UKAEA-CCFE-CP(23)30

G. Szepesi, L.C. Appel, E. de la Luna, L. Frassinetti,
P. Gaudio, M. Gelfusa, S. Gerasimov, N.C. Hawkes,
M. Sertoli, D. Terranova

Advanced equilibrium reconstruction for JET with EFIT++

Advanced equilibrium reconstruction for JET with EFIT++

G. Szepesi, L.C. Appel, E. de la Luna, L. Frassinetti, P. Gaudio, M. Gelfusa, S. Gerasimov, N.C. Hawkes, M. Sertoli, D. Terranova

This paper has been submitted to
47th EPS Plasma Physics Virtual Conference, 21-25 June 2021

Advanced equilibrium reconstruction for JET with EFIT++

G. Szepesi[1], L.C. Appel[1], E. de la Luna[1,2], L. Frassinetti[3], P. Gaudio[4], M. Gelfusa[4], S. Gerasimov[1], N.C. Hawkes[1], M. Sertoli[1], D. Terranova[5] and JET contributors*

[1] *CCFE, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[2] *Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain*
[3] *KTH Royal Institute of Technology, SE-100 44 Stockholm, Sweden*
[4] *Department of Industrial Engineering, University of Rome "Tor Vergata", via del Politecnico 1, Rome, Italy*
[5] *Consorzio RFX, Corso Stati Uniti, 4, 35127 Padova, Italy*
(*) 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 reports from the 28th Fusion Energy Conference (Nice, France, held remotely, 10-15 May 2021)

Introduction

Many of the essential data analysis procedures for a tokamak experiment rely on the knowledge of the magnetic field structure obtained from MHD force balance. On JET, the code that is responsible for computing the magnetic equilibrium is called EFIT++ [1,2,3]. Interpretation of JET data has been challenging due to inconsistencies between diagnostic measurements and properties of the computed equilibrium (such as the separatrix, strike point and magnetic axis positions) [4,5]. In a recent code update, the most dominant discrepancy has been resolved, and a robust, automatic reconstruction mode, labelled as EFTP, has been enabled as part of the intershot analysis chain. This paper provides details of this successful run mode, its validation procedure and limitations.

A crucial improvement has been achieved by reviewing the calibration factors of the magnetic diagnostic system, especially of four poloidal field pick-up probes following their replacement. The input magnetic data has been extended to include all available measurements around the tokamak. The numerical representation of the flux functions p' and ff' have been adjusted so that the EFIT algorithm is able to find an equilibrium that is consistent with the estimated input pressure profiles both in the core and the pedestal. The results have been validated against the High- Resolution Thomson Scattering (HRTS) and Electron Cyclotron Emission (ECE) measurements of the electron temperature profiles, showing good agreement with the expected location of the magnetic separatrix at the midplane, and symmetry of the profiles around the magnetic axis. Infra-red (IR) camera images of the divertor show good agreement with the computed strike point locations.

Inconsistency between equilibrium and Thomson scattering measurements

One of the notable observations regarding the limitations of the standard automatic intershot equilibrium reconstruction for JET has been that the computed location of the last closed flux surface (LCFS) is systematically and significantly outside of the foot of the temperature pedestal (by up to ~5cm). Moreover, the discrepancy also shows a strong variation between experimental campaigns (fig. 1. A). The location of the pedestal foot was approximated with the 100eV temperature point from fits to the HRTS) measurements. This estimate comes from the two-point model of the parallel heat flux in the scrape-off-layer of JET H-mode plasmas [6].

The equilibria for fig. 1 were produced with the intershot version of the free-boundary EFIT++ code using only magnetic signals as input. In the standard configuration, labelled as EFIT, only a subset of all the available magnetic measurements (deemed to provide sufficient poloidal coverage) is used in the equilibrium reconstruction. The numerical setup of this equilibrium run-mode is optimized for performance and robustness in terms of convergence, achieved by a simple 2nd degree polynomial representation of the flux functions p' and ff'. However, this representation does not have the flexibility to fit the H-mode pressure pedestal, and typically also leads to an overestimated core pressure (fig. 1. B).

