Staircase Resiliency in a Fluctuating Cellular Array

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   c) Zonal Flows
   d) $E \times B$ Staircase
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   b) Transport in the VA
5) **Conclusion**
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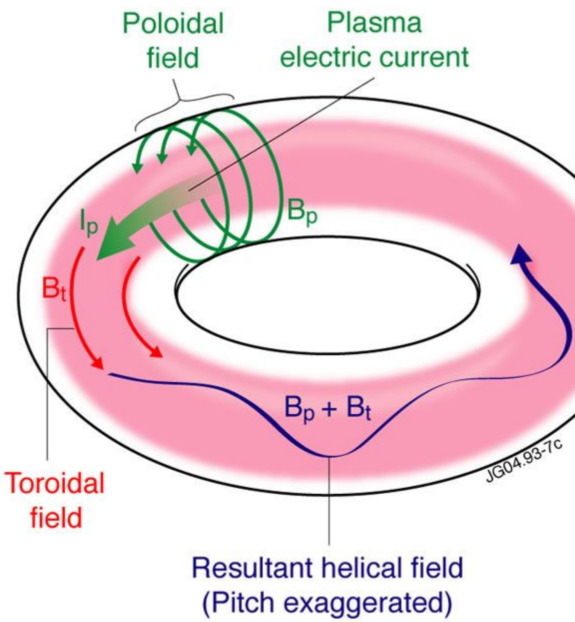
Background

Tokamak Physics Basics

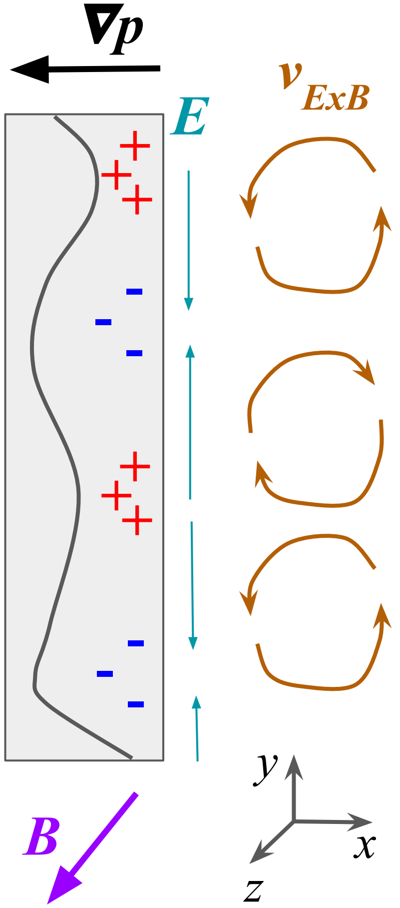
- Tokamaks are toroidal fusion devices that use a strong helical magnetic field to confine plasma.

- Key challenge:
  - $\langle n \rangle \langle T \rangle \tau_E > 10^{21}$ keV s/m^3 (Lawson criterion) → maximize confinement time τ_E → minimize losses due to transport.
  - But: n, T gradients → instabilities → turbulence → anomalous transport.

- Anomalous transport in tokamak plasmas can be attributed to drift-wave turbulence.



Drift-Wave Turbulence

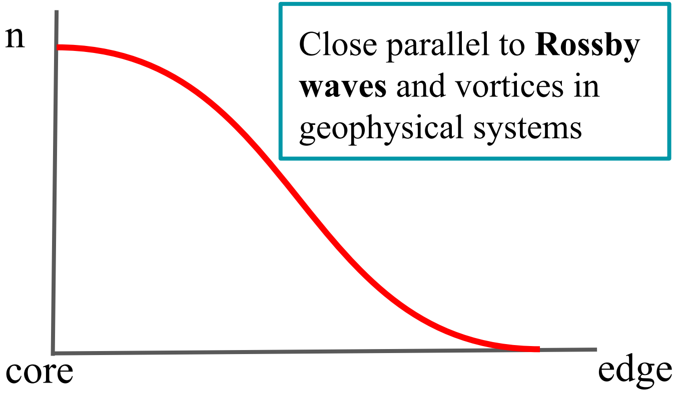


Plasma transport across the magnetic field is largely controlled by low-frequency drift-wave (DW) fluctuations.

- Heat and particle loss are attributed to this DW mechanism of plasma turbulence.

DW: collective oscillations associated with ion/electron diamagnetic drifts which form in response to temperature/density gradients $v_d = 1/(qnB^2)\,\nabla p \times \boldsymbol{B}$.

Structure: cell convecting around $\tilde{n}$ at $v_E = -c/B\ \nabla \varphi_1 \times \boldsymbol{B}$ traveling at v_d.



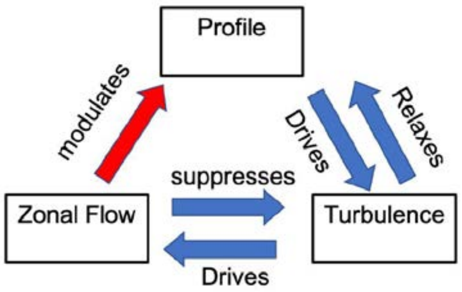
Close parallel to **Rossby waves** and vortices in geophysical systems

- $\tilde{n}$ coupled tightly to φ_1 by fast parallel "Boltzmann" electron response (from force balance) $\tilde{n}/n_0 \simeq e\,\varphi_1/T_e$.
- Collisions and resonances → phase shift $\tilde{n}_{\mathbf{k}}/n_0 \simeq e\,\varphi_{1\mathbf{k}}/Te\,(1 - i\,\delta_{\mathbf{k}})$ → instability!
- Turbulence results when many drift modes become unstable, nonlin. interaction becomes important!

Zonal Flows

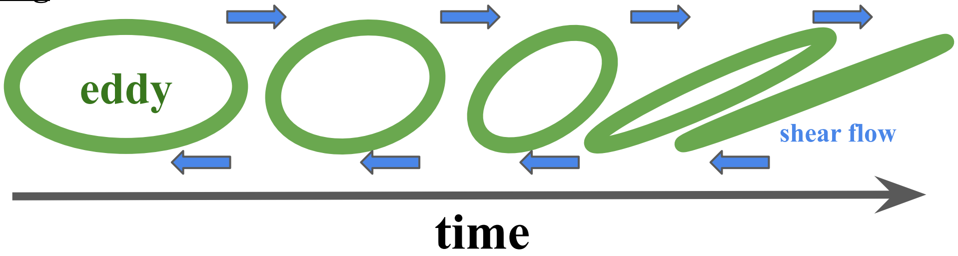
- DW turbulence features complex interaction between mean density profiles, zonal flow (ZF), and turbulence.
- ZF are special modes with $m = n = 0$. Turbulence-driven, sheared poloidal flows.
  - **No radial flow** → do not cause harmful transport.
  - ZF shear stretches turbulent eddies → **regulate turbulence**!
- ZF are extremely important for confinement problem!

Feedback Loop



ZFs also important in **geophysical** flows.

Eddy shearing



Transport Barriers

Why do this?

- **Plasma confinement in magnetic fusion devices.**

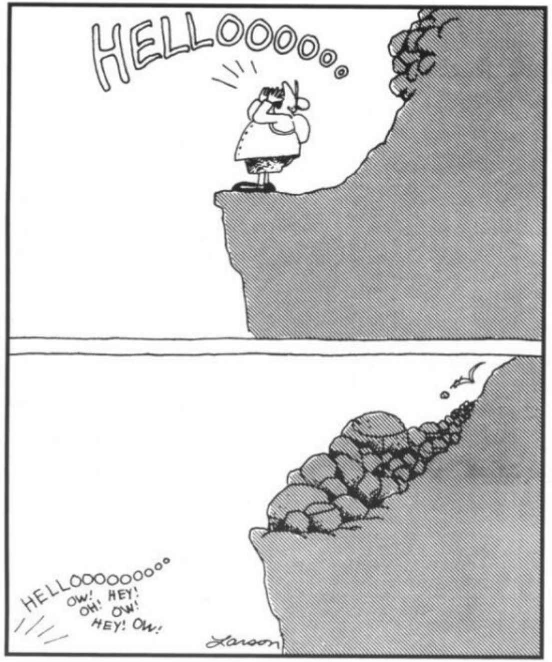
To achieve this, a transport barrier is critical!

- Most likely candidate for the formation of a transport barrier is some effect of a shear flow on the plasma. **Goal**: Regulate turbulent heat flux.

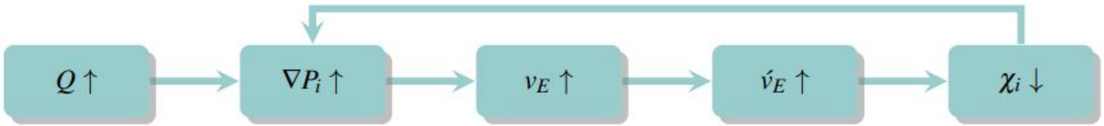
The radial ion force balance gives us insight:

$$0 = \left(\frac{q}{m}\mathbf{E} + \frac{q}{mc}\mathbf{v} \times \mathbf{B} - \frac{\boldsymbol{\nabla} P_i}{n m_i} \right) \cdot \hat{r}$$

- A balance between the E-field, Lorentz force, and pressure gradient results in an enhanced shear as the pressure gradient is increased.



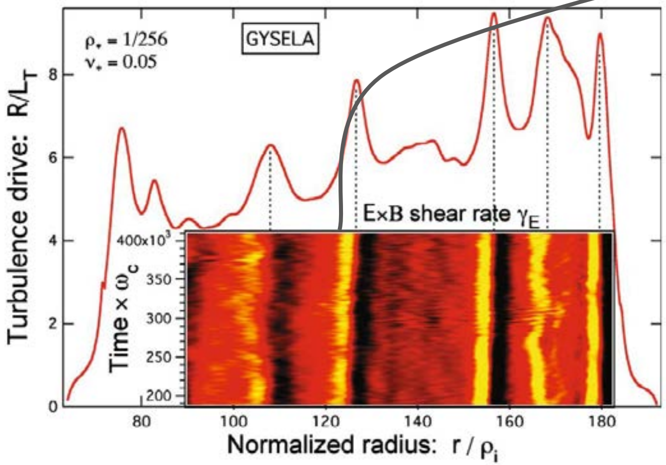
This triggers a "**feedback loop**"!



