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BWR MOX core monitoring at Kernkraftwerk Gundremmingen

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Abstract

The replacement of the core monitoring system for twin KWU Boiling Water Reactors (BWR) is presented. The reactors, Kernkraftwerk Gundremmingen B and C (KGG), are located in Germany. Core monitoring for KGG is more challenging than for most BWR reactors due to its core composition with about 30% MOX fuel assemblies.

The objectives of this paper are to discuss the specific MOX modelling aspects in CASMO-4/Simulate-3, the impact of the MOX fuel on several core monitoring aspects like the LPRM detector modelling and to present some core monitoring results since the beginning of GARDEL's operation.

The available core monitoring results confirm the accuracy of the underlying physical methods.

The core monitoring system replacement att KGG was a common project of Studsvik Scandpower and NIS Ingenieurgesellschaft GmbH, where Studsvik Scandpower supplied its standard core monitoring system GARDEL and NIS was responsible for the computer hardware, system integration and plant specific add-ons.

1. Introduction

KGG commissioned its earlier core monitoring system, KSIM, during 1994. KSIM's physical methods were based on a core simulator of an earlier generation, which made use of 1.5 neutronic groups solution.

After several years of KSIM operation, KGG recognized the need for replacing the underlying KSIM physical methods with proven, state-of-the-art methods, initiating an evaluation of the different alternatives available in the market.

Among the considered alternatives, KGG concluded that Studsvik Scandpower's GARDEL system would best fit to its needs because of the proven accuracy of the underlying methods, CASMO-4/Simulate-3[1], the available adaptive methods[2], as well as its graphical capabilities and

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the documented operational experience[3,4] with MOX cores.

1.1. *Kernkraftwerk Gundremmingen (KGG)*

KGG consists of two twin BWR units of KWU design containing 784 fuel assemblies. About 30% of the fuel assemblies contain MOX fuel.

TABLE 1 presents the general reactor parameters required for the KGG core model.

Table 1

General Reactor Specifications

Reactor characteristics	Value	Units
Core rated thermal power	3840	MWth
Core rated mass flow rate	14306	kg/s
Steam dome pressure	70.5	bar
Number of assemblies	784	
Number of control rods	193	
Number of movable detector channels (TIP)	44	
Number of fixed in-core detectors (LPRM)	176	

Figure 1 shows a quadrant of KGG unit B cycle 23's core indicating location of MOX fuel assemblies, control rods and movable detectors.

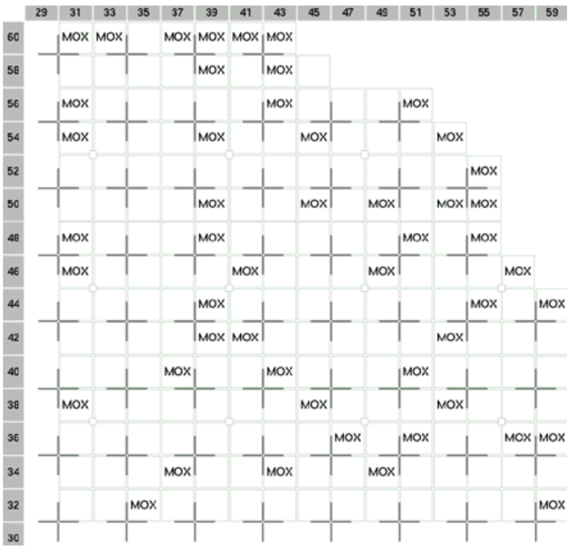

Fig. 1. Unit B core layout

Figure 2 shows the same quadrant of KGGC cycle 22's core.

