CONFERENCE PRE-PRINT

RECENT PROGRESS ON THE SUNIST-2 SPHERICAL TOKAMAK

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Abstract

SUNIST-2 is a spherical tokamak aimed to study the confinement at higher magnetic field, ion heating by magnetic reconnections, and repetitive pulsed operations. Its major parameters are: R_0, 0.53 m; a, 0.33 m; B_{T0}, 1.0 T; I_P, 500 kA. The first plasma of SUNIST-2 was obtained in 2023. Since then, plasma startup by merging and plasma gun was tried on SUNIST-2 to save the flux of central solenoids. With the help of those methods, plasma current of SUNIST-2 has reached 480 kA. Dual pulses operation was succeeded by programming the power supplies. An initial plasma control system was also applied to SUNIST-2 enabling both diverted plasmas with triangularities up to 0.6 and spherical tokamak plasmas with negative triangularities up to -0.6. Plasma heating scaling by magnetic reconnection during merging was also studied and showed a proportion to the square of the plasma current before reconnections. Lithium coating was also tried on SUNIST-2 and greatly reduced the carbon and oxygen impurities from the wall of the vacuum vessel.

1. INTRODUCTION

Spherical Tokamaks (STs), a derivative of the most extensively studied concept for controlled nuclear fusion—the conventional tokamak—have exhibited numerous distinctive characteristics since their inception. These unique features endow future ST-based fusion reactors with potentially superior performance, leading governments, research institutions, and private enterprises worldwide to adopt the ST as a key pathway in their fusion energy development strategies.

One of the most widely recognized attributes of STs is their high plasma beta (β), defined as the ratio of plasma pressure to magnetic pressure. Record β values of up to 42% (achieved in START) and even 60% (in TS-3/4) have been reported. In medium-sized STs such as NSTX and MAST, peak β values consistently exceed 30%, with routine operational β levels maintained above 20%. By contrast, conventional tokamaks typically achieve maximum β values of only around 12%, and often operate at levels below 1%. For magnetically confined fusion reactors, the fusion power scales as $P_{fus} \propto R^3 B^4 \beta^2$, where P_{fus} is the fusion power, R is the major radius of the toroidal plasma, B is the magnetic field strength, and β is the plasma beta. The substantial disparity in achievable β implies that, for a given fusion power output, ST-based reactors can significantly reduce both plasma size and required magnetic field strength, thereby substantially lowering capital costs and shortening construction timelines.

Another noteworthy and somewhat unexpected characteristic of STs is their more favourable scaling of energy confinement time, τ_E with respect to key plasma parameters. From early devices such as MAST and NSTX to recent experiments on Globus-MII and ST-40, STs have consistently demonstrated a distinct τ_E scaling law $\tau_E \propto B^{1.0}$, in contrast to the much weaker dependence observed in conventional tokamaks $\tau_E \propto B^{0.15}$. This implies that increasing the magnetic field in STs yields a pronounced improvement in energy confinement, whereas increasing plasma current provides comparatively modest gains — unlike in tokamaks, where current plays a more dominant role. This behavior is highly advantageous, as higher plasma currents are typically associated with enhanced magnetohydrodynamic (MHD) instabilities and more severe plasma disruptions. Consequently, the ST scaling law suggests that future ST-based reactors should prioritize higher magnetic fields over higher plasma currents, thereby enhancing operational stability and safety.

Furthermore, the dependence of energy confinement time on collisionality (ν^*) and plasma beta also differs markedly between STs and conventional tokamaks. Experimental results from MAST, NSTX, and Globus-M/II indicate that in STs, $\tau_E \propto {\nu^*}^{-0.5}\beta^{0.5}$, whereas tokamaks typically exhibit $\tau_E \propto {\nu^*}^{0.2}\beta^{0}$ }.This trend is particularly encouraging for reactor-relevant conditions, where operating temperatures exceed 10 keV and collisionality is significantly lower than in present-day ST experiments. Under such conditions, ST reactors could achieve even longer energy confinement times while maintaining high β — a highly desirable combination for efficient fusion power production.

