig. 13. The gross energy confinement time, τ_E, at the time of peak neutron emission plotted against the Dα emission (a. u.) from the target plasma. The data is from sequence 1. The symbols are the same as those in Fig. 1.

Fig. 14. The gross energy confinement time, τ_E, at the time of peak neutron emission plotted against the peakedness of the beam deposition, H_{ne}. The data is from sequence 1. The symbols are the same as those in Fig. 1.

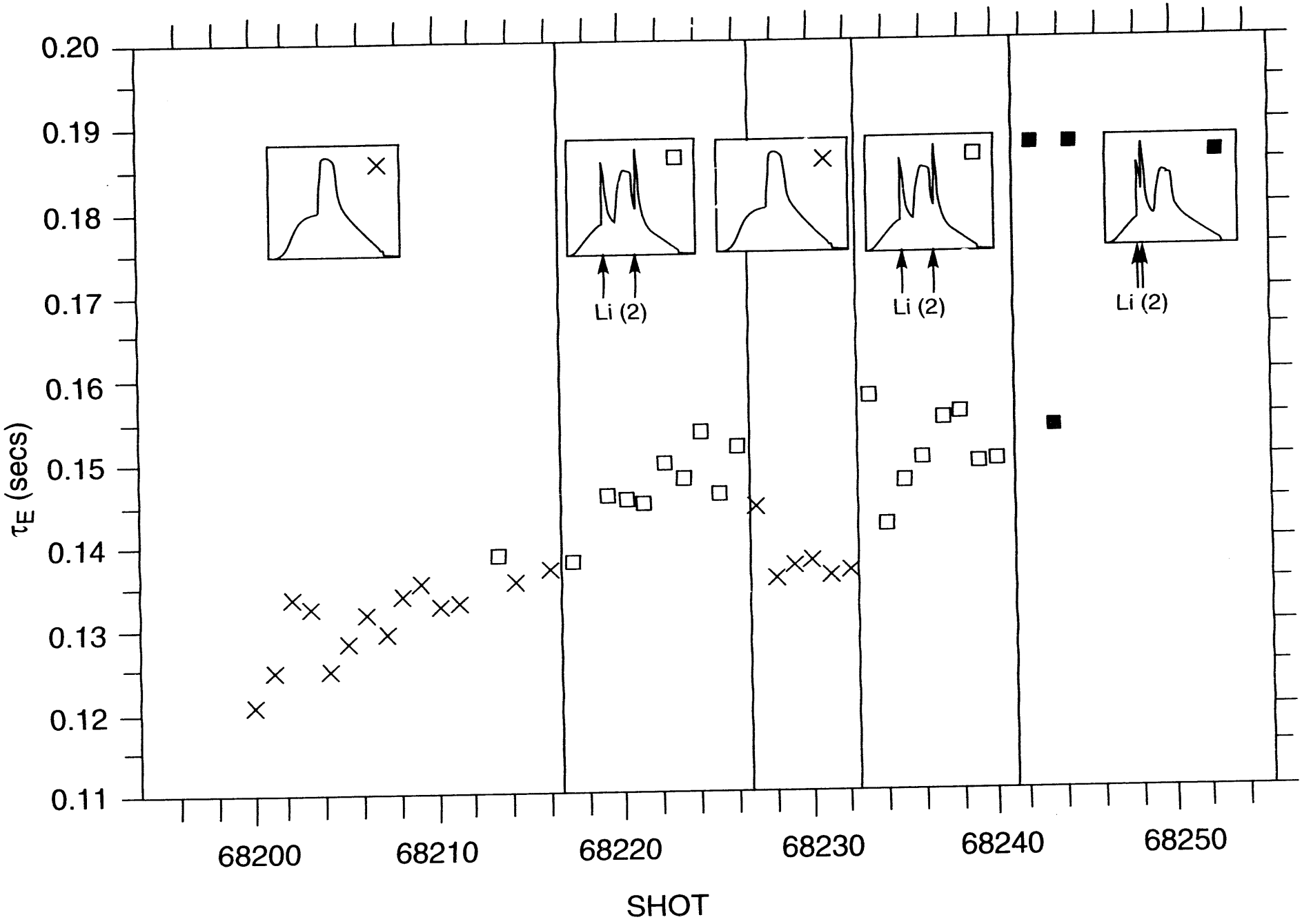
0.20
0.19
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
τ_E (secs)
Li (2)
Li (2)
Li (2)
68200
68210
68220
68230
68240
68250
SHOT

Fig. 1

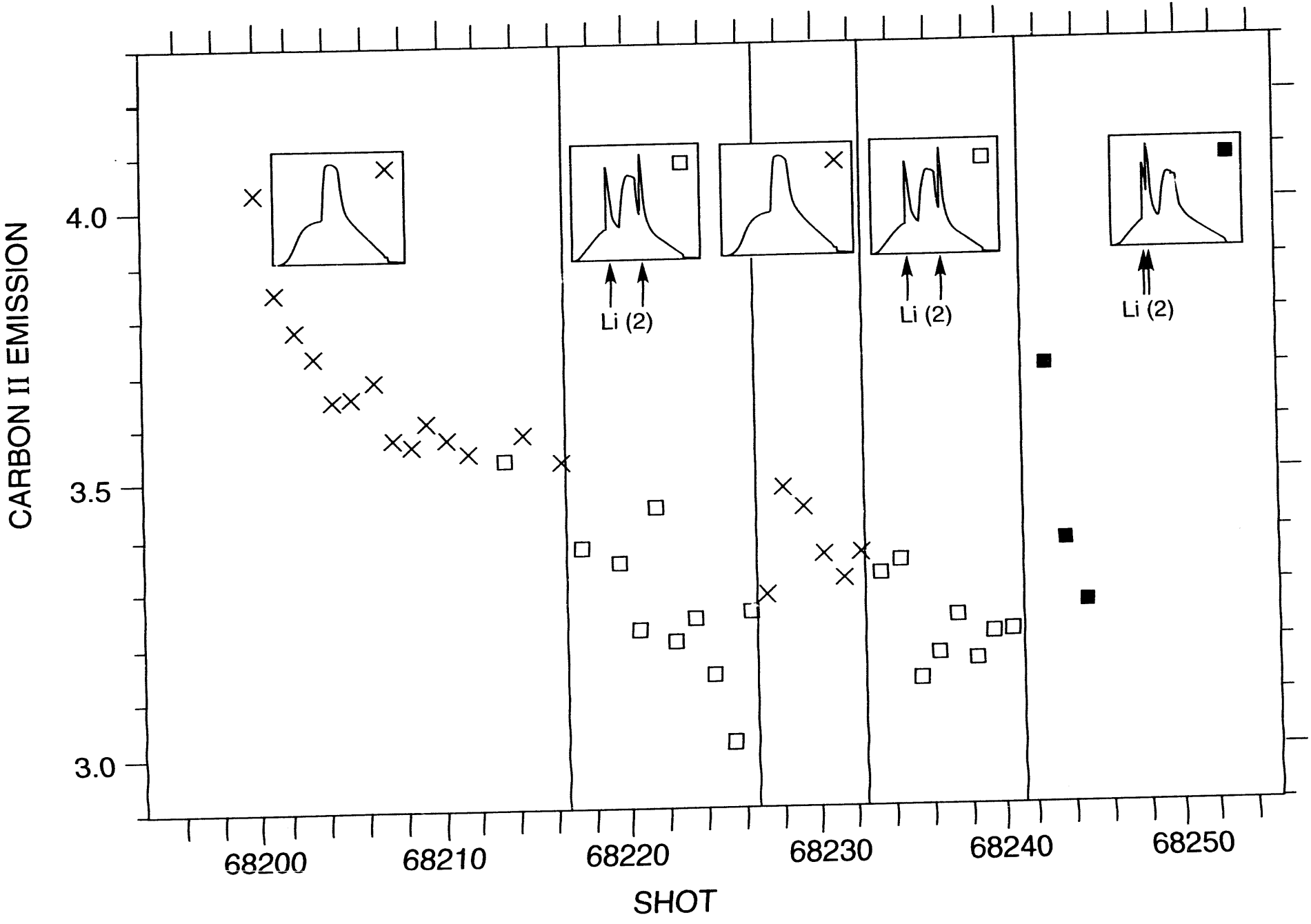
CARBON II EMISSION
4.0
3.5
3.0
68200
68210
68220
68230
68240
68250
SHOT
Li (2)
Li (2)
Li (2)

