MAX-PLANCK-INSTITUT FÜR PLASMAPHYSIK

ASDEX Upgrade

Dynamic Pulse Scheduling
in ASDEX Upgrade

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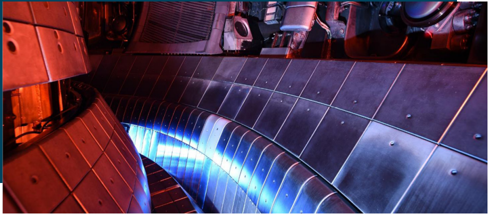

EUROfusion

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Overview

Introduction

ASDEX Upgrade

Discharge Control System

(Dynamic) Pulse Scheduling

Examples
- Disruption Avoidance
- NTM Sudies
- Runaway Electrons

Conclusions and Lessons Learned

Introduction

This talk aims to

- give an overview of the ASDEX Upgrade tokamk and its control system.
- illustrate how continuous control in combination with decision logic is enabling plasma operation.
- introduce dynamic pulse scheduling which can be used to implement
  - exception handling
  - advanced disruption avoidance schemes
  - more sophisticated physics studies

ASDEX Upgrade

ASDEX Upgrade

Axial**S**ymmetrisches **D**ivertor**EX**periment Upgrade or short ASDEX Upgrade

- Located in Garching near Munich (Germany)
- Operational since 1991 with a fully digital control system.
- Demonstration of a reactor relevant design of the coil system.
- First tokamak to demonstrate operation with all tungsten plasma facing components.

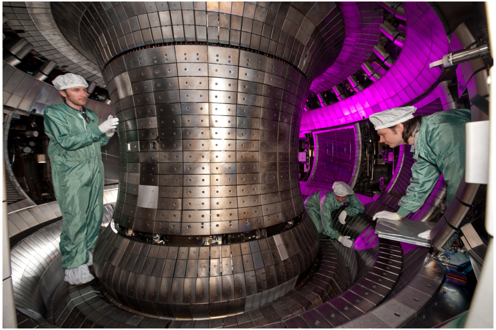
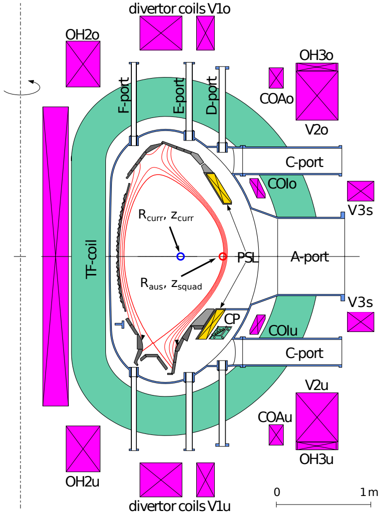


Figure: The inside of ASDEX Upgrade.

ASDEX Upgrade - Main Parameters

Major plasma radius	R_0	$1.65\,\mathrm{m}$
Minor plasma radius	a	$0.5\,\mathrm{m}$
Plasma height	b	$0.8\,\mathrm{m}$
Plasma elongation	$\kappa = b/a$	1.6
Plasma aspect ratio	A	3.3
Plasma volume	V_{plasma}	$13\,\mathrm{m}^3$
Plasma surface	S_{plasma}	$42\,\mathrm{m}^2$
Plasma current	I_{plasma}	$0.4 - 1.6\,\mathrm{MA}$
Pulse duration	t_{D}	$< 10\,\mathrm{s}$
Heating	P_{aux}	up to $32\,\mathrm{MW}$
Ohmic heating	P_{OH}	$1\,\mathrm{MW}$
NBI heating	P_{NBI}	$20\,\mathrm{MW}$
ICR heating	P_{ICRH}	$6\,\mathrm{MW}$
ECR heating	P_{ECRH}	$6\,\mathrm{MW}$



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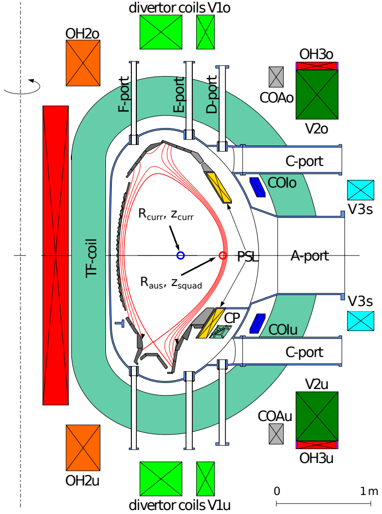


Discharge Control System (DCS)

Discharge Control System (DCS)

ASDEX Upgrade is operated using the **D**ischarge **C**ontrol **S**ystem (DCS).

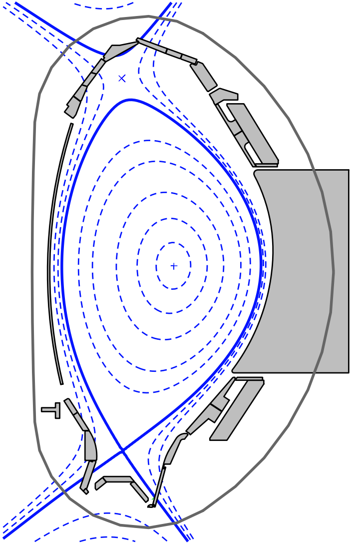
- DCS is not a monolithic system but is implemented using modular micro services (both rt and non-rt).
- DCS is a distributed system, e.g. it is not limited to one control computer.
- The majority of custom services are implemented in C++.
  Core DCS has 260k lines of code.
  AUG DCS has 200k lines of code.
- The concept is to define its behaviour via configuration.

