PREPARED FOR THE U.S. DEPARTMENT OF ENERGY,
UNDER CONTRACT DE-AC02-76CH03073

PPPL-3526
UC-70

PPPL-3526

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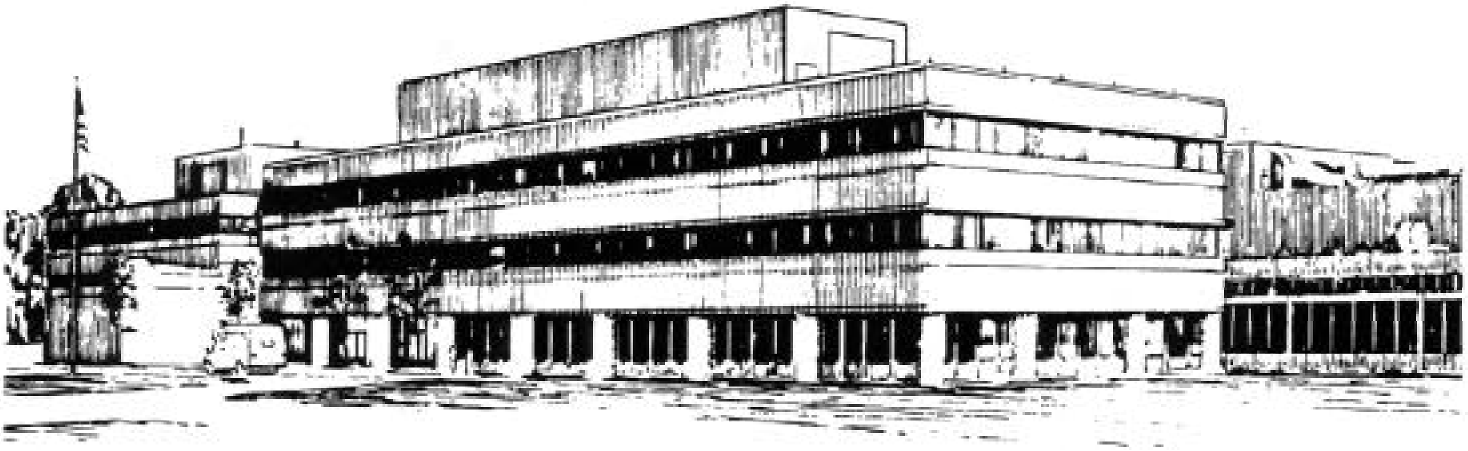
December 2000



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Abstract

A new method of actively modifying the plasma-wall interaction was tested on the Tokamak Fusion Test Reactor. A laser was used to introduce a directed lithium aerosol into the discharge scrape-off layer. The lithium introduced in this fashion ablated and migrated preferentially to the limiter contact points. This allowed the plasma-wall interaction to be influenced *in situ* and in real time by external means. Significant improvement in energy confinement and fusion neutron production rate as well as a reduction in the plasma Z_{eff} have been documented in a neutral-beam-heated plasma. The introduction of a metallic aerosol into the plasma edge increased the internal inductance of the plasma column and also resulted in prompt heating of core electrons in Ohmic plasmas. Preliminary evidence also suggests that the introduction of an aerosol leads to both edge poloidal velocity shear and edge electric field shear.

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1. Introduction

It has been well documented that the fusion performance of discharges in the Tokamak Fusion Test Reactor (TFTR) was strongly dependent on the physical and chemical condition of the graphite surface forming its limiter [1, 2]. In particular, the high-performance supershot mode of operation was attainable at high currents (>2.0 MA) only when the graphite inner wall had previously been “scoured” by repeated discharges heated by high-power neutral beam injection (NBI) in order to render the limiter surface free of loosely-bound carbon and loosely-adsorbed hydrogenic material. At the end of a series of such pre-conditioning discharges, plasma fueling from the limiter typically reached a minimum. Moreover, only when this low-recycling condition had been attained did high levels of fusion performance become accessible.

It has also been well documented that dramatic improvements in supershot fusion performance were attainable by the deposition of elemental lithium (Li) onto the limiter surface once it had been brought into the low-recycling condition. This deposition was carried out in earlier experiments by the injection and ablation of a few small (3 mg each) Li pellets [3, 4, 5, 6]. In order to improve plasma performance during NBI, Li pellets were typically injected into the Ohmic phase of discharges and the ablated Li was allowed to condense out of the plasma column and onto the limiter surface before the application of auxiliary heating. While the use of Li pellets did improve plasma performance, the technique was, nonetheless, highly perturbing. In order to reduce the perturbation to the plasma, brief but successful experiments with a Li effusion oven were also carried out on TFTR and are described elsewhere [7, 8]. While the use of an oven did result in an increase in the amount of Li deposited onto the inner wall as compared to pellet injection, deposition could only take place between discharges and not during the discharge of interest.

In this work, an alternate wall-conditioning technique is described in which Li was injected into the scrape-off layer (SOL), during plasma operation, and allowed to migrate onto the limiter surface quasi-continuously and with minimal perturbation to the plasma core. DOLLOP (Deposition Of Lithium by Laser Outside the Plasma), the system employed to carry out this deposition, was evaluated during the final weeks of TFTR operation. While these initial attempts to introduce Li into the SOL were both brief and incomplete, they, nonetheless, resulted in significant increases in TFTR fusion performance by favorably moderating the plasma-wall interaction.

It should be noted that the DOLLOP experiments were carried out with Li^6, instead of natural Li^7, in order to accommodate RF-heating experiments that were carried out contemporaneously on TFTR. The RF experiments were intended to heat Deuterium ions resonantly. The use of Li^6 ensured that the cyclotron resonant frequency and all associated harmonics of fully-stripped residual Li would be degenerate with the harmonic frequencies of deuterium ions. This degeneracy minimized the interaction between the two sets of experiments.

The experiments with DOLLOP fall into several broad categories. The DOLLOP system is described in section 2 of this work. Initial efforts to improve TFTR fusion performance using DOLLOP are described in section 3. In section 4, several experiments are described that were directed at understanding how the Li aerosol was incorporated into the edge of the plasma. In particular, efforts were made to determine to where on the limiter the injected Li migrated and what effects it had on plasma fueling once it was deposited on the inner wall. Further experiments were carried out to assess the effect of DOLLOP on energy confinement -- particularly electron energy confinement -- and on current density in Ohmic discharges. In section 5 a mechanism that might have contributed to the success of the DOLLOP concept is described. A summary of the experiments with DOLLOP is presented in section 6.

2. The DOLLOP System

The DOLLOP system is shown schematically in Fig. 1. Because it is light (0.52 g/cm^{-3} @ 200^{o} C) and has a high surface tension (397 ergs/cm^{2} @ 200^{o} C), liquid Li readily forms a upward-directed aerosol when its surface is perturbed abruptly by a focused laser beam. In this work, the Li was contained in a small (17.5 cm^{3}) boron nitride cauldron positioned near the plasma edge on a movable probe. The cauldron was heated Ohmically using tantalum wire and monitored with a thermocouple. Approximately 4 W was required to reach the Li melting temperature (160^{o} C). During plasma experiments, a 250^{o} C operating temperature was maintained with a heating power of 7 W. After an initial bake-out, the heated container assembly caused no noticeable change to the vacuum pressure inside the TFTR torus (1-5 x 10^{-8} Torr). Moreover, because the container was positioned about 15 cm below the shadow of the TFTR RF limiter, no measurable increase in cauldron temperature was observed either during normal plasma operation with neutral beam heating or as a result of violent plasma disruptions.

During plasma operation, a directed aerosol was created quasi-continuously by the action of a pulsed YAG laser beam directed onto the molten Li. The laser operated at 1064 nm and delivered 1.6 J/pulse in 8 ns-wide Q-switched pulses at a repetition rate of 30 Hz. The beam was focused onto the Li surface using a lens doublet with variable spacing located just above a quartz input window.

In prior laboratory experiments using the YAG laser, it was observed empirically that the amount of misted Li ejected from a molten surface exhibited a clear maximum as a function of the laser beam diameter at the liquid surface. Hence, to control the influx of Li into the plasma edge, the spacing of the lens doublet was controlled remotely by computer to adjust the size of the laser focal spot at the surface of the Li. Under conditions of near-optimal focusing, the aerosol particles created by the action of the laser were directed upward to a height of at least 1 m above the liquid surface in vacuum (in the absence of a plasma). During the TFTR experiments described in this work, the container was inspected after approximately 4000 laser pulses. It was determined that under conditions of optimal focusing (beam diameter 1-2 mm), an average of approximately 20 mg/s (2 x 10^{21} atoms/s) of Li was injected into the plasma edge while the laser was operating [9].