It turns out that a global pattern of isolated transport micro-barriers and sectors of high transport can coexist in plasma. This phenomenon resembles a **staircase**!

$E \times B$ Staircase

***E* × *B* <u>staircase</u> current subject in M.F.E**



Yellow and black colors are a rapid transition of the direction of flows around peaks in turbulence drive. This is the shear layer, which is interspersed with a regular pattern of shear layers and profile corrugations.

Dif-Pradalier, 2017

<u>Context</u>: Flat spots of high transport and nearly vertical layers acting as mini-barriers coexist. In plasmas, avalanches happen in flat spots and shear layers due to zonal flows occur in the areas of mini-barriers.

Suggested ideas:

- ***E* × *B*** shear feedback, predator-prey
  - Zonal flows predator and turbulence intensity prey
- Jams

<u>But</u>… is there an even **simpler** physical mechanism that can produce **layering?**
Answer: Yes (e.g., pattern of cells)

Some Questions

- How does staircase beat homogenization?
- Is the staircase a meta-stable state?
- What is the minimal set of scales to recover layering?

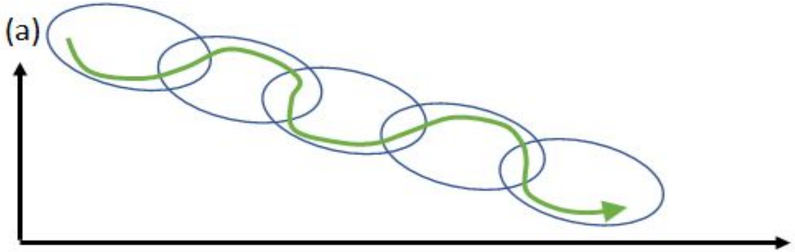
<u>Next</u>:
Fixed-Cell Array…

FCA Problem
(another way to get a Staircase)

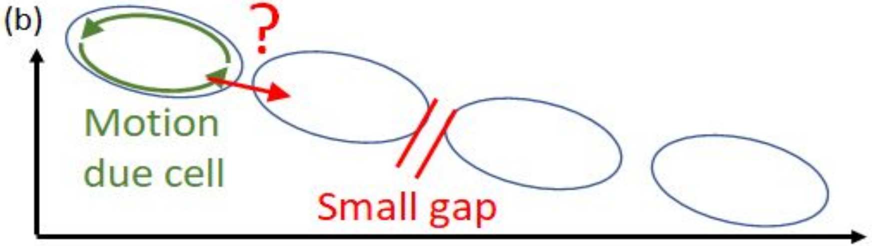
FCA Problem (similar to $E \times B$ convection)

Transport of particle between non-overlapping or marginally overlapping cells (**characteristic of near marginal**) is an important topic in fusion plasma.

Overlapping case: particles can transport directly from cell to cell, wandering along streamlines



Nearly-overlapping case (cells sit at near overlap): transport is a synergy of motion due to cells and random kicks (Collisional diffusion, ambient scattering) thru gap regions.



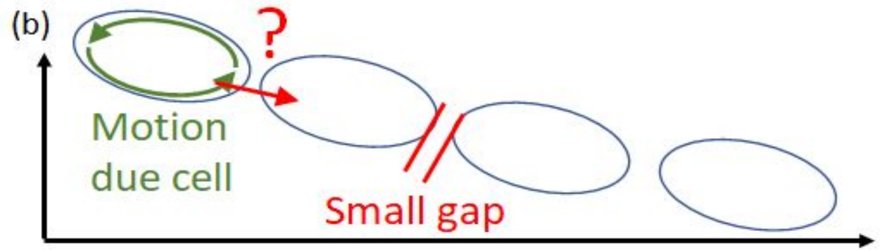
→ Characteristic of **near marginal**.

→ The transport over gap is random kicks (ambient diffusion): collisions, micro-turbulence.

→ **Coexistence** of:
~ **Fast transport** - Mixing in cell
~ **Slow transport** - Kicks between cells

N.B.: "Profile stiffness" → Cells near overlap
→ Rapid increase in transport prevents strong overlap

What of Interest?



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→ **Coexistence** of:
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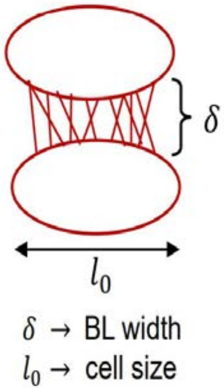
- **Relevant to key question of "near marginal stability"**

→ Representative of state in <u>marginal stability</u>.
- Stiff systems hovering near threshold (relevant question)

→ **Natural candidate to near marginal stability!**
- Zonal (mean) flows
- similarities SOC (fronts, spreading,...)
- **<u>Staircases</u>**

<u>Back-of-Envelope Calculation</u>



$D^* \approx f_{active}((\Delta x)^2 / \Delta t)$;

$f_{active} \equiv$ active fraction $\sim \delta / \ell_o$

$\Delta t \sim \ell_o / v_o \rightarrow$ cell circulation time

So, $\delta^2 \sim D\,\Delta t \sim D\,\ell_o / v_o$

$D^* \sim [(D\,\ell_o / v_o)^{1/2}\, 1 / \ell_o]\, (\ell_o^2 / \ell_o)\, v_o \sim [D\, D_{cell}]^{1/2}$

$\sim D\, Pe^{1/2}$

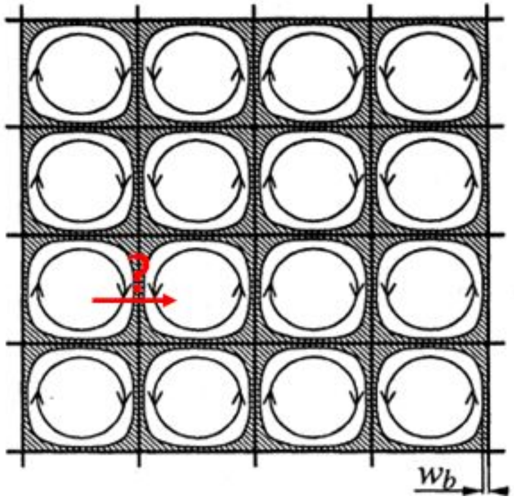
FCA Problem (cont.d)

Consider a **general** case of a system of eddies not overlapping but tangent → **Staircase**

Transport? Answer: $Deff \sim D\, Pe^{1/2}$ {**Not a simple addition of process!**}

→ Two time rates: $\tau_H = d / v$ (fast), $\tau_D = d^2 / D$ (slow)

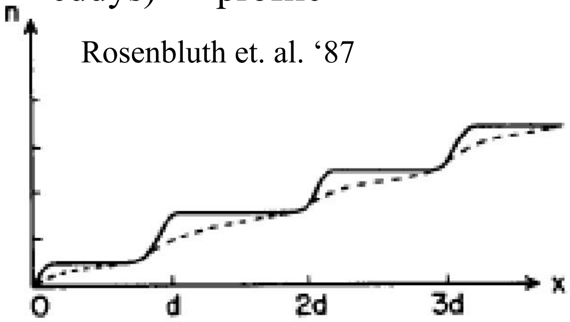
→ $Pe = v\, d / D >> 1$



Staircase arises in an array of stationary eddies!

Profile?

Consider concentration of injected dye (passive scalar transport in eddys) → profile



"Steep transitions in the density exist between each cell."

→ Layering!

→ **Simple** consequence of **two rates**

→ "Rosenbluth Staircase"

Relevant to key question of "near marginal stability"

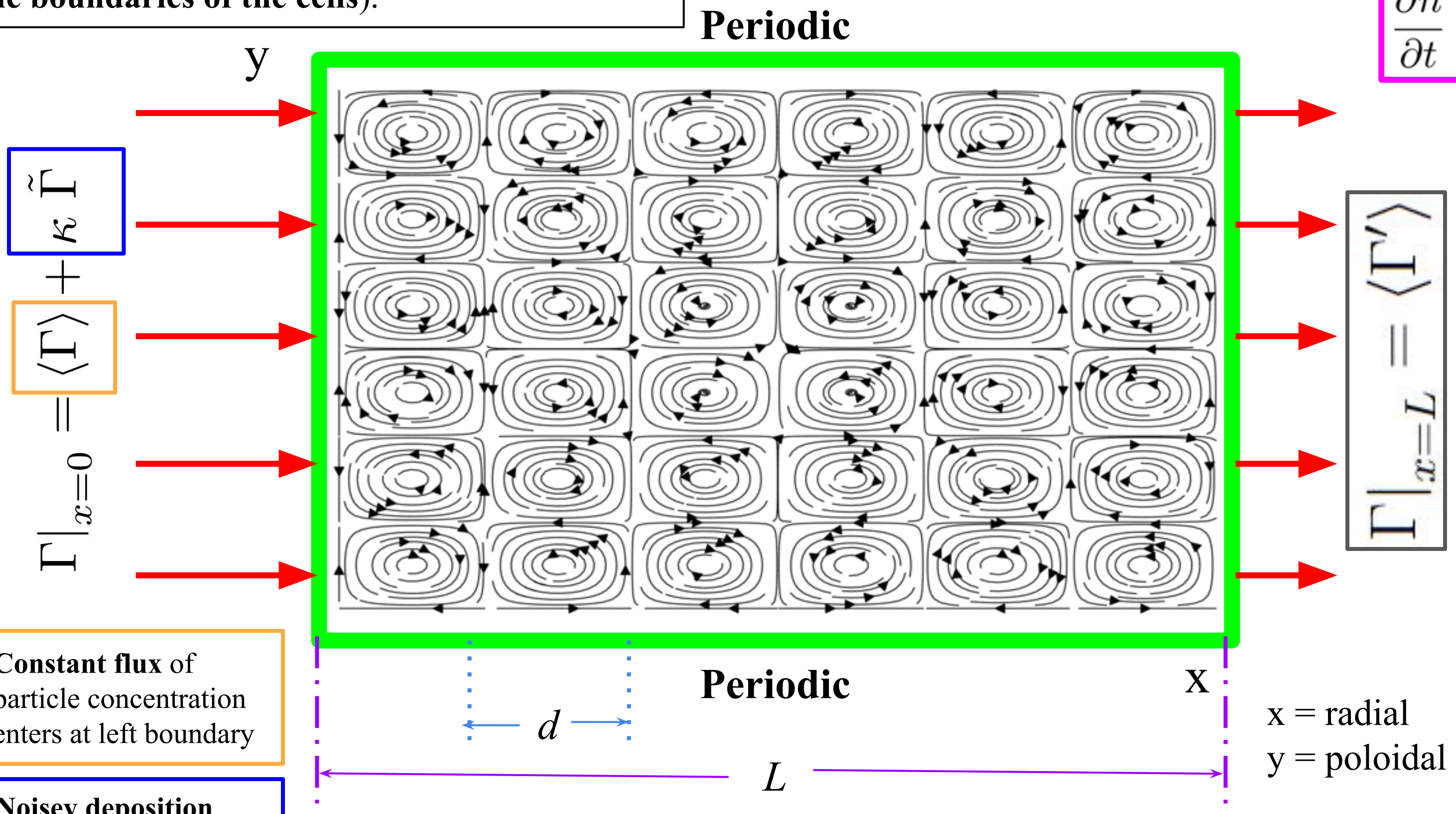
Important:

- **Staircase** arises in stationary array of passive eddies (Note that there is no FEEDBACK)
- Global transport hybrid:
  - → fast rotation in cell
  - → slow diffusion in boundary layer
- Irreversibility localized to inter-cell boundary.