(Dynamic) Pulse Scheduling

Pulse Scheduling

A plasma discharge requires a timed sequence of events / actions to be executed.

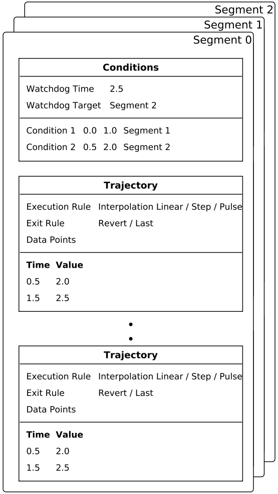
- Configuration of the plant prior to the discharge.
- Initialization/startup of plant systems (e.g. fly wheel generators) and diagnostics.
- Control of the plant (coils, power supplies, gas system, heating systems, etc) before, during and after the pulse.
- Transition of the plant to a safe state after the pulse.



Pulse Scheduling

At ASDEX Upgrade the discharge sequence is described in a so called discharge program (DP).

- The DP defines the complete discharge sequence, including
  - plant setup and shutdown.
  - the nominal path.
  - exception handling and alarms.
- The DP is part of the DCS configuration, set by the session leader prior to the discharge.
- The DP itself is defined using XML.



Pulse Scheduling

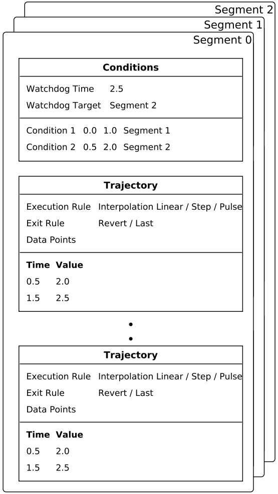
Segments contain

- trajectories which specify control targets (control modes, references, etc).
- conditions on which to execute another segment, enabling exception handling.

Trajectories contain

- data points (segment time, value). The value passed from the previous segment is used as start value, if no point at time zero is defined.
- an execution rule which specifies the interpolation type (linear, step, pulse).
- an exit rule. This specifies which value is passed to the next segment.

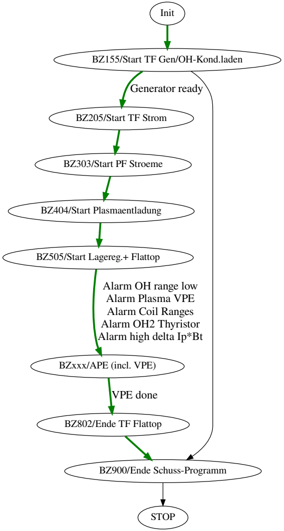
Last: The last evaluated value is passed on.
Revert: The value that was passed to the current segment is passed on.



Dynamic Pulse Scheduling

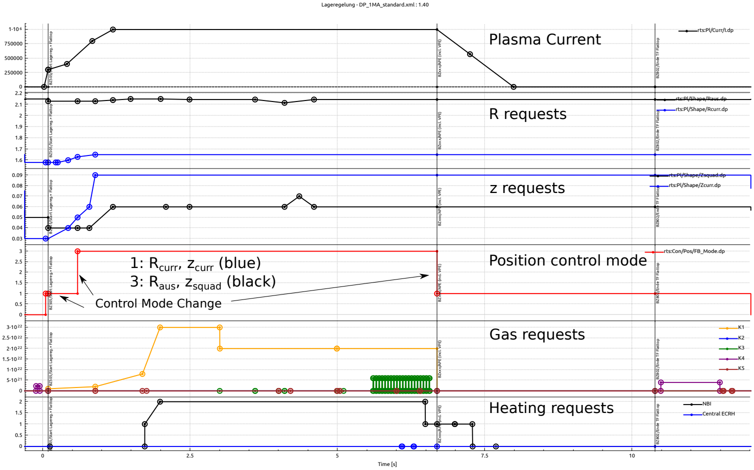
- Dynamic pulse scheduling, e.g. the control system decides which path to take, is available and used in every discharge on ASDEX Upgrade.

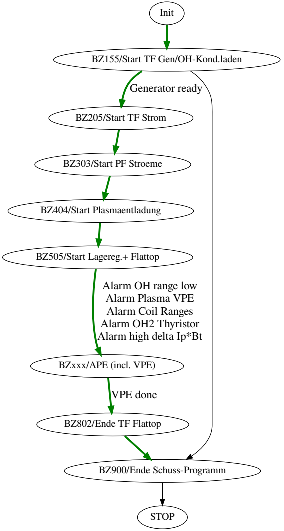
- The graph on the right illustrates the segment sequence of a typical ASDEX Upgrade discharge.
    - Ellipses represent segments. BZ505 is the main segment containing the plasma discharge after breakdown.
    - The arrows indicate possible segment transition.
    - The labels at the arrows indicate conditional segment changes.



Dynamic Pulse Scheduling

A simple example: The sequence during ramp-up and flat top is static.





Dynamic Pulse Scheduling - Exception Handling

- The capability to act on events during a discharge is important for current fusion experiments and will only gain importance / be essential for larger devices such as ITER.

- On ASDEX Upgrade exception handling is implemented using segments in combination with condition for segment changes.

- Exception handling provides the capability to
  - react on unwanted events that pose a potential risk.
    - Disruption avoidance.
    - Handling of e.g. NTMs.
    - Plant failures.
  - react on expected events in order to
    - control the desired discharge sequence
    - aid the experiment (scenario setup, physics investigations, ...)

