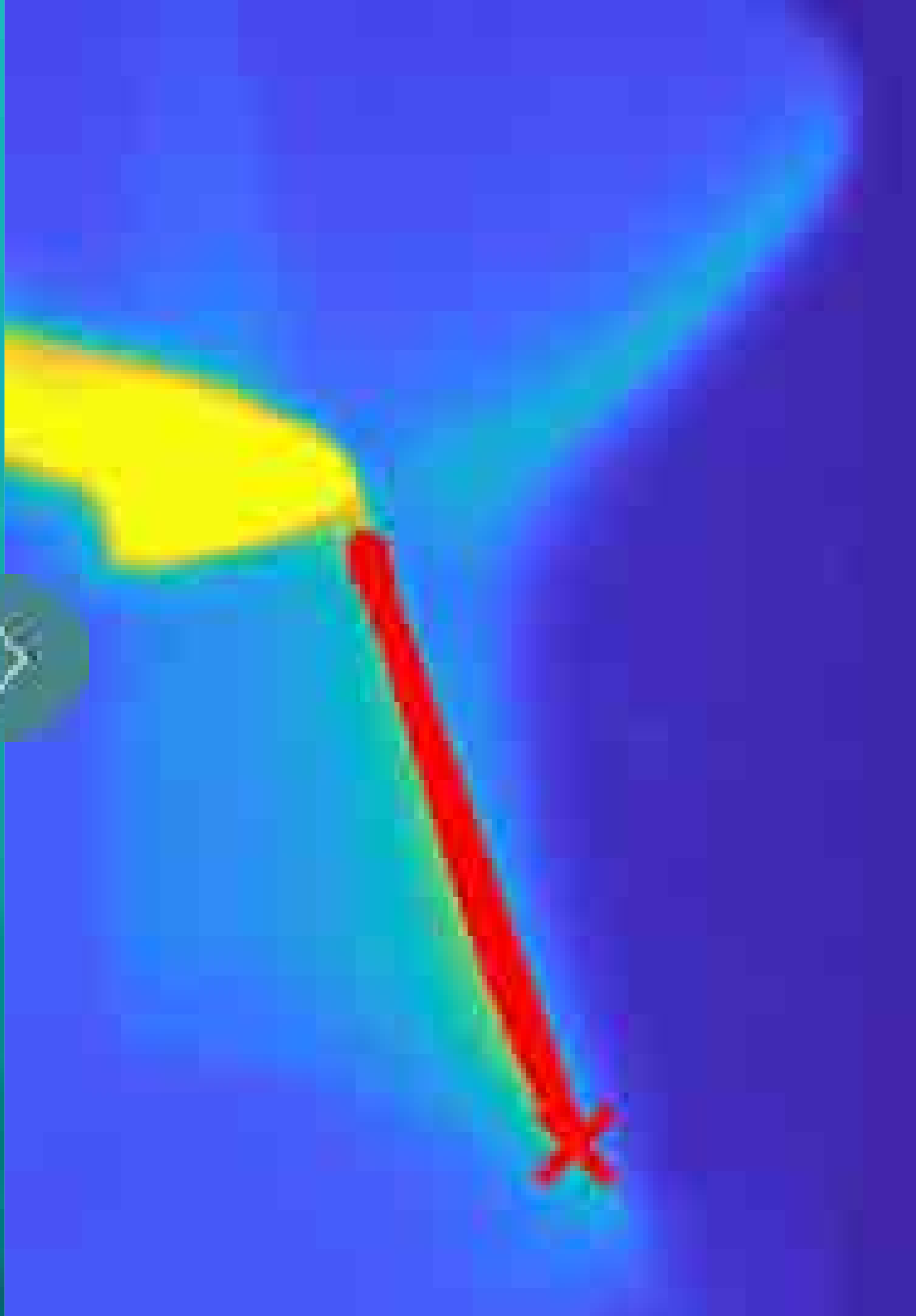
Control of thermal systems in nuclear fusion and industry: data-driven and model-based approaches

Group leader ESCEnergy Systems & Control

DEMO control: detachment control (WPDES), diagnostics and control (WPDC), tritium fueling cycle (TFV)

Matthijs van Berkel



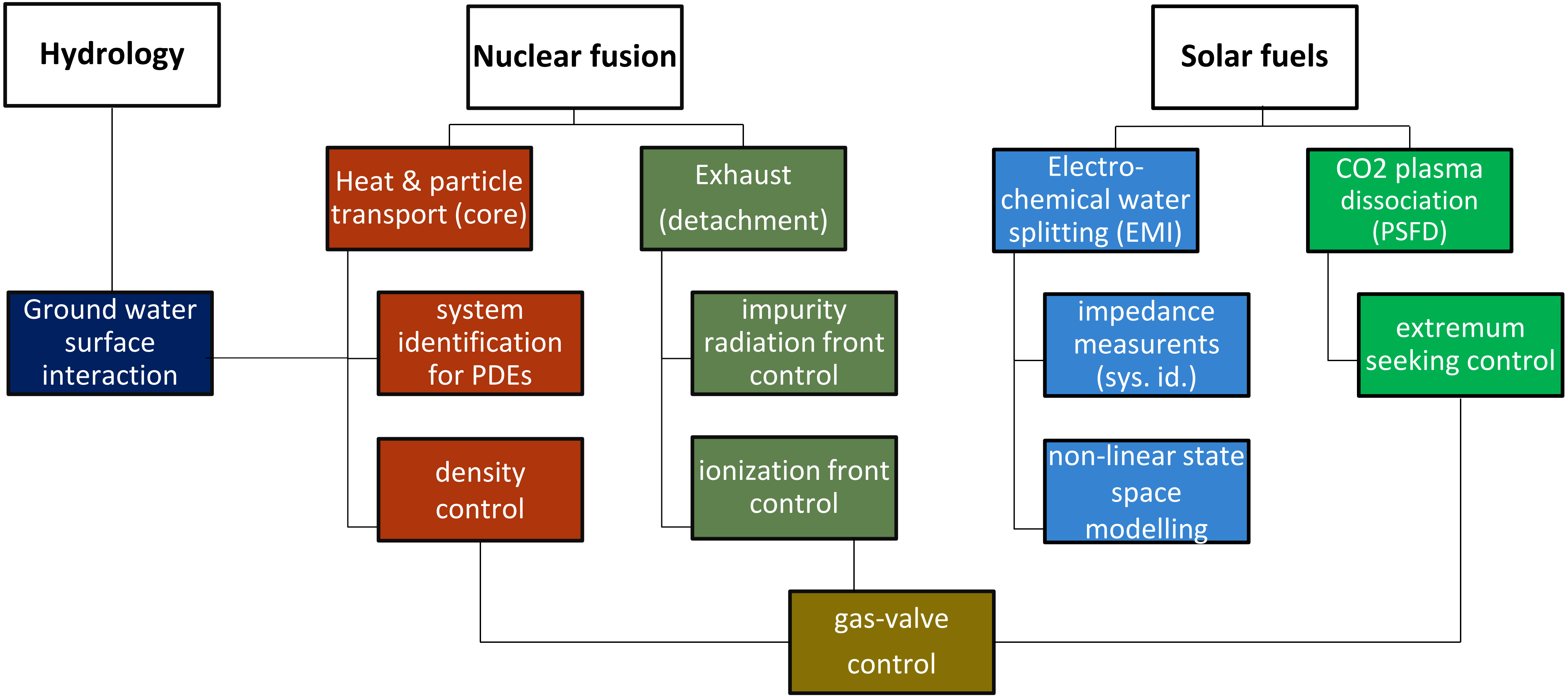
Regeltechniek van thermische systemen in kernfusie en industrie: data-gedreven en model-gebaseerde methodes

regeltechniek
systeem identificatie

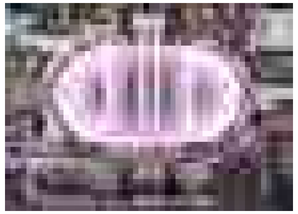
thermisch
natuurkunde

Matthijs van Berkel
namens
DIFFERen
TU Eindhoven

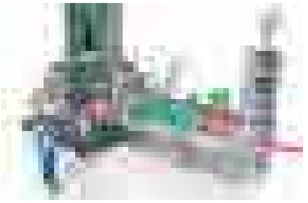
Overzicht systeem en regeltechniek onderzoek (Energy Systems & Control group @ DIFFER)



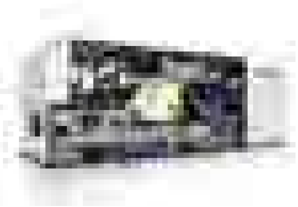
Modelleren en regelen cruciaal voor thermische systemen in hightech industrie en big science



Kernfusie-reactoren
DIFFER



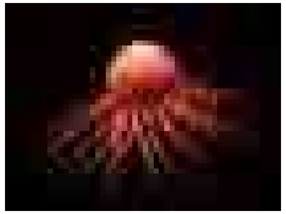
Zwaartekracht-golfdetectie
Nikhef



Chip-machine

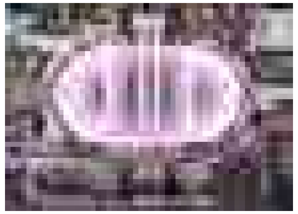
2D/3D-printen

Elektronen-Microscoop

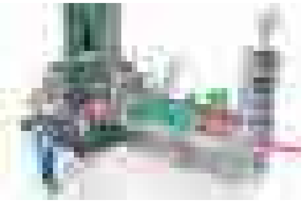


Kankercellen en tumoren

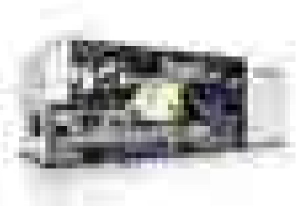
Verleggen technologische grenzen rekening houdend met thermische belastingen



efficiëntie



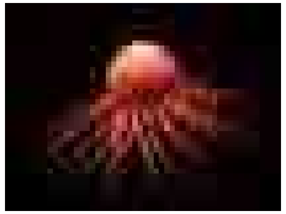
gevoeligheid



<< nanometer

sneller drogen en printen

reductie kalibratie tijd en precisie



nauwkeuriger lokaal verwarmen

Gemeenschappelijk: dezelfde wiskundige beschrijvingen

Partieel differentiaal vergelijking (PDV) voor thermisch transport

kernfusie

$$\frac{\partial T}{\underbrace{\partial t}_{\text{tijdsevolutie}}} = \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\underbrace{\rho D n \frac{\partial T}{\partial \rho}}_{\text{diffusie}} + \underbrace{\rho V n T}_{\text{convectie}}\right) + \underbrace{KT}_{\text{demping}} + \underbrace{Q(\rho, t)}_{\substack{\text{verhitting} \\ \text{e.g. microgolven}}}$$

lithografie

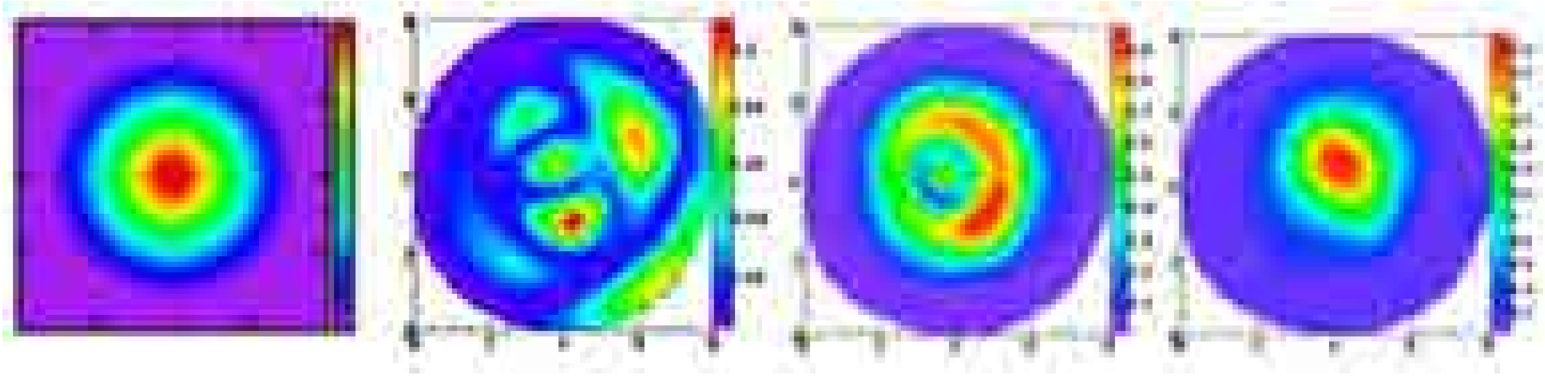
$$\underbrace{\rho c H}_{\text{warmte-capaciteit}}\frac{\partial T}{\partial t} = \underbrace{kH\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2}\right)}_{\text{conductie}} - \underbrace{hT}_{\text{koeling}} + \underbrace{Q_{exp}}_{\substack{\text{verhitting} \\ \text{door licht}}}$$

medisch (weefsel)

$$\rho c \frac{\partial T(r,t)}{\partial t} = \underbrace{k\nabla^2 T(r,t)}_{\text{conductie}} - \underbrace{w_b(r) c_b (T(r,t) - T_b)}_{\text{convectie (perfusie)}} + \underbrace{Q(r,t)}_{\text{verhitting (echo)}}$$

Detectie en correctie van laser wavefront in gravitatiegolfdetector (Einstein telescoop)

- verhoging van circulerend laser vermogen betere sensitiviteit
- verhoging van gedeponeerde hitte van de laser
- thermo-optische effecten en thermo-elastische deformatie
- wavefront distorsies die weggeregeld moeten worden



Toepassing regeltechnische modellen zal de prestaties en nauwkeurigheid verbeteren

Figures: Fafone, AdV Thermal Compensation System AdV/aLIGO, joint technical meeting, 2004

