MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Model based formation of Advanced Tokamak discharges

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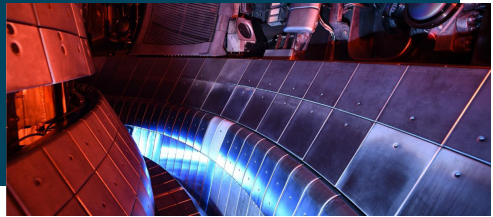

EUROfusion

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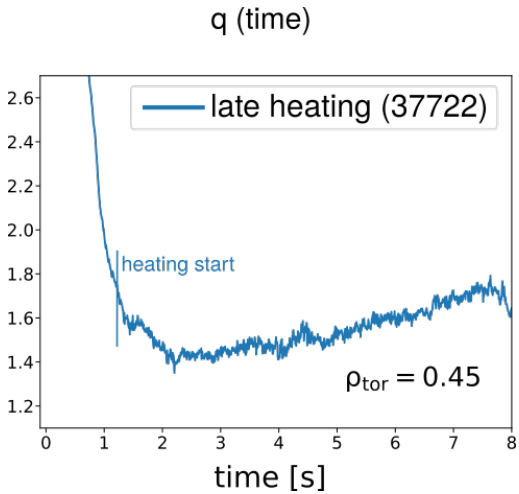
Outline

- **Motivation**
- **Model**
- **Validation of the model**
  - Design of a $q_{95} \sim 5$ discharge
- **Application to a higher current discharge ($q_{95} \sim 4$)**
  - Comparison to a different model
  - Stability considerations
- **Summary**

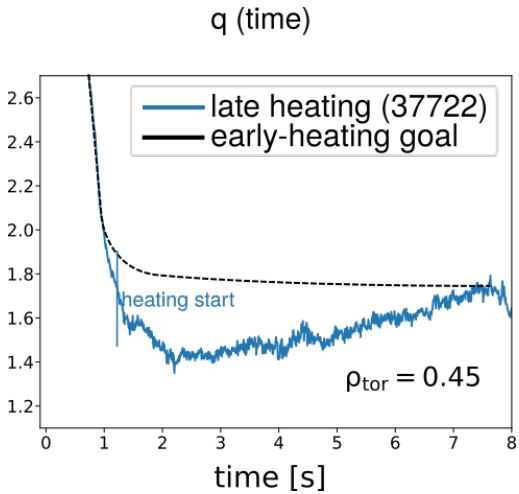
How to get to a desired q-profile



- **The "simple" option: "Late heating"**
- Stationary state before additional current drive is applied
  - ⇒ Safety factor drops below target
    - Increase of q is dependent on the current diffusion time
- At AUG acceptable ($\tau_B \sim 1.5s$)
- For ITER: $\tau_B \sim 400s$ (based on [1])
  - ⇒ Not feasible
- A power plant would be even longer

[1] Zohm, Nucl. Fusion 57 086002

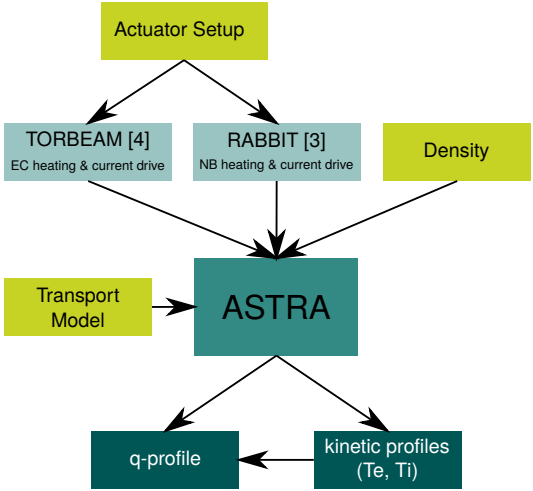
How to get to a desired q-profile



- **The alternative: "Early heating"**
- Additional current drive is applied during the ramp-up
  - Desired q is reached "directly"
  - **BUT:** Much less stable

⇒ Fully experimental scenario design usually requires a lot of iterations

Simulation with ASTRA [2]



- ASTRA: 1.5D transport code
- Inputs: Actuator setup and density
- Gyro-Bohm based transport
  - Run-time of 5-10 min
- Scaling law for pedestal behaviour
- L-H transition based on heating power at separatrix
- Outputs: T_e, T_i, q, ... profiles

