# Enabling Research project: Predictive model for pedestals

**Abstract**

The project will develop a predictive model for the H-mode pedestal integrating MHD analysis of pedestal limiting instability, gyrokinetic modelling of pedestal microturbulence, two-fluid simulations of the ELM triggering and scrape-off layer modelling of fuelling and impurities. Together these components will form a model that can be used to predict pedestal properties of future tokamak devices such as ITER or DEMO and integrated into a global transport code for scenario optimisation. The planned main improvement from current pedestal prediction models include a more accurate determination of pedestal gradient limiting kinetic ballooning mode onset (e.g. including the influence of global effects and impurities); a study of any role for microtearing modes in pedestal development; extension of the ELITE MHD stability analysis to low toroidal mode numbers (with flow); self-consistent pedestal-core model; inclusion of non-ideal effects on pedestal stability; density and impurity model and assessment of fast ion effects on pedestal stability.

## Introduction and Background

The most common operating mode for tokamaks has been the so-called high confinement mode or H-mode since its discovery in the 1980s [1]. This is characterised by steep density and temperature gradients in a “pedestal” region near the plasma edge and good global plasma confinement. The global performance of the plasma is strongly correlated with the height of the pedestal, i.e. temperature and density at the top of the pedestal [2-4], and core transport modelling to predict fusion performance in ITER is highly sensitive to the pedestal properties [5]. It is therefore crucial to have a good understanding of the pedestal in order to develop optimised scenarios for futire fusion devices, including ITER.

In most experiments it has been observed that the pressure pedestal height is limited by so called Edge Localised Modes or ELMs, which are periodic eruptions of plasma originating from the pedestal region. The onset of ELMs in various tokamaks has been found to be associated with pedestal gradients (e.g. pressure and current density) being close to the ideal MHD stability limit for peeling-ballooning modes [6-10]. One simple model for the fully developed edge pedestal is to find the peeling-ballooning limit of the pedestal height (for an assumed width) in a given configuration, and this approach has been used in simple ELMy H-mode transport simulations [11]. The peeling-ballooning stability limit, however, is insufficient on its own as it provides only a single constraint on the pedestal height and width – specifically, a wider pedestal permits a higher pedestal height before the instability is triggered. A second constraint is needed in order to uniquely determine the pedestal height. Such a constraint was introduced by P. Snyder et al. [12] who used the experimentally observed dependency of the pedestal height and width, namely $∆\~\sqrt{β\_{p,ped}}$, where  is the width of the pedestal normalised to the plasma minor radius and p,ped is the ratio of the pedestal top pressure to the energy density stored in the poloidal magnetic field: pped/(Bp2/2μ0). This observed scaling of the pedestal width is consistent with the theoretical hypothesis that the pedestal gradient between ELMs is limited by the kinetic ballooning modes (KBM).

This so-called EPED model has been successfully tested for various tokamaks yielding predictions with an overall error of 20% [13]. However, although EPED provides a major advance in our predictive capability, there are some significant inconsistencies with certain trends observed in JET experiments. For example, in high triangularity baseline plasmas it was found that the pedestal width could grow by a factor of close to two through gas fuelling without a significant change in p,ped [14]. Hence, several aspects of the EPED model could be further developed to improve its predictive capability.

