Zachodniopomorski Uniwersytet Technologiczny w Szczecinie

Tokamak modelling

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Outline

- ITM-TF: Verification and validation of ETS
- Simulations of JET ILW discharges with COREDIV code
- Modelling of DEMO reactor with COREDIV code
- Novel Divertor Configurations – TECXY simulations of SF divertor
- Monte-Carlo Codes Comparison
- Neutron heating at the inboard divertor rail
- Assessment of ANSYS non-linear analyses capabilities
- Fast ion driven plasma modes
- Modeling of the spectrum structure of tungsten ions

ITM-TF: Verification and validation of ETS

WP12-ITM-IMP3-ACT1-01/IPPLM/PS Maintenance, continuing development, verification and validation of the ETS and other core components

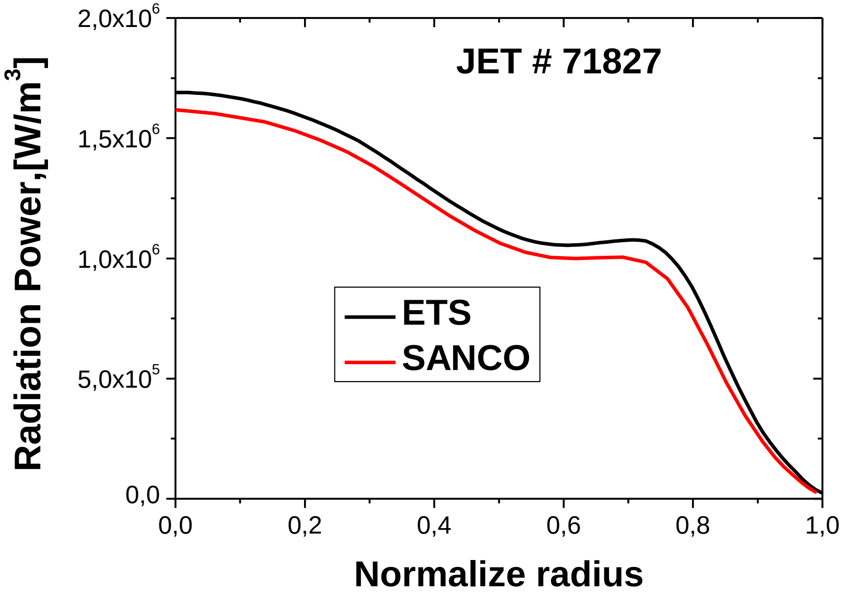
- *T2. Release of a number of standard Kepler workflows, including (but not limited to) workflows incorporating pellets, neutrals, impurities, heating and current drive modules, sawteeth, NTMs [in collaboration with other IMPs]*
- *T4. Verification of the ETS [in collaboration with ISM-ACT1]*
- *T5. Validation of the ETS [in collaboration with ISM-ACT1 and other IMPs]*

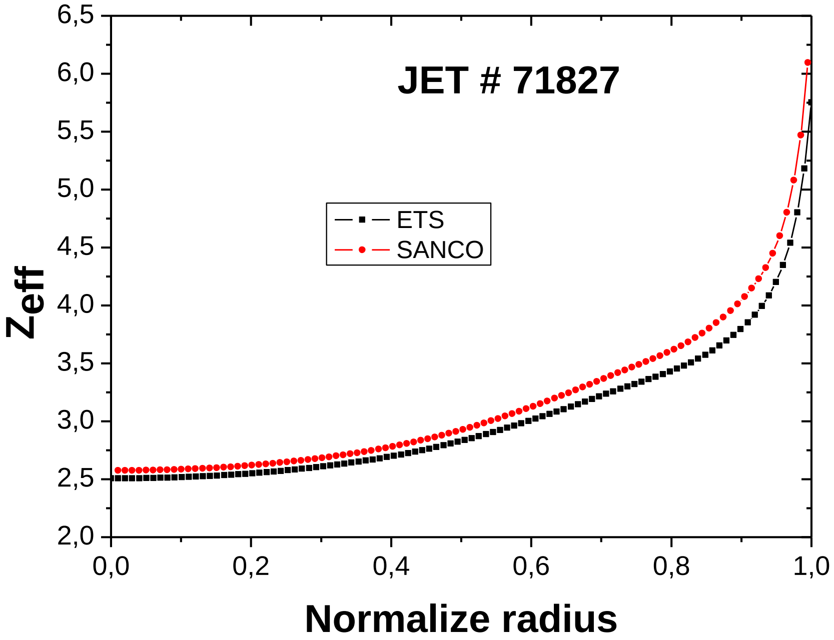
WP12-ITM-ISM-ACT1-01/IPPLM/PS Support to the validation and physics application of the ETS and ITM tools

- *Benchmarking of impurity transport for Be and W. ETS/impurity – SANCO simulations (in collaboration with AMNS and IMP3).*
- *Benchmarking of core neutral module. Provide ASTRA and JETTO runs for benchmarking of neutral module for main species.*
- *SANCO runs for benchmarking the neutral module for impurity (in collaboration with IMP3)*

WP12-ITM-ISM-ACT1-01/IPPLM/PS: Benchmarking of impurity transport for Be and W. ETS/impurity – SANCO simulations

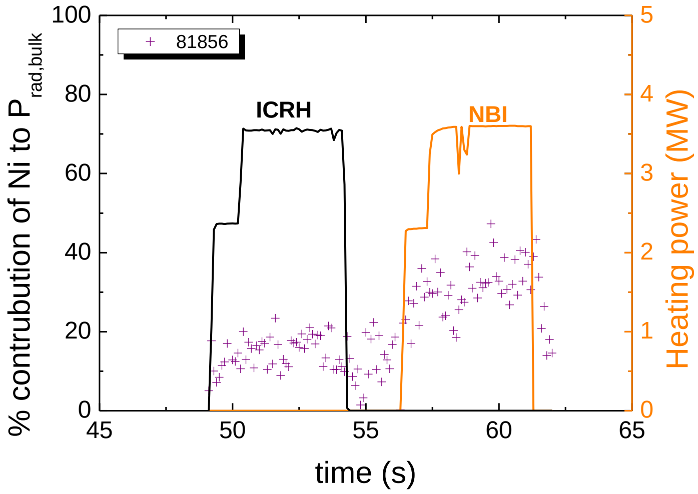
ITS/ETS solver has been developed by IPPLM team

