ANALYSIS OF THE JSI TRIGA PULSE EXPERIMENTS

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ABSTRACT

Systematic statistical analysis of all 289 pulse experiments and measurements performed in 26 years of pulse operation of the TRIGA Mark II research reactor at the Jožef Stefan Institute is presented. Dependence of pulse experimental parameters (Pulse peak power, energy released and FWHM) on the inserted reactivity was analysed. The results are in relatively good agreement with the predictions of the adiabatic Fuchs-Hansen model. The sources of uncertainties in inserted reactivity are explained and investigated. Sensitivity study of uncertainties in Fuchs-Hansen model is performed where high relative uncertainties arise below 1.5 $. Clear dependence of pulse parameters on the number of fuel elements in the reactor core is observed. Pulse parameters (FWHM, P_{max}, E_{tot}, T_{max}, P(t), T(t), inserted reactivity, control rod calibration, core configuration schematic) for all pulses are compiled in the pulse experimental database. The database is publicly available at the JSI TRIGA webpage.

1. Introduction

In 1991, a major reconstruction of the TRIGA Mark II reactor at the Jožef Stefan Institute (JSI) in Ljubljana was performed which also included the upgrade of the reactor to the pulse operation. After the reconstruction several experiments were performed, first in steady state and in the pulse mode of operation. All experiments were performed with a fresh, compact, homogeneous core and at well-known operating conditions. The experimental results were used for benchmarking of steady-state [1] and pulse mode [2] operation. In the latter only the first set (14 pulses) of pulse operation was analysed. Since then 275 pulses were performed on different core configurations. Together with complete steady-state reactor operation analysis [3], a pulse benchmark database can be constructed for further pulse operation studies and validation of improved Fuchs-Hansen models as well as pulse simulations with deterministic or stochastic neutron transport codes. This paper presents the pulse experimental database, presented in the last section, which contains information of every pulse performed in the history of TRIGA operation; i.e. such as the energy released, maximum power, fuel temperature and full width at half maximum (FWHM) of the pulse. In addition control rod calibration curves and their positions are provided as well.

The presented database can be of help in validation of computer codes, as well as predictions of operational parameters for TRIGA reactors. It is one part of the complete analysis of operation history, where all parameters and notes performed in 50 years of operation will be digitalized and prepared for further analysis. The pulse experiments are interesting, because high powers, not possible in a research reactors are achieved and therefore high pulses of flux reaching up to $10^{16}\ {}^{1}/_{cm^2 s}$. This pulses lasts only couple of milliseconds, therefore low power pulses should be used with higher uncertainties. This paper provides the explanation into the discrepancies with a complete analysis of all pulses performed in the history of the JSI TRIGA.

2. Pulse parameter analysis

In the JSI TRIGA reactor the pulse is performed by quickly ($\approx$ 10 ms) ejecting transient (pulse) control rod from fully inserted (subcritical or critical core) position to a pre-set position that determines inserted reactivity, leading to prompt supercritical power excursion ($P_{max} \leq 1$ GW). TRIGA reactors can be safely operated in pulse mode, due to the homogeneous fuel mixture of uranium and hydrogen; therefore featuring a prompt negative reactivity coefficient. At the JSI TRIGA reactor, pulse mode operation is mainly used for demonstration purposes, practical exercises for students and for validation of computational codes and models. This allows the study of pulse parameter dependence on the inserted reactivity (e.g. with the adiabatic Fuchs-Hansen pulse model [4]).

In a pulse mode operation, a pulse detector channel (uncompensated ion chamber) is used for measuring reactor power. All pulses (neutron detector signal versus time) are automatically recorded on a processing computer for off-line analysis with a sampling rate of 20 kHz. The position of the pulse channel detector is shown in Fig. 1. During the pulse automatic data logging of the following quantities is provided: pulse power and integrated power for the pulse channel, fuel temperature from two temperature measuring channels connected to fuel elements with a thermocouple inside, and water temperature in the reactor tank.