Fig. 2

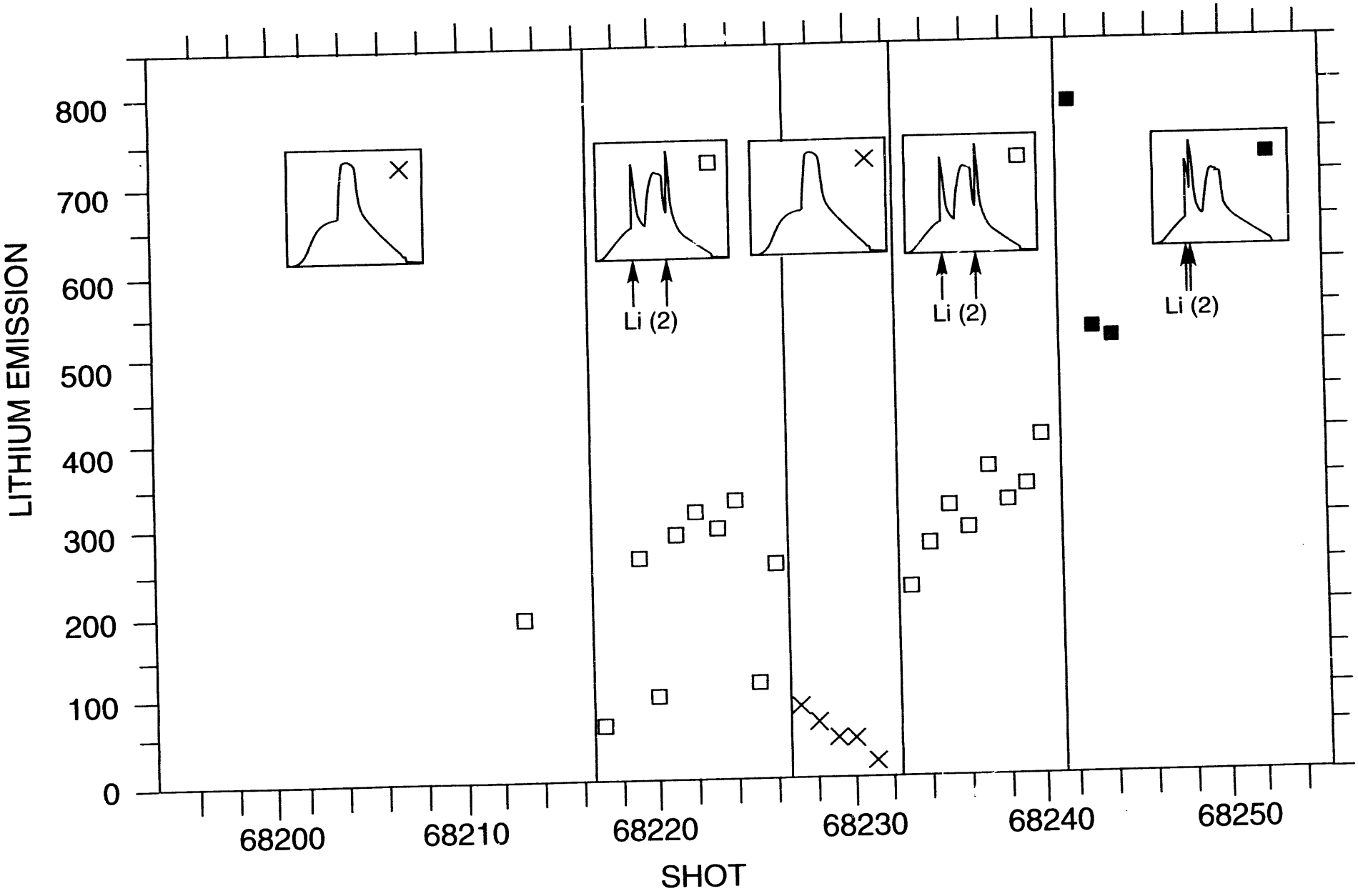
LITHIUM EMISSION
800
700
600
500
400
300
200
100
0
68200
68210
68220
68230
68240
68250
SHOT
Li (2)
Li (2)
Li (2)

