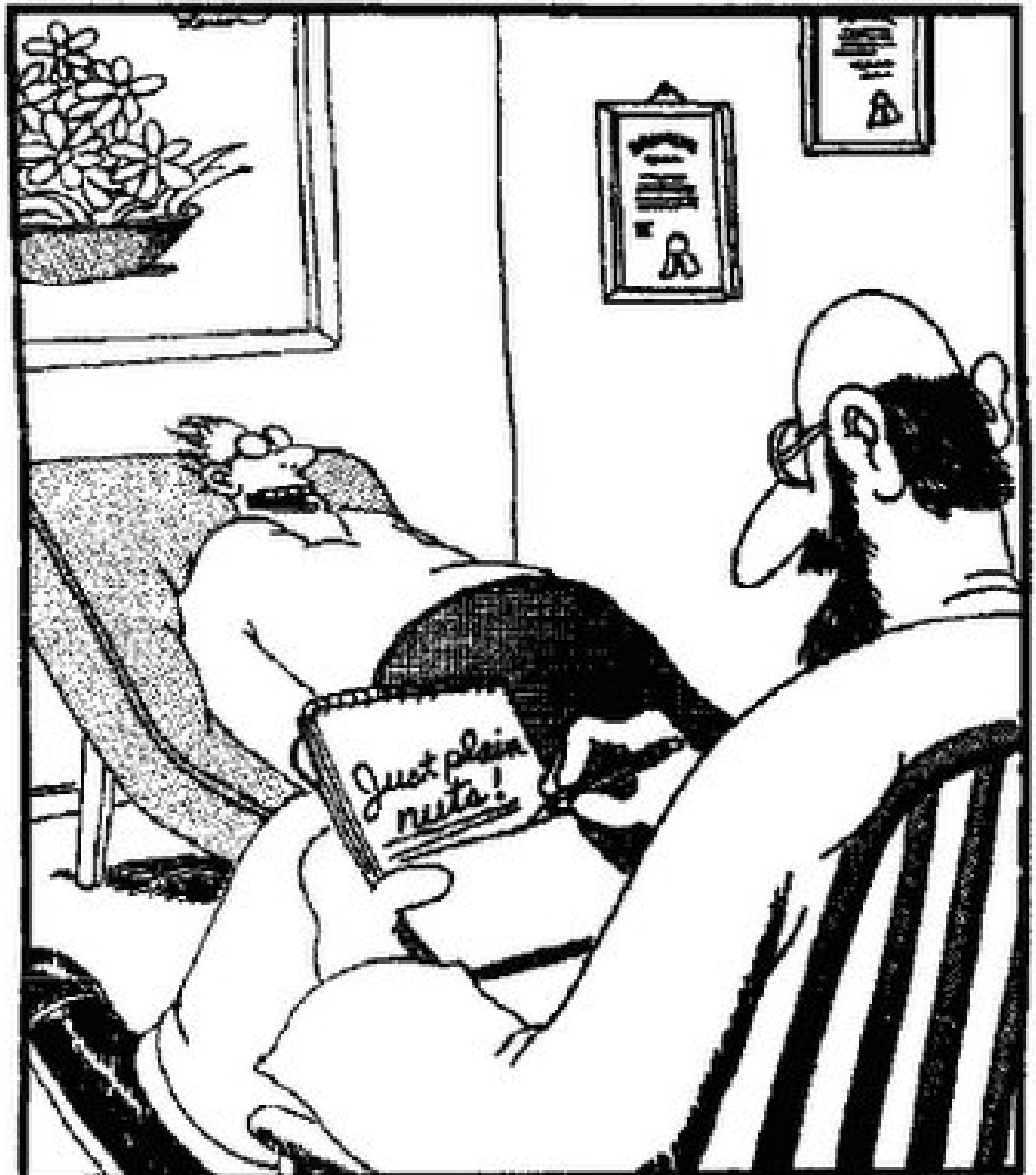
Dutch Nuclear Fusion program

Marco de Baar

A physicist's dream???



International landscape: Roadmap (1)

- Eurofusion consortium & Nuclear Fusion Roadmap
- ITER key facility in the roadmap.
- Solution for heat exhaust in fusion power plant needed. Probably main challenge towards realization of magnetic confinement fusion. ITER Baseline strategy cannot be extrapolated to fusion power plant.
- Aggressive programme on alternative solutions for the divertor is necessary. Some concepts are tested at proof-of-principle level. Technical feasibility in a fusion power plant is being assessed.

Roadmap (2)

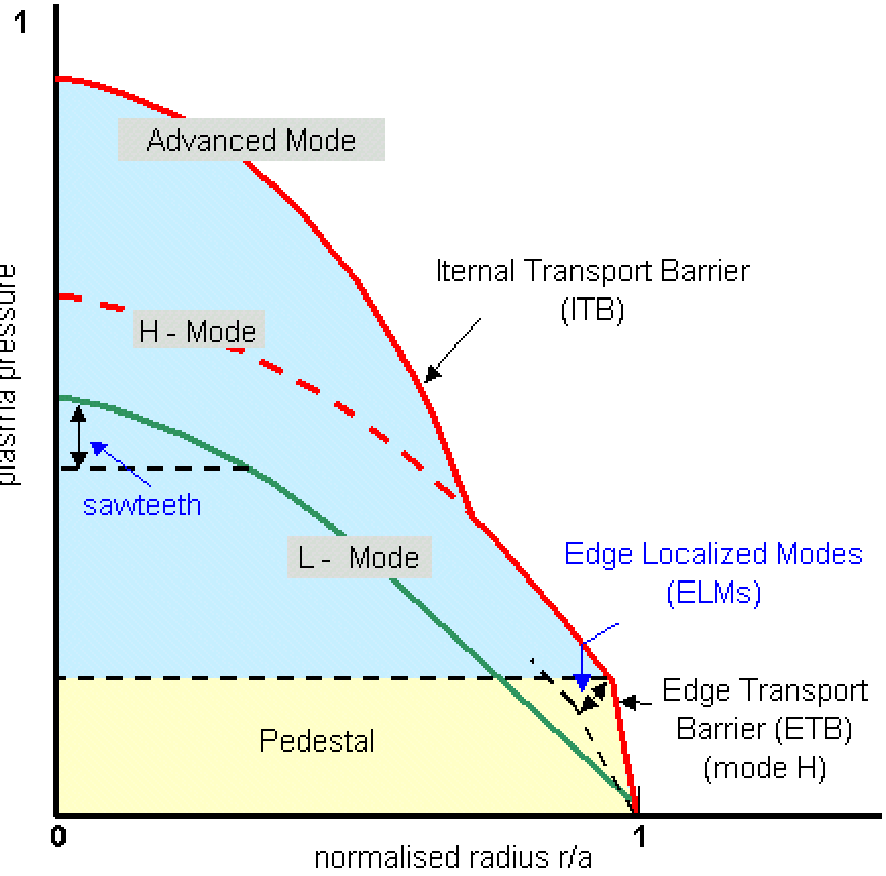
- Seeking synergy with programmes outside fusion for advanced materials
  - structural
  - plasma-facing and high-heat flux zones of the breeding blanket
  - divertor areas of DEMO.

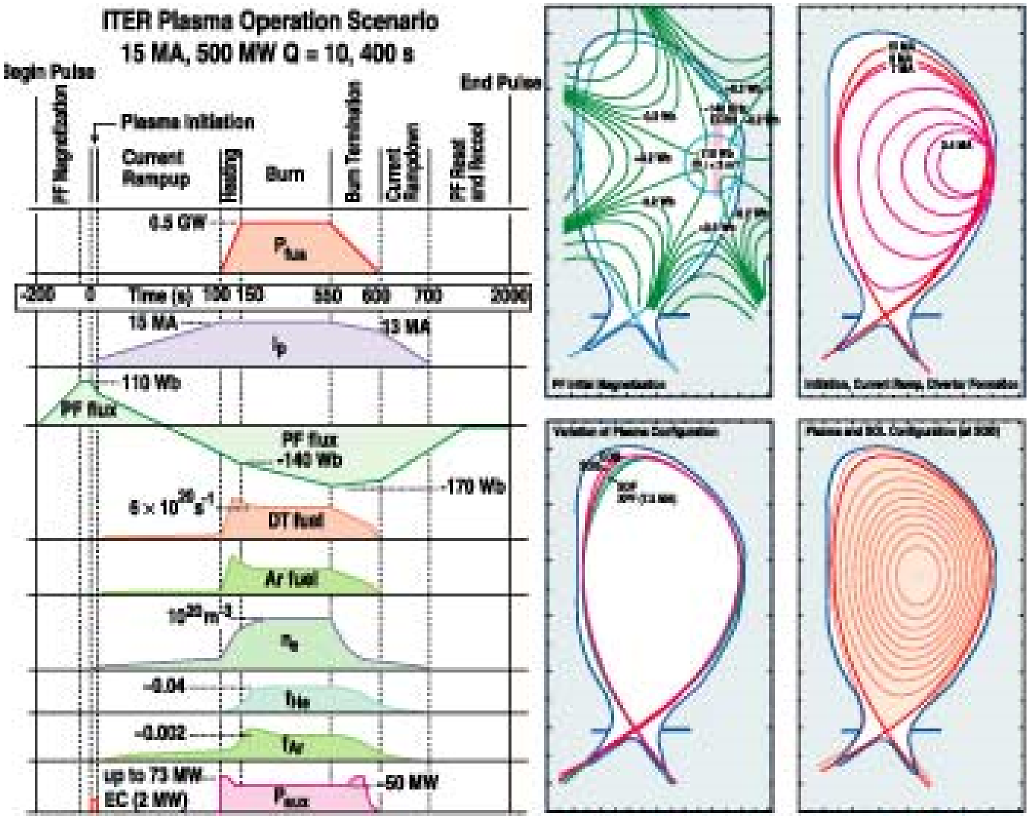
- Theory and modelling effort in plasma and material physics is crucial for the extrapolation of the core and edge plasma dynamics for both tokamaks and stellarators.

Thrusts in Roadmap

1. Plasma regimes of operation
2. Heat exhaust
3. Neutron resistant materials
4. Tritium self-sufficiency
5. Intrinsic safety
6. Integrated DEMO design
7. Competitive cost of electricity
8. Stellerator line to maturity

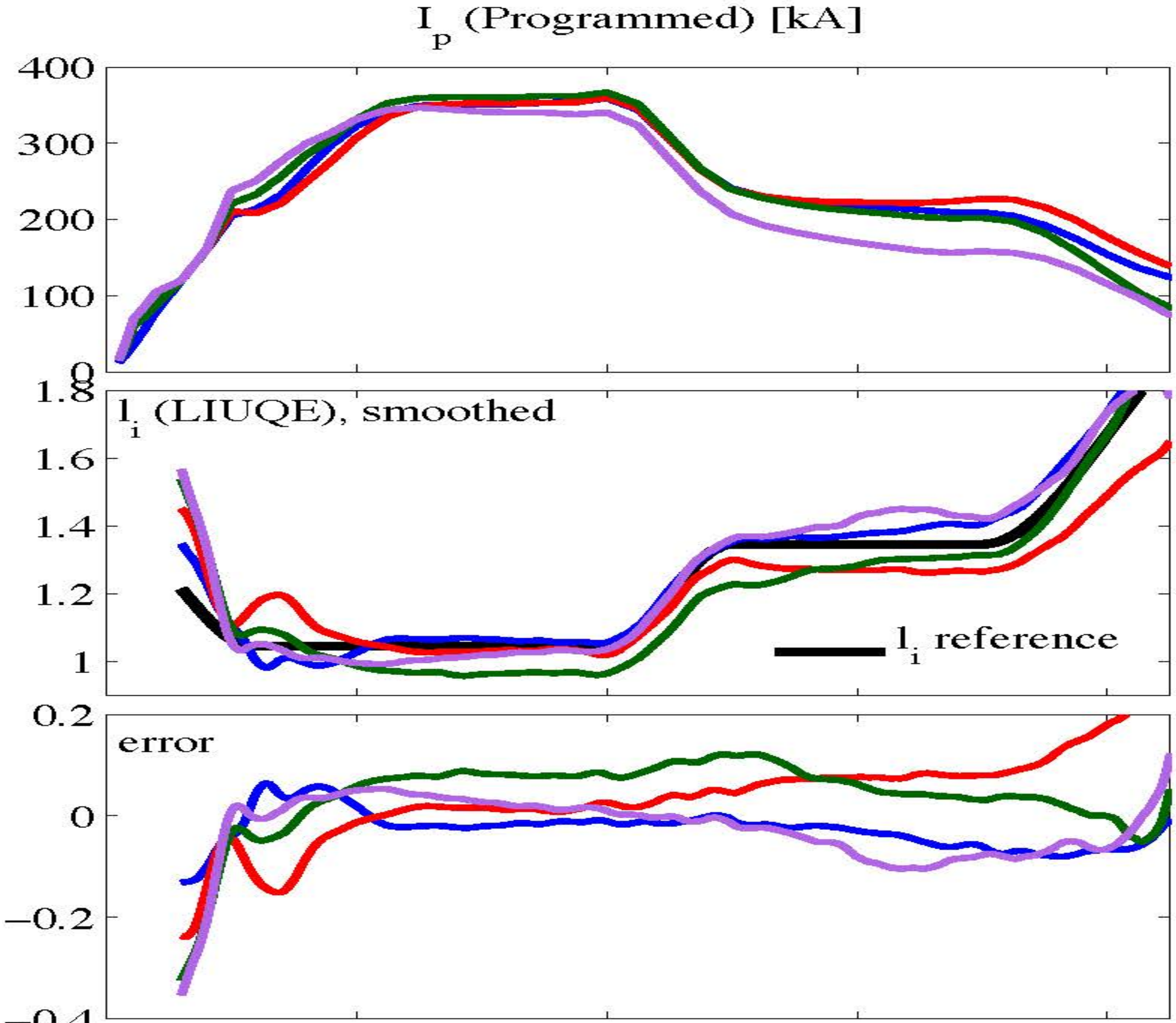
What is a plasma scenario?





