A Complementary Survey of Radiation-Induced Soft Error Research: Facilities, Particles, Devices and Trends

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Abstract— **Soft errors caused by external radiation sources have historically affected the reliability of electronic devices. The radiation effects community has dedicated significant effort to understanding and addressing circuit failures, offering insights and techniques for their mitigation. Nevertheless, the broad nature of the radiation field research poses challenges to identifying the overall progress made by its community. This survey analyses a collection of 174 out of 295 selected articles, published between 2018 and 2022, with the aim to characterise the current stage of radiation-induced errors research. The focus is on experimental research considering radiation effects on electronic devices, excluding from consideration works that solely involve simulation and radiation modelling. Furthermore, it limits the analysis scope to effects of particle radiation originating from space, overlooking device- or material-related radiation sources such as those due to specific chip packaging or used solder bumps. The survey contributes to the characterization of particles, facilities, and devices used in current radiation-induced experiments, bringing both quantitative and qualitative analyses of the literature over the past five years. Lastly, this review reports trends in radiation research, revealing which particles are currently considered most relevant, highlighting the most used facilities available for testing radiation effects, and emphasising which technological nodes and/or devices are addressed preferentially with regard to radiation-induced effects studies.**

Index Terms— **Radiation; radiation effects; radiation facilities; soft errors.**

I. INTRODUCTION

In the 120 years since Maria Skłodowska-Curie published the first systematic study of radioactivity in her PhD Thesis [1] huge amounts of knowledge have been amassed by the research of such phenomena. This knowledge is the basis of numerous methods and procedures essential to current human activities: from enhanced healthcare to air- and spacecrafts; from structural building analysis to fossil dating; and many other uses.

In particular, electronic equipment interacts with natural or artificial radioactivity in multiple ways. As electronics, and more specifically computational systems, become widespread in every field of human activity, dealing with radiation-induced effects in electronics is mandatory to develop reliable systems. The radiation sources affecting electronic parts may originate outside the Earth (cosmic rays), or be produced by natural or man-made materials.

Cosmic rays consist of high-energy particles, mostly protons, alpha particles, and heavy ions atomic nuclei [2] constantly entering Earth's atmosphere. Upon entering the atmosphere, they interact with it, creating a cascade of many secondary particles, such as muons, neutrons, and pions, leading to the formation of an extensive air shower [3]. The interaction of cosmic rays with materials can have many effects, including high electric charge doses [4] and atoms ionisation [5].

In electronic devices, the interaction with cosmic rays can produce harmful effects, categorised under phenomena collectively known as Single Event Effects (SEEs), also known as soft errors [6]. SEEs can manifest when a single ionising particle strikes a sensitive region within the electronic device, generating a current surge. If this surge occurs around sequential logic located near the drain of a transistor in its off-state mode, it holds the potential to modify the value stored in memory cell(s) without the occurrence of a specific write operation, thus leading to a Single Event Upset (SEU). On the other hand, if the surge occurs around combinational logic, it can propagate through the circuit, giving rise to a Single Event Transient (SET) that may propagate to connected circuits [7].

The susceptibility of an integrated circuit to SEEs can vary depending on the electronic device. Several works have investigated the impact of radiation-induced errors in electronic devices, ranging from cryptography hardware implementations on SRAM-based FPGAs [8, 9] to the running of modern machine learning algorithms [10–12]. For instance, Zhang and Li [13] suggest that smaller devices or those operating under reduced voltage supply are more susceptible to radiation-induced errors. Various techniques have been recently proposed to mitigate the impact of radiation-induced errors. These include the use of error-correcting codes [14], the employment of radiation-hardened materials and design techniques [15], the incorporation of redundant circuitry coupled to voting strategies for decision taking [16], and more recently the use of specialised compiler-based techniques [17]. In this context, engineers know they must prioritise reliability to prevent catastrophes, especially in safety-critical applications [18].

Due to the unpredictable nature of cosmic rays and the inability to control their initial energy, employing particle accelerators emerges as a preferable choice for investigating SEEs. Particle accelerators are machines designed to boost subatomic particles to high speeds, which is typically achieved through a succession of dedicated structures. These

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structures, often employing electric and/or magnetic fields, serve to augment a particle's velocity and kinetic energy as it traverses them [19]. Particle accelerators enable scientists to investigate the effects of particle collisions within electronic devices, facilitating tasks such as assessing a device's vulnerability to radiation or validating novel mitigation techniques.

Although several works delve into single event effects and employ particle accelerators, there exists a gap in providing a comprehensive overview of contributions from the radiation research community. Moreover, there is a deficiency in fundamental information on the topic, including guidance on selecting suitable facilities for specific particles or determining the most pertinent particle for evaluating a given device or technology. This survey contributes to the characterisation of particles, facilities, and devices employed in current radiation-induced experiments, offering both quantitative and qualitative analyses of the published literature spanning from 2018 and 2022, as well as trends that the radiation community is following. This period was selected since the current literature already contains encompassing similar surveys for previous periods, see details in Section II.. To keep the size of the discussion manageable, this work omits the consideration of papers that address cumulative effects such as total ionising dose (TID) or displacement damage (DD), focusing mostly on articles related to single event effects (SEEs).

The rest of this paper is organised as follows. Section II. provides an overview of previous related surveys and elucidates the distinctive characteristic of this survey compared to them. Section III. outlines the methodology employed for article selection, along with the reasons for the conducted article exclusions. Next, Section IV. presents a quantitative analysis, while Section V. delves into a qualitative analysis, drawing connections to the quantitative findings. Moving forward, Section VI. describes the identified trends in the reviewed radiation works. Finally, Section VII. brings about some conclusions and points out some direction for future work in this and other surveys.

