

Summary

- Restricted volume of the central solenoid in Spherical Tokamak devices poses a major challenge for reaching MA-scale plasma current required for a reactor ST. Consequently, non-inductive current drive is essential not only for flux saving but also for assisting the current ramp-up and Helicity Injection (HI) is a possible candidate for these purposes.
- A Jensen-Chu HI formalism [5] was recast as a **reduced 0D HICD model** using key controllable injector parameters.
 - The model was integrated with the 0D plasma initiation code DYON [9] to reproduce the plasma current evolution and line emission trends in VEST discharges.
 - The resulting framework is envisaged to evaluate HI operation scenarios for the VEST upgrade and future reactor-scale STs.

I. Introduction

Non-Inductive Current Drive (NICD) for plasma start-up in Spherical Tokamak (ST)

- For the start-up in ST (such as VEST [1]), NICD is important due to its limited space for central solenoid.
- **Helicity Injection** using arc plasma guns [2] has demonstrated substantial potential in experiments. [3,4]

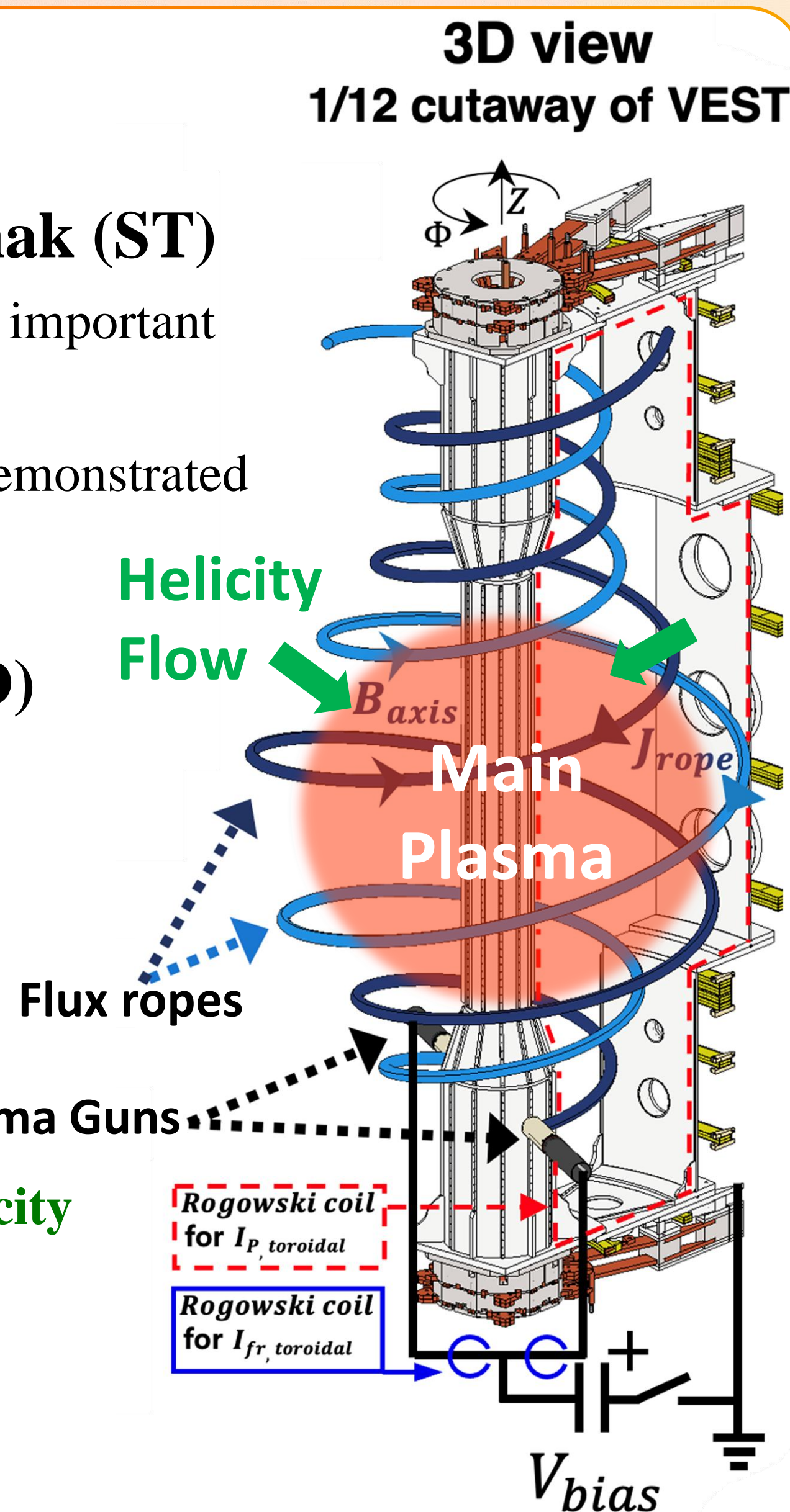
Helicity Injection Current Drive (HICD)