Dynamische metingen cruciaal voor modelvorming

Totale temperatuur verdeling gevolg van combinatie van componenten

$$\frac{\substack{\partial T \\ 0}}{\partial t} = \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\underbrace{\rho D n \frac{\partial T}{\partial \rho}} + \underbrace{\rho V n T}\right) + \underbrace{KT} + \underbrace{Q(\rho, t)}$$

ti statisch e diffusie convectie demping verhitting e.g. microgolven

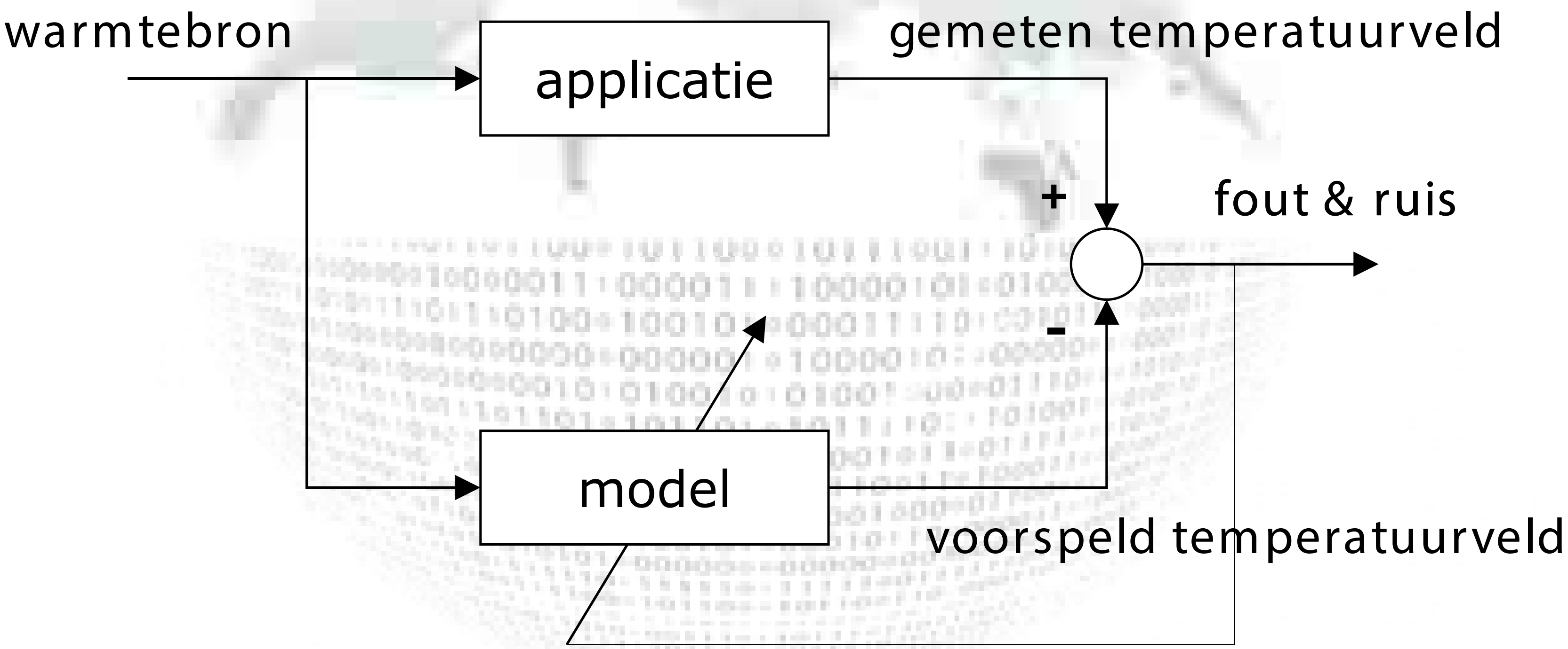
Individuele processen acteren op verschillende tijdsschalen

Conclusie:

- (slimme) variatie in tijd identificatie van componenten
- regeltechniek gebaseerd op dynamische verandering van het systeem
- dynamische metingen beste karakterisatie van complexe systemen

80% modellen in regeltechniek: meetdata(-gestuurd)

Identificatie van model (open-lus)



warmtebron

applicatie

gemeten temperatuurveld

+

fout & ruis

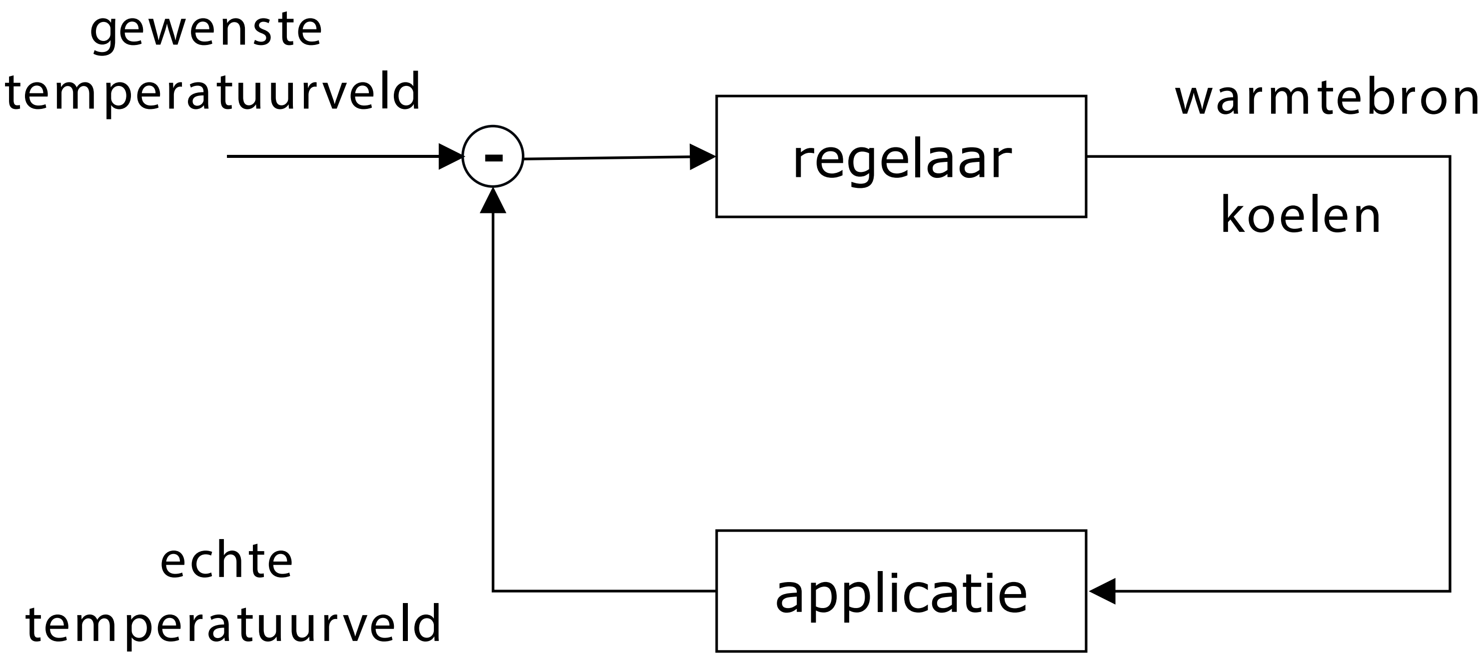
-

model

voorspeld temperatuurveld

Highlights:
Ravensbergen, van Berkel et al. *Nature Comm. 12 (1105)* 2021 (DIFFER, EPFL, TU/e)
van Berkel, Vandersteen et al. *Automatica 50 (8)* 2014 (DIFFER, VUB, TU/e)
van Berkel, Kobayashi et al. *Nuclear Fusion 58 (9)* 2018 (DIFFER, NIFS)
Schneidewind, van Berkel et al. *Water Resources Research* 52 (8), 2016 (RWTH, DIFFER)

Principe van regeltechniek (gesloten-lus)



gewenste temperatuurveld

-

regelaar

warmtebron

koelen

applicatie

echte temperatuurveld

Modelvorming voor regeltechniek (soms) complexer

Modelvorming voor thermische systemen cruciaal

grondbegrippen

white-box

(first-principles)

- finite element
- finite difference (ANSYS, COMSOL)
- model reductie
- regel modellen

hybride

grey-box

Energy Systems & Control group DIFFER

- PDE estimation
- large-scale finite dimensional descriptions
- optimale sensor plaatsing
- maximum-likelihood
- Bayesian
- experimenteel ontwerp

data-driven

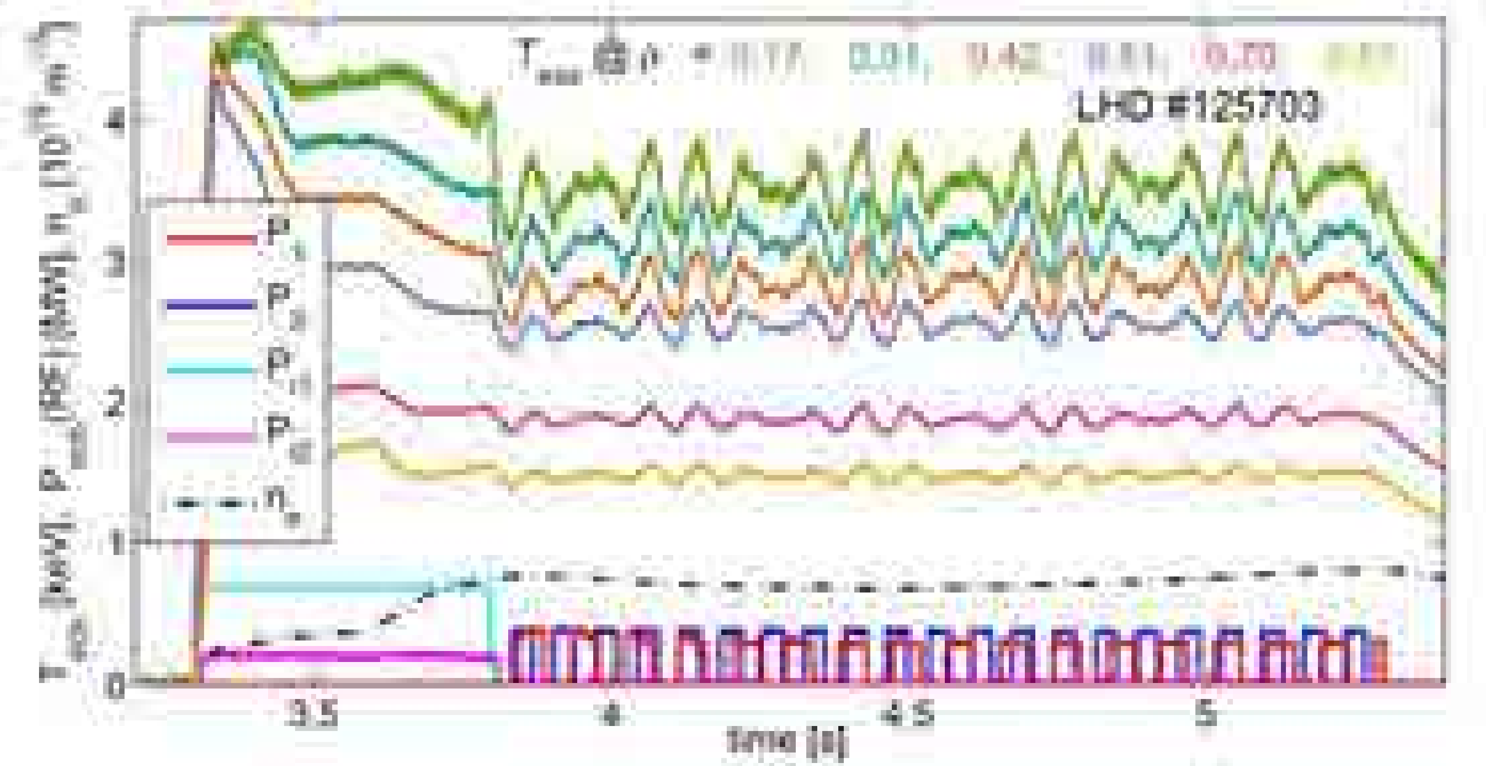
black-box

Control Systems (Technology) ME/EE (TU/e)

- state-space estimation
- frequency response functions
- machine learning
- local parametric models (transients)

Voorbeelden

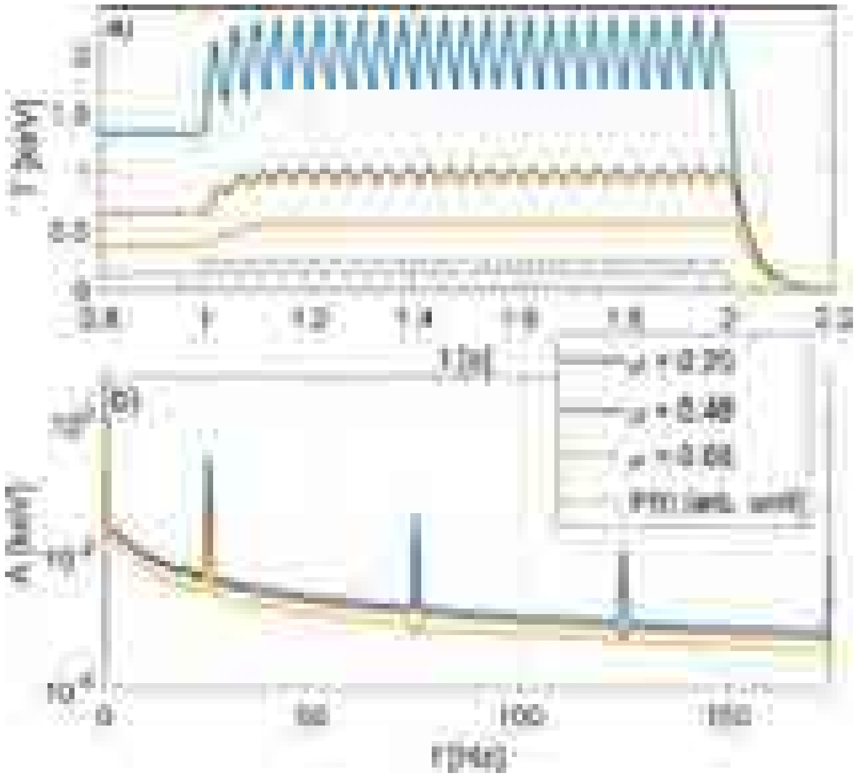
Voorbeeld: hoe bepalen accurate thermische modellen (grey-box)

