Theoretical Plasma Physics at FZJ IEK-4
Tokamaks, Stellarators and Linear Devices

Plasma Day at Ruhr-Universität-Bochum, 26 Sep 2016 | D. Reiser |

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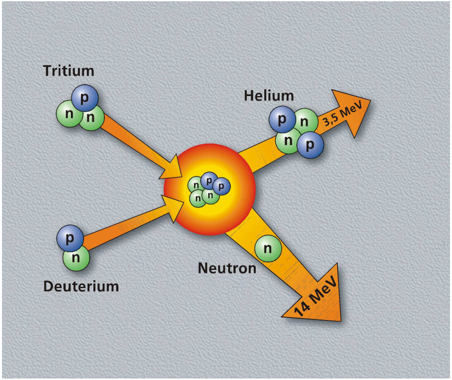
Controlled Nuclear Fusion



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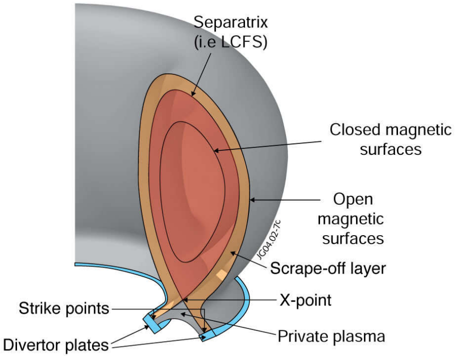
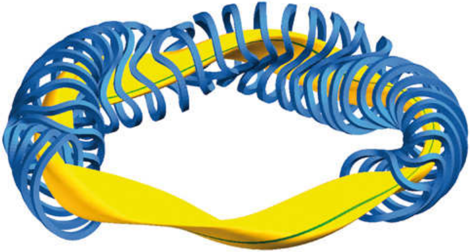
Divertor Tokamak - Edge and Scrape-Off Layer Physics

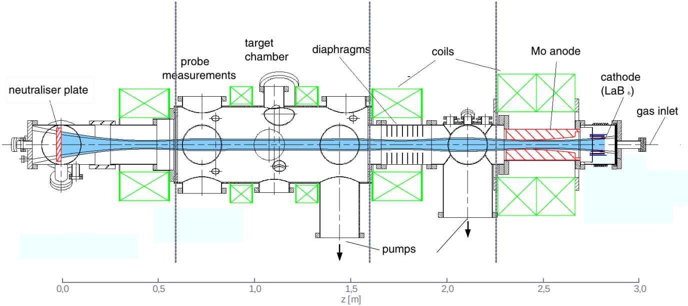


Stellarator - Edge and Scrape-Off Layer Physics



Theoretical Plasma Physics at FZJ - IEK-4

Linear Device



Framework of physical models and research:

- Non-relativistic
- No quantum mechanical effects (except atomic processes)
- Plasma as a classical gas of charged particles
- Kinetic theory
- Fluid theory
- Heavy use of numerical approaches

Kinetic Theory

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Boltzmann equation and Fokker-Planck equation

$$\frac{\partial f}{\partial t} + \mathbf{v} \cdot \nabla_r f + \frac{\mathbf{F}}{m} \cdot \nabla_v f = \left(\frac{\delta f}{\delta t}\right)_{coll}$$

$$\left(\frac{\delta f}{\delta t}\right)_{coll} = \begin{cases} \int \left(f' f_1' - f f_1\right) \, g \, \sigma_c \, d\Omega d\mathbf{v}_1 & \text{Boltzmann} \\ -\sum_i \frac{\partial}{\partial v_i} \left(K_i f\right) + \frac{1}{2} \sum_{i,j} \frac{\partial^2}{\partial v_i v_j} \left(D_{ij} f\right) & \text{Fokker-Planck} \end{cases}$$