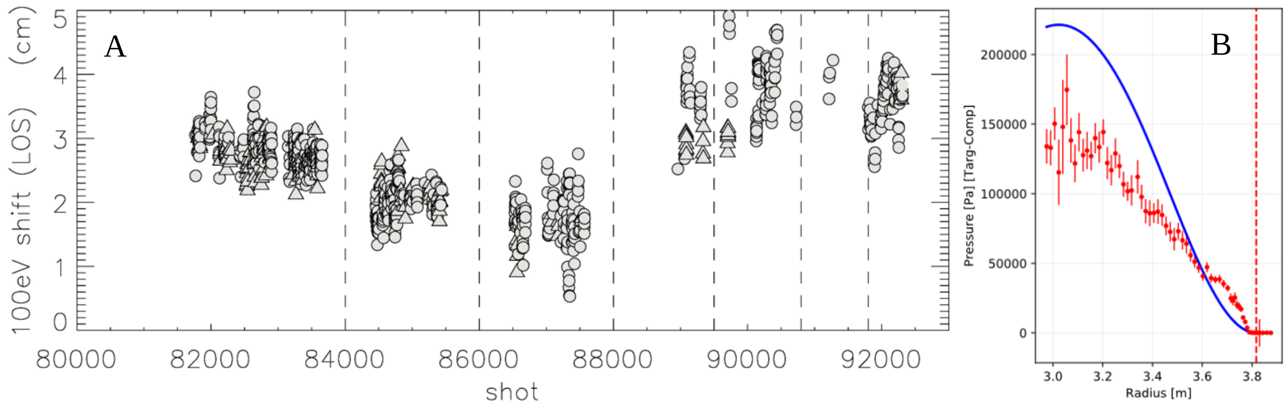

*Figure 1: **A.)** Discrepancy between the computed LCFS location with the intershot equilibrium and the measured pedestal foot (100eV location) on the HRTS line-of-sight across several JET campaigns. **B.)** Example of a computed pressure profile (blue) compared to "measured" pressure (red) in a standard magnetics only equilibrium, and a ~3cm gap between the separatrix (dashed) and the pressure pedestal foot.*

In order to remedy the above shortcomings, a new equilibrium run-mode, called EFTP, has been developed including two major changes: i.) the addition of a pressure constraint with appropriate numerical settings and ii.) review of the magnetic input data.

Pressure constraint and numerical configuration

The target for the pressure constraint is constructed from HRTS electron density and temperature profiles as well as NBI fast ion pressure from the PENCIL code by default, assuming $T_i=T_e$ and $Z_{eff}=1$. EFIT++ has recently been upgraded with an extensive data preparation layer written in Python. The simplifying assumptions used in the default pressure target are intended for intershot operation, but the data preparation code is capable of setting up more advanced cases if ion charge exchange data, ICRH modelling with PION or TRANSP analysis is available for a pulse.

The numerical configuration of the flux functions has been adjusted to enable the algorithm to fit the target pressure accurately. Both p' and ff' are represented with tension splines with a sufficiently dense knot point placement in the pedestal region. The selected knot point locations in terms of normalized poloidal flux are: 0.0, 0.2, 0.4, 0.6, 0.8, 0.9, 0.95, 0.98, 1.00. The splines are subject to a weak regularization acting on the second derivative of the flux functions, linking each set of three neighbouring knot-point values (a_i) with the following relational constraint equation: $-a_{i-1} + 2a_i - a_{i+1} = 0$. In effect, this provides spatial smoothing for the flux functions. EFIT++ solves a χ^2 minimization problem to find the best overall match with the measured signals as well as with the numerical constraints. The weight of the relational constraint in this algorithm is set to a low value of 0.0001 by default (compared to 1 used for the diagnostic constraints). Higher weights lead to smoother solutions and better convergence but a reduced level of agreement with the diagnostic constraints. Lower weights allow more variation of the flux functions and therefore better agreement with diagnostics but can lead to physically unlikely profile features and tend to reduce convergence. Finally, the flux functions are allowed to have a finite value (i.e., non-zero current) on the separatrix which was found to be essential to achieve an accurate pressure fit in the pedestal region.

It should be noted that the numerical setup used for the pressure constrained runs are not suitable for magnetics-only reconstructions: due to the higher degree of freedom on the flux functions the algorithm can converge to unphysical solutions (e.g., strongly hollow central pressure) without an appropriate fitting target.

It should also be noted that equilibrium reconstructions with internal constraints (pressure, polarimetry and MSE) have been routinely made for JET with a different version of the EFIT code. However, these runs are made with less emphasis on accurately fitting the pressure pedestal, while the goal of the EFTP run-mode is to fit the pressure well across the whole profile.

Review of magnetic processing and input magnetic signals

The magnetic input data to EFIT++ have been reviewed and two changes were introduced for the advanced reconstructions: i.) the calibration factors of four poloidal field pick-up probes were updated and ii.) all available magnetic measurements were enabled. The magnetics processing code has been rewritten in Python to allow the implementation of the above improvements.

