# Neutron Irradiation Effects on High-Power Thyristors in Fusion Environments

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## Abstract

High-power thyristor devices are widely employed in the power supply systems of large-scale fusion installations due to their excellent cost-effectiveness and applicability. Prolonged exposure of thyristors to high-dose neutrons generated by deuterium-tritium (D-T) fusion reactions leads to alterations in their electrical characteristics, culminating in irreversible damage. This study focuses on thyristor switches within the commutation circuits of Quench Protection Systems (QPS) for superconducting magnets in fusion devices. The relationship between the internal physical structure of irradiated thyristors and their external electrical parameters is established. Subsequently, a series of targeted physical simulations and neutron irradiation experiments on thyristors are performed to validate the theoretical analysis. Additionally, through accurate simulations, the influence of electrical characteristic variations in irradiated thyristors on QPS performance is investigated, offering valuable guidance for the maintenance and upgrading of QPS.

## Full Text

## Preamble

**Study on the Influence of Neutron Irradiation on High-power Thyristor Device in Fusion Environment**

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High-power thyristor devices are widely employed in power supply systems of large fusion devices due to their excellent economy and applicability. The high-dose neutrons produced by Deuterium-Tritium (D-T) fusion reactions irradiate thyristors continuously, leading to changes in their electrical characteristics and potentially causing irreversible damage. This paper investigates the thyristor switch of the commutation circuit in the Quench Protection System (QPS) of fusion devices, establishing the relationship between the internal physical structure and external electrical parameters of irradiated thyristors. A series of targeted physical simulations and neutron irradiation experiments are conducted to verify the theoretical analysis. Additionally, the impact of irradiated thyristor electrical characteristic changes on the entire QPS is studied through accurate simulation, providing valuable guidance for the maintenance and renovation of QPS.

**Keywords:** Fusion device, Neutron Irradiation effects, Thyristor, Quench protection Switch (BPS)

The QPS operates as follows: Once a quench occurs, the Bypass Switch (BPS) quickly opens, and the magnet current is transferred to the Vacuum Circuit Breaker (VCB) by the arc voltage. The thyristors then turn on, generating a pulse current from the charged capacitor C and pulsed inductor L to force the current in the VCB down to zero [?, ?]. Finally, the magnet current is transferred to the Discharge Resistor (DR), and the energy stored in the magnet is continuously dissipated until it reaches zero.

## Introduction

Tokamak is an experimental device for developing nuclear fusion energy, in which the most easily achieved fusion reaction is Deuterium-Tritium (D-T) fusion, whose reaction formula is shown in Eq. (1) [?, ?]. When D-T fusion reaction occurs in a Tokamak, approximately 80% of the energy is released in the form of 14.1 MeV fast neutrons [?]. Currently, Tokamak is still in the experimental exploration stage, and some windows and channels need to be established for observation, which may lead to increased neutron irradiation flux in the fusion environment. Taking the ITER Tokamak as an example [?], when conducting a 500 MW D-T fusion reaction experiment, the number of fast neutrons produced by the plasma is $1.78 \times 10^{20}\ \mathrm{n \cdot s^{-1}}$ [?]. After installing the shielding layer and considering neutron attenuation, the calculated neutron flux rate in the entire host hall still reaches up to $10^5\ \mathrm{n \cdot cm^{-2} \cdot s^{-1}}$, which is far greater than the safety threshold and has drastic impacts on the performance of electrical devices around the Tokamak [?, ?].

$\mathrm{D + T \rightarrow n\ (14.1\ MeV) + {}^4He\ (3.5\ MeV)}$,

The Quench Protection System (QPS) is typically designed to ensure the safety of superconducting magnets in Tokamaks [?, ?], in which thyristors are commonly used as the trigger unit of the commutation circuit, as shown in Fig. 1 [Figure 1: see original paper] [?, ?]. To effectively protect the superconducting magnetic coils in the fusion device, the QPS needs to respond as quickly as possible. To ensure this rapid response, the QPS should be located as close as possible to the magnetic coils. Unfortunately, this is also where there is a high fast neutron flux rate, making neutron damage unavoidable. The typical layout of a fusion device and irradiation nephogram are shown in Fig. 2 [Figure 2: see original paper] [?, ?]. If the thyristor switch is damaged due to neutron irradiation and cannot operate normally, the current would not be interrupted quickly by the VCB with the help of the auxiliary pulse current, resulting in QPS failure and destruction of the superconducting magnet [?].

