Single trace HQC shared key recovery with SASCA

TrustNet

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23 May 2024

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Modern cryptography

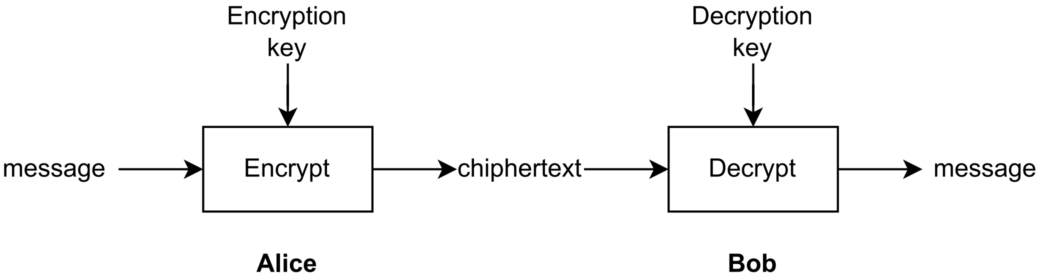

Figure – Overview of a cryptosystem

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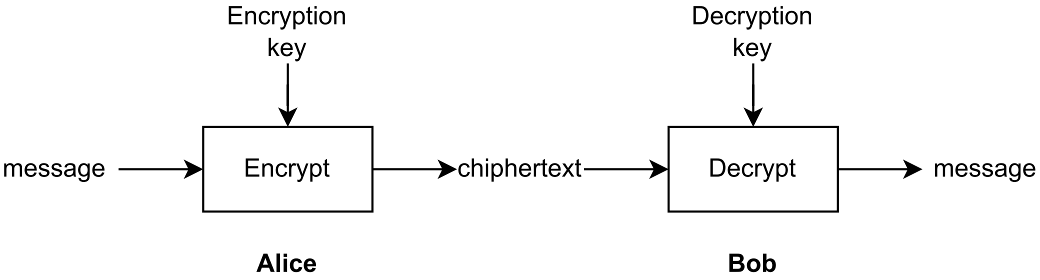

Figure – Overview of a cryptosystem

RSA [RSA78] - Elliptic Curves Cryptography (ECC) [Kob87, Mil85]

Post-Quantum Cryptography [AMAB+17, ABB+17, BCL+, BDK+18, DKL+18]

Cryptographic Security

We have three levels of security : (I) 2^{128}, (II) 2^{192} and (III) 2^{256}
This represents the **minimal number of operation an attacker needs to pay to recover a secret information**.
And often also **The number of different secret keys**.

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$2^{256} \approx\approx 10^{80} \leftarrow$ Number of atoms in the observable universe

Side-Channel Attacks

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Goal : Recover secret information using side-channel leakage :

- Execution time
- **Power consumption**
- **Electromagnetic emanations**
- Sound
- Heat, $\cdots$

Timing attack example

Algorithm Naive PIN verification

Require: $C = (c_1, c_2, c_3, c_4)$ the fair password
Require: $T = (t_1, t_2, t_3, t_4)$ user attempt
Ensure: True si $C = T$, False otherwise.

```
if c1 = t1 then
    if c2 = t2 then
        if c3 = t3 then
            if c4 = t4 then
                return True
return False
```

Leakage models

We consider that the power consumption / electromagnetic emanations leakage follows a Leakage model :
Hamming weight leakage model :

$$L(t) = \alpha \cdot \mathtt{HW}(\mathbf{v}(t)) + \beta + \mathtt{Noise}(t) \quad (1)$$

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Binary leakage model :

$$L(t) = \sum_{i=1}^{m} (\alpha_i \cdot v_i(t)) + \beta + \mathtt{Noise}(t) \tag{2}$$

Attack can be perform in Simulation or in a real case scenario.

