Observing 1D Reaction-Diffusion Waves in Belousov-Zhabotinsky Systems

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Abstract

A single-syringe pump system was developed to investigate the conditions required for the formation of standing waves in a Belousov-Zhabotinsky (BZ) reaction. Various reaction mixtures were tested, showing potential for future definitive findings. Fluid velocity was measured before and after advection in a 1D system to assess nonlinear reaction-diffusion-advection dynamics, though no conclusive evidence of standing waves was obtained. Future research is encouraged to focus on adjusting pump speed, exploring different BZ reaction formulations, and using a smaller advection component.

The Belousov-Zhabotinsky Reaction & Reaction-Diffusion-Advection

The BZ reaction is a nonlinear chemical oscillator that forms self-organized waves through coupled redox reactions and diffusion, classifying it as a reaction-diffusion system [1].

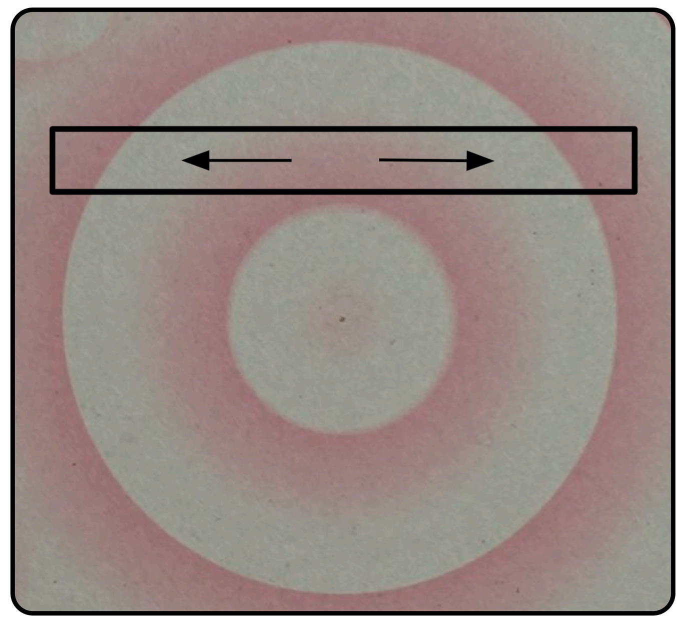

Fig. 1 Target pattern in a 2D BZ solution. The rectangle outlines a region analogous to the 1D capillary system, with arrows pointing towards the direction of the propagated waves. Photographed by Aidan Mason '24.

- Airflow introduced through a capillary adds advection, creating a reaction-diffusion-advection system.
- 1D BZ wave propagation under airflow was studied to observe the effect of flow direction on wave speed.
- Can produce stationary wave patterns, highlighting how boundary conditions influence wave behavior in confined systems.

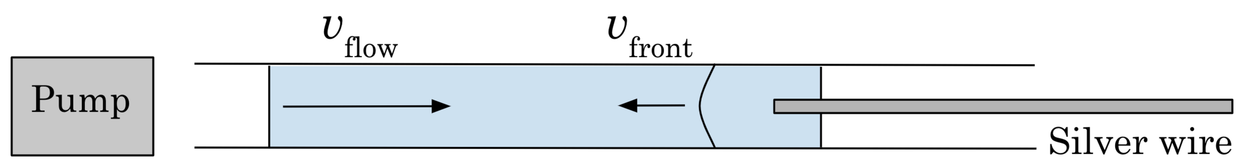

Fig. 2 Fluid–flow diagram within a capillary, where v_{flow} represents the velocity of the fluid flow from the pump and v_{front} is the velocity of the propagating wavefront, denoted with a curve within the capillary.

Quasi-1D System

- This system enables continuous fluid flow using syringe pumps with precise infusion control [2].
- Five NEMA 17 stepper motors were used for their ability to incrementally step, each paired with a DRV8825 driver.

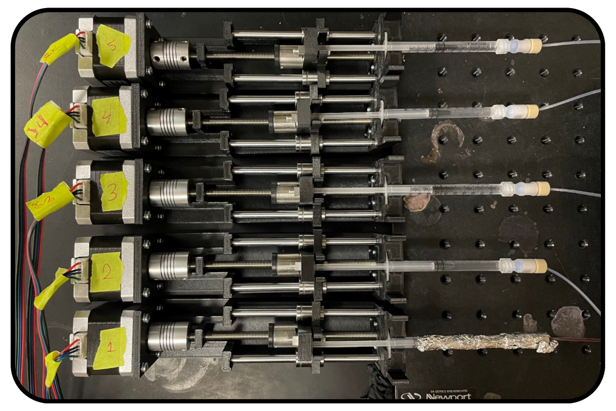

Fig. 3 Quasi-1D stepper motor system with one syringe per BZ component.