1. EPED assumes that the global  is an independent input parameter.As already noted, the core performance is strongly coupled to the pedestal properties [2], but also pedestal stability will be influenced by global beta (e.g. through its influence on local shear), and hence the core confinement. This complex interaction requires the pedestal and core models to be integrated to provide a self-consistent solution for performance .
2. The peeling-ballooning stability that lies at the heart of pedestal prediction can be affected by several factors that are usually ignored, eg. effects of scrape-off layer (SOL) currents and the exact form of diamagnetic stabilisation (noting that the diamagnetic frequency varies significantly across the pedestal). With the new ITER-like Wall on JET, and also experiments with a tungsten wall on AUG, it has been found that impurities have a significant impact on the pedestal structure and ELMs. Such impurities will dilute the plasma, lowering the ion density relative to that of the electrons, and directly influence the bootstrap current –- both of these effects will influence peeling-ballooning stability. Impurities will also likely influence the kinetic ballooning mode properties, and therefore pedestal transport processes – this has received very little attention. Fuelling can also influence the pedestal structure by modifying the ratio of the density to temperature gradient scale lengths, i,e – this will influence the diamagnetic stabilisation of peeling-ballooning modes, but also affect the stability of the KBM and micro-tearing modes. Our new model will take this (at least) dual role of the impurities into account, as well as explore the sensitivity to i,e.
3. Fast ions may play a role in the pedestal stability by changing the pedestal stability directly and modifying the equilibrium by diluting the thermal ion content. So far they have been ignored in the pedestal models.
4. The SOL plasma lies immediately outside the pedestal, and is characterised by magnetic field lines on open flux surfaces that connect to material target plates. Pedestal stability models rarely take account of the coupling between the pedestal and SOL, which is complicated by the change in magnetic topology and complex boundary conditions at the target plates. Fluid simulations with state of the art codes like JOREK[15] and BOUT++[16] can address this coupling and quantify the impact on pedestal stability and structure.
5. The peeling-ballooning stability codes currently have limitations for calculating the stability boundary both to low n-numbers, n=1-2 (relevant for low collisionality plasmas) as well as very high n-numbers, n>50 (relevant for high collisionality plasmas). The ELITE [17] MHD stability code will be improved to widen the n-number range from n=1 to n=100, as well as incorporating a model for plasma flows.
6. All current pedestal analyses assume that the edge current profile can be calculated using formulas derived from the neoclassical theory. The experimental measurement of the actual current profile in the pedestal region would give more confidence in using such formulas or give insight on the missing components in the theory.

Some aspects of this project are a continuation of previous projects or connected to other projects. The investigations of global gyrokinetic effects on the pedestal region were started in the 2014 project GKPIC (PI Laurent Villard). The JOREK code development in the proposed project by Mathias Hoelzl will be used in the ELM simulations of this project. The project is also part of the JET-PPPL collaboration of using XGC0 and XGC1 codes to study JET pedestals. The extension of ELITE to low n is part of an ongoing collaboration with General Atomics.

**References:**

[1] F Wagner et al, Physical Review Letters 49 (1982) 1408

[2] Beurskens M.N.A. et al. Nucl. Fusion 53 (2013) 013001

[3] Maggi C.F. et al Nucl. Fusion 47 (2007) 535

[4] Maggi C.F. et al Nucl. Fusion 50 (2010) 025023

[5] R V Budny et al, Nuclear Fusion 48 (2008) 075005

[6] Snyder P.B. et al Phys. Plasmas 12 (2005) 056115

[7] Huysmans G.T.A. Plasma Phys. Control. Fusion 47 (2005) B165

[8] Medvedev S. Yu. et al Plasma Phys. Control. Fusion 48 (2006) 927

[9] Saarelma S. et al Plasma Phys. Control. Fusion 49 (2007) 31

[10] Oyama N. et al Nucl. Fusion 45 (2005) 871

[11] Lönnroth J-S. et al Plasma Phys. Control. Fusion 46 (2004) 767

[12] Snyder P.B. et al Phys. Plasmas 16 (2009) 056118

[13] Snyder P.B. et al Nucl. Fusion 51 (2011) 103016

[14] Leyland M.J. et al Nucl. Fusion 53 (2013) 083028

[15] Huysmans G.T.A. et al Plasma Phys. Control. Fusion 51 (2009) 124012

[16] Dudson B.D. et al., Comput. Phys. Commun. 180 (2009),1467

[17] Wilson H.R., Snyder P.B., et al.,Phys. Plasmas 9 (2002) 1277

## Objectives

The project will contribute to building a comprehensive **predictive model for the tokamak pedestal**. The ultimate model should take as an input only so called engineering parameters, i.e. parameters that can be controlled during the tokamak operation, such as plasma shape, toroidal magnetic field, plasma current, heating power and fuelling. Using these constraints it should predict the pedestal height and width that are consistent with the peeling-ballooning stability limit and the pedestal gradients set by the turbulent and neoclassical transport. The boundary conditions, temperature and density at the separatrix, should be based on the scrape-off layer (SOL) modelling and the pedestal model should be integrated self-consistently with a model for the core performance.