Fig. 3

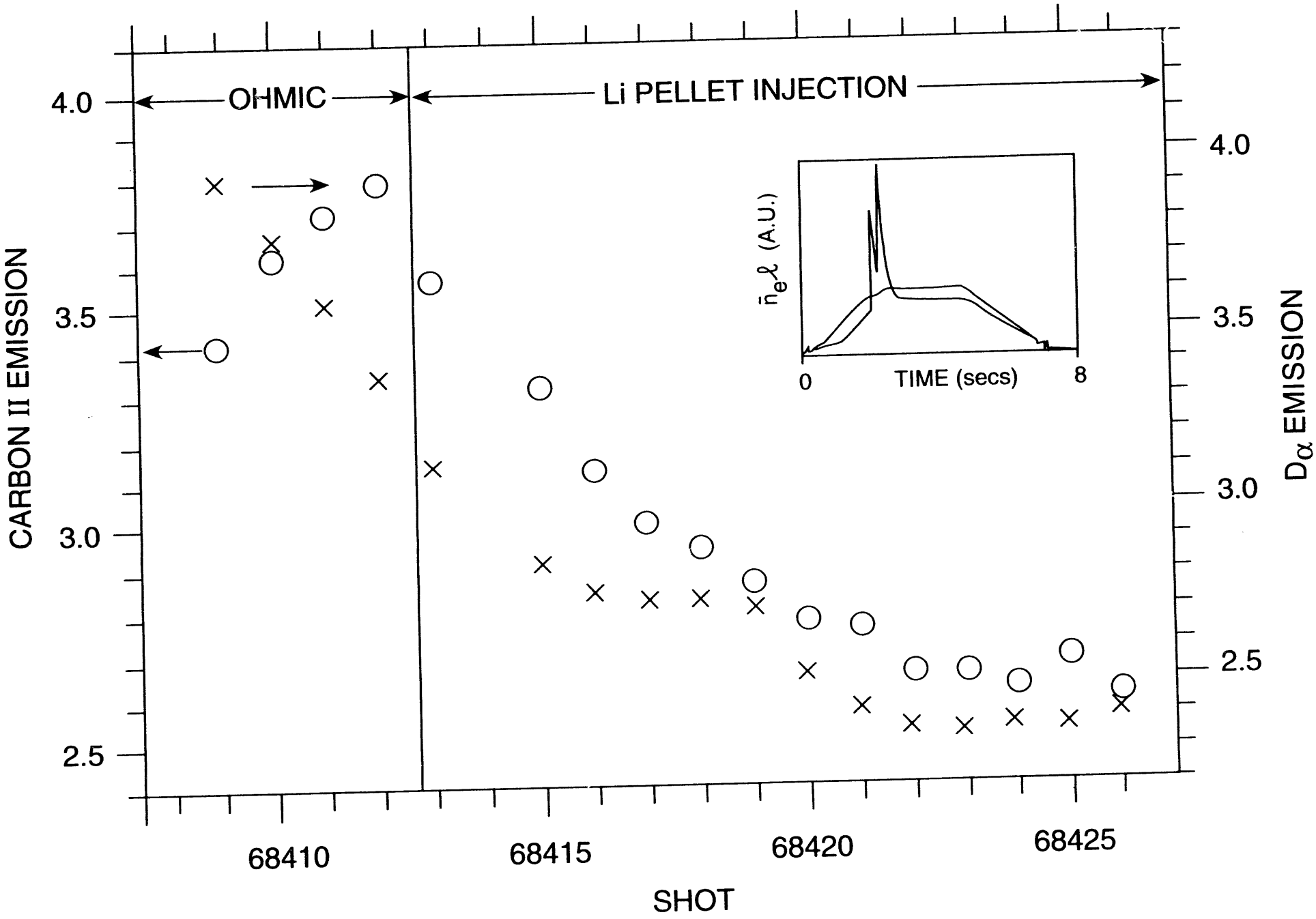
OHMIC
Li PELLET INJECTION
CARBON II EMISSION
D_α EMISSION
4.0
3.5
3.0
2.5
68410
68415
68420
68425
SHOT
$\bar{n}_e \ell$ (A.U.)
0
TIME (secs)
8

Fig. 4

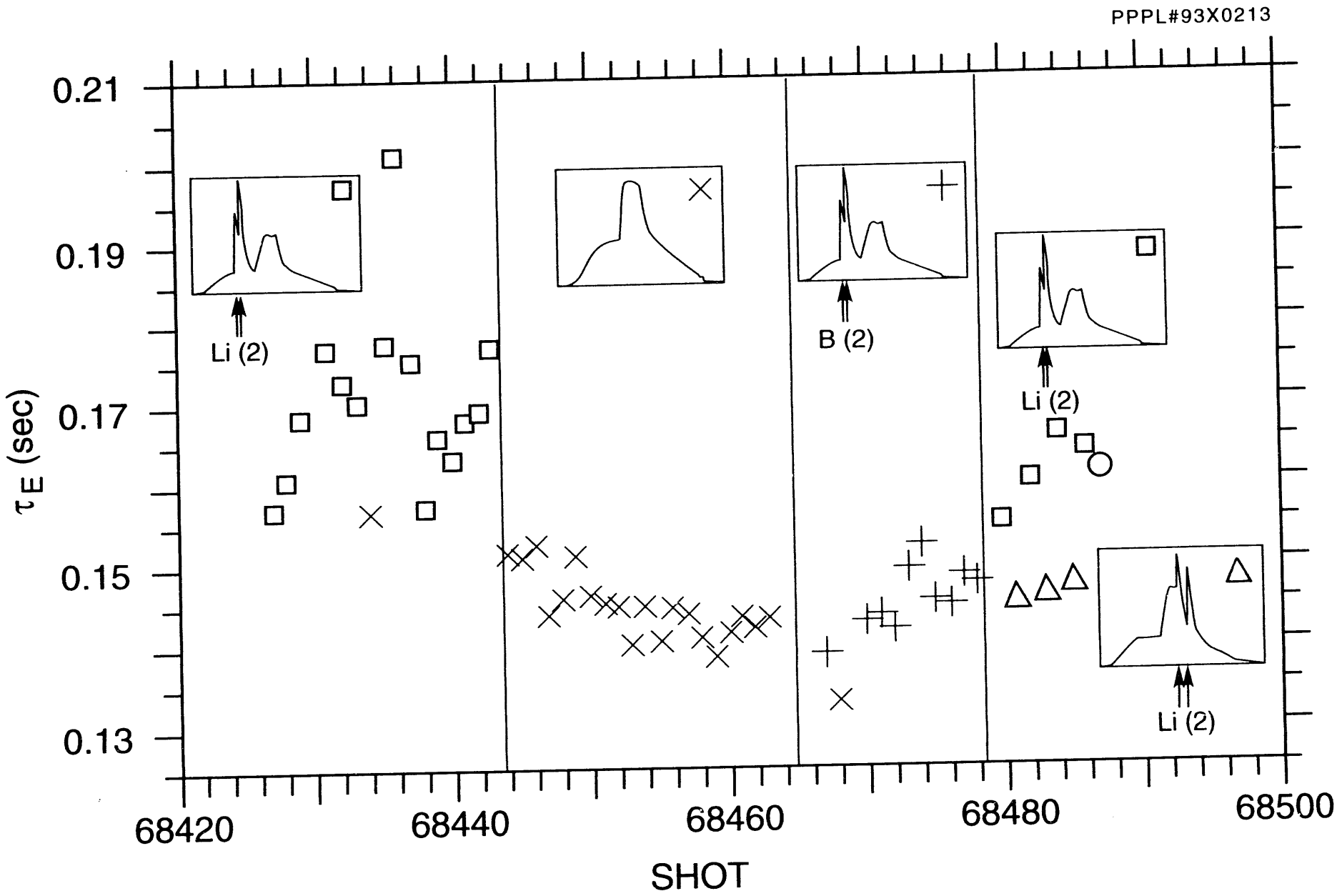
PPPL#93X0213
0.21
0.19
0.17
0.15
0.13
τ_E (sec)
68420
68440
68460
68480
68500
SHOT
Li (2)
B (2)
Li (2)
Li (2)