[2] Pereverzev, IPP-report 5/42 1991

[3] Weiland, nuclear fusion, 58 082032

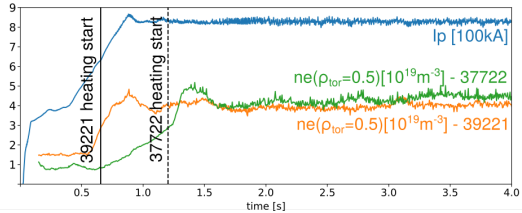
[4] Poli, Computer Physics Communications 136 90–104

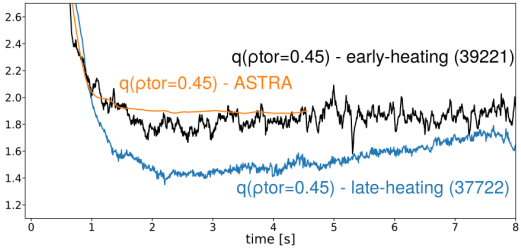
Model validation - $q_{95} \sim 5$

- Validate the model by using it to design a new scenario

- **Starting point**:
  - Late-heating reference shot (800kA, co-ECCD)
- **Targets:**
  - Switch to early heating, achieve higher safety factor q
  - Test performance of the scenario

Designing a new scenario

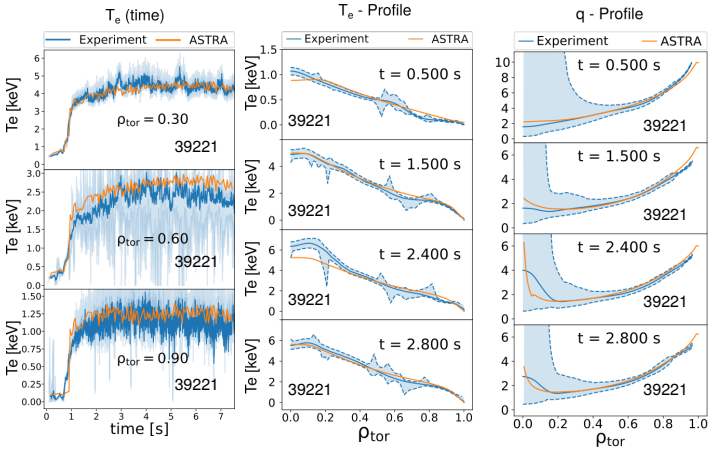




- Adjusted reference density/fuelling for earlier heating
  - Higher density earlier
  - Increased slope
- First simulation with an arbitrary current drive setup
  - Evaluate q-profile
- Iterative changes to the setup until q-profile evolution is satisfactory

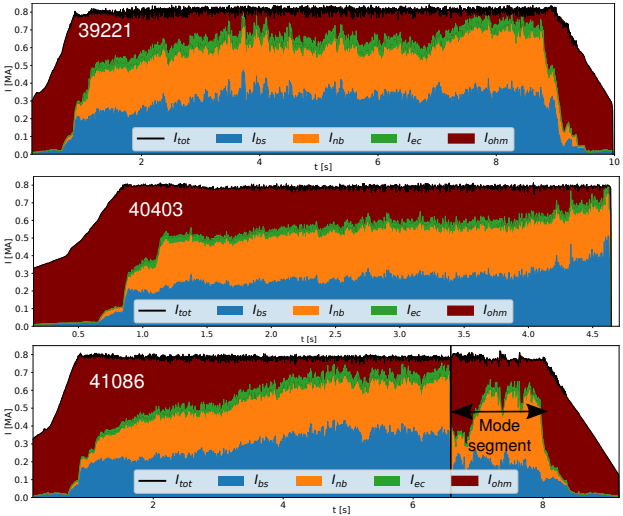
⇒ **Experiment follows predicted behaviour**

Closer look at the validation scenario



- Good agreement between model and experiment
- Fluctuations in model from density input
- Ti (not shown) only reproduces trends, but low impact

f_{ni} can reach >85% in steady state



- Current distribution 39221
- 2 current drive beams after 7s

- Current distribution 40403
- Stability limit found at β_N=3.2
- Transiently fully non-inductive

- Current distribution 41086
- $\beta_N = 2.7$; f_{BS} stable at $\sim 50\%$
- $q_{95} \sim 5.2$, $H_{98} \sim 1.05$

Model validation - Results for $q_{95} \sim 5$

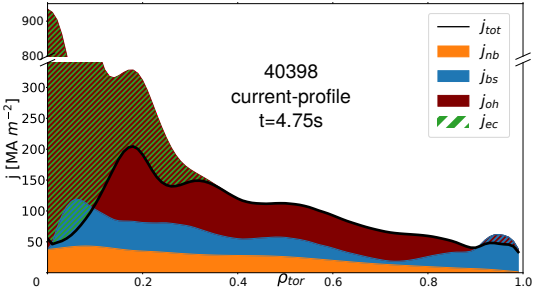
- **Starting point**:
  - Late-heating reference shot (800kA, co-ECCD)
- **Targets:**
  - Switch to early heating, achieve higher safety factor
  - Test performance of the scenario

