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A new discriminating high temperature fission chamber filled with xenon designed for sodium-cooled fast reactors

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ABSTRACT

Xenon high temperature fission chamber, designed for sodium-cooled fast reactors, unlike the argon filled fission chambers, can operate at temperatures greater than 500°C without partial-discharges and discriminate neutrons and partial-discharges at temperatures up to 650°C.

1. Introduction

High temperature fission chambers [1] (HTFC) are designed to detect neutrons and to operate at temperatures above 400 °C, and thus be suitable for sodium cooled fast reactors [2 4]. Reactor power control and fuel cladding failure detection [5] are possible applications. If used in core, the HTFCs will have to withstand temperatures up to 650 °C, and high irradiation, up to 10^{10} n/cm^2.s.

When operating at temperatures above 400 °C, an extra signal, not due to neutron flux, has been observed [3,4]. This unwanted signal has been attributed to partial discharge or PD, activity, and is more or less similar in amplitude and shape to the signal resulting from neutron interactions.

During reactor start up, the PD signal count may potentially be on the same order of magnitude as the neutron signal count [4], which increases the uncertainty of the reactor power measurement. Fission chambers may also be used for the detection of fuel cladding failures which is based on very precise neutron count in the sodium coolant circulation lines. Reduced reliability of the neutron count from the HTFCs due to partial discharge activity thus represents a security risk for nuclear reactor operation.

This study describes experiments on fission chambers in which the usual working gas (argon) is replaced by xenon. It is found that the high dielectric strength of xenon renders the HTFCs immune to PD at temperatures up to 500 °C. In addition, it will be shown that discrimination between pulses due to neutrons and PDs may be made at temperatures up to 650 °C when using xenon as opposed to argon as the filling gas.

A brief recall of basic theory of electrical discharges will be made in the next section. The HTFC used in this work are described in Section 3. All results about comparisons between fission chambers filled with argon and xenon are presented in Section 4. The conclusions and the perspectives are presented in Section 5.

2. Notions of eletrical discharge theory

In the presence of high electric fields, free electrons may gain sufficient energy to ionize the bulk gas atoms/molecules. This may then lead to a so called electron avalanche. The initial free electrons, sometimes referred to as seed electrons, are formed from background radiation sources including cosmic rays.

Fig. 1 describes the basic process of an electric discharge in a plane to plane geometry. In this simplified case of infinite planar electrodes, it may be shown that the conditions for a self sustained discharge are given by what is known as Paschen's Law Eq. (1) [6 8]:

$$V = \frac{B \times P \times d}{\ln(A \times P \times d) - \ln\left(\ln\left(1 + \frac{1}{\gamma}\right)\right)} \tag{1}$$

P and d are the filling gas pressure and the inter electrode distance, γ is the secondary emission coefficient (yield of electrons from the impact on the cathode of positive ions, typically of order $\sim 10^{-4}$ 10^{-2}) and A and B are coefficients which depend on the ionization energy and electron collision cross section of the bulk gas and are tabulated, for several noble gases, in Table 1.

Paschen curves for several noble gases are depicted in Fig. 2. The abscissa is the product of the pressure and the inter electrode distance,

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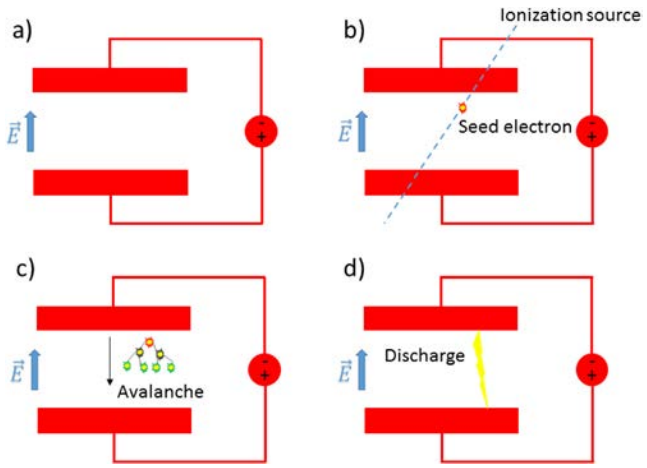

Fig. 1. Electric discharge scheme in a plane-to-plane geometry.
Source: Figure taken from [9].

Table 1
Paschen's law empirical coefficients [10].

	A ($\text{Torr}^{-1}\text{cm}^{-1}$)	B (V $\text{Torr}^{-1}\text{cm}^{-1}$)
He	3	34
Ne	4	100
Ar	14	180
Xe	26	350

Table 2
HTFC parameters.

Diameter	Inter-electrode distance	Bias voltage	Gas pressure	N. electrodes
48 mm	1,5 mm	400 V	3,5 bar	3

and the ordinate is the voltage above which a discharge should occur. Depending on gas nature, this so called breakdown voltage passes by a minimum value on the order of a few hundred volts.

