

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

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

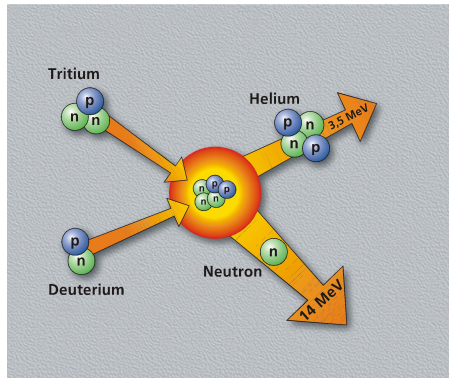
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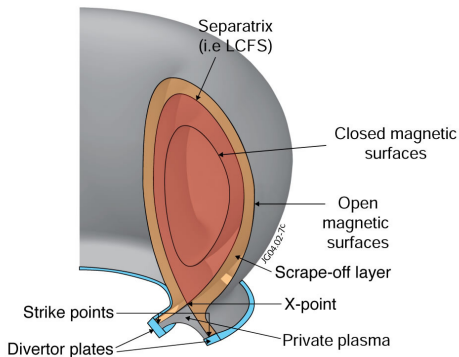
with contributions from

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M. Rack, F. Reimold, D. Reiser, J. Romazanov, M. Tokar, S. Wiesen

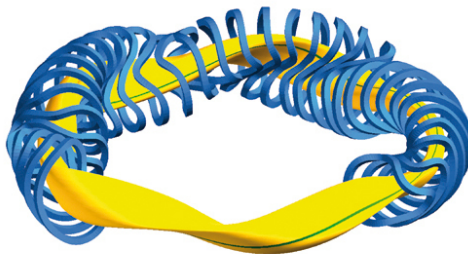
## Controlled Nuclear Fusion



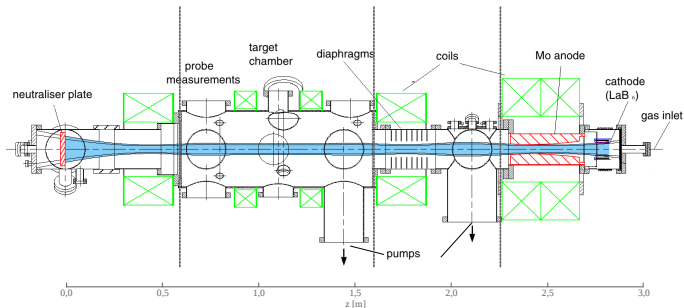
## Divertor Tokamak - Edge and Scrape-Off Layer Physics



## Stellarator - Edge and Scrape-Off Layer Physics



## 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

## Boltzmann equation and Fokker-Planck equation

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

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

## 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

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

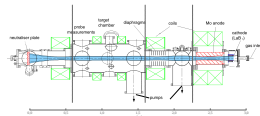
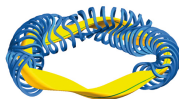
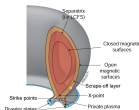
## Langevin equations

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

## Reaction-Diffusion Equations

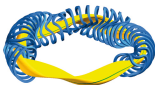
$$\frac{\partial N_i}{\partial t} = -\nabla \cdot (\mathbf{D}_i \cdot \nabla N_i) + \sum_j R_{ij}$$

- 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

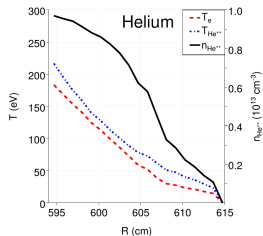
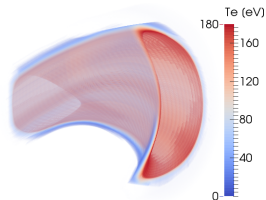


- **Monte-Carlo methods**  
used for linear kinetic problems, Fokker-Planck type fluid problems in complex geometry
- **Finite differences and finite volumes**  
used for fluid dynamics in smooth geometry, turbulence
- **MPI parallelization**  
used for all approaches
- **Semi-Analytical methods**  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

- 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



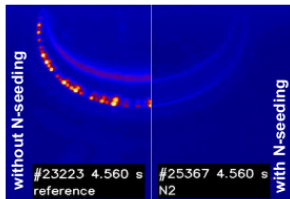
- next step: self-consistent calculation of el. fields, comparison to spectroscopic data, synthetic diagnostics