The following elements that are lacking in current pedestal prediction models will be developed:

1. The pedestal gradient limiting kinetic ballooning mode (KBM) onset will be studied using global and local-global gyrokinetic approaches and compared with earlier local gyrokinetic and ideal MHD results.
2. The roles of impurities, density and temperature profiles and fast ions on the KBMs will be quantified.
3. The MHD stability codeELITE code will be extended to low-n modes to study pedestals at low collisionality. The effect of flow shear will be included.
4. We will investigate the 2-fluid effects, such as diamagnetic stabilisation, and the effects of scrape-off layer (SOL) profiles on the linear stability using non-linear fluid codes BOUT++ and JOREK.
5. We will use JOREK to study the physics of ELM triggering when the stability boundary is crossed by increasing self-consistent pressure gradient and bootstrap current. This will help to determine the relationship between the linear and non-linear stability limits.
6. We will develop a model for pedestal density and impurities by simulating JET plasmas using SOL fluid code EDGE2D and Monte-Carlo neutrals code EIRENE.
7. We will develop a simple core model that is self-consistent with the pedestal prediction.
8. We will quantify the effect of fast ions on pedestal stability.
9. We will measure the edge current of NSTX and MAST using SAMI system.
10. We will test the model predictions against tokamak experiments.

All these elements enable us to build a pedestal model that will be capable of reliable predictions for future tokamaks and be of value in optimising operational scenarios of ITER, and designs of demonstration fusion power plants.

Additionally we will investigate the following important issues related to the pedestal, but not directly associated with the predictive model:

1. The transition of micro-tearing modes (MTM) to KBMs at the top of the pedestal which we believe to play an important role in the pedestal development will be studied using gyrokinetic codes.
2. The dynamic model for small ELMs as a transition from general to isolated mode will be investigated using the local-global gyrokinetic approach.

## Description

The goal of this project is to make a significant contribution to developing a predictive pedestal model that can be readily integrated into core transport simulations for optimising scenarios and predicting the performance of tokamak fusion devices. The ultimate goal is a challenging one - to predict the pedestal height and width using only inputs that can be externally controlled, with all the internal dependencies built into the model. To build such a model, several aspects of the pedestal physics have to be further developed, and then integrated together. To complete the work, we will test the model predictions against experimental observations on JET, ASDEX Upgrade and MAST-U.

**Framework**

The predictive model will be implemented as a computer code. In the beginning of the project, the code will perform simple “EPED1” calculations, but would rapidly build through the project to incorporate more complex models for the different physics components.

Some parts of the model will include real-time computations, such as MHD stability code runs, each of which takes only seconds on a simple processor to complete, and the many stability calculations required will parallelise perfectly. Other parts of the model, such as those based on gyrokinetic or fluid calculations can take hours on a supercomputer (or even longer for nonlinear runs). These computationally heavy parts will be implemented either using simplified models constructed based on the simulation results or by look-up tables based on parameter scans. The framework will be developed so that it will use the ITER IMAS interface to enable our pedestal predictions to be readily incorporated into global transport simulations.

**Global GK to clarify whether Type-I pedestals are always close to the KBM limit.**

One of the key components is to develop a model for pedestal gradient limiting micro-turbulence. In the EPED model, the gradient is set either by the relation $∆\~\sqrt{β\_{p,ped}}$ (EPED1) or by the “ballooning critical gradient” model based on ideal MHD n=∞ ballooning mode threshold (EPED1.62). Both of these are used as proxies for underlying KBM turbulence onset (although the former is motivated by experimental scaling studies). Our goal is to investigate the KBM onset using gyrokinetic simulations and form a model based on these simulations.

Local gyrokinetic studies of typical MAST pedestals at relatively high collisionality, find that the pedestal pressure gradient is very close to the KBM stability threshold [18,19], but in lower collisionality MAST pedestals [20] and in JET pedestals [21], where the bootstrap current is higher and the magnetic shear is lower, the local KBM stability limit is well above the experimental pressure gradient. These lower collisionality MAST and JET pedestal plasmas are in the so called second stability region, and appear to contradict the EPED model’s assumption that the fully developed pedestal must lie close to the KBM limit.

Local gyrokinetic simulations assume that equilibrium profiles and the gradients, are constant across the radial extent of the mode, but this assumption is challenged in the steep and narrow pedestal region as the mode may extend radially across regions with substantial equilibrium variation. A global approach to micro-stability analysis may therefore be required in this region of the plasma.