3. Enhancements in Plasma Fusion Performance

The introduction of Li onto the TFTR limiter by DOLLOP contributed to obvious improvements in plasma performance during high-power NBI. Fig 2 summarizes the characteristics of two beam-heated discharges. Discharge 104017 did not receive any Li while discharge 104039 received the benefit of Li from three sources: (1) In Ohmic discharges taken just prior to 104039, the graphite limiter was pre-conditioned by the injection of Li pellets (totaling about 10 mg) applied in a “painting” technique described elsewhere [6]. (2) During the Ohmic phase of 104039 additional Li was supplied by the injection of two Li pellets (3 mg each). (3) Li was supplied continuously by DOLLOP from breakdown until the termination of the discharge. As can be seen in Fig 2, the discharge treated with Li exhibited enhanced fusion performance until it was terminated by a major disruption brought on by high pressure in the plasma core. Three TFTR records were attained by this, the initial attempt at high-power operation using DOLLOP. First, this discharge attained the highest total energy confinement time (τ_E = 270 ms) of any deuterium-fueled TFTR supershot. It should also be noted that the confinement time continued to rise throughout the duration of NBI except at t= 4.5 s (detail I). The transient drop in confinement at that time has been associated with a pressure-driven core MHD event occurring just before the termination of the discharge. This rising confinement time can be compared to the falling confinement time in the discharge that did not receive Li. The roll-over of confinement was a typical feature of TFTR supershot plasmas without Li conditioning and has been associated with the influx of low-energy hydrogenic material from the limiter [10]. The fact that the confinement time in 104039 continued to rise during NBI suggests that the Li supplied by DOLLOP and other sources was effective at suppressing the influx of material from the limiter during the entire course of the discharge. Second, the Li-treated discharge also attained the highest ratio of DD fusion power to input power ($Q_{DD} = 2.2 \times 10^{-3}$) of any TFTR discharge. This observation suggests that the large amount of Li being injected into the scrape-off layer was not accumulating to any significant degree in the plasma core. Further evidence of this, as well as a discussion of the confinement roll-over phenomenon, is presented in section 4.1. Lastly, in addition to enhanced confinement and improved neutron production, discharge 104039 also attained the lowest level of central effective charge (Z_{eff} = 1.2-1.3) of any TFTR discharge with similar levels of neutral beam heating. This extremely low Z_{eff} is particularly noteworthy because it was achieved under conditions of high-power auxiliary heating without the benefit of a divertor. The Z_{eff} value shown in Fig 2 was determined from the measured visible Bremsstrahlung emission profile. The central Z_{eff} value determined by carbon charge exchange spectroscopy was slightly higher. The charge exchange method is, however, considered to be less reliable in this discharge because the Li and carbon impurity levels in the core were determined spectroscopically to be comparable. Analysis of the carbon exchange data was, therefore, problematic.

It may also be noted that the discharge that did not receive Li exhibited sawtooth oscillations while shot 104039 remained free of sawteeth during NBI. The absence of sawteeth in 104039 is consistent with previous experiments involving the injection of Li pellets into high-current supershots. It is, therefore, asserted that the suppression of sawteeth during NBI was an additional consequence of the deposition of Li onto the TFTR limiter [6].

4. Details of the Incorporation of the Li Aerosol into the Plasma

A distinction must be made between the effects of transient (<500 ms) and long-term (>500 ms) injection of Li aerosol, although the dividing point is only approximate. As demonstrated below, Li injected transiently into the SOL of TFTR required roughly 500 ms to migrate along magnetic field lines, accumulate on the “nude” limiter and begin to modify the plasma-wall interaction. Once deposited, the Li acted (among other effects) to suppress particle recycling from the TFTR graphite limiter surface. This temporary reduction in recycling lasted only until physical or chemical processes caused the deposited Li to lose efficacy [11, 12].

The experiments described below (supported by previous experiments with Li pellets) suggest that the loss of efficacy took place on a time scale longer than 500 ms -- perhaps as long as 1-50 s of continuous plasma operation [4]. Accordingly, a salient feature of the DOLLOP system is that, when employed in Ohmic discharges for times longer than about 500 ms, the resulting *sustained* reduction in limiter fueling tended to overwhelm the edge-localized fueling due to Li ablation. Hence, during Ohmic discharges, DOLLOP produced a net *global* sink of particles (when compared to fueling by recycling from the nude TFTR graphite limiter) while simultaneously acting as an edge-localized source of fueling.

When used for times longer than 500 ms, the fueling behavior of DOLLOP during NBI-heated discharges was different from that observed in Ohmic plasmas. As discussed below, during Ohmic discharges roughly 5% of the neutral Li atoms injected into the SOL remained un-ionized long enough to penetrate beyond the last closed flux surface (LCFS) hence acting as a particle source to the plasma column. During high-power NBI, however, the Li broadcasted into the SOL ablated and ionized more quickly so that virtually no Li penetrated beyond the LCFS. During NBI, therefore, DOLLOP acted as a net global sink of particles while *not* acting as an edge-localized source. Examples of both types of behavior are shown below.

4.1. Fueling Effects on Ohmic and Neutral-Beam-Heated Plasmas

The initial effects of DOLLOP operation on Ohmic plasmas may be seen in Fig 3 A and B. Shown are traces of the total number of electrons (N_{TOT}) contained in discharges in the 103979-104003 sequence each with identical externally-controlled parameters (R = 261 cm, a = 96 cm, I_p = 1.6 MA , B_t = 3.8 T). During this sequence, there were 18 discharges into which brief (0.5-1 s) bursts of Li were injected in order to study transient effects on particle fueling as well as to investigate effects due to the accumulation of Li over a large number (>10) of discharges. In addition, during this sequence, the focusing of the laser was adjusted between discharges in a preliminary attempt to influence the rate of Li deposition into the plasma edge. The four solid traces in Fig 3 A and B represent the initial discharges in the experiment. These discharges did not receive any Li and were, therefore, fueled only by recycling from the nude TFTR graphite limiter. The absence of shot-to-shot variation indicates that these baseline discharges were operating near the TFTR low-recycling limit. The indicated trace in Fig 3 A represents discharge 103984 in which the initial use of DOLLOP was accomplished. The effects of a 1s-long train of 30 laser pulses can be clearly seen on N_{TOT}. The initial build-up of particles ceased after about the first 500 ms of laser operation. Thereafter, as the injected Li reached the limiter and began to reduce the particle recycling, a slow particle pump-out took place (detail I). Finally, when the laser was turned off at the end of the 1-sec pulse train, an accelerated pump-out of particles occurred (detail II). This was the first indication of the dual nature of particle fueling from DOLLOP. For the first 500 ms of laser operation, the Li aerosol acted as an edge-localized source of particles; after 500 ms DOLLOP began to act as a global sink because of the suppressed net influx of material from the limiter caused by the deposition of Li. When the laser was turned off, the source of edge fueling ended and an accelerated particle pump-out was observed.

The dotted line in Fig 3 A represents shot 103985, the next discharge after the initial use of DOLLOP. In this discharge, the residual effects of the Li from shot 103984 can clearly be seen.

Lithium was not injected into shot 103985 which was fueled only by recycling from the limiter At most, a few mg of Li had been deposited on the limiter from the previous discharge. (The limiter received much less than 20 mg of Li during shot 103984 because the DOLLOP laser focus had not yet been adjusted to maximize the influx of Li from the container. See the discussion below). Two clear features appear in the 103985 data: (1) N_{TOT} was reduced well below the value that would have obtained had the limiter not been treated with the Li from shot 103984. This is definitive evidence of a reduction of recycling from the graphite limiter due to Li implantation/deposition. (2) N_{TOT} increased as a function of time as the residual Li slowly lost its efficacy (detail III). Both observations are consistent with previous work describing the effects of Li pellets on recycling in TFTR [4].

In Fig 3 B are shown again the baseline discharges as well as the last two discharges in the 103979-104003 sequence. During the next-to-last discharge in this sequence, a 500 ms-long train of laser pulses was used to deposit Li into the plasma. Prior to this discharge the laser was defocused at the liquid surface. This defocusing caused an increase in the amount of Li into the plasma and subsequently an increase in the number of electrons added to the plasma as compared to shot 103984. The initial rate of rise of N_{TOT} in shot

104002 was about 3 x 10^{20} electrons/s. This observation allows one to estimate that during these Ohmic discharges no more than 5% of the injected Li atoms penetrated past the LCFS and into the discharge column. It may also be noticed in Fig 3 B that N_{TOT} continued to fall from shot to shot as Li from previous discharges (103984 through 104001) gradually accumulated on the limiter. This accumulation was a consequence of the fact that the deposited Li lost its efficacy on a long time scale -- as long or longer than the 8 s duration of the discharges in the 103979-104003 sequence. These observations of Li accumulation are also consistent with previous studies of Li deposition carried out with pellets [4].

The long-term (>500 ms) effects of the use of DOLLOP on Ohmic plasmas can be seen in Fig 4. In this figure are shown traces of the line-integrated edge density, the central density, the density profile peakedness (= $n_e(0)/\langle n_e \rangle$ where $\langle n_e \rangle$ is the volume-average electron density) and the total number of electrons for three discharges having identical externally-controlled plasma parameters (R = 252 cm, a = 86 cm, I_p = 2.0 MA, B_t = 5.0 T, P_{NBI} = 18 MW) and operating near the TFTR low-recycling limit. The first in this series of discharges (104017) received no Li. The second discharge 104026 received Li from DOLLOP continuously from the beginning of the discharge until termination. The third discharge (104027) received

Li only during the Ohmic phase of the discharge. In this last discharge the DOLLOP laser was turned on at the start of the discharge and turned off at 3.4 s, 600 ms before the start of neutral beam heating. A clear pump-out of particles can be seen following the laser turn-off. This pump-out indicates that the Li broadcasted into the plasma edge by the DOLLOP laser acted as a localized source of electrons fueling the plasma edge density as well as the total number of electrons in the plasma column. It is interesting to note, however, that both the edge density and N_{TOT} are lower in the second discharge during which Li was continuously broadcast into the plasma edge than in the first discharge that received no Li. This is consistent with the behavior seen in Fig 3 A (detail I) during which a slow pump-out of particles can be seen after the first 500 ms of laser operation. For periods of operation longer than 500 ms, the Li that migrated to the limiter acted as a net sink of particles by reducing the graphite recycling. Eventually, this effective global sink overwhelmed the local source of particles created by injecting the Li aerosol into the scrape-off layer.

