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A SysML Model of the Tokamak Subsystems involved in a DEMO pulse.

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A model has been developed using the systems modelling language, SysML™ to provide a mechanism for analysing the inherent complexity of Tokamak subsystem modes of operation during specific Tokamak states on DEMO. By capturing the attributes and functions of the various subsystems for each substate during a DEMO pulse the model is able to illustrate, using a series of diagrams, how various subsystems are composed along with aspects of subsystem generalisation and specialisation. It can also provide details of tokamak behaviour during a pulse using a state machine. In future the model will be expanded to give details about the state transition criteria, an examination of additional (contingency) cases and will be expanded to contain additional subsystems.

Keywords: System engineering, system modelling, SysML

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1. Introduction

A project on the scale of DEMO requires a formal systems engineering approach. Mapping the interfaces, dependencies and relationships between subsystems permits an understanding of a conceptual design from a set of complementary and consistent perspectives. It also helps to prevent clashes and incompatibility between subsystems at a later stage of engineering design.

The first stage of this work has focussed on the DEMO Plasma Operation State (POS), where the tokamak executes a pulse sequence (shown schematically in Fig. 1). The pulse sequence has been analysed as a series of substates from pre-pulse through to post-pulse dwell and for each of the substates within the POS, information gained from experience on JET has been used to create a matrix detailing which subsystems will be active. This involves attempting to define, characterise and, if possible, quantify the salient attributes and functions for each required subsystem.

For instance, while the TF system will remain on and at constant current throughout a pulse sequence, the PF system will only commence operation in the pre-pulse substate with the function (amongst possible others) of charging the solenoid. These functions will be associated with a matrix which will contain the attributes of the current waveforms in each of the poloidal shaping coils and the central solenoid. For each subsequent substate, the associated functions of the PF, such as ramping the solenoid current during the plasma initiation substate and shaping the plasma once established in subsequent substates, will each be associated with their own attribute matrices.

This process has been repeated for several proposed sub-systems on DEMO which have analogues on JET, and the resulting information has been incorporated into a model using the Object Management Group Systems Modelling Language, OMG SysML™ [1]. This forms part of a broader Based Systems Engineering (MBSE) activity within the DEMO WPPMI.

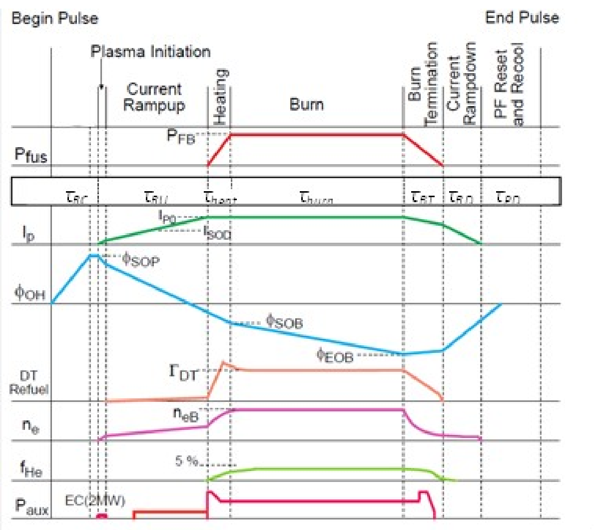

Fig. 1.Schematic showing sequence of events in a plasma pulse. Parameters**:** Ip: Plasma Current; Φ_{OH}: Ohmic Heating Flux; n_e: Electron Density; f_{He}: Helium fraction; P_{aux}: Power for auxiliary heating; P_{fus}: Fusion Power

Times / Events:

RC: Recharge Coil; RU: Ramp Up: BT: Burn Termination; RD: Ramp Down; PD: Pump Down; SOP: Start of Pulse; SOB: Start of Burn; EOB: End of Burn

2. The Tokamak Model

2.1 Definitions.

The model is an abstraction, or logical construct, that allows modelling specific features of interest. Here, several diagrams serve to illustrate a number of different perspectives, or views.