FCA Setup

We are primarily concerned with Pe >> 1, where <u>layering</u> occurs (**physics explained by fast mixing within the cells and slow mixing across the boundaries of the cells**).

$$\frac{\partial n}{\partial t} + \mathbf{u} \cdot \nabla n = D \nabla^2 n,$$



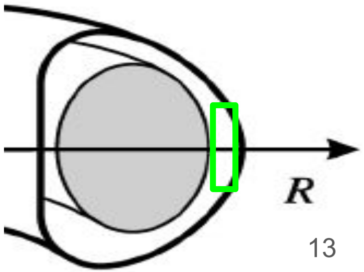
Constant flux of particle concentration enters at left boundary

Noisey deposition (<u>Pulse Train</u>)

Combination of fixed flux and periodic boundary conditions are used to model the physics of **core to edge** in <u>**fusion**</u> devices.

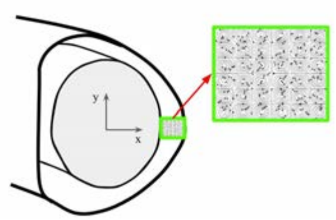
Constant flux of particle concentration exits at right boundary

x = radial
y = poloidal



FCA Problem (cont.d)

The governing equation that produces layering is the **passive-scalar transport** equation.



$$\mathbf{u} = \hat{z} \times \boldsymbol{\nabla}\psi$$

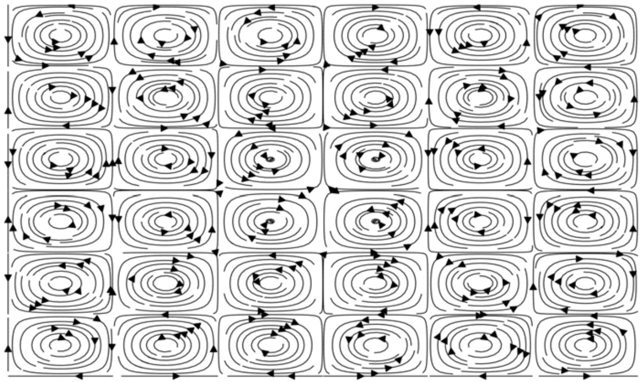
$$\frac{\partial n}{\partial t} + \mathbf{u} \cdot \boldsymbol{\nabla} n - D\nabla^2 n = 0$$

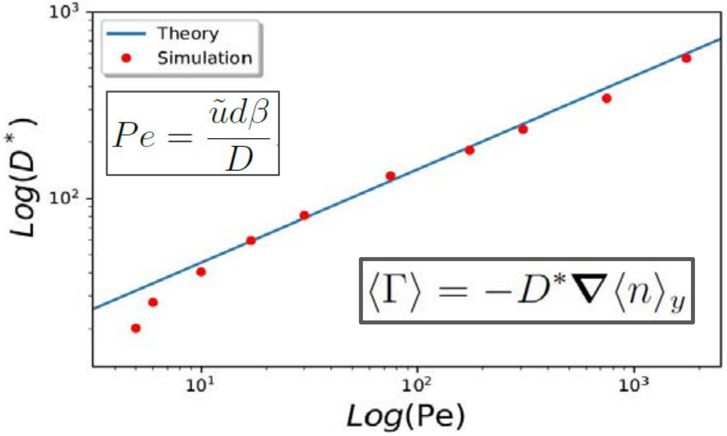
Pe is defined as the ratio between the advective term and diffusion term! (*Pe* >> 1)

A preliminary study is done to verify that code reproduces known theoretical results!

BUT, this setup is contrived, NOT self-organized!!! Cellular array is severely constrained!

Constrained (6x6) cell array





What about the dynamics of a **less constrained** cell array (i.e., vortex array with fluctuations) ?

Next:

Relaxing FCA with FVA

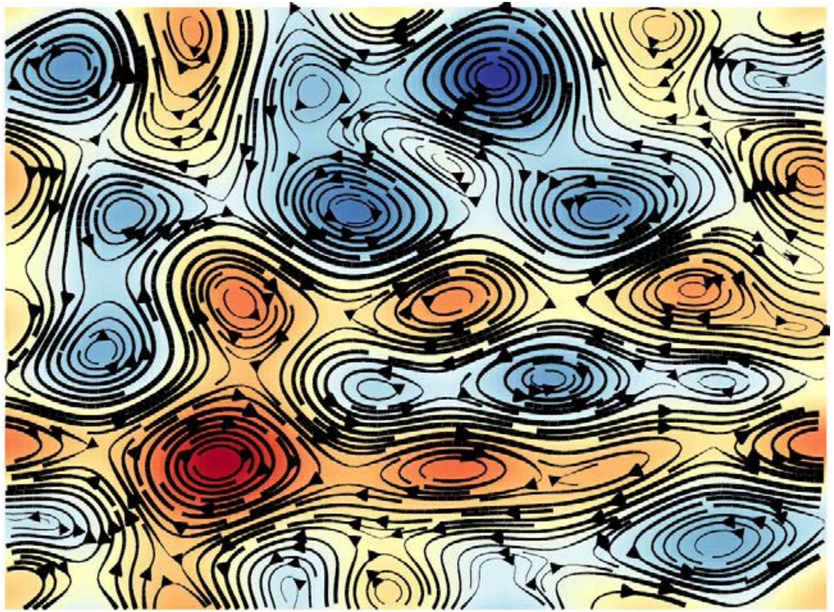
Consider Another Approach

- We want to study a much more **general** and **less constrained** version of the cell array.
    - Consider a vortex array with fluctuations; jitters.
- How **resilient** is the staircase in the presence of these small variations to a fixed vortex array?

In the process of studying the **resilience** of the staircase, we aim to answer the following:

1. What happens to interspersed regions of strong scalar concentration mixing as cells relax? What about general cell interactions/behavior?
2. What is the behavior of the scalar trajectory through the VA?
3. How does the increase of scattering in the VA affect the transport of scalar concentration?

Example of **less constrained** cell array



To answer these questions, we use the idea of a **Melting Vortex Crystal**…

Novel representation of array of cells in tokamaks

Fluctuating Vortex Array

Why are we doing this? We know that a system with two disparate time scales forms a staircase!

- Now consider fluctuations… → Will staircase survive?

Vortex array is an alternative way to view convection cells!

→ We begin with the 2D NS equation that can be written in nondimensional form (Perlekar and Pandit 2010),

$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla}\right)\omega = \frac{1}{\Omega}\nabla^2\omega + F_\omega - \alpha\omega, \qquad \nabla^2\psi = \omega.$$

$$Re = \frac{(\mathbf{u}'\cdot\boldsymbol{\nabla}')\,\mathbf{u}'}{\nu\nabla'^2\mathbf{u}'} = \frac{F_{\text{amp}}}{\nu^2k^3}$$

→ The "vortex array" is simply the array of cells and "fluctuation" is related to turbulence induced variability in the structure. The fluctuating vortex array (FVA) allows us to study a **less constrained** version of the array! **Improved model of cells near marginality.**

→ The fluctuating flow structure is created by **slowly increasing the Reynolds number** in the NS equation

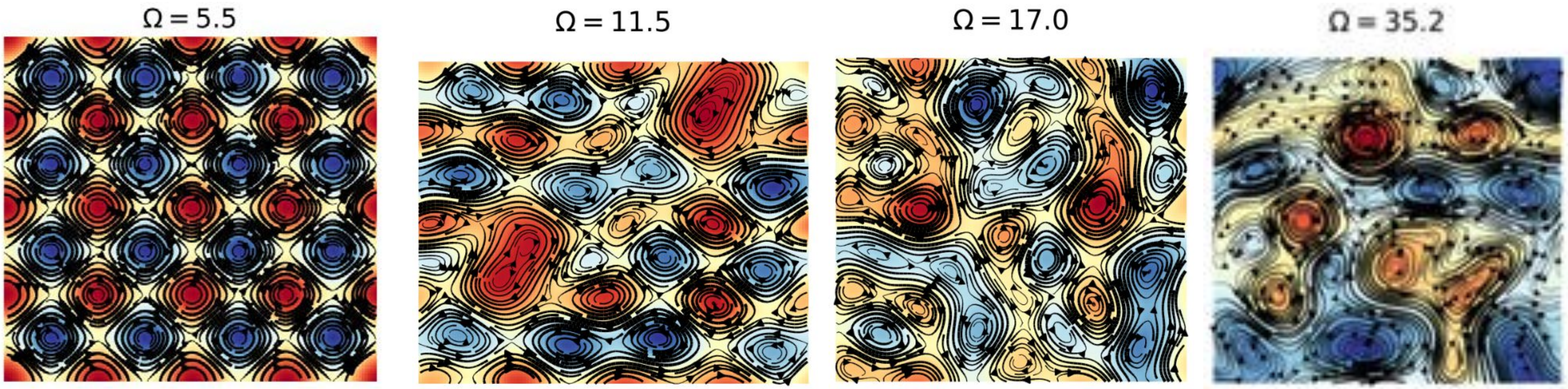
$$\Omega \equiv nRe$$

→ By increasing the Reynolds number this modifies the forcing and drag term, thus, **scattering** the vortex array. The **resilience** of the staircase is studied by **increasing disorder** in the vortex crystal through F_ω

$$F_\omega \equiv -n^3\left[\cos(nx) + \cos(ny)\right]/\Omega$$

The streamfunction, ψ, at different evolutionary stages of the "fluctuating" vortex array is inserted into the passive scalar equation to study the resilience of the staircase structure.

