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UPDATED KIT RESULTS FOR THE EXERCISE 2 OF KALININ3 BENCHMARK

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Reactor Physics and Dynamic Group (RPD)

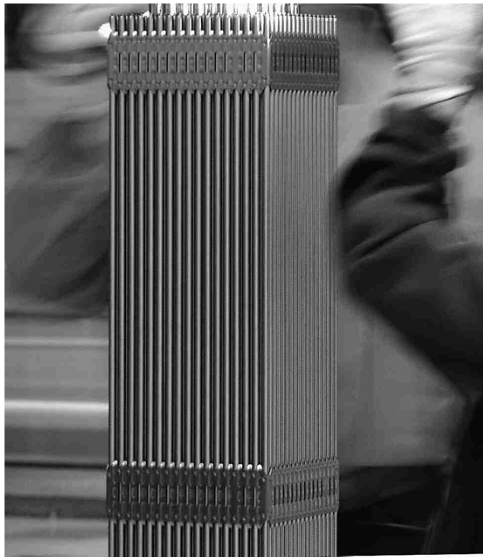
Content

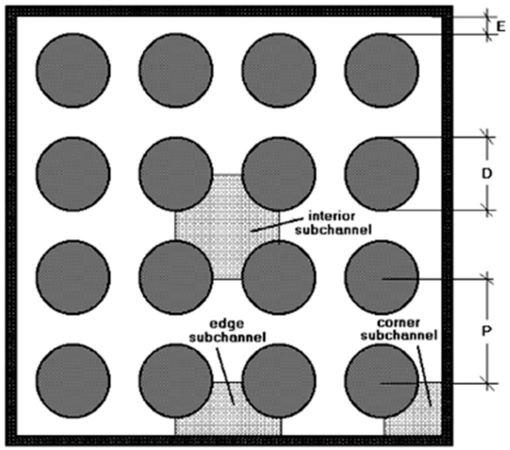
- Summary of results presented in the 5th Kalinin-3 Workshop 2013
  - Description of COBAYA3/SUBCHANFLOW coupled code
  - Reactor core model and cross section library
  - Results for Exercise 2
    - Steady States
    - Transient
  - Conclusions
- New results using DYNSUB tool (PhD M. Däubler)
  - Description of DYNSUB
  - Results for Exercise 2
    - Steady states
    - Transient
  - Conclusions
- EXTRA: VVER Fuel Assembly preprocessor for subchannel analysis
  To be presented in the 2nd COBRA-TF User group Meeting
- Acknowledgements

SUBCHANFLOW

Description of the KIT code SUBCHANFLOW

- Single and two phase (mixture) subchannel code for **water**, **sodium**, **lead** and **gas cooled** reactors
- Mass, momentum, enthalpy (3)-equation solver for strictly upward flow
- Fast running implicit fix-point iteration solver with axial plane wise matrix solution
- Hexagonal and square bundle geometry
- Stationary and transient solutions
- Applicable to LWR & Innovative reactors (SFR)
- Capability for coupling with a system code





Sub-channel analysis of SUBCHANFLOW

COBAYA3

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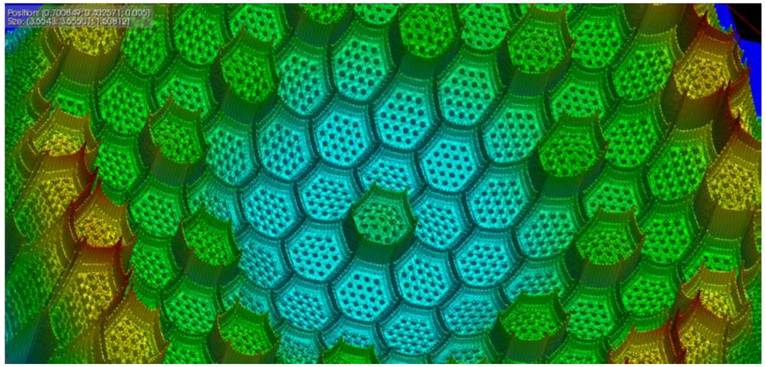
Description of the UPM code COBAYA3

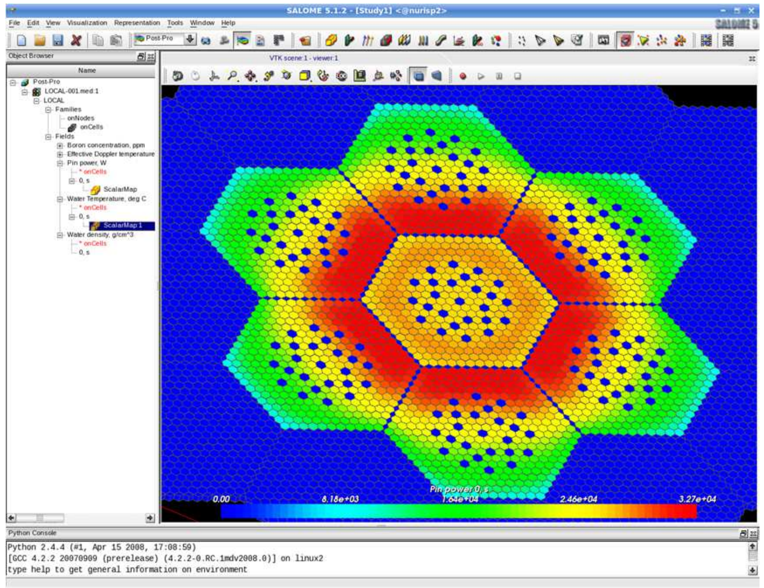
- COBAYA solves the 3D diffusion equation in multi-group for hexagonal and square FA for steady state and transient conditions

- Peculiarities:
  - Domain decomposition methodology
  - Nodal (ANDES) and pin-level (COBAYA3K) neutronics solvers.
  - Coupled to COBRA-III, COBRA-TF and SCF: Data exchange at the channel/nodal and sub-channel/pin scales via internal memory.

- Full core pin by pin calculations possible thanks to parallelization!

- COBAYA3 is being developed by Universidad Politécnica de Madrid (UPM)

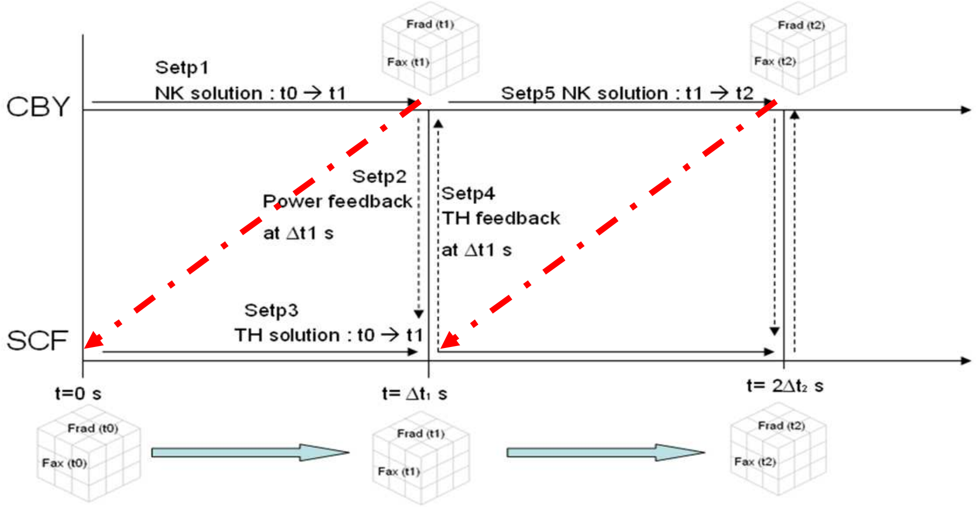


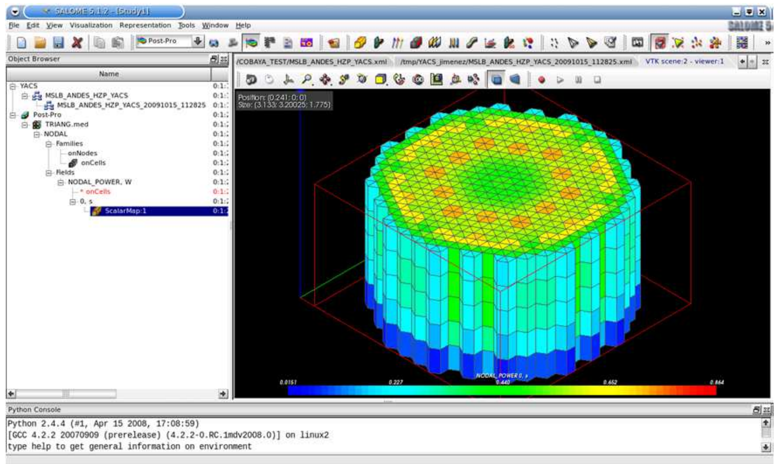


COBAYA3 post-processing in SALOME

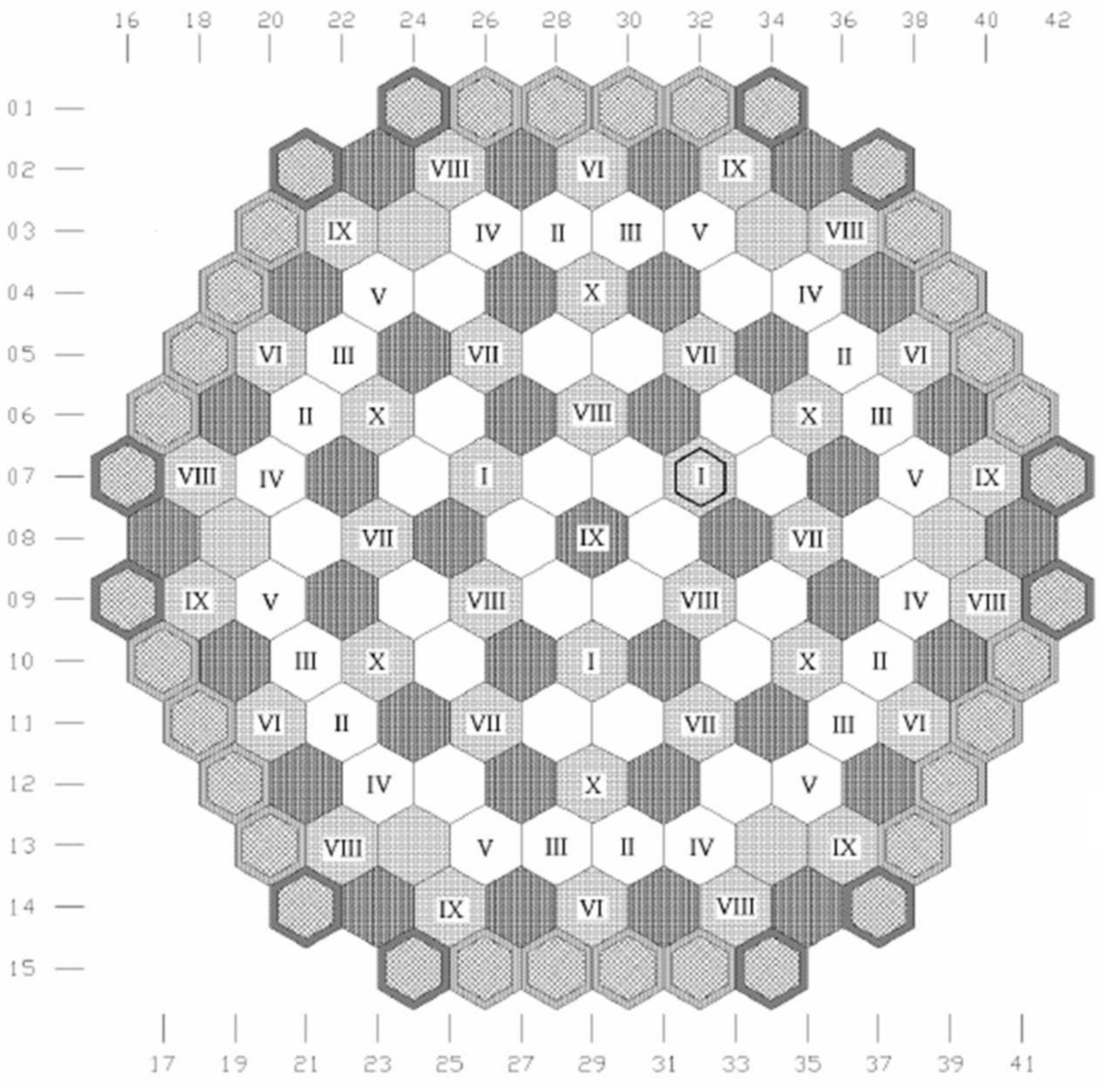
The Coupled Code COBAYA3/SUBCHANFLOW

- There are two coupling approaches:
  - Internal coupling (PhD. work from R. Ochoa UPM)
  - Coupling inside the SALOME Platform (**PhD. work of M. Calleja KIT**)
- Transient coupling
  - COBAYA3 was chosen to be the “master” code (providing the time step discretization) and SUBCHANFLOW the “slave”
  - An explicit scheme for the temporal coupling is used.





Exercise 2 – Reactor core model



Fuel assembly numbering and location of control rods.