II. PREVIOUS RELATED SURVEYS

The literature encompasses several surveys that explore the reliability of electronic devices under radiation-induced effects. These range from investigating soft error impacts on sea-level semiconductor devices to exploring techniques aimed at protecting electronic devices and mitigating soft errors.

Heijmen [20] provided a seminal historical survey of the literature on the soft error rate (SER) of semiconductor devices at sea level. The SER problem was first detected in DRAMs in the 1970s, evolving to SRAMs and later including logic circuits, as technology nodes scaled. The survey explores various topics, including: (i) radiation sources that generate ionising particles in semiconductors; (ii) the physical mechanisms leading to data bit upsets; (iii) works on soft error modelling, simulation, and testing methods; (iv) techniques proposed to enhance the soft error rate sensitivity of circuits; and (v) the influence of technology scaling on the SER. The survey also delves into the SER challenges in deep-submicron designs in the coming years. However, this survey is over 20 years old, and its analysis of impacts is outdated, no longer aligning with the reality of current electronic circuits. Furthermore, the survey only addresses three radiation sources: alpha particles, high-energy cosmic neutrons, and neutron-induced boron fission. Unlike it, the survey proposed herein provides a comprehensive and up-to-date quantitative and qualitative analysis of all major particles currently employed in radiation-induced research.

Mittal and Vetter [21] introduced a survey addressing techniques for modelling and improving the reliability of computing systems. Their approach is more generic than a typical soft error survey, as it incorporates more diverse aspects other than SEs. It provides recent data on SE scaling. For instance, Authors highlight that at a 16 nm technology node, the soft-error failure rate was expected to be over 100 times higher than at a 180 nm node. Another significant finding is that, as transistor sizes shrink, components become more susceptible to SEs. The scaling of operating voltages leads to a steady decrease in the critical charge required to flip a stored value. These observations are in line with the results presented by Chatterjee [22], who explores trends in SE scaling. Furthermore, the survey [21] reveals that in atmospheric radiation, lower energy particles occur far more frequently than those of higher energy. Consequently, as new technologies pledge the use of reduced supply voltages, more particles can become prone to cause SEs. Due to the capacity of a single energetic particle to lead to a burst of consecutive errors, the probability of multi-bit errors is also on the rise [23].

In another survey, Mittal [24] focused on techniques aimed at mitigating soft errors in non-volatile memories (NVMs). However, this work does not explore soft errors induced by radiation, since the investigated NVMs, including Phase Change Memories (PCMs) and spin transfer torque (STT-RAMs), are insensitive to radiation-induced SEs. In fact, investigated soft errors are caused by factors such as resistance drift in PCMs. The findings indicate that the presented techniques are applicable to other NVMs, such as Resistive RAMs (RRAMs). Additionally, the paper advocates the usefulness of architecture-level techniques alongside device-level techniques for correcting SEs in NVMs.

Sayil [25] conducted a survey that specifically reviews circuit-level soft error mitigation techniques, focusing on combinational logic circuits affected by SETs and SEU masking effects, and their evolution with technology. This survey is driven by the changing landscape of technology, including: (i) reductions in node capacitances; (ii) decreases in supply voltage; and (iii) the increasing density of chips. According to it, the primary causes of SE generation are atmospheric neutrons and alpha particles, with the latter predominantly emitted due to the radioactive decay of uranium and thorium impurities within the chip packaging. This suggests that neutron-induced boron fission may no longer be a concern, as previously mentioned when commenting on Heijmen's survey [20], due to advancements in technology implementation techniques. Furthermore, the circuit-level methods explored in this survey include: (i) Triple Modular Redundancy (TMR); (ii) Logic duplication plus buffering; (iii) Temporal redundancy methods; (iv) Driver sizing; (v) Mitigating techniques based on the use of lower threshold

Table I. A qualitative comparison of soft error surveys. Legend: SE - Soft Error; NM - Not Mentioned in survey; NA - Not Applicable.

Survey	Soft error coverage	Approach	Particles	Devices / Technologies	Observations
Heijmen [20] 2002	Sea-level radiation effects	SE sources, mechanisms, modeling, simulation and test	α, cosmic rays, neutron-induced boron fission	DRAMs, SRAMs, logic / NM	Seminal survey
Mittal & Vetter [21] 2016	Not limited to radiation-induced SEs	Techniques to improve reliability of computing system micro-architectural components	Atmospheric radiation	Registers, functional units, cache, main memory, recent NVMs / Planar & 3D CMOS	Out of NVMs, flash memories are ignored
Mittal [24] 2017	SEs caused by non-radiation effects (e.g. resistive drift, write/read heating)	Techniques to address recent NVM technologies	NA	PCMs and STT-RAMs / NM	Architecture-level coupled to device-level techniques
Sayil [25] 2019	Generic	Circuit-level SE mitigation (TMR, DTMOS, CVSL, low pass)	α, neutrons	Logic gates, flip-flops / Planar CMOS	DTMOS plus driver sizing recommended
Oz & Arslan [26] 2019	Generic	Techniques based on redundant software multi-threading	α, cosmic rays, thermal neutrons	Multi-threading processors / NM	Techniques claimed as applicable also to permanent faults
Kasap *et al.* [27] 2020	SEs in space applications	Hw redundancy, Sw redundancy, combined Hw/Sw redundancy	Neutrons, heavy ions	LEON3 soft processor in FPGAs / planar CMOS and advanced nodes	Techniques claimed as extensible to other soft processors
Ko [28] 2022	Generic	Sw-only SE hardening techniques and Sw considering the specific Hw nature	α, neutrons, muons, cosmic rays	GPPs and SPPs / NM	Fault injection alone is insufficient, requiring radiation campaigns for better test coverage
This survey 2023	**Sea-level and space radiation effects**	**Complementary survey on radiation-induced SEs (facilities, particles, devices, trends)**	**Encompassing (α, neutron, laser, proton, X-ray, electron, muon, γ, photon, pion, heavy ions)**	**Irradiated electronic devices in general, including from discrete devices to memories, processors and FPGAs, to complete electronic systems / Tech node range: from 500 nm to 7 nm**	**Many works address heavy ions. Trends suggest that the emphasis is on investigating smaller, lower power devices**