FVA Cell Dynamics

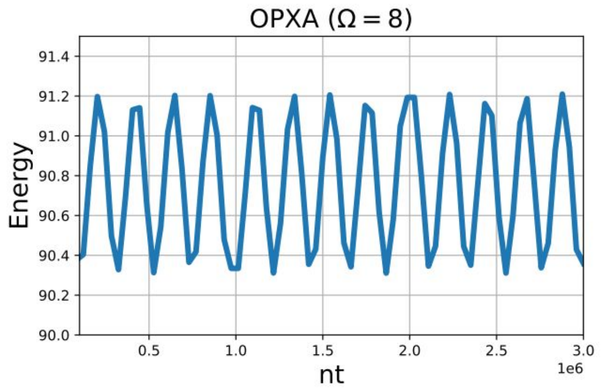


- Contour plots of the streamfunction (ψ), illustrating the different stages of a FVA.
- As Ω is slowly increased, there is a merger of vortices along with distortions of the cellular array.
  - Vibrating vortex crystal that goes into melting state!

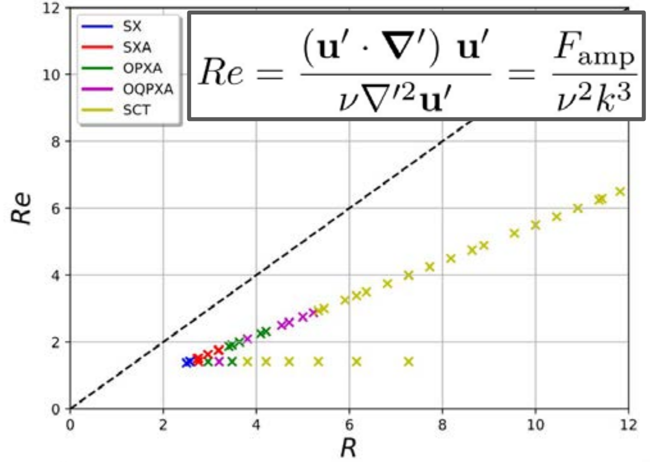
We characterize different stages of the fluctuating process by analyzing the contour plot of the FVA and the FVA's energy trace during each different stage. There are five different stages:

- Stable (SX) [$\Omega < 6.5$]
- Stable Distorted (SXA) [$6.5 < \Omega < 8$]
- Periodic (OPXA) [$8 < \Omega < 10$]
- Quasiperiodic (OQPXA) [$10 < \Omega < 13$]
- Spatiotemporal chaotic/turbulent (SCT) [$13 < \Omega$]

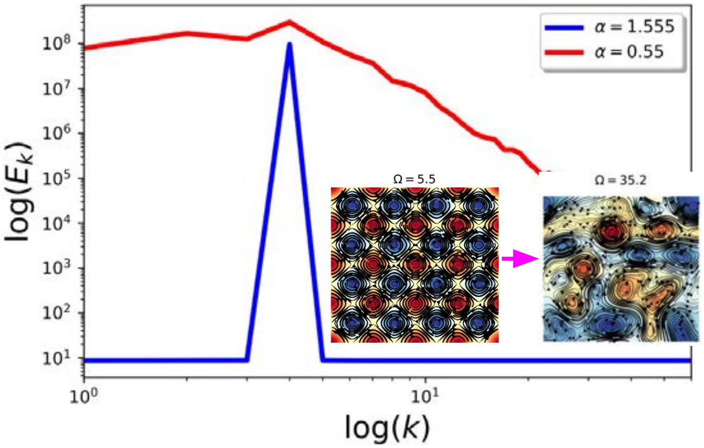
Streamfunction (ψ) is inserted into passive scalar equation.



FVA Cell Dynamics



$$Re = \frac{(\mathbf{u}' \cdot \nabla')\ \mathbf{u}'}{\nu \nabla'^2 \mathbf{u}'} = \frac{F_{\text{amp}}}{\nu^2 k^3}$$



To understand the dynamics of the flow, it is necessary to introduce a nondimensional number which measures the ratio of the nonlinear term to the damping term in the NS equation.

$$\left(\frac{\partial}{\partial t} + \boxed{\mathbf{u} \cdot \nabla}\right)\omega = \frac{1}{\Omega}\nabla^2\omega + F_\omega - \boxed{\alpha\omega}$$

We will call this ratio R,

$$R = \frac{(\mathbf{u}' \cdot \nabla')\mathbf{u}'}{\alpha'\ \mathbf{u}'} = \frac{F_{\text{amp}}}{k\nu\alpha'} = \frac{n}{\alpha}$$

Note: R and Re are coupled together via the amplitude of the forcing!

Here R is a measure of large scale flow and Re is a measure of turbulence in the flow ($Re \neq R$).

- α **controls large scale flow** structures (when α is large, α damps large scale flows).

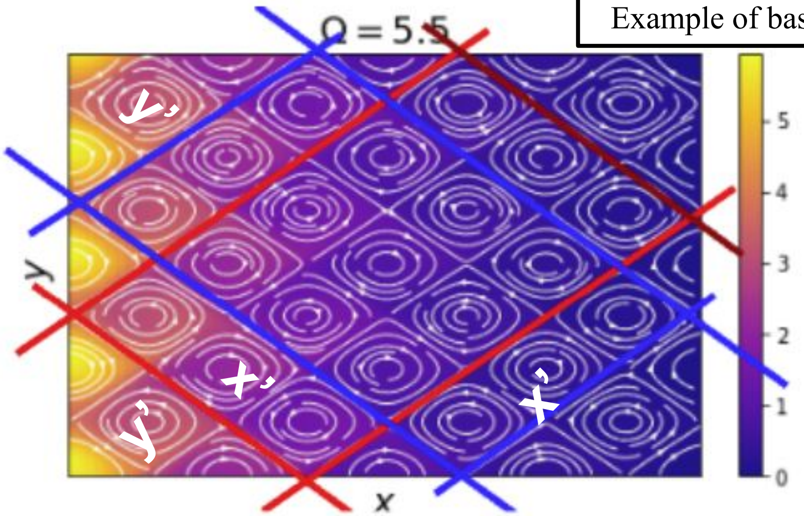
Our simulations, operate in the $R > Re$ **regime**. Here large scale flows dominate the flow structure.

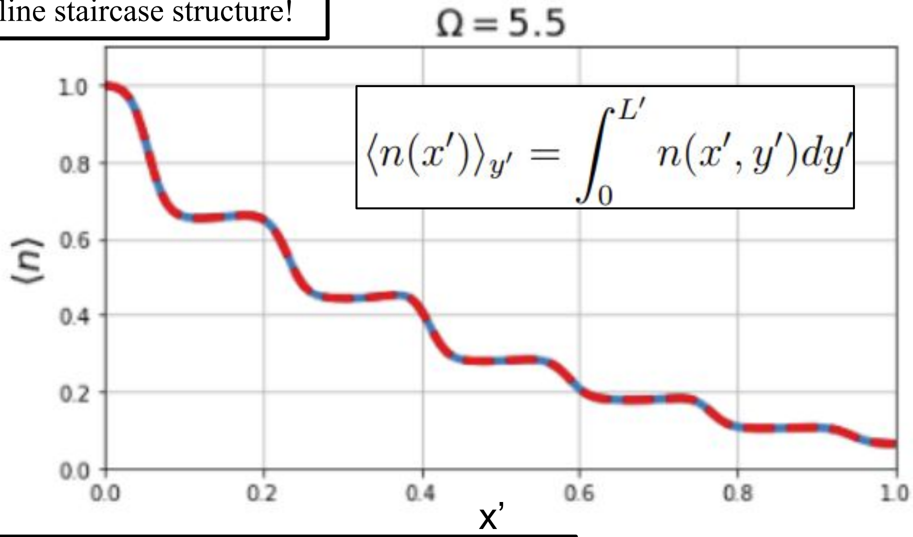
What Happens to Staircase?

	Vortex Field	Drift-Wave Turbulence (tokamak)
Inhomogeneity (free energy source)	∇n	B_0, ∇n, and ∇T
Reynolds number (Re)	$Re = 1 - 10$	$Re = 10^1 - 10^2$ (Landau Damping)
Flux	Scalar	Turbulent Heat
Zonal Flow	Boundary layer between cells	$\mathbf{E} \times \mathbf{B}$ shear flow (poloidal)

The Staircase

Example of baseline staircase structure!