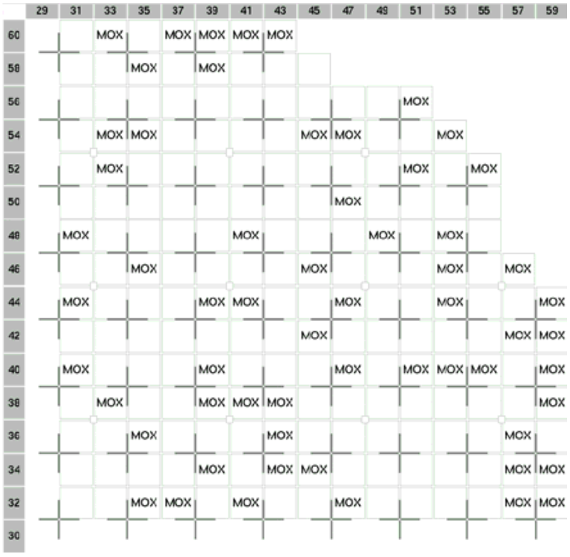

Fig. 2. Unit C core layout

1.2. *Parallel core monitoring period at KGG*

The new core monitoring system has been working in parallel to the previous core monitoring system since July 2007. In the following we concentrate on the results of the current cycles: unit B (cycle 23, start: July 2007) and unit C (cycle 23, start November 2007).

Since then, more than 15 TIP calibrations were performed; the units underwent a start-up each and experienced several power manoeuvres. The collected data will be used to support the licensing process of the new system.

2. CASMO/SIMULATE's MOX modeling

The SIMULATE-3 neutronics models in KGG's Gardel core monitoring system utilize a pre-generated data base of neutronics parameters. All neutronics parameters have been computed with single-assembly CASMO-4 (the lattice physics code in Studsvik's CMS) calculations using the physical data that uniquely describe each type of fuel assembly.

The tabulated neutronics database covers the full range of the isotopic depletion of the fuel, as well variations in the anticipated local properties (such as fuel temperature, average void, xenon concentrations, control rods, etc.). The neutronics model employed in SIMULATE-3 solves the three-dimensional, two-group neutron diffusion equations using the semi-analytic advanced nodal method (SANM).

Because of large spectrum differences between UO2 and MOX assemblies, SIMULATE-3 employs several instantaneous and historical spectral correction models to eliminate many of the inaccuracies of conventional two-group models. In addition, special models are employed to treat spatial transport effects at the MOX/UO2 interfaces -which cannot be modelled accurately using diffusion theory. SIMULATE-3 also tracks the intra-assembly shape of fuel burnup within each assembly using multidimensional fourth-order polynomials. Consequently, the SIMULATE-3 depletion model can accurately capture the effects of large spatial flux gradients and spectral mismatches on fuel burnup. Reconstruction of individual pin powers and burnups (required for monitoring of thermal margins) is achieved in SIMULATE-3 by a superposition of homogeneous intra-assembly power shapes and heterogeneous CASMO-4 pin-wise power distributions.

The SIMULATE-3 thermal-hydraulic model employs one radial node per fuel assembly and 25 axial planes. Active channel and bypass channel flow splits are computed using a detailed water rod, bypass, and channel flow model. The parallel channel bundle thermal-hydraulics is modelled using the EPRI-Void drift flux correlation to convert nodal enthalpies into nodal void fractions.

3. The new-KSIM system with GARDEL

The modernization of the KSIM system at KGG consisted of the replacement of the physical methods with the CASMO/SIMULATE-based system GARDEL[5], while keeping unchanged other peripheral core monitoring computation methods like heat balance and decay heat calculations.

In addition to the Studsvik physics model, GARDEL includes a highly automated core physics model update throughout the cycle, triggered by monitoring changes of plant process computer signals. All data is archived in a database system.

GARDEL also includes a flexible configurable, graphical user interface as well as international language support. All data (both calculated parameters, as well as collected plants signals) are accessed via the user interface for analysis or via included automatic reporting functions, which simplifies the verification and validation of the system.

The on-line core monitoring calculations require an accurate modeling of the power distribution in the core -which is achieved by the underlying physical methods in GARDEL- and the reduction of remaining deviations by means of adaptive methods.

GARDEL simultaneously calculates purely predicted fuel thermal margins as well as two alternative sets of adaptive fuel thermal data. The first set of adaptive results is based on the prediction biased using detector comparison information from the latest movable detector measurement (TIP), the second set combines comparisons between measured and calculated TIP and fixed in-core (LPRM) detector data.

The adaptive methods assume that the relative local power density deviations are the same as the deviations between measured and calculated detector readings. Those local deviations are expanded geometrically to non-instrumented locations to obtain bias functions for the whole core[2].

Only one set of results is presented to the operator in the control room as official core monitoring data, while the other two sets are being used by the reactor physicists for an assessment of the accuracy of the results and for the decision, which adaption method to use as the official one.