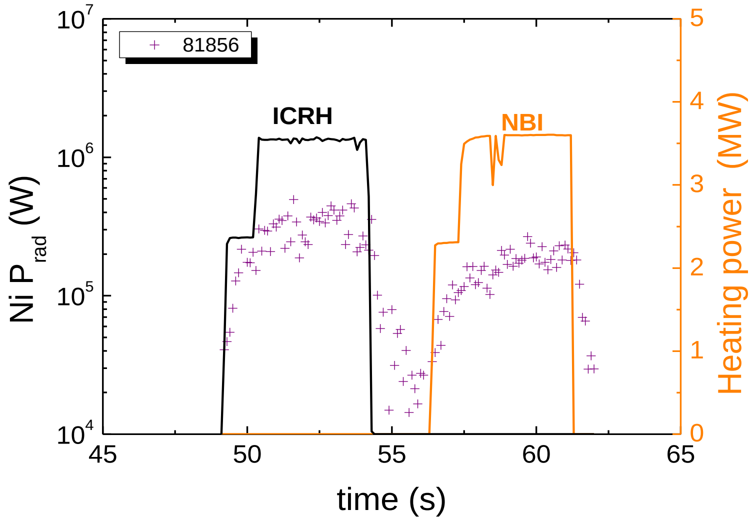




Very good correlation of Z_{eff} , impurity density for different ionization stages, radiative power

WP12-ITM-ISM-ACT1-01/IPPLM/PS: Simulations of Ni radiation in JET experiments





<u>Radiation form ETS at t = 52.2s (ICRH):</u>

P^{rad}_{Ni}= 0.307MW

% contribution Ni $P_{rad,bulk(experiment)}$ ~15%

<u>Radiation form ETS at t = 59.0s (NBI):</u>

P^{rad}_{Ni}= 0.145MW

% contribution Ni $P_{rad,bulk(experiment)}$ ~30%

Very good agrement between simalation and experimantal data

Simulations of JET ILW discharges with COREDIV code

- **Simulation of L-mode JET ILW discharges without impurity seeding.**

3 well diagnosed **discharges** heated by **ICRF** were **selected**

P_{ICRH} = 3 MW; line average density **n_e = 1.65, 2.3 and 2.8 x 10^{19} m^{-3}**

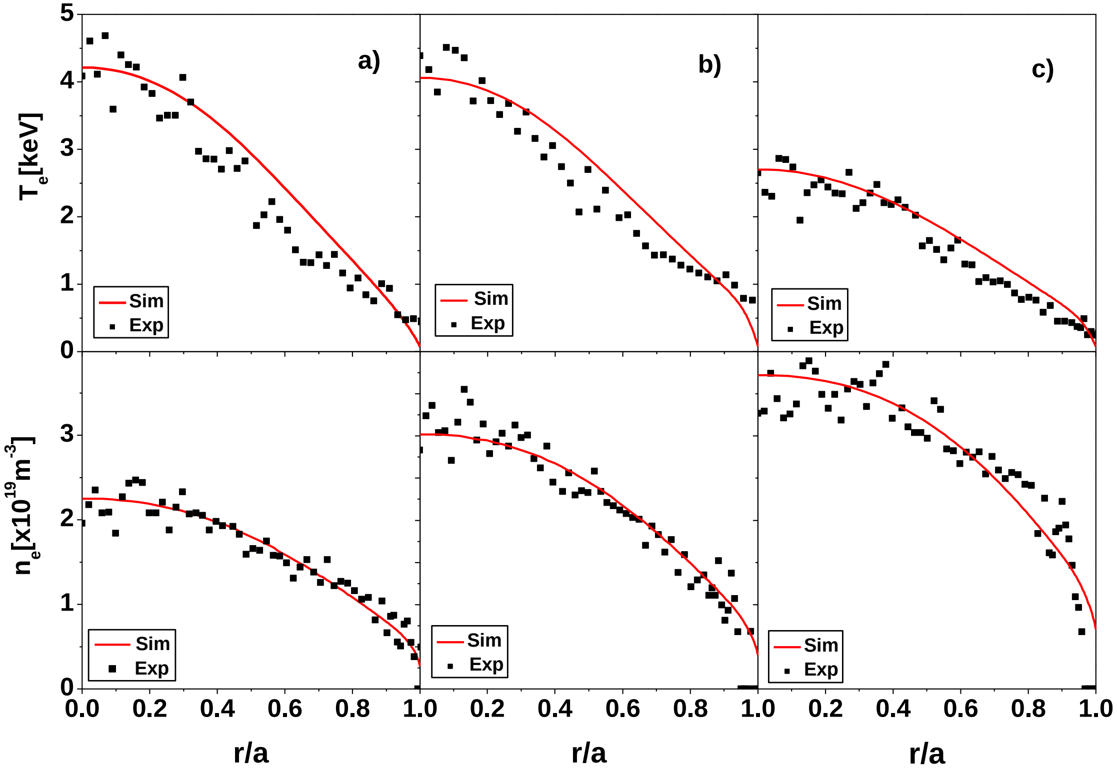
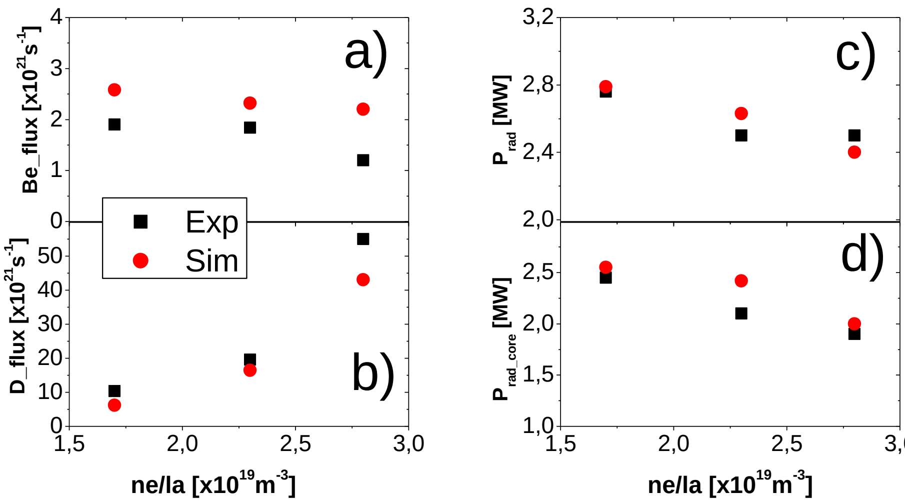