Examples: Disruption Avoidance

Disruption Avoidance

- Disruptions, a sudden loss of plasma confinement, induce significant thermal and mechanical loads onto the device.
- Disruption mitigation techniques such a scattered pellet injection (SPI) are foreseen for ITER to mitigate the impact of a disruption.
- Disruption avoidance aims to prevent the plasma from becoming disruptive via
  - continuous control.
  - exception handling.

Disruption Avoidance

- Both disruption avoidance and mitigation require
  - an observer which detects a critical state.
  - a suitable actuator.
  - a decision logic which can issue the correct response.
- In case of continuous control a suitable controller is required.

Examples: Disruption Avoidance

H-Mode Density Limit

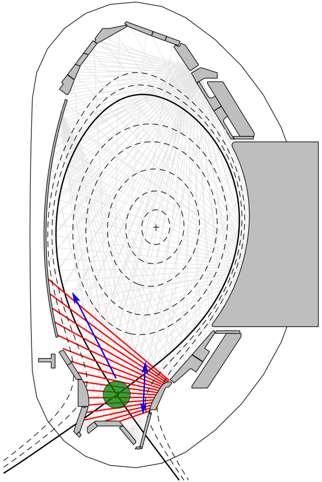
Disruption Avoidance - H-Mode Density Limit

- H-Mode (High Confinement Mode) discharges exhibit a disruptive operation limit at high densities.

  But: Operation at high density is required for a fusion reactor.

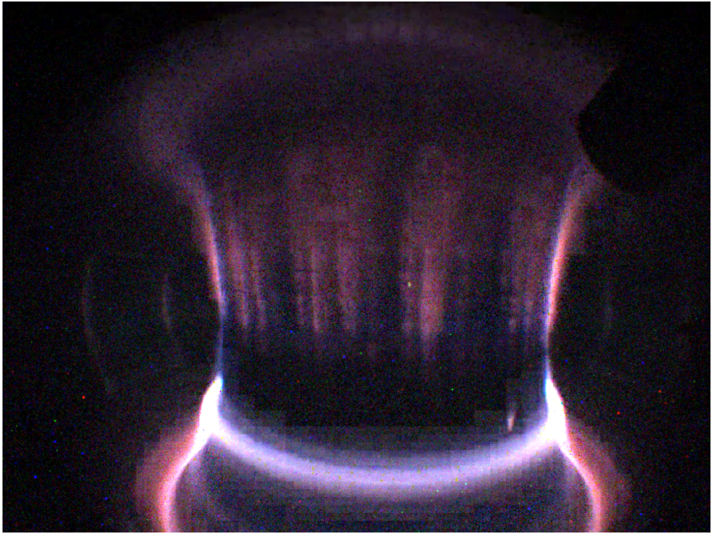
- The H-Mode density limit (HDL) is commonly preceeded by a radiative phenomenon the so called X-Point Raditor (XPR) / MARFE. (See green area in the illustration).

- The location of the XPR/MARFE is reconstructed in real time using the mesaurements from fast photo diodes (red lines).



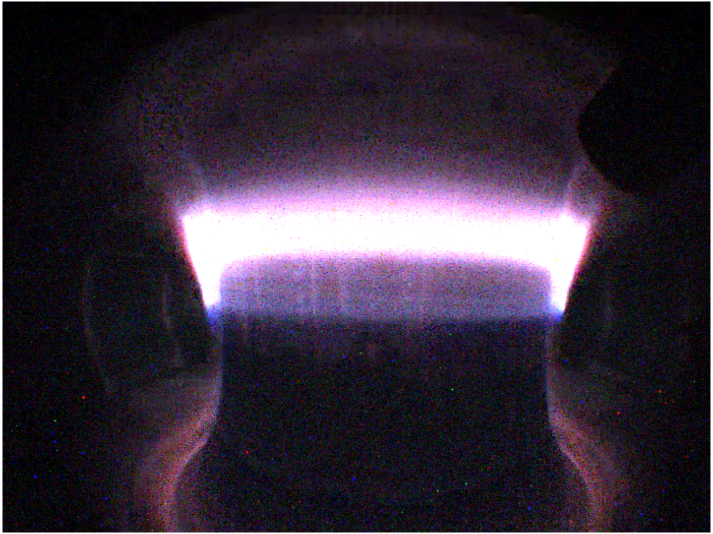
Disruption Avoidance - H-Mode Density Limit

- The measurements can be used for continuous control and as input for the decision logic.
- For disruption avoidance different actuators have been tested, avoiding the disruption, once the XPR/MARFE position exceeded a certain threshold.



Disruption Avoidance - H-Mode Density Limit

- The measurements can be used for continuous control and as input for the decision logic.
- For disruption avoidance different actuators have been tested, avoiding the disruption, once the XPR/MARFE position exceeded a certain threshold.
- Validated actuators:
  - Auxiliary heating.
  - Gas flow.
  - Upper triangularity.

