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Implementing the Asynchronous Reversible Computing Paradigm in Josephson Junction Circuits

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    - *Others may be forthcoming...*

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Original abstract (for reference)

An important figure of merit for practical computing systems is energy-delay efficiency, which characterizes the number of operations a given device can perform per unit energy dissipated, per unit time taken for the operation. This efficiency metric appears to be limited in existing superconducting logic styles, motivating the search for novel, potentially more efficient forms of superconducting logic. One path to improving efficiency might be if we could remove the need for external control driven by slow clocks that is present in existing *adiabatic* SCE logic styles such as AQFP/RQFP. The Asynchronous Ballistic Reversible Computing (ABRC) paradigm offers an alternative model for *ballistic*, data-driven reversible computation. In an ongoing project at Sandia, we are attempting to demonstrate how the ABRC model can be implemented using Josephson junction circuits, while minimizing the energy-delay product. In this talk, we review the progress that has been made to date in this effort. An interesting direction for future research is to design physical mechanisms that explicitly invoke quantum processes exhibiting *superadiabaticity* (a.k.a. "shortcuts to adiabaticity") to improve energy-delay efficiency in concrete computing technologies. We briefly review what is known about the potential applicability and limits of this approach.
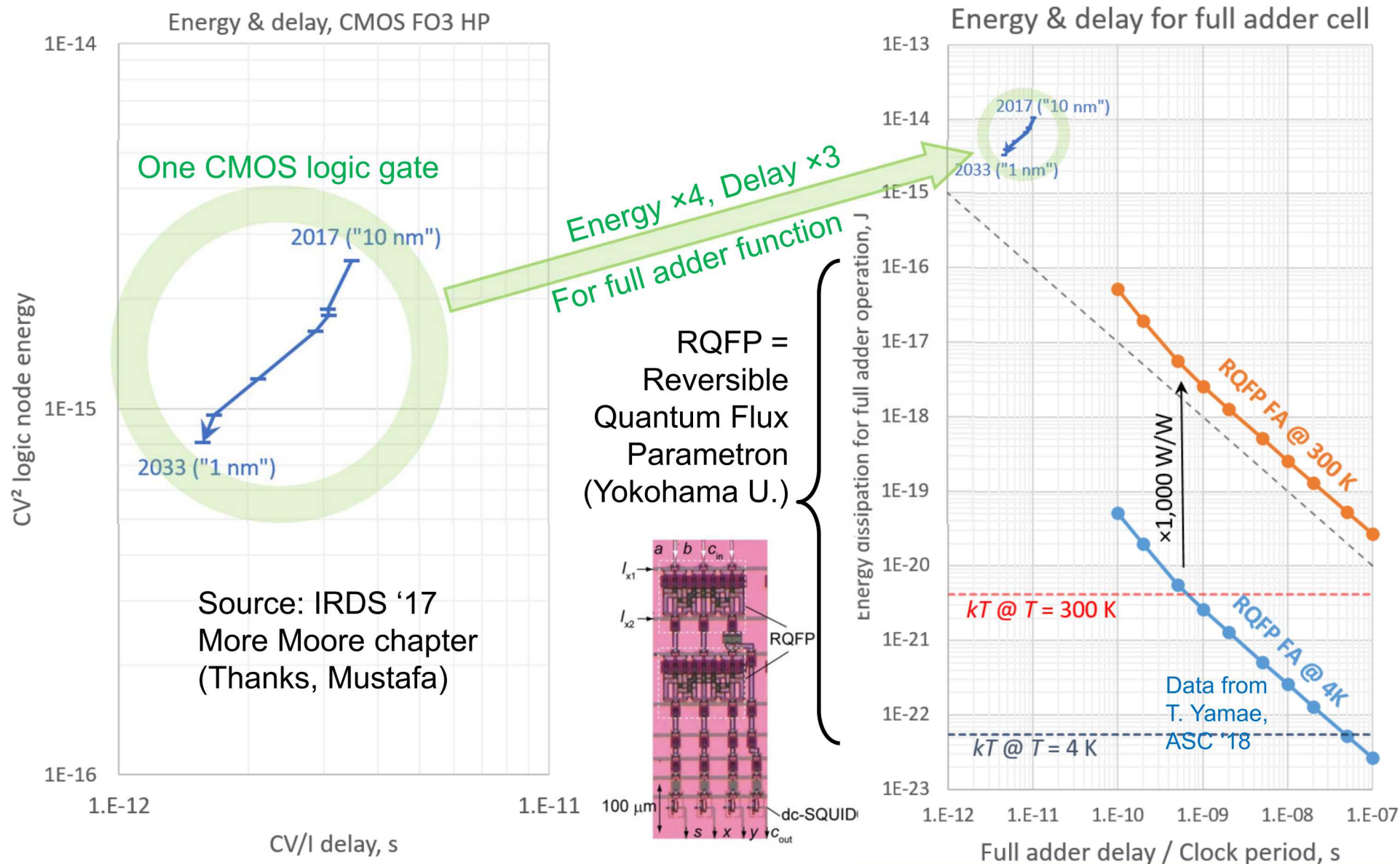
Outline of talk

- **Motivation:** Improving dissipation-delay efficiency in SCE
  - Appears limited in existing logic families
  - Can we find a new SCE logic style that may give a path forward?
- **Approach:** Reversible computing without clocking overhead?
  - Adiabatic SCE logic families have dissipation/op $\propto$ transition time
    - Typical in *classical* adiabatic processes: *e.g.* resistance, friction, viscosity
  - However, *quantum* adiabatic processes can do better than this!
    - Exponential adiabaticity of Landau-Zener transitions in scattering procs.
  - Can elastic scattering of fluxons do *ballistic* reversible computing?
    - Use *Asynchronous Ballistic Reversible Computing* model of computation
- **Current effort at Sandia:**
  - Review of progress to date: LJJ interconnect, RM cell, test plans
- **An interesting direction for future work:**
  - Investigating whether methods of *superadiabaticity / shortcuts to adiabaticity* (STA) might be applied to fluxon systems

Dissipation-delay Efficiency (DdE)

- The key motivating Figure of Merit (FOM) in the present study.

- For a single *primitive* transition of the digital state of a system between two distinct informational states, consider:

  - The *energy dissipation D* incurred by that transition process.
    - Relates to costs associated with supply of energy and cooling.
  - The *delay d*, defined as the time interval from start to end of process.
    - Relates to costs associated with achieving a given level of parallel performance.

- Then define the *dissipation-delay product* $\mathrm{DdP} = D \cdot d$.

  - Note that since D refers specifically to energy *dissipation*, not to energy *invested* in the signal, in reversible processes, it is *not subject to the "quantum speed limit"* (QSL) lower bound of $\sim h$!
    - No *fundamental* lower bound to DDP is yet known!
      - In fact, it would be identically zero for any perfectly-known unitary time-evolution.
  - Of even more general interest than DdP per se is dissipation as a *function* of delay, $D(d)$, considered over a range of practical (tolerable) delay values…
    - We'd like to extend the *pareto frontier* of this function within the useful range.

- *Dissipation-delay efficiency* (DdE) of a computing technology just refers to the reciprocal of DdP, $\eta_{\mathrm{Dd}} = (Dd)^{-1}$.