- Enrichment of U-235 1.3 % - 48 FA
- Enrichment of U-235 2.2 % - 42 FA
- Average enrichment of U-235 2.98 % - 37 FA (303 FA with enrichment 3 %, 9 gad-FA with enrichment 2.4 %
- Average enrichment of U-235 3.9 % - 24 „profiled" FA (243 FA with enrichment 4.0 %, 60 FA with enrichment 3.6 %, 9 gad-FA with enrichment 3.3 %)
- Average enrichment of U-235 3.9 % - 12 „profiled" FA (240 FA with enrichment 4.0 %, 66 FA with enrichment 3.6 %, 6 gad-FA with enrichment 3.3 %)
- Enrichment of U-235 1,6 (stainless steel)

Details of the Neutronic and TH Core Model

- Neutronic model:
  - Radial nodalisation:
    - *Six triangular nodes per FA*
    - Radial reflector: modelled
  - Axial nodalisation:
    - 20 axial nodes for active core
    - 2 nodes for axial reflectors
  - Void radial and axial boundary conditions for the external surface of the core.

- Thermal-hydraulic model:
  - Radial:
    - One channel per FA (163)
  - Axial: 20 nodes
  - Cross flow between FA considered
  - Pin radial nodalisation:
    - 10 nodes in fuel
    - 2 nodes in cladding

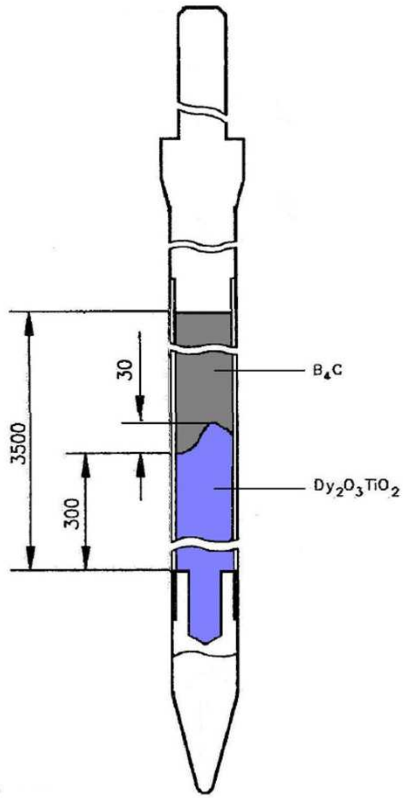
Mapping between Neutronic and TH is done by mesh overlapping

Exercise 2 – cross-section library

- PennState - Risk Engineering Ltd. - library (28.07.2011)
  - **nemtab_load_1** – unrodded composition for original fuel load
  - **nemtabr1_load_1** – rodded (B_4C absorber part of CR)
  - **nemtabr2_load_1** – rodded (Dy_2O_3*TiO_2 absorber part of CR)
  - **nemtab_load_2** – unrodded composition for original fuel load (only assembly with coordinates 07-32 replaced by fresh assembly)
  - **nemtabr1_load_2** – rodded (B_4C absorber part of CR) (only assembly with coordinates 07-32 replaced by fresh assembly)
  - **nemtabr2_load_2** – rodded (Dy_2O_3*TiO_2 absorber part of CR) (only assembly with coordinates 07-32 replaced by fresh assembly)

Exercise 2 – cross-section library

- Creation of COBAYA3 nemtab library with 1006 materials:
  - **nemtab_load_1 (283)**: input head and all materials from
  - **nemtab_load_2 (283)**: all materials from 284 to 566
  - **nemtabr2_load_1 (110)**: Dy_2O_3*TiO_2 (bottom tip of CR) all materials from 567 to 676
  - **nemtabr1_load_1 (110)**: B_4C (main CR composition) all materials from 677 to 786
  - **nemtabr2_load_2 (110)**: Dy_2O_3*TiO_2 (bottom tip of CR) all materials from 787 to 896
  - **nemtabr1_load_2 (110)**: B_4C (main CR composition) all materials from 897 to 1006



Exercise #2a – HZP: steady-state results

- **HZP state (using PSU-REL library):**

Power = 0.1% Nominal Power

Fuel and moderator temperature = 552.15 K

Boro concentration = 660 ppm

Moderator density = 767.1 kg/m^3

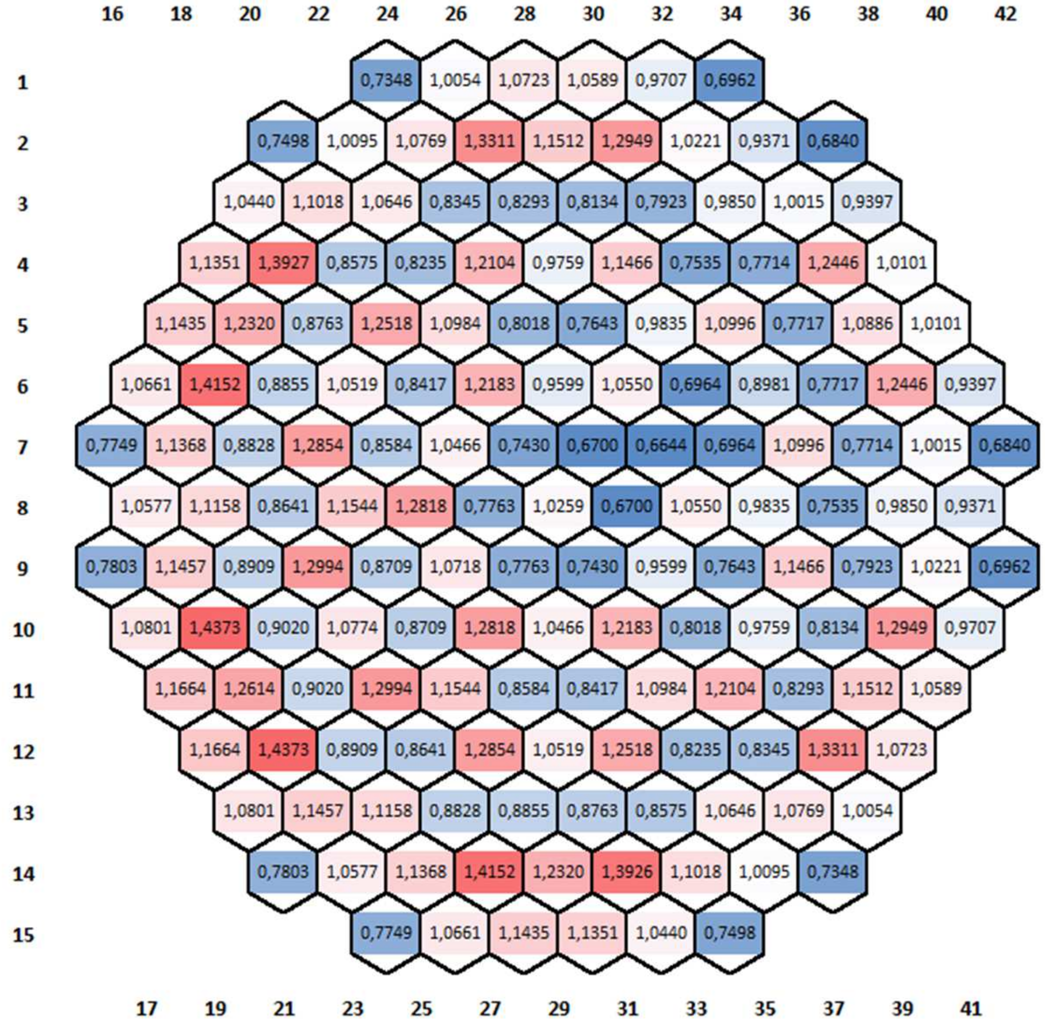
CR#10 is 82,95%

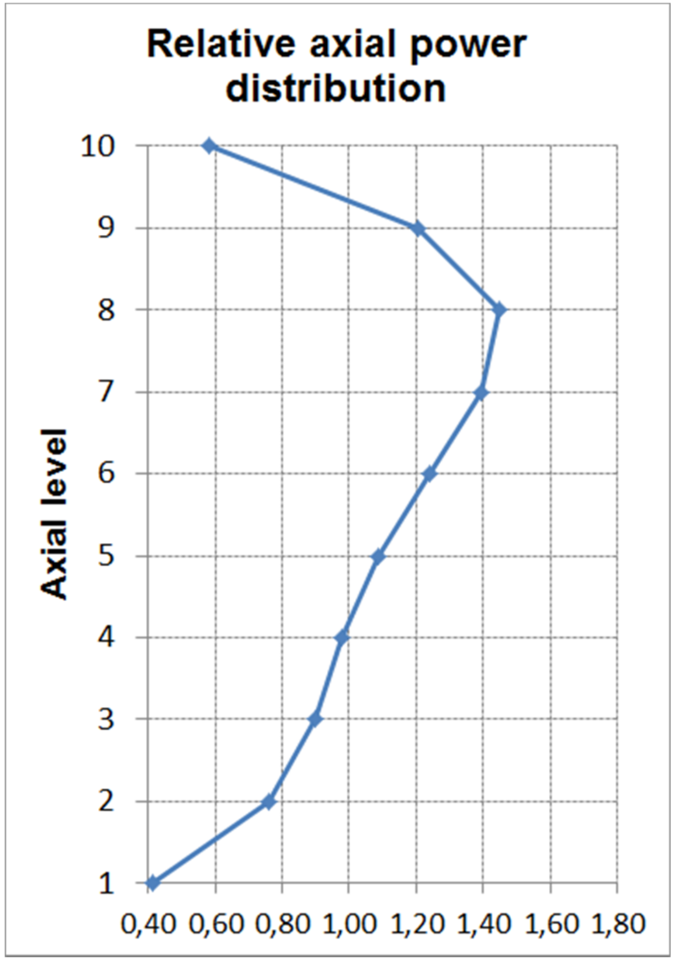
	K_{eff}
ARO	1.01241
ARI	0.91006

	Value
K_{eff}	1. 01157
F_{xy}	1.4373
F_z	1.4612
Axial Offset	0.1726
SRW [% dk/k]	10234.0 pcm
CRW #9 [% dk/k]	967.6 pcm
CRW #10 [% dk/k]	866.7 pcm