This section provides a snapshot in time of this model to facilitate understanding of the Tokamak subsystem modes and states from a number of different perspectives. It should be borne in mind that this is very much on ongoing investigation, and that the modelling approach offers a flexible foundation for further analysis in this field. The following definitions should be borne in mind (see also [2]):

A *Property* is a specific feature of a system (or subsystem) that can take on different values and is represented by a noun.

A *Mode of Operation* shows what a system (or subsystem) does and is represented by a verb. (Modes of Operation have associated goals and outcomes.)

Parameters may be used to describe Properties that relate specifically to the Mode of Operation.

A *Function* is linked to a Mode of Operation to describe associated behaviour, and must occur within one or more system (Tokamak) states, where associated parameter values are consumed or modified during operations.

2.2 Tokamak Composition.

A Tokamak Composition Diagram (Fig. 2) is a structural diagram showing the Composition of the Tokamak in terms of composition (symbol **---◆**) and specialisation (symbol **◀----**). Note in particular that for example the Gas Injection and Pellet Injection subsystems are both of the general type Fuel Injection subsystem. This is a useful abstraction in modelling and exploited when describing subsystem behaviours and data (see also [3]).

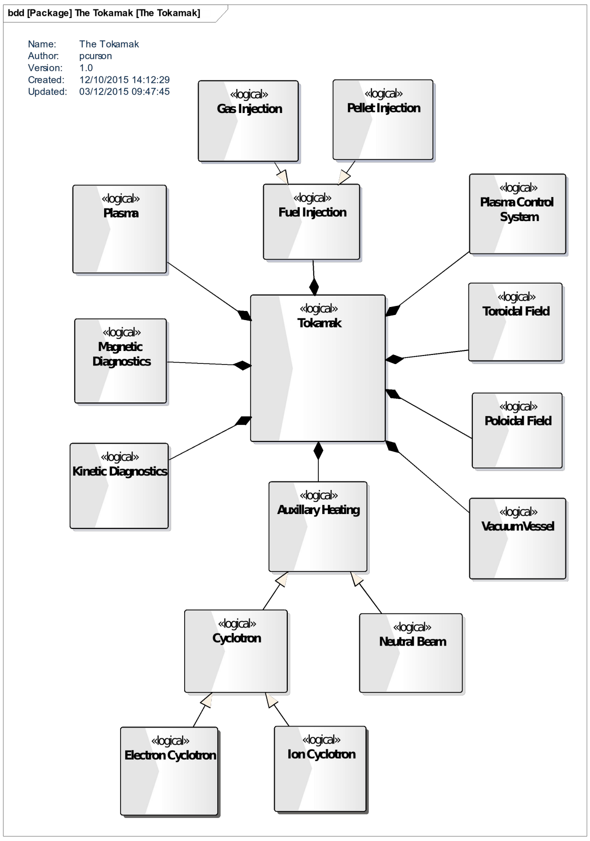

Fig. 2. Tokamak Composition Diagram

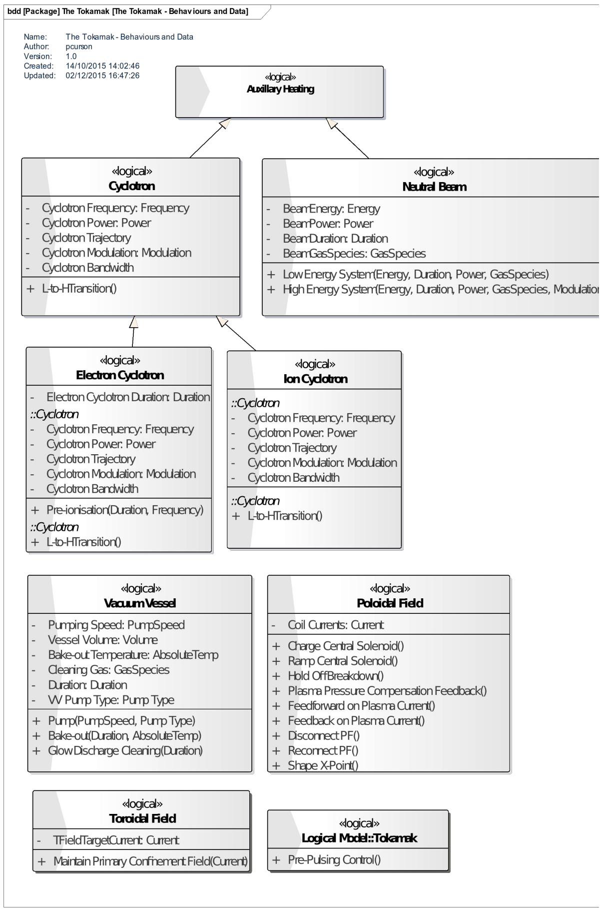

Fig. 3. Tokamak Subsystems and Behaviours

2.3 Tokamak Subsystems Methods and Data.

A Tokamak Subsystems and Behaviours diagram (Fig. 3) is another structural diagram showing each of the Tokamak subsystems. Each subsystem has attributes (row beneath the title), and methods. Most methods will have associated parameters. Note this is a static model; the actual behaviour manifest in use of the methods executed with specific parameter values requires another perspective (not yet analysed). Also, note the use of the generalisation relationship for the Cyclotron subsystem, which defines the method L-to-H transition, inherited by Electron and Ion Cyclotron subsystems.

2.4 Tokamak State Machine.

The Tokamak State Machine Diagram (Fig. 4) is a behaviour diagram showing the Tokamak states during a plasma pulse. The state transitions are only those applicable to a successful outcome, in that no disruptions, for example, have occurred. Note that, within each state, a 'do / <Function> ' is defined. These have not yet been further analysed, but are included here to illustrate that each state has associated with it a high-level function, i.e. each state is active in some way. In future work, these high-level functions shall be responsible for the overall behaviour during each state, and shall feature the low-level subsystem methods (modes)