The fueling efficiency of the Li aerosol during periods of auxiliary heating with injected neutral beams may also be determined by reference to Fig 4. During the NBI heating phase of the three discharges shown, both N_{TOT} and the edge density were lower in the discharges that received Li from DOLLOP (104026 and 104027) than in the discharge that did not receive Li (104017). Comparing 104026 and 104027 it may also be noted that, during NBI, the edge density was almost unchanged in consecutive discharges whether the DOLLOP laser was on or off. Further, N_{TOT} remained unchanged whether or not the DOLLOP laser is employed -- except during the first 200 ms of NBI. From these observations it appears that virtually no Li penetrated beyond the LCFS during NBI. This can be compared to the 5% that penetrated during the Ohmic discharges of the 103979-104003 sequence. The larger *change* in N_{TOT} that occurred during the first 200 ms of NBI in shot 104027 when the DOLLOP laser was off (Fig 4, detail (I)) as compared to shot 104026 (when the laser was on) might be explained by the influx of carbon that was *not* suppressed when the laser was off. Some support for this argument can be seen in the behavior of the density profile peakedness. The peakedness can be seen to sag as a function of time with the laser off during shot 104027 as compared to the sustained peakedness seen in shot 104026 with Li being provided continuously (Fig 4, detail (II)). Because carbon has twice as many electrons per atom as Li, an influx of carbon from the plasma edge would certainly be expected to cause a decrease in peakedness. It should also be noted that the sag in peakedness seen in Fig 4 has been associated with the roll-over of energy confinement time demonstrated in Fig 2 [13, 14]. In this regard, an important advantage of using DOLLOP is that it appears to eliminate the roll-over in confinement by suppressing the influx of material from the limiter on a continuous and sustained basis.

4.2. The Trajectory of Injected Lithium

The 103979-104003 experimental sequence discussed above and described in Fig 3 was run primarily to assess the effect of DOLLOP on plasma fueling and limiter recycling. These discharges were also used for another purpose: to study the trajectory of the Li ions introduced into the SOL. In this regard, TFTR was equipped with an array of collimated detectors to monitor CII radiation emitted from the scrape-off plasma close to the limiter surface. These detectors, shown schematically in Fig 5, provided information about the limiter location to which the Li ions migrated when introduced into the SOL. As an example, also shown in Fig 5 are traces of CII emission associated with each detector. The pattern of deposition for Li ions flowing along field lines in the SOL to the limiter was calculated using the magnetic configuration appropriate to the experimental sequence shown. The modeling was done assuming an exponential decrease of Li density with distance from the LCFS with a characteristic length of 2 cm. As seen in the figure, most of the flow was calculated to be deposited slightly inside the upper and lower tips of the limiter. The data shown represent the sequence of discharges described in Fig 3 B. The four discharges taken before the introduction of Li (103979, 80, 82, 83) are represented by dark solid lines. Also shown is the discharge in which a 500 ms-long train of laser pulses was used to introduce Li into the plasma edge. This particular discharge (104002) was taken after Li had been allowed to accumulate on the high flux region of the limiter by the restricted (<10 mg/discharge) use of DOLLOP on the previous 18 discharges. The last discharge in the sequence is represented by a dotted line; no Li was introduced into this discharge.

In Fig 5 it can be seen that before the introduction of Li, the limiter location associated with the highest particle flux from the SOL exhibited the highest level of CII radiation and was, therefore, the area responsible for the largest influx of carbon into the plasma. After 18 discharges in which a few milligrams of Li was allowed to accumulate on the limiter, the level of CII radiation from the neighborhood of the contact point(s) dropped by roughly a factor of two. In addition, during the next-to-last discharge in the sequence (104002), the transient effects of the laser were seen predominantly at the tip(s) of the limiter -- the location associated with the highest particle flux from the SOL. These observations can be interpreted to indicate that the Li introduced by DOLLOP migrated preferentially to the region(s) of highest particle and power flux. The Li that migrated to the high-flux point tended to suppress the influx of material from the limiter (carbon, hydrogen, deuterium and tritium); this suppression, in turn, led to lower densities in Li-treated plasmas that were fueled only by recycling (Fig 3).

It is also possible that a more global modification of the scrape-off parameters by the lithium could produce the results presented in Fig 5 because the measured CII emission is so localized at the contact point under all conditions. However, additional empirical support for the assertion that Li introduced by DOLLOP tended to migrate along field lines toward the limiter contact point(s) was inferred from video pictures taken of the Li aerosol being deposited into the plasma edge.

In particular, shown in Fig 6 are images taken with a fast video camera that has been described elsewhere [15]. A few individual aerosol particles have been captured in Fig 6 A -- an image taken in white light. These particles can been seen to be toroidally displaced from the region immediately above the cauldron. Further, because these particles are localized and radiating near the plasma edge, it appears that they are ablating in the SOL. In Fig 6 B is seen an image taken through a Li^{+1} filter. In this picture, ionized ablatant can clearly be seen streaming along field lines. Because these video images were taken during discharges similar to those displayed in Fig 5, they lend support to the inferences presented above concerning the trajectory of the Li injected by DOLLOP.

4.3. Transient Effects on Electron Confinement

The effect of DOLLOP on the electron temperature of Ohmic discharges was also investigated using discharges from the 103979-104003 experimental sequence. Shown in Fig 7 are the central density and electron temperature for a 1.6 MA Ohmic discharge (104002, See Figs 3 and 5). Li was introduced into this discharge by DOLLOP from 3.0 to 3.5 s. Also indicated in this figure are the 15 individual Q-switched laser pulses that constituted the 500 ms-long pulse train. By reference to the density trace it can be seen that the Li broadcasted into the plasma edge had no effect on the central density for approximately 150 ms (4-5 laser pulses). During this time, however, the electron temperature increased dramatically. The sawtooth period can also be seen to increase soon after laser turn-on and certainly well before any particles reached the core. Further, about 500 ms after the first laser pulse, the central density can be seen to have almost doubled before eventually pumping out. At the end of the pump-out, the sawteeth period returned to the pre-injection level.

It may be speculated that the transient heating of electrons seen in Fig 7 is a manifestation of the non-local heating observed in several tokamaks in response to a sudden edge perturbation. This phenomenon was first reported by Gentle [16] outlining experiments on TEXT and later described by Kissick [17] reporting on TFTR experiments. In both works, the authors describe the response of the plasma to single, isolated perturbations produced by laser blow-off. In both cases a rapid drop in edge temperature was accompanied by a prompt (i.e., not on a thermal propagational time scale) rise in the core electron temperature. It was also reported that, during the interval after the perturbation, the edge temperature re-heat took place *faster* than the cool-down of the core. One can, therefore, conjecture that a series of judiciously-timed edge perturbations might cause a ratcheting upward of the core temperature. The introduction of a Li aerosol by DOLLOP can be viewed as a series of randomly-timed edge perturbations from the individual aerosol particles that might give rise to a ratcheting effect. In Fig 7, the decline in central temperature beginning 250 ms after laser turn-on can be explained by noting that by that time the core density had risen significantly, because of the small fueling rate of the injected Li.

Whatever the cause, the observed heating of central electrons in reaction to the introduction of metal droplets into the plasma edge is not easily explained by classical notions of thermal transport. Further, there was a small but discernible drop in the loop voltage associated with the laser turn-on for the Ohmic discharges studied in this work. This observation taken together with a concomitant rise in plasma internal inductance (outlined in 4.4 below) suggests that an improvement in Ohmic energy confinement resulted from the introduction of a metallic aerosol into the plasma edge.

4.4. The Influence of DOLLOP on the Current Density

Shown in Fig 8 are temporal traces of the plasma internal inductance (ℓ_i) that was measured magnetically for three Ohmic discharges with identical externally-controlled parameters (R = 260 cm, a = 96 cm, I_p = 1.6 MA, B_t = 3.8 T) [18]. During two of these discharges the DOLLOP laser was turned on for different intervals of time. Contrasted against these is a discharge that did not receive any Li from DOLLOP. It may be clearly seen that, in both cases, ℓ_i

increased when the laser was turned on and continued to rise for the entire duration of the laser pulse train.

Because ℓ_i is a direct measure of the plasma current density peakedness, it appears that the effect of the Li aerosol was to push current density away from the edge of the plasma column and into the core. This inference is consistent with the heating of central electrons discussed in 4.3 above. A rise in central electron temperature would be expected to result in more current flowing in the core; conversely, a decrease in edge temperature brought on by the ablation of aerosol particles would prevent the flow of edge current. Hence, a more peaked current profile would be expected, empirically. In that sense, while the DOLLOP laser was turned on in these discharges, the injected aerosol defined the edge of the plasma current distribution thereby acting as a quasi-limiter. This behavior is similar to that observed during liquid limiter experiments on T-3M [19].