The assumption of a completely homogeneous electric field is of course rarely the case in practice. In the case of a fission chamber, there is the added complexity that the electrodes are held in place and electrically insulated from each other by a ceramic insulating component. In addition to the fact that the complex geometry of a real system typically gives rise to an inhomogeneous electric field, the presence of a dielectric material, which may become electrically charged, and whose dielectric properties may depend on temperature, is likely an important aspect of this type of system.

3. Description of fission chambers

Fig. 3 shows the fission chamber used in this work and manufactured by Photonis (Brive la Gaillarde, France). The principal parameters of the fission chamber used in this work are shown in Table 2. This fission chamber consists of an active zone with cylindrical electrodes covered in fissile material, and a zone, which serves to assure the electrical connection between the active zone and the cable, which conducts signals to an amplifier.

Following previous work [9], it was chosen to replace argon with xenon as filling gas because, in the pertinent range of values of P·d (10 1000 Torr·cm), xenon has a higher breakdown voltage compared to argon at room temperature.

4. Comparison between argon and xenon

4.1. Discharges

Two chambers with the same geometry, shown in Fig. 3, and with the same filling pressure but with different fill gases, argon and xenon, are compared via their average pulse count frequency versus temperature, in Fig. 4.

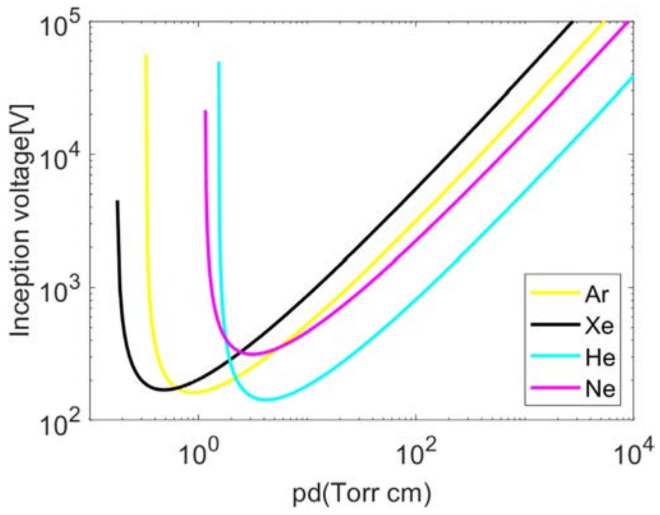

Fig. 2. Paschen curve for different gasses at room temperature.

Fig. 4 shows that the use of xenon as filling gas resolves the problem of PD up to 650 °C. For temperatures up to 650 °C, the PD count remains zero for the chamber filled with xenon. In contrast, the fission chamber filled with argon exhibits increasing partial discharge activity at temperature above 400 °C, which was verified in all tested fission chambers filled with argon [3,9]. For the data shown in Fig. 4, the chambers were tested during a minimum of 50 h for each point.

4.2. Neutrons

Fission chambers are used to monitor the neutron flux in a nuclear reactor, and therefore give an indication of the reactor power. While the replacement of argon by xenon led to a marked reduction in partial discharge activity, it is important to demonstrate that a xenon filled chamber would also perform adequately for the measurement of neutron flux in a reactor. Therefore, experiments were made using two chambers with the same geometry (Fig. 3), and with the same filling pressure but with different fill gases (argon and xenon), and placed inside the ISIS [11] nuclear reactor.

The two chambers were used to monitor the reactor power in which the reference was obtained by an ionization chamber placed inside the reactor and used in current mode [1].

Figs. 5 and 6 show that both tested chambers, thanks to the three detection modes used (Pulse, K2 and K3 deeply explained by *A. Dabat Blondeau* [12]), are able to properly monitor the reactor power. For varying reactor power, the power measurement is seen to overlap when using the different modes allowing a smooth transition between one mode and another.

The maximum power of the reactor for this test varied between 0 and 7 kW, because the thermal neutron flux in the ISIS reactor at 7 kW is comparable, in terms of the reactivity of the tested fission chambers to the fast neutron flux, to that a IVth generation reactor at full power.

Finally, we can see that the two fission chambers react quite similarly to the power variation of the reactor power as measured by the ionization chamber.

This last point is very important because it leads to consider that xenon, in addition to the advantage, of its elimination of the problem of electric discharges at high temperatures, does not change the performance of the fission chamber with respect to neutron detection.

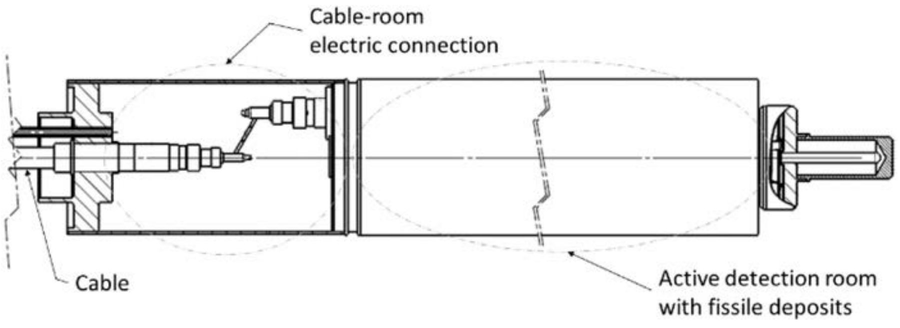

Fig. 3. Drawings of HTFC manufactured by PHOTONIS and used in this work.