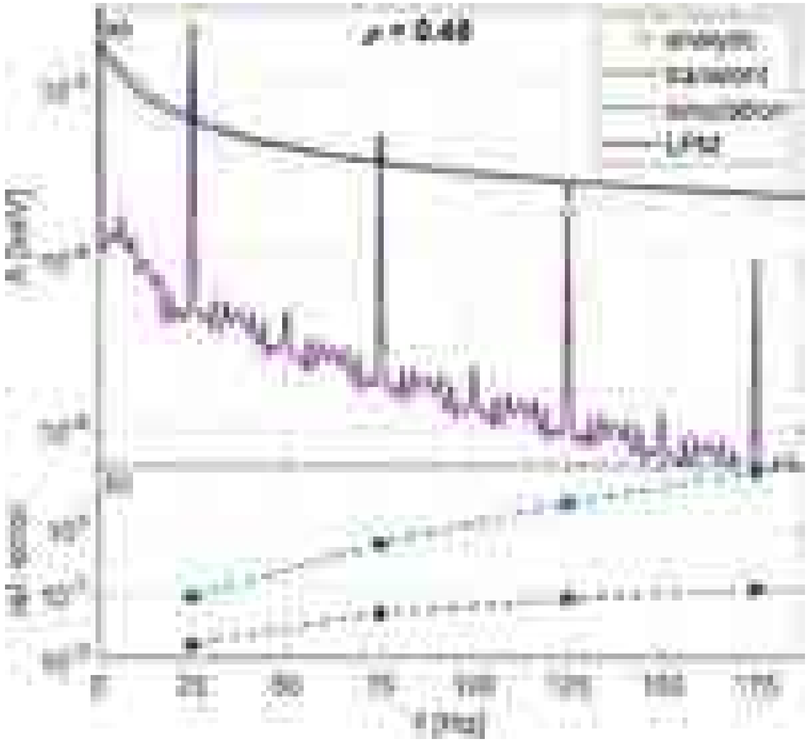


$$\underbrace{\frac{\partial T}{\partial t}}_{\text{tijdsevolutie}} = \frac{1}{\rho}\frac{\partial}{\partial \rho}\left(\underbrace{\rho D n \frac{\partial T}{\partial \rho}}_{\text{diffusie}} + \underbrace{\rho V n T}_{\text{convectie}}\right) + \underbrace{KT}_{\text{demping}} + \underbrace{Q(\rho, t)}_{\substack{\text{verhitting} \\ \text{e.g. microgolven}}}$$

Voorbeeld gemeenschappelijk probleem: transienten

Versnellen van modelvorming: local parametric methods





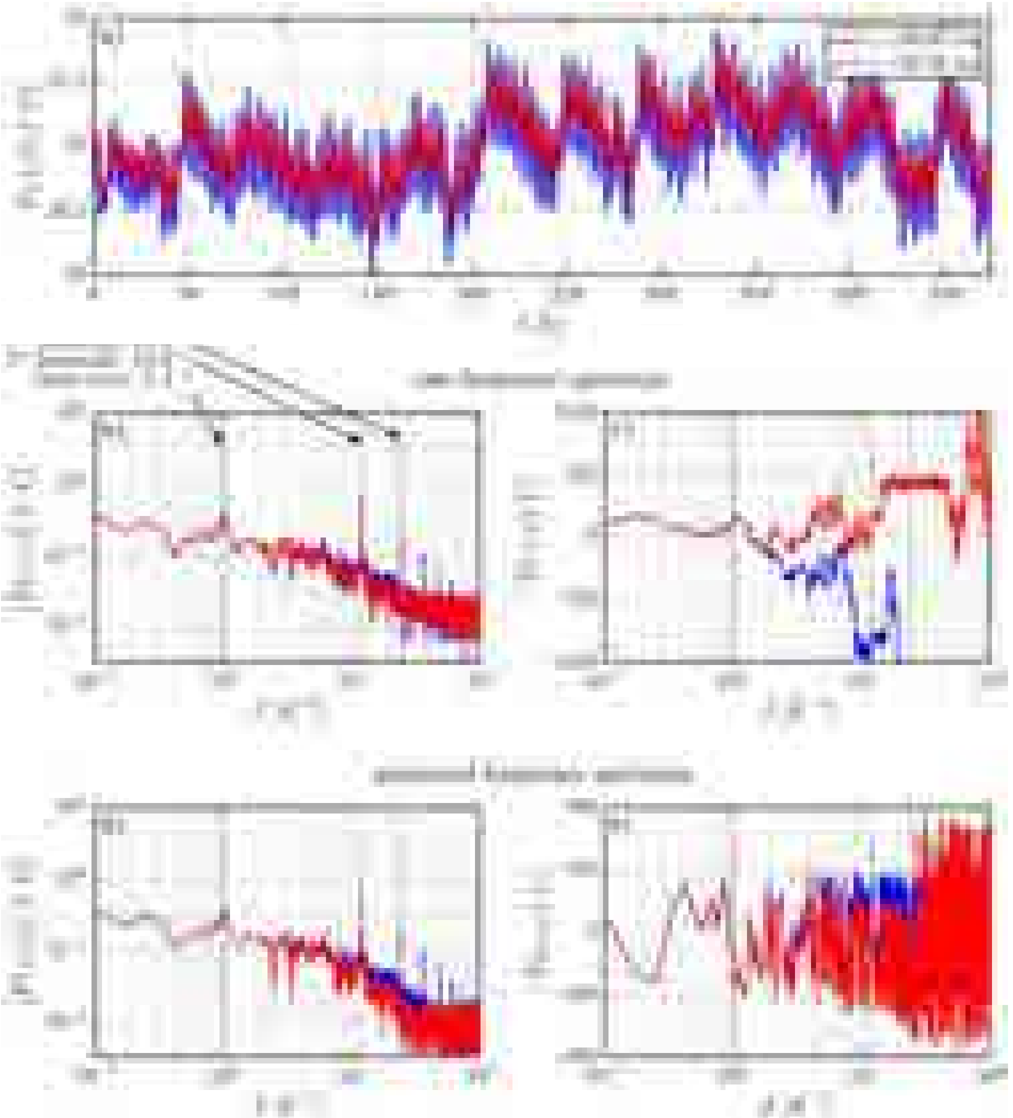
Kernfusie: van Berkel, Kobayashi et al. *Nuclear Fusion 57 (12)*, 2018
Lithografie/FEM: Evers, de Jager et al. proceedings of 18th IFAC Symposium on System Identification, Sweden, 2018
Hydrologie: Schneidewind, van Berkel et al. *Water Resources Research* 52 (8), 2016

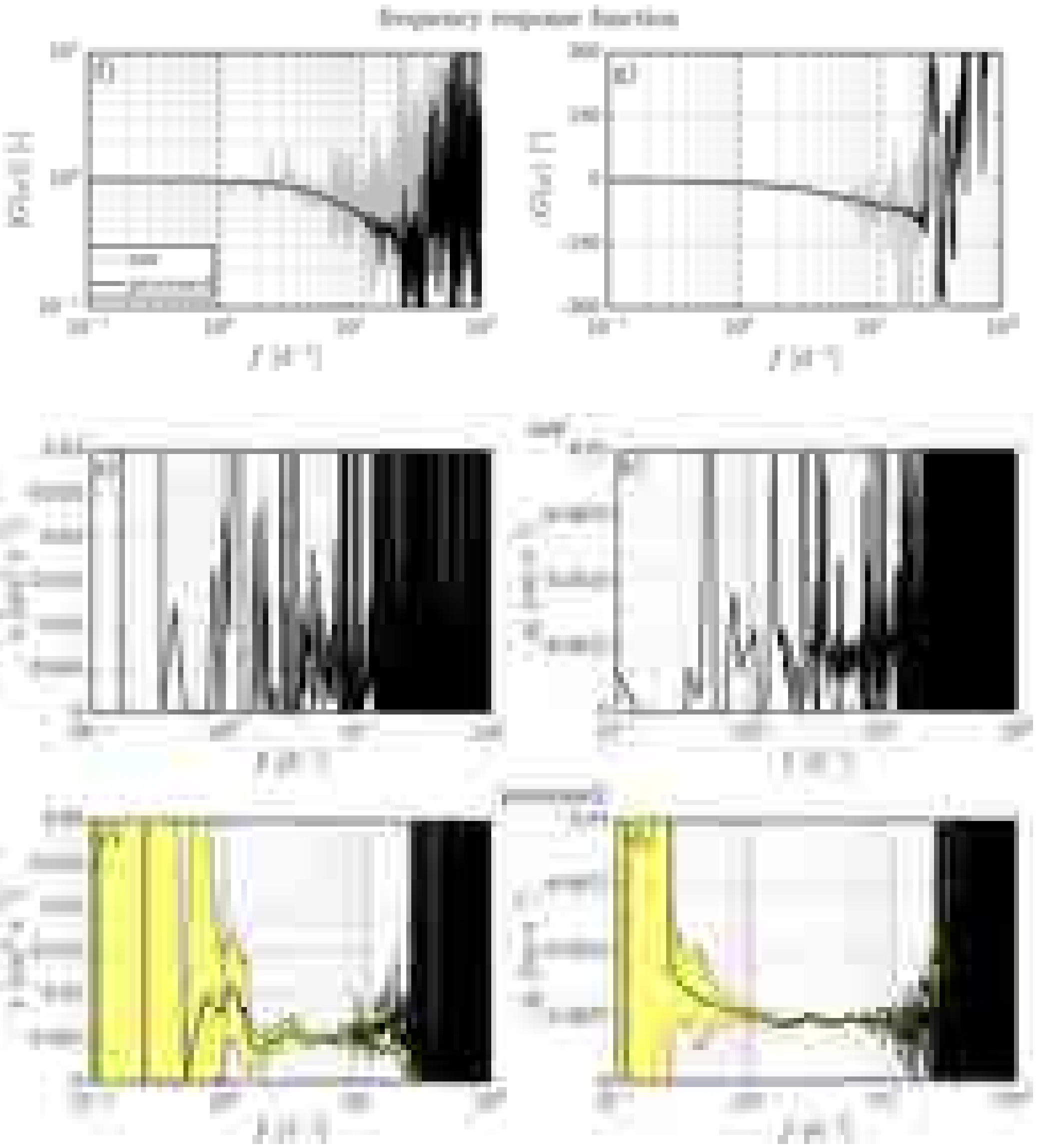
Hydrologie

Bepalen van transport coefficienten in oppervlakte-grondwater interactie

Hydrologie: Luce, Tonina, et al. *Water Resources Research*, vol. 53 (11), 2017

Hydrologie





Hydrologie: van Berkel, Luce, van Kampen et al. *Water Resources Research*, to be submitted, 2021

Dichtheid 's (profiel) regeling in een fusie reactor

- Partieel differentiaal vergelijking (PDV) voor deeltjes transport:

$$\underbrace{\frac{\partial}{\partial t}\left(n_e\frac{\partial V}{\partial \rho}\right)}_{tijdsevolutie} = \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho}\left(\underbrace{\langle(\nabla\rho)^2\rangle\chi\frac{\partial n_e}{\partial \rho}}_{diffusie} - \underbrace{\langle|\nabla\rho|\rangle v n_e}_{convectie}\right)\right] + \underbrace{\left(\frac{\partial V}{\partial \rho}\right)S_e}_{bron}$$

  - Regelbare bronnen: Gas injectie → continue bron| Pellet injectie → discrete bron
- Van PDV naar gewone differentiaal vergelijking voor regelaar ontwerp

$$n_e(\rho,t) = \sum_{\alpha=1}^{m}\Lambda_\alpha(\rho)b_\alpha(t)$$

  - Spatiele discretisatie met basis functies
  - Tijds discretisatie

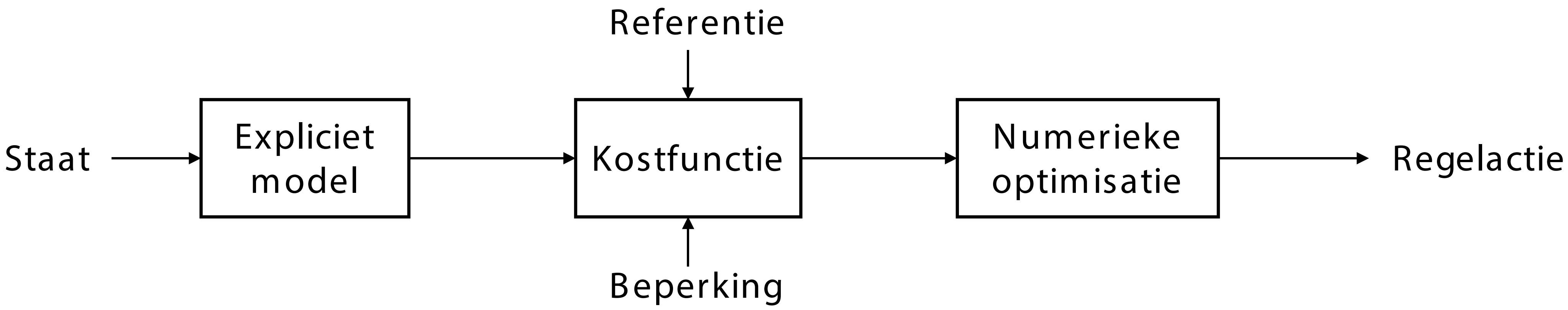
→ Niet lineaire state-space

$$x_k = f(x_{k-1}, u_{k-1})$$

Ontwerp voor een dichtheid’s profiel (functie) regelaar in een kernfusie reactor

- Regeling van PDV
  - Meerdere bronnen
  - Meerdere metingen
- Dichtheid’s limiten

Robust Model Predictive Controller



Referentie

Staat

Expliciet model

Kostfunctie

Numerieke optimisatie

Regelactie

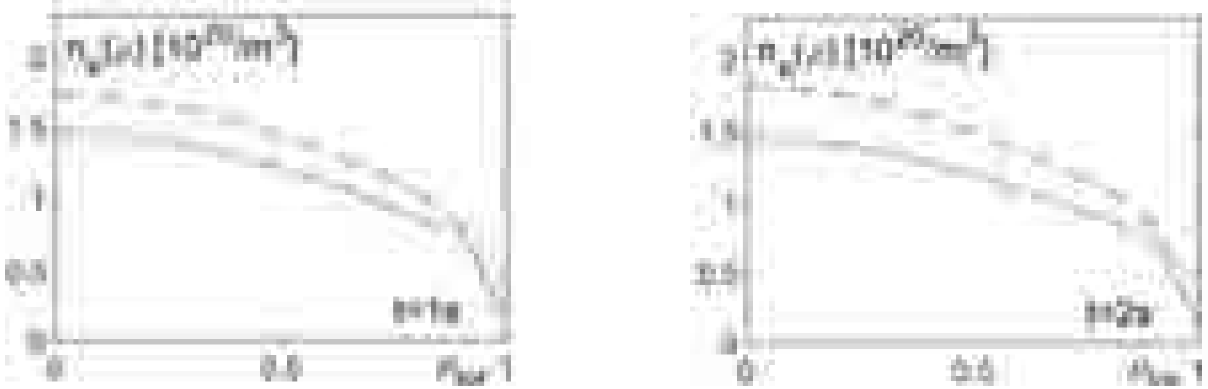
Beperking

Ontwerp voor een dichtheid’s profiel (functie) regelaar in een kernfusie reactor: resultaten en uitdagingen

