The Tokamak Exhaust Designer: a new tool for enhanced divertor control on MAST-U

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Introduction

Exhaust physics experiments are the flagship of the MAST-U research program [1], facilitated by an extensive poloidal field (PF) coilset and baffled divertor chambers. A key enabler thereof is robust, flexible, intuitive control over the divertor magnetic geometry. This contribution describes the development, implementation, and testing of a new scenario development tool, the Tokamak Exhaust Designer (TED), and its exploitation off-line and inter-shot to accelerate the creation and control of a wide range of divertor magnetic geometries throughout the 2024/5 campaign.

Methods

The method implemented in TED is based on the vacuum spherical harmonic (SH) constraints introduced in [2]. Keeping the vacuum field over the core plasma chamber – expanded as four SH basis functions – fixed as the PF currents change, the core plasma shape is held constant without need to iterate the Grad-Shafranov equation for plasma equilibrium. These SH constraints are linear in the PF currents, meaning the optimization is reduced to the linear least squares problem $\min_{\boldsymbol{I}} \|\boldsymbol{W}(\boldsymbol{I}-\bar{\boldsymbol{I}})\|_2^2$, subject to $G_{SH}\boldsymbol{I} = \boldsymbol{c}_{SH}$, $G_{div}\boldsymbol{I} = \boldsymbol{c}_{div}$, $\boldsymbol{I}_{min} \leq \boldsymbol{I} \leq \boldsymbol{I}_{max}$, and $M_{fixed}\boldsymbol{I} = \boldsymbol{I}_{nom}$, where $\boldsymbol{I}$ is the vector of PF currents, $\bar{\boldsymbol{I}}$ is a set of reference currents (either the 'nominal' currents $\boldsymbol{I}_{nom}$, or $\boldsymbol{0}$), $\boldsymbol{W}$ is a diagonal matrix of PF weights, G_{SH} is the matrix from PF currents to SHs, $\boldsymbol{c}_{SH}$ contains the reference equilibrium SHs, G_{div} and $\boldsymbol{c}_{div}$ implement divertor geometry constraints, $\boldsymbol{I}_{min/max}$ are PF current limits, and M_{fixed} is used to fix some currents to their nominal value. TED is simply a set of MATLAB objects which allow a user to configure this problem to their needs, which can be run through scripts, but far more often through the intuitive Graphical User Interface (GUI) shown in Figure 1. Users get instant feedback on the success – or equally importantly, failure – of a particular input because the optimization is extremely fast and robust. The palette of divertor constraints, all applied at specific point(s), are: (normalized) flux, iso-flux, poloidal field ($\boldsymbol{B}_p$)

