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Verification and validation of plasma burn-through simulations in preparation for ITER First Plasma

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**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

1. Background

Motivation

ITER first plasma is planned in 2025. Reliable modelling capability is needed to develop and optimize the plasma initiation scenario. Plasma burn-through modelling codes never been compared one another, although there have been comparison of modelling results against (limited) experimental data. This motivated the code benchmark activity in ITPA-IOS group as a Joint Analysis #14 for 2018-2020. The summary of the code benchmark was published in Hyun-Tae Kim *et al* 2020 *Nucl. Fusion* **60** 126049.

Codes for plasma burn-through modelling

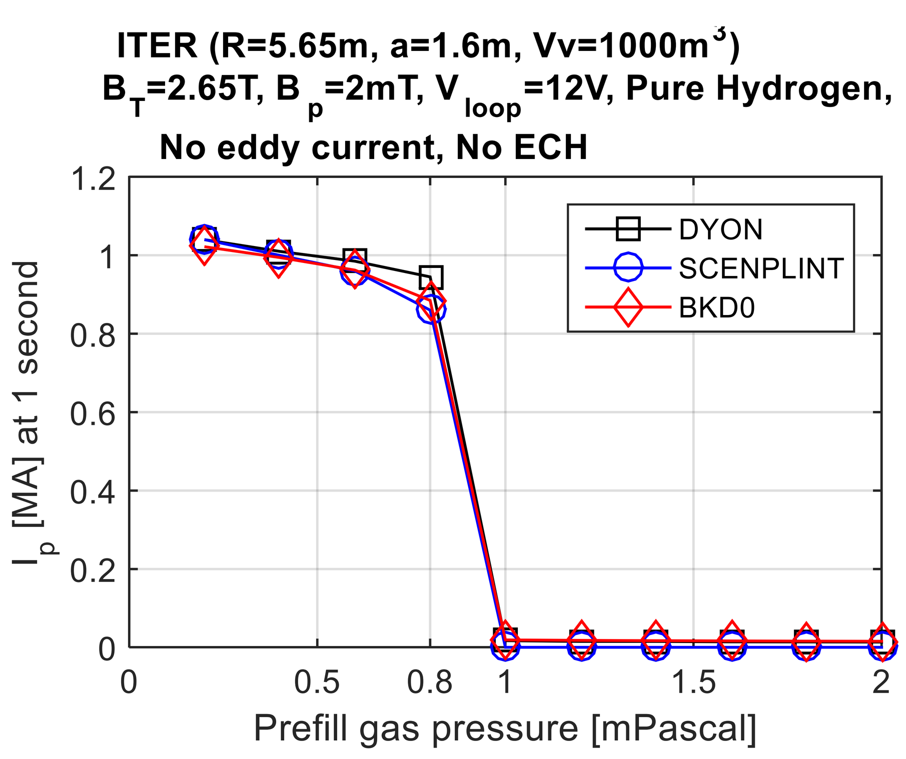
- **DYON** [1][2][3][4][6]**:** used to model JET, DIII-D, KSTAR, and MAST
- **SCENPLNT** [6][7][8][9]: used to model ITER
- **BKD0** [10][11][12]: used to model AUG-U, TCV, and JT60-SA

[1]Hyun-Tae Kim et al, Nuclear Fusion, 52 2012 103116, [2]Hyun-Tae Kim et al, Nuclear Fusion 53 2013 083024, [3]Hyun-Tae Kim et al, PPCF 53 2013 124032, [4]Hyun-Tae Kim et al, JNM, 438 2013 S1271, [5] 2007 ITER Physics basis, Nuclear Fusion 47 2007 S385-S403, [6]Jeongwon Lee et al, 2019 ITPA-IOS (16 Oct 2019), [7]V. A. Belyakov et al, Plasma devices and operations, 2003, V.11, no.3, pp.193-202, [8]V. A. Belyakov et al, Proc. Of Int. Conf. "Physics and Control", August 20-22, 2003, Saint Petersburg, Russia, [9]V. A. Belyakov et al, Tokamak: initial stage of plasma discharge, Spb-Moscow-Krasnodar: Lanbook, 2014 (in Russian), [10] G. Granucci et al 2015 Nuclear Fusion 55 093025, [11] D. Ricci et al, proc. 43rd EPS, Leuven 4-8 July 2016 ECA Vol.40A, [12] D. Ricci et al, proc. 45th EPS, Prague 4-8 July 2018 ECA Vol.42A