transistors, notably Dynamic Threshold Voltage MOS (DTMOS); (vi) Cascode Voltage Switch Logic (CVSL); and (vii) Utilisation of the low-pass filter characteristics of transmission gates. All the revised techniques are qualitatively compared based on trade-offs involving area, delay, and power overheads. The Author concludes that the best characteristics are achieved by combining DTMOS and driver sizing. However, the latter necessitates the use of either triple-well CMOS or SOI technologies and requires a voltage supply of less than 0.6V.

Another review, provided by Oz and Arslan [26], focus on software thread-level mitigation techniques. The survey introduces redundant multithreading (RMT) implementations at different architectural levels, showing their application as a fault tolerance method for mitigating soft errors induced by radiation, with specific mention to alpha particles, cosmic rays and thermal neutrons.

In terms of applied mitigation techniques, Kasap [27] conducted a survey presenting methods to harden a LEON3 softcore processor in FPGA devices, addressing both FPGA configuration and the system user memories. Authors claim that the revised techniques can be extended for application to any soft core processor implemented in SRAM-based FPGAs. All investigated hardening techniques employ some manner of redundancy, whether in circuit or in software. These techniques, categorised into four classes within the survey, include: (i) spatial redundancy (e.g., TMR); (ii) temporal redundancy (e.g., memory checkpoints); (iii) combined spatial and temporal redundancies (e.g., new system on reconfigurable integrated circuit design flow); and (iv) spatial, software, and information redundancies combined. Most techniques involve partial or total FPGA reconfiguration to tackle FPGA bitstream SEUs. It's noteworthy that the survey values mostly techniques that have been validated through real radiation campaigns.

Finally, Ko [28] proposes a survey that categorises and compares software-based redundancy techniques for protecting general or specific-purpose processors against soft errors. The motivation comes from the high costs associated with hardware hardening, particularly in resource-constrained embedded systems. The surveyed literature encompasses pure software approaches, including instruction duplication, software signature control flow checking, and mixed and optimised variations of these techniques. Furthermore, methods such as software profiling are demonstrated in optimising software-based redundancy techniques for mitigating soft errors. The Author concludes that the validation of software-based protection schemes requires a balance between accuracy and performance. Additionally, fault injection alone is insufficient, as soft errors are induced by external radiation. However, the Author did not present any research comparing the fault coverage of different software-level protection schemes under real radiation campaigns.

Summarising this Section discussion, Table I brings a qualitative comparison of the revised surveys and puts them in perspective with the proposed survey, whose characteristics are present in the Table´s last line. Note that this line highlights both the number of particles covered in this survey and the broad range of technological nodes included, which span from 500 nm (0.5 μm) to 7 nm.

III. METHODOLOGY

This Section outlines the methodology employed to gather and select articles discussed in this survey. For this purpose, we utilised the "Scopus advanced search" functionality (`https://www.scopus.com/search/form.uri?display=advanced`) on the Scopus website to identify articles meeting our specified criteria. The search string crafted for this work is shown in Algorithm 1.

Algorithm 1 Scopus search string.

```
(TITLE-ABS-KEY("radiation"))
AND (TITLE-ABS-KEY("bitflip")
OR TITLE-ABS-KEY("bit flip")
OR TITLE-ABS-KEY("Single Event")
OR TITLE-ABS-KEY("Single-Event"))
AND (TITLE-ABS-KEY("proton")
OR TITLE-ABS-KEY("neutron")
OR TITLE-ABS-KEY("heavy ion")
OR TITLE-ABS-KEY("laser")
OR TITLE-ABS-KEY("x-ray")
OR TITLE-ABS-KEY("muon")
OR TITLE-ABS-KEY("electron")
OR TITLE-ABS-KEY("alpha"))
AND NOT TITLE-ABS-KEY("simulation")
AND (SUBJAREA(COMP) OR SUBJAREA(ENGI))
AND (LANGUAGE(English))
AND (DOCTYPE(ar) OR DOCTYPE(ip))
AND PUBYEAR > 2017
```

The search string started with terms associated with radiation and single events, encompassing SEE, SEU, and SET, which are the keywords of this survey. Then, some particles used in acceleration facilities were included. Note that the intention is to compile articles relevant to the fields of computer science and engineering. Moreover, these articles must be written in English and hold the status of either "article" or "in press".