Existing Dissipation-Delay Relations

Energy & delay, CMOS FO3 HP

One CMOS logic gate

2017 ("10 nm")

CV² logic node energy

2033 ("1 nm")

CV/I delay, s

Source: IRDS '17
More Moore chapter
(Thanks, Mustafa)

Energy ×4, Delay ×3
For full adder function

RQFP =
Reversible
Quantum Flux
Parametron
(Yokohama U.)

Energy & delay for full adder cell

2017 ("10 nm")

2033 ("1 nm")

energy dissipation for full adder operation, J

×1,000 W/W

RQFP FA @ 300 K

kT @ T = 300 K

RQFP FA @ 4K

kT @ T = 4 K

Data from
T. Yamae,
ASC '18

Full adder delay / Clock period, s

Exponential Scaling of Efficiency?

- Can we do better than linear scaling of dissipation with speed? → **YES!**
  - Some observations from Pidaparthi & Lent, 2018 →

- Landau-Zener '32 (!) formula for quantum transitions in *e.g.* atomic scattering problems with a missed level crossing… $P_{\mathrm{D}} = \mathrm{e}^{-2\pi\Gamma}$
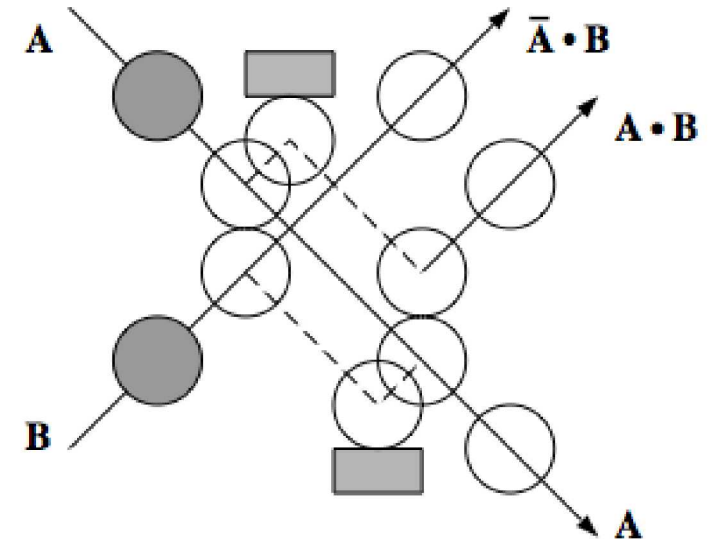 - Shows that the probability of exciting the high-energy state scales down *exponentially* as a function of speed…
    - This *exponential* adiabaticity is a commonly-seen feature of many quantum systems!

- ∴ Dissipation-delay *product* has **no lower bound** for quantum adiabatic transitions!
  - Also… With *superadiabaticity* a.k.a. *shortcuts to adiabaticity,* we can do even better!
    - Approach zero diabaticity even at *fast* speeds!
      - More on this later…

Excess energy transferred to system

$$E_{excess} \approx E_{c,final}\, e^{-\beta}$$

Legend:
- $\gamma = 0.05, \Delta E_c = 5\ eV$
- $\gamma = 0.05, \Delta E_c = 10\ eV$
- $\gamma = 0.10, \Delta E_c = 5\ eV$
- $\gamma = 0.10, \Delta E_c = 10\ eV$

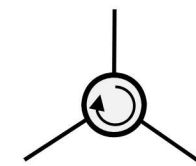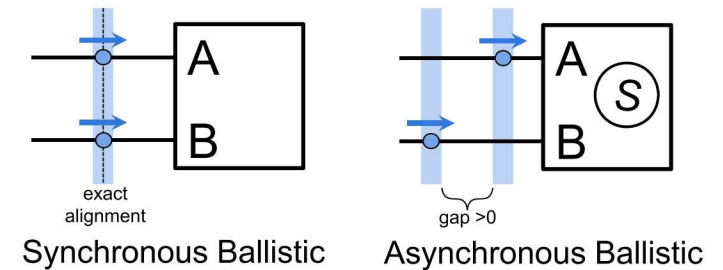Axes: E_{excess} (eV) vs β

Ballistic Reversible Computing

- **Can we envision reversible computing as a *deterministic* elastic scattering process?**
- Original concept:
  - Fredkin & Toffoli's *Billard Ball Model* of computation ("Conservative Logic," IJTP 1982).
    - Based on elastic collisions between moving objects.
    - Spawned a subfield of "collision-based computing."
      - Localized pulses/solitons in various media.
- No power-clock driving signals needed!
  - Devices operate when data signals arrive.
  - The operation energy is carried by the signal itself.
    - Most of the signal energy is preserved in outgoing signals.
- However, existing design concepts for ballistic computing invoke implicitly *synchronized* arrivals of ballistically-propagating signals…
  - Making this work in reality presents some serious difficulties, however:
    - Unrealistic in practice to assume precise alignment of signal arrival times.
      - Thermal fluctuations & quantum uncertainty, at minimum, are always present.
    - Any relative timing uncertainty leads to chaotic dynamics when signals interact.
      - Exponentially-increasing uncertainties in the dynamical trajectory.
    - Deliberate resynchronization incurs an inevitable energy cost.
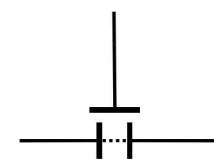- Can we come up with a new ballistic model that avoids these problems?

Asynchronous Ballistic Reversible Computing
in Superconducting Electronics (LDRD at Sandia)

- **Problem:** Conservative (dissipationless) dynamical systems generally tend to exhibit chaotic behavior…
  - This results from direct nonlinear *interactions* between multiple continuous dynamical degrees of freedom (DOFs)
    - *E.g.*, positions/velocities of ballistically-propagating pulses

- **Core insight:** In principle, we can greatly reduce or eliminate this tendency towards dynamical chaos…
  - We can do this by *avoiding* any direct interaction between continuous DOFs of different ballistically-propagating signals

- Require localized pulses to arrive *asynchronously*—and furthermore, at clearly distinct, non-overlapping times
  - Device's dynamical trajectory then becomes *independent* of the precise (absolute *and* relative) pulse arrival times
    - As a result, timing uncertainty per logic stage can now accumulate only *linearly*, not exponentially
      - Only occasional re-synchronization will be needed
  - For devices to still be capable of doing logic, they must now maintain an internal discrete (digitally-precise) state variable

- No power-clock signals, unlike in adiabatic designs
  - Devices simply operate whenever data pulses arrive
  - The operation energy is carried by the pulse itself
    - Most of the energy is preserved in outgoing pulses
      - Signal restoration can be carried out incrementally