Fig. 5

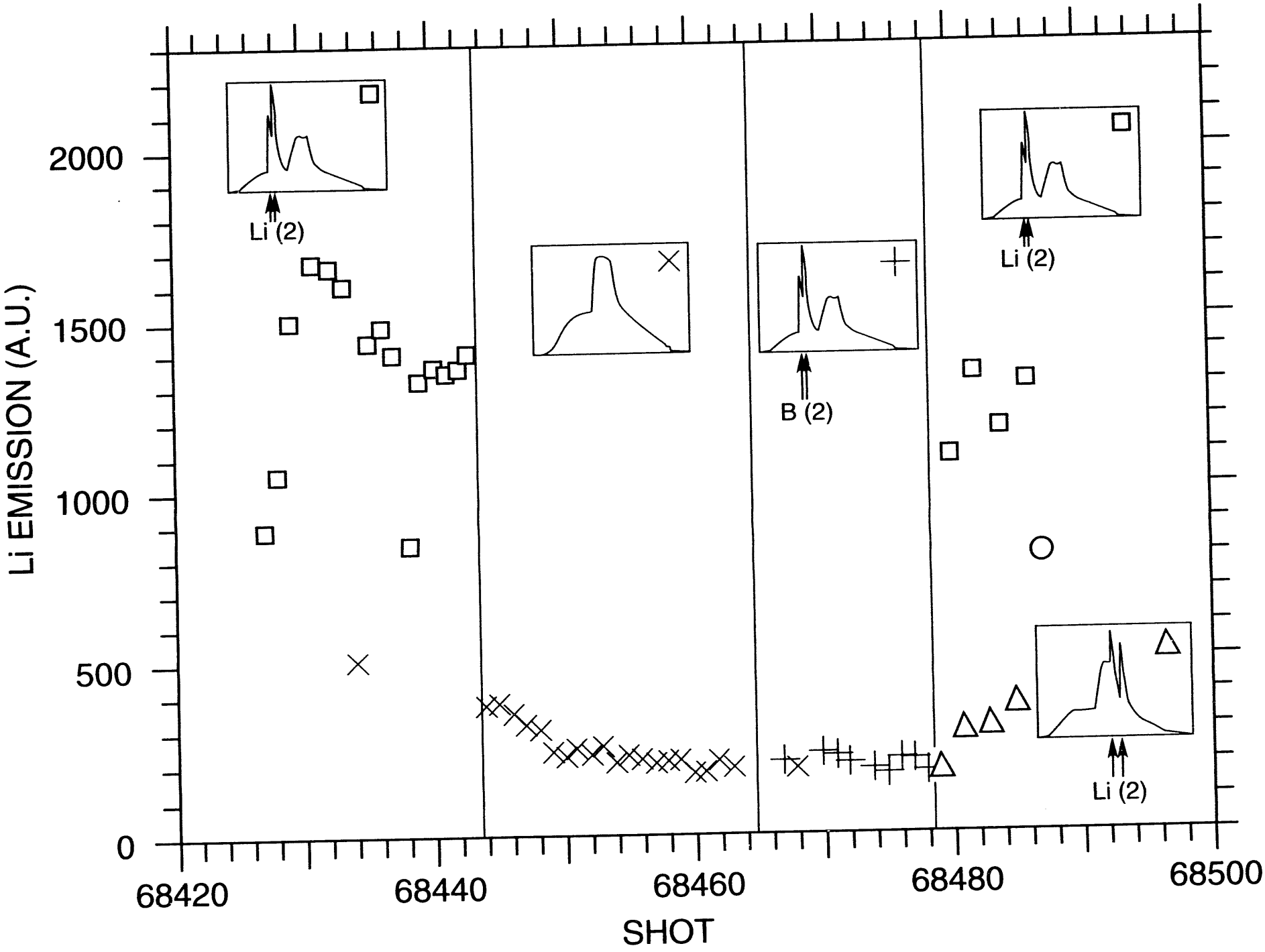
Li EMISSION (A.U.)
2000
1500
1000
500
0
68420
68440
68460
68480
68500
SHOT
Li (2)
B (2)
Li (2)
Li (2)

Fig. 6

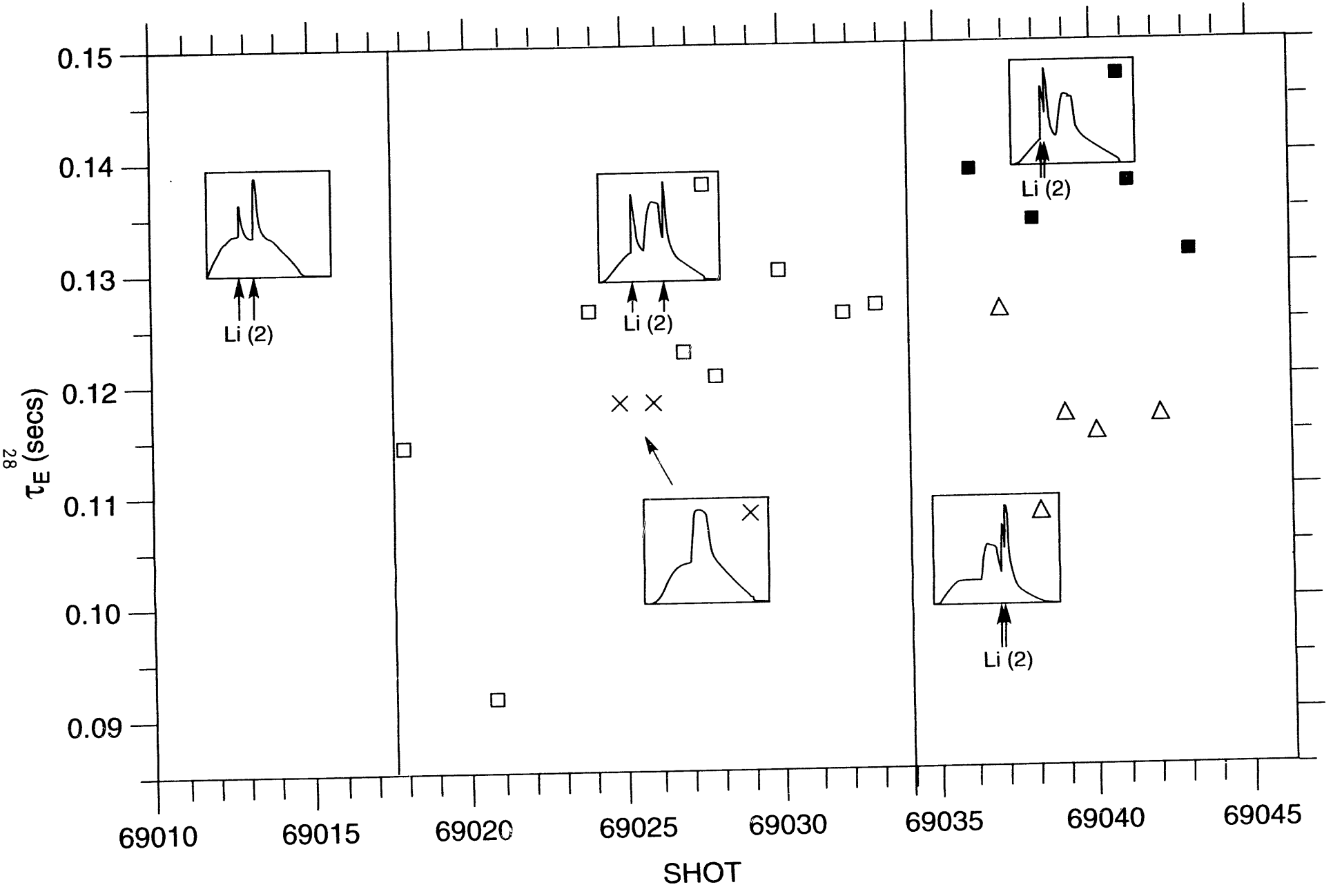
0.15
0.14
0.13
0.12
0.11
0.10
0.09
τ_E (secs)
Li (2)
Li (2)
Li (2)
Li (2)
69010
69015
69020
69025
69030
69035
69040
69045
SHOT