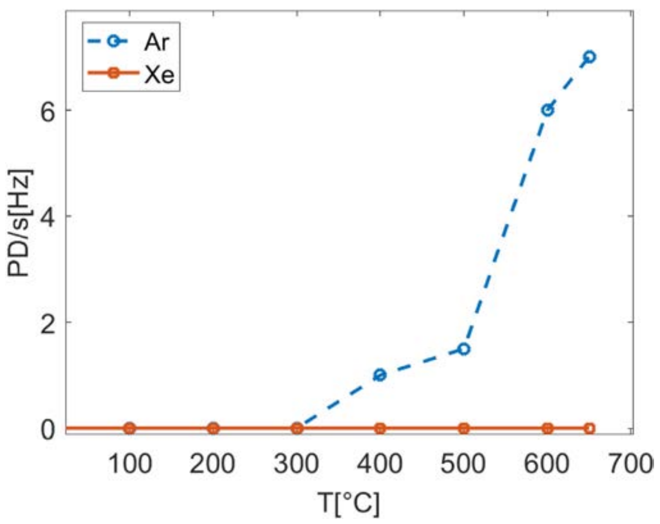

Fig. 4. Average count of PD pulses over time as a function of temperature, without neutron source, at 400 V; for the HTFC with argon, in blue, and with xenon, in red.. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

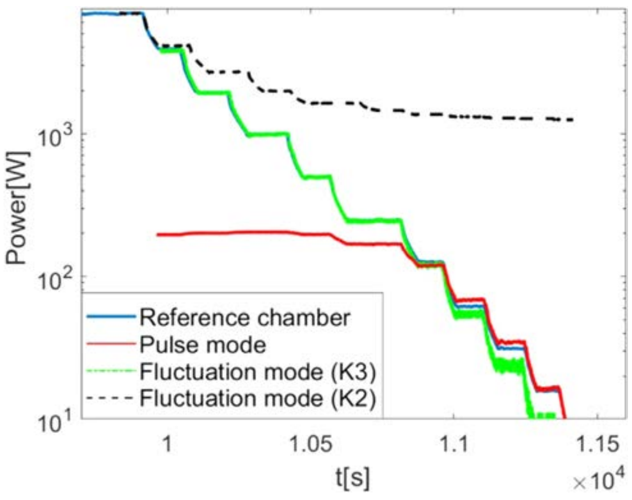

Fig. 5. Measurements of the ISIS reactor power by the fission chamber, filled with argon, in pulse mode (in red), in K2 fluctuation mode (in black) and in K3 fluctuation mode (in green). The measured power obtained by the tested fission chamber is compared with the power measured by reference ionization chamber used in current mode (in blue).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

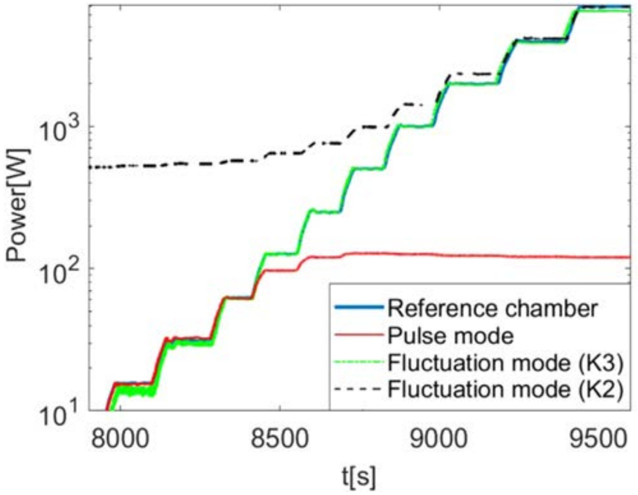

Fig. 6. Measurements of the ISIS reactor power by the fission chamber, filled with xenon, in pulse mode (in red), in K2 fluctuation mode (in black) and in K3 fluctuation mode (in green). The measured power obtained by the tested fission chamber is compared with the power measured by reference ionization chamber used in current mode (in blue).. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Conclusions and perspectives

Results presented in this paper show firstly that replacing argon with xenon as the filling gas in HTFC, without changing any other parameters, eliminates the problem of electrical discharges up to 650 °C.

It also shows that replacing argon with xenon does not change the HTFC neutron detection performance in a nuclear reactor with a thermal neutron flux.

Following these results, further tests will be performed to test a fission chamber filled with xenon in a IVth generation nuclear reactor, in which the fission chamber will be exposed to a fast neutron flux, to high temperature (up to 650 °C) and to a strong γ radiation.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

G. Galli: Investigation, Data curation, Writing. **H. Hamrita:** Investigation, Supervision. **M.J. Kirkpatrick:** Writing, Supervision. **E. Odic:** Supervision. **C. Jammes:** Supervision.

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