Title: Purifying qubits in NMR quantum information processing

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Abstract: Any implementation of a quantum computer will require the ability to reset qubits to a pure input state, both to start the computation and more importantly to implement fault-tolerant operations. Even if we cannot reset to a perfectly pure state, heat-bath algorithmic cooling provides a method of purifying mixed states. By combining the ability to pump entropy out of the system through a controllable interaction with a heat bath and coherent control of the qubits, we are able to cool a subset of the qubits far below the heat bath temperature. Here we show an implementation of this cooling in a solid state NMR quantum information processor which offers high fidelity control of the qubit system and controllable access to a heat bath.   We demonstrate an implementation of multiple rounds of heat-bath algorithmic cooling on three qubits and discuss the improvements in control techniques which have allowed us to show the purification of a single qubit to one and a half times the heat bath polarization.

A spin-based heat engine

Multiple Rounds of Heat-Bath Algorithmic Cooling

Colm Ryan

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The need for purification

- Pure qubits in some fiducial state are needed for the standard model of quantum computing
  - Initial state
  - Fault-tolerance
- Need method for dynamically pumping entropy out of system

Bias, Polarization and Temperature

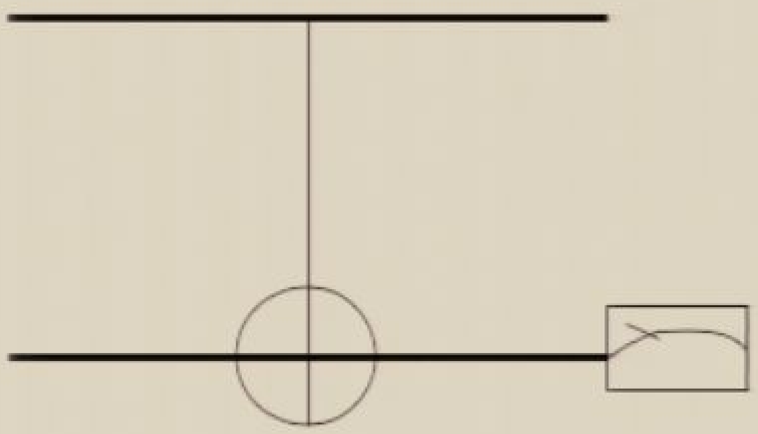
- We care about relative population differences
- Increasing bias = decreasing temperature

$$\begin{pmatrix} \frac{1+\epsilon}{2} & 0 \\ 0 & \frac{1-\epsilon}{2} \end{pmatrix}$$

State	Probability
00	$\frac{1}{4}(1+\epsilon)^2$
01	$\frac{1}{4}(1+\epsilon)(1-\epsilon)$
10	$\frac{1}{4}(1-\epsilon)(1+\epsilon)$
11	$\frac{1}{4}(1-\epsilon)^2$

Simple Purification

- If we have many almost pure qubits we can purify a subset



- Post-selected on measuring a zero on the second qubit we have purified first qubit

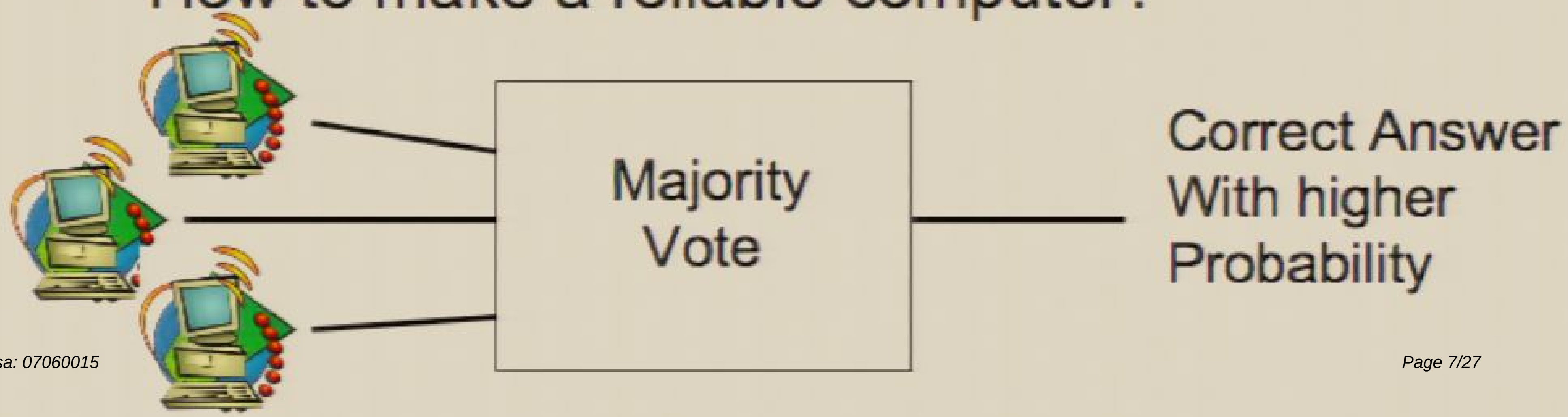
All the way back to von-Neuman

- How to make a balanced coin?

~~0~~01001~~1~~1~~0~~0~~0~~001~~1~~101~~0~~0….

1000….

- How to make a reliable computer?



Closed System Algorithmic Cooling

- Schulmann and Varizani applied this to bias amplification
- Recursively apply majority gates
- Scalable NMR quantum computing!
- Impractical for room temperature biases
  - For one pure qubit need ~ 10^{12} spins

Limits to Cooling

- Closed system implies limits to cooling
  - Entropy of closed system in conserved
  - Cooling limited by Shannon Entropy
  - Cannot change sum of square of eigenvalues
- Unitary dynamics imposes further Sorrensen limit
  - Cannot change eigenvalues

Heat-Bath Algorithmic Cooling

- Many algorithms to take advantage of heat bath
  - Optimal Partner Pairing Algorithm
- Threshold effect

$$\epsilon \ll \frac{1}{2^n}$$ Can cool to only $\epsilon 2^{n-2}$

$$\epsilon \gg \frac{1}{2^n}$$ Can purify arbitrarily

Heat-Bath Algorithmic Cooling

- Certain qubits can come in contact with heat-bath and rethermalize in a controlled manner
  - If spin hotter than heat bath then this will cool the qubit and remove entropy from the system
  - Allows us to bypass the Shannon/ Sorrensen bound

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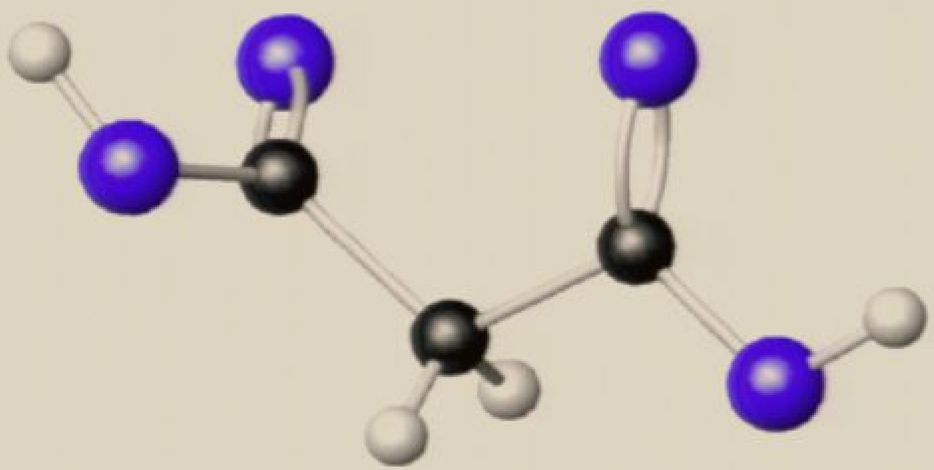
Nuclear Magnetic Resonance

- Qubits spin 1/2 particle in a strong magnetic field
- Control through radio frequency fields
- Can measure only expectation values

System: Malonic Acid

- Three carbon qubits
- Proton bath



Selective Refresh

- Cross Polarization transfers polarization from one spin species to another

$$\sigma_z\sigma_z \longrightarrow \sigma_z\sigma_z + \sigma_y\sigma_y$$

- Swap time is proportional to coupling strength so for short time only strongly coupled proton-carbons will swap

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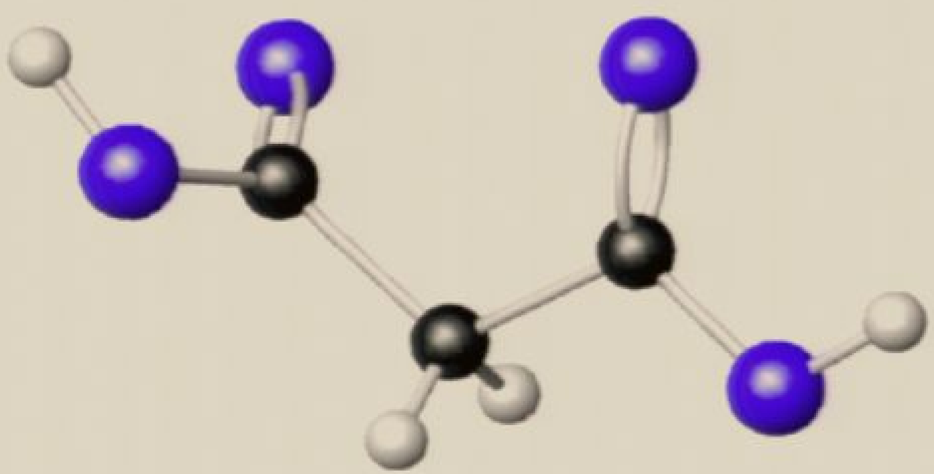

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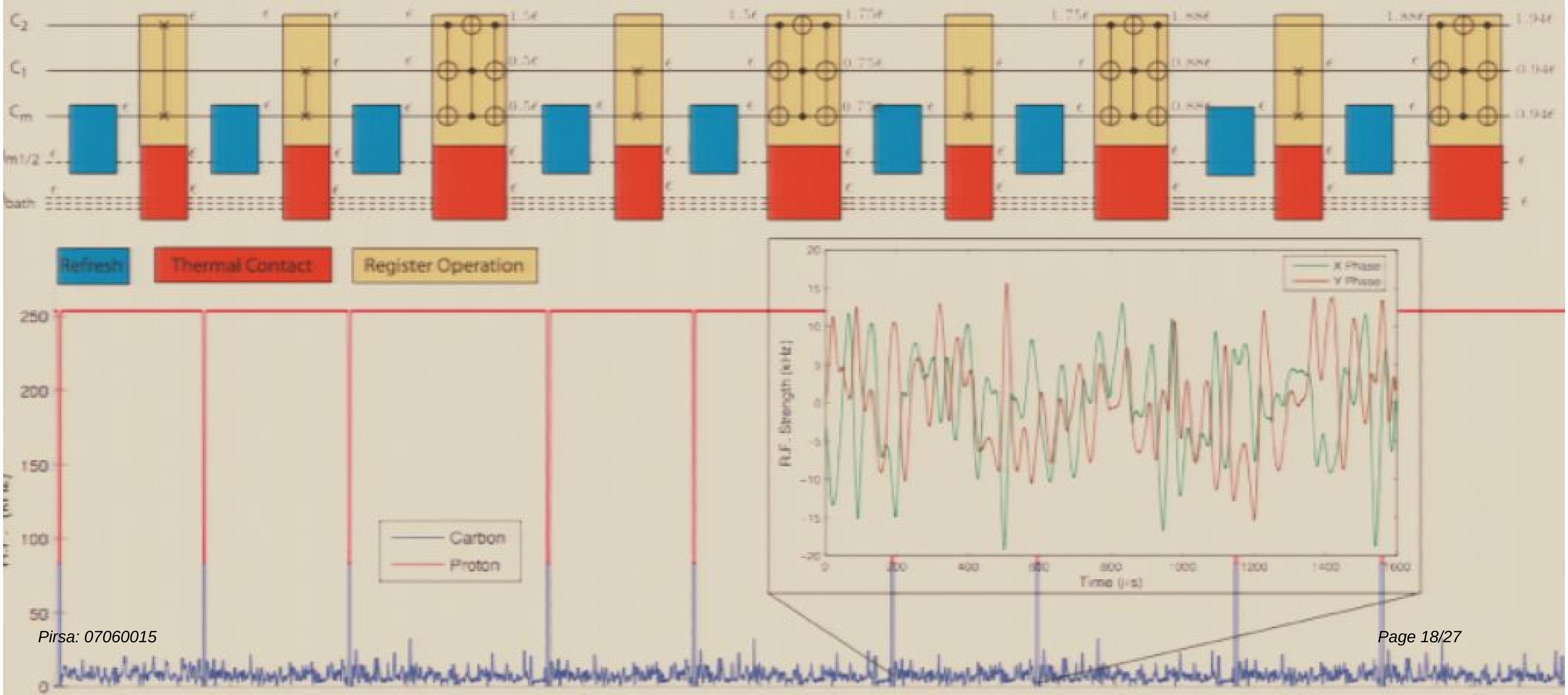
The whole circuit

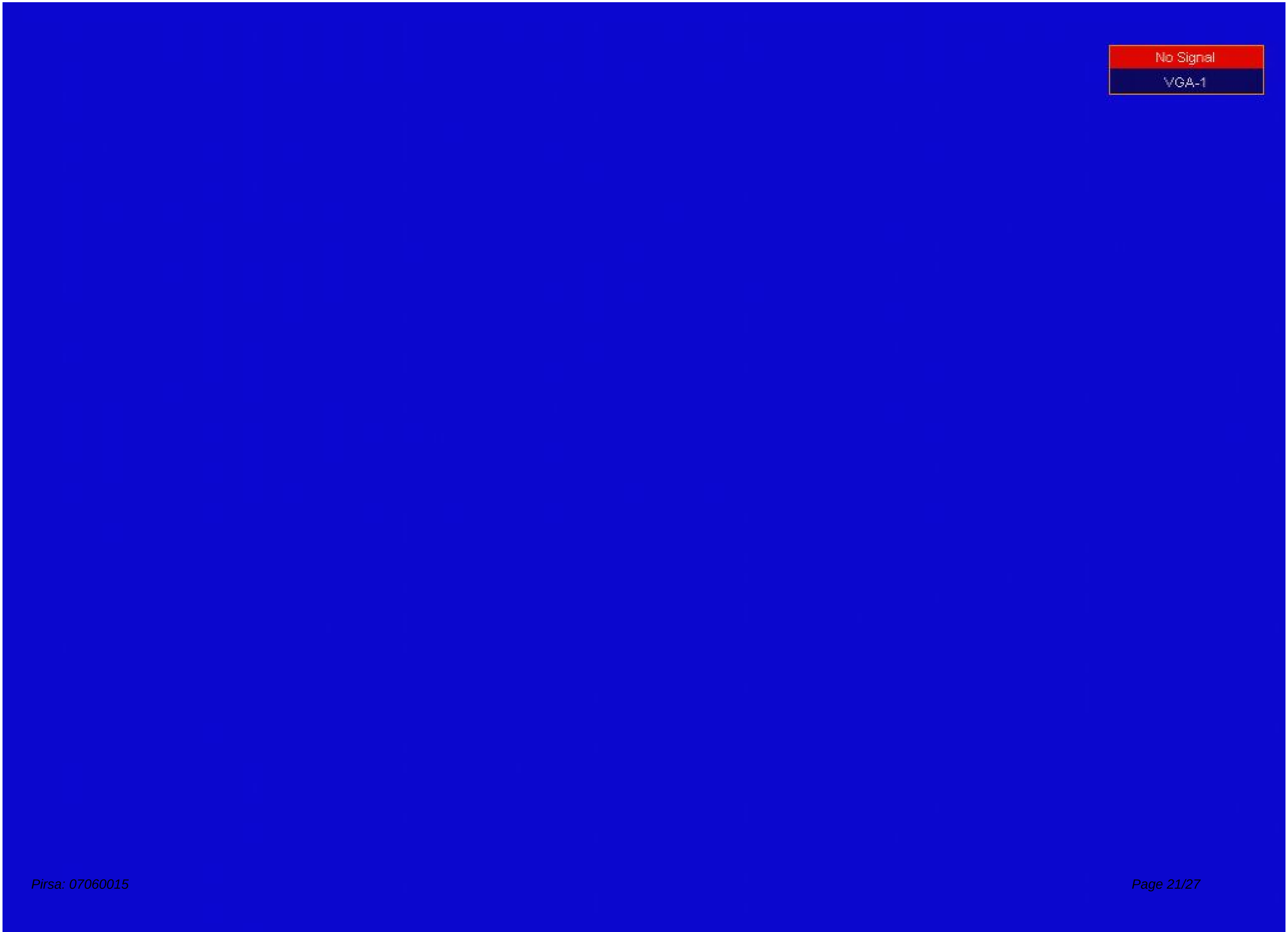


No Signal

VGA-1

No Signal

VGA-1


No Signal
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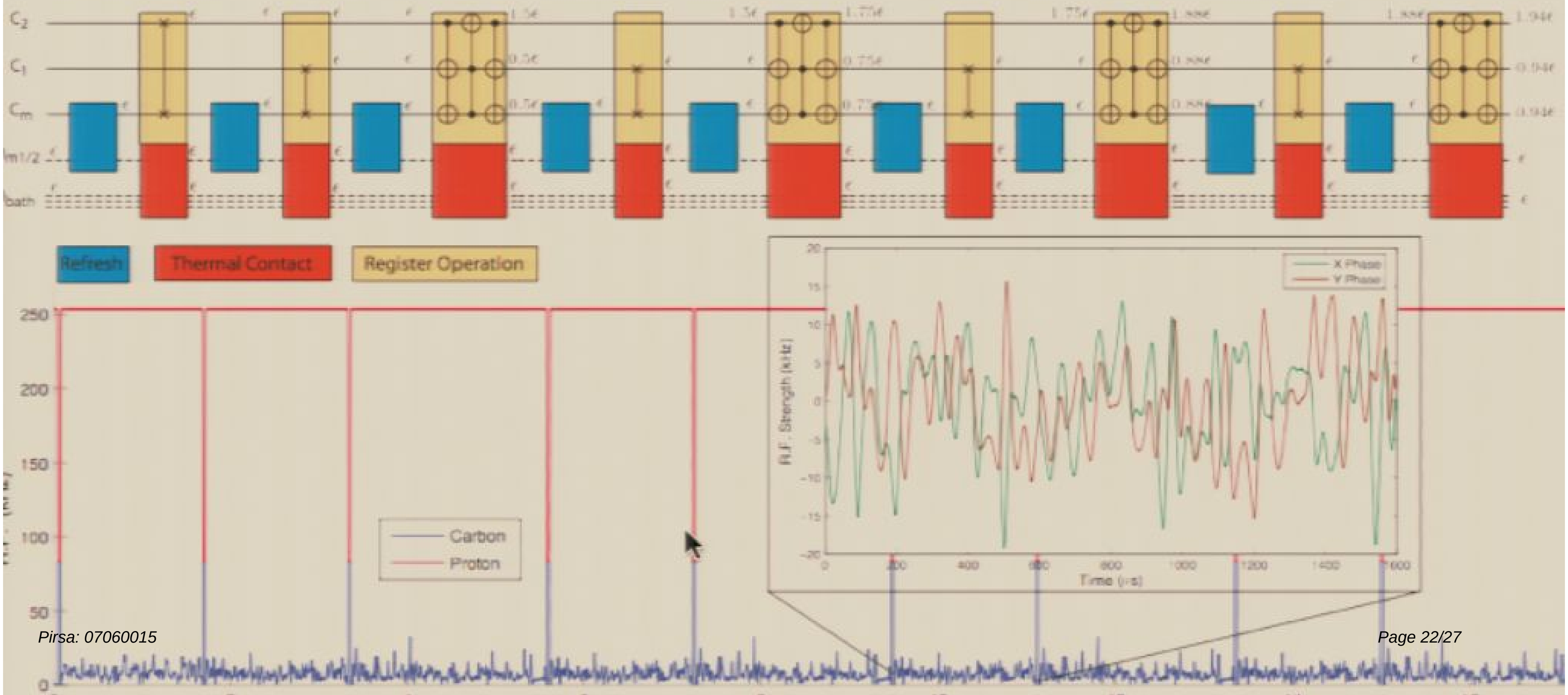
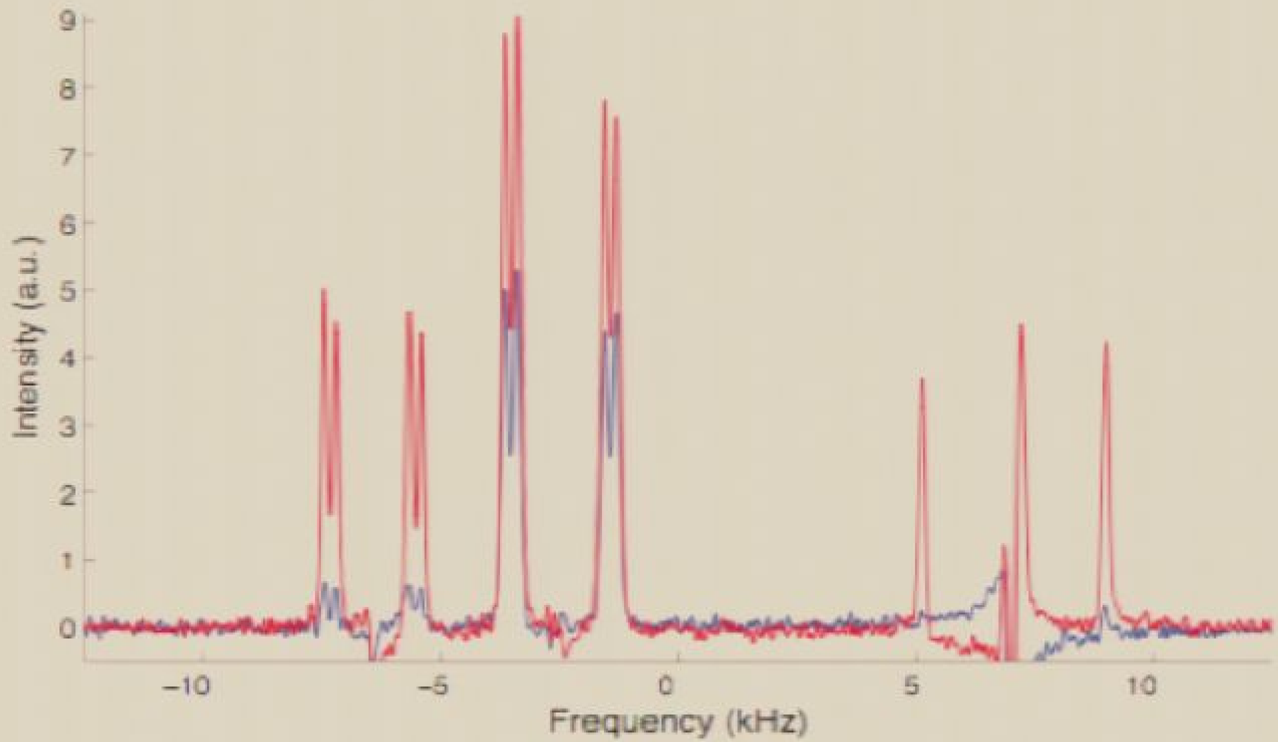
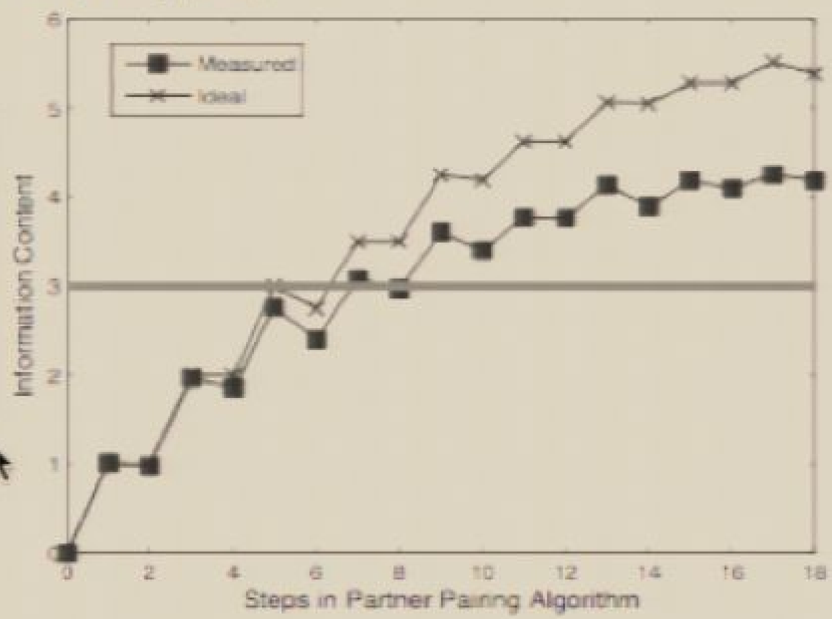
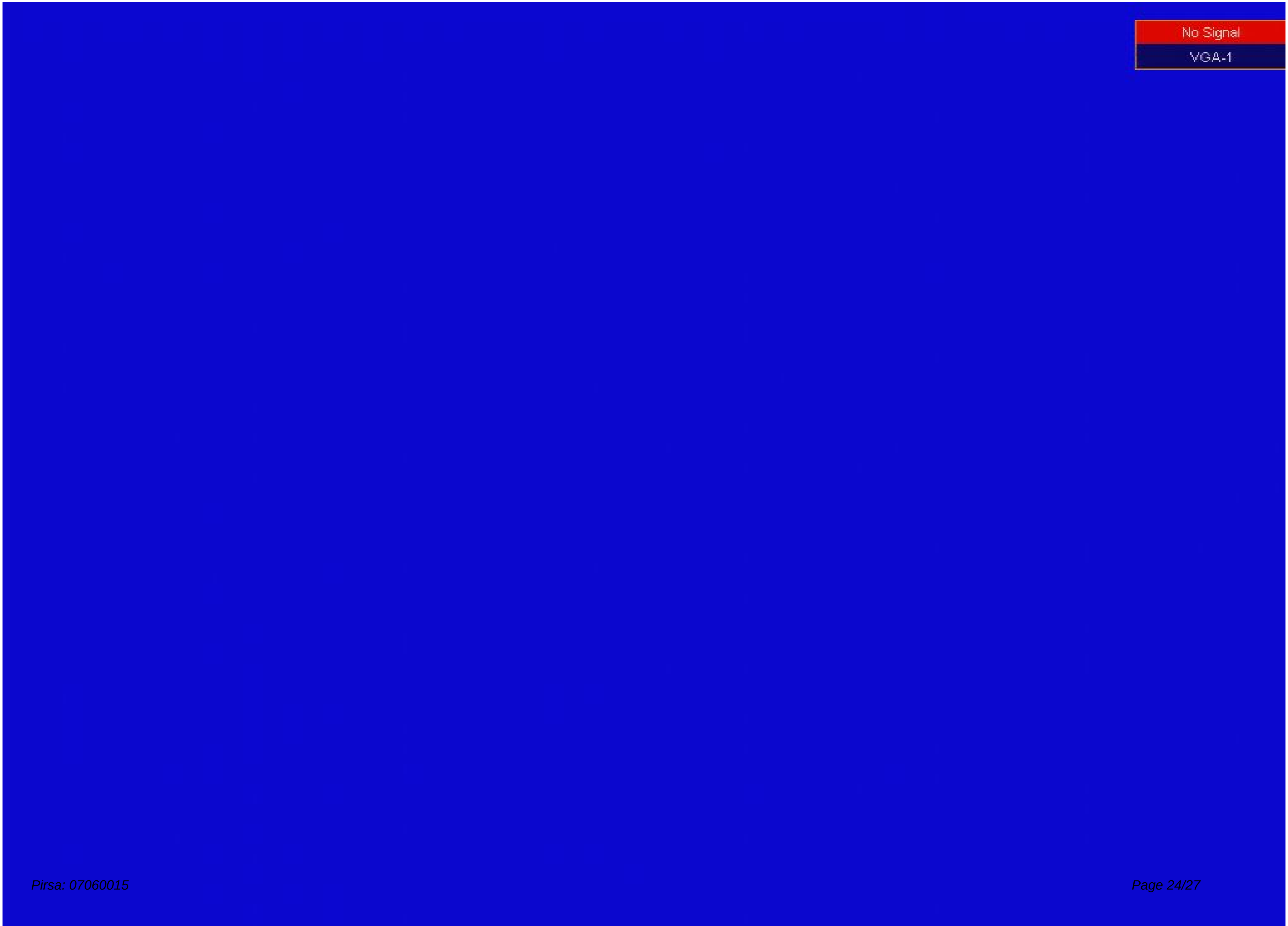




Compression Step	C_2	C_1	C_m
1	1.39	0.47	0.49
2	1.56	0.68	0.71
3	1.64	0.76	0.79
4	1.69	0.79	0.84

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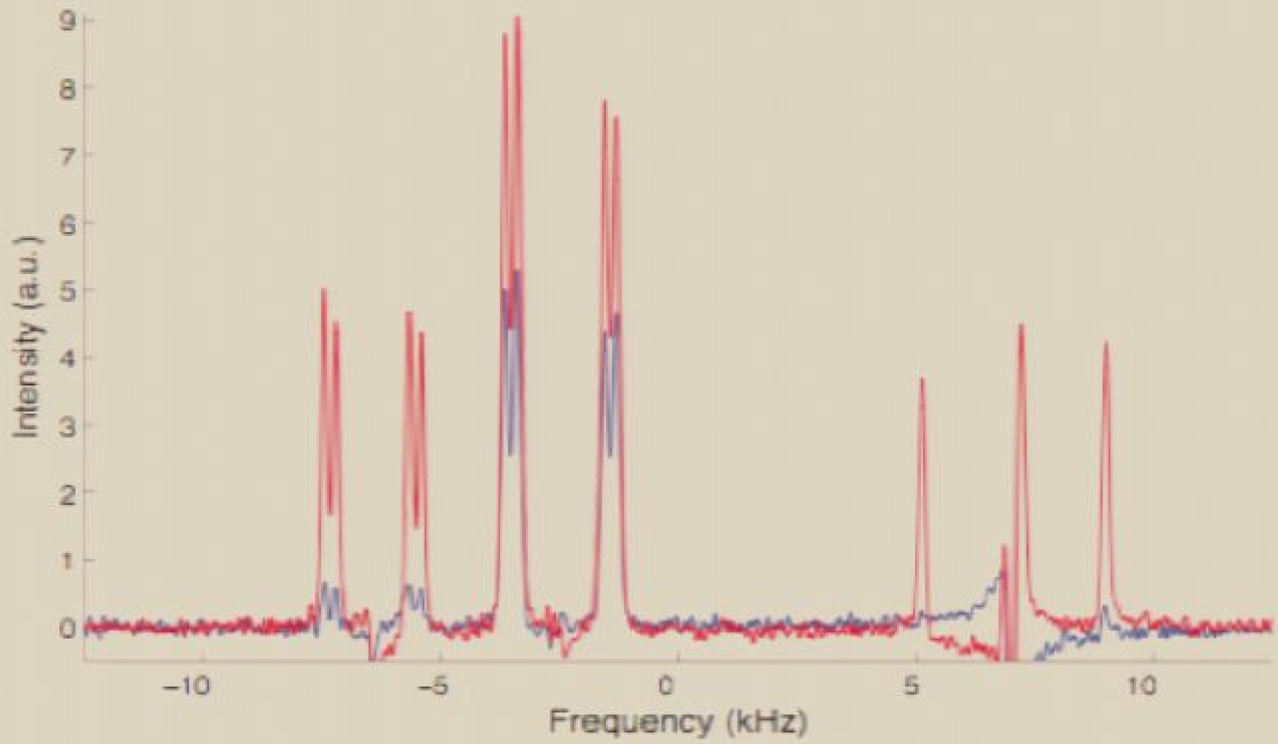

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