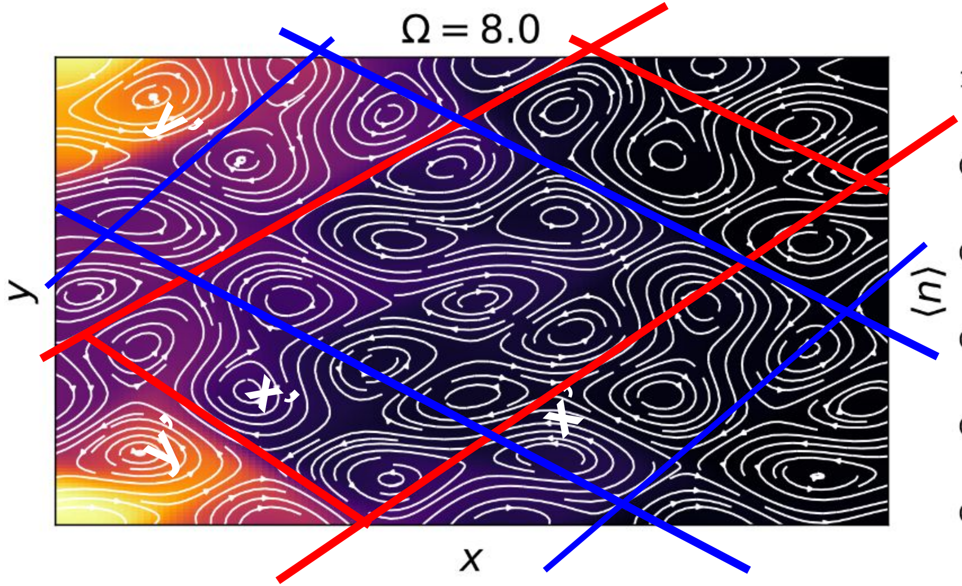


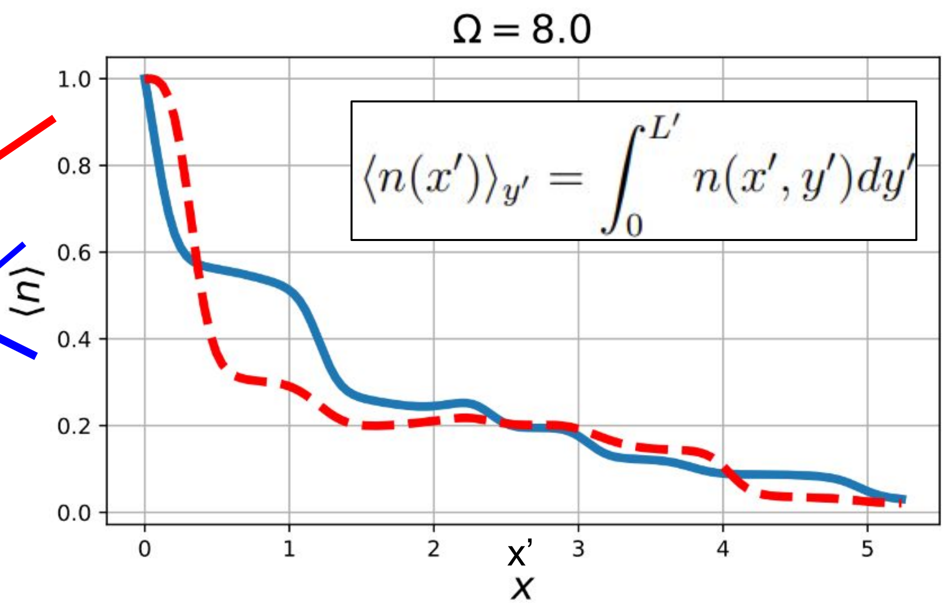


- For a weakly FVA we get a **baseline staircase** structure.
- On the left figure the blue and red box correspond to the blue and red plot line on the right. Note that **steps** are **evenly** spaced!
  - Both blue and red average scalar concentration have the same profile in stable stage.

So what happens to the staircase if we increase the Reynolds number in the VA?

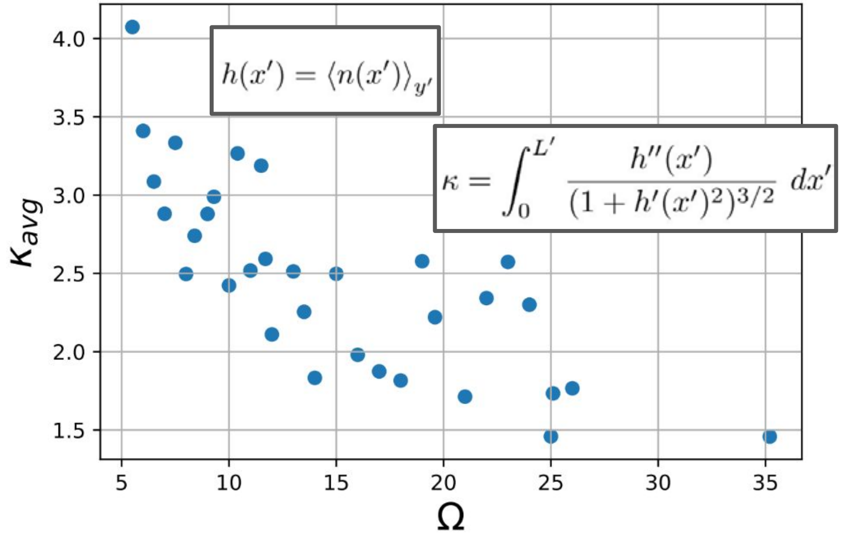
Staircase Resiliency to Fluctuations

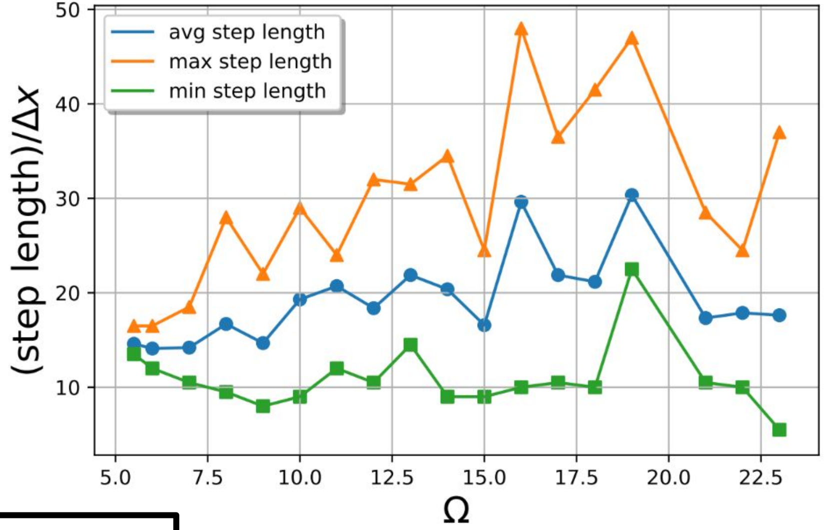




- As we **increase fluctuations in VA** through *Ω*, we can see **merger/connections** of vortex structures in the flow.
- These **vortex mergers** are shown in the scalar profile plot as **mergers in steps**.
  → As we increase jittering, staircase steps merge together.

Behaviour of Staircase as Cells Fluctuate





- To quantify the different stages of the fluctuating process, we look at the <u>**curvature & step length**</u> in scalar concentration.
- In general, as we **increase *Ω***, the **curvature decreases**.
  - Steps are starting to merge together as we increase *Ω*, thus scalar profile has less curvature.

<u>**Main Point**</u>: Despite that vortex array becoming more turbulent, the staircase structure does not collapse.

- Staircase steps become **less regular**. They merge into longer steps.

The Scalar Field

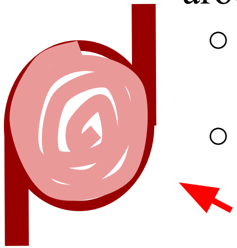
(transport in the VA)

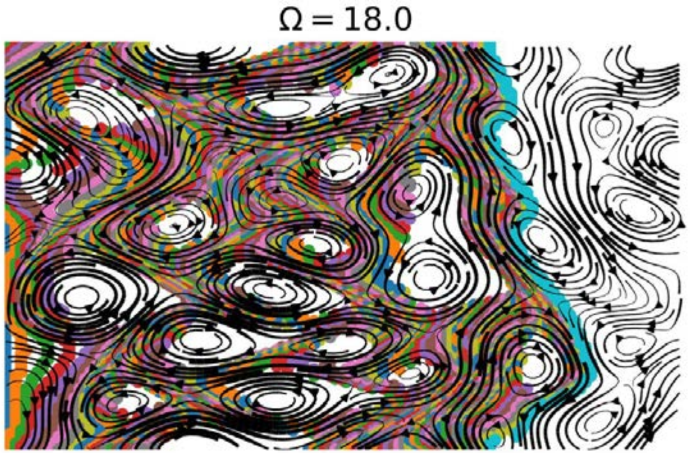
The Web

Λ = mean sq. vorticity - mean sq. shear

Before the **staircase** structure forms, scalar concentration field forms a “**web**”:

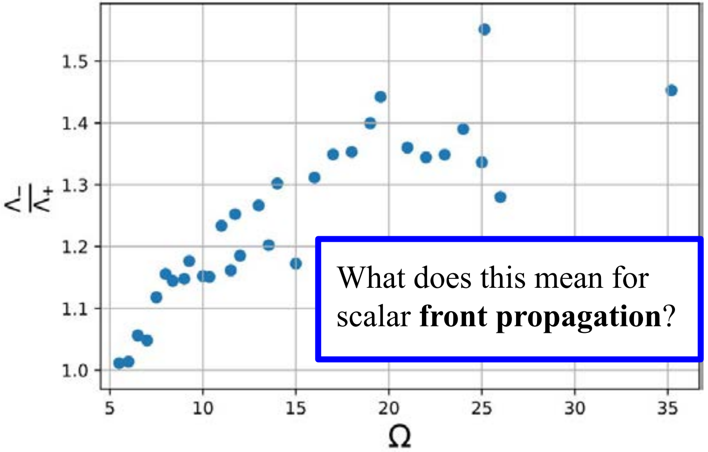
- Scalar flows **quickly in regions of strong shear** and around vortices!
  - Staircase **barriers form first**! Scalar travels along cell boundaries.
  - Overtime, vortex **entrains** scalar by a kind of “**homogenization**” process via the synergy of differential rotation and diffusion.



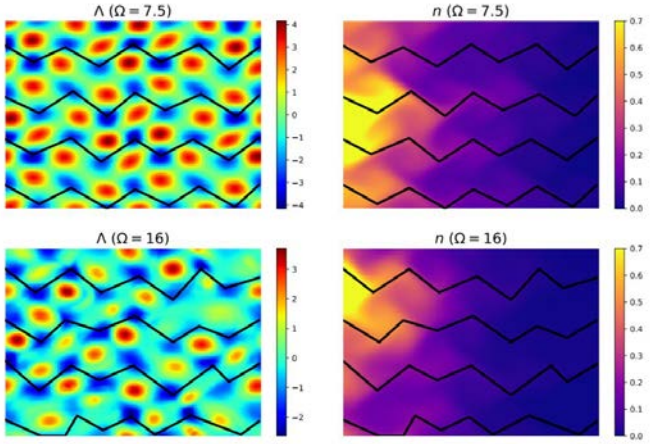


We use **Okubo-Weiss field** (Λ) to study the **evolution** of the flow structure as we increase Ω.

