Validation of equilibrium tools on the COMPASS tokamak

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Abstract

Various MHD (magnetohydrodynamic) equilibrium tools, some of which being recently developed or considerably updated, are used on the medium-size COMPASS tokamak [R. Pánek et al., Czech J Phys 56, B125, 2006]. MHD equilibrium is a fundamental property of the tokamak plasma, whose knowledge is required for many diagnostics and modelling tools. Proper benchmarking and validation of equilibrium tools is thus key for interpreting and planning tokamak experiments. We present here benchmarks and comparisons to experimental data of the EFIT++ reconstruction code [L.C. Appel et al., to be submitted to Nucl. Fusion], the free-boundary equilibrium code FREEBIE [J.-F. Artaud, S.H. Kim, EPS 2012, P4.023], and a rapid plasma boundary reconstruction code VacTH [B. Faugeras et al., PPCF 2014, accepted]. We demonstrate that FREEBIE can calculate the equilibrium and corresponding poloidal field (PF) coils currents for given plasma parameters. Both EFIT++ and VacTH can reconstruct equilibria generated by FREEBIE from synthetic diagnostic data (including an artificial noise) and hence might be suitable for real-time control. Optimum reconstruction parameters are estimated; in addition, possible enhancements using more diagnostics are discussed and simulated using synthetic diagnostics. FREEBIE can also calculate the temporal evolution of the poloidal field coils currents for a whole plasma scenario.

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1. Introduction

We report here on validation and verification of tokamak equilibrium tools used for the COMPASS tokamak [1]. We particularly focus on fundamental global plasma parameters and the shapes of magnetic flux surfaces, which are crucial in diagnostics interpretation and other analyses. EFIT++ [2] is used for routine equilibrium reconstruction on COMPASS. FREEBIE [3] is a recent free-boundary equilibrium code; FREEBIE enables predictive equilibrium calculation consistent with the poloidal field (PF) components of the tokamak. In this study, FREEBIE is used in the so-called inverse mode, which predicts PF coils currents from a give plasma boundary and profiles. The third code employed in this study is VacTH [4], which provides a fast reconstruction of the plasma boundary from magnetic measurements using a toroidal harmonics basis.

In order to verify and validate the aforementioned tools, we analyse EFIT++ and VacTH reconstructions of equilibria constructed with FREEBIE. Synthetic diagnostics (e.g., magnetic probes or flux loops) with optional artificial errors provide inputs for the reconstructions.

2. Verification and validation procedure

Reliable MHD equilibrium reconstruction is very important for tokamak exploitation. Numerous diagnostics and subsequent analyses require as inputs equilibrium properties such as flux surface geometry, magnetic field, stored energy, internal inductance etc. We have set up a set of benchmarking tasks, which verify and validate equilibrium tools that are currently employed on COMPASS. The procedure is fundamentally following:

1. Equilibrium reconstruction of selected experimental cases using EFIT++.
2. Recalculate the equilibria using FREEBIE in inverse mode.
3. Optionally alter the equilibria in FREEBIE using e.g. experimental pressure profiles.
4. Reconstruct FREEBIE equilibria using EFIT++ and VacTH with various parameters and artificial input noise.

The first step employs a routine EFIT++ set-up for COMPASS with heuristically tuned parameters. In addition to the total plasma current I_p and the currents in individual PF circuits, 16 partial Rogowski coils and 4 flux loops are employed in this reconstruction and p' and FF' are assumed to be linear functions of the poloidal flux ψ. In the second step, FREEBIE inputs I_p, $p'\,(\bar{\psi})$ and $FF'\,(\bar{\psi})$ profiles, the plasma boundary coordinates and an initial guess for the PF coils currents. Here, p is the plasma pressure, $F = RB_\phi$ and $\bar{\psi}$ is the normalized poloidal magnetic flux ($\bar{\psi} = 0$ on the magnetic axis and $\bar{\psi} = 1$

