THE WENDELSTEIN 7-X ECRH PLANT - EXPERIENCE WITH RELIABLE LONG PULSE OPERATION OF A MULTI MW GYROTRON INSTALLATION

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Wendelstein 7-X

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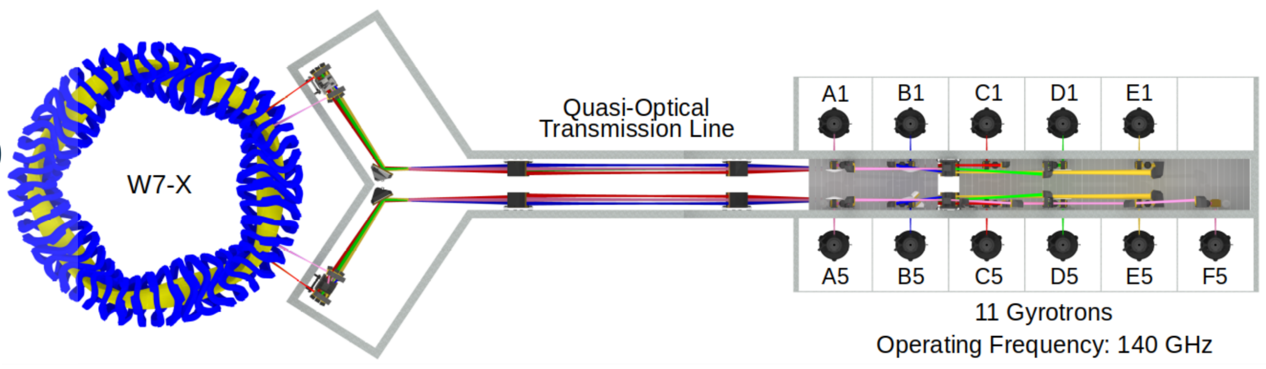
INTRODUCTION

W7-X 10MW ECRH plant

- 11 gyrotrons
- CW operation (1800s)
- Total power ⇒ 8.5MW in torus
- Quasi optical transmission line



Gyrotron reliability

- Automatic recovery systems in case of
  - Mode loss ⇒ Acceleration voltage is reduced to operate reliably at max. power
  - Overcurrent on body ⇒ Body voltage is switched off for a few ms
  - Arcing ⇒ Gyrotron is switched off for ~100ms
- Hardening of transmission line to prevent arcing

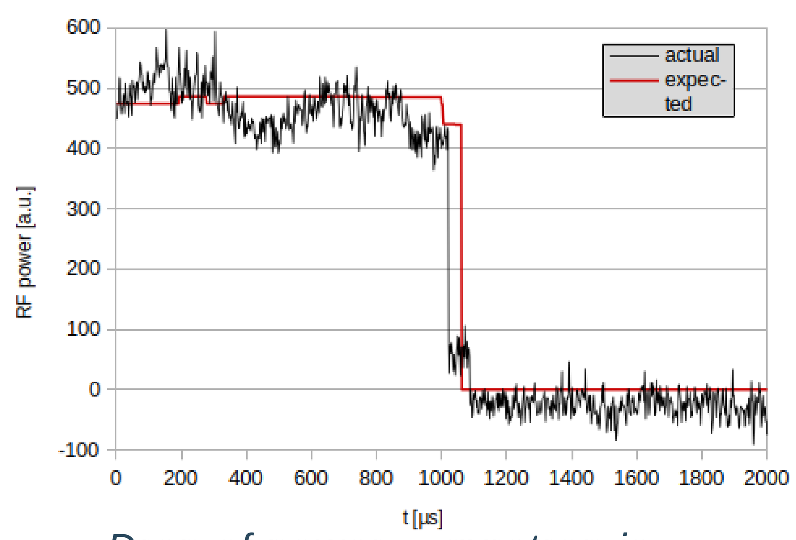
System level reliability

- High performance plasma scenarios require sufficient power continuously
- Lost power must be compensated
- New concept tested in OP2.3 ⇒ total power feedback control