- Helicity (\mathcal{K}) is defined as $\mathcal{K} \equiv \int \vec{A} \cdot \vec{B} dV = \psi_t \psi_p$, representing the linkage of magnetic flux.
- Helicity Transport Equation [5] determines the **helicity injection rate** from arc plasma guns.

$$\frac{\sigma}{2} \frac{d\mathcal{K}}{dt} \Big|_{inj} = V_{inj} I_{inj} N_{inj}$$

- Based on the ‘Taylor Principle [5,6]’, **injected helicity** is related to the **variation of magnetic energy** under the framework of ideal MHD equilibrium.

$$\frac{d(W - W_v)}{d\mathcal{K}_c} = -\frac{\sigma}{2\mu_0}$$



III. Model description (DYON-HI)

Reduced 0D HICD model

- The **injected helicity** determines the plasma’s magnetic energy variation, which contributes to plasma current evolution.

- **Poynting’s theorem** [8] connects the magnetic energy variation ($\frac{dW}{dt}$) to the plasma current (I_p).

$$\frac{dW}{dt} + \vec{E} \cdot \vec{j} = -\frac{1}{\mu_0} \vec{\nabla} \cdot (\vec{E} \times \vec{B}) \Rightarrow \frac{1}{I_p} \frac{d}{dt} \left(\frac{1}{2} L I_p^2 \right) - V_{HI} + R I_p = V_{loop}$$

- The **HICD formulation** and **Poynting’s theorem**, with **fast-slow** time-scale separation, yield a modified circuit equation with the **effective loop voltage (V_{HI})**.

$$V_{HI} = \frac{1}{I_p} V_{inj} I_{inj} N_{inj}$$

Integrated DYON with 0D HICD model (DYON-HI)

- **DYON** is a 0D plasma initiation code, solves self-consistent circuit equation, particle balance and power balance. [9]
- V_{HI} is incorporated into the DYON circuit equation, enabling the simulation of helicity-driven current ramp-up.
- The resulting **DYON-HI** framework provides a first step toward predictive modelling of HI-assisted plasma initiation.

0D HICD model

$$V_{HI} = V_{inj} \frac{I_{inj} N_{inj}}{I_p}$$

DYON

0D Plasma initiation code [9]