There are three important questions that we seek to address using a global treatment of the pedestal region. Firstly, for locally unstable KBMs how strong is the impact of the radial extent of the mode into the stable regions? Secondly, when KBMs are locally stable in the second stability region, could a global calculation find that KBMs are unstable? Thirdly, if KBMs are indeed stable in the pedestal, which modes are limiting the pedestal gradients? Whilst global gyrokinetic simulations have been performed in the pedestal [22-24], these questions remain open. We will seek to answer these questions using two approaches. In one we will compare micro-stability results from two global gyrokinetic codes (ORB5 [25,26] and GKW[27]) with local gyrokinetic results (GS2 [28]) for the same equilibrium. The studies using global code calculations will help clarify whether the pressure gradient is, or is not, always close to the KBM stability limit in fully developed pedestals prior to Type-I ELMs (as it is assumed in the EPED model). In the other complementary approach we will use multiple local GK simulations combined with the higher order analytic theory for the radial mode structure to reconstruct the global mode and calculate its stability, based on the WKB approach outlined in [29]. This second “local-global” approach will require the development of a tight wrapper around the local gyrokinetic code GS2. It will be tested and benchmarked against the direct global simulation codes ORB5 and GKW, as well as simpler gyro-fluid models. If successful, reconstructing the global mode characteristics from local calculations offers significant computational advantages over direct global simulations as the procedure is trivially parallelisable, enabling rapid calculation on many-core systems whilst also being suitable for use on typical desktop machines – this speed-up compared to direct global calculations will be key for incorporating our advanced pedestal model into a transport code. This will allow us to explore the mode evolution over the transport timescales associated with the pedestal.

We will develop a model for the stability threshold that uses either a parameterisation of the global gyrokinetic results or calculates the threshold in real time using the computationally fast local or local-global approach.

A particular application for the local-global approach is to investigate pedestal transitions between so called “general modes”, which are relatively benign, and the more violent “isolated modes” [29], which are only predicted to occur at critical values of flow shear. This could provide a new dynamic model for small ELMs, trigged by (for example) the evolving flow shear profile passing through the critical value required to release the isolated mode before the pedestal becomes unstable to the peeling-ballooning mode (and the associated large ELM). This model could then help identify whether small ELM regimes are accessible on ITER.

**Mode Transition at the Pedestal Top**

Local gyrokinetic calculations for MAST H-mode plasmas reveal that the dominant microinstabilities at kyρI ~ 1 undergo a striking transition across the pedestal top: micro-tearing modes (MTMs) dominate on the plateau side where the gradients are weaker, and KBMs prevail in the steeper gradients on the pedestal side [18,19]. During the MAST ELM cycle the radial location of the MTM-KBM transition tracks the inward progression of the pedestal top [19,20]. This mode transition is therefore anticipated to be important for the inter-ELM pedestal recovery. We will use local gyrokinetic simulations of this MTM-KBM transition at the pedestal top to: (i) explain the transition mechanism and reveal how it impacts on quasilinear transport estimates; (ii) explore the conditions under which both MTMs and KBMs become simultaneously unstable, and check their experimental relevance; and (iii) assess the sensitivity of the transition to including varying levels of impurities which are known to impact on pedestals experimentally.

**Empirical core transport model**

The new pedestal predictive code can eventually be coupled to advanced core transport codes through an integrated modelling approach. However, as a starting point the pedestal-core coupling is proposed to be taken into account using experimental evidence from various tokamaks including JET, AUG, DIII-D and MAST. For JET a wide database study was conducted across a wide range of baseline and hybrid scenario plasmas for both the C and Be/W wall materials. A tight coupling between the pedestal pressure and thermal core pressure was found. Therefore, the core pressure in the pedestal prediction model will not be prescribed, but will be parameterised and coupled to the pedestal in a self-consistent model that simultaneously solves for the pedestal and core confinement. The coupling in the experiment is largely caused by temperature profile stiffness, whereas some variation between the pedestal and total pressure may be explained by a variation in density profile peaking across the scenarios. The latter can largely be described by the empirical collisionality scaling of density peaking [30,31] and can be implemented in the empirical core transport model. This model will provide the thermal temperature and density profile shapes that put a constraint on the total normalised pressure. For the ITER scenarios of interest a strong coupling of the ion and electron temperature is expected and Ti=Te will be assumed in the model. An additional estimate of the non-thermal contribution to the total pressure will be provided by the model for the fast ion estimates, which wjll be developed as part of this project (see below).