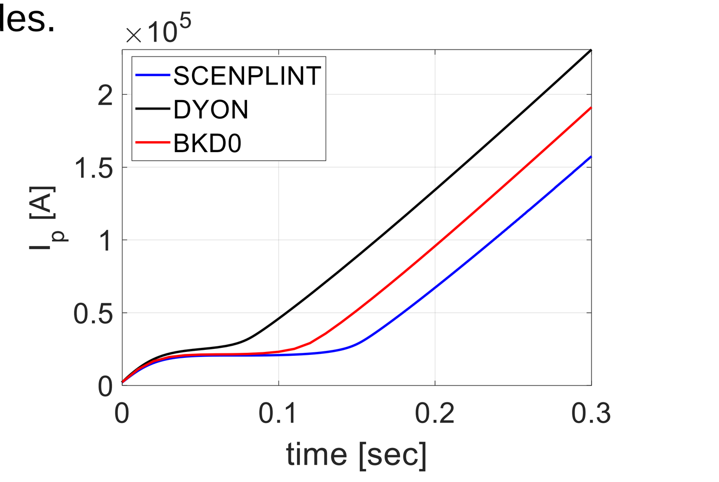
Code benchmarking strategy

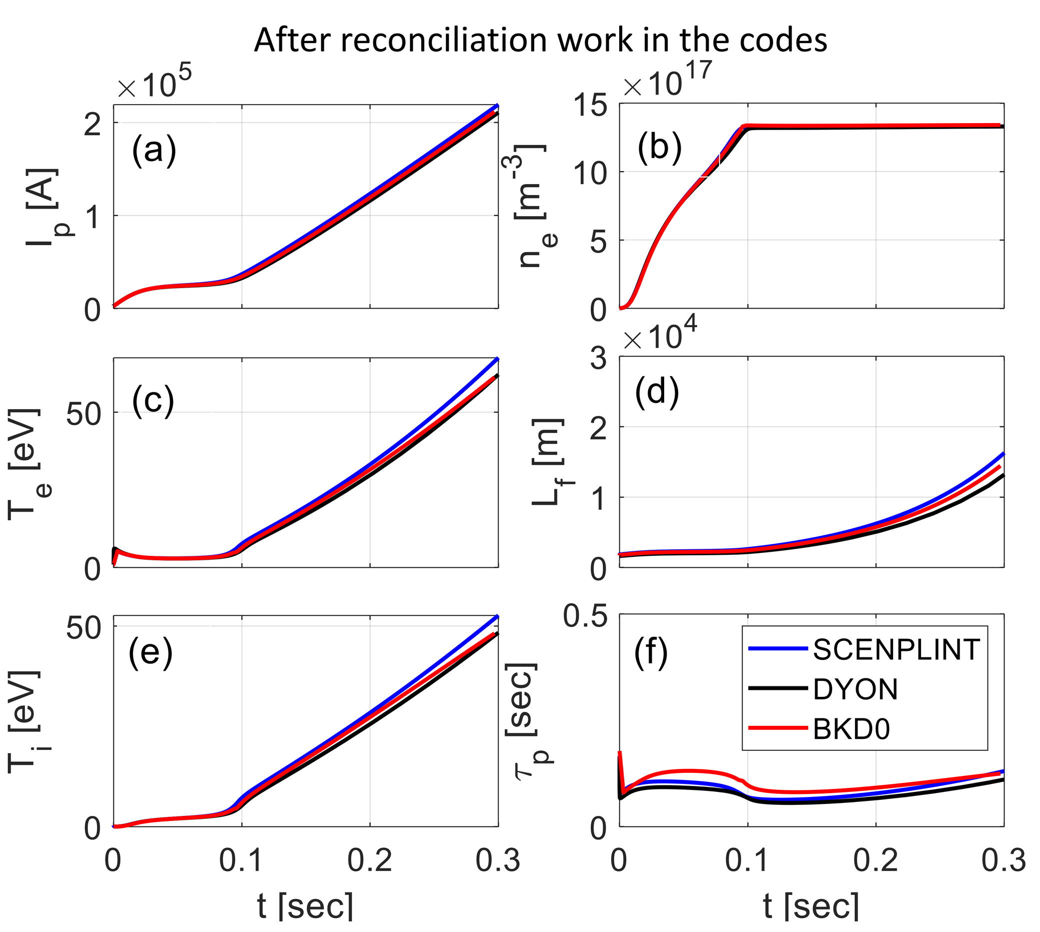
1. First benchmark case: ITER, constant input data, no impurity, no eddy current, no ECH
2. Second benchmark case: JET, time-dependent input data, impurity modelling, eddy current modelling, no ECH
3. Third benchmark case: KSTAR, time-dependent input data, impurity modelling, no Eddy current modelling, with ECH modelling

