16th IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems

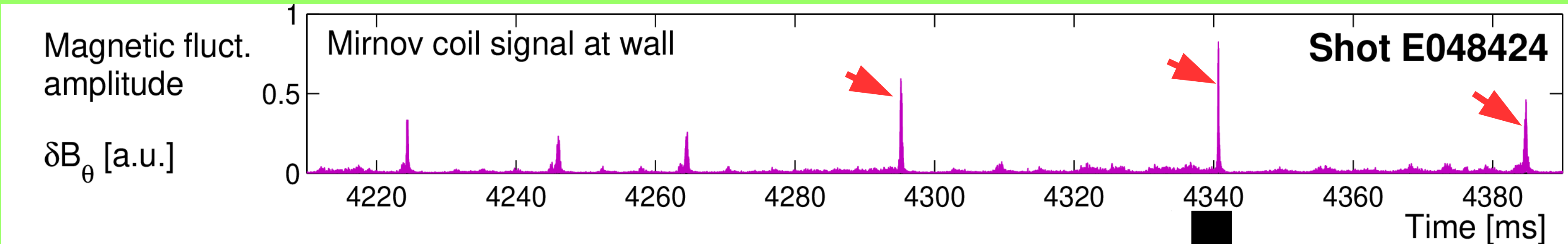
Magnetic Reconnection during Fast Ion Driven Alfvenic Activity

3-6 September 2019
Shizukoa City, Japan

Presented by **Andreas Bierwage**

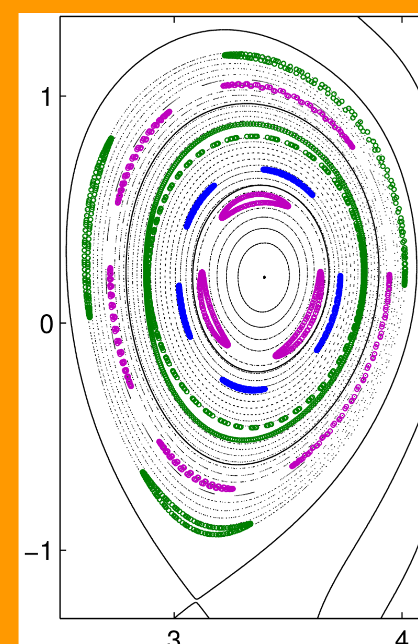
QST Fusion Institutes

JT-60U experiments: **Abrupt Large-amplitude Events (ALE)**



Shinohara et al, *Nucl. Fusion* **41** (2001) 603.
Shinohara et al, *Plasma Phys. Control. Fusion* **46** (2004) S31.
Ishikawa et al, *Nucl. Fusion* **45** (2005) 1474.

ALE simulation (MEGA):



Bierwage et al, *Nature Comm.* **9** (2018) 3282.

Found <u>magnetic islands</u> after large event.

Why?

Collaborators:

Kouji Shinohara (QST),
Yasushi Todo (NIFS),
Nobuyki Aiba (QST),
Masatoshi Yagi (QST)

HPC:

- Helios, JFRS-1 at IFERC-CSC in Rokkasho, JP
- ICE X of JAEA in Tokai, JP
- K Computer of the RIKEN AICS in Kobe, JP

Funding:

- JSPS Grant-in-Aid for Scientific Research (16K18341)
- MEXT "Priority Issue on Post-K computer" (Accel. Development of Innovative Clean Energy Systems)

- Outline -

1. Code & model
   Hybrid MHD-PIC

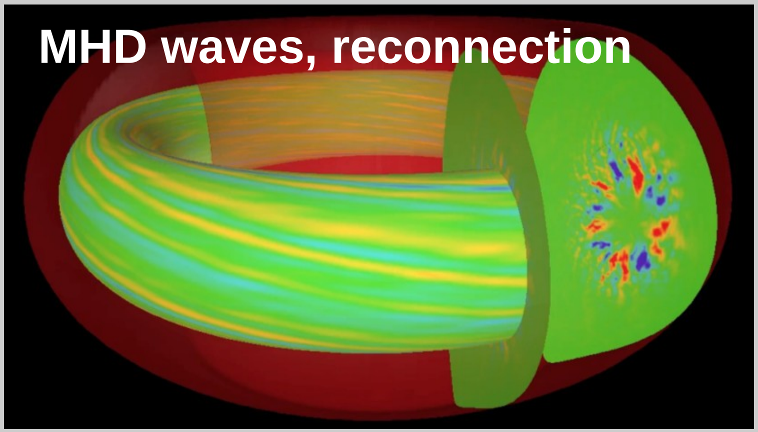
2. Sensitivity study for ALEs
   Numerical resolution, dissipation

3. EP-induced magnetic islands
   Magnetic chaos, resistive decay

Hybrid model

Bulk plasma: Single-fluid MHD

Long-wavelength Alfvén modes.
Dissipation of small-scale struct.

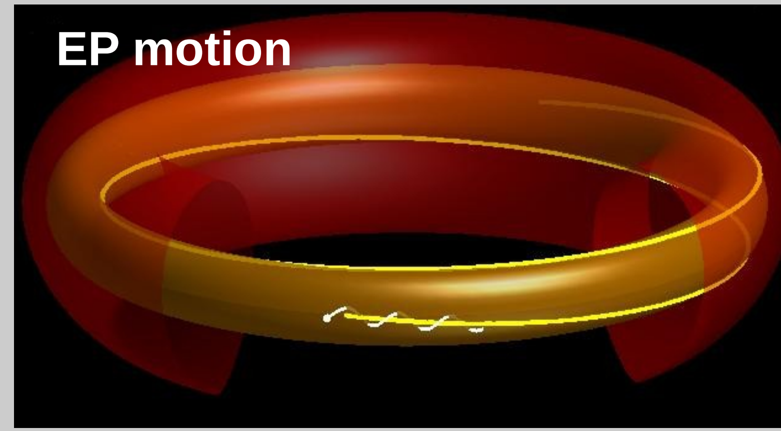


MEGA code
[Y. Todo, NIFS]

Todo et al, *Phys. Plasmas* **5** (1998) 1321; *Nucl. Fusion* **45** (2014) 104012.

Energetic particles: Gyrokinetic PIC

∥ streaming, ⊥ drifts, gyroaverage, collisions, sources, wall losses.



$$\frac{\partial \rho_b}{\partial t} = -\nabla\cdot(\rho_b \delta \boldsymbol{u}_b), \qquad \mu_0 \boldsymbol{J} = \nabla\times\boldsymbol{B}$$

$$\rho_b \frac{\partial \boldsymbol{u}_b}{\partial t} = -\rho_b \boldsymbol{u}_b\cdot\nabla \boldsymbol{u}_b - \nabla p_b + (\boldsymbol{J}-\boldsymbol{J}_{h,eff})\times\boldsymbol{B} - \left[\nabla\times(\nu\rho_b\nabla\times\boldsymbol{u}_b) + \frac{4}{3}\nabla(\nu\rho_b\nabla\cdot\boldsymbol{u}_b)\right]$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}, \qquad \boldsymbol{E} = -\boldsymbol{u}_b\times\boldsymbol{B} + \eta\delta\boldsymbol{J}$$

$$\frac{\partial p_b}{\partial t} = -\nabla\cdot(p_b\boldsymbol{u}_b) - (\Gamma-1)[p_b\nabla\cdot\boldsymbol{u}_b + \eta(\boldsymbol{J}-\boldsymbol{J}_{h,eff})\cdot\delta\boldsymbol{J}] + \nu\rho_b(\Gamma-1)\left[(\nabla\times\boldsymbol{u}_b)^2 + \frac{4}{3}(\nabla\cdot\boldsymbol{u}_b)^2\right] + \chi\nabla^2 p_b$$

← $\boldsymbol{J}_{h,eff}$

Gyro-avg.

$\boldsymbol{B}, \boldsymbol{E}$ →

$$\frac{d\boldsymbol{R}_{gc}}{dt} = \overbrace{-\frac{\mu}{qB^*}\nabla B\times\hat{\boldsymbol{b}}}^{\boldsymbol{v}_B} + \overbrace{\frac{v_\parallel}{B^*}(\boldsymbol{B} + \rho_\parallel B\nabla\times\hat{\boldsymbol{b}})}^{\boldsymbol{v}_\parallel^*} + \overbrace{\frac{\boldsymbol{E}\times\hat{\boldsymbol{b}}}{B^*}}^{\boldsymbol{v}_E^*} \equiv \boldsymbol{U}_{gc}$$

$$m v_\parallel \frac{dv_\parallel}{dt} = \boldsymbol{v}_\parallel^*\cdot(q\boldsymbol{E} - \mu\nabla B)$$

$$\frac{d\mu}{dt} = 0 + O(\beta\epsilon_\delta) \text{ with } \epsilon_\delta \sim \frac{\rho_\perp}{L_B} \sim \frac{\omega}{\Omega_L} \ll 1$$

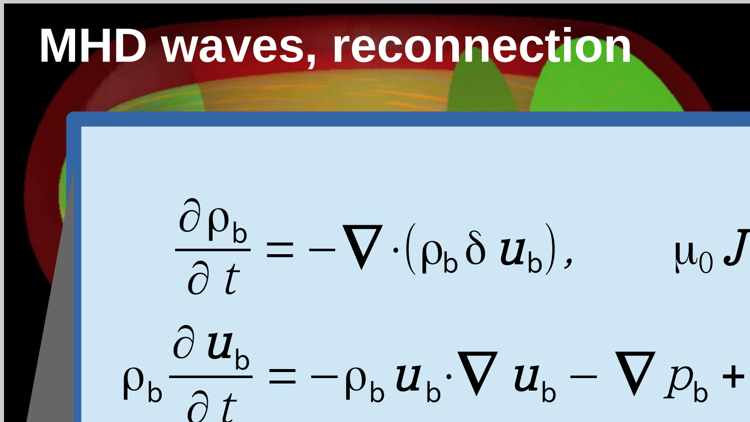
$$\mu \equiv \frac{m v_\perp^2}{2B}, \quad \rho_\parallel \equiv \frac{v_\parallel}{\omega_L}, \quad B^* \equiv B[1+\rho_\parallel\hat{\boldsymbol{b}}\cdot(\nabla\times\hat{\boldsymbol{b}})], \quad \hat{\boldsymbol{b}} \equiv \frac{\boldsymbol{B}}{B}$$

$$v'_\parallel = \frac{v_\parallel}{v}(v+\Delta v_L) + \frac{v_\perp}{v}\Delta v_T \sin\Omega, \quad v'_\perp = \sqrt{(v_L+\Delta v_L)^2 + \Delta v_T^2 - (v'_\parallel)^2}$$

Hybrid model

Bulk plasma: Single-fluid MHD

Long-wavelength Alfvén modes.
Dissipation of small-scale struct.



