PLARE Plasma Laboratory for Advanced REsearch

Self-consistent Modelling of Non-Inductive Current Drive via Helicity Injection with Integrated Plasma Initiation Code

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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)

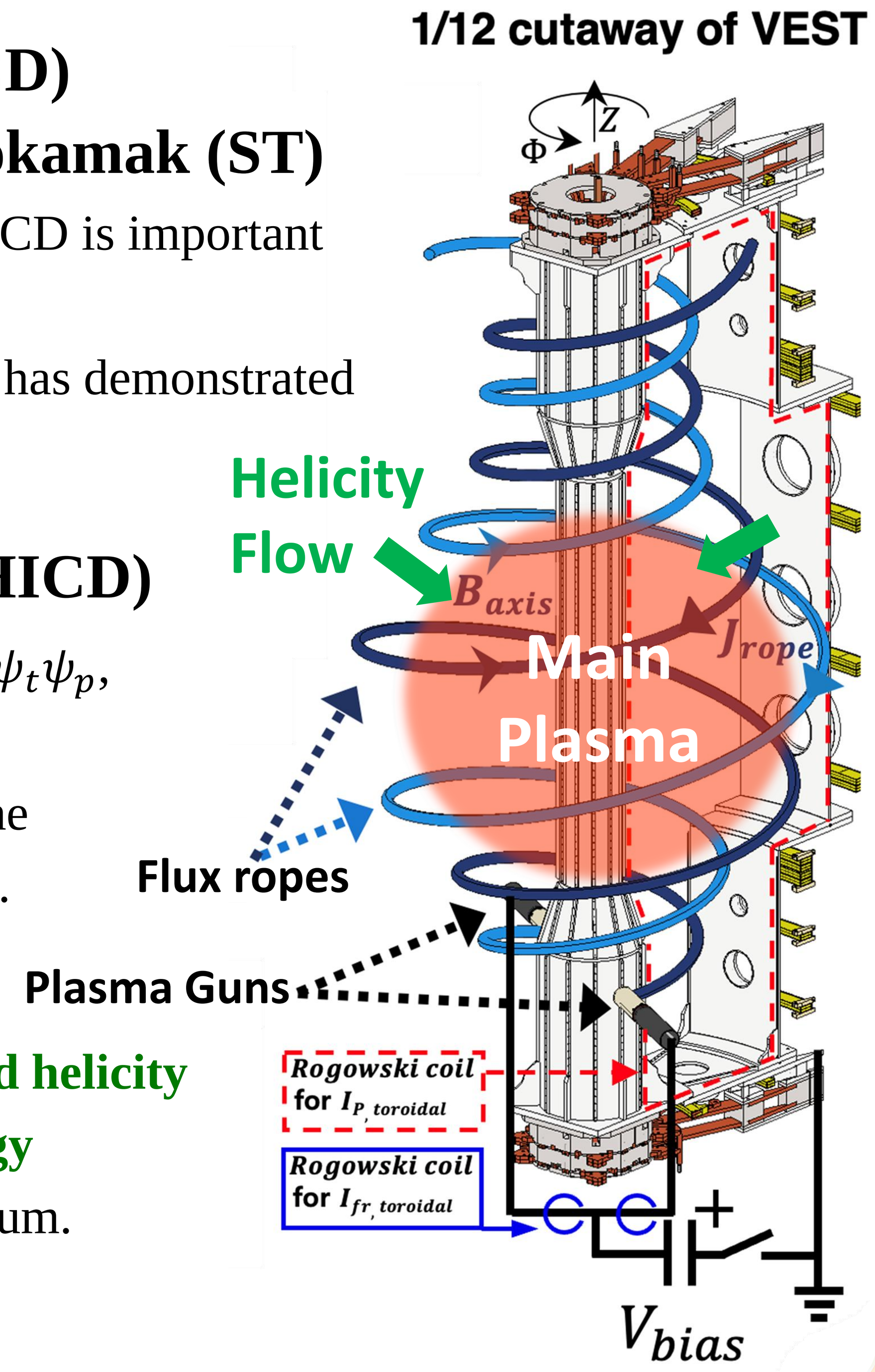
- Helicity ($\mathcal{K}$) is defined as $\mathcal{K} \equiv \int \vec{A}\cdot\vec{B}\, dV = \psi_t \psi_p$, representing the linkage of magnetic flux.
- Helicity Transport Equation [5] determines the **helicity injection rate** from arc plasma guns.