Fig. 7

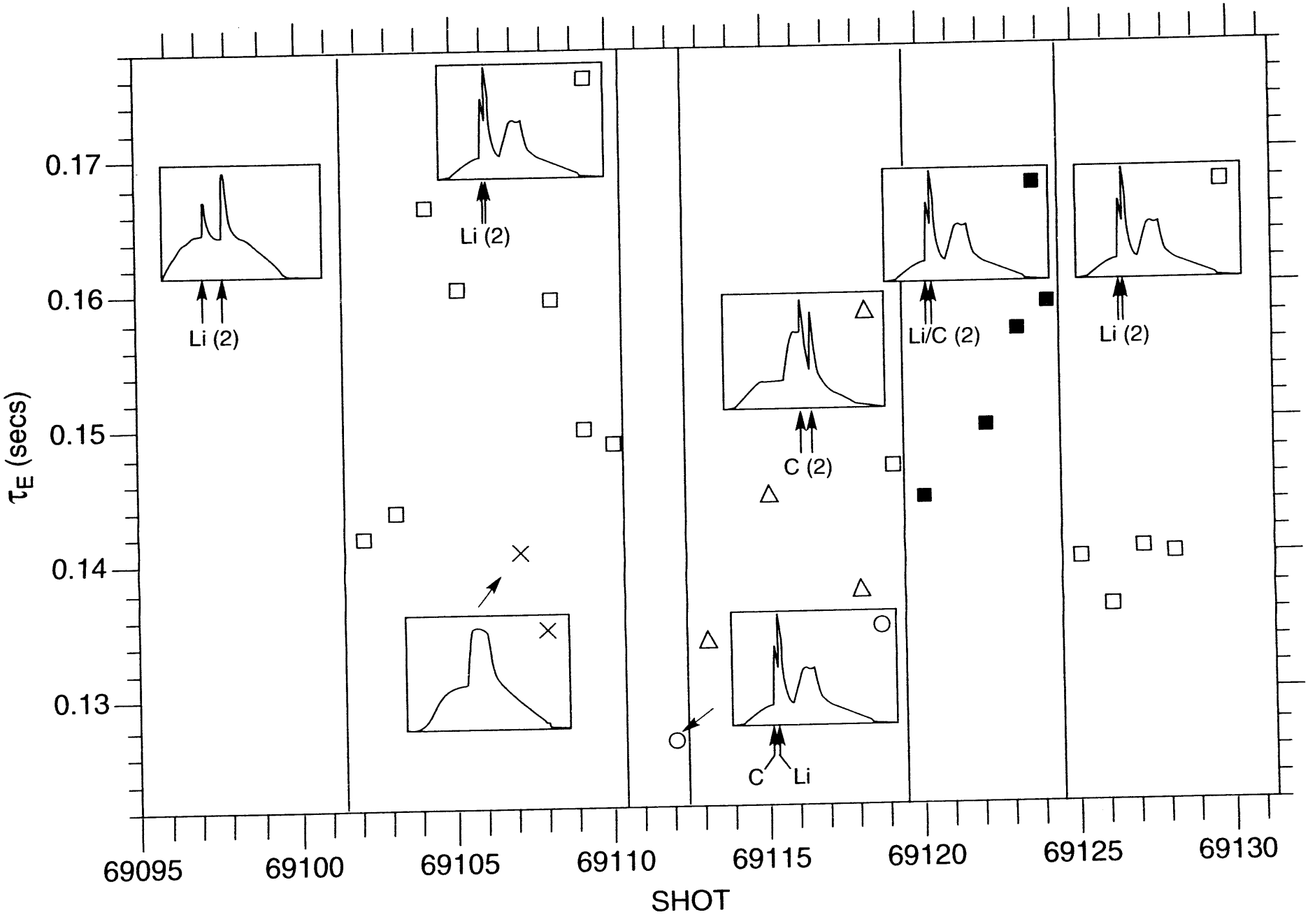
0.17
0.16
0.15
0.14
0.13
τ_E (secs)
Li (2)
Li (2)
C (2)
C
Li
Li/C (2)
Li (2)
69095
69100
69105
69110
69115
69120
69125
69130
SHOT

Fig. 8

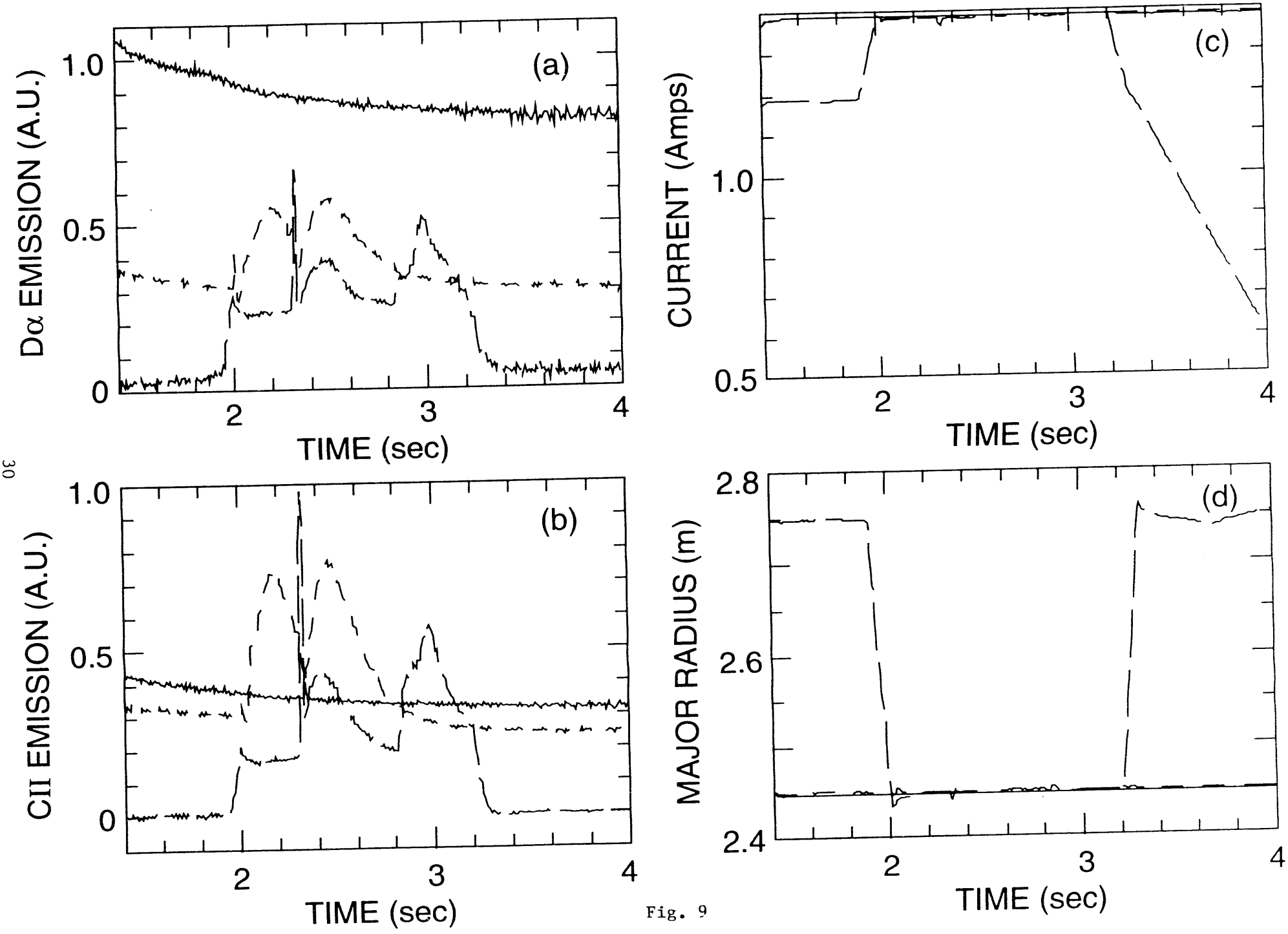
(a)
Dα EMISSION (A.U.)
1.0
0.5
0
2
3
4
TIME (sec)
(b)
CII EMISSION (A.U.)
1.0
0.5
0
2
3
4
TIME (sec)
(c)
CURRENT (Amps)
1.0
0.5
2
3
4
TIME (sec)
(d)
MAJOR RADIUS (m)
2.8
2.6
2.4
2
3
4
TIME (sec)