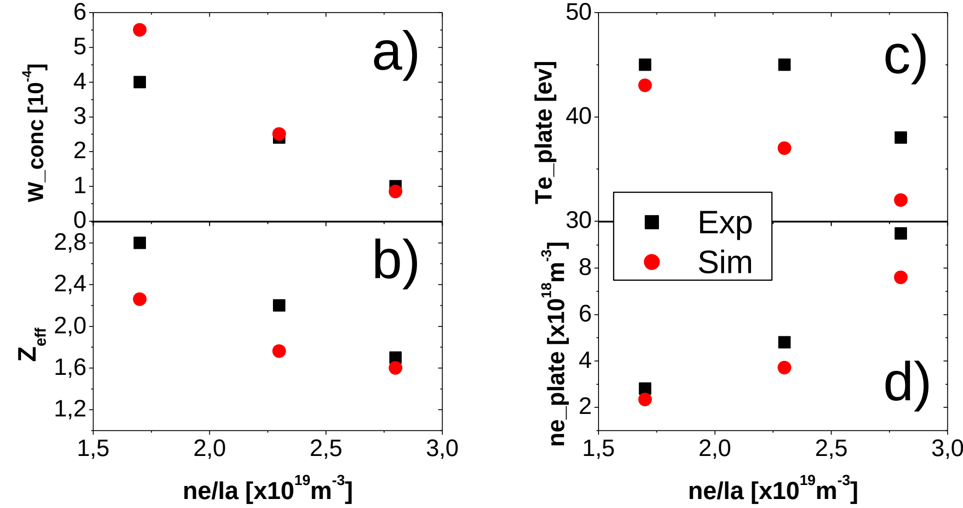
Fig. Electron temperatute (top) and density (bottom) profiles from HRTS diagnostic and COREDIV simulations as function of the normalized minor radius. From left to right : shot 80896, shot 80889, shot 80893 at t = 59.5 s.

Simulations of JET ILW discharges with COREDIV code

L-mode



Be fluxes (a), D fluxes (b) total radiated power (c) and power radiated inside the separatrix (d) for the three discharges considered.



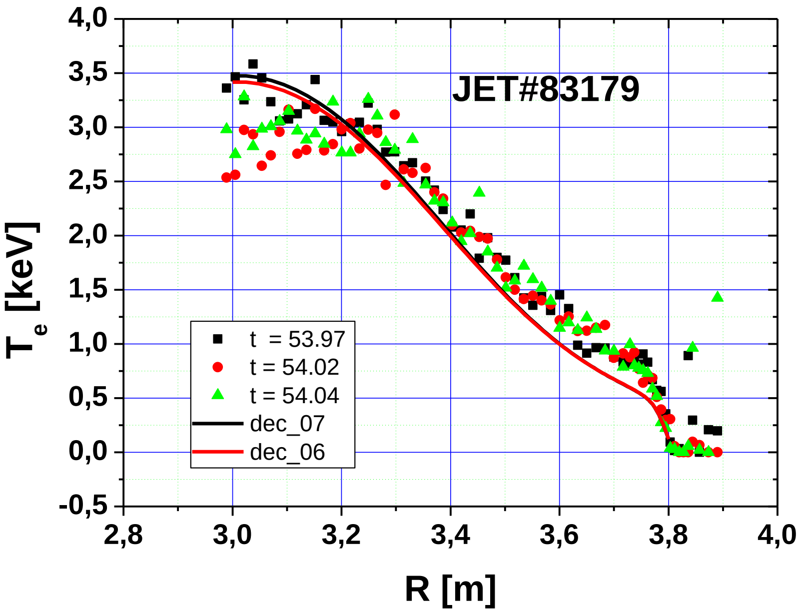
W concentration (a), Z_{eff} (b), electron temperature (c) and density (d) measured at the outer strike point for the three discharges considered,

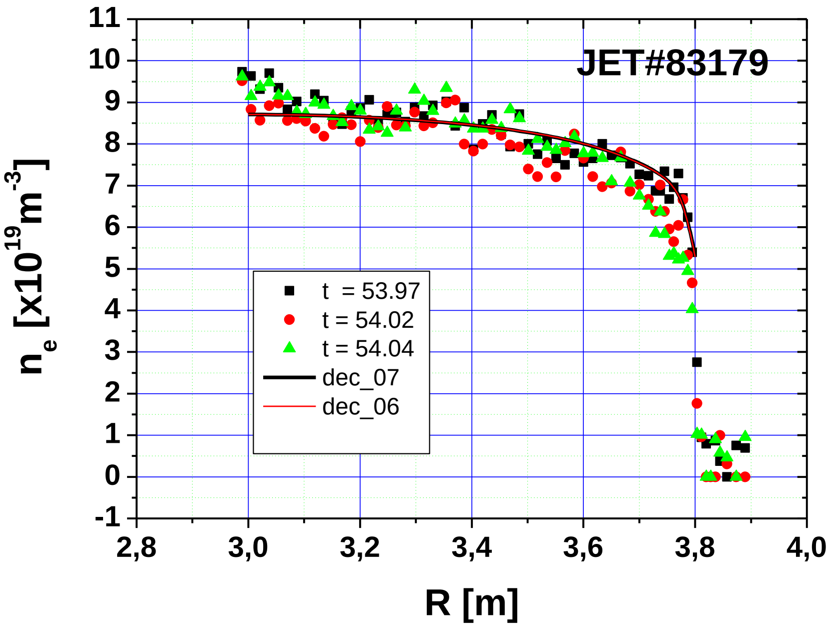
Good agreement with experiment

Simulations with COREDIV of H-mode and hybrid discharges

Shot	83179	Dec_07	Dec_06
P_{NBI}	16.68	17	17
Ne	6.8	7.9	7.9
H_{98}	0.76	0.75	0.75
Z_{eff}	1.36	1.32	1.185
P_{CORE}	4.13	4.367	4.02
P_{TOTAL}	7.8	8.71	7.7
N_{puff}	15.4	1e21	0.5e21
tau		2.9	2.9

Work in progress !!