Since ITER adopts the D-T fusion route, neutron irradiation damage is an issue that must be considered. Previous studies have primarily focused on the main structural materials of fusion reactors, such as the First Wall, Blanket Modules, and Divertor [?]. Gradually, ITER realized the threat of neutron irradiation to auxiliary equipment and conducted irradiation calculations, established exposure limits, and provided mitigation measures [?, ?, ?]. Researchers have carried out radiation reliability analysis based on ITER guidelines, but it is far from sufficient, especially for high-power thyristors.

Semiconductor damage via high-energy neutron irradiation is a topic of interest not only in the context of Tokamaks and Stellarators but also for spacecraft and satellites, where electronics are similarly bombarded with a complex mix of high-energy particles [?]. Currently, literature has separately studied the displacement damage effect and total ionization effect in electronics and a few power devices at macro and micro levels. However, given the particularity of the fusion neutron irradiation environment and the requirement for effective irradiation reinforcement, the relationship between internal physical structure changes and external electrical characteristic changes should be deeply studied and accurately established.

The neutron irradiation damage and internal physical structure changes of semiconductor devices are mainly investigated through experiments. S. Yue et al. studied the synergistic effect of electrical stress and neutron irradiation on silicon carbide power MOSFETs, characterizing defects using Low Frequency Noise (LFN) and Deep-Level Transient Spectrum (DLTS) methods [?]. R. Chen et al. carried out Displacement Damage Dose (DDD) and Total Ionization Dose (TID) irradiation experiments with a 14.1 MeV neutron high-voltage multiplier and $^{60}$Co gamma-ray to study the synergistic effect of TID and DDD in neutron-irradiated GaN HEMT [?]. However, the relationships between various physical parameters and electrical characteristics of semiconductor devices need further study.

On the other hand, F. Ravotti and J. Mekki studied the I-V characteristics of PIN photodiodes under 1 MeV neutron irradiation at CERN [?, ?]. Through extensive irradiation experiments and tests, they obtained relationship curves of forward conduction voltage drop and leakage current under different neutron fluxes. C. Liu et al. studied the influence of fast neutron irradiation on the high di/dt switching characteristics of the pulse power supply Insulated

Gate Triggered Thyristor (IGTT) through experiments [?]. The simulation and test results indicate that neutron irradiation causes a significant decrease in threshold voltage and on-state voltage of IGTT. However, these studies did not provide a detailed description and exploration of the physical causes leading to the electrical characteristic changes.

This paper focuses on studying the characteristic changes of the thyristor switch within the fusion device's QPS shown in Fig. 1. We first introduce the internal physical structure changes of the thyristor caused by neutron irradiation to identify the physical parameters that may cause electrical characteristic changes. Then, regarding various key electrical parameters of the thyristor, we theoretically analyze the relationship between physical and electrical characteristics after neutron irradiation. Additionally, a series of targeted thyristor physical simulations and neutron irradiation experiments are carried out to verify the theoretical analysis results. Furthermore, the effect of irradiated thyristor characteristic changes on the entire QPS is studied through performance simulation. This study not only establishes a clear relationship between the changes in physical and electrical characteristics of neutron-irradiated thyristors but also provides valuable guidelines for the maintenance and renovation of QPS.

## II. Theoretical Discussion of the Relationship Between Physical and Electrical Characteristics Change of the Thyristor After Neutron Irradiation

### A. Damage Mechanism Analysis of Physical Characteristics of Thyristor after Neutron Irradiation

Since neutrons are electrically neutral and have very strong penetrability, they can approach sufficiently close to the atomic nucleus of lattice atoms in the irradiated material and collide elastically with the atomic nucleus [?, ?]. The lattice atom gains energy during the collision process, leaving its normal lattice position and becoming an interstitial atom in the lattice while leaving a vacancy at its original position. If the vacancy and interstitial atom remain within the Coulomb force field of its elastic force field, recombination can occur. If this force field is exceeded, the interstitial atoms will not recover, thus causing atomic displacement. The production process of vacancies and interstitial atoms is shown in Fig. 3 [Figure 3: see original paper].

