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Feasibility of Reactor Pulse Operation at the JSI TRIGA Reactor for Nuclear Instrumentation Detector Testing at Very High Neutron Flux Levels

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ABSTRACT

A vital phase in the development of nuclear instrumentation detectors and associated electronic data acquisition systems is experimental testing and qualification in a well-characterized and representative radiation field in a reference irradiation facility. The neutron flux levels in modern material testing reactors (MTRs) are in the range of 10^{14} – 10^{15} n cm^{-1} s^{-1}. However, the number of dedicated test facilities in Europe is currently decreasing, with numerous research reactors recently and soon-to-be shut down. The 250 kW JSI TRIGA reactor is a very well characterized reactor in terms of the knowledge of the neutron and gamma fields, a product of the work performed at the JSI over the last decade, mostly in collaboration with the Instrumentation, Sensors and Dosimetry Laboratory at CEA, Cadarache. Therefore it fulfils very well the first criterion for a reference facility. However, in steady state operation it is able to generate a maximum neutron flux level of around 2×10^{13} n cm^{-1} s^{-1}, i.e. several orders of magnitude lower than the MTR-relevant range. In steady-state mode the requirement of representativeness is therefore not fulfilled well. On the other hand, the JSI TRIGA reactor can operate in pulse mode, due to its prompt negative temperature coefficient of reactivity. Depending on the inserted reactivity, the peak power can reach up to 1 GW, the pulse duration is of the order of a few seconds (low and long pulses), to 5-10 milliseconds (high and short pulses). The neutron flux level is proportional to the reactor power level, therefore the highest attainable flux is nearly 10^{17} n cm^{-1} s^{-1}, albeit for a short amount of time. In 2019, a bilateral collaboration project between the CEA and JSI was initiated, to investigate the possibility of neutron flux measurements performed at very high neutron flux levels in reactor pulse operation, made possible by a modern, validated, wide dynamic range neutron acquisition system. The project aims at demonstrating the feasibility of nuclear instrumentation and associated electronic data acquisition system tests at the JSI TRIGA reactor at neutron flux levels relevant to MTRs. This paper presents the first measurements in reactor pulse operation, performed during an experimental testing campaign in collaboration with researchers from the CEA, as well as with colleagues from the Instrumentation Technologies (I-Tech) company, using a Keithley electrometer based acquisition system and an I-Tech-developed current meter. A more exhaustive experimental campaign is scheduled to be carried out at the JSI TRIGA reactor jointly by CEA and JSI researchers in the autumn of 2020.

1. INTRODUCTION

In the development of nuclear instrumentation detectors and associated electronic readout systems, testing activities are performed in reference neutron and gamma fields to characterize and qualify the system performance (detector sensitivity, detector time response, signal treatment, data throughput, etc.). For the qualification of detector systems under development for use in nuclear facilities (nuclear power plants, research reactors, etc.), representative and well-characterized experimental conditions are required. The operating neutron flux range in modern high-flux material testing reactors (MTRs) is of the order of 10^{14}-10^{15} n cm^{-2} s^{-1}, which allows testing of nuclear fuel in representative experimental conditions corresponding to the neutron flux range in the cores of nuclear power plant reactors. Currently in Europe we are experiencing a decline in the number of available research nuclear facilities, in particular research reactors. According to the International Atomic Energy Agency (IAEA) Research Reactor Database (RRDB) [1], in the last decade 16 research reactors in Eastern and Western Europe have entered extended shutdown or have been shut down permanently, and 10 reactors are under construction or planned. In the last five years, the Jožef Stefan Institute (JSI) TRIGA reactor in Ljubljana, Slovenia, has seen increased interest as a reference facility to support detector development and testing activities [2-4].

The 250 kW JSI TRIGA reactor is mainly used for research purposes, in particular for the verification and validation of computer codes and underlying nuclear data, as a reference irradiation facility for experimental activities in different research fields, e.g. neutron activation analysis, studies of radiation induced effects in matter (radiation damage to materials and electronic components, aging), neutron dosimetry methods, validation of dosimetry data, and education and training. Thanks to efforts at the JSI over the past two decades [5-7] computational models of the reactor have been established using several Monte Carlo particle transport codes, most importantly MCNP and SERPENT, and have been continuously tested and refined on the basis of experimental data. A significant contribution to these efforts is due to numerous collaboration projects between the JSI and the French Atomic and Alternative Energies Commission (CEA). In steady state operation, the reactor experimental conditions are very well characterized in terms of the knowledge of the neutron and gamma fields. However, in steady state operation the reactor is able to generate a maximum neutron flux level of around 2×10^{13} n cm^{-2} s^{-1}, i.e. at least two orders of magnitude lower than the range relevant to high flux MTRs.