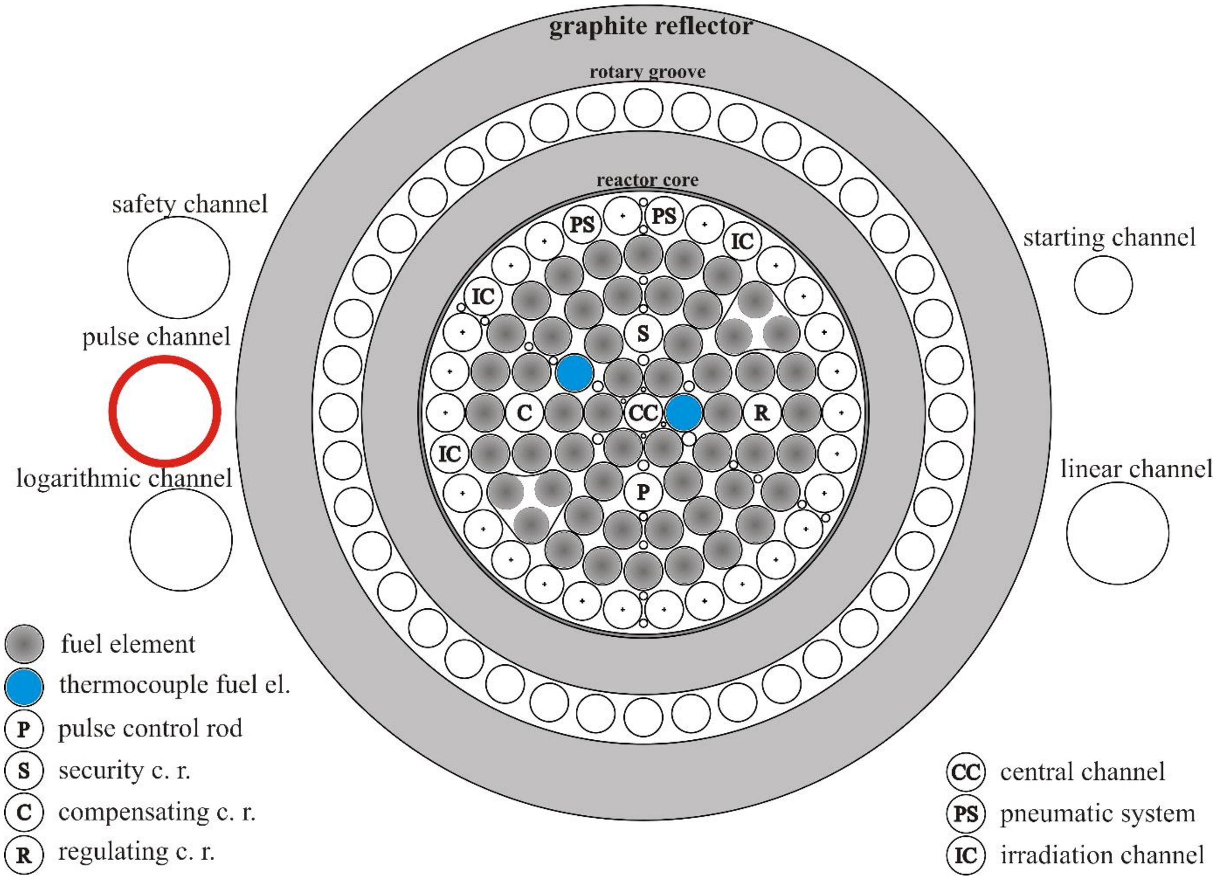

Fig 1. Schematic diagram of the TRIGA reactor core, rotary groove and graphite reflector with the locations of power signal detectors. Fuel element configuration for cycle No. 215 is presented, which operated from 3.11.2014 until 11.11.2014. During this period 22 pulse experiments were performed using only standard fuel elements with 12 wt% of 20% enriched uranium. The schematic was adapted from [5].

From the acquired digitalized pulse signal the peak power, energy released and the pulse full width half maximum (FWHM) are determined and included in the database. Pulse signals for 7 different inserted reactivities ρ_i are presented in Fig. 2, where a typical shape of the reactor power during a pulse is presented. For pulse experiment study we define prompt reactivity ρ_p

$$\rho_p = \rho_i - \beta,$$

where ρ_i is the inserted reactivity and β is the delayed neutron fraction and was measured to be:

$$1\,\$ = \beta = 0.73\ (1\ \pm 0.05)\ \%\frac{\Delta k}{k} = 730\ (1\ \pm 0.05)\ pcm, [6,7,8].$$

Energy deposited in the fuel elements and other reactor components is defined as the area (integral) under the power versus time signal curve, which was determined with numerical square and trapezoidal integration. Both methods provided results that varied from each other for less than 0.1 %. Integration borders were set to be 1 % of the pulse peak power. The results comply with the measurements of energy generated during the latest pulses, therefore the integration method was used to analyse all of the 289 pulses. FWHM of a pulse is defined as the full width of a pulse at the half of its peak power. Pulse experiments where the inserted reactivity ρ_i is under 1.5 \$ are inadequate for analysis, because background noise in the pulse channel is larger than the actual pulse signal.