- **Result:**
  - Experiment data shows good agreement with the modelled behaviour
  - q-profile follows the prediction
  - Scenario reaches high non-inductive fraction after optimizing β

$\Rightarrow$ **Model can be used for scenario development**

Approaching DEMO-relevant parameters

- $q_{95} \sim 4.1$ and I_p=1MA to get closer to EU-DEMO parameters
  - Relevant q-profiles not achievable with co-current ECCD



- ECCD less efficient off-axis
- Counter-current ECCD on axis can generate current profiles similar to co-current ECCD off-axis with higher efficiency
  - Not how this would be done in a future non-inductive machine

The counter-ECCD scenario

- High counter current drive on axis $\Rightarrow$ transient zero or negative values
  - Fixed by artificially increasing current,
    BUT Simulations not trustworthy in affected regime ($\rho_{\mathrm{tor}} \lesssim 0.2$)

- ASTRA model does changes only by trial and error
  - Cooperation with Lausanne (EPFL)
  - Non-linear optimizer for relevant parameters in their model RAPTOR [6]

  $\Rightarrow$ More informed changes to the actuators are possible

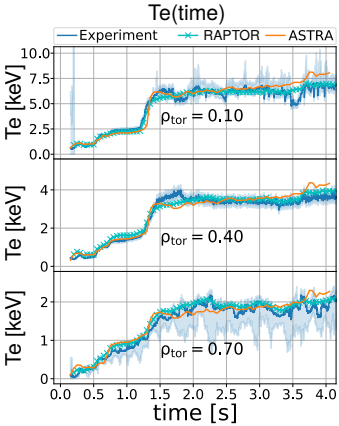
[6] Felici. Plasma Phys. Control. Fusion 54 025002

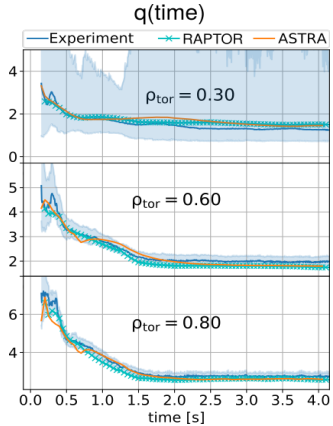
Plans for the counter-ECCD scenario ($q_{95} \sim 4$)

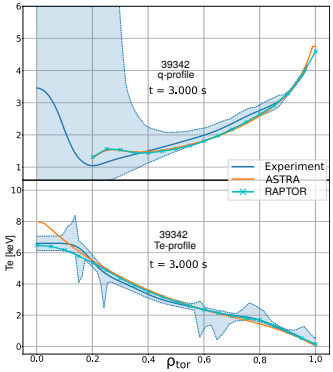
- **Starting point**:
  - Early heating reference scenario with some mode issues
  - Only one of two dedicated current drive NBI beams available

- **Targets:**
  - Compare the ASTRA and RAPTOR models
  - Reproduce the scenario with the available heating systems
  - Use the RAPTOR optimizer to improve the confinement by reducing mode effects
  - Show that ASTRA model is applicable to considerably different scenario