Vacancies can combine with adjacent atoms or with other vacancies. Vacancies can also move to the vicinity of doping to form vacancy-impurity complexes, preventing dopants from participating in conductivity and thus changing the doping density. The displacement of a single atom forms a simple defect called a Frenkel Defect [?]. If the incident neutron energy is large enough, the displaced interstitial atoms will gain sufficient energy. The collision of such interstitial atoms will displace a large number of atoms in the lattice, forming a large defect cluster.

Literature [?] indicates that when the incident neutron energy is 1 MeV, the average energy obtained by the initially displaced atom is 72.5 keV, while the displacement threshold for a Si atom is 15 eV. The D-T reaction produces neutrons with energy of 14.1 MeV, which is about one million times the Si atomic displacement threshold, thus obviously having a great impact on Si materials. Additionally, it shows that a defect cluster generated by a 1 MeV neutron can include about 200 to 1000 displaced lattice atoms. Although the collision cross-section between neutrons and lattice atoms is only between $10^{-23}$ $cm^2$ and $10^{-24}$ $cm^2$, the energy transferred to lattice atoms by collision is quite large, and a series of lattice atoms can eventually be displaced.

Semiconductor materials have three microscopic physical parameters: minority carrier lifetime $\tau$, doping density n, and mobility µ. Neutron irradiation introduces defects and defect clusters in the semiconductor, thus changing these three microscopic physical parameters and altering almost all parameters of the semiconductor device.

Defects formed by neutron irradiation can introduce additional energy levels into the forbidden band of semiconductor materials, which increases the probability of recombination between minority and majority carriers, increases the recombination rate, and thus reduces the minority carrier lifetime. The relationship between neutron flux and minority carrier lifetime is given by:

$\tau( ) = \tau(0) + k\tau \times$

where $\tau(0)$ and $\tau( )$ are the minority carrier lifetimes before and after neutron irradiation, $k\tau$ is the minority carrier lifetime damage coefficient of semiconductor materials, and  is the neutron flux. Since the thyristor is a semiconductor device with minority carriers as the conductive mechanism, minority carrier lifetime damage greatly affects device performance.

Additionally, neutron irradiation reduces the doping density of semiconductor materials through the carrier removal effect. The relationship between neutron flux and doping density is given by:

n( ) = n(0) - (Δn/Δ ) ×

where n(0) and n( ) are the doping densities before and after neutron irradiation, Δn/Δ  is the carrier removal rate, and  is the neutron flux.

Furthermore, when neutron irradiation introduces defects in semiconductor materials, these defects can act as scattering centers for carriers, effectively reducing carrier mobility. The influence of neutron irradiation on mobility can be expressed as:

µ( ) = µID + µL × [1 - exp(( T -  f)/kT)] × (At ×  )/(1 + Bt ×  )

where µ( ) is the mobility of carriers after neutron irradiation, µID is the mobility due to impurity scattering, µL is the mobility due to collision with thermally vibrating lattice atoms, At and Bt are coefficients,  T and  f are the defect level and Fermi level respectively, k is the Boltzmann constant, T is the thermodynamic temperature, and is the neutron flux.

### B. Establishment of Relationship Between Physical and Electrical Characteristics Change after Neutron Irradiation

As thyristors have longer lifetimes, higher reliability, lower maintenance requirements, and high rated power capability compared to other semiconductor devices, they become the first choice for QPS in Tokamak superconducting systems.

**1. Blocking Characteristic** The blocking characteristic of a thyristor is essentially an expression of the reverse current of a PN junction under reverse voltage, which can be divided into two conditions as shown in Fig. 4 Figure 4: see original paper. The forward leakage current IDRM and the reverse leakage current IRRM are the two most crucial parameters for evaluating the blocking characteristic of a thyristor. Fig. 5 [Figure 5: see original paper] shows the change of the PN junction barrier region with reverse bias. When the applied electric field E is in the same direction as the self-built electric field $E_0$, the electric field in the depletion layer is strengthened. This enhancement causes the barrier region to change in two ways: first, the barrier region becomes wider, and second, the barrier height increases.