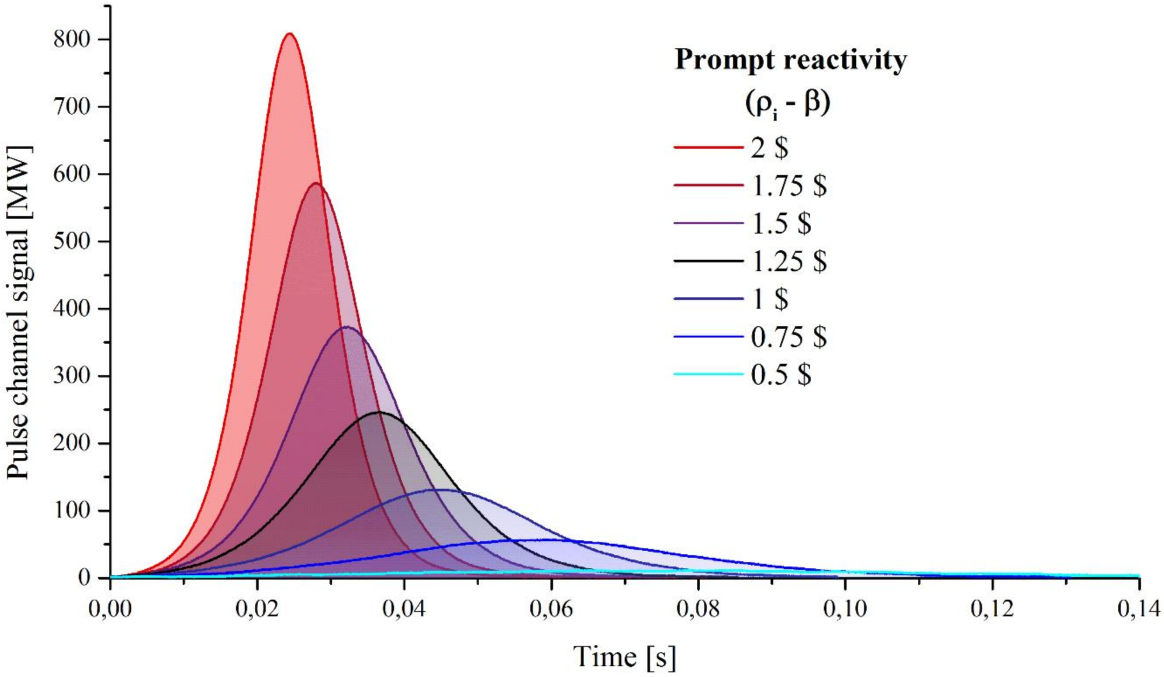

Fig 2. Reactor power during a pulse experiment as a function of time from the beginning of the power rise. Pulses are indicated by prompt reactivity ranging from 2 \$ to 0.5 \$. The area under the pulse curve directly represents deposited energy used in the analysis.

2.1 Reproducibility of the pulse

Taking all pulse experiments into consideration the statistical study of pulses performed at (presumably) same transient rod positions and prompt reactivity can be made. Statistical analysis of pulse peak power, energy and FWHM for typical prompt reactivities is presented in Tab. 1. The theoretical relation between prompt reactivity and pulse parameters derived from the adiabatic Fuchs-Hansen model are presented below

$$P_{max} = \frac{\rho_p^2}{2\gamma\Lambda} \qquad E_{tot} = \frac{\rho_p}{\gamma} \qquad FWHM \ \propto \ \frac{1}{\rho_p},$$

where γ is the effective fuel temperature reactivity coefficient and Λ average neutron generation time. The P_{max}, E_{tot}, and FWHM are each proportional to prompt reactivity, its square and inverse, respectively, according to Fuchs-Hansen model and are presented on Fig. 3 and 4, respectively.

Tab 1. Statistical values for pulse peak power, energy generated and its full width half maximum (FWHM) at different prompt reactivities.

ρ_p [$]	Peak Power P_{max} [MW]			Pulse Energy E_{tot} [MWs]			FWHM [ms]		
	Average	1 σ	Median	Average	1 σ	Median	Average	1 σ	Median
0.5	57.2	32.8	61.8	2.3	2.0	2.3	54.5	13.5	43.5
0.75	109.8	63.9	72.3	3.0	1.3	2.8	44.4	13.7	46.7
1	265.7	101.3	280.0	6.3	2.3	6.3	25.0	4.6	21.7
1.25	423.6	115.4	490.9	7.4	1.6	7.5	19.0	3.7	16.4
1.5	576.6	199.1	593.0	9.1	2.3	7.9	16.3	2.5	16.6
1.75	730.2	130.3	718.0	10.1	1.7	10.8	13.6	1.4	14.1
2	899.1	74.2	897.0	12.2	1.1	12.0	12.5	0.4	12.8

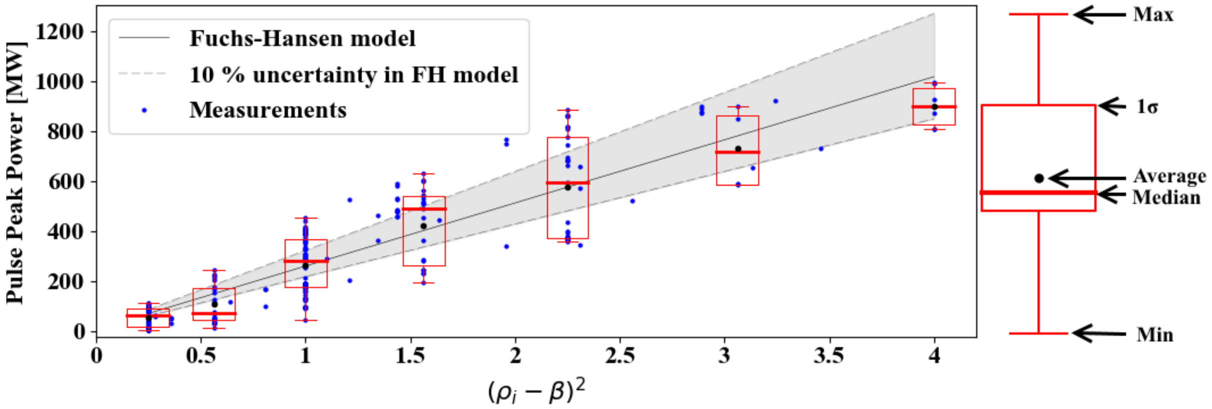

Fig 3. Statistical values for pulse peak power, energy generated and its full width half maximum (FWHM) at different prompt reactivities.