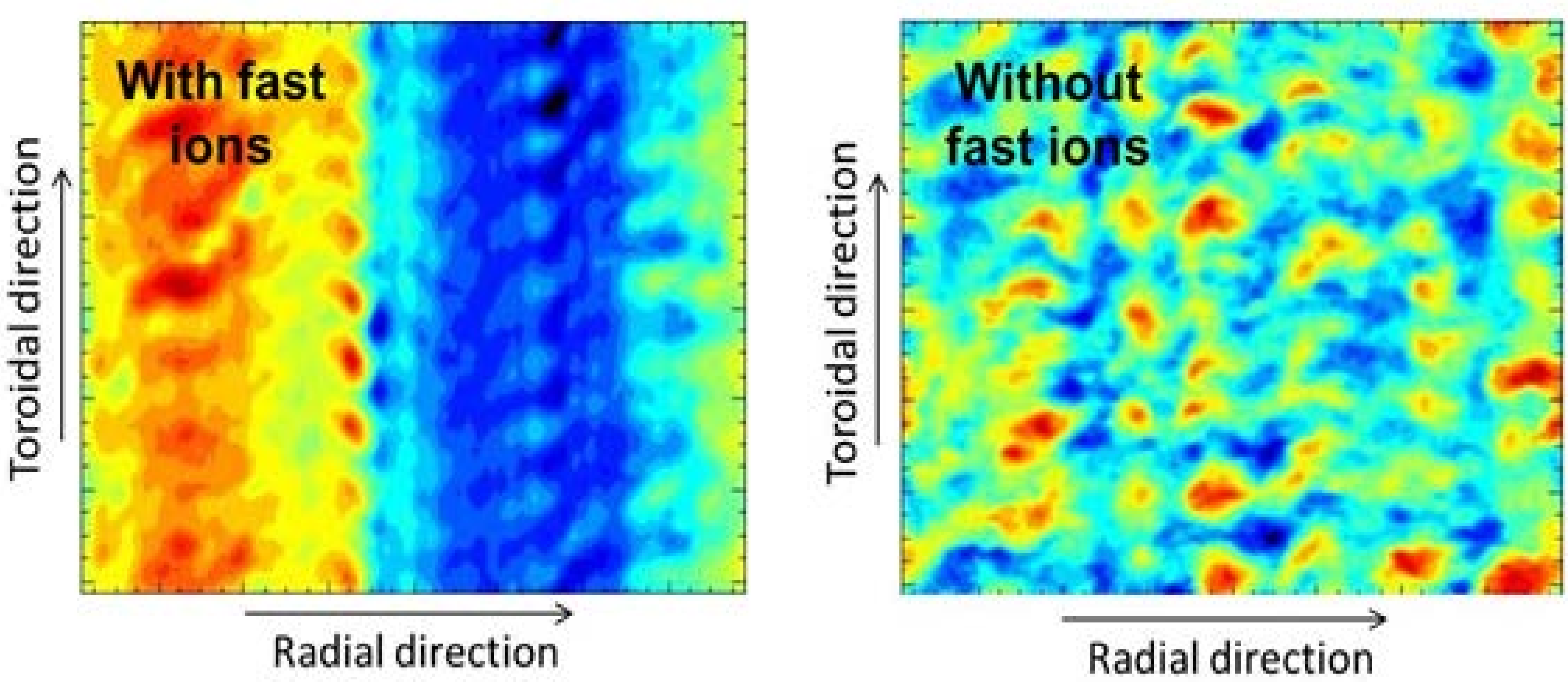
Courtesy General Atomics, DIII-D team

Model based scenario development ILC



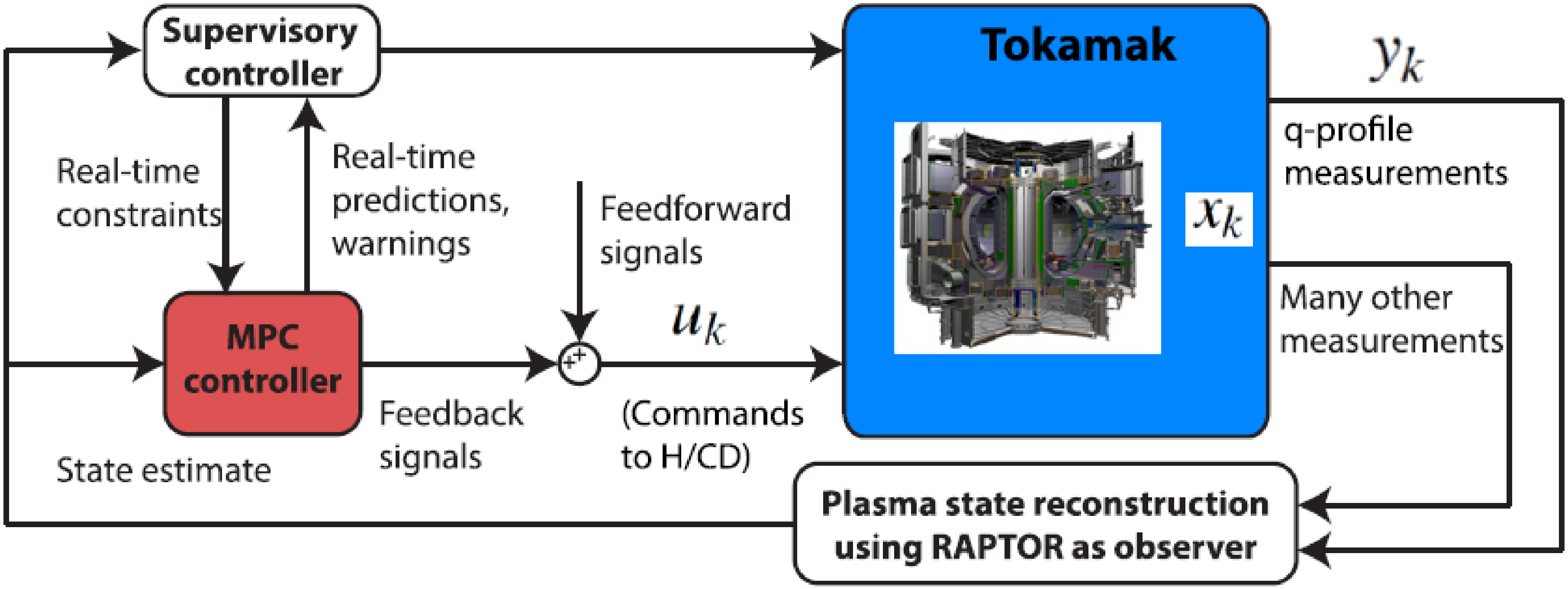
Physics approach: Effect fast ions on confinement. Signature of zonal flows

JET low-stiffness discharge 73224: ~60% suprathermal pressure at $\rho = 0.33$



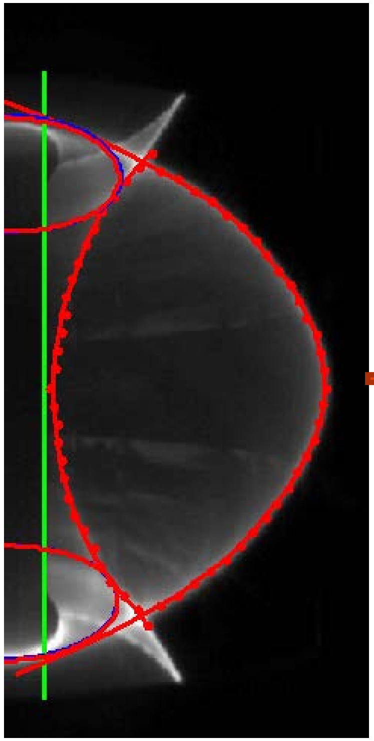
Contour plots of electrostatic potential from GENE EM-simulation: With fast ions, an stronger zonal flow component is clearly observed. Underlying physics of ZF coupling in EM system for future work.

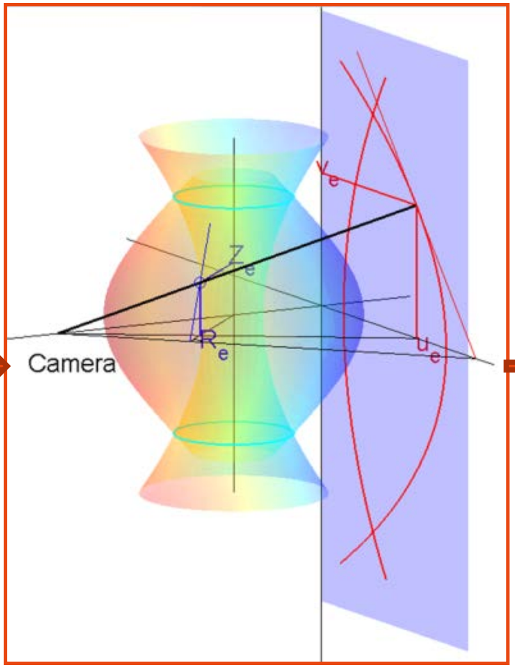
Engineering approach: Model predictive control of current distribution