on the plasma boundary). p' comes either from the EFIT++ reconstruction or from Thomson scattering pressure profile $p_{\mathrm{TS}} = 1.3 n_{\mathrm{e}} p_{\mathrm{e}}$. FREEBIE then seeks a solution to the Grad-Shafranov equation, including the PF coils currents, which minimizes the given plasma shape constraint. (This regime is called the inverse mode.) FREEBIE can naturally output arbitrary synthetic diagnostics. We use here additional 24 poloidally and 24 radially oriented partial Rogowski coils (which are actually mounted on COMPASS) and an artificial set of 16 flux loops located at the same positions as the basic magnetic probes. Hereafter, the number of magnetic probes and flux loops are denoted n_{mp} and n_{fl}. $n_{\mathrm{mp}} = 16$, $n_{\mathrm{fl}} = 4$ refers the basic set of magnetic measurements, $n_{\mathrm{mp}} = 64$ refers to a set of all presently mounted partial Rogowski coils on COMPASS and $n_{\mathrm{fl}} = 16$ implies artificial flux loops positioned at the same locations as the basic magnetic probes. In the optional third step, an artificial random noise is added to the calculated values of I_{p}, magnetic probes and flux loops. In particular, for a given noise level ϵ, $\tilde{X} = \left(1 + U(-\epsilon, \epsilon)^{\mathrm{T}}\right) X$, where X is a row vector of the synthetic diagnostics data and $U(-\epsilon, \epsilon)$ is a random vector of the same shape as X with a uniform distribution on $(-\epsilon, \epsilon)$.

The final fourth step consists of reconstructing the equilibria form synthetic FREEBIE data using EFIT++ and VacTH. The reconstructions are then compared to the original equilibrium, focusing on global parameters and geometry. VacTH does not provide a full equilibrium but the plasma shape only (the target of VacTH is to provide such reconstructions in real time for a feedback control). Scans are performed over noise levels (ϵ) and selected code parameters: p' and FF' polynomial degrees in EFIT++ ($n_{p'}$, $n_{FF'}$) and the number of harmonics (n_{p}, n_{q}) in VacTH. The following quantities are used for the comparison.

$R_{\mathrm{ax}}, Z_{\mathrm{a}x}$	R, Z coordinates of the magnetic axis
$R_{\mathrm{i}n}, R_{\mathrm{o}ut}$	inner/outer R coordinate of LCFS at $Z = Z_{\mathrm{a}x}$
$Z_{\mathrm{m}in}, Z_{\mathrm{m}ax}$	minimum/maximum Z coordinate of LCFS
$\kappa = \frac{(Z_{\mathrm{max}} - Z_{\mathrm{min}})}{(R_{\mathrm{out}} - R_{\mathrm{in}})}$	elongation
$l_{\mathrm{i}} = \bar{B}_{\mathrm{p}}^2 / B_{\mathrm{a}}^2$	normalized internal inductance
$\beta_{\mathrm{p}} = 2\mu_0 \bar{p} / B_{\mathrm{a}}^2$	poloidal beta
$W = \int_0^V \frac{3}{2} p \mathrm{d}V'$	stored plasma energy
q_0, q_{95}	safety factor at $\bar{\psi} = 0,\ 0.95$

Here, $\bar{x} = \int_0^V x/V \mathrm{d}V'$ is a volume average, V is the total plasma volume, $B_{\mathrm{a}} = \mu_0 I_{\mathrm{p}} / l_{\mathrm{a}}$, l_{a} is the poloidal LCFS perimeter.

3. Results

We have selected five time slices from COMPAS shots 4275 and 6962 (i.e. 10 cases in total) for the analysis. These cases include circular, elongated and diverted plasmas with different currents. A comparison of plasma shapes for shot 4275 is shown in Fig. 1. Numerical values of reconstruction errors are presented in Table 1. We can observe a very good agreement between the original equilibrium and the reconstructed shapes. In this case, FREEBIE was using linear p' and FF' polynomials so that the EFIT++ model agrees with the target data. VacTH uses 8 magnetic probes and 16 flux loops. As we discuss later, flux loops are essential for reliable VacTH results. Even global kinetic properties are well reconstructed in EFIT++; the largest error around 10 % is in l_{i} (i.e. basically in the toroidal current density profile).

The second shot for the comparison is 6962, which has been chosen because Thomson scattering (TS) profiles are available. In Fig. 2 we show reconstructions for more realistic equilibria and an artificial noise in the synthetic diagnostic signals. TS pressures were used in FREEBIE equilibria, which course no longer feature linear p' and FF' profiles. It is apparent that the reconstruction is not as good as in the previous case. Nevertheless, the plasma shape is well reconstructed with EFIT++ and VacTH, except for the last time slice in which VacTH yields too large plasma in the upper part. $n_{\mathrm{p}} = n_{\mathrm{q}} = 4$ is used in this case as these values are minimum for reasonable VacTH results, while higher values are too sensitive to the input noise. Expectedly, EFIT++ reconstruction with magnetic data only cannot reliably reconstruct kinetic plasma parameters, such as the stored energy or q_0. Rather unexpected is a relatively good agreement of l_{i}. However, this agreement is compensated by a large error of β_{p} so that the quantity $\beta_{\mathrm{p}} + l_{\mathrm{i}}/2$ remain within a 10 % error bar.