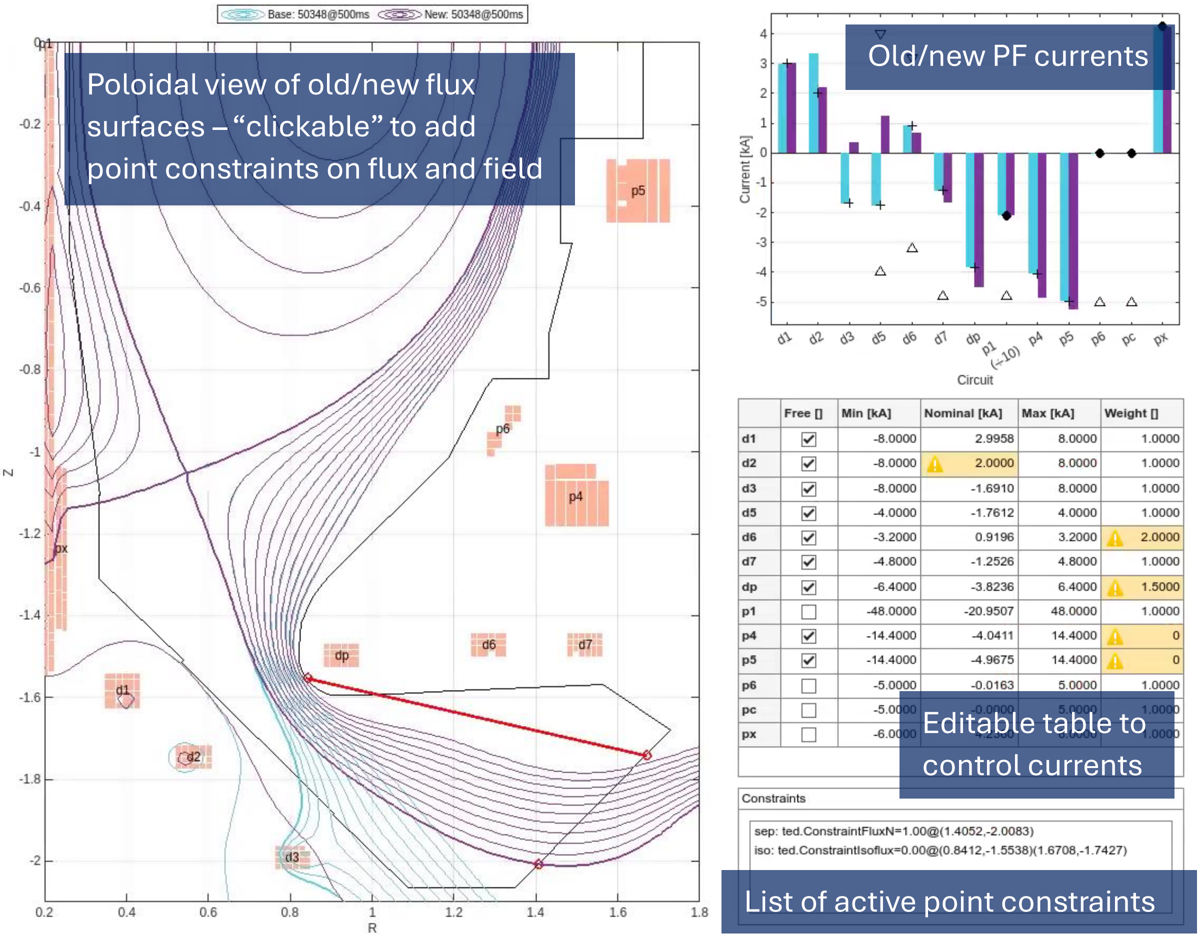

Figure 1: Screenshot of TED GUI with panels labelled. Interactive control over divertor geometry and PF current distribution is made accessible, fast, and robust.

components, $\boldsymbol{B}_p$ direction, and flat field ($\boldsymbol{\nabla B}_p = 0$), which has proved sufficient for all divertor design objectives. Note how the optimization objective is purely related to the PF currents, and not a closeness-of-fit to a set of control points as would be typical for an inverse equilibrium solve [3][4][5], meaning very little expertise is required to use TED, and it becomes possible to deploy on an inter-shot timescale.

Results

The main application of TED in the 2024/5 campaign has been “divertor design”: making large changes such as going from conventional to super-X geometries. This can typically be done with feed-forward application of a PF current change in just one shot. Commissioning this capability involved using TED to create various divertor geometries, starting from a 750kA Ohmic plasma with conventional divertor as reference – see Figure 2. Excellent agreement is found between TED designs and experimental outcomes across a range of divertor geometries, with differences mainly due to induced passive currents or variation in plasma current distribution, which are easily corrected using feedback control. Upon moving to operational exploitation, TED has been successfully applied to a broad range of MAST-U

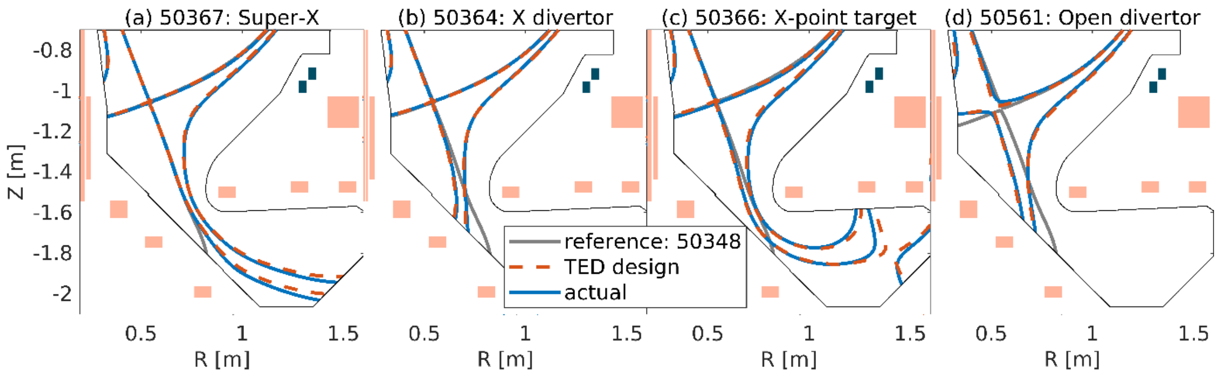

Figure 2: Example divertor geometries designed using TED, compared to experimental realization in feed-forward.

core plasma configurations, including NBI-heated L- and H-modes, single-null, and at various plasma currents.

Physics operators can also use TED to create virtual actuators (sets of PF current weights) for minor changes to any aspect of the divertor geometry (strike point, flux expansion, etc.), to be used in feedforward or feedback. We give an example which exploits a new feedback control capability on MAST-U for divertor closure, as measured by the radius of the separatrix at the “throat” (intersection with pink line in Figure 3). This is estimated in real-time with the LEMUR reconstruction algorithm [6], and feedback controlled using an actuation direction designed in TED which is specifically intended to keep the strike point fixed. Figure 3 shows experimentally measured step responses, with a settling time of <50ms and no visible perturbation to core plasma shape (volume as proxy) or strike point. TED has also been used to design strike point controllers in both conventional and super-X geometries.