- **Goal of current project:** Demonstrate ABRC principles in an implementation based on fluxon dynamics in SCE
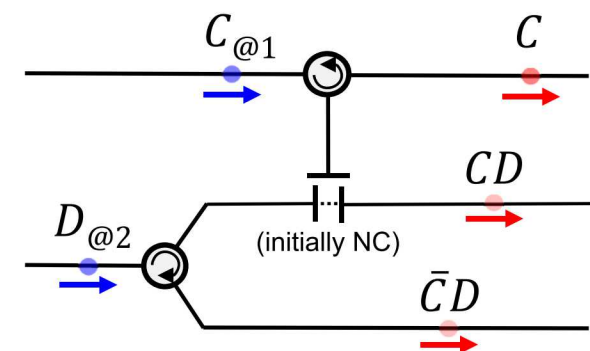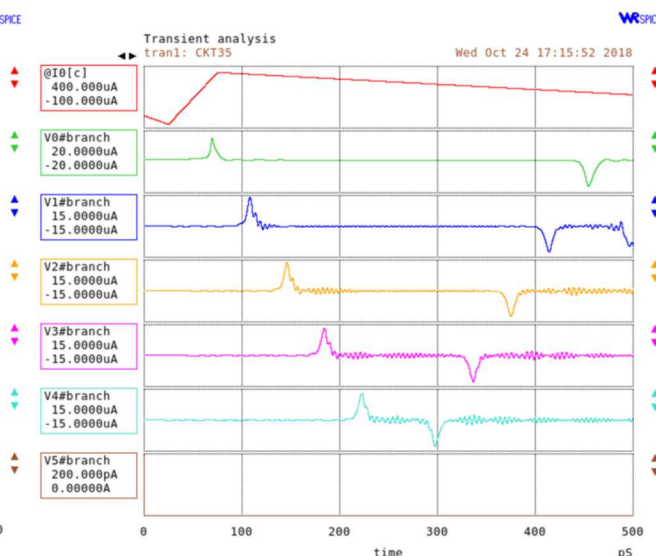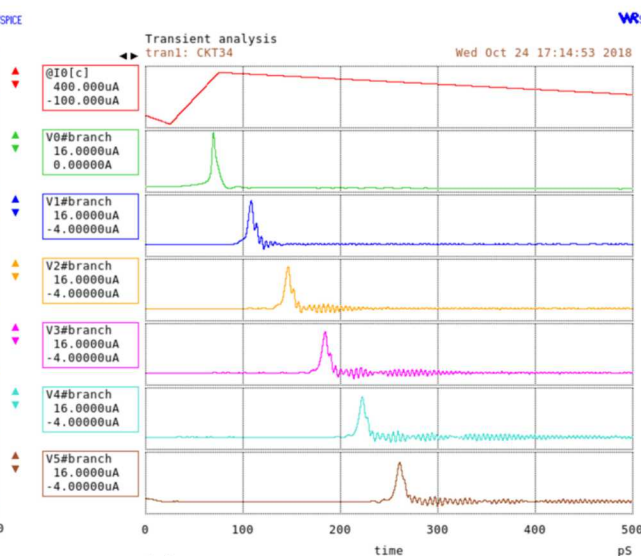

Synchronous Ballistic   Asynchronous Ballistic

Rotary (Circulator)   Toggled Barrier

Example ABR device functions

$C_{@1}$ C

$D_{@2}$ (initially NC) CD

$\bar{C}D$
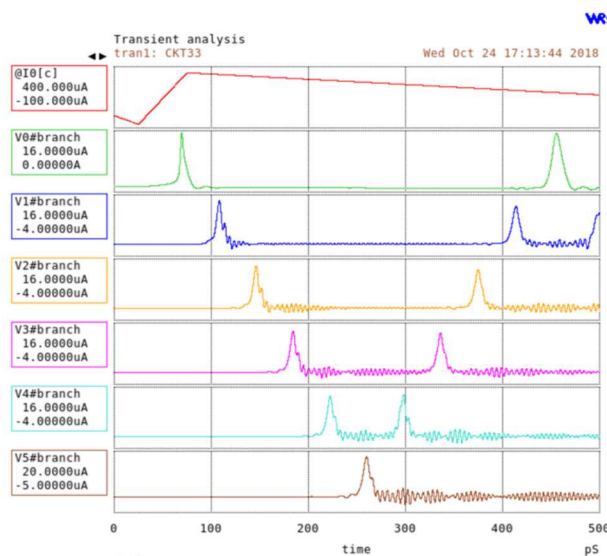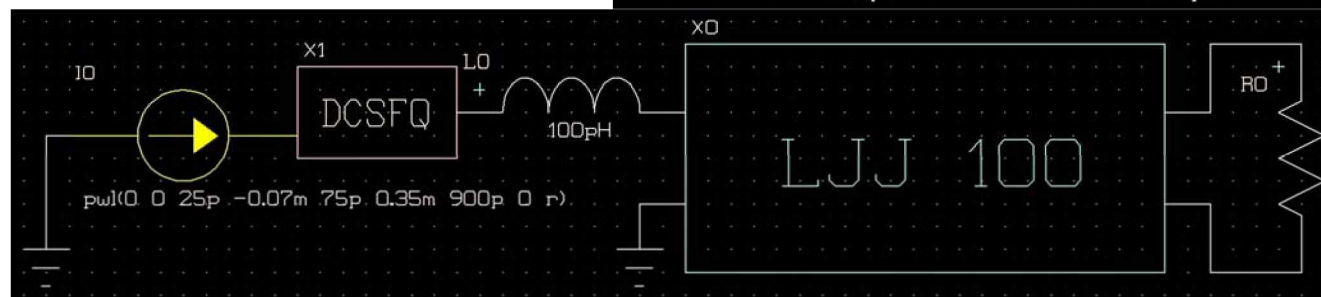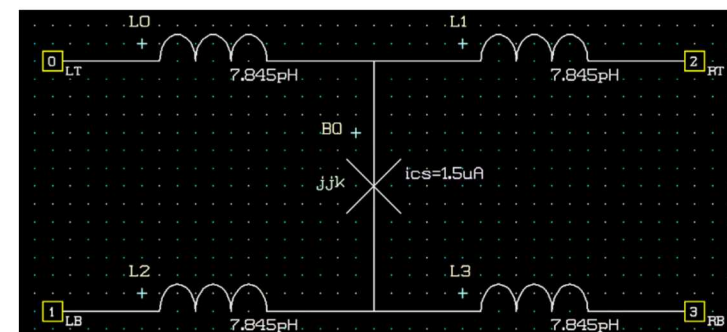
Example logic construction

