# Model based formation of Advanced Tokamak discharges

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## Introduction

The pulsed operation of the standard tokamak configuration, resulting from the inherently limited current drive through the central solenoid poses a potential problem for future fusion reactors. By using the external heating systems to drive current off-axis, the safety factor $q$ and thereby the bootstrap current ($j_{bs} \propto q\nabla p$) is increased through redistribution of the plasma current, which allows advanced Tokamak scenarios to be less reliant on inductive current drive. Starting the additional current drive during the ramp-up (early-heating) allows for an optimal entry into a desired $q$-profile, avoiding an intermittent drop, which would otherwise occur after the current profile has completed relaxation through diffusion (late-heating). The rise of the $q$-profile after this drop takes place on the current diffusion time ($\tau_r$). For present non superconducting devices, using the early heating approach is beneficial to optimally utilize the short pulse duration, whereas a future reactor might require this approach, since their much long $\tau_r$ may otherwise lead to a desired $q$-profile taking to long to achieve.

Due to the volatility of the plasma in the early phase, developing such a scenario usually costs a lot of discharges. A possible solution to this issue, by using modelling to assist with scenario development is presented here.

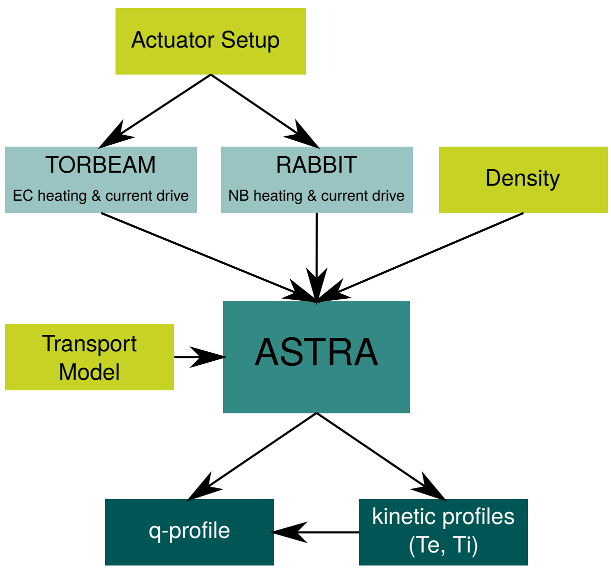


Figure 1: Schematic view of the ASTRA model

## The model

A model has been developed in the transport code ASTRA [3, 4] capable of simulating an early heating AT scenario. Initial input is the actuator setup and the plasma density. ASTRA then uses the RABBIT [6] and TORBEAM [5] codes to calculate heating and current drive respectively. The density is feedback controlled and its shape does not change significantly between similar discharges. Therefore experimental data, modified to match the timing of the heating systems is used here. For the transport model a simple Bohm/Gyro-Bohm model with multiple free parameters, including simplified ITG and TEM mode contributions, is used to achieve a sufficiently short run-time of only a few minutes for a full discharge. Edge transport via a scaling law [2] and the L-H transition based on the heating power at the separatrix are included. A more detailed description can be found in [1]. The model does include multiple free parameters, which have been determined by a set of reference pulses. These parameters are consistent for similar plasmas, allowing predictive use of the model. With this setup it is possible to quickly test various changes to a reference discharge, allowing for a large part of scenario development to be done through modelling only.

**Designing a new scenario**

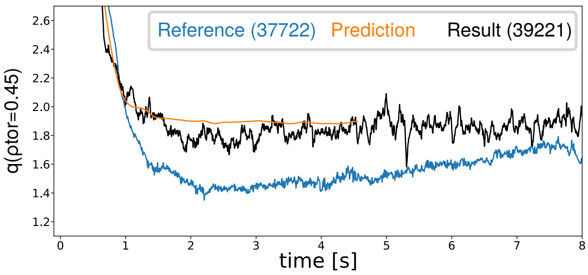


Figure 2: Time evolution of $q$, comparing the reference scenario (blue) with the designed scenario (black). The new scenario follows the predicted behaviour (orange)