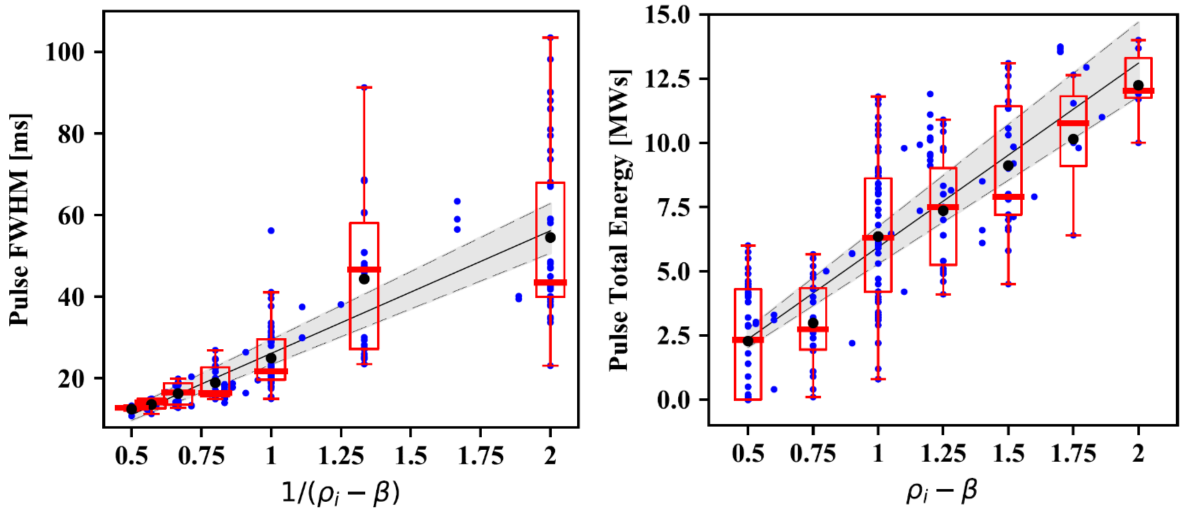

Fig 4. Statistical values for pulse peak energy (left) and its full width half maximum (FWHM) (right) as a function of prompt reactivity, taking into account the 10 % uncertainty in prompt reactivity.

It can be observed in figures that the average values of pulse parameters are in agreement with the Fuchs-Hansen model predictions, however discrepancies in reproducibility of pulses are also evident. These discrepancies are due to uncertainties in control rod calibration curves, approximations made in the Fuchs-Hansen model itself, where instantaneous rod extraction is approximated and the uncertainties in nuclear data [7]. A study was done, where actual rod extraction time was taken into consideration, where differences up to 2 % between the prompt reactivity with and without the rod extraction time were demonstrated [11]. For this analysis uncertainties in prompt reactivities were set to 10 %, represented by Fig. 3, 4a, 4b, 6. By increasing the prompt reactivity the uncertainties in FWHM decrease, which is expected and can be observed in Fig. 2. In order to analyse experimental and calculation uncertainties the pulse experimental database includes other parameters, such as core configuration, fuel element burnup, fuel temperature and control rod worth curves.

2.2 Uncertainties in inserted reactivity

Peak power, energy released and FWHM of a pulse are directly related to the prompt reactivity ρ_p of the reactor core. Therefore it is essential to accurately estimate excess reactivity of the core and the inserted reactivity, which is determined from a rod worth calibration curve of the transient rod. Most notable uncertainties in the inserted reactivity and the Fuchs-Hansen model are presented in Tab. 2 and shown as a band in the Fuchs-Hansen model. Two different methods for control rod worth measurements were used. The well known *rod-exchange* (also known as rod-swap) that can be used as a relative or absolute method by measuring the rod worth relative to a previously calibrated control rod or the reactivity changes due to control rod movement that are calculated from the asymptotic period by the doubling time method. The second so-called rod-insertion method has been developed for research reactors and was later applied to power reactors [9] [10]. Transient and other three control rod worth measurements were performed before each set of pulse experiments and are included in the pulse database, which also includes the position of each control rod when the pulse was performed. The rod insertion method was used for all pulse experiments, except the first 14 for which the rod exchange method was used. The rod calibration itself depends on xenon poisoning of the core, control rod burnup and most importantly the type, number and the position of fuel elements in the reactor core. The other main source in the inserted reactivity determination is the uncertainty in reactor kinetic parameters, such as delayed neutron fraction β.