Soft Analytical Side-Channel Attacks (SASCA)

Idea : combine several weak physical leaks to obtain strong information

- Introduced by Veyrat-Chravrillon et al. [VCGS14] to attack AES in 2014
- Application against Kyber [PPM17, PP19, HHP^{+}21, HSST23, AEVR23]

  $\rightarrow$ Information Propagation through NTT

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  - $\rightarrow$ Information Propagation through NTT
- Attack against hash function Keccak [KPP20] in 2020
- First attack against code-based cryptography [GMGL23]

➔ Mainly based on **Belief Propagation** [Mac03, KFL01].

Message passing with Belief Propagation

The goal of Belief Propagation is to compute a **Marginal Distribution** for every **Intermediate values** involved in a given algorithm.

Toy Example : Galois Field Multiplication $v = a \times b$ $(= \alpha^{\log(a)+\log(b)})$:

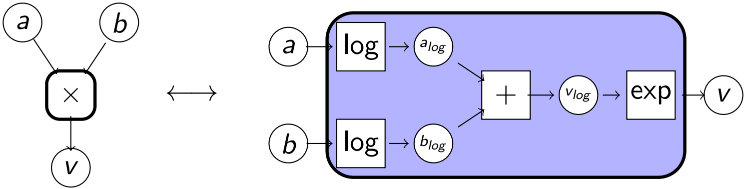

Figure – Graphical representation of a Galois Field Multiplication

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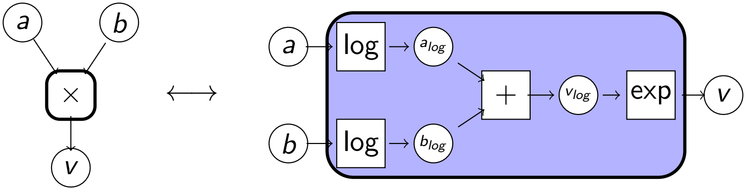

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The Goal is to compute : $\mathbb{P}(a \mid b, v), \mathbb{P}(b \mid a, v), \mathbb{P}(v \mid a, b)$

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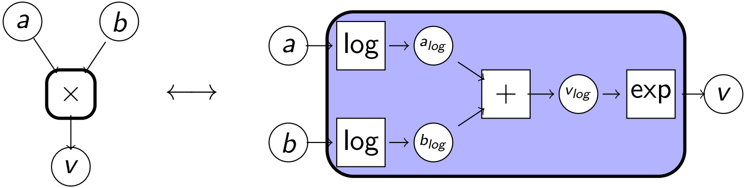

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Sum Product Algorithm [KFL01] gives a solver for this problem.

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Hamming Quasi-Cyclic

Algorithm Keygen

Input : param
Output : (pk, sk)

$\mathbf{h} \xleftarrow{\$} \mathcal{R}$
$(\mathbf{x}, \mathbf{y}) \xleftarrow{\$} \mathcal{R}_{\omega}^{2}$
$\mathbf{s} = \mathbf{x} + \mathbf{h}\mathbf{y}$
$\mathrm{pk} = (\mathbf{h}, \mathbf{s})$
$\mathrm{sk} = (\mathbf{x}, \mathbf{y})$

Algorithm Encrypt

Input : $(\mathrm{pk}, \mathbf{m} \in \mathbb{F}_2^{\lambda})$
Output : ciphertext $\mathtt{ct}$

$\mathbf{e} \xleftarrow{\$} \mathcal{R}_{\omega_e}$
$(\mathbf{r}_1, \mathbf{r}_2) \xleftarrow{\$} \mathcal{R}_{\omega_r}^{2}$
$\mathbf{u} = \mathbf{r}_1 + \mathbf{h}\mathbf{r}_2$
$\mathbf{c} = \mathtt{Encode}(\mathbf{m})$
$\mathbf{v} = \mathbf{c} + \mathbf{s}\mathbf{r}_2 + \mathbf{e}$
$\mathtt{ct} = (\mathbf{u}, \mathbf{v})$