Exercise #2a – HZP: steady-state results

Relative radial power distribution

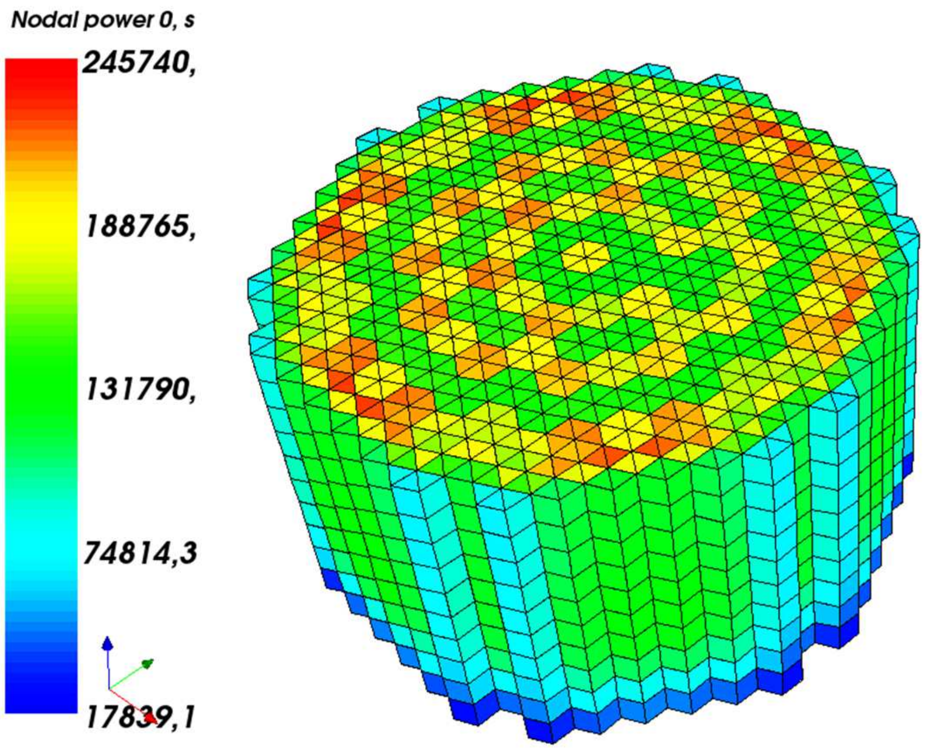




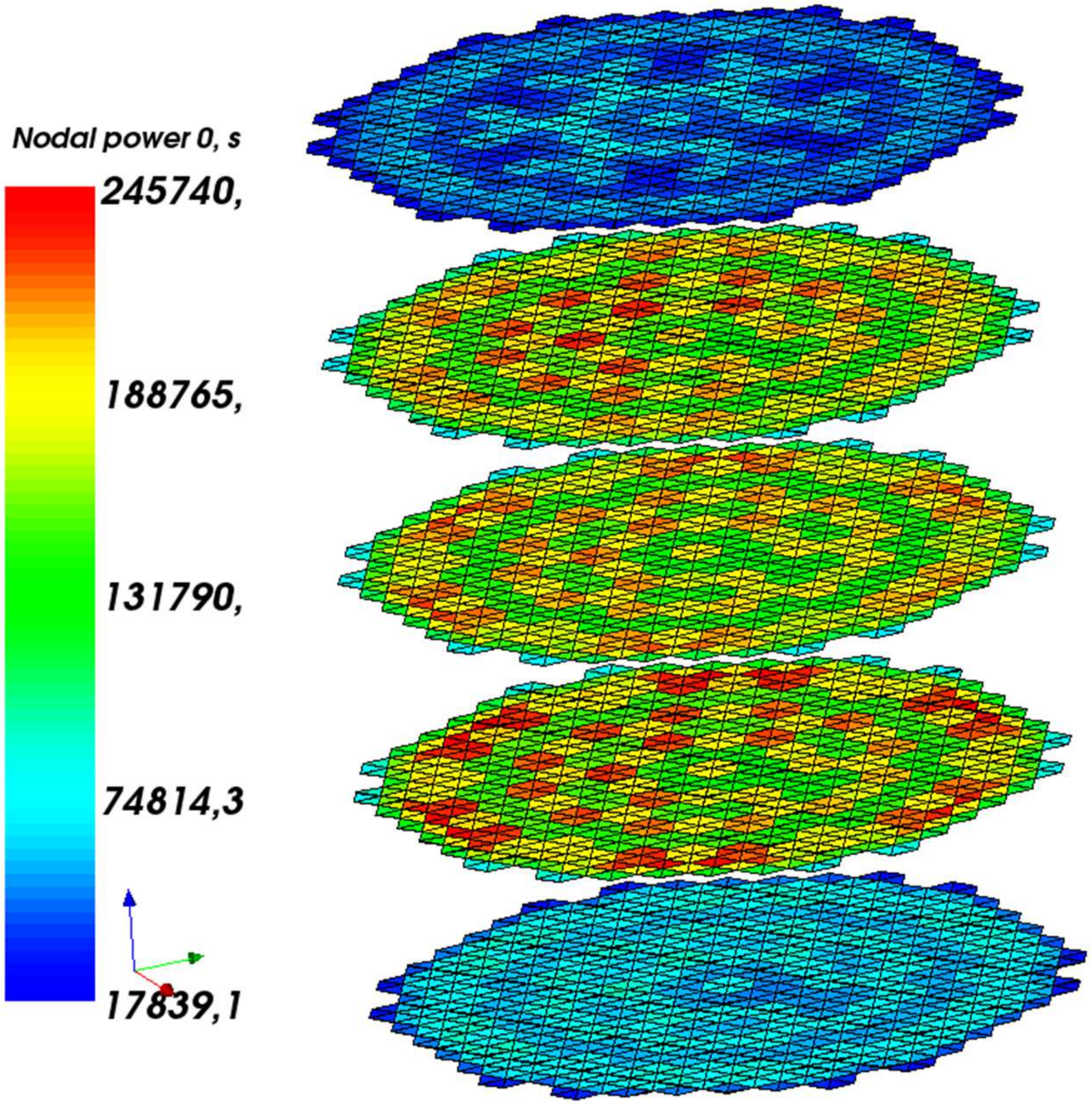
Exercise #2 – HFP: Initial steady-state results

- HFP state (using PSU-REL library): Conditions previous to the initialization of the transient

	Value
Total core Power	2875 MW
K_{eff}	0.99853
F_{xy}	1.3356
F_z	1.1922
Axial Offset	-0.0466

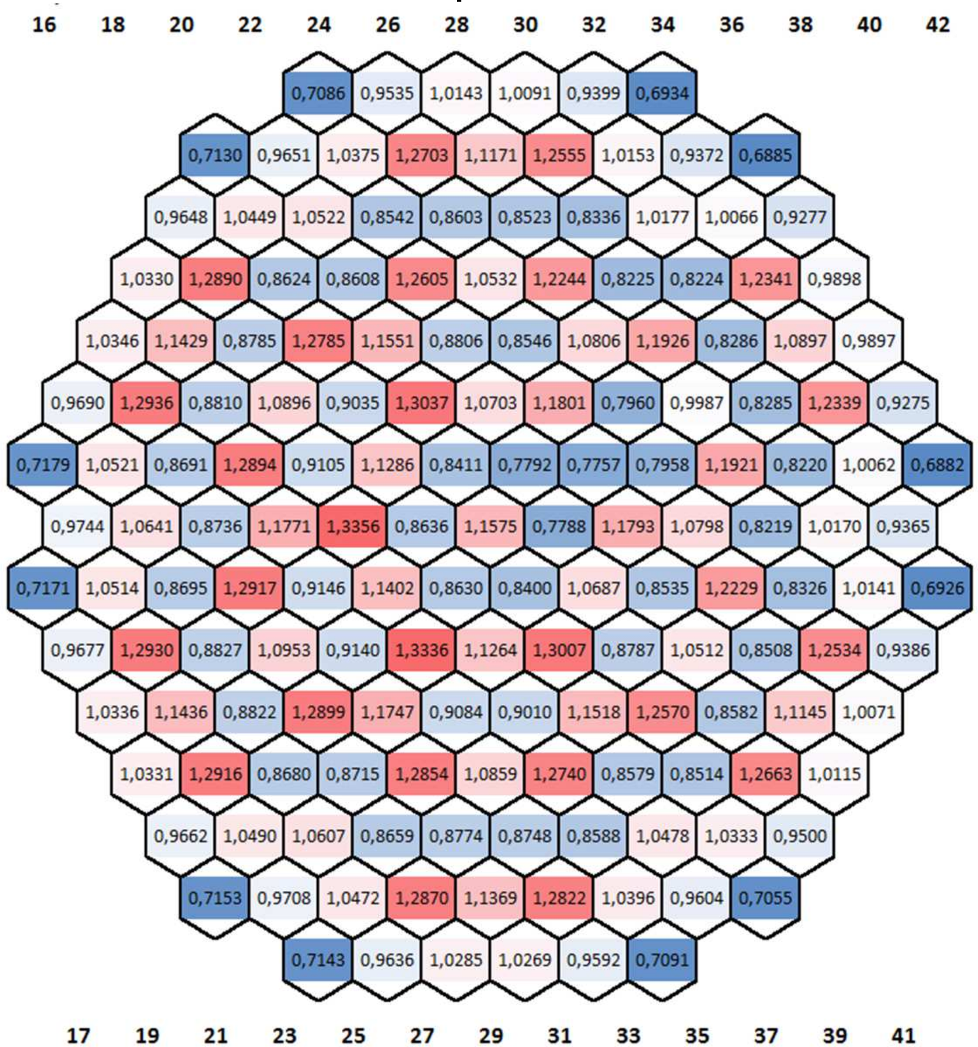


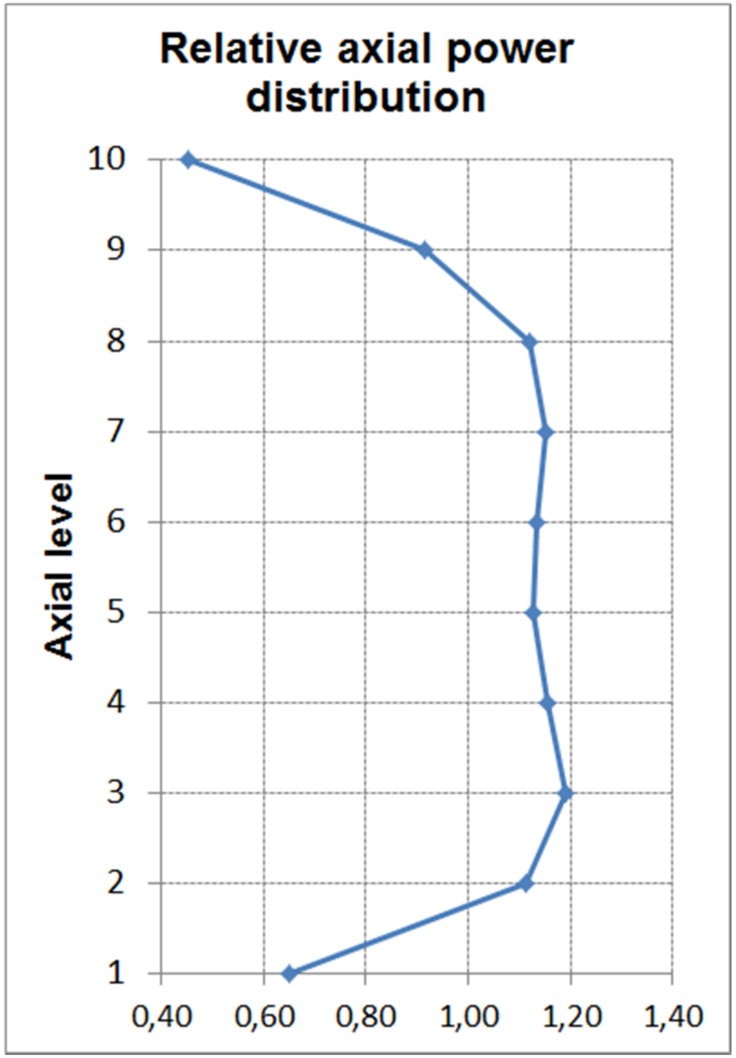
Exercise #2 – HFP: Initial steady-state results



Exercise #2 – HFP: Initial steady-state results

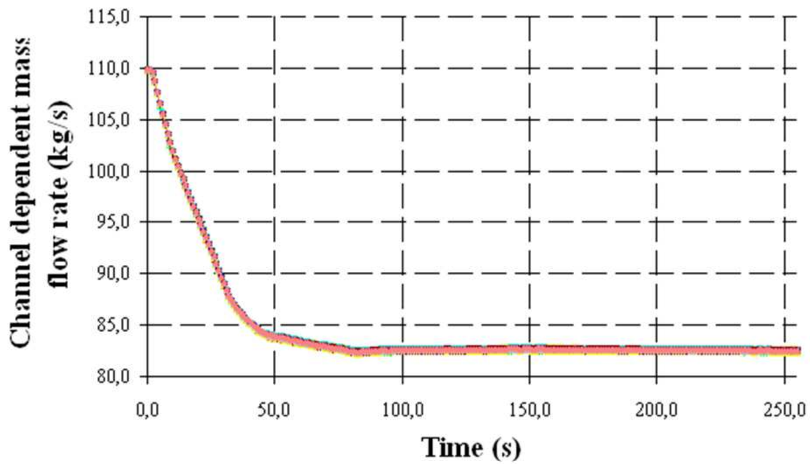
Relative radial power distribution

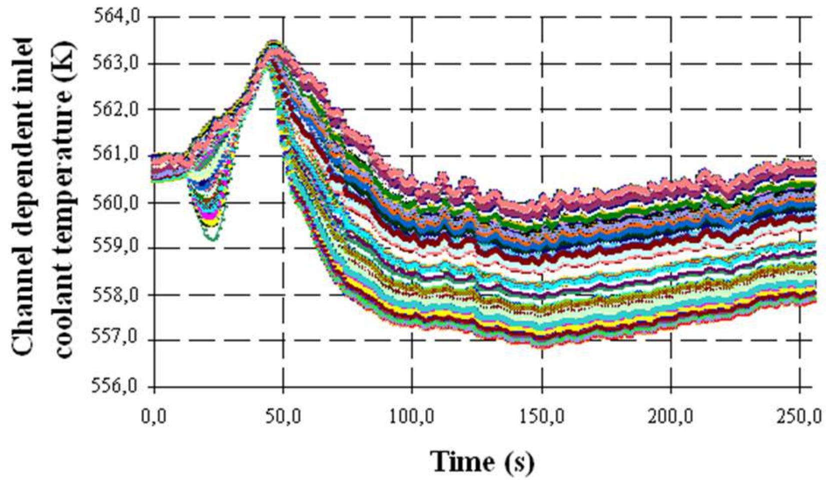


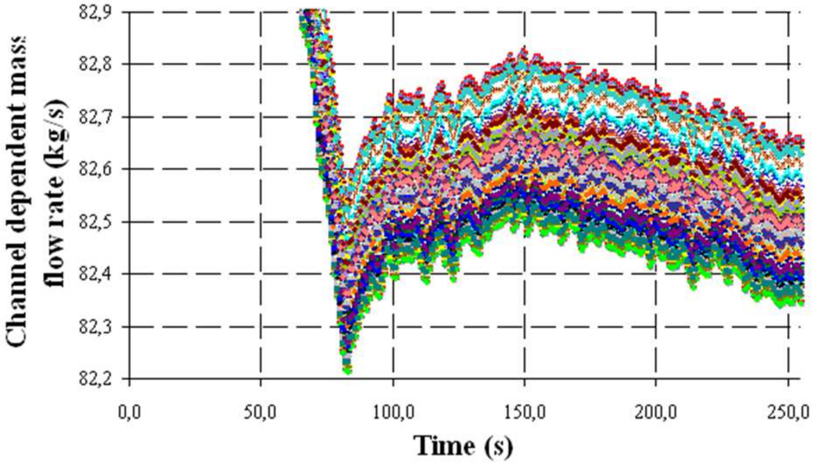


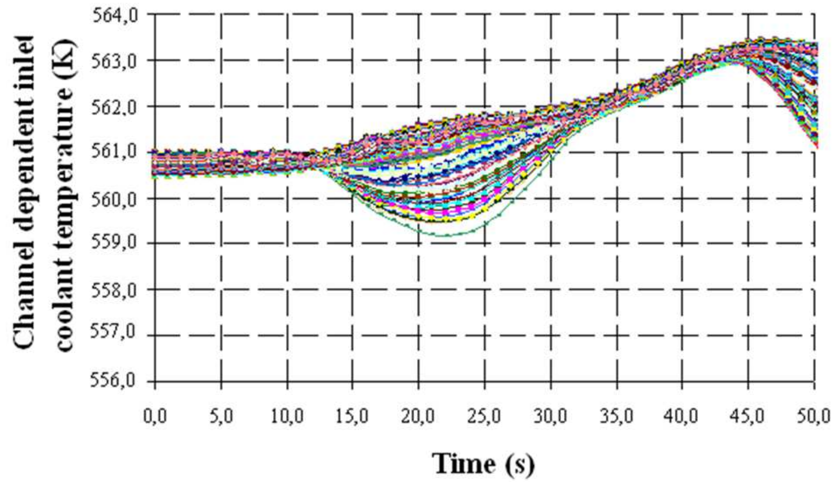
Exercise #2 – HFP: time dependent boundary conditions