DYON-HI

DYON coupled with 0D HICD model

Plasma parameters $I_p, n_e, T_e, n_I, \dots$

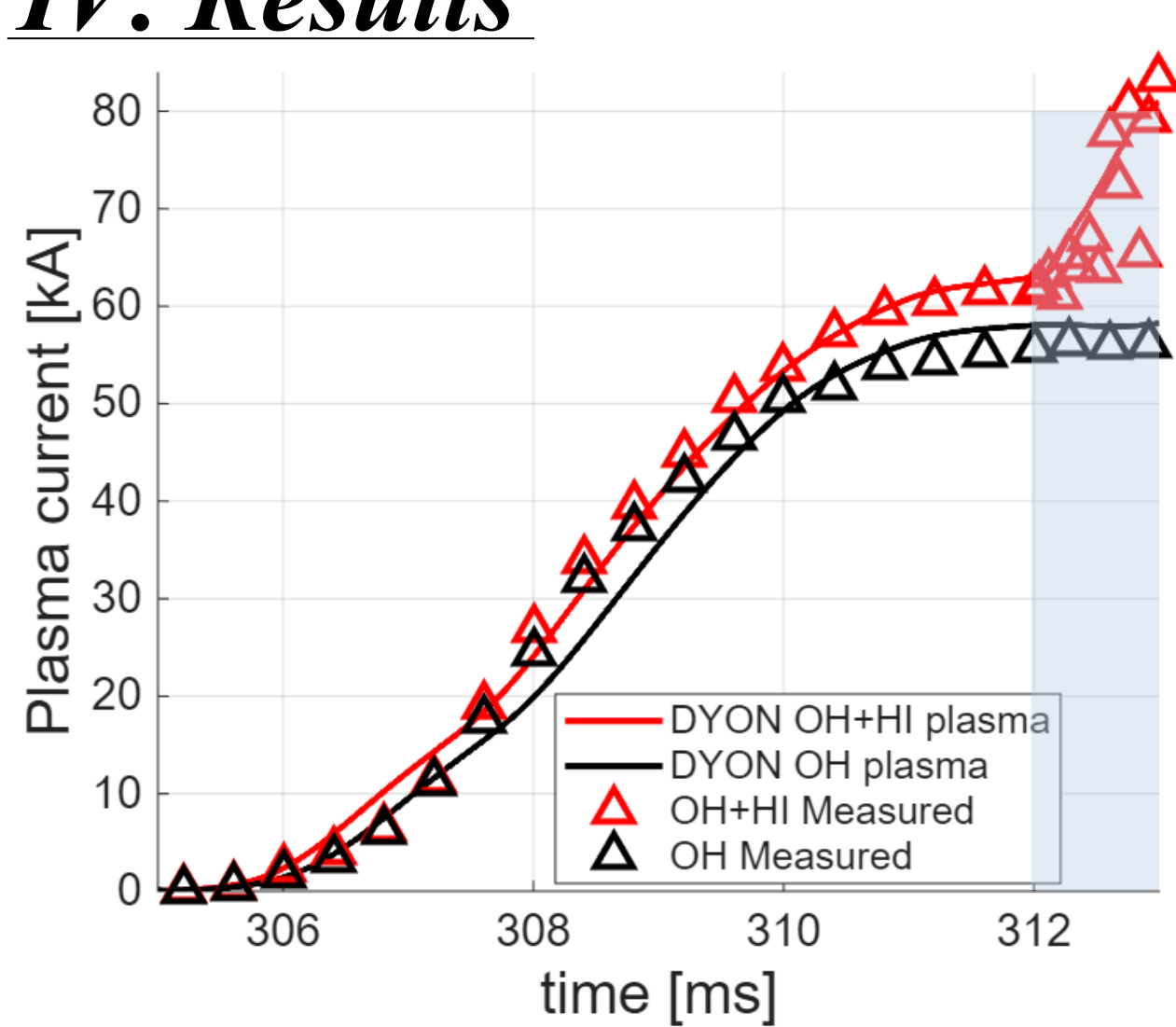
II. Motivation

Need for predictive HICD modelling toward reactor-scale STs

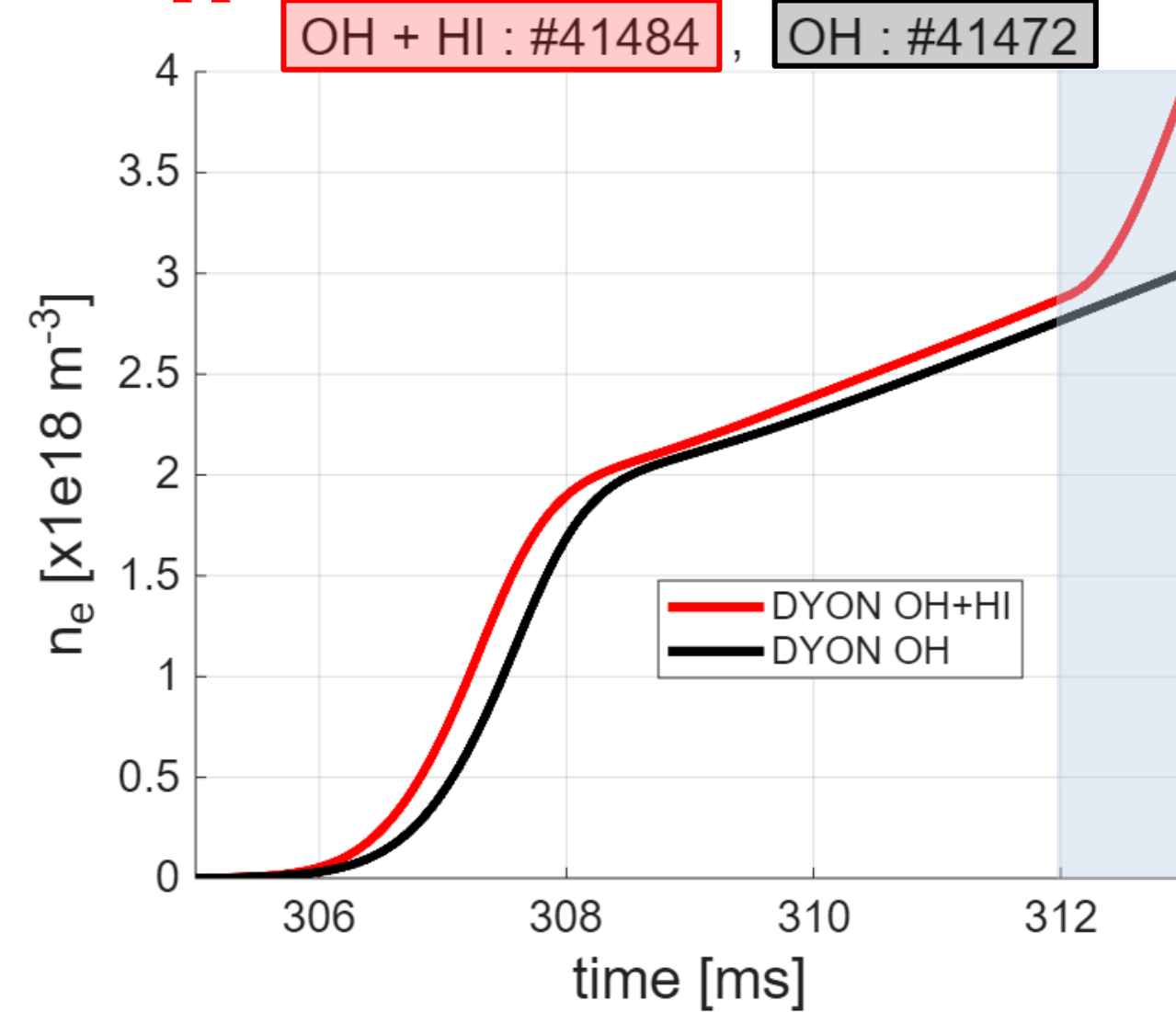
- Gap: HI has shown experimental promise [3,4], but existing power-balance model for HI [7] remains interpretive and not yet coupled to self-consistent plasma initiation modelling.
- Goal: Develop DYON-HI by coupling a Jensen-based [5] reduced 0D HICD model to DYON.
- Objective: Assess DYON-HI against VEST OH-only and OH+HI discharges.