WRSPICE simulations of discrete LJJ

■ Preliminary effort completed in FY18

   ■ ASC (Sep. '18) 10.1109/TASC.2019.2904962

■ Modeled buildable test structures in XIC

■ Confirmed ballistic fluxon propagation

   ■ Confirmed predicted dLJJ line impedance of 16 Ω
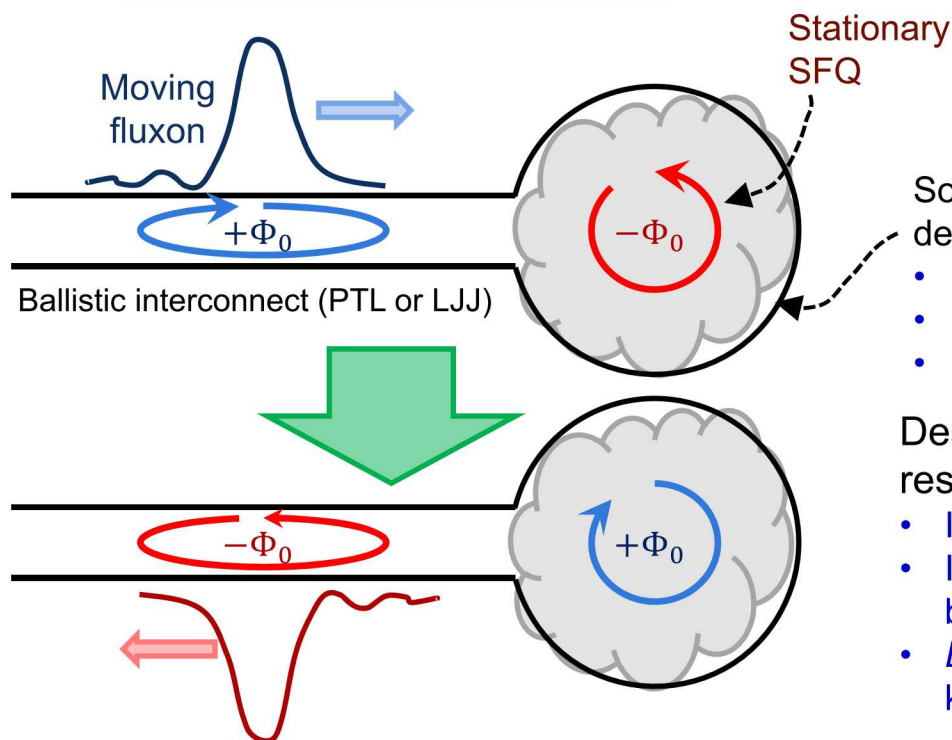
Simplest Fluxon-Based ABRC Function

- Another FY18 task was: Characterize the simplest nontrivial ABRC device functionalities, given a few simple design constraints applying to an SCE-based implementation, such as:
  - (1) Bits encoded in fluxon polarity; (2) Bounded planar circuit conserving flux; (3) Physical symmetry.

- Determined through theoretical analysis that the simplest such function is the following
  ### *1-Bit, 1-Port Reversible Memory Cell (RM):*
  - Due to its simplicity, this is the preferred target for our detailed circuit design efforts looking forwards…

═══ RM Transition Table ═══

Input Syndrome		Output Syndrome
$+1(+1)$	$\rightarrow$	$(+1)+1$
$+1(-1)$	$\rightarrow$	$(+1)-1$
$-1(+1)$	$\rightarrow$	$(-1)+1$
$-1(-1)$	$\rightarrow$	$(-1)-1$

RM icon:

Moving fluxon

$+\Phi_0$

Ballistic interconnect (PTL or LJJ)

Stationary SFQ

$-\Phi_0$

$-\Phi_0$

$+\Phi_0$

Some planar, unbiased, reactive SCE circuit (to be designed) w. a continuous superconducting boundary
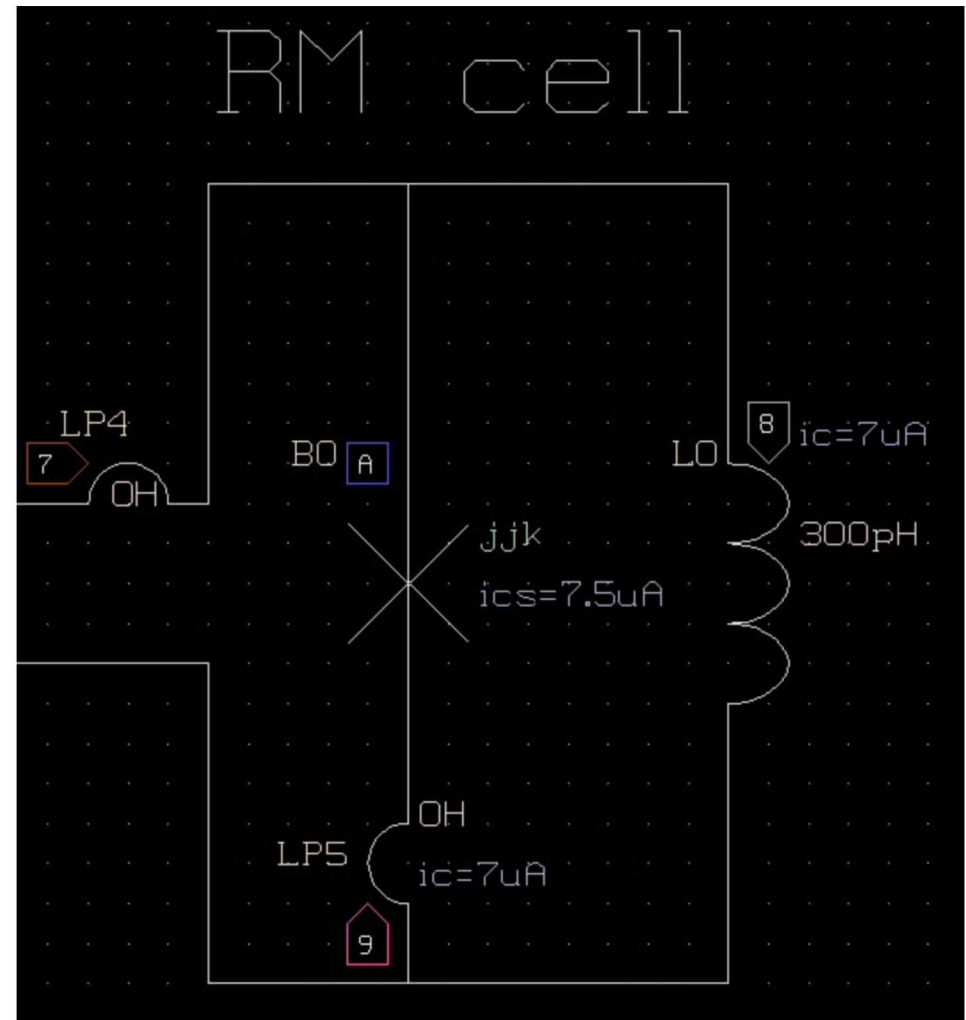- *Only* contains L's, M's, C's, and *unshunted* JJs
- Junctions should mostly be *subcritical* (avoids R_N)
- Conserves total flux, approximately nondissipative