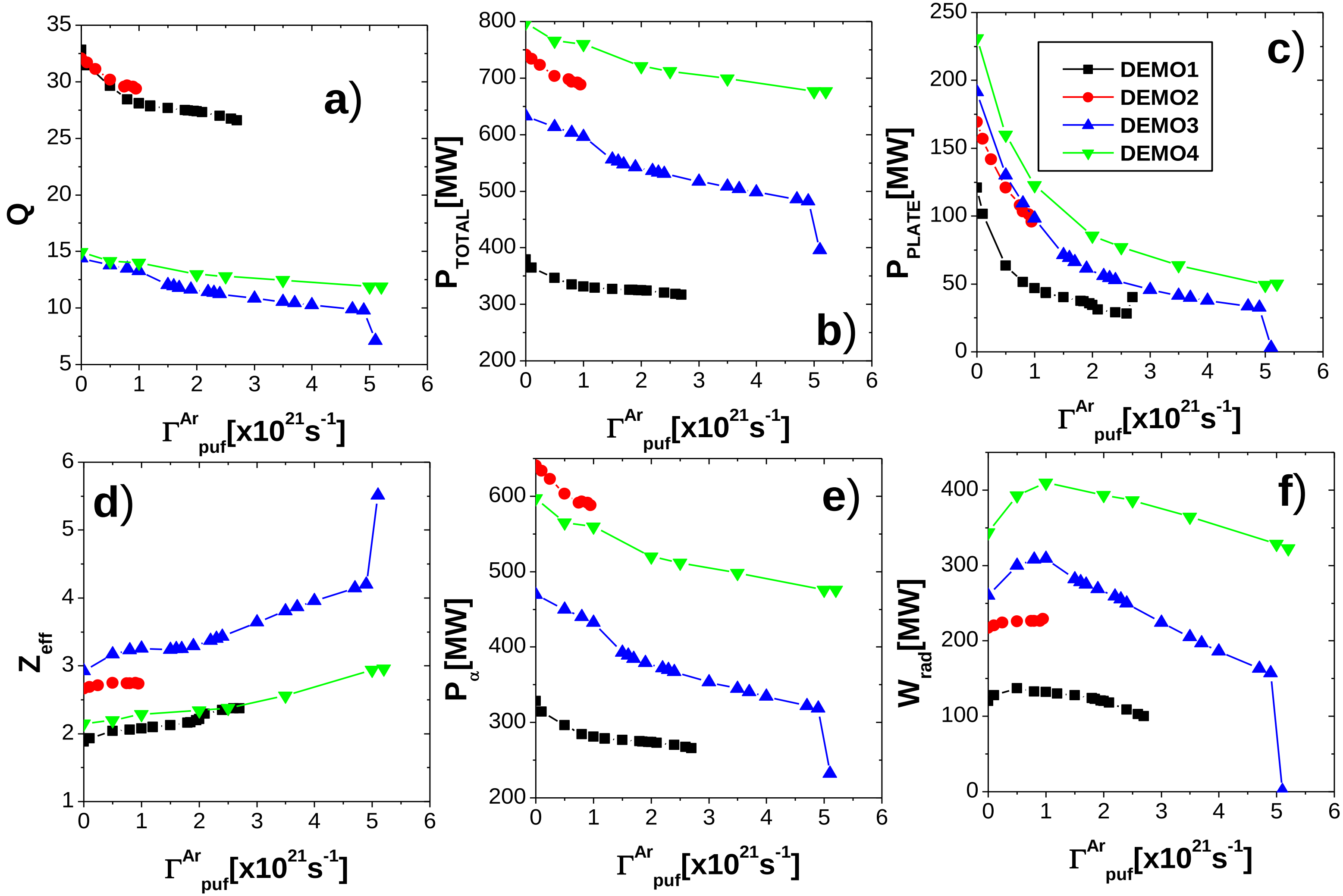
Modelling of DEMO reactor with COREDIV code

- WP11-SYS-01-ACT5-02/IPPLM Preliminary analysis of baseline DEMO concepts
- WP12-SYS-02-T02-01/IPPLM Check the consistency of the density, temperature and impurity concentration profiles for both DEMO options
- WP12-SYS-02-T03-01/IPPLM Sensitivity analysis of the simulations codes on the assumptions made on the simplified modelling
- WP12-PEX-01-T04-01/IPPLM –Calculation of radiation profiles inside the separatrix

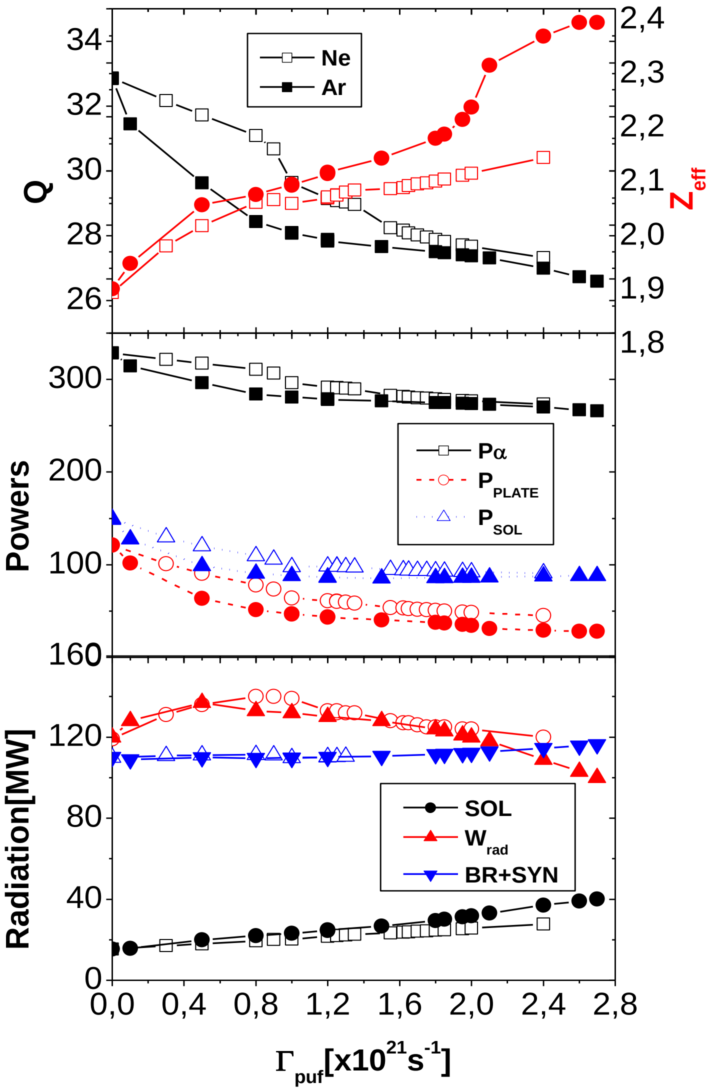
Basic input parametres for DEMO1-4

PARAMETERS	PULSED		STEADY STATE	
	DEMO1	DEMO 2	DEMO 3	DEMO 4
R_0, a (m)	9.0, 2.25	9.6, 2.4	8.5, 2.83	8.5, 2.83
Plasma current, I_P (MA)	16.44	18	19.75	23
Toroidal magnetic field, BT (T)	7.2	7.45	4.9	5.74
Density, $\langle n_{e,vol} \rangle$ (10^{20} m^{-3})	0.88	1	0.75	0.91
Separatrix density (10^{19} m^{-3})	3.5	4	3.5	4
H-factor (IPB98(y,2))	1	1.2	1.3	1.3
Auxiliary heating, P_{inj} (MW)	51.8 /100	100	163	200
Seeding impurity	Ar/Ne	Ar	Ar	Ar