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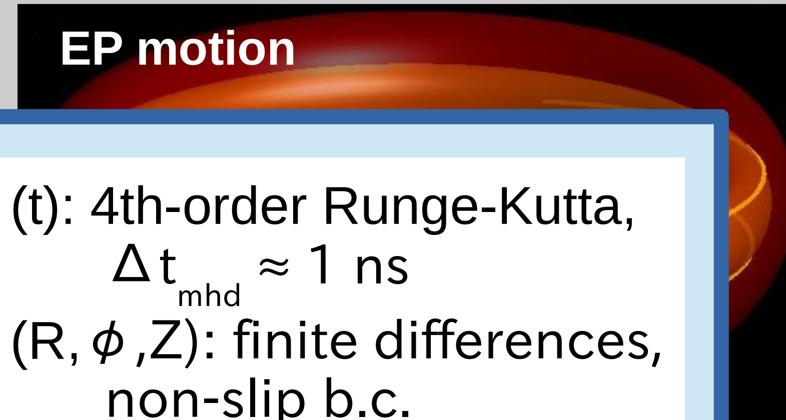

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(t): 4th-order Runge-Kutta,
$\Delta t_{mhd} \approx 1$ ns
(R, ϕ, Z): finite differences,
non-slip b.c.
EP current density pert.
Viscous,
resistive,
thermal diffusion.

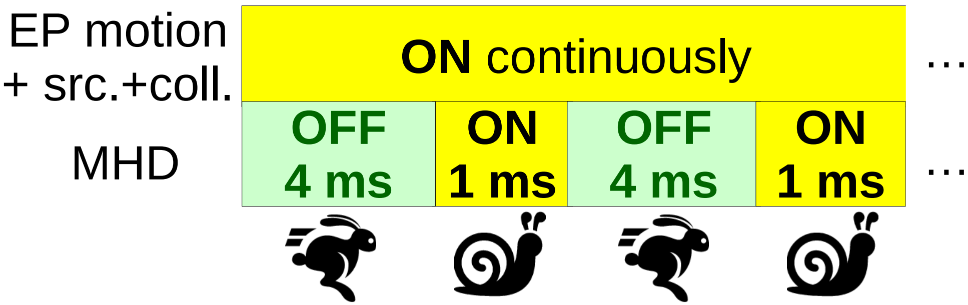
U_{gc}

$\frac{\boldsymbol{B}}{B}$

$V'_{\perp} = \sqrt{(V_L + \Delta V_L)^2 + \Delta V_T^2 - (V'_{\parallel})^2}$

Long-time simulation (100 ms scale)

► **Multi-phase method:** **Speeds up the simulation by a factor 2-3.**



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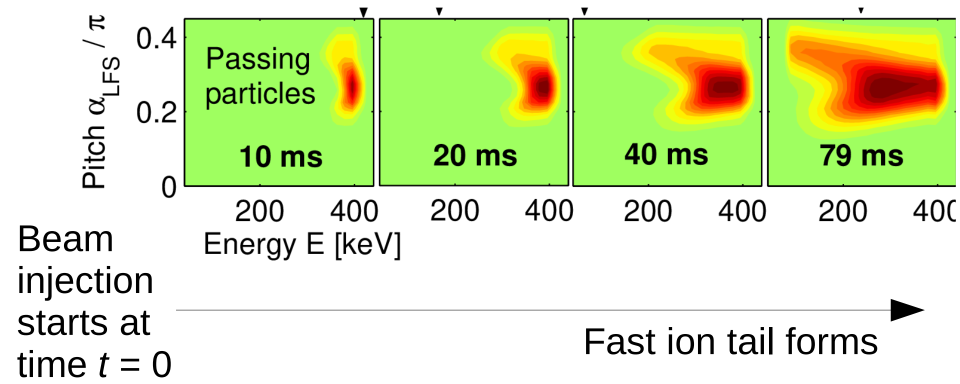

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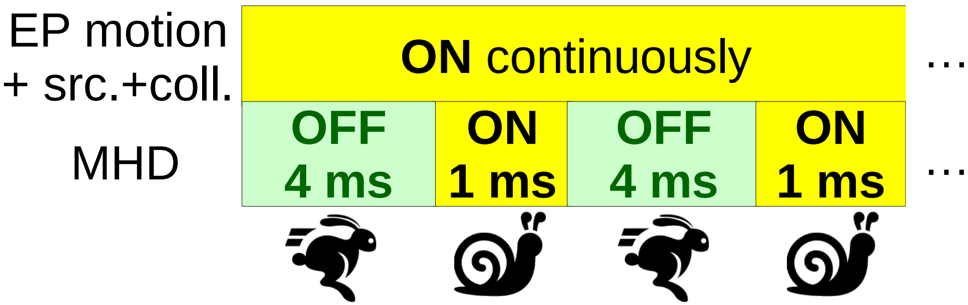
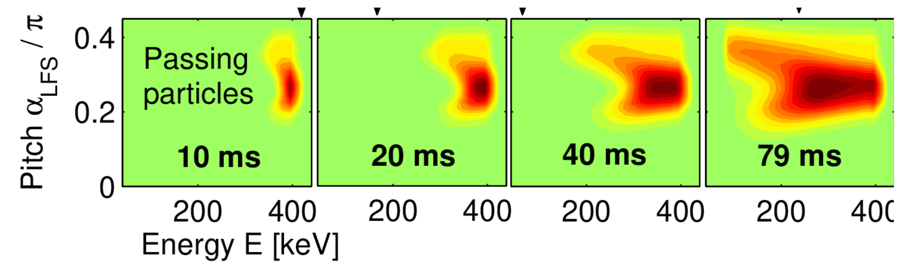
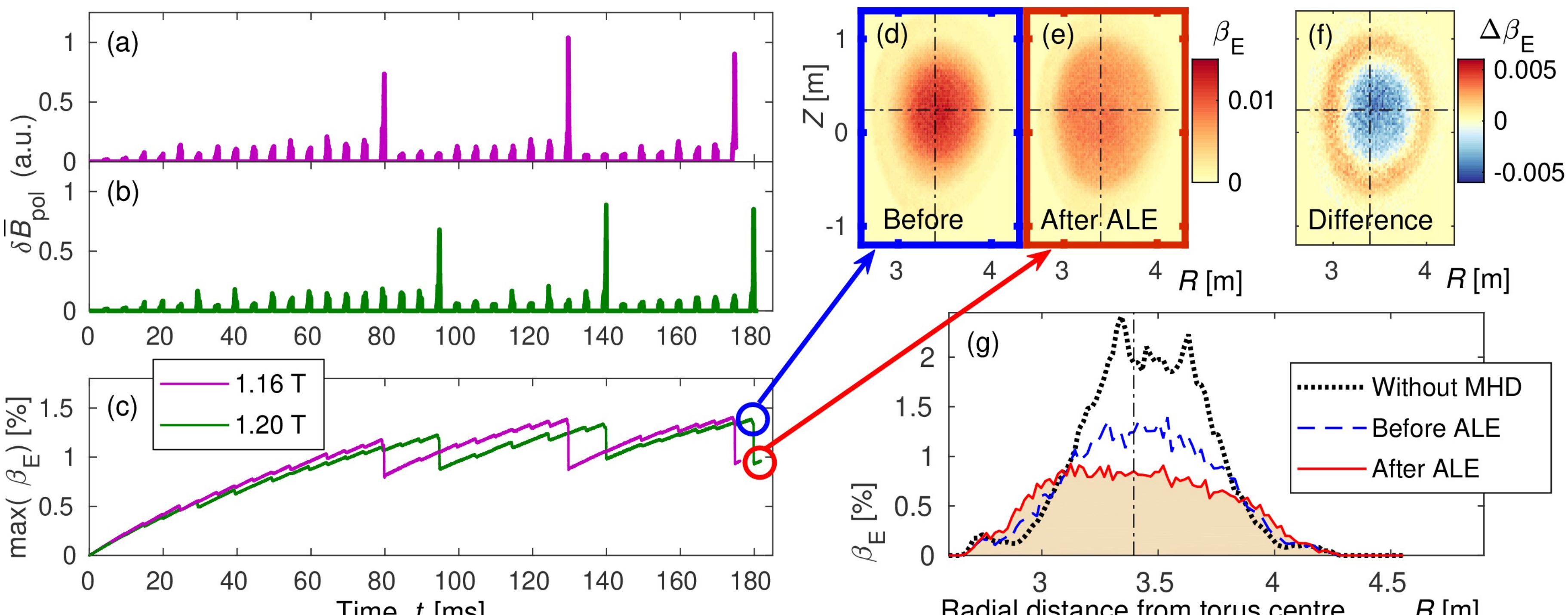




▶ **Major milestone reached: Simulated sequences of 3 ALEs.**



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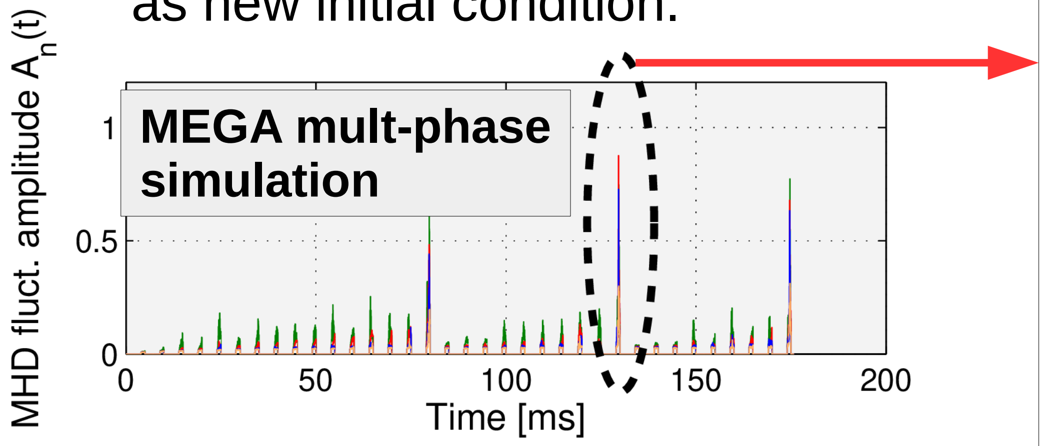
Sensitivity study for ALEs