Desired circuit behavior (NOTE: conserves flux, respects T symmetry & logical reversibility):
- If polarities are opposite, they are swapped (shown)
- If polarities are identical, input fluxon reflects back out with no change in polarity (not shown)
- *Elastic scattering* type interaction: Input fluxon kinetic energy is (nearly) preserved in output fluxon
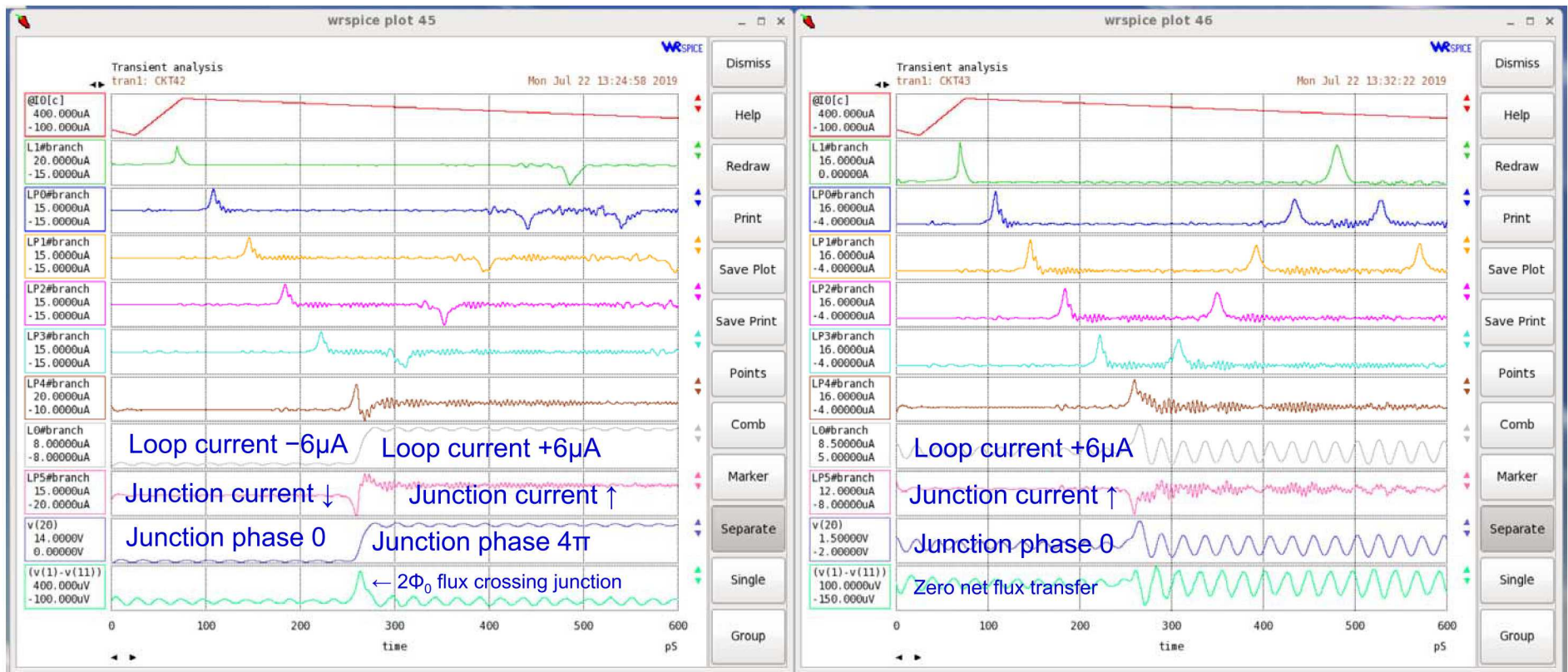
RM—First working implementation!

- DeBenedictis: "Try just strapping a JJ across that loop."
  - This actually works!
- JJ sized to = about 5 LJJ unit cells (~1/2 pulse width)
  - I first tried it twice as large, & fluxons annihilated instead…
    - 🤔 "If a 15uA JJ rotates by 2π, maybe ½ that will rotate by 4π"
- Loop inductor sized so 1 SFQ will fit in the loop (but not 2)
  - JJ a bit below critical with 1
- WRspice simulations with +/−1 fluxon initially in the loop
  - Uses `ic` parameter, & `uic` option to `.tran` command
    - Produces initial ringing due to overly-constricted initial flux
      - Can damp w. small shunt *G*

RM cell

LP4
7
OH

BO [A]