2. First benchmark case – ohmic burn-through in ITER



- Initial H atom density n_0
  $= 2 * p_0 / (0.026 * 1.6\times10^{-19})$
  $= 4.8\times10^{20} * p_0$ [Pascal]
- In the first benchmark case, all three codes consistently predict that 0.8mPascal is the threshold prefill gas pressure for successful plasma burn-through at V_{loop}=12V in ITER.
- However, the predicted time evolution of plasma parameters are different in the three codes.





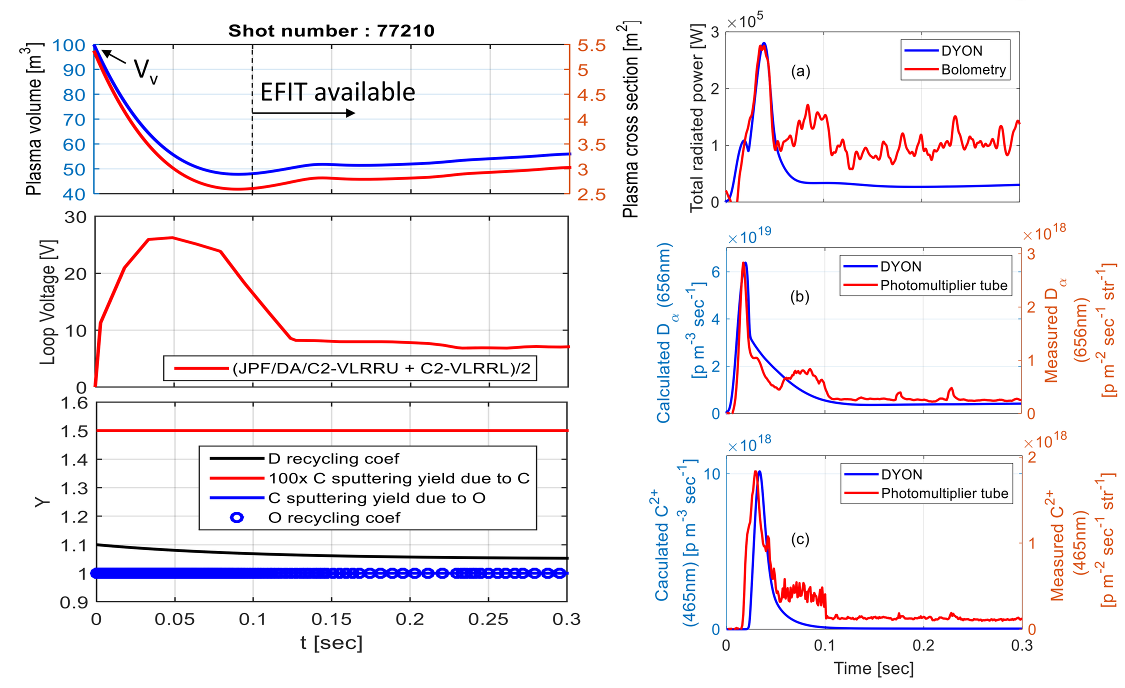
Revisiting mathematical models in the source codes enabled identifying differences, and good agreement of the modelling results after the reconciliation work confirms that the findings are the main sources for the differences in the first benchmark case .