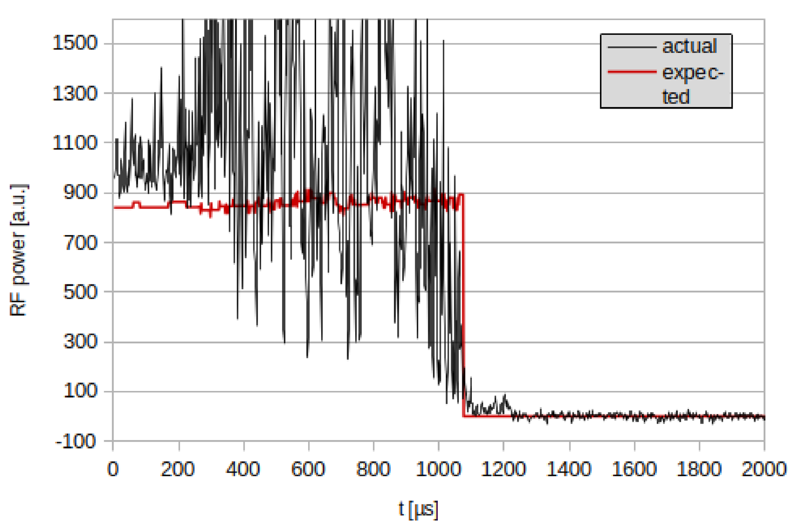
FASTER ARC DETECTION

- Fast arc detection crucial for reliable operation
  - Fully developed arc pollutes atmosphere ⇒ all gyrotrons affected
  - Risk of further arcs strongly increased
- Classical arc detection: optical fibre viewing at mirror surface
  - Only fast enough if arc develops at mirror surface
- Faster arc detection by power measurement at end of transmission line
  - Comparison with power measured at MOU
  - Sensitive to arc at any position
  - Detection within some 10 µs possible
- Installed for almost all W7-X gyrotrons
- OP2.2/2.3 used to gain experience with system
- Arcs close to detector system cause strong fluctuations
  - Stray radiation due to multiple reflections of beam at arc and metallic surfaces enters detector
- Arc detection algorithm only reacts on loss of signal (absolute threshold)
- New version reacting on amplitude of high pass filtered signal planned for OP2.4

Comparison of actual and expected power at end of transmission line



Drop of power ⇒ gyrotron is switched off within 20µs

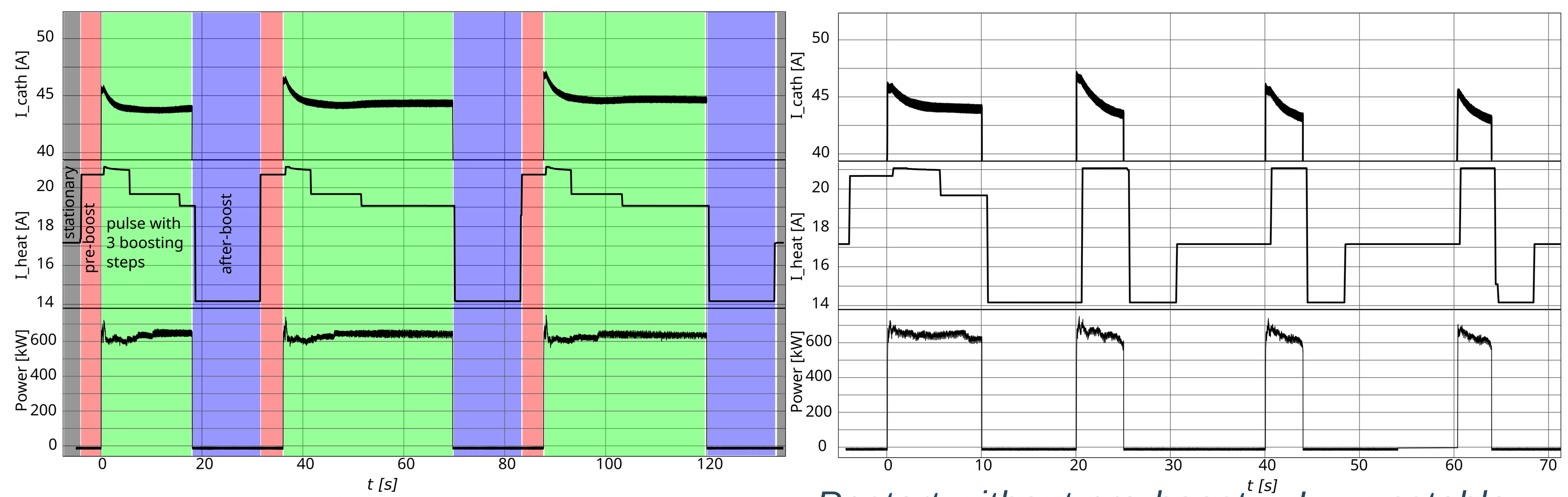


Strong fluctuations due to stray radiation entering detector ⇒ gyrotron is switched off after >1ms