**Extending ELITE to low n**

The ELITE code is used in the predictive model to determine the peeling-ballooning stability. This code was pivotal in confirming the peeling-ballooning mode as the trigger for ELMs and then, more recently, as a key component of the EPED model for pedestal structure. The code was based on a theoretical formalism that relies on an expansion in inverse toroidal mode number, which is typically valid down to *n*5. However, the pedestal can be limited by low toroidal mode number kink-like instabilities, especially at low collisionality when the bootstrap current is large - a situation likely to be relevant on ITER. This provides the main motivation for extending ELITE to arbitrary toroidal mode number.

An initial approach to develop the theoretical formalism was to select variables for the perturbed quantities that take account of cancelations to leading order in *n*. Benchmarks with the original version of ELITE for n=10 showed that the eigenfunctions agreed reasonably but the growth rate of the new code failed to converge. Analysis of the theory indicates a requirement to cancel leading order terms to a level B2p/nB2, which is typically of O(10-2) or less – this could be the source of the discrepancy. To deal with this, we propose to develop new eigenmode equations for variables that incorporate this higher order cancelation analytically. This will lead to a highly efficient ideal MHD code, valid for arbitrary toroidal mode number.

Sheared toroidal flows are a feature of the pedestal. A second phase of this part of the project will be to extend the new version of ELITE to incorporate toroidal flow shear. This could be important in some situations (e.g. access to QH mode, a possible no-ELM scenario for ITER, is thought to require a critical flow shear.

**Modification of the stability limit by non-ideal effects**

The stability limit of the pedestal set by large-scale modes which span the pedestal is one of the key ingredients in a predictive model such as EPED. The ideal MHD peeling-ballooning mode is able to predict the pedestal stability limits in many experiments, in particular type I ELMy H-mode scenarios. In order to do this, ideal MHD calculations using codes such as ELITE must be supplemented by a semi-heuristic model of the diamagnetic stabilisation. We propose to improve the accuracy of these stability calculations by investigating the impact of non-ideal physics on the pedestal stability, and hence on the predicted pedestal height and width. To do this we will exploit the ability of the BOUT++ framework to simulate a range of 2-fluid and gyro-fluid models incorporating sophisticated models for Landau damping and heat conduction. BOUT++ simulations were used to construct the diamagnetic stabilisation model in EPED.

BOUT++ is an initial-value code, which can evolve a wide range of plasma models in both linear and non-linear regimes. Initial-value codes are not ideally suited to linear stability studies, because they require a lot of computing power to simulate a single case and typically can only be used to study the most unstable mode. We propose to use the SLEPSc library of eigenmode solvers to enable BOUT++ to calculate eigenmodes and complex growth rates (as eigenvalues) more efficiently, and to study sub-dominant modes. The modular design of the BOUT++ code facilitates these kinds of extensions. Since BOUT++ is open-source, this will provide the community with a powerful tool: the same model source code and inputs could be used to study linear mode spectra, then time-evolved to study the linear and subsequent non-linear evolution.

Linear stability studies will focus initially on 2-fluid effects in determining stability limits. Both BOUT++ and JOREK [16] include these effects, and so will be used to benchmark against each other. Previous studies using BOUT++ [32] have indicated that increasing pedestal temperature at fixed pressure can improve stability due to both diamagnetic stabilisation and parallel heat conduction: parallel heat conduction tends to elongate the mode structure along the magnetic field, increasing the perturbation amplitude in the inboard good curvature region, and so stabilising ballooning modes. We will perform a systematic study of these effects, with the aim of constructing a computationally efficient model for pedestal stability as a function of density, electron and ion temperature. This model could form a component of a model for predicting both density and temperature pedestals.

The triggering of ballooning modes will be studied using heating sources and particle injection derived from experimental data, together with perpendicular diffusion coefficients derived from turbulence codes and experimental observations in JOREK. The simulations will be started from stable pedestal pressure gradients. Then using a heating source the gradient and self-consistent bootstrap current is progressively increased until the ballooning modes take off. At that point, simulations may become too difficult to continue, but information about the ELM onset will have been obtained, determining the non-ideal stability boundary.