References

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code	time	ΔR_{in}	ΔR_{out}	ΔZ_{min}	ΔZ_{max}	$\delta\kappa$	$E_{\rm mp}$	$E_{\rm fl}$	δW	$\delta l_{\rm i}$	$\delta\beta_{\rm p}$	δq_0	δq_{95}
EFIT++	0.97	0	0.002	0.001	0.001	0.003	0.001	0.0009	0.04	0.09	0.03	0.03	0.007
EFIT++	0.99	4e-05	9e-05	0.001	0.001	0.004	0.001	0.0006	0.04	0.09	0.04	0.02	0.005
EFIT++	1.02	0.0005	0.0002	0.002	0.002	0.008	0.002	0.002	0.02	0.1	0.02	0.02	0.009
EFIT++	1.05	0.001	0.0008	4e-05	0.0003	0.004	0.003	0.005	0.01	0.07	0.02	0.01	0.009
EFIT++	1.1	0.001	0.0005	0.005	0.0002	0.005	0.004	0.002	0.04	0.09	0.03	0.02	0.05
VacTH	0.97	0	0.001	0.0006	0.0002	0.002	8e-07	7e-05	–	–	–	–	–
VacTH	0.99	4e-05	0.0004	0.001	0.0008	0.004	4e-07	0.0001	–	–	–	–	–
VacTH	1.02	0.002	0.0008	0.005	0.002	0.01	2e-06	0.002	–	–	–	–	–
VacTH	1.05	0.006	0.002	5e-05	0.002	0.01	3e-06	0.02	–	–	–	–	–
VacTH	1.1	0.005	0.002	0.002	0.003	0.02	2e-06	0.003	–	–	–	–	–

Table 1: Errors for the same cases as in Fig. 1.

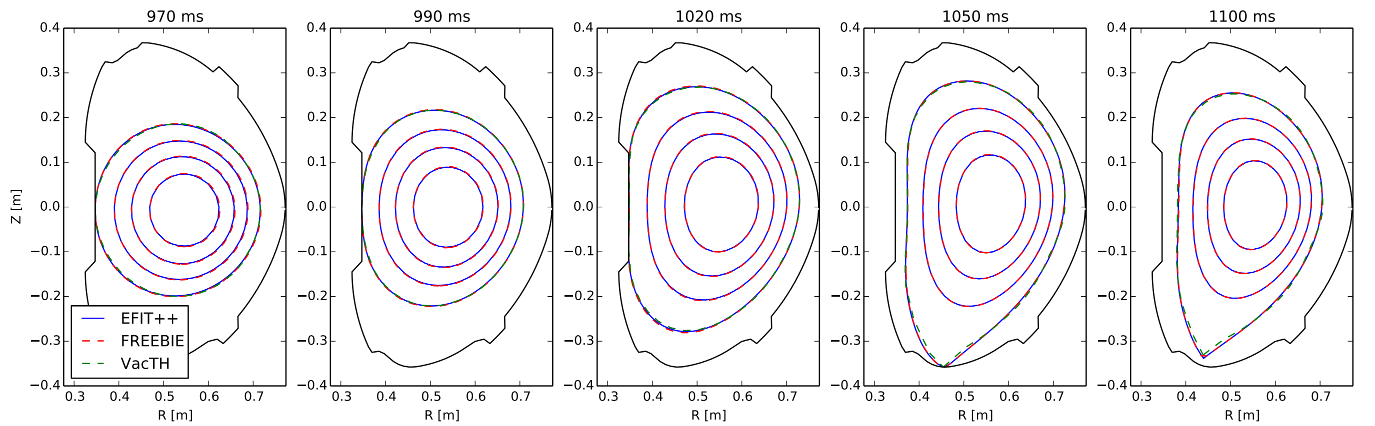

Figure 1: Contours of $\bar{\psi} = (0.25, 0.5, 0.75, 1)$, reconstruction from FREEBIE data, shot 4275. EFIT++ parameters: $n_{\rm mp} = 16$, $n_{\rm fl} = 4$, $n_{p'} = n_{FF'} = 1$. VacTH parameters: $n_{\rm mp} = 8$, $n_{\rm fl} = 16$, $n_{\rm p} = n_{\rm q} = 5$.