Comparison with RAPTOR

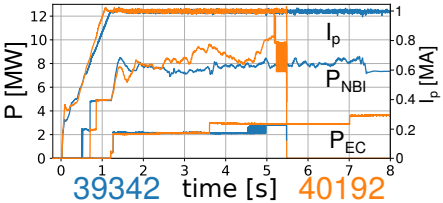


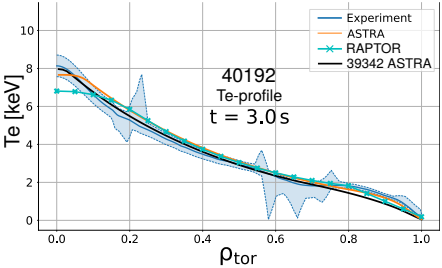


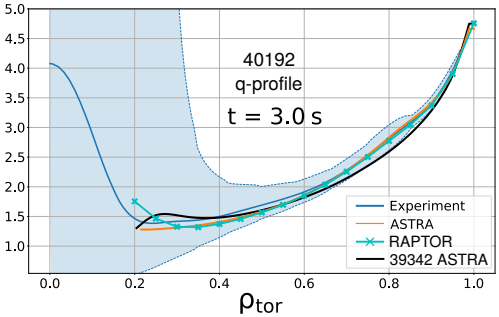


- ASTRA and RAPTOR show good agreement

Counter ECCD scenario with a new heating setup

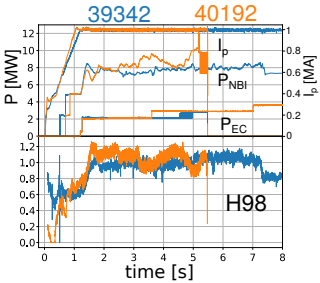


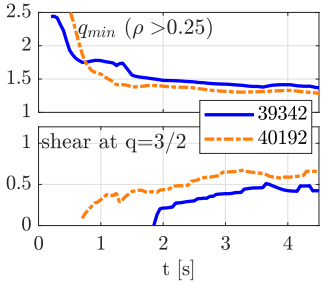


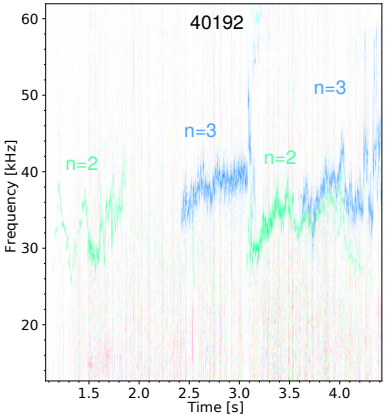


⇒ **Scenario runs with adjusted heating setup**

Safety factor profile optimization

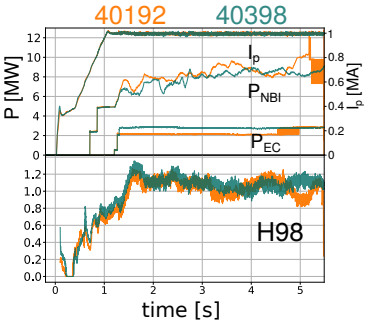


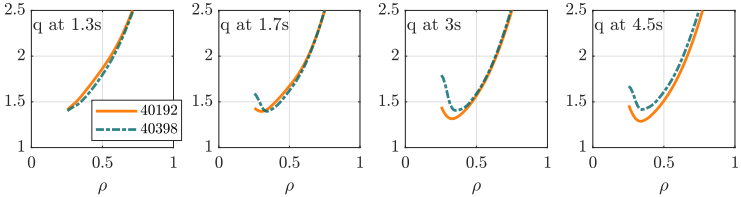




- Increased shear at q=3/2, go through $q_{min} = 3/2$ earlier and faster
  - ⇒ Reduced size of first n=2 mode
    - ⇒ Significant improvement in confinement up to 3s
- Large n=2 mode develops in area below q=3/2, likely triggered by growing n=3

Reducing mode effects





- Increased P_{EC} to reduce area below q=3/2

$\Rightarrow$ Reduced mode effect $\Rightarrow$ improved confinement

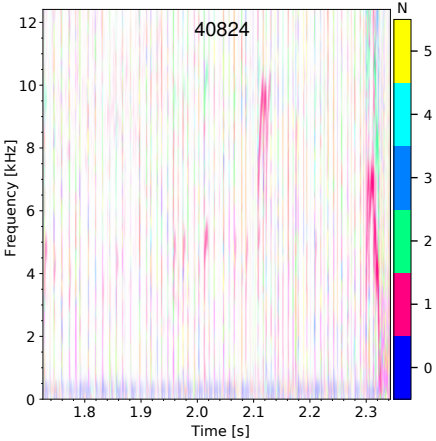
- Mode still present
  - Increasing q_{min} above 3/2 should solve this

Stability issues after redesign of density control

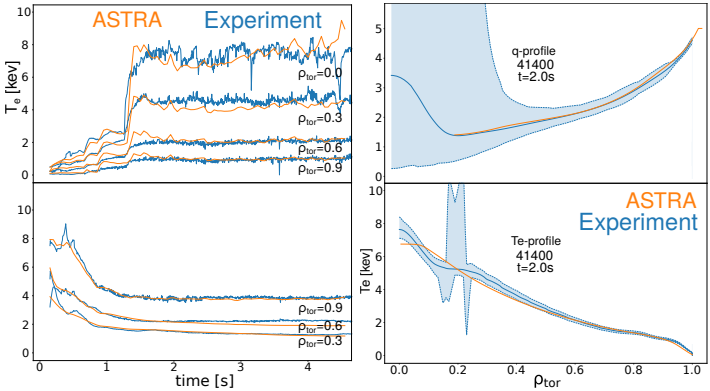
- NTM onset after a significant fraction of ELMs
- 2/1 mode can not be stabilized consistently enough
  - Better q data might help
- Theory: ELMs trigger large enough seed islands, that the scenario is unstable, even if it would be conventionally expected to be stable