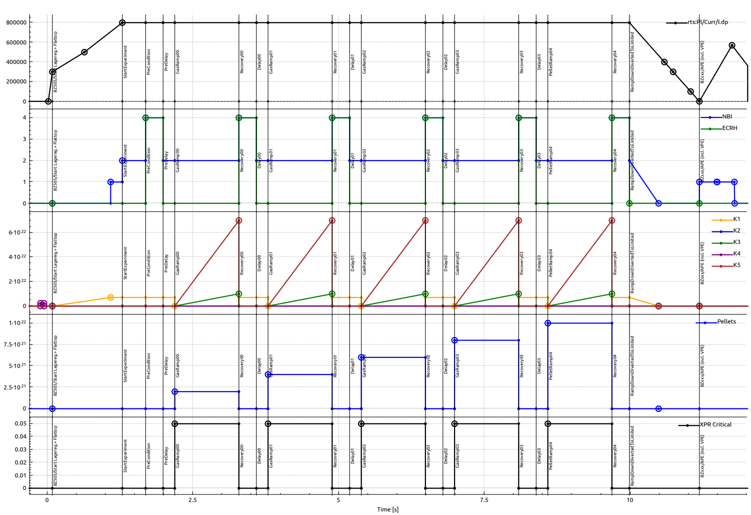


Examples: Disruption Avoidance

H-Mode Density Limit - Multiple Experiments

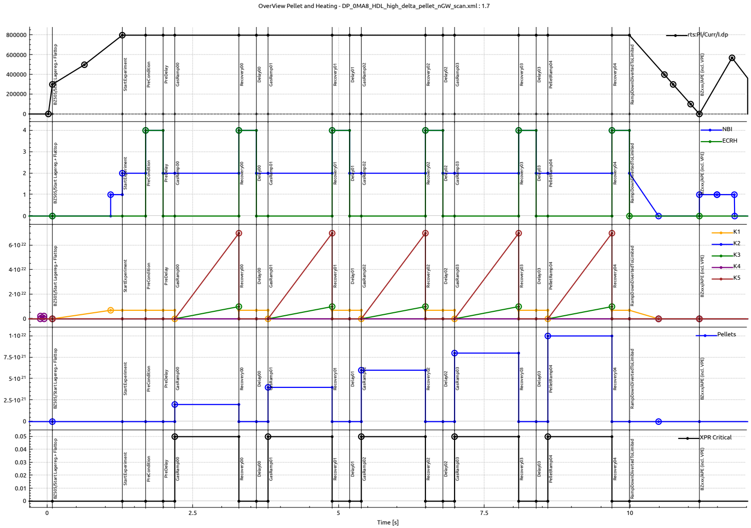
Disruption Avoidance - H-Mode Density Limit

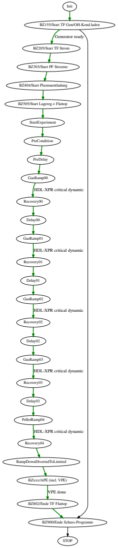
OverView Pellet and Heating - DP_0MA8_HDL_high_delta_pellet_nGW_scan.xml : 1.7



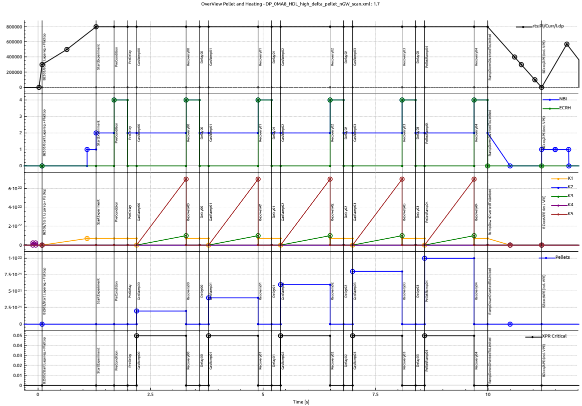
- Avoiding the disruption allows multiple experiments within one discharge.
- The example shows the planned schedule for multiple gas ramps with increased constant fuelling via pellets.
- The critical XPR threshold is always set to 5 cm.
- Avoidance is performed via auxiliary heating in this case.

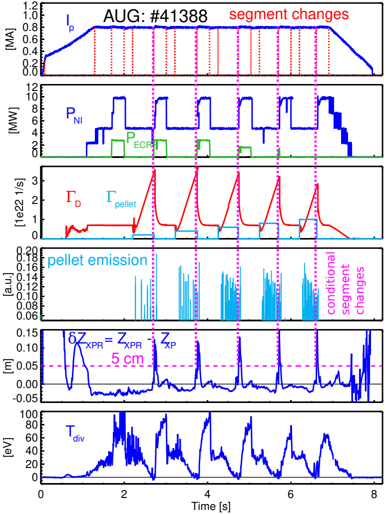
Disruption Avoidance - H-Mode Density Limit





Disruption Avoidance - H-Mode Density Limit



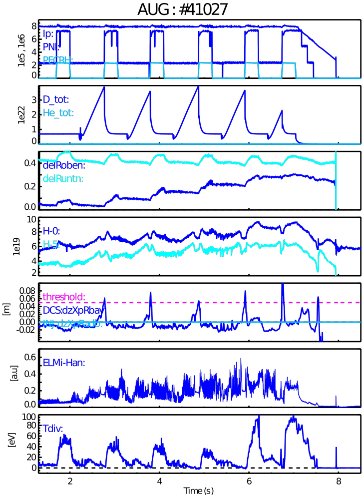


- Discharge was executed as planned. Duration was shorter then the nominal length due to dynamic segment changes.
- Detection of the XPR and avoidance is robust.