On the other hand, the JSI TRIGA reactor has the capability for pulse operation, where one of the control rods of the reactor – the transient rod – is ejected to a pre-set height, thus introducing a sufficient amount of reactivity to make the reactor prompt supercritical. The reactor power increases very quickly to a peak value, after that the reactor power drops, due to the negative reactivity which is a consequence of the elevated fuel temperature. In pulse operation during which significantly higher instantaneous power levels can be reached - up to 1 GW, albeit for a short duration - a few milliseconds - depending on the inserted reactivity. In 2019, a bilateral collaboration project between the CEA and JSI was initiated, to investigate the possibility of neutron flux measurements performed at very high neutron flux levels during reactor pulse operation. Such measurements are made possible by modern, validated, wide dynamic range acquisition systems. The main expected outcome of this project, in which the use of several experimental techniques is proposed in reactor pulse operation mode, are indications on the feasibility of the use of pulse operation to extend the neutron flux range, for irradiation testing activities at the JSI TRIGA reactor.

2. REACTOR PULSE OPERATION

Reactor pulse operation is made possible by a strong, negative and prompt temperature coefficient of reactivity, which is a property of the TRIGA reactor design, in particular the nuclear fuel. The physical phenomena determining the temperature coefficient of reactivity are the neutron spectral shift and the Doppler-broadening of neutron resonances. In pulse operation at the JSI TRIGA reactor, the reactor is made critical using the Transient control rod only. A reactor pulse is initiated by the ejection of the transient control rod to a pre-set height, thus introducing a positive reactivity, making the reactor prompt-supercritical. The reactor power rises quickly with an exponential behaviour; the released energy causes the fuel temperature to increase. As this occurs, the equilibrium thermal energy to which neutrons are thermalized increases (spectrum shift). Due to the 1/v behaviour of the ^{235}U fission cross section in the thermal range, at increased fuel temperatures the effective fission cross section and thus the effective multiplication factor decrease. Additionally, due to Doppler broadening of neutron resonances, in particular in ^{238}U, at increased fuel temperatures a larger fraction of neutrons is absorbed during the thermalization process, further decreasing the effective multiplication factor. In pulse operation, we therefore observe an exponential increase of the reactor power at first, followed by a rapid decrease. A reactor SCRAM (rapid shutdown with the insertion of all control rods) is triggered approximately 6 seconds after the reactor pulse is initiated, in order to safely terminate the pulse. Figure 1 shows a sequence of three photographs taken from the reactor platform during the initial phase of a reactor pulse.

Figure 1: Sequence of three photographs taken from the reactor platform during a pulse.

The time dependence of the reactor power during a reactor pulse is well described by the Fuchs-Hansen model [8]. After the reactor reconstruction in 1991 in which the capability of pulse operation was established, a first sequence of reactor pulses was performed in order to obtain relevant pulse operation data, showing the validity of the main model predictions [9].

Subsequent experimental data triggered a more detailed study of reactor pulse operation. The available experimental data was compiled into a pulse operation database, made available online at http://trigapulse.ijs.si/. The data were systematically analysed, resulting in the introduction of improvements to the model as well as a detailed estimation of the uncertainties [10-12]. The improved model is able to predict the pulse peak power and released energy within 30 %, however it is worth noting that the determined model uncertainties resulting from the analysis are high, around 50 %.

3. PLANNING OF THE EXPERIMENTAL CAMPAIGN

In the framework of the bilateral collaboration project, a 2-week experimental campaign is in preparation at the JSI TRIGA reactor in pulse operation. On-line measurements will be performed using miniature fission and ionization chambers (FCs and ICs), developed and manufactured at the CEA Instrumentation, Sensors and Dosimetry laboratory in Cadarache, France. The experiments are aimed at precise measurements of the neutron flux behaviour in the core of the reactor and at the determination of the total neutron fluence delivered to samples irradiated in the most important irradiation channels of the reactor.