LO
8 ic=7uA
300pH

jjk
ics=7.5uA

LP5
OH
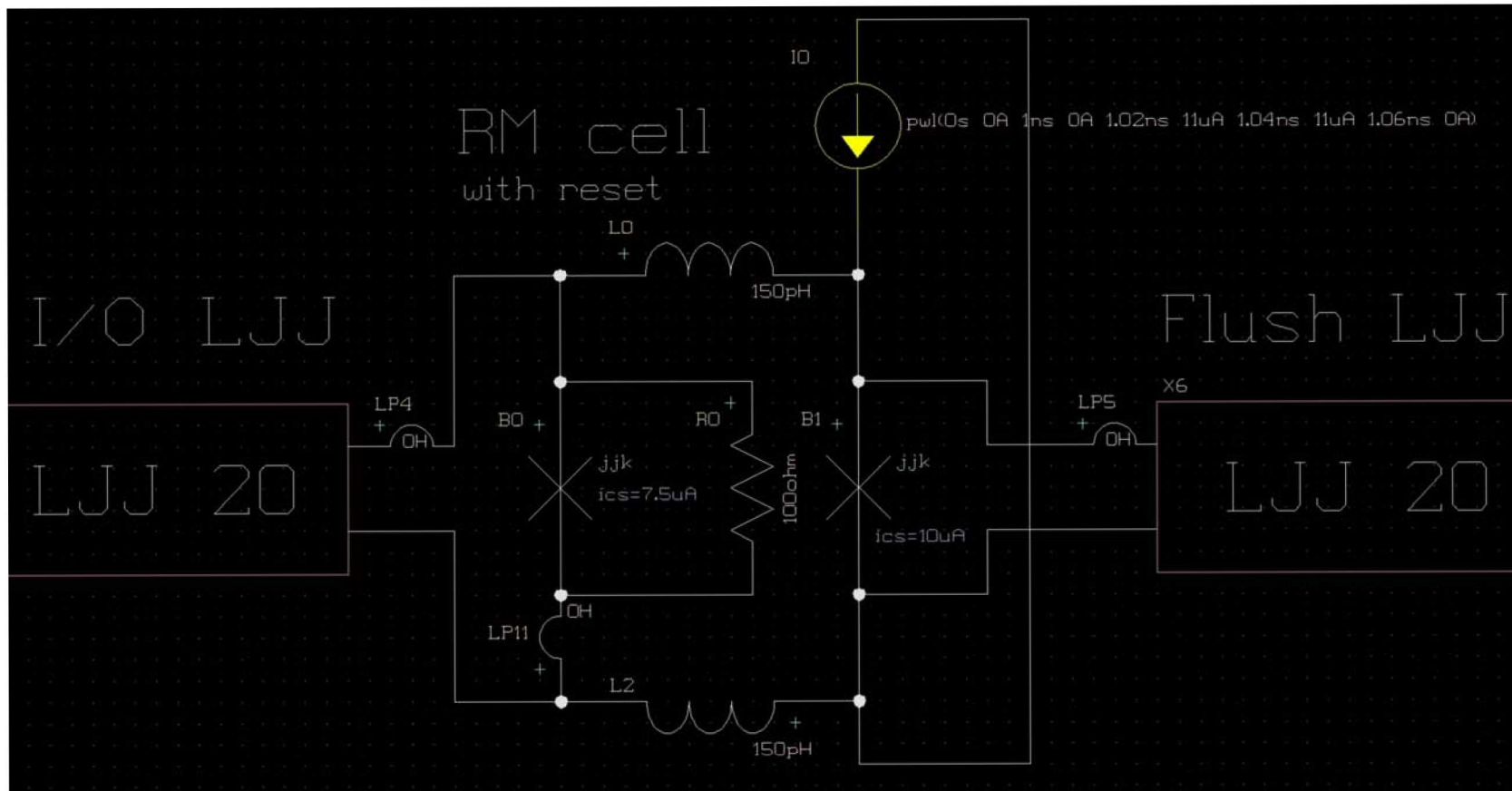ic=7uA
9

WRspice simulation results

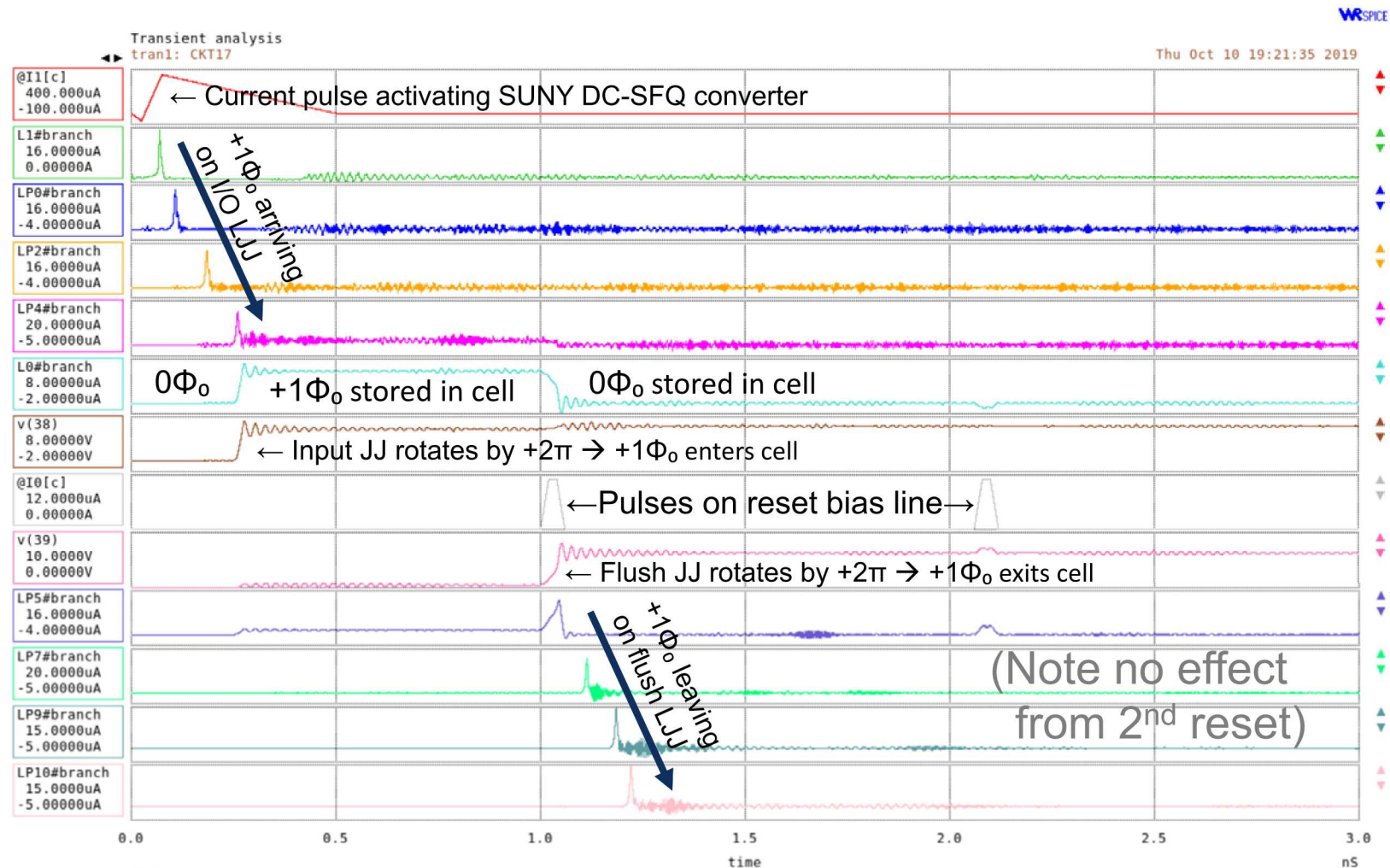Polarity mismatch → Exchange   Polarity match → Reflect (=Exchange)

Resettable version of RM cell

- For testing—apply current pulse of appropriate sign to flush the stored flux (the pulse here flushes out positive flux)
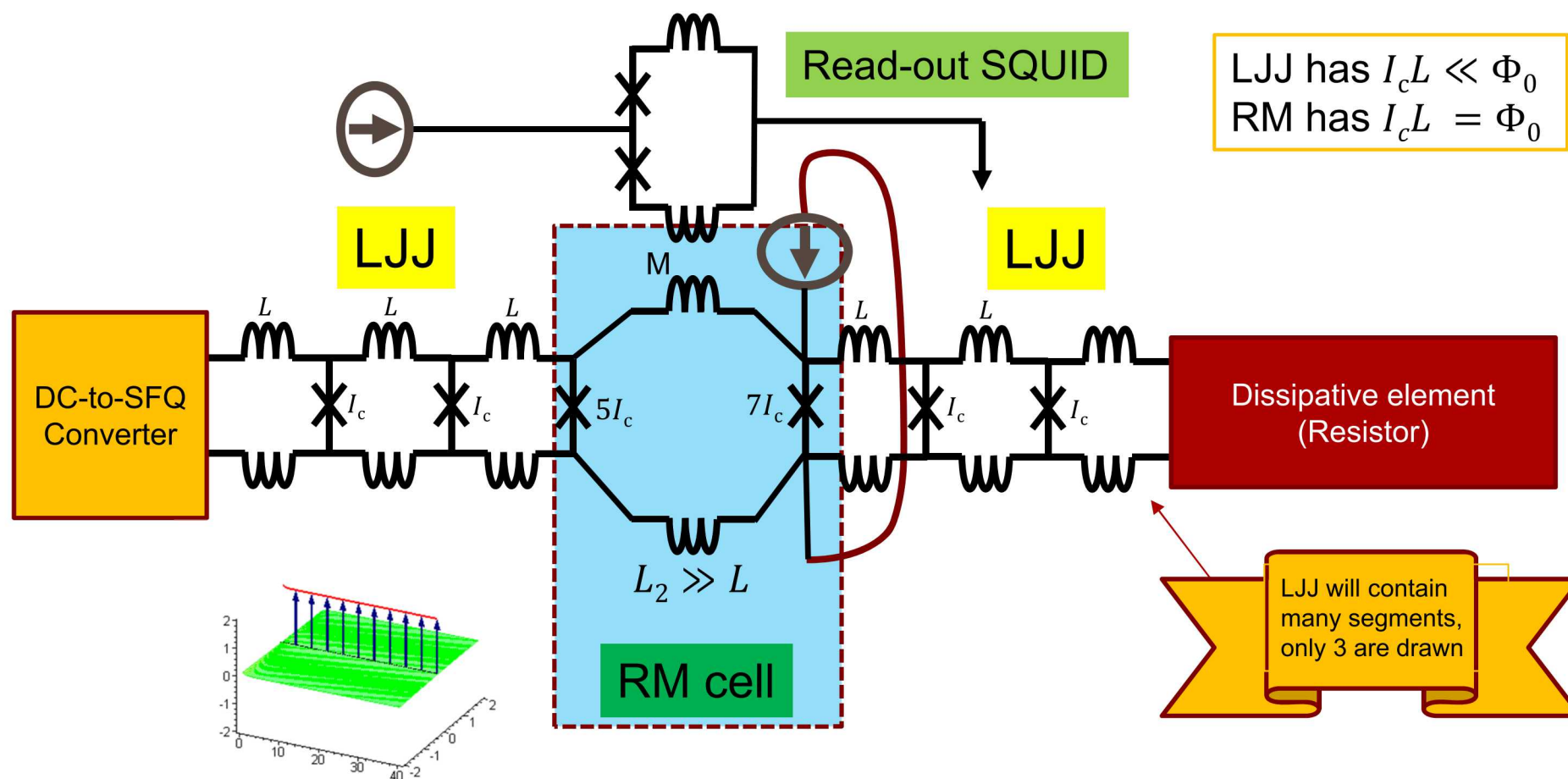 - To flush either polarity → Just do both (±) resets in succession