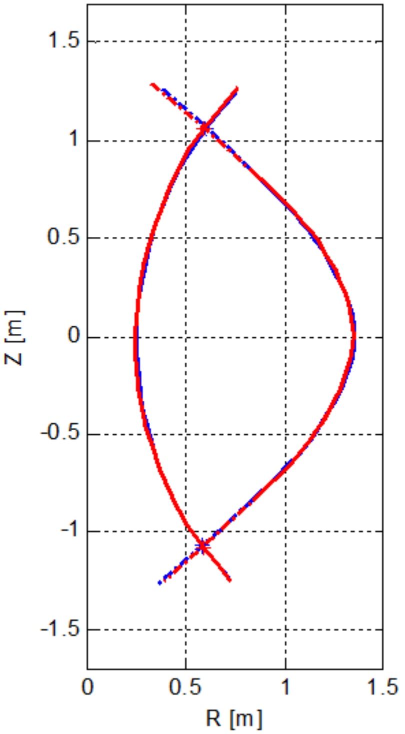


Optical plasma boundary measurement

Extract plasma edges, solve the geometry problem…

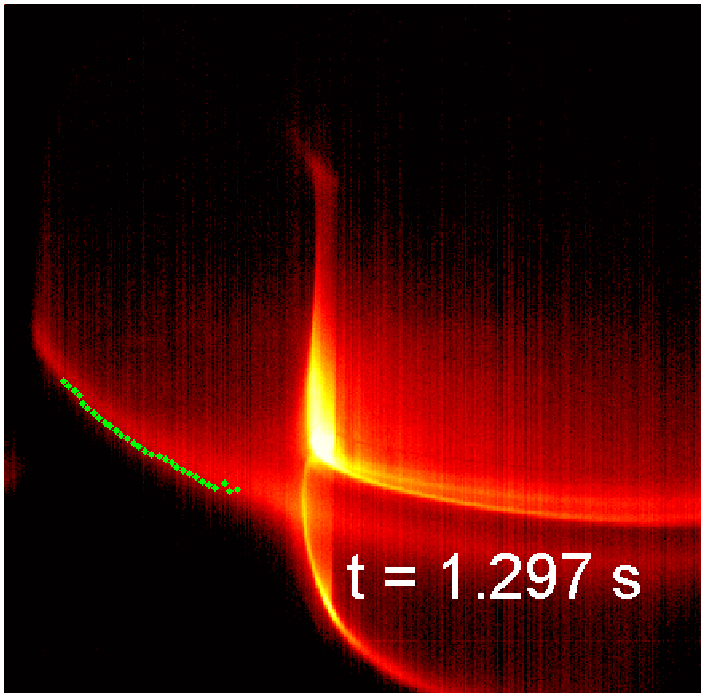


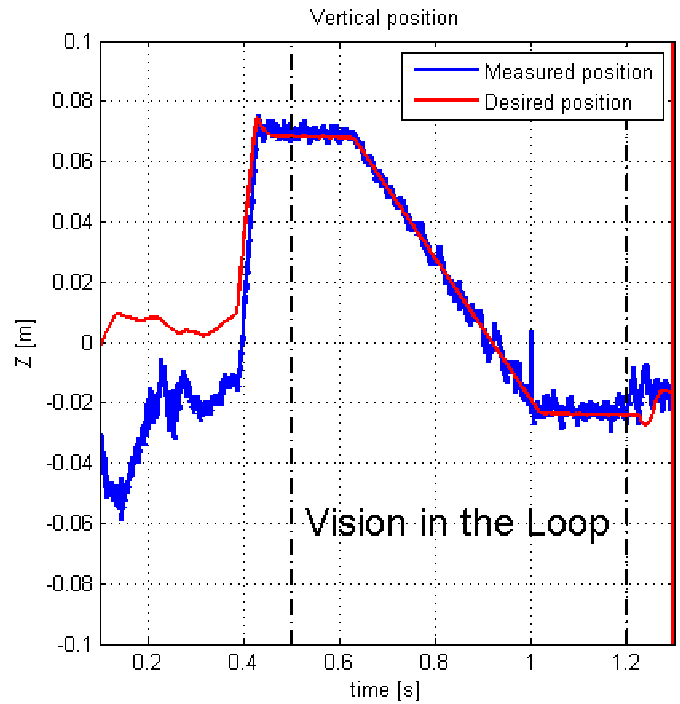


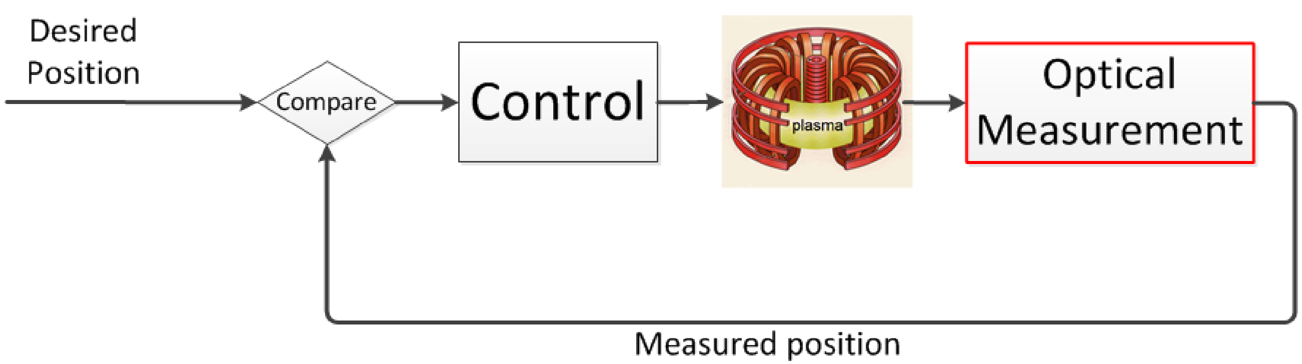


- …and we can measure the plasma boundary directly!

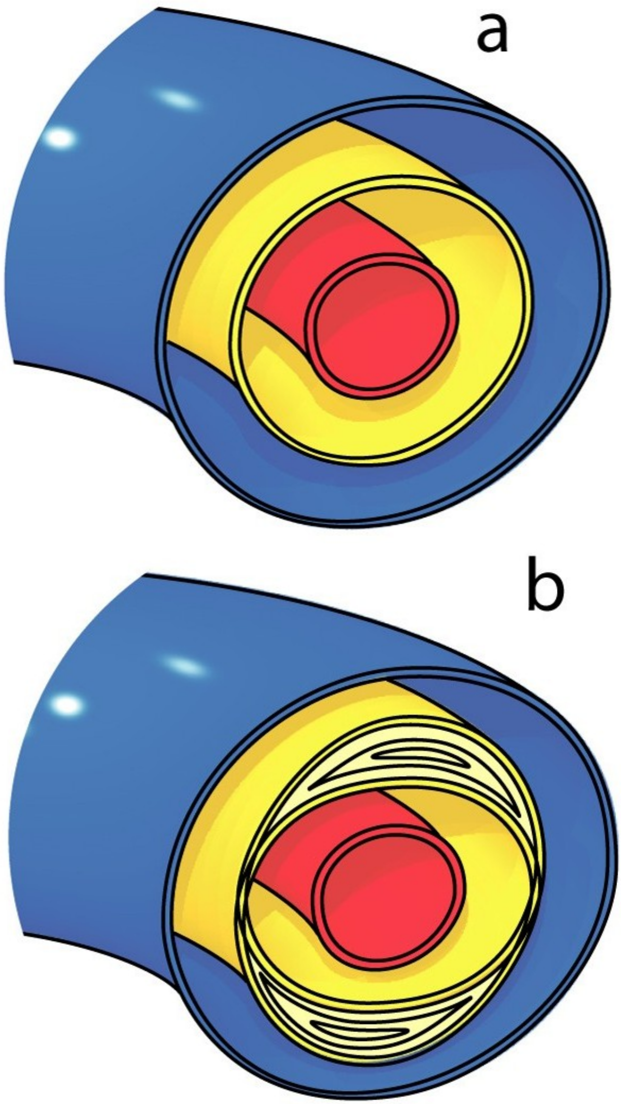
Vision in control loop!



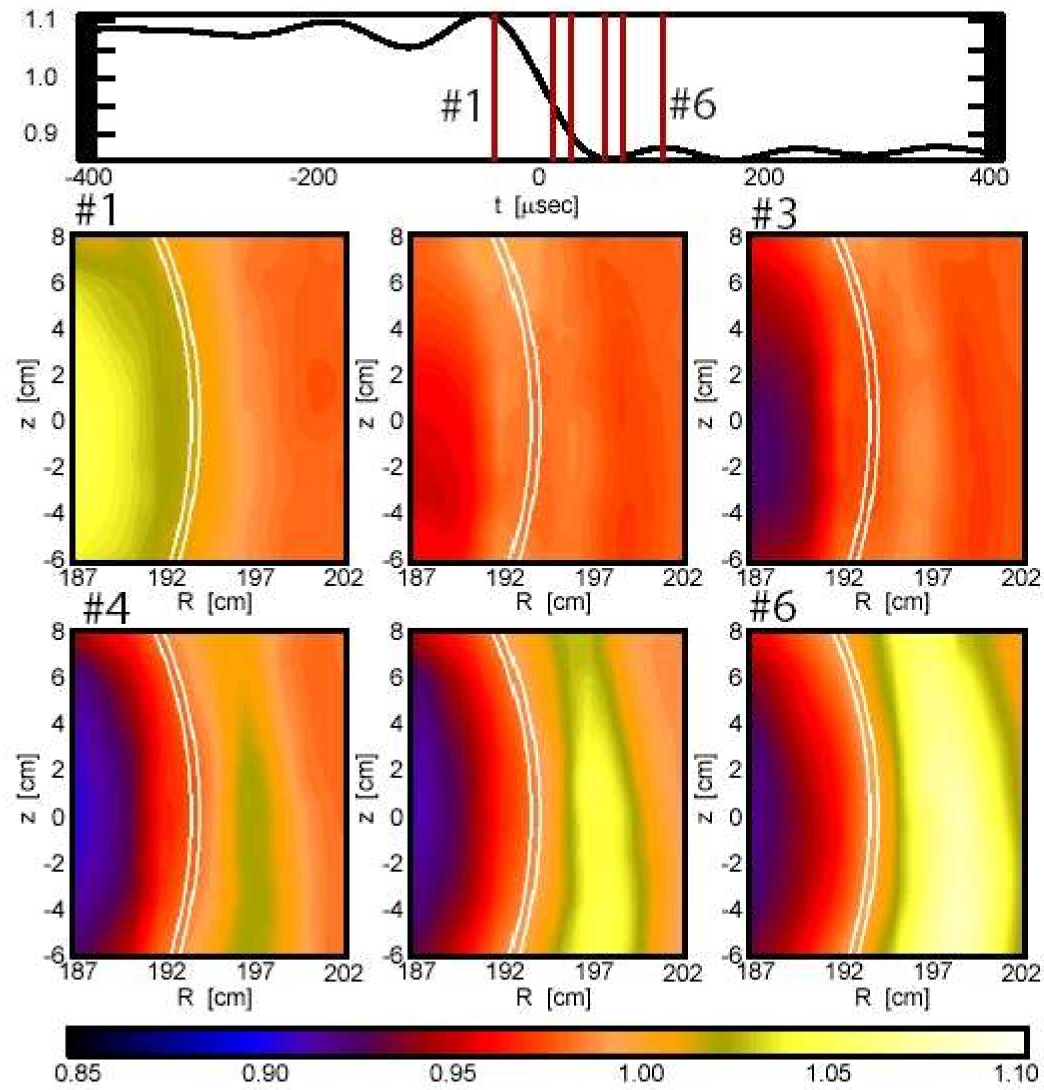




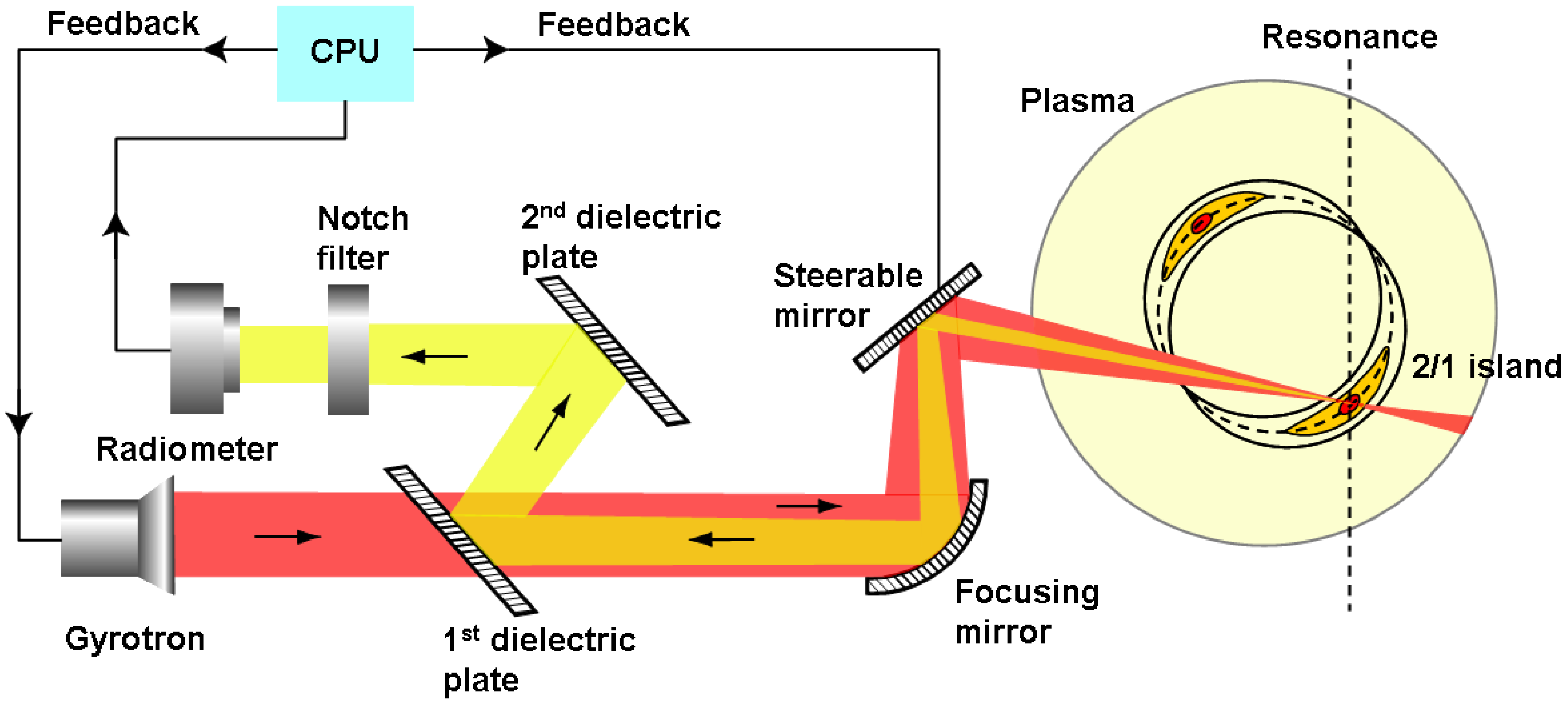
Magnetohydrodynamics (MHD)



