EM-Fault It Yourself: Building a Replicable EMFI Setup for Desktop and Server Hardware

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Abstract—Electromagnetic fault injection (EMFI) has become a popular fault injection (FI) technique due to its ability to inject faults precisely considering timing and location. Recently, ARM, RISC-V, and even x86 processing units in different packages were shown to be vulnerable to EMFI attacks. However, past publications lack a detailed description of the entire attack setup, hindering researchers and companies from easily replicating the presented attacks on their devices.

In this work, we first show how to build an automated EMFI setup with high scanning resolution and good repeatability that is large enough to attack modern desktop and server CPUs. We structurally lay out all details on mechanics, hardware, and software along with this paper. Second, we use our setup to attack a deeply embedded security co-processor in modern AMD systems on a chip (SoCs), the AMD Secure Processor (AMD-SP). Using a previously published code execution exploit, we run two custom payloads on the AMD-SP that utilize the SoC to different degrees. We then visualize these fault locations on SoC photographs allowing us to reason about the SoC’s components under attack. Finally, we show that the signature verification process of one of the first executed firmware parts is susceptible to EMFI attacks, undermining the security architecture of the entire SoC. To the best of our knowledge, this is the first reported EMFI attack against an AMD desktop CPU.

Index Terms—Hardware Fault Attack, Electromagnetic Fault Injection, EMFI, SoC

I. INTRODUCTION

Nowadays, hardware security is an important requirement for chip vendors because all kinds of processors and systems on a chip (SoCs) are commonly used as trust anchor for devices and platforms. Immutable and sometimes even secret code or data is embedded into chips to verify and authenticate the boot process, protect intellectual property (IP), and enable technologies like digital rights management (DRM) or trusted computing. Modern SoCs include dedicated processor cores to handle security-related tasks and to protect digital secrets from the main cores, which execute untrusted and potentially vulnerable software components. Intel’s Converged Security and Management Engine (CSME) and AMD’s Secure Processor (AMD-SP) are security processors integrated into the main CPU die [1], [2]. Their attack surface is reduced by restricted communication interfaces, separated resources, and authenticity and integrity checks of code and data through cryptographic signatures. Nevertheless, recent research has shown that these dedicated security processors can be vulnerable to hardware attacks, such as fault injection (FI) [3].

FI attacks exploit the essential operating conditions of electronics required for their intended functionality. Altering the supply voltage or clock frequency and inducing energy by optical or electromagnetic (EM) effects may destabilize an integrated circuit or processor so that faults occur. As a prominent and easy-to-use technique, voltage glitching was applied to, e.g., circumvent firmware protection [3]–[5] and attack secure enclaves [6]–[8] on modern SoCs and CPUs. While voltage glitching affects the entire device under test (DUT), laser and electromagnetic fault injection (EMFI) are more precise and only affect a specific area of the DUT by locally injecting charge carriers or applying a quickly changing electromagnetic field, respectively. Furthermore, both techniques do not require an electrical connection to the power delivery network, potentially allowing non-invasive attacks. While laser FI requires optical access to the decapsulated chip backside, EMFI can be leveraged through a non-shielding package. When attacking a processor, both laser FI and EMFI are powerful methods to skip or alter instructions and change the software execution flow [9]–[11].

Traditional EMFI attacks exhibit three problems: Firstly, they require more complex setups than, e.g., voltage glitching, making the reliable reproduction of research results more challenging. Such setups, secondly, often comprise proprietary and/or undocumented components, hindering the reproduction of specific attacks and the reuse of hardware components for related use cases, such as laser FI. Thirdly, they often lack a large working area for attacking desktop and server hardware.

A typical setup consists of a pulse generator, an XYZ table, a motion controller, and software to orchestrate all components. Apart from self-built EM pulse generators [12]–[15], commercial devices are used frequently and were characterized and compared in [16]. For repeatability reasons, a setup additionally provides means of calibrating the probe position. However, such a sophisticated EM setup built from commercial off-the-shelf hardware has, to the best of our knowledge, not been described in past publications. On the other hand, commercially available setups do not support larger targets, such as server and desktop motherboards altogether (Riscure EM Probe Station 5 [17]) and lack the possibility to modify most of their parts.