Table 1. Summary of the reconciliation work for code benchmark of ITER first plasma simulation.

	Before the reconciliation work	Reconciliation work
DYON	a) $<P>_{\mathrm{line}}$ in ADAS (plt96_h.dat)	a) $<P>_{\mathrm{line}} = \mathrm{S_{iz}} \times 16.4$ eV from [1]
	b) $<\sigma\upsilon>_{cx}$ in ADAS (ccd96_d.dat)	b) $<\sigma\upsilon>_{cx} = 1.066 \times 10^{-14} \times \mathrm{T_i}^{0.327}$ from [1]
SCENPLINT	a) lnΛ in [2]	a) $\ln\Lambda = 10$
	b) $\eta_{en} = 2.3e-6 \times n_0/n_e$	b) $\eta_{en} = 0$
	c) $\tau_{p,\perp} = \tau_{Bohm} = 3 \times a^2B_t/T_e$	c) $\tau_{p,\perp} = \tau_{Bohm} = 8 \times a^2B_t/T_e$
BKD0	a) lnΛ in [3]	a) $\ln\Lambda = 10$
	b) $\tau_{p,\perp} = \tau_{Bohm} = 3 \times a^2B_t/T_e$	b) $\tau_{p,\perp} = \tau_{Bohm} = 8 \times a^2B_t/T_e$
	c) $\mathrm{I_{ref}} = 16$ kA	c) $\mathrm{I_{ref}} = 100$ kA

[1] B Lloyd *et al* 1996 *PPCF* **38** 1627
[2] Braginskii S.I. 1965 Transport processes in a plasma *Rev. Plasma Phys.* **1** 205
[3] U.S. Naval Research Laboratory 'NRL Plasma Formulary' (http://www.nrl.navy.mil/ppd/content/nrl-plasmaformulary)

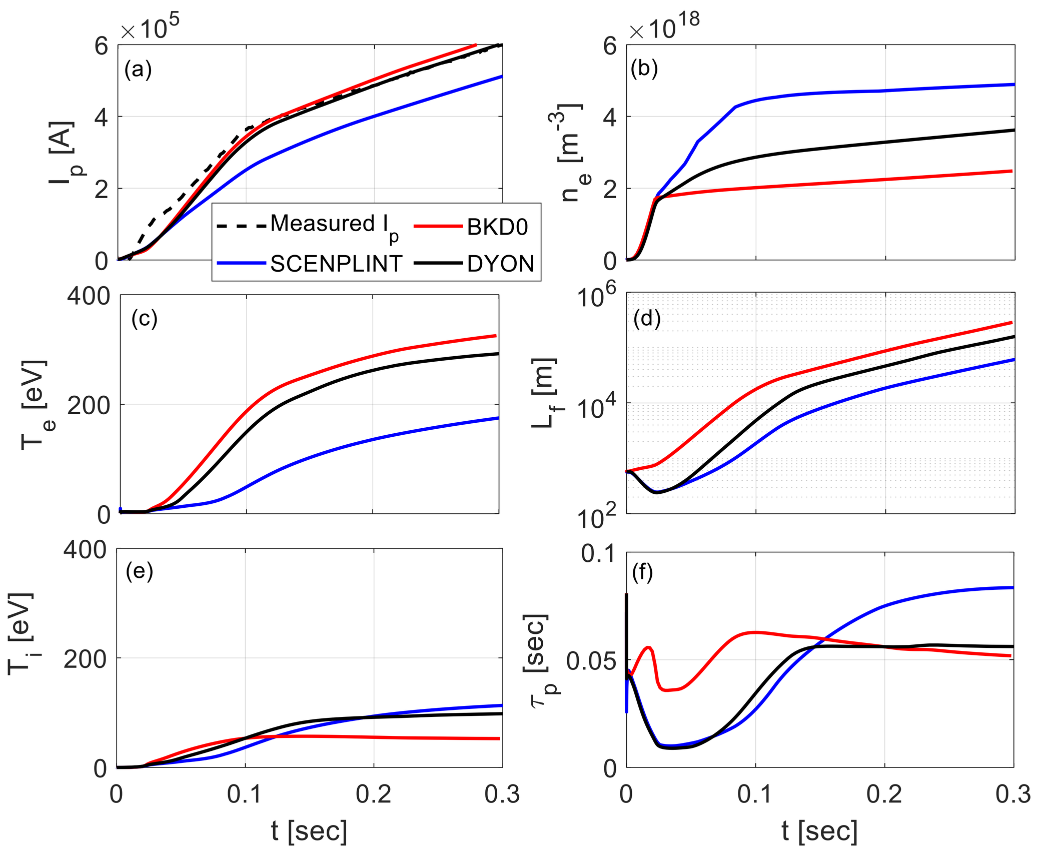
3. Second benchmark case – ohmic burn-through in JET-C