- Resultaten met continue regelbronnen

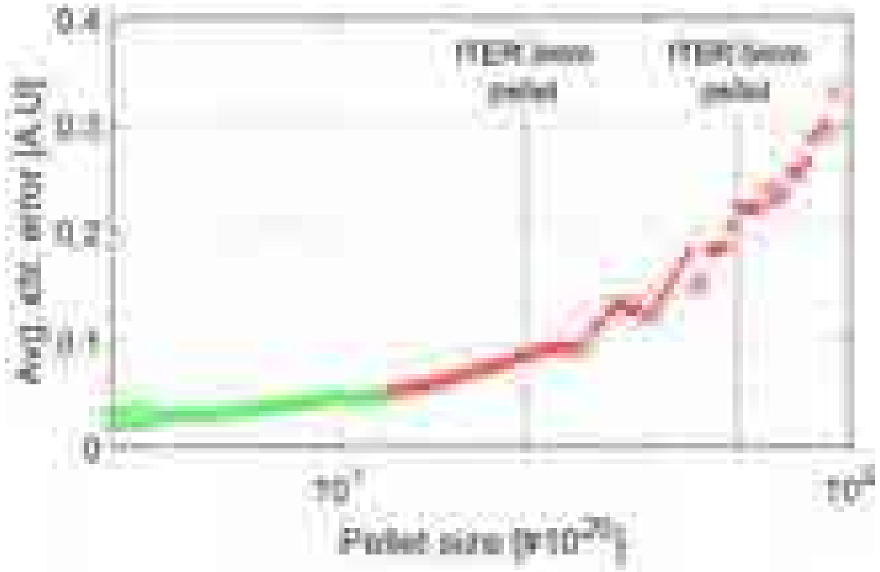
  → Goed regelbaar

- - open lus   -·- gesloten lus   · · · referentie



- Resultaten met discrete regelbronnen
  - Discrete bron dynamica is limiterend
  - Regeltechniek strategie die discrete dynamica meenemen zijn noodzakelijk

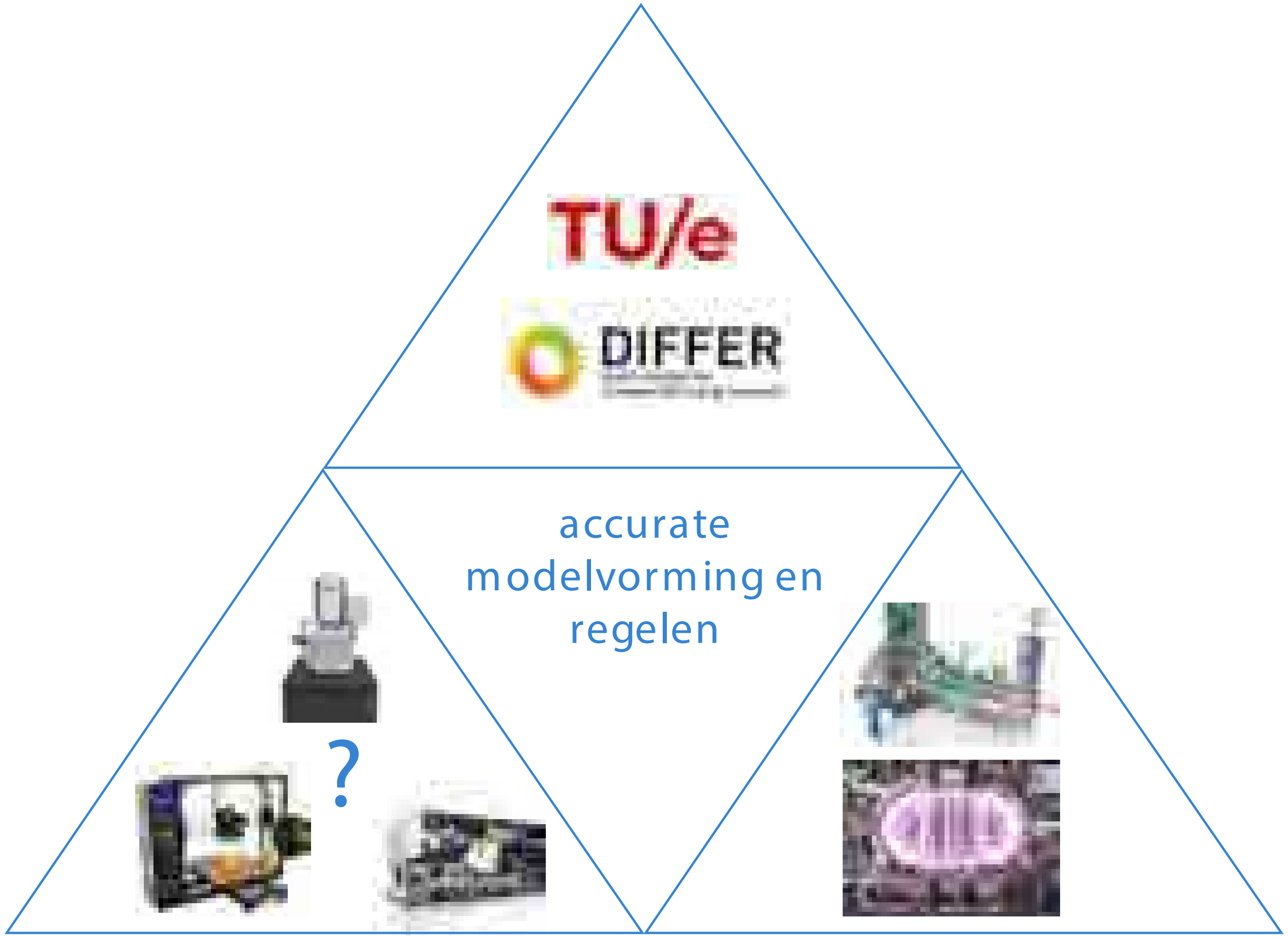
  → Voor regeling van PDV met discrete bronnen bestaat de theorie nog niet!



Uitdagingen thermisch transport

- plasma-gas-vloeistof-vast interfaces
- gekoppeld transport: thermo-mechanisch deeltjes – thermische koppeling
- snel meten (kalibreren) en regelen
- sensoren plaatsing
- regelen met limitatie op verwarmen/koelen
- regelen van distributies (large-scale)
- niet-lineair gedrag
- discrete ingangen

Gemeenschappelijke uitdagingen voor industrie en big science



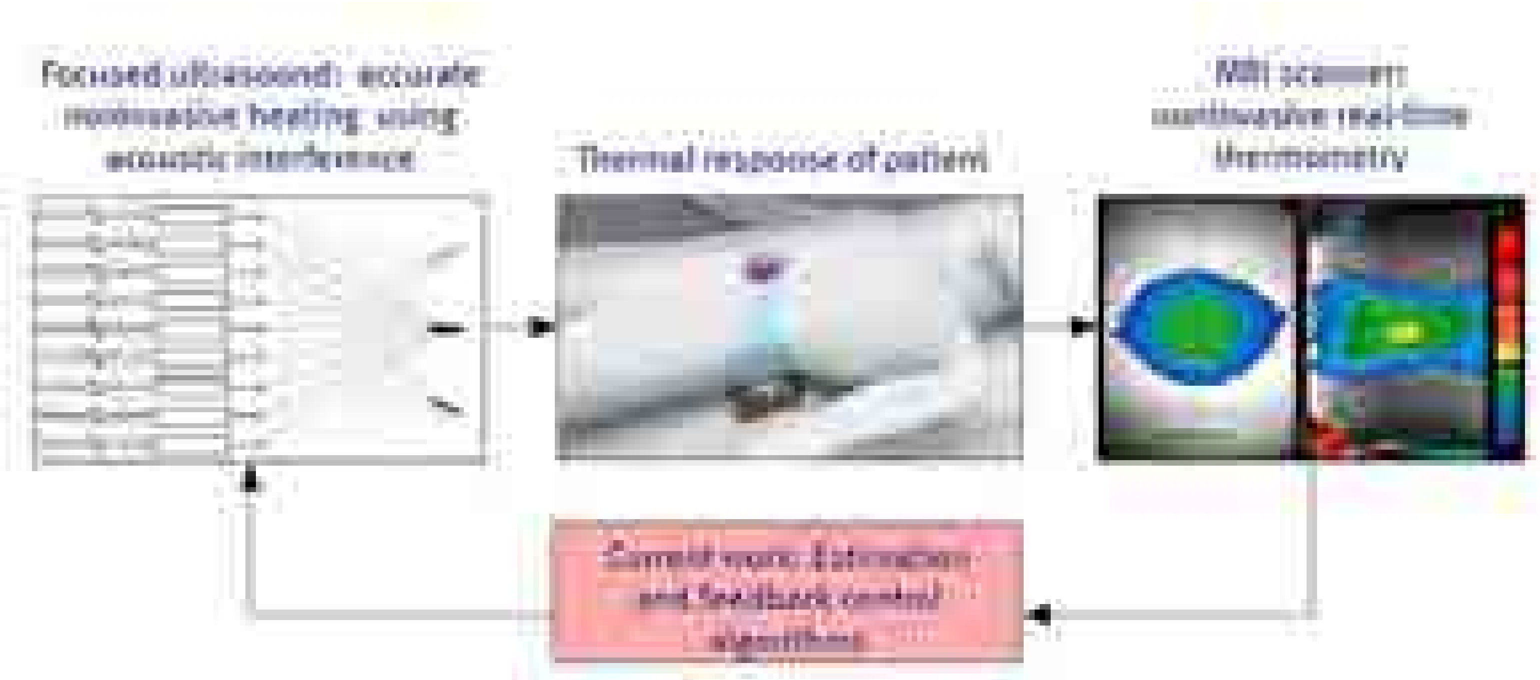
accurate modelvorming en regelen

EXTRA SLIDES

Hyperthermie (introductie)

- Heating the tumor to 43 degrees Celsius
- Enhances treatment efficiency of chemo- and radiotherapy
- Treatment outcome related to achieved temperatures

→ Requires accurate 3D temperature control



Courtesy: Offset-free model predictive control for enhancing MR-HIFU hyperthermia in cancer treatment, Deenen, Maljaars et al., (submitted)

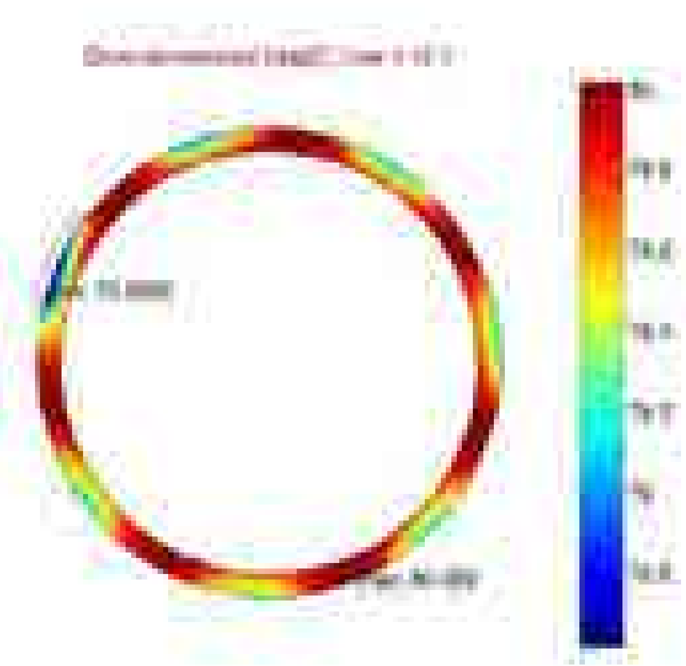
Printen

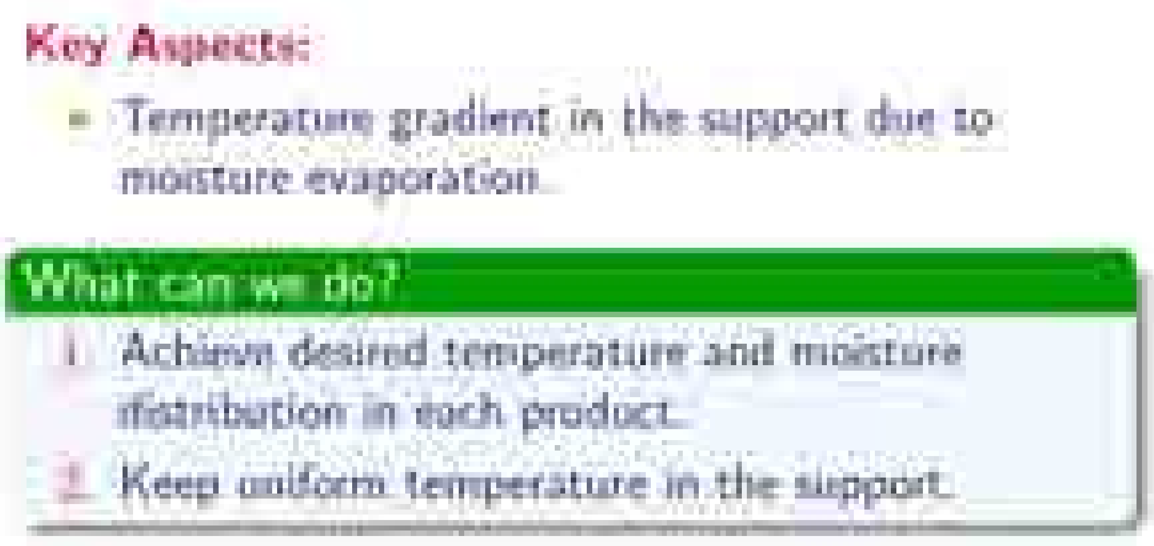
Drying Unit:

How to achieve desired level of **moisture** on the media and **uniform temperature distribution** on the dryer?