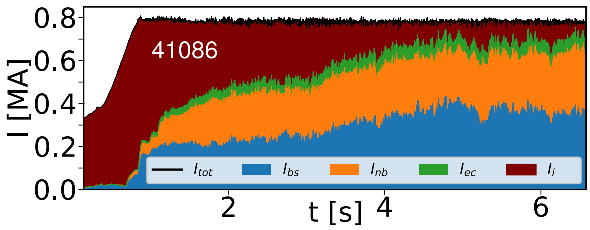


Figure 3: Current distribution for the newly designed scenario, after optimizing $\beta$, showing the different contributions to the plasma current; The bootstrap current reaches close to 50% at its maximum

A new early-heating scenario for ASDEX-Upgrade (AUG), operating at $q_{95} \sim 5.2$ and $\beta_N \sim 3$, was developed using the model. Starting point was a late heating reference case. The time to start heating was set as early as possible and the density was set such that it matches the density from the reference case at the time when heating starts.

From there the actuator setup was modified in an iterative approach until the predicted safety factor evolution was deemed satisfactory. The new setup was then run on AUG. Figure 2 show the reference case, the behaviour predicted by the model and the result of running the newly designed discharge. There is excellent agreement between prediction and experiment. A comparison of representative profiles for both $T_e$ and $q$ is shown in figure 4 and also matches very well.

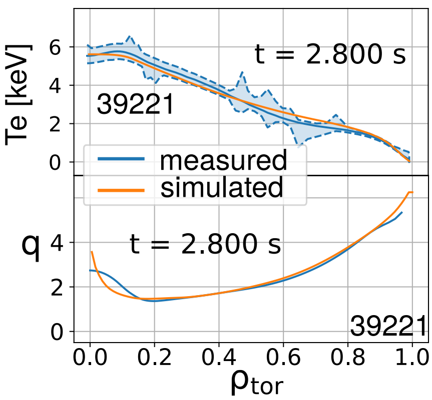


Figure 4: Representative $T_e$ and $q$ profiles for the modelled case. There is excellent agreement

In order to further increase the bootstrap fraction via the pressure gradient, $\beta$ was optimized by increasing the NBI power without significantly changing off-axis current drive. A current distribution for the resulting scenario is shown in figure 3. It can be seen that a significant non-inductive current fraction is achieved, with a bootstrap fraction of almost 50%. For technical reasons this discharge is not using the entire available current drive at AUG. From previous discharges it seems likely, that enough NBI current drive is available to have this scenario become fully non-inductive.

**Application to a different scenario**

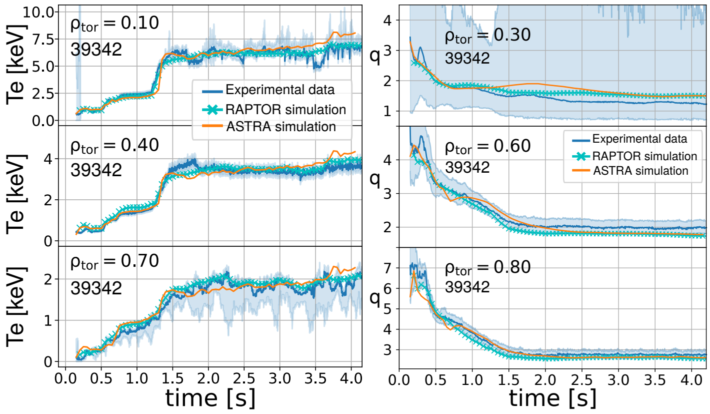


Figure 5: Comparison of the ASTRA and RAPTOR models for a reference counter-ECCD case. A good agreement can be seen

A second scenario, using a higher plasma current of 1kA in order to achieve a more DEMO-relevant $q_{95}$ of $\sim 4.1$ has been investigated. Due to the reduced efficiency of ECCD off-axis, relevant $q$-profiles for this setup at AUG can only be achieved when using counter-current drive on axis. A comparison to a model in the RAPTOR fast core transport solver [8] was done for this scenario.