Fluid Theory

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Braginskii's equation for plasma dynamics

$$\frac{dn}{dt} = -n\,\nabla \cdot \mathbf{v}$$

$$m\,n\,\frac{d\mathbf{v}}{dt} = -\nabla \cdot \mathbf{P} + \mathbf{R} + Z\,e\,n\,(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$$\frac{3}{2}\,n\,\frac{dT}{dt} = -\nabla \cdot \mathbf{q} - \mathbf{P} : \nabla \mathbf{v} - Q$$

Maxwell's equations for electrodynamics

$$\nabla \cdot \mathbf{B} = 0 \quad , \quad \nabla \times \mathbf{B} = \mu_0\,\mathbf{J} \quad , \quad \epsilon_0\,\nabla \cdot \mathbf{E} = \rho \quad , \quad \nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

Stochastic Approaches and Reaction-Diffusion Models

Langevin equations

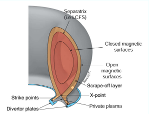
$$\frac{dx}{dt} = v \qquad , \qquad \frac{dv}{dt} = -\frac{\gamma}{m} v + \frac{\xi}{m}$$

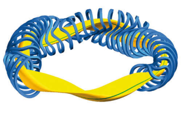
Reaction-Diffusion Equations

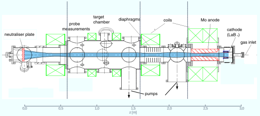
$$\frac{\partial N_i}{\partial t} = -\boldsymbol{\nabla} \cdot (\mathbf{D}_i \cdot \boldsymbol{\nabla} N_i) + \sum_j R_{ij}$$

Challenges

- Geometrical details of magnetic fields and devices
- Numerical approaches for multi-scale problems
- Simulation runs at the limit of modern computers
- Still several unknowns in underlying models





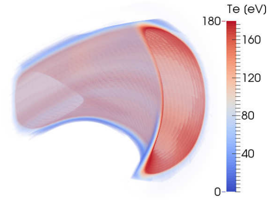


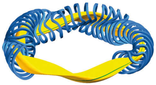
Numerical Methods

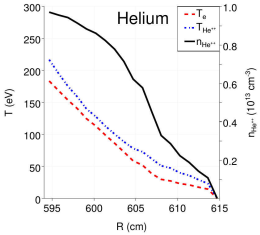
- **Monte-Carlo methods**
  used for linear kinetic problems, Fokker-Planck type fluid problems in complex geometry
- **Finite differences and finite volumes**
  used for fluid dynamics in smooth geometry, turbulence
- **MPI parallelization**
  used for all approaches
- **Semi-Analytical methods**
  for several basic questions

Plasma Transport in 3D configurations

- 3D, stationary fluid model
- coupled to kinetic model for neutrals
- linear Monte Carlo code EMC3-EIRENE
- experiment-modeling comparison for the stellarator Wendelstein 7-X







- next step: self-consistent calculation of el. fields, comparison to spectroscopic data, synthetic diagnostics

Power Exhaust Studies

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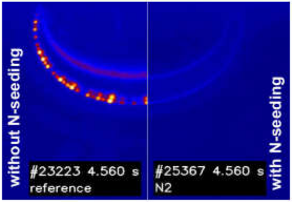
- Large power fluxes are a challenge for power exhaust ($q_{\parallel,mid} \approx$GW/m²)
- Increasing difficulty in future devices:
  - → Increasing P_{sep}/R = 15 → 80 MW/m
  - → Constant $\lambda_{q,SOL}$ ≈1 mm [Lackner -PPCF (1994)]
  - → Unkown S ≈1.5-4.5 mm [Eich -PRL (2011)] [Wenniger NF54 (2014)]
- Geometric countermeasures, e.g. flux expansion & inclination, can reduce power fluxes (q_{tar}) to ~100 MW/m²
- Material limit is lower at 5-10 MW/m²

[ITER Physics Base – NF (2007)]

Additional power dissipation required!