In the second benchmark case, reading time-evolving input data in JET-C, and modelling the eddy current and PWI, DYON reasonably reproduced the measured data.

The good temporal agreement of the peaks in the synthetic D_a and C^{2+} emission with measurement indicates that the time-evolution of T_e , n_e , and $n^{c2+}$are reasonably modelled.

However, despite the same modelling setting used in the first benchmark case, the three codes showed different time evolution of plasma parameters in the second benchmark case.



Reconciliation work recovered the good agreement (not shown), and confirmed the reasons.

L_f evolution with the eddy current in BKD0
→**EM modelling including passive structure is necessary.**

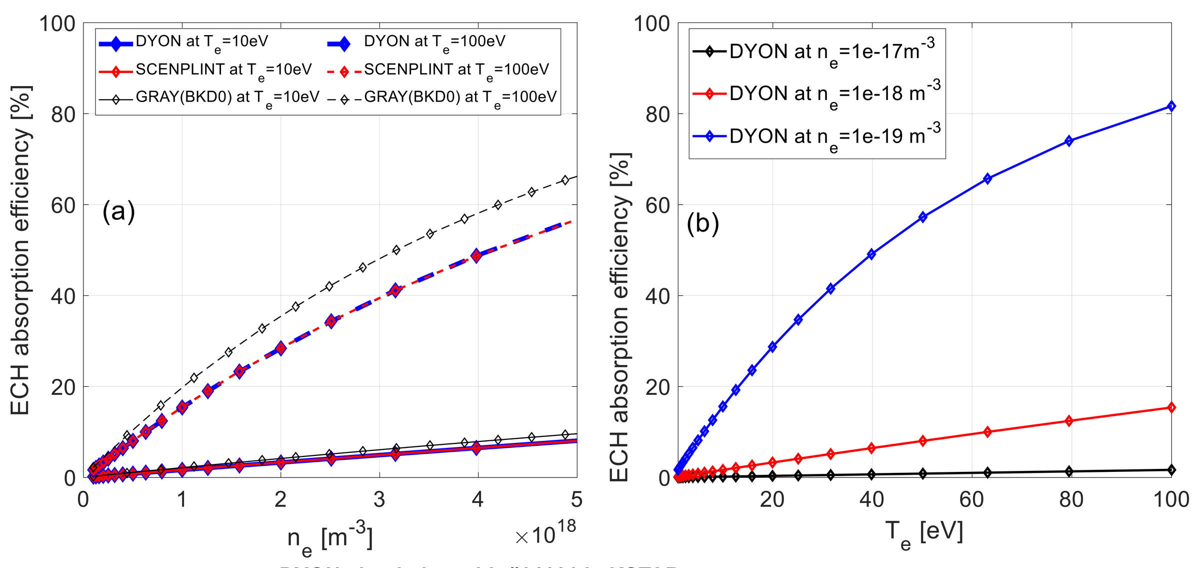
$$V_l = I_p R_p + L_p \frac{dI_p}{dt} + \boxed{M\frac{dI_{MK2}}{dt}}$$

$$\boxed{V_l = I_{MK2} R_{MK2} + L_{MK2} \frac{dI_{MK2}}{dt} + M\frac{dI_p}{dt}}$$