Examples: Disruption Avoidance

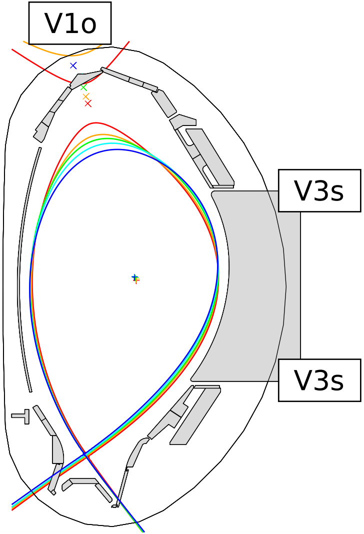
H-Mode Density Limit - Triangularity

HDL - Influence of triangularity on XPR: Intro



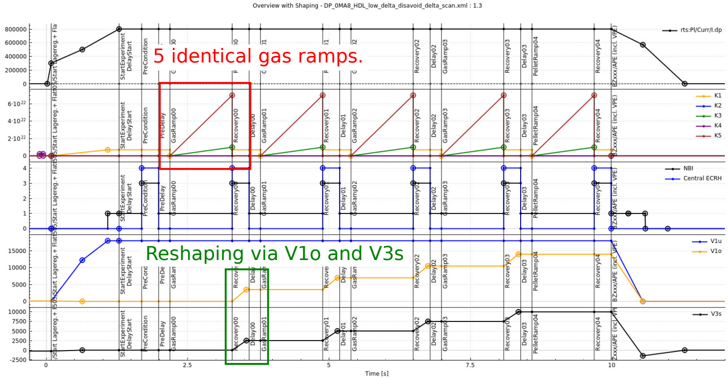
- Strong influence of upper triangularity on tolerable gas flow observed.
- Less gas needed to reach the HDL at high triangularity.

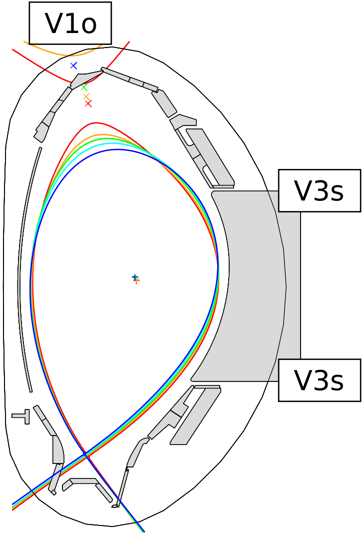
→ Investigate upper triangularity as actuator.



HDL - Influence of triangularity on XPR: Pulse Schedule

Step wise scan of upper triangularity.





HDL - Influence of triangularity on XPR: Pulse Schedule

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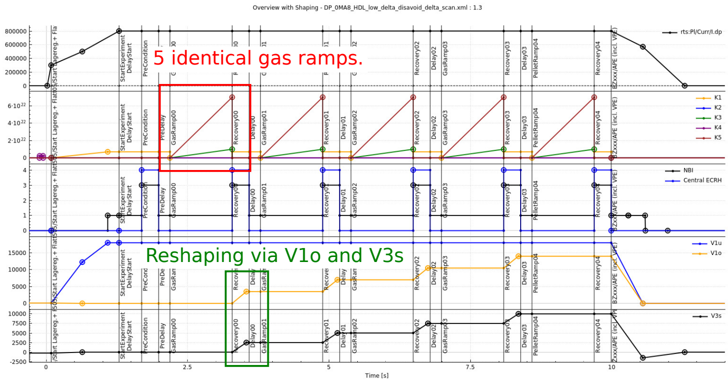

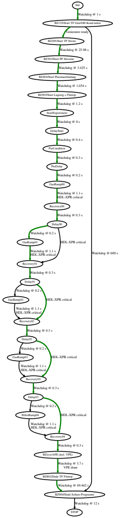

HDL - Influence of triangularity on XPR: Pulse Schedule

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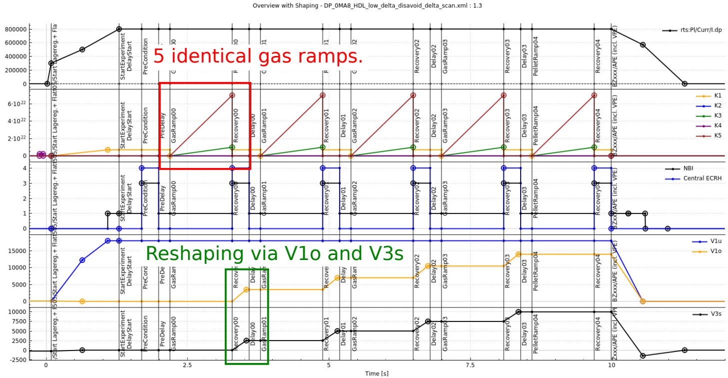
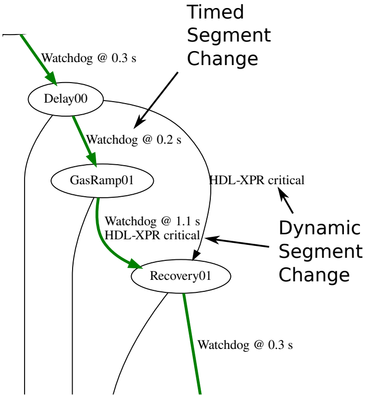
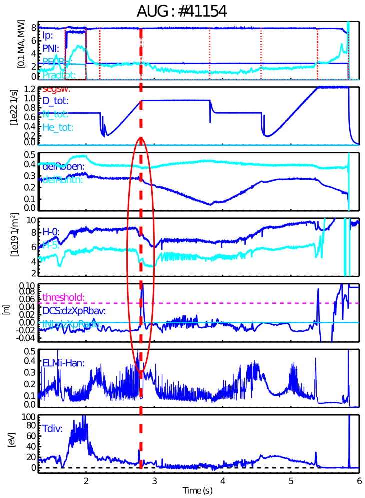
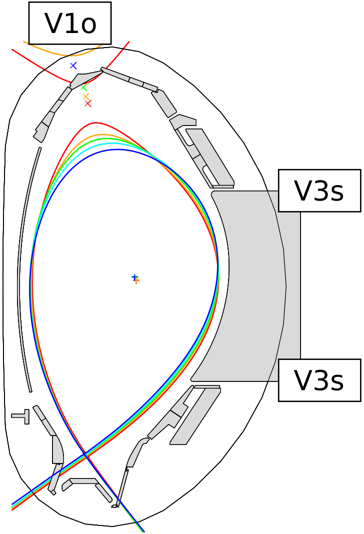




HDL - Upper triangularity as actuator



- Start with high upper triangularity.
- Gas ramp until XPR is critical.
- Freeze gas and reduce upper triangularity.
- XPR becomes uncritical → disruption avoided.