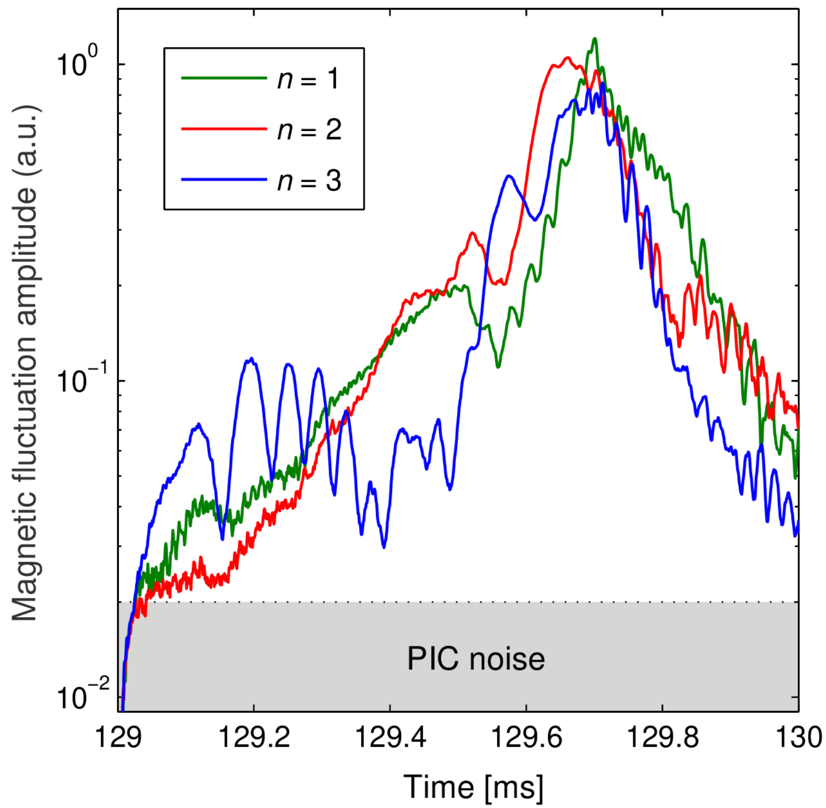
- Numerical resolution
- Dissipation

Procedure

- ▶ **Selected ALE #2 at t = 129~130 ms.**
  - → Use snapshot at t = 129 ms as new initial condition.



Short-time initial-value simulations.
Without sources and collisions.



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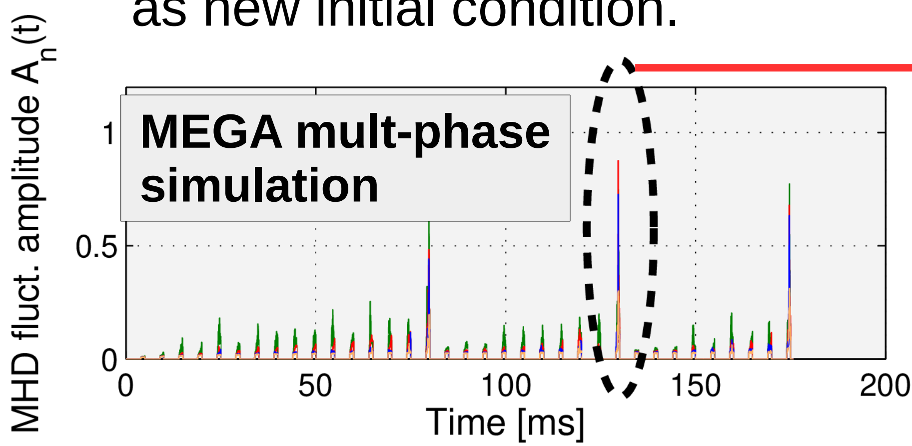

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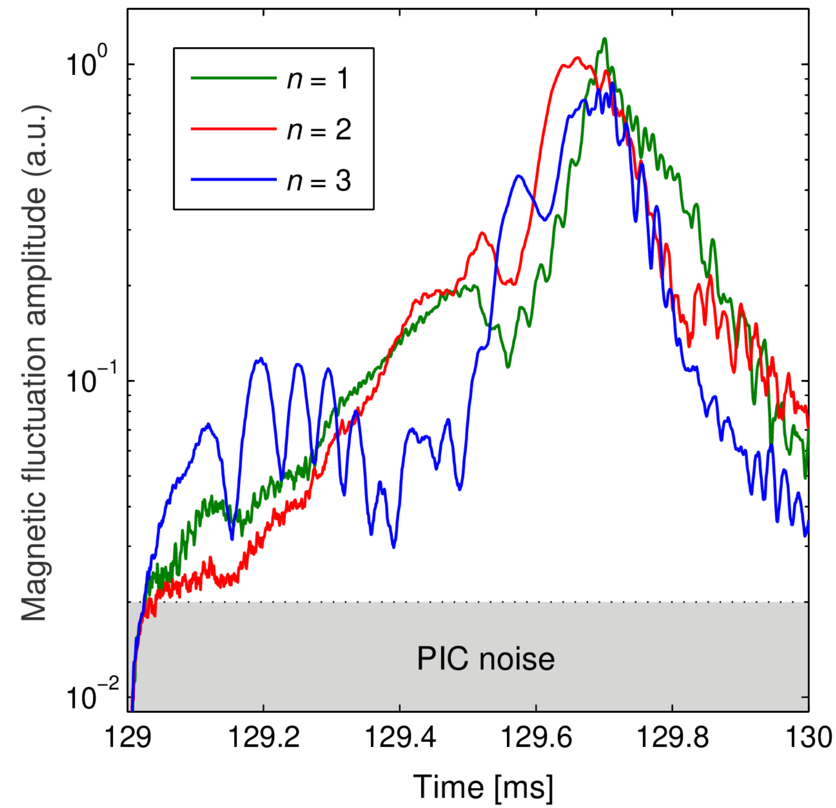


► **Simulate few millisecs. with different parameter settings:**

(1) Check numerical sensitivity

Resolution, noise

$N_R \times N_Z \times N_\varphi$	N_P	Δt / ns
384×352×96	6.9 M	1.0
800×720×96	27.8 M	0.5

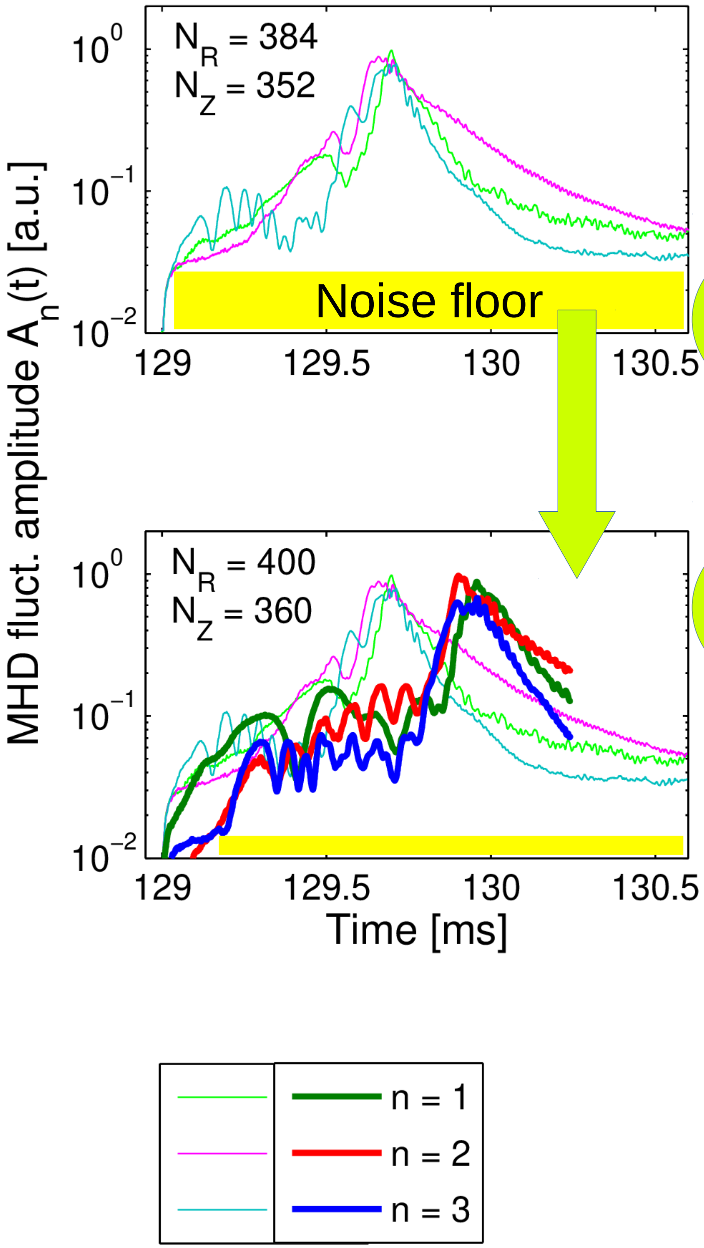
(2) Reduce dissipation coeff.

$\mu_0^{-1}\eta = \nu = \chi = 1.0 \times 10^{-6}\, v_{A0} R_0$

0.5×10^{-6}

0.3×10^{-6}

Sensitivity study: 1. PIC noise effects (# particles)



7M particles

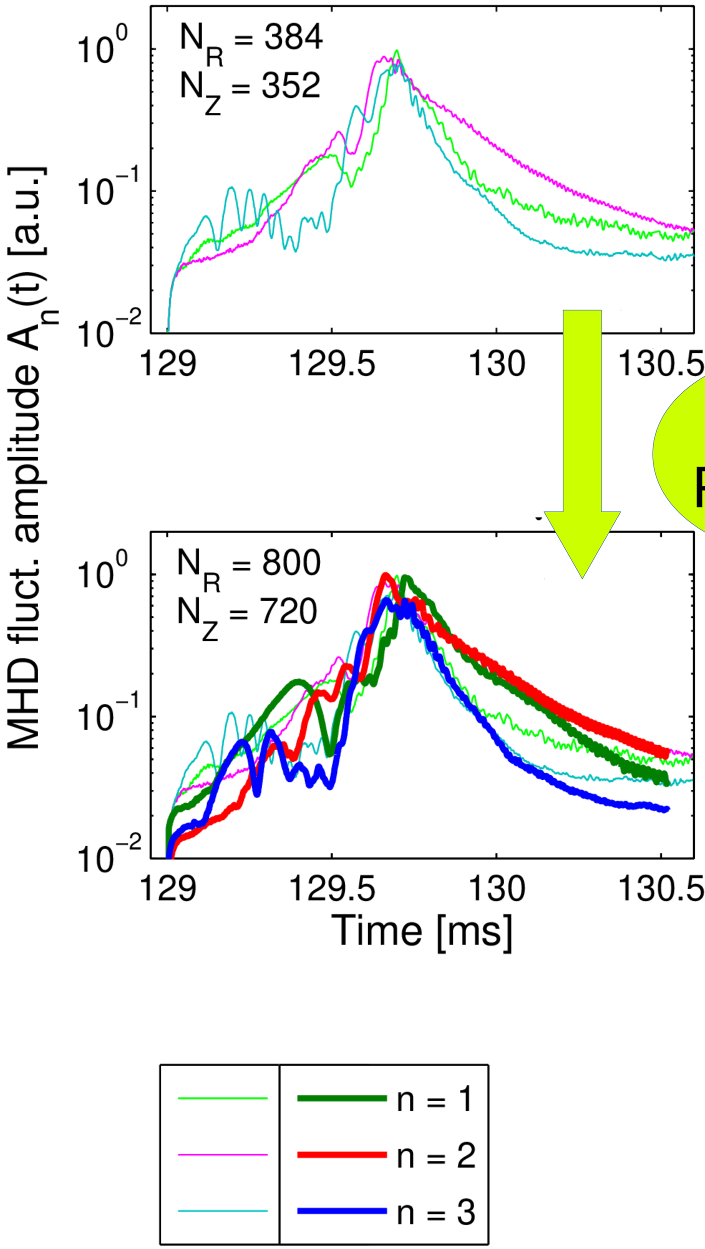
28M particles

More particles per cell give lower noise level

Suspicion:

PIC noise aids ALE trigger (a little).