Our Contributions. Consequently, this work contains the following two main contributions. Firstly, we build a setup for EMFI incorporating the NewAE ChipShouter as a pulse gen-
through an injection probe tip. The high current flowing
4 mm
ChipShouter with a
Fig. 1: Voltage and current of a pulse generated by the
high voltage of up to
electromagnetic field [12]: After a capacitor is charged to a
flip in the SRAM included in an embedded processor. Most
This EM field induces a voltage into the chip's inner circuits,
such, it belongs to the class of non-invasive FI techniques [18].
A. Electromagnetic Fault Injection (EMFI)
first EMFI attack on a subsystem of a modern x86 CPU.
attack and demonstrate that EMFI offers significantly higher
bypass a security-critical check in the boot loader, which gives
Data stored in SRAM is susceptible to EMFI as well.
control flow of code running on the ARM-based subsystem
how to prepare the device for EMFI.

The conducted experiments demonstrate that the intended
execution flow of code running on the ARM-based subsystem
can be altered to break out of a loop or even to bypass critical
checks. Data stored in SRAM is susceptible to EMFI as well.
Our target had previously been attacked using voltage FI to
bypass a security-critical check in the boot loader, which gives
an adversary full control over the device [3]. We reproduce this
attack and demonstrate that EMFI offers significantly higher
success rates than voltage FI. To the best of our knowledge,
this is the first EMFI against an AMD desktop CPU and the
first EMFI attack on a subsystem of a modern x86 CPU.

II. BACKGROUND
A. Electromagnetic Fault Injection (EMFI)
Electromagnetic fault injection leverages quickly changing
EM fields to trigger faults in a device in close proximity. As
such, it belongs to the class of non-invasive FI techniques [18].
This EM field induces a voltage into the chip’s inner circuits,
potentially resulting in transient or persistent faults, e.g., a bit-
flip in the SRAM included in an embedded processor. Most
EMFI tools follow the same working principle to generate the
electromagnetic field [12]: After a capacitor is charged to a
high voltage of up to 1200 V [13], it is quickly discharged
through the coil of the injection probe tip creates an EM field
around it and is characterized by its peak voltage, peak current,
rise time, fall time, and pulse width as depicted in Fig. 1.
Injection probe tips consist of a copper coil with a ferrite
core to concentrate the magnetic flux. The resulting pulse and
EM field are determined by the number of windings, winding
sense, copper wire diameter, and ferrite diameter [19]. Therefore,
probe tips need to be carefully selected to achieve desired
pulse characteristics for a specific target. Especially, the ferrite
diameter and distance to the DUT, as well as the number of
windings, should be tuned for best results. Furthermore, targets
may require removing the protective cover or heat spreader to
minimize the physical gap between the probe tip and the DUT
[20]. However, this process of decapsulation or delidding turns
the theoretically non-invasive EMFI attack into a semi-invasive
hardware attack [18].

B. AMD Secure Processor
Since 2013, AMD has embedded the AMD-SP into its
x86 processors and graphics cards. It has an ARMv7 core
with segregated SRAM and uses an SPI flash as non-volatile
storage. The AMD-SP’s proprietary firmware is cohosted on
the SPI flash along with the BIOS/UEFI firmware [1], [21]
The AMD-SP operates before the x86 cores are enabled and
boots as follows: At first, the immutable on-chip bootloader is
loaded and executed from the internal ROM. It then loads the
AMD root key (ARK) from the SPI flash and verifies it
by comparing it to an immutable hash. Afterward, the off-
chip bootloader (responsible for the rest of the boot process)
is loaded, its ARK signature verified, and executed [3]. This
process aims to ensure the authenticity and integrity of all
code run on the AMD-SP.
Thus, acting as the root of trust for the whole x86 system,
the AMD-SP poses an attractive target for fault injections,
effectively compromising the system’s chain of trust.

III. EMFI Setup
This section describes the general experimental setup built
to perform EMFI attacks. All details and source files needed
to replicate our setup can be found in the accompanying
repository of this work\(^1\). The setup (Fig. 2) consists of five
main parts: an EM pulse generator (blue), an XYZ precision
positioning stage with additional sensors (green), a motion
control unit (red), the main control unit (yellow), and the target
(violet).