A thyristor is composed of P-type and N-type semiconductors alternating Figure 4: see original paper. As shown in Fig. 4, a depletion layer forms at the junction of P-type and N-type semiconductors. If no external power supply is applied to the thyristor gate, there will always be at least one reverse-biased depletion layer regardless of the voltage direction of the external circuit, as shown in Fig. 4(a). If the thyristor gate is applied with an additional voltage (gate trigger), a large number of electrons are injected into the P-region of the thyristor, and the P-region eventually becomes N-region, causing the depletion layer width to gradually decrease and eventually almost disappear, as shown in Fig. 4(b). Since the injected electrons have already entered the N-region, the thyristor can maintain the conducting state even without additional gate voltage.

Therefore, both the blocking and conducting states of a thyristor after neutron irradiation can be analyzed by simplifying it to a PN diode. Fig. 6 [Figure 6: see original paper] shows the diagram of reverse current generation and minority carrier distribution. Meanwhile, the balance between diffusion and drift of carriers is broken by the growth of the barrier region, with drift playing a dominant role. Consequently, electrons at the boundary of the P-region can be pulled to the N-region, and holes at the boundary of the N-region can be pulled to the P-region. Simultaneously, electrons in the P-region and holes in the N-region will move to the boundary to supplement, thus forming the reverse current IF directed from the N-region to the P-region, as shown in Fig. 6. However, since there are few electrons in the P-region and few holes in the N-region, the reverse current IF is very small.

Ignoring the recombination of electrons and holes in the barrier region, the current density J through the PN junction can be considered as the sum of the hole diffusion current density Jp(xN) passing through xN and the electron diffusion current density Jn(xP) passing through xP [34]:

$J = Jp(xN) + Jn(xP)$

Jp(xN) can be calculated by the following equations if the hole and electron density distributions are obtained:

$Jp(xN) = -qDp\ (d\Delta pn(x)/dx)|\_\{x=xN\}$

where dΔp/dx is the hole density gradient and Dp is the hole diffusion coefficient.

If the P and N regions are long enough, the non-equilibrium carrier concentration in the PN junction should be distributed exponentially:

$\Delta pn(x) = [pn(xN) - pn0]\ exp((xN - x)/Lp)$

where Lp is the hole diffusion length:

$Lp = \surd(Dp\tau p)$

$pn(xN) = pn0\ exp(qU/kT)$

where pn0 is the equilibrium minority carrier concentration in the N-region and U is the applied reverse voltage. Hence, Jp(xN) can be calculated by:

$Jp(xN) = qDppn0/Lp\ [exp(qU/kT) - 1]$

By the same token:

$Jn(xP) = qDnnp0/Ln\ [exp(qU/kT) - 1]$

Consequently:

$IF = AJ = A(qDppn0/Lp + qDnnp0/Ln)\ [exp(qU/kT) - 1]$

As U approaches negative infinity, exp(qU/kT) approaches 0:

$IF = -A(qDppn0/Lp + qDnnp0/Ln) = -I0$

Hence, IF would increase as the carrier lifetimes $\tau$p and $\tau$n are greatly shortened after neutron irradiation. Additionally, for silicon PN junctions, the recombination current density Jrg in the barrier region also plays a crucial role in the reverse current. After neutron irradiation, the number of recombination centers in the barrier region of the PN junction increases, and the carrier generation rate increases, which leads to the rise of recombination current.

As a result, after neutron irradiation, the reverse current IF in the PN junction increases, leading to increased forward leakage current IDRM and reverse leakage current IRRM of the irradiated thyristor.

**2. Conducting Characteristic** The conducting characteristic of a semiconductor can be characterized by the on-state resistance or on-state voltage drop UTM. The lower the UTM, the better the high-current performance of the device, which is a significant parameter for semiconductors applied in QPS of fusion devices due to the extremely high current breaking requirement of superconducting magnets.

To achieve high working voltage capability, the substrate resistivity of the PN junction diode is generally high, meaning the substrate doping concentration is low and the substrate region is wide. Therefore, the defects caused by neutron irradiation lead to a more apparent carrier removal effect in the semiconductor material, resulting in many conductive carriers being constrained and not participating in conduction. Consequently, the resistivity increases, raising the conducting voltage of the PN junction.