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

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

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

3D view
1/12 cutaway of VEST



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.

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 $\left(\frac{dW}{dt}\right)$ to the plasma current (I_p).

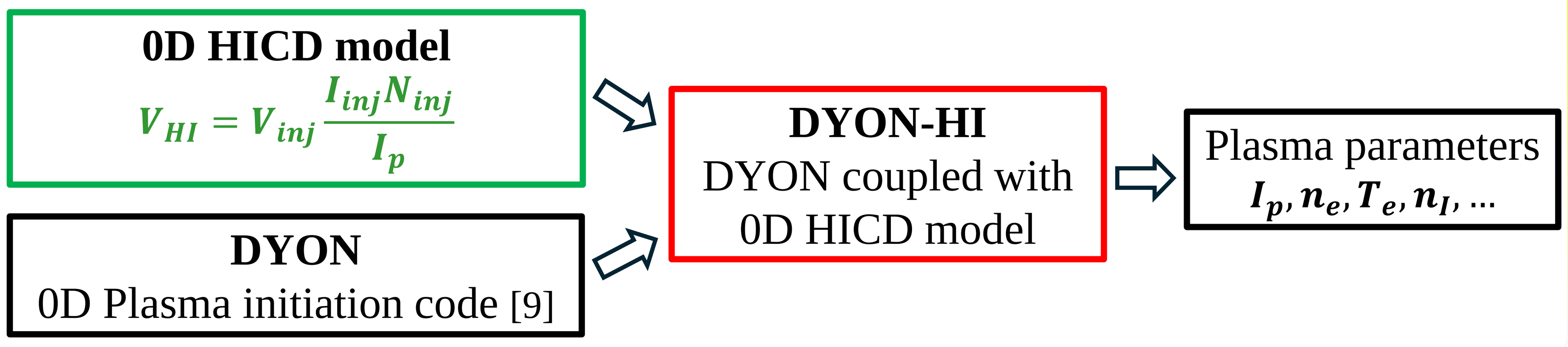
$$\frac{dW}{dt} + \vec{E}\cdot\vec{J} = -\frac{1}{\mu_0}\vec{\nabla}\cdot(\vec{E}\times\vec{B}) \Rightarrow \frac{1}{I_p}\frac{d}{dt}\left(\frac{1}{2}LI_p^2\right) - V_{HI} + RI_p = V_{loop}$$

- 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})**.