5. A Possible Contributing Mechanism

Plotted in Fig 9 is the measured poloidal rotation of shot 104039 (discussed in Fig 2) [20]. A 10 cm-wide region of shear in the poloidal flow is a robust feature that may be seen in both the Ohmic and beam-heated phases at the plasma edge. This shear layer is evident in discharges that received Li aerosol from DOLLOP but was not seen in discharges that did not receive Li. Shown for three different times in Fig 10 are plots of the radial electric field calculated from the measured poloidal and toroidal rotations and the measured plasma pressure gradient. A striking feature of this data is the edge-localized region of sheared radial electric field that appears to be a consequence of the use of DOLLOP. Such a region of sheared field has been associated with the occurrence of transport barriers in other fusion devices [21, 22, 23, 24]. Moreover, a similar region of sheared field located about 10 cm inside the LCFS was seen to occur in TFTR discharges that exhibited enhanced performance as a response to intense puffing of noble gases [25, 26]. A region with such a shear-induced transport barrier would tend to prevent low-energy material leaving the wall from entering the plasma core while simultaneously preventing hot particles from diffusing out of the plasma and striking the limiter. The existence of an edge transport barrier may be the common thread that ties together the seemingly disparate consequences of injecting a Li aerosol into the plasma edge. Such effects as the apparently non-local heating of electrons in Fig 7, the rise in plasma inductance shown in Fig 8, the dramatic improvement in energy confinement and the simultaneous lowering of Z_{eff} shown in Fig 2 may be consequences of the structure shown in

Figs 9 and 10. More work, however, must be done before a link can be established between these phenomena.

6. Summary

During the last few weeks of TFTR operation, a Li aerosol was successfully delivered by the DOLLOP system into the edge of both Ohmic and high-power supershot discharges without apparent trauma to the plasmas. Moreover, several effects that were profoundly beneficial to plasma performance were observed in discharges heated by NBI. These effects included increased energy confinement and neutron production as well as lowered Z_{eff}. In addition, improvement in electron energy confinement was observed during Ohmic discharges.

Because Li is delivered quasi-continuously by the DOLLOP system, the benefits to plasma performance outlined above could be *sustained* during future long-pulse operation. Further, the Li introduced by DOLLOP appears to follow field lines in the SOP until those field lines intersect the limiter at the plasma contact point. Hence, DOLLOP offers the possibility of delivering Li dynamically to where it is most needed (i.e. the contact point) even if the contact point moves as plasma conditions change. In this sense DOLLOP represents a new concept in the modification of the plasma-wall interaction.

It should be noted, however, that owing to a lack of run time, no optimization of *any* parameter associated with the use of DOLLOP is claimed in this work. It appears, therefore, that DOLLOP has the potential to deliver Li at much higher rates and, perhaps, to much greater effect than has been described herein. Because of the success experienced in TFTR, it appears that the DOLLOP concept may lead to enhanced performance in other tokamaks. Further, the concept, raised in this work, of an externally-controllable edge transport barrier is an intriguing possibility -- but unproved at this point. If the edge structure shown in Figs 9 and 10 does, in fact, act as a transport barrier, then such an edge barrier might prove useful in the control of impurity influx in future fusion devices.

Acknowledgments

The authors wish to acknowledge the excellent technical contributions made to the DOLLOP system by M. Vocaturo, G. LeMunyon, J. Gorman and G. Labik. The authors are also indebted to the Oak Ridge National Laboratory for providing the Li^6 used in the experiments. This work was supported by U.S. Department of Energy contract No. DE-AC02-76CH03073.

Figure Captions

Fig 1. DOLLOP, shown schematically, delivered a directed Li aerosol into the plasma scrape-off layer. The computer-controlled YAG laser was located about 50 meters from the TFTR vessel. The distance from the cauldron to the center of the vacuum vessel cross section was 1.1 m.

Fig 2. The improvement in plasma performance brought about by Li conditioning is summarized in this diagram. This particular discharge (104039) represents the first attempt to improve a high-power discharge using DOLLOP to influence the plasma-wall interaction.

Fig 3. These traces record the first transient use of DOLLOP in discharges being fueled by limiter recycling only. The limiter was brought into a low-recycling condition prior to the running of these discharges. In (A) it may be seen that a clear reduction in recycling resulted from the deposition of just a few milligrams of Li. In (B) it may be noted that the recycling continued to fall after a sequence of 18 discharges in which less than 10 mg of Li per discharge was deposited. This is evidence of the net accumulation of Li on the limiter.

Fig 4. Shown are density-related traces for three discharges. Shot 104017 received no Li. Shot 104026 received Li via DOLLOP from the beginning of the discharge until termination. Shot 104027 received Li from the beginning of the discharge until 600 ms before the start of NBI. The edge density trace was taken from the inner-most vertical channel of the TFTR laser interferometer that passed with 15 cm of the limiter at the midplane. All other traces were derived from inversion of the ten-channel interferometer signals.

Fig 5. Shown are the sight-lines of an array of CII detectors viewing the TFTR limiter, as well as traces in arbitrary units of CII emission associated with these detectors. The scale of each of the five traces is the same. The 500 ms interval during which the DOLLOP laser was on is also indicated. The data are from the discharges summarized in Fig 3 B. Plotted on the inner wall are the modeled patterns of deposition from the SOL onto the limiter.

Fig 6 .Two video images of the Li injected by DOLLOP into the plasma edge are displayed. Image A was taken in white light with an exposure time of 0.2 ms and shows individual Li particles that are displaced from the region above the cauldron marked by the tip of the arrow. Image B was taken through a Li^{+1} filter with an exposure of 0.3 ms. It is interesting to note the dark area just above the cauldron indicating an absence of Li ions and the obvious subsequent streaming of Li^{+1} ions along field lines.

Fig 7. The central density and central electron temperature for shot 104002 are plotted together. Also indicated are the individual laser pulses used to introduce Li into this discharge.

Fig 8. In this diagram are shown traces of the plasma internal inductance for three Ohmic discharges. The plasma internal inductance clearly increased when the DOLLOP laser was turned on and, therefore, the plasma current density became more peaked under the influence of the Li aerosol.

Fig 9. Displayed in this diagram is the measured edge poloidal rotation for shot 104039, a high-power supershot in which the DOLLOP laser was turned on from the beginning to the end of the shot. A distinct region of flow shear may be seen both during the

Ohmic and the NBI-heated phases of the discharge. This feature was only seen in discharges that received an injected Li aerosol.

Fig 10. Shown are the calculated radial electric fields at three different times during shot 104039. The region of edge electric field shear appears unchanged from t = 4.0 s, just after the start of NBI until t = 4.4 s -- well into the heating phase.