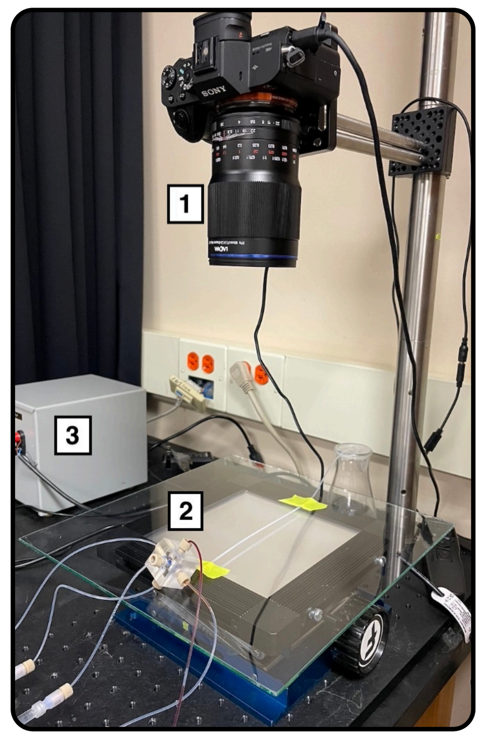

Fig. 4 Experimental setup: (1) camera for 1D observation, (2) backlight with six-channel mixer, and (3) power supply for the backlight.

Single-Syringe System

- BZ solution and air were introduced from one end of a capillary, while a metal wire (e.g., silver) was inserted at the other to initiate a wave (Fig. 4), with the goal being for the wave to reflect back without further input.
- Slow pumping and low-excitability BZ recipes reduced wave speed and increased sensitivity to flow and boundary effects.

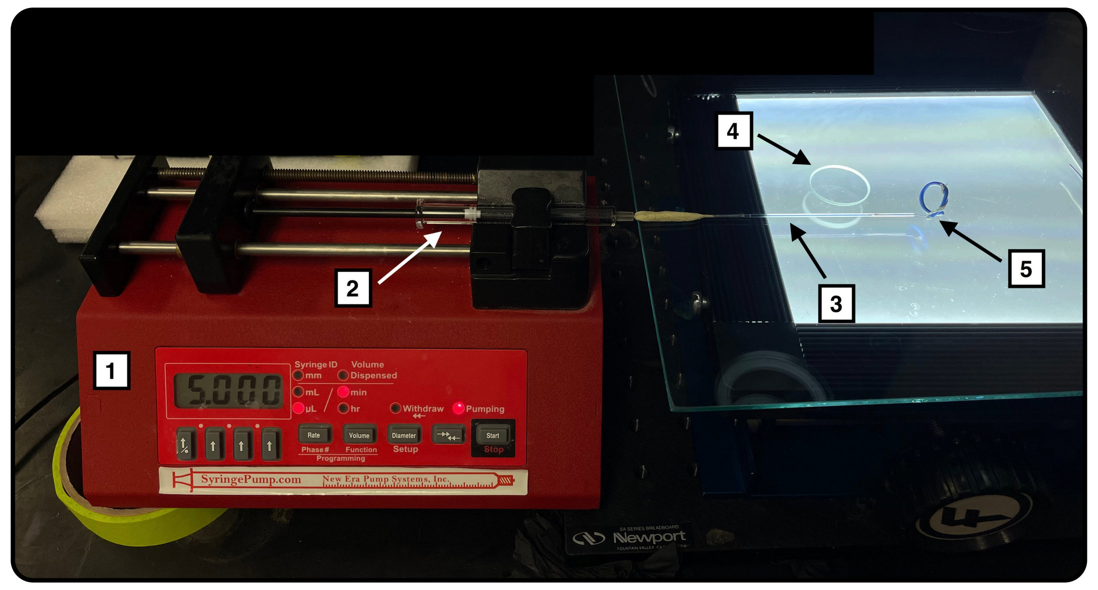

Fig. 5 Single syringe pump setup: (1) NE-1000 pump, (2) 1 mL glass syringe, (3) 100 µL capillary sealed with modeling clay, (4) silver wire inside capillary, and (5) diffraction grating for calibration. Pump operated at 1.5 µL/hr to the right.

Results & Analysis

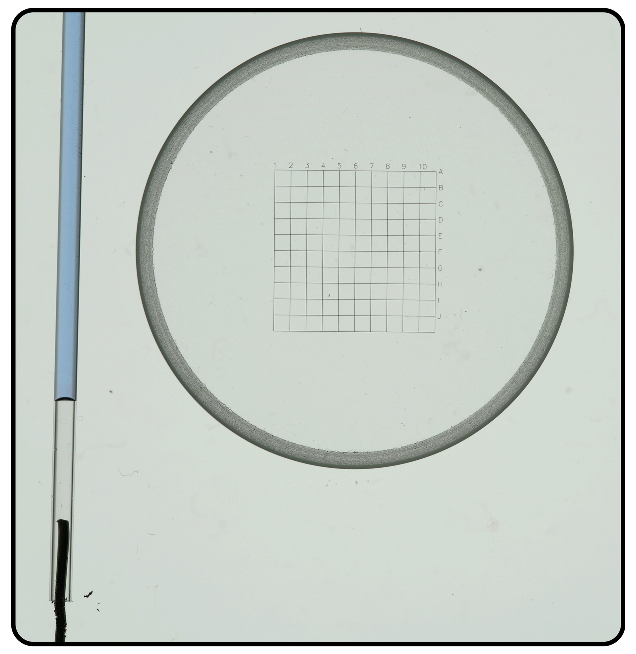

Fig. 6 27–mm Diameter Contact Reticle, Metric Index Square Scale diffraction grating.