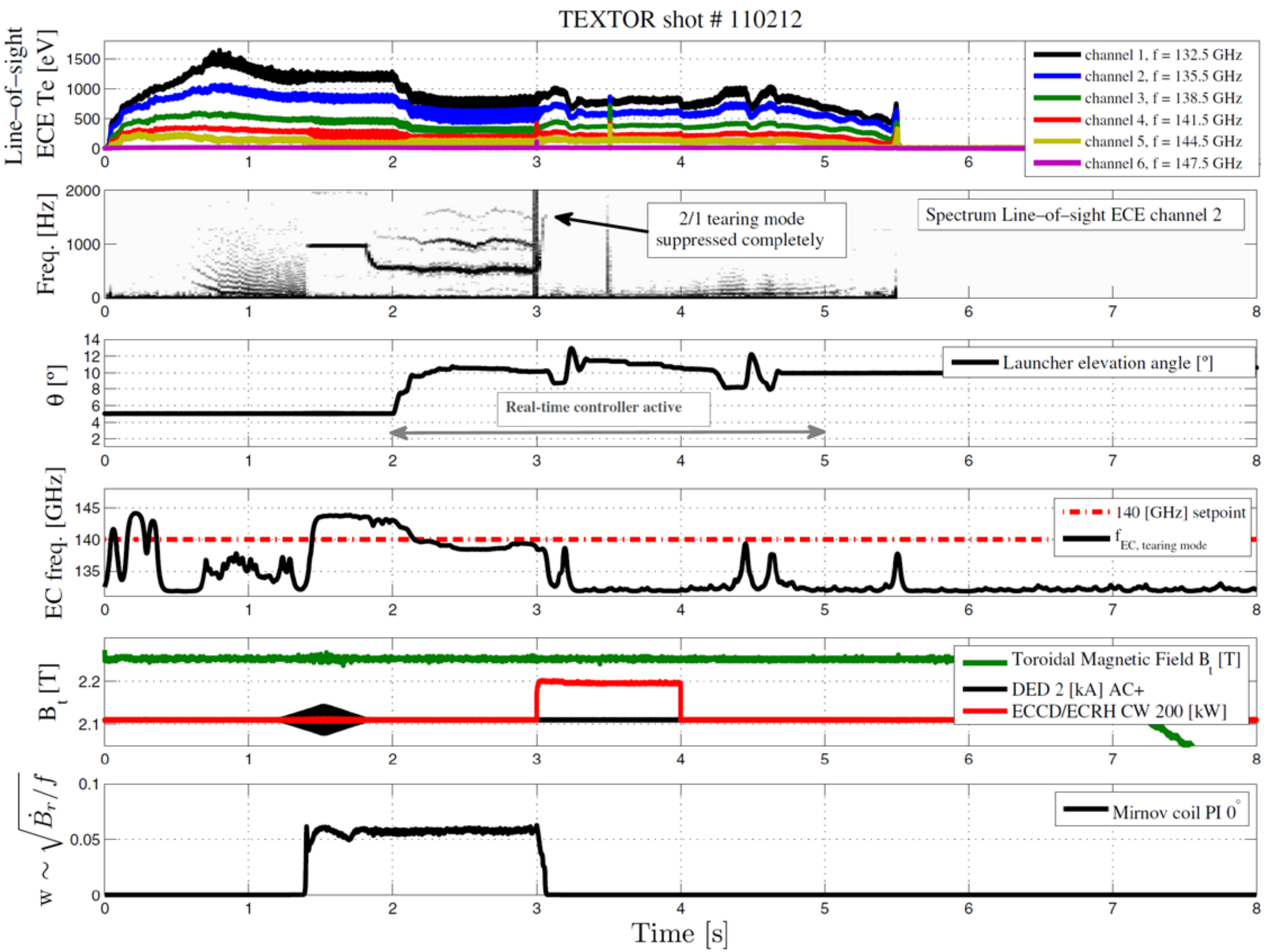
Physics approach: MHD



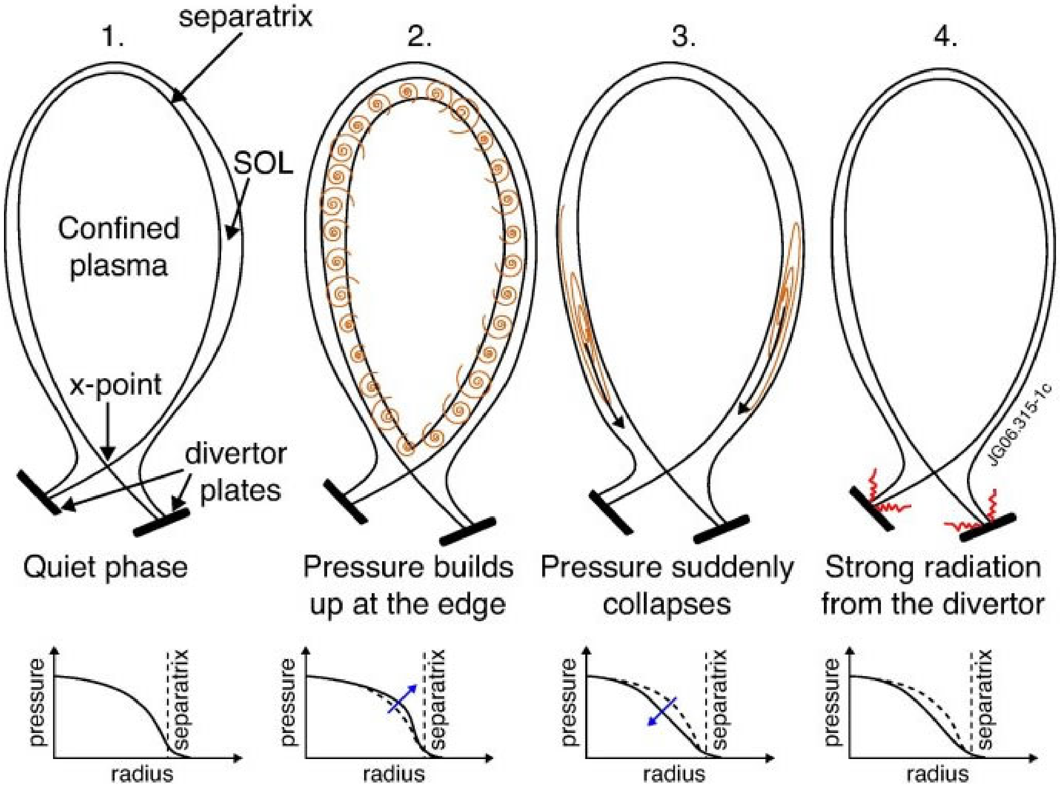
Engineering approach: Control of MHD using CO-LOCATED actuator-sensor

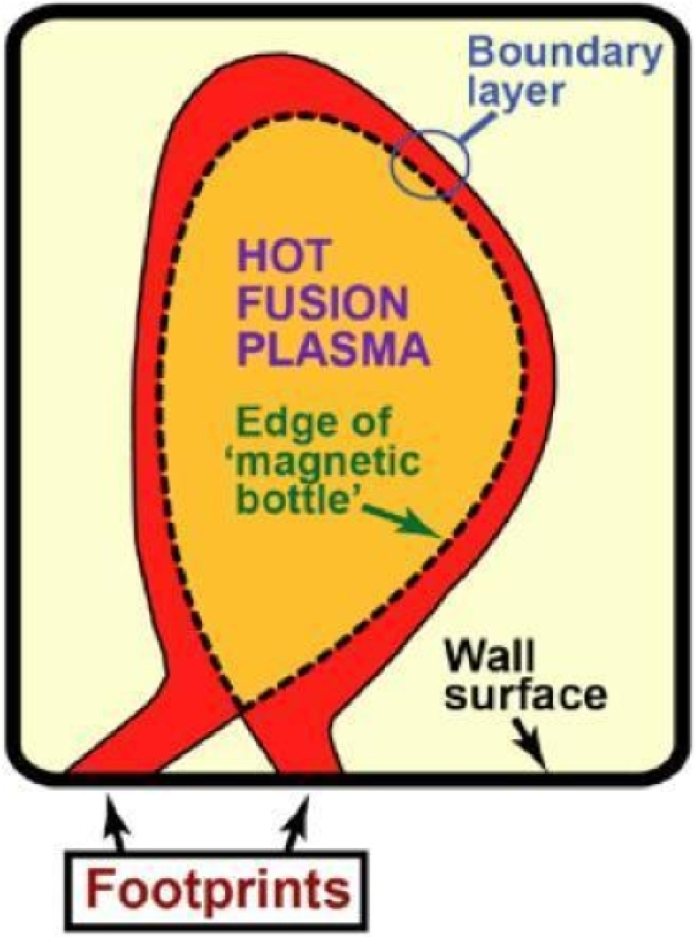


Closed loop control of MHD in TEXTOR

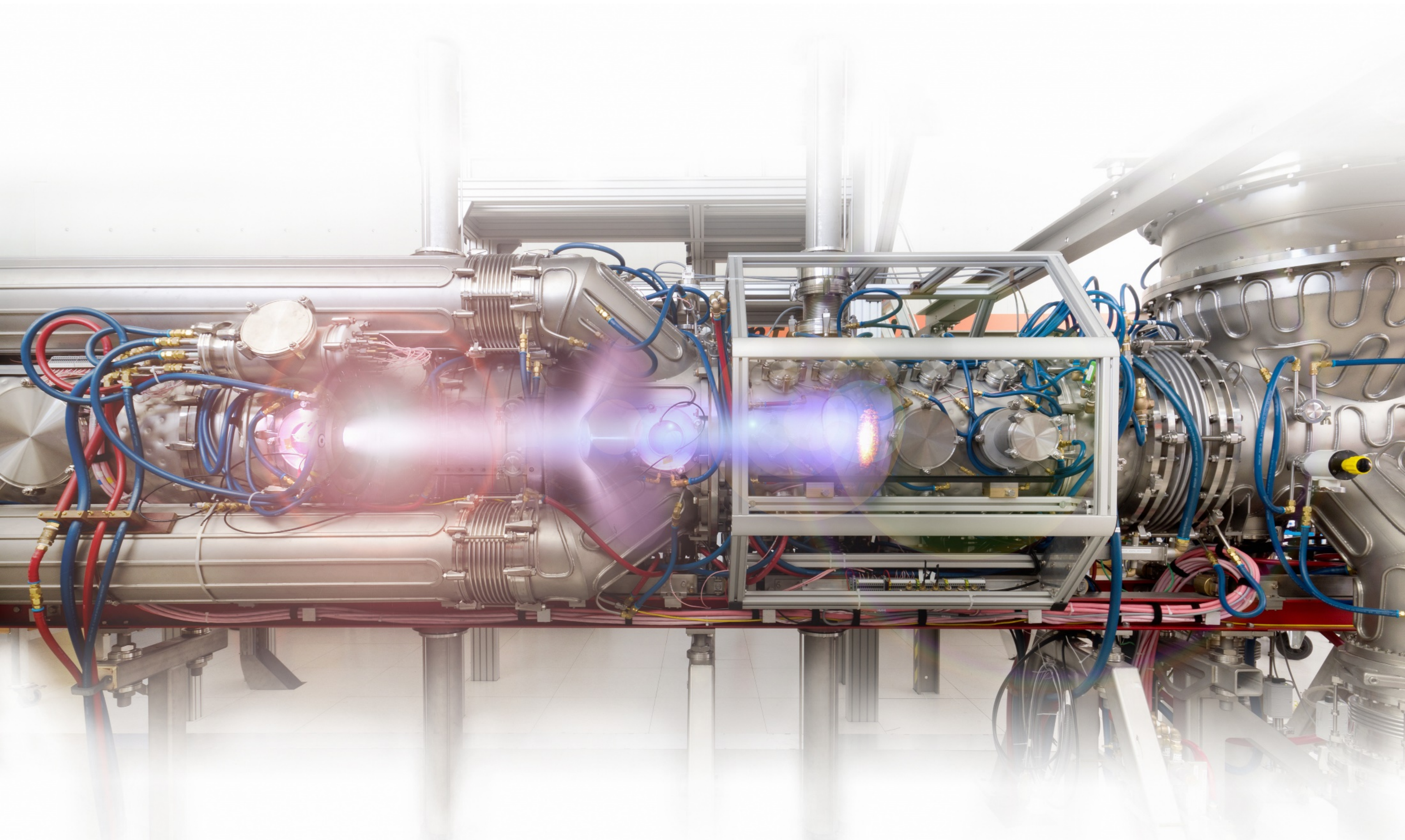


Exhaust of heat and particles



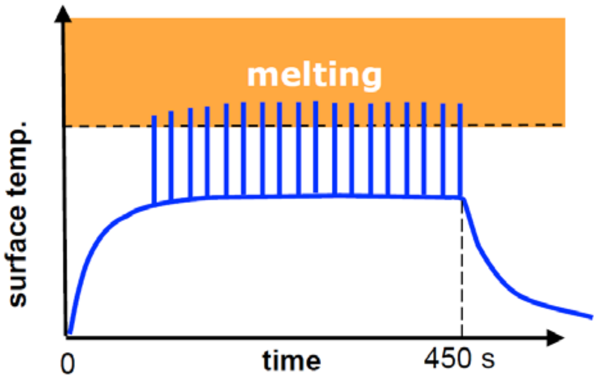


Magnum PSI



Highlight 2: Impact of ELM-induced melting in ITER

- ❑ Full W divertor from the beginning of operation in ITER
- ❑ Strong potential for ELM-induced melting
- ❑ What surface modifications will evolve during a large number of ELM-like melting events ?
- ❑ How does the power handling capability of the surface perform under subsequent normal operation?