According to the above analysis, the conducting characteristic of a thyristor can be analyzed by simplifying it to a PN diode. The on-state voltage drop of a PN diode UTM can be divided into two parts: the junction voltage Uj formed by the internal electric field, and the voltage related to the substrate epitaxial layer Ub. Uj is very small and negligible:

UT = Uj + Ub   Ub

According to literature [33], Ub can be expressed as:

Ub = (I × wd)/(A × $\sigma$p)

where wd is the base region width of the PN junction and $\sigma$p is the conductivity of the P-region. The conductivity of irradiated material can be derived as:

$\sigma$( ) = $\sigma$(0) e^(-$\alpha$ )

When   approaches 0:

[$\sigma$(0) - $\sigma$( )]/$\sigma$(0) = $\alpha$

where $\sigma$ = qμp, μ is the majority carrier mobility of the PN diode, and p is the base doping concentration of the PN diode. The carrier removal rate is:

R = (1/$\sigma$(0)) (d$\sigma$( )/d )|_{ \$→\$0}

Substituting into the previous equation:

[$\sigma$(0) - $\sigma$( )]/$\sigma$(0) = qμ( )p(0)/$\sigma$(0) × R

where R is the carrier removal rate. According to Eq. (16), substituting Eq. (24) into Eq. (23):

Ub( )/Ub(0) = exp(qμ( )p(0)R /$\sigma$(0))

It can be concluded from the above analysis that Ub will increase due to the majority carrier removal effect in the PN junction. Additionally, the change in the on-state voltage drop UTM of the irradiated thyristor is determined by the irradiation intensity, which will be discussed through further neutron irradiation simulation and experiment.

**3. Reverse Recovery Characteristic** Reverse recovery involves "turning off" a thyristor after it has been in a conducting state, and the time taken to switch from conducting to blocking state is critical and needs to be minimized. Typically, neutron damage decreases reverse recovery time because the minority carrier lifetime of the thyristor is significantly shortened after irradiation.

The typical reverse recovery current waveform is shown in Fig. 7 [Figure 7: see original paper]. IP is the peak value of the forward current. ts = t2 - t1 is the time for the reverse current to grow from zero to its maximum value IRM, called the storage time. tf = t3 - t2 is the time for the current to drop from IRM to 0.1IRM, called the fall time. The total reverse recovery time is trr = ts + tf, and Qrr is the reverse recovery charge [35].

When the thyristor is in the conducting state, most of the charges stored in the base region are formed by minority carriers. The charge continuity equation is given by:

$iT(t) = dQ/dt + Q/\tau$

where iT(t) is the current flowing through the thyristor, Q is the stored charge in the base region, and $\tau$ is the minority carrier lifetime.

The thyristors in QPS serve as the trigger unit of the commutation circuit composed of the pulsed inductor L and charged capacitor C. To simplify the analysis, the forward conducting current is considered to be sinusoidal: $iT(t) = IP \sin(\omega t)$. According to Eq. (26), we can obtain:

$Q(t) = (K0IP\tau)/(1 + \omega^2\tau^2)\ [\omega\tau\ e\hat{}(-t/\tau) + \sin(\omega t) - \omega\tau \cos(\omega t)]$

where K0 is the current gain of the thyristor.

At time t1, the charge Q(t1) can be calculated using Eq. (27):

$Q(t1) = (K0IP\omega\tau^2)/(1 + \omega^2\tau^2)\ [1 + e\hat{}(-\pi/\omega\tau)]$

When the forward current drops to zero, there are still a large number of non-equilibrium carriers in the thyristor, which will be dissipated through sweeping out and recombination. At time t2, the current reaches IRM, and the thyristor begins to recover its reverse blocking capability. At this point, only a small amount of stored charge remains in the base region. This charge will disappear through recombination, which is classified as low injection condition. Actually, high-power semiconductor devices generally operate under large injection condition, so it can be approximately considered that Q(t2) = 0. According to Eq. (27), we can calculate:

$\sin(\omega t2) = \omega\tau\ [\cos(\omega t2) - e\hat{}(-t2/\tau)]$

As t2 = t1 + ts = $\pi/\omega$ + ts, then $\omega$t2 = $\pi$ + $\omega$ts. Also, $\omega$ts is much less than $\pi/2$, so $\omega$ts can be approximated as zero. Then, it can be deduced that sin($\omega$ts) $\omega$ts and cos($\omega$ts) 1. Therefore:

sin($\omega$t2) = sin($\pi$ + $\omega$ts) = -sin($\omega$ts) -$\omega$ts cos($\omega$t2) = cos($\pi$ + $\omega$ts) = -cos($\omega$ts) -1

Approximating Eq. (29), the expression for t2 can be obtained:

ts $\tau$ [1 + e^(-t2/$\tau$)]

Since t2 is much longer than $\tau$, ts $\tau$. Then, the maximum reverse current IRM can be expressed as:

IRM k(t2 - t1) = k$\tau$

where k is the forward current change rate at point t1.

Based on the above analysis, it can be concluded that after high-dose neutron irradiation, which reduces the minority carrier lifetime $\tau$, the reverse recovery characteristics will change significantly. According to Eq. (33) and Eq. (34), the storage time ts and the maximum reverse current IRM will decrease with the reduction of $\tau$, meaning that the total turn-off time trr of the semiconductor will be shortened as a result of high-dose neutron irradiation. Additionally, the reverse recovery charge Qrr will sharply decrease after irradiation.

## III. Neutron Irradiation Simulation

To verify the correctness of the above theoretical analysis of the thyristor damage mechanism under fusion neutron irradiation, qualitative verification through material and device-level simulation based on a simplified thyristor model is necessary. The simulation approach in this paper is that after neutron irradiation, the lattice of the device material is damaged, and the defects introduce additional energy levels, which affect the electrical characteristics of the device. Therefore, two types of defects are mainly considered: donor defects characterized by EC-0.12 eV and acceptor defects characterized by EV+0.21 eV.

APSYS, an advanced semiconductor device physical model simulation software, is used for simulation in this paper. The thyristor is an extremely complex device, and its designs are often patented and proprietary commercial secrets. Therefore, a general and widely used physical model of a thyristor is established to simulate the effect of neutron irradiation on the electrical characteristics of thyristor devices. The 2D model of the device and doping concentration are shown in Fig. 8 [Figure 8: see original paper].

The mathematical models mainly include basic models and key models. The basic models include the drift-diffusion model, Poisson equation, continuity equation, ohmic contact electrical boundary, etc. The key models include the mobility model, collision ionization model, bulk defect model, etc. After determining the physical parameters of the thyristor model, the basic semiconductor equations can be solved numerically by combining the initial conditions and boundary conditions, and the electrical parameters under specific bias voltage are obtained.

The blocking characteristic of the thyristor is shown in Fig. 9a [Figure 9: see original paper]. It can be seen that the leakage current of the thyristor increases sharply when the reverse voltage is 350 V. When UAK = -400 V, the 2D electric field distribution is shown in Fig. 9b, where the main electric field falls in the N-region.

The on-state characteristic of the thyristor is shown in Fig. 10 [Figure 10: see original paper]. It can be seen that when the triggering voltage VG = 0.5 V, the thyristor does not turn on, while when VG = 1 to 5 V, the thyristor triggers on.

The comparison of the blocking characteristics of the thyristor before and after neutron irradiation is shown in Fig. 11 [Figure 11: see original paper] and Fig. 12 [Figure 12: see original paper]. It can be seen that when the thyristor is subjected to the same voltage, the forward and reverse leakage currents IDRM and IRRM increase under both donor and acceptor defect effects.

The comparison of on-state characteristics of thyristors before and after neutron irradiation is shown in Fig. 13 [Figure 13: see original paper] and Fig. 14 [Figure 14: see original paper]. It can be seen that when the thyristor conducts the same current, the on-state voltage drop UTM increases after irradiation under both donor defect and acceptor defect effects.

The simulation results show that the forward and reverse leakage currents and on-state voltage of the thyristor increase after neutron irradiation, which is consistent with the theoretical analysis above.

## IV. Neutron Irradiation Experiment

This paper uses the D-T neutron generator for irradiation, which is based on an accelerator neutron source and affiliated with the China Academy of Engineering Physics (CAEP) in Mianyang, China. The experiment is carried out on the K-400 accelerator, using an accelerated Deuterium (D) beam to irradiate a Tritium (T) target, where D-T reaction occurs, producing fast neutrons with energy of about 14.1 MeV.