Courtesy: Das, Weiland

Printen





Key Aspects:

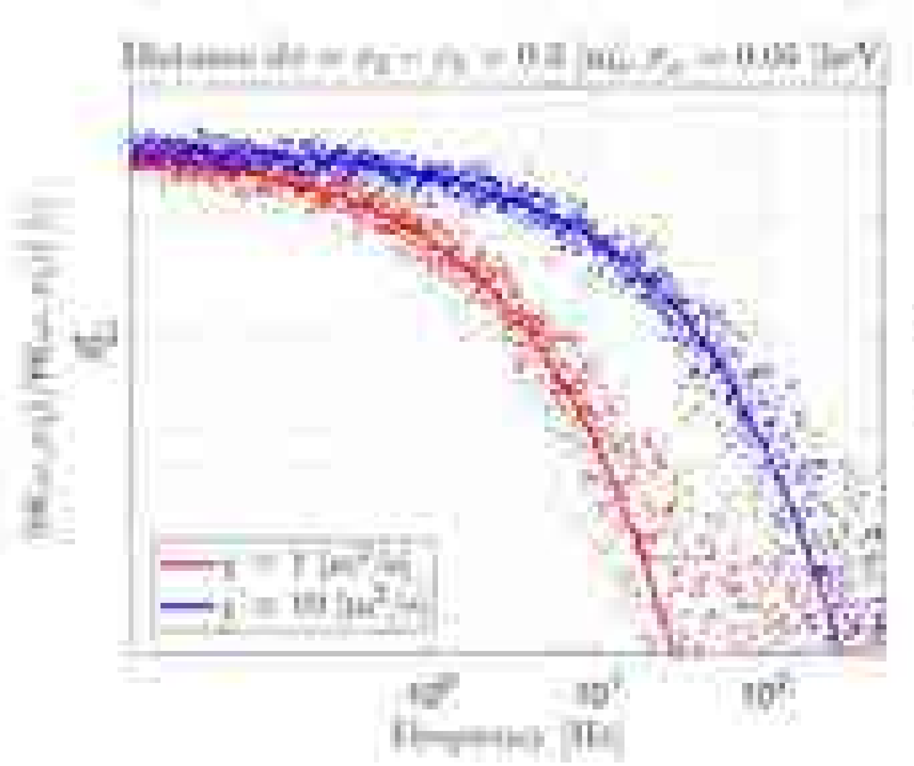
- Temperature gradient in the support due to moisture evaporation.

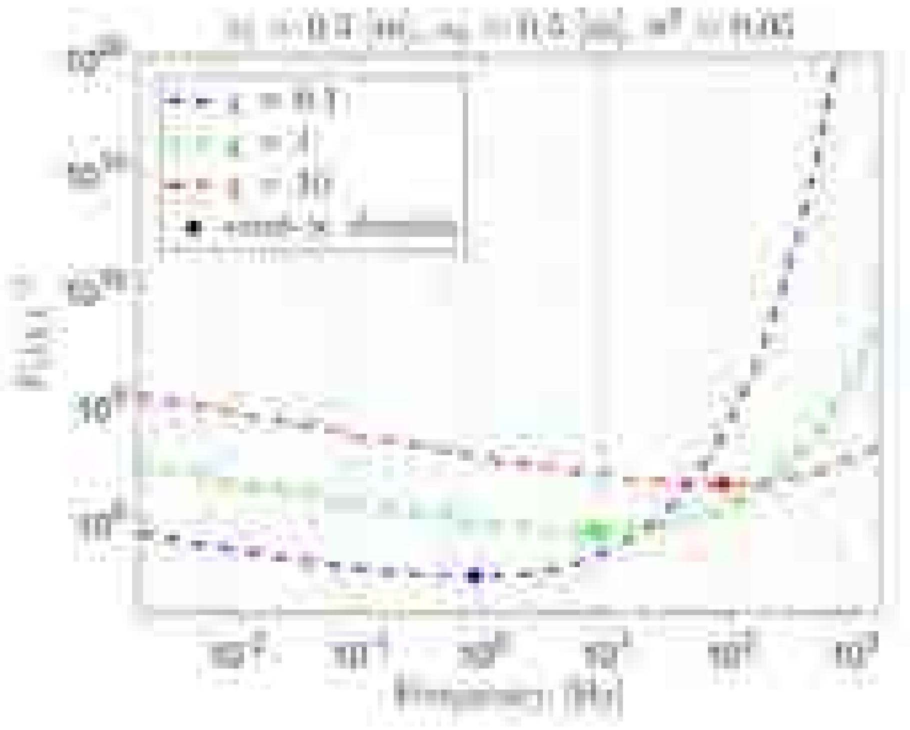
What can we do?

1. Achieve desired temperature and moisture distribution in each product.
2. Keep uniform temperature in the support.

Courtesy: Das, Weiland

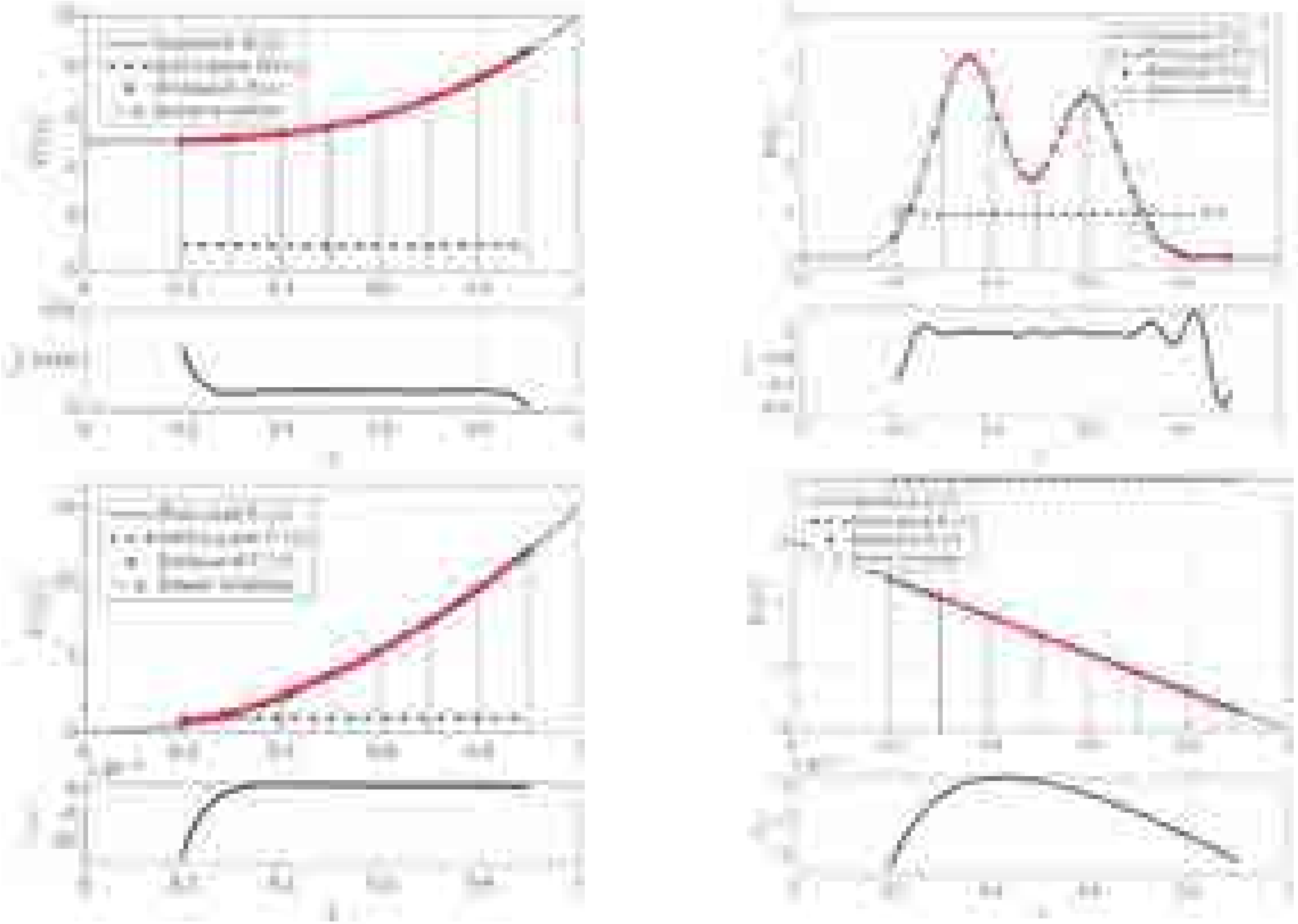
Warmtebron modulatie





van Berkel, de Cock et al. *Physics of Plasmas, 2018*(DIFFER-VUB)s, van Berkel, Weiland, *IEEE Conference on Dec*

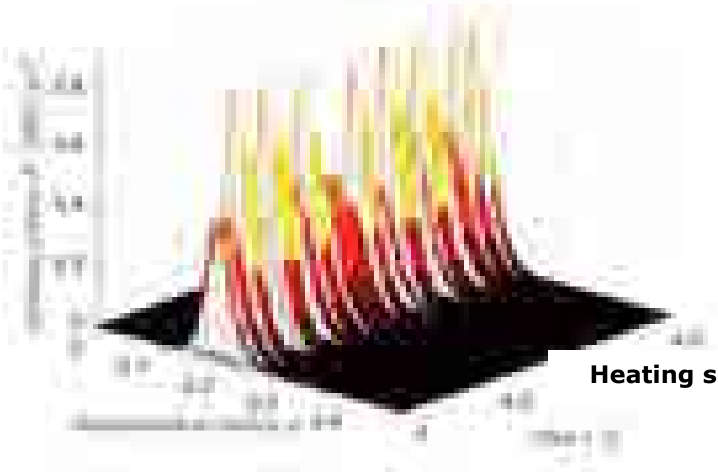
Schatten transport coëfficiënten



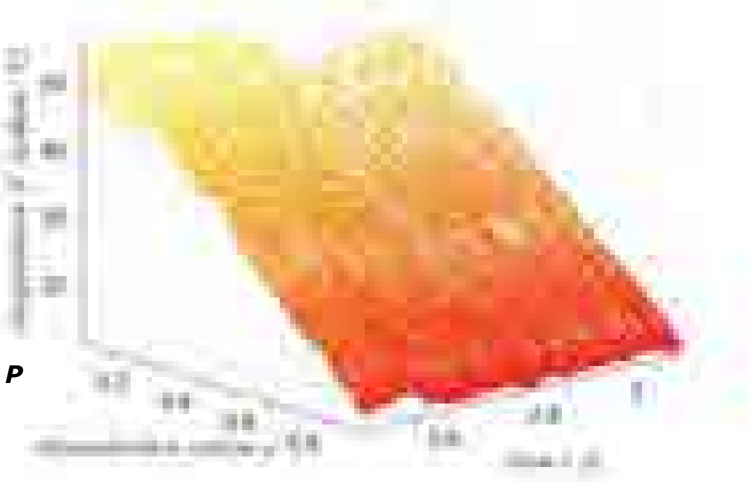
Das, Weiland, van Berkel, Frequency Domain Estimation of Spatially Varying Parameters in Heat and Mass Transport, (accepted) American Control Conference, 2019*on Dec*