Dedicated miniature FCs and ICs are currently being manufactured for the experiments. The fissile (^{235}U) deposit mass present on the interior FC electrode will be very low (below 1 μg), in order to allow measurements in (fission chamber) pulse mode up to higher neutron flux levels than encountered in steady-state reactor operation. ICs will be used to measure the time behaviour of the gamma field. FCs and ICs will be positioned in the Measurement Positions in the reactor core using dedicated aluminium guide tubes. Two electronic acquisition systems will be employed to perform the measurements, i.e. the MONACO system [13,14], developed and refined over the past decade at the CEA, and a commercially available current meter, manufactured by Instrumentation Technologies [15].

The reactor pulses will be monitored by neutron dosimetry. Samples of certified reference materials, obtained from the European Commission (EC) Joint Research Centre (JRC) in Geel, Belgium, will be irradiated during reactor pulses within the JSI TRIGA irradiation channels. The materials used and the nuclear reactions to be measured (in brackets) are: Al-0.1%Au (^{197}Au(n,γ), ^{27}Al(n,α)), Al-1%Co (^{59}Co(n,γ)), Ni (^{58}Ni(n,p)), to cover the thermal / resonance and fast neutron energy ranges. Activation measurements will be carried out using two High Purity Germanium (HPGe) detectors operated at the JSI Reactor Physics Department. As an alternative experimental technique enabling the determination of the pulse shape, Cherenkov light intensity measurements are proposed using a setup consisting of a photodiode or Silicon Photomultiplier (SiPM) and a Red Pitaya board, currently under development at the JSI.