Sensitivity study: 2. Spatial resolution

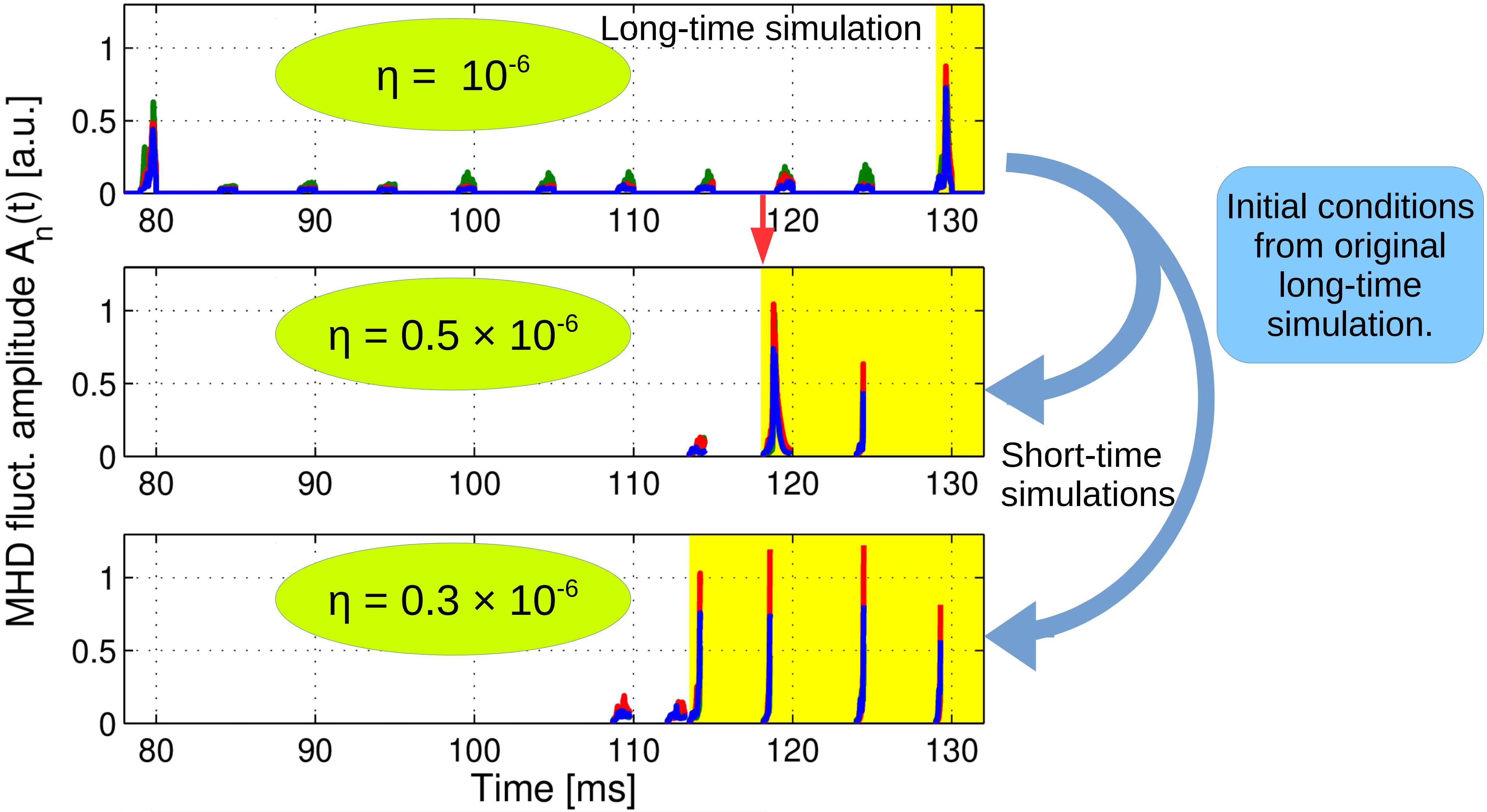


2 × finer R,Z mesh

Constant # of particles per cell

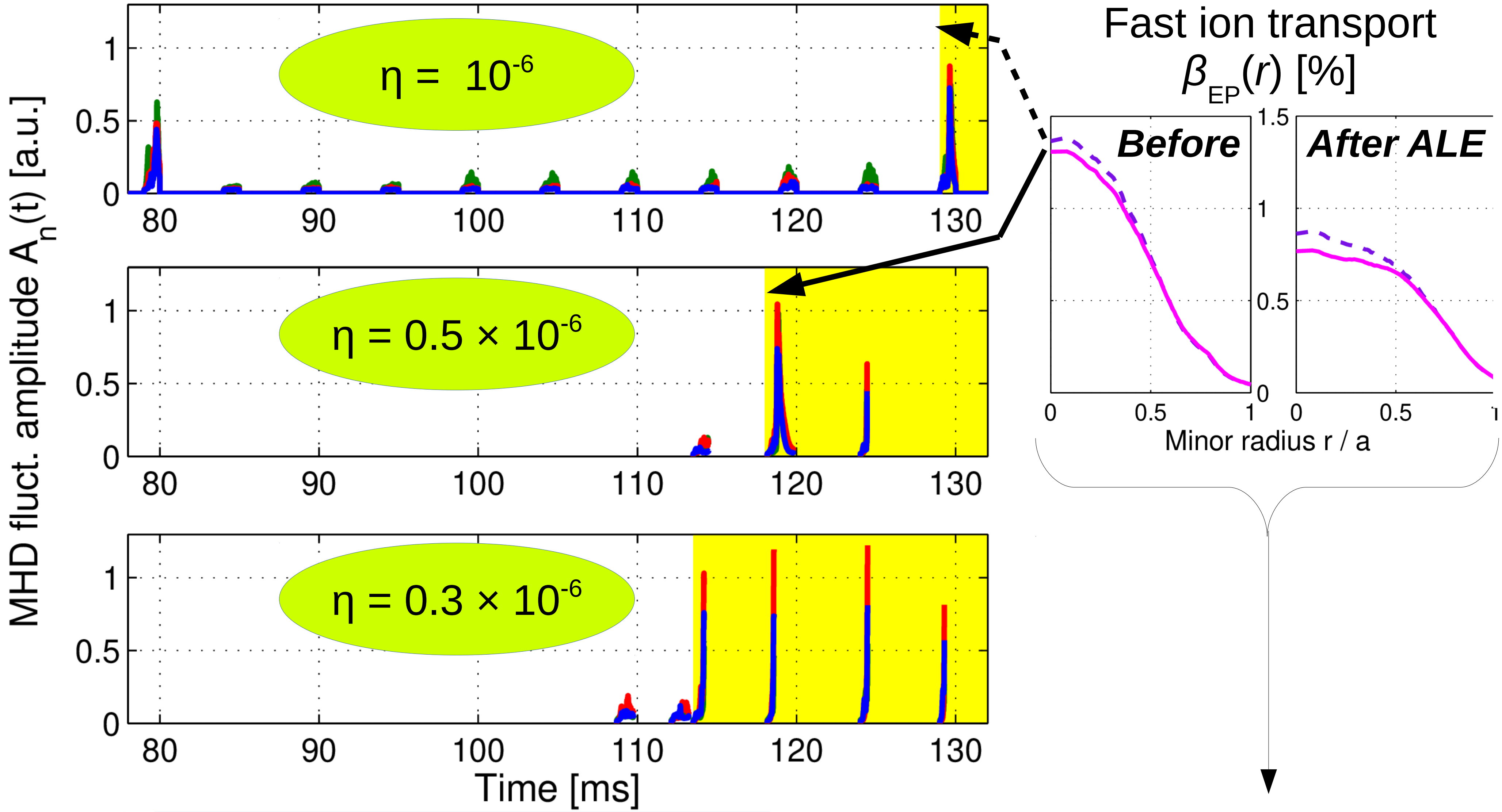
Well reproduced.

Sensitivity study: 3. Dissipation effect ($\eta = \nu = \chi$)



Weaker dissipation ...
(a) reduces ALE threshold
(b) causes similar EP transport

Sensitivity study: 3. Dissipation effect ($\eta = \nu = \chi$)



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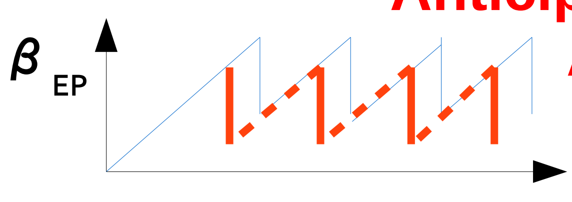
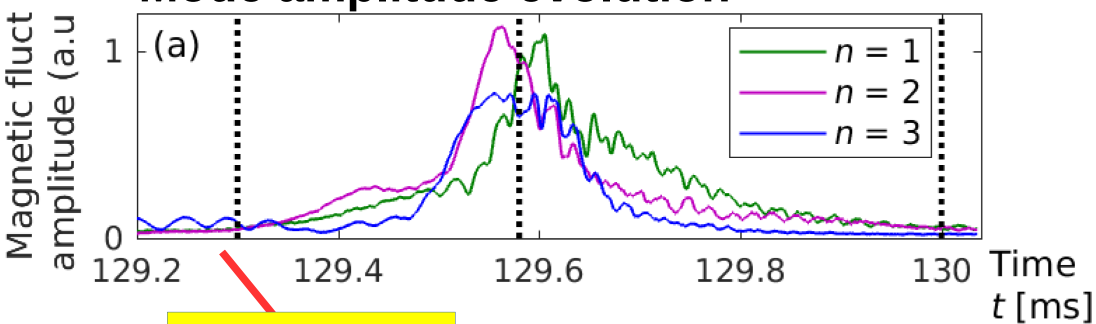


