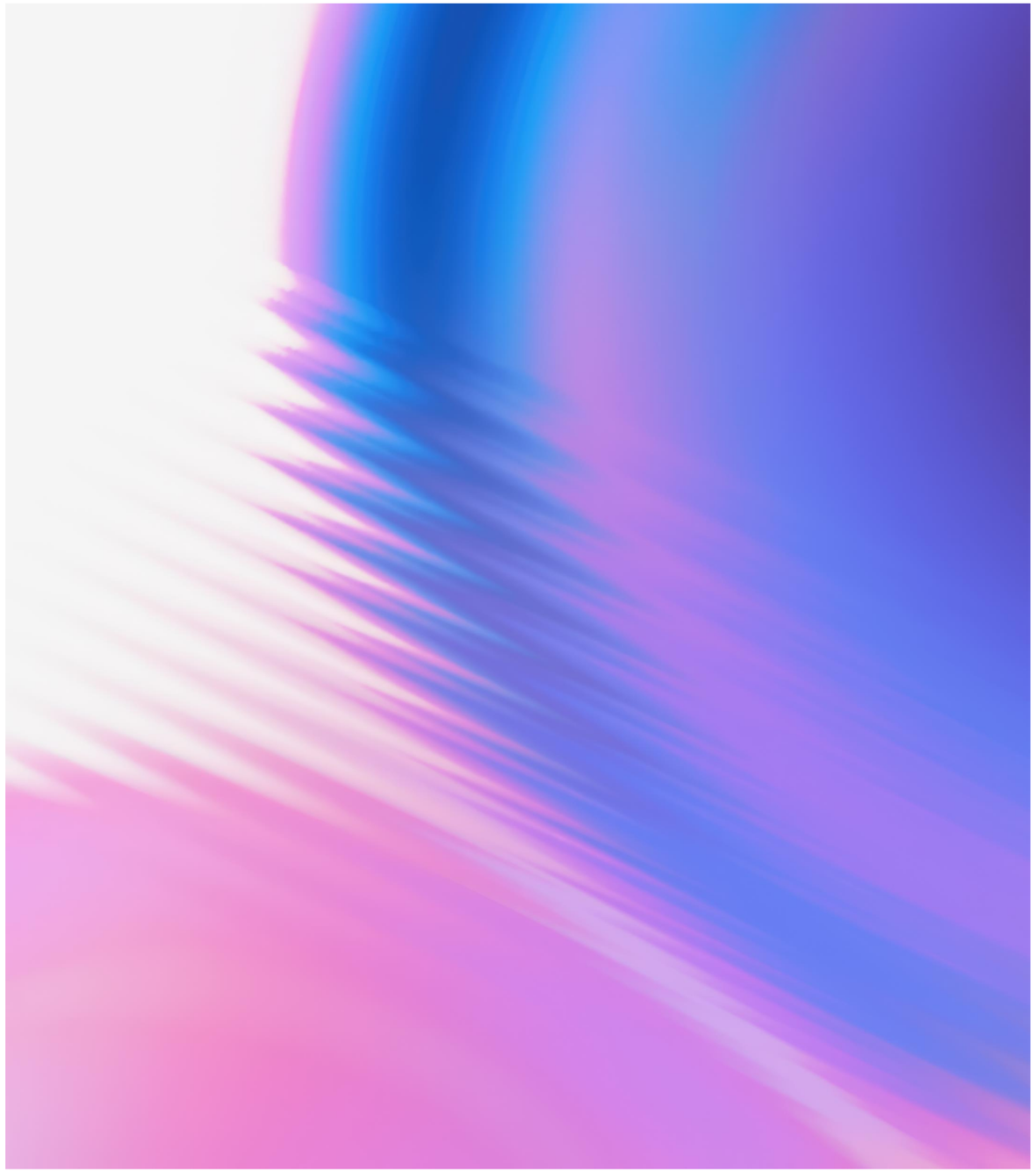
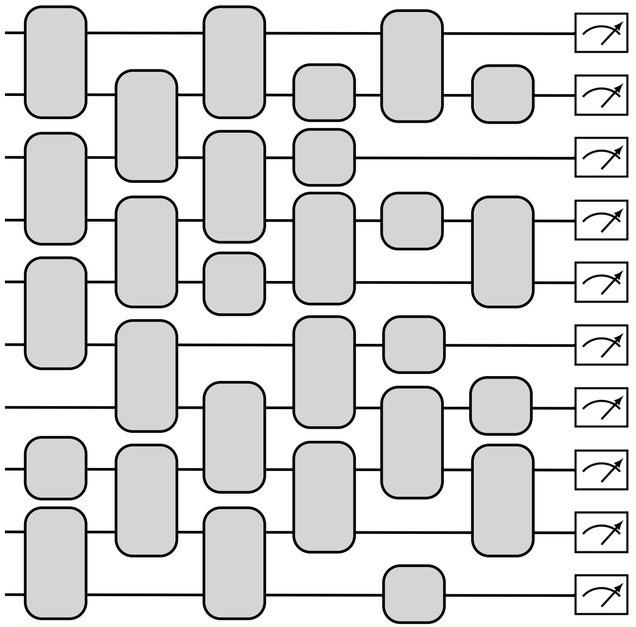
Utility scale dynamic circuits

Mirko Amico
Technical Lead – Quantum Algorithm Engineering
IBM Quantum

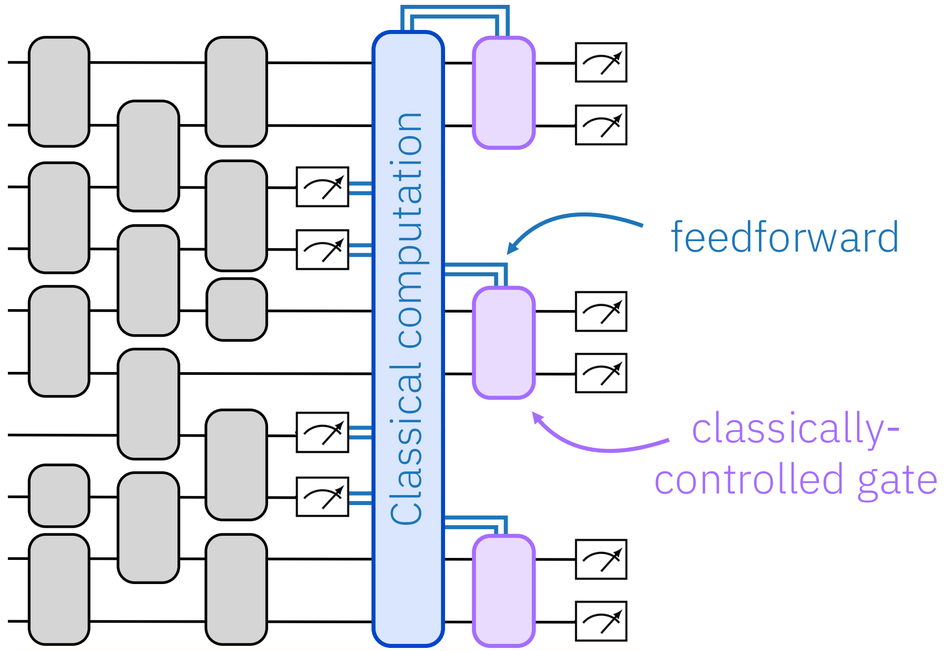


What is dynamic circuit?

Unitary quantum circuit



Dynamic quantum circuit



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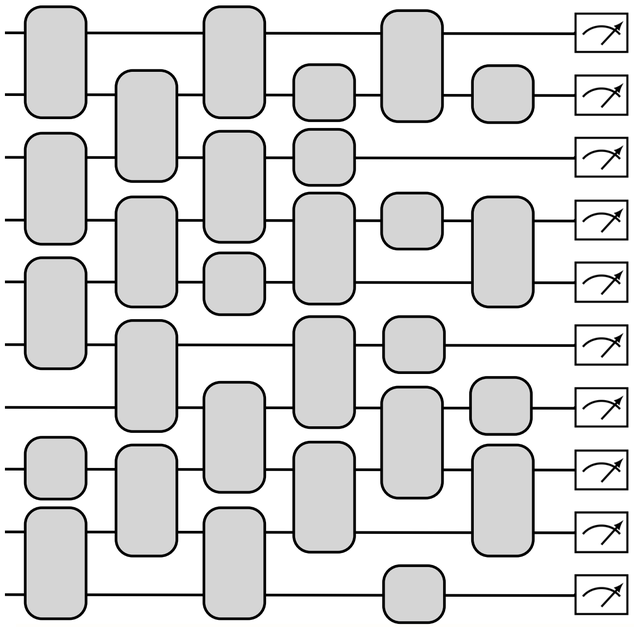

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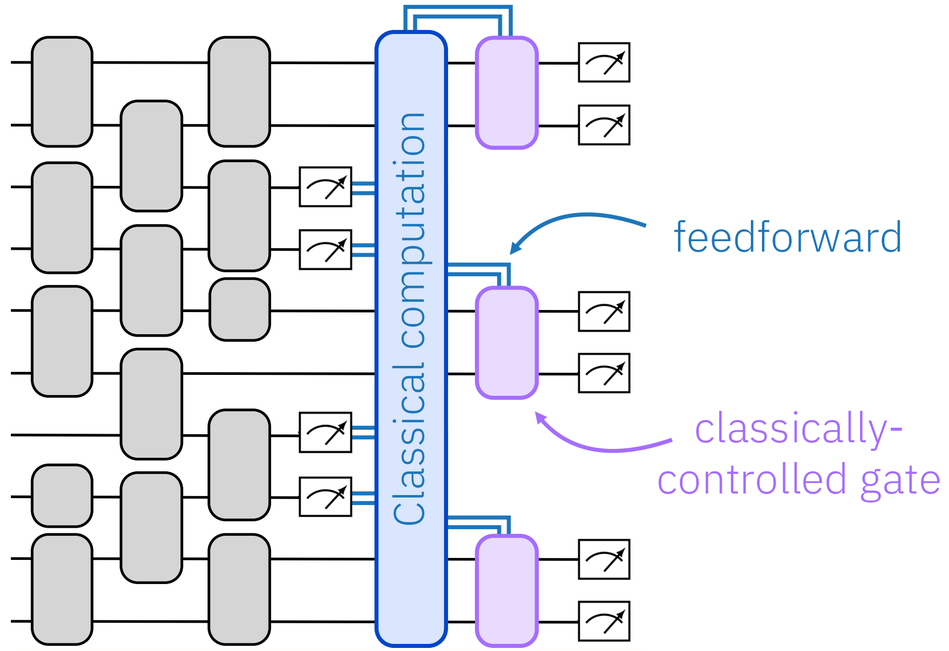

Dynamic circuits → can implement *any* allowed quantum process, not just unitary evolution.

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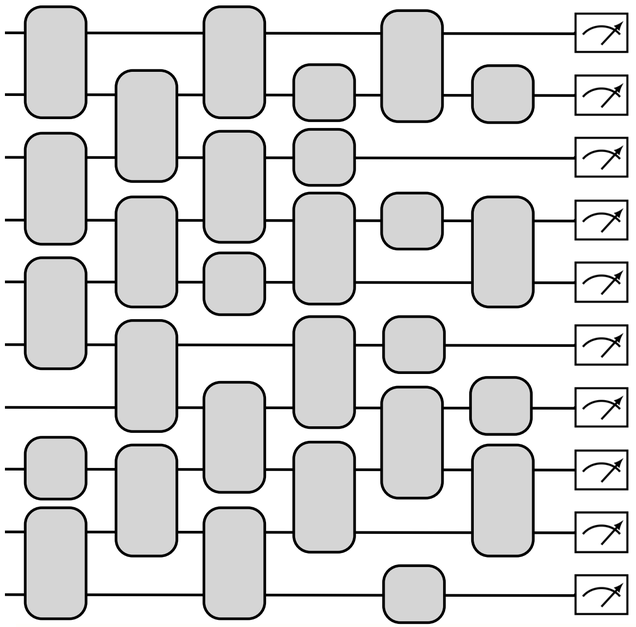

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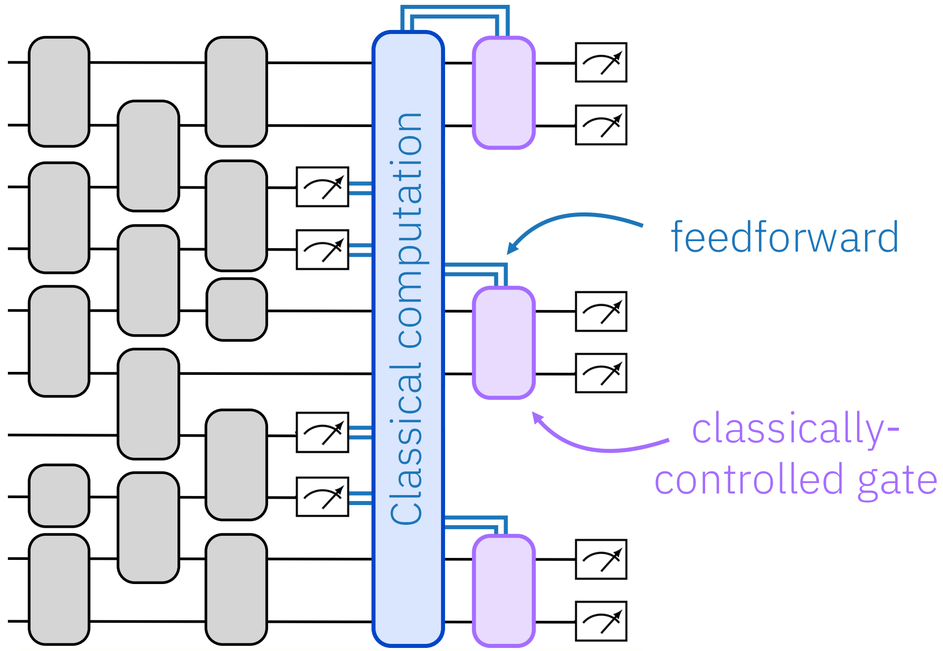
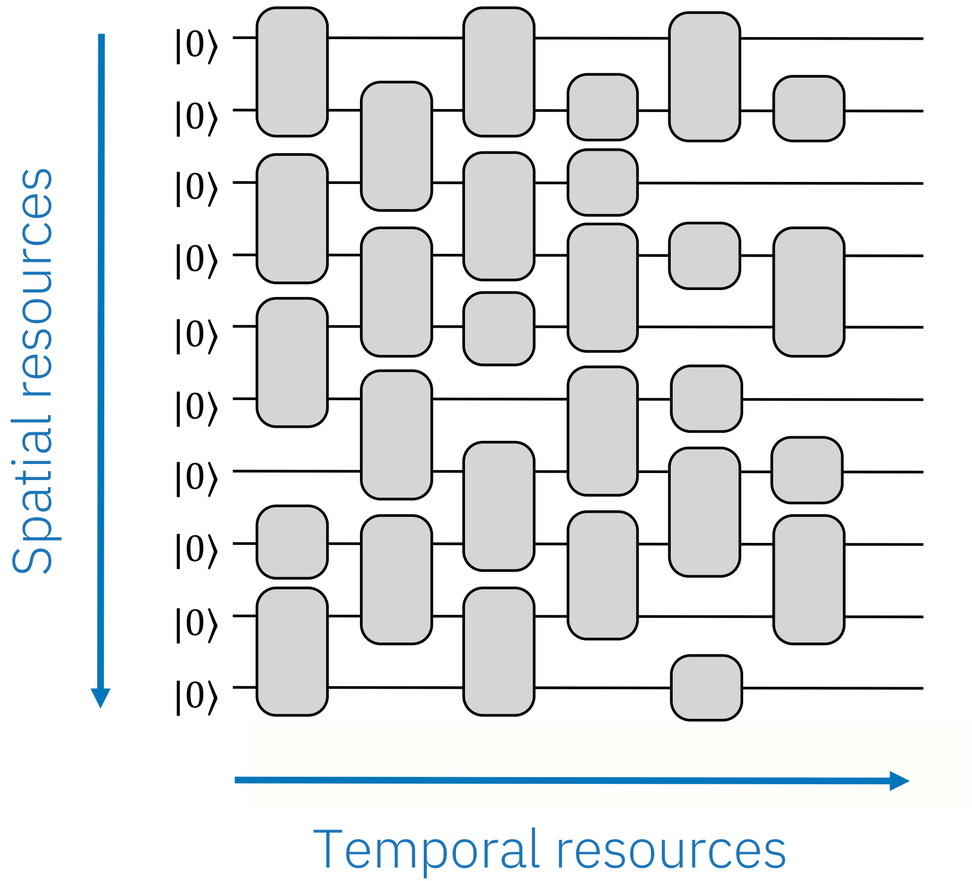


Dynamic circuits → can implement *any* allowed quantum process, not just unitary evolution.

Measurements and feedforward → new quantum algorithms?

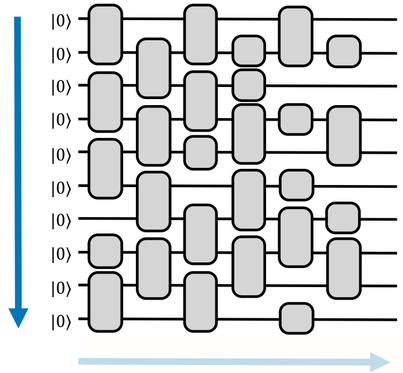
What makes dynamic circuits powerful?

A spacetime view:



What makes dynamic circuits powerful?

1. The ability to **reset** & **reuse** qubits can reduce **spatial** overhead



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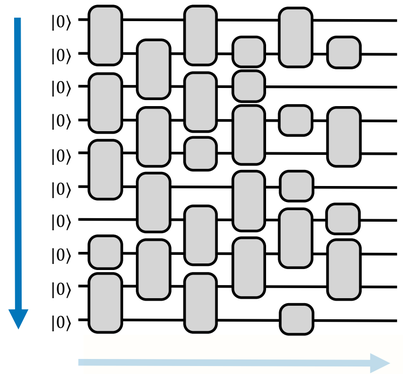

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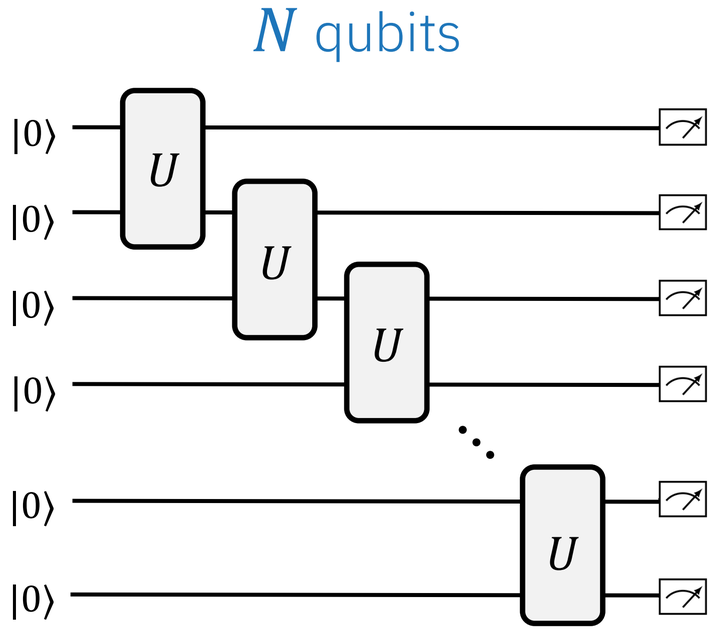
Example: staircase circuit



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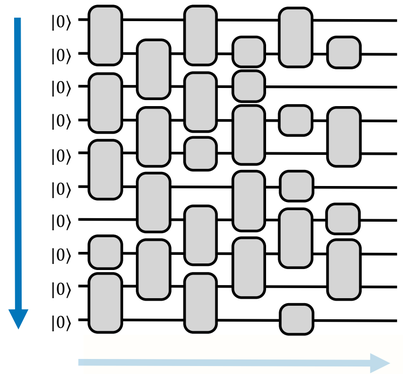

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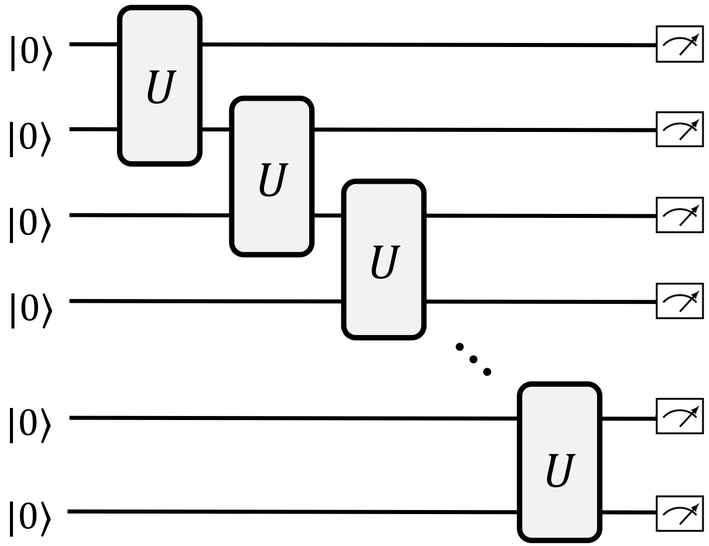
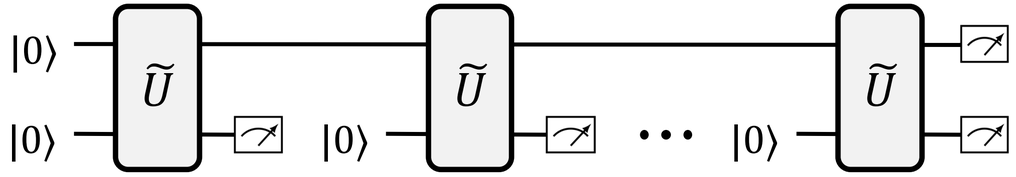
N qubits



2 qubits!