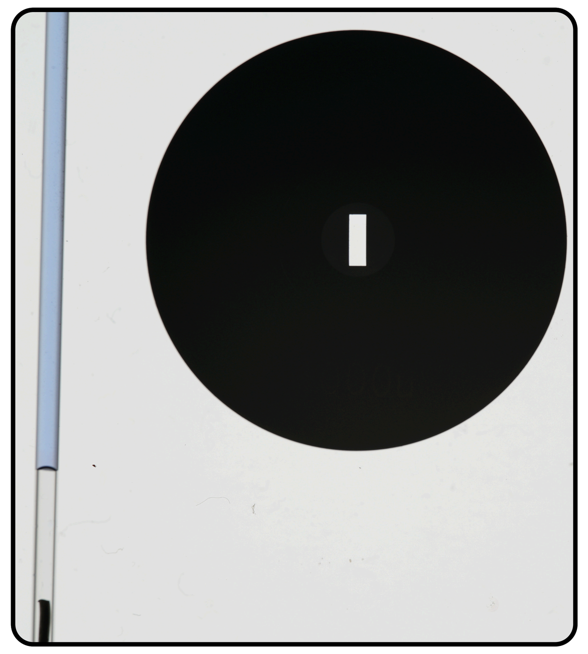

Fig. 7 1000 µm x 3 mm, Mounted, Precision Air Slit.

- A total of 10 trials were conducted with various methods for maintaining a constant air stream from the syringe to the capillary.
- A Sony A7RII camera with a Laowa 99-mm macro lens was used for optimized magnification.
- Images were remotely controlled via USB using the Image Edge Desktop application.
- Image acquisition and batch editing were done in Adobe Lightroom.
- Images were converted into a time-space plot (kymograph) using Fiji.

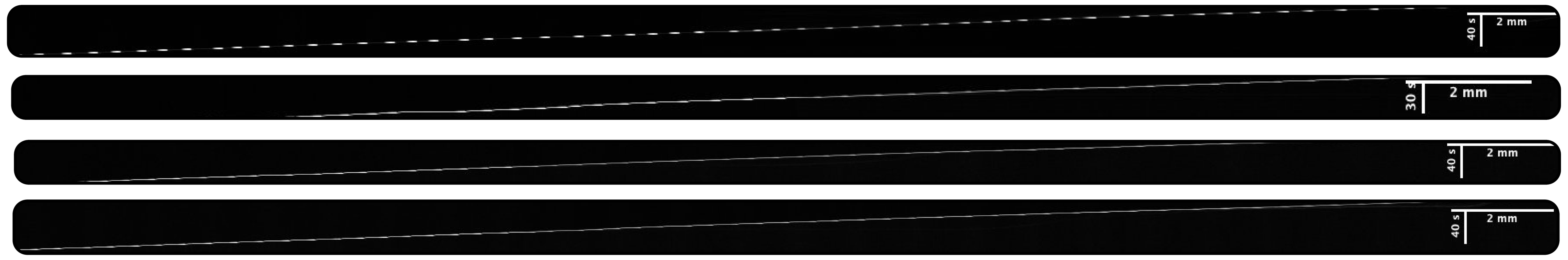

Fig. 8 Kymographs for trials 1–4, with time over space increasing in the $+x$–direction. Respective scaling is shown on the right.

Future Work

- Use thinner wires to reduce surface tension effects and minimize disturbance of fluid motion within the capillary.
- Adjust pump speed in advance to allow the system to reach steady-state conditions before wave initiation.
- Increase camera magnification to better observe and evaluate conditions that support standing wave formation.
- Explore alternative boundary conditions—such as physical obstructions, varying capillary diameter, or different BZ recipes—to further investigate wave behavior.
- Utilize the quasi-1D system to observe boundary conditions, where the components can be varied on the spot.

References

[1] Sitabhra Sinha and S. Sridhar. Patterns in Excitable Media: Genesis, Dynamics, and Control. CRC Press, 2014.

[2] Aidan Mason. Fabricating a Flow Chemistry System to Investigate Reaction-Diffusion Waves in Advected Belousov–Zhabotinsky Systems. Bachelor Thesis, The College of Wooster, Wooster, OH, USA, March 2024.

[3] Schindelin, J.; Arganda-Carreras, I.; Frise, E.; Kaynig, V.; Longair, M.; et al. Fiji: An Open-Source Platform for Biological-Image Analysis. Nat. Methods 2012, 9 (7), 676–682. https://doi.org/10.1038/nmeth.2019. Software accessible at https://imagej.net/software/fiji.

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