IV. Results

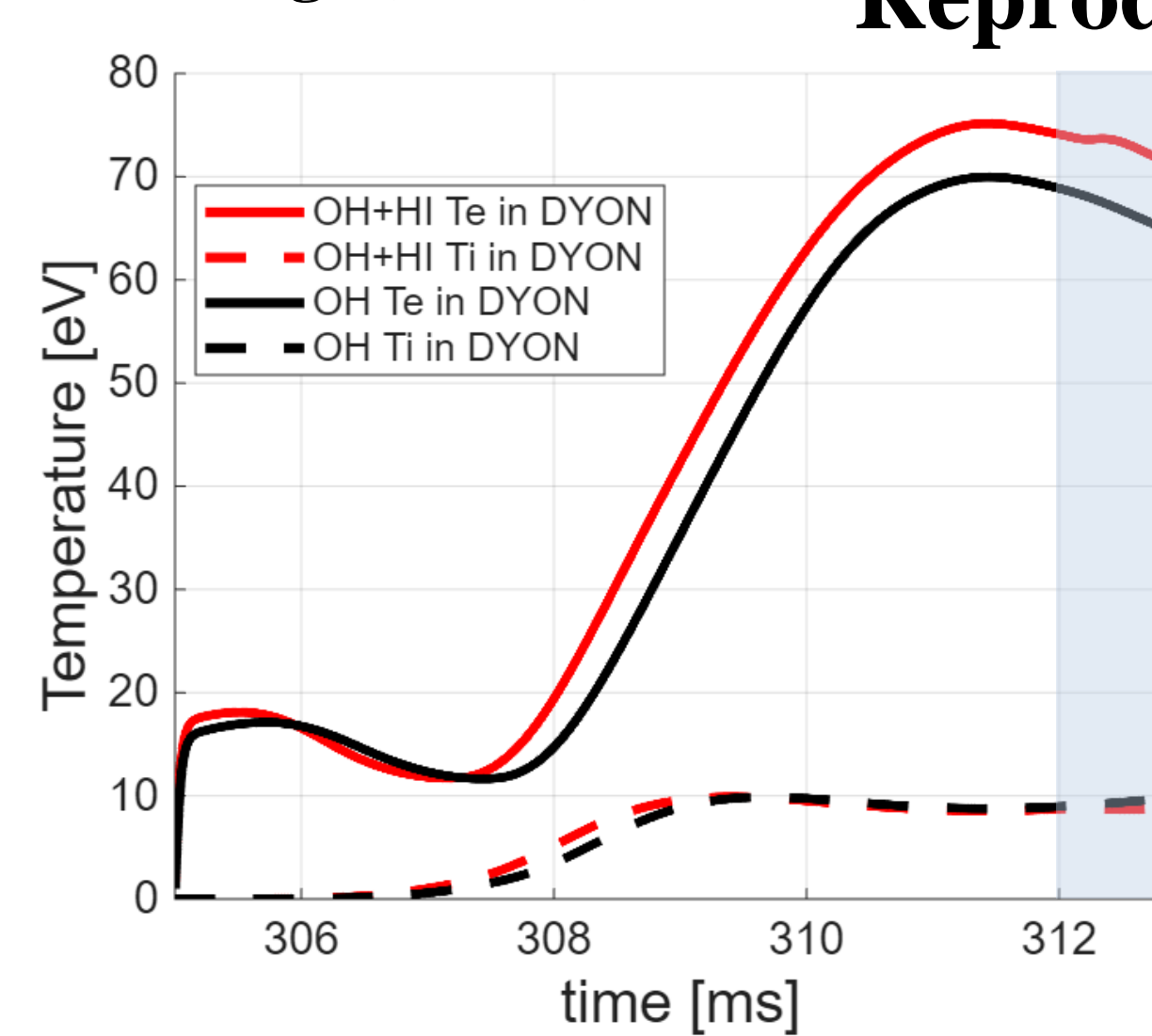
Ohmic + HI (HI applied at 312 ms)



Ohmic reference discharge (No HI)