- Channel dependent mass flow rate from G_T_R_CORE_IN.OUT file (13.07.2011)



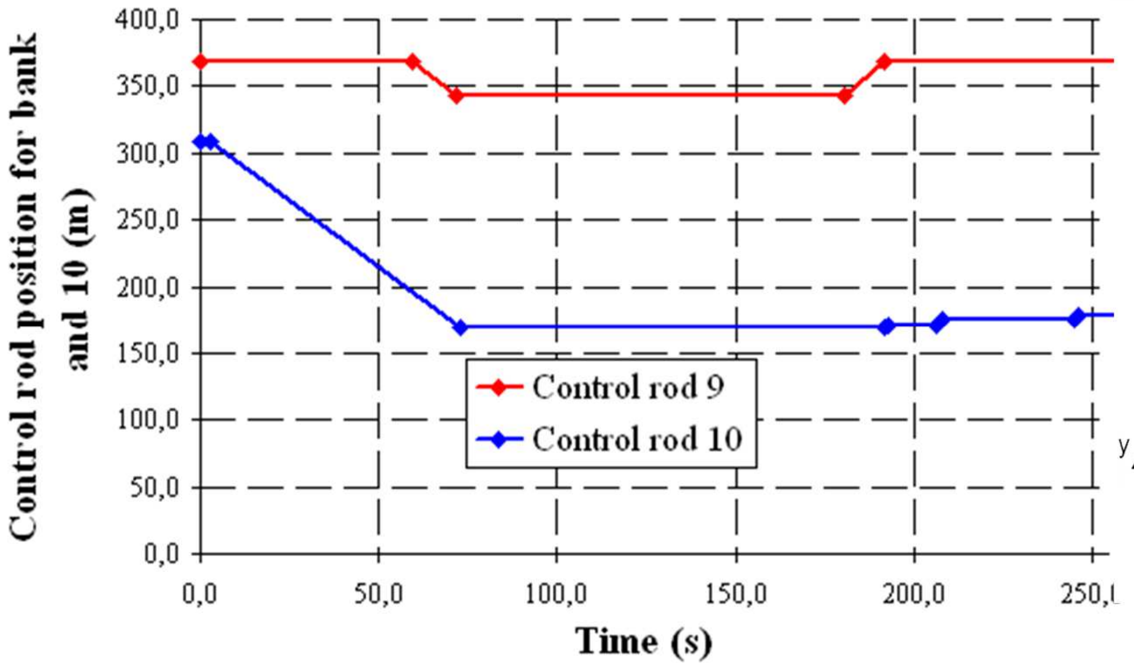


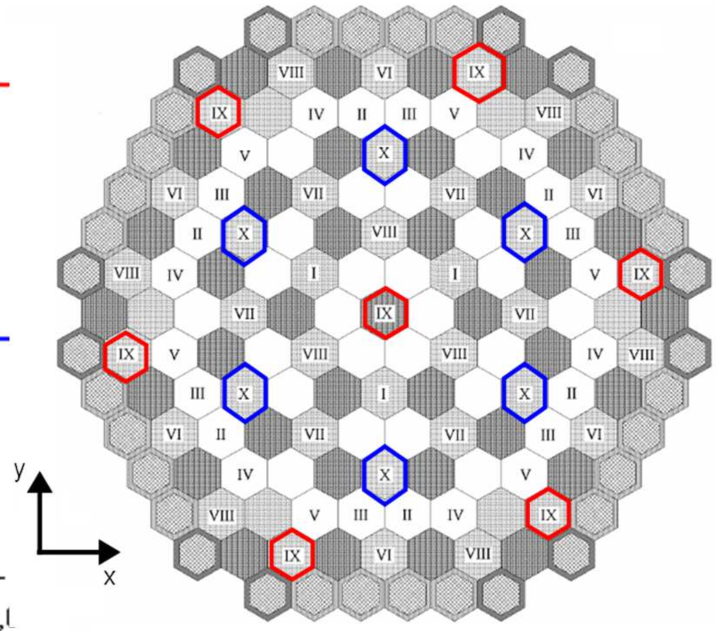




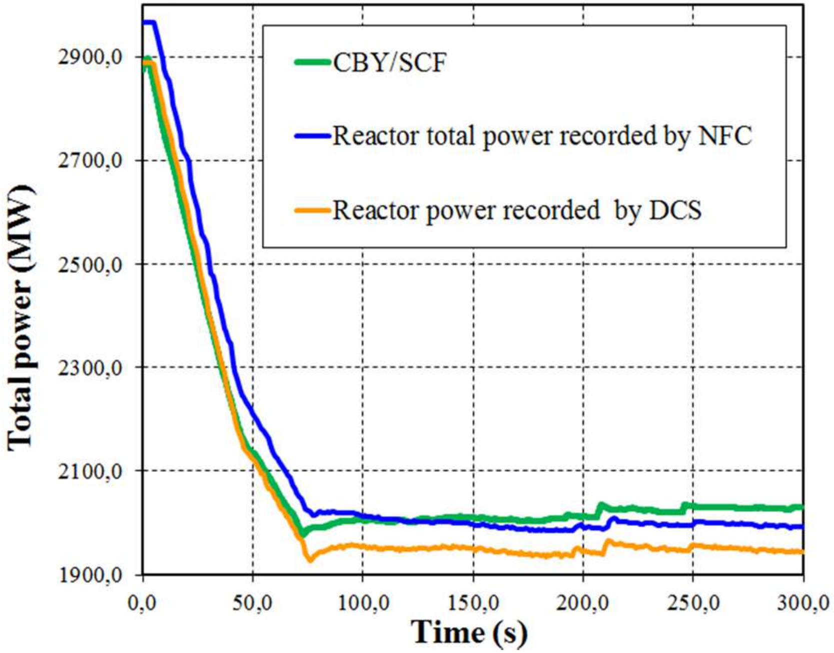
Exercise #2 – HFP: time dependent boundary conditions

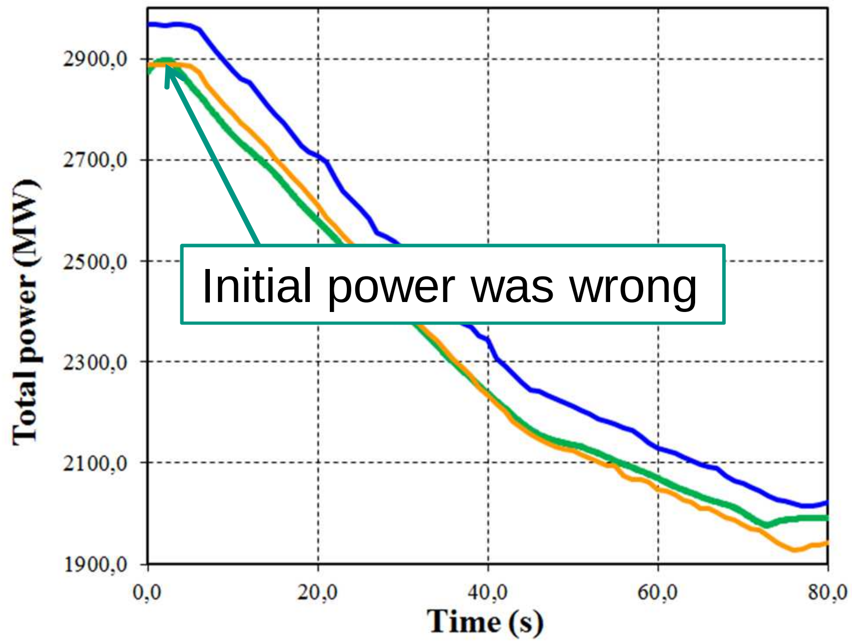
- Control rod movement of banks 9 and 10 according to specifications.

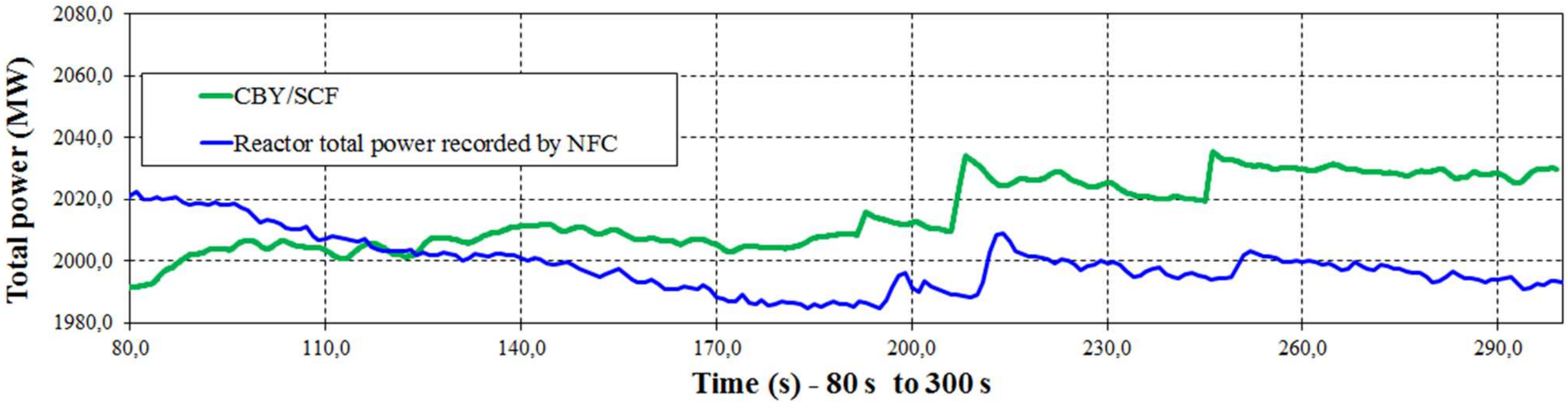




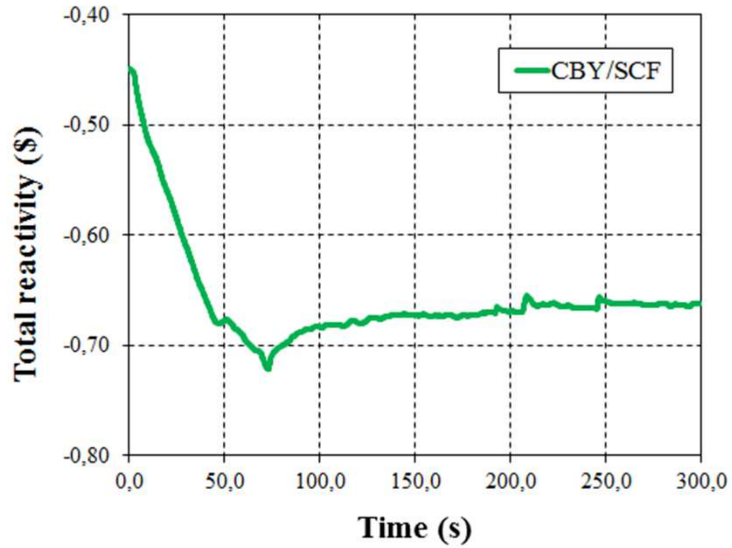
Exercise #2 – Transient results
Total power evolution

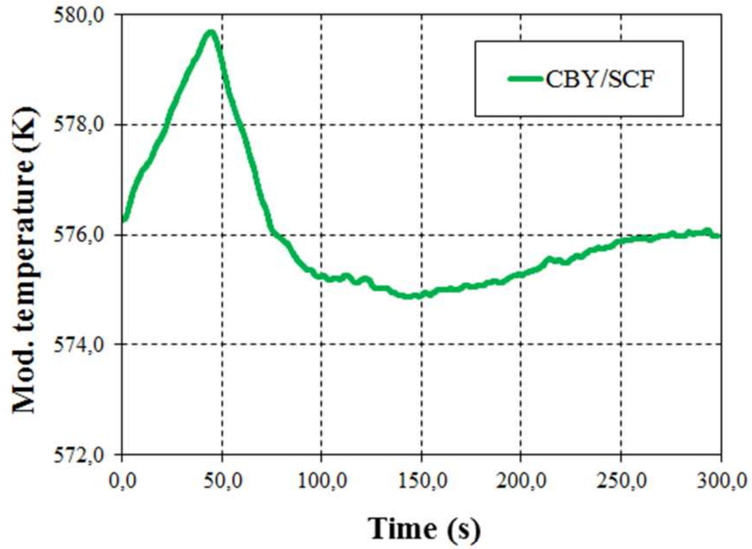


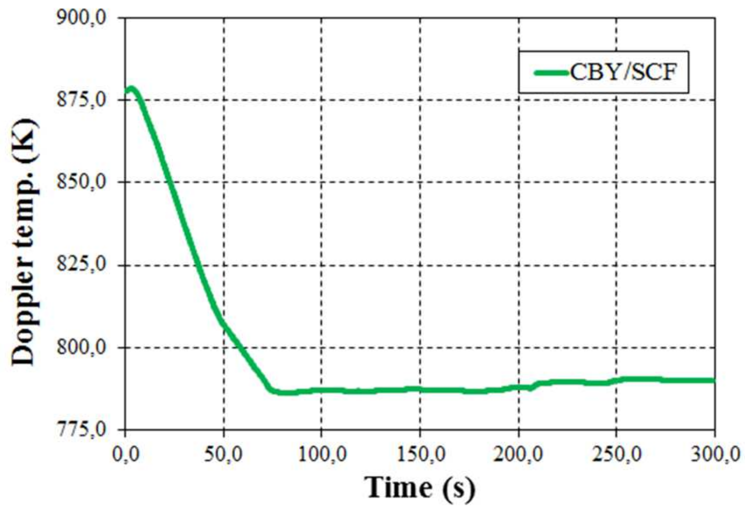


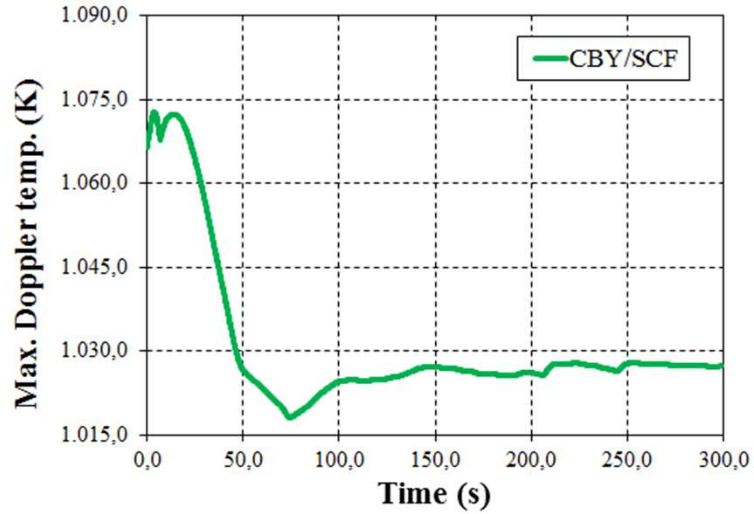


Results for main global parameters









Conclusions

- External coupling using the SALOME platform interface.
- The results obtained with the coupled code COBAYA3/SCF are in good agreement with the measured data for both Steady State and Transients.
- A time step size of 0.1s was used for the whole transient which is small enough to keep the accuracy of the explicit coupling scheme.
- Results published in a journal:

"*Coupling of COBAYA3/SUBCHANFLOW inside the NURESIM Platform and Validation Using Selected Benchmarks*", Calleja, M., Jimenez, J., et al., Annals of Nuclear Energy, volume 71, pages 145-158, 2014, http://dx.doi.org/10.1016/j.anucene.2014.03.036

New results using DYNSUB tool (PhD M. Däubler)

DYN3D-MG version released December 2009

Description of the HZDR code DYN3D

- Diffusion and simplified transport approximation (SP_3) of neutron transport equation.
- Square and hexagonal geometries.
- Multi-group nodal expansion method (NEM) on fuel assembly and pin scale applying a quadratic transverse leakage approximation
- Iterative procedure to determine critical boron concentration and reactor power corresponding to a given multiplication factor
- Time dependency treated by fully implicit finite difference scheme using exponential transforms
- Pin level homogeneization corrections, SPH (Super Homogeneization Factors) and GET-IDF (Interface Discontinuity Factors derived from Generalized Equivalence Theory).
- Updated to DYN3D-MG svn revision 511 (2013).

The Coupled code DYNSUB

- Internal coupling of DYN3D-MG and SUBCHANFLOW.
  - INITIAL DYNSUB (PhD. work from A. Gomez KIT)
  - EXTENSION OF DYNSUB (PhD. work of M. Däubler KIT)
- Main coupled code features:
  - Pin level calculations from single fuel assemblies up to full reactor cores
  - Steady-state and transient solution
  - Geometry currently limited to PWR fuel lattices
  - Programmed in Fortran 77 and 95
  - Can be used with WINDOWS or LINUX, installation procedure based on python
  - Parallel execution on shared memory architectures using OpenMP
  - Dynamic memory management
  - Modular structure and automatized non-regression tests

The Coupled code DYNSUB

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SCF 1.8 | SCF 2.0 | SCF 2.3

DYNSUB3

- Communication via internal arrays
- Transient implementation
- Optimized coupling for updating versions of the code
- DYNSUB as a Linux distribution package
- Fitting pre-proc for SCF 1.8

DYNSUB4

- Platform independence established
- Extension of steady-state and transient functionalities
- Systematic code verification performed
- Automatized non-regression testing
- Doxygen
- Code documentation
- OpenMP

DYNSUB5

- DYN3D MG 2013
- Implementation of boron transport
- Wall clock time measurement
- Relaxed Picard iteration
- SCF standard output optional
- MED file generation
- XS table range warnings
- Flexible spatial mapping

time

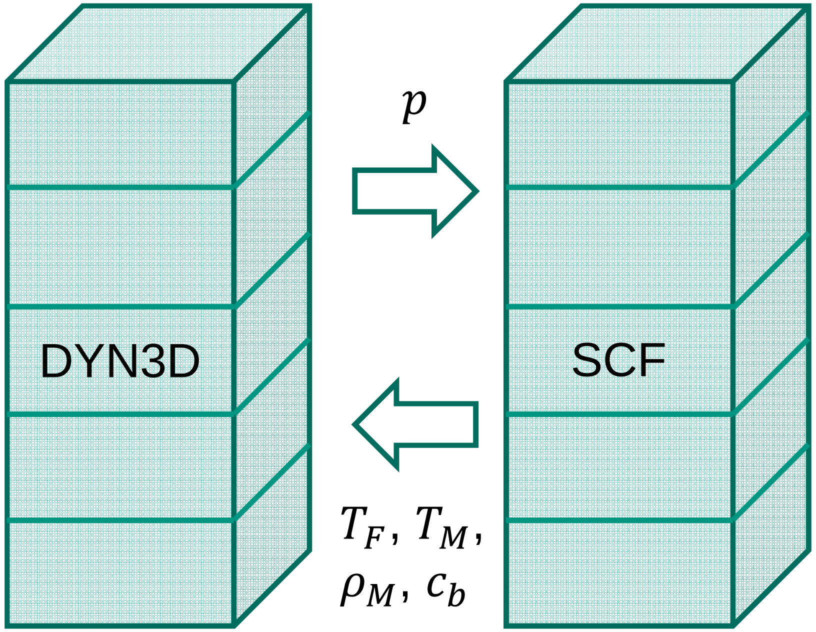
Internal coupling approach

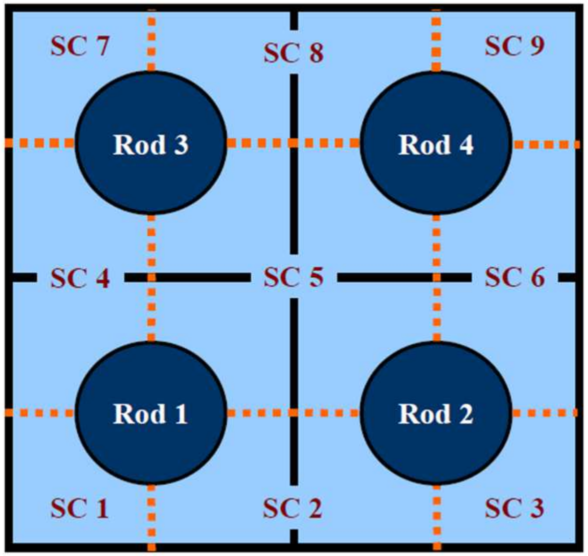
- Doppler temperature calculation scheme $T_{dopp} = (1 - \alpha)\, T_{f,c} + \alpha\, T_{f,s}$

if α exceeds 1.0, volume weighting instead of the above formula is used.

- Relaxation scheme $\varphi_{new} = (1 - \omega)\, \varphi_{old} + \omega\varphi_{new}$

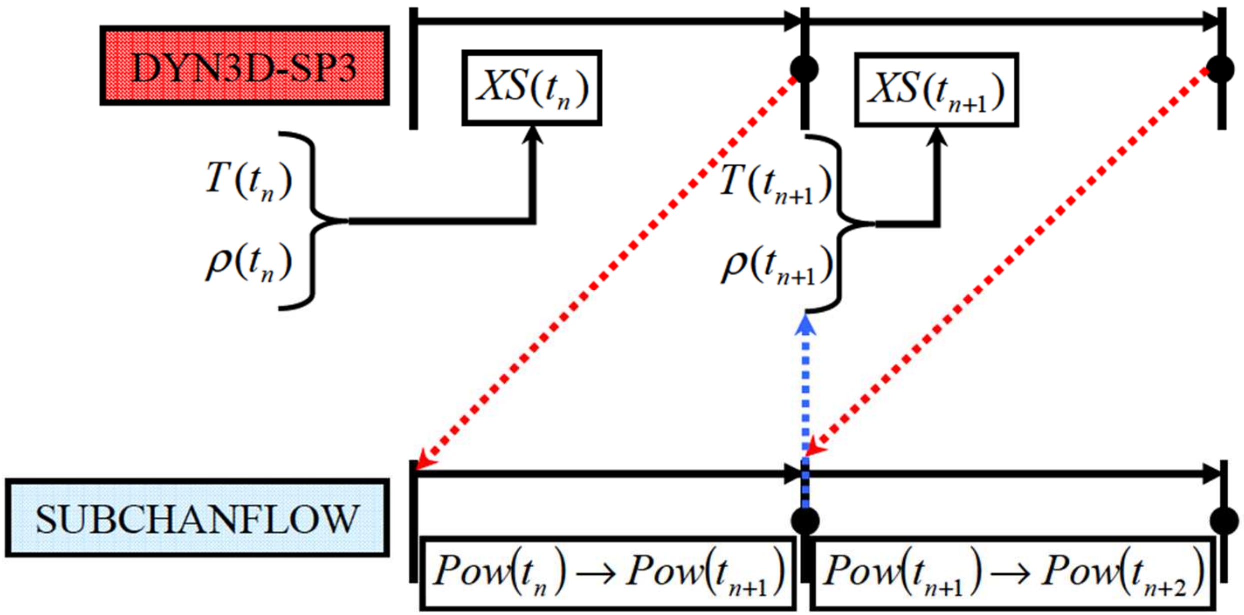
with φ being any field involved in the internal coupling



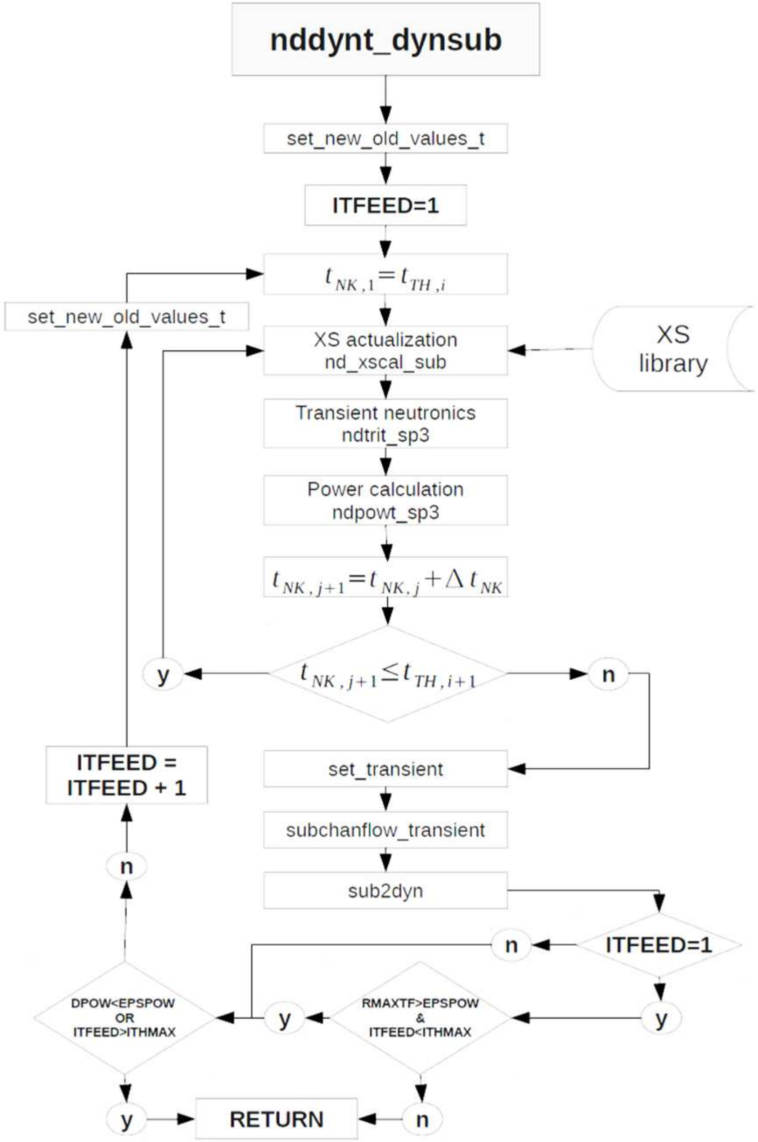


DYNSUB's coupling numerics

- Explicit marching scheme:
  t_n corresponding to nth steady-state iteration or nth time step in a transient run



DYNSUB transient algorithm



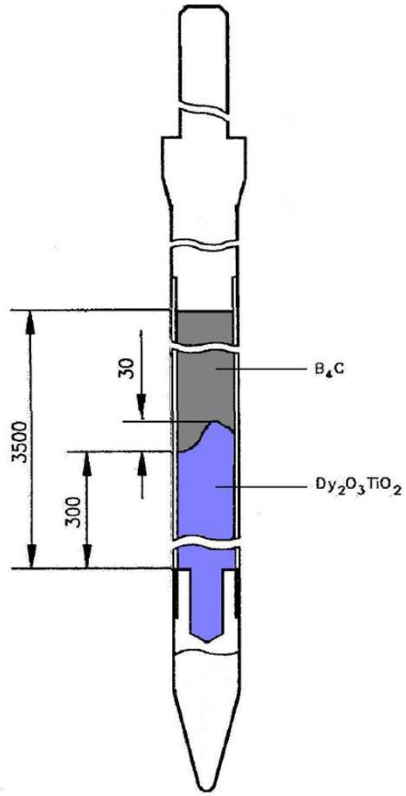
DYN3D-MG new CR decusping model

- DYNSUB-MG (2009) could not handle grey CRs as Kalinin 3 has them.
- Decusping model of DYN3D MG did not work properly.
- Very poor correction model.
- Implemented approximate flux weighting method.
- Tested against high axial resolution reference models.