We use NewAE’s ChipShouter as an EM pulse generator. It
can generate high voltage pulses up to 500 V with a pulse
width between 80 ns and 960 ns [22]. Pulses can be triggered
by internal trigger logic, an internal programmable pattern
generator, or a hardware trigger driven by external circuitry.
Our setup uses the latter to avoid the inherent delay of
software-based trigger logic. The ChipShouter communicates
via a serial interface that allows us to configure all its settings
from the main control unit.

\(^1\)https://github.com/fgsect/EM-Fault-It-Yourself
Faults injected by electromagnetic fields are location-dependent. Hence, the XYZ stage is used to move the injection probe tip to different positions. The process of probing the DUT’s surface at different positions for EMFI sensitive areas along a grid is called scanning in this work.

Our setup is based on a frame made of aluminum construction profiles that are easily adjustable and extendable. Three motorized linear stages (Standa 8MT175-100) are placed on the aluminum crossbar (orange), forming an XYZ positioning system. Each stage has a travel range of 100 mm, an accuracy of 2.5 μm and a maximum speed of 10 mm s⁻¹. All three stages combined are remountable along the crossbar, allowing us to place a complete computer and even a rack-mountable server under the crossbar. We can then move the XYZ stage along the X-axis until its travel range covers a chip’s surface. Smaller targets like computer mainboards or embedded boards can be screwed to the construction profiles using our custom 3D-printed mounting brackets and T-slot nuts. A 3D-printer with only mounted linear stages (Standa 8MT175-100) can be screwed to the construction profiles that are easily adjustable and extendable. Three motorized linear stages (Standa 8MT175-100) are placed on the aluminum crossbar (orange), forming an XYZ positioning system. Each stage has a travel range of 100 mm, an accuracy of 2.5 μm and a maximum speed of 10 mm s⁻¹. All three stages combined are remountable along the crossbar, allowing us to place a complete computer and even a rack-mountable server under the crossbar. We can then move the XYZ stage along the X-axis until its travel range covers a chip’s surface. Smaller targets like computer mainboards or embedded boards can be screwed to the construction profiles using our custom 3D-printed mounting brackets and T-slot nuts. A 3D-printer board (Bigtreetech SKR Pro v1.2) and its stepper motor drivers (based on Trinamic TMC2209) control the acceleration, speed, and holding torque of each stepper motor. The board acts as the motion controller, runs a slightly modified version of the open-source 3D-printer firmware Marlin [23] and can communicate via a USB-to-UART connection to the main control unit. As Marlin handles low-level real-time movement and positioning, the main control unit only has to issue high-level commands to move to an absolute or relative position.

The pulse generator, a microscope camera, and a thermal camera are mounted on the Z-stage using an aluminum adapter plate and 3D-printed mounting brackets. The microscope camera (positioning camera) is mounted along the ChipShouter and directed to the bottom to determine the target’s position relative to the origin of all stages. Its position relative to the different injection probe tips has to be measured after every tip change since the probe tips all have a different shape caused by manufacturing tolerances. To determine the offset between the center of the positioning camera and the center of the injection probe tip, an additional microscope camera (calibration camera) is used. The calibration camera is temporarily placed below the ChipShouter mount, pointing upwards so that it can provide a view from below to locate the center points of both positioning camera (Fig. 3a) and injection probe tip (Fig. 3b). A CPU die corner can then be accurately located using the positioning camera (Fig. 3c). To align a CPU die corner and the center of the injection probe tip, the exact position of the probe tip can be computed using the offset and the precise position of the die corner.

The maximum Z-depth can be measured by manually moving down in small steps until a piece of paper is nearly jammed between the injection probe tip and DUT. If the attack target needs active cooling, one or multiple fans can be attached to the frame and connected to the motion control unit for speed regulation. Temperature monitoring is provided by the thermal camera, which is directed to the DUT.

All mentioned devices are connected to the main control unit, a Raspberry Pi that manages and monitors the devices and orchestrates all actions such as manual movements or attacks. It runs a custom EMFI server application that provides a web interface to control the XYZ stage, start task scripts, as well as stream the positioning, calibration, and thermal camera information. Attacks and other repetitive tasks are implemented through Python task scripts, making the experiments easily adaptable and reproducible. They use an internal programming interface provided by the EMFI server that allows access to the pulse generator, sensor data, and movement control.

