

Self-consistent modelling of non-inductive current drive via Helicity Injection with integrated plasma initiation code

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1. Introduction

In spherical tokamaks (ST), the compact center stack limits the central-solenoid volt-seconds available during plasma initiation, making non-inductive current drive (NICD) essential for saving inductive flux and assisting current ramp-up. Helicity injection current drive (HICD) using arc plasma guns is a promising candidate and has demonstrated substantial potential in experiments [1,2]. Assessing HI-assisted start-up in reactor-scale STs requires a predictive framework that self-consistently evolves the plasma current and relevant plasma parameters from the plasma initiation phase.

DYON is a 0D plasma initiation code that self-consistently solves the particle balance, energy balance, and circuit equations validated in multi-machines [3,4]. Because HICD involves intrinsically 3D processes [1,5], its integration into DYON requires a reduced 0D formulation that represents the net current-drive effect in the so-called circuit equation. A previous 0D power-balance model has provided an interpretive description of HI operation [6], but the plasma evolution was largely prescribed rather than solved self-consistently. In this work, we develop DYON-HI by recasting the Jensen-Chu HI formalism as an effective loop voltage contribution and coupling the modified circuit equation with the HI correction to DYON. The resulting framework is applied to Versatile Experiment Spherical Torus (VEST) discharges with and without HI to assess its prediction capability of reproducing plasma current evolution and line emission signals.

2. Reduced 0D model for helicity injection current drive

The present reduction does not resolve the full 3D HI dynamics, such as flux-rope MHD activity and reconnection-associated turbulence [1,5], but represents their net effect on plasma current evolution. The reduced model is constructed from three theoretical elements: magnetic helicity and Taylor relaxation [7], helicity transport [8], and Poynting's theorem [9]. Magnetic helicity is an ideal MHD invariant and provides the physical basis for relating injected helicity to magnetic energy variation:

$$\mathcal{K} \equiv \int \vec{A} \cdot \vec{B} dV \quad (1)$$

where $\vec{B}$ is magnetic field, and $\vec{A}$ is magnetic vector potential.

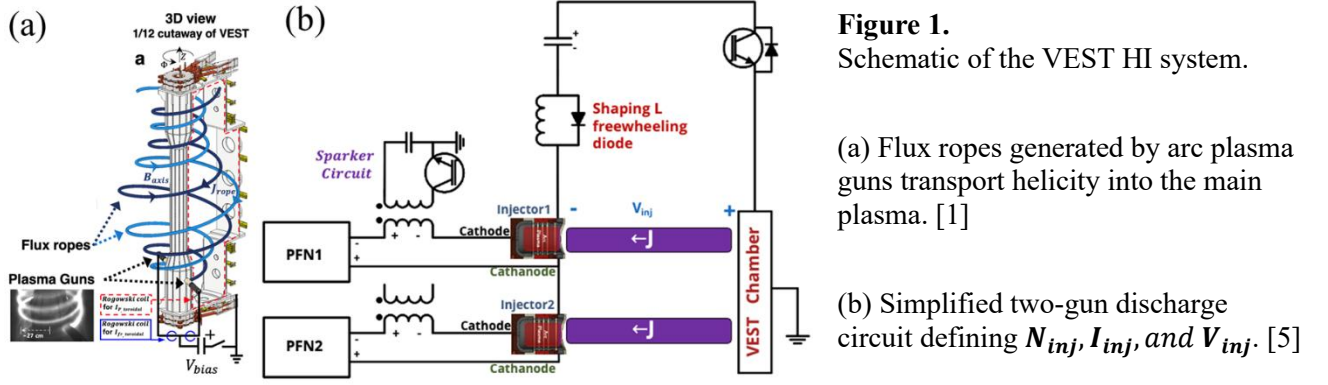


Figure 1.
Schematic of the VEST HI system.