$$\Sigma_g = \frac{(1-f)\ \Sigma_{NR,g}\, \phi_{NR,g} + f\, \Sigma_{R,g}\, \phi_{R,g}}{(1-f)\ \phi_{NR,g} + f \phi_{R,g}}$$

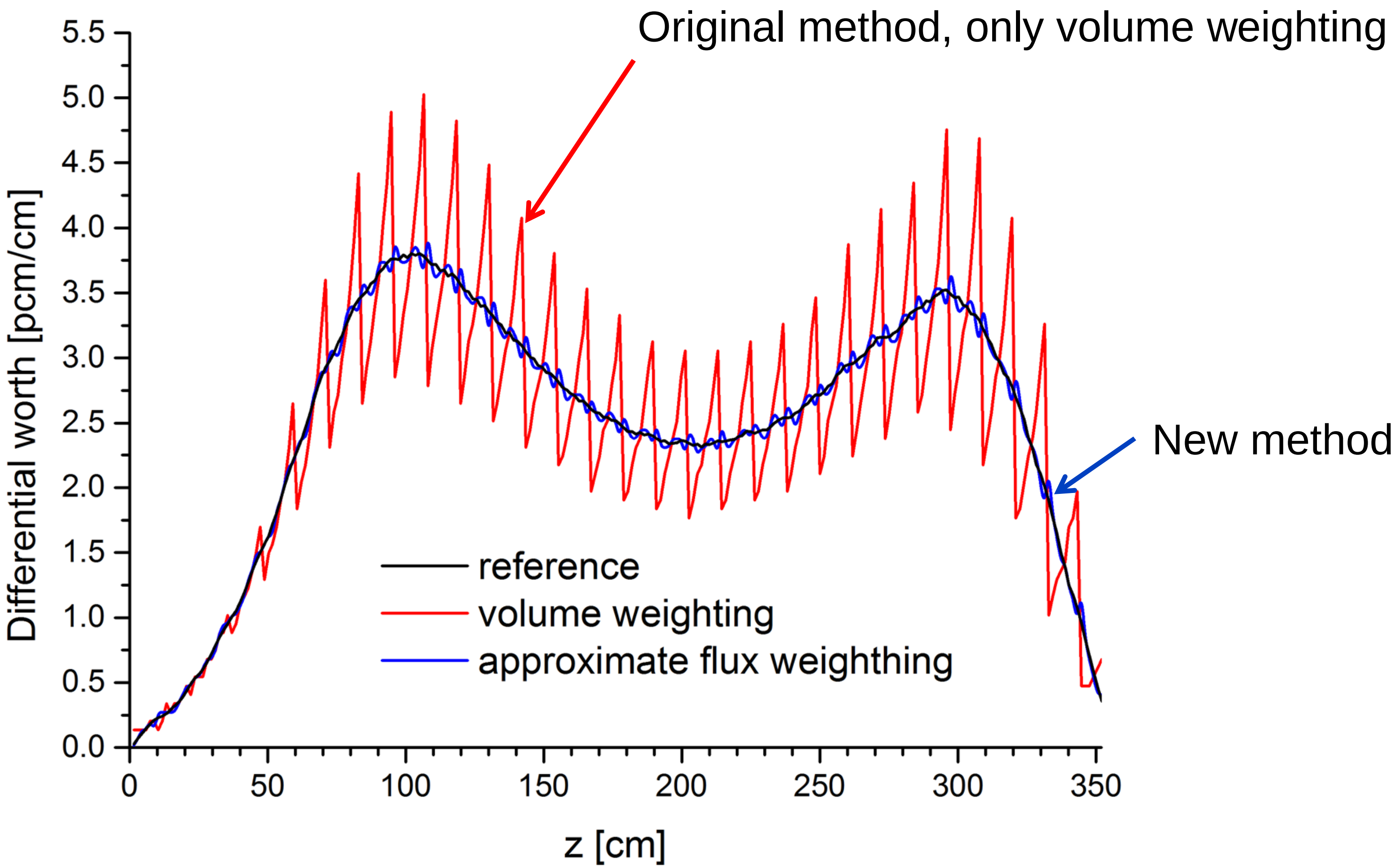
$$\phi_{NR,g} = \frac{\Delta z_{k-1}\, \phi_{k-1,g} + (1-f)\, \Delta z_k\, \phi_{k,g}}{\Delta z_{k-1} + (1-f)\, \Delta z_k}$$

$$\phi_{R,g} = \frac{\Delta z_{k+1}\, \phi_{k+1,g} + f\, \Delta z_k\, \phi_{k,g}}{\Delta z_{k+1} + f\, \Delta z_k}$$



DYN3D-MG new CR decusping model

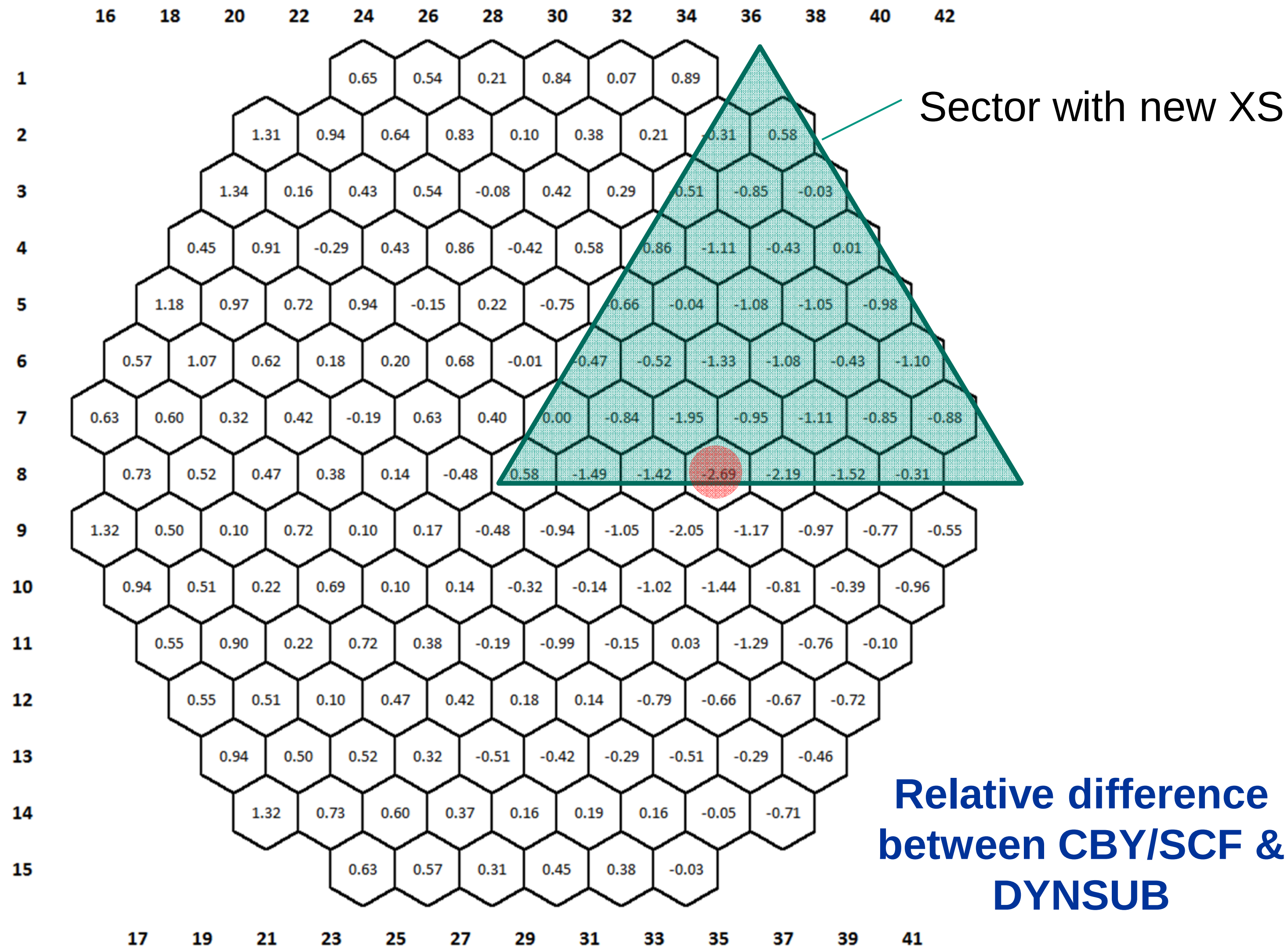
- Reference is computed using 240 axial layers. The other uses 30.



Kalinin 3 – Exercise #2a, HZP steady state

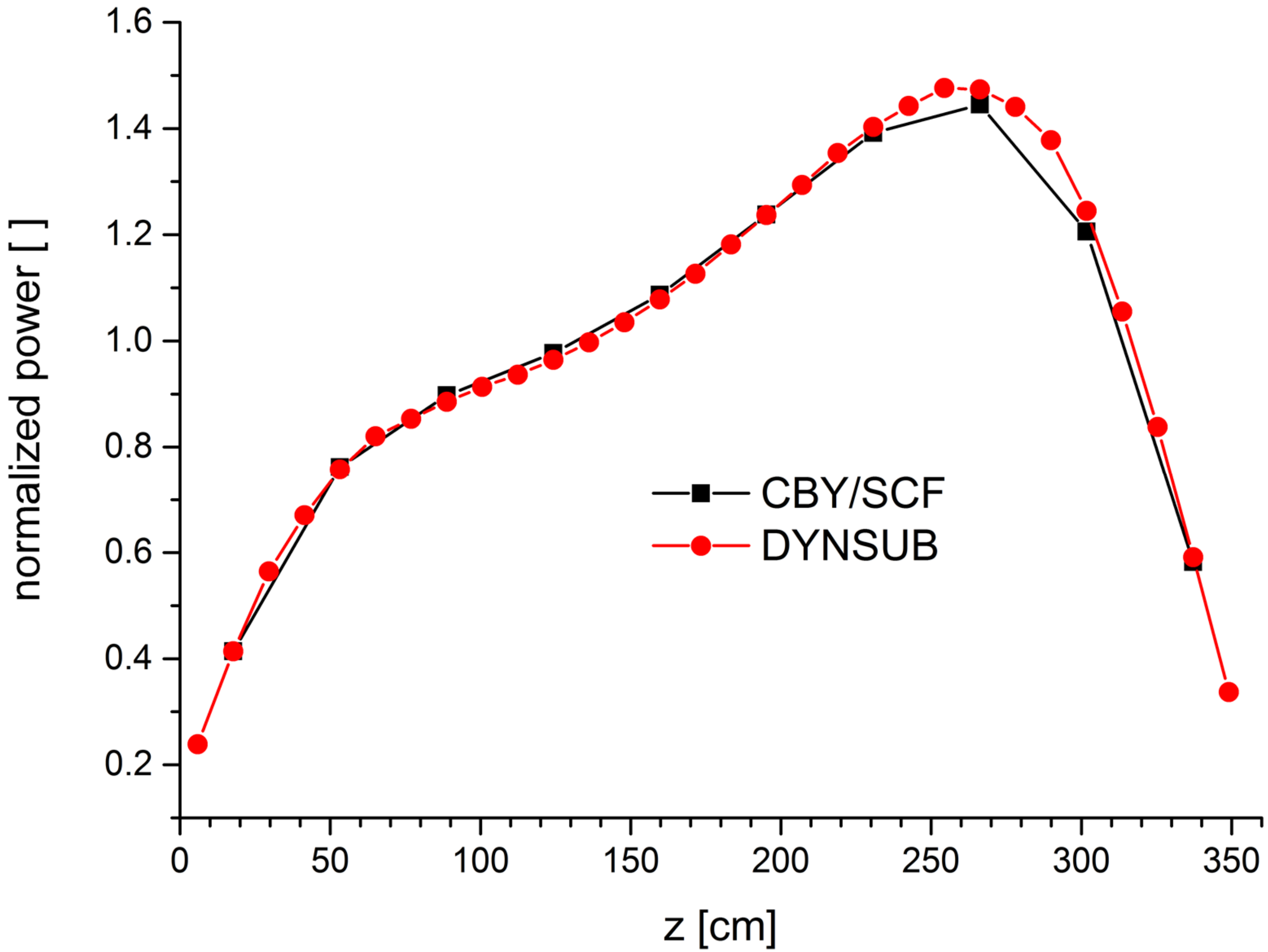
	CBY/SCF	DYNSUB
K_{eff}	1. 01157	1.011406
F_{xy}	1.4373	1.4262
F_z	1.4612	1.4760
SRW [% dk/k]	10234.0 pcm	10311.0 pcm
CRW #9 [% dk/k]	967.6 pcm	968.4 pcm
CRW #10 [% dk/k]	866.7 pcm	869.7 pcm