To improve the efficiency of the neutron irradiation experiment, a new device layout mode called stepped layout mode is proposed and shown in Fig. 15 [Figure 15: see original paper]. Six ABB 5STP 52U5200 thyristor devices are distributed in three spherical spaces with different radii for irradiation, with two thyristors at each radius facing the neutron source with anode and cathode, respectively.

According to the neutron calculation report of ITER, the neutron flux rate at QPS could be up to $10^5$ $n \cdot cm^{-2} \cdot s^{-1}$ with local shielding. In this paper, the average neutron flux rate is taken as $10^4$ n • cm$^{-2}$ • s$^{-1}$. Assuming the duty cycle of ITER operation is 0.5, the operating time in a year is estimated as $1.58 \times 10^7$ s, so the neutron flux at QPS could reach $1.58 \times 10^{11}$ n • cm$^{-2}$. To obtain more extreme results, the neutron flux at 20 cm away from the neutron source is set to $4.3 \times 10^{11}$ n • cm$^{-2}$, which is 2.7 times larger than the actual irradiation environment. The output number of the neutron source can be calculated by:

nTotal = $\times 4\pi r^2 = 2.16 \times 10^{15}$ n

In the irradiation experiment, the cumulative irradiation time was 95,373 s, and the final number of neutrons produced by the D-T neutron generator is $2.55 \times 10^{15}$ n (uncertainty is 4%), which meets the experimental requirement.

Additionally, the neutron flux ratio of the devices from near to far is 1:1/4:1/9, and the cross-sectional area of the irradiated thyristor is 233 cm$^2$. Therefore, the neutron flux and neutron injection number of the thyristors at each position can be calculated.

Since the thyristor stack in QPS is used as the trigger unit of the commutation circuit shown in Fig. 1, the temperature of the thyristor is not significant after flowing through 1 ms/100 kA pulse current. Hence, the electrical parameters tested at 25°C are taken as the key test data. The tested thyristor numbers and locations are shown in Table 1 .

**TABLE 1.** The thyristor number and location in 14.1 MeV neutron irradiation experiment.

| Location | Neutron Flux | Number |
|---|---|---|
| 20 cm | $4.3 \times 10^{11}$ n/cm$^2$ | #1, #2 |
| 40 cm | $1.07 \times 10^{11}$ n/cm$^2$ | #3, #4 |
| 60 cm | $0.48 \times 10^{11}$ n/cm$^2$ | #5, #6 |

The change in each thyristor parameter before and after neutron irradiation is shown in Fig. 16 [Figure 16: see original paper]. It can be seen that the tested electrical parameters of the thyristors have obvious changes after neutron irradiation. As the thyristors are placed 20 cm, 40 cm, and 60 cm away from the neutron source respectively, the neutron flux received by the thyristors can be calculated as $4.3 \times 10^{11}$ n/cm$^2$, $1.07 \times 10^{11}$ n/cm$^2$, and $0.48 \times 10^{11}$ n/cm$^2$ respectively.

The forward and reverse leakage currents IDRM and IRRM, which represent the blocking characteristic of the thyristor, increase to 637 µA, 528 µA, and 452.5 µA respectively for IDRM, and to 615.5 µA, 458 µA, and 422.5 µA respectively for IRRM. The on-state voltage drop UTM of the irradiated thyristors at different distances from the neutron source increases from 1.26 V to 4.325 V, 1.84 V, and 1.415 V respectively. Additionally, the values of Qrr and trr show significant reduction after neutron irradiation, as shown in Fig. 16d and

Fig. 16e, meaning the severity of the reverse recovery process is reduced and its duration is shortened after neutron irradiation.

In terms of impact degree, the blocking characteristic and reverse recovery characteristic of irradiated thyristors have been seriously affected, with hundredfold changes in their key parameters. Meanwhile, the conducting performance of the most severely irradiated thyristors has also decreased by about 3/4, as shown by the rise in on-state voltage drop UTM. Moreover, it can be concluded from Fig. 16 that the higher the irradiation flux received by the thyristor, the greater the impact on the thyristor electrical parameters and the greater the performance damage to the thyristor.