A precondition for accurate thermal margin calculations based on TIP+LPRM adaption is an accurate modeling and calibration of the LPRM detectors. The use of MOX fuel implied some challenges in this respect, since the traditional BWR methodology of assuming that gamma TIP signals are proportional to power density in the detector neighborhood loses validity; the ratio of gamma flux to power density differs significantly in the neighborhood of MOX fuel from the ratio in core regions dominated by UO2 fuel.

4. Core monitoring results

The parallel core monitoring period at Gundremmingen has been used to demonstrate GARDEL's accurate calculation of core thermal margins. Of particular interest during the parallel operation period was the assessment of GARDEL's capability to properly model MOX fuel assemblies.

4.1. Start-up measurements

Given GARDEL's capability to monitor core conditions also during reactor start-ups, the reactor engineers were able to trigger SIMULATE calculations at the moment of cold critical measurements, saving the results for later analysis. Figure 3 shows some of the critical measurements recorded by GARDEL during KGGB cycle 23's start-up.

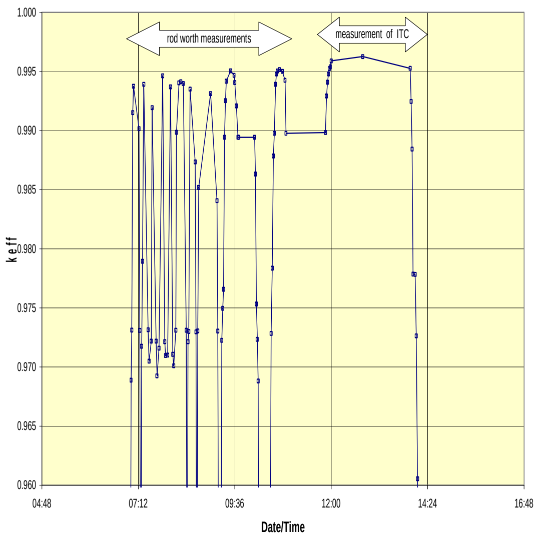

Fig. 3. Unit B, cycle 23: start-up measurements

The cold critical measurements can be subdivided into two phases: In the first phase the shutdown margin and several control rod's worth are measured. In the second phase the isothermal temperature coefficient (ITC) is measured. During this phase the reactor is critical and is heated up with very low power (<1%) from ~20°C to ~80°C. It can be seen, that Gardel correctly tracks the rod movement events and shows a low dispersion in the reactivity peaks around a cold critical k_{eff} near to 0.99350.

4.2. Core monitoring global accuracy

The accumulated operational experience has shown that GARDEL's LPRM+TIP adaptive method provides reliable core thermal margin results during the whole cycle, also several weeks after the latest TIP calibration. Figures 4 and 5 show whole cycle MFLCPR and MFLPD trends for unit B, cycle 23, comparing the purely predictive results with those biased with the latest TIP measurement data and those biased with TIP + LPRM data. The three MFLCPR curves basically fall on top of each other apart from a short period of time in November 2007 during which a drifting LPRM affected the quality of the results. The MFLPD comparisons show differences of up to 4% between the purely predictive and the adaptive results. However, the two adaptive methods agree within 2% during the whole cycle.

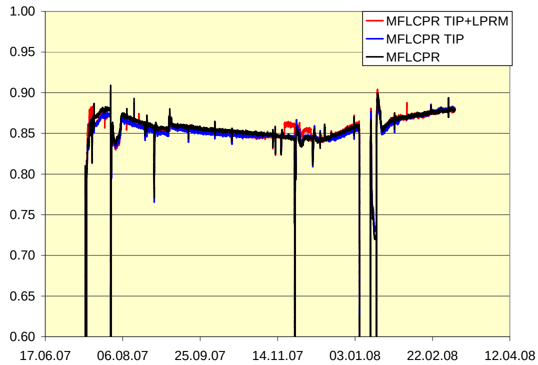

Fig. 4: Unit B, cycle 23:MFLCPR comparison

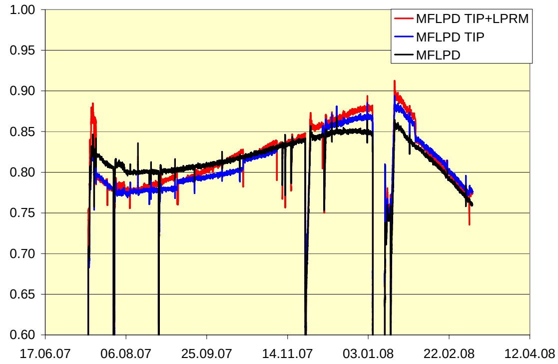

Fig. 5: Unit B, cycle 23: MFLPD comparison

Figure 6 shows the functionality of the adaption methods during a TIP measurement: the un-adapted