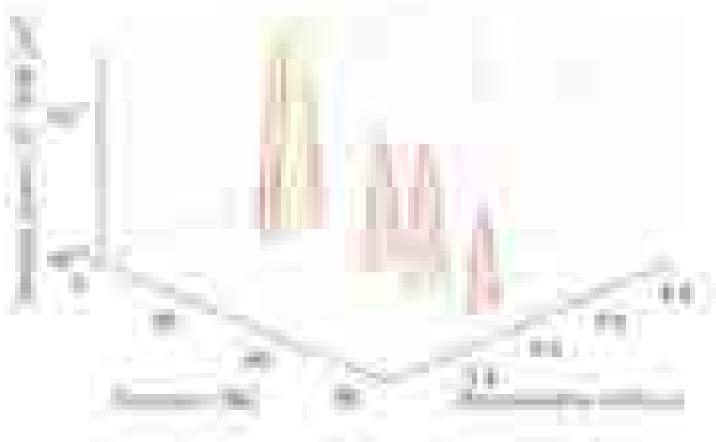
Figuur 2

Heating source input *P* → LHD → Temperature **output *T***



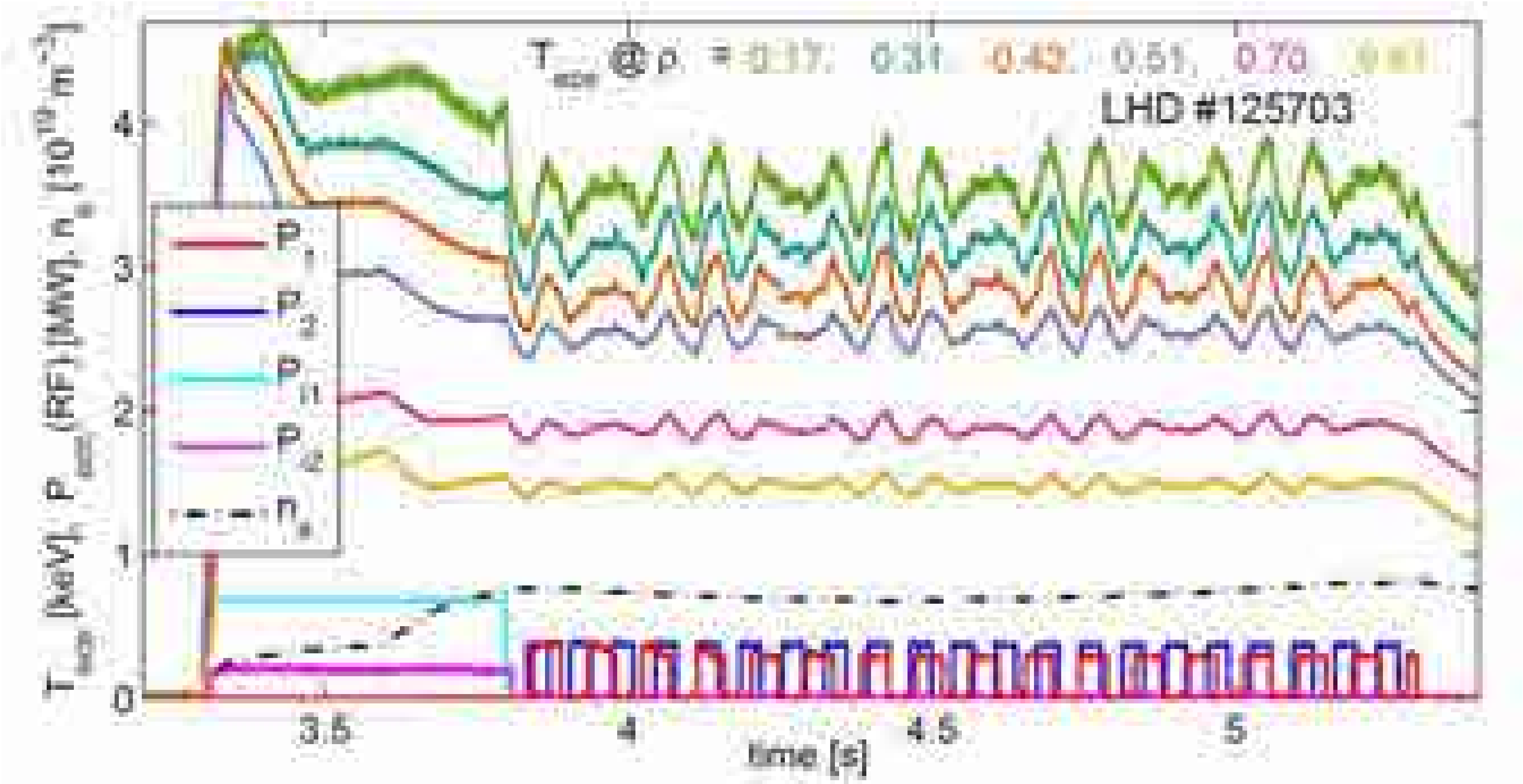
Heating source input *P*



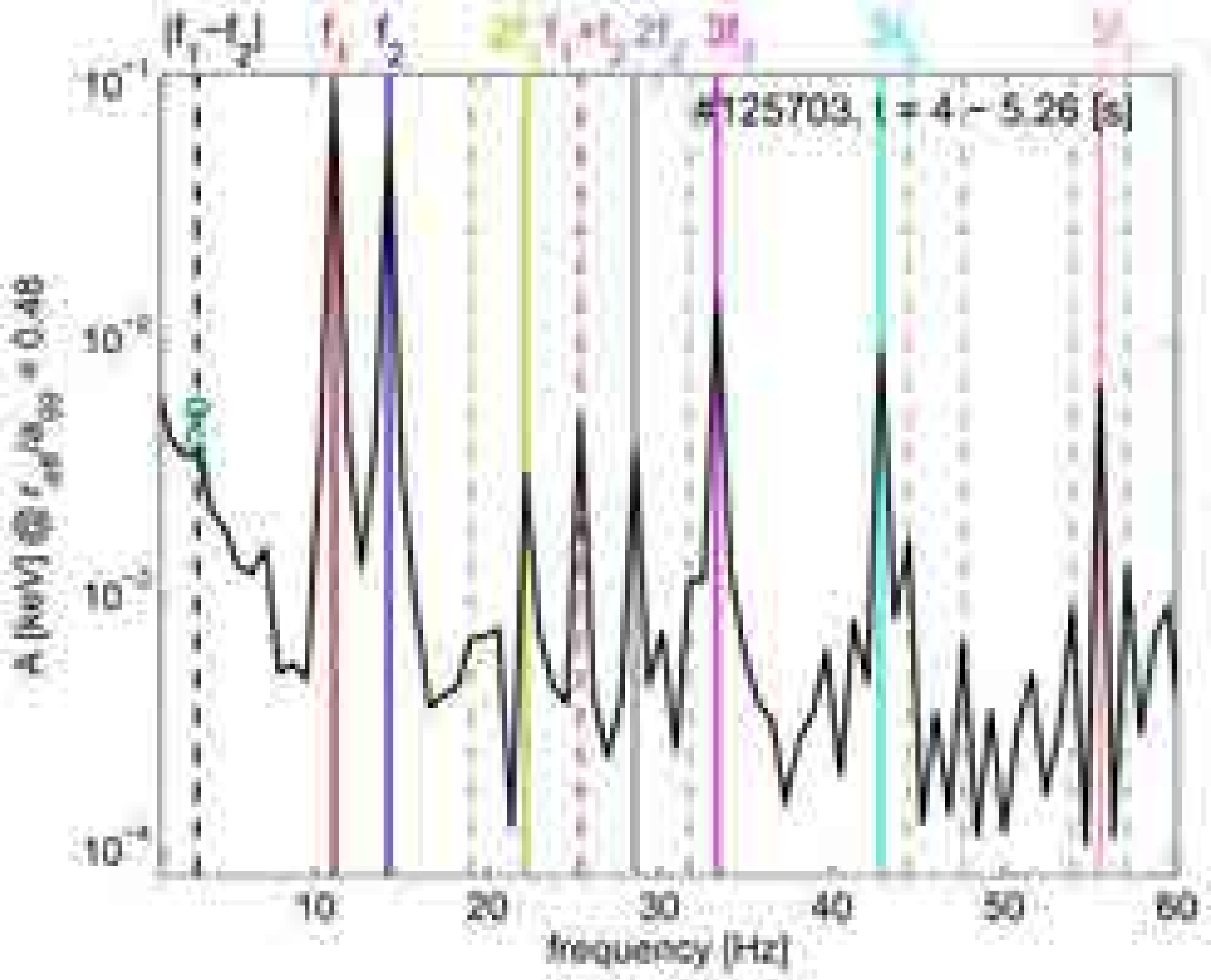


Van Berkel, 2017, Nucl. Fusion

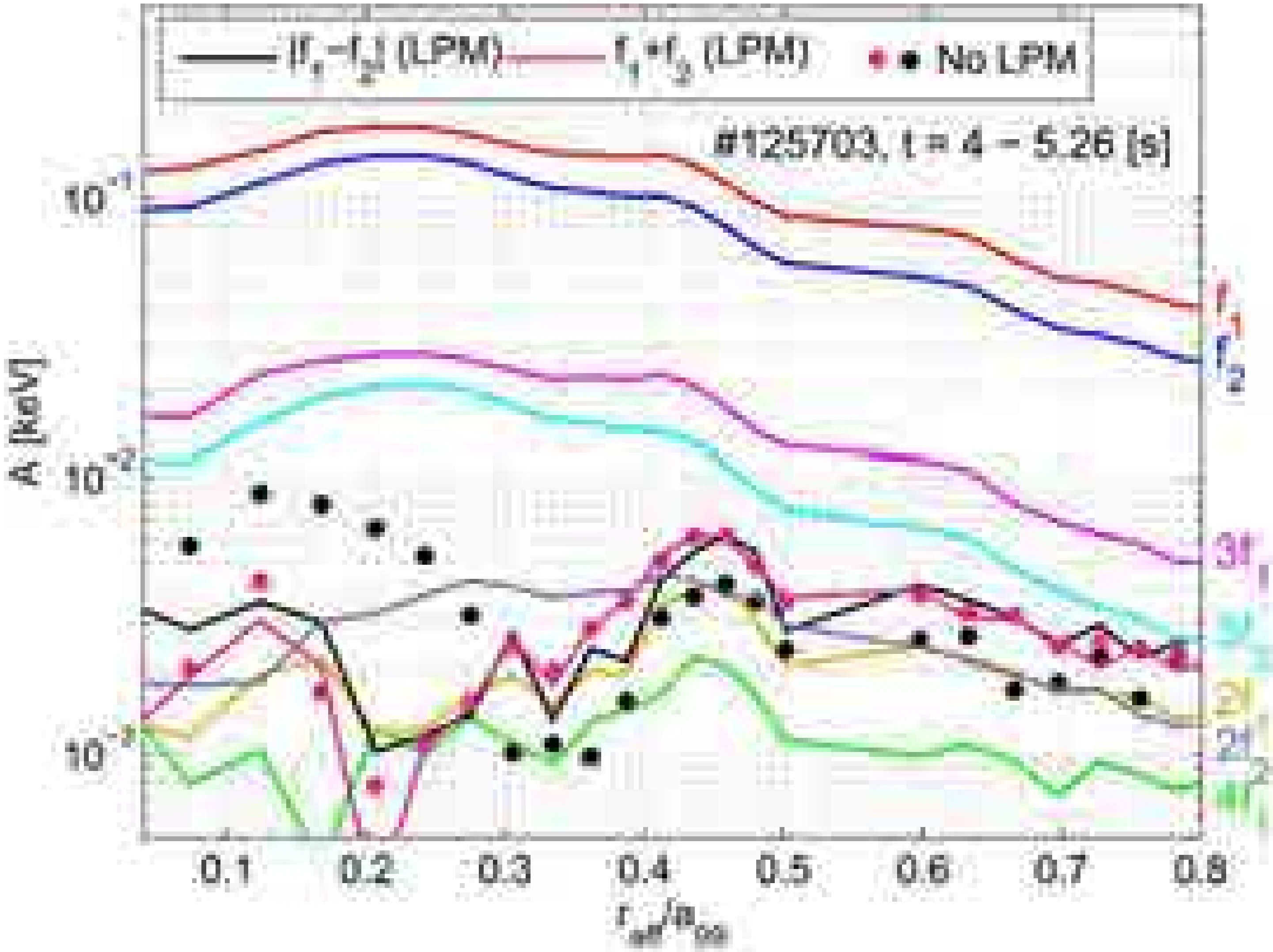
LHD experiment



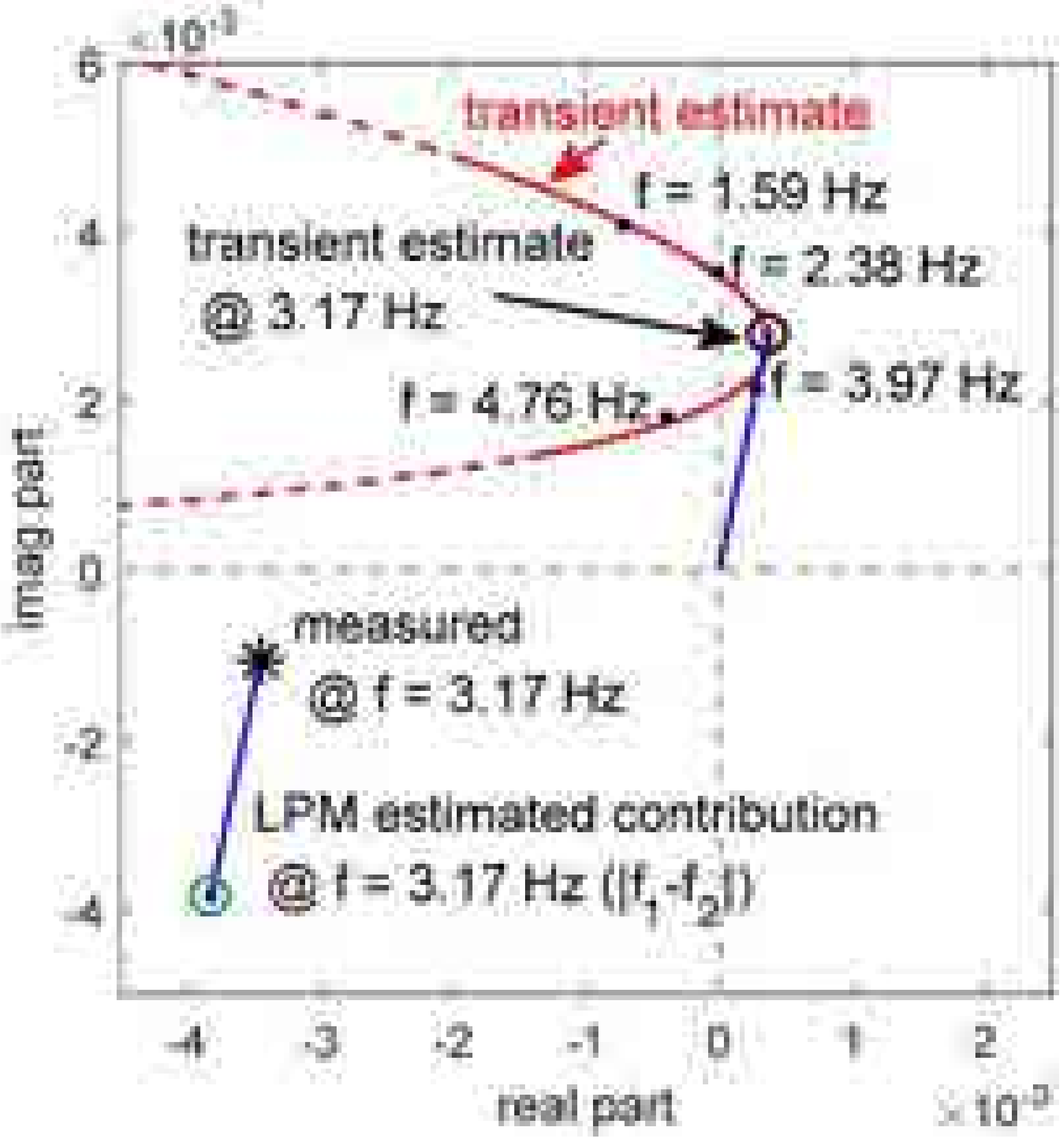
Nieuwe harmonische componenten



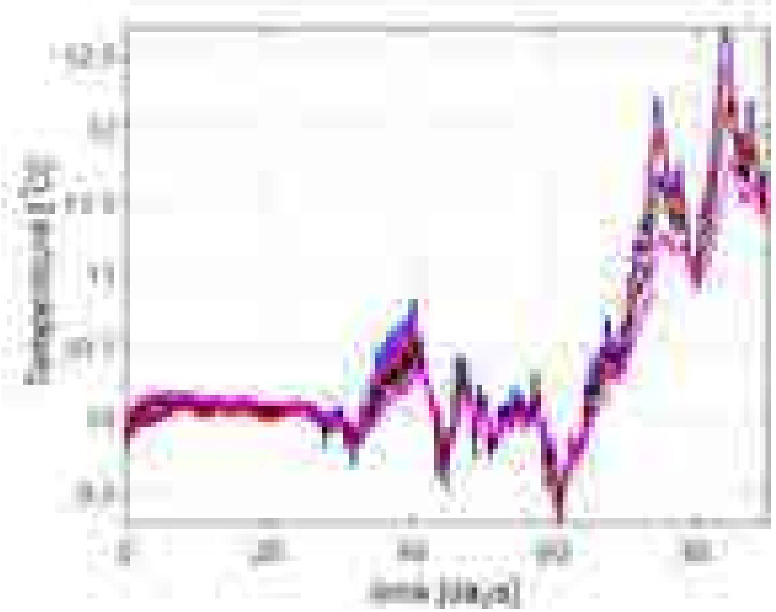
Nieuwe harmonische componenten (distributie)