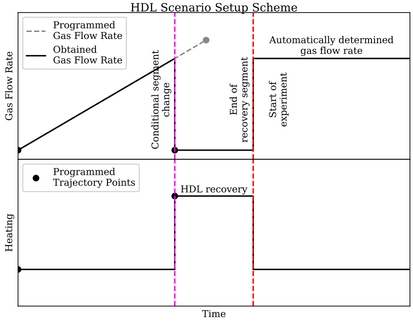


Examples: Disruption Avoidance

H-Mode Density Limit - Automated setup

H-Mode Density Limit - Automated scenario setup

- The onset of the H-Mode density limit depends on the actual machine conditions (impurity content, wall conditioning, ...).
- In case no feedback control is established yet an automated scenario setup is desired to increase reproducibility.



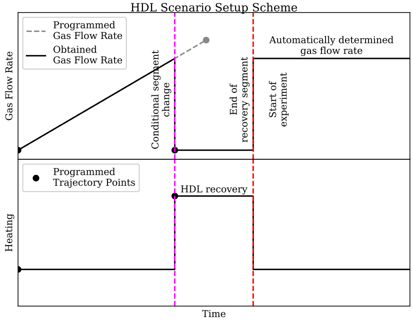
H-Mode Density Limit - Automated scenario setup

1. Gas ramp until HDL (e.g. XPR) is detected.

2. Pass last value of gas and heating reference to the avoidance segment.

3. Avoidance segment:
   - applies heating and reduces gas.
   - passes references it got from the previous segment to the next.

4. Next segment contains no trajectory points
   $\rightarrow$ Dynamically determined gas flow for HDL is set.



Examples: NTM Studies

Example - NTM Studies

- Neoclassical tearing modes (NTMs) appear at sufficiently high β and are detremental to the confinement.
- Robust triggering of NTMs is desired to enable experimental studies.
- Triggering on ASDEX Upgrade by application of sufficient heating power.
- Reaction on mode appearance to avoid a disruption.

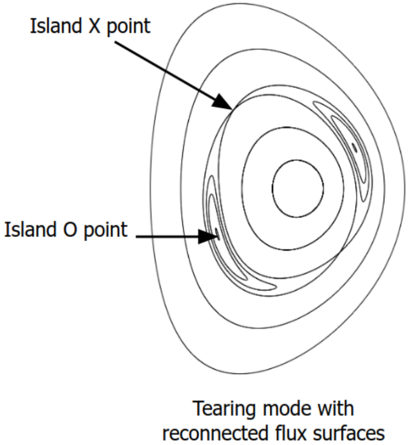
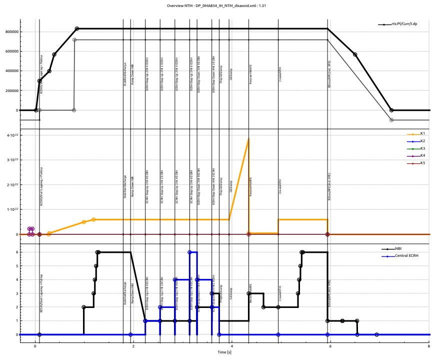


Figure: F.Felici, PhD thesis, 2011

Example - NTM Studies - Pulse Plan

1. Trigger NTM
2. Stabilize NTM at reduced heating power.
3. Increase ECRH heating to slow the mode.
4. Replace ECRH by NBI to increase mode rotation if
    - mode has locked.
    - maximum ECRH power has been reached.
5. Suppress NTM using gas puff.
6. Retrigger NTM to compare influence of current profile.



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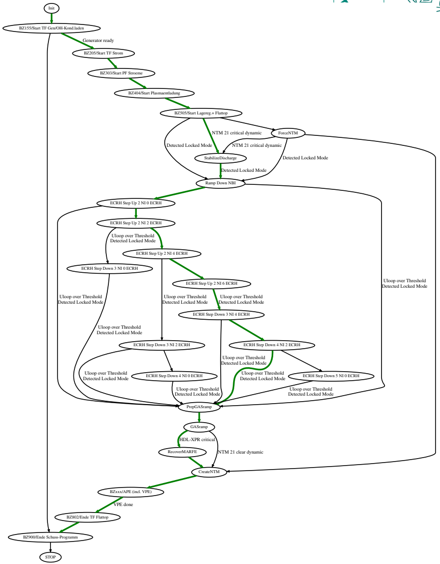
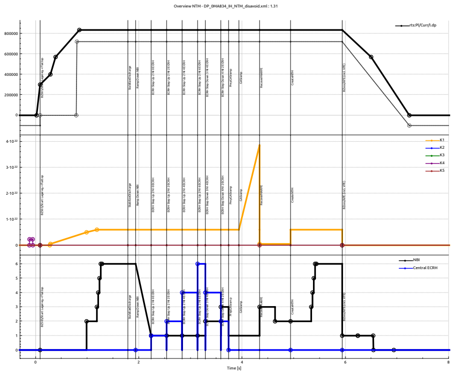
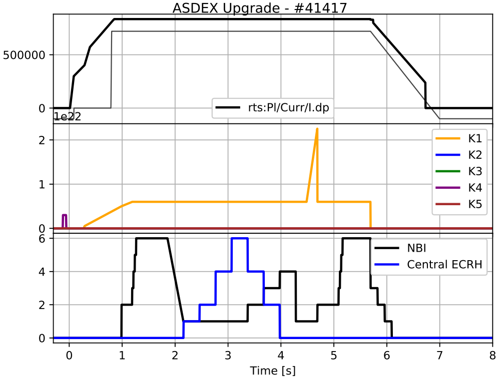