SPICE simulation of RM cell reset

- Simulates as expected (one-polarity reset shown)
  - Reset of an already-flushed cell is a no-op

Sketch of SQUID-based test setup
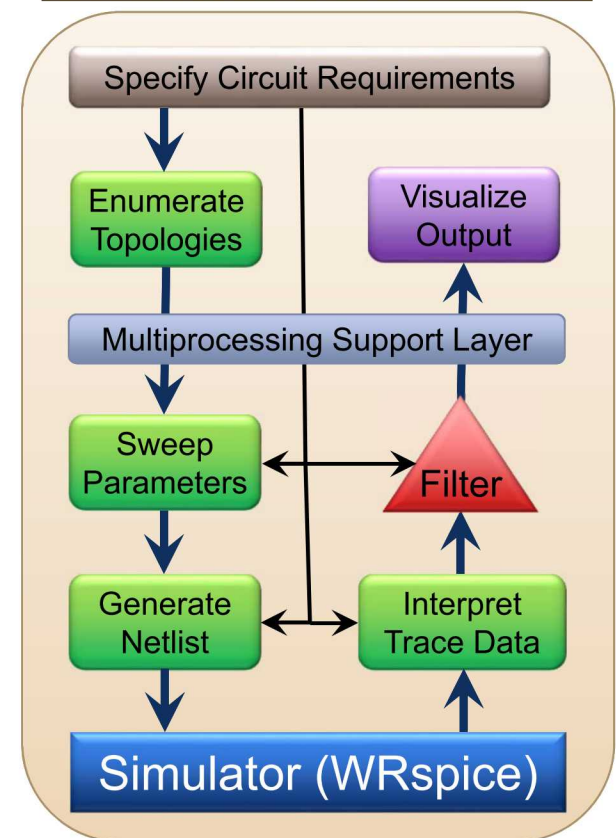
Next Steps re: RM Cell

- Need to understand better, at a theoretical level, the engineering requirements for this circuit to work properly.
  - And, can we generalize this understanding to more complex cases?
    - Goal: Design circuits for a wide variety of other ABRC functions.
- Detailed design & empirical testing of a physical prototype.
  - Design experiment, lay out artwork, extract parasitics, fabricate a test chip, and experimentally measure the circuit in our lab.
- Carry out further elaborations of design to fine-tune dynamic response for high-fidelity preservation of pulse shape.
  - Should be able to use 3D physics modeling, solve inverse problem to craft a very high-quality custom layout (similar to metamaterials).
- Investigate applications, *e.g.*:
  - Can this be extended to become the basis for a dense memory fabric?
    - Develop row/column interface logic
    - Optimize the cell design for more compact area
      - Try smaller loop inductance, larger I_c in I/O junction

Automation of Circuit Discovery

- Due to the novelty of our new logic style, the principles to design much improved/more complex ABRC circuits aren't obvious...

  - **Solution:** Automate our circuit-discovery methodology!

- Started developing a new tool, named **SCIT**

  - ***Superconducting Circuit Innovation Tool***

- Outline of the SCIT processing flow:

  1. Define circuit design requirements
  2. Enumerate possible circuit topologies
     - In order of increasing complexity
  3. Delegate topologies to MPC nodes
  4. Sweep over device parameter space
  5. Generate a netlist for each test design
  6. Simulate netlist locally (in e.g. WRspice)
  7. Interpret & summarize resulting traces
  8. Filter for results with desired properties
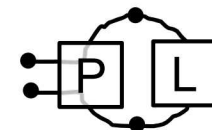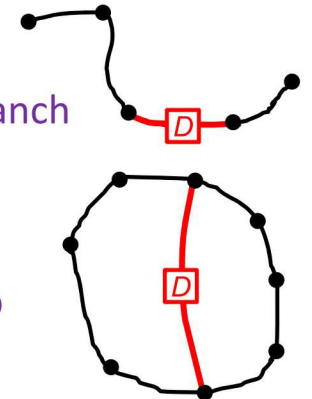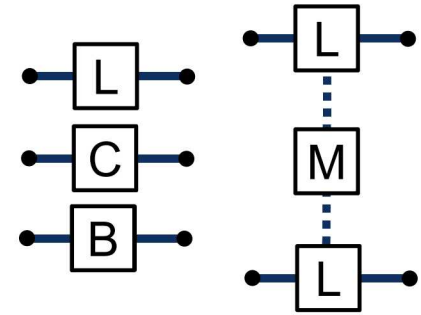 9. Facilitate visualization of candidate designs

SCIT Software Architecture

Topology Enumeration Algorithm

- Two-terminal circuit primitives:
  - L – Wire segment with inductance.
  - C – Capacitive coupling between nodes.
  - B – Josephson junction.
  - M – Mutual inductive coupling between wire segments.
- An algorithm to enumerate all N-primitive planar circuits:
  - Recursively, enumerate all $(N - 1)$-primitive circuits; for each:
    - For each primitive branch in the circuit,
      - For each device type L,C,B:
        » Generate each possible in-line device insertion on that branch
    - For each primitive loop in the circuit,
      - For each device type L,C,M,B:
        » Generate each possible device placement across that loop
        » Special case for M: Couple two wire segments.
  - Base case for recursion:
    - One loop with two primitives, I/O port (P) and wire (L).

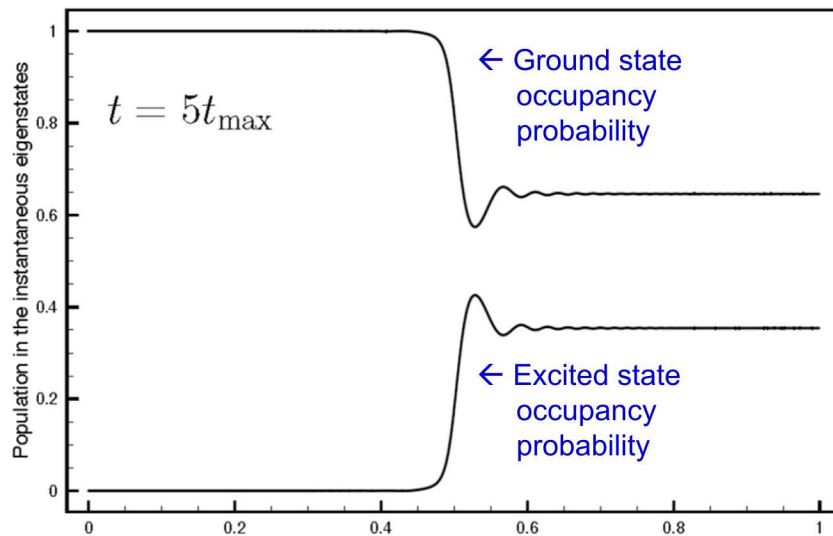# Superadiabaticity / Shortcuts to Adiabaticity (STA)