BOUT++ can also simulate gyro-fluid models. We will use these models along with the SLEPSc library to first study the impact of Landau damping and temperature anisotropy effects. These more sophisticated models can also incorporate multiple ion species, and can potentially identify differences in pedestal stability caused by impurity ions, which cannot be captured by ideal MHD. We will develop these models, and use them to study the impact of carbon, nitrogen, and tungsten impurities on pedestal stability. This will contribute to the understanding of JET ILW pedestal results, and form the foundation of further work in this area.

**Pedestal density and impurity modelling using SOL fluid codes**

A reliable, predictive pedestal simulation tool must capture the scaling of the fuel and impurity density profiles as a function of the engineering operation parameters as they can strongly affect the achieved pedestals and core confinement [33,34]. The pedestal profiles of fuel species and impurities are dominantly determined by particle ionization sources inside the pedestal, transport within the pedestal, and scrape-off layer conditions at the separatrix. While stand-alone pedestal simulation tools are expected to provide adequate description of the particle transport within the pedestal, a satisfactory treatment of the SOL conditions at the separatrix and pedestal ionization sources can only be obtained with SOL multi-fluid code analysis. The SOL fluid codes provide two-dimensional map of ion, impurity, and neutral densities, temperatures, flow profiles, and electric fields, assuming radial diffusive-convective transport for particles and heat conduction for energy. The radial transport coefficient profiles in these codes are manually adjusted, such that the simulated profiles represent the measured plasma profiles. As a result, the SOL multi-fluid codes are not expected to self-consistently capture the scaling of the radial transport as a function of the operation parameters. However, these models can be used to provide physics based insight on the SOL conditions at the separatrix, on the impurity density profiles within the pedestal and SOL plasma, as well as on the two dimensional pedestal neutral fuelling and fuel density profiles, all of which are expected to strongly impact the pedestal performance in H-mode plasmas. In this contribution, the multi-fluid code package EDGE2D [35] coupled to Monte-Carlo neutrals code EIRENE [36] will be used to investigate the physics in H-mode plasmas in the JET tokamak. Using numerical simulations validated against experimental measurement, the impact of deuterium fuelling, impurity seeding with nitrogen and neon gases, divertor geometry, and first wall configuration (JET-C and JET-ILW) on the SOL conditions at the separatrix, on the pedestal fuelling, and on the impurity and fuel density profiles will be investigated. This allows us to develop a model for predicting JET deuterium and impurity pedestals, which can be expanded to other devices at least for parameter scans. It also provides the separatrix values of the temperature profile that can play an important role in the pedestal stability.

**Fast ion effects on pedestal**

A fast particle population contributes to the plasma pressure and affects the thermal ion density. It has been demonstrated in TRANSP and JETTO modelling that it modifies the edge bootstrap current by 10-40% as compared to the cases without fast particle contribution. We will conduct a systematic investigation of the effect of fast particles on edge stability through their impact on the edge current profile and equilibrium by reconstructing equilibria with and without fast ions and comparing how the stability limits change due to the inclusion of the fast ion contribution.

**Edge current profile measurements**

The edge current profile that plays an important role in the edge stability is usually constructed using formulas derived from the neoclassical theory and particle simulations[37]. We will use novel Synthetic-Aperture Microwave Imaging (SAMI) technique [38] to measure the edge current profile in NSTX and MAST in order to test the validity of the formulas.

**References**

[18] Dickinson D. et al. Plasma Phys. Control. Fusion 53 (2011) 035001

[19] Dickinson D. et al., Phys. Rev. Lett. 108 (2012), 135002

[20] Roach C.M. et al., Proc. of 24th IAEA FEC October 8–13, 2012, San Diego, USA, TH/5–1

[21] Saarelma S. et al. Nucl. Fusion 53 (2013) 123012

[22] Wan W. et al., Phys. Rev. Lett. 109 (2012) 185004

[23] Wan W. et al., Phys. Plasmas 20 (2013) 055902

[24] Wang E. et al., Nucl. Fusion 52 (2012) 103015

[25] Jolliet S., et al., Comput. Phys. Commun. 177 (2007) 409

[26] Bottino A., T. Vernay, B. Scott, et al., Plasma Phys. Control. Fusion 53 (2011) 124027