Plasma parameters versus gas puff levels



CONCLUSIONS



DEMO1 parameters for different gas puff levels of Ar (full symbols) and Ne (open symbols)

- For all considered DEMO scenarios significant fusion power can be achieved
- Increase of the Γ_{puff} leads to the reduction of P_{α} and Q due to plasma dilution (Z_{eff} increases). Helium contributes predominantly to Z_{eff} . Power to the targets reduced due to reduction of fusion power.
- Total radiation almost independent on Γ_{puff}, dominated by core radiation (> 90%): (W+Bremst.+Synch). Negligible radiation due to seeding impurity!
- W radiates predominantly inside separatrix.
- Power crossing separatrix close to L-H threshold, in particular for strong seeding.
- The radiation due to seeding impurity is small and the results are weakly affected by seeded impurity type.
- For pulsed DEMO concepts, accessible seeding level is limited. There is no steady state solution for stronger puffing.
- Solution terminates due to Helium accumulation, if confirmed by more detailed investigations, might strongly affect DEMO concepts.

Novel Divertor Configurations – TECXY simulations of Snow Flake divertor (FAST)

MAIN FEATURES OF THE CODE:

Simple flexible and fast code. All physics included for the particle motion and energy as well as for the impurities.
Neutrals model analytical - details of detachment unreliable
Divertor geometry simplified: Private divertor region not considered, Target perpendicular to the poloidal field lines

MAIN AIMS OF THE RUNS

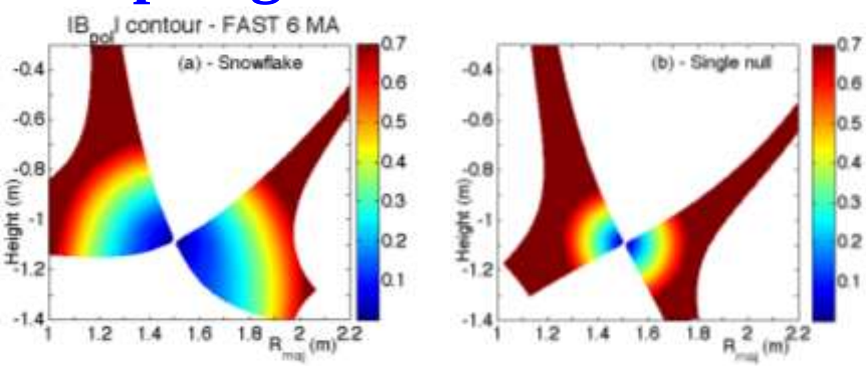
1) To highlight possible macro differences with respect to the conventional – Single Null configuration
2) To see whether new phenomena are likely to occur with the new configuration

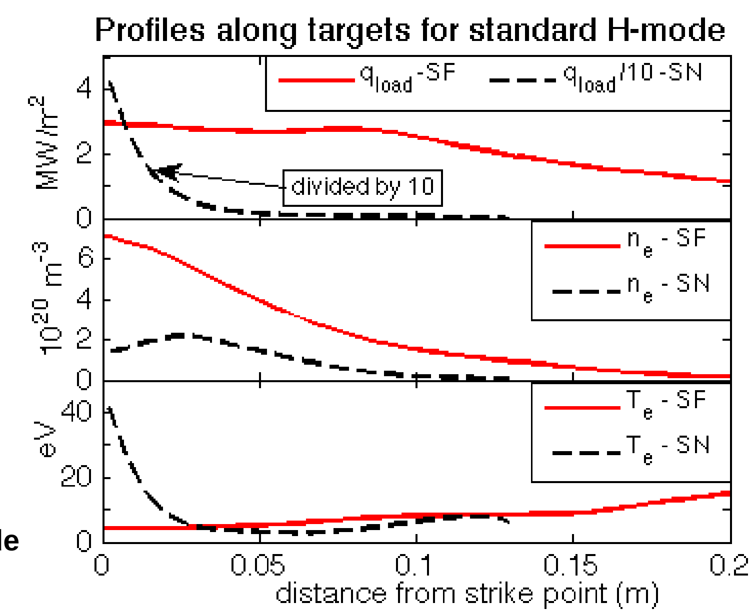
We considered three different scenarios:

a) H-mode reference $<n_e>=2\times10^{20}$; $n_{e,s}=0.7\times10^{20}$ m^{-3}
b) Extreme H-mode $<n_e>=5\times10^{20}$; $n_{e,s}=1.8\times10^{20}$ m^{-3}
c) Advanced scenario $<n_e>=1.3\times10^{20}$; $n_{e,s}=0.5\times10^{20}$ m^{-3}

WITH NO ADDED IMPURITY IN THE SOL

Topological differencies





Comparison SF/SN of the profiles along the target of (from top to bottom): power load, density, electron temperature. Standard H mode case with P_{SOL}=20 MW and $n_{es}=0.7\times10^{20}$ m^{-3}

CONCLUSIONS

- The mitigation of the load onto the divertor targets is even larger than expected from the expanded poloidal flux.

- The reason is mostly the longer time spent by the travelling particles in the divertor because of the **much longer magnetic lines around the X point region:**

  - The interaction with the neutrals is particularly enhanced in touch with the separatrix (i.e. strike point), further spreading out the incoming power flux on a larger area and generating the large mitigation factors
  - The consequent particle cooling and hence slowing down further increases for a deeper radial cross-diffusion further exhalted by, and then, of the particles
  - The larger number of collisions raises the volume non-convective losses, strongly depending on LCMS density

- **Peak load reduction for the outer targets**
  - <u>H-mode standard</u>: **~44 → ~3 MW/m^2** : ~15 times
  - <u>Advanced scenario</u>: **~105 → ~17 MW/m^2** : factor ~6
  - <u>H mode extreme</u>: **~34 → ~0.67 MW/m^2** : >45 times: Additional mitigation mechanisms are very effective due to the high working density.