EP-induced magnetic islands

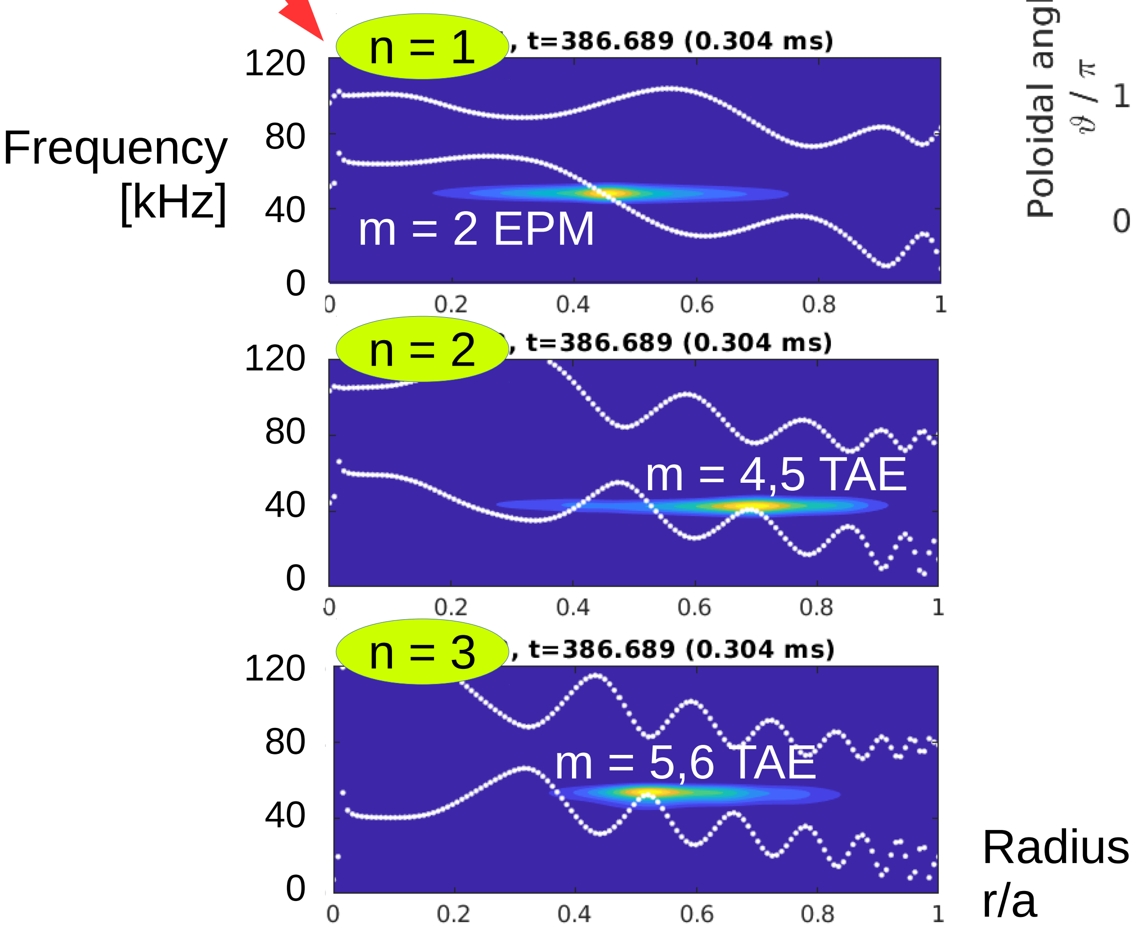
- Magnetic chaos
- Resistive decay

Before large event

Mode amplitude evolution

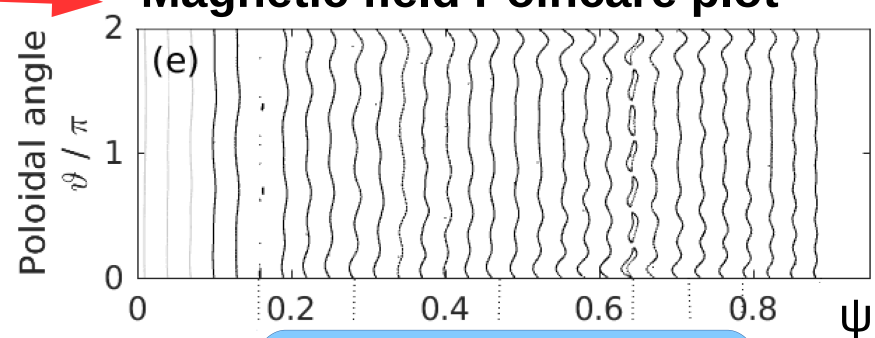


Before ALE



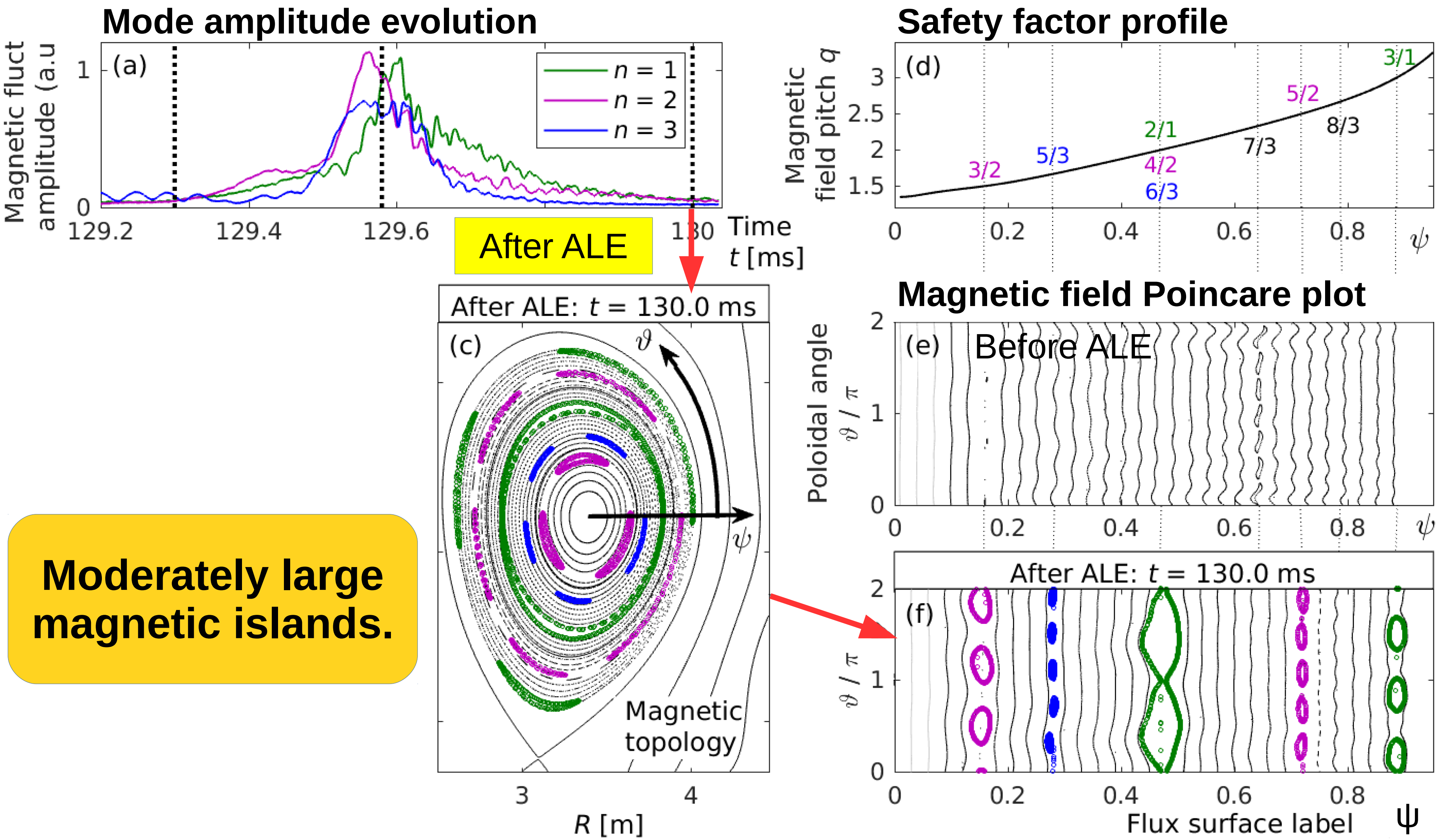
No islands.
Only waves
(40-50 kHz).

Magnetic field Poincaré plot



Wiggly flux surfaces
= shear Alfvén waves.

After large event



Moderately large magnetic islands.

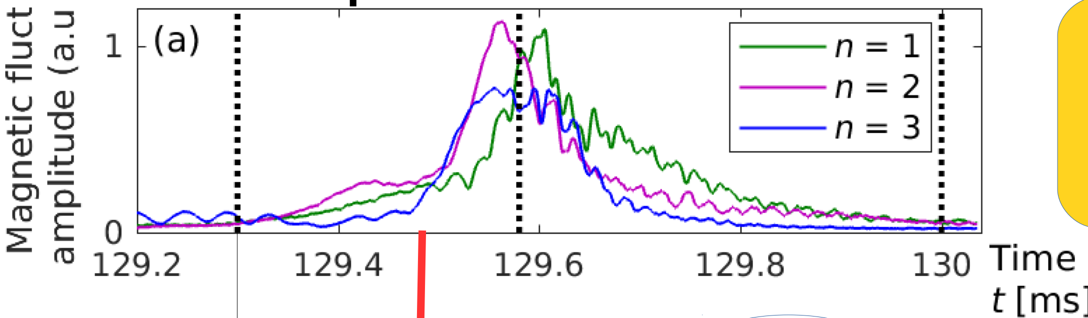
Questions:

(1) How did they form?

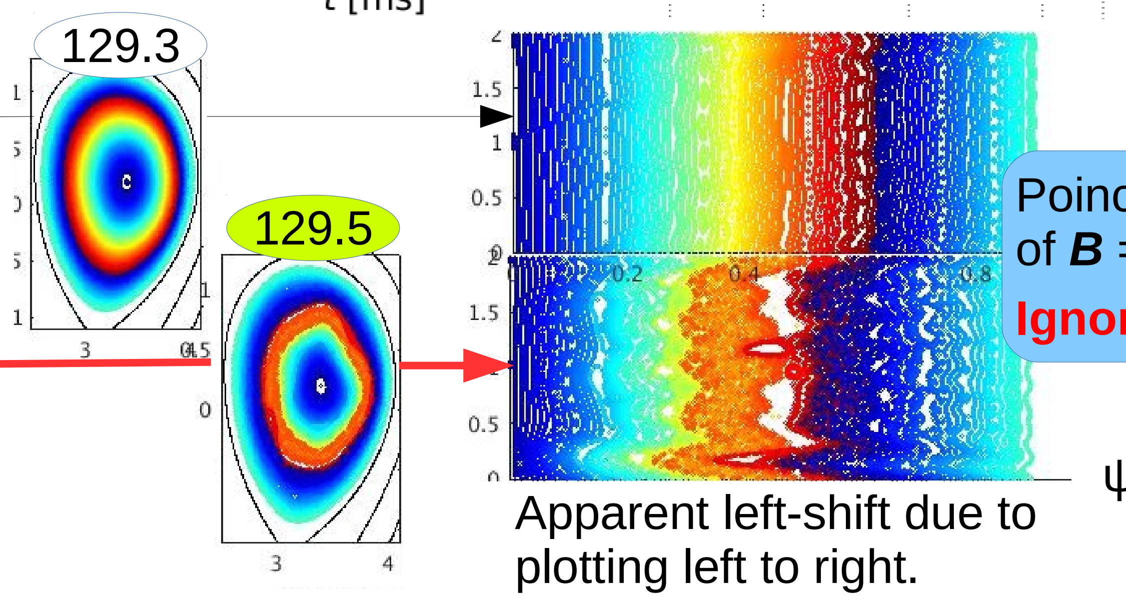
(2) How do they evolve?