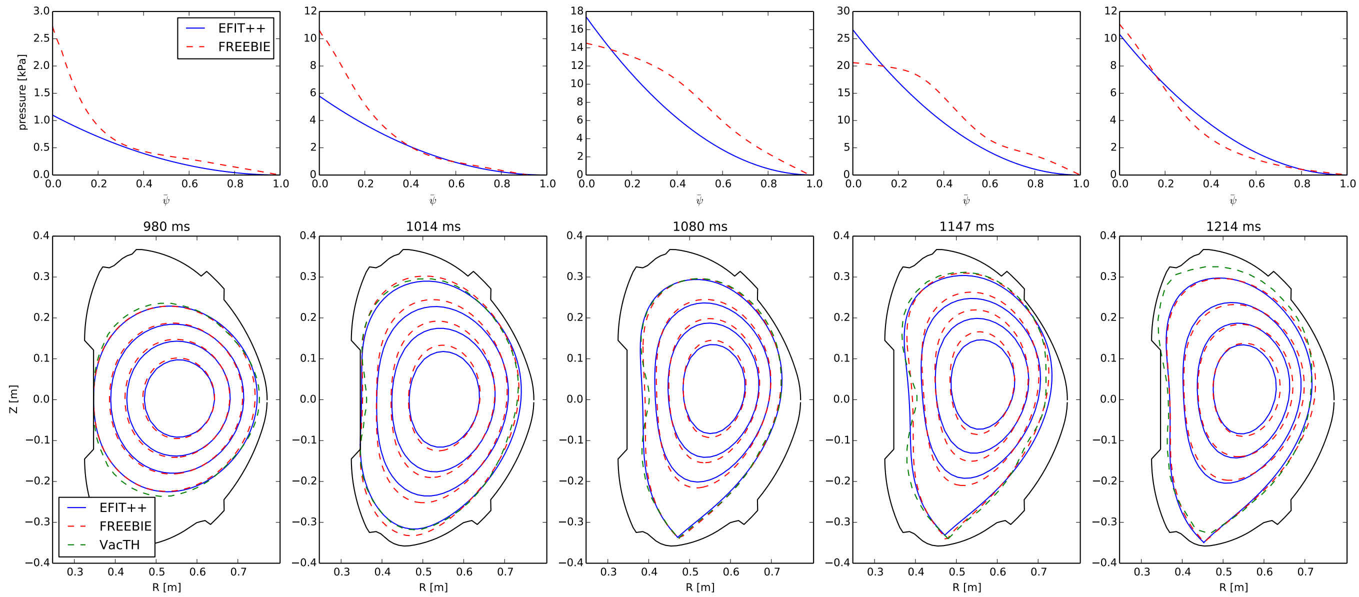

Figure 2: Pressure profiles and contours of $\bar{\psi} = (0.25, 0.5, 0.75, 1)$, reconstruction from FREEBIE data, shot 6962 with Thomson scattering pressure profiles. EFIT++ parameters: $n_{\rm mp} = 16$, $n_{\rm fl} = 4$, $n_{p'} = n_{FF'} = 1$. VacTH parameters: $n_{\rm mp} = 8$, $n_{\rm fl} = 16$, $n_{\rm p} = n_{\rm q} = 4$.

code	time	ΔR_{in}	ΔR_{out}	ΔZ_{min}	ΔZ_{max}	$\delta\kappa$	E_{mp}	E_{fl}	δW	δl_{i}	$\delta\beta_{\mathrm{p}}$	δq_0	δq_{95}
EFIT++	980	0	0.005	0.001	8e-06	0.01	0.01	0.01	0.4	0.03	0.4	0.2	0.0008
EFIT++	1014	0.003	0.006	0.02	0.01	0.06	0.03	0.03	0.3	0.008	0.3	0.2	0.08
EFIT++	1080	0.007	0.002	0.005	0.002	0.04	0.03	0.03	0.3	0.01	0.3	0.2	0.02
EFIT++	1147	0.008	0.008	0.01	0.006	0.06	0.03	0.02	0.3	0.06	0.3	0.3	0.05
EFIT++	1214	0.0002	0.008	0.002	0.001	0.02	0.02	0.01	0.04	0.2	0.06	0.1	0.01
VacTH	980	0	0.01	0.01	0.007	0.02	0.0001	0.01	–	–	–	–	–
VacTH	1014	0.006	0.0002	0.01	0.007	0.03	3e-05	0.01	–	–	–	–	–
VacTH	1080	0.009	0.0007	0.003	0.0007	0.02	3e-05	0.01	–	–	–	–	–
VacTH	1147	0.02	0.007	0.0009	0.002	0.01	5e-05	0.01	–	–	–	–	–
VacTH	1214	0.03	0.009	0.02	0.03	0.02	0.0002	0.02	–	–	–	–	–

Table 2: Errors for the same cases as in Fig. 2.