[27] Peeters, A. G., et al.. Comput. Phys. Commun. 180 (2009) 2650

[28] Kotschenreuther M., et al., Comput. Phys. Commun. (1995) 128

[29] Dickinson D., Phys. Plasmas, 21 (2014), 010702

[30] Angioni C. et al., Nucl. Fusion 47 (2007) 1326

[31] Beurskens M.N.A. et al., Nucl. Fusion 54 (2014) 043001

[32] B.Dudson et al. ICCP8, Hong Kong, January 2013

[33] Giroud C. et al., Nucl. Fusion 52 (2012) 063022

[34] Schweinzer J. et al., Nucl. Fusion 51 (2011) 113003

[35] Simonini R. et al., Contrib. Plasma Phys. 34 (1995) 1391

[36] Reiter D., J. Nucl.Mater. 196 - 198 (1992) 80

[37] Sauter O. et al., Phys Plamas 6 (1999) 2834

[38] Freethy S.J., et al., Plasma Phys. Control. Fusion 55 (2013) 124010

## Scientific and technical deliverables

**Year 1 deliverables:**

1. Develop framework allowing
2. Easy comparison of the model predictions with the experiments
3. Addition of physics modules (as they are developed in the following deliverables) into the predictive tool (S. Saarelma)
4. Linear electromagnetic gyrokinetic benchmarking of global (ORB5 and GKW), local (GS2, GKW) and global-local (GS2, global result reconstructed from local runs) codes in a realistic pedestal. (S. Saarelma, F. Casson, D. Dickinson, J. Martin-Collar, H. Wilson)
5. Confirm whether global effects have to be included in the pedestal prediction of stability of kinetic ballooning modes. (S. Saarelma)
6. Develop a physics based model for small ELMs based on the interaction of flow shear with toroidal drift wave structures (H. Wilson and A. Bokshi)
7. Detailed investigation of the striking MTM-KBM observation at the MAST pedestal top during the ELM cycle, to explain the transition mechanism(C. Roach, D. Dickinson)
8. Coupling of BOUT++ to the SLEPSc eigenmode solver library (B. Dudson, D. Dickinson)
9. Quantification of SOL profiles on pedestal stability. (B. Dudson, S. Pamela)
10. Simple core model in pedestal prediction tool to allow self-consistency between core and the edge. (M. Beurskens, I. Chapman)
11. Extension of ELITE code to handle low-n instabilities for peeling-limited pedestal predictions (H. Wilson, A Dowsett)

**Year 2 deliverables:**

1. Interface the model prediction to the ITER framework (M. Romanelli)
2. Develop simplified model for pedestal gradient limits from the gyrokinetic calculation based on results from global-local benchmark study. (S. Saarelma, D. Dickinson)
3. Determine how the quasi-linear transport changes in pedestal due to MTM-KBM transition. Explore the conditions under which both MTMs and KBMs become simultaneously unstable and assess the transition’s sensitivity to varying impurity levels. (C. Roach, D. Dickinson)
4. Quantification of non-ideal effects on peeling-ballooning mode marginally critical gradient (S. Pamela, B. Dudson, J. Leddy)
5. Pedestal density prediction model for JET based on SOL-modelling (M. Groth, A. Järvinen, C. Maggi)
6. Impurity profile prediction using the density and temperature profiles and wall geometry. (M. Groth, A. Järvinen, C. Maggi)
7. Quantification of fast ion effects on pedestal stability (Y. Baranov)
8. Evaluation of the model predictions against experimental data from JET, ASDEX Upgrade and MAST-U (M. Leyland, M. Dunne, R. Scannell, C. Maggi)
9. Extension of ELITE to include flow shear at finite toroidal mode number, and assess implications for low collisionality pedestals (including QH mode) (H Wilson, A Dowsett)
10. Measurement of edge current profile and comparison to neoclassical formulas (S. Freethy, V. Shevchenko, R. Vann)

## Mobility support

Year 1:

M. Groth, 2 weeks (Finland to UK)

A. Järvinen, 2 weeks (Finland to UK)

S. Saarelma, 1 week (UK to USA, PPPL)

H. Wilson, 1.6 weeks (UK to USA…General Atomics)

B. Dudson, 1 week (UK to UK, York to CCFE)

R. Vann, 1 weeks (UK to UK, York to CCFE)

J. Leddy, 0.5 weeks (UK to USA, LLNL)

Year 2:

M. Groth, 2 weeks (Finland to UK)

M. Dunne 1 week (Germany to UK)

S. Saarelma, 0 week (UK to USA, PPPL)

B. Dudson, 1 week (UK to UK, York to CCFE)

R. Vann, 1 week (UK to UK, York to CCFE)

## Hardware costs

None (SAMI systems will be funded from other sources)

Required computational resources will be acquired from IFERC-HELIOS and national HPC centres.

## Manpower

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Name** | **Affiliation** | **1st year py** | **2nd****year py** | **Project work** |
| S. Saarelma, PI | CCFE | 0.5 | 0.5 | Pedestal prediction framework, global KBM simulations using ORB5, peeling-ballooning stability |
| Y. Baranov | CCFE | 0.3 | 0.3 | Investigation of fast ion effects on pedestal |
| M. Beurskens# | CCFE | 0.0 | 0.2 | Core model |
| F. Casson | CCFE | 0.2  | 0.0 | Global-local investigation of MTMs and KBMs using GKW |
| I. Chapman | CCFE | 0.2 | 0.0 | Core model |
| S. Freethy | CCFE | 0.1 | 0.0 | Edge current density measurements |
| C. Maggi | CCFE | 0.2 | 0.2 | Density and impurity modelling, validation against JET data |
| C. Roach | CCFE | 0.2 | 0.2 | Investigation of MTM-KBM transition |
| S. Pamela | CCFE | 0.2 | 0.2 | ELM triggering simulations using JOREK, evaluation of SOL effects on pedestal |
| M. Romanelli | CCFE | 0 | 0.2 | Interface of the pedestal model to the ITER integrated modelling framework |
| R. Scannell | CCFE | 0.0 | 0.2 | Model validation against MAST-U data |
| V. Shevchenko | CCFE | 0.1 | 0.0 | Edge current density measurements |
| J. Martin-Coller | CCFE | 0.7\* | 0.7\* | Global KBM simulations using ORB5 |
| A. Bokshi | Univ. of York | 0.5 | 0.0 | Small ELM model |
| D. Dickinson\*\* | Univ. of York | 0.0 | 0.57 | Expansion of local gyrokinetic model for global simulation, MTM-KBM transition |
| 1. Dowsett
 | Univ of York | 0.5\* | 0.5\* | Extension of ELITE to low n |
| B. Dudson | Univ. of York | 0.3 | 0.3 | BOUT++ investigation of SOL-effects and non-ideal stabilisation and destabilisation mechanisms on pedestal stability |
| J. Leddy | Univ. of York | 0.5\* | 0.5\* | BOUT++ development, pedestal stability |
| M. Leyland | Univ. of York | 0.2 | 0.2 | Model validation against JET data |
| R. Vann | Univ. of York | 0.2 | 0.2 | Edge current density measurements |
| H. Wilson | Univ. of York | 0.3 | 0.3 | Extension of ELITE to low n and small ELM model |
| M. Groth | Aalto University | 0.2 | 0.2 | Density and impurity modelling |
| A. Järvinen | Aalto University | 0.25 | 0.0 | Density and impurity modelling |
| M. Dunne\*\*\* | IPP | 0 | 0.2 | Model validation against AUG data |
| **Total ER funded** |  | **4.25** | **4.32** |  |
| **Total (including funding outside of ER)** |  | **6.75** | **6.30** |  |

\* PhD student, who is funded outside of ER-funding. Py-values given here not included in the total of ER funded part.

\*\* Will work on this project both years at 0.5 ppy, but is funded via EUROfusion fellowship until 1/3/2016.

\*\*\* Will work on this project both years at 0.2 ppy, but is funded via EUROfusion fellowship until 2015.

# Will work on this project both years at 0.2 ppy, ER funded only in 2016.

Assuming €72,000/py for those funded within ER, the total cost for the first year: €306,000, total cost for the second year: €311,040, of which ER funding share (50%): €153,000 and €155,520.