- A line of fundamental physics research showing that we can theoretically attain or approach 0 diabaticity (dissipation) even in evolutions occurring at fast, *constant* speeds.
  - This relates to my more general point from earlier about the dissipationlessness of unitary transformations.
- Some (at least theoretical) applications of this so far:
  - Fast Carnot-efficient heat engines!
  - General thermodynamic engines for manipulating the state of quantum systems (*e.g.* Maxwell's Demon type setups).
  - Faster superconducting circuits for quantum control!
- Why not also investigate using these methods to achieve fast *classical* dissipationless reversible computing?
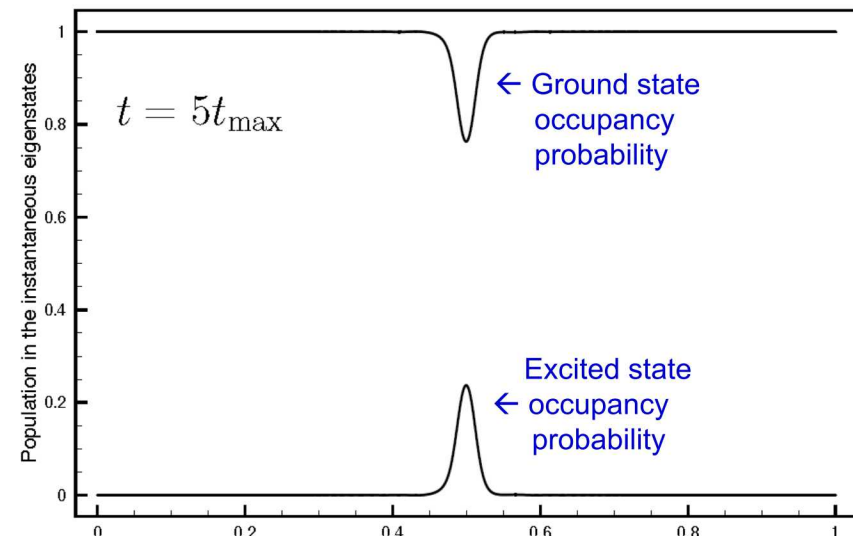
Example Use of STA: Fast Dissipationless Transitions of a Quantum Dot System

- Credit: David Guéry-Odelin (U. Toulouse)
- Example system:
  - A quantum-dot system previously described by Lent for use in reversible logic, undergoing an (externally-driven) transition between two different Hamiltonians.
- Figures show occupancy of ground (top) & 1st excited eigenstate (bottom).
  - t is the total time over which the transition takes place (adjustable)
  - t_{max} is a somewhat arbitrary duration when the system is transitioned at certain designated "maximum speed" (at which dissipation is near maximum)
- If system later relaxes from an excited state → state energy will be dissipated.
  - But, we assume here that the relaxation time is large compared to the transition time itself.
- Both figures below show an example calculation at which transition speed = 1/5 maximum
  - But, the same method works in principle to achieve zero dissipation at *any* speed!

Normal quantum adiabatic process:
Substantial excitation/dissipation

Using counterdiabatic protocol:
Zero net excitation/dissipation

Open Problems in STA for RC

- Can any of the various STA protocols actually be implemented practically?
    - Describe some engineering mechanisms for doing so.
    - What are the limits on their efficiency *in practice*, if any?
- Can the STA protocols be applied (in a complete way) to various specific examples of physical implementations of reversible computing?
    - In particular, is there any way to apply them to fluxon dynamics, specifically in ABRC-type circuits?
        - Certain classical-quantum equivalences suggest maybe yes.
        - Could an appropriate counterdiabatic Hamiltonian be introduced spatially, through appropriate tailoring of the structure at which the fluxon dynamics occurs?
- Best way to proceed is still very unclear!
    - This is a wide-open research area…

Superadiabaticity / STA references

Lim, R., and M. V. Berry. (1991) "Superadiabatic tracking of quantum evolution." *Journal of Physics A: Mathematical and General*, vol. 24, no. 14, pp. 3255–3264.

Gelbwaser-Klimovsky, David, Robert Alicki, and Gershon Kurizki (2013) "Minimal universal quantum heat machine." *Physical Review E*, vol. 87, no. 1, art. 012140. doi:10.1103/PhysRevE.87.012140

Del Campo, Adolfo, John Goold, and Mauro Paternostro (2014) "More bang for your buck: Super-adiabatic quantum engines." *Scientific Reports* vol. 4, art. 6208. doi:10.1038/rep06208

Santos, Alan C., and Marcelo S. Sarandy (2015) "Superadiabatic controlled evolutions and universal quantum computation." *Scientific Reports*, vol. 5, art. 15775. doi:10.1038/srep1577510.1038/srep15775

Pidaparthi, Subhash, and Craig Lent (2018) "Exponentially Adiabatic Switching in Quantum-Dot Cellular Automata." *Journal of Low Power Electronics and Applications*, vol. 8, no. 3, pp. 30. doi:10.3390/jlpea8030030

Landau, Lev Davidovich (1932) "Zur Theorie der Energieübertragung. II," *Physikalische Zeitschrift der Sowjetunion*, vol. 2, pp. 46–51. English translation: "A Theory of Energy Transfer. II," Ter Haar, Dirk, ed. Collected papers of LD Landau. Elsevier, 2013. doi:10.1016/B978-0-08-010586-4.50014-6

Zener, Clarence (1932) "Non-adiabatic crossing of energy levels." *Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character*, vol. 137, no. 833, pp. 696-702. doi:10.1098/rspa.1932.0165

D. Guéry-Odelin, A. Ruschhaupt, A. Kiely, E. Torrontegui, S. Martínez-Garaot, J. G. Muga (2019) "Shortcuts to adiabaticity: Concepts, methods and applications," preprint, arXiv:1904.08448 [quant-ph], https://arxiv.org/abs/1904.08448

Conclusion

- Some path to further **increase dissipation-delay efficiency** of superconducting circuits over the long term is needed.
    - **No *fundamental* limit** on this quantity is yet known!
- Inspired by **collision-based computing**, we have simulated the first concrete working example of an SCE circuit implementing one of the reversible functions in the new ABRC model of computation.
    - This is a **reversible memory (RM)** cell functionality using just 1 JJ.
    - **Next steps** for the RM cell development include:
        - **Prototype & test** this circuit in a suitable process.
        - **Identify additional functions** in the ABRC model that may be amenable to similarly straightforward implementations.
        - **Implement circuit search tool** (SCIT) for more rapid discovery of circuits for more complex ABRC functionalities.
- In the bigger picture, there is a significant need to begin investigating new quantum (or quantum-inspired) techniques for reducing dissipation in reversible computational processes.
    - **Shortcuts-to-adiabaticity** (STA) is just one example of such an approach
    - **Other ideas:** Use topological invariants, quantum Zeno effects, etc.
- Many possible paths still remain to be explored for **continuing to improve dissipation-delay efficiency** far into the future.