[Reimold – NF 55 (2015)]
[Kallenbach – NF 55 (2015)]



IR camera view into the lower divertor of ASDEX Upgrade

	AUG	JET	ITER	DEMO
P_{sep}/R [MW]	16(11)	7	16	50-100
$q_{\parallel,mid}$ [GW/m²]	3.5	2	5	>30

[M.Wischmeier – DPG (2013)]

Power Exhaust Studies

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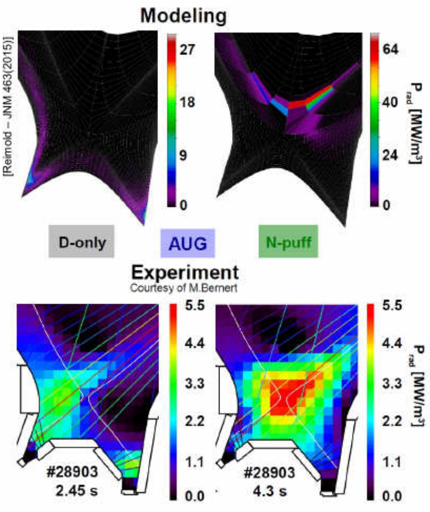


The Problem:

- Large power fluxes tokamak Scrape-Off Layer ($q_{\parallel,mid} \approx$ GW/m²)
- Remaining target power fluxes to material surfaces fluxes are ~100 MW/m²
- Material limit is lower at 5-10 MW/m²

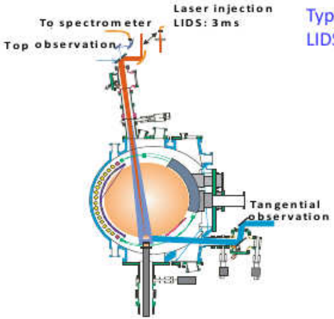
→ **Additional power dissipation required!**

- Additional impurity line radiation can help to increase f_{rad} from 50% to 80-90%
- Modeling can recover (most) experimental effects of seeding

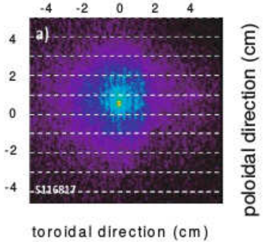
Laser Diagnostics and Plasma Response

Interpretation of signals from laser-based diagnostics of plasma facing components (PFC)

Example: Laser Induced Desorption Spectroscopy (LIDS)
Aim: Assessment of hydrogen content absorbed in PFC
Method: Particle desorption by laser pulse on PFC during discharge and recording of emission from plasma
Problem: Plasma parameters are changed by LIDS



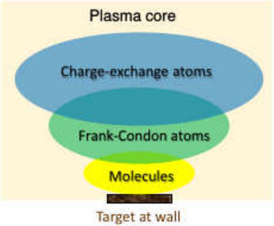
Typical time integrated (~10ms) D_α-light pattern by LIDS applied on D_2-rich C-layer (top observation)



Laser Diagnostics and Plasma Response

Species and processes included into modeling of LIDS-signals:

- D_2-molecules desorbed
- Franck-Condon atoms are generated by molecule
  - Dissociation
  - Ionization
  - Charge-exchange
- Charge-exchange atoms produced from molecules and fc-atoms
- Impact on plasma through ionization and excitation of neutrals:
  - Increase of plasma density
  - Drop of electron and ion temperatures



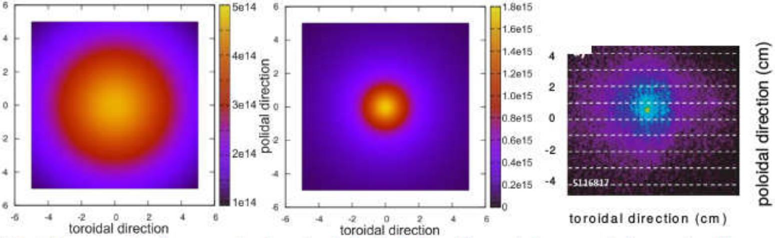
Pattern of D_α-radiation from atoms:

Modeling

Experiment

W/o impacts on plasma

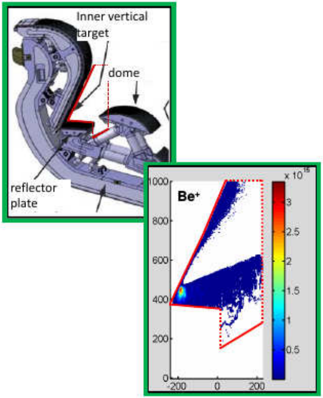
With impacts on plasma



Modeling reveals: atom penetration depth is diminished through increased plasma density

Modeling predicts: much stronger effect on tritium atoms in denser hotter plasma of ITER

Plasma-Wall Interaction



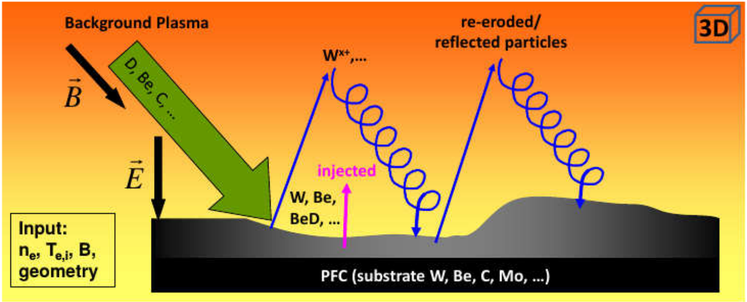
Main aim:

Prediction of **material migration**, **erosion/deposition** and resulting **tritium retention** and **wall life time** for future fusion devices (ITER, DEMO)

Approach:

- **Developing of modelling tools**
- Applying these tools to existing experiments for **benchmarking**
- **Predictive simulations** for future devices

Plasma-Wall Interaction



Local impurity transport:
- ionisation, dissociation (Monte-Carlo)
- friction, thermal force (Fokker-Planck)
- Lorentz force in E, B field
- cross-field diffusion

Plasma-surface interaction (PSI):
- physical sputtering, reflection
- chemical erosion (C_xD_y, BeD)
- (re-)erosion and (re-)deposition
- coupling with SDTrimSP

Continuous development/enhancement of ERO is important: major upgrade of ERO to ERO2.0 is an ongoing project

Plasma-Wall Interaction

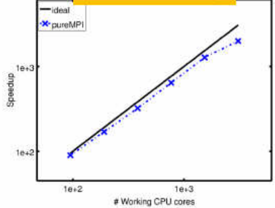
Limitations of ERO:

- originally developed for simulation volumes of ~(10 cm)
- typically covering one or a few PFC parts

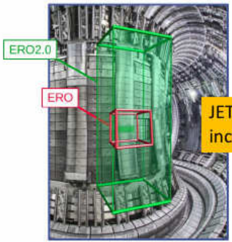
Aims of ERO2.0:

- increase simulation volume to relevant sizes (e.g. JET octant?)
- requirements:
  - universal description of wall geometry and 3D plasma
  - computational performance (massive parallelisation)

Linear speed-up
(ERO2.0 test run)



JET's Iter-like Wall



JET application:
increased simulation volume

Plasma-Wall Interaction

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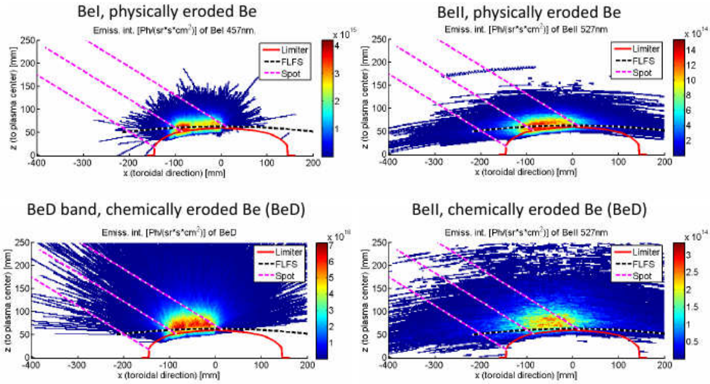
ERO modelling: *physical sputtering (Be) and chemical erosion (BeD)*