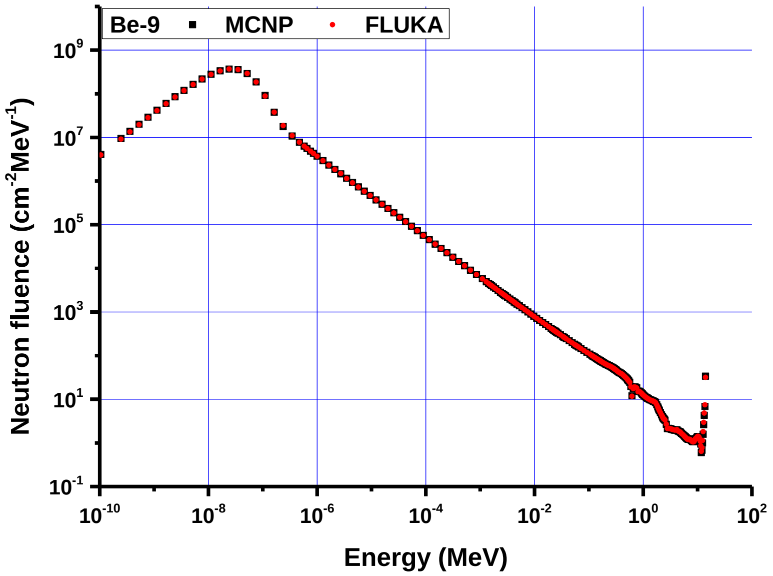
- Loads ⊥ ***to the target surface*** are always ≤18 MW/m^2 →minimizing the strike angle is no more critical and the divertor design can be carried out on a safer basis.

- **A more refined modelling is however necessary (EDGE2D)**
- **The same study to be performed for DEMO SF divertor configuration**

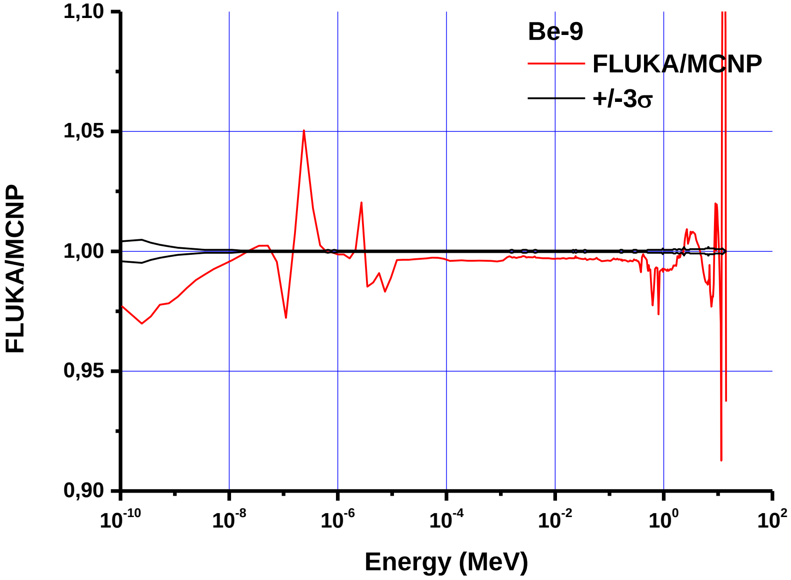
WP12-DTM-04-T11-01/IPPLM/PS
Monte-Carlo Codes Comparison

- MCNP is the reference code for fusion neutronics design calculations.
- Alternative Monte Carlo (MC) codes shall be evaluated for use with DEMO neutronics and integration into the simulation platform due to increasing uncertainty of long-term access to MCNP.
- IPPLM carried out the evaluation for FLUKA in comparison with MCNP using very simple geometrical model for 5 light nuclides.
- Results of FLUKA neutronic calculations (including the thermal neutron energy region) are consistent with the MCNP results
- WP13-SYS-02-T10-01/IPPLM/PS in 2013 - continuation of the work done in 2012

WP12-DTM-04-T11-01/IPPLM/PS
Monte-Carlo Codes Comparison



^{9}Be neutron spectra calculated by MCNP and FLUKA



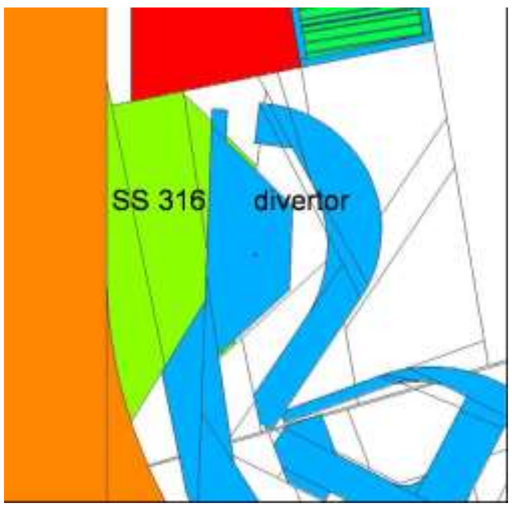
^{9}Be neutron spectrum relative to MCNP

Neutron heating at the inboard divertor rail

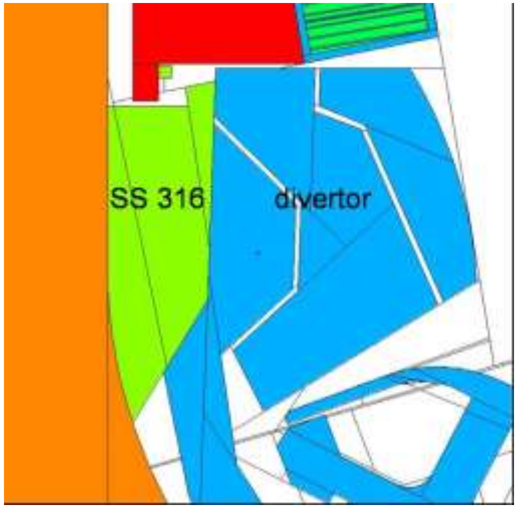
Grzegorz Tracz: *Institute of Nuclear Physics PAN, Kraków*

Scope of this task was to estimate the heat load on the divertor inboard rail as input for a subsequent thermal analysis in order to investigate if the inboard divertor support can be used in DEMO.