EMFI attacks often have a huge parameter search space composed of spatial position, timing, EM pulse characteristics, and possible target-specific parameters. Exploring these parameters is necessary prior to a successful attack but can take days to weeks. Hence, it is crucial that our server application tracks and logs all actions and responses of a target. Moreover, it makes all data available to the scripting API for evaluation.

IV. ATTACK SETUP

In the following section, we describe how we extended the setup to target the AMD-SP of an AMD Ryzen 5 2600 CPU and how the target itself had to be prepared. These modifications are target-specific and have to be implemented differently for other targets.
ON line of the PSU by controlling it through the Teensy via its USB-to-UART interface. It monitors the mainboard’s SPI bus to precisely time the fault injection and trigger an EM pulse through the hardware trigger input of the pulse generator.

D. Software

It is not trivial to detect whether faults were injected into a processor running proprietary software, as its behavior is only observable from the outside. To tackle this problem, we used a vulnerability in the on-chip bootloader to run arbitrary code on the AMD-SP [21]. Running our own test code allows us to examine the target for different fault types as described in Section V as well as to use the mainboard’s UART and SPI interfaces for communication.

The AMD-SP loads its firmware from the mainboard’s SPI flash chip, which also stores the BIOS/UEFI files. We use a DediProg EM100Pro-G2 flash emulator to replace the soldered flash chip and allow easy and fast modification of the SPI flash contents. Instead of replacing the SPI flash, it could also be reprogrammed non-invasively using a flash programmer and test clip. PSPTool [25] is able to analyze and modify those flash images easily.

E. Cycle Time

The cycle time is the amount of time it takes to move to a position, power up the system, run the attack, and fully power down the system so the procedure can start from the beginning. In some cases, a simple reset is sufficient, and a complete power cycle is not needed. As some attack parameters may have to be brute-forced, the cycle time should be kept as low as possible. The fastest way of resetting our target is to hijack the PS_ON line of the PSU by controlling it through the Teensy microcontroller board. To power up the target, only PS_ON of the PSU and PWR_SW (power switch) of the mainboard have to be enabled successively by the Teensy. On the other hand, the Teensy only has to disable the PS_ON pin for a power-down since it completely cuts the power.

V. EXPERIMENTS

In this section, we describe the conducted experiments, how we found areas susceptible to our EM pulses, and which faults were successfully injected while running our test code.

A. Scan for EMFI Susceptible Areas

Multiple parameters like the spatial position of the injection tip, pulse width, pulse voltage, and trigger delay must be determined for a successful attack. Brute-forcing all of these parameters is impractical because of the huge number of possibilities. Therefore, we first explored the die surface for EMFI susceptible regions using a counter loop that returns a wrong value in case of a successfully injected fault. This code increases a counter value stored in a register by looping a specified number of cycles while an EM pulse is triggered. Afterward, the counter is compared to an expected value, and
if the expected value and counter differ, we can assume that a fault was injected. During this experiment, the following procedure is repeated a hundred times at every intersection of a 1 mm grid on the CPU surface: At first, the injection probe tip is moved to the desired position, and the pulse generator is charged. Then, the Teensy powers on the target, simultaneously waits for SPI messages, and then triggers an EM pulse. Afterward, the main control unit checks if a fault was injected successfully and powers the target off.

We optimized the EM pulse parameters of the ChipShouter to have the highest success rate. Furthermore, we tested several injection tips (1 mm/4 mm clockwise/counterclockwise coil) combined with a configured pulse voltage of 500 V and a pulse width of 40 ns for the 1 mm tips and 73 ns for the 4 mm tips. We moved the injection tip as close as possible to the die to increase the probability of success even further. This experiment was performed with each injection probe tip on a 1 mm grid without success. No effects on the DUT were observed at all. Thus, we assumed that no fault was injected. One complete chip scan took about 25 h to finish.

To increase the success probability further, we lowered $V_{\text{SoC}}$ from 0.9 V to 0.59 V as proposed by Liao et al. [24]. We determined this voltage by lowering $V_{\text{SoC}}$ until the AMD-SP failed to boot (0.56 V), chose a voltage slightly above this threshold and confirmed that the co-processor still boots and works reliably. The experiment was repeated with all four injection probe tips and the same pulse parameters. Each experiment showed that faults were injected successfully at multiple positions but the 4 mm clockwise injection probe tip had the most impact. Fig. 5 depicts where on the die and how many faults occurred.

### B. Faulting the SRAM

Having confirmed that the AMD-SP is generally vulnerable to EMFI, we tried injecting faults into its SRAM to, e.g., flip one or multiple bits. To detect altered values in the SRAM, we again used the capability to execute our own code: With the cache disabled, it copies the same value n times onto the stack and then waits for a specified amount of time before reading back the values. Meanwhile, an EM pulse is triggered, attempting to inject a fault into the SRAM. If read values differ from the written ones, a fault counter is increased, and both, the fault counter and values, are printed via UART. For this experiment, the 1 mm clockwise injection probe was attached to the ChipShouter while pulse parameters remained 500 V pulse voltage and 40 ns pulse width.

### C. Faulting the ARK Verification

As explained in Section II-B, the on-chip bootloader of the AMD-SP loads and verifies the ARK. Thus, it first loads the AMD root key from the connected SPI flash and computes a hash of the key. This hash is compared to an immutable value stored in an internal ROM. If the key is replaced or modified, this check fails, and execution stops. An adversary who can bypass or alter the hash comparison could also inject his ARK to let the AMD-SP execute firmware signed by themselves [3].

We used 500 V pulse voltage, 73 ns pulse width, and the 4 mm clockwise injection probe tip. The area previously discovered to be most susceptible to EMFI (Section V-A) served as a starting point to improve the position with a finer 0.5 mm grid scan further. Subsequently, we attempted

### Table I: Waiting period/window (in wait cycles) and success rates of EMFI attack on ARK verification

| Delay/ΔDelay | Success/Attempts | Success Rate |
|--------------|------------------|-------------|
| 128/4        | 158/10000        | 1.58%       |
| 2364/4       | 2206/10000       | 22.06%      |
| 2384/4       | 352/10000        | 3.52%       |
| 2391/2       | 68/10000         | 0.68%       |
to fault the ARK verification at the refined point that is most susceptible to EMFI. Furthermore, we brute-forced the timing of the EM pulse after the generated SPI trigger, as the correct delay is unknown but limited because the regular verification takes 53 μs. To incorporate all found delays, we chose the median delay of each group of similar delays and a delay window around it (ΔDelay). Multiple working parameters were found and evaluated for their success rates (Table I). The results illustrate that precise timing is required to attack the hash comparison, supposedly because only bypassing or altering some specific instructions in a tiny time frame lead to a successful attack.

VI. DISCUSSION

A. Spatial Resolution and Localization Capabilities

The spatial resolution of our setup is much higher than needed for the presented attack (Section V). We scanned the SoC’s surface using a 1 mm grid and raised the resolution to a 0.5 mm grid to scan for more susceptible positions around the previously discovered positions to refine the coordinates of the most vulnerable position. If a high spatial resolution is necessary also depends on the diameter of the injection probe tips. A large diameter creates a greater EM field that is less location-dependent considering the injected faults.

Scanning the entire chip surface showed that the fault locations are distributed over most parts of the chip (see Fig. 5). Therefore, localization or identification of the AMD-SP on a die shot is not possible using only EMFI. Nevertheless, our fault injection experiments revealed that susceptible areas differ based on the targeted component (SRAM vs. register counter loop).

B. Electromagnetic vs. Voltage Fault Injection

Previous work showed that the ARK verification of AMD’s Zen CPUs is vulnerable to voltage FI [3]. We replicated the voltage FI attack using our target to compare EMFI and voltage FI. The success rate of the voltage FI attack is 0.49% (98 successful glitches in 20000 attempts). As described in Section V-C, the success rate of the EMFI attack is by a factor of 45 higher (0.49% voltage FI vs. 22.06% EMFI). While our EMFI attack provides a much higher success rate, it also requires a more complex attack setup. Lowering $V_{SoC}$ requires similar hard- and software requirements as a full voltage FI attack. While AMD’s mobile CPUs are not equipped with a heat spreader, our target CPU had to be delidded for a successful attack, which is not required for voltage FI.

C. Lower SoC Voltage vs. Higher Pulse Voltage

Instead of lowering $V_{SoC}$, one could attempt to use a higher pulse voltage. The ChipShout er is limited to 500 V, but other pulse generators support a higher voltage of 750 V (Avtech pulse generator [16]) or even 1200 V (SiliconToaster [13]). Recently, researchers discovered that injecting faults into an Intel i3 CPU requires a pulse voltage of 600 V which is higher than the configured 500 V of the ChipShout er [27]. As the packaging of AMD and Intel CPUs are similar, our attack could benefit from a higher pulse voltage because the hard- and software requirements for lowering the SoC voltage could potentially be omitted.

D. Scan and Attack Duration

One attack cycle consists of three phases: (1) boot of the AMD-SP, (2) one fault injection attempt, and (3) shutdown of the AMD-SP. Therefore, both the scan and attack duration depend on the irreducible boot and shutdown duration of the AMD-SP. During a complete chip scan (Fig. 5), this cycle repeats a hundred times per position, making the scan slow. To decrease the overall scan time, a more powerful pulse generator that allows the injection of multiple same-shaped faults in a small interval could be used. This would increase the success probability per attack cycle.

The duration to successfully fault the ARK verification depends on the attack cycle duration and the success rate. As one attack cycle takes less than four seconds, a successful attempt occurs within a minute, making the attack feasible. Both the voltage FI and EMFI success rates could be improved by triggering the fault injection more precisely, e.g., by using an field-programmable gate array (FPGA) instead of the Teensy.

E. Setup Costs and Availability

Our self-built setup consists of commercially available as well as 3D-printed parts. Two aluminum adapter plates were specially produced based on our design. However, since these are simple in design, they should be producible in any metal workshop. The total price sums up to around €7k, see Table II. Our motion controller based on 3D-printer hardware is customizable and cheap compared to commercially available solutions. Riscure’s EM Probe Station 5 [17] has nearly the same step size but a smaller travel range of 50 mm and a smaller working area compared to our setup. Their pulse generator, the EM-FI Transient Probe [28], has a maximum coil voltage of 450 V and a maximum internal current of 64 A. Thus, ChipShout er and Riscure’s pulse generator have similar characteristics but vary greatly in their price. The EM Probe

| Part                               | Price  |
|------------------------------------|--------|
| ChipShout er NAE-CW520-KIT          | €3149.25 |
| Teensy 4.0                         | €24.80 |
| Raspberry Pi 3B+                    | €38.40 |
| BTT SKR Pro v1.2                    | €69.99 |
| TMC2209 Motor Drivers              | €32.53 |
| USB Microscope                      | €59.00 |
| Adafruit MLX90640                   | €77.20 |
| Power Supply                        | €39.99 |
| Standa 8MT175-100 Stages            | ~€3000 |
| Aluminum Profiles                   | €283.72 |
| Aluminum Adapter Plates             | ~€15.00 |
| Angle Bracket                       | €65.00 |
| Wires                              | ~€50.00 |

TABLE II: Part prices and total costs
Station 5 and the EM-FI Transient Probe together cost more than €20k, which is more than double the price of our setup. In case less accuracy is sufficient, cheaper stages could be integrated to nearly halve the costs [14]. If high accuracy stages are beneficial, a self-built pulse generator could be used to lower the costs [13].

VII. CONCLUSION

In this work, we first demonstrated how an EMFI setup could be built with a high spatial resolution and that is large enough to target desktop and server systems. All setup components are commercially available or 3D-printable, and the deployed software is available as open-source software. Additionally, all CAD files, the controller software, and a parts list is released along this work. We used the setup to target the AMD-SP inside an AMD Ryzen CPU and were able to inject faults to break out of a loop or to alter values stored in SRAM. Finally, we successfully break the ARK verification of the AMD-SP as previously carried out via voltage FI. Our EMFI attack offers a significantly higher success rate than the voltage FI attack and can be readily adapted for future desktop and server targets.

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