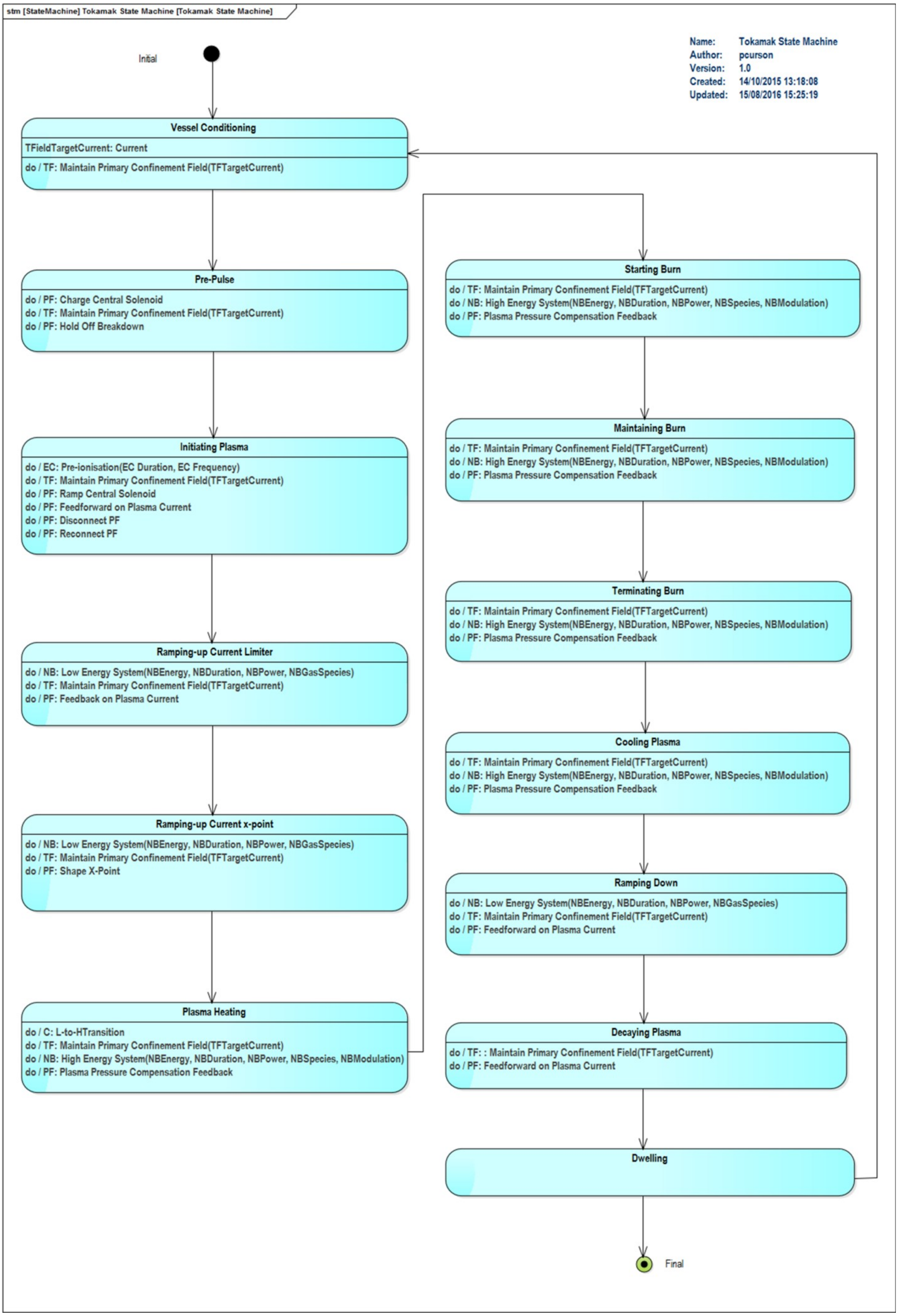

Fig. 4. Tokamak State Machine Diagram.

3. Summary and Future Work

The Tokamak SysML model provides a mechanism for analysing the inherent complexity of Tokamak subsystem modes of operation during specific Tokamak states on DEMO.

The model makes explicit the types of data, and the relationships between these types of data, also offering a mechanism for presenting particular views of interest, based on this underlying data. It captures information which can be scrutinised now for completeness and conflicts and will be a (the) reference for successive engineers and scientists over the next 20+ years.

The work so far has created a partial model describing Tokamak composition, state machine (changes that may occur in logical time), subsystem modes and associated data. Going forward, a view should be developed for the dynamic aspects of the system, covering, where possible:

- The specification of specific run-time values for the data associated with each mode.
- Exploring how, for a given Tokamak state, the modes of each of the subsystems collaborate, or run alongside each other.
- How the transitions occur between each of the Tokamak states.

Although the scope of work so far has been limited to describing Tokamak composition, Modes of Operation, and state behaviour (for successful transitions) during the high-level POS, future work for the POS should cover the specification of parameter values for each Mode of Operation, state transition criteria, and an examination of additional (contingency) cases. The model will also increase its breadth by extending to include other subsystems e.g. gas processing, balance of plant, breeder blanket etc. and will also be updated with experience from ITER.

The application of SysML modelling to the Tokamak States and Modes analysis has proved be a very effective method for capturing and encoding the key concepts involved, and highlighting where further work needs to be done.

Acknowledgments

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[2] https://www.researchgate.net/publication/269710922_On_a_Useful_Taxonomy_of_Phases_Modes_and_States_in_Systems_Engineering

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