Kalinin 3 – Exercise #2a, HZP steady state



Relative difference between CBY/SCF & DYNSUB

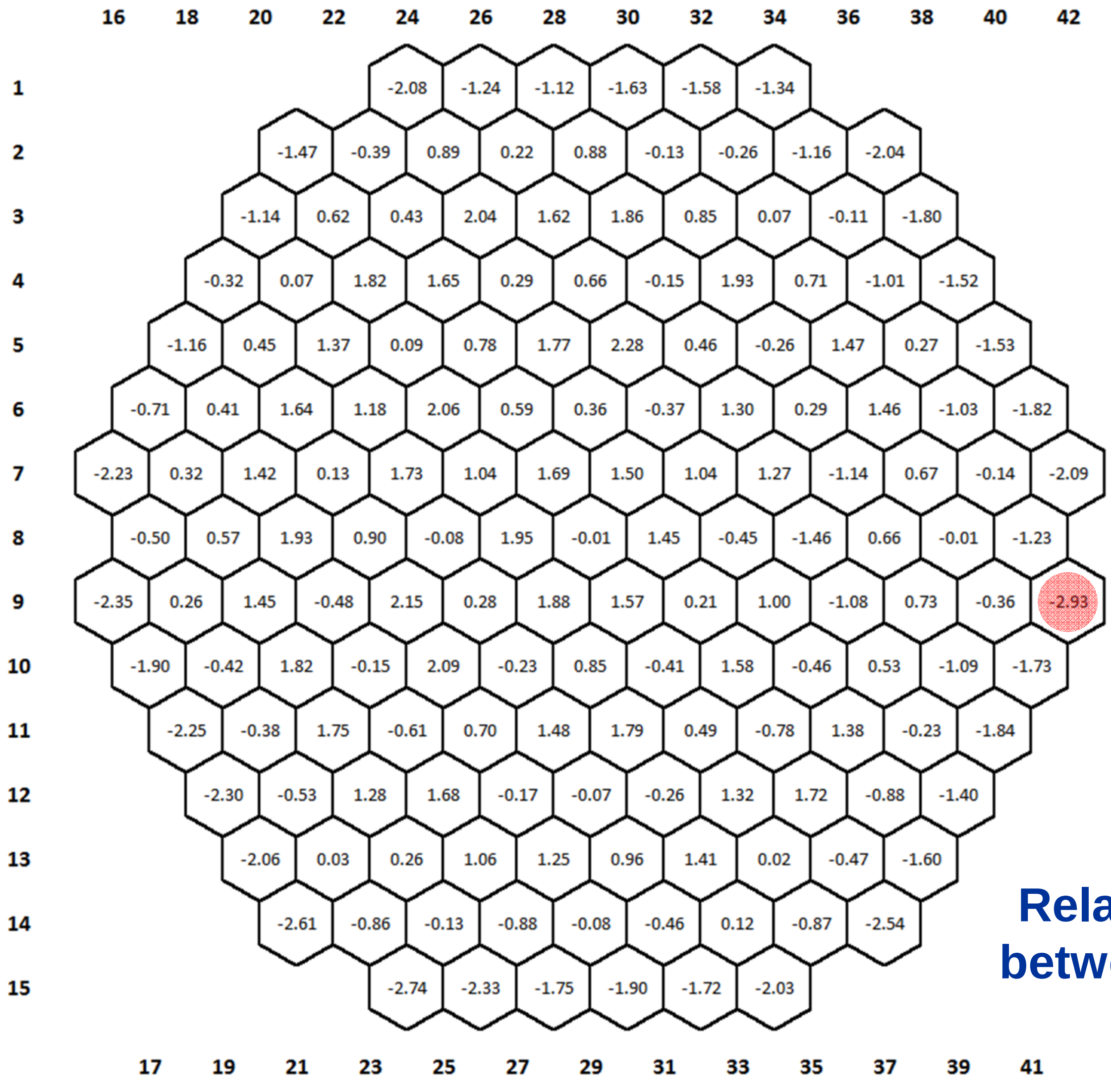
Kalinin 3 – Exercise #2a, HZP steady state



Kalinin 3 – Exercise #2a, HFP steady-state

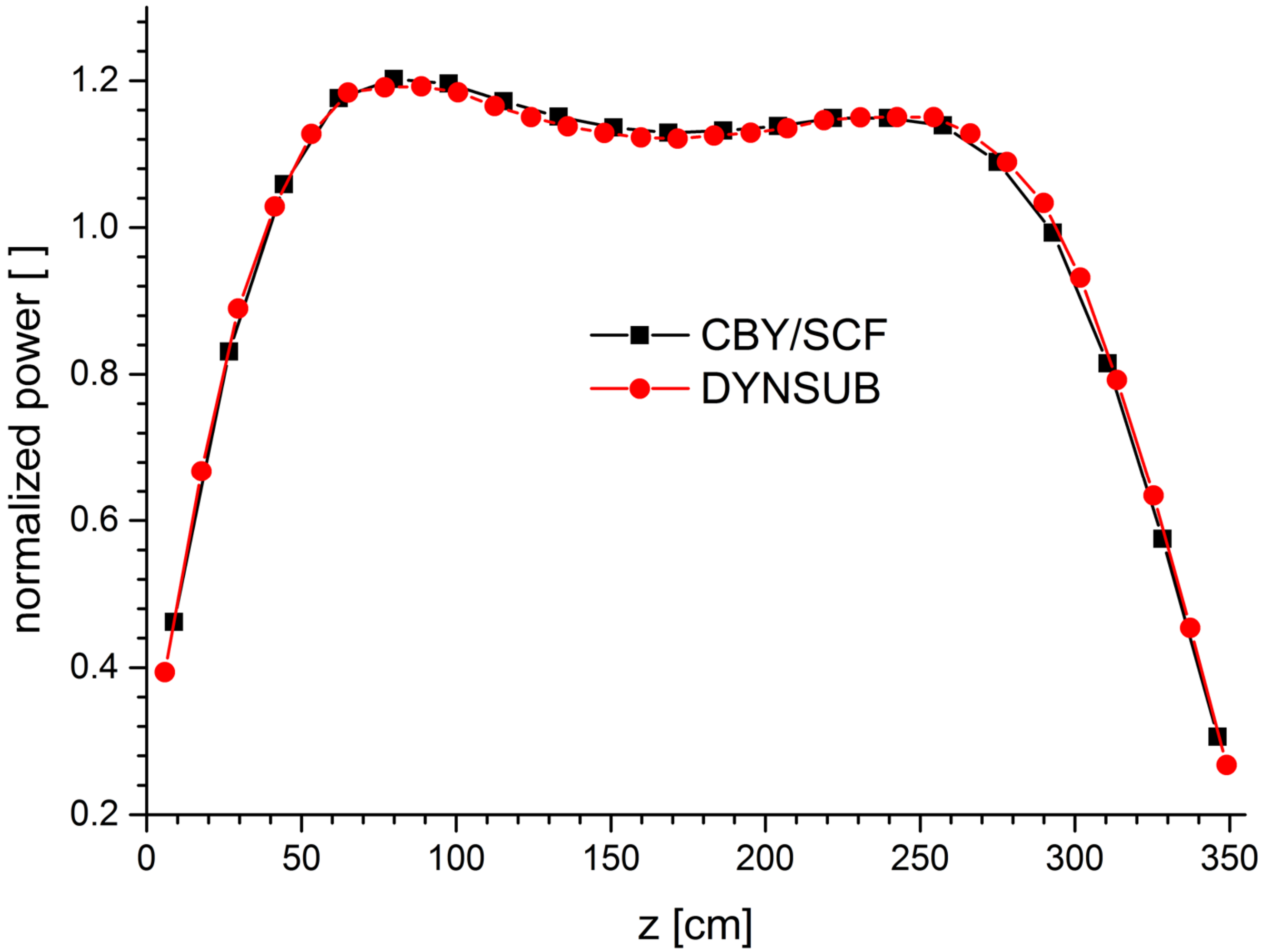
	CBY/SCF	DYNSUB
K_{eff}	0.996818	0.996944
F_{xy}	1.3289	1.3282
F_z	1.202	1.1920

Kalinin 3 – Exercise #2a, HFP steady-state

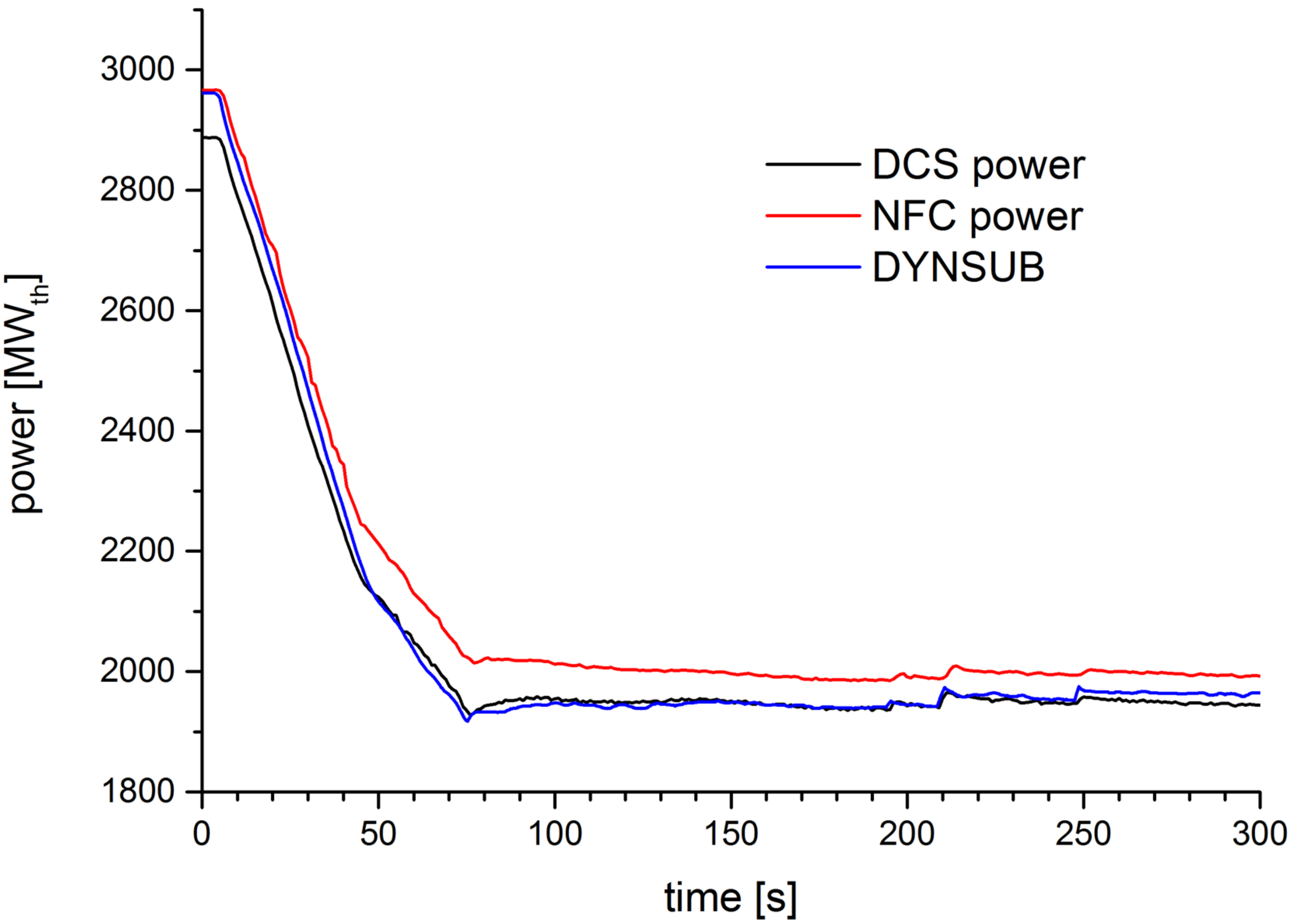


Relative difference between CBY/SCF & DYNSUB

Kalinin 3 – Exercise #2a, HFP steady-state



Kalinin 3 – evolution of total reactor power



Conclusions

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- DYNSUB´s coupling routines for hexagonal fuel lattices and reflector models have been implemented correctly.
- It was shown that the new CR decusping model performs significantly better than its predecessor.
- Good agreement between COBAYA/SCF and DYNSUB in all the steady states.
- DYNSUB reproduces the transient power evolution accurately.
- COBAYA/SCF is able to capture better the radial gradients due to the triangular based solution.

- A time step size of 0.1s was used for the whole transient which is small enough to keep the accuracy of the explicit coupling scheme.