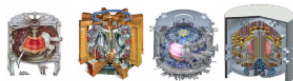
- Large power fluxes are a challenge for power exhaust ( $q_{\parallel, \text{mid}} \approx \text{GW/m}^2$ )
- Increasing difficulty in future devices:
  - Increasing  $P_{\text{sep}}/R = 15 \rightarrow 80 \text{ MW/m}$
  - Constant  $\lambda_{q, \text{SOL}} \approx 1 \text{ mm}$  [Lackner -PPCF (1994)] [Eich -PRL (2011)]
  - Unkown  $S \approx 1.5\text{-}4.5 \text{ mm}$  [Wenniger NF54 (2014)]
- Geometric countermeasures, e.g. flux expansion & inclination, can reduce power fluxes ( $q_{\text{tar}}$ ) to  $\sim 100 \text{ MW/m}^2$
- Material limit is lower at  $5\text{-}10 \text{ MW/m}^2$  [ITER Physics Base – NF (2007)]

**Additional power dissipation required!**

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

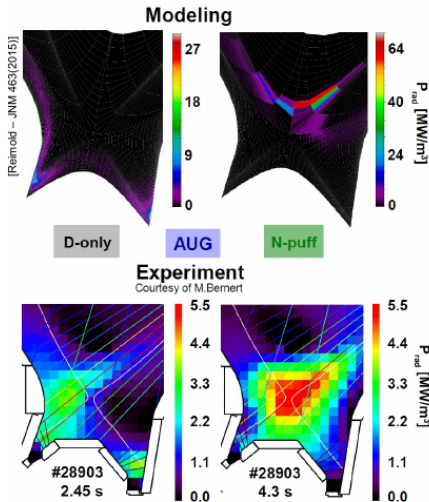


IR camera view into the lower divertor of ASDEX Upgrade



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

[M.Wischmeier – DPG (2013)]



## The Problem:

- Large power fluxes tokamak Scrape-Off Layer ( $q_{\parallel, \text{mid}} \approx \text{GW/m}^2$ )
- Remaining target power fluxes to material surfaces fluxes are  $\sim 100 \text{ MW/m}^2$
- Material limit is lower at 5-10  $\text{MW/m}^2$

→ **Additional power dissipation required!**

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

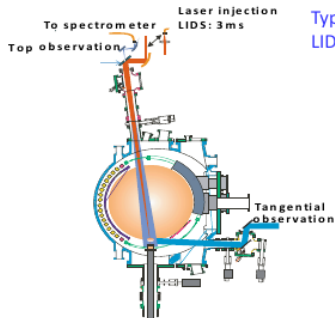
## Interpretation of signals from laser-based diagnostics of plasma facing components (PFC)

**Example:** Laser Induced Desorption Spectroscopy (LIDS)

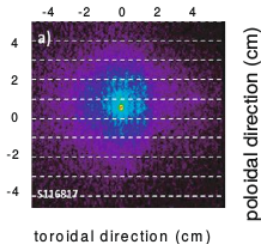
**Aim:** Assessment of hydrogen content absorbed in PFC

**Method:** Particle desorption by laser pulse on PFC during discharge and recording of emission from plasma

**Problem:** Plasma parameters are changed by LIDS

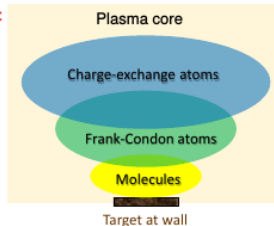


Typical time integrated ( $\sim 10\text{ms}$ )  $D_{\alpha}$ -light pattern by LIDS applied on  $D_2$ -rich C-layer (top observation)



## Species and processes included into modeling of LIDS-signals:

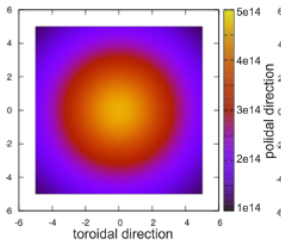
- $D_2$ -molecules desorbed
- Franck-Condon atoms are generated by molecule
  - Dissociation
  - Ionization
  - Charge-exchange
- Charge-exchange atoms produced from molecules and fc-atoms
- Impact on plasma through ionization and excitation of neutrals:
  - Increase of plasma density
  - Drop of electron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



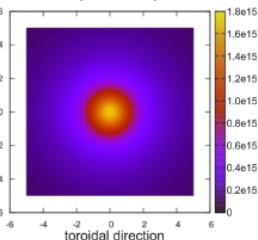
## Pattern of $D_\alpha$ -radiation from atoms:

### Modeling

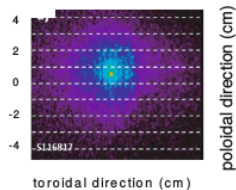
W/o impacts on plasma



With impacts on plasma



### Experiment

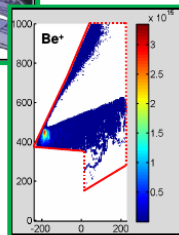
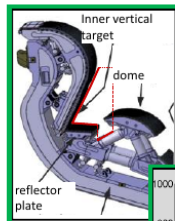


Modeling reveals: atom penetration depth is diminished through increased plasma density

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

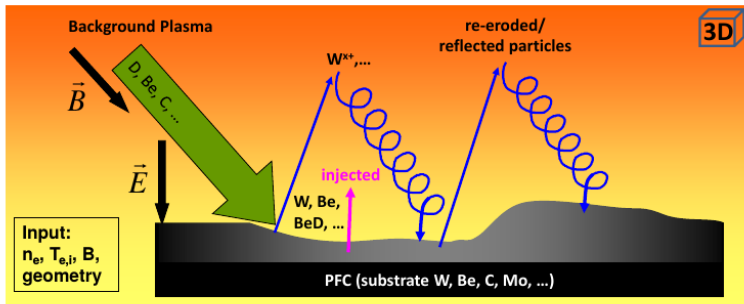
## Main aim:

**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



## 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

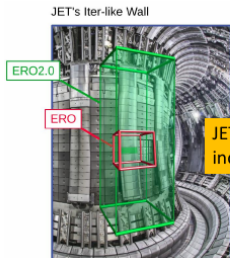
**Continuous development/enhancement of ERO is important:  
major upgrade of ERO to ERO2.0 is an ongoing project**

## Limitations of ERO:

- originally developed for simulation volumes of  $\sim(10 \text{ cm})$
- typically covering one or a few PFC parts

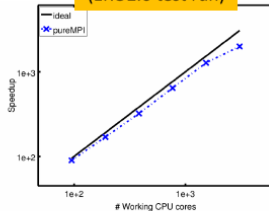
## Aims of ERO2.0:

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

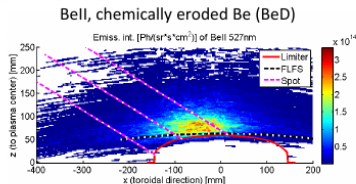
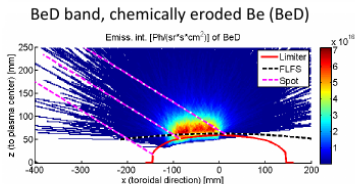
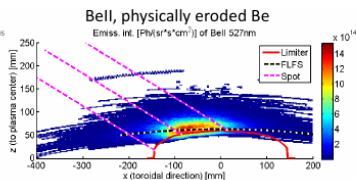
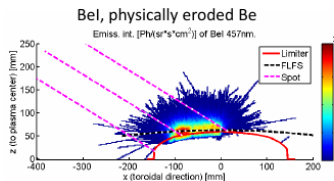


JET application:  
increased simulation volume

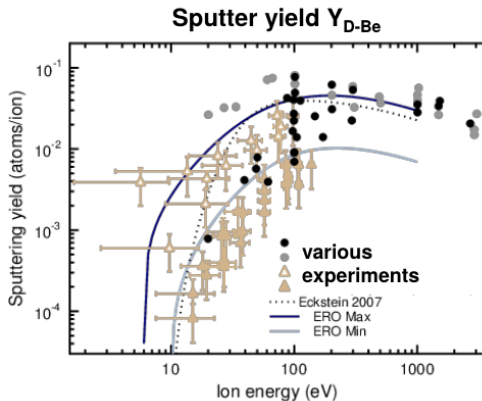
Linear speed-up  
(ERO2.0 test run)



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

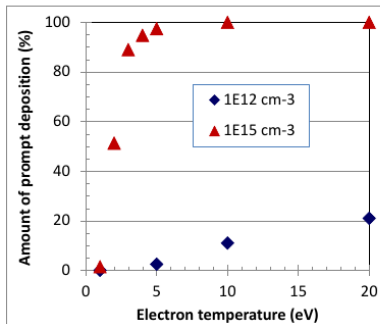
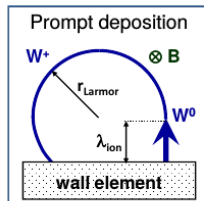
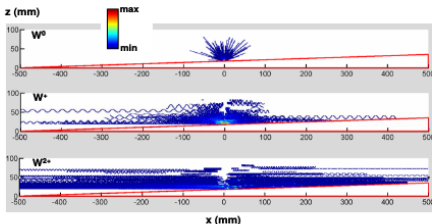