(a) Flux ropes generated by arc plasma guns transport helicity into the main plasma. [1]

(b) Simplified two-gun discharge circuit defining N_{inj} , I_{inj} , and V_{inj} . [5]

A. Helicity transport from arc plasma guns

The helicity injected by the arc plasma guns is described using the helicity transport equation. Starting from the definition of magnetic helicity and Maxwell's equations, it's written by

$$\frac{\partial \mathcal{K}}{\partial t} + \vec{\nabla} \cdot \vec{Q} = -2\vec{E} \cdot \vec{B} \quad (2)$$

where $\vec{E}$ is electric field, and $\vec{Q} = 2\Phi\vec{B} + \vec{A} \times \frac{\partial \vec{A}}{\partial t}$ is the ‘‘Poynting vector’’ for helicity [8].

The surface integral of $\vec{Q}$ surrounding the in-vessel boundary gives the helicity injection rate from the flux ropes into the main plasma.

B. Magnetic energy change under Taylor relaxation

Once helicity is injected into the main plasma, the magnetic configuration is no longer at its minimum-energy state. The system is then relaxed toward a force-free state while conserving the total magnetic helicity [7,8]. This connects the injected helicity to the magnetic energy change of the main plasma.

For the early plasma initiation phase considered here, the plasma pressure is negligible. The relaxed magnetic configuration can then be represented by the force-free equilibrium condition

$$\vec{\nabla} \times \vec{\nabla} \times \vec{A} + \sigma \vec{\nabla} \times \vec{A} = 0 \quad (3)$$

where σ is force-free eigenvalue. Following Jensen and Chu [8], the decomposition of equilibrium $\vec{A}$ yields

$$\frac{d(W - W_v)}{d\mathcal{K}_c} = -\frac{\sigma}{2\mu_0} \quad (4)$$

Since $\mathcal{K}_c$ is determined by the $\vec{Q}$ in Eq. (2), Eq. (4) provides a relation between the injected helicity and the magnetic energy variation of the main plasma.

C. Effective loop voltage formulation and modified circuit equation

The magnetic energy variation associated with helicity injection can be represented as an effective loop voltage contribution. Combining Eq. (2) and Eq. (4) yields

$$V_{HI} = \frac{N_{inj} I_{inj} V_{inj}}{I_p} \quad (5)$$

where N_{inj} , I_{inj} , and V_{inj} are the number of guns, injection current, and injection voltage, and

I_p is the plasma current. Using Poynting's theorem and assuming fast relaxation process associated with HI compared with resistive 0D circuit evolution, V_{HI} is included in the circuit equation as

$$\frac{1}{I_p} \frac{d}{dt} \left(\frac{1}{2} L I_p^2 \right) - V_{HI} + R I_p = V_{loop} \quad (6)$$

Here L and R are the plasma inductance and resistance. Equation (6) is the modified circuit equation used in DYON-HI.

3. DYON-HI implementation and comparison with VEST experiments

The modified circuit equation derived in Sec. 2 was implemented in DYON by incorporating the effective loop voltage contribution, V_{HI} , into the DYON. The modified circuit equation is solved with the particle and energy balance equations, allowing the HI-assisted plasma current evolution and relevant plasma parameters to be advanced self-consistently.