Algorithm Decrypt

Input : $(\mathrm{sk}, \mathtt{ct})$
Output : $\mathbf{m}'$

$\mathbf{c} + \mathbf{e}' = \mathbf{v} - \mathbf{u}\mathbf{y}$
$\mathbf{m}' = \mathtt{Decode}(\mathbf{c} + \mathbf{e}')$

Hamming Quasi-Cyclic

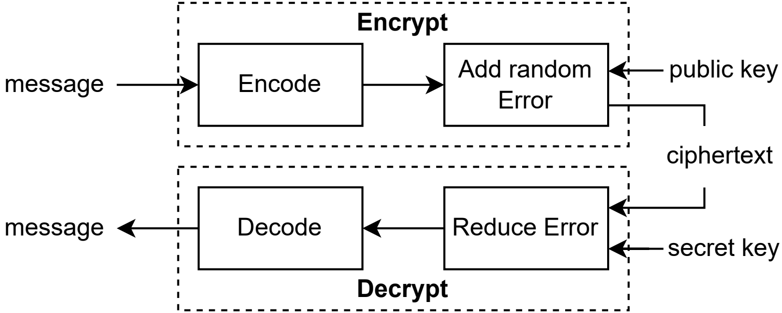

Figure – Hamming Quasi-Cyclic Overview

- Decryption Failure Rate (DFR) is ensured by the error correction capability and analysis of the hamming weight distribution of the error **e**' [AGZ20]
- Most of the Side-Channel Attacks against HQC target the **decoding step**.

Concatenated code structure

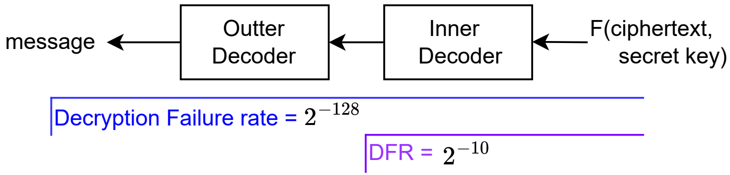

Figure – HQC Concatenated codes structure

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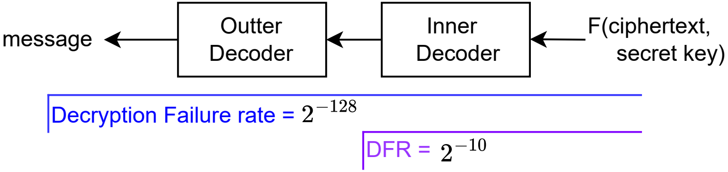

Figure – HQC Concatenated codes structure

(i) **Secret key** recovery attacks : [SHR+22, GLG22a, BMG+24]

(ii) **Shared key** (message) recovery attacks : [GLG22b, GMGL23, BMG+24]

Reed-Solomon Syndrome Computation

Algorithm Compute Syndromes from HQC RS Decoder from [AMAB+23]

Require: parameters : k, n the dimension and length of the code
Require: parity check matric $H \in \mathbb{F}_q^{(n-k,n)}$
Require: codeword $c \in \mathbb{F}_q^{n_1}$
Ensure: $s := H^T \times c$ the syndrome of c

1: Initialize s to 0^{n-k}
2: **for** i from 0 to $n-k$ **do**
3:     **for** j from 1 to n **do**
4:         $s[i] = s[i] \oplus c[j] \times H[i, j-1]$ $\triangleright$ $\times$ is the Galois Field multiplication
5:     $s[i] = s[i] \oplus c[0]$

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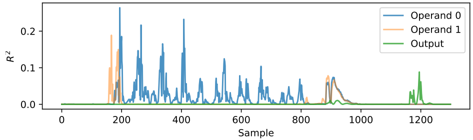
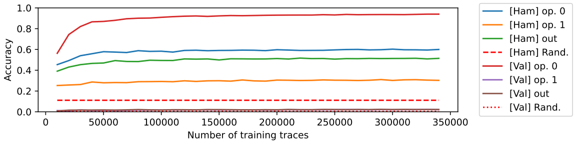
Attacker Model