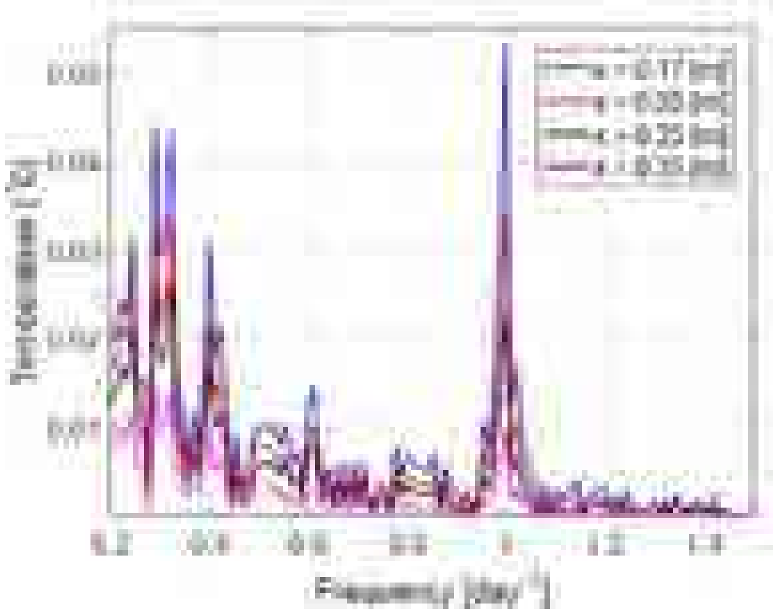


Local parametric techniques



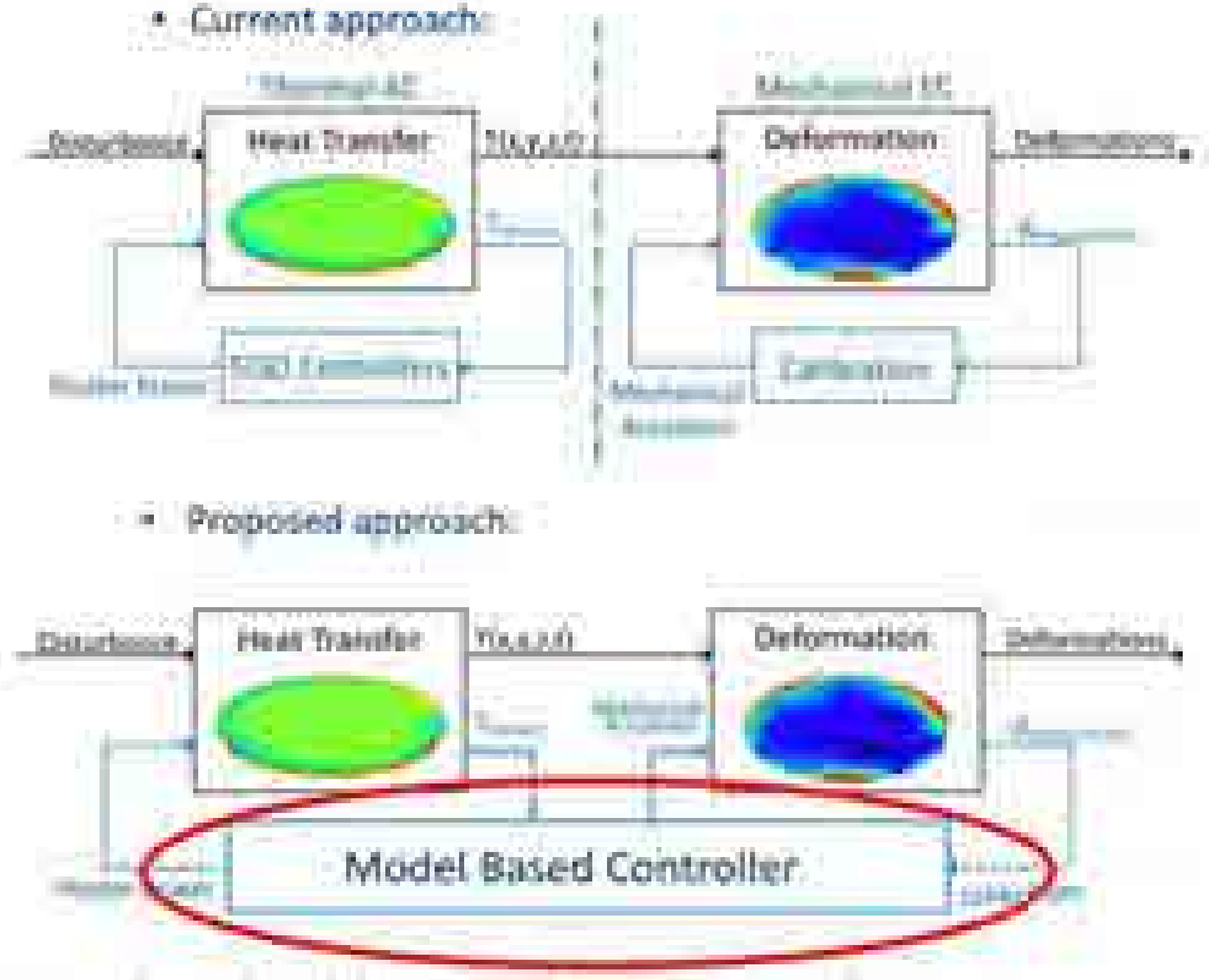
Hydrologie bepalen verticale water flux





Schneidewind, van Berkel et al. *Water Resources Research* 52 (8), 2016 (RWTH-DIFFER)

Regeltechniek van mechanische waferdeformaties a.g.v. thermische belasting

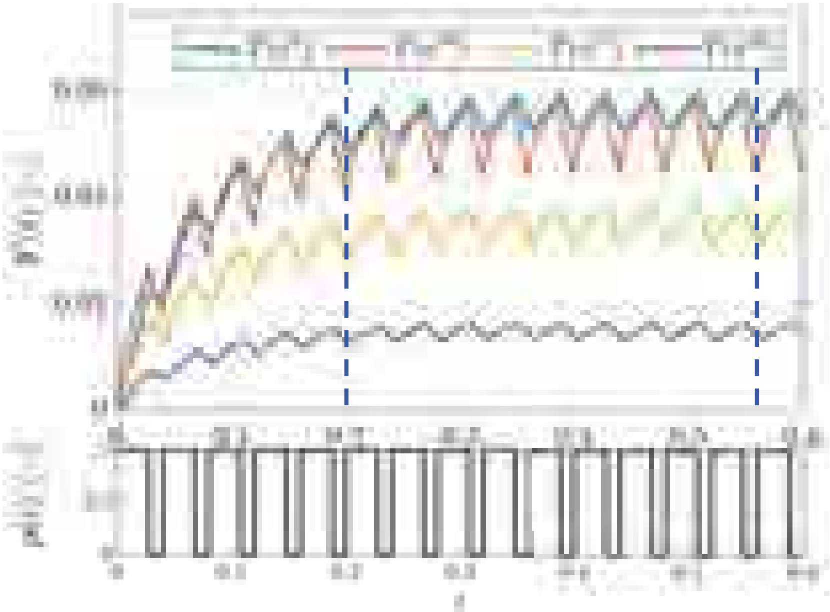


Courtesy: Weiland et al., *2019* (Control Systems, EE, TU Eindhoven)s, van Berkel, Weiland, *IEEE Conference on Dec*

THE END

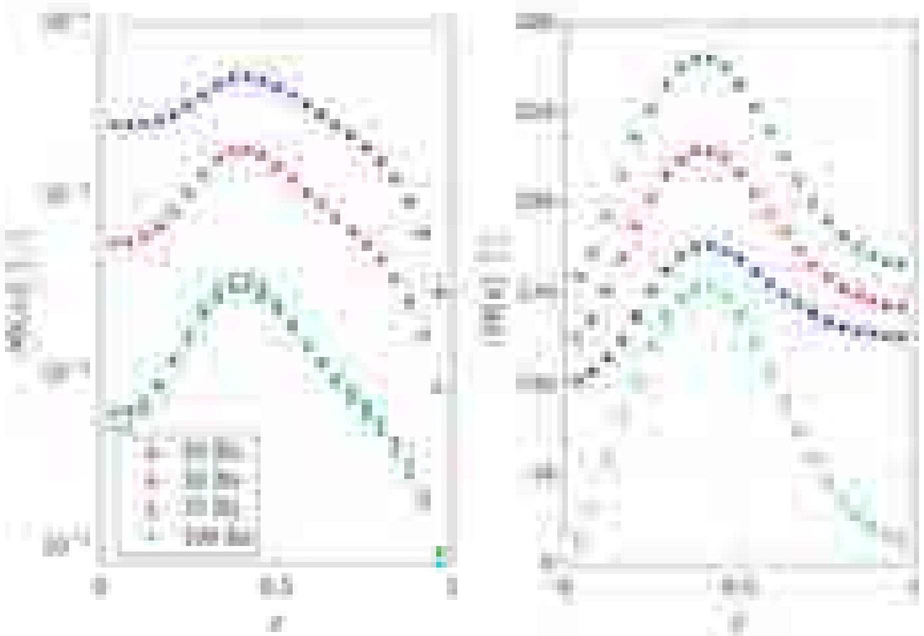
B. Perturbative transport experiments: are used to determine and analyze heat and mass transport

time domain

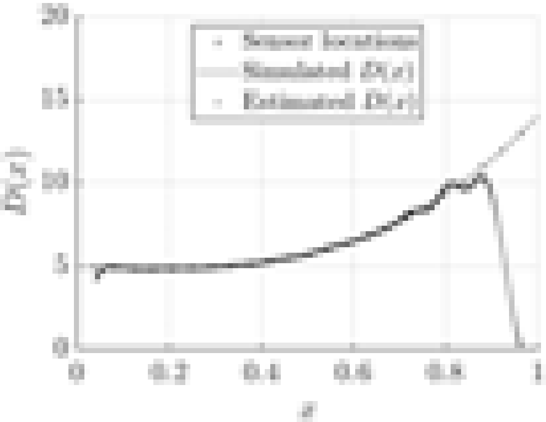


Temperature as function of time and space

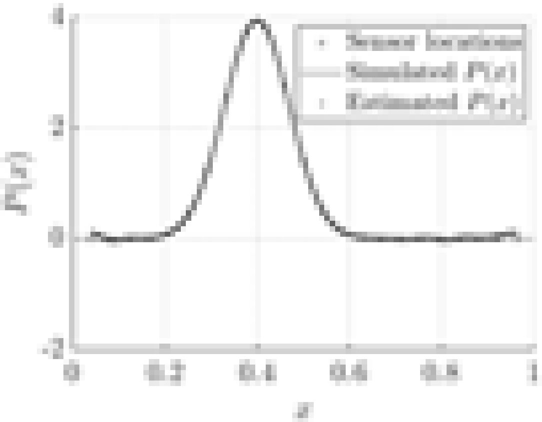
frequency domain



Temperature as function of frequency (bins) and space



Estimate diffusion



Estimate source domain

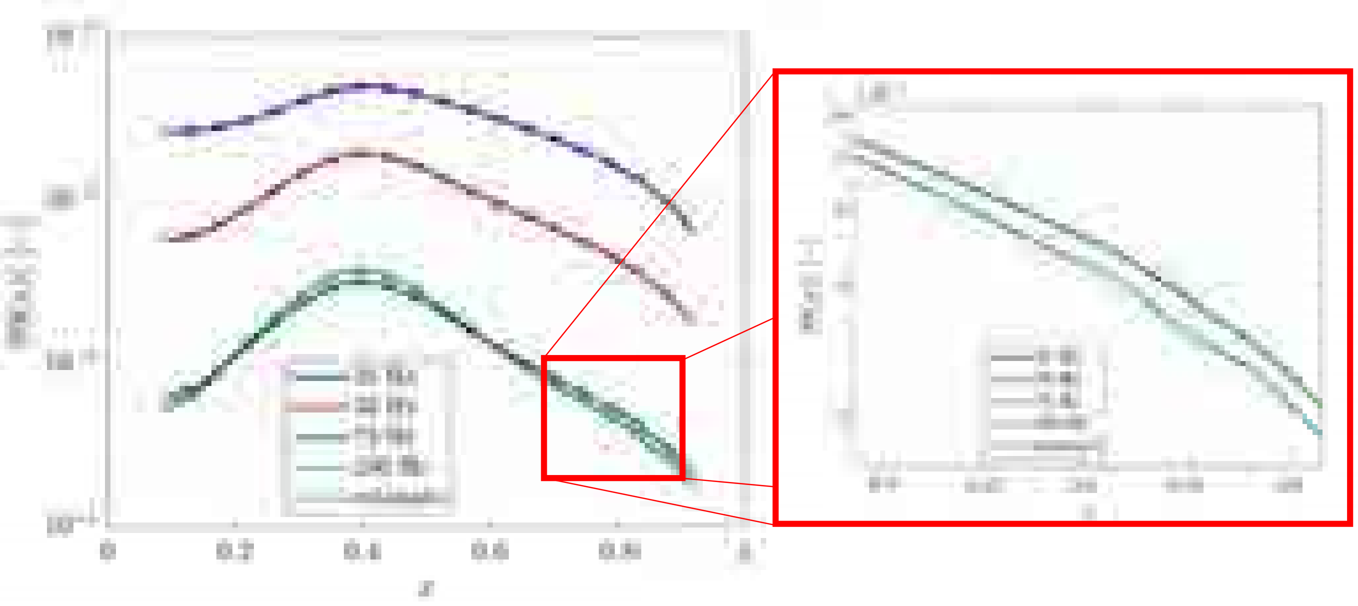
B. Example: Temperature fitting in frequency domain using machine learning tools (CGPR)