- As we steadily increase Ω, the regions of saddles ($\Lambda<0$) **increase** compared to areas of centers ($\Lambda>0$).
  - Recall increase in large flow structures!
- Increase in regions of strong shear means the web will **form thicker web fibers**.
  - **Wider** scalar concentration **path**!



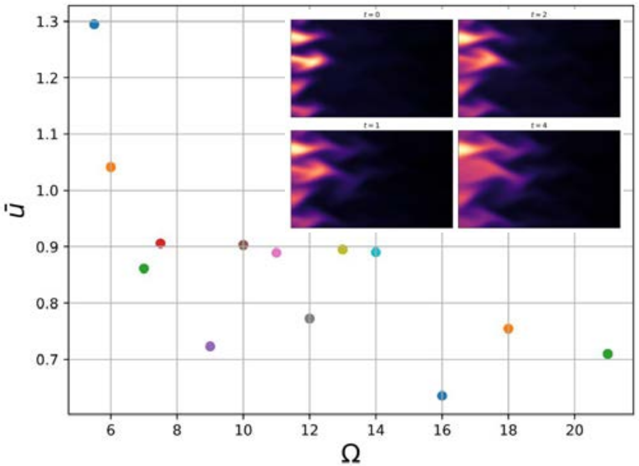
Trajectory in Scattered VA → How Avalanches Propagate



Scalar concentration **travels fast along** areas of **strong shear** ($\Lambda<0$)

- Using Okubo-Weiss field, we can **connect** regions of strong shear to their **nearest strong shear neighbor**.
- Path can be **mapped** to scalar concentration contour to show that indeed scalar travels along areas of strong shear.
  - Distance travel can be quantified.

Idea relevant here is the **<u>least time criterion</u>**. As the **vortex array fluctuates**, the **path of least time would increase in length**.



In addition to distance travel, we also **quantify the time** scalar takes to travel from one end to the other using a **<u>pulse train</u>**.

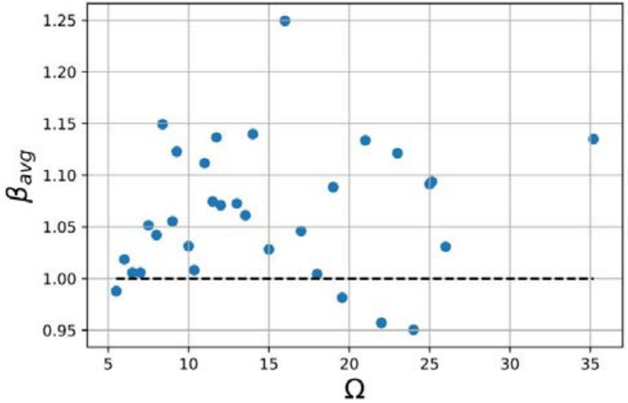
- As the scalar concentration gets injected into the flow, a **<u>flamelet</u> <u>network pattern</u>** forms (Pocheau 2008).
  - **Fingers propagate through array. Over time, the scalar slowly enters the vortex structures.**

The **scattering of vortices** leads to an overall **decrease** in scalar concentration **velocity**! Agrees with least time criterion (similar idea to scattered path of light in atmosphere).

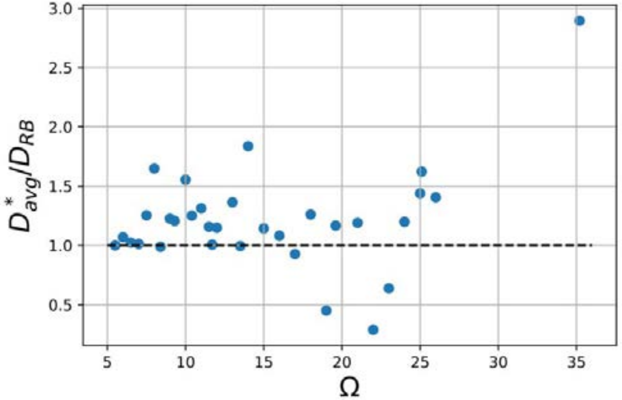
- **Staircase curvature** and **scalar velocity** are **proportional**.

Transport in FVA

$$D^* \propto D\sqrt{Pe}$$



$$D^* \propto \sqrt{d_x \beta}$$



As cells fluctuate, the **effective diffusivity** deviates but **remains close** to the Rosenbluth effective diffusivity.

- **<u>Note:</u>** we fix flow velocity and background diffusivity.
  - Only **dimensions** of cells **affect transport**.

This **suggests** that the Rosenbluth effective diffusivity is a **good approximation** even if **<u>cells are irregular</u>**!

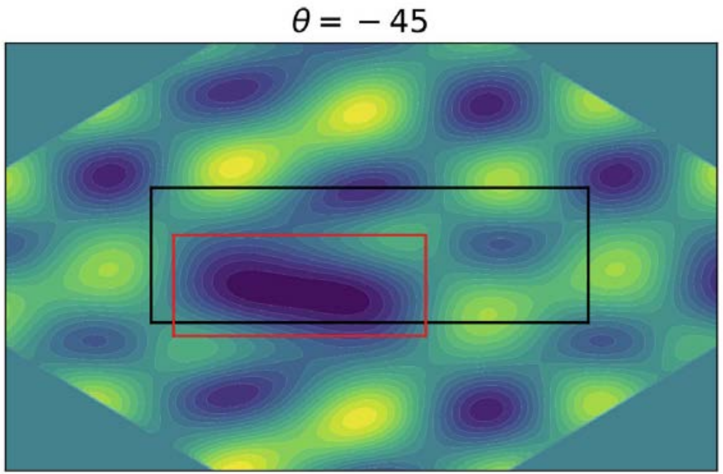
We find that as long as the **boundaries** and **speed** of the cells are **maintained**, the effective diffusivity and transport **does not change**.

- Since effective diffusivity is **proportional** to $\beta = d_x/d_y$, only through **geometric properties** of the cells does **<u>transport change</u>**!

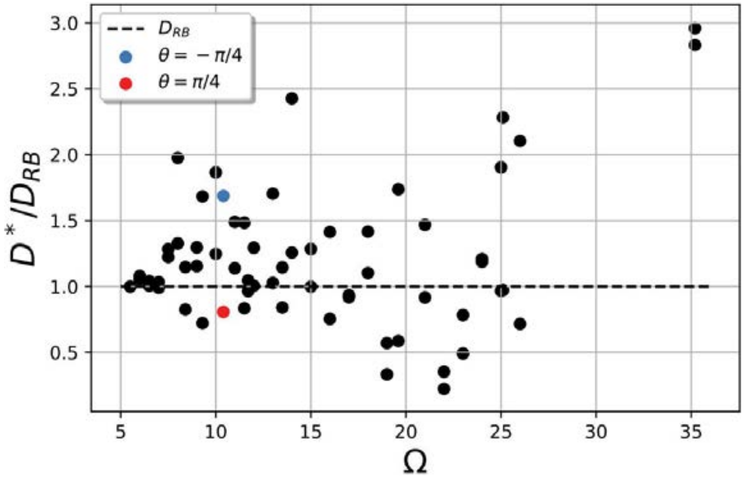
Effective diffusivity **increases/decreases** if the cells length along the gradient (d_x) increases/decreases compared to the length perpendicular to the gradient (d_y).

Transport in FVA

$$D^* \propto D\sqrt{Pe}$$



$$D^* \propto \sqrt{d_x \beta}$$



Effective diffusivity **increases/decreases** if the cells length along the gradient (d_x) increases/decreases compared to the length perpendicular to the gradient (d_y).

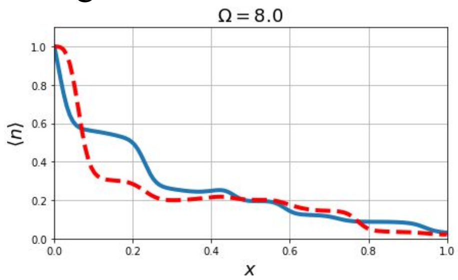
- Cells on average remain around $\beta \sim 1$, but there are cells that are larger in size due to cell mergers which cause the deviation of the effective diffusivity.

Summary

Summary

In a much more general and less constrained version of a cell array, we study the behaviour and flow structure of a scalar concentration (AGAIN, all in a very simple model with no feedback). In this study, we find the following:

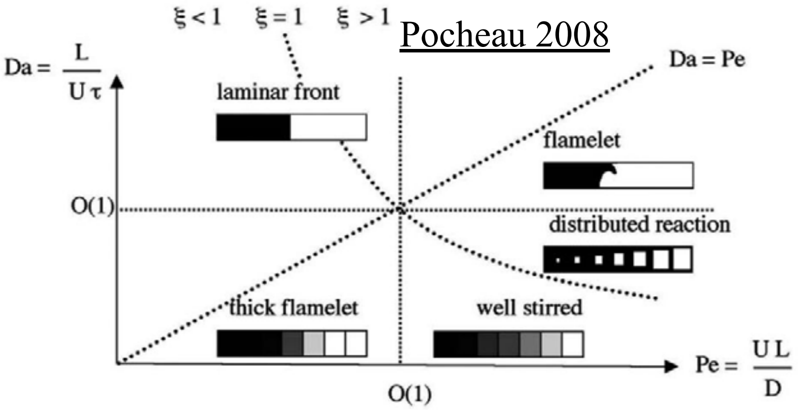
- Staircase form and are **resilient** and **persistent** to increasing Reynolds number (i.e., fluctuating vortex array).
  - Mean **<u>curvature decreases</u>** with increase in Reynolds number.
  - Average **<u>step size increases</u>** due to cell mergers.
- Scalar concentration **travels along** regions of **strong shear** creating a "**<u>web</u>**" structure.
  - Web area correlates with **increase in shear** regions.
    - **Web fibers become thicker**!
  - **IMPORTANT**: Staircase barriers form first in the regime of $R > Re$! Vortex "homogenizes" scalar at a later time!
- The scattering of vortices leads to an overall decrease in scalar concentration velocity.
  - Agrees with **<u>least time criterion</u>**.
  - Plot of scalar concentration velocity and curvature imply there is a linear relationship between the two.
    - As curvature decreases, the scalar velocity decreases linearly.
- If flow velocity and background diffusion are kept fixed, only **cell geometric properties** affect the effective diffusivity!
  - Effective diffusivity of the perturbed VA **does not deviate** significantly!