It has been found that four of the poloidal field pick-up probes on the low-field-side (LFS) limiter had additional calibration factors (on top of their bench-calibration) that were introduced to maintain backward compatibility following hardware changes. Several of these probes got damaged (typically due to disruptions) and eventually replaced during the shutdown between campaigns 34-35. This coincides with the large change in the LCFS-pedestal foot discrepancy shown in fig. 1 (around pulse 88000). It has been decided that the extra calibration factors should be removed for the improved equilibrium reconstruction. These four probes are part of the array that is nearest to the plasma (poloidal limiter coils), therefore this change had a large impact on the LCFS location near the midplane, moving it substantially inwards.

The standard intershot magnetics only equilibrium uses a subset of all the available magnetic sensor signals. This limitation is in fact imposed by the legacy magnetics processing code, magn_ep. A new version of this code, called magn_py, has been developed to enable the uniform processing of all available signals. It also tests the status of every magnetic sensor for each pulse to disable incorrect signals in the reconstruction. Although many of the additional magnetic signals (compared to the legacy mode) are not increasing the poloidal coverage (i.e., they are at the same poloidal location as other previously included probes but in a different toroidal segment), this change still had a significant impact on the LCFS location near the midplane.

Validation of the EFTP run-mode

The new EFTP equilibrium run-mode, including a pressure constraint as well as the updated magnetic configuration, has been validated by three external tests: i.) comparison of the LCFS location to the 100eV point on the HRTS LOS in the JETPEAK database [7], ii.) checking the symmetry of the ECE profiles and iii.) comparison of the computed strike point locations to the IR camera images of the divertor.

The JETPEAK database (at the time this test was done) consisted of ~1000 JET H-mode baseline pulses during the high-power phase. The discrepancy between the LCFS and the pedestal foot in this database has been significantly reduced by EFTP compared to the standard EFIT equilibrium (fig. 2. A): the time-averaged difference is within 1cm for the most pulses, and the largest variation between C34 and 35 has been reduced. This improvement is dominantly due to the reviewed magnetic setup. The remaining variation between the campaigns is still under investigation.

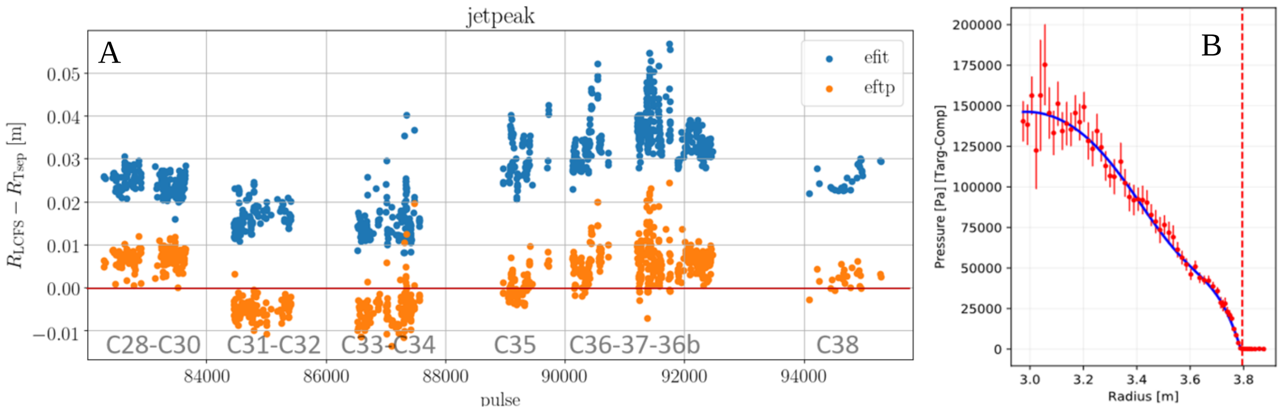

*Figure 2: **A.)** Discrepancy between the computed LCFS location and the measured pedestal foot (100eV location) on the HRTS line-of-sight in the JETPEAK database. Blue: standard intershot equilibria with legacy magnetics (EFIT). Orange: pressure constrained equilibria with reviewed magnetics (EFTP). **B.)** Example of a computed pressure profile (blue) compared to "measured" pressure (red) with EFTP.*

The target pressure is accurately fitted (fig. 2. B), and the electron temperature profiles obtained from ECE with the KK3 diagnostic are more symmetric around the magnetic axis computed by EFTP (fig 3. A), even in a high beta scenario.

EFTP also improves the agreement between the computed and measured strike point locations (fig. 3. B): the discrepancy is reduced from ~2cm in the magnetics only runs to near zero, although the lower extreme of the strike point sweeping is clearly not captured by the equilibrium. The change of the strike point location is not caused by the reviewed magnetic configuration, but either by the pressure constraint or the changes in the numerical setup (e.g., finite edge current).