This RAPTOR-model [7] is simpler and not fully predictive, but does feature a non-linear optimizer for relevant plasma parameters. As can be seen in figure 5, comparing post shot simulations for a reference discharge between the two models and experimental data, the models agree well.

Using the RAPTOR optimizer to propose changes, which are then double-checked in ASTRA, the heating system of this scenario has been redesigned. The $q$-profile has been optimized to avoid a deleterious 3-2 tearing mode, by increasing the shear at q=1.5 and moving the time point, when $q_{min}$ is close to 1.5 earlier in the discharge and reduced the time spending around that point. As can be seen in figure 6, a considerable improvement can be achieved, since the mode no longer reduces the confinement. In the later parts of the discharge, the confinement drops back to previous levels due to effects from a different mode, that was not optimized for.

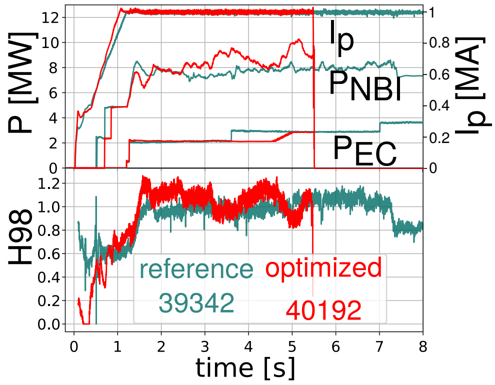


Figure 6: The confinement degradation by the mode is reduced for a comparable amount of input power after optimizing the safety factor

**Looking at a different machine**

In order to test if this process can be generalized to other machines, the ASTRA model was tested on JET data. As can be seen in figure 7, $T_e$ is well reproduced. We note here that a small adjustment of free parameters in the model was required. The experimental drop after $\sim 6.5$

seconds is caused by a tearing mode, which is not included in the model. Unfortunately the situation for the $q$-profile is much less clear:

For JET, only MHD markers, such as the appearance of a $q$=1 surface are available for comparison. While trends in the $q$-profile between consecutive discharges are recovered, as is shown in figure 8, the absolute values are not reproduced. This behaviour does align with findings from [9], that the neoclassical conductivity seems to not reliably describe the JET ramp-up. Variations in the machine conditions which may lead to variations of e.g. $Z_{eff}$ or the initial $q$-profile may explain why in some cases the modelled behaviour does match the observations.

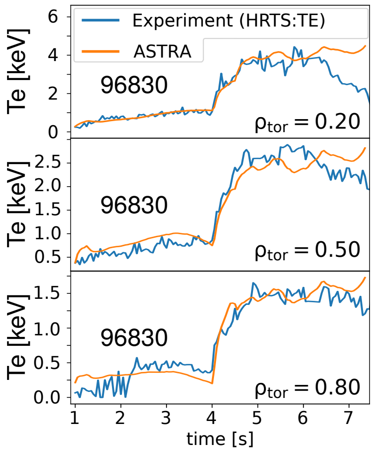


Figure 7: Comparison of the modelled and experimental $T_e$ evolution for a JET discharge. A good agreement can be seen

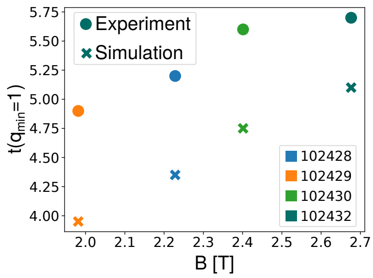


Figure 8: Time of the first q=1 appearance for a set of consecutive discharges with different magnetic field. Only the trend is reproduced

## Conclusions

A model has been developed which can predict the temperature and safety factor time evolution for varying heating setups in an early-heating AT discharge. Using this model, a new early-heating scenario has been developed for AUG and was run successfully showing the applicability of this model for scenario design. Further test at AUG with a higher plasma current and different EC current drive direction still show good agreement. It has been shown, that using this model to improve the $q$-profile, a considerable improvement in tearing mode stability and thereby confinement can be achieved.

The applicability of the model to different machines has been tested by looking at JET data. While the model is capable to reproduce $T_e$, the $q$-profile so far only reproduces trends reliably.

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