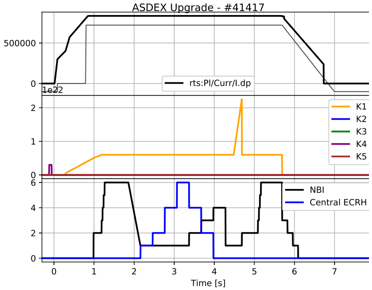
Example - NTM Studies - Plan vs Reality

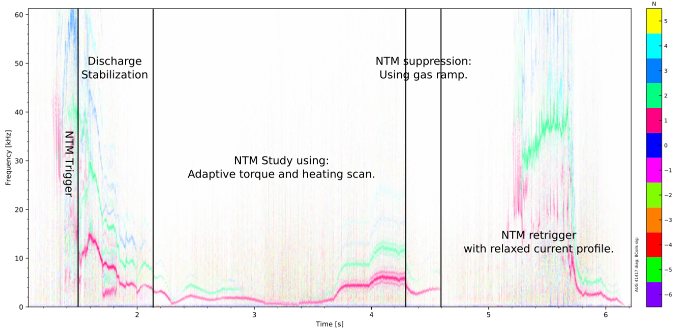




- The real discharge matches closely to the planed behaviour.
- Real pulse path is not known before the pulse.

Example - NTM Studies - Plan vs Reality





- 2/1 NTM triggered and mode rotation influenced as planned.
- NTM suppression via gas puff.
- Different NTM behaviour during retriggering → Influence of relaxed current profile.

Examples: Runaway Electrons

Example - Runaway Electrons

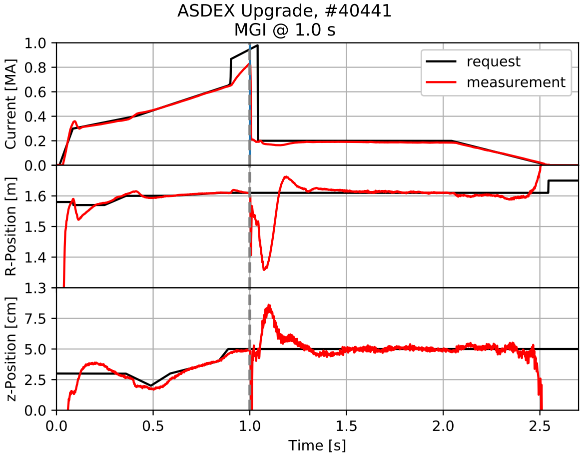
- During disruptions electrons can be accelerated up to relativistic energies. These electrons decouple from the main plasma and can form a *runaway electron* (RE) beam.

- For large fusion devices, like ITER, these RE beams are predicted to be up to several MA which poses a significant risk to plasma facing components.

- Stabilization and control of runaway electron beam desired to study e.g. benign termination.

Example - Runaway Electrons

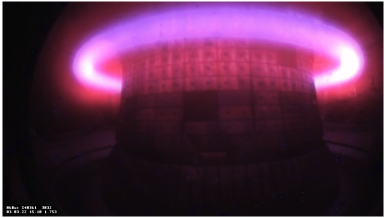
- On ASDEX Upgrade RE beams are triggered using massive gas injection (MGI) during the current ramp up of a circular limiter plasma.
- Disabling vertical displacment event (VDE) detection is required to allow stabilization of RE beam.
- Position, current and shape of RE beam can be controlled.
- Controlled current ramp down possible.



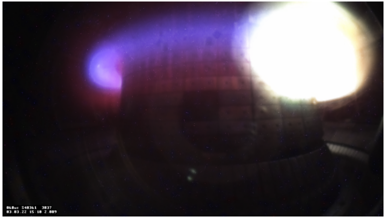
Example - Runaway Electrons

- Sustained control of the RE beam allows study of benign termination.
- Non benign termination leads to high electron energies (see synchrotron radiation) and localised loads onto the first wall.
- Benign termination aims to de-confine the RE isotropically to avoid localised heat loads.

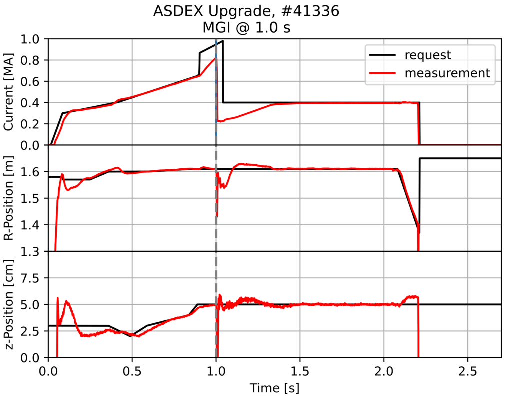
#40361: Stabilized RE Beam



#40361: Non benign termination.