BeII intensity and fraction coming to the observation chord depends on the erosion mechanism

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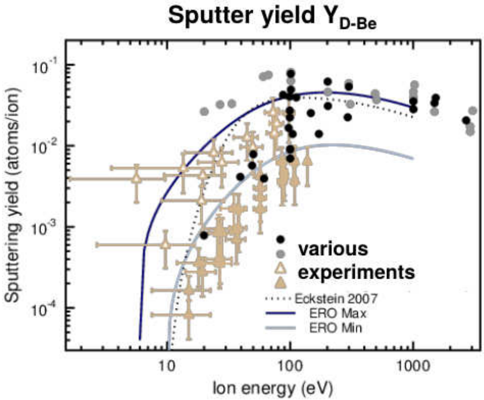
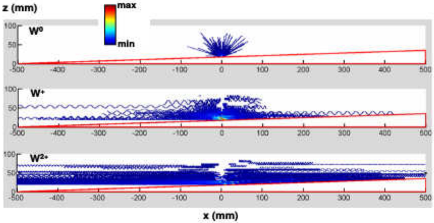
Plasma-Wall Interaction

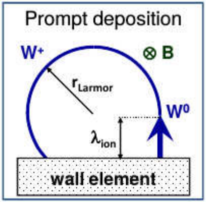


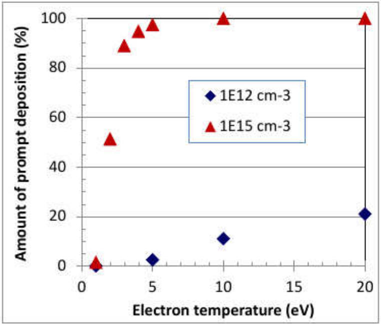
Literature data scatter within a factor of up to 100 !!!

S/XB approach in combination with ERO modelling: "ERO min" gives best agreement !

Plasma-Wall Interaction







Prompt deposition of sputtered tungsten:

- decrease of net erosion
- up to 100% at high electron density and temperature
- within studied parameter range: no runaway sputtering (self-sputtering yield always well below one)

Reaction-Diffusion Modeling for Materials

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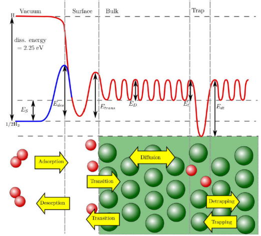
- hydrogen in crystalline materials: implantation, diffusion, trapping, desorption
- multiple hydrogen atoms per trap site and hydrogen accumulation on the surface accounted for
- finite differences (method of lines, implicit differential-algebraic solver[IDA, SUNDIALS, Wolfram Mathematica])
- numerical experiments: outgassing/thermal desorption of hydrogen (deuterium) from tungsten and beryllium after ion beam or plasma irradiation
- interpretation of real desorption experiments based on ab-initio (DFT) data and hydrogen transport models

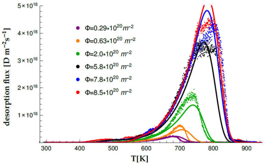
$$\frac{\partial c_i(x,t)}{\partial t} = \underbrace{D_0 \exp\left(-\frac{E_D}{k_B T(t)}\right)\frac{\partial^2 c_i(x,t)}{\partial^2 x}}_{\text{Diffusion}} + \underbrace{(form-dest)}_{\text{Trap exchange}} + \underbrace{S(x,t)}_{\text{Source}}$$

$$form-dest = \sum_{j,k=1}^{N} \gamma^{i}_{j,k}(T)\, c_j c_k \,; \quad \gamma(T) = \nu_0 \exp\left(-\frac{E_a}{k_B T(t)}\right)$$