The search string was run on March 6, 2023, identifying more than 300 articles potentially relevant. To restrict the analysis to a five-year period, articles from 2023 were intentionally excluded since it did not constitute, at the time, a full year. This resulted in a dataset of 295 articles. Following the Scopus search, the article were downloaded and a spreadsheet was compiled with the basic results for each article. Next, articles were revised, to determine which ones met or did not meet this survey´s specific requirements, formulated as follows:

- Articles containing particle acceleration and collision facilities involving electronic devices, which aim to investigate phenomena such as single-event effects, single-event upsets (i.e., bit flips) and single-event transients.
- Articles falling into the following categories were excluded from our analysis:
  - ✓ Simulation-only articles;
  - ✓ Articles relying on radiation modelling only (we focused on works that employ particles accelerated in facilities);
  - ✓ Articles that, despite featuring physical experiments, omitted crucial details about the facility, particles, or specific electronic devices under test.

The outcome was a set of 174 articles that satisfied the established criteria, and these articles constitute the focus of this survey.

IV. QUANTITATIVE ANALYSIS

This Section conducts a quantitative analysis of radiation-induced soft error research from the past five years. The analysis encompasses the entire dataset of 174 articles compiled using the criteria from established in the previous Section that correspond to references [29–202]. A major objective is to unveil the number of published articles, providing insight into the size of this research community. Furthermore, understanding which are the preferred communication channels not only helps new researchers focus their own studies but also guides them in targeting specific journals for publication. Also, it is crucial to identify the most active countries within this community to foster potential partnerships and determine the facilities employed for conducting radiation campaigns. Lastly, this Section delves into the most commonly used particles to assess the impacts of radiation on electronic circuits.

A. *Annual Number of Published Articles*

Given the global impact of the COVID-19 pandemic within this five-year period, the annual distribution of research studies may be relevant. Figure 1 illustrates the quantity of articles published per year based on our search criteria.

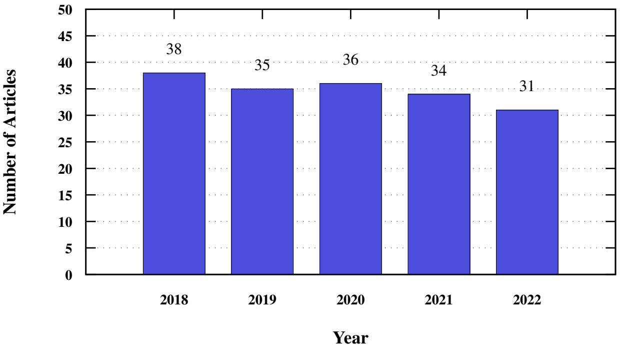

Fig. 1 Number of publications per year.

The results indicate a consistent number of articles published throughout this period, aligning with an average of 35 articles per year. Note that some of the articles published in 2020 were grounded in experiments and simulations conducted in 2018 and 2019, with subsequent data analysis carried out in 2020. This suggests that the pandemic had no significant impact on the overall quantity of articles published during this five-year period.

B. *Journals Targeted by Articles*

Concerning the preferred communication channels within the radiation research community, Figure 2 depicts the number of publications per journal. The findings highlight two main journals, IEEE Transactions on Nuclear Science (TNS) and Microelectronics Reliability (MR). Notably, TNS exhibits a significant publication volume compared to any other journal. One possible explanation is that TNS publishes special issues based upon manuscripts presented at the RADiation and its Effects on Components and Systems (RADECS) Conference. This conference, held annually in Europe, serves as a scientific and industrial forum focusing on the effects of radiation on electronics and photonic materials, devices, circuits, sensors, and systems. A notable criterion for acceptance at this conference is a strong emphasis on presenting works with experiments describing result from real radiation campaigns. On the other hand, Microelectronics Reliability is a journal with a broader scope, encompassing topics related to the reliability of microelectronic devices. This includes the measurement, evaluation and mitigation of failures induced by radiation. Consequently, it serves as a communication channel catering to the radiation and systems reliability communities.

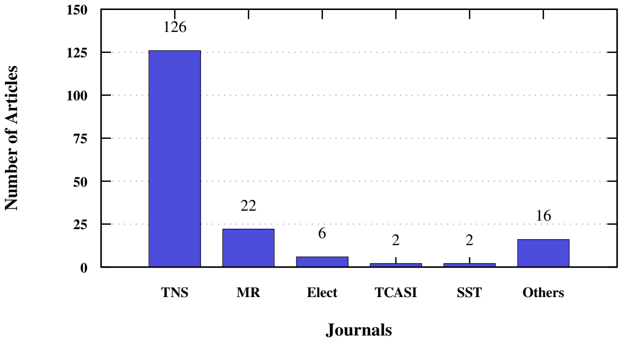

Fig. 2: Publication per journals – **TNS**: IEEE Transactions on Nuclear Science, **MR**: Microelectronics Reliability, **Elect**: Electronics (Switzerland), **TCASI**: IEEE Transactions on Circuits and Systems I, **SST**: Semiconductor Science and Technology.

C. *Radiation Facilities and Country Locations*

Figure 3 displays a heat map illustrating the distribution of publications by country. This map elucidates the nations that have exhibited the highest number of publications in radiation-induced research over the past 5 years. Unsurprisingly, United States of America and China emerge as the primary contributors, reflecting their substantial investments in research and development in this field [203].

In Europe, a notable number of experiments were also conducted, with Belgium and France standing out as significant contributors. Japan helped push the Asian continent forward in this field with 17 publications. In contrast, Brazil stands as the sole representative from South America, with four publications, while South Africa is the only African representative with just one publication. The global distribution of these research endeavours underscores the international collaboration and diverse geographical representation in the field of radiation-induced research, as depicted in Figure 3.