ALE ramp

Mode amplitude evolution



Islands appear within < 0.2 ms, during *B* chaos & avalanche.



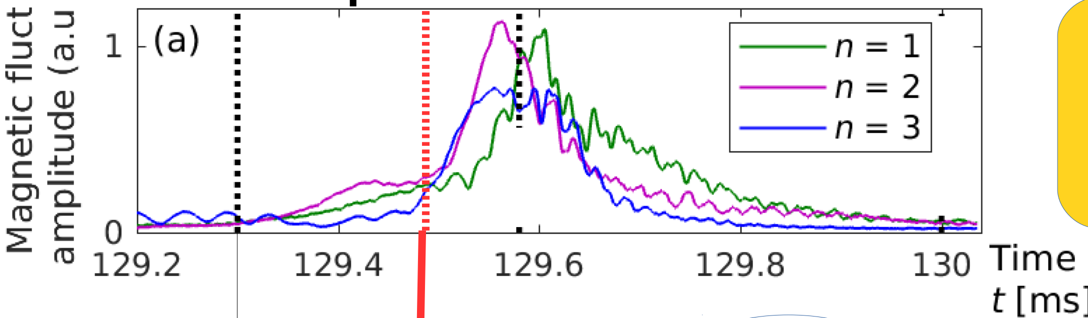
Poincaré plots of $\boldsymbol{B} = \boldsymbol{B}_{eq} + \delta\boldsymbol{B}$.

Ignored $\delta\boldsymbol{E}\times\boldsymbol{B}$.

Apparent left-shift due to plotting left to right.

ALE ramp

Mode amplitude evolution



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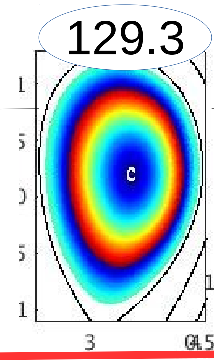
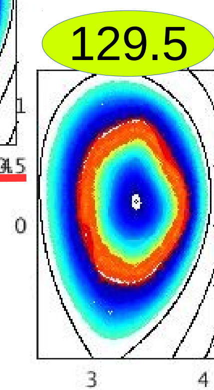
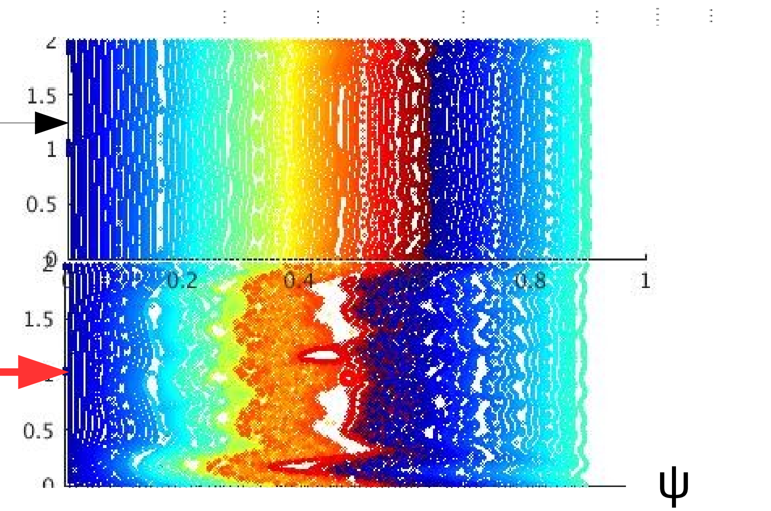
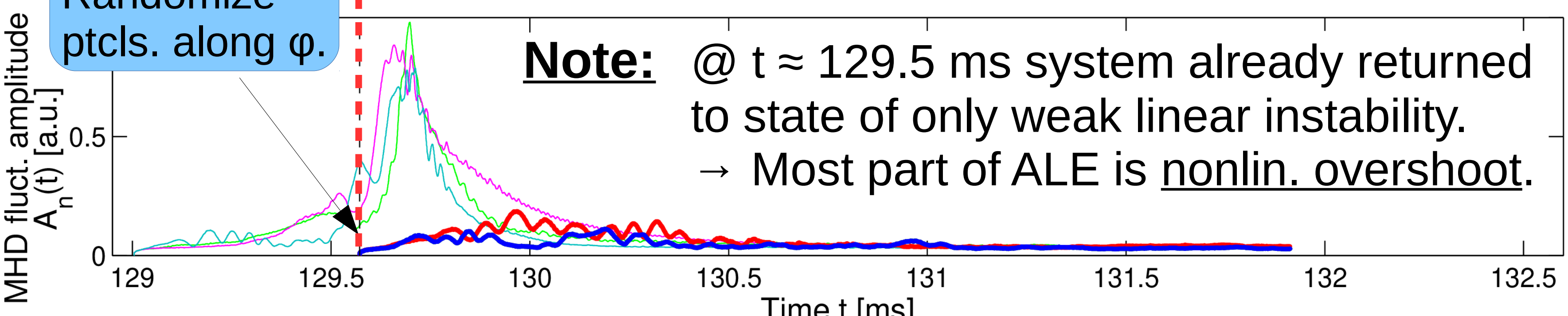




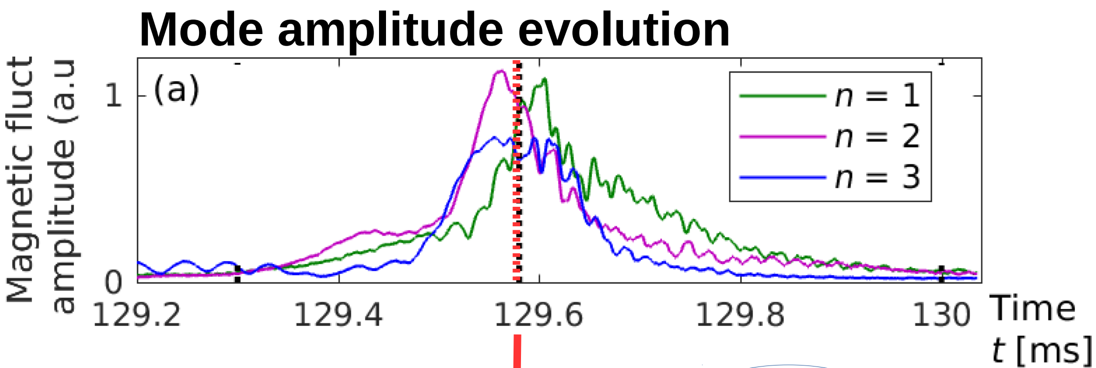


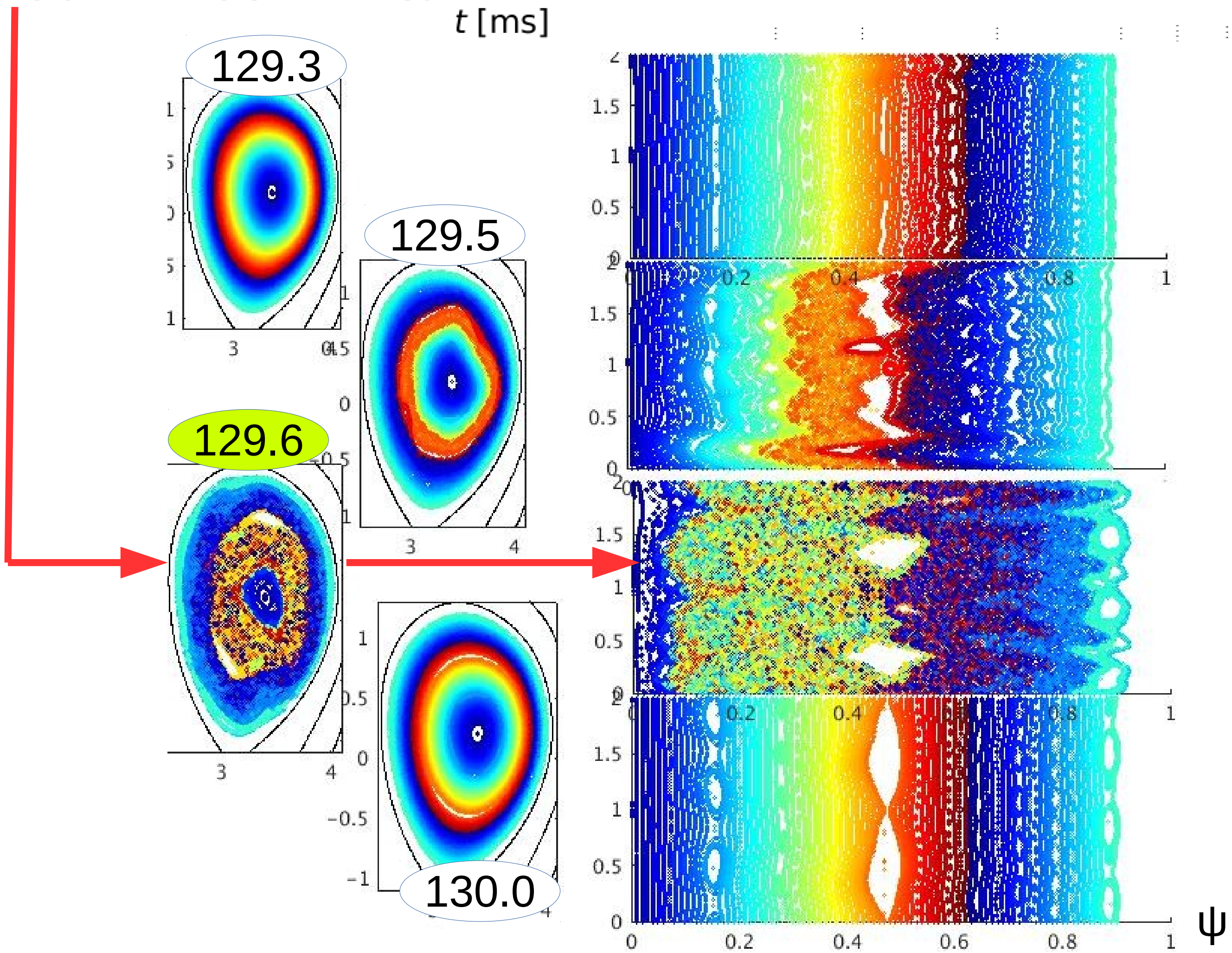
Reset fields. Randomize ptcls. along φ.