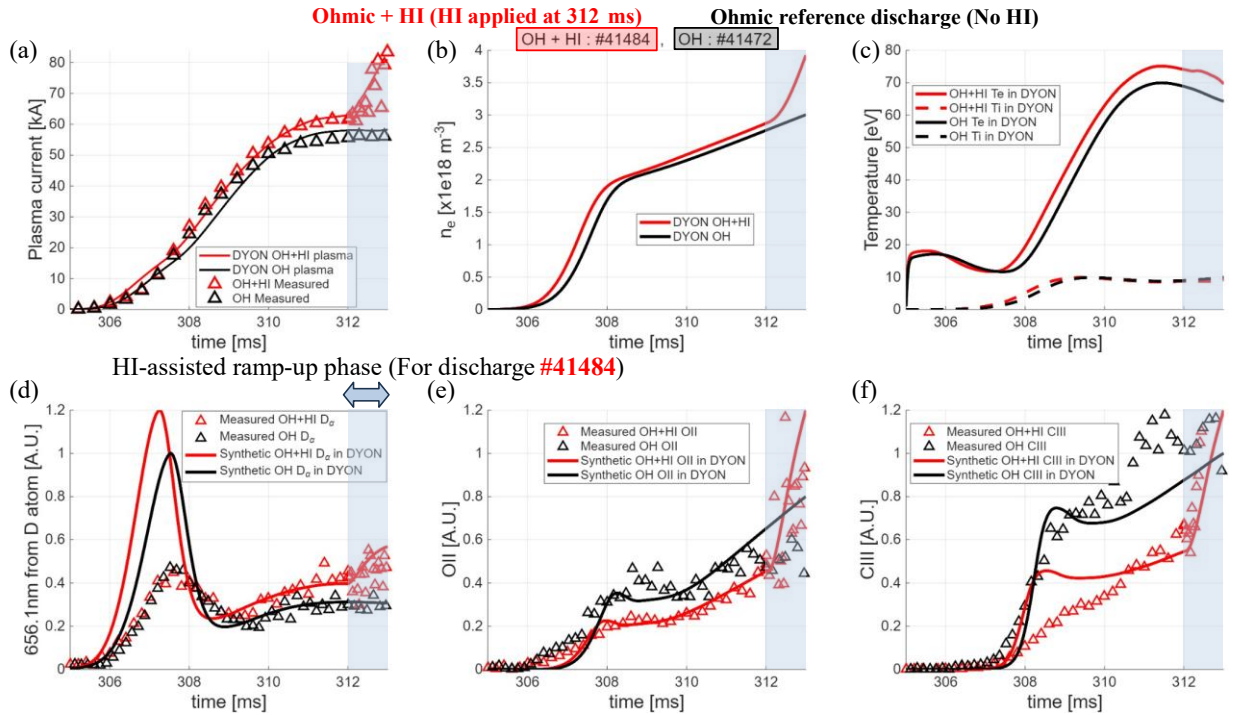


Figure 2. Comparison of DYON-HI simulations and VEST measurements for the OH+HI discharge #41484 and the ohmic-only reference discharge #41472. Lines and triangular markers denote simulations and measurements, respectively; red and black denote #41484 and #41472.

(a) I_p , (b) simulated n_e , (c) simulated T_e and T_i , (d) D_α , (e) O II, and (f) C III line emission signals.

A. VEST discharge and comparison observables

Two VEST discharges were selected for comparison [10,11]: an ohmic-only reference discharge #41472 and an OH+HI discharge #41484. In #41484, HI is applied after the initial ohmic phase at 312 ms, allowing the additional HI-assisted current ramp-up to be separated from the ohmic reference evolution. Because direct measurements of density and temperature were not available, the direct comparison is limited to the plasma current and line emission signals, D_α , O II, and C III. An effective HI coupling factor of $\eta_{HI} = 0.5$ was used for the VEST comparison.

B. Comparison with VEST measurements

Figure 2(a) shows that DYON-HI reproduces the main plasma current evolution in both discharges. This comparison checks that the baseline inductive plasma initiation remains consistently described after introducing the HI module (#41472), and the model reproduces the additional current ramp-up following HI application (#41484). The line emission signals in Fig. 2(d-f) show broadly consistent temporal trends. Since density and temperature are not directly measured, I_p and line emission signals provide the primary basis for assessing the present DYON-HI comparison.

4. Summary and conclusions

We developed DYON-HI by recasting the Jensen-Chu HI formalism as an effective loop voltage contribution, V_{HI} , and solving the modified circuit equation self-consistently with the DYON particle and energy balance equations. VEST OH-only and OH+HI comparisons show that DYON-HI reproduces the main plasma current evolution and line emission trends, supporting a proof-of-principle assessment of DYON-HI as a first step toward a predictive framework for HI-assisted plasma initiation. Because V_{HI} depends directly on experimentally controllable injector parameters, DYON-HI provides a basis for evaluating HI operation scenarios for the VEST upgrade and future reactor-scale STs.

Acknowledgement

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