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

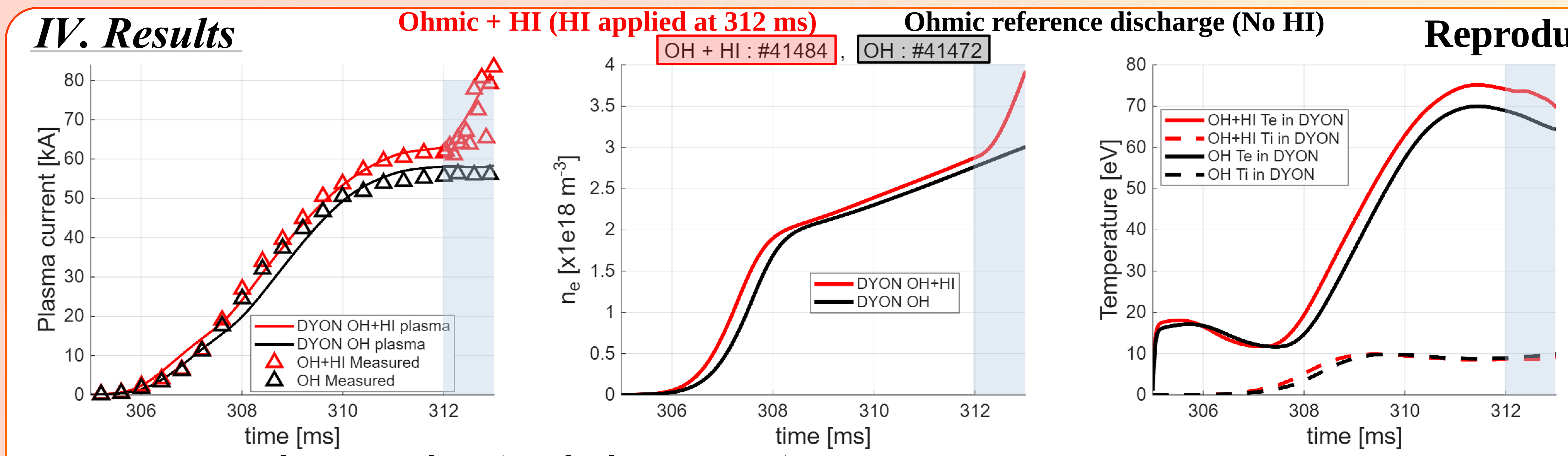
Integrated DYON with 0D HICD model (DYON-HI)

- **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.

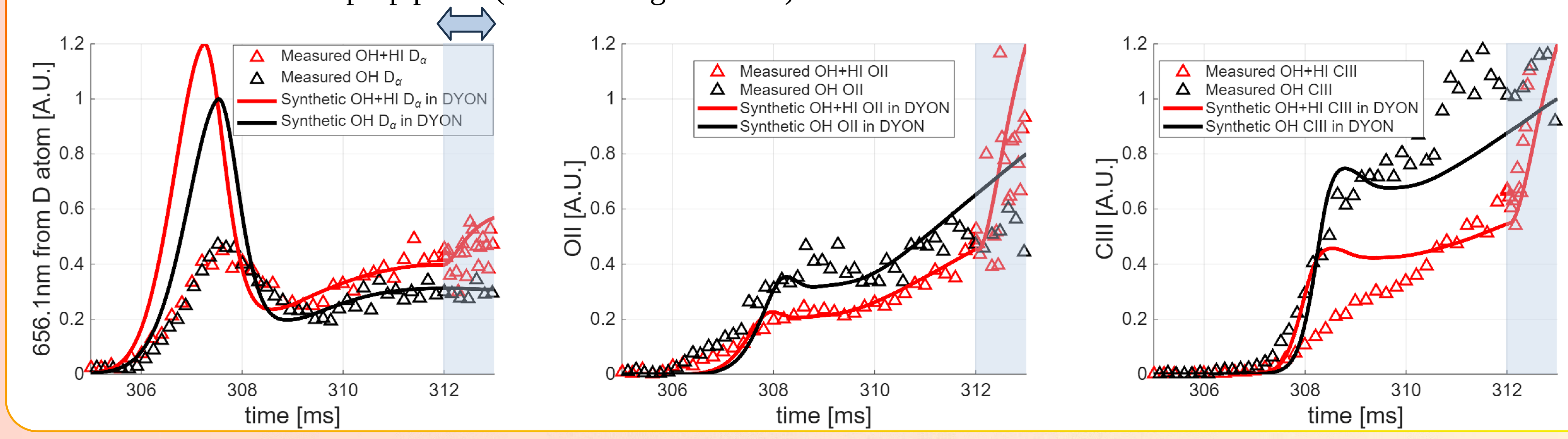


IV. Results

Ohmic + HI (HI applied at 312 ms) Ohmic reference discharge (No HI)



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



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 ($D_\alpha, O-II, C-III$) 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.

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

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Acknowledgement

This research was supported by two R&D Programs of "KSTAR Experimental Collaboration and Fusion Plasma Research (EN2601-17)" through the Korea Institute of Fusion Energy (KFE) funded by Korea Ministry of Science and ICT (MSIT).

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