CATHODE HEATER BOOSTING

- Cathode current I_{cath} drops exponentially due to cooling by electron emission
- Compensated by actively boosting heater current
- Boosting has to start 5s before pulse (pre-boost)
- Surplus energy in heater extracted by reducing current after pulse (after-boost)
- Lost gyrotron cannot be replaced by spare one immediately
- Restart scenarios for tripped gyrotrons during a pulse:
  - Within <3s ⇒ compatible with automatic restart attempts
  - Full cycle of after- and pre-boost, typically >20s

Comparison of different boosting schemes when restarting a gyrotron

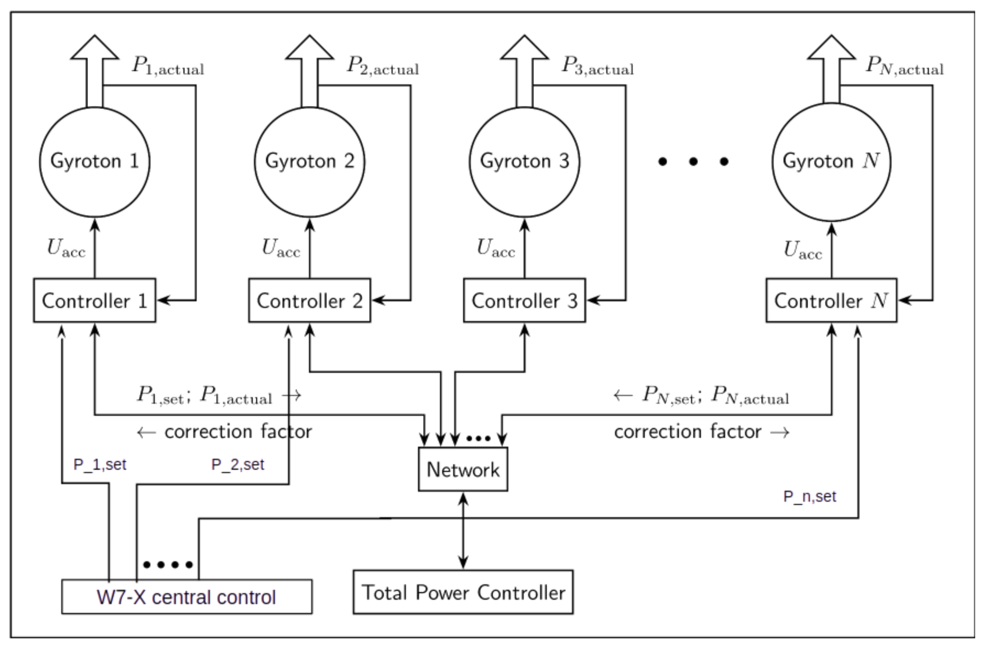


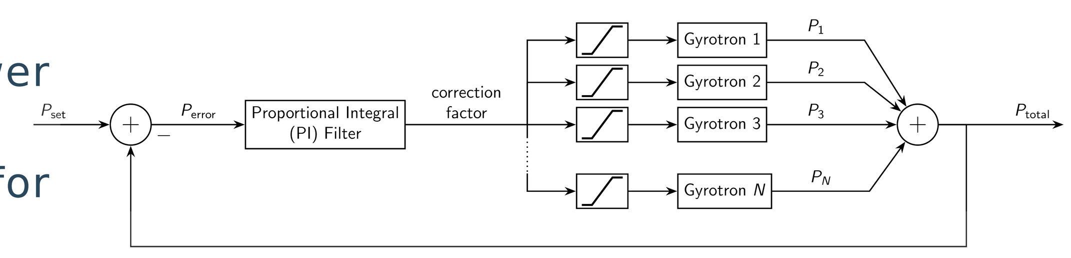
Restart with after- and pre-boost ⇒ I_{cath} stable

Restart without pre-boost ⇒ I_{cath} unstable, mode loss after a few seconds

TOTAL POWER FEEDBACK CONTROL

- Basic idea ⇒ Equally increase power of all gyrotrons if one is lost
- Gyrotron power: $P_{ECRH} \propto V_{acc}$
- HV supplies act as amplifiers ⇒ set point generated by FPGA based controller
- Software based feedback control on top of individual gyrotron control
- Implemented on RaspberryPi
- Ethernet communication with gyrotron controller
- Input ⇒ actual power, power set point
- Output ⇒ correction factor for power set point