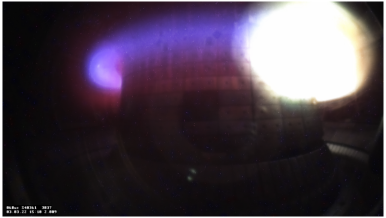


Example - Runaway Electrons

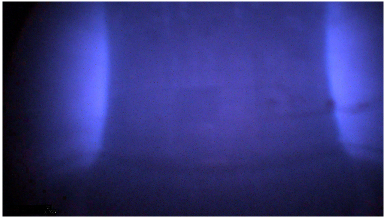


- RE beam (reduced R_{curr} request).
- Feedback control of the neutral gas pressure during RE phase.

#40361: Non benign termination.



#41336: Benign termination.

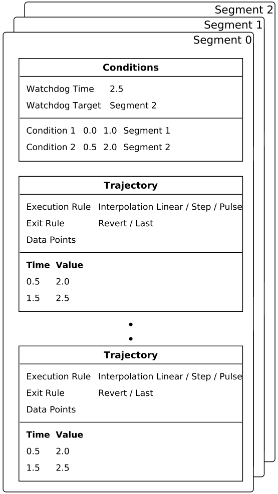


Conclusions and Lessons Learned

Conclusions

- Dynamic pulse scheduling is a powerful tool combining
  - exception handling.
  - continuous control.

  and enabling
  - disruption avoidance.
  - more complex experiments.
- The combination of segments and conditions allows complex pulse schedules using *simple* building blocks.

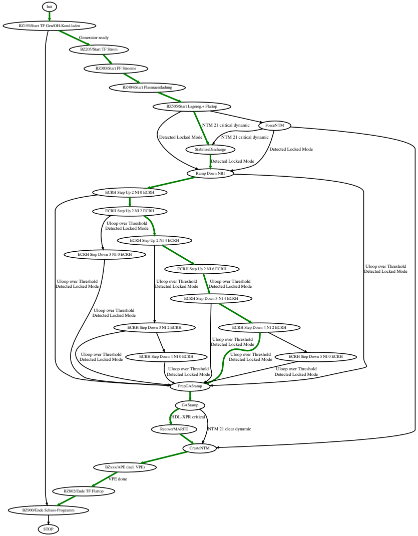


Lessons Learned

- Complex pulse schedules require
  - time and expert knowledge for the development.
  - good visualisation / tools.

- Robust discharges can be achieved by putting exception handling at the critical phases.

  An all knowing decision logic is not essential.



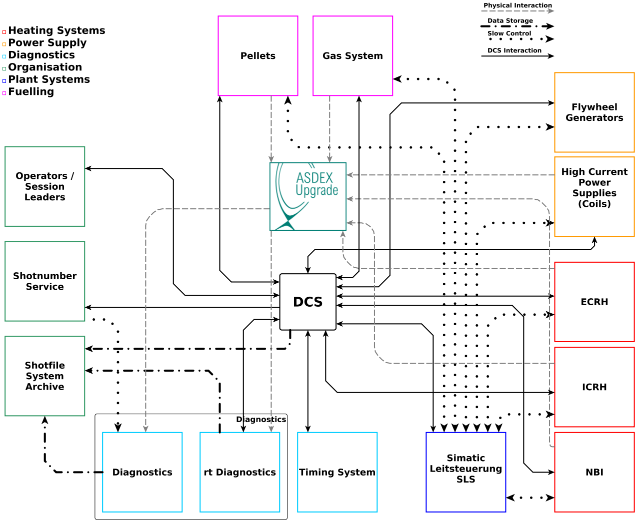
Discharge Control System (DCS)

ASDEX Upgrade is operated using the **D**ischarge **C**ontrol **S**ystem (DCS).

- DCS is not a monolithic system but is implemented using micro services.
- The system uses both off the shelf solutions as well as custom components.
- The majority of custom services are implemented in C++.
  Core DCS has 260k lines of code.
  AUG DCS has 200k lines of code.
- Aims to define its behaviour via configuration.
- Provides mechanisms for modular extensions.

Interconnection overview (not complete, DCS *internals* not shown)

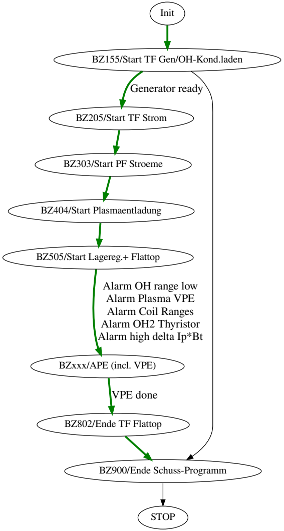
- DCS is connected to various systems of ASDEX Upgrade.
- Many connection types are required / supported.
  - Slow control (e.g. state information).
  - Event notifications.
  - Real time connections (e.g. heating requests).
  - Configuration management.
  - Offline storage.



Dynamic Pulse Scheduling

A simple example: The sequence during ramp-up and flat top is static.

- The dynamic part of the pulse schedule here is used to
  - start the toroidal and poloidal field sequence once the flywheel generator are ready.
  - trigger the automated ramp down in case of an *Alarm*.
  - indicate the completion of the automated ramp down.
- Dynamic pulse scheduling enables more sophisticated discharges including exception handling.



DCS - Control Task

- The control task aims to keep the plasma in the desired state (e.g. position, shape, density, etc.).
- DCS operates with control cycles ($t \sim 1\,\mathrm{ms}$) during which
  - the diagnostics publish their latest measurements.
  - the plasma state is reconstructed (e.g. equilibrium, position, ...).
  - control requests are calculated and issued to the actuators.
  - the actuators act onto the plasma.