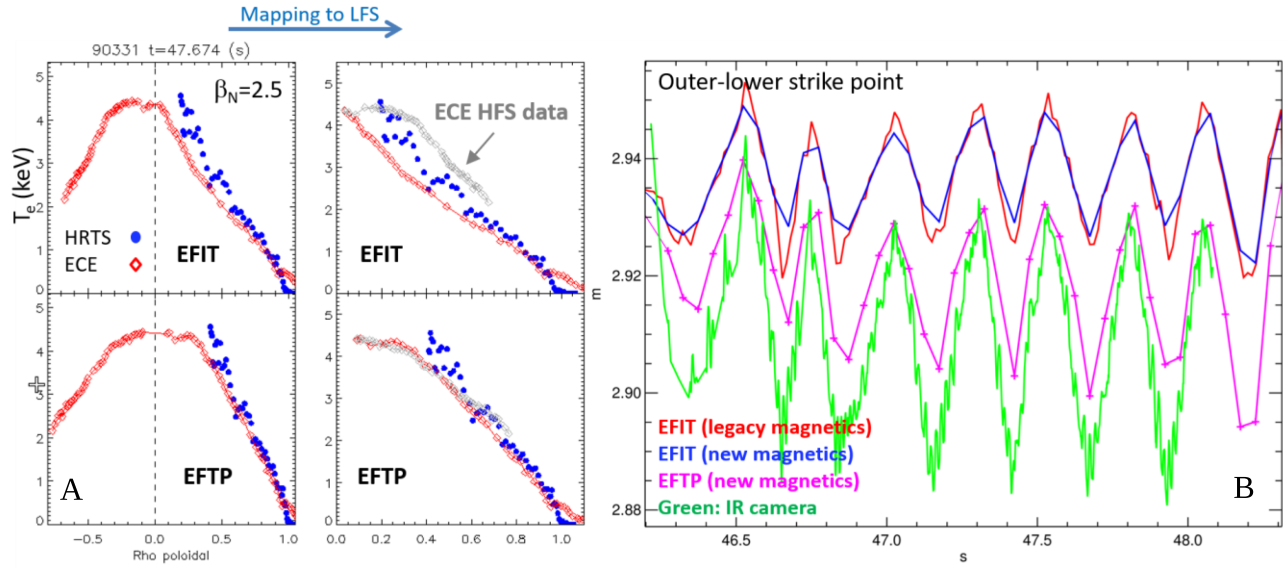

Figure 3: A.) Mapping of the ECE electron temperature profile from high-field-side to low-field-side with EFIT or EFTP equilibria. B.) Computed and measured major radius of the outer lower strike point.

Summary, limitations and outlook

A new pressure constrained equilibrium reconstruction has been released for JET that provides good fit to the whole pressure profile, resolves a long-standing issue with the inconsistent LCFS location, improves agreement with the IR strike point measurements and the symmetry of ECE profiles. As a result, EFTP is typically the preferred equilibrium for flux surface mappings. A converged solution has been found for over 90% of the total time slices in the JETPEAK analysis, making this run-mode sufficiently robust for automatized intershot operation. It does not replace the standard EFIT run as a fast reconstruction is still required early in intershot analysis chain.

However, the default method in EFTP for computing the target pressure is not accurate during high power plasma phases. The pressure model is limited by data availability during intershot analysis and can be improved for subsequent runs. Nonetheless, this can cause issues in applications when more precise knowledge of the magnetic axis location is essential, such as for heating models. It has also been observed that the computed q-profile in EFTP is often not in close agreement with the MHD markers, such as the sawteeth inversion radius. This is attributed to the lack of diagnostic information on the ff' flux function and can be significantly improved by constraining the q-profile with pitch-angle data from the Motional Stark Effect (MSE) diagnostic. Intensive work is going on to achieve similar results with the line-integrated polarimetry data which is more routinely available.

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053 and from the RCUK Energy Programme [EP/T012250/1]. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

[1] L Lao et al., Nuclear Fusion, vol. 25, no. 11 (1985)
[2] L Appel et al., 33rd EPS Conference, Rome, 2006, P2.184
[3] L Appel et al., Comp. Phys. Comm. 223 (2018) 1–17
[4] M Gelfusa et al., Rev. Sci. Instrum. 84, 103508 (2013)
[5] M Brix at al., Rev. Sci. Instrum. 79, 10F325 (2008)
[6] R Goldston, Nuclear Fusion 52, 013009 (2012)
[7] P. Sirén *et al* 2019 *JINST* 14 C11013