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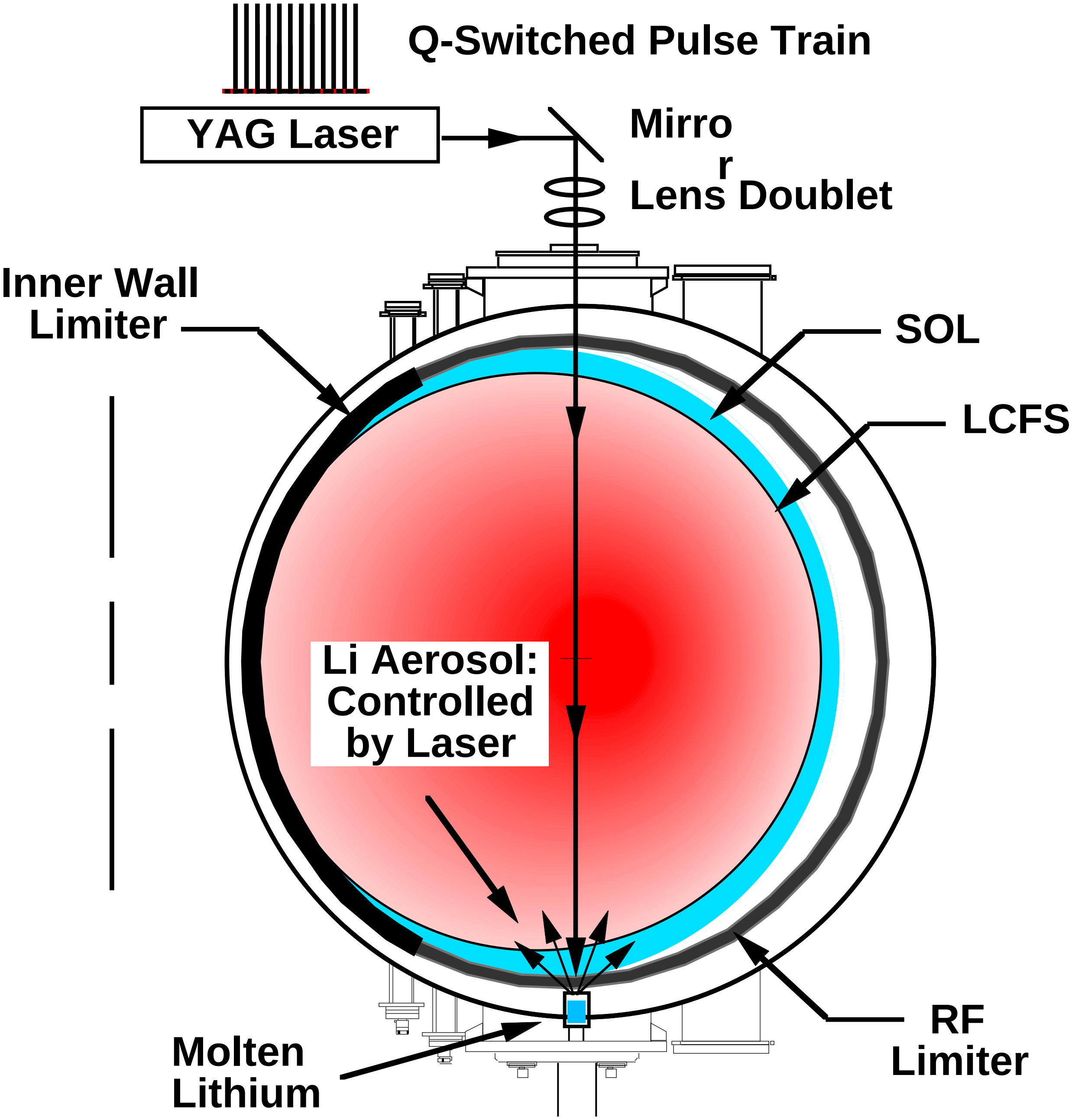
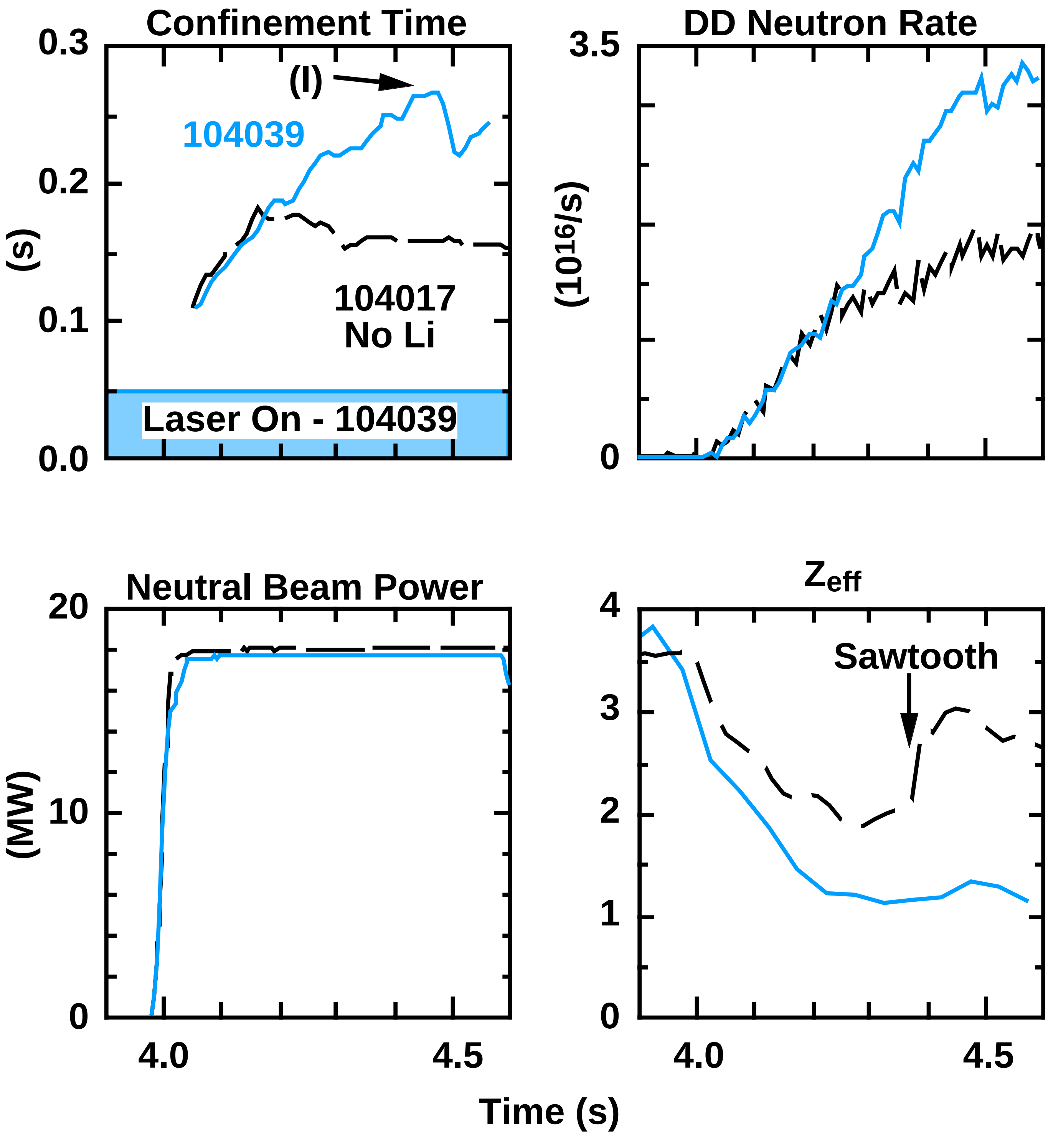