Fig. 9

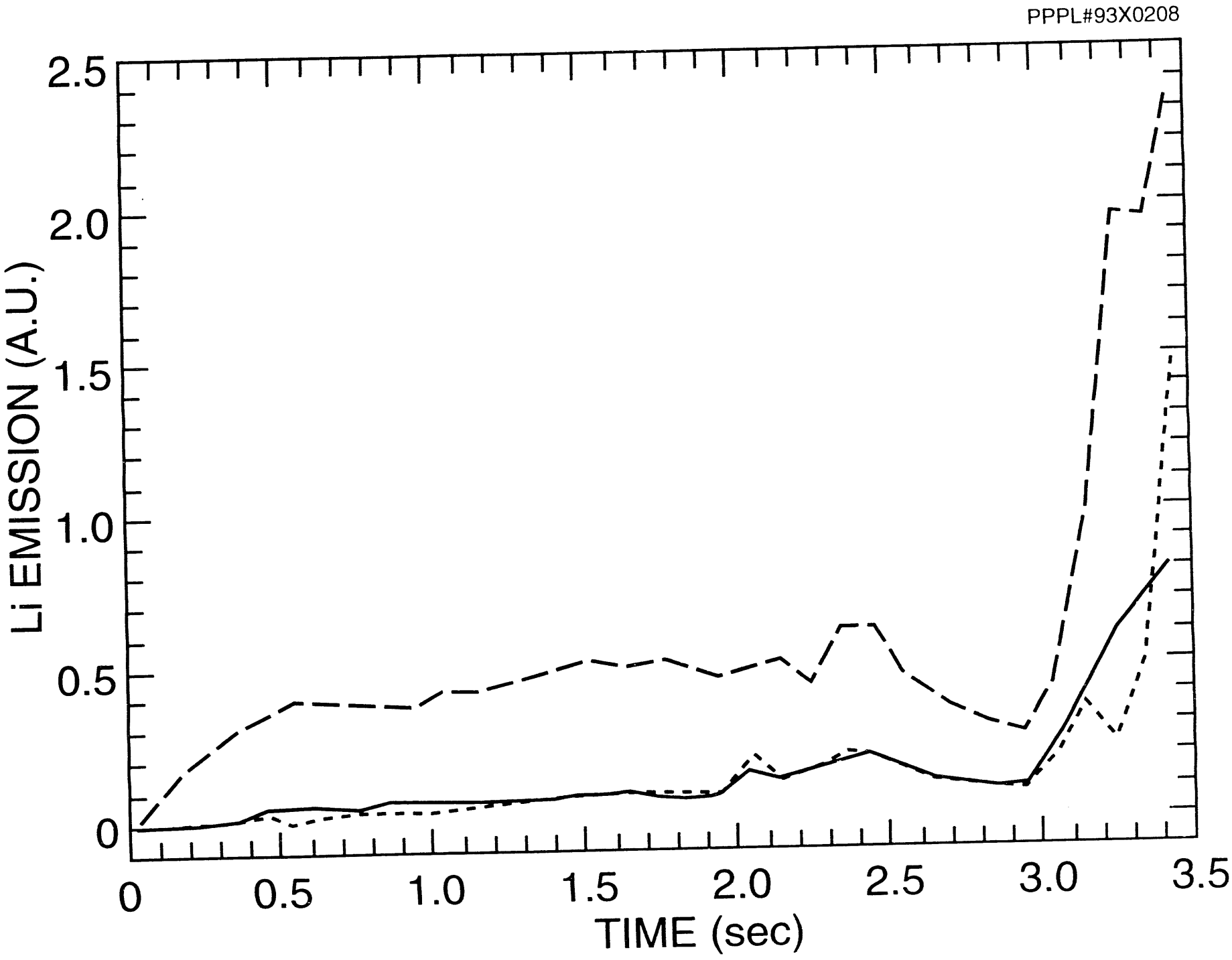
PPPL#93X0208
Li EMISSION (A.U.)
2.5
2.0
1.5
1.0
0.5
0
0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
TIME (sec)