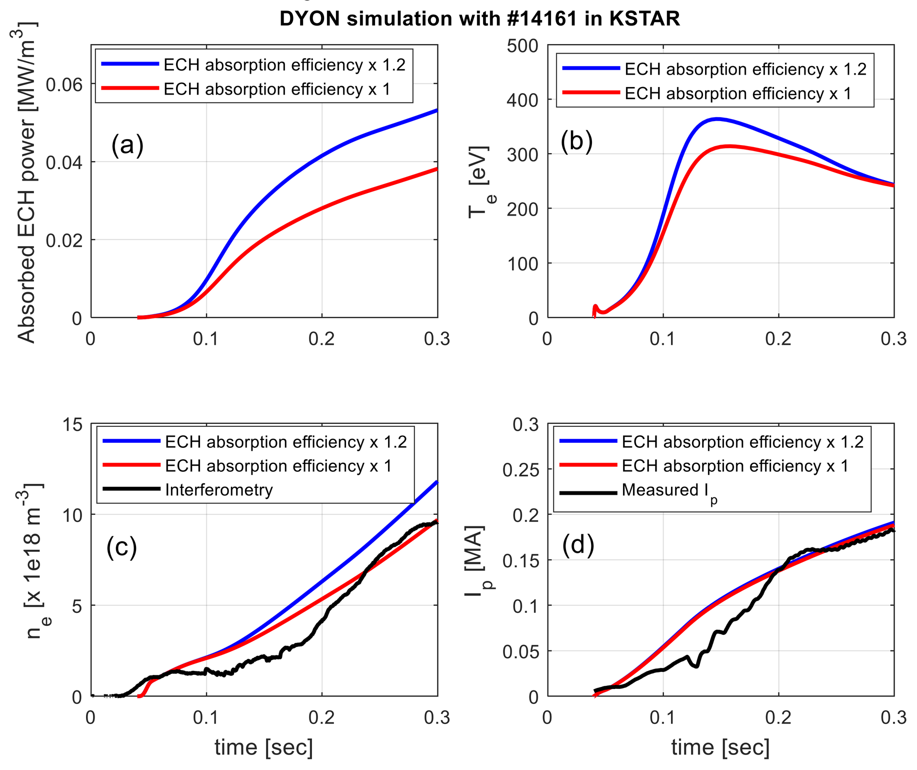
dV_p/dt =0 in SCENPLINT.
→**Volume evolution with correct $V_p(t)$ should be modelled.**

$$\frac{dn_D^{1+}}{dt} = n_e n_D^0 <\sigma\upsilon>_{iz} - n_e n_D^{1+} <\sigma\upsilon>_{rec} + \sum_I \sum_{Z>1} n_D^0 n_I^{Z+} <\sigma\upsilon>_{cx} - \frac{n_D^{1+}}{\tau_p} \boxed{- \frac{n_D^{1+}}{V_p}\frac{dV_p}{dt}}$$

4. Third benchmark case – ECH-assisted burn-through in KSTAR



With the ITER-like ECH setting, stand-alone comparison of ECH models in the three codes shows that the calculated ECH absorption efficiency is identical in DYON and SCENPLINT, while it is about 20% higher in BKD0 (GRAY).



- 2nd harmonic ECH absorption efficiency is small at the typical plasma parameters during the plasma burn-through phase e.g. $T_e = 1 \sim 20$ eV and $n_e = 1\times10^{17} \sim 5\times10^{18}$ m^{-3}, and increases almost linearly with T_e and n_e.
- The 20% discrepancy in ECH absorption efficiency between DYON and BKD0 is maintained over the typical range of plasma parameters during the plasma burn-through phase.
- With the 20% higher ECH absorption efficiency, T_e and n_e appear to be somewhat higher in turn, consistently maintaining the plasma pressure to be about 20% higher.

5. Summary

Benchmark of plasma burn-through modelling codes (DYON, SCENPLINT, and BKD0) has been performed for the first time. The three codes consistently predict the threshold prefill gas pressure as 0.8mPascal at 12V loop voltage, but the predicted time evolution of plasma parameters are not the same. Extensive code comparison carried out over the three cases (ITER, JET-C, and KSTAR) enabled identifying the main differences, and what needs to be further developed to improve the plasma burn-through prediction capability:

- **Electromagnetic modelling of passive structure**
- **Plasma volume evolution model during the burn-through phase**

Further details can be found in Hyun-Tae Kim et al 2020 Nucl. Fusion 60 126049.

JET iter KSTAR

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