Tab 2. Statistical values for pulse peak power, energy generated and its full width half maximum (FWHM) at different prompt reactivities.

Uncertainty origin	**Approximated uncertainty value**
Rod-insertion method [9] [10]	3 %
Reactor kinetic parameters [6] [7] [8]	5 %
Instantaneous rod extraction approximation [11]	2 %
	10 %

2.3 Sensitivity study of Fuchs-Hansen parameters

Taking into account the definition of prompt reactivity ρ_p we can write the equation for P_{max}, according to Fuchs-Hansen model into form with inserted reactivity ρ_i and delayed neutron fraction β

$$P_{max} = \frac{{\rho_i}^2 - 2\rho_i\beta + \beta^2}{2\gamma l(1-\rho_i)},$$

here l is the average prompt neutron generation time and $\Lambda = {}^{l}/_{k}$, where k in the multiplication factor. Taking into account that every single parameter has its own uncertainty we can derive the equation for complete uncertainty of P_{max}

$$\sigma_{max} = \sqrt{\left(\frac{\sigma_{\rho_i}\left(\rho(2-\rho_i\,) - \beta(2-\beta)\right)}{2\gamma l(1-\rho_i\,)^2}\right)^2 + \left(\sigma_\beta \frac{\beta-\rho_i}{\gamma l(1-\rho_i)}\right)^2 + \left(\sigma_l^2 + \sigma_\gamma^2\right)\left(\frac{-\beta^2 + 2\rho_i\beta - \rho_i^2}{2\gamma l^2(1-\rho_i)}\right)^2}\,.$$

The graphical representation of the mentioned equation is presented on Fig. 5 taking into account 10 % uncertainty in each of the parameter.

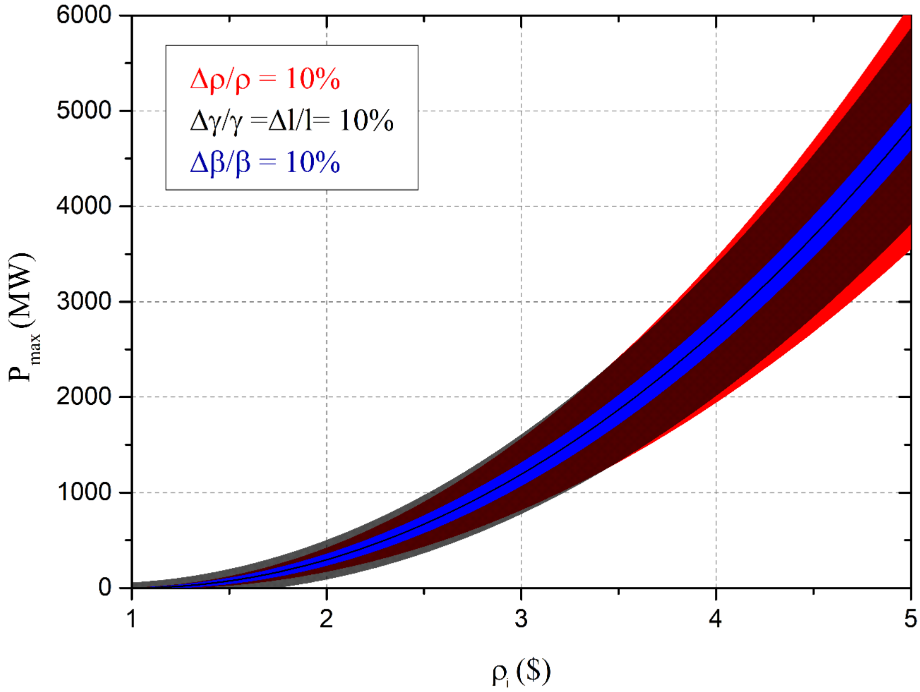

Fig 5. Sensitivity study of Fuchs-Hansen uncertainty in P_{max} for 10 % uncertainty in each of the parameter.

It is evident that largest contribution to the uncertainty of P_{max} according to the Fuchs-Hansen model is in inserted reactivity. From this we can conclude that analysis of control rod worth and consequently the determination control rod position is of most importance. More information can be extracted from this analysis if relative uncertainty of P_{max} normalized by the uncertainty of analysed F-H parameter is plotted with respect to inserted reactivity, as shown on Fig 6. The analysis confirms the decision to neglect the pulse experiments performed with inserted reactivity lower than 1.5 $.