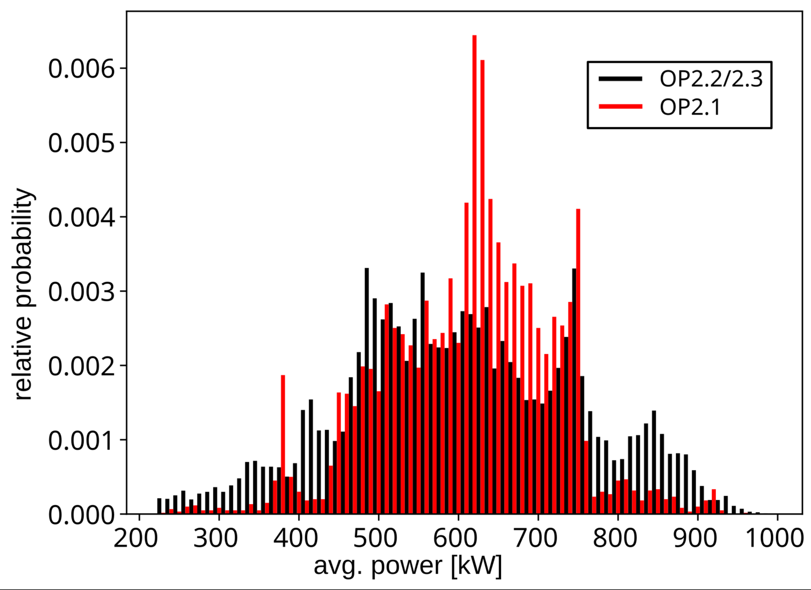
- All gyrotrons are operated at 80…90% P_{max} ⇒loss of 1 or 2 gyrotrons can be compensated
- PI feedback controller increases power in ~100ms after loss of gyrotron

PERFORMANCE IN OP2.2/2.3

4300 W7-X experiment programs ⇒ 99% successful

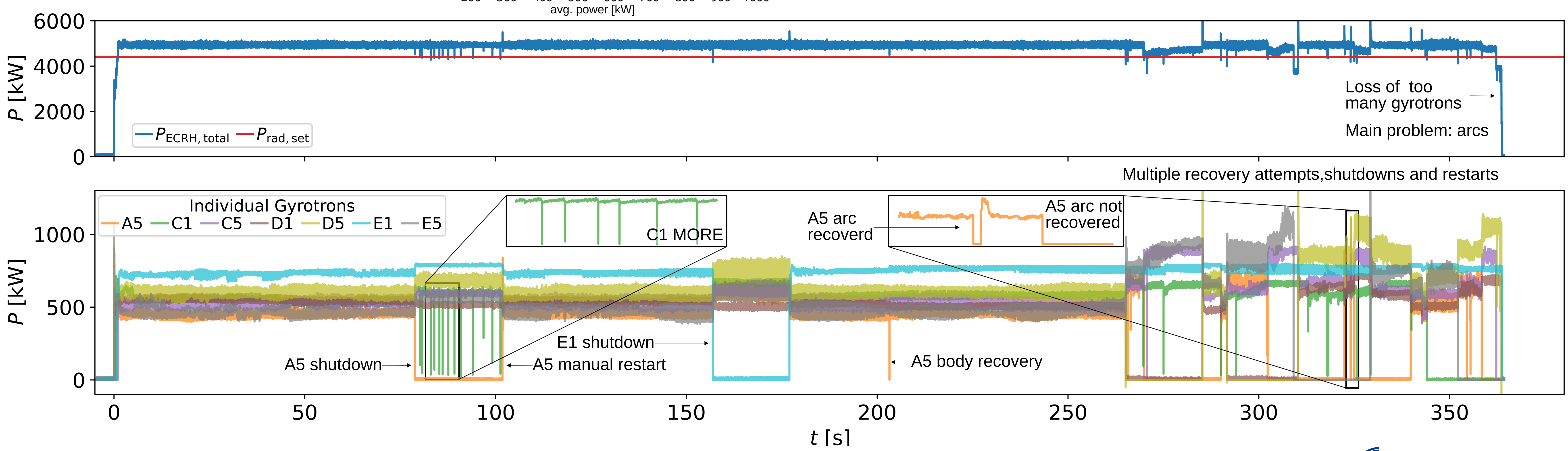
Gyrotron reliability

- More than 14000 individual gyrotron pulses
- 94% of pulses ran through without failure (92.4 in OP2.1)
- Average power during pulse increased



System level reliability

- Envisaged milestone in OP2.3 ⇒ 2GJ energy turnaround
- Achieved ⇒ 1.8GJ, 5MW total power for 360s with feedback control
  - Multiple automatic recovery intervertions ⇒ time scales irrelevant for plasma
  - Loss of 2 gyrotrons was compensated by feedback controller, constant total heating power for 270s
- Still problems with arcing after ~5min. high power operation
  - Thermal effect, further improvement of air conditioning planned for OP2.4



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