Although STs can access the high-confinement mode (H-mode), the associated improvement in energy confinement is surprisingly modest. Measurements from MAST and NSTX show H-factors (the ratio of H-mode to L-mode confinement times) of only approximately 1.2. This suggests that H-mode operation may not be essential for ST-based reactors. Instead, STs could operate effectively in L-mode, retaining reasonably good confinement while avoiding the problematic edge-localized modes (ELMs) that accompany H-mode. In contrast, conventional tokamak reactors must operate in H-mode with H-factors well above 2 to meet performance targets, inevitably triggering ELMs that require additional mitigation strategies.

Another advantageous feature of STs arises from their strong shaping: the magnetic field strength on the inboard (high-field) side is typically more than five times that on the outboard (low-field) side. This results in a significantly shorter magnetic pitch on the high-field side compared to the low-field side. For divertor design, this asymmetry yields a critical benefit: the connection length along field lines to the high-field-side divertor target is much longer than that to the low-field-side target. Consequently, the peak heat flux on the spatially constrained high-field-side divertor plate is dramatically reduced—by as much as a factor of 50 compared to the low-field side, as observed in MAST. This implies that, for ST reactors, engineering efforts can focus primarily on managing the heat load on the more accessible low-field-side divertor, greatly simplifying divertor design and heat-handling requirements.

Finally, due to the pronounced toroidicity of STs, a large fraction of particles are trapped, leading to a high bootstrap current fraction. This reduces the external current drive requirements, further enhancing the attractiveness of the ST concept for steady-state, economically viable fusion power plants.

Although spherical tokamaks offer numerous advantages as a candidate for fusion power reactors, significant uncertainties remain that must be addressed before their viability can be fully established.

First, the energy confinement performance of STs under high magnetic fields remains poorly understood. Existing confinement scaling laws have been derived predominantly from experiments conducted at magnetic fields below 1 T. Only ST40 operates above 1 T, which has achieved a toroidal field of 2.2 T. Consequently, dedicated experiments at significantly higher magnetic fields are essential to verify whether the favorable confinement scalings observed at low fields—such as the strong dependence of energy confinement time on magnetic field strength—persist under reactor-relevant conditions.

Second, the compact central column of the ST geometry imposes severe constraints on available magnetic flux, making both plasma initiation and long-pulse operation particularly challenging. Furthermore, the high plasma inductance (or equivalently, high loop voltage requirement) in STs, combined with their high plasma density and relatively low aspect ratio, results in a very high plasma dielectric constant. This impedes efficient current drive via electromagnetic waves (e.g., lower hybrid wavs), which are commonly employed in conventional tokamaks. Therefore, the development of optimized, ST-specific operational scenarios—tailored to the intrinsic geometric and electromagnetic constraints of the configuration—is a critical prerequisite for the realization of a practical ST-based fusion reactor.

Third, neutral beam injection (NBI) remains the most effective heating method demonstrated on STs to date. The search for alternative, more efficient ion heating techniques specifically suited to the ST geometry is an active area of research.

In summary, while the spherical tokamak presents a compelling pathway toward compact, cost-effective fusion energy, critical physics and engineering challenges—particularly concerning high-field confinement validation, optimal operating scenarios, and efficient heating—must be resolved through targeted experimental and theoretical efforts before its potential as a fusion power plant can be fully realized.

The SUNIST-2 spherical tokamak was specifically designed, constructed, and commissioned to address these challenges. It’s aimed to study the confinement at higher magnetic field, ion heating by magnetic reconnections, and repetitive pulsed operations. The first plasma of SUNIST-2 was obtained in 2023. Since its commissioning, SUNIST-2 has carried out a series of experimental investigations, encompassing plasma startup, heating, control, and wall conditioning. This paper presents a concise overview of these recent research activities.

2. MAIN PARAMETERS AND FEATURES OF SUNIST-2

Main parameters of SUNIST-2 are: major radius (R_0), 0.53 m; minor radius (a), 0.33 m; maximum on-axis toroidal field (B_{T0}), 1.0 T; nominal plasma current (I_P), 500 kA; maximum elongation (κ), 2.0; triangularities (δ), -0.6 – 0.6.