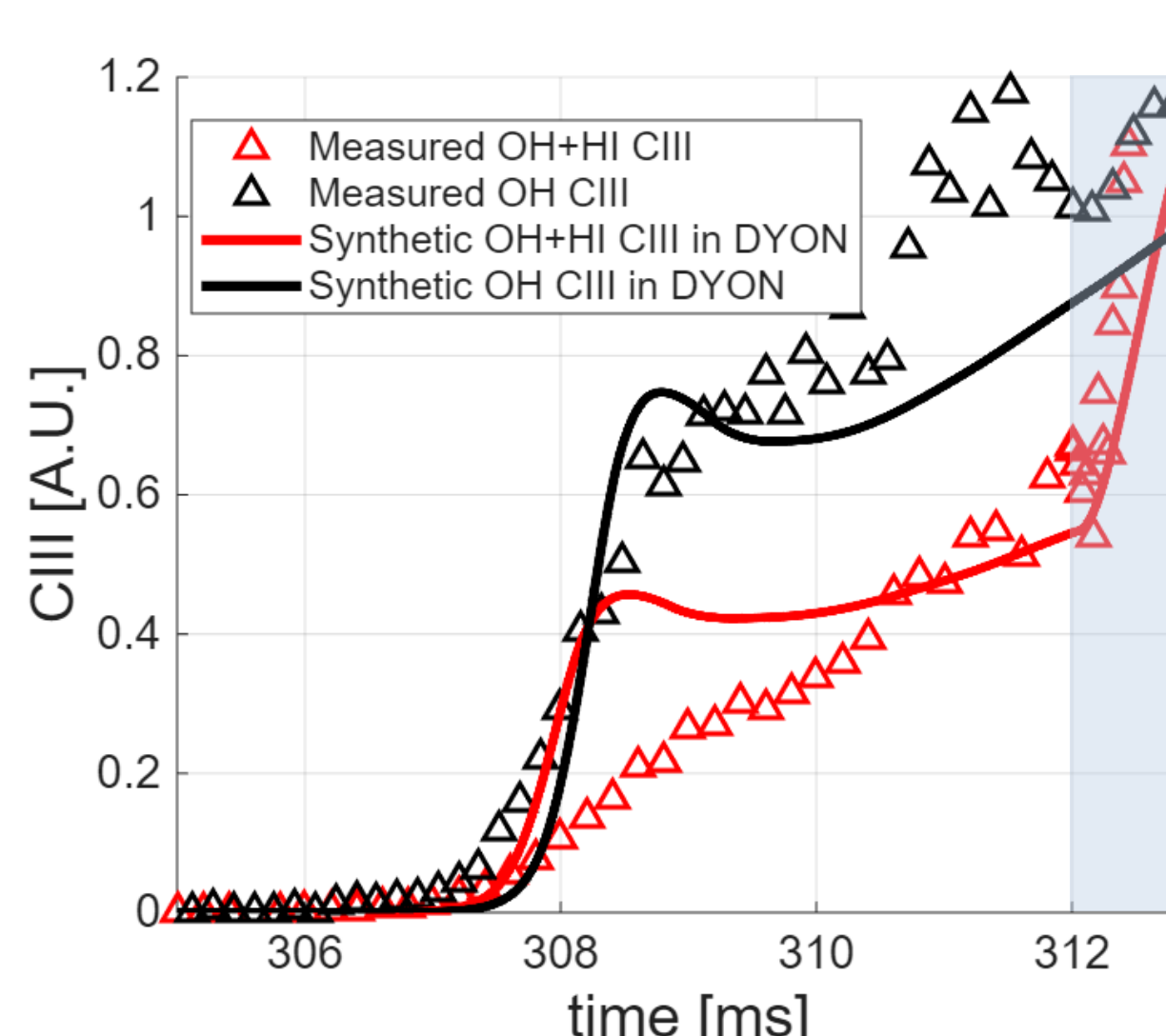
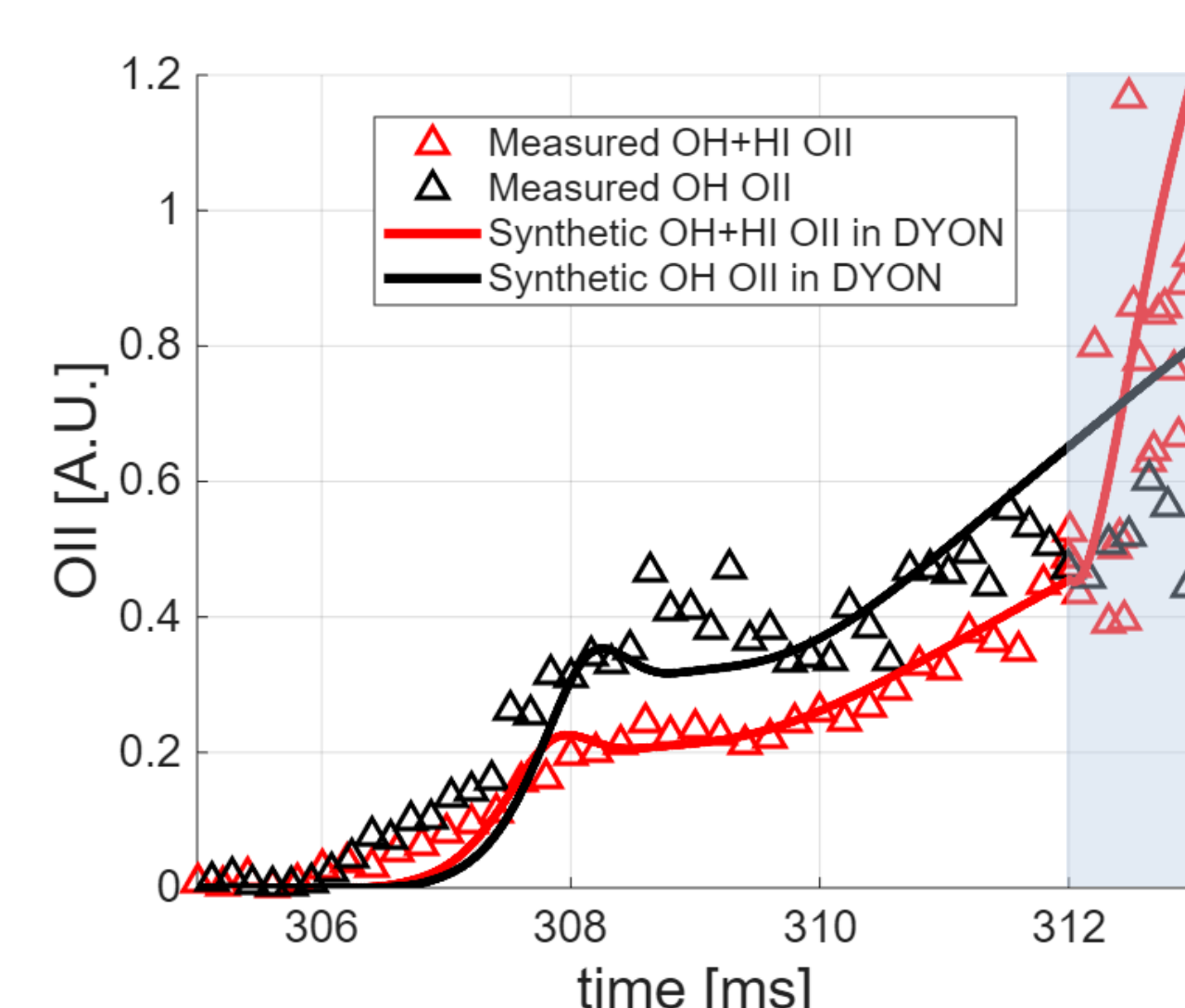