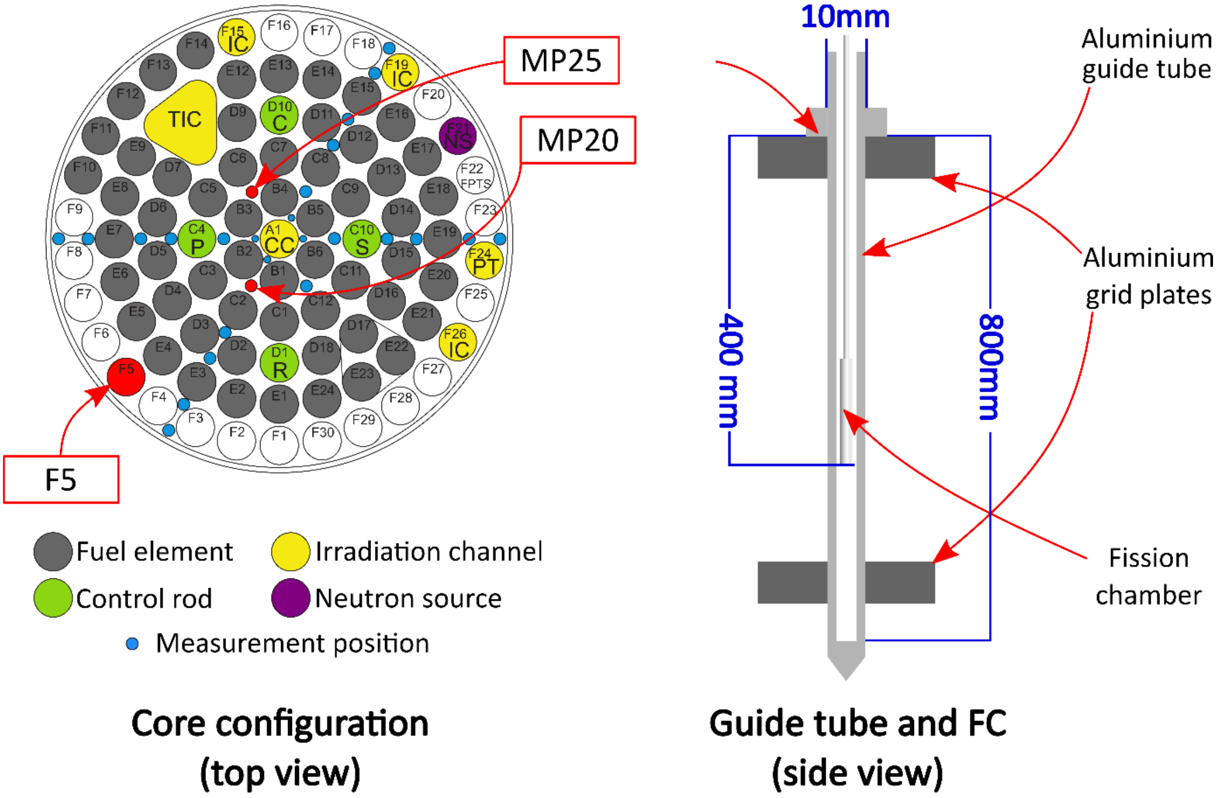
4. PRE-CAMPAIGN TESTING

In August and September 2019, test measurements in reactor pulse mode were carried out using miniature FCs already present at the JSI TRIGA reactor and a Centronic FC165 fission chamber. Two data acquisition systems were tested: a Keithley 6517B picoammeter operated by a LabView user interface, and an I-Tech Libera current meter. A sequence of 10 reactor pulses was performed with different inserted reactivity values. Table 1 reports the unique pulse ID numbers, the inserted reactivity, the final transient control rod position after ejection, the peak power, energy released and the pulse full width at half-maximum (FWHM), as measured using the pulse instrumentation channel. Figure 2 displays the reactor core configuration and the experimental positions used in the testing, and a schematic side view of a CEA Ø 3 mm fission chamber located in the reactor core.

Table 1: Pulse parameters for the pulse sequence, performed on 21.8.2019, as measured by the pulse instrumentation channel.

Pulse ID	Inserted reactivity [$]	Transient rod position [steps]	Peak power [MW]	Energy released [MWs]	FWHM [ms]
360	1.10	444	1.0	0.1	503*
361	1.15	437	1.3	0.1	6471*
362	1.20	430	1.9	0.2	3818
363	1.25	423	3.3	0.3	2378
364	1.30	416	6.0	0.5	267
365	1.35	409	10.3	0.9	166
366	1.40	402	16.7	1.4	119
367	1.40	402	20.0	1.6	106
368	1.40	402	19.9	1.6	107
369	2.00	299	240.2	7.5	27

* Data obtained from the pulse recorder is considered reliable for high peak power pulses.



Core configuration (top view)

Guide tube and FC (side view)

Figure 2: Left: core configuration and experimental positions used in the testing experiments. Right: schematic side view of a CEA Ø 3 mm fission chamber located in the reactor core.

4.1 Measurements with FC165 / Keithley 6517B

The FC165 was inserted into a dry irradiation channel installed in the F5 position in the reactor core. The acquisition system was operated with a sampling rate of around 28 s^{-1}. Figure 3 displays the recorded time dependence for four reactor pulses with increasing inserted reactivity up to 1.3 \$. The Keithley 6517B based acquisition system is able to record the FC signal during the reactor pulses reliably for inserted reactivity values of up to 1.1 \$ - the recorded time dependence of the signal is smooth up to the automatic reactor SCRAM (top left graph). However, for higher inserted reactivities there is observable saturation during the pulse peak and only the initial and final signal behaviour is recorded reliably.