How does a damaged surface evolve over time under combined steady-state and transient plasma loading ?

Pilot-PSI : Repetitive shallow melting (1^{st} step)

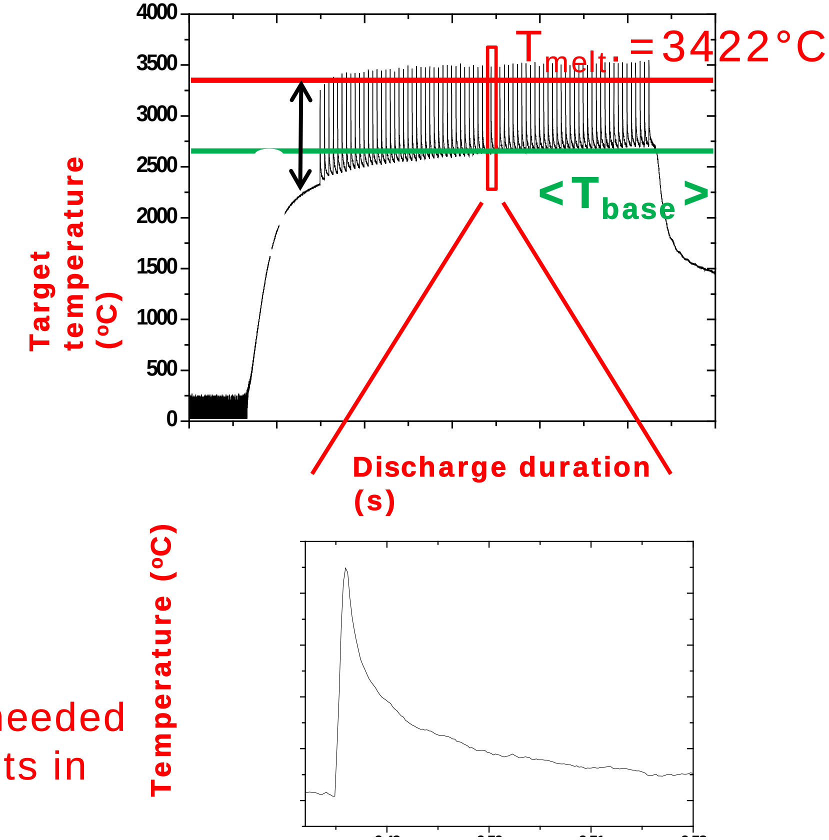
❑ T_{base} ~ 2600°C

Exposure conditions

- ❑ Normal incidence with respect to B
- ❑ Pure H plasma
- ❑ ΔT_{ELM} ~ 1100 °C
- ❑ 72 plasma discharges (684s of plasma exposure)
- ❑ 4100 ELM-like transients

Comparison to ITER

- ➢ T_{base} >> $T_{recrystallization}$ in ITER but needed to induce melting during transients in this experiment
- ➢ Analagous to divertor re-attachment scenario where ELMs will induce melting



S. Bardin, T.W. Morgan, X. Glad, R.A. Pitts, G. De Temmerman

New programmes

1. New free FOM programme submitted. Final Request 7 PhDs. Activities on impurity transport, physics of plasma detachment, H-mode physics. Pre-proposal (positively assessed by the SAC) had to be modified at the expense of the control engineering part.

1. Impulse programme ‘Extreme Materials for Energy Applications’ granted by TU/e. Six PhD projects on extreme materials for energy applications. Three PhD students at DIFFER.

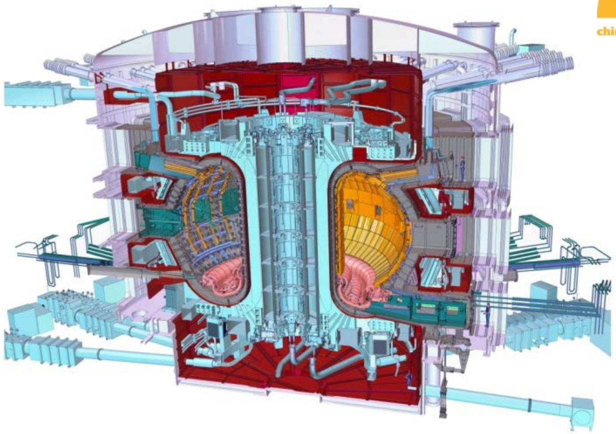
2. FOM strategic programme FP148 to support the funding of Magnum/Pilot-PSI operations and transform the device in a world-class user facility.

Personal Grants

Thomas Morgan	Liquid Lithium as a PFC
Sebastien Bardin	Tungsten dust
Ivo Classen	Spatial Structure of Edge Localised Modes using 3D ECE
Wouter Vijvers	Hyper imaging spectrometer for advanced divertor concepts
Jonathan Citrin	YES!

2 PhD projects granted by the Erasmus Mundus scheme. One PhD student full-time at DIFFER, the other in Julich (but participates in experiments at DIFFER).

Design superconducting coils for ITER



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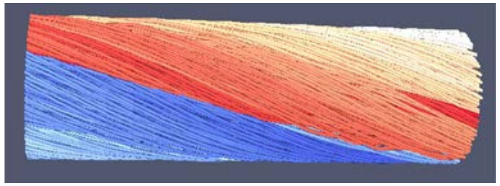
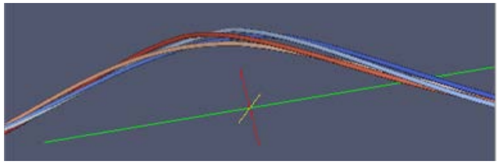
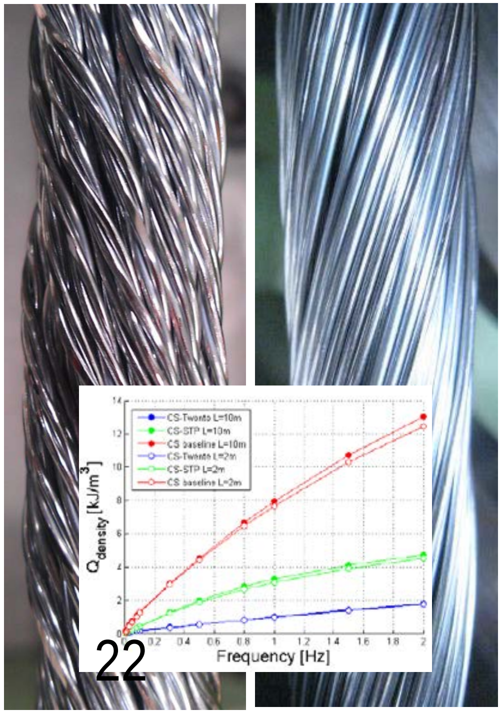
Dutch team has solution for troubled ITER nuclear fusion reactor

February 8, 2012

(PhysOrg.com) -- The superconducting cables designed for the ITER fusion reactor (cost: 16 billion euros = $21.2 billion) are unable to withstand the planned forty to sixty thousand charge cycles. Barring a solution, the troubled mega-experiment will suffer still more delays and cost overruns. About one third of total expenditures for the reactor are devoted to the superconducting magnet system. UT researcher Arend Nijhuis thinks he has the solution. He has calculated that a different configuration will make the cables more robust. In the first week of March, ITER will run an experiment costing half a million euros to see whether this theoretical solution will actually work in practice.

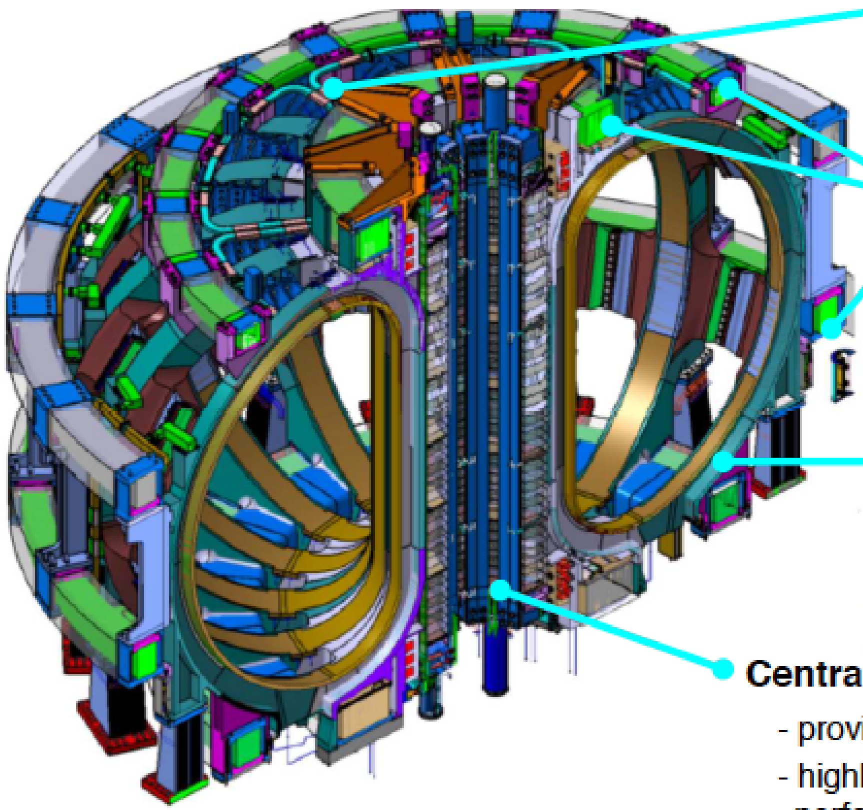






Superconducting coils DEMO

WPMAG Project thematically covers the <u>totality of the DEMO magnet system</u>



Correction Coils (CC) magnet system

- provides residual field for plasma control

Poloidal Field (PF) magnet system

- provides poloidal field that ensures the plasma equilibrium
- highlights : manufacture, schedule

Toroidal Field (TF) magnet system

- provides toroidal field and plays a role on plasma performance
- highlights : radial build, cost, schedule

Central Solenoid (CS) magnet system

- provides flux for plasma shot
- highlights : radial build, machine performance, high cycling

Rijnhuizen Remote Handling Study Centre for reactor maintenance

Design and testing of RH compatible components

System approach to tooling and procedures

Development of advanced control for multi operator, ill sensed tasks for cases with deformation

See presentation Heemskerk

Dutch Fusion prorgamme well aligned with Roadmap

1. Plasma regimes of operation	FP120, EuroFusion contracts
2. Heat exhaust	FP75, Magnum, New FP?
3. Neutron resistant materials	Magnum, Pilot upgrade + IBA, Materials
4. Tritium self-sufficiency	
5. Intrinsic safety	
6. Integrated DEMO design	Diagnostics & Control, Remote Handling, Super Conducting Coils
7. Competitive cost of electricity	
8. Stellerator line to maturity	

Conclusions

Very cool science and engineering in variety of topics

KEY to all of this is the co-development of physics and engineering oriented modelling

No nightmares:

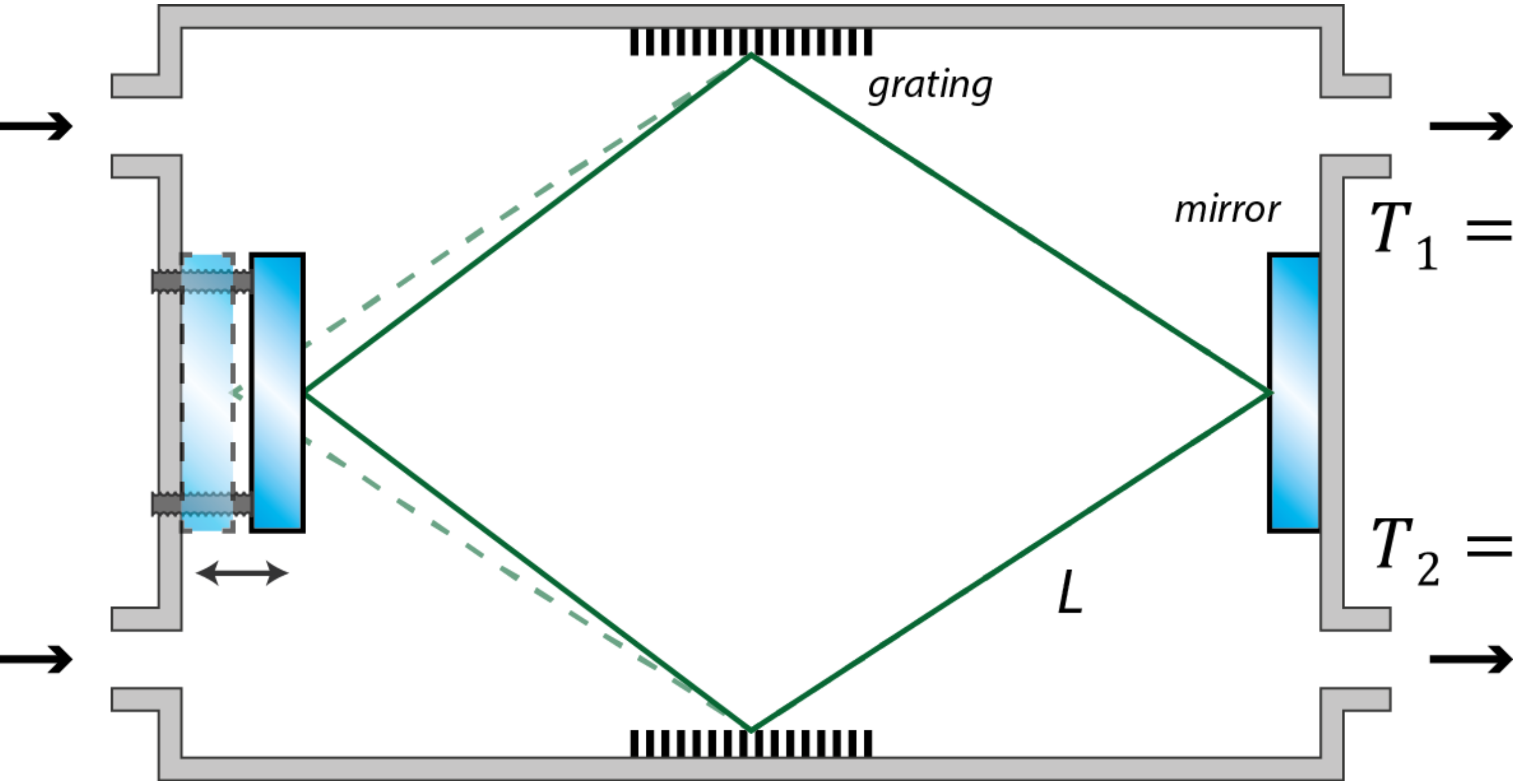
- Multiple Universities and FOM DIFFER teaming up
- New programmes are being launched
- Well aligned with Eurofusion
- Unique facilities and strong key-competencies
- Diagnostics, sensing, modeling and control, materials, super conducting magnets..

μ-wave cavity FADIS

Textor results proof of principle. But how to implement with

-Corrogated wave guides?

-CW?



$$T_1 = h(f, g, L)$$

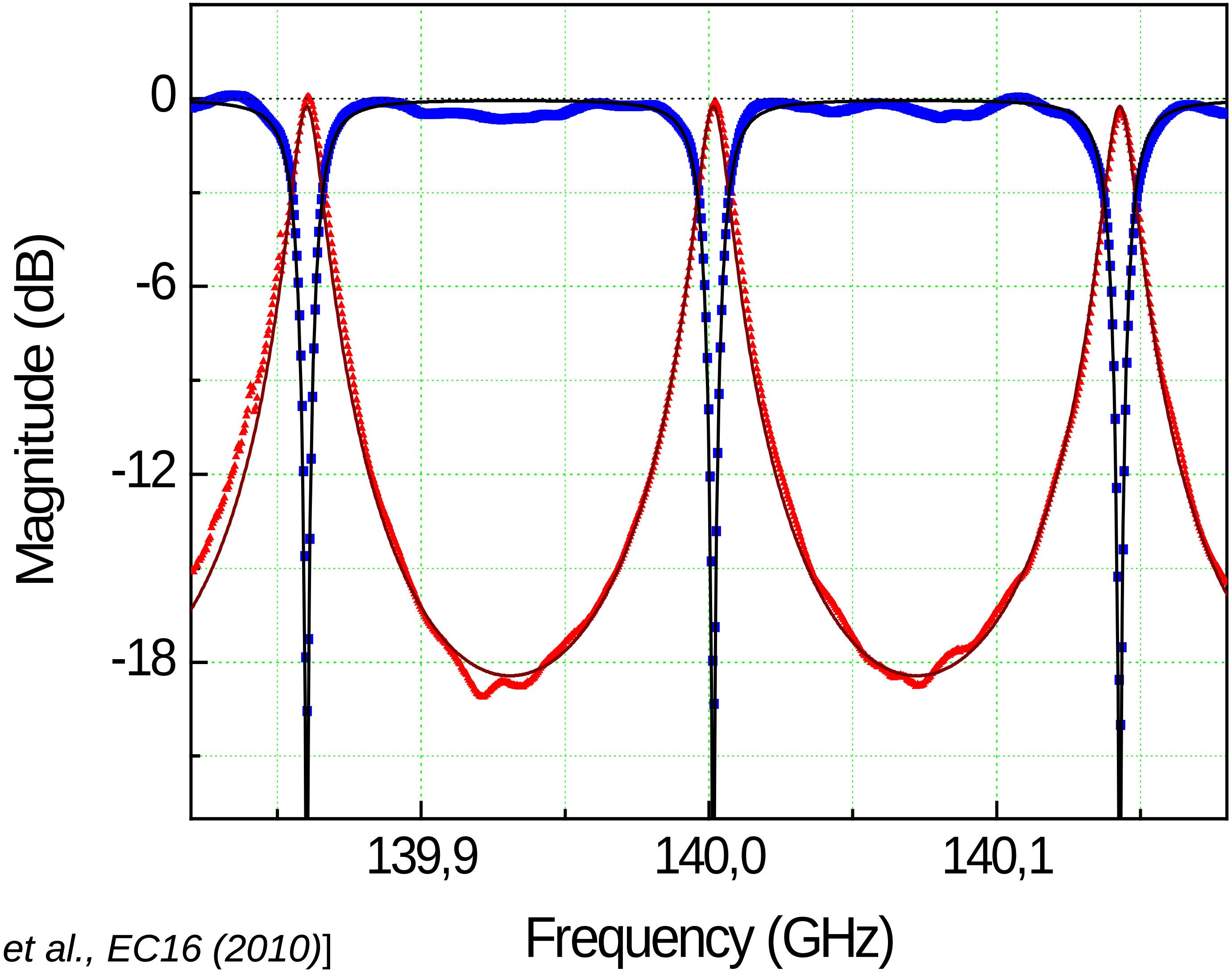
$$T_2 = k(f, g, L)$$

Kasparek et al., IFP Stuttgart

FADIS for in-Line ECE isolation

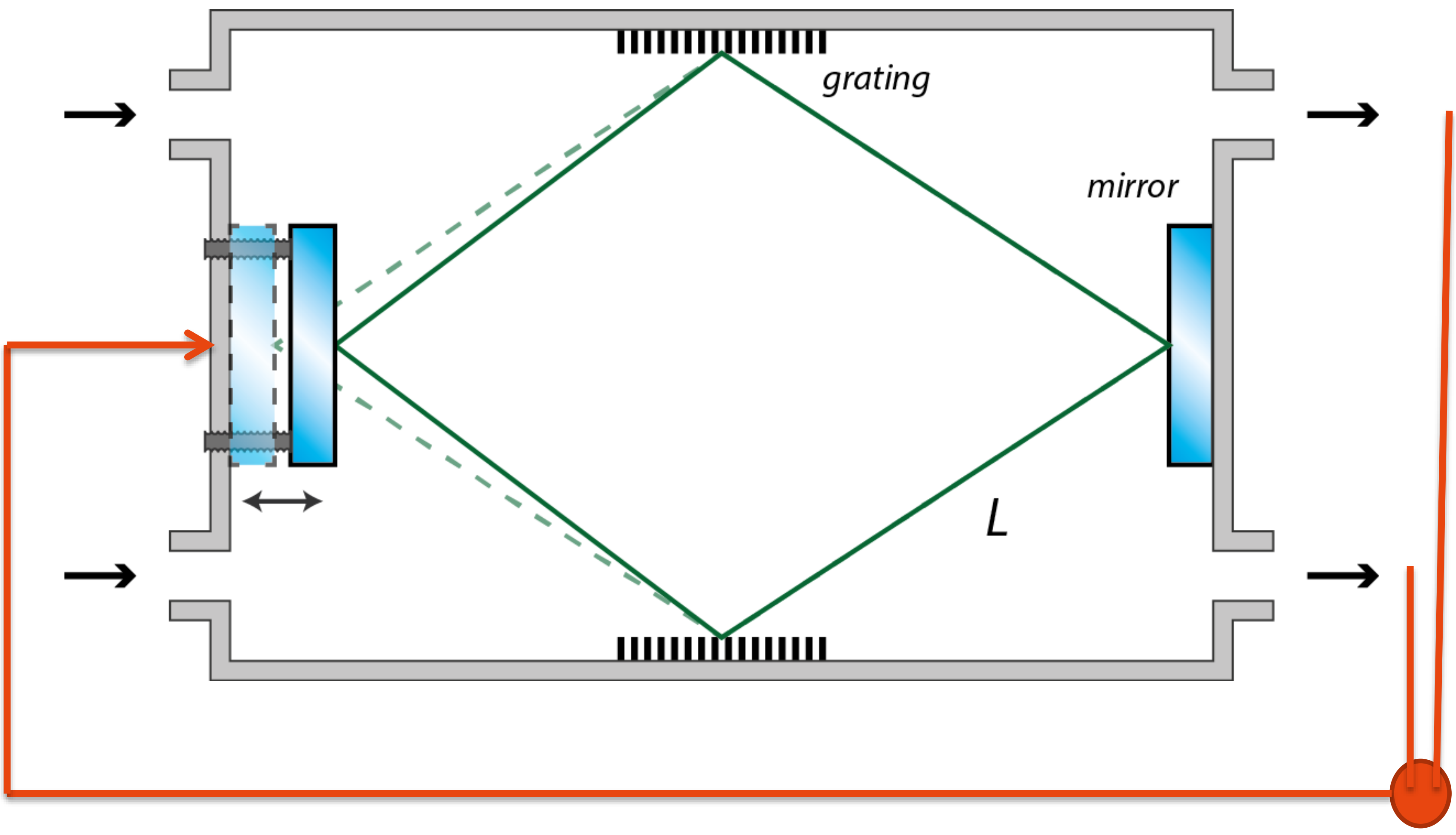
FADIS Transmission:

- Mk IIa with matched HE11: **non-resonant channel (blue)**

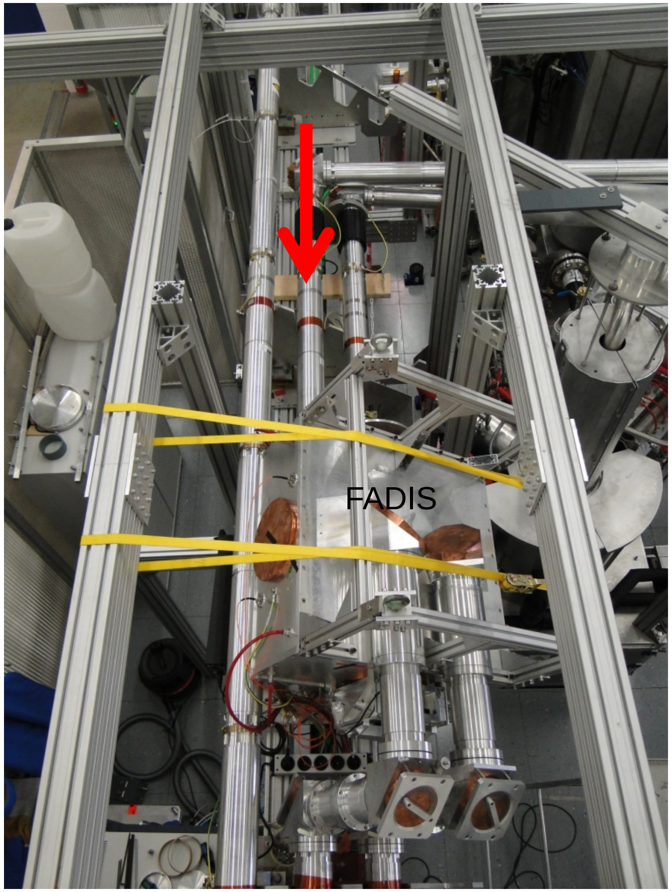


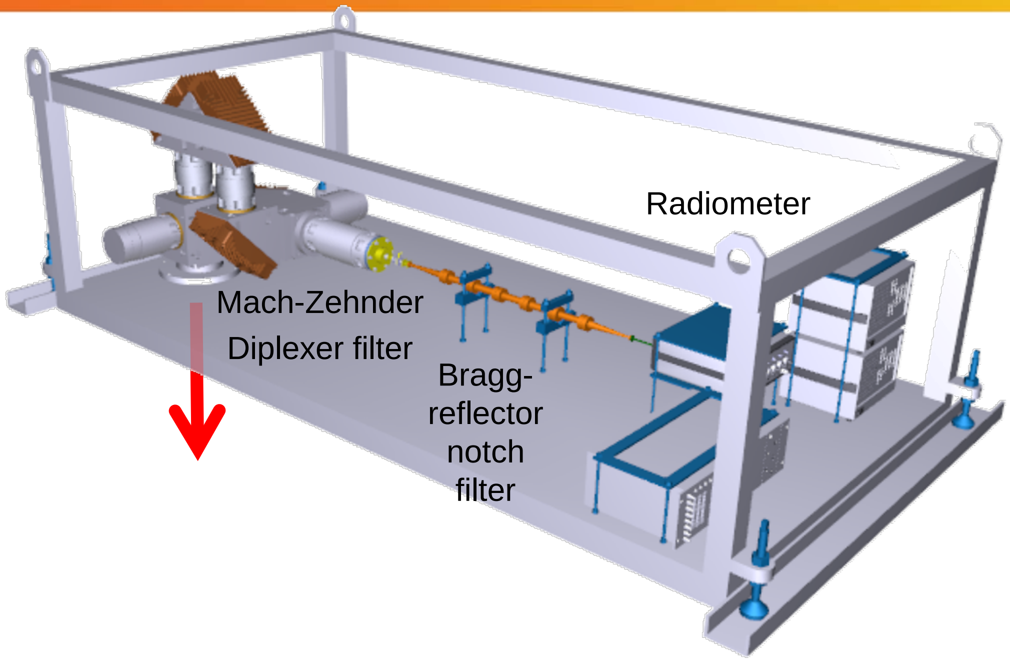
[*Kasparek et al., EC16 (2010)*]

FADIS: Active, RT, Tunable Cavity

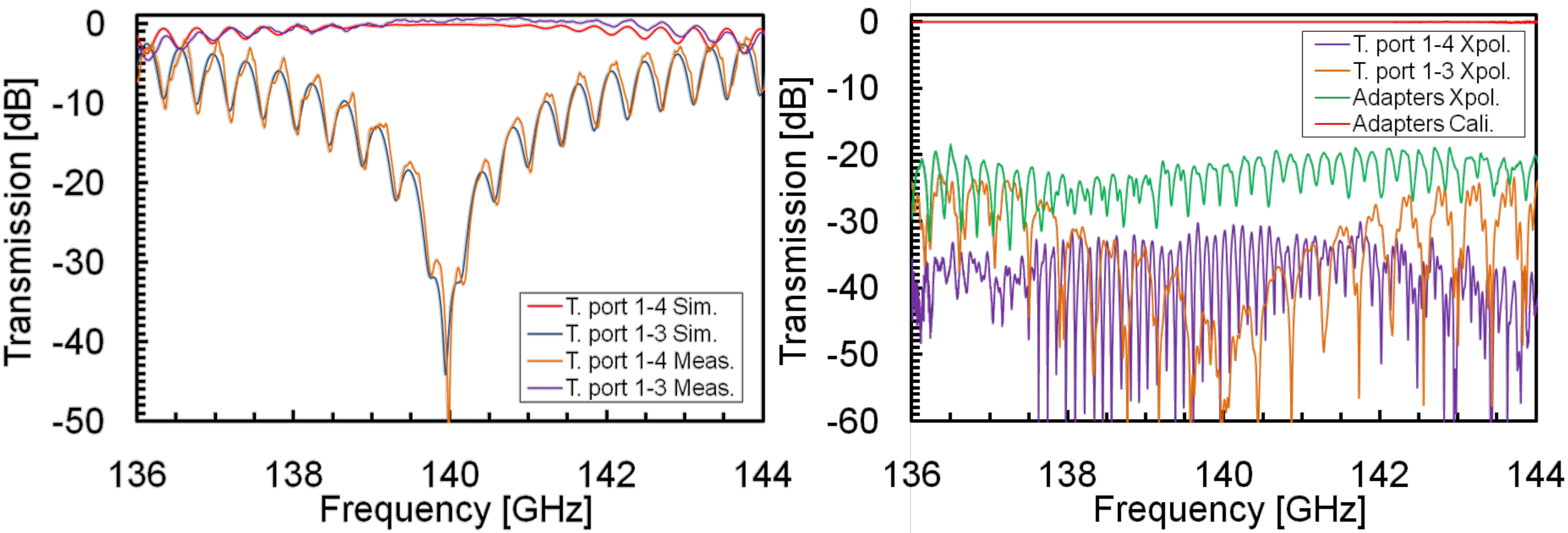


AUG inline ECE setup



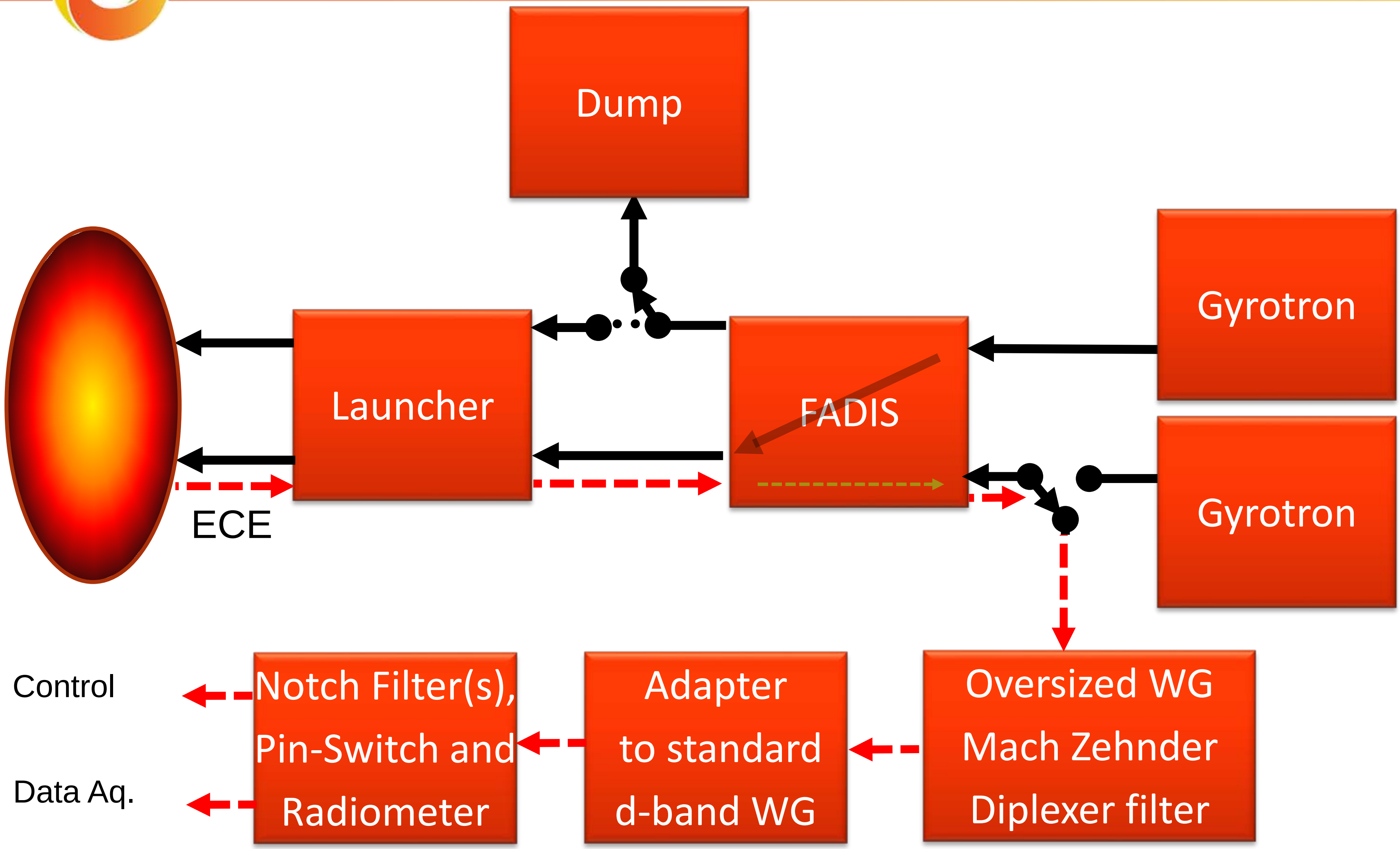


Performance Mach-Zehnder diplexer



- ✓ Measured diplexer filter curves for the parallel-polarization (left: orange: path to diagnostic, purple: path to absorber) and X-polarization (right: green: quality of adapters. Perpendicular-polarization curves same as left
- ✓ The measurements were in agreement with the simulations
- ✓ Ready for installation on AUG

setup AUG ECRH in-line ECE system



Status + Outlook

FADIS MKII + Mach Zehnder installed in AUG

Low power notch was not according to specs

- Rectified

First measurements with poor insertion loss

- Rectified

ECE measured during ECCD, Mode marginally traceable.