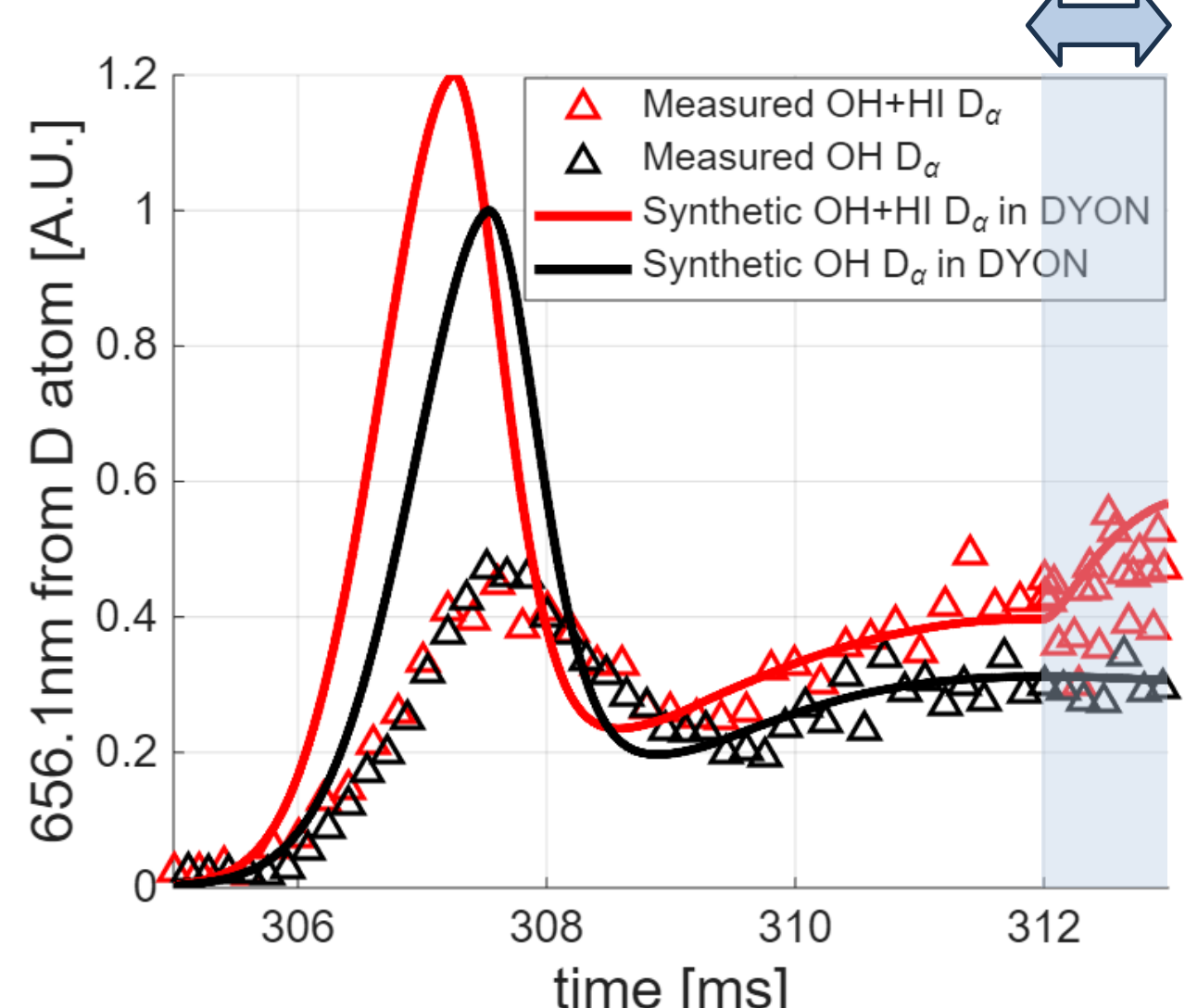