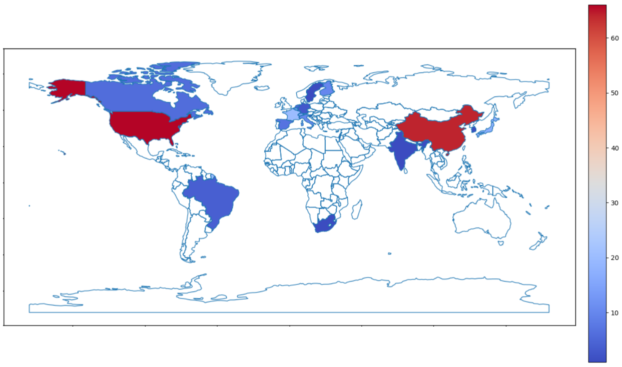

Fig. 3 Heat map indicating the number of publications by countries.

In terms of facilities, Table II shows the paper-to-facility distribution, arranged by the number of publications each of these has generated, restricted to facilities mentioned by four or more articles. Two Chinese facilities, the HI-13 in Beijing and the HIRFL in Lanzhou, lead the list; several papers mention the use of both facilities. Follows the HIF-UCL, the heavy ion facility at the Université Catholique de Louvain in Belgium and some major labs in USA (the Los Alamos Neutron Science Center facility - LANSCE and the Lawrence Berkeley National Laboratory - LBNL). A variety of other countries contribute with the rest of mentioned facilities in Europe, Asia and Americas.

It is interesting to note that, although the United States leads in the number of experiments (Figure 3), the extensive range of facilities contributes to a dispersion in the count of articles published per facility. Some notable facilities in the United States comprise the Los Alamos Neutron Science Center (LANSCE), the Lawrence Berkeley National Laboratory (LBNL), and the U.S. Naval Research Laboratory (US-NRL).

In Europe, all experiments conducted at CERN were attributed to Switzerland. Additionally, in France, many experiments took place at the GEnérateur à NEutrons Pulsés Intenses (GENEPI2) neutron source. The ISIS Neutron and Muon Source (ChipIr) in the UK, along with facilities in Spain, Italy, and the Netherlands, further contribute to the robust development of the European radiation research community.

D. *Particles*

A key aspect involves understanding the specific particles employed in facilities to induce soft errors due to radiation in electronic devices. This knowledge unveils the intended application environments for these devices, such as space or sea-level, and provides insights into the challenges that researchers presently identify in the development of electronic device technology, which these particles can help clarify.

Table III provides a summary of particles and the frequency with which they are mentioned in the surveyed papers. Note that the total number of papers (211) exceeds the 174 articles selected based on the criteria outlined in Sec-

Table II. Relationship between facilities and publications originating from these in the years 2018-2022.

Number of Papers	**Facility Name**	**Country**	**Articles**
20	HI -13	China	[175], [181], [191], [31], [33], [34], [35], [39], [43], [69], [71], [79], [92], [94], [96], [109], [112], [124], [135], [155]
20	HIRFL	China	[145], [161], [162], [174], [181], [191], [34], [35], [43], [58], [69], [71], [73], [78], [80], [94], [96], [109], [114], [136]
14	HIF-UCL	Belgium	[163], [172], [189], [199], [50] [84], [98], [105], [118], [130], [144], [147], [150], [156]
13	LANSCE	USA	[152], [182], [187], [30], [37], [44], [47] , [66], [77], [85], [90], [128]
12	LBNL	USA	[93], [185], [195], [46], [49], [89], [117], [120], [129], [138], [141], [154]
10	CERN	Switzerland	[158], [180], [192], [86], [88], [104], [105], [107], [139], [140]
10	USNRL	USA	[157], [164], [195], [49], [56], [87], [89], [119], [121], [123]
9	RADEF	Finland	[41], [166], [186], [192], [33], [86], [97], [139], [148]
8	NSSC	China	[169], [181], [31], [71], [73], [80], [110], [113]
8	GENEPI2	France	[48], [167], [168], [62], [63], [76], [115], [146]
8	ISDE-SE-VU	USA	[193], [194], [196], [42], [45], [91], [122], [149]
7	TAMU	USA	[101], [127], [159], [185], [201], [116], [129], [133]
6	Peking University	China	[161], [32], [54], [58], [92], [100]
6	ChipIr	U.K.	[190], [196], [36], [59], [70], [108]
5	ILL	France	[48], [165], [167], [168], [143]
5	INFN	Italy	[163], [53], [72], [125], [151]
5	TIARA	Japan	[173], [197], [102], [126], [142]
5	CNA	Spain	[48], [134], [186], [47], [66]
5	PSI	Switzerland	[165], [170], [177], [178], [61]
5	APS-ANL	USA	[195], [46], [82], [103], [148]
4	LAFN-USP	Brazil	[176], [179], [29], [51]
4	TRIUMF	Canada	[57], [75], [95], [133]
4	KVI - CART	Netherlands	[171], [186], [84], [105]

Table III. An account of particles and the frequency with which survey papers mention their use.