Fig. 10

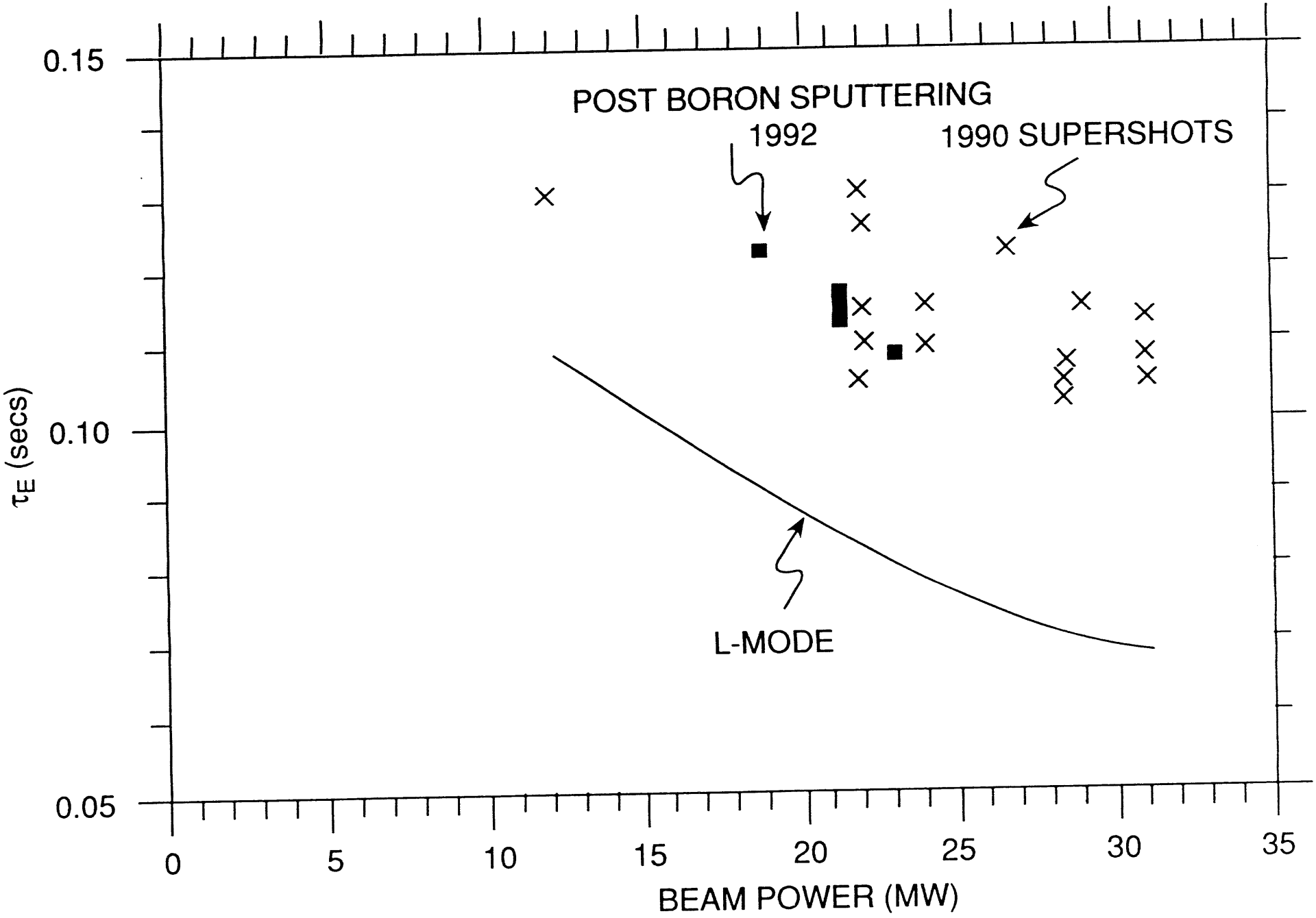
POST BORON SPUTTERING
1992
1990 SUPERSHOTS
L-MODE
0.15
0.10
0.05
τ_E (secs)
0
5
10
15
20
25
30
35
BEAM POWER (MW)

Fig. 11

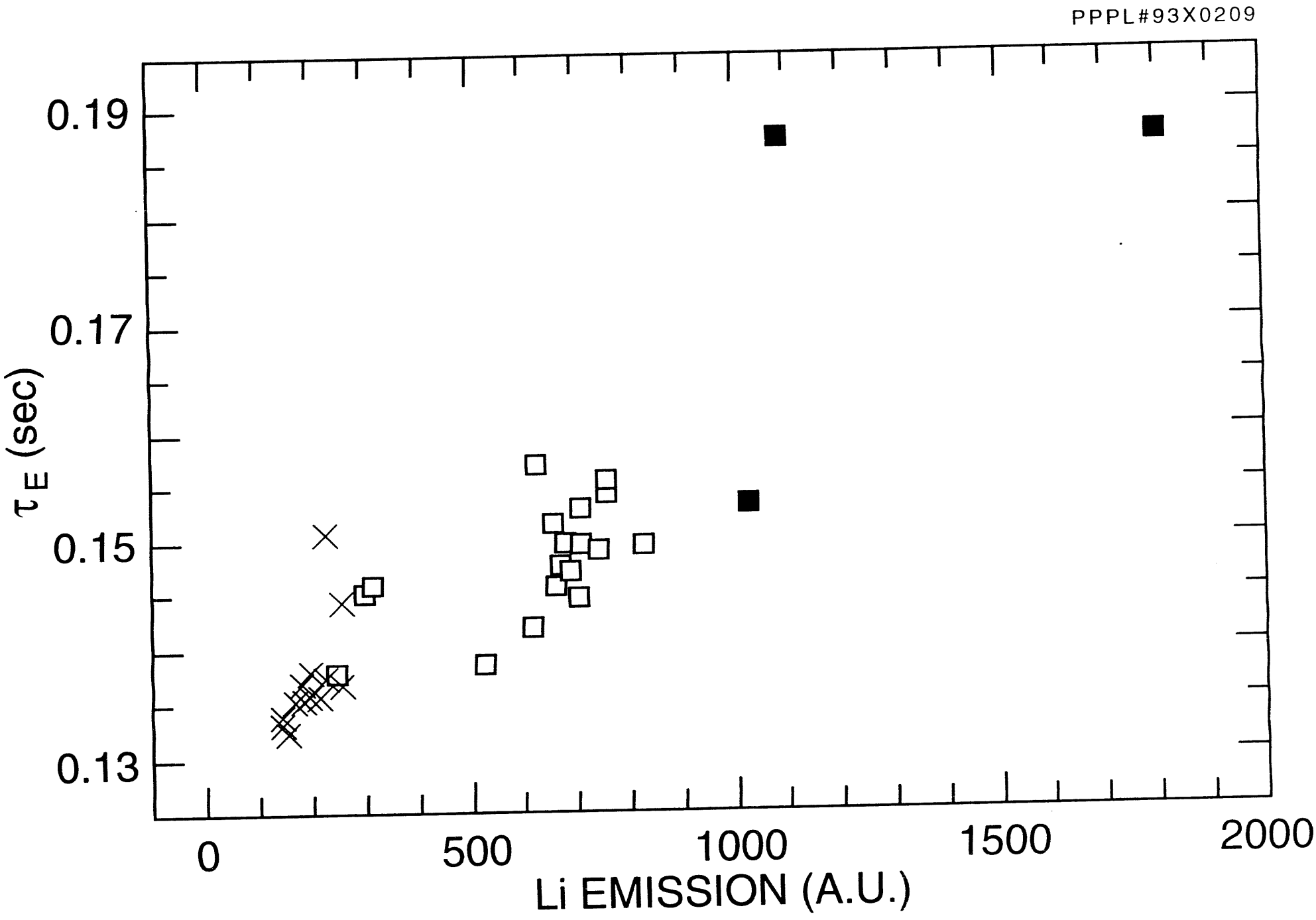
PPPL#93X0209
0.19
0.17
0.15
0.13
τ_E (sec)
0
500
1000
1500
2000
Li EMISSION (A.U.)