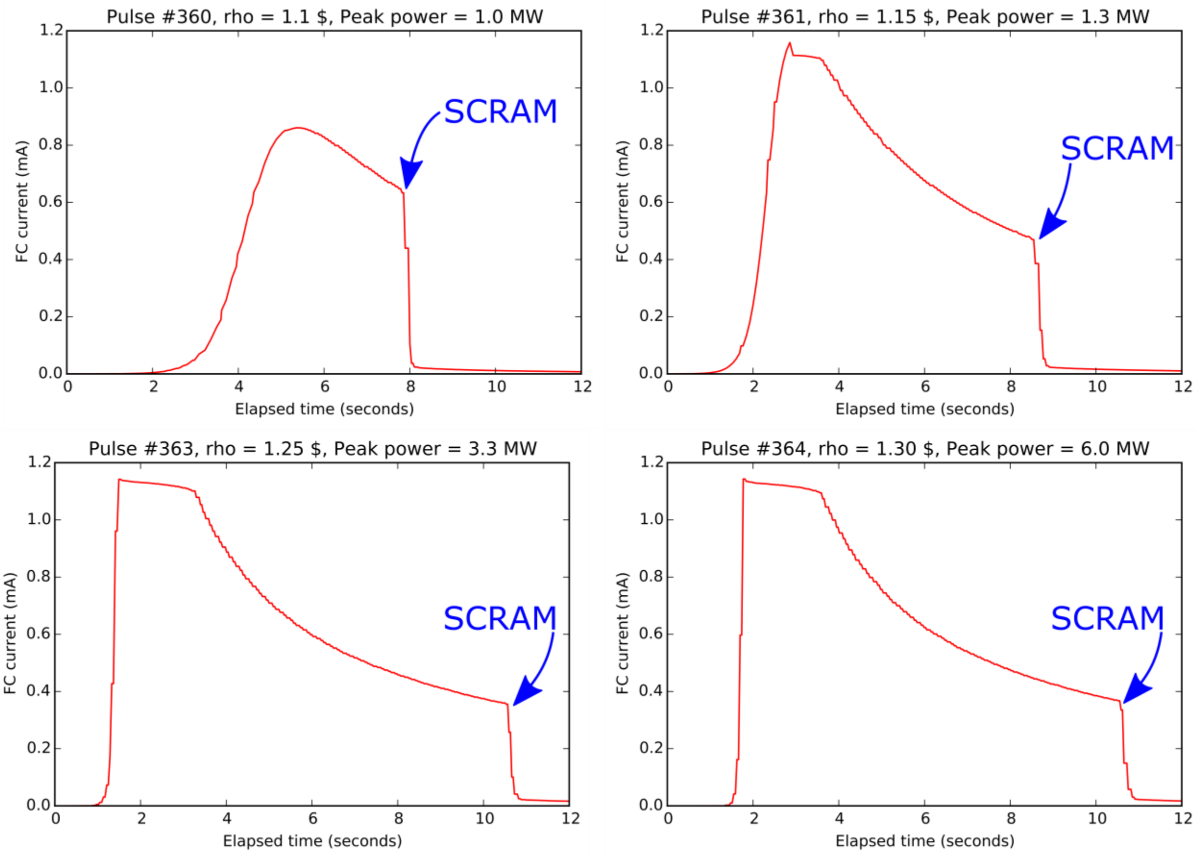


Figure 3: Recorded time dependence for four reactor pulses with increasing inserted reactivity from 1.1 to 1.3 \$ using a FC165 and a Keithley 6517B.

4.2 Measurements with miniature FCs and an I-tech Libera current meter

Two miniature FCs, No. 2260 (3 Bq ^{235}U) and No. 2288 (40 Bq ^{235}U) were inserted into aluminium guide tubes and positioned in measurement positions MP25 and MP20, respectively. The vertical position of the chambers was set by inserting them fully into the guide tubes, the bottom of which is at a distance of 800 mm, measured from the top surface of the top reactor grid plate. The chambers were then raised by approximately 400 mm from the bottom, for the active part to be in proximity of the core mid-plane. Figure 4 displays the recorded signal from the fast ADC stream of the Libera current meter for the same four reactor pulses displayed in Figure 3. It is clearly observable that the Libera current meter is able to reliably record the signal during the reactor pulses. However, at the time of testing, the fast ADC stream was not absolutely calibrated, therefore the signal is represented in arbitrary units. An absolutely calibrated Libera current meter will be provided for the scheduled experimental campaign. Figure 5 displays the recorded signals for two pulses with a higher inserted reactivity, 1.4 $ and 2.0 $. Even for the highest pulse, the current meter was able to reliably record the FC signal. The acquisition data-rate was 100 kS/s.