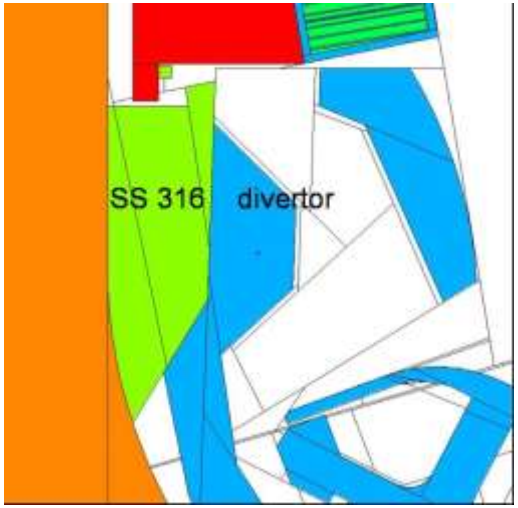
- Neutron and photon heating [W/cm^3] as well as the helium in the area between the blanket and the divertor were evaluated
- stainless steel 316(L)N was assumed as the material of the divertor inboard rail
- two divertor modifications were examined



reference case



case A



case B

The heating and the He production can be significantly (3 ÷ 4 times) reduced when the arrangement proposed in **case A** is used.

Evaluation/ test of CAD-based computation tools for engineering analysis: Assessment of ANSYS non-linear analyses capabilities (WP12-DTM-01-T03-02)

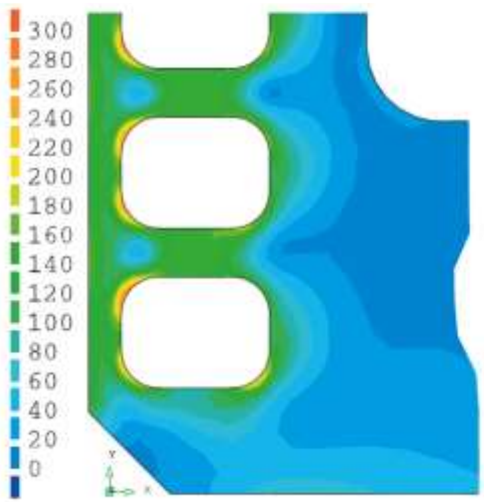
- **Goal:**
  - **ANSYS capability for non-linear calculation shall be carefully investigated**
  - To this end, a non-linear creep-fatigue calculation case shall be evaluated in reasonable details and compared to the existing ABAQUS experience.

- **Approach:**
  - Coupled deformation damage model developed by Karlsruhe Institute of Technology (KIT) and implemented in ABAQUS as user sub-routine has been considered for comparison purposes
  - A complex material model has been proposed in ANSYS based on tools already available in the package and combining viscoplasticity and Chaboche non-linear kinematic hardening as well as non-linear isotropic hardening plasticity
  - Behaviour of a test blanket module (TBM) box loaded cyclically by different heat flux and active cooling was modelled under ANSYS and compared with previously reported KIT results in ABAQUS

Evaluation/ test of CAD-based computation tools for engineering analysis: Assessment of ANSYS non-linear analyses capabilities (WP12-DTM-01-T03-02)

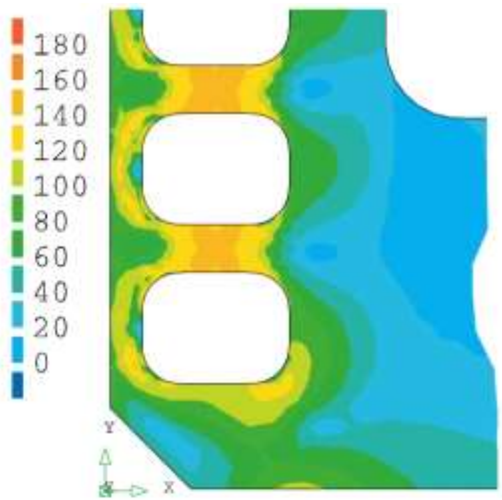
KIT results (ABAQUS)

„standard”



$\sigma_{vm}^{max} = 287\, MPa$

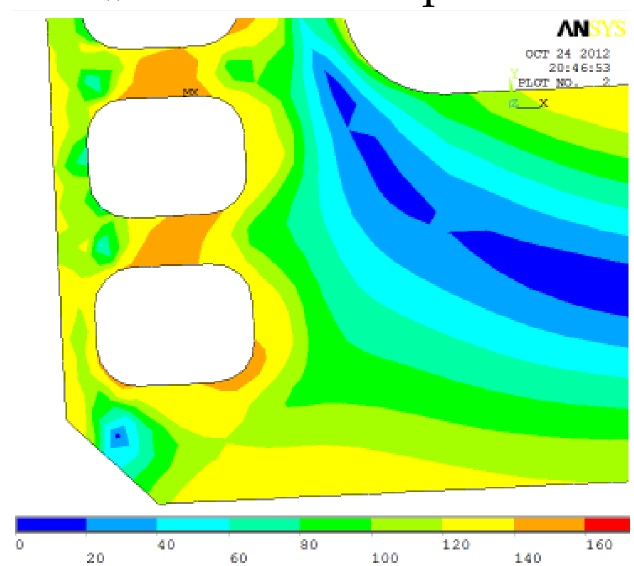
user sub-routine



$\sigma_{vm}^{max} = 154\, MPa$

WUT results (ANSYS)

„standard complex”



$\sigma_{vm}^{max} = 162\, MPa$

TBM box model: Von Mises stresses after 300 heating cycles

Evaluation/ test of CAD-based computation tools for engineering analysis: Assessment of ANSYS non-linear analyses capabilities (WP12-DTM-01-T03-02)

- **Conclusions**

  Using the standard ANSYS commands the coupled deformation damage material model, as developed by KIT, cannot be implemented for the whole live cycle of a material

  - ANSYS allows to simulate material behaviour from the beginning of the creep-fatigue characteristic up to some 90% of the cycles

  - ANSYS platform allows building own material models by user defined procedures that was not considered during this phase of the work

  - The results, obtained for the TBM box subjected to 300 loading cycles, show that the complex material model implemented via ANSYS standard available tools is capable of predicting the material behaviour under low cycle fatigue loading with a reasonable accuracy.

Fast ion driven plasma modes – theoretical basis for Integrated Tokamak Modelling

Dr inż. P. Berczyński: West Pomeranian University of Technology in Szczecin

Importance of the energetic alpha particle population in a burning DT plasma (with Q>10):

✓will contribute a considerable part of the total plasma pressure (10-20%)

✓ substantial impact on achieving and maintaining high temperatures

✓ considerable impact on plasma stability

✓fundamentally new physics phenomena

✓ variety of Alfvénic instabilities driven by fast ions

e.g. Alfvén Cascade (AC) eigenmodes, Toroidal Alfvén Eigenmodes (TAE), compressional Alfvén eigenmodes (CAE)

In spite of the significant differences in the nature of the modes (shear Alfvén or CAE), and in the corresponding excitation mechanisms, the nonlinear evolution of these modes is determined by the type and strength of relaxation processes of the fast particles driving the waves.