MFLPD value, which is the direct result of the Simulate-3 calculation does not change at all, as the reactor conditions are stable. After the TIP measurement a new adaptive data base is generated for the TIP as well as for the LPRM adaption forcing the LPRM adapted MFLPD to match the newly “measured” value. Typically, TIP calibrations modify the adaptive MFLPD between 1 and 2%.

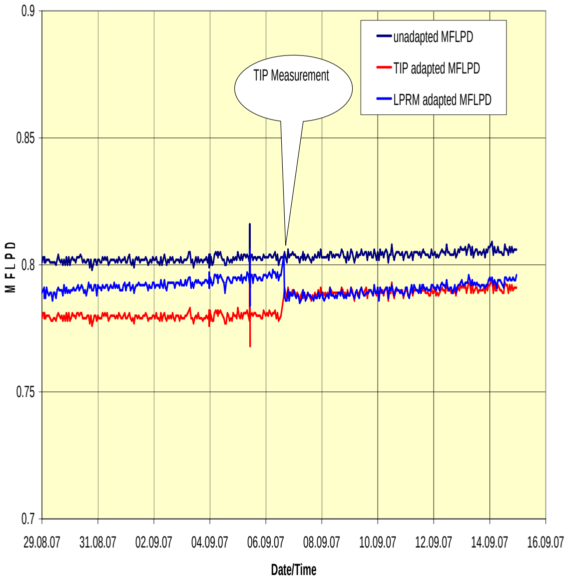

Fig. 6: Unit B, cycle 23: Influence of Adaption on MFLPD

4.3. *Local core monitoring results*

Gundremmingen presently relies for core surveillance on the thermal margins evaluated applying a TIP bias only. However, as already discussed, GARDEL supports an additional adaptive level, which makes use of the calibrated LPRM readings to bias the power distributions. A precondition for the accuracy of this adaptive method is the access to accurate and reliable calibrated LPRM readings.

Although the global results show satisfactory accuracy, important local deviations may still occur in core locations with power densities below the core maximum. In order to assess the quality of the results throughout the core, GARDEL performs a continuous evaluation of a so-called LPRM difference distribution, defined as the difference between current and at latest TIP calibration of Calculated to Calibrated LPRM readings.

Deviations in individual locations indicate either problems in the detector itself or modelling inaccuracies. Overall deviations would indicate the necessity of performing a new TIP calibration.

Figure 7 shows unit B’s relative power level during cycle 23 together with the LPRM r.m.s. differences and its maximum absolute value. The LPRM r.m.s. differences were systematically below 2% with the exception of some fast power manoeuvres during which the r.m.s. differences would grow to about 3.5%. However, the maximum differences in the core show fast increments several times during the cycle. One of those increments lays behind the step change in the MFLCPR TIP+LPRM values observed around November 19, 2007, c.f. Figure 4.

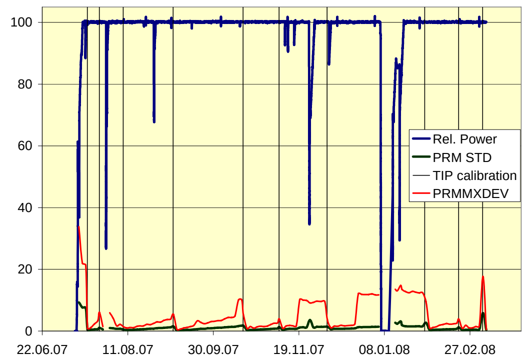

Fig. 7: Unit B, cycle 23: Relative power, LPRM differences’ maximum and r.m.s. values

The fast changes difference increments in Figure 7 could be traced to one particular drifting LPRM detector. The detector signal experienced stepwise changes several times during the cycle, as shown by the blue curve in figure 8. The red curve shows the maximum absolute LPRM differences in the core.