⇒ Move q=2 surface away from edge

⇒ Go to 900 kA



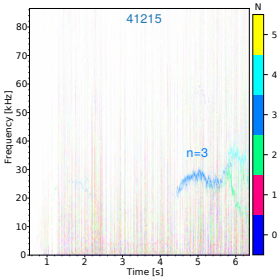
Increased stability with lower current

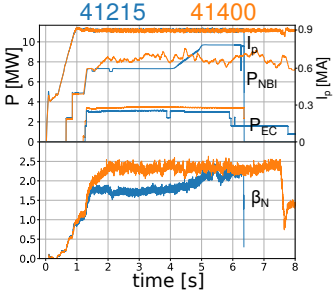


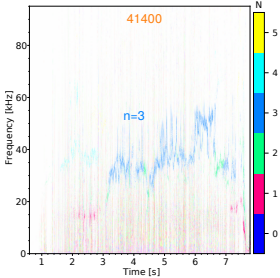
- Only reduced current, kept other parameters
  - $\Rightarrow$ $q_{95} \sim 4.5$
- Good agreement between simulation and experiment
- No more stability issues

$\Rightarrow$ **Successful**

Mode activity in reduced current scenario



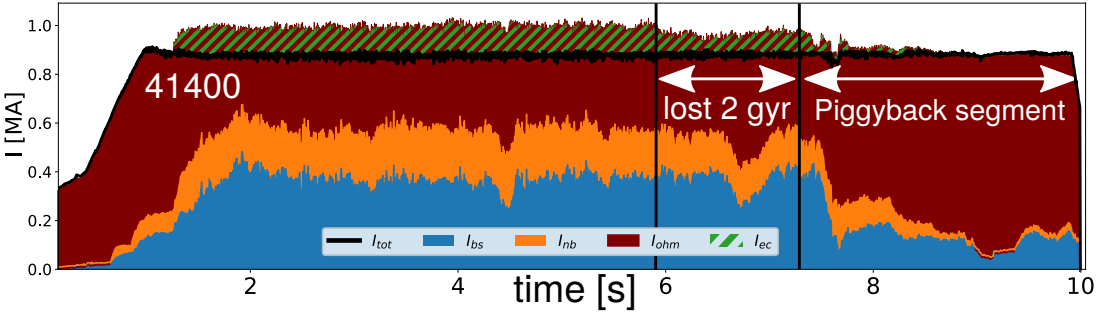




- Lower β early, then ramp
- Very low activity early
- Modes appear during β-ramp

- High β early
- No significant n=2 activity
- More activity after technical difficulties at t $\sim$ 6s

High β operation in 900 kA



- Operation at $\beta_N \sim 2.3$, limit at $\beta_N \sim 2.8$
- Bootstrap fraction stable at 45%, transient at $\sim$ 50%
- One gyrotron failed immediately $\Rightarrow$ higher f_{bs} may be achievable

Results of the counter-ECCD scenario ($q_{95} \sim$ 4 - 4.5)

- **Targets:**
  - Compare ASTRA and RAPTOR models
  - Reproduce the reference scenario with the available heating systems
  - Use the RAPTOR optimizer to improve the confinement by reducing mode effects
  - Show that ASTRA model is applicable to considerably different scenario

- **Results:**
  - The two models agree well
  - ASTRA model in good agreement with experiment
  - Scenario does run with adjusted current drive setup
    - Effect of modes on confinement can be reduced by optimizing q-profile
    - But has stability issues
  - Moving the q=2 surface away from the edge significantly improves stability

Summary and outlook

- ASTRA model can predict Te and q profile development for AT discharges
  - Validated at different plasma current and ECCD direction
  - ASTRA agrees with RAPTOR
  - Useful tool for scenario development of early heating AT

- 800 kA scenario stable at $H_{98} \sim 1.05$, $q_{95} \sim 5.2$, $\beta_N \sim 2.7$, $f_{BS} \sim 0.5$
- 1 MA scenario achieved $H_{98} \sim 1.1$, $q_{95} \sim 4.1$, $\beta_N \sim 2.55$, $f_{BS} \sim 0.4$
  - Stability issues
  - May require better q measurements to sort out
- 900 kA scenario achieved $H_{98} \sim 1.05$, $q_{95} \sim 4.5$, $\beta_N \sim 2.3$, $f_{BS} \sim 0.45$
  - Higher f_{BS} may be achievable

- Currently assisting in scenario development for flux-pumping experiments at JET