To maximize the available volt-seconds, the toroidal field (TF) coils of SUNIST-2 employ a segmented design, comprising a central conductor surrounded by C-shaped outer conductors. The central solenoid is wound directly onto the central conductor of the TF coil assembly. This coil configuration not only enhances electromagnetic performance but also facilitates a more manufacturable vacuum vessel design.

The vacuum vessel of the SUNIST-2 spherical tokamak is composed of three main sections: (i) an outer cylindrical shell welded to the bottom endplate as a single integrated component, (ii) a central cylindrical section, and (iii) a removable top endplate. To increase the toroidal electrical resistance and thereby mitigate induced eddy currents, the central cylinder is fabricated from 1-mm-thick Inconel 625 alloy. All other vessel components are constructed from 316L stainless steel. The top and bottom endplates are 5 mm thick and reinforced with internal stiffening ribs to withstand atmospheric pressure loads, while the outer cylindrical shell has a thickness of 7 mm.

The toroidal magnets of SUNIST-2 contains a central column segmented into 24 wedges, and eight "C"-shaped limbs of three turns each, carrying 2.64 MA in total. SUNIST-2 is equipped with a total of five pairs of poloidal field (PF) coils—arranged symmetrically above and below the midplane—and one dedicated divertor coil (DF) pair, primarily used to establish divertor magnetic configurations. Furthermore, a pair of internal coils, referred to as the merging-compression (MC) coils, is installed inside the vacuum vessel. These MC coils are primarily employed to facilitate the merging-compression plasma startup scheme but can also be utilized for active control of vertical instabilities.

To enable in-depth studies of reconnection heating physics, the MC coils are adjustable vertically in the vacuum vessel (*FIG. 1*). While also serving as standard flux source for plasma initiation, these coils are mounted on movable supports with 200 mm of vertical adjustments. By varying their position and spacing, flexible experiments can be conducted to optimize the reconnection process for heating. The internal coils can also be fully retracted outside the main plasma region, enabling highly elongated ST configurations. This unique design provides unmatched flexibility to research fusion plasma heating via magnetic reconnection on SUNIST-2.

Another unique feature of SUNIST-2 is its central solenoid (CS) is divided into six independently powered sections, contributing 0.6 Wb flux. This enables precision current profile control to optimize reconnection heating during the merging process. All poloidal field coils (including CS, CS, DF coils) the have a current rating up to 20 kA.

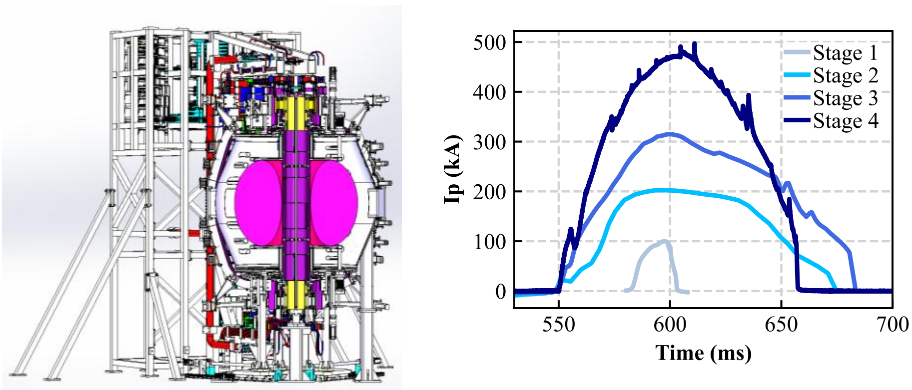

FIG. 1. The SUNIST-2 spherical tokamak (left), plasma current waveforms (right)

3. STARTUP EXPERIMENTS

Multiple non-central-solenoid startup methods have been successfully applied to SUNIST-2. The movable internal coils (the MC coils) can breakdown the working gas without the need of zero-field configurations. Two plasma rings were generated from the bottom and the top, and then were pushed to be merged together forming a single but larger plasma torus (*FIG. 2*).