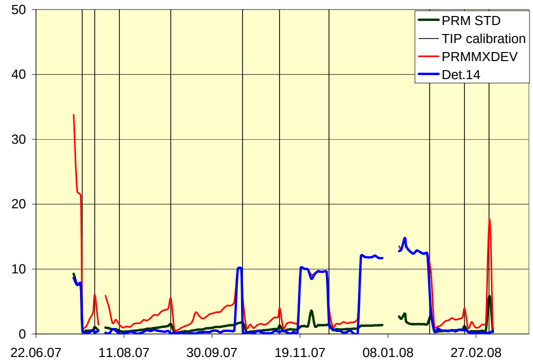

Fig. 8: Unit B, cycle 23: Drifting LPRM detector

Unit C, however, has not shown any unexpected behaviour, as shown by Figure 9.

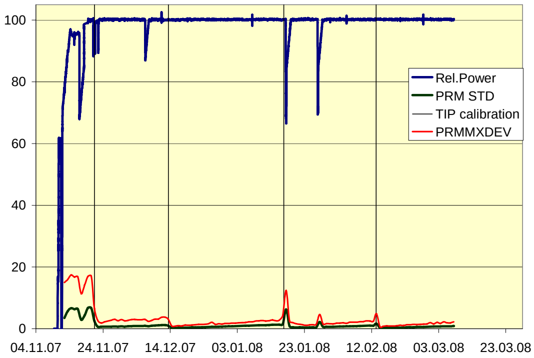

Fig. 9: Unit C, cycle 22: Relative power, LPRM differences' maximum and r.m.s. values

Detailed analysis of individual detectors did not show any particular differences due to the influence of neighbouring MOX fuel assemblies. The same applies to TIP calibration calculations. Figure 10 shows in red TIP channels with ratios measured/calculated TIP signals > 1.02, in blue ratios below 0.98 and in green all those in the range 0.98 to 1.02. The red and blue locations are scattered across the core independently from the surrounding fuel types.

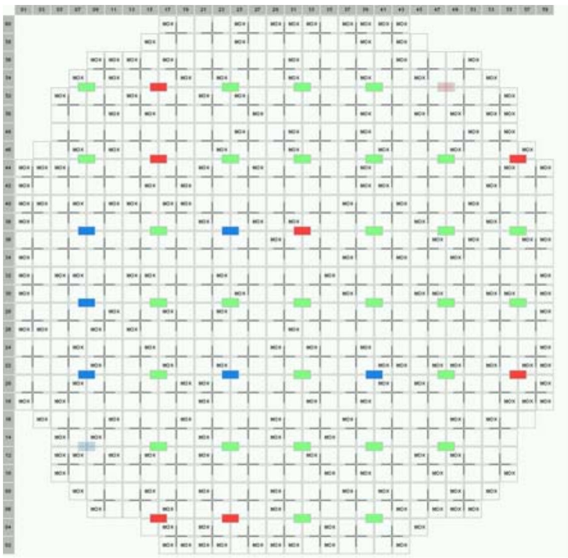

Fig. 10: Unit B, MOC23: TIP ratios

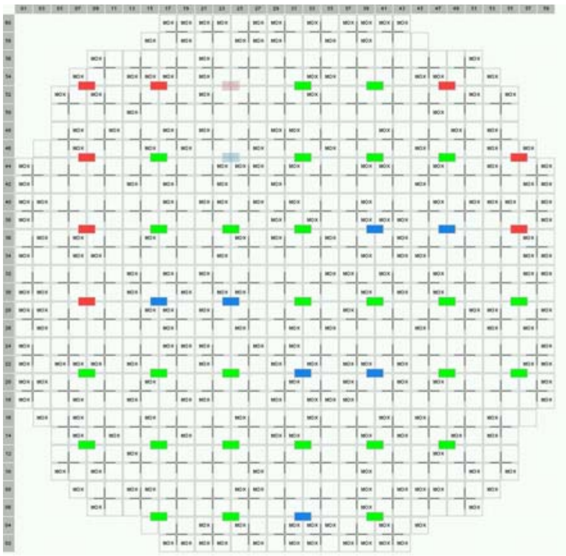

Fig. 11: Unit C, MOC22: TIP ratios

5. Conclusions

The accumulated operational experience with GARDEL at Gundremmingen shows that the system is providing accurate and reliable thermal margins data. Should the system had been in use as official core monitoring system already during Cycle 22 at unit B, it would have warned the control room personnel of the abnormal behaviour of one particular LPRM detector, giving them the possibility of excluding it from further calculations and eliminating the MFLCPR changes observed around November 19, 2007.