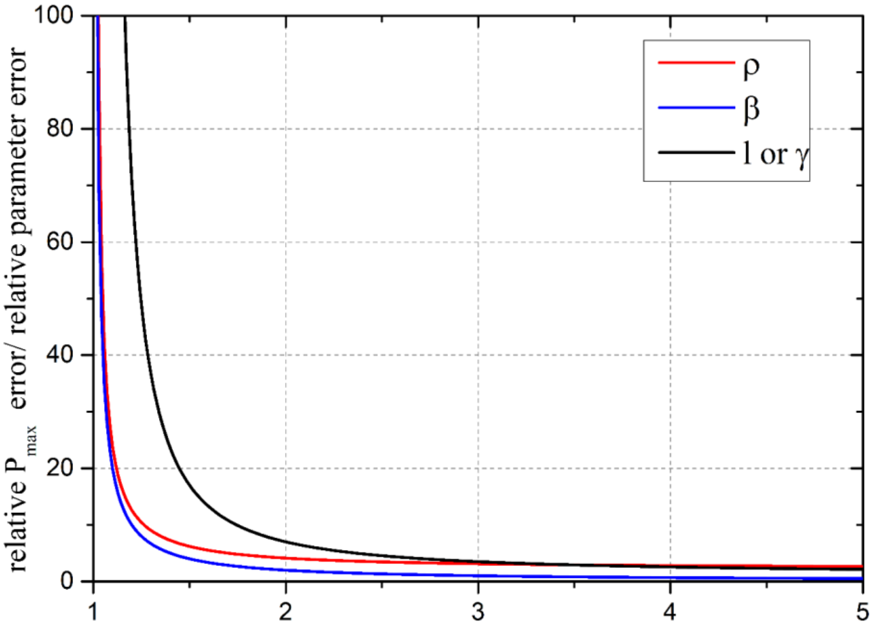

Fig 6. Sensitivity study of Fuchs-Hansen relative P_{max} uncertainty normalized by the uncertainty of F-H parameter as a function of inserted reactivity.

2.4 Fuel element configuration in the reactor core

The majority of sets of pulse experiments were performed on unique fuel element configurations in the reactor core. Schematics of all reactor core configurations are included in the pulse experimental database. Due to long steady-state operation between sets of pulse experiments, the isotopic composition of each fuel element at a given time is also included in the database. The isotopic composition was calculated with the deterministic TRIGLAV diffusion code [12], which uses WIMS [13] for burnup calculations. Activities are going on to perform burnup calculations also by using stochastic Serpent burnup code [14]. The results of which will also be included in the database. With this the possibility of detailed analysis and pulse experiment re-creation with Monte Carlo codes is given.

Taking into account only number of fuel elements in the reactor core, core configurations can be divided into two groups presented in Fig.7. The number of fuel elements notably effects the peak power, energy released and FWHM of a pulse and its dependence on prompt reactivity. This is presented in Fig. 8, where all measurements of peak power at different prompt reactivity are divided into mentioned groups of different number of fuel elements in the reactor core. The difference between both groups can be explained by significant change in the total fuel mass and consequently significantly changed heat capacity of the core.

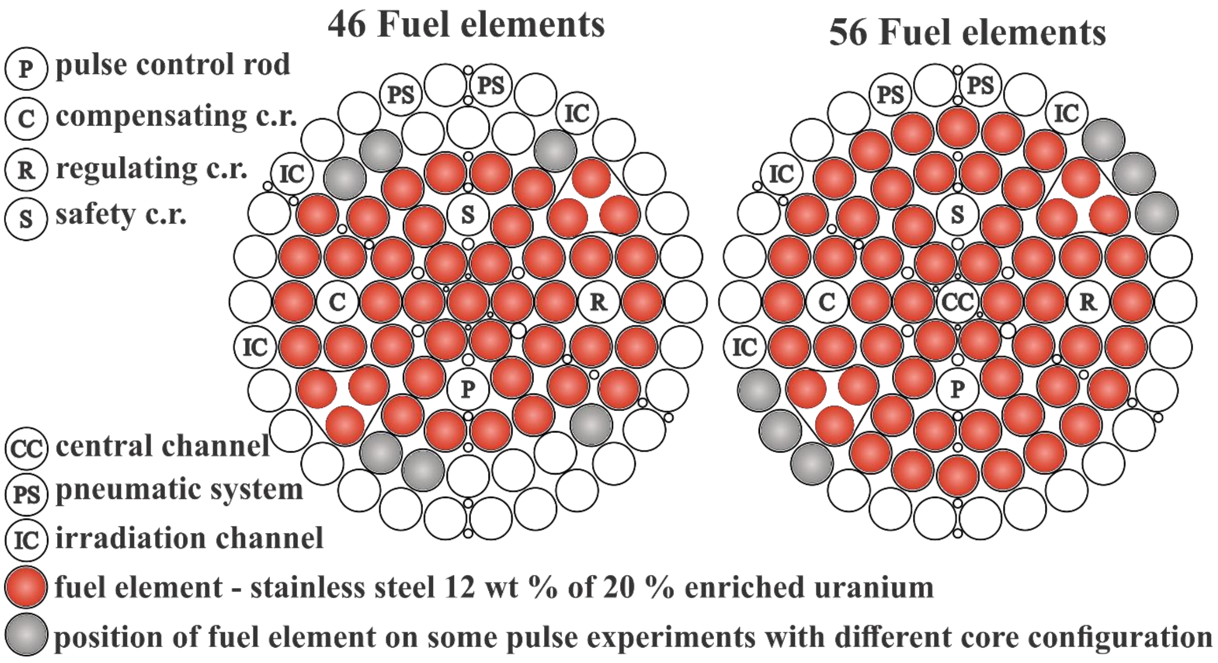

Fig 7. Schematic of the TRIGA pulse experiment reactor core with different numbers of fuel elements; 46(left) and 56(right). Fuel element positions depicted on the schematic represent a typical core configuration with defined number of fuel elements. It should be noted that the positions of fuel elements on some pulse experiment core configurations may be slightly different. These positions are denoted with colour grey.