Number of Papers	**Percentage of total**	**Particle**	**Articles**
87	50.00%	heavy ion	[29], [31], [33], [34], [35], [39], [41], [43], [46], [49], [50], [51], [53], [58], [65], [69], [71], [73], [74], [78], [79], [80], [81], [84], [86], [89], [92], [93], [94], [96], [97], [98], [99], [101], [102], [104], [105], [107], [109], [110], [112], [114], [116], [117], [118], [120], [124], [125], [126], [127], [129], [130], [133], [135], [136], [138], [142], [144], [145], [147], [148], [150], [151], [154], [155], [158], [159], [161], [162], [163], [166], [172], [173], [174], [175], [176], [179], [180], [181], [185], [186], [189], [191], [195], [197], [199], [201]
43	24.71%	neutron	[30], [36], [37], [38], [44], [47], [48], [52], [55], [57], [59], [62], [63], [64], [66], [70], [75], [76], [77], [83], [85], [90], [95], [106], [108], [115], [128], [140], [143], [146], [152], [160], [165], [167], [168], [182], [184], [187], [190], [196], [198], [200], [202]
34	19.54%	laser	[31], [33], [45], [49], [56], [62], [71], [73], [78], [80], [86], [87], [89], [91], [101], [102], [110], [111], [113], [119], [121], [122], [123], [130], [137], [144], [157], [164], [169], [171], [181], [192], [193], [195]
33	18.97%	proton	[32], [35], [40], [42], [47], [48], [54], [60], [66], [72], [81], [84], [86], [92], [97], [100], [105], [129], [133], [134], [153], [154], [156], [165], [170], [171], [177], [178], [183], [186], [188], [194], [197]
8	4.60%	xray	[46], [53], [82], [97], [103], [148], [149], [195]
8	4.60%	alpha	[36], [57], [98], [141], [149], [159], [196], [200]
7	4.02%	gamma	[58], [84], [88], [97], [161], [179], [201]
5	2.87%	electron	[88], [131], [132], [139], [192]
3	1.72%	muon	[67], [68], [200]
1	0.57%	pion	[61]

tion III.. This discrepancy arises, of course, because certain articles present radiation experiments involving more than one particle. For instance, Clemente *et al.* [48] conducted experiments with both neutrons and protons, while Bosser *et al.* [148] used heavy ions and x-rays. The outcomes reveal a significant number of experiments conducted with heavy ions, followed by neutrons, lasers, and protons. Collectively, the remaining particles are mentioned in only 16.67% of the articles.

Half of the articles employ heavy ions to assess their influence on electronic devices. However, the category of heavy ions is extensive, encompassing various chemical elements. Figure 4 provides a heat map featuring the elements corresponding to ions employed in heavy ion experiments within the articles reviewed in this survey.

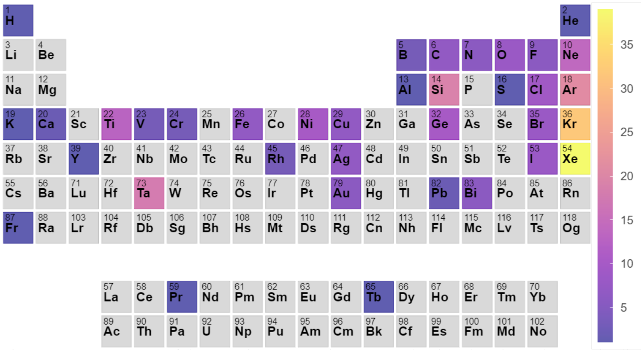

Fig. 4: Heat map of heavy ion experiments (obtained using the Periodic Trend Plotter Tool [204]).

The diversity of ions in Figure 4 is attributed to the common use of ion cocktails in various experiments. Ion cocktails are mixtures of ions of near-identical mass-to-charge (m/q) ratios. The injector mass-analysing magnet cannot separate the ions, so it ejects them together from the ion source [205]. When simulating the space radiation environment, it is crucial to consider beam modification and dosimetry, since the beam intensity must be low, and new processing techniques require more energetic beams, posing a challenge for accelerator and ion source physicists. The spectroscopic properties of the beam must be defined in each test run, and calibration and monitoring of parameters like homogeneity, flux, and fluence are necessary during irradiation. Time-saving solutions are also important in building irradiation facilities for space projects, since this decreases costs, and quick ion changes can be achieved with cocktail beams [206], making them the best option for space radiation simulations.

V. QUALITATIVE ANALYSIS

This Section brings a qualitative analysis of the research on radiation-induced soft errors conducted over the last five years. The objective is to delve into the nuances and characteristics of the surveyed studies, providing insights into how certain studies use particular particles to analyse their impact on electronic devices. Another goal is to establish connections between these studies and technology advances in electronic devices.

A. *Particles and Countries*

Research on bit flips has been consistently undertaken over the last five years. As demonstrated in Section D., the particles predominantly employed in the reviewed studies encompass heavy ions, neutrons, and protons. Heavy ions and protons are considered high-energy particles capable of penetrating materials and inducing ionisation. This characteristic makes them pivotal in comprehending the effects of space radiation. Furthermore, heavy ions are extensively employed due to their high linear energy transfer and their potential to induce single-event upsets in electronic devices.

Through a careful analysis of each particle, it becomes evident that heavy ions stand out as the preferred choice due to their capability to induce significant damage, enabling a prompt observation of their effects. This is particularly advantageous in radiation experiments, considering their costliness. This feature facilitates the planning of experiments, such as case studies, where there is a higher likelihood of obtaining results that reveal defects. In the United States, numerous articles have been published on the utilisation of heavy ions, with Texas A&M University (TAMU) and the Lawrence Berkeley National Laboratory (LBNL) serving as primary facilities for heavy ion research.