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VVER Fuel Assembly preprocessor for subchannel analysis

To be presented in the 2nd COBRA-TF User group Meeting

J. Jiménez and V. Sanchez

Institute for Neutron Physics and Reactor Technology (INR)
Reactor Physics and Dynamic Group (RPD)

Hexagonal fine-mesh preprocessor

- Developed within NURESAFE WP1.4 framework.
- Fully operational for SUBCHANFLOW and COBRA-TF geometry tables generation.
- Coded in FORTRAN.
- Few input parameters:

  Number of rods in the bundle (fuel and guide tubes). (**37**)

  Pitch between the fuel pins. (**12.81380e-3 m**)

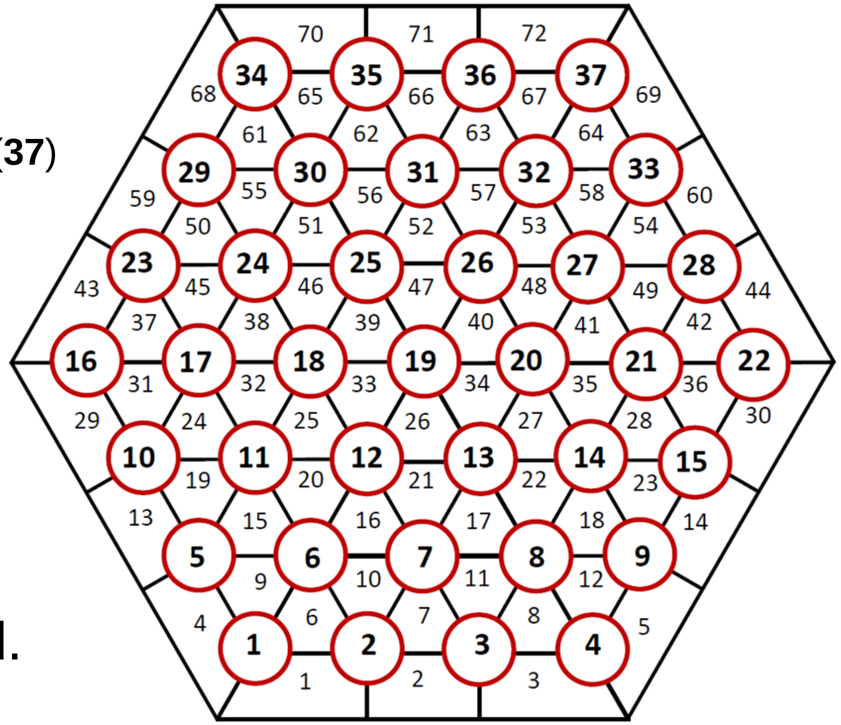
  Side length of the aristae. (**47.408e-3 m**)

  Rod diameter. (**9.1455e-3 m**)

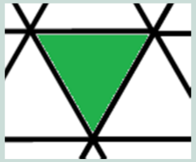
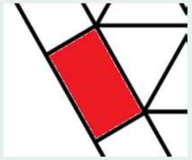
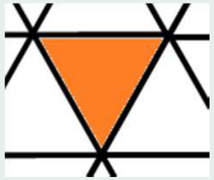
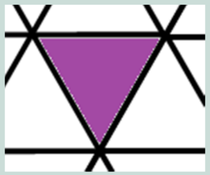
  Guide tube diameter. (**12.663e-3 m**)

  Instrumentation rod diameter. (**11.256e-3 m**)

- Any number of rods can be modelled.

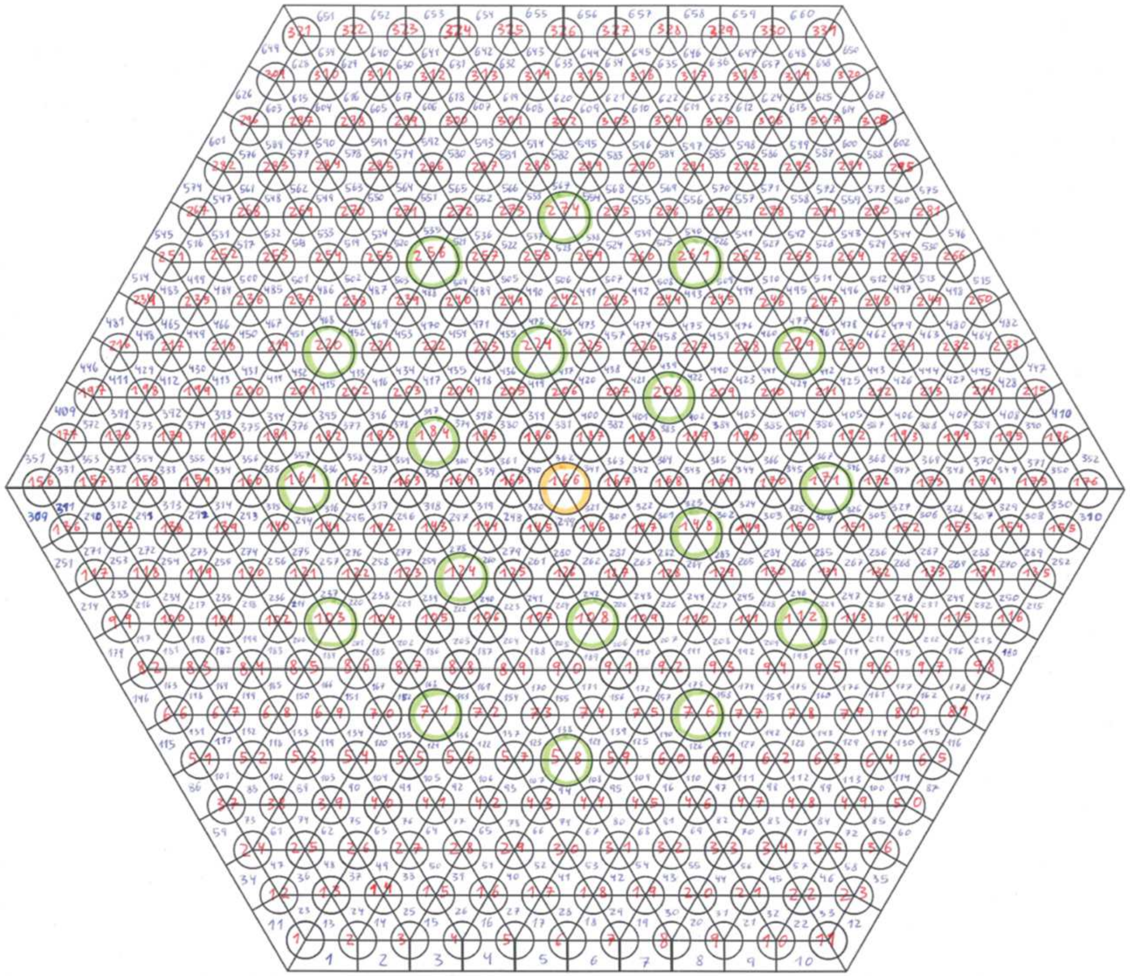


Hexagonal fine-mesh preprocessor (2)

Type (tchan)	Shape	Area	Wetted Perimeter	Heated Perimeter
1 Central subchannel		$pitch^2 \cdot \sqrt{3}/4 - 0.5 \cdot rod\_area$	0.5·rod_perimeter	0.5·rod_perimeter
2 Lateral subchannel		pitchb·pitch - 0.5·rod_area	0.5·rod_perimeter	0.5·rod_perimeter
3 Corner subchannel		$pitchb \cdot pitch + 0.5 \cdot pitchb^2 \cdot \tan(30) - rod\_area \cdot (7/12)$	rod_perimeter· (7/12)	rod_perimeter· (7/12)
4 Guide tube subchannel		$pitch^2 \cdot \sqrt{3}/4 - 1/3 \cdot rod\_area - 1/6 \cdot guideT\_area$	1/3·rod_perimeter+ 1/6·guideT_perimeter	1/3·rod_perimeter
5 Instrumentation rod subchannel		$pitch^2 \cdot \sqrt{3}/4 - 1/3 \cdot rod\_area - 1/6 \cdot InstR\_area$	1/3·rod_perimeter+ 1/6·InstR_perimeter	1/3·rod_perimeter

Hexagonal fine-mesh preprocessor (3)

- It is possible to mesh a single FA



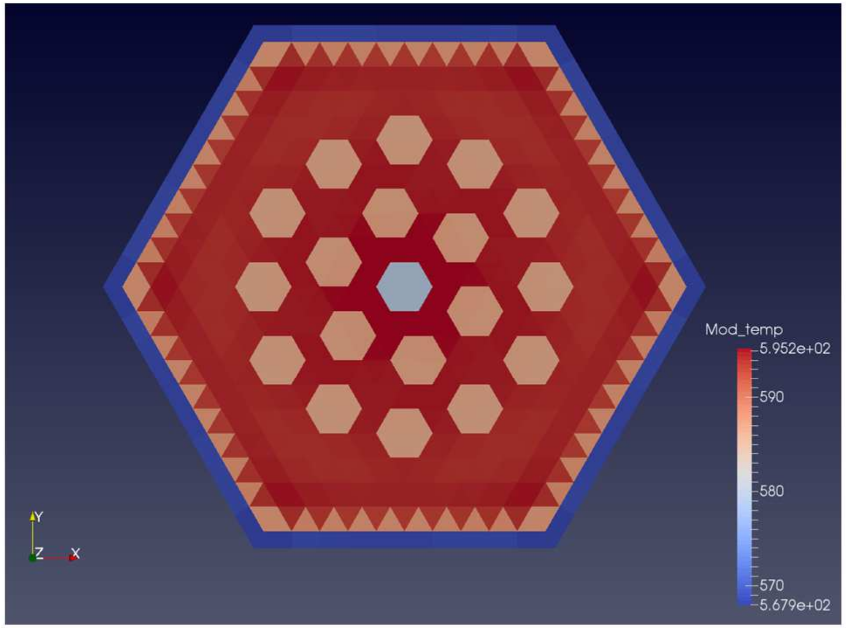
MESH DETAILS:
331 fuel rods
660 subchannels
990 gaps

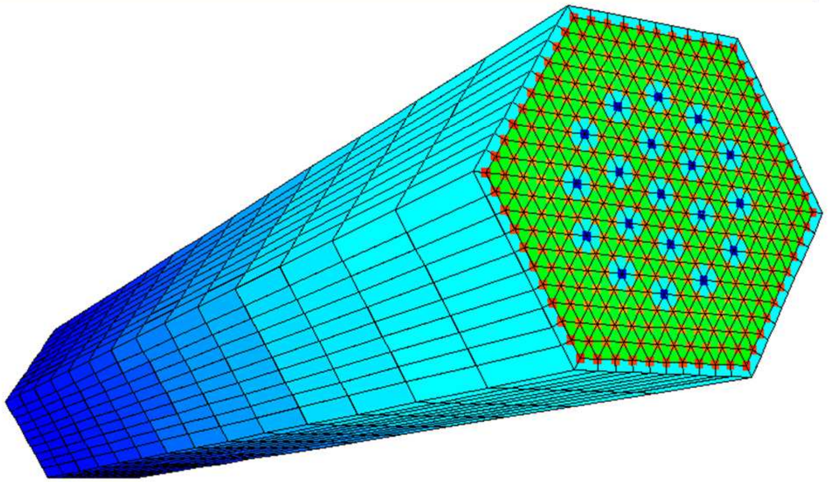
Hexagonal fine-mesh preprocessor (4)

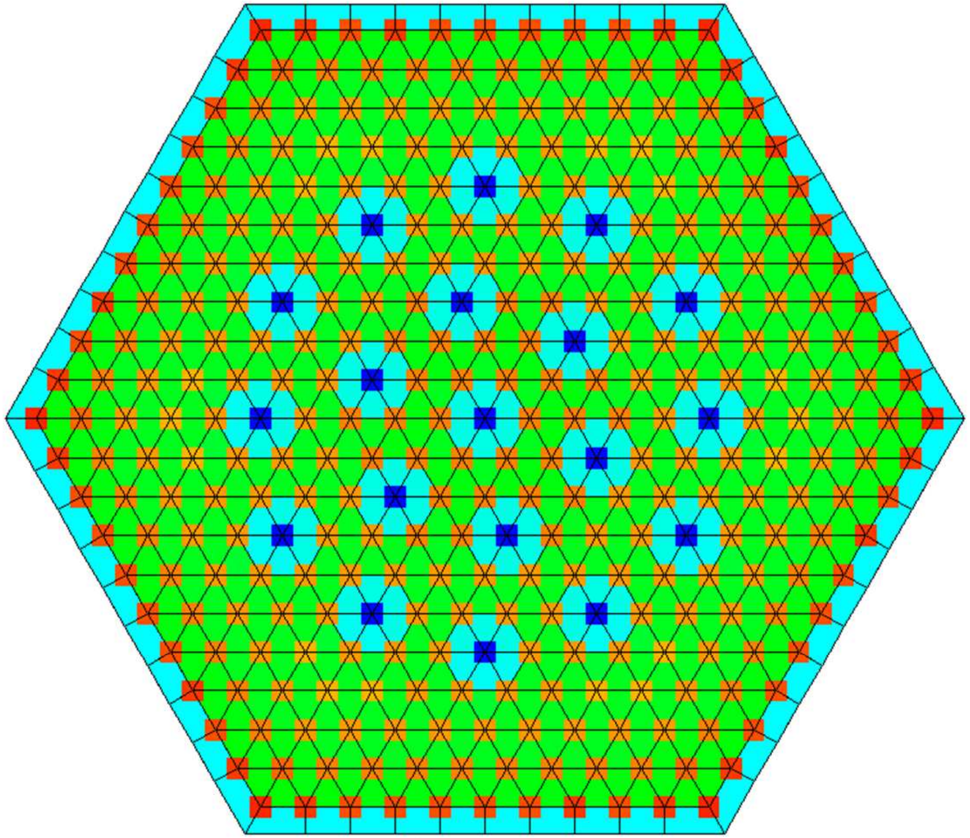
Karlsruher Institut für Technologie

- Within NURESAFE project, the preprocessor has been used to generate the geometry tables (channels and rods) of COBRA-TF (GRS) and SUBCHANFLOW (KIT).
- Some input decks (37 pins and 331 pins) have been generated.
- Using SUBCHANFLOW SALOME component, the MEDCoupling interface was extended for allowing:
  - Coupled NK-TH analysis.
  - Post-processing via PARAVIS. See next slide.

Thermal and fluid mesh visualization using SCF







SHOW VIDEO

Conclusions

- Development of a generic VVER FA preprocessor:
  - Suitable for COBRA-TF and SUBCHANFLOW
- The geometry information is also used within the code components under the SALOME platform (NURESAFE EU project).
- Extension to model mini-cores are subjected to future work.

Acknowledgements

- This work has been performed at the Institute for Neutron Physics and Reactor Technology (INR) of the Karlsruhe Institute of Technology (KIT).

THANKS FOR YOUR ATTENTION, QUESTIONS?

UPDATED KIT RESULTS FOR THE EXERCISE 2 OF KALININ3 BENCHMARK

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