<u>Note:</u> @ t ≈ 129.5 ms system already returned to state of only weak linear instability.
→ Most part of ALE is <u>nonlin. overshoot</u>.

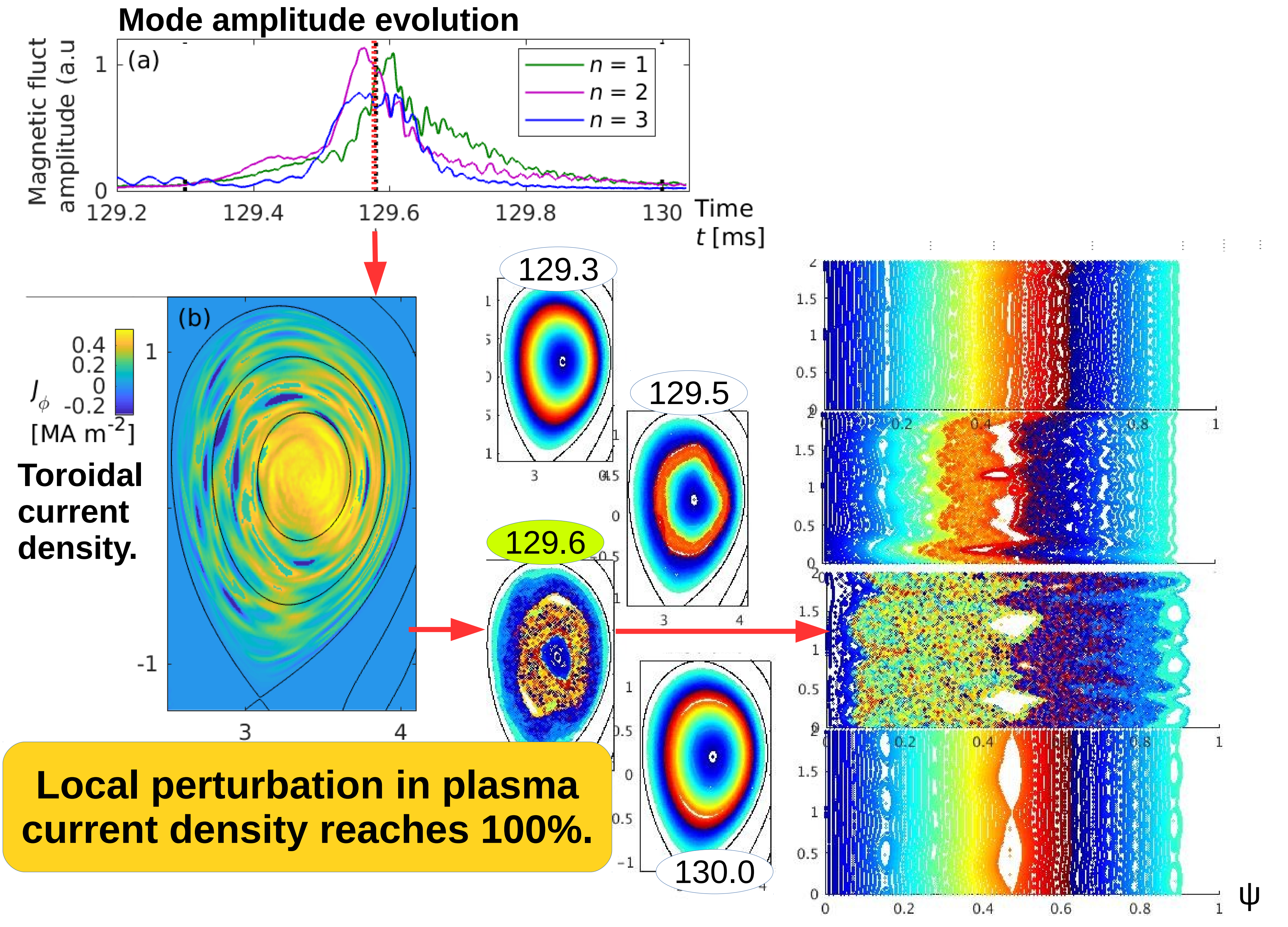
ALE peak





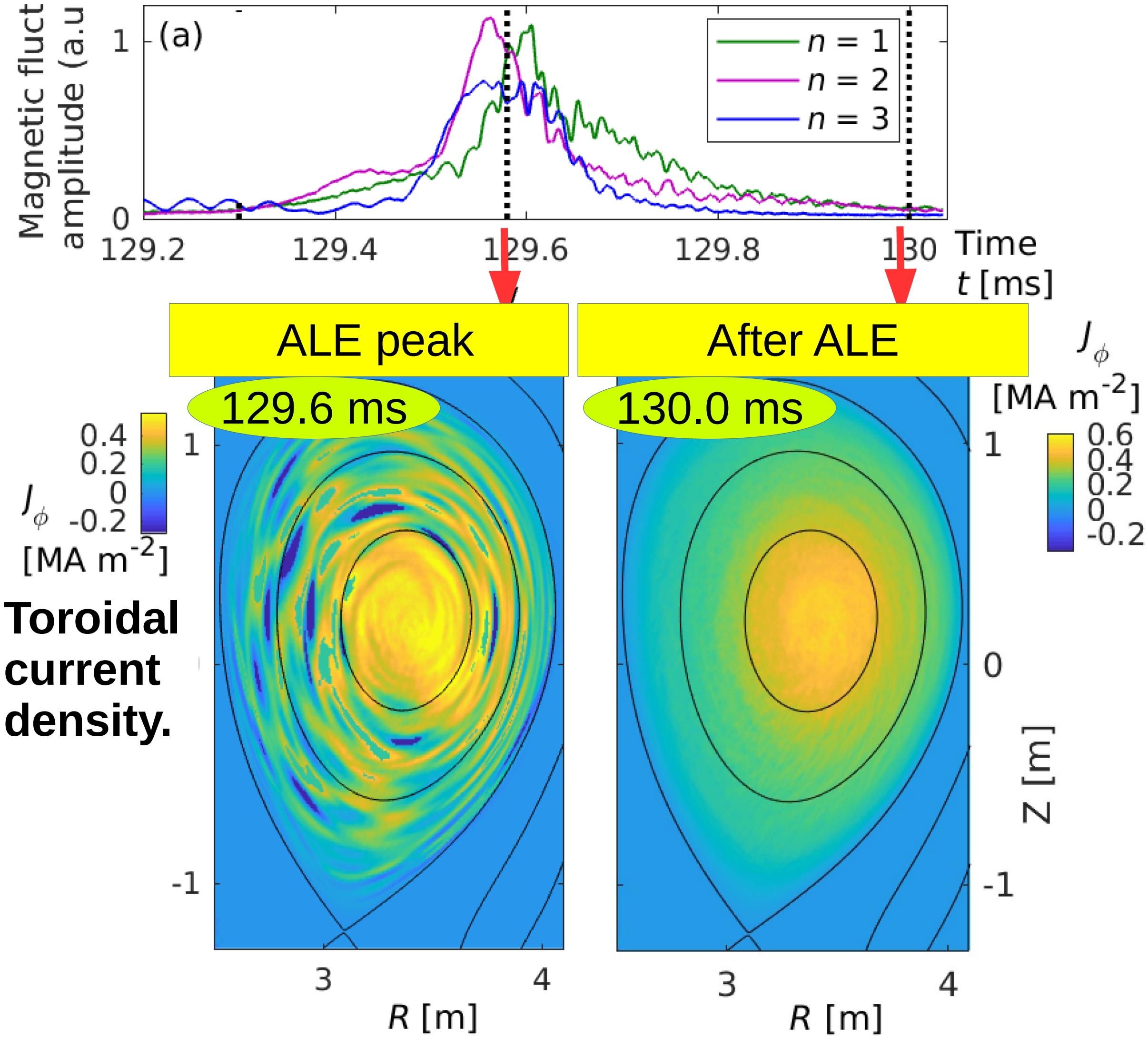
***B* chaos in entire core plasma. Island width w / a ~ 20%.**

ALE peak



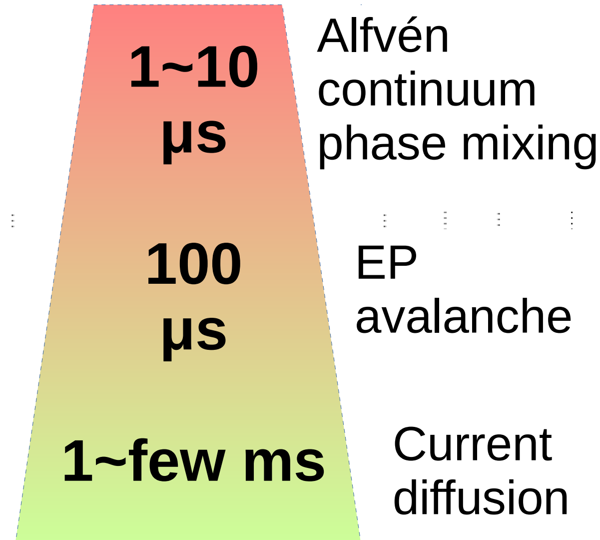
Local perturbation in plasma current density reaches 100%.

After ALE: Multi-time-scale decay



Toroidal current density.