Fig. 12

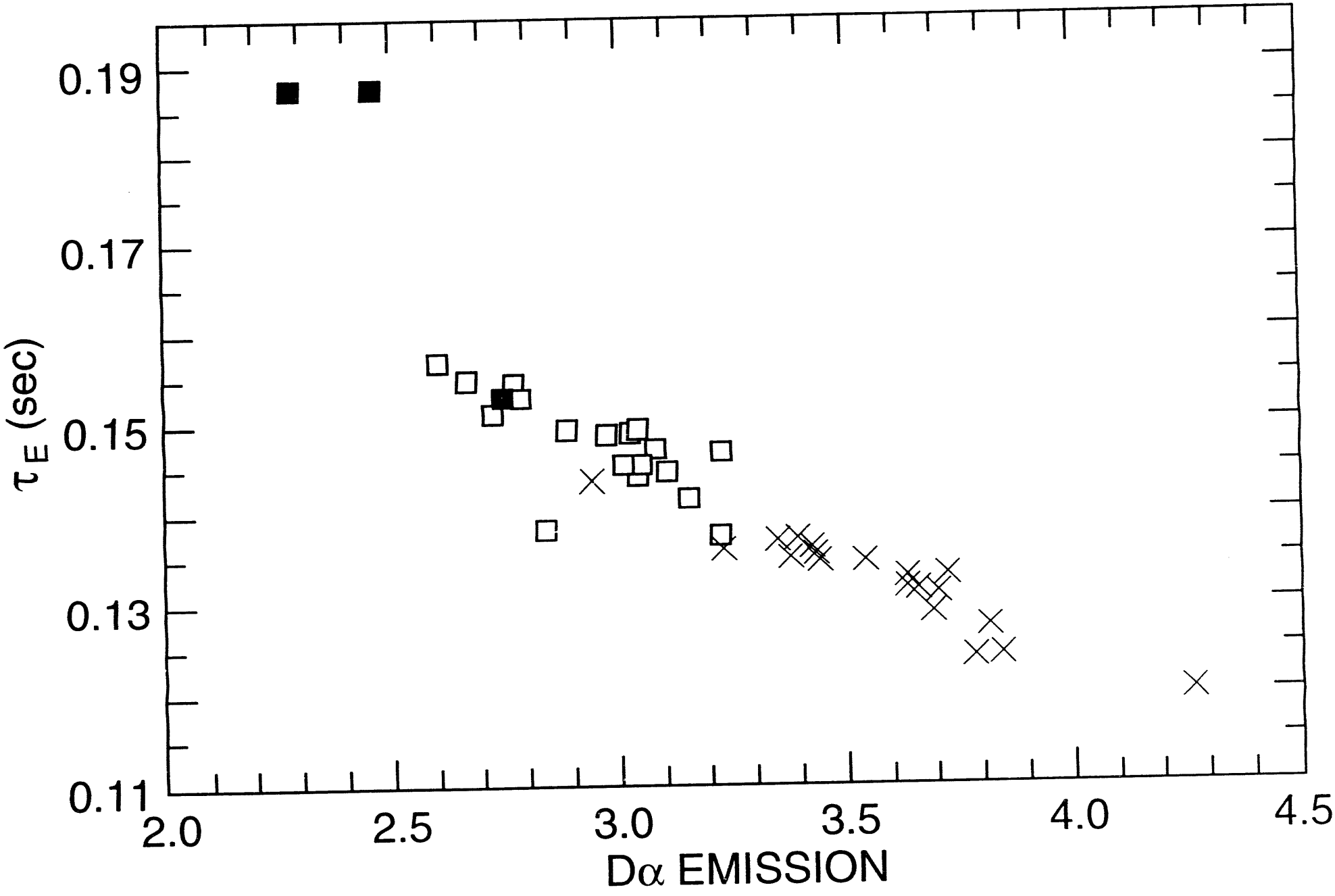

Fig. 13

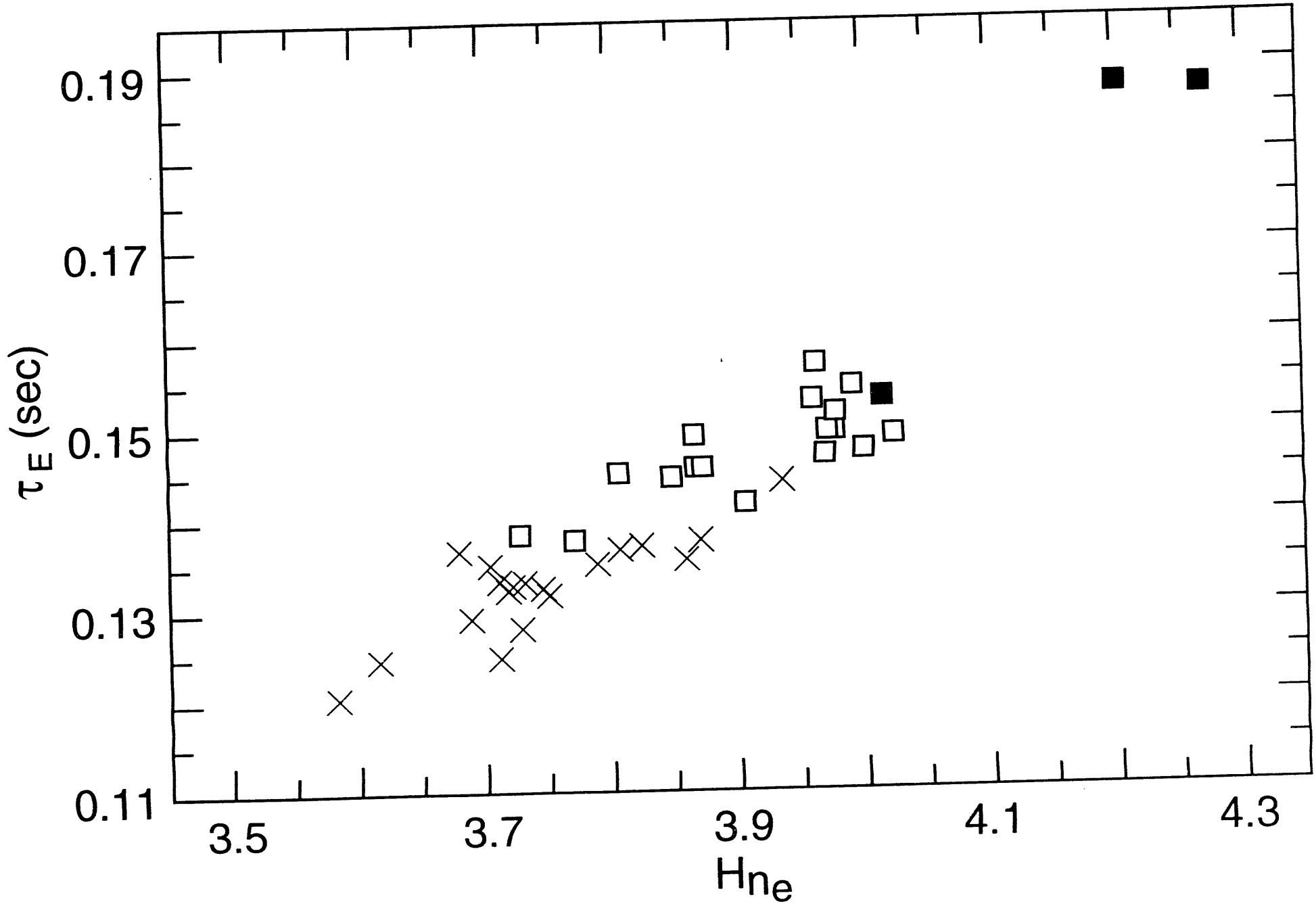

Fig. 14

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