- Radiometer improved

Ready for experiments @ AUG

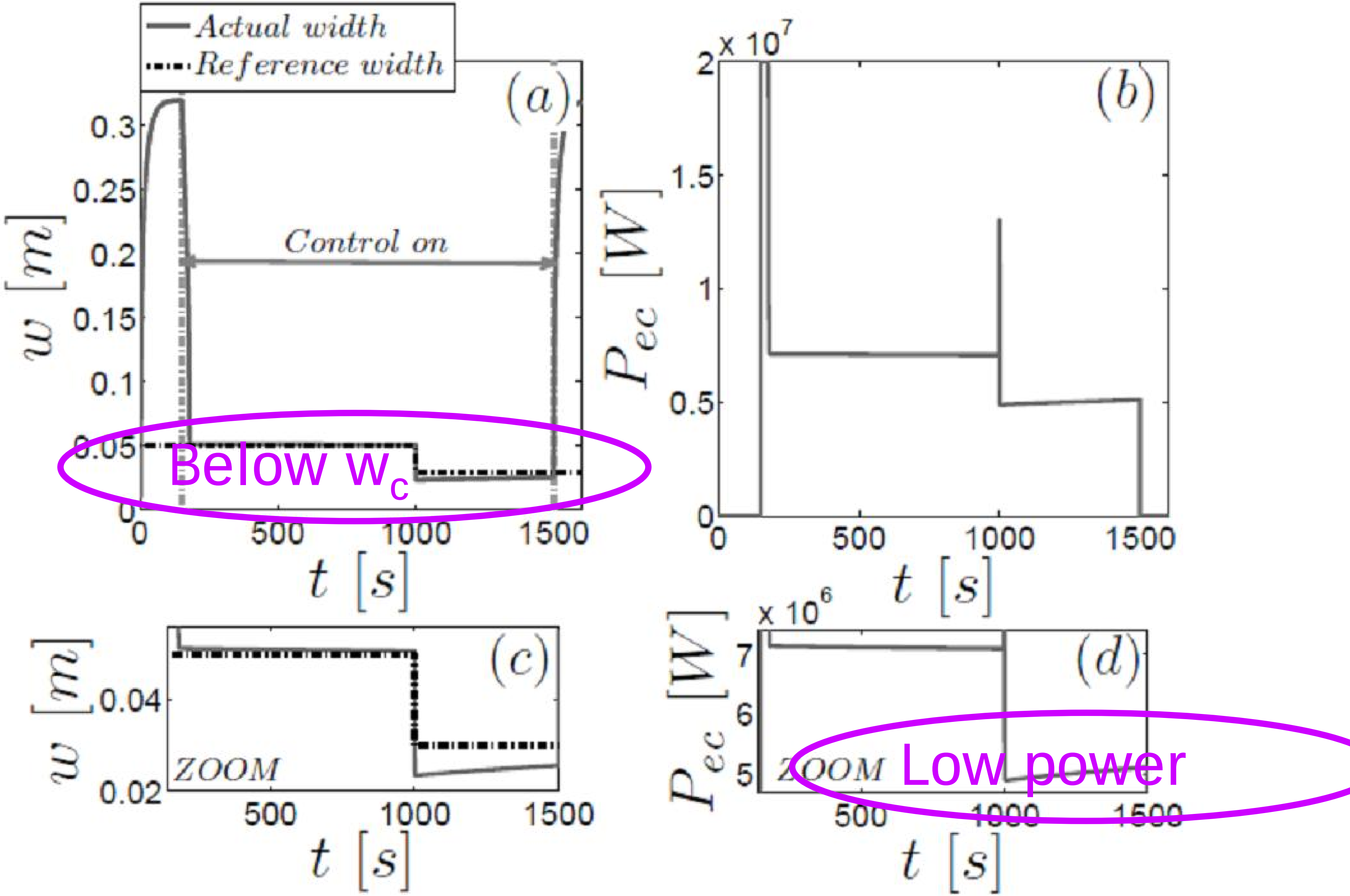
Actuation, Process, State and Output

Rutherford equation

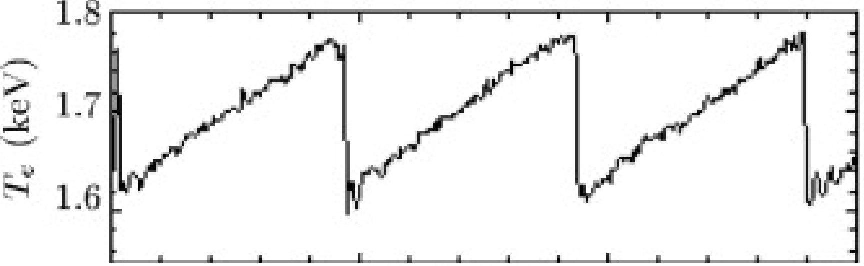
$$0.82\frac{\tau_r}{r_s}\frac{dw}{dt} = r_s\Delta'_0 + r_s\Delta'_{des} + r_s\Delta'_{CD}$$

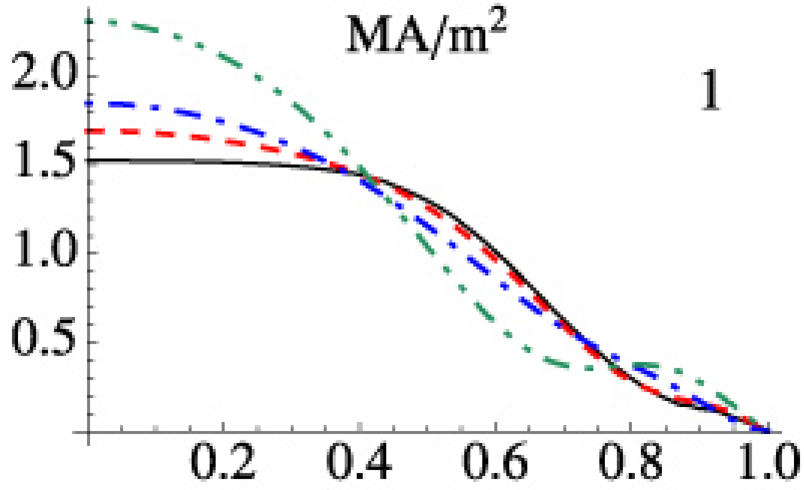
- Modified, Generalized Rutherford eq.
  - Nonlinear 1st order Ordinary Differential Equation
- Local linearization of the (non-linear) ODE
- Reformulate in state-space description around multiple operating points
- Compute transfer functions for different operating points
- Conceive Control structure
- Ensure performance and stability
- Carry-out closed loop simulations

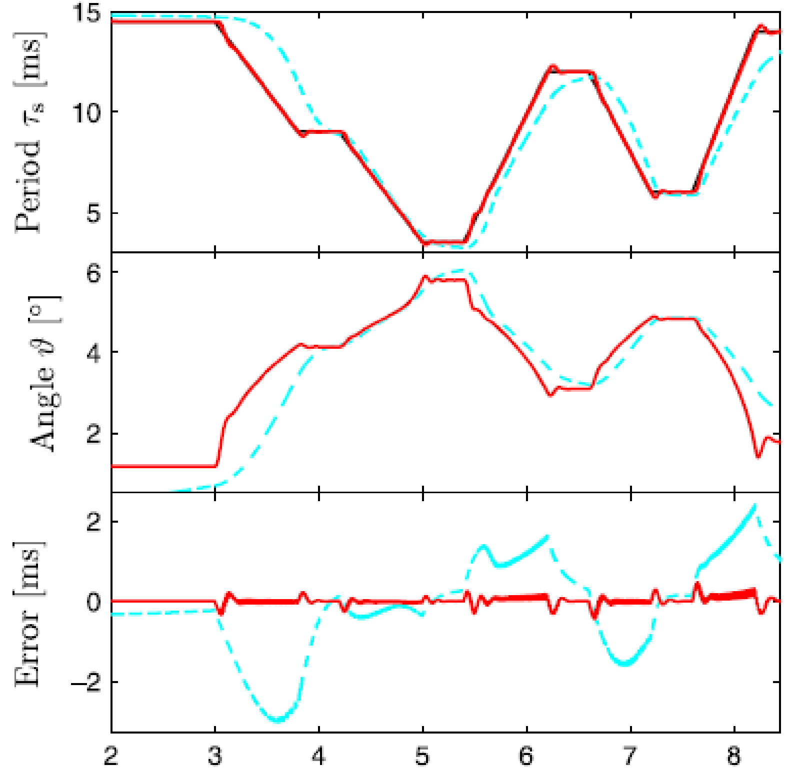
Simulation NTM control

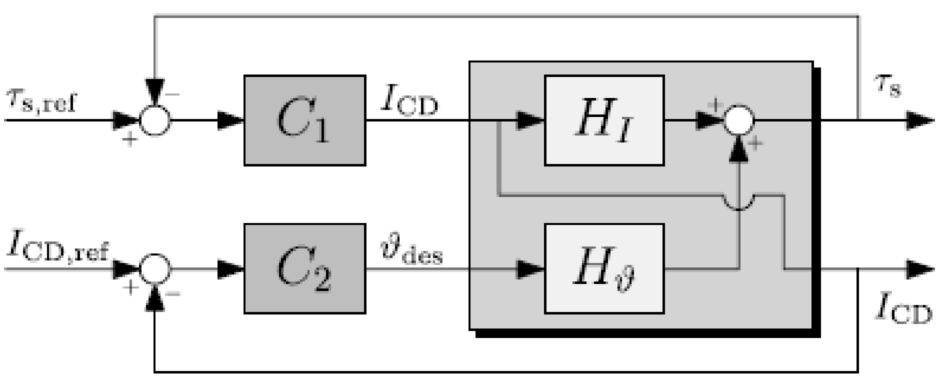


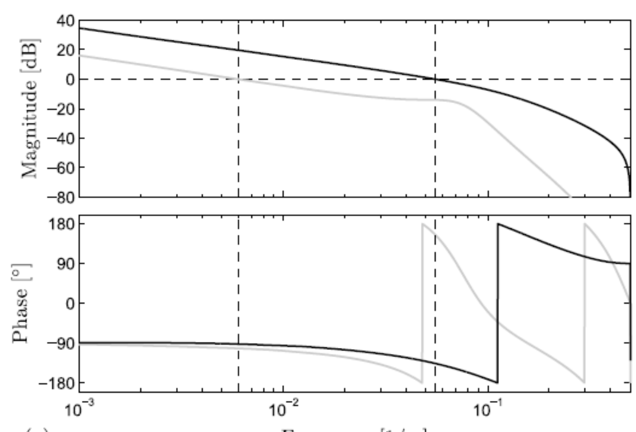
MIMO Sawtooth control

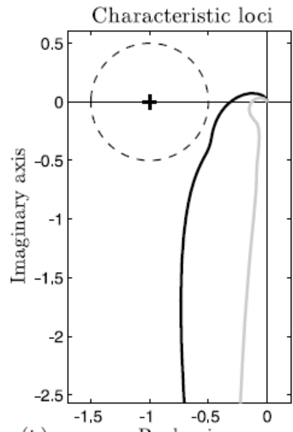




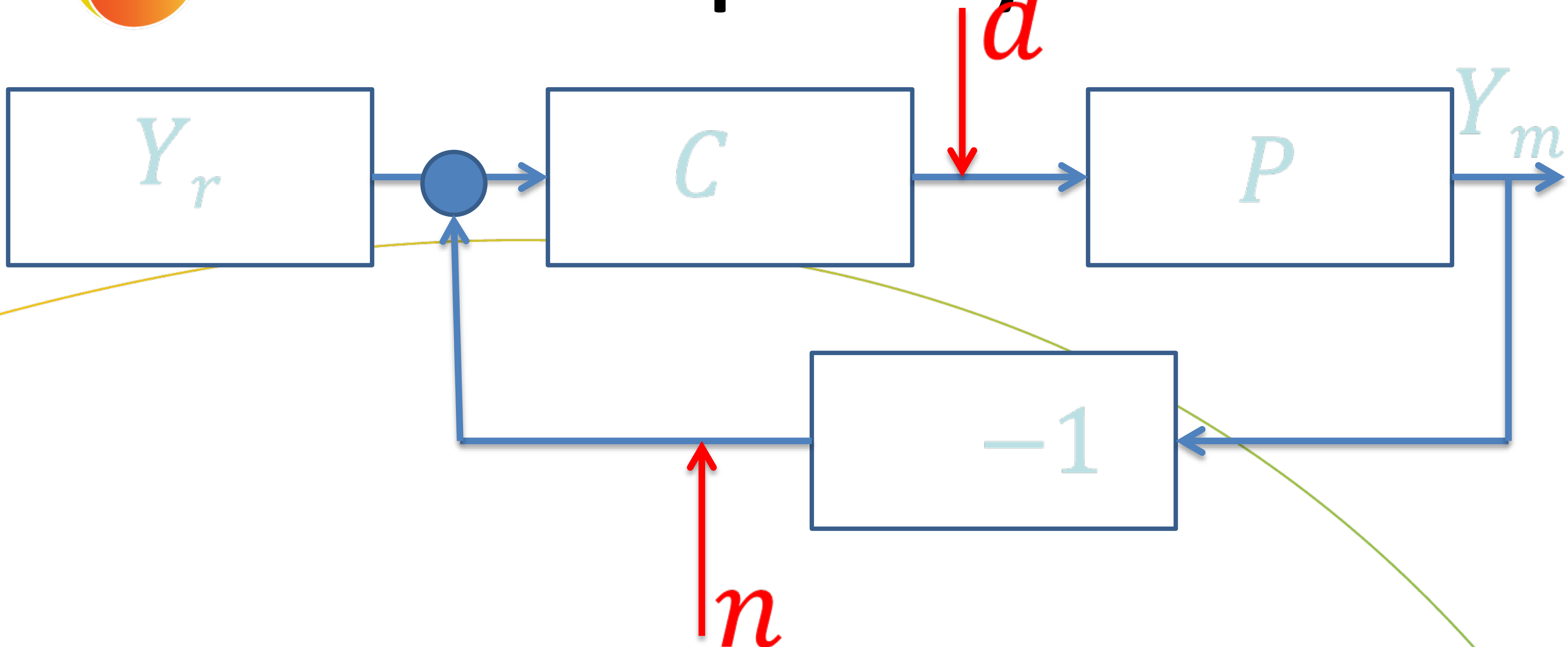








Are you sure that closed loop is for you?



$$Y_m = \frac{Y_r CP}{1+CP} + \frac{dP}{1+CP} - \frac{nCP}{1+CP}$$

DIFFER Diagnostics vs. Sensors

Diagnostic

- High spatio-temporal resolution
- High latency acceptable
- Should work often in various configurations

Sensor

- Spatio-temporal resolution optimal for control problem
- Latency ruins bandwidth
- Should work always for limited set of predefined configurations

Can we actively control without sensors?

Sawtooth locking