Schematic energy profile & involved processes

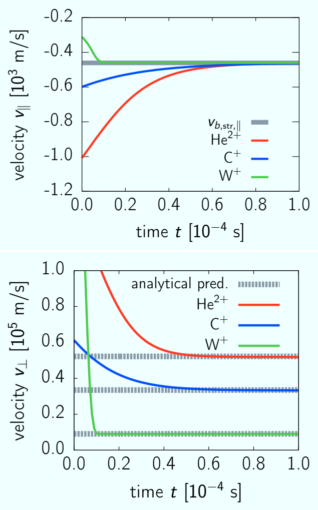


Comparison to experimental data at low fluence



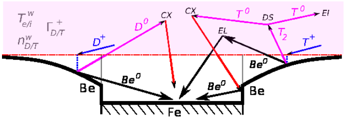
Trace Impurity Transport in Edge Plasmas

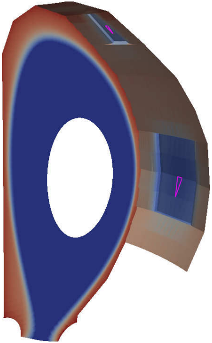
- 3D, stationary, Fokker-Planck model for ions
- linear Monte Carlo code EIRENE
- trace impurity dynamics in 3D configurations (W7-X)
- next steps: variational symplectic integration for trajectories, improved divergence-free interpolation of magnetic fields



Neutral transport and engineering applications

- Problem: Deposition in remote areas in ITER
- Application: Contamination of optical diagnostics



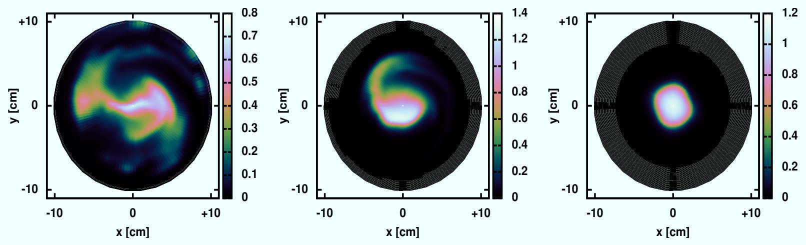


- Method: Kinetic Monte-Carlo simulations of neutral particles on fixed plasma
- EIRENE: FZJ in house legacy code
- Present: Erosion and deposition balance on the diagnostic components
- Next: Mitigation of deposition by gas flow

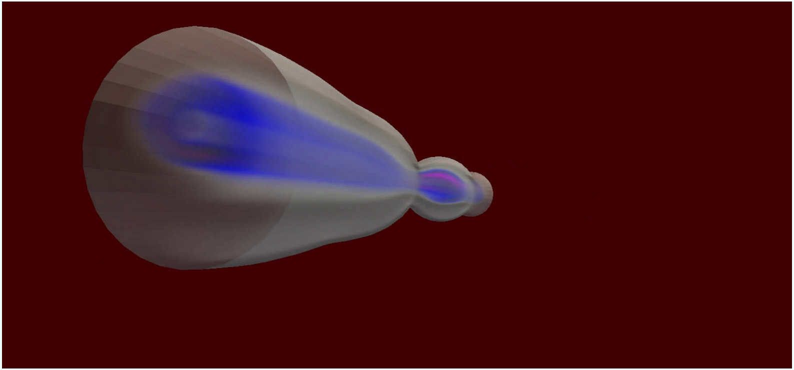
Global Dynamics in Linear Machines

- 3D, time-dependent fluid model for plasma
- finite difference code ATTEMPT

- PSI-2 machine at the IEK-4
- assessment of vorticity equation and boundary conditions



Fundamentals in Global Dynamics



Movie of PSI-2 intermittencies

Relevance for PWI

Continuous Development

- mathematical methods for many-body systems
- improved description of solid state physics
  for plasma-surface interaction
- multiscale and multiphysics approaches
  for fluids and solid state system
- simplified models for complex/turbulent transport phenomena
  (diffusion models, Langevin equation, ...)
- hybrid particle-fluid methods
- efficient numerical methods and algorithms
  for solving PDEs (Monte Carlo, finite difference/volume)
- massive parallelization of computer codes