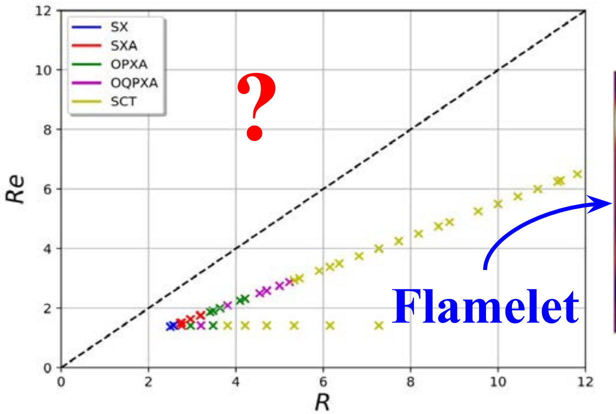


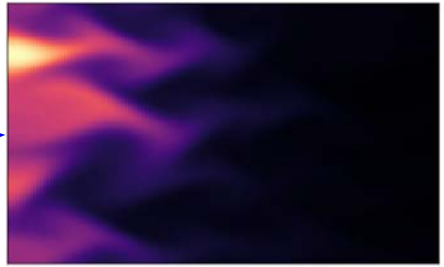
<u>Next:</u> Future plans

Future Work

1) *Re > R* Regime



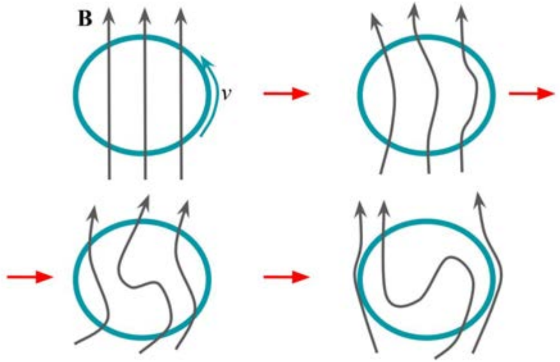




In this project we only explored the regime where <u>*R > Re*</u>, but what about the regime where <u>*Re > R*</u> instead?

- We found that flow structure creates a **network pattern of Flamelet structures**, which appear only in the case where *Pe >> 1* and *Da >> 1*.
  - Here shear velocity is stronger than cell velocity, thus scalar will travel around vortex before its homogenized.
- We might expect that scalar flow will resemble the <u>**well-stirred**</u> case in *Re > R* regime (*Pe >>1* and *Da << 1*).
  - Here **vortex structures will be dominant** in the flow compared to large scale flows.
  - Since *Re* will grow faster than *R*, we could expect that vortex structures will grow in size compared to large scale flows (crit. *R* value?). Increase in *Re* could result in regions of **stronger mixing**!
  - We predict a much more **rigid staircase** structure with larger difference in height between steps.

2) Active Scalar



Flux expulsion:

- Background $\boldsymbol{B}$ is wind up and folded by an eddy → field inside eddy drops → expelled to boundary layer of eddy.
- Time scale for flux expulsion is, $\tau_{fe} = R_m^{1/3}\,\tau_H$
- **Note:** Larger R_m results in greater expulsion (weaker field in interior).

A logical next step to explore is the effects than an *active* scalar has on the cellular array and inhomogenous mixing.

- Converting passive to active will result in effects such as flux expulsion
    - Flux expulsion is simplest dynamic problem in non-ideal MHD.

Why this model?

- $\boldsymbol{B}$ expelled to boundaries, thus holds cells together! → Rigid staircase.

We turn passive scalar into an active scalar, creating a feedback between magnetic field and vortices:

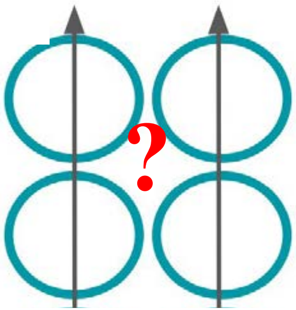
$$\frac{\partial n}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla} n - D\nabla^2 n = 0 \longrightarrow \left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla}\right) A = \eta\nabla^2 A$$

$$\left(\frac{\partial}{\partial t} + \mathbf{u}\cdot\boldsymbol{\nabla}\right)\omega = \frac{1}{\Omega}\nabla^2\omega + \boxed{\mathbf{B}\cdot\boldsymbol{\nabla}\nabla^2 A} + F_\omega - \alpha\omega$$

Now, forcing of turbulence induced mixing on the cellular array will include the forcing of cell turn-over.

- Combination of large and small scale forcing (three controls Re, R, and R_m)
- Can combine two by using Prandtl number ($P_m = R_m/Re$).

2) **Active Scalar** (cont.d)

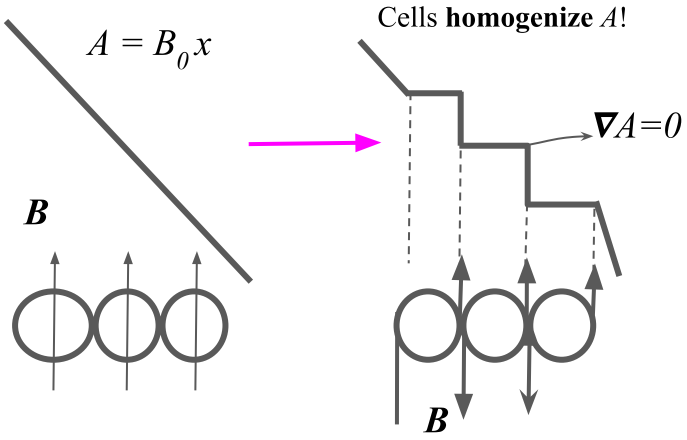


Consider a **linear** magnetic potential profile:

- We expect that the vortex array will homogenize ($\nabla A=0$) the profile in areas of vortices.
- Expect that magnetic field will maintain or restore the cell array structure when fluctuations are present (i.e., B_0 will elasticise the cell array).

$$(v_A^{\,2} / \langle v^2 \rangle)\, R_m < 1 \text{ (Flux expulsion)}$$

$$(v_A^{\,2} / \langle v^2 \rangle)\, R_m \geq 1 \text{ (Vortex bursting)}$$



__**Important:**__ Flux expulsion only occurs in the **kinematic** regime

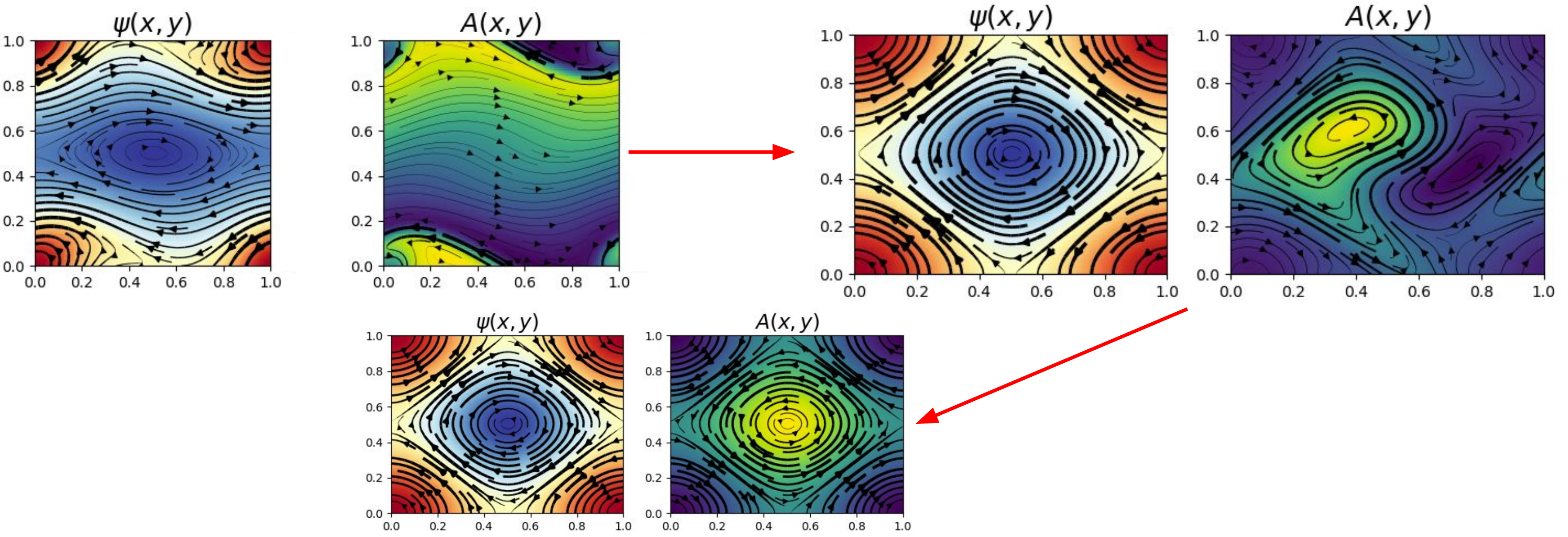
- Useful to explore **dynamic** regime (aka Vortex bursting).

Since $v_A \propto B_0$, the strength of the magnetic field will play a role in the dynamics of the cellular array.

- If B_0 is sufficiently small, we get cell strengthening.
- If B_0 is large, vortices will not be allowed to form.

Through scans of B_0, we will address what **occurs** to expulsion of **neighbor cells** and their **interaction**… Will there be 'interference' of boundary layers? What about staircase dynamics? As magnetic fields get threaded around vortices, will this result in a more robust staircase?