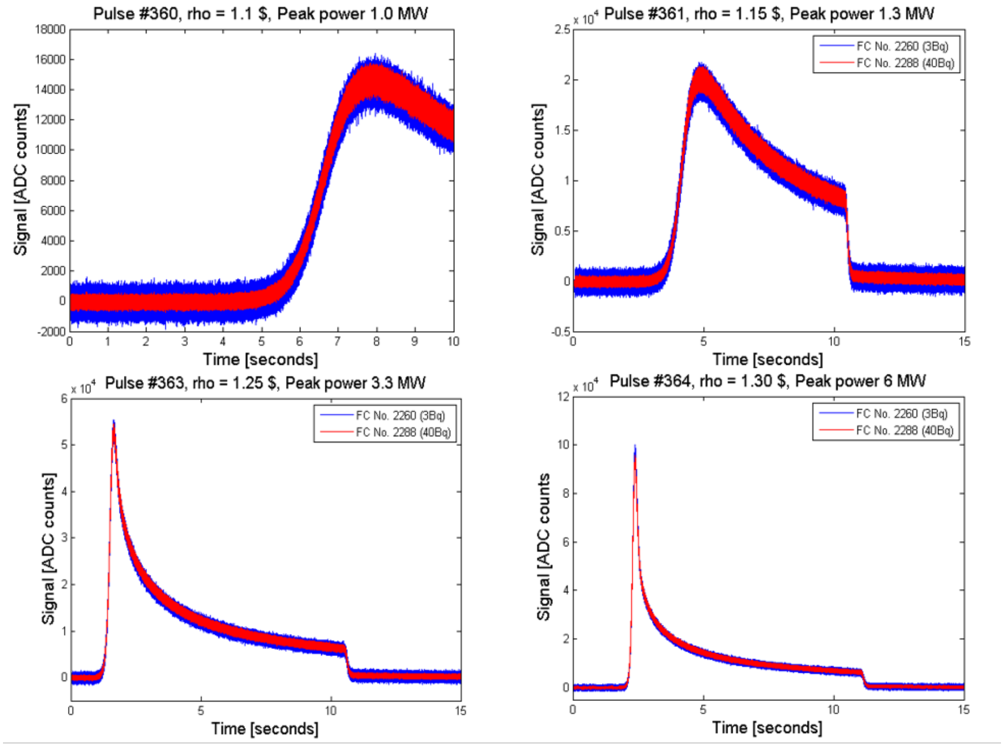


Figure 4: Recorded time dependence for four reactor pulses with increasing inserted reactivity from 1.1 to 1.3 $ using two miniature FCs and an I-Tech Libera current meter. The pulse sequence corresponds to the sequence in in Figure 3.

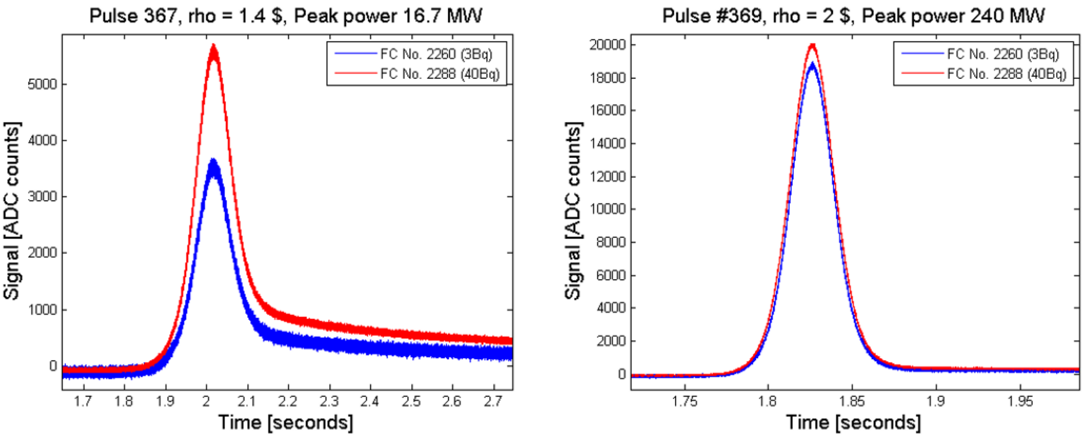


Figure 5: Recorded time dependence for two reactor pulses with higher inserted reactivity (1.4 $, 2.0 $) using two miniature FCs and an I-Tech Libera current meter.

5. CONCLUSIONS

This paper gives and overview of the planned activities during the bilateral collaboration project between the JSI and CEA on reactor pulse operation and presents the first measurements in reactor pulse operation mode, performed using fission chambers and two data acquisition systems. The first results clearly show that an acquisition system based on an I-Tech Libera current meter is suitable for such measurements, as it is able to reliably measure the FC signal even for high peak power pulses, with inserted reactivity values of up to 2 $. The results of the first measurements provide experimental indications, relevant for the planning of the experimental campaign, scheduled in the autumn of 2020.

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