Reproducing VEST Discharges (#41472, #41484)



- VEST discharge **#41484 (OH+HI)** consists of an initial Ohmic phase followed by an **HI-assisted ramp-up phase** at 312–313 ms.
- The **additional ramp-up** in **#41484** indicates an **HI-assisted** current drive contribution relative to the **Ohmic-only reference #41472**.
- DYON-HI reproduces the main evolution of I_p and the line emission signals (D_α , $O-II$, $C-III$) with reasonable consistency.
- The comparison supports the consistent implementation of the reduced 0D HICD model and its capability to capture the main HI-assisted current evolution.
- An effective HI coupling factor of $\eta_{HI} = 0.5$ was adopted for this proof-of-principle VEST comparison.
- Direct n_e , T_e , and T_i measurements were not available; therefore, comparison focuses on I_p and line emission signals.

HI-assisted ramp-up phase (For discharge #41484)



V. Conclusion and Future work

- A Jensen-Chu formalism [5] was recast into a reduced 0D HICD model with an effective loop voltage term, V_{HI} , directly linked to controllable injector parameters ($V_{inj}, I_{inj}, N_{inj}$), enabling HI scenario scans.
- In DYON-HI, the resulting modified circuit equation with V_{HI} is solved self-consistently with DYON particle and energy balance equations; DYON-HI reproduces I_p and line emission trends in VEST comparisons, supporting its role as a first step toward a predictive framework for HI-assisted plasma initiation.

Future work: Optimize HI operation scenarios for the upcoming VEST-upgrade.

VI. Reference

- [1] K. J. Chung *et al.* 2013 *Plasma Sci. Technol.* **15** 244.
- [2] J. Y. Park *et al.* 2015 *Fusion Eng. Des.* **96** 269-273.
- [3] J. M. Perry *et al.* 2018 *Nucl. Fusion* **58** 096002.
- [4] J. Y. Park *et al.* 2025 *Nature* **644** 59-63.
- [5] T. H. Jensen and M. S. Chu. 1984 *Phys. Fluids* **27** 2881.
- [6] J. B. Taylor. 1974 *Phys. Rev. Lett.* **33** 1139.
- [7] J. L. Barr *et al.* 2018 *Nucl. Fusion* **58** 076011.
- [8] S. Ejima *et al.* 1982 *Nucl. Fusion* **22** 1313.
- [9] H-T Kim *et al.* 2012 *Nucl. Fusion* **52** 103016.

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