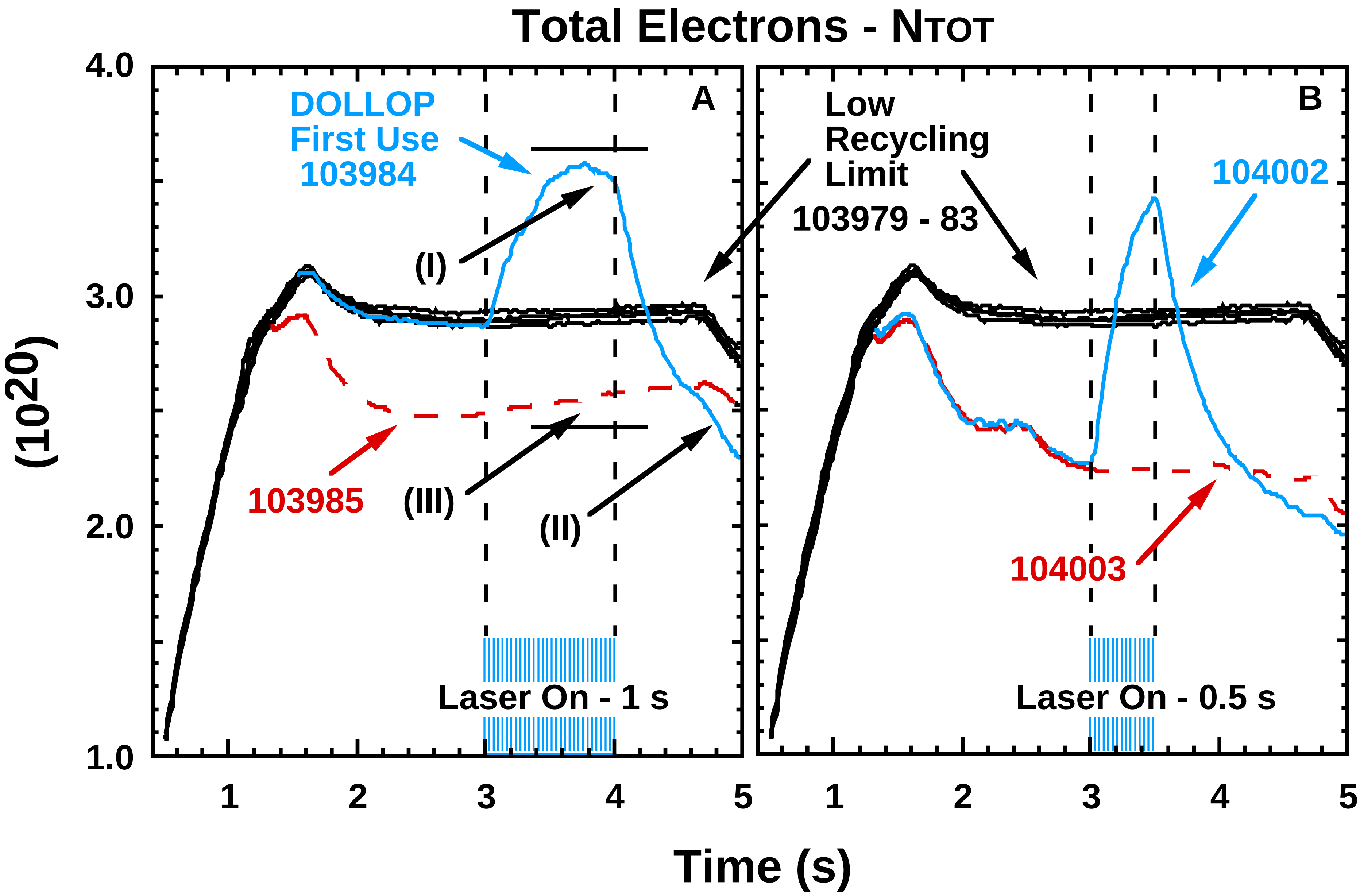
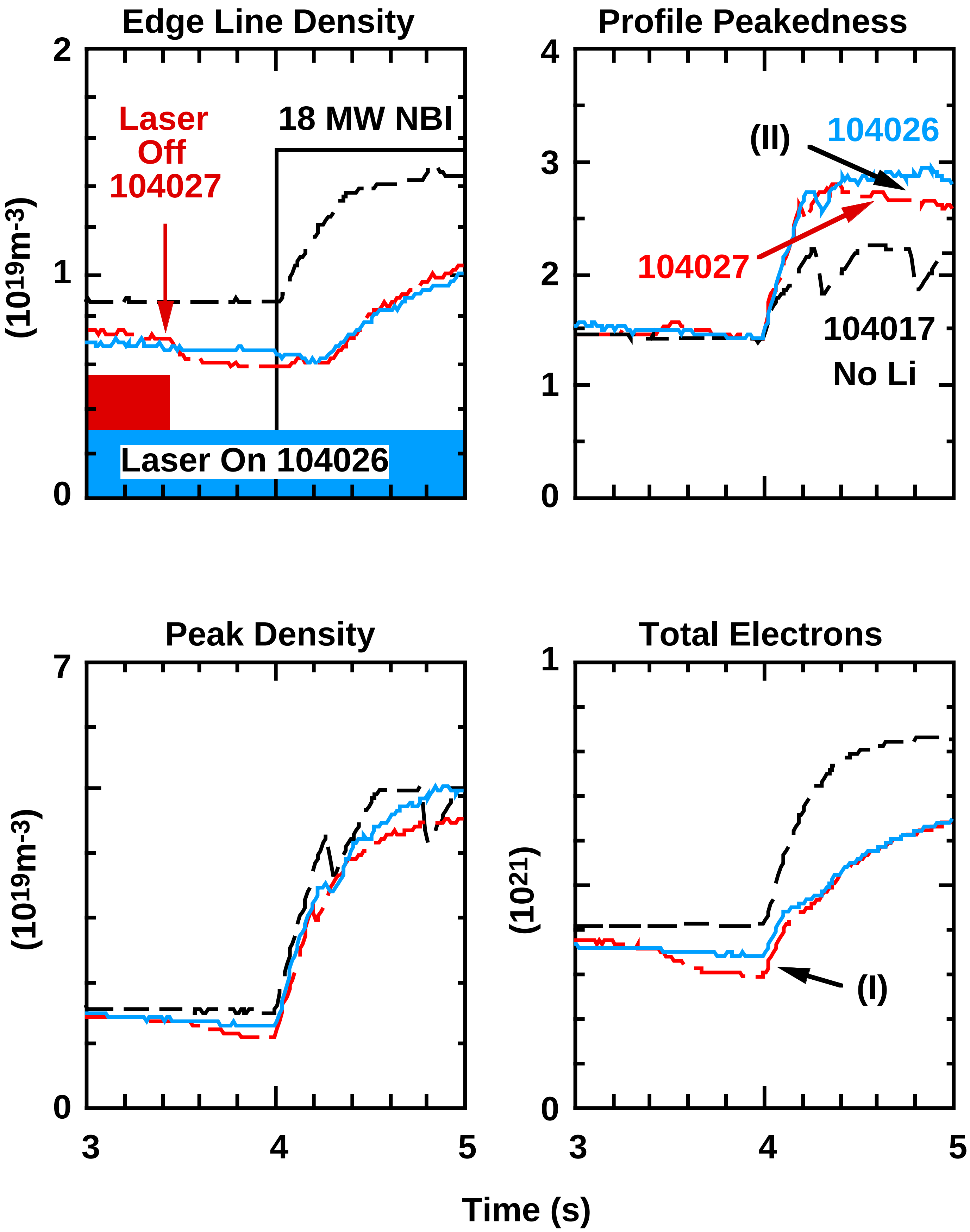
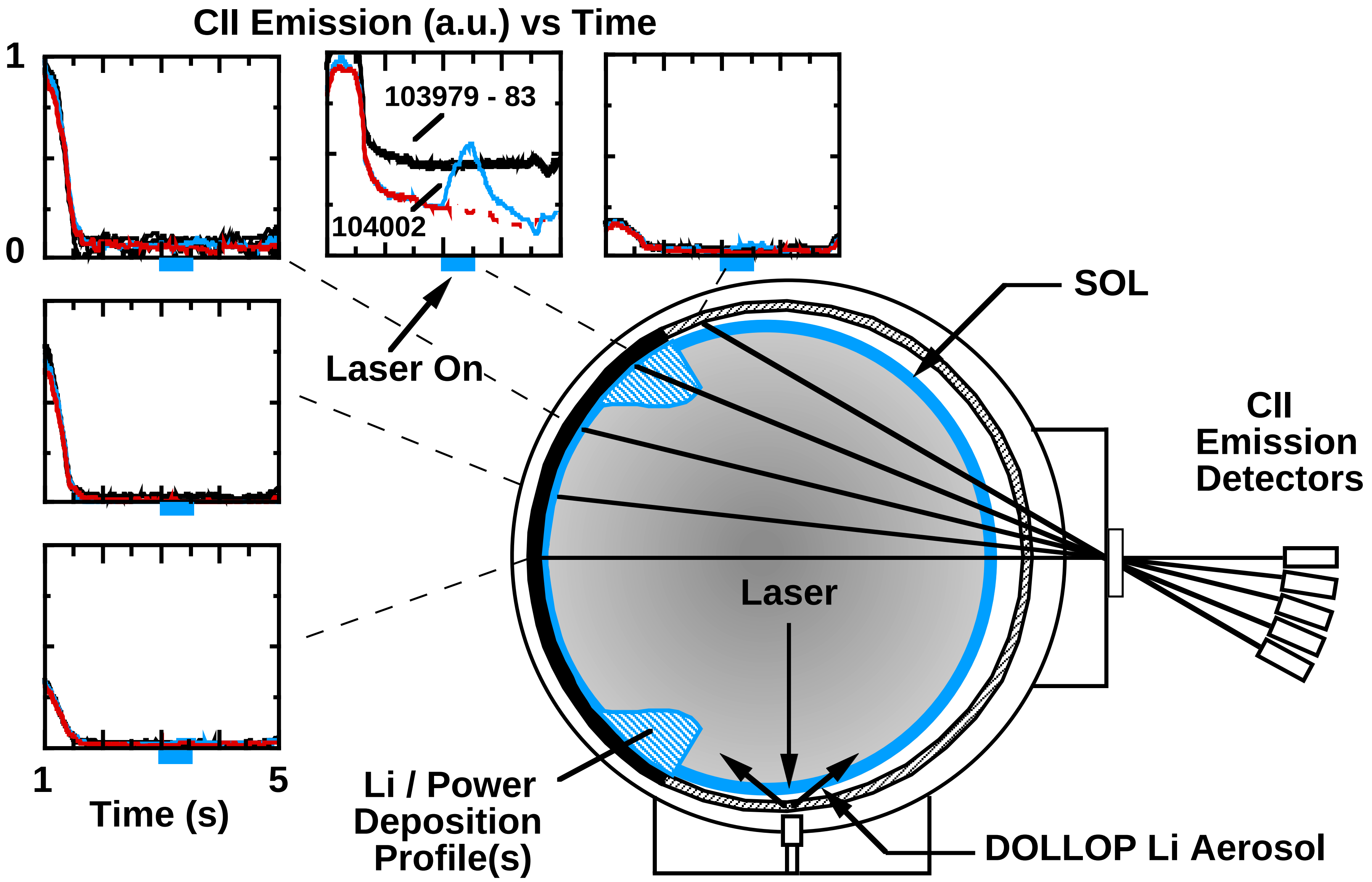
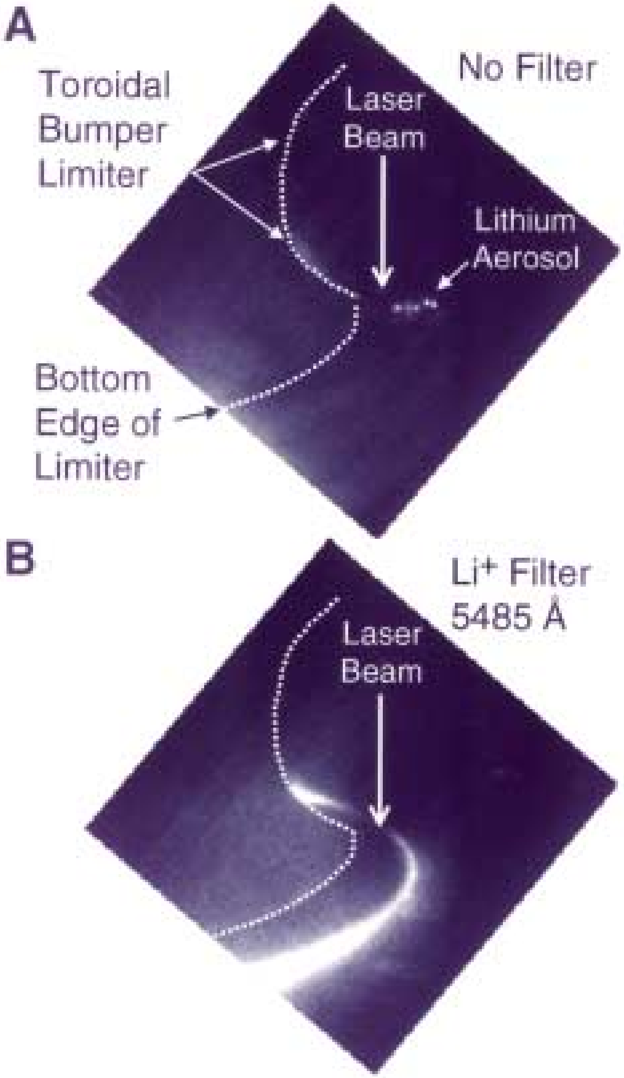