## V. Simulation Analysis of the Influence of Neutron Irradiation on QPS

The QPS is a crucial system for both superconducting magnets and fusion devices. It is impractical and risky to conduct irradiation experiments on the actual system. With the development of simulation technology and PLECS software, simulation accuracy has been greatly improved, enabling effective simulation of real QPS electrical performance in normal and operating states. Therefore, the simulation method is used to study the impact of neutron irradiation on QPS.

The influence of high-dose neutron irradiation on the thyristor stack may bring huge risk of breakdown to the QPS in fusion devices. Hence, it is of great significance to analyze the impact of neutron irradiation on QPS. Conducting irradiation experiments on QPS is risky and unreasonable, so a simulation method for prediction is adopted in this paper. The simplified circuit of QPS in PLECS software and the typical working current waveform are shown in Fig. 17 [Figure 17: see original paper] [36].

According to the results of irradiation experiments, both static parameters (IDRM, IRRM, UTM) and dynamic parameters (Qrr, trr) changed significantly after irradiation and may cause QPS failure.

The thyristor stack will be turned off and remain in blocking state when QPS is in steady state, during which the capacitor in the commutation circuit should be charged to the preset voltage. Therefore, the increase in IDRM may cause a decrease in capacitor voltage. Once the capacitor voltage drops to a certain value, the pulse current generated by the commutation circuit cannot force the current in VCB down to zero, resulting in QPS failure. The larger the IDRM, the shorter the time for the capacitor voltage to drop to the threshold. The breaking failure waveform is shown in Fig. 18 [Figure 18: see original paper]. The capacitor does not remain in the reverse blocking state, so IRRM has almost no obvious impact on QPS.

The thyristor stack will be turned on and remain in on-state condition only when the commutation circuit generates the reverse pulse current. Therefore, the change in UTM will affect the characteristics of the pulse current, as indicated in Fig. 19 [Figure 19: see original paper]. It can be seen that the pulse currents before and after irradiation are almost the same, suggesting that the impact of UTM change on QPS is relatively minuscule.

Theoretical analysis and experimental verification show that the reverse recovery characteristics of the thyristor are significantly changed. Qrr and trr decrease after irradiation, meaning the reverse recovery speed of the irradiated thyristor is accelerated. In QPS, multiple thyristor devices are connected in series to improve the withstand voltage capability. As each thyristor receives different neutron irradiation doses, the change ratio of the reverse recovery speed differs. The voltage waveforms of series-connected thyristors are shown in Fig. 20 [Figure 20: see original paper]. It can be seen that before neutron irradiation, the series voltage sharing effect of the four thyristors is good. By contrast, after neutron irradiation, higher recovery voltage is applied to the thyristor with faster reverse recovery speed. This unexpected event will cause device damage due to overvoltage, leading to damage of the entire thyristor stack and ultimately resulting in failure of QPS quench current interruption and transfer actions.

## VI. Summary

This paper studies the influence of neutron irradiation on high-power thyristor devices in fusion environments. By constructing the relationship between the internal physical structure and external electrical parameters of the thyristor, the effect of neutron irradiation on the thyristor is comprehensively analyzed. To verify the correctness of the theoretical analysis, a series of targeted thyristor physical simulations and neutron irradiation experiments were carried out. The simulation and experimental results indicate that the dynamic and static characteristics of the irradiated thyristors have obviously changed, which is consistent with the theoretical analysis. Additionally, the effect of irradiated thyristor changes on QPS in fusion devices is simulated using PLECS software. The simulation results show that UTM change has little impact on QPS, while the increase in IDRM may lead to VCB breaking failure as the preset voltage of the capacitor in the commutation circuit decreases, and inconsistent reverse recovery speeds of irradiated thyristors will lead to high reverse voltage in devices, which may cause breakdown and reduce the reliability and stability of QPS. In future mature fusion devices, neutrons would be confined in the main engine, and the irradiation problem might be greatly improved.

In future work, the assessment of safe operational limits for thyristors in irradiation environments will be deeply studied to further ensure the reliability of operating thyristors in QPS of Tokamak fusion devices, including irradiation-sensitive area localization, the changing relationship between neutron flux and key electrical parameters, and the degradation threshold of those parameters.

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*Note: Figure translations are in progress. See original paper for figures.*