Discussion

TED has become the default tool for divertor control in the 2024/5 MAST-U experimental campaign. Fundamental to its success has been the fast, robust underlying method with no internal parameter tuning required, and proven reliability in translating from simulation to reality. However, the key to achieving widespread use of the tool amongst physics operators was creation of an intuitive GUI with suitable design flexibility over both geometry and PF currents, which is interoperable with the plasma control system because the virtual actuators it produces are suitably normalised for feed-forward or feedback control.

The underlying method, using vacuum harmonic constraints, lends itself to exciting further applications in tokamak equilibria. For example, optimal and model-predictive divertor control subject to linear constraints which fix core plasma and account for the contribution of induced passive currents as well as PF voltage limits. Furthermore, rapid optimisation of PF coil locations for future tokamaks is possible, by enforcing non-linear (but

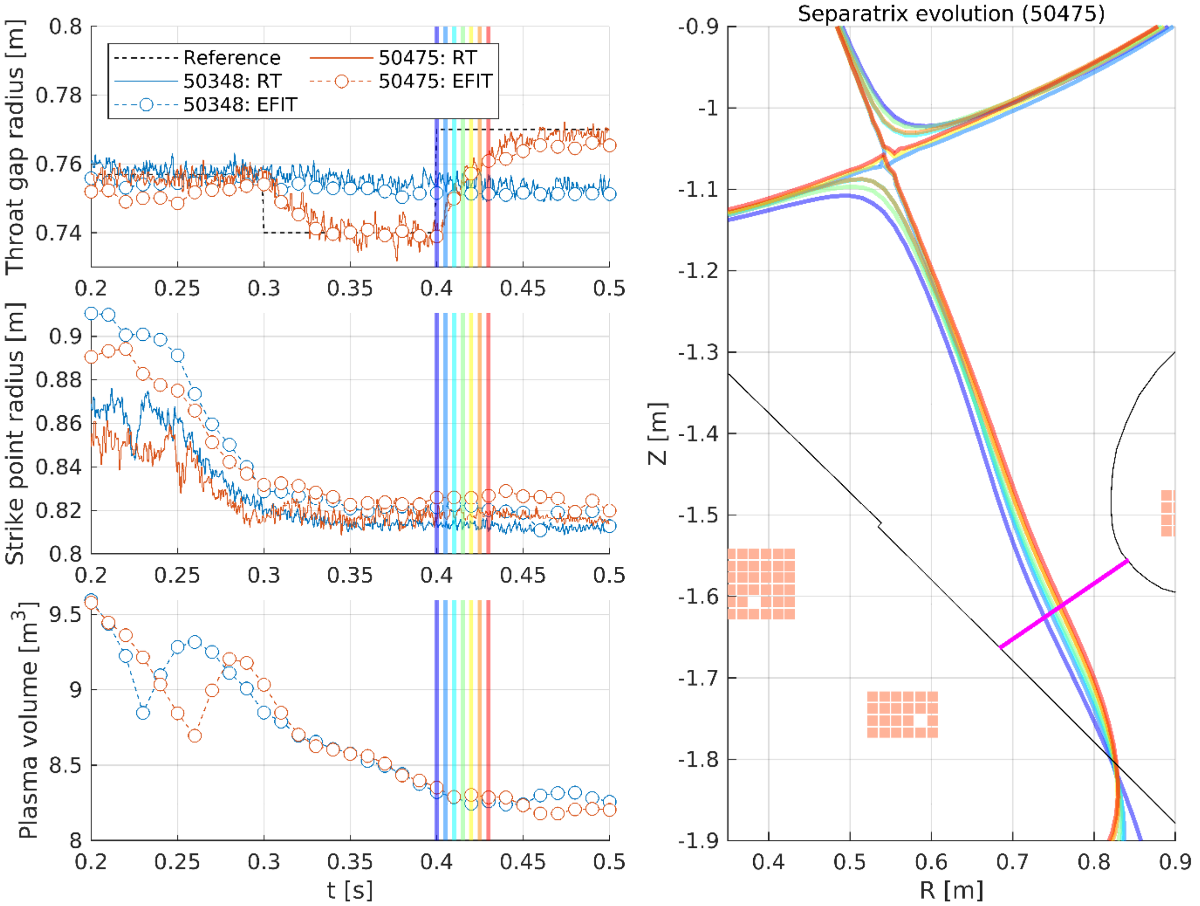

Figure 3: Feedback control of divertor closure ("throat gap radius" = R co-ordinate of intersection between separatrix and pink line, reconstructed in real-time (RT) with LEMUR [6]) using a TED-designed virtual actuator which keeps strike point fixed. A 2cm inwards step at 0.3s and 3cm outwards step at 0.4s are requested in shot 50475 vs the reference 50348. Separatrices on the right pane correspond to times marked with vertical lines in left pane. Plasma volume used as proxy for core shape.

still easily implemented) constraints which are functions of coil positions as well as currents. Furthermore, translation to conventional aspect ratio tokamaks can be achieved by employing toroidal (rather than spherical) vacuum harmonics.

In summary, TED has revolutionized control of the MAST-U divertor by restricting the problem domain to changes with fixed core shape, then wrapping a fast, robust underlying solution method into an accessible, practical GUI.

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