Time scales (Δr / a ~ 0.1):



Tearing-stable system returns to unperturbed state.

$$\frac{\partial B}{\partial t} = -\nabla \times E,$$

$$E = -u_b \times B + \eta \delta J$$

$\eta/\mu_0 = 10^{-6}\, v_{A0} R_0 \sim w^2/\tau_\eta$

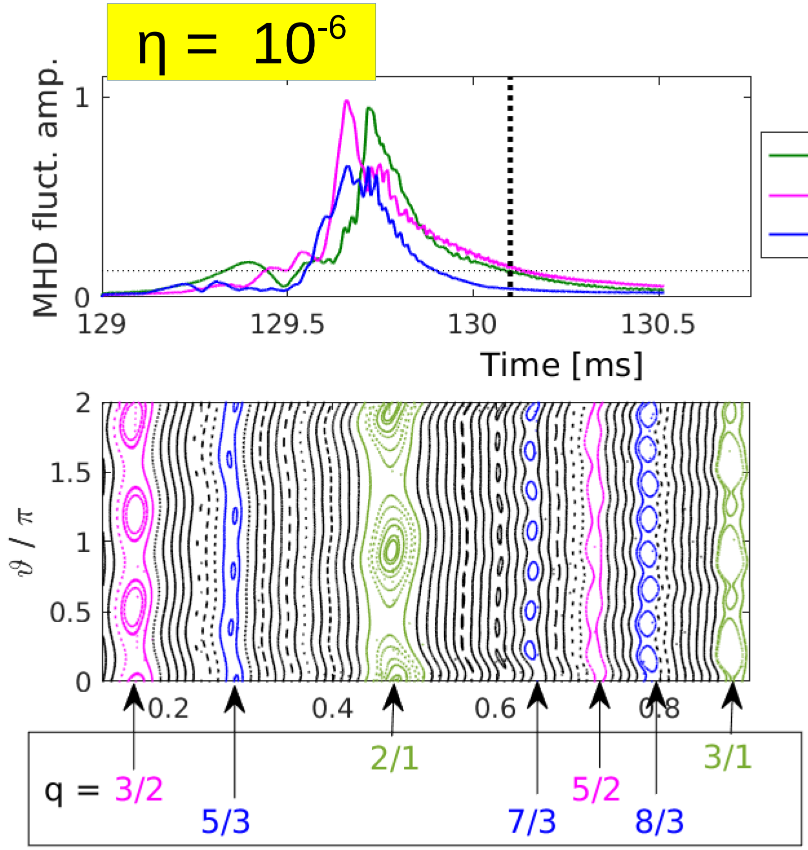
$v_{A0}/R_0 \sim 10^6 s^{-1}$, $R_0/a \sim 3$

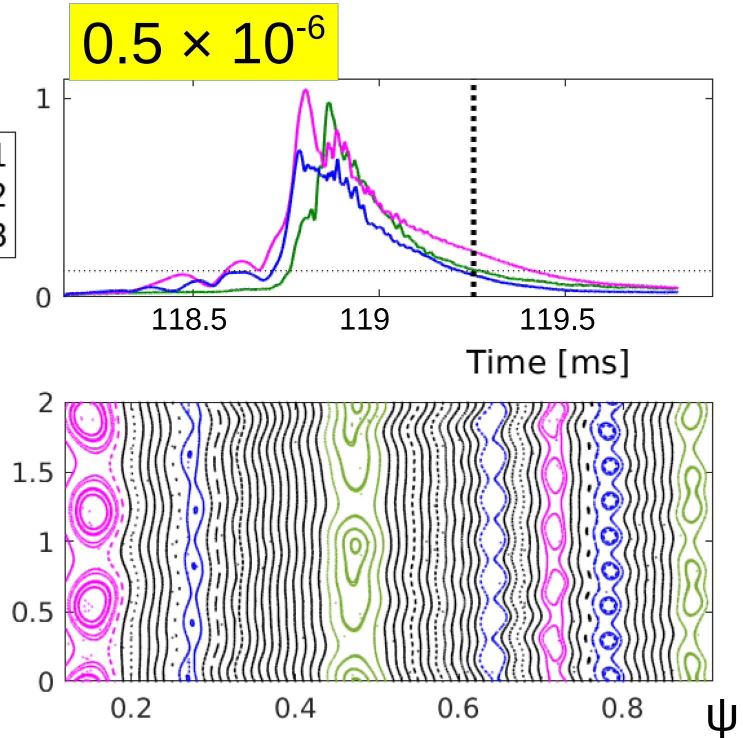
w/a = 0.1 → τ_η ~ 1 ms

Major part of pert. decays faster (~ 0.2 ms) than resistive time (~ 1 ms).

Presumably: NL structs. vanish with avalanche.

ALE-induced islands: Resitivity dependence



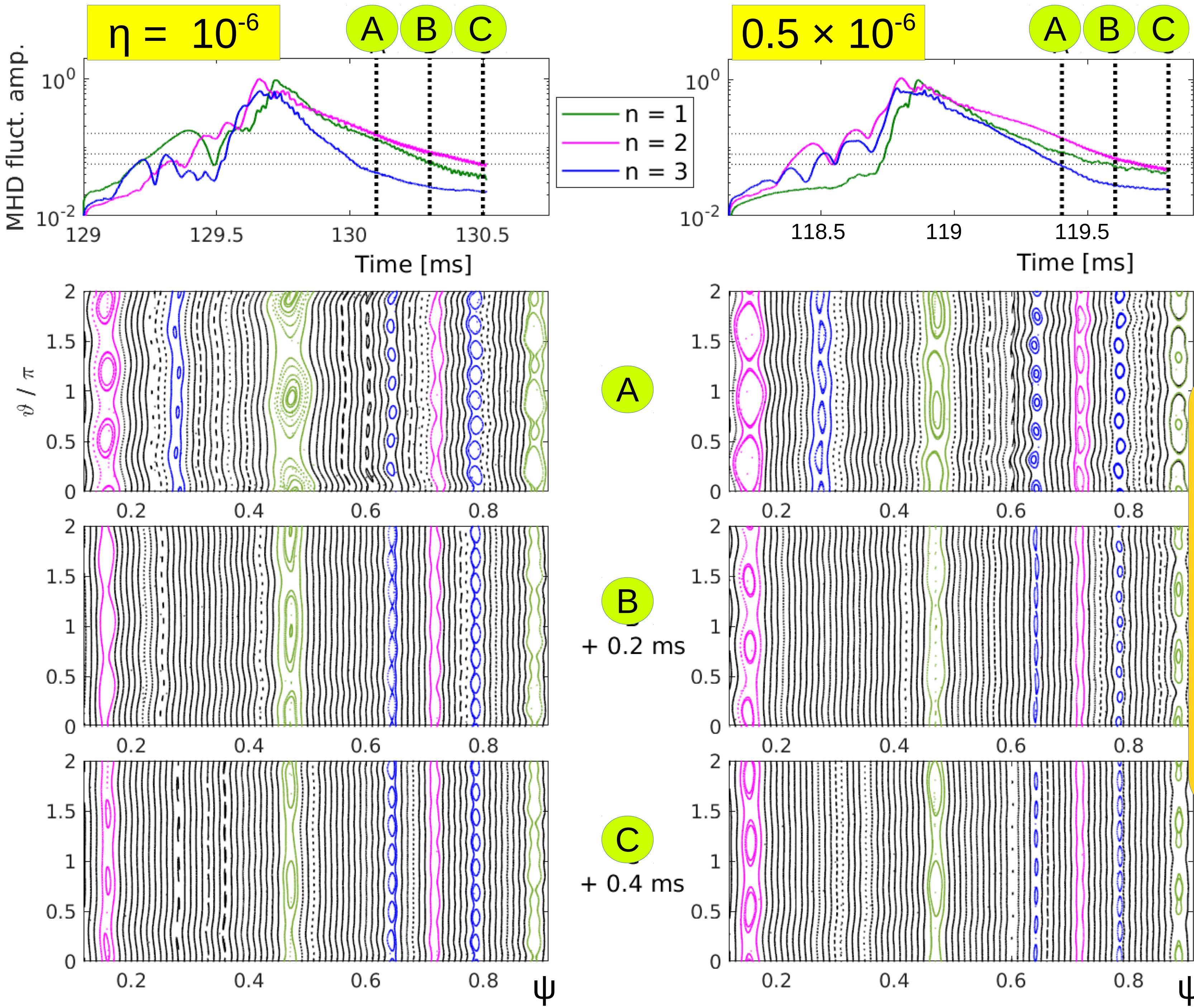


Snapshot 0.5 ms after ALE:
n=1 similar
n=2,3 larger

Smaller resisitivity yields
<u>similar or larger</u> islands!

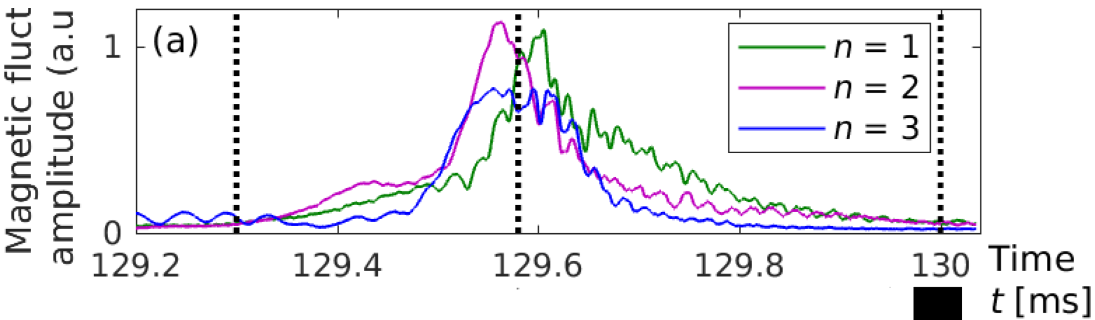
Because:
similar/larger ALE, slower decay

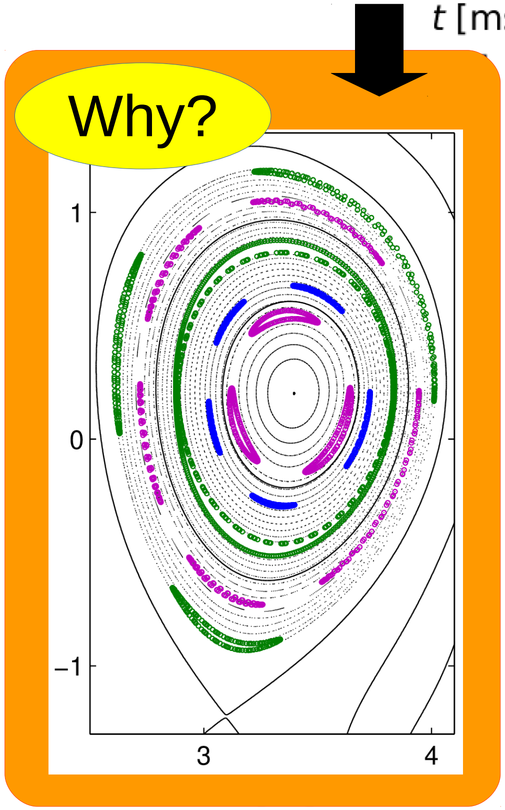
Somewhat irregular decay on millisec scale



Besides resistive decay:
- nonlin. coupling
- EPs
- waves
may still play a role.

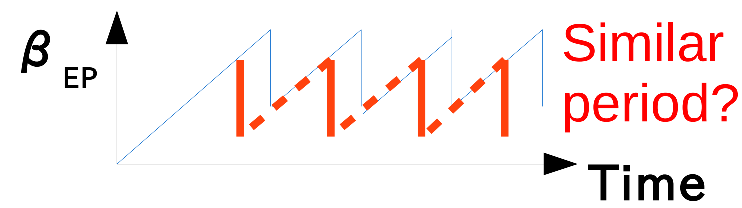
Summary: **Simulations show reconnection during ALEs**





Results:

- Confirmed sim. results with higher resolution & lower noise.
- Lower dissipation reduces threshold for ALE onset but amplitude remains large.