Neutrons, as uncharged particles, do not have a direct impact on electronic devices, except for thermal neutrons. These low-energy neutrons, with energy below 25 MeV, can undergo exothermic reactions with specific isotopes, particularly boron-10 in semiconductor devices [62]. Nevertheless, high-energy neutrons can interact with the atomic nuclei of materials, resulting in the emission of secondary ionising particles, either a charged alpha particle (+2) or a proton (+1) [83]. These ionising particles have the potential to alter internal logic states in electronic devices, leading to SEUs. Studies indicate that energetic neutrons are responsible for 95% of soft errors [57]. However, gaining access to neutron facilities can be challenging. In this context, France stands out in neutron incidence research, in part, due to the availability of suitable facilities (GENEPI2 and ILL).

Similar to neutrons, protons also have a particular significance given their substantial impact within the atmosphere [62, 111]. Therefore, works involving protons exhibit a wide range, spanning applications in deep learning processors [188] and error correction codes [48] to the assessment of highly complex circuits, such as mixed-signal ASICs [101]. It is noteworthy that a substantial amount of research on protons is conducted in Europe, given that facilities are distributed across multiple countries, including Switzerland (Paul Scherrer Institute, PSI), the Netherlands (Kernfysisch Versneller Instituut, KVI-CART), and Spain (Centro Nacional de Aceleradores, CNA).

Lasers, in turn, consist of focused photon beams and are preferred for their experimental convenience. The United States has conducted a greater number of laser experiments than any other country, indicating their emphasis on cost reduction. As highlighted in Hales *et al.* [93], there is an increasing interest in using lasers to simulate excitation-induced SEEs caused by heavy ions, particularly in cases where access to heavy-ion test facilities is limited. This accounts for the widespread adoption of laser-based experiments globally.

Some works, including Ryder *et al.* [195] and Ildefonso *et al.* [89], have identified x-rays as a viable alternative for reproducing single event effects induced by heavy ions. However, due to variations in dosimetry between heavy-ion and laser sources, the outcomes of pulsed-laser-induced SEEs are predominantly qualitative. Consequently, researchers endeavour to establish a quantitative relationship between measurements induced by heavy ions and lasers, aiming to correlate experiments conducted with lasers to those with heavy ions.

As devices decrease in size and incorporate a larger number of transistors, the occurrence of SEUs per unit area increases [77]. In such a scenario, particles such as alpha become increasingly significant. As elucidated by Chandrashekhar *et al.* [57], the reduction in charge induced by alpha particles is similar to that caused by neutrons. However, in this scenario, charges result from the Coulombic interaction between the alpha particle and silicon atoms as the former traverses the floating gate. These particles exhibit robust ionising capabilities, generating a multitude of electron-hole pairs within the crystalline lattice of silicon.

Regarding other particles that are less commonly employed in radiation experiments for electronic circuits, electrons demand high energy, and photons have the potential to harm the sample, making them less suitable for specific applications. These factors contribute to their limited usage. On the other hand, muon and pion accelerators are more accessible than facilities for protons and neutrons. However, they hold lesser significance due to their reduced interaction with electronics devices. Nonetheless, Kato *et al.* [200] have shown that muons, particularly negative ones, can induce SEUs and multiple-cell upsets (MCU). As semiconductor components scale down, the probability of muon affecting devices increases due to the reduction in critical charge required for low-linear energy transfer (LET) events. In this regard, Japan is notably concerned about SEUs caused by muons, as evidenced by the majority of related articles originating from the country [67, 68, 200].

B. *Impacts from Circuit Technology*

The effects of radiation on electronic circuits are intricately linked to technological advancements, indicating that specific technological nodes are more or less utilised in particular applications. For instance, this survey illustrated that older technology nodes, specifically 130 nm and above, are widely employed in developing space applications. Fan *et al.* [155] present the work that utilises the oldest technology in this survey (500 nm or 0.5 µm CMOS technology). They introduce a radiation-tolerant circuit design for a four-channel 12-bit digital-to-analogue (DAC) converter. Chen *et al.* [73] also present development work targeted at space applications, specifically a radiation-hardened phase-locked loop (PLL) fabricated in a 130-nm technology node. Another device extensively utilised in space applications is the CMOS image sensor, employed as star trackers and image generators for astronomical observations [207]. To address this device, Cai *et al.* [71] evaluated the soft error susceptibility of digital peripheral circuits within commercial CIS fabricated in 180 nm (0.18 μm) CMOS process.

In the intermediate range of technological nodes, we find radiation research applied to FPGAs. For instance, Keren *et al.* [98] introduced a novel approach to analyse the effects of single-event transients in SRAM-based FPGA devices. The experiments were conducted using a 45-nm SRAM-based FPGA, and the results provide a cross-sectional analysis for both SET and SEU effects at low linear energy transfers. The experiments took place at the UCL Cyclotron (Belgium) accelerator, involving heavy ions and alpha source irradiation. Wang *et al.* [54], on the other hand, conducted proton experiments, while Fabero *et al.* [63] assessed neutron particles using 28-nm FPGAs. Both studies focused on characterising the sensitivity of FPGAs to single-event effects. Moreover, Cai *et al.* [78] also assess the radiation sensitivity of an FPGA. The significant distinction lies in the technological shift, transitioning from CMOS to FinFET through the evaluation of a 16 nm FinFET SRAM-based FPGA.