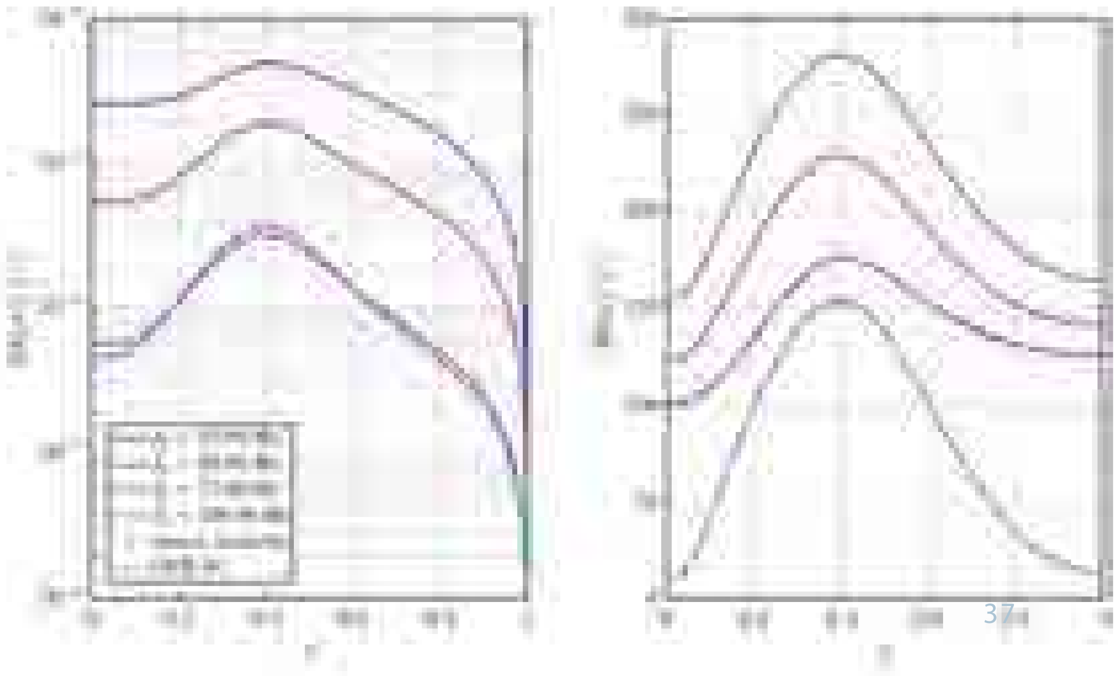
Problem: multiple solutions through the same measurements points

- No knowledge about profiles for diffusion and convection
- Multiple solutions for temperature results in multiple results for diffusion and convection
- Knowledge about temperature profile smoothness

Solution: to constrain using complex gaussian process regression

- Smoothness of temperature $\Theta(x)$ can be imposed in CGPR
- Only single solution with the best approximation in between measurements
- Results in unique profiles for diffusion and convection





Section A

Physics analysis

Two main projects (side -projects)

A. Detachment control (control of the heat-exhaust)

B. Perturbative transport analysis (system identification)

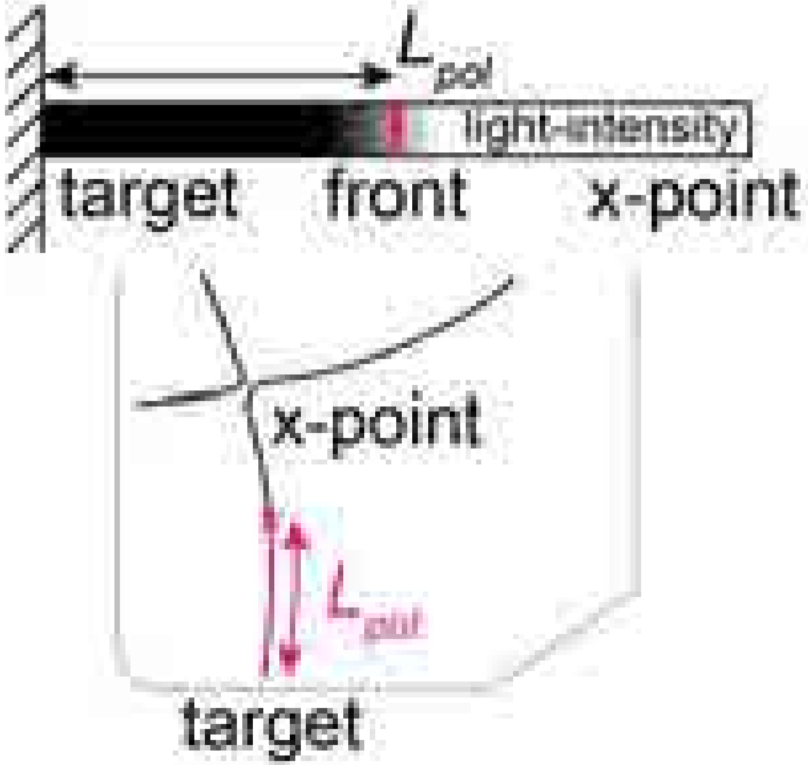
- A number of side projects: SPARC, density control, start-up control

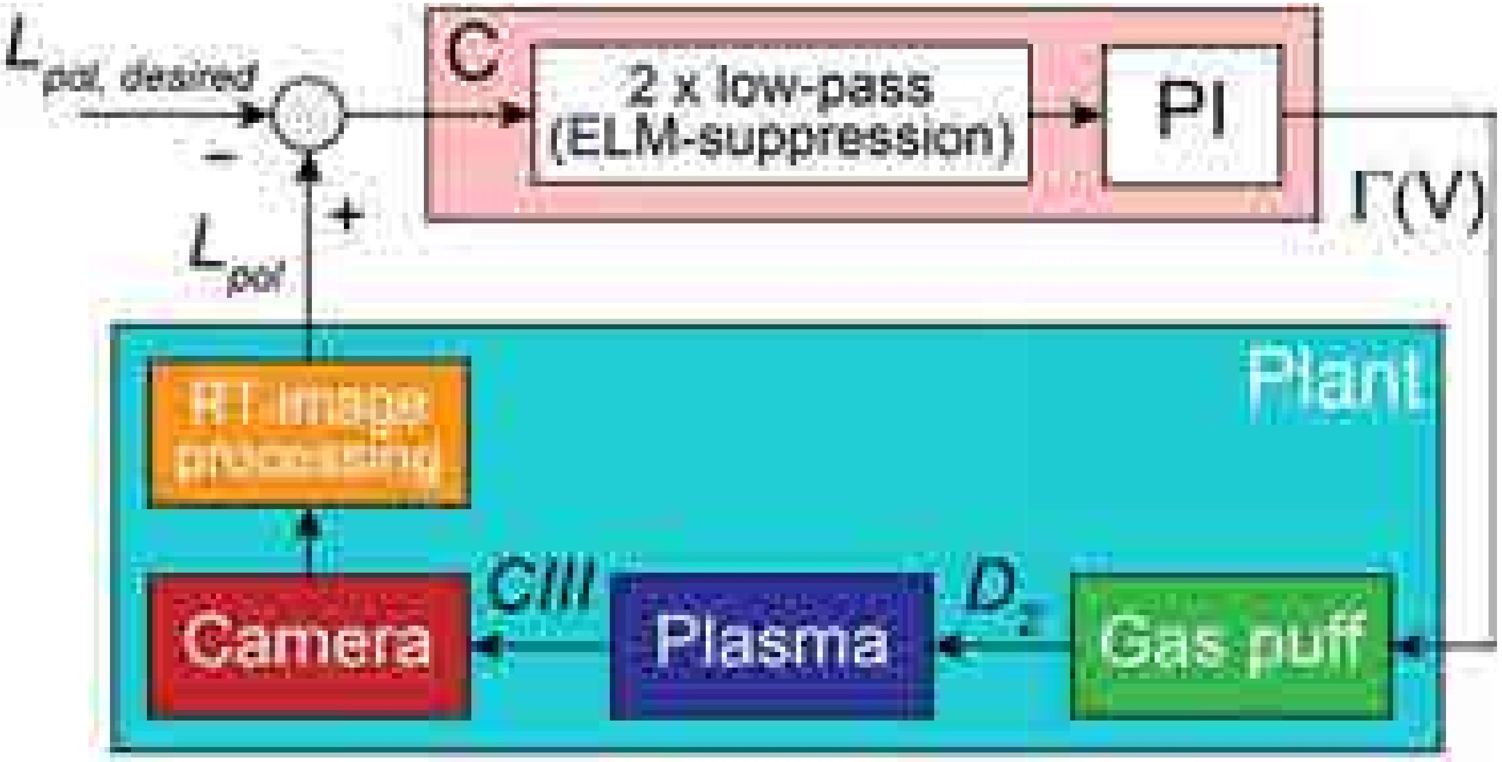
Details:
https://www.differ.nl/research/energy -systems -and - control/research

Section B
Control analysis

A. Detachment control at TCV (Lausanne)

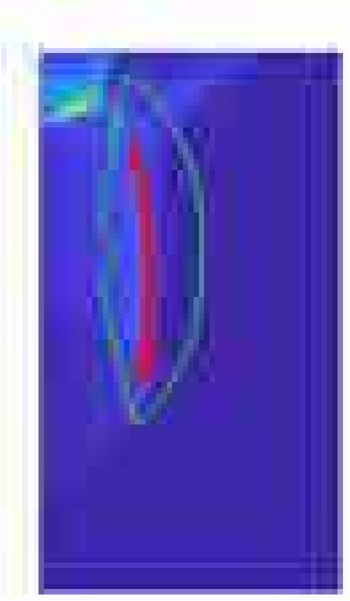
Graphical overview of control loop with the different components



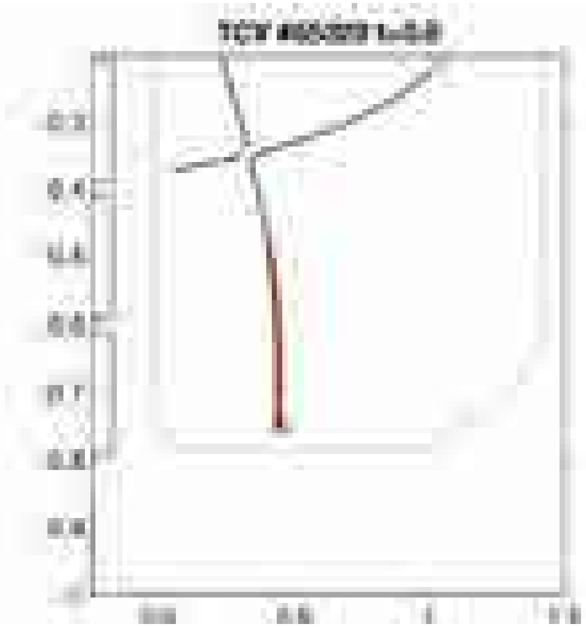


A. Detachment control at TCV (Lausanne)

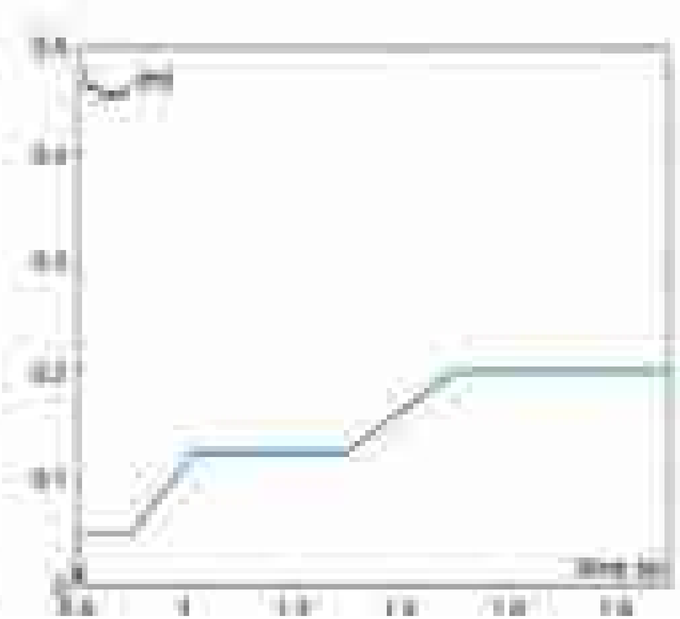
Using light from real-time camera, we can control the plasma using gas



Real-time camera images (CIII)

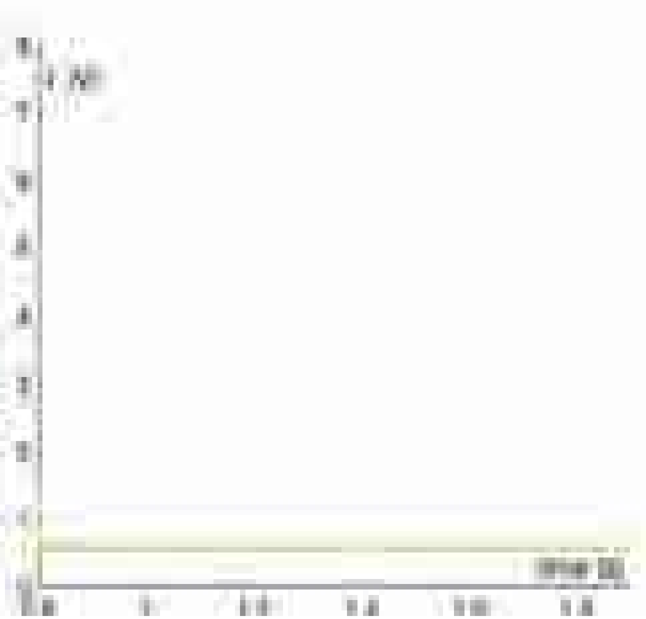


Detecting front location



Reference signal (blue)

Controlled experimental signal (red)



Actuator signal (amount of gas-puffed)

H-mode small ELM regime, I_p =170kA, 1MW NBH

Interested (in internships, master thesis projects)?

Check:

https://www.differ.nl/research/energy-systems-and-control/research

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