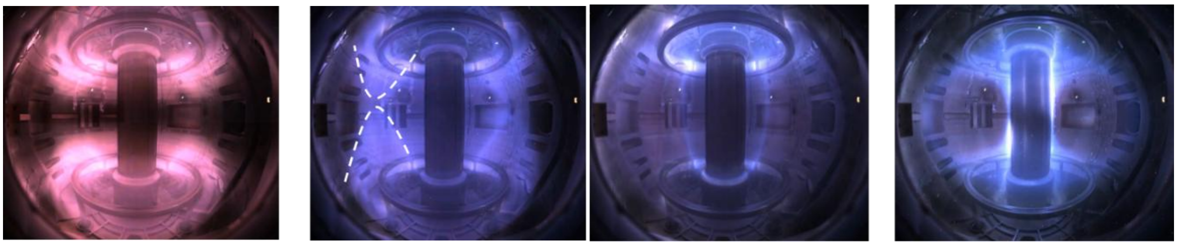

FIG. 2. The merging startup of SUNIST-2

Plasma guns are also important methods for startup in SUNIST-2. Recently, the breakdown characteristics, impurity content, and plasma parameters of the plasma gun are experimentally studied.

The breakdown voltage exhibits a strong dependence on the structural configuration of the washer stack. Specifically, straight and unobstructed geometries, as well as shorter electrode gaps, are more susceptible to electrical breakdown. This susceptibility is further exacerbated with increasing discharge count, as repeated operation leads to the deposition of a molybdenum (Mo) coating along the discharge channel, effectively lowering the breakdown threshold. Additionally, elevated neutral gas pressure combined with weaker magnetic fields at critical locations can further reduce the breakdown voltage. From the perspective of Paschen's law and gas breakdown physics, conventional washer stack designs—lacking intentional obstructions—are suboptimal for reliable and stable plasma gun operation.

Spectroscopic analysis reveals that the dominant impurity species in the plasma are carbon (C), oxygen (O), iron (Fe), and molybdenum (Mo), primarily originating from the vacuum chamber wall and the Mo electrodes within the plasma gun, both of which are directly exposed to the plasma. Under stable operating conditions, however, the impurity levels remain relatively low. Notably, the relative intensity of Mo spectral lines—normalized to the H-β line—shows no significant difference between measurements taken inside and outside the plasma gun. This indicates that Mo ions generated by electrode erosion are not confined within the gun but are instead transported into the main plasma, thereby affecting plasma purity. Comparative studies of different washer configurations demonstrate that introducing obstructive washers can modestly mitigate Mo impurity influx, likely by altering the erosion dynamics or plasma flow paths.

The electron temperature (T_e) and density (n_e) of the generated plasma are found to be largely insensitive to variations in extraction voltage and valve backpressure. Typical values under standard operating conditions are $T_e \approx 20\ eV$ and $n_e \approx 4 \times 10^{20}\ m^{-3}$. While the plasma gun structure exerts only a subtle influence on these parameters, optimized washer stack designs—particularly those incorporating controlled obstructions—can lead to measurable improvements in both T_e and n_e. This suggests that geometric tailoring of the washer stack not only enhances breakdown reliability and reduces impurity influx but also contributes to modest enhancements in core plasma parameters.

In summary, the structural design of the plasma gun—especially the presence and configuration of obstructive washers—plays a critical role in determining breakdown behavior, impurity generation, and overall plasma quality. These findings underscore the importance of integrated engineering design in optimizing plasma gun performance for fusion applications.

Different washer structures have been compared to study their impact on discharge. Two washer guns were installed inside the vacuum vessel of SUNIST-2. These two guns could initiate two plasma rings, which were then coupled by merging, without any loop voltages (*FIG. 3*).

FIG. 3. One design of the washer guns (left and center) and a doublet plasma initiated by dual washer guns for merging (right)

4. PLASMA CONTROL

SUNIST-2 has implemented a preliminary Plasma Control System (PCS) to enable real-time feedback and feedforward control of plasma equilibrium and dynamics. The system's sensor suite consists of a magnetic diagnostic array comprising dozens of magnetic probes (pickup coils) and flux loops, which provide essential measurements of the plasma current, position, and shape. The actuators consist of nine independently controlled power supplies, including those for the poloidal field (PF) coils and the central solenoid (CS).

The PCS software is developed in C and Python and runs on an x86-based server equipped with a real-time Linux kernel (Xenomai 4). Magnetic diagnostic data are acquired via a DTACQ high-speed data acquisition system and streamed in real time to the control server over a 10 Gb/s network using the UDPX protocol. Communication between the control server and the power supply actuators operates at a 5 kHz update rate using the EtherCAT industrial real-time communication protocol.

In support of discharge design, startup optimization, control modeling, and post-shot analysis, a Free-Boundary Equilibrium (FBE) code has been developed. This code is used for equilibrium reconstruction, MHD stability analysis, and the validation of control algorithms against experimental data. To date, three distinct control algorithms have been implemented within the PCS framework: (i) a linear feedback controller, (ii) a Model Predictive Control (MPC) algorithm, and (iii) a Multi-Input Multi-Output (MIMO) controller.

For discharge optimization, a Genetic Algorithm (GA) has been employed to automate the tuning of coil current waveforms. This optimization framework incorporates first-order compensation for stray magnetic fields (zero-field compensation) and second-order correction for eddy currents induced in the conducting structures, thereby improving the fidelity of the desired magnetic configuration during plasma initiation.

Divertor plasmas were formed with PCS (*FIG. 4* left). With the help of multiple poloidal field coils of SUNIST-2, negative triangularity low aspect ratio plasmas were successfully formed in SUNIST-2 (*FIG. 4* right). The properties of both configurations are under investigated.

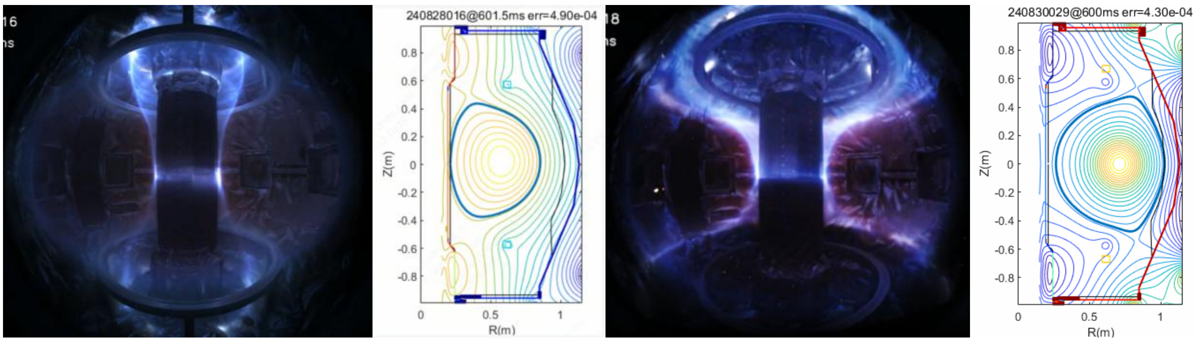

FIG. 4 The diverted plasma of SUNIST-2 (left two, R_0: 0.61 m, a: 0.38 m, κ: 1.51, δ: 0.6), the negative triangularity plasma (right two, R_0: 0.57 m, a: 0.33 m, κ: 1.42, δ: -0.65)

The FBE suite have the abilities to reconstruct both doublet and normal discharges. The reconstructed equilibriums from different discharges including are shown in *FIG. 5*.

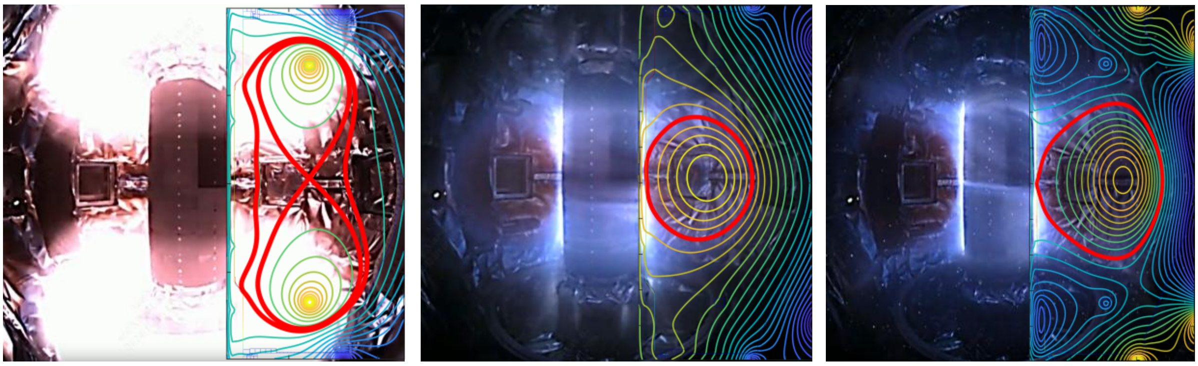

FIG. 5 The reconstructed equilibriums of a doublet plasma of SUNIST-2 (left), a limiter plasma (center) and a negative triangularity plasma (right)

5. WALL CONDITIONING

Lithium coating is applied for wall conditioning in SUNIST-2 [Tingzhi Chang et al 2025 Plasma Phys. Control. Fusion 67 075023]. The plasma facing area is around 15 m^2. The plasma facing material is 316L stainless steel except for two graphite limiter on the low field side and a graphite limiter covering the central column. The pumping system includes two turbo-molecular pumps and a cryopump, with a total effective pumping speed of 14 m^3/s for H_2 and 8 m^3/s for N_2. The basic vacuum pressure is $1 \sim 6 \times 10^{-5}$Pa. For wall conditioning, H_2 and He are routinely used for glow discharge conditioning (GDC) in SUNIST-2. Two GDC electrodes are equipped, and the total GDC current is $1 \sim 3$ A. Baking of vacuum vessel is frequently used with a maximum temperature of 120 degree Celsius. Before evaporation, a novel method using stainless steel covering the wall is applied, which makes it extremely easy to clean lithium after experiment.

The key diagnostics used in this experiment include a fast camera, filterscopes, an ion doppler spectroscopy (IDS) system, absolute extreme ultraviolet (AXUV) photodiode arrays, a terahertz microwave interferometer (THz), a laser-induced breakdown spectroscopy (LIBS) system, as shown in *FIG. 6*. The fast camera is a coloured visible camera with a maximum frame rate of 25 kfps at full resolution. The filterscopes are of 'filter + PMT' structure, which is able to measure line emission of Hα (656.3 nm), C III (464.7 nm), O II (441.6 nm) and N II (500.5 nm). The IDS system gives the ion temperature by measuring the Doppler broadening of passive C VI emission (529.1 nm). The time resolution of IDS is 2 ms and the spatial resolution is 22 mm with 35 channels horizontally distributed. The 112 channel AXUV array measures the line inte grated radiation power. The single channel THz interferometer measures the line integrated electron density. The LIBS system analyses surface condition. It uses a 100 mJ Nd:YAG laser to ionize the surface element of PFCs and measure the emission spectrum. It could give the surface element composition qualitatively with a scan range of 1 m in Z direction of SUNIST-2 central column.

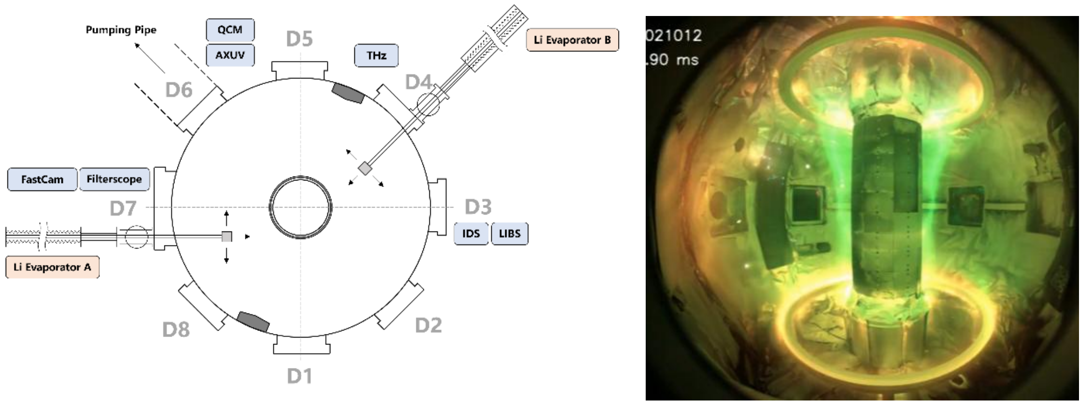

FIG. 6 Schematics of diagnostics and Li evaporators of SUNIST-2, in top view(left), a plasma discharge after Li coating(right)

In the experiment with lithium coating, it is observed that the line emission of carbon, oxygen and nitrogen all decrease by more than one order of magnitude, which indicates a strong mitigation of impurities. In the merging compression startup, the plasma current increases about 30% with the same voltseconds of coils, and consequently the ion heating during plasma merging clearly increases after lithium coating. The energy confinement time is not observed to increase, however it exceeds the LOC scaling after lithium coating due to a decrease of LOC confinement time. See *FIG. 7*.

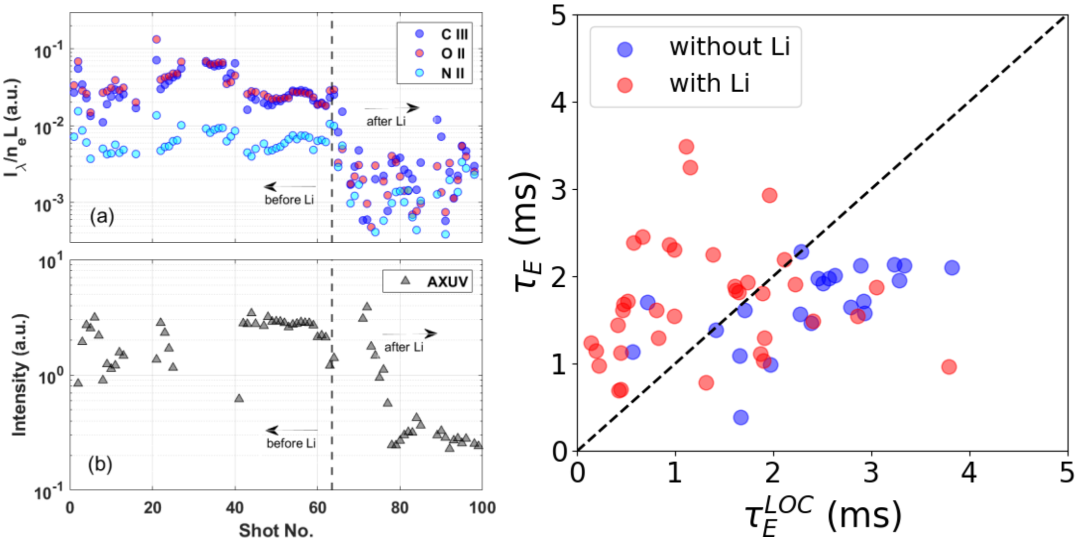

FIG. 7 (left a) impurity emission including the carbon III line, oxygen II line, and nitrogen II line, and (left b) AXUV intensity for shots before and after lithium coating, (right) energy confinement time before and after lithium coating, compared to LOC scaling

6. SUMMARY

This paper reports recent progress on the SUNIST-2 spherical tokamak (R_0 = 0.53 m, B_T= 1.0 T, I_P = 500 kA), which achieved first plasma in 2023. Designed to study high-field confinement, magnetic reconnection heating, and repetitive operation, SUNIST-2 has demonstrated non-solenoidal startup via merging-compression and plasma guns, reaching 480 kA and enabling dual-pulse operation. A real-time Plasma Control System (5 kHz, EtherCAT) supports shaping of both diverted (δ≈+0.6) and negative triangularity (δ≈-0.6) plasmas. Lithium wall conditioning reduced C, O, and N impurities by over an order of magnitude, boosting plasma current and reconnection heating during startup. Engineering features—including a segmented TF coil, Inconel central cylinder, and modular central solenoid—enhance flexibility and performance. These results establish SUNIST-2 as a versatile platform for advancing spherical tokamak physics and technology.

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