Over the past five years, transformations have occurred not only in technological nodes but also in applications exposed to radiation. Currently, assessments are underway to understand the impact of radiation in machine learning applications using devices with newer technological nodes. Maillard *et al.* [188] introduced a platform and design methodology aimed at facilitating radiation-tolerant deep learning acceleration on FPGAs. They devised a solution tailored for executing image classification applications on a 20-nm SRAM-based FPGA. The study included experiments involving a proton beam test with the ResNet-18 convolutional neural network (CNN) for image classification on the radiation-tolerant platform. Additionally, a technique called fault-aware training (FAT) was employed to effectively mitigate single-event effects in the CNN datapath. The findings indicate that employing FAT resulted in a 50% reduction in the overall cross-section of the radiation-tolerant system compared to the design without mitigation during training. In turn, Wang *et al.* [188] assessed the effects of SEUs on CNNs through the utilisation of a 28 nm SRAM-based FPGA. Similarly, Benevenuti *et al.* [29] evaluated a CNN on a 28 nm SRAM-based FPGA. They delved into the main aspects of vulnerability and accuracy degradation of an image classification engine implemented on SRAM-based FPGAs subjected to faults induced by heavy-ion accelerated irradiation.

Lastly, there is radiation research focusing on newer technologies, including FinFETs with nodes ranging from 16 nm down to 7 nm. Yaqing *et al.* [162] and Takeuchi *et al.* [173] conducted a characterisation of single-event effects on 16-nm bulk FinFETS, evaluating both single-bit upsets and multiple-cell upsets resulting from heavy ion irradiation. Their findings suggest that the parasitic bipolar effect remains a significant concern for 16-nm FinFET SRAMs, similar to planar SRAMs in previous technologies. Nevertheless, the charge-sharing effect is efficiently mitigated due to the narrow connection between the fin and the bulk region in FinFETs. Furthermore, it was observed that works involving recent technologies are carried out using simpler circuits. For instance, Huang *et al.* [174] performed a heavy ion experiment involving a 14/16 nm bulk FinFET inverter chains. Similarly, Ball *et al.* [196] investigated the reliability of inverters, NAND gates, and D flip-flop chains when subjected to radiation from neutron and alpha particles.

VI. TRENDS

This Section unveils the Authors' perspective on trends they believe the radiation community is currently embracing, drawing insights from the articles reviewed over the past five years.

The research into particle acceleration to investigate bit flips and single-event effects in electronic devices is marked by diverse trends, encompassing different radiation sources and international research collaborations. Heavy ions have emerged as a primary choice for simulating space radiation and assessing the resilience of electronic components. Notably, countries such as the United States, China, Belgium, and Switzerland, along with facilities like LBNL, HIRFL, HIF-UCL, and CERN, have been at the forefront of heavy ion experiments.

Heavy ions and protons pose significant challenges in microelectronics research. Their prevalence in space, coupled with their ability to penetrate materials and induce ionisation, has a profound impact on electronic devices. Looking ahead, we can expect an increasing dependence on these high-energy particles, particularly as space exploration and satellite technologies advance. Due to their capacity to swiftly induce substantial damage, heavy ions are likely to see heightened usage for prompt effect observation.

The use of laser experiments in radiation research is anticipated to expand, with USA taking a leading role and pursuing cost reduction. Researchers are increasingly working towards establishing a quantitative relationship between heavy-ion and laser-induced measurements to enable correlation with space radiation and heavy-ion experiments. The global interest in laser experiments has the potential to surge, particularly as they provide a means for assessing single-event effects induced by heavy ions.

Continued exploration of muons and pions is anticipated. Despite their lower interaction with electronic circuits, there is a growing concern regarding their potential to induce SEUs and MCUs. This concern is particularly noteworthy as semiconductor components scale down, increasing the susceptibility to muon-induced effects.

Looking ahead, it seems that the focus is shifting towards the research of lower-power and smaller-sized devices. This shift is driven by their increased susceptibility to soft errors caused by accelerated particles. In the last five years, there has been a rise in studies concentrating on SEEs in more advanced technologies, such as FINFET technology, while research on SRAMs has remained consistent, as they continue to be among the most affected components in electronic devices.

VII. CONCLUSIONS AND FURTHER WORK

This survey aimed to characterise the current state of radiation-induced research by reviewing 174 out of 295 articles selected among publications between 2018 and 2022. Through the analysis of these articles, we identified prominent trends, emphasising the active involvement of countries such as the USA, China, Belgium, and France, due to facilities such as LANSCE, HIRFL, HIF-UCL, and GENEPI2. Concerning the USA, there is a wide array of facilities available. Notably, experiments involving heavy ions and investigations on FPGAs and SRAMs were among the most common. In summary, this survey provided valuable insights into the evolution of radiation-induced research, an essential aspect for ensuring the reliability of electronic systems across various applications.

Along the process of conducting this survey, several interesting subjects appeared that could be the target of complementary surveys. Citing example subjects, a large amount of revised articles address the issue of particle angle of incidence with significant effect variations, specially in newer technologies that increase the use of tri-dimensional structures in electronic design. A second example is the question of variations of supply voltage, threshold voltage and other electrical parameters and the relationship of these with radiation. These certainly deserve a proper survey.

Other future works regard enhancement of the survey itself. For example, the original search string limited the results to journal papers only. The enhancement of the search string may lead to find some relevant missed papers such as [208], published in a conference, and also to discover additional facilities not listed in Table II. Nonetheless, this would entail a major rework of the survey, and a much larger account of works. Another idea would be to create an open repository, for example in Github, to contain the results of this survey and allow it to be extended with further consideration of publication years and types, facilities and particles, and even types of radiation effects.

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