**Bell intensity and fraction coming to the observation chord depends on the erosion mechanism**



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

**S/XB approach in combination with ERO modelling:  
“ERO min” gives best agreement !**



## Prompt deposition of sputtered tungsten:

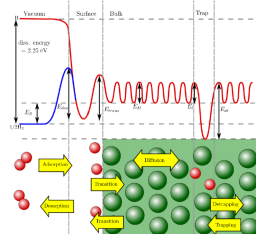
- decrease of net erosion
- up to 100% at high electron density and temperature
- within studied parameter range: no runaway sputtering (self-sputtering yield always well below one)

- 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

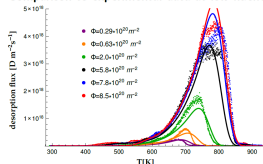
$$\frac{\partial c_i(x,t)}{\partial t} = D_0 \exp\left(-\frac{E_D}{k_B T(t)}\right) \frac{\partial^2 c_i(x,t)}{\partial x^2} + \underbrace{(form - dest)}_{\text{Trap exchange}} + \underbrace{S(x,t)}_{\text{Source}}$$

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

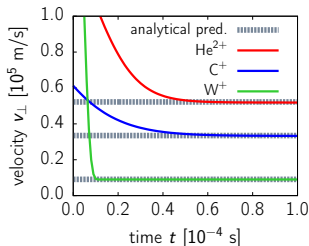
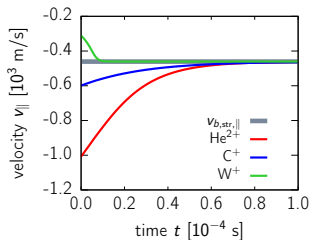
Schematic energy profile & involved processes



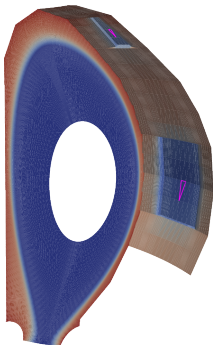
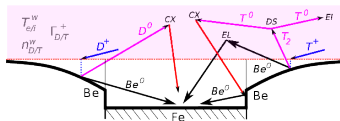
Comparison to experimental data at low fluence



- 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

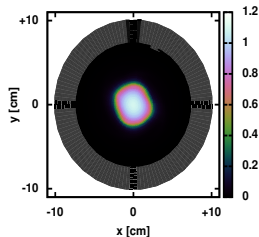
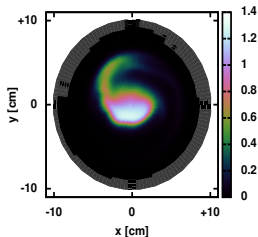
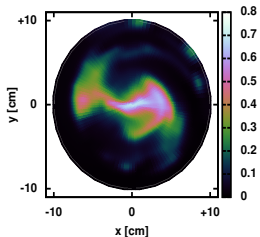


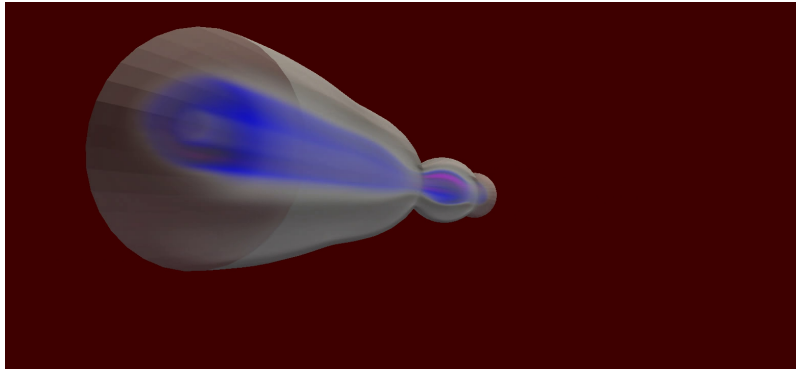
- Problem: Deposition in remote areas in ITER
- Application: Contamination of optical diagnostics



- 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

- 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





Movie of PSI-2 intermittenancies  
Relevance for PWI

- 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