Dynamical approach as an alternative to the kinetic approach - modified Fermi-like model

In the Fermi-like model model particle trapping effects are described through elastic collisions of particles with two barriers separated by a fixed length and whose amplitude (proportional to the wave energy) can increase or decrease in time, due to the sequence of stochastic collisions.

$$x_k^{(n+1)} = \sigma_k^{(n)} \qquad x_k^{(n+1)} = -\sigma_k^{(n)}$$

$$\sigma_k^{(n+1)} = -\sigma_k^{(n)} \qquad \sigma_k^{(n+1)} = \sigma_k^{(n)}$$

$$A_{n+1} = \sqrt{A_n^2 + \Delta I} \qquad A_{n+1} = A_n.$$

$$x_j^{(n+1)} = x_j^{(n)} + v_j \Delta t_k^{(n)} \qquad (j \neq k).$$

Mathematically, the Fermi-like model, is described by mapping equations.

The bump on tail instability can be easily modeled in the Fermi-like model by appropriate choice of the velocity distribution function. Moreover, there is also some freedom in the choice of the potential wells. Therefore the original Fermi-like model supplied with dissipation processes can be a suitable and relatively simple model for investigations wave-particles resonant interaction phenomena in various physical context. Its additional advantage is numerical simplicity.

The **nonlinear map**, on which the Fermi-like model is based, **capture**s the basic physics of the **linear** growth of the bump-on-tail instability and of the particle trapping effects which produce the saturation of the instability and drive the **nonlinear** phase of wave-particle interaction.

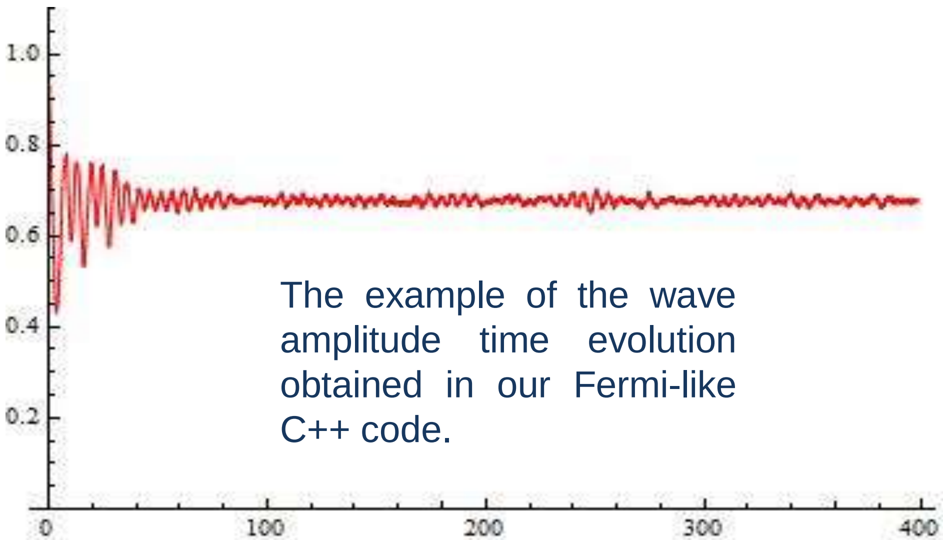
- To have a tool for evaluation of the mode amplitude in Fermi-like model C++ code has been developed.

- Any results for the wave mode dynamics need numerical simulations involving many particles (~10^5) (a kind of Monte Carlo simulations).

- To prove the validity of the numerical code the results obtained in literature for collisionless case were reproduced.

- To develop the model some simplified dissipative processes were added. Further development of the model and proper inclusion of various types of relaxation processes needs reasonable and more subtle physical ideas.

- The work is in progress. It is our main task for 2013.



J. Zalesny, Instabilities in the simplified Fermi-like model with Krook-type collisions,intrinsic damping and source, submitted to Physics of Plasmas in 2013.
G. Galant, Nonlinear Dynamics of Plasma Waves Driven Unstable by Energetic Ions Near the Stability Threshold. The generalized multi-mode model, submitted to Physics of Plasmas in 2013.

Modeling of the spectrum structure for N-like (W^{67+}) through Na-like (W^{63+}) tungsten ions

M. Polasik, K. Słabkowska, K. Kozioł, J. Starosta, E. Szymańska

Nicolaus Copernicus University, Toruń, Poland

RESULTS

1. Modeling of the spectrum structures for N-like (W^{67+}) through Na-like (W^{63+}) tungsten ions at plasma electron temperature of 15, 20 and 30 keV using the FAC code within the framework of CRM approach [1].

2. Theoretical predictions of energy shifts for various Lα, Lβ and Lγ x-ray lines of tungsten as a function of outer-shell electron stripping, evaluated using the multiconfiguration Dirac-Fock method [2].

3. Theoretical predictions of $K\alpha_{1,2}$, $K\beta_{1,3}$ and $K\beta_2$ energy shifts as a function of outer-shell electron stripping for high-Z elements (Dy, Ho, Yb and Ir [3]), evaluated using the multiconfiguration Dirac-Fock method.

4. Proposition of a new hard x-ray spectroscopic diagnostic technique (independent of the other plasma parameters) for the direct measurement of the ionization distribution in plasmas of the heavy elements for W through U [4].

[1] K. Słabkowska, M. Polasik, K. Kozioł, J. Starosta, E. Szymańska, J. Rzadkiewicz, M. Scholz, N. R. Pereira: *Modeling of the spectrum structure for N-like (W^{67+}) through Na-like (W^{63+}) tungsten ions*, prepared for publication.

[2] K. Słabkowska: *Influence of multiple outer-shell electron stripping on the Lα, Lβ and Lγ x-ray energies of tungsten*. Physica Scripta T (2013), accepted for publication.

[3] J. Rzadkiewicz, K. Słabkowska, M. Polasik, J. Starosta, E. Szymańska, K. Kozioł, M. Scholz, N. R. Pereira: *Influence of multiple outer-shell electron stripping on the Kα and Kβ x-ray energies of iridium*, Physica Scripta T (2013), accepted for publication.

[4] J. F. Seely, B. V. Weber, D. G. Phipps, N. R. Pereira, D. Mosher, K. Słabkowska, M. Polasik, J. Starosta, J. Rzadkiewicz, S. Hansen, U. Feldman, L. T. Hudson, J. W. Schumer: *Tungsten L Transition Line Shapes and Energy Shifts Resulting from Ionization in Warm Dense Matter*, High Energy Density Physics (2013), submitted for publication.