Q-Switched Pulse Train
YAG Laser
Mirro
r
Lens Doublet
Inner Wall
Limiter
SOL
LCFS
Li Aerosol:
Controlled
by Laser
Molten
Lithium
RF
Limiter

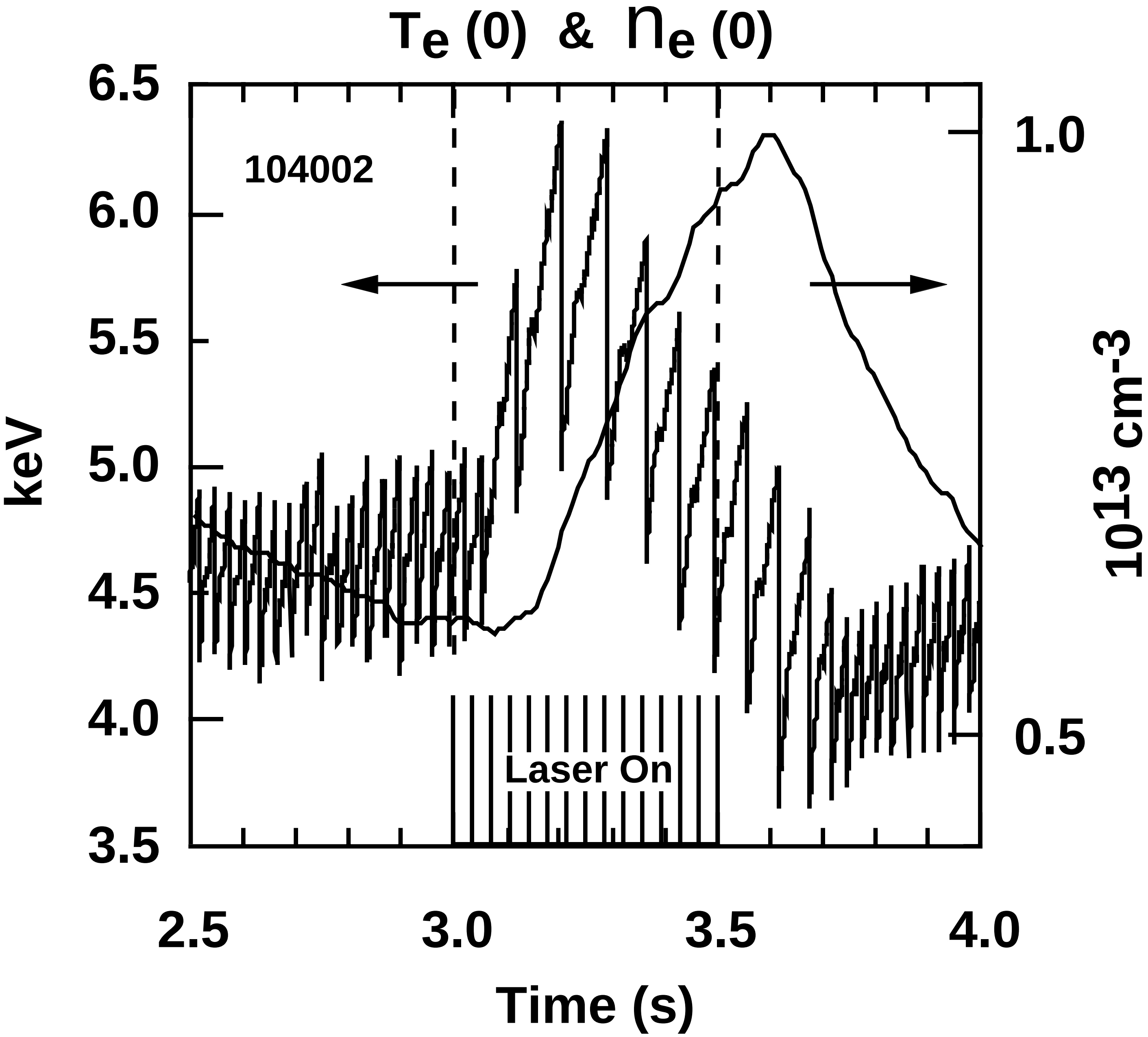

Confinement Time
0.3
0.2
0.1
0.0
(s)
(I)
104039
104017
No Li
Laser On - 104039
DD Neutron Rate
3.5
0
$(10^{16}/s)$
Neutral Beam Power
20
10
0
(MW)
Z_{eff}
4
3
2
1
0
Sawtooth
4.0
4.5
4.0
4.5
Time (s)


Total Electrons - NTOT
(10^{20})
4.0
3.0
2.0
1.0
A
B
DOLLOP
First Use
103984
(I)
(III)
(II)
103985
Low
Recycling
Limit
103979 - 83
104002
104003
Laser On - 1 s
Laser On - 0.5 s
1
2
3
4
5
Time (s)

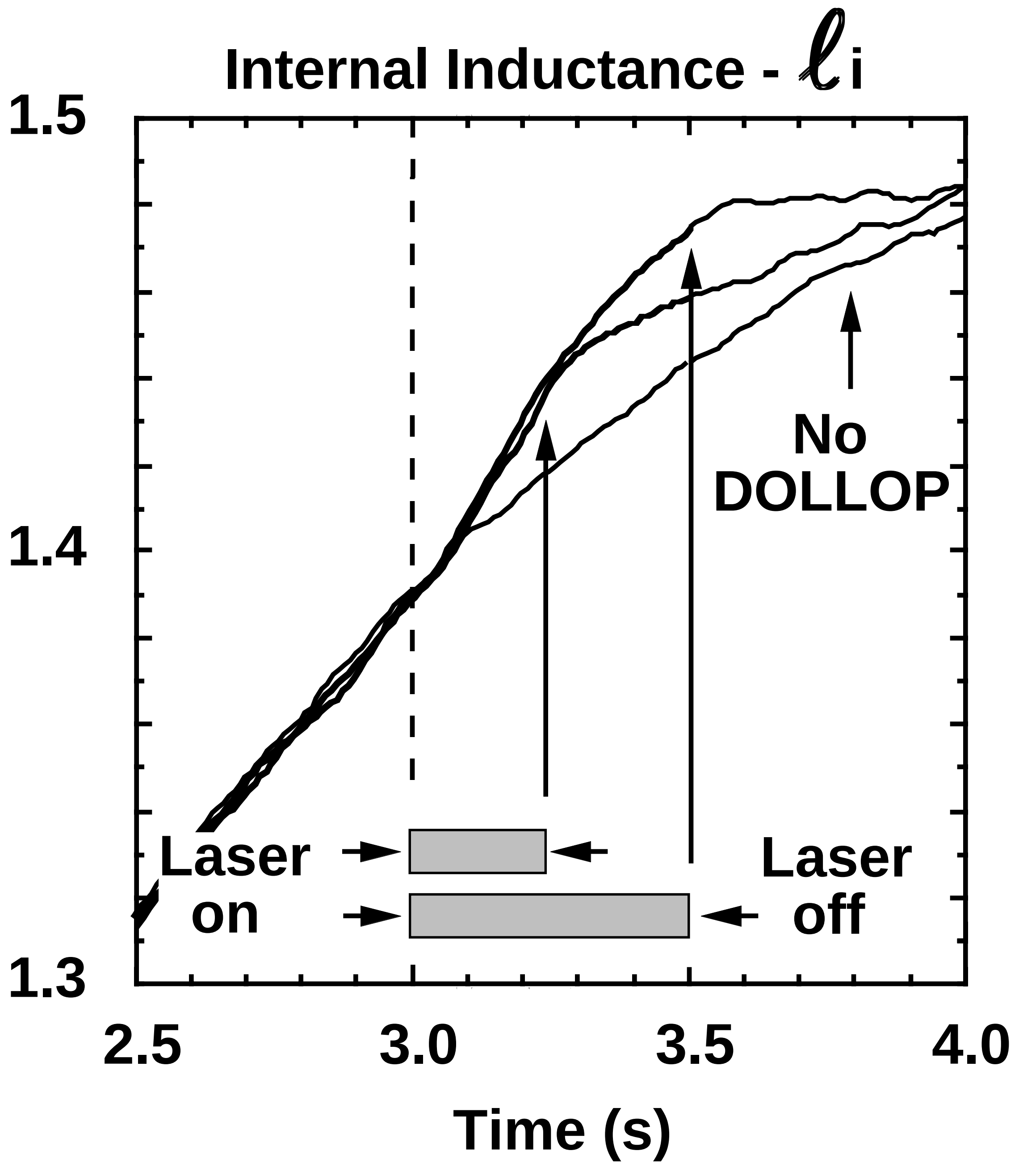

Edge Line Density
2
1
0
(10^19m^-3)
Laser
Off
104027
18 MW NBI
Laser On 104026
Profile Peakedness
4
3
2
1
0
(II)
104026
104027
104017
No Li
Peak Density
7
0
(10^19m^-3)
Total Electrons
1
0
(10^21)
(I)
3
4
5
3
4
5
Time (s)