There is however room for improvement -and further accuracy gains- in some areas.

Though the measured vs. predicted radial TIP comparisons are excellent (radial r.m.s of 1.3% (unit B) and 1.6% (unit C), some systematic axial deviations can be observed, as illustrated in figure 12.

This figure presents the ratio measured/calculated TIP readings as a function of the core height for all available TIP measurements during cycle 23 of unit B. The thick dashed line shows the BOC TIP comparison.

The systematic under predictions at the bottom of the core seem to indicate inaccuracies in the modelling of the reflector or the thermal-hydraulics. Besides the systematic problems at the core bottom, the analysis shows an over prediction of the bottom peak at BOC, which gradually diminishes to change signs to an over prediction from MOC.

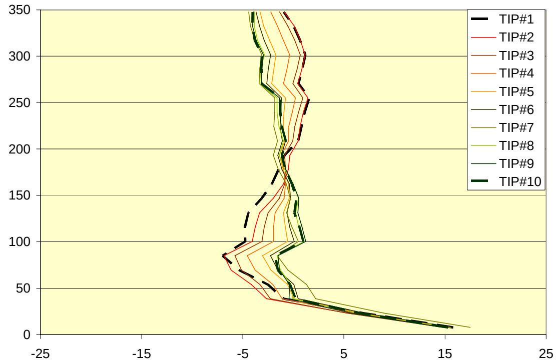

Fig. 12: Unit B, cycle 23: axial TIP differences

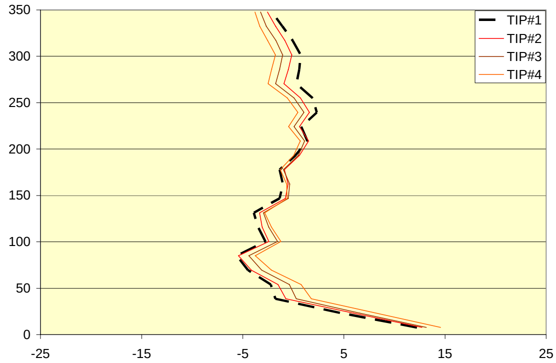

Fig. 13: Unit C, cycle 22: axial TIP differences

In addition, in some cases the LPRM differences grow due to depletion effects up to 1% in between TIP calibrations as shown by the next two figures (red: detector near MOX fuel, blue: detector near UO2 fuel)

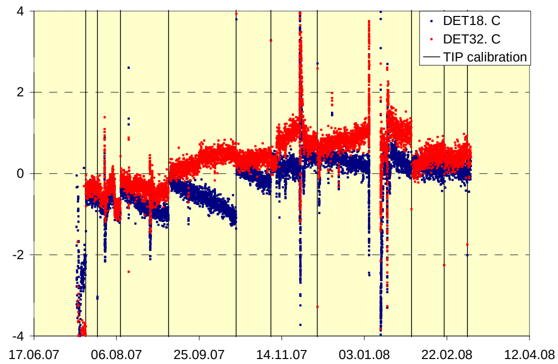

Fig. 14: Unit B, cycle 23: detailed tracking of individual detectors

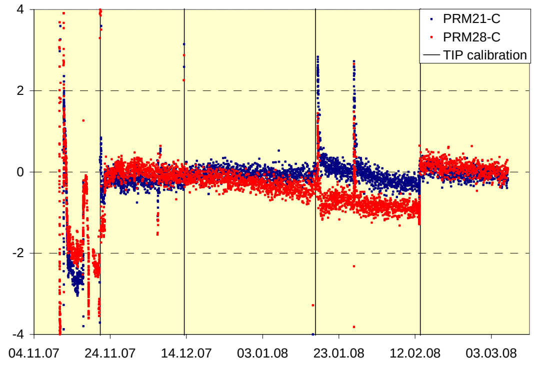

Fig. 15: Unit C, cycle 22: detailed tracking of individual detectors

We intend to investigate these effects more systematically, as they may indicate some weakness in the vendor defined LPRM burnup dependent sensitivity model.

Acknowledgement

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