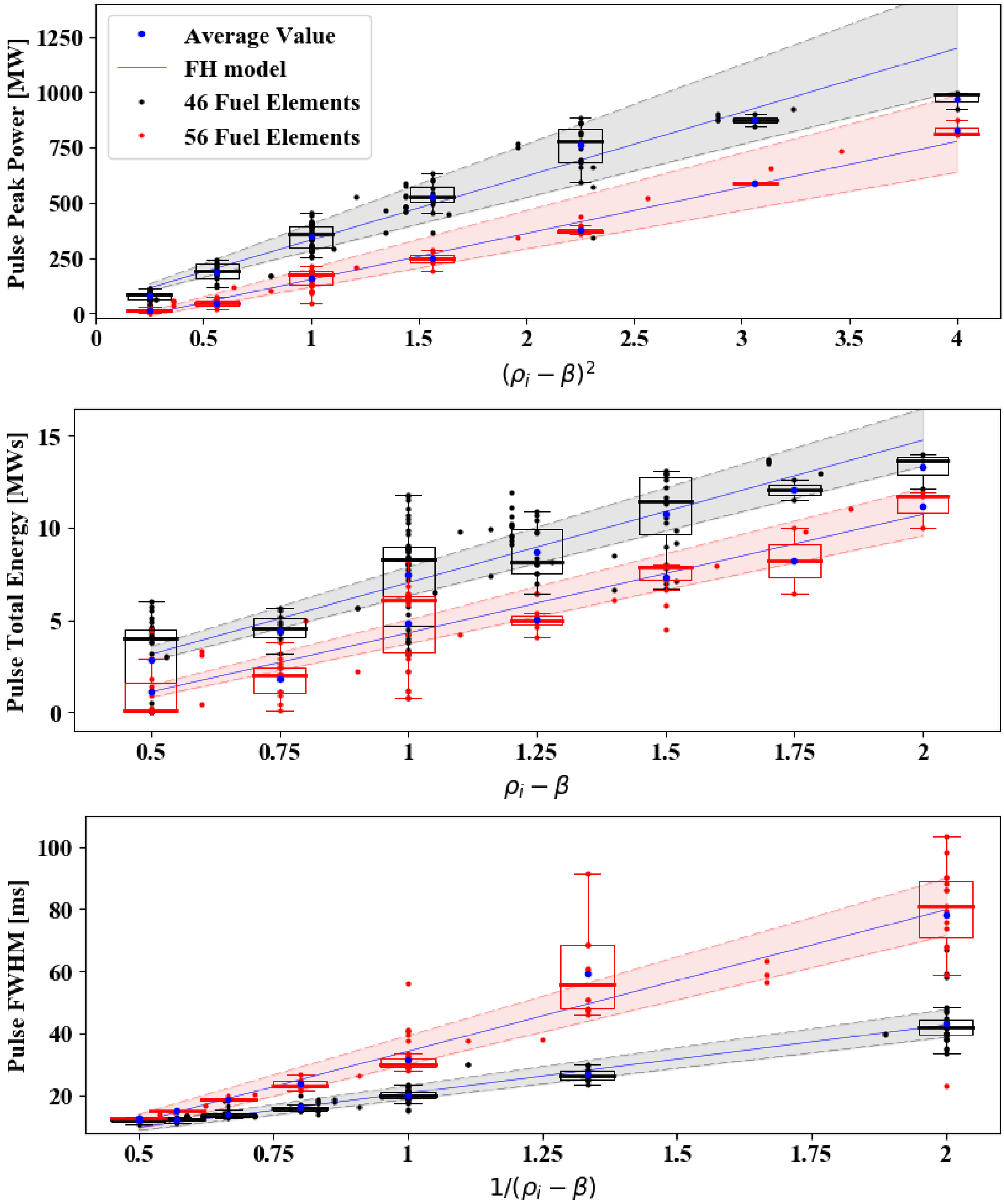

Fig 8. Pulse peak power, energy and Full Width Half Maximum as a function of prompt reactivity for two different numbers of fuel elements in the reactor core. Statistical analysis for most reproduced pulses is shown, with the linear fit of the Fuchs-Hansen model, taking into account the 10 % uncertainty in prompt reactivity.