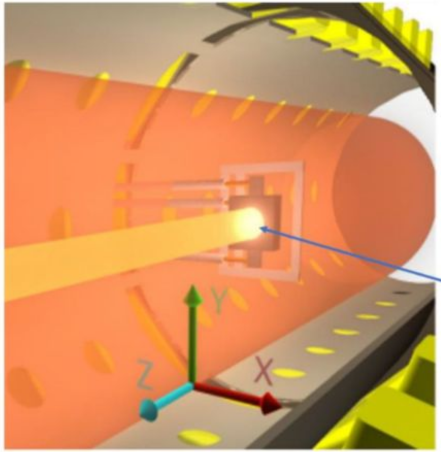
2) Main Idea of Active Scalar Problem (Preliminary Results)

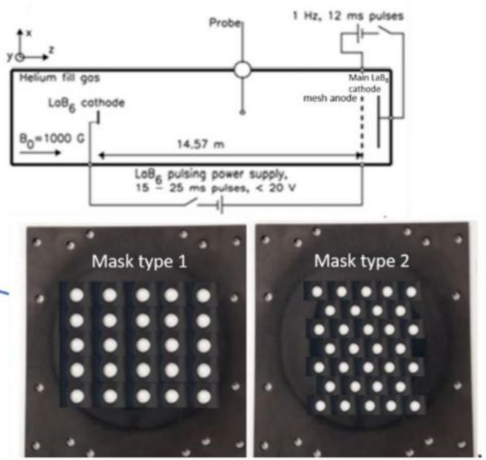


This problem is **<u>important</u>** and can be related back to the idea of **feedback**!

- We have only address the idea that staircases are resilient and robust in the presence of cell fluctuations.
- But could the scalar affect the dynamics or maintain the cell structure which is responsible for the staircase? Preliminary results show that **magnetic field restores cell structure**!
    - Only a small window where this occurs (i.e., small ***Bo***)...

3) LAPD Experiment





A vortex array can be created in the large linear magnetized plasma device (LAPD)

- Modification of a cathode plasma source with designer masks that form multiple current channels in a cellular pattern → form staircase!
  - Experiment will be conducted in the afterglow phase of the main discharge.
- Staircase structure can be subject to controllable amount of of low frequency density fluctuations, which act as a noise source.
  - Allow us to test hypotheses and models of staircase resiliency!

Results of experiment will yield a unique set of observations that can be used to test staircase models.

3) LAPD Experiment (cont.d)

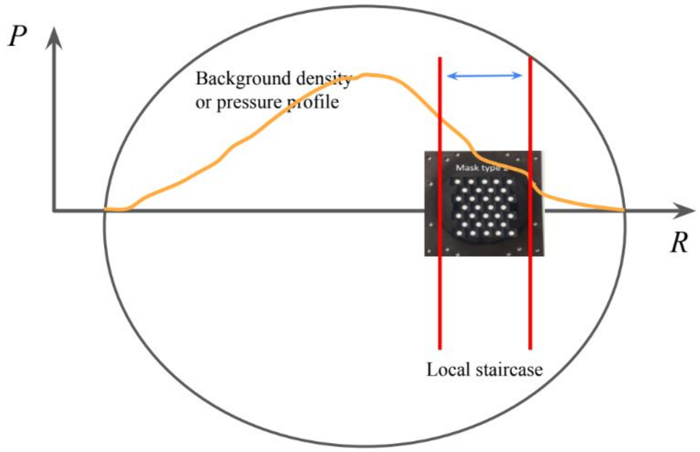
The vortex/filament array is a compelling realization of an inhomogeneous mixing flow. It allows us to investigate the following scientific questions:

1) Will a vortex cellular flow produce a staircase in the density profile of the afterglow? What are the structural characteristics of the staircase? How does the staircase evolve in time?

2) Is the staircase robust in a fluctuating VA? Do vortex mergers occur and do these induce step mergers? Here “fluctuating” can be realized by lowering the external axial *B*-field, thus allowing filaments to interact, scatter, and wander.

3) How does controllable external noise affect the staircase? Here noise can be produced by residual resistive drift waves, generated during the main discharge. The amplitude - noise strength - can be adjusted via profile variation, $\boldsymbol{B}_0$ field scans, etc.

Addressing the above will yield new insights into profile evolution, layering, and staircase resiliency.



Experimental results can be compared to the fluctuating VA calculations and to BOUT++ simulations of LAPD plasmas.

Experiment happening July 2023!

Thank you!

Supported by:

US DOE Award #
DE-FG02-04ER54738

Extras

Global Transverse Shear Effects on FCA

(Why? → time scale ratio)

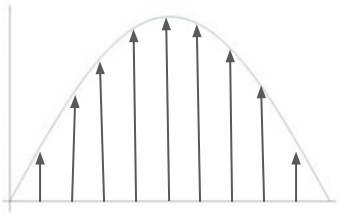
Global Transverse Shear

The streamline function used to create the Bénard convection patterns in the fluid flow is,

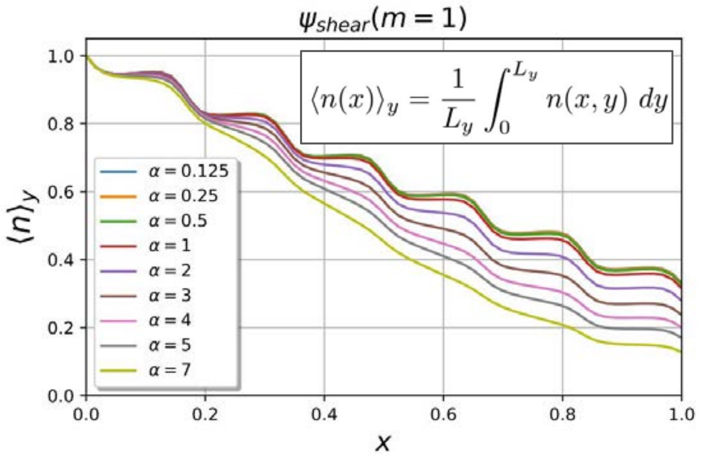
$$\psi = \sin \pi(x/d) \sin \pi\beta(y/d) + \alpha \; \psi_{\text{shear}}.$$

$$\psi_{\text{shear}} = -\cos\frac{mx}{2}$$

$m = 1$



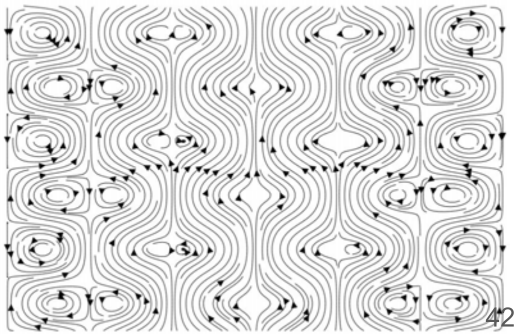
The addition of global shear introduces a shear dispersion time scale, $\tau_{sh} = 2\pi/\tilde{u}\alpha m$.



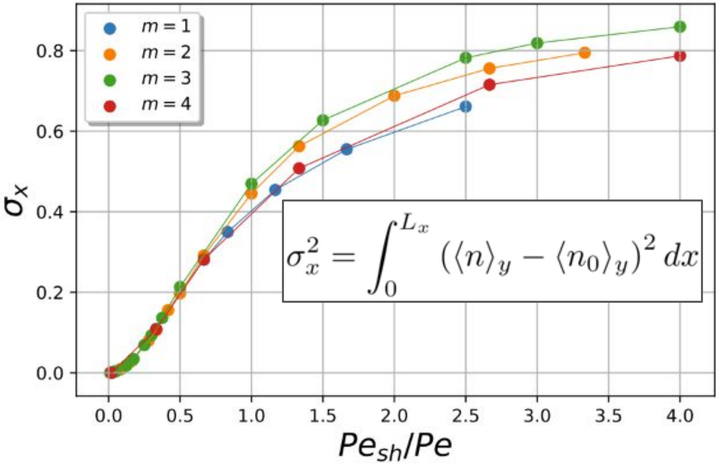
As the shear strength increases, the staircase profile **breaks down**. Global shear flow dissolves staircase steps, by destroying the cellular mixing structure:

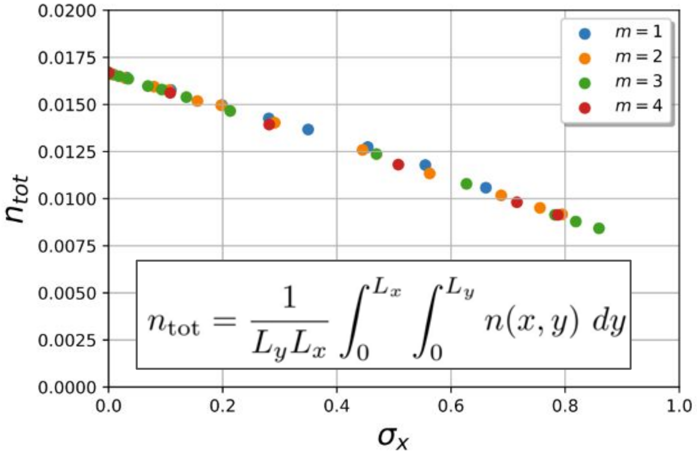
Important:

- Corrugation breaks down for critical α and m.
- Shear dispersion rate gives effective mixing rate faster than diffusion.
- Let's introduce $Pe_{Sh} = \tau_D/\tau_{Sh}$ (measure of diffusion to shearing time).



Global Transverse Shear (cont.d)





- $Pe_{Sh} = \tau_D/\tau_{Sh} \sim \alpha m/D >> 1$
  Corrugation decays!
- $Pe_{Sh}/Pe = \tau_H/\tau_{Sh} = \alpha m/6$
  Shear gives **effective mixing rate faster** than circulation when $\alpha m > 6$.
- Global shear flow **reduces** the **slow-fast** time scale ratio.

- Variance measures the **deviation/breakdown** of the scalar staircase profile.
- For different mode numbers *m*, the variance grows logistically. Linear up to $Pe_{Sh}/Pe \sim 1$.
- Conclude that for large *α*, the average scalar concentration profile will be of **similar form** for different *m*.

- As staircase **steps break down** what happens to scalar concentration **confinement**?
- Plot of n_{tot} vs σ_x, shows that as profile **deviates** from staircase profile, scalar concentration **decreases**.
- **Increase** in global shear **strengthens mixing** (i.e., increases irreversible process).

Next: lets relax FCA