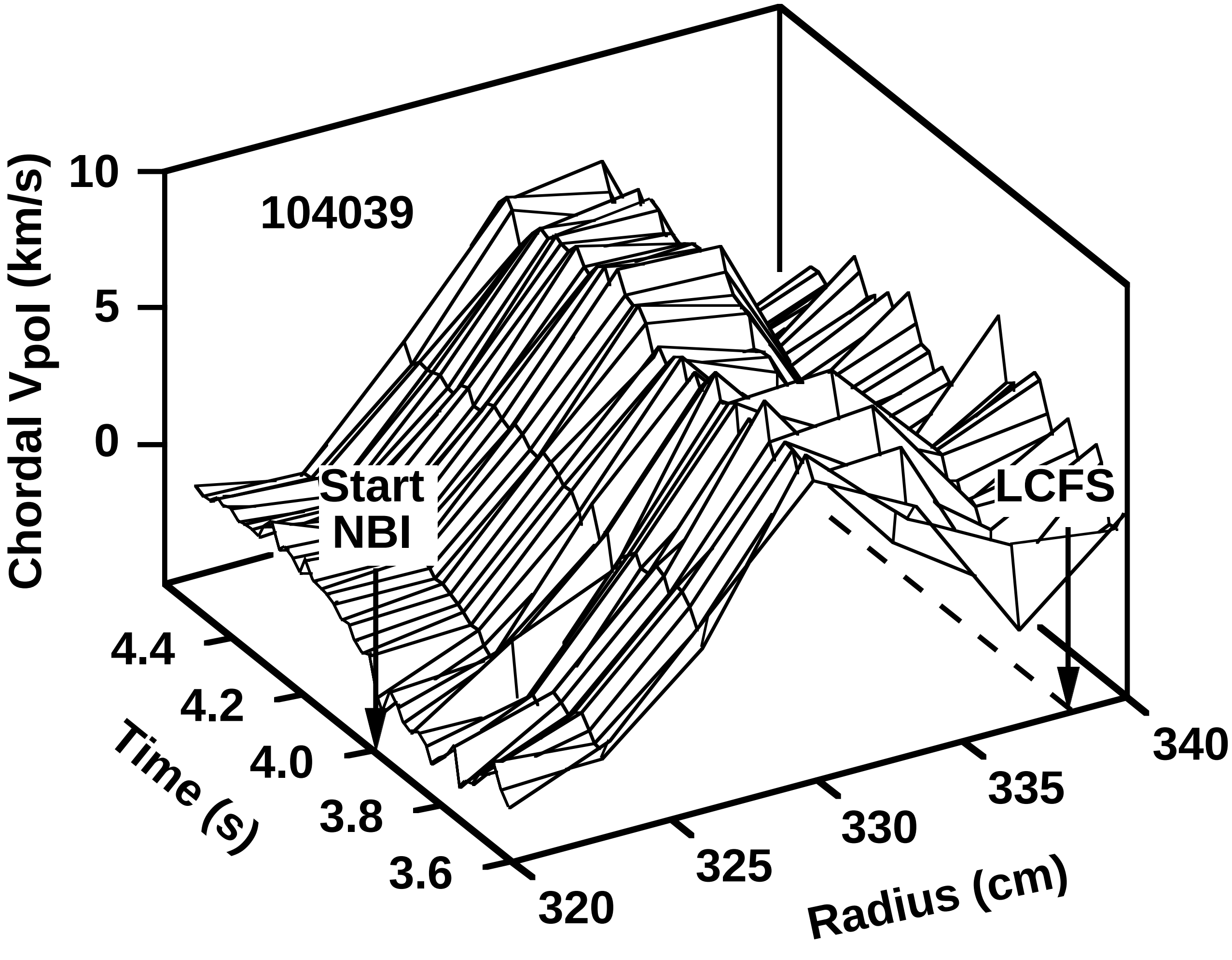

CII Emission (a.u.) vs Time
1
0
103979 - 83
104002
Laser On
SOL
CII
Emission
Detectors
Laser
1
5
Time (s)
Li / Power
Deposition
Profile(s)
DOLLOP Li Aerosol

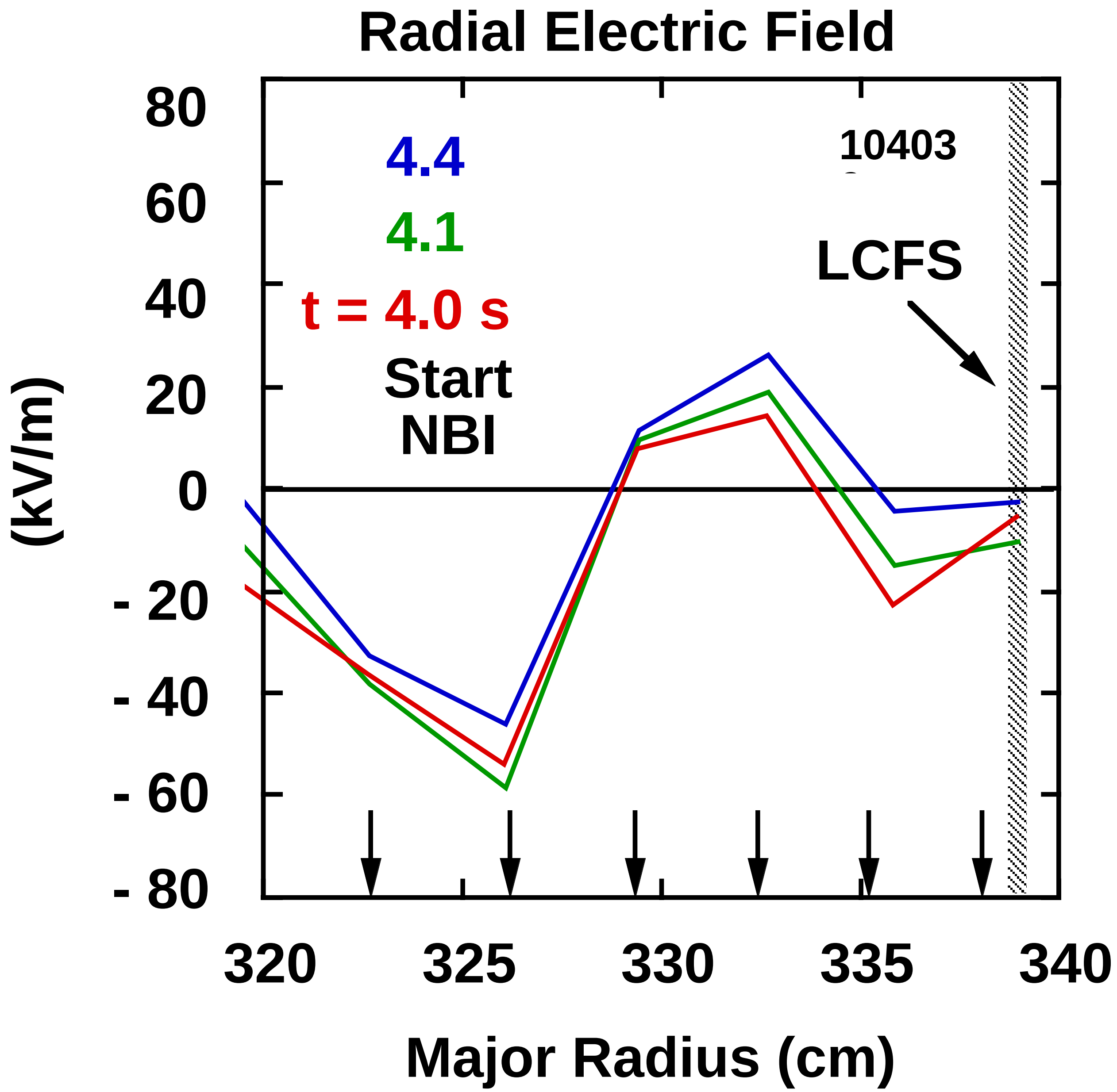

A
No Filter
Toroidal Bumper Limiter
Laser Beam
Lithium Aerosol
Bottom Edge of Limiter
B
Li+ Filter 5485 Å
Laser Beam



T_e (0) & n_e (0)
104002
keV
6.5
6.0
5.5
5.0
4.5
4.0
3.5
1.0
0.5
10^13 cm^-3
Laser On
2.5
3.0
3.5
4.0
Time (s)


Internal Inductance - ℓi
1.5
1.4
1.3
2.5
3.0
3.5
4.0
Time (s)
Laser
on
Laser
off
No
DOLLOP


104039
Chordal Vpol (km/s)
10
5
0
Start
NBI
LCFS
4.4
4.2
4.0
3.8
3.6
Time (s)
320
325
330
335
340
Radius (cm)


Radial Electric Field
(kV/m)
80
60
40
20
0
- 20
- 40
- 60
- 80
320
325
330
335
340
Major Radius (cm)
4.4
4.1
t = 4.0 s
Start
NBI
10403
LCFS

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