2.5 Fuel Temperature

Fuel temperature is measured by K-type thermocouples located in two instrumented fuel elements. One was permanently located in the inner B ring while the other was relocated several times between A, B, C and D rings. Fuel temperature measurement versus time after rod ejection are presented in Fig. 9. The difference between the actual peak temperature in a fuel element and the measured maximal temperature must be noted, due to the heat conduction between the fuel element and the thermocouple. Therefore the actual maximum fuel temperature cannot be measured and a heat conduction model should be used to approximate the actual temperature in the center of the fuel element.

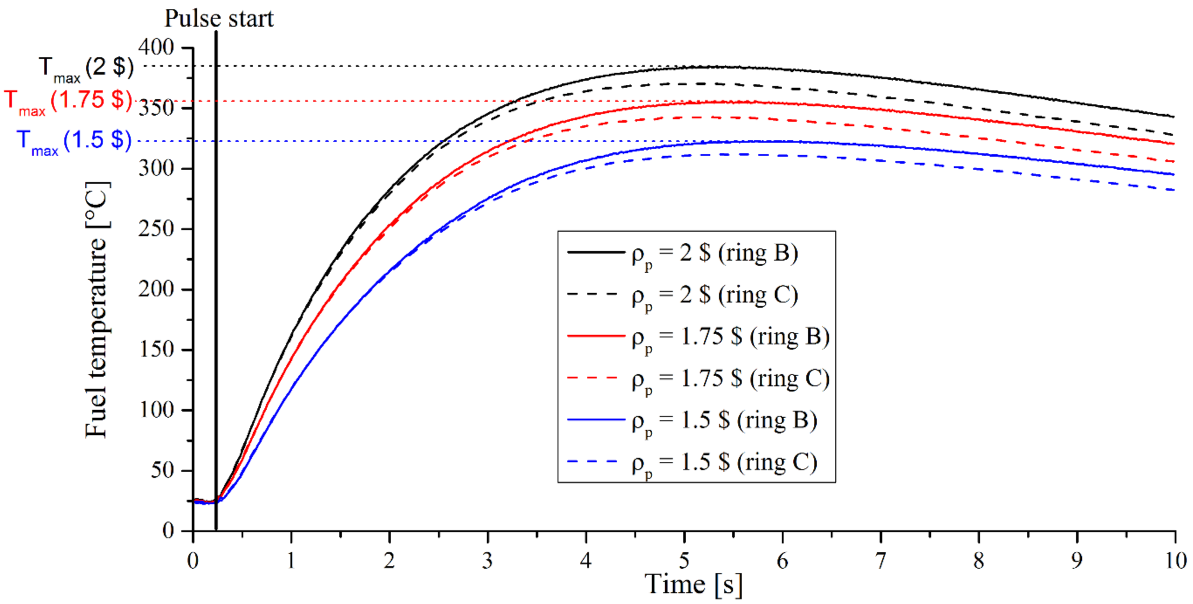

Fig 10. Fuel temperature measurements on both fuel elements instrumented with a thermocouple. Location of instrumented fuel elements is presented on Fig. 1. Measurements for three different prompt reactivities are presented.

3. Pulse experimental database

The analysis of pulse parameters demonstrates that taking all pulses into consideration at once gives rise to considerable uncertainties in peak power, energy and FWHM. To avoid this, sets of pulses on same cycle should be analysed individually, due to changes in reactor core parameters. Pulse experimental database provides the needed information to simulate or analyse each pulse separately.

The pulse experimental database contains the following data:

- **Inserted reactivity ρ_i**
- **Peak power**
- **Energy of a pulse**
- **FWHM**
- **Fuel temp. maximum**
- **Control rod calibration and position**
- **Core configuration schematic**
- **Fuel isotopic composition**
- **Power and temperature signals.**

4. Conclusion

Characteristics of all pulse experiments at the TRIGA Mark II at JSI after the reconstruction in 1991 are described. The results of pulse measurements like peak power, total energy and FWHM are analysed and compared to adiabatic Fuchs-Hansen pulse model, where good agreement is evident, despite the large uncertainties when all pulses were taken into consideration. The sources of uncertainties in inserted reactivity are explained and consist of uncertainties in rod-insertion control rod calibration method, instantaneous rod extraction approximation and reactor kinetic parameters. Sensitivity study of these uncertainties in the Fuchs-Hansen model is performed. Inserted reactivity parameter is the most important one. Pulse experiments below 1.5 $ of inserted reactivity were neglected and justified with relative uncertainties study in the Fuchs-Hansen model. In the future sets of pulses performed on the same reactor core configuration will be analysed separately to isolate the uncertainty in rod calibration curves. For the purpose of separate analysis on different core configurations, detailed pulse experimental database is presented, which provides the needed information to be proposed as a TRIGA benchmark test case for pulse mode analysis and simulations. Due to a high number of parameters extracted from the operational analysis, the database would be also useful for validation of Monte Carlo calculations of transients, a feature currently under development in the Serpent Monte Carlo neutron transport code [14]. The database is publicly available at http://trigapulse.ijs.si.

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