- Hypothesis
  - Access to a clone device
  - One target function only
  - Isolate and order each occurence
  - No control on the SNR
- In Practice :
  - Both training and attack on the same device
  - Target the Galois field multiplication
  - Pattern matching
  - No trace averaging (true single trace attack)
- Set-Up :
  - STM32F407
  - Langer Near Field Probe
  - Rhode-Schwarz RTO2024

Templates on the Galois field multiplication operands

Galois field multiplication based on FFT strategy [BGTZ08]





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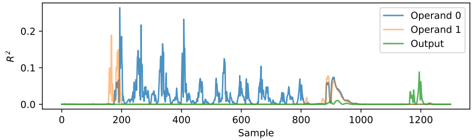
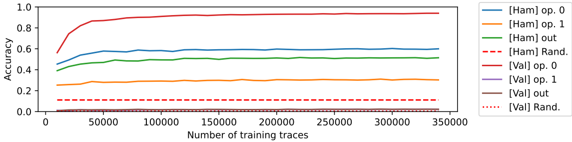




	Value template accuracy	Hamming weight template accuracy
Input 1	**0.9389**	0.5929
Input 2	0.0211	**0.3035**
Output	0.0221	**0.5178**

Table – Hamming weight and value templates accuracies on `gf_mul`. Each attack has been performed 400 times. 10%/90% validation/training segmentation.

Outer Decoder syndrome computation graphical representation

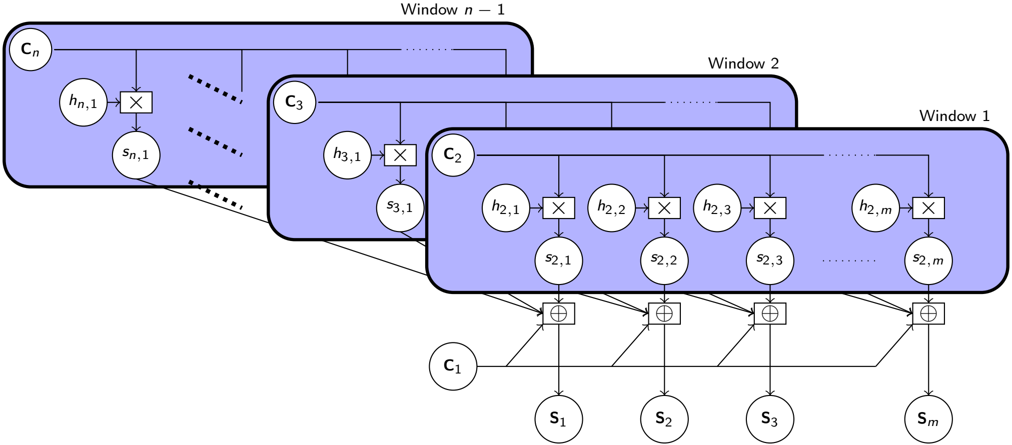
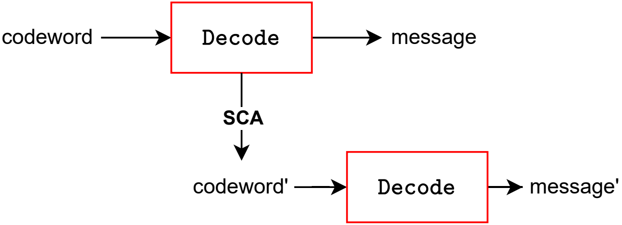


Figure – Graphical representation of the RS syndrome computation from HQC

Re-decoding Strategy



Security level	HQC parameters			List decoder
λ	k_1	n_1	t	τ_{GS}
HQC-128	16	46	15	19
HQC-192	24	56	16	19
HQC-256	32	90	29	36

Table – Reed-Solomon error correction capability of the RS decoder for each HQC set of parameters, given for a classical decoder and the Guruswami-Sudan list decoder.

Attack Accuracy in Simulation

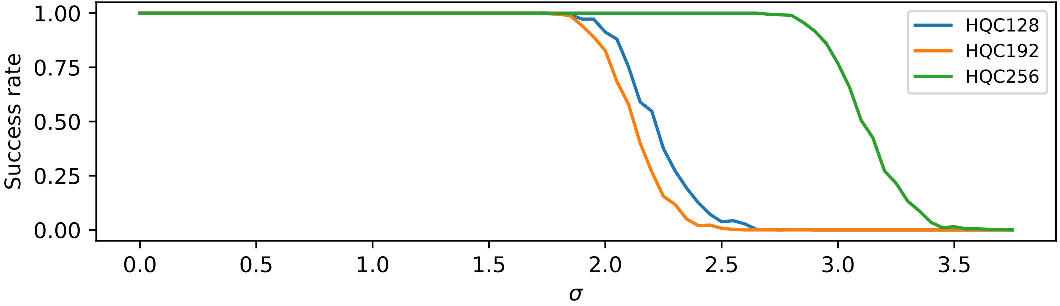


Figure – Simulated success rate of SASCA on the decoder, with re-decoding strategy, depending on the selected security level of HQC

Breaking shuffling countermeasures

- Fine Shuffling (Adapted from a Kyber countermeasure)
  $\rightarrow$ Randomly choose $a \times b$ or $b \times a$.

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- Fine Shuffling (Adapted from a Kyber countermeasure)
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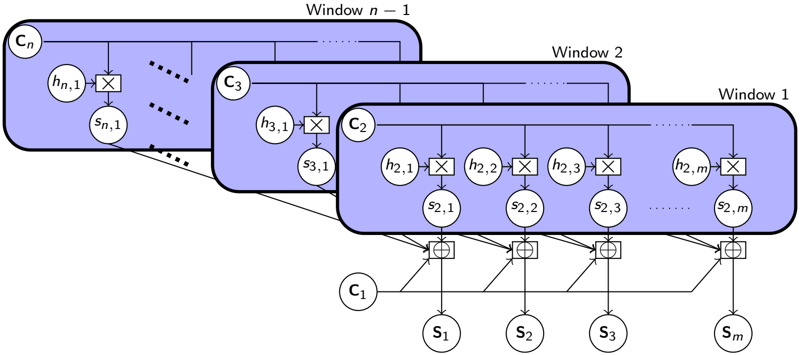
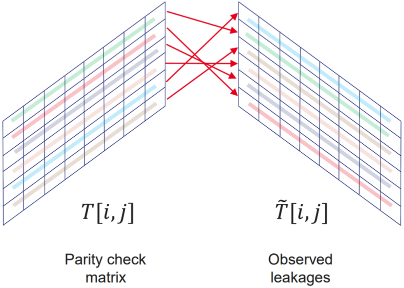
- Coarse shuffling (Adapted from a Kyber countermeasure)
  - $\rightarrow$ Randomly shuffle columns of the parity check matrix



Breaking shuffling countermeasures 2

- Window Shuffling (Novelty)
  $\rightarrow$ Randomly shuffle lines of the parity check matrix



$$D[i,i'] = \sum_{j=1}^{256} \mathrm{d}\left(\tilde{T}[i,j], T[i',j]\right)$$

Instance of the assignment Problem.
$\rightarrow$ Solver : Hungarian algorithm.

Breaking Codeword Masking (High Level Masking)

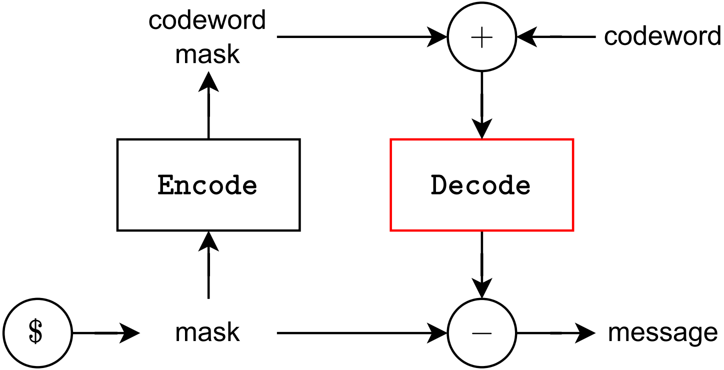
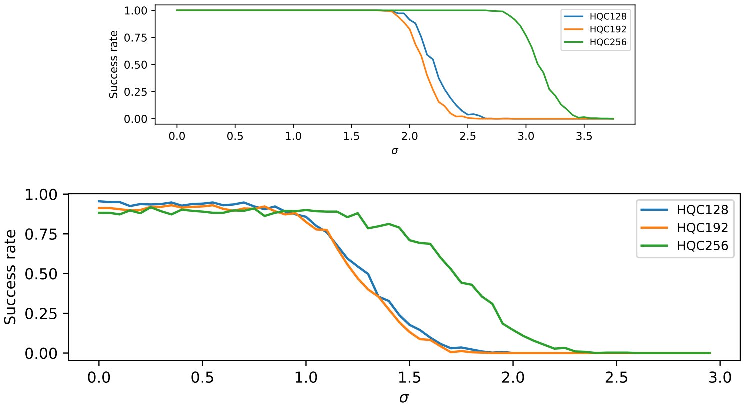


Figure – High level Masking of a decoder (Codeword Masking) [MSS13]

Encoder Attack Accuracy in Simulation



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re-encryption step from HHK transform

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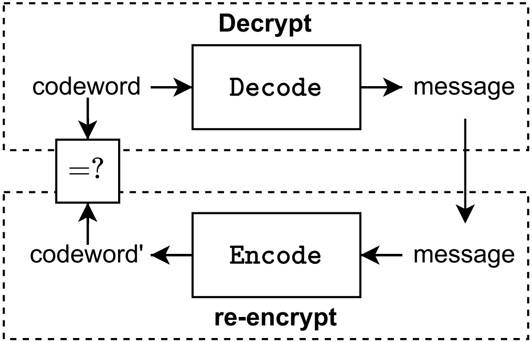

Figure – HQC Structure with HHK transform

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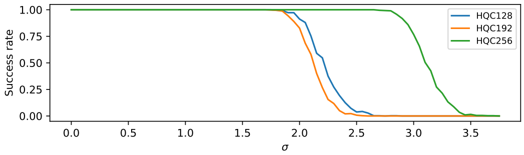
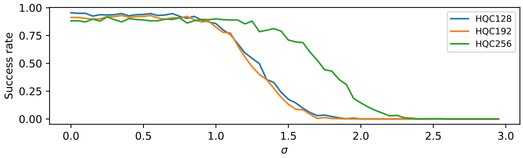


Decoder



Encoder

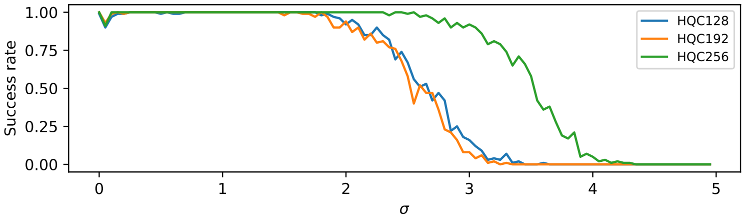


Figure – Simulated success rate of SASCA on the decoder and encoder exploiting re-encryption

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Full Shuffling Countermeasure

- The idea is to shuffle the entire matrix, instead of only rows or columns, during the matrix vector multiplication.
  - $\rightarrow$ Even if an attacker exactly recover the shuffled matrix, there exists 2^{504}, 2^{614} and 2^{1030} different permutations for the three security levels respectively.

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- The encoder could be change to a classical multiplication with a generator matrix to benefit from the same countermeasure.

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Conclusion and Perspectives

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Thank you for your attention !

Any questions ?

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