<u>See related work on so-called *holographic* algorithms</u>

Foss-Feig et al., Phys. Rev. Research (2022)

Chertkov et al., Nat. Phys (2022)

Decross et al., PRX (2023)

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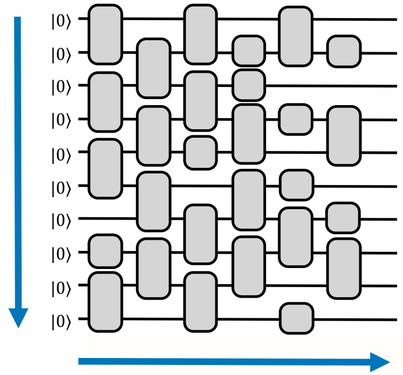
2. **Measurements** and **feedforward** can reduce **temporal** overhead



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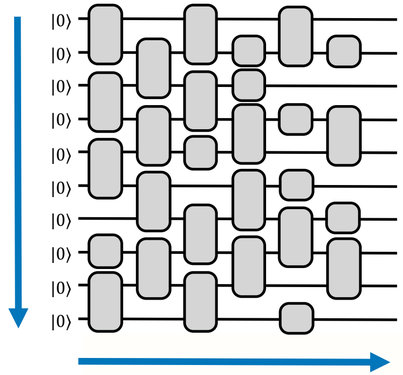

2. **Measurements** and **feedforward** can reduce **temporal** overhead

Example: GHZ state preparation

$$|\Psi\rangle = \frac{1}{\sqrt{2}}(|000\ldots0\rangle + |111\ldots1\rangle)$$

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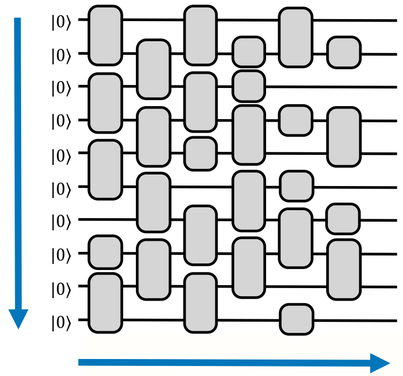

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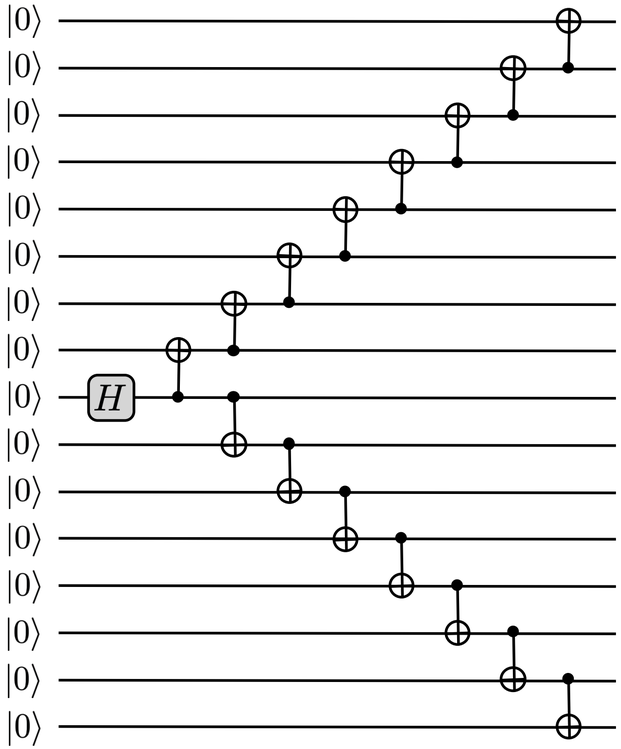
Unitary: $O(N)$ depth



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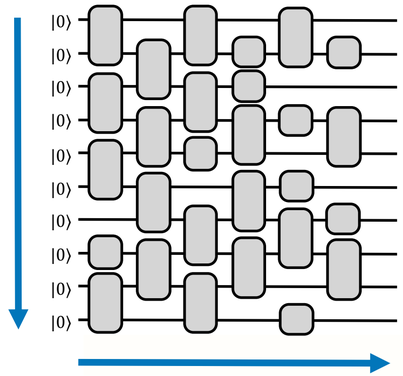

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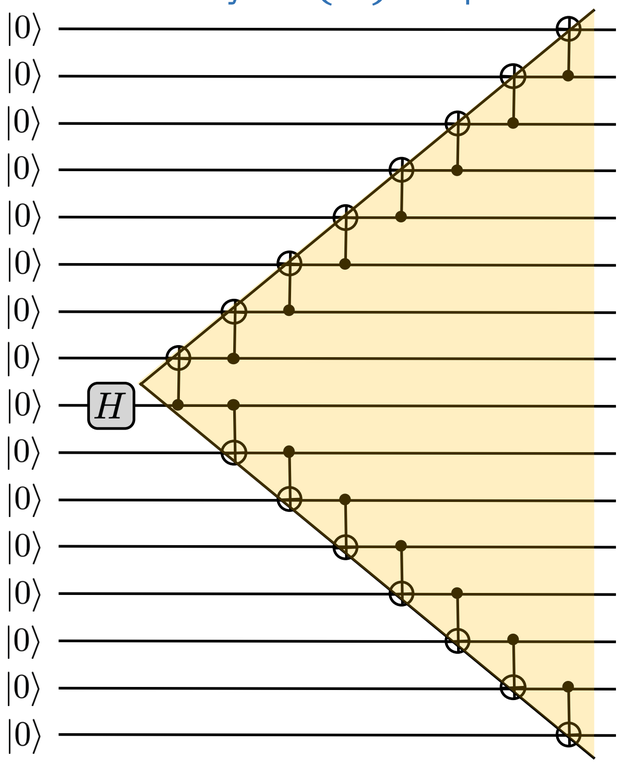

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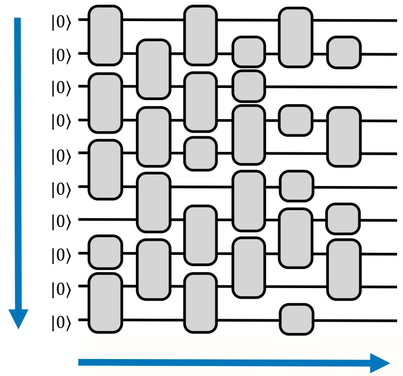

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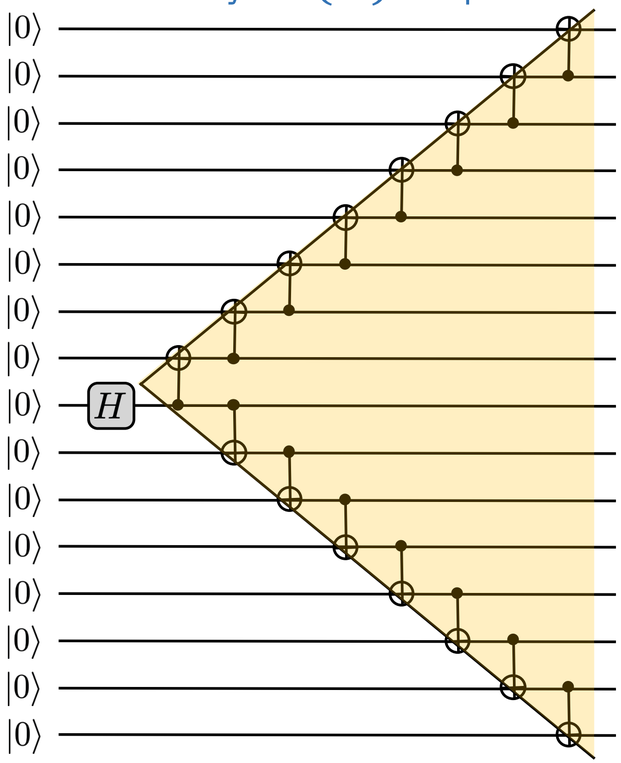

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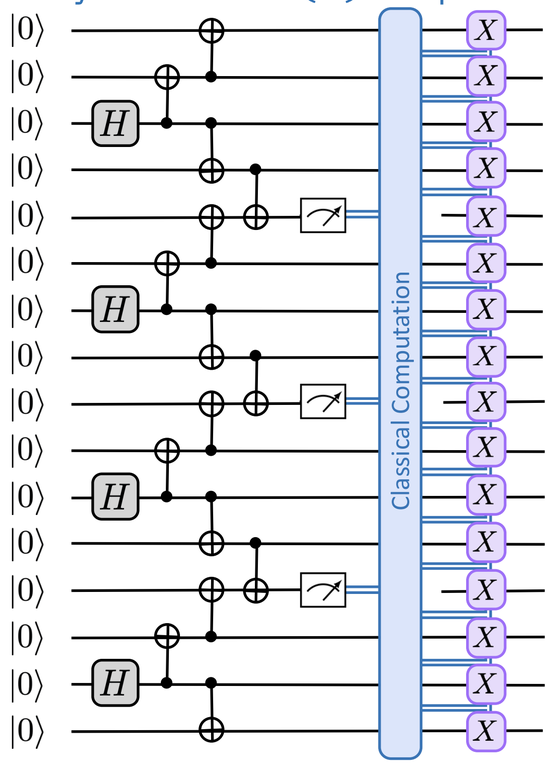
Dynamic: $O(1)$ depth



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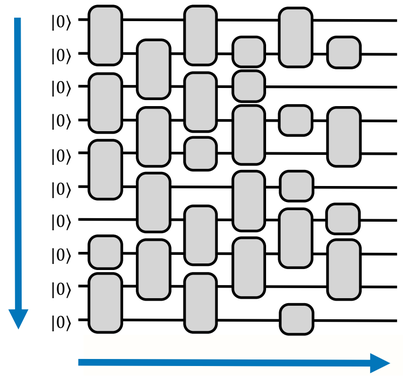

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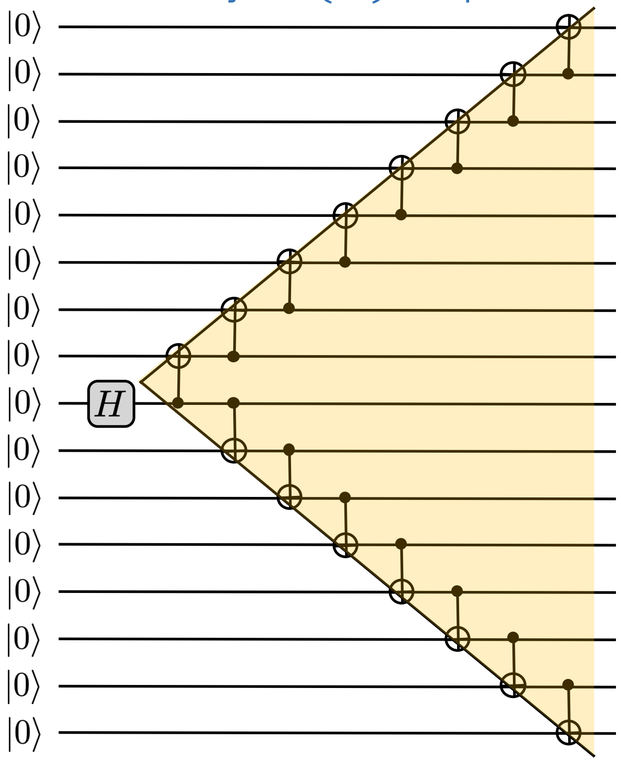

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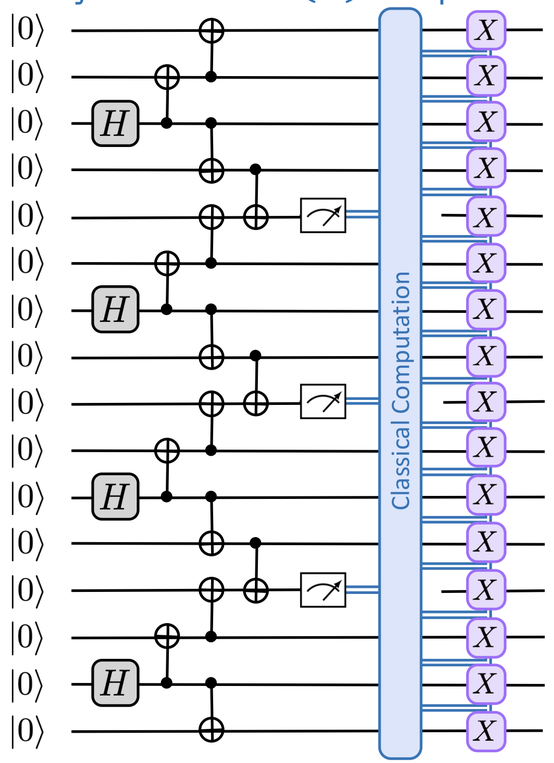
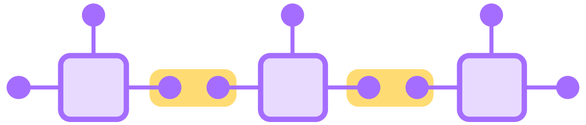


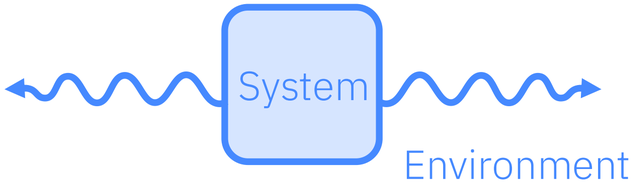
Applications of dynamic circuits

(beyond error correction)



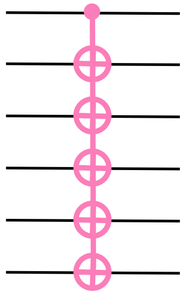
State preparation

- Long-range entangled states [1]
- Matrix product states [2]
- Topologically ordered states [3]
- Gibbs states [4]



Non-unitary processes

- Driven-dissipative dynamic
- Measurement-induced phase transitions [5]
- Nonlinear transformations [6]



Unitary compilation

- Long-range entangling gates [1]
- Many-qubit gates (e.g. fanout) [7]
- Distributed quantum computing

[1] Bäumer et al., PRX Quantum (2024); [2] Smith et al., PRX Quantum (2024); [3] Tanitasadakarn et al., PRX Quantum (2023);
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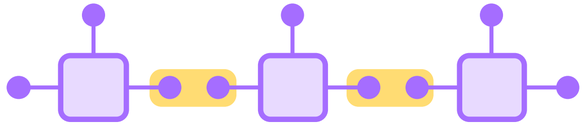

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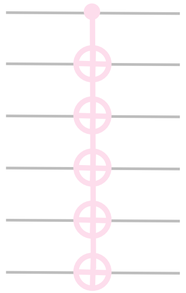

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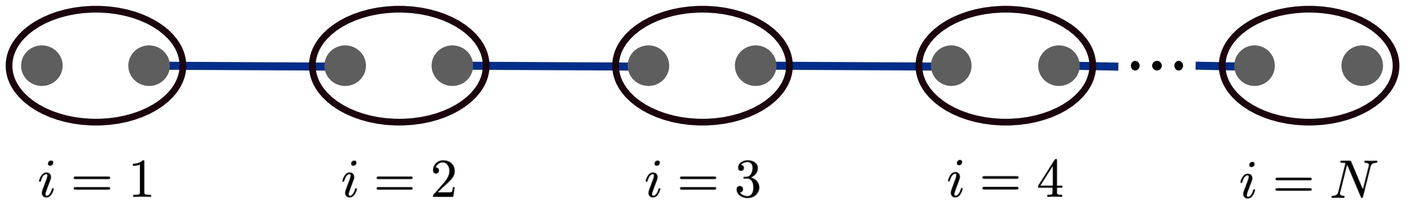
Affleck-Kennedy-Lieb-Tasaki (AKLT) state

Spin-1 chain: encode each spin-1 site with a pair of qubits



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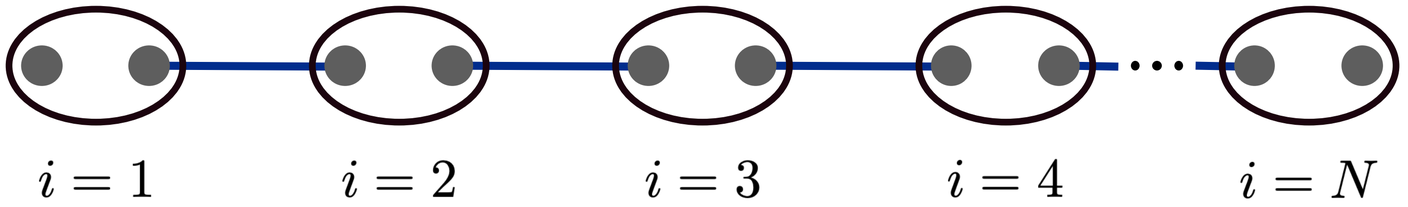

- A prototypical example of a matrix product state (MPS)

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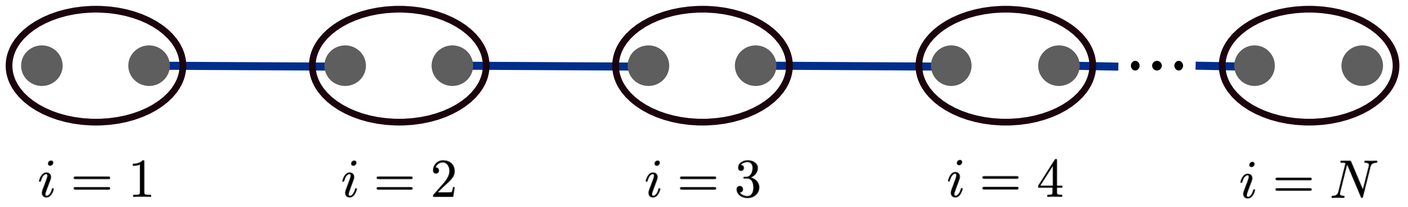

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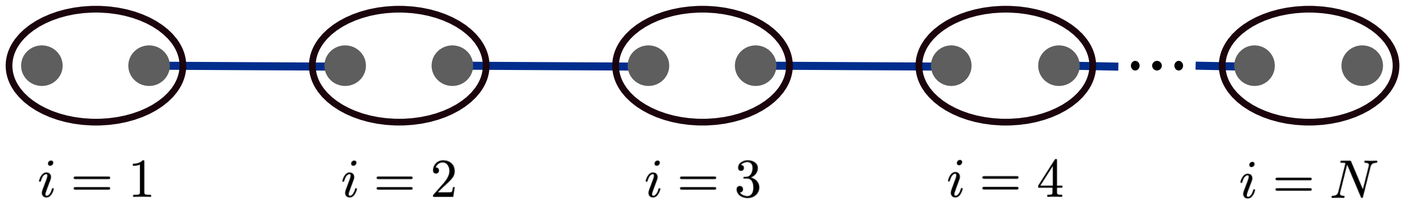

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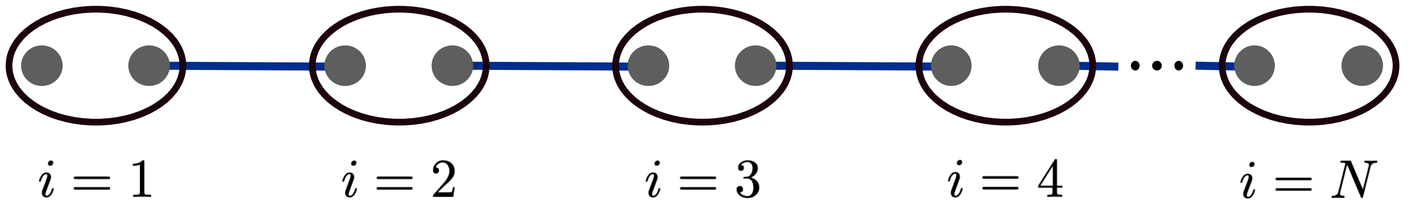

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- Preparation: $O(N)$ depth unitary circuit → $O(1)$ depth dynamic circuit [4, 5]

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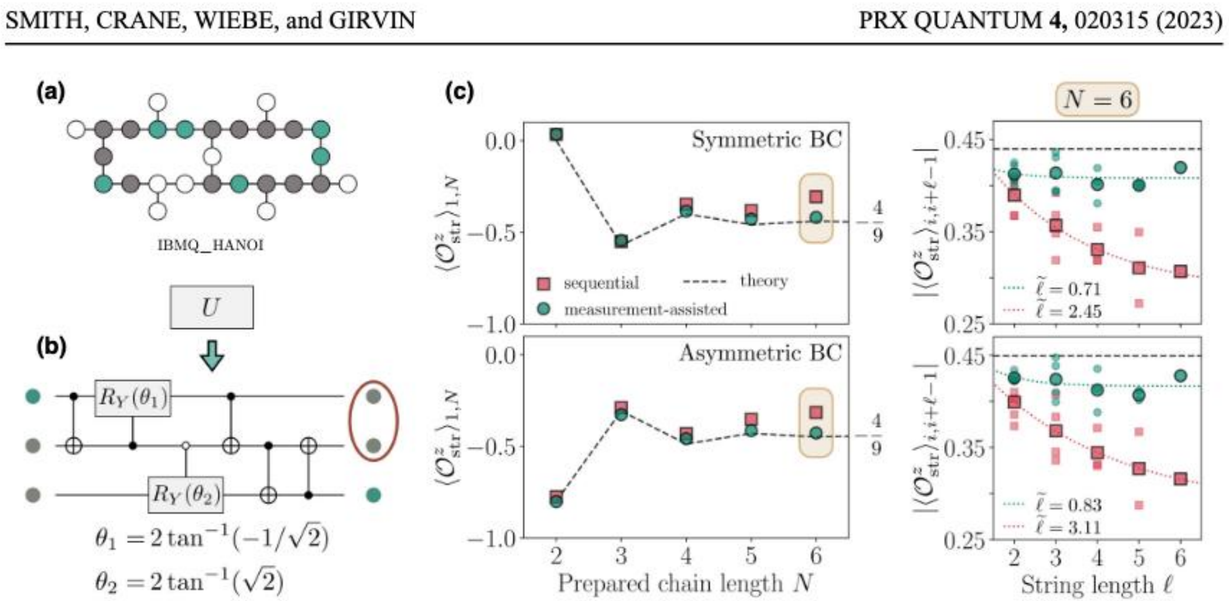
Dynamic circuits (initial release)



Presented at IBM Quantum Summit (2022)

- Up to $N_{\mathrm{sites}} = 6$ AKLT state preparation
  - 14 qubits (unitary)
  - 18 qubits (measurement based)
    - 4 used as fusion qubits
- Post-process only (no ffwd)

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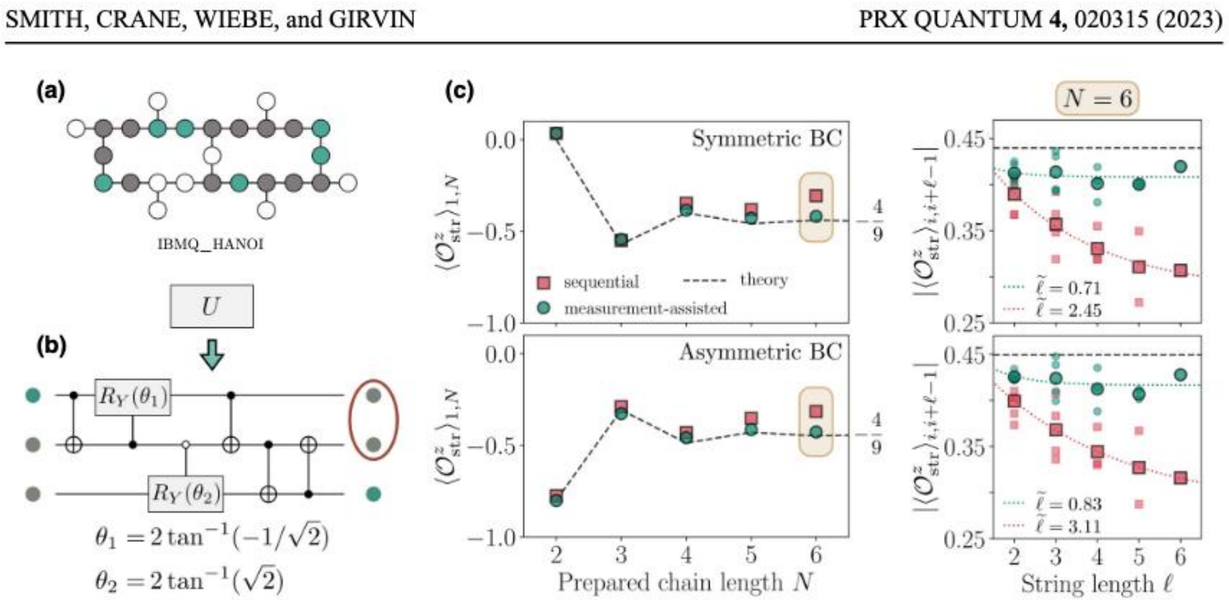

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Dynamic circuits capability introduced at the summit in 2022 enabled this experiment to run with **real time feed-forward**!

But with some challenges and limitations…

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Previous version

- Parallel feed forward operations limited to 10 bit input using `Switch`
  - Up to 12 site AKLT state

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- Parallel `if`s / feed forward operations
  - Demonstrate up to 30 site AKLT state using 90 qubits

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- `Stretch` enables better implementation of dynamical decoupling during feed-forward time
- Scheduled circuits are returned (beta) to help with debugging and optimization

AKLT state preparation with utility scale dynamic circuits

- Different methods to prepare the AKLT states:
  1. Unitary
  2. Measurement based without dynamic circuits (post-process)
  3. Measurement based with dynamic circuits (real-time feed-forward)
  4. Hybrid (combine unitary and dynamic)

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- What changes in the circuit:
  1. Extra ancilla qubits needed
  2. Depths of the circuit: 2Q gate and measurement layers

AKLT state preparation with utility scale dynamic circuits

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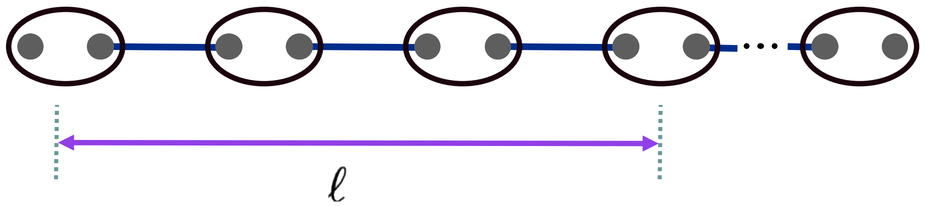
Validation of AKLT state preparation

String order

$$\langle O^z_{\mathrm{str}} \rangle_{\ell,i} = \langle S^z_i \prod_{k=1}^{\ell-2} e^{i\pi S^z_{i+k}} S^z_{i+\ell-1} \rangle$$



Non-zero value: fingerprint of symmetry-protected topological (SPT) order

Validation of AKLT state preparation

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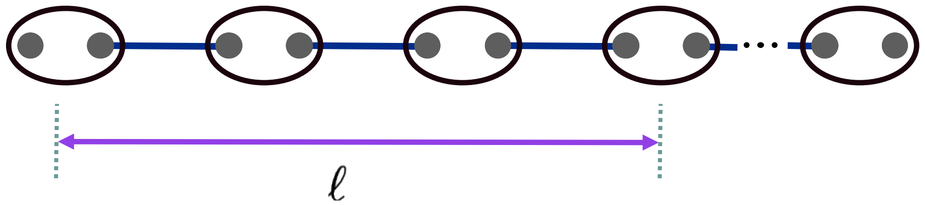
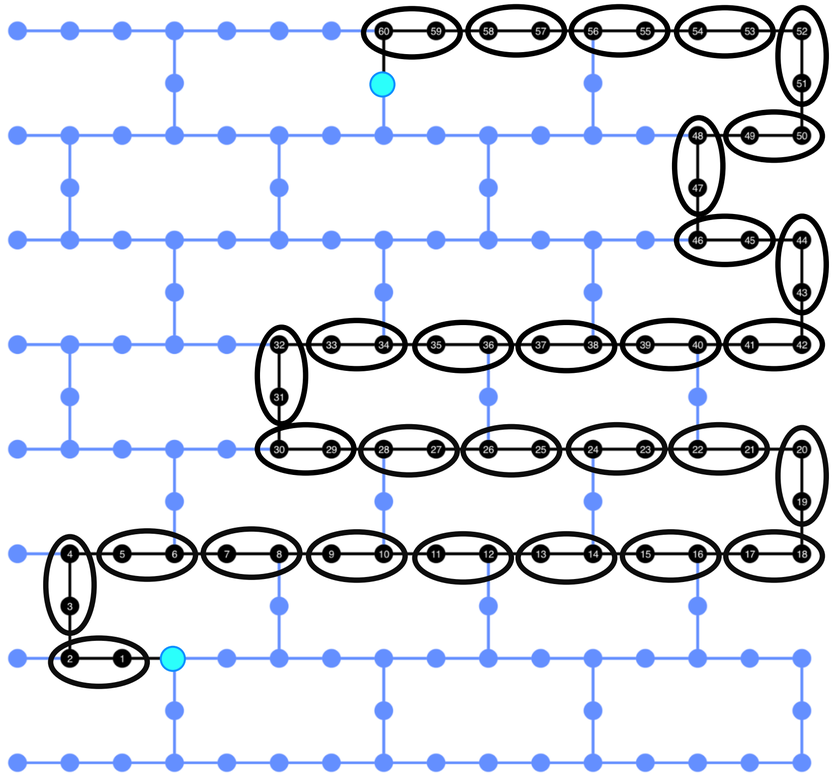


Non-zero value: fingerprint of symmetry-protected topological (SPT) order

$N_{\mathrm{sites}} = 30$ on Heron processor



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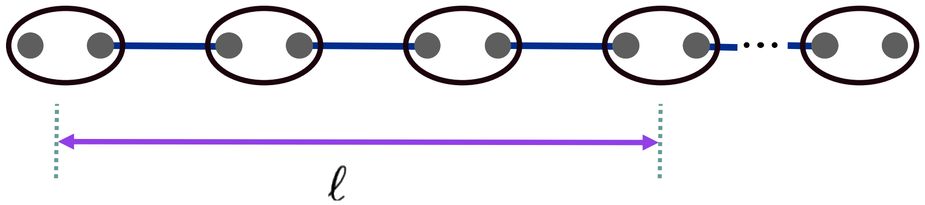
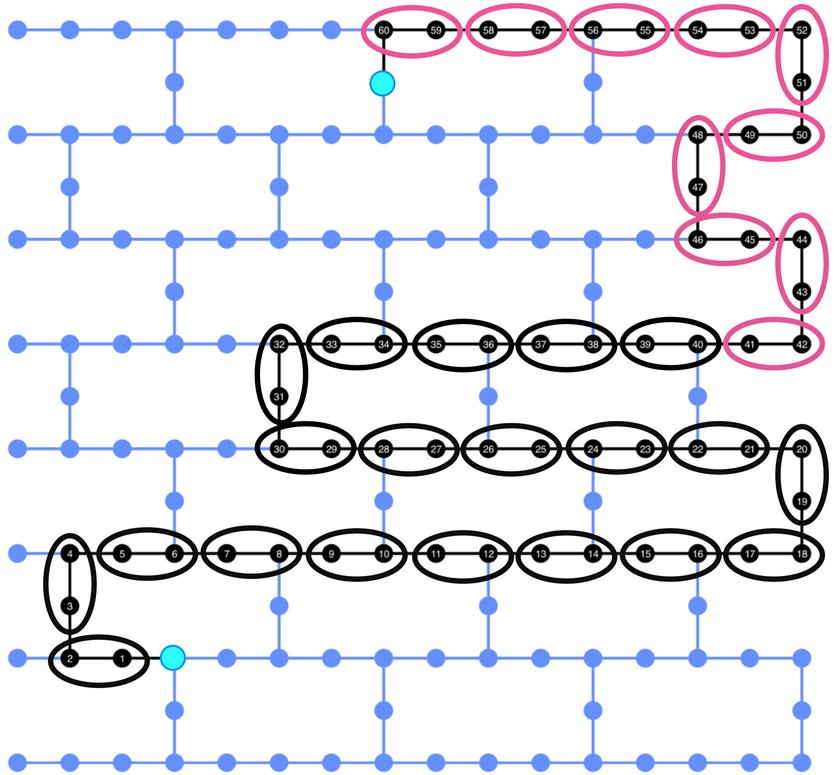


Non-zero value: fingerprint of symmetry-protected topological (SPT) order

Ex) $l = 10$

$N_{\mathrm{sites}} = 30$ on Heron processor



21 total $length\ 10$ chains

AKLT state preparation with utility scale dynamic circuits

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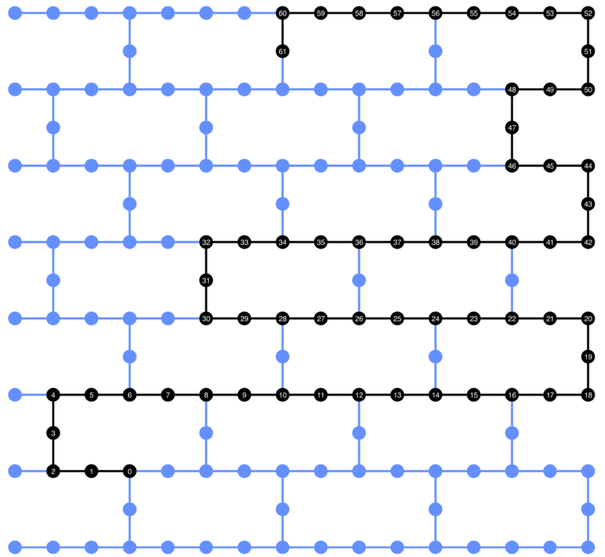
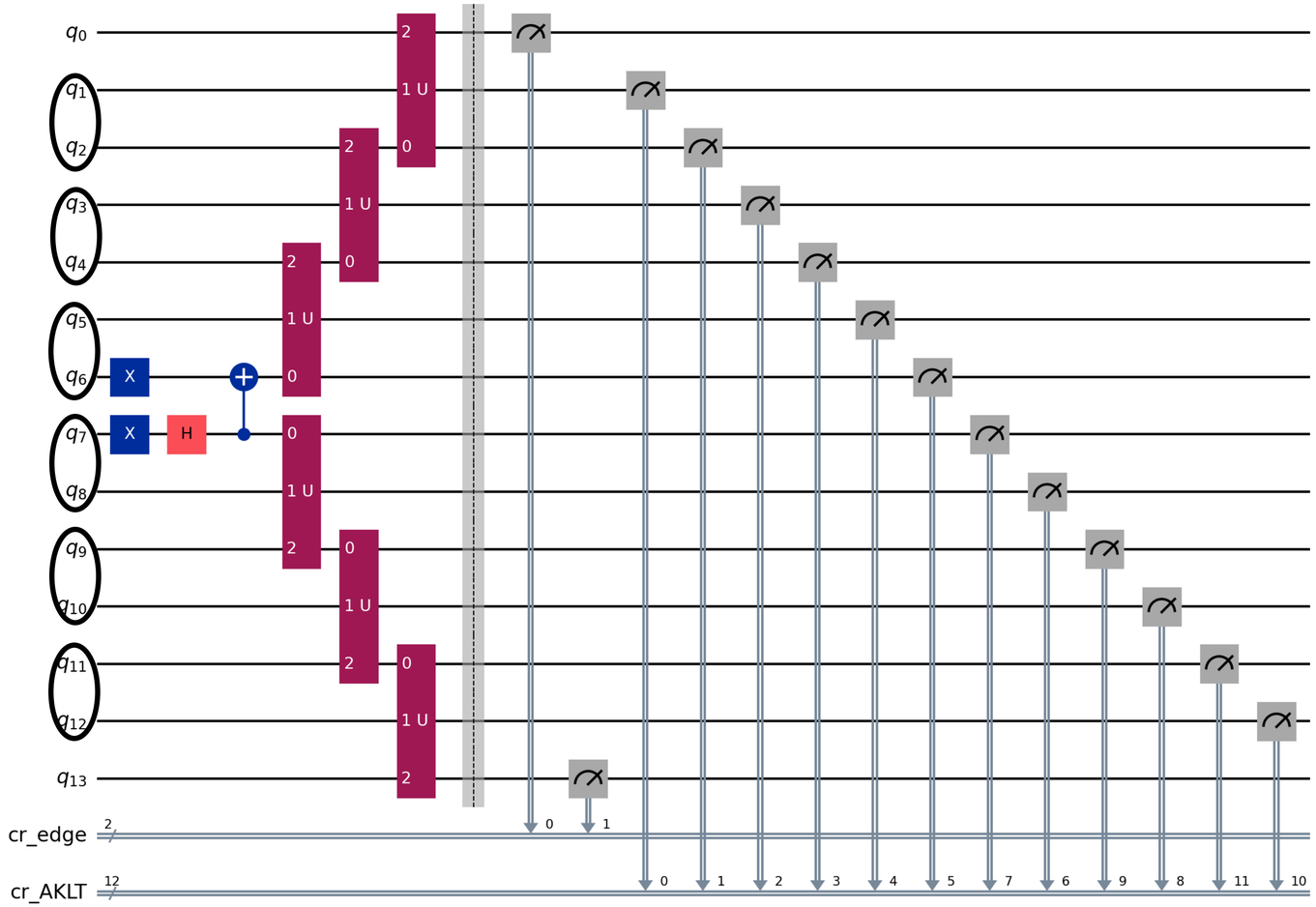
62 qubits for $N_{\text{sites}} = 30$



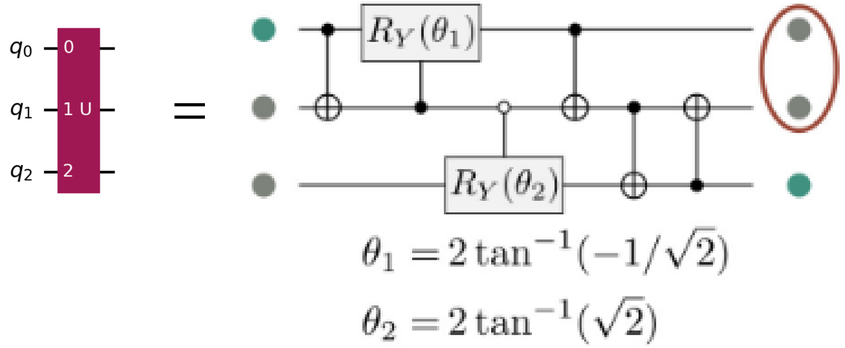
Unitary AKLT state preparation ($N_{\text{sites}} = 6$)



Total number of qubits needed

$= N_{\text{sites}} \times 2 + ancillas$

$= N_{\text{sites}} \times 2 + 2 = 14$



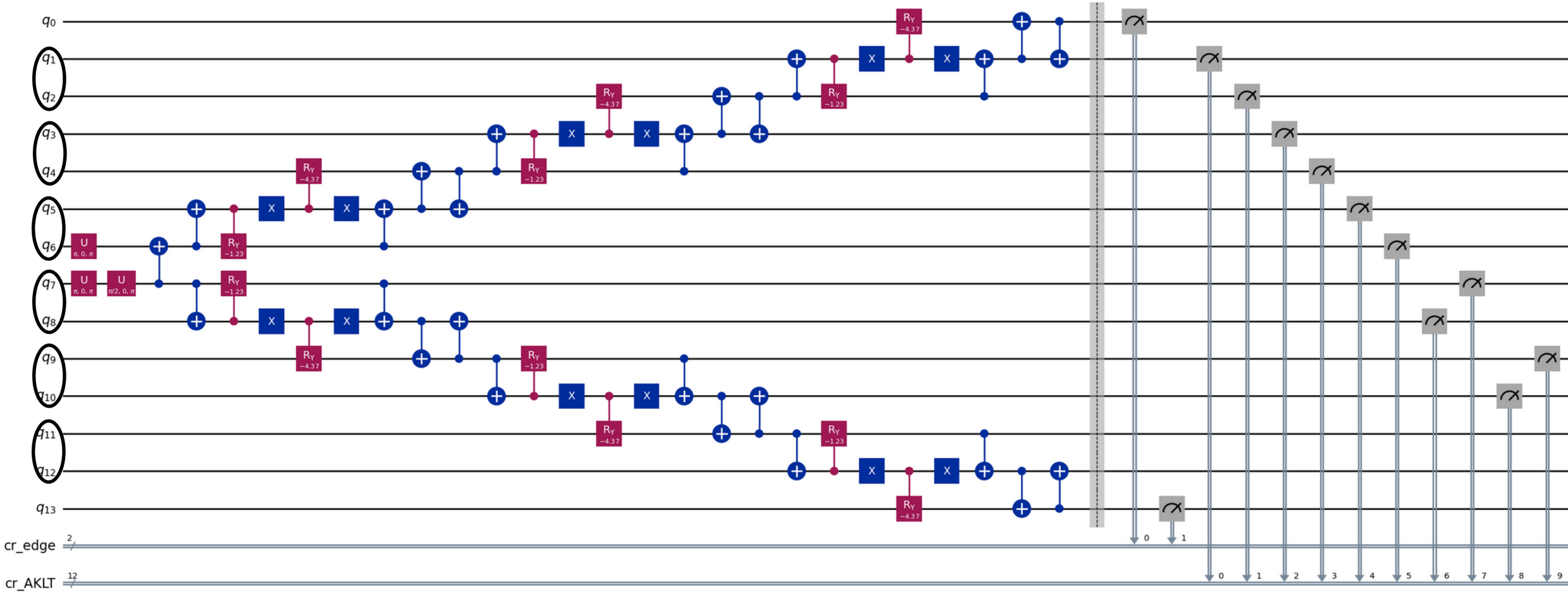
On IBM Herons, transpiles to Rz(θ)'s plus:

$7CZ + 10Sx$

per 2 N_{sites}

Unitary AKLT state preparation ($N_{\text{sites}} = 6$)

Total number of qubits needed
$= N_{\text{sites}} \times 2 + ancillas$
$= N_{\text{sites}} \times 2 + 2 = 14$



AKLT state preparation with utility scale dynamic circuits

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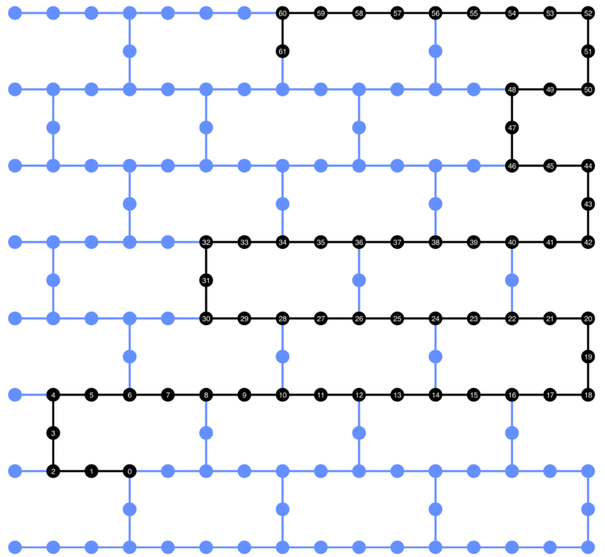
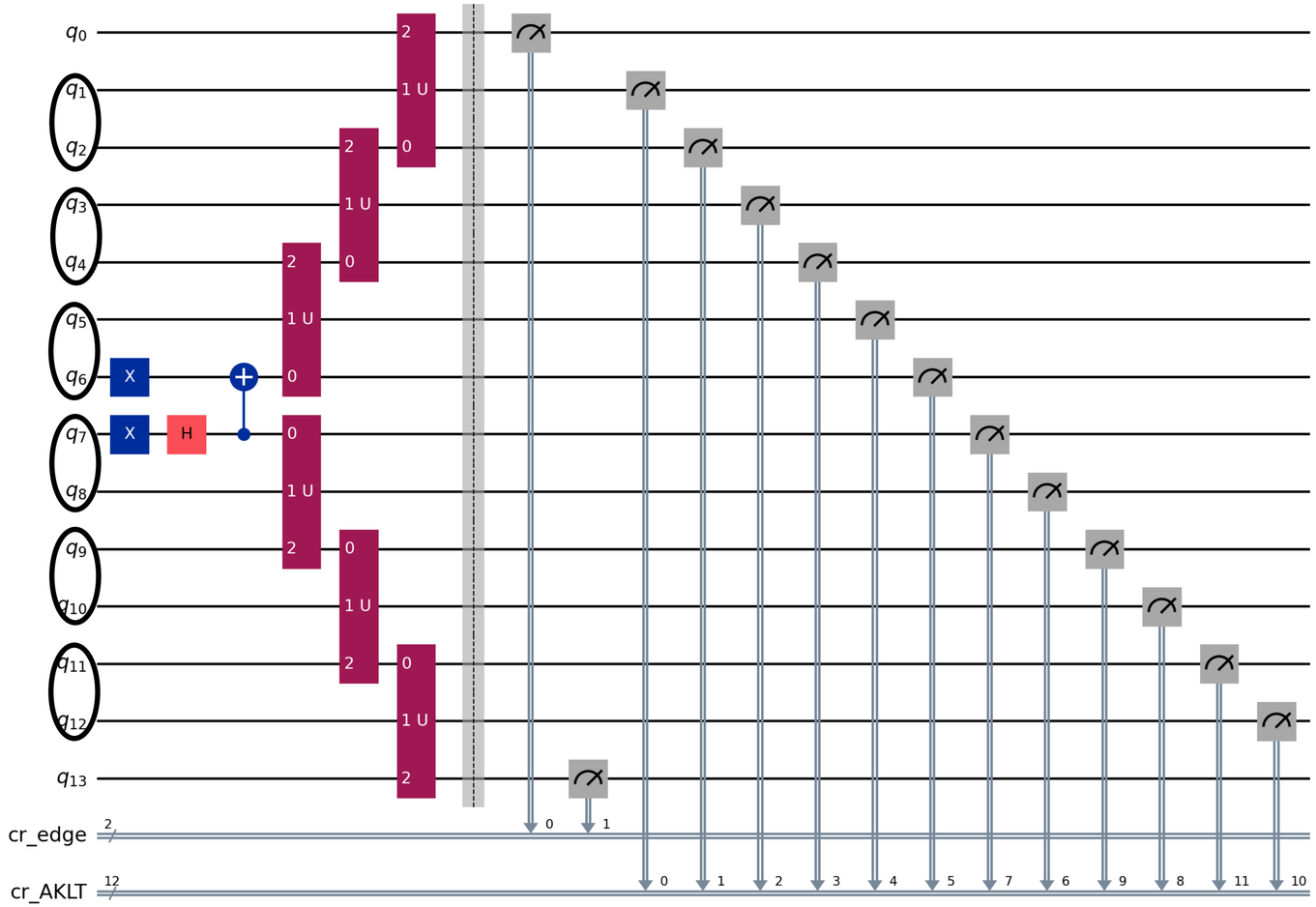
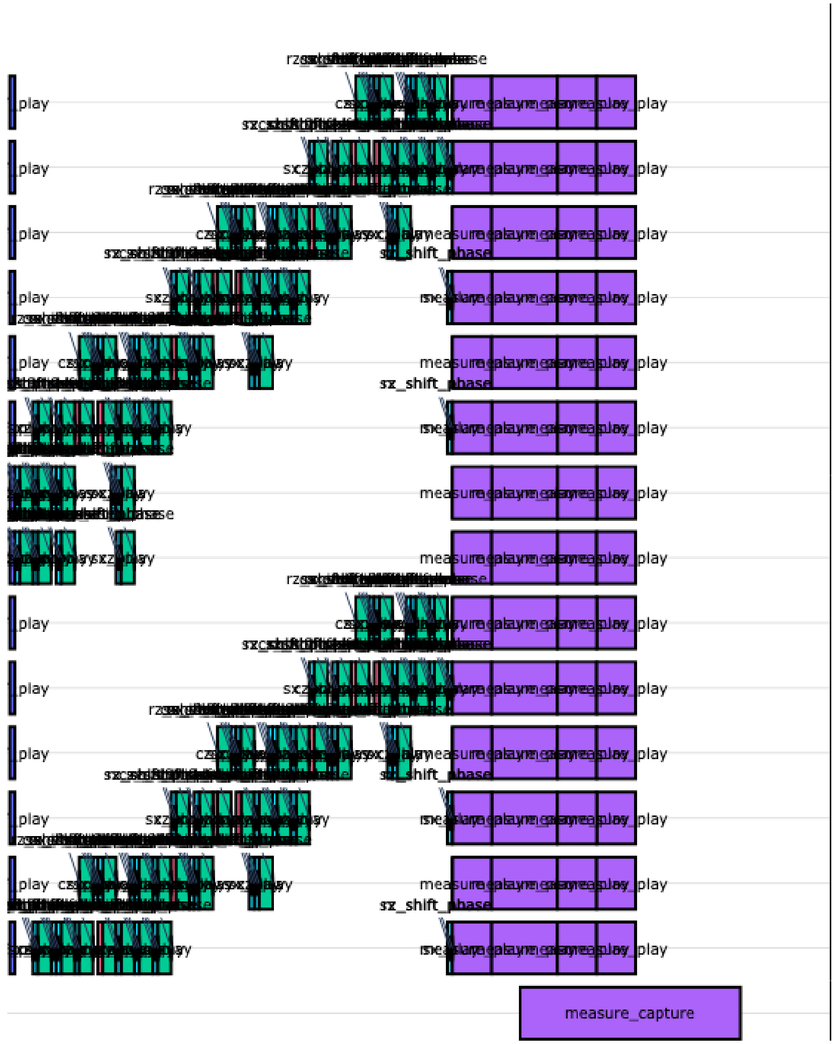


Unitary
scheduled circuit ($N_{\mathbf{sites}} = 6$)





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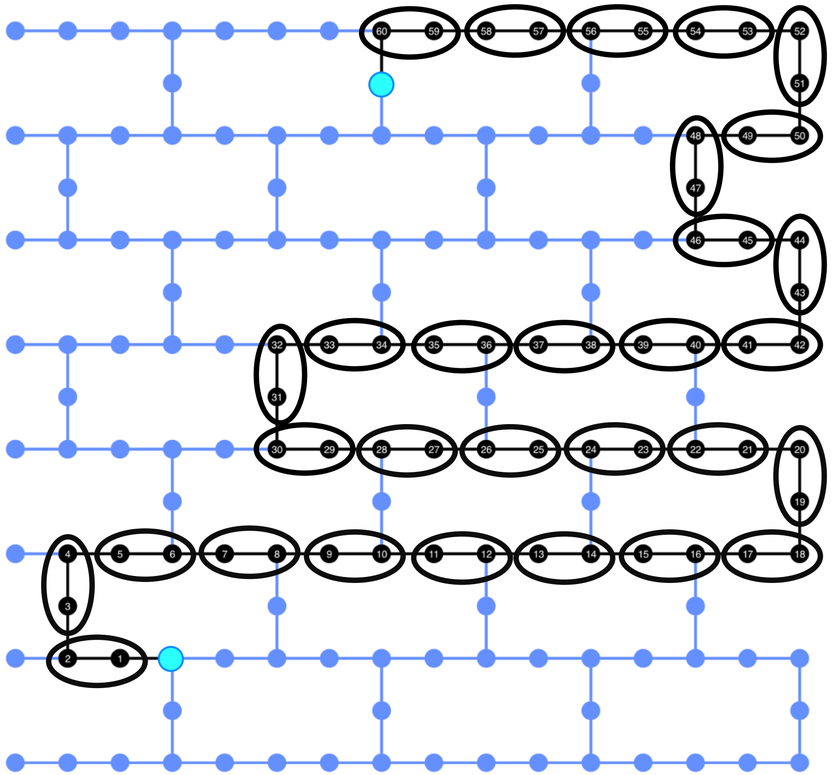
Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Unitary (62 qubits)

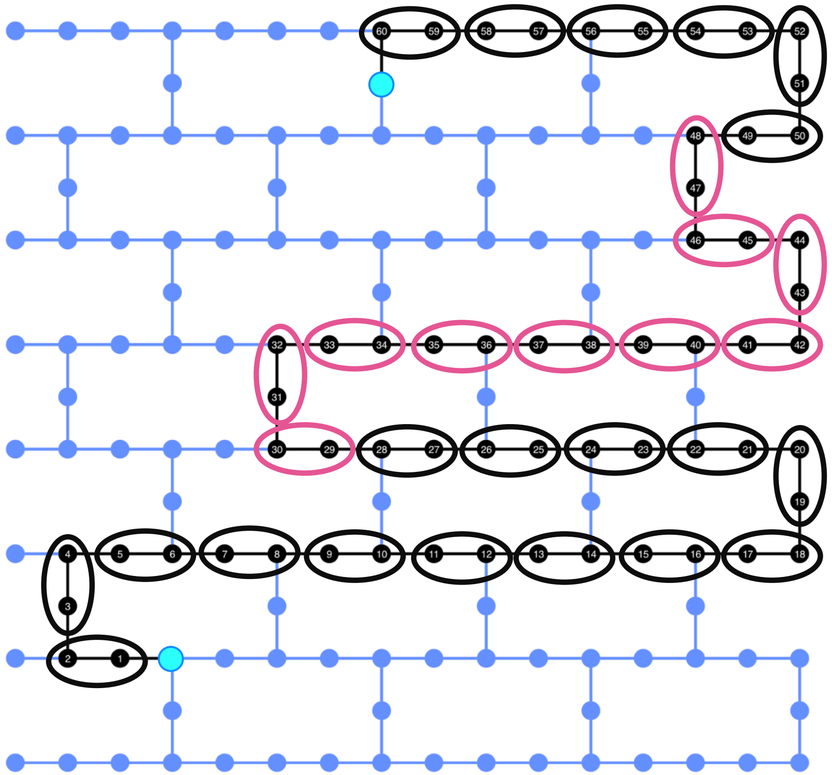


Circuit duration: $\sim 16.3 \mu s$

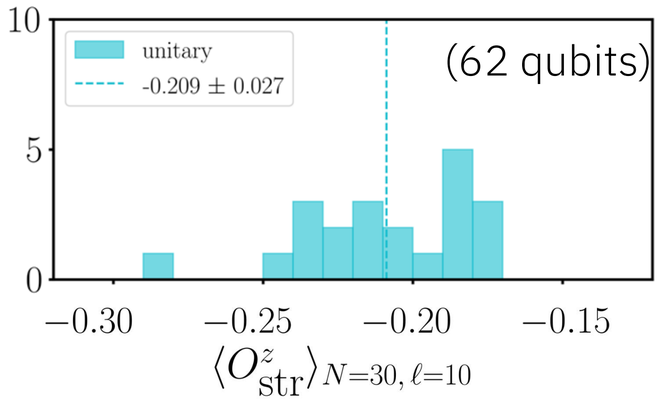
Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Unitary (62 qubits)

$l = 10$



Circuit duration: $\sim 16.3 \mu s$



21 x length-10 chains

AKLT state preparation with utility scale dynamic circuits

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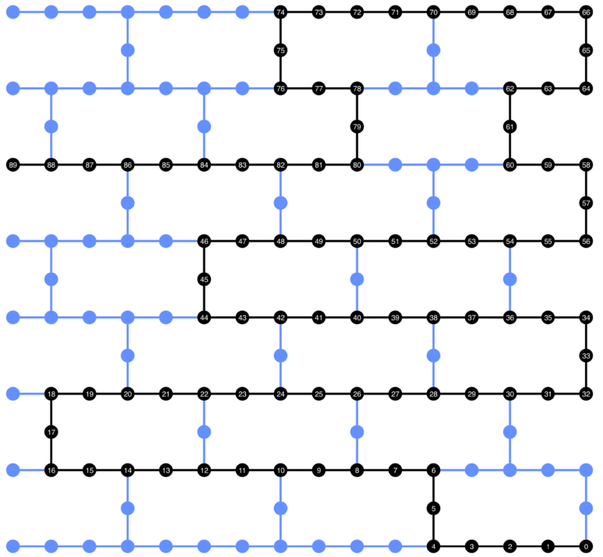
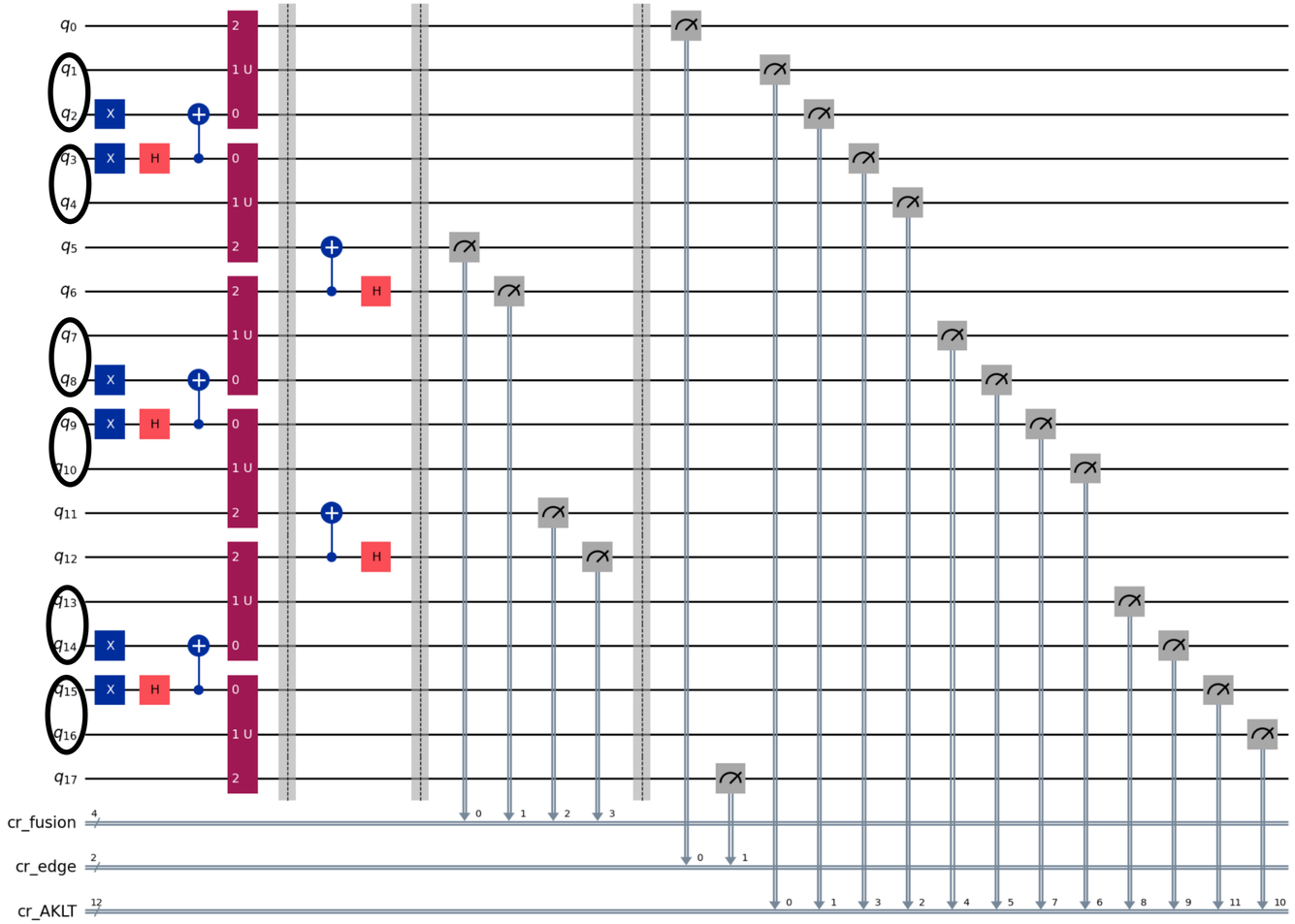
90 qubits for $N_{\text{sites}} = 30$

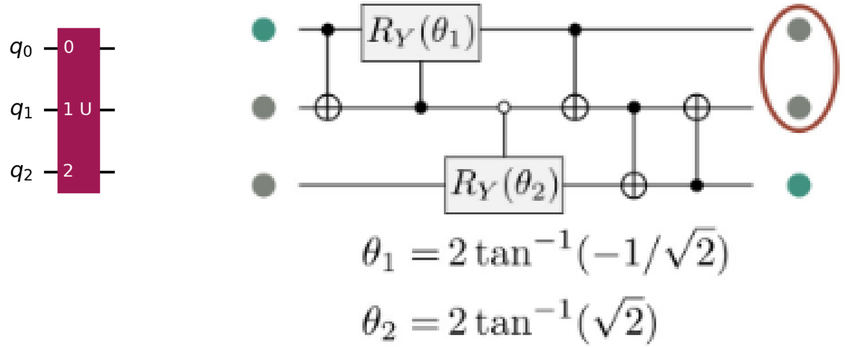


Measurement based AKLT state preparation ($N_{\text{sites}} = 6$)



Z(θ)'s plus: $7 \times CZ + 10 \times Sx$

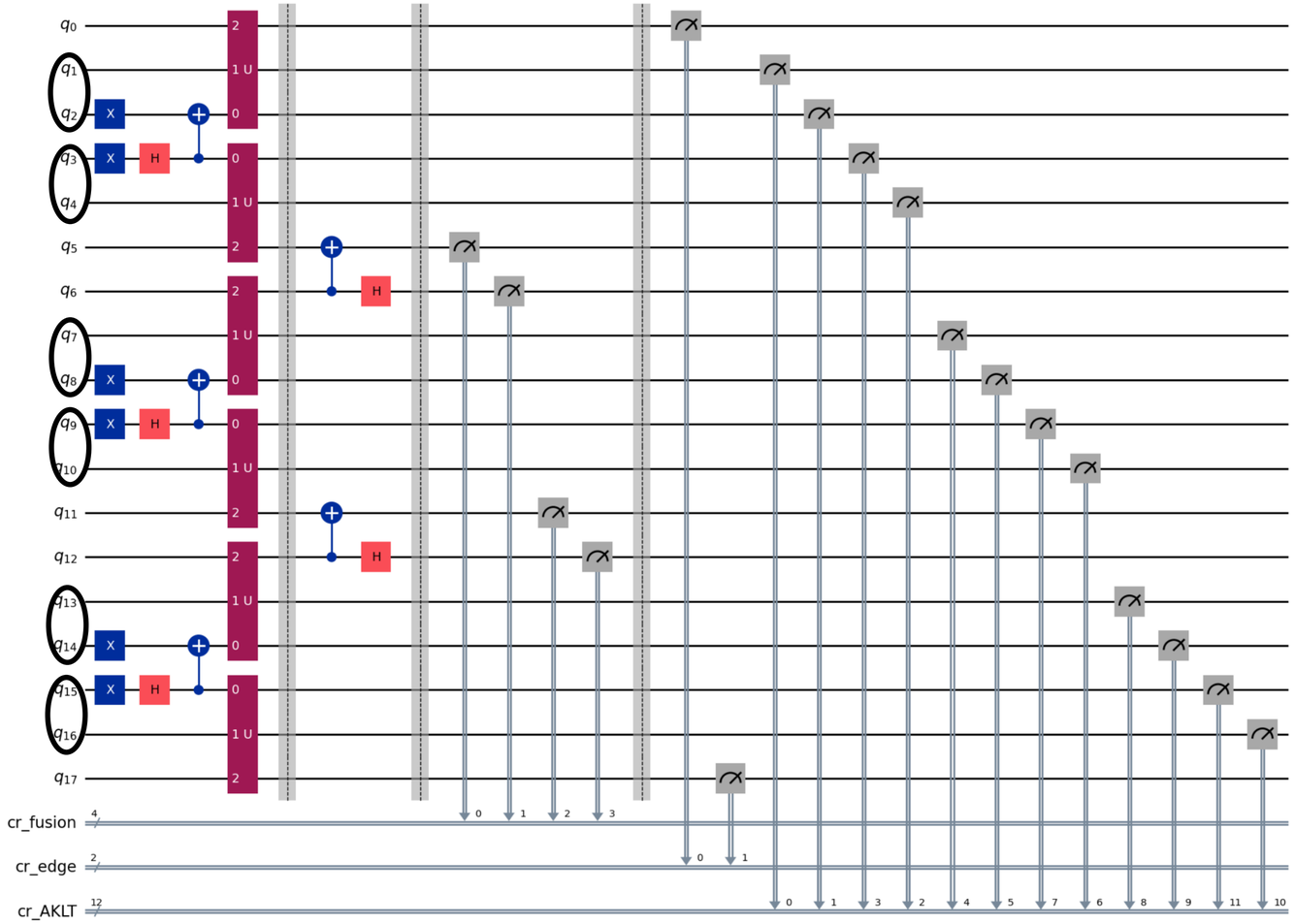
Total number of qubits needed
$= N_{\text{sites}} \times 2 + ancillas$
$= N_{\text{sites}} \times 3 = 18$

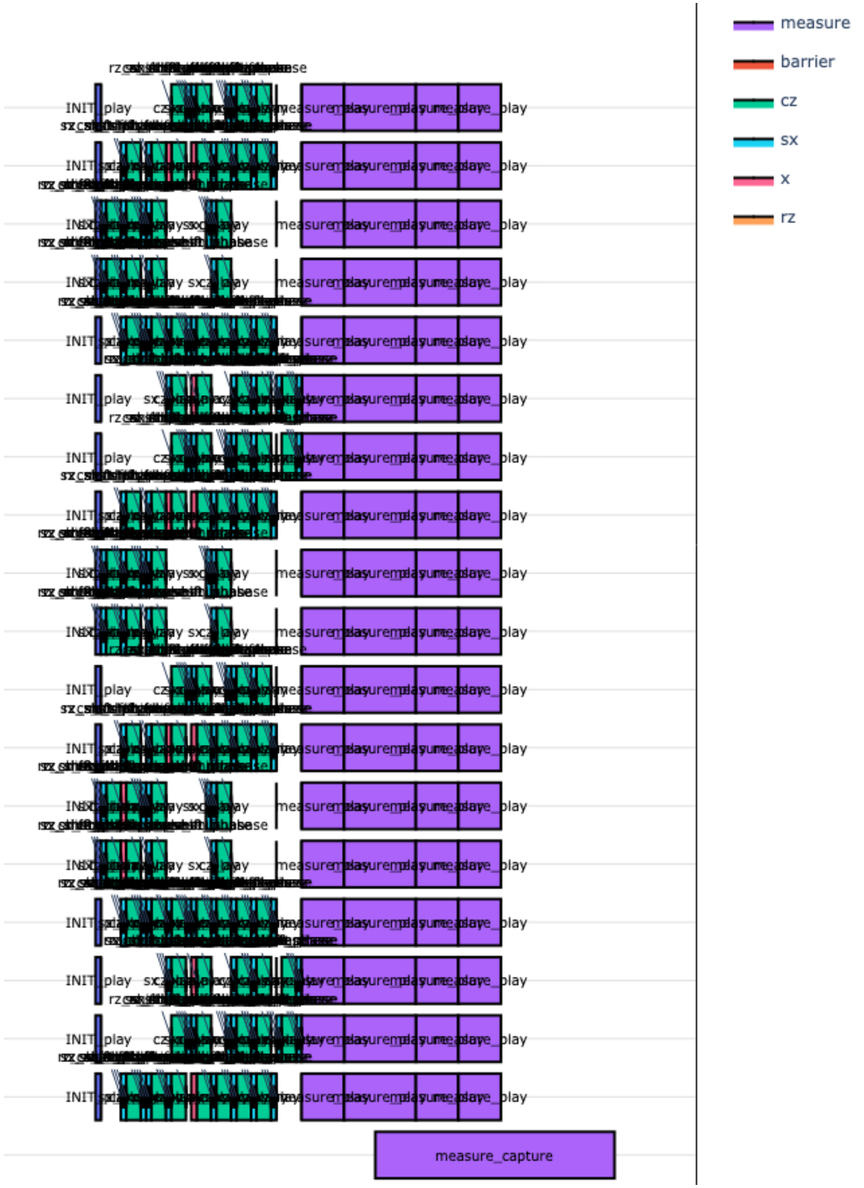


On IBM Herons, transpiles to Rz(θ)'s plus:

$7CZ + 10Sx$
for any N_{sites}

Measurement based scheduled circuit ($N_{\mathbf{sites}} = 6$)

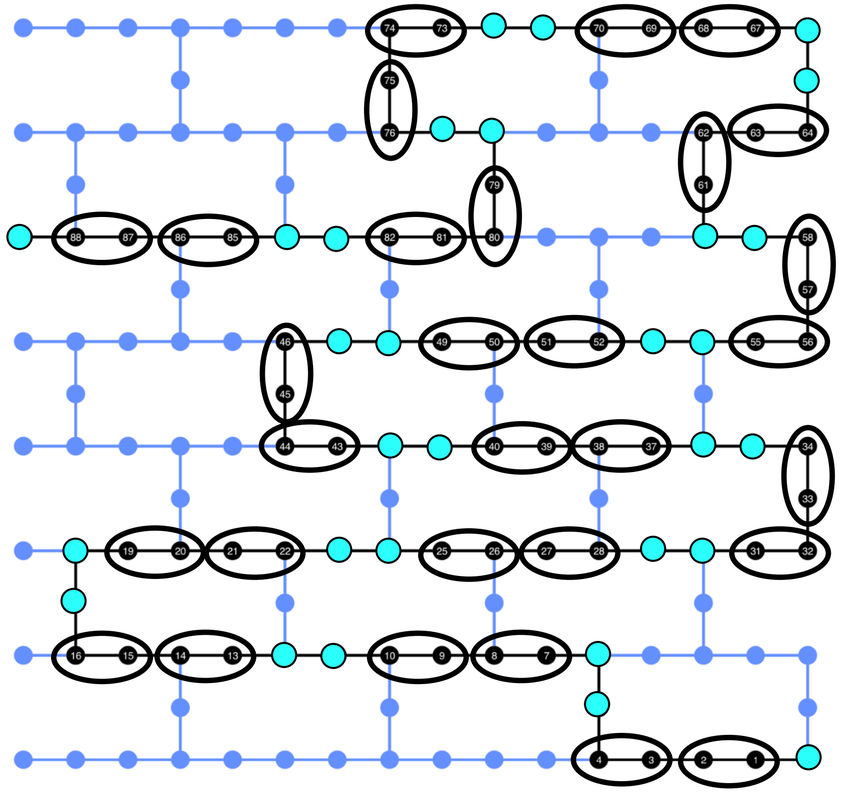




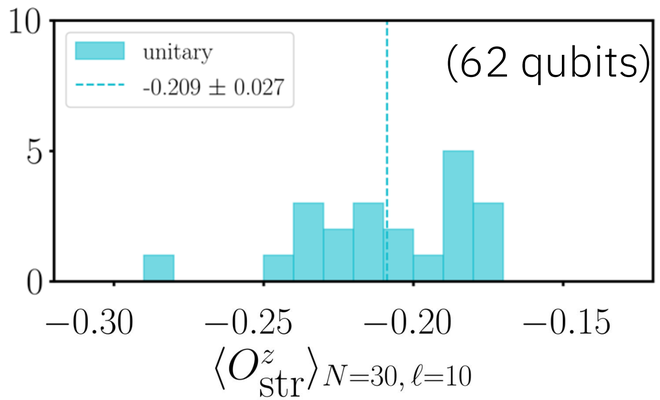
Z(θ)'s plus: $7CZ + 10Sx$

Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Measurement based (90 qubits)



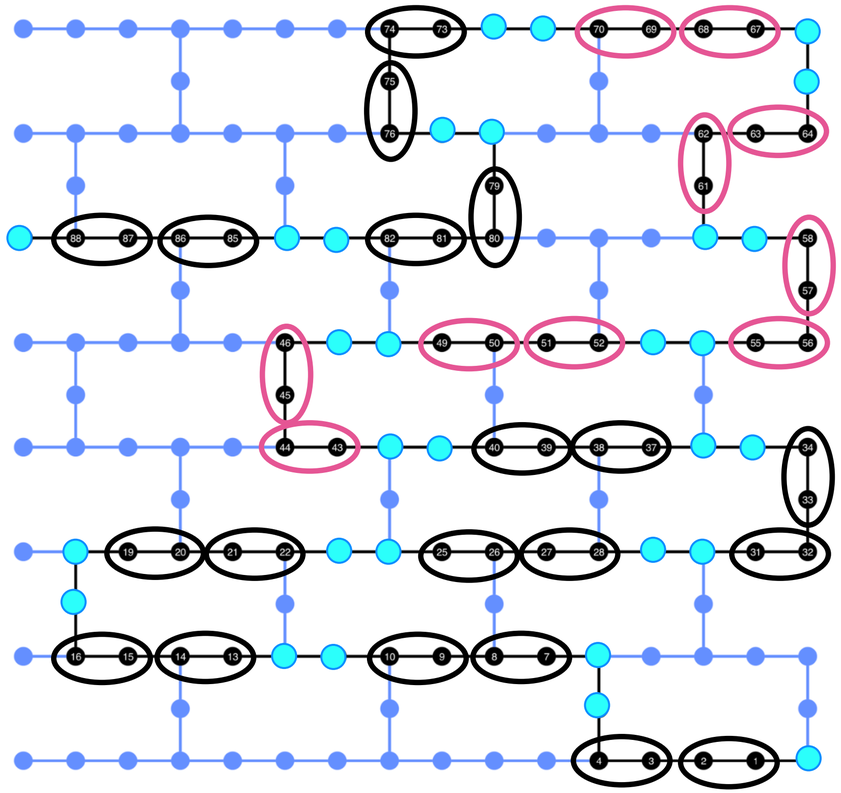
Circuit duration: $\sim 3.8\mu s$



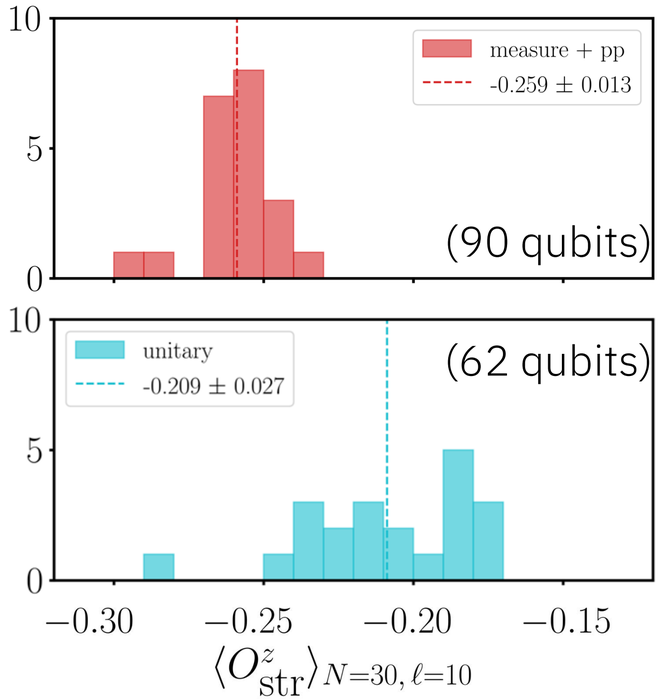
21 x length-10 chains

Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Measurement based (90 qubits) $l = 10$



Circuit duration: $\sim 3.8\mu s$



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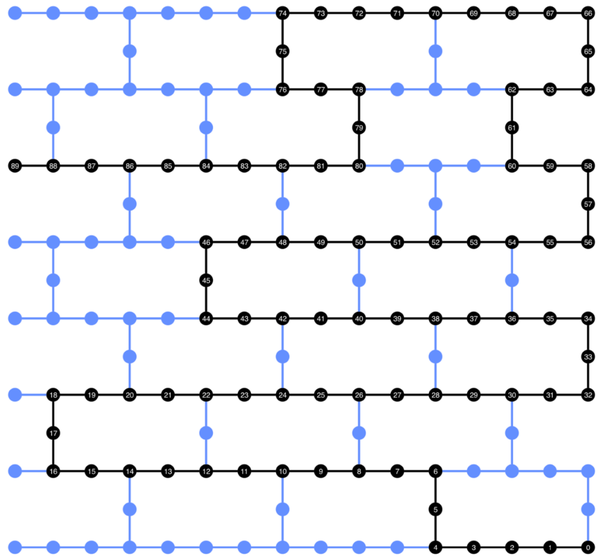

Dynamic AKLT state preparation ($N_{\text{sites}} = 6$)

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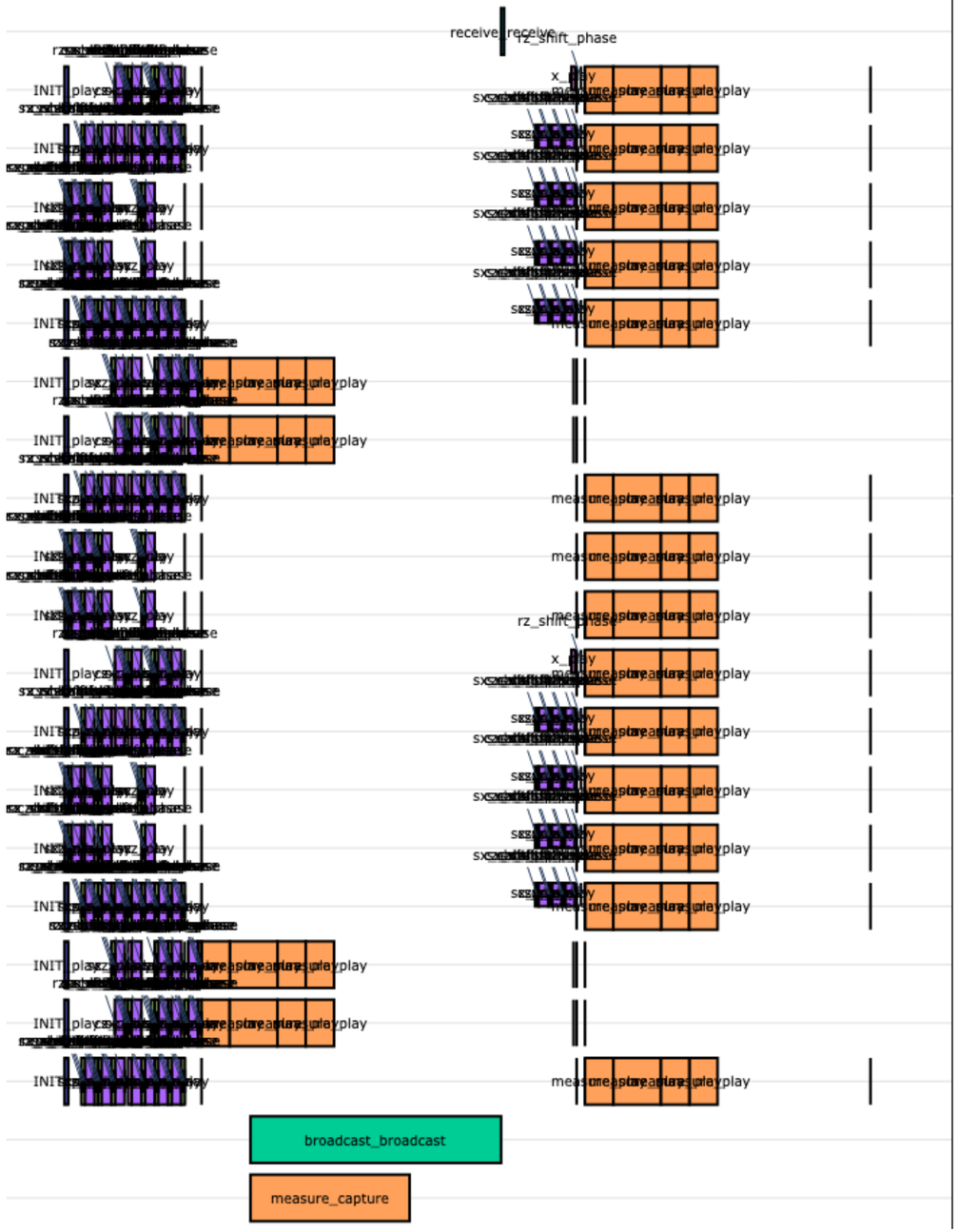
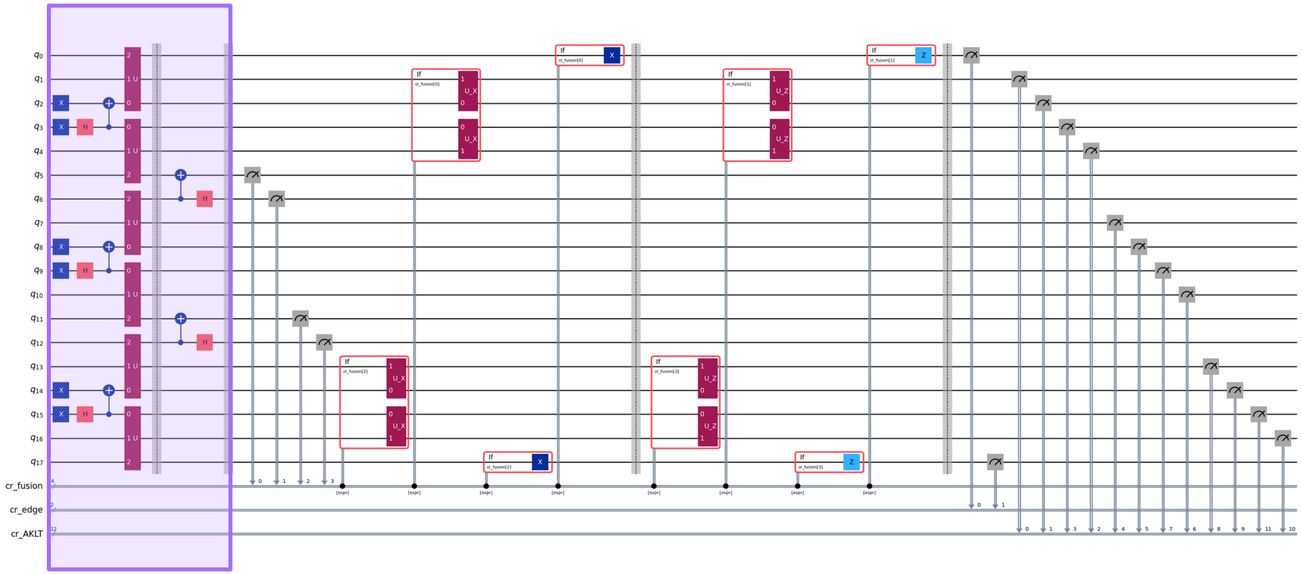
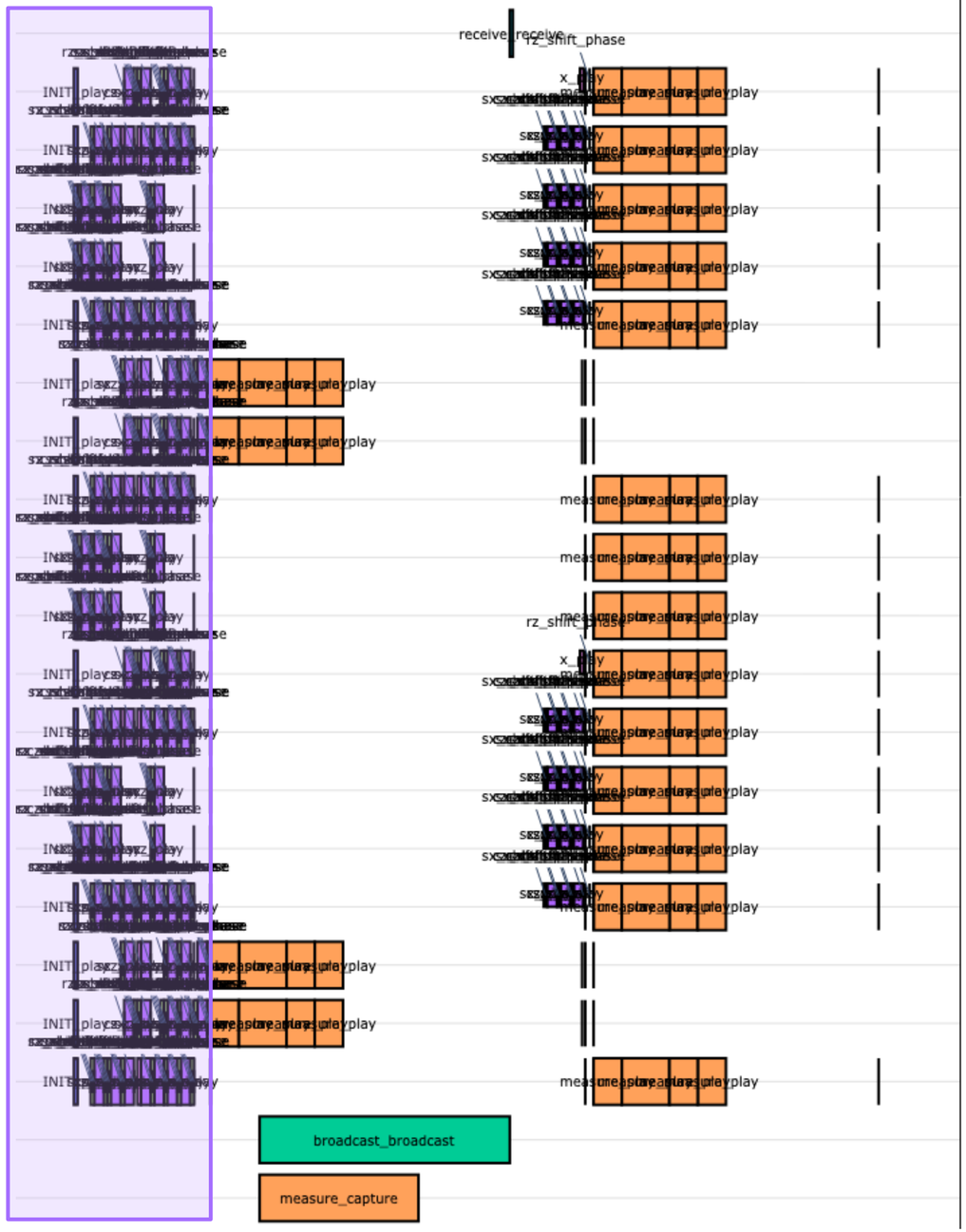
Z(θ)'s plus: $7CZ + 10Sx + SWAP\ (3CZ + 3Sx) + ffwd$

Dynamic scheduled circuit ($N_{\text{sites}} = 6$)



Dynamic
scheduled circuit ($N_{\text{sites}} = 6$)





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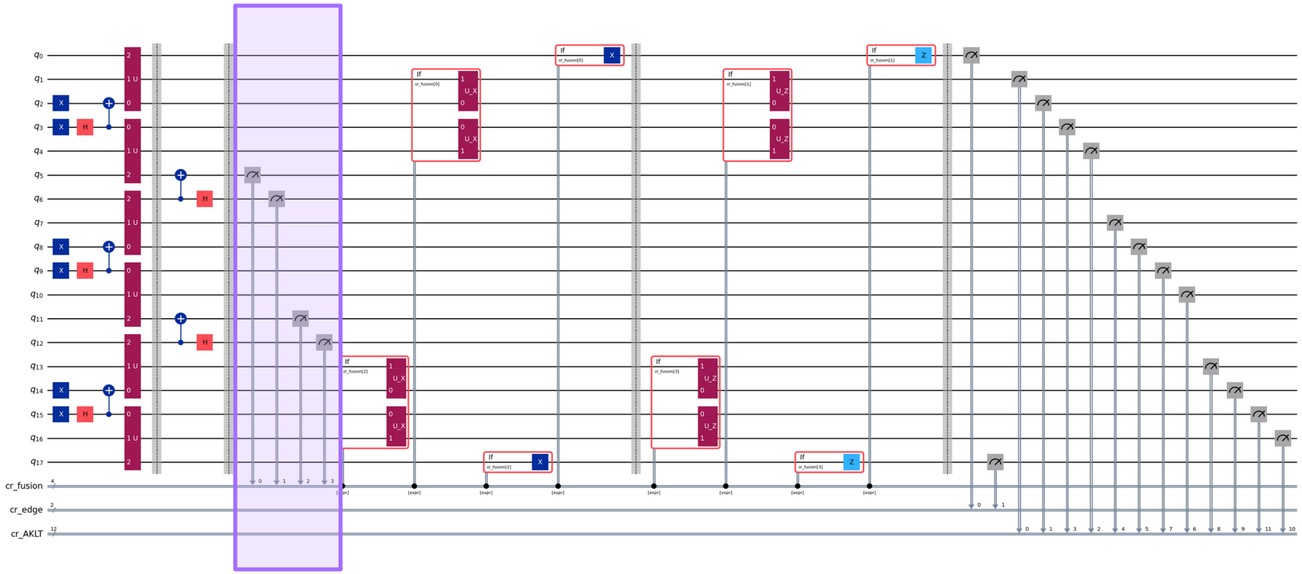
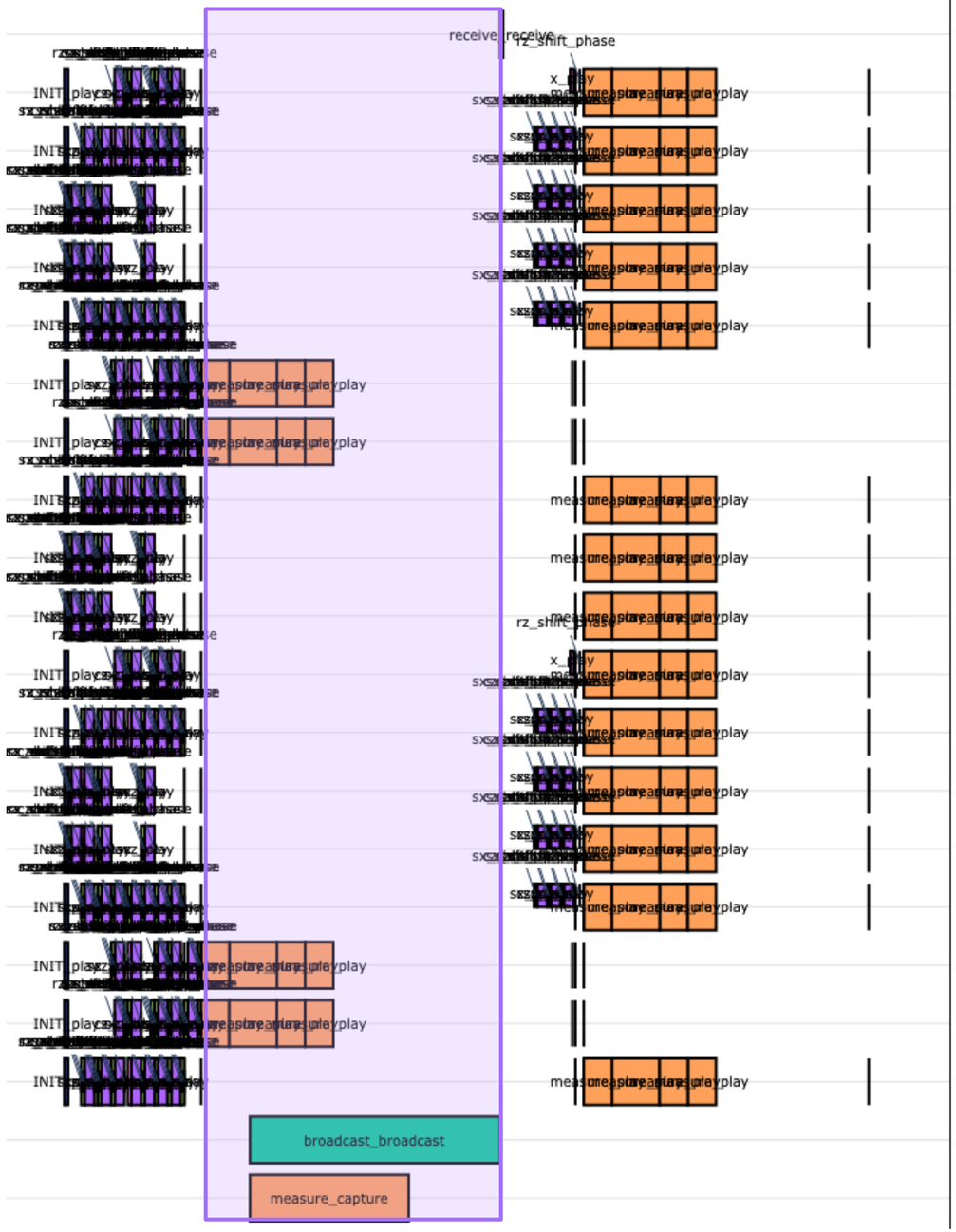
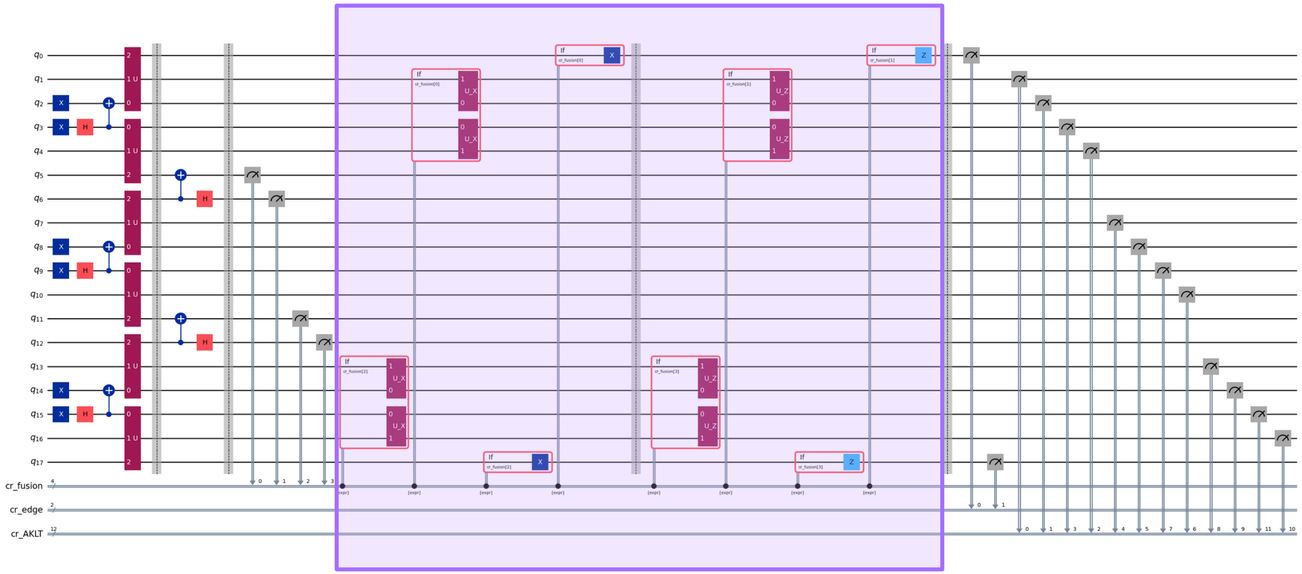
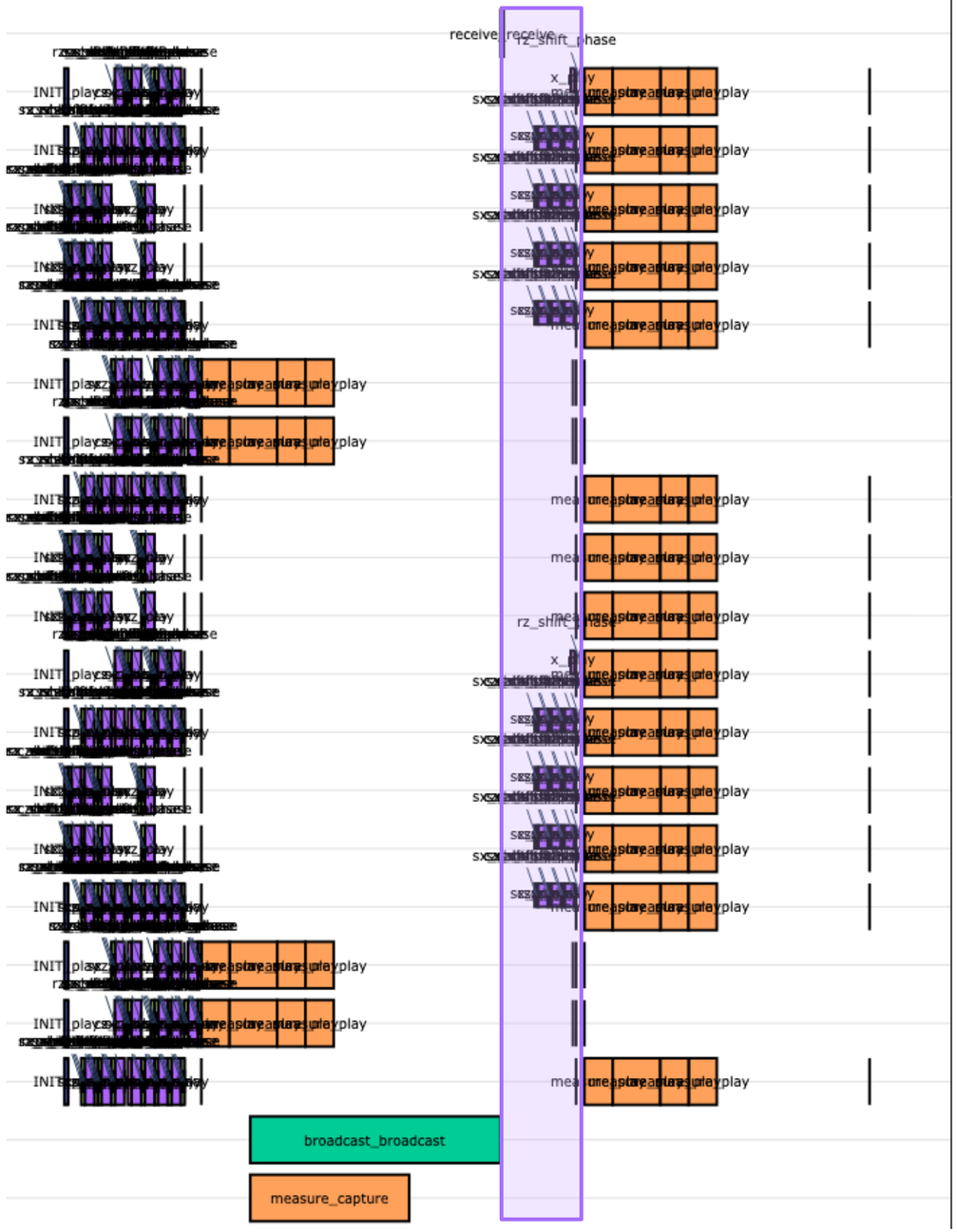


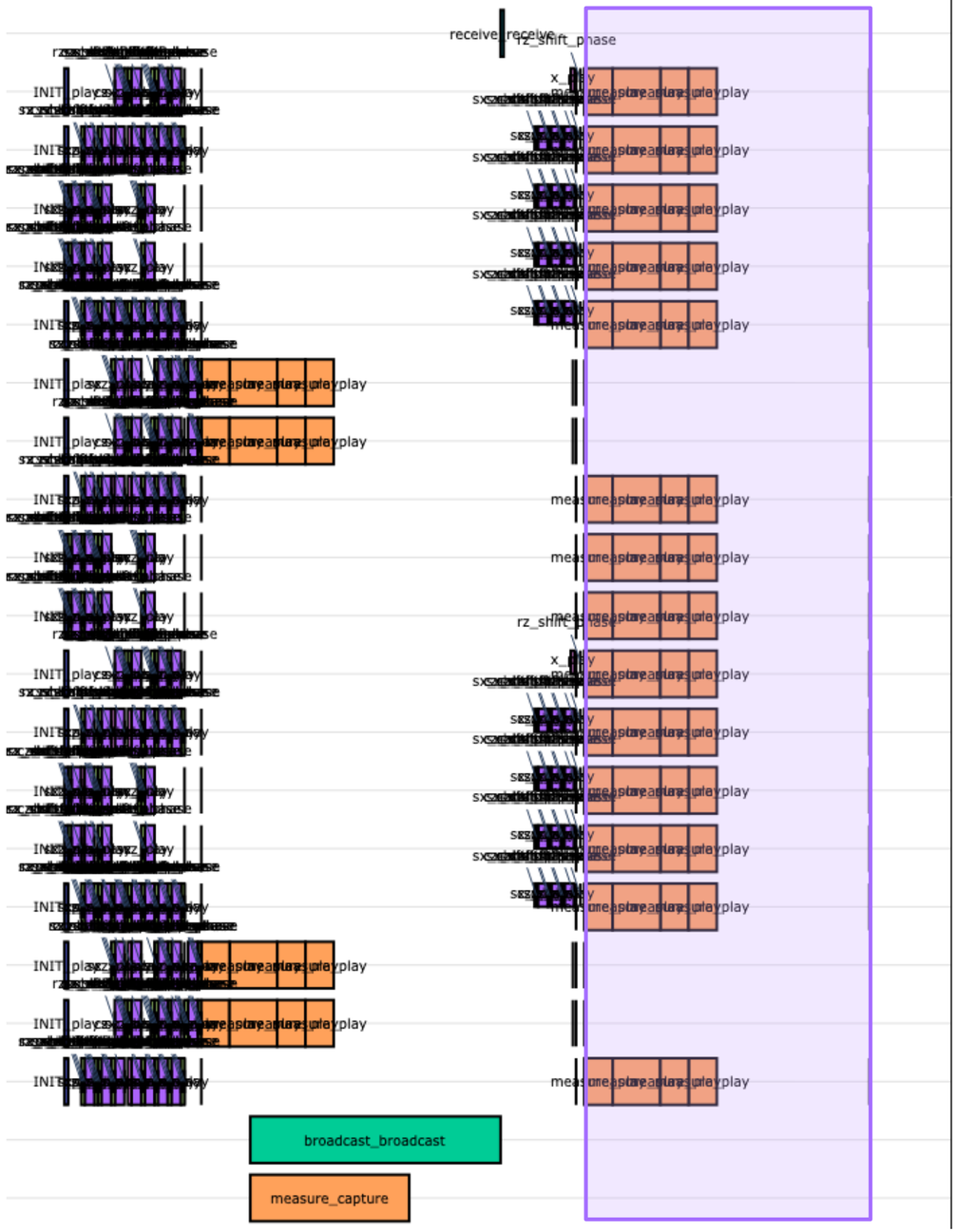


Dynamic scheduled circuit ($N_{\text{sites}} = 6$)





Dynamic scheduled circuit ($N_{\text{sites}} = 6$)



AKLT state preparation with utility scale dynamic circuits

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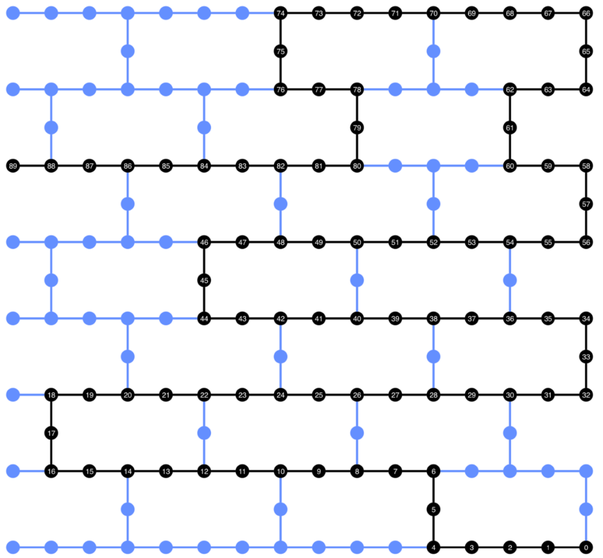
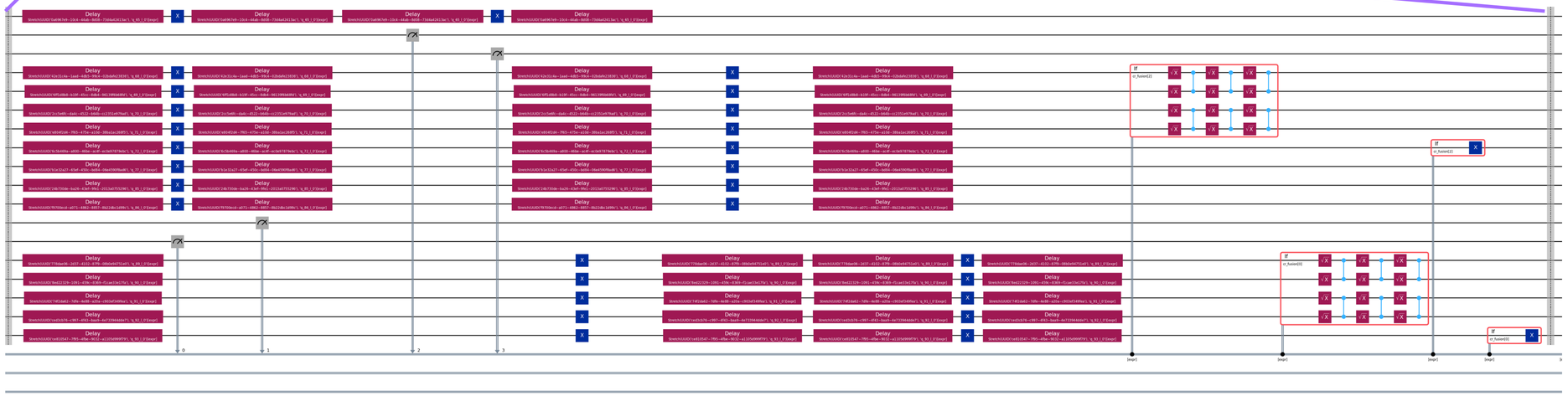
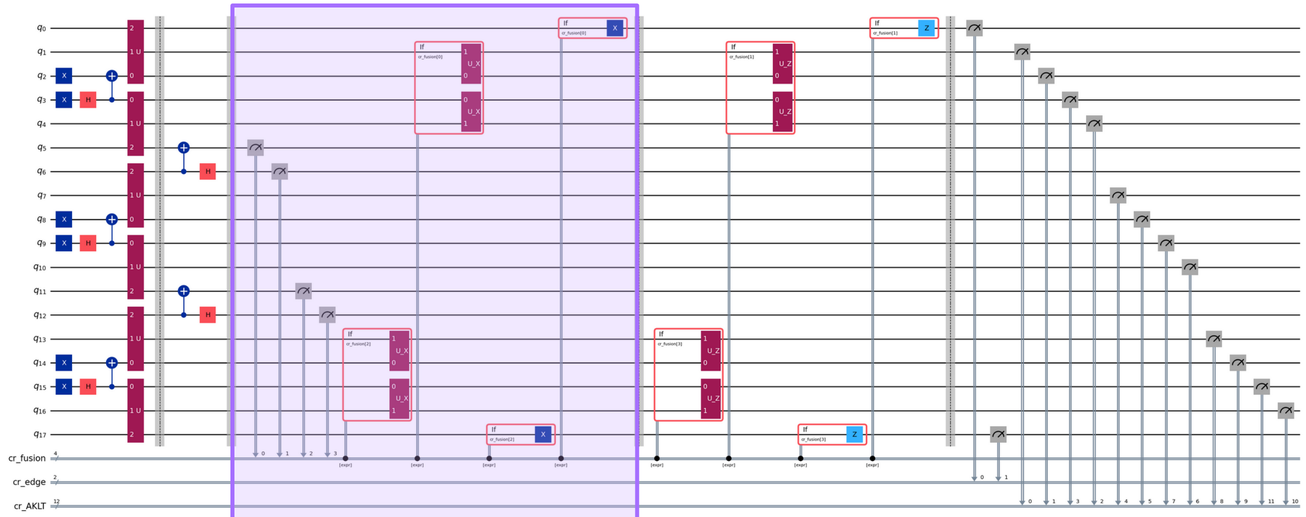
90 qubits for $N_{\text{sites}} = 30$

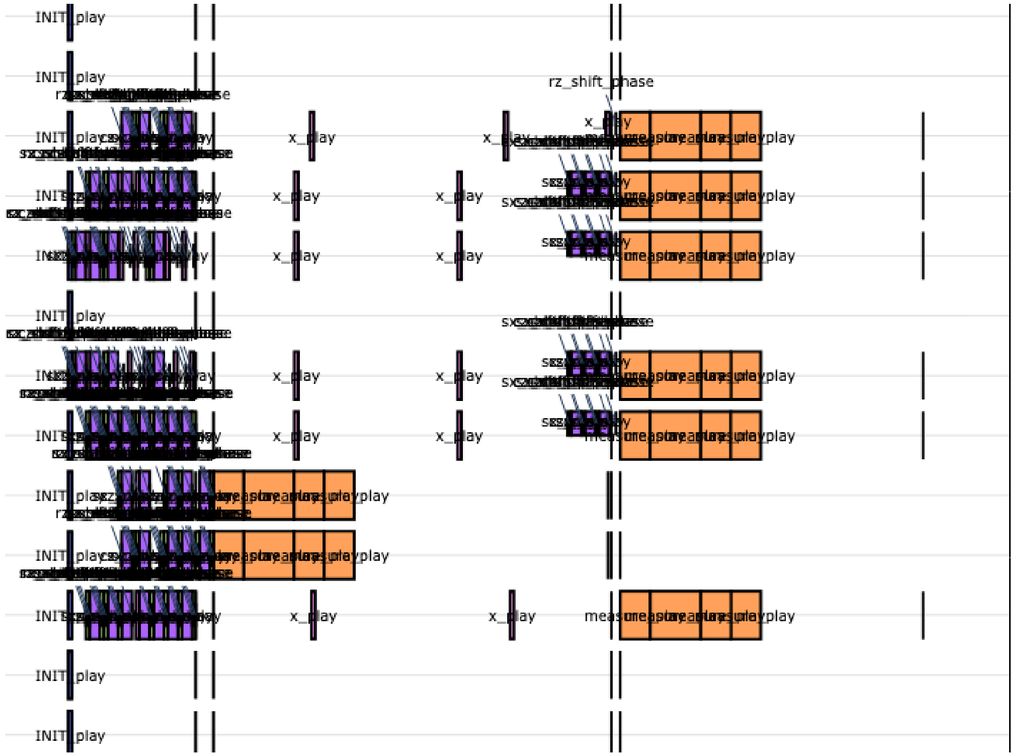


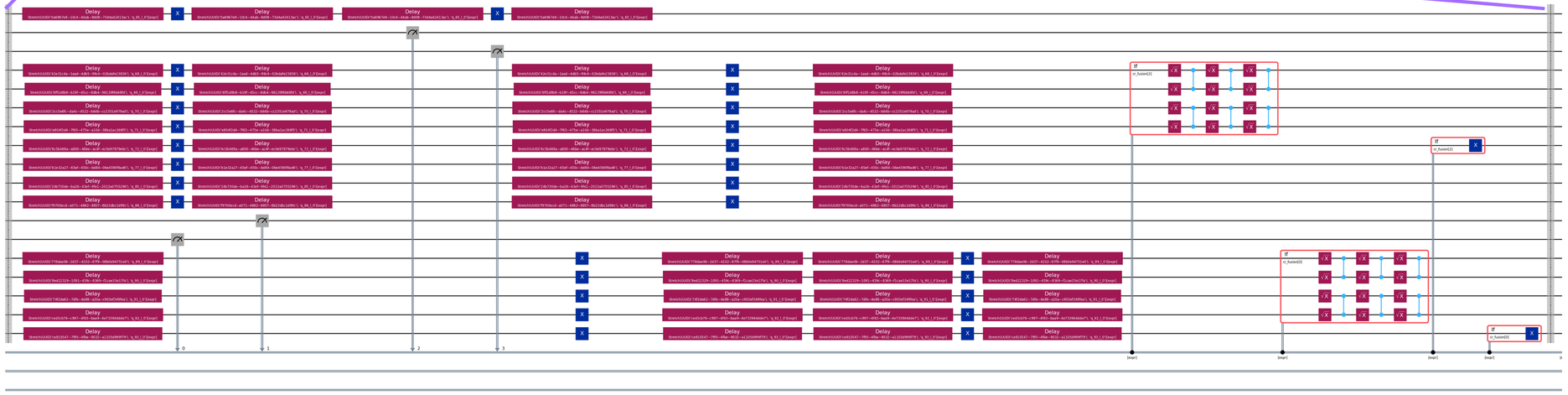
Dynamic with stretch scheduled circuit ($N_{\mathbf{sites}} = 6$)



Dynamic with stretch scheduled circuit ($N_{\text{sites}} = 6$)







AKLT state preparation with utility scale dynamic circuits

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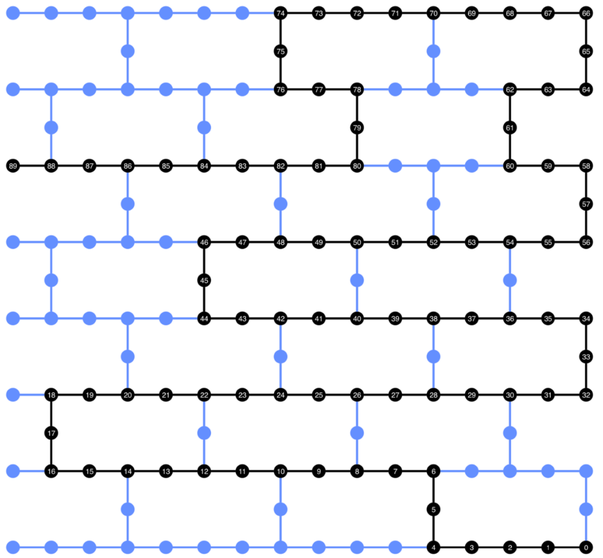
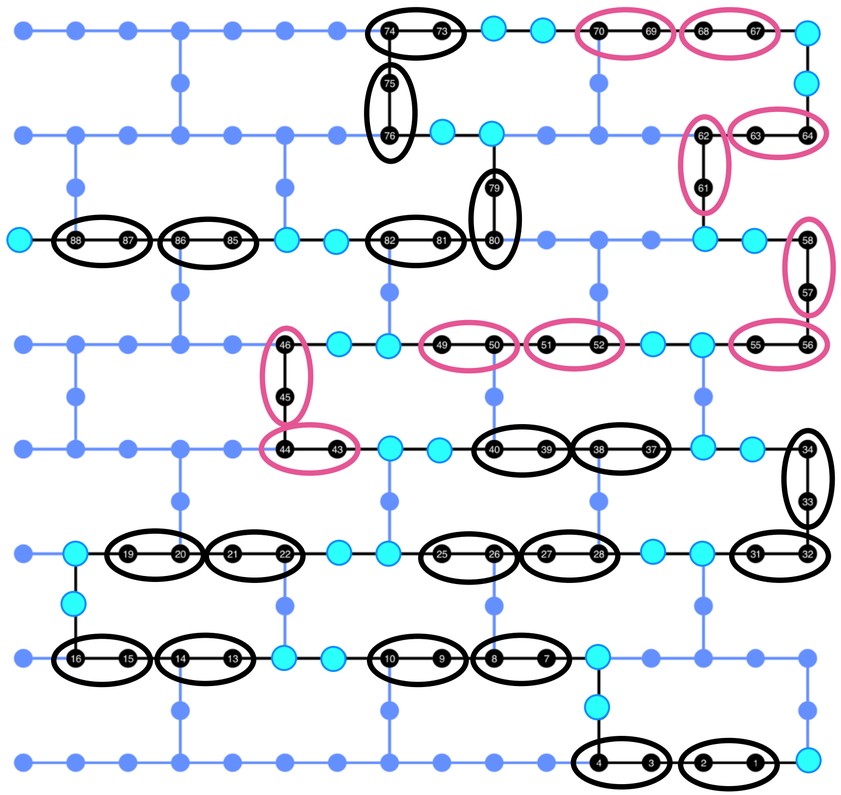


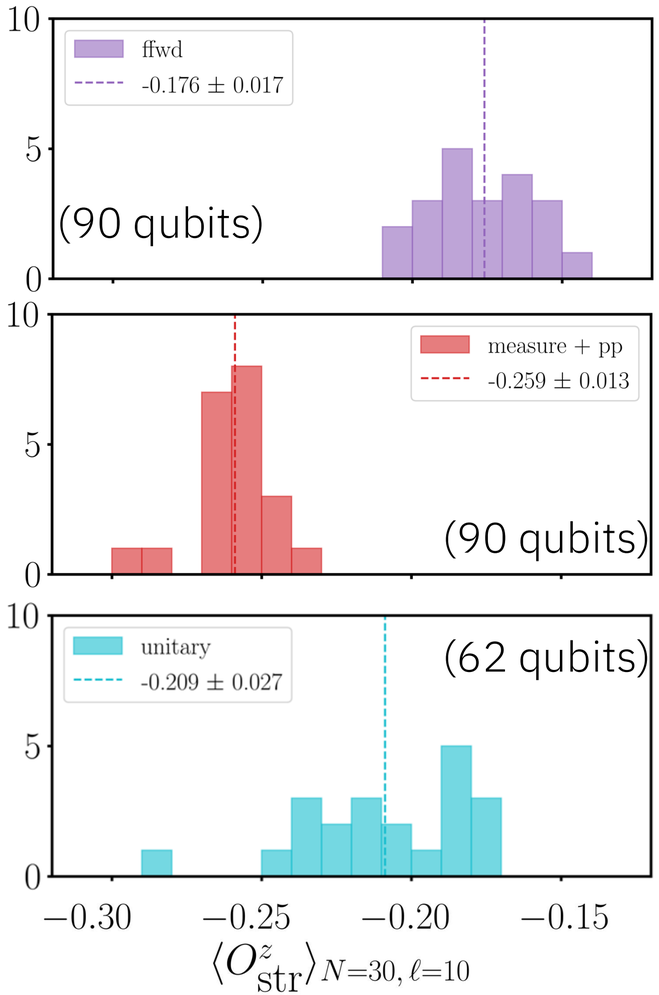
Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Dynamic (90 qubits)

$l = 10$



Circuit duration: $\sim 8\mu s$



21 x length-10 chains

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Dynamic (90 qubits)

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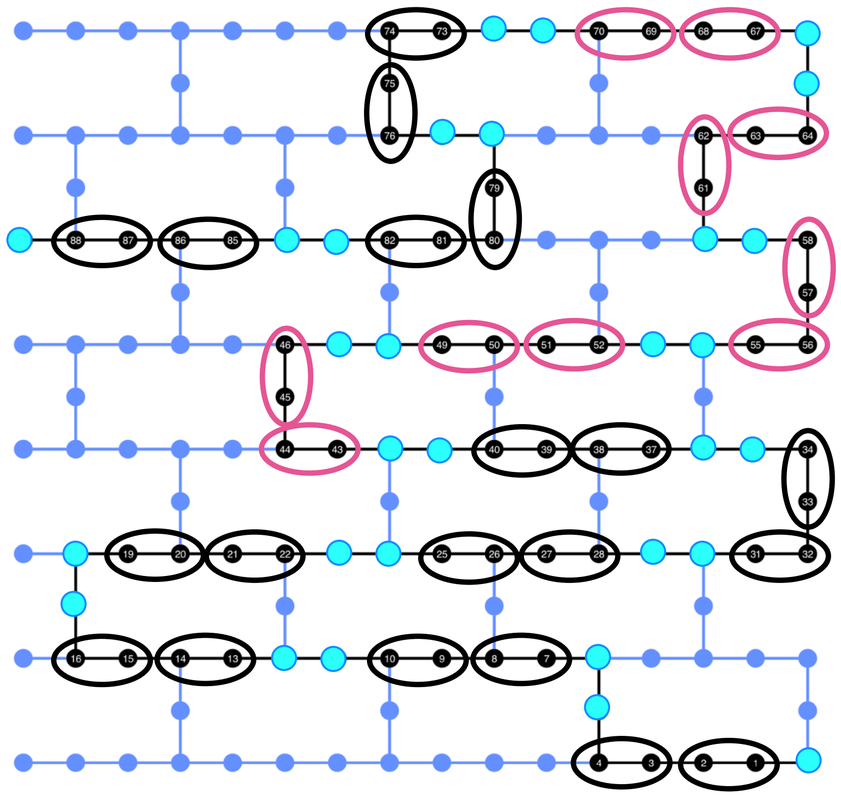
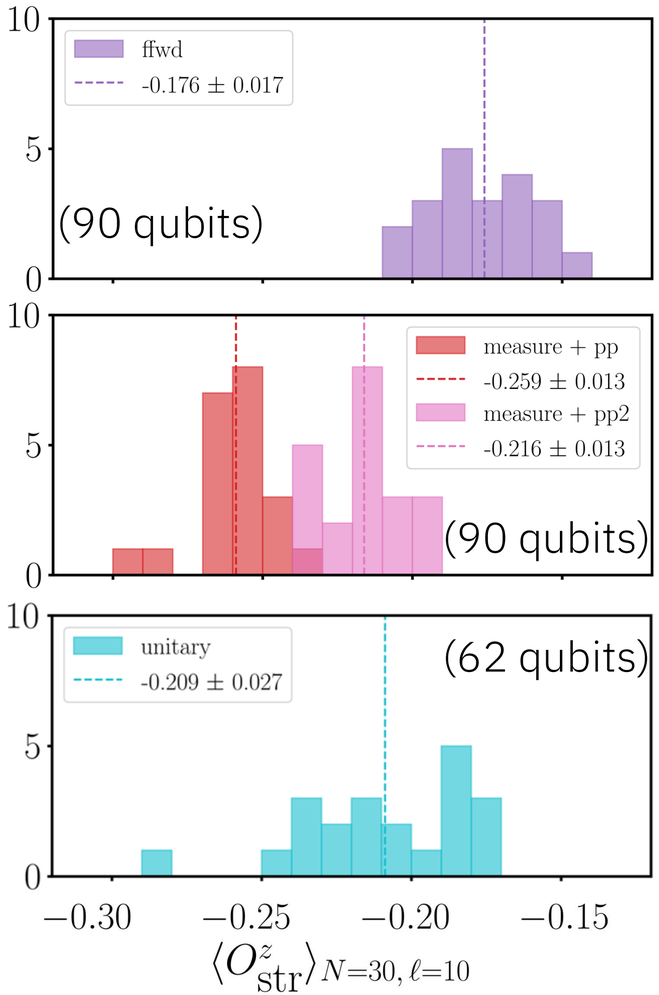


Circuit duration: $\sim 8\mu s$



21 x length-10 chains

AKLT state preparation with utility scale dynamic circuits

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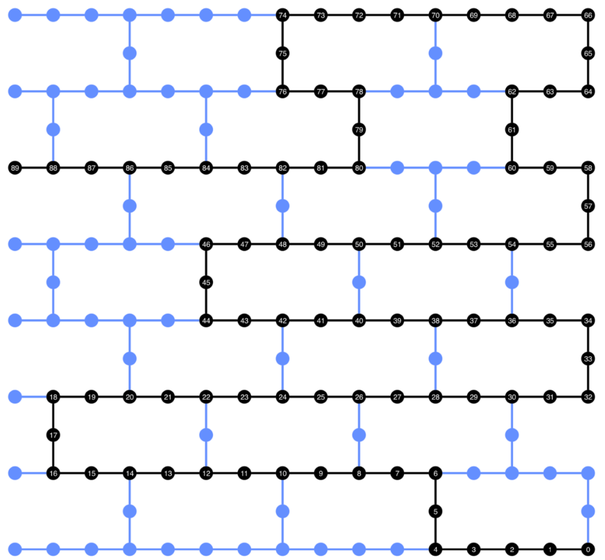
  2. Measurement based without dynamic circuits (post-process) ($\sim 3.8\mu s / \sim 6.4\mu s$)
  3. Measurement based with dynamic circuits (real-time feed-forward) ($\sim 8\mu s$)
  4. Hybrid (combine unitary and dynamic)

- What changes in the circuit:
  1. Extra ancilla qubits needed
  2. Depths of the circuit: 2Q gate and measurement layers

- What features could be used to improve:
  1. Parallel `if`s for larger state preparation
  2. Different measurement types
  3. `Stretch` DD
  4. Visualization (beta) for optimization and debugging

90 qubits for $N_{\text{sites}} = 30$



AKLT state preparation with utility scale dynamic circuits

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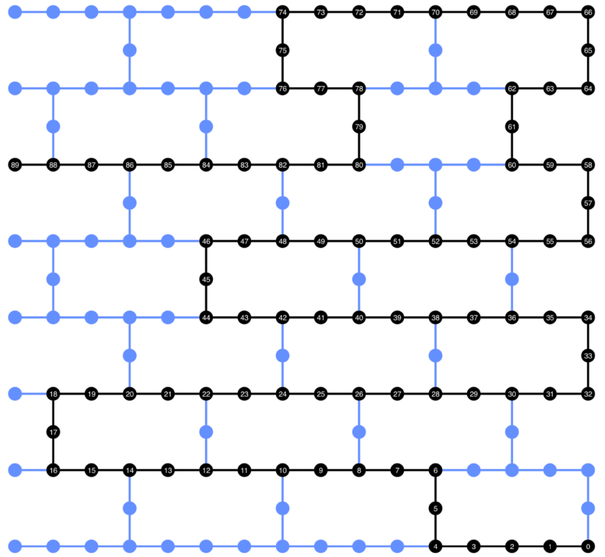
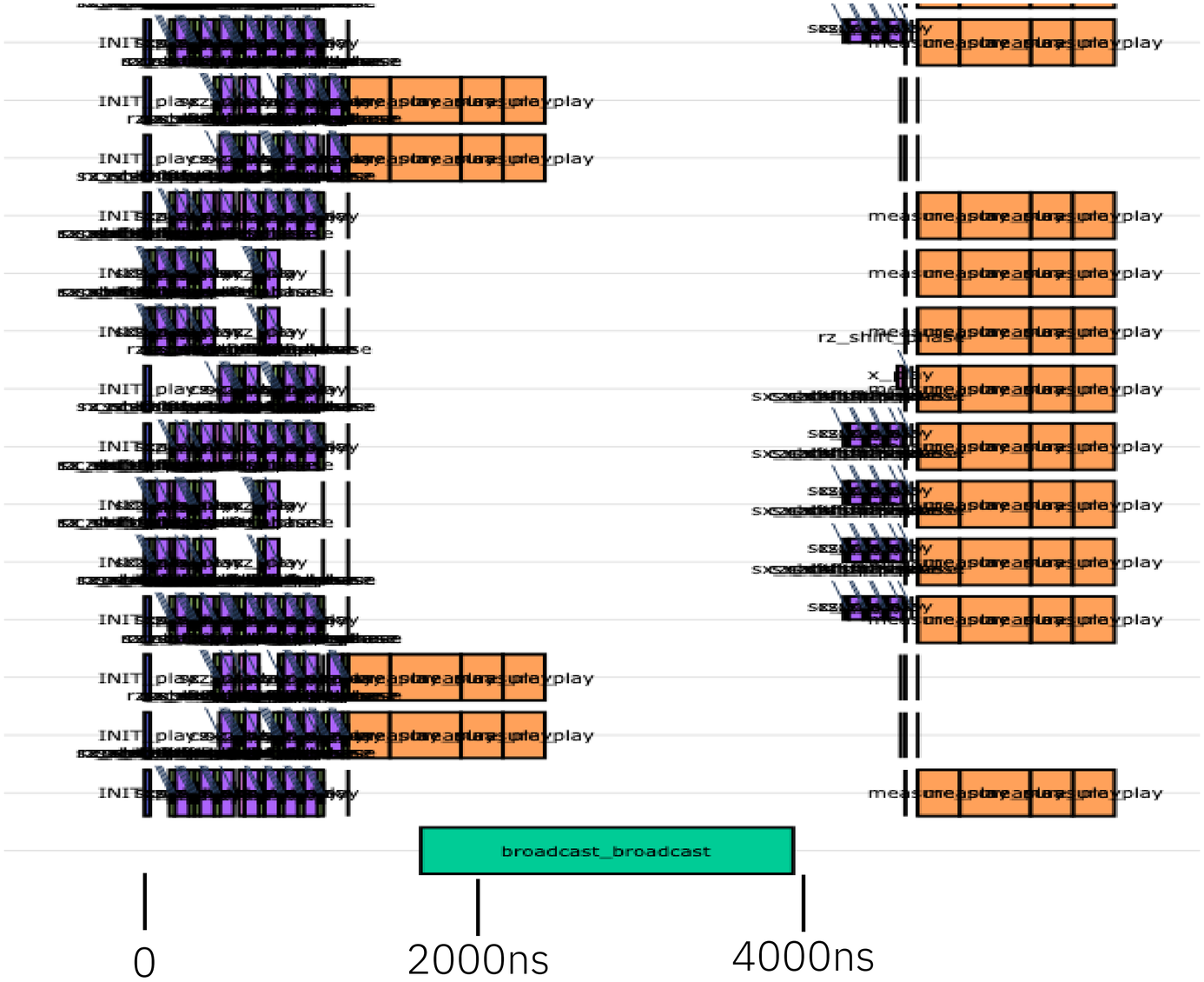


Dynamic AKLT state preparation ($N_{\mathbf{sites}} = 6$)

MidCircuitMeasure instruction

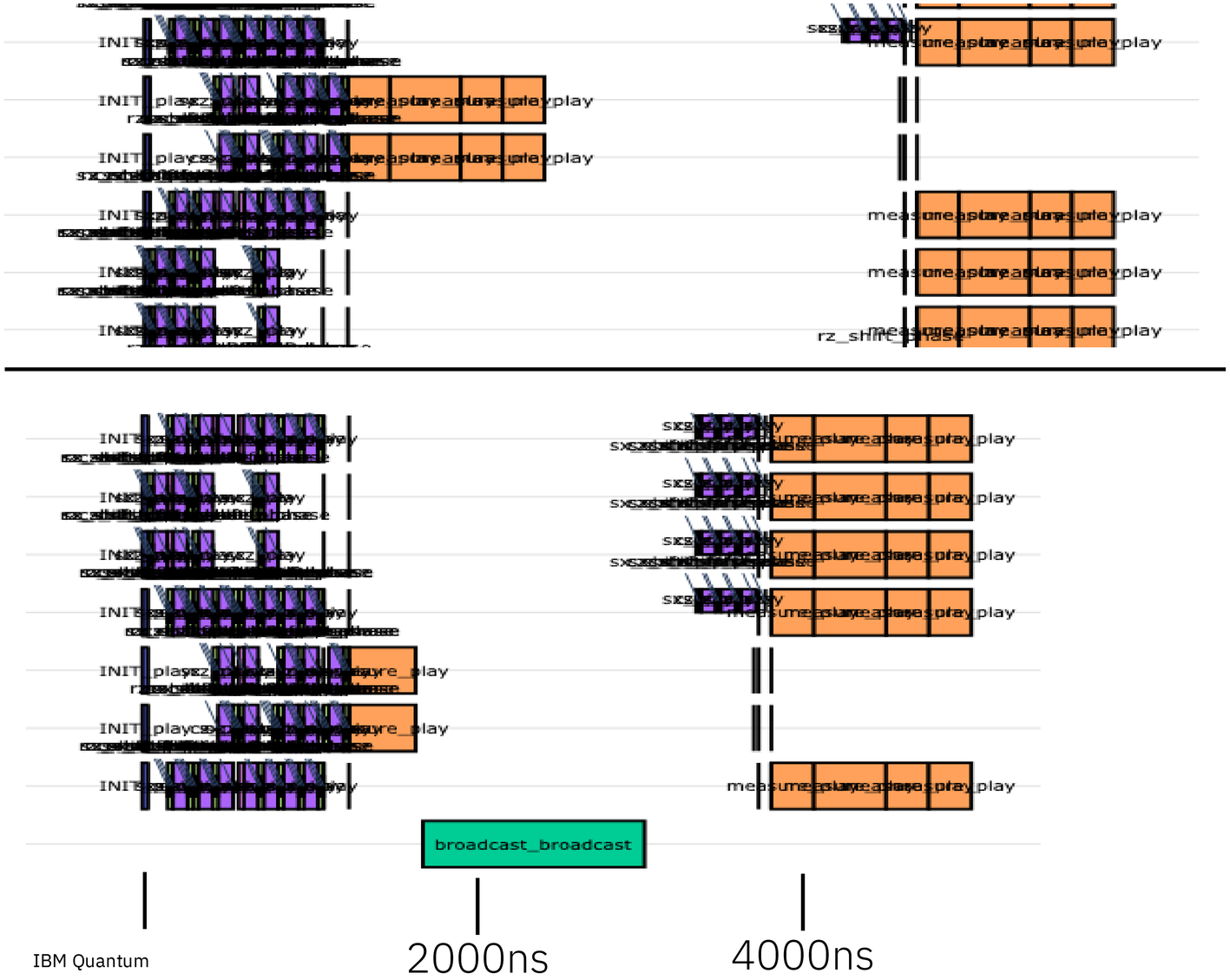
Dynamic with original *measure* scheduled circuit



`measure`

Capture length: 1440ns

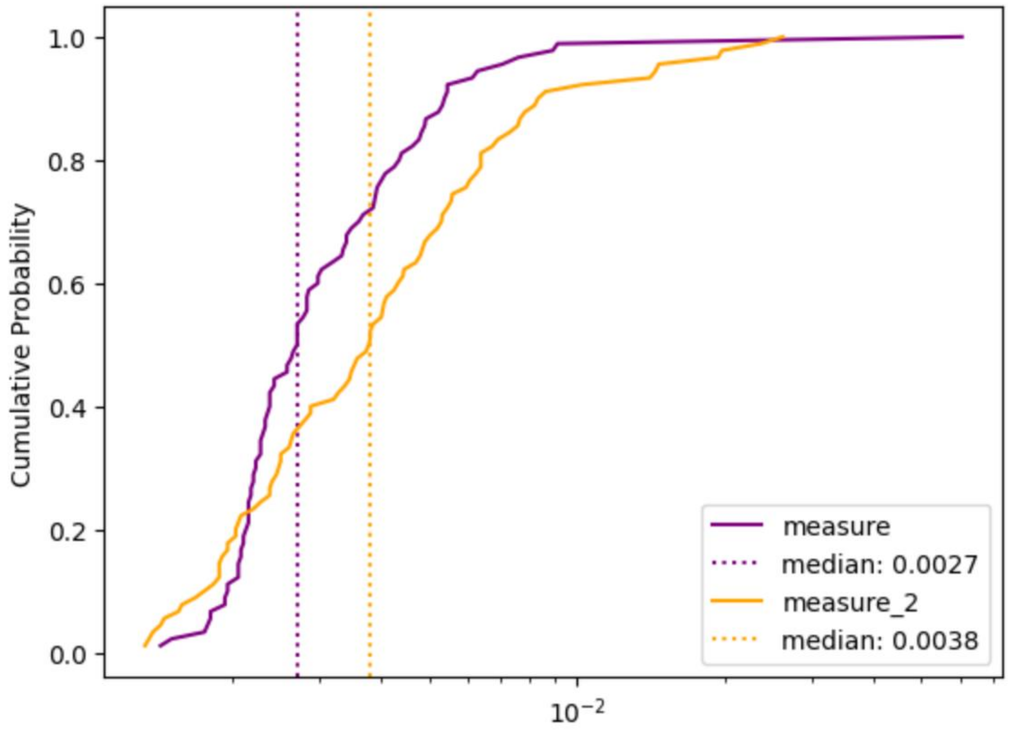
Dynamic with *measure_2* scheduled circuit



measure

Capture length: 1440ns

Readout error



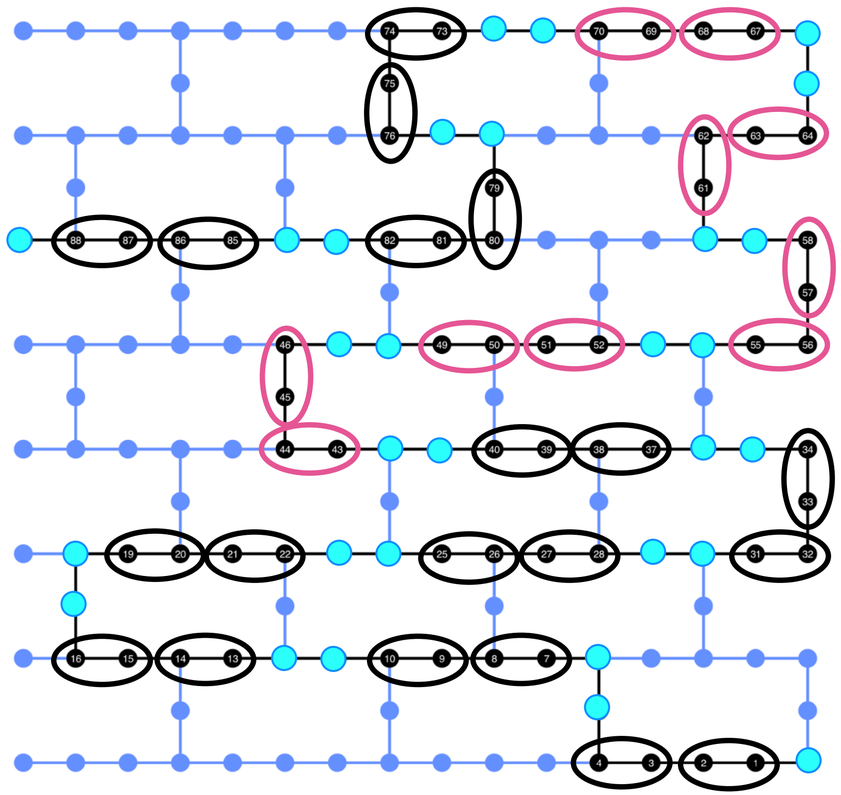
measure_2

Capture length: 500ns

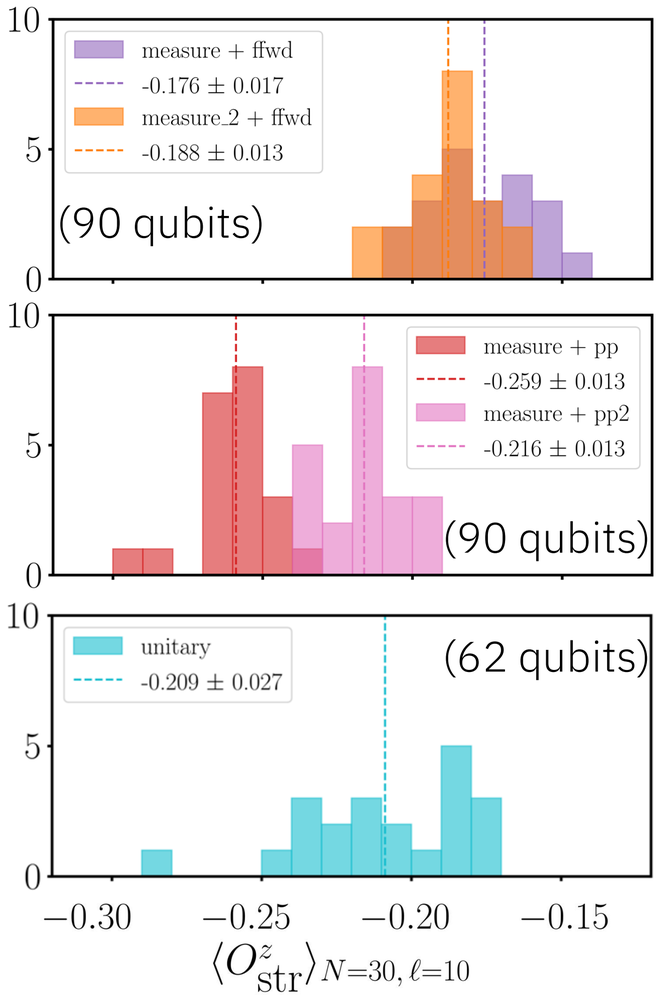
Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Dynamic (90 qubits)

$l = 10$



Circuit duration: $\sim 7.1 \mu s$



21 x length-10 chains

AKLT state preparation with utility scale dynamic circuits

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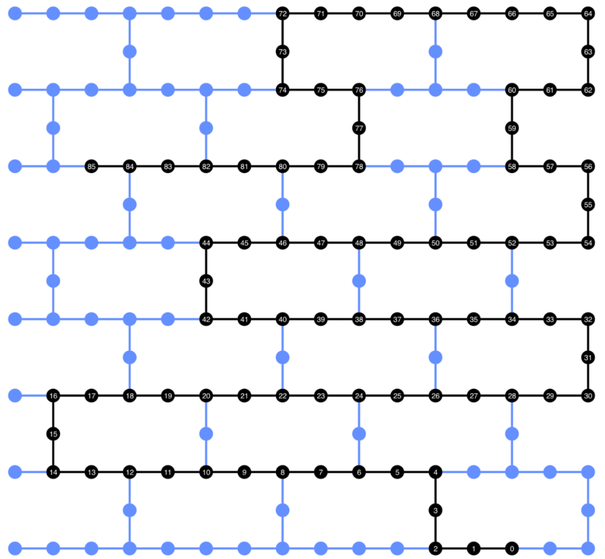
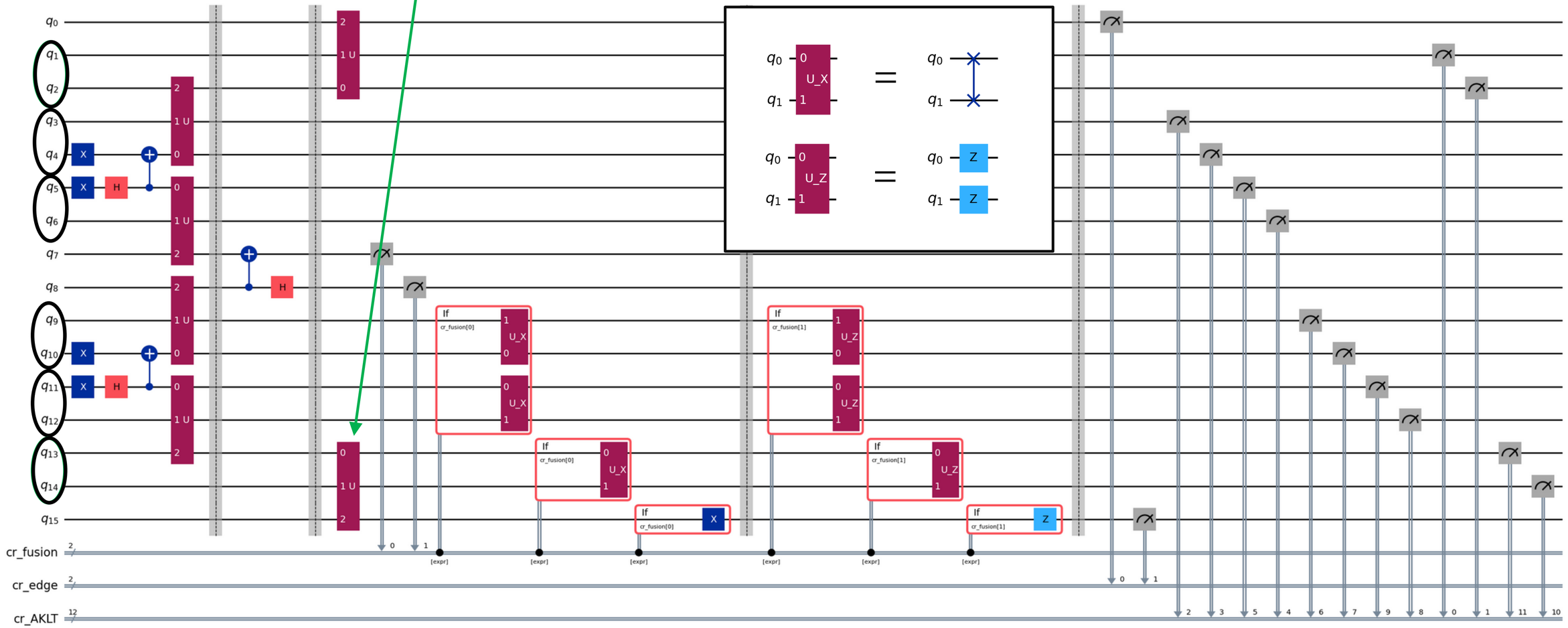
86 qubits for $N_{\text{sites}} = 30$



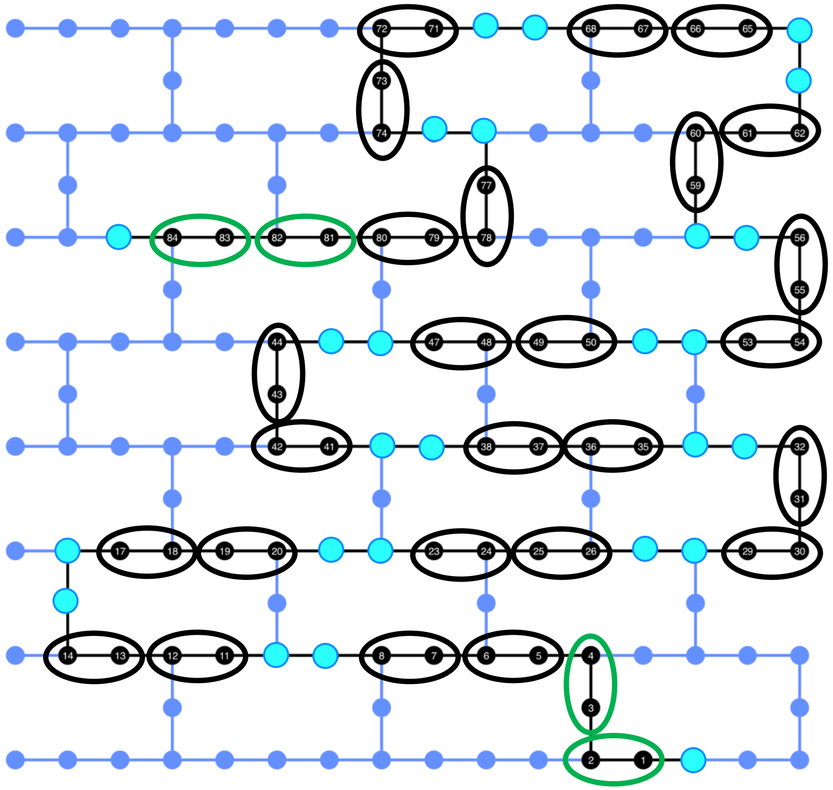
Dynamic ($N_{\text{sites}} = 4$) plus unitary ($N_{\text{sites}} = 2$) extension

Total number of qubits needed
$= N_{\text{sites}} \times 2 + ancillas$
$= N_{\text{sites}} \times 2 + (N_{\text{sites}} - 2)$
$= 16$

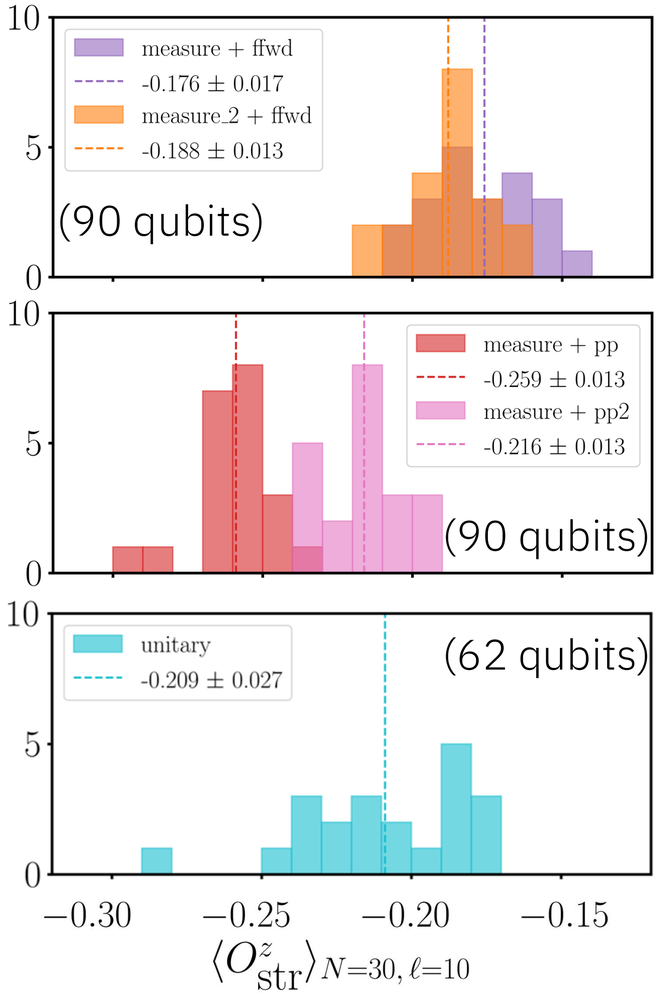


Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Dynamic + (L2+R2) unitary extension (86 qubits)



Circuit duration: $\sim 6.9\mu s$

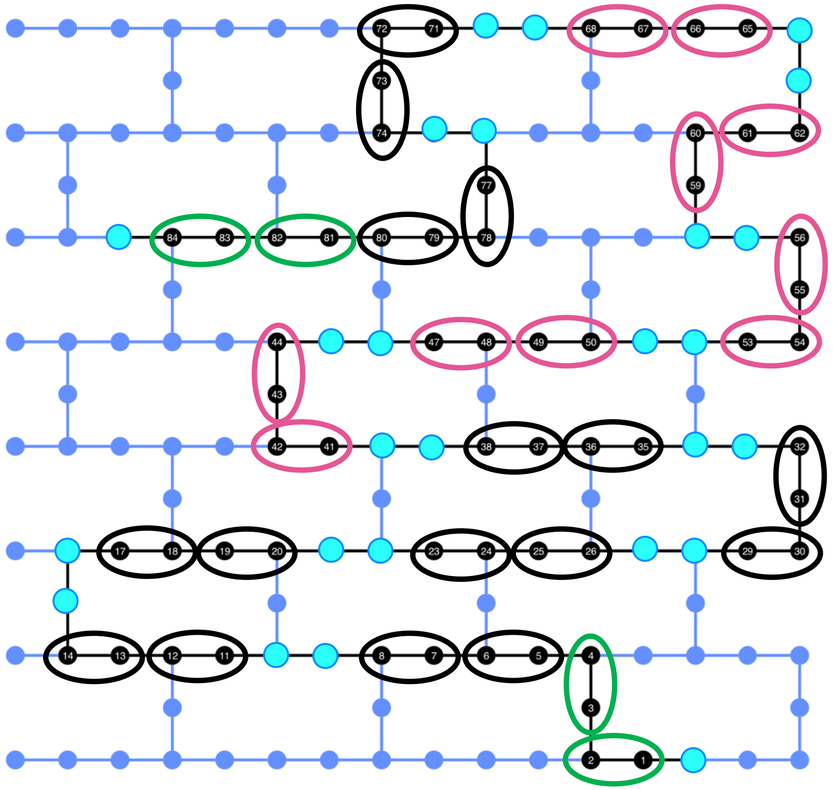


21 x length-10 chains

Validation of AKLT state preparation ($N_{\mathbf{sites}} = 30$)

Dynamic + (L2+R2) unitary extension (86 qubits)

$l = 10$



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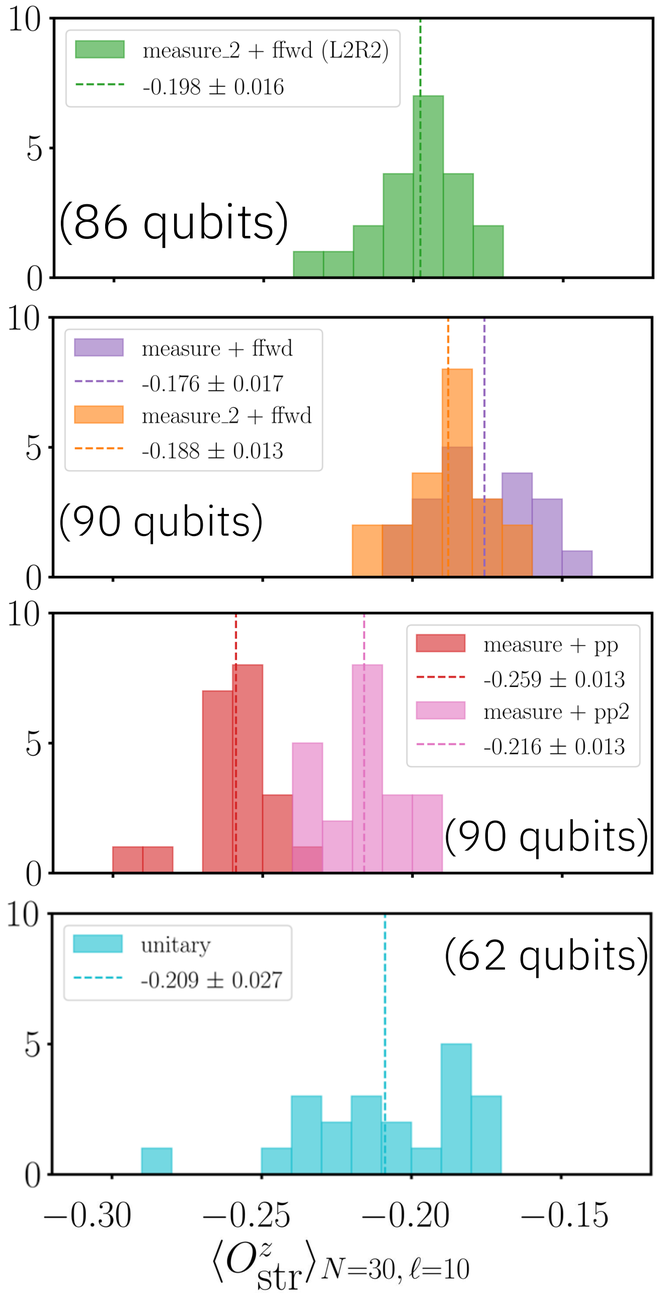
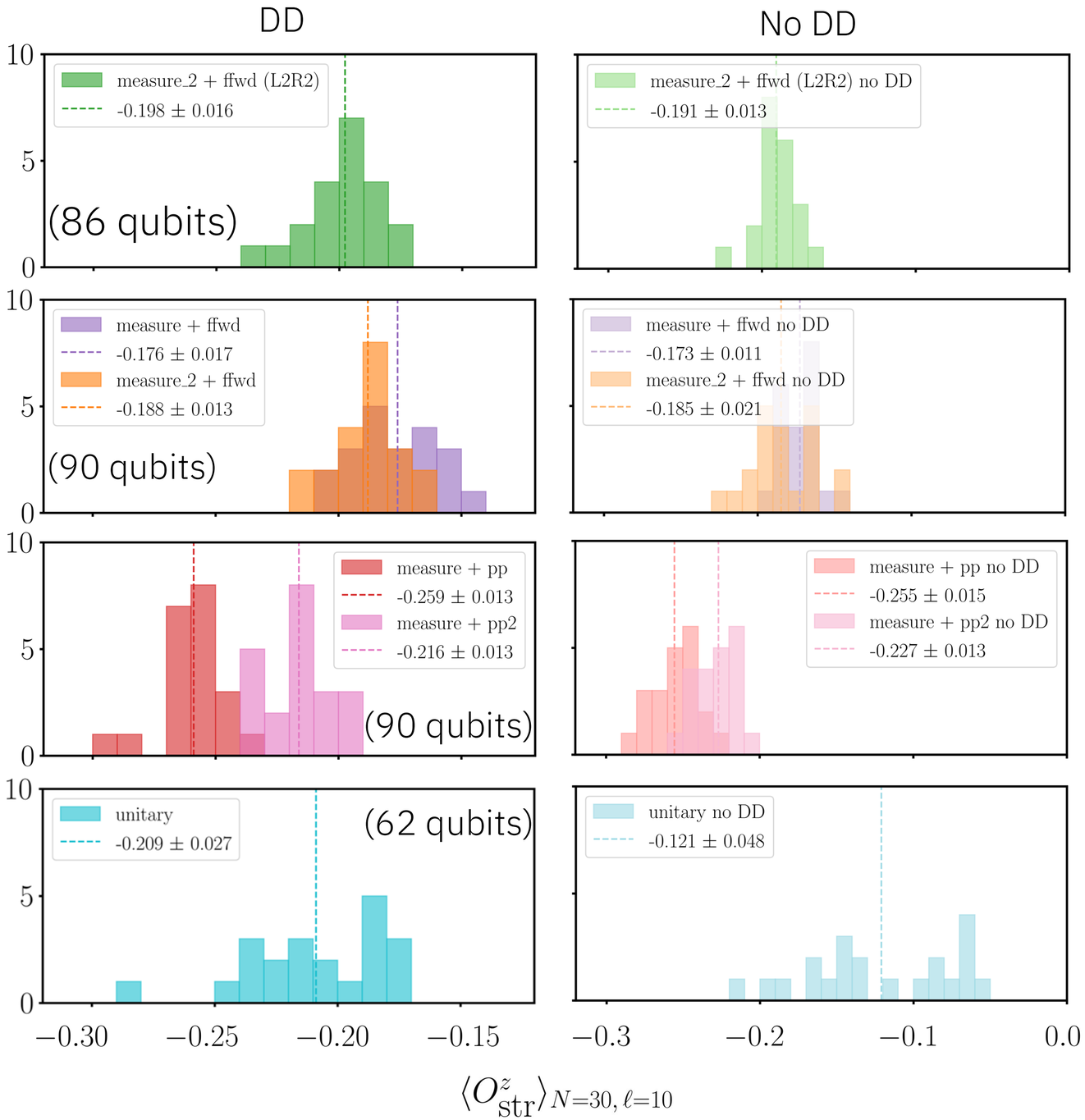


21 x length-10 chains

DD or no DD???


DD
No DD
measure_2 + ffwd (L2R2)
-0.198 ± 0.016
(86 qubits)
measure_2 + ffwd (L2R2) no DD
-0.191 ± 0.013
measure + ffwd
-0.176 ± 0.017
measure_2 + ffwd
-0.188 ± 0.013
(90 qubits)
measure + ffwd no DD
-0.173 ± 0.011
measure_2 + ffwd no DD
-0.185 ± 0.021
measure + pp
-0.259 ± 0.013
measure + pp2
-0.216 ± 0.013
(90 qubits)
measure + pp no DD
-0.255 ± 0.015
measure + pp2 no DD
-0.227 ± 0.013
unitary
-0.209 ± 0.027
(62 qubits)
unitary no DD
-0.121 ± 0.048
10
5
0
−0.30
−0.25
−0.20
−0.15
−0.3
−0.2
−0.1
0.0
$\langle O^z_{\mathrm{str}} \rangle_{N=30,\,\ell=10}$

AKLT state preparation ($N_{\text{sites}} = 30$)

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Summary

1. Parallel `if`s enable utility scale experiments

2. More than one type of measurement enabled: `MidCircuitMeasure` instruction that maps to `measure_2`

3. Added `Stretch` as durations for `Delay` instructions for deferred timing resolution

4. Circuit timing visualization (beta) on dynamic circuits returned to users