Non-Inductive Current Start-up and Optimized Ramp-up in EXL-50U for Next-Generation Spherical Torus Devices

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Abstract

Achieved a 1 MA hydrogen–boron (p–11B) discharge in the ENN Xuanlong-50U (EXL-50U) spherical torus (ST).

1. Non-Inductive Current Start-up: Enabled by non-inductive electron cyclotron resonance heating (ECRH) in a trapped particle configuration (TPC)
2. Boron-Rich Fueling: A boron-rich fueling scheme (30% diborane and real-time boron powder injection) enhanced current ramp-up rate by 78% compared to hydrogen-only plasmas.
3. Stable Operation: Achieved stable, repeatable operation at 1 MA, with active control of the ramp-up rate.
4. Optimized Ramp-up: Current ramped from 20 kA to 1 MA with the fastest speed reaching 7 MA/s and an average of 3.4 MA/s.

Synergy between EC and CS, along with real-time boronization, contributed to a 100% discharge success rate and a rapid ramp-up, presenting a promising integrated approach for future high-current fusion reactors.

1.Validated framework for high-performance plasma

Synergistic interaction of CS, PF, and EC drives success.

- → Multi-harmonic ECRH-driven energetic electron generation
- → Real-time boron fueling
- → Current ramp-up using both CS and non-inductive methods.

Future Directions: Optimizing plasma start-up, ramp-up, and confinement for future devices like ENN He Long-2 (EHL-2) and advancing the hydrogen-boron fusion path (I_p ~ 3 MA)[1-4].

- → Limited Vs budget due to compact ST geometry.
- → Impurity control and heating constraints during start-up and ramp-up.

2.Early discharge optimized framework

The discharge process is divided into the following stages:

- The non-inductive start-up phase
- The early phase prior to magnetic surface evolution
- The current ramp-up phase during which the last closed flux surface (LCFS) gradually expands or stabilizes, the flat-top phase
- The ramp-down phase
- The flat-top and ramp-down phases are beyond the scope of this discussion

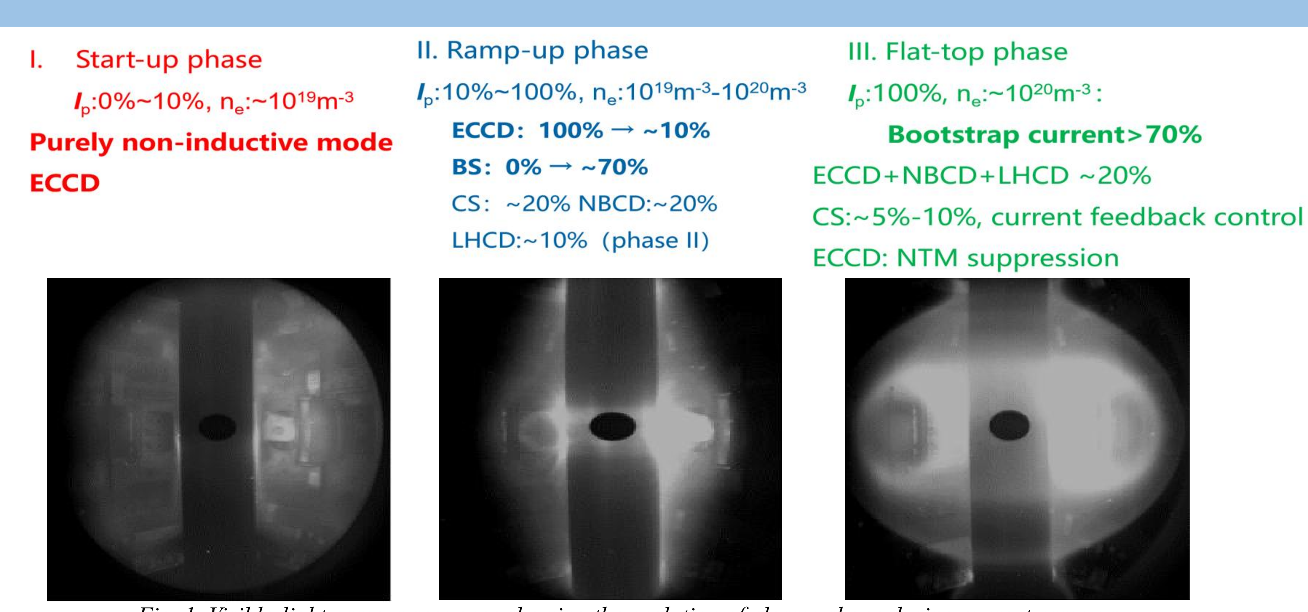
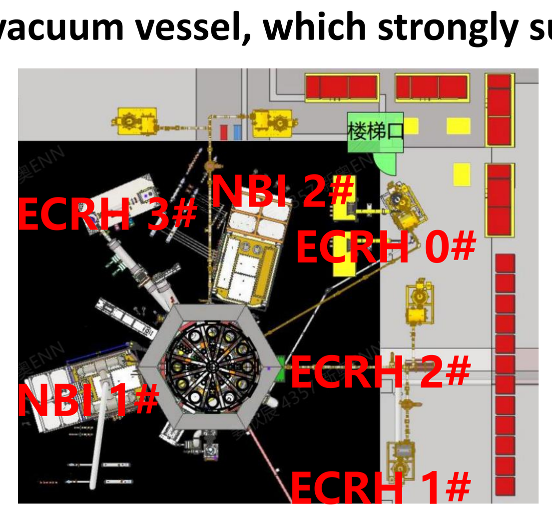


Fig. 1. Visible-light camera sequence showing the evolution of plasma shape during current ramp-up.

3.Experimental analysis and optimization of EXL-50U

By adjusting the toroidal field to B_t = 1.0 T, 50 GHz EC enables multi-harmonic resonance absorption (Fig. 3). Compared with the 28 GHz scheme at lower B_t, the 50 GHz configuration significantly improves the formation of non-inductive current. Multiple harmonic layers are observed to overlap within the vacuum vessel, which strongly supports efficient electron acceleration.



Parameters	Values
Plasma current	1MA
Major radius	0.6-0.8 m
Toroidal magnetic field	1.2T@0.6m
Aspect ratio	1.4-1.85
Elongation	2
NBI	1.5MW/50kV/5s 1MW/25kV/2s
EC	3×0.4MW/28GHz/5s 2×0.4MW/50GHz/1s
IC	1MW/25MHz~40MHz/1s
LH	2×0.2MW/2.45GHz
Discharge TF flattop duration	2s @ 1.2 T

Fig. 2. EXL-50U parameters

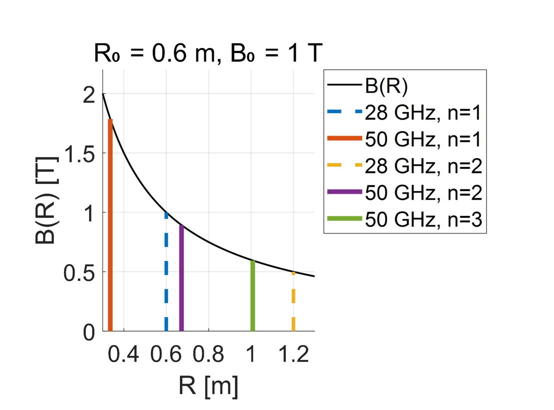


Fig. 3. EC wave resonance area at B0 = 1T

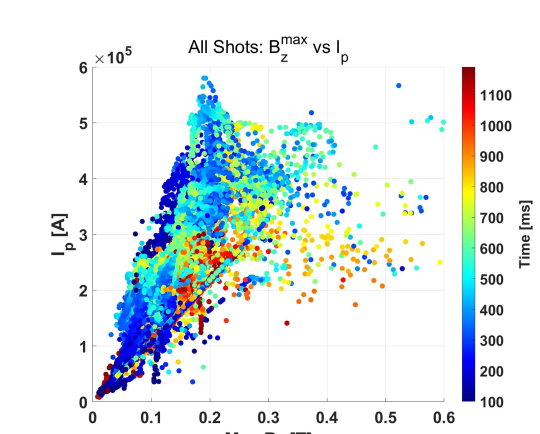


Fig. 4. The plasma current vs max vertical field Bz

3.1 Non-inductive start-up phase

Experimental observations also show that the EC-driven current in EXL-50U deviates from the conventional I_{ECCD} scaling, pointing to distinct physics of energetic electron confinement in ST geometry. However, due to the absence of inductive diagnostics in EXL-50U, a strict quantitative validation cannot yet be performed. H_2 was chosen as the standard pre-fill gas to maximize the probability of successful breakdown and stable start-up.

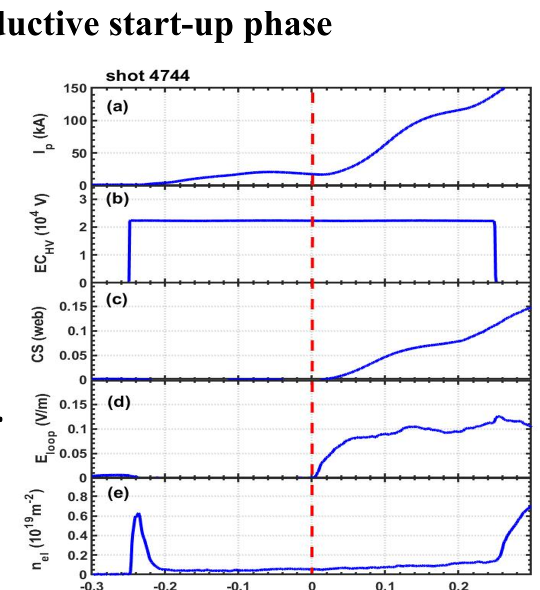


Fig. 5. Typical start-up waveforms with 28 GHz ECRH in EXL-50U [1]. The vertical red dashed line indicates the start of CS current. Waveforms from top to bottom are: (a) plasma current; (b)gyrotron anode high voltage; (c) flux consumption of CS coils; (d) toroidal electric field which is below 0.15V/m in whole ramp-up phase (e) line integrated density.

3.2 The early phase prior to magnetic surface evolution

EC power and its deposition is particularly critical. The metallic wall of the vacuum vessel enables multiple reflections and enhances absorption at high multi-harmonic resonances, thereby increasing the efficiency of accelerating energetic electrons with energies typically ranging from keV to MeV. These electrons contribute to the formation of LCFS and are well confined under the TPC. Due to the asymmetric nature of their orbits, they drive boundary currents at the LCFS, effectively sharpening the edge current profile. Thus, the main control parameters in this stage are the total EC power, its deposition location, and the evolving absorption characteristics as the plasma expands.

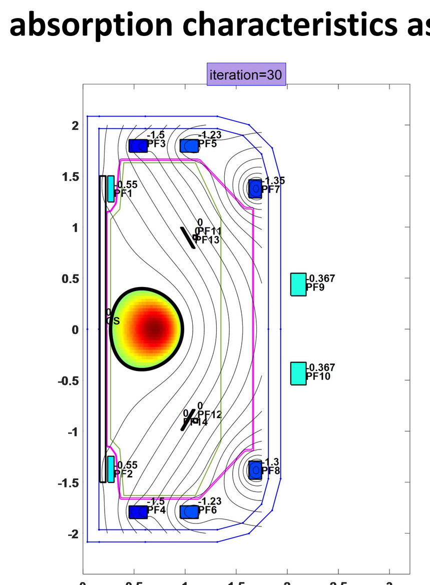
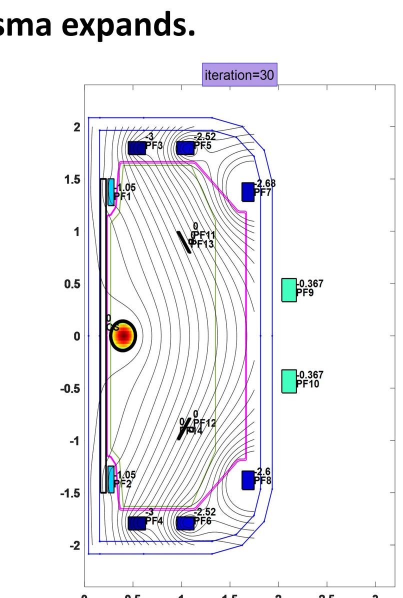


Fig. 6 (a) . #9390 plasma current to 40 kA



(b) . With #9390 increased PF7–10 negative settings, resulting in an Ip increase to 60 kA.

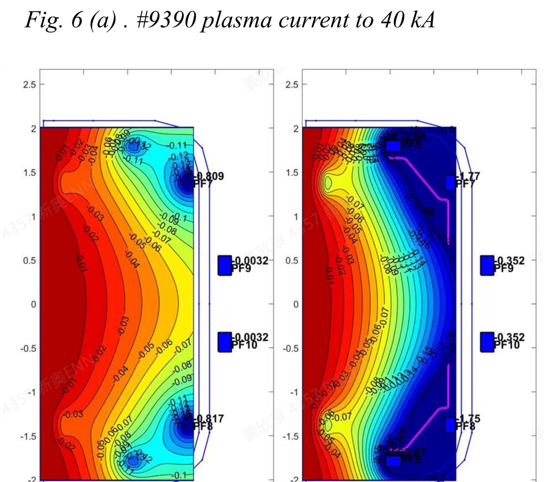


Fig. 7. Poloidal flux (ψ) distributions in EXL-50U under different PF coil conditions. (Left) Reduced negative PF7–10 currents lead to weaker vertical field and broader flux surfaces. (Right) Increased negative PF7–10 currents compress the flux contours and enhance vertical confinement.

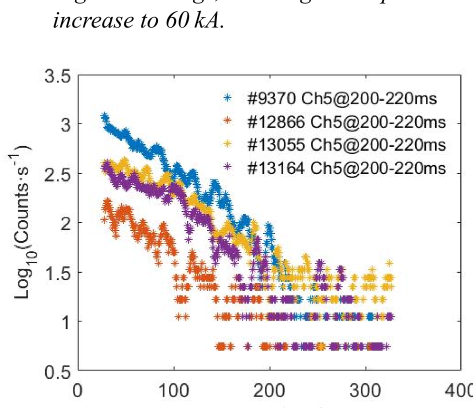


Fig. 8. Hard X-ray (HXR) spectra measured at 200–220 ms under different shots in EXL-50U.

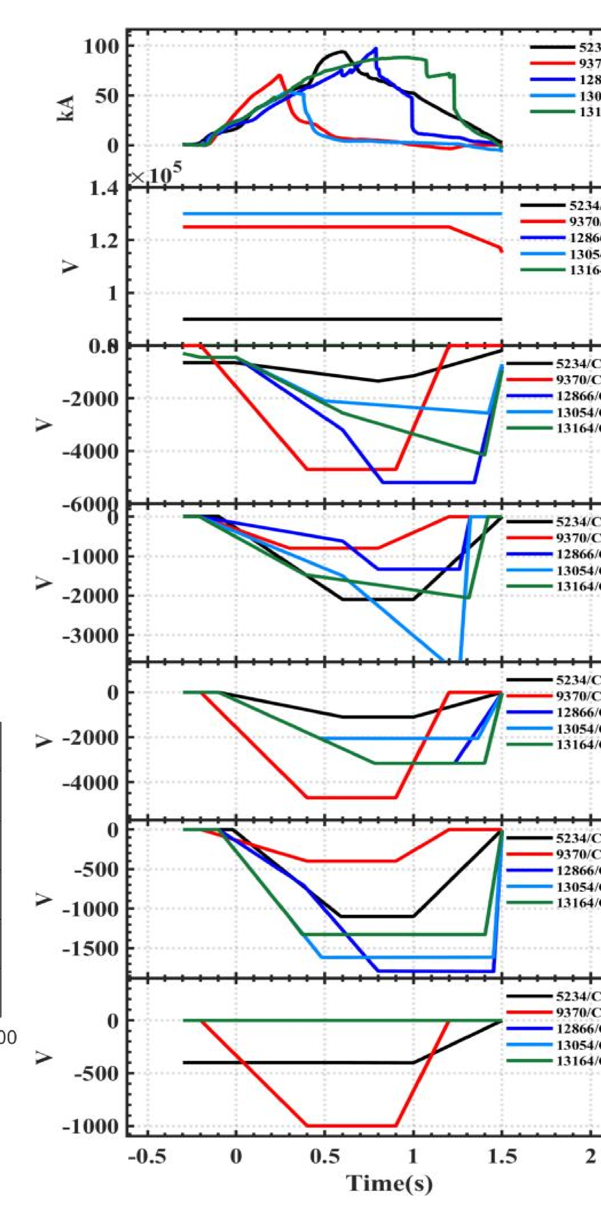


Fig. 9. non-inductive start-up optimization with TPC under different shots in EXL-50U

TPC has played a central role in EXL-50U experiments, enabling efficient, repeatable, and stable non-inductive plasma initiation. By combining optimized PF coil settings, 50 GHz ECH, and precise fueling control, EXL-50U demonstrates the operational advantages of TPC in advancing spherical tokamak non-inductive start-up physics.

3.3 The ramp-up phase

The fastest ramp-up rate reached 7 MA/s.
Normal ramp-up rate reached 3.2 MA/s.

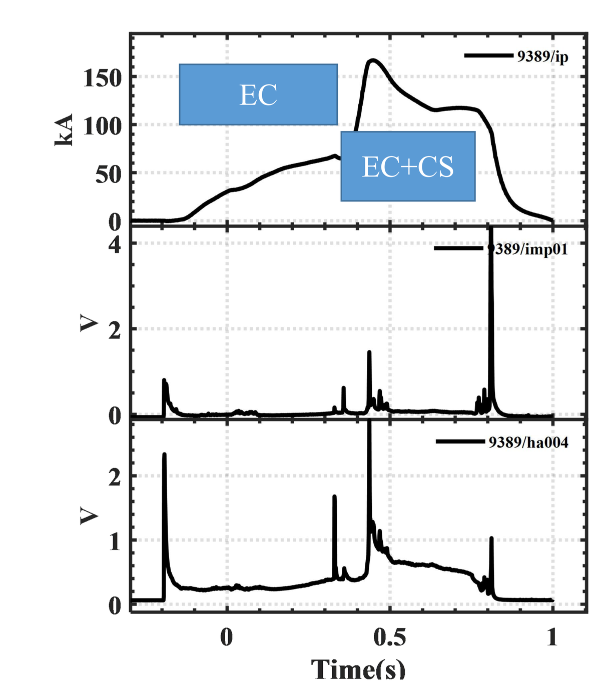


Fig. 10. Plasma current ramp-up by EC alone and by EC+CS synergy. 50 GHz ECRH alone generated ~64 kA of plasma current, which was amplified to ~160 kA by applying a staged negative CS pulse(imp01:O).

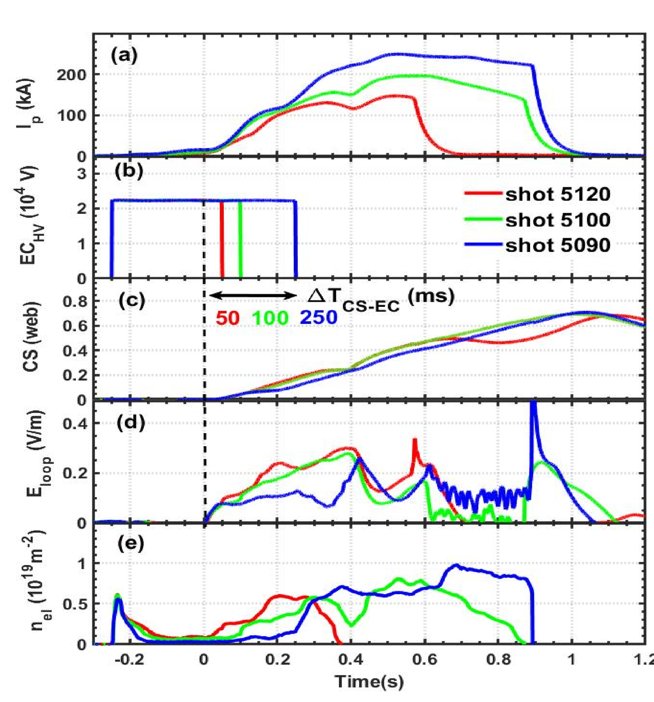


Fig. 11. Dedicated shots for the verification of synergetic effects between ECRH and CS. The vertical black dashed line indicates the start of CS current. Waveforms from top to bottom are: (a) plasma current; (b) gyrotron anode high voltage; (c) flux consumption of CS coils; (d) toroidal electric field; (e) line integrated density.

4.1 MA discharge achievement

EXL-50U has reproducibly achieved 1 MA hydrogen–boron discharges. A controlled CS swing from +30 kA to –40 kA was applied, consuming approximately 1.08 Vs (~90% of the available flux). Combined with boron-rich fueling (30% B_2H_6 + 70% H_2) and synchronized boron injection, enhanced the initial ramp-up rate by 78%, reaching 3.4 MA/s within the first 70 ms. During this stage, Thomson scattering measurements indicated a core electron temperature exceeding 3 keV with a line-averaged density of ~1 × 10^{19} m^{-3}.

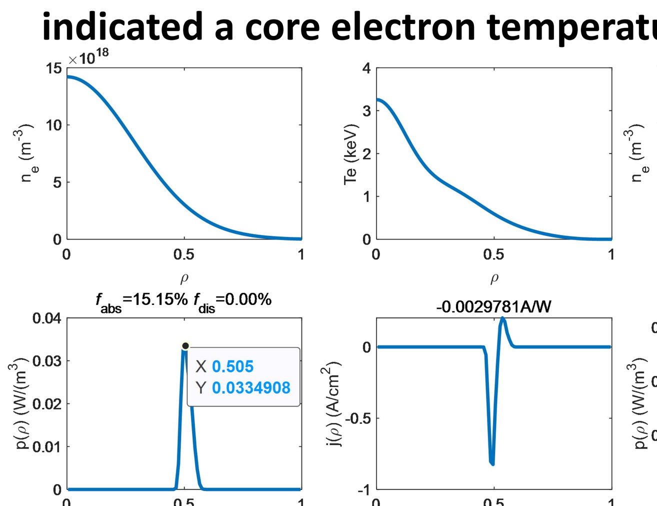


Fig. 12(a). X-mode simulation: central electron density and temperature profiles, with power deposition broadly distributed around ρ ≈ 0.5 (peak ~0.03 W/m³) and a bipolar driven-current distribution. The total absorption fraction is about 15%.

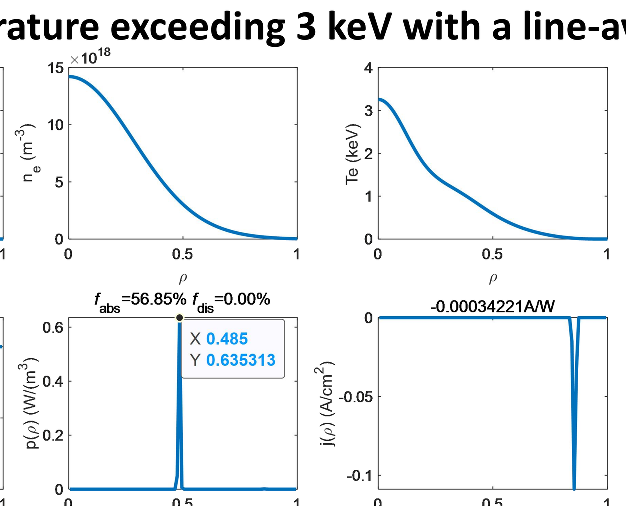


Fig. 12(b). O-mode simulation: more concentrated power deposition at ρ ≈ 0.5 (peak ~0.64 W/m³) with a nearly unipolar driven-current profile. The total absorption fraction reaches 57%, indicating much stronger coupling efficiency.

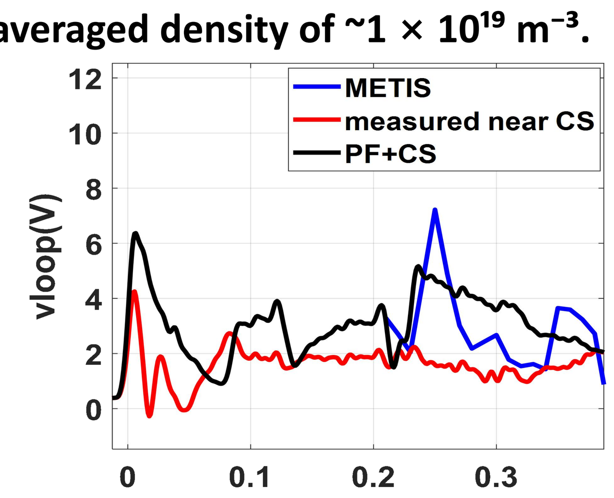


Fig. 12(c). Loop voltage decomposition: comparison between measured loop voltage near CS, reconstructed PF+CS contribution, and METIS simulation, highlighting the dominant role of non-inductive processes during early current formation.

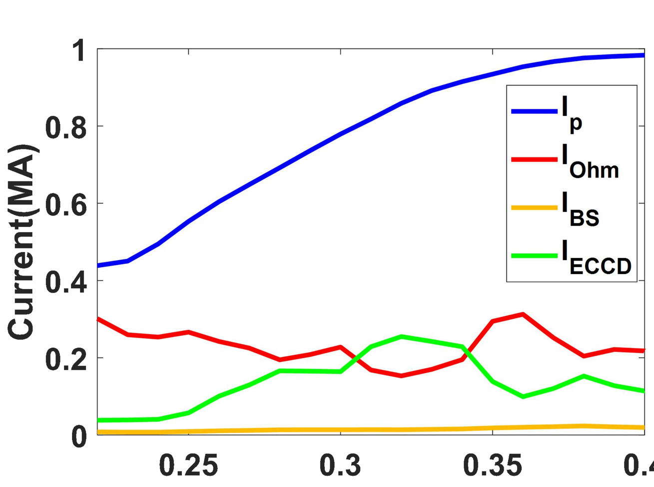


Fig. 12(d). Time evolution of plasma current components in a 1 MA EXL-50U discharge, showing contributions from total plasma current (Ip), Ohmic current (Iohm), bootstrap current (IBS), and ECCD.

5.Summary and future plans

1. TPC outperforms FNC by broadening operational windows, reducing PF flux consumption, and ensuring stable non-inductive initiation.
2. PF coil shaping is critical in the early phase: optimized vertical fields compress flux surfaces, enhance mirror ratio, and improve confinement, supporting faster and more stable ramp-up.
3. ECRH–CS synergy enables efficient current amplification: the relative timing between EC initiation and CS drive was found to decisively control ramp-up efficiency, flux usage, and current stability.
4. Loop voltage decomposition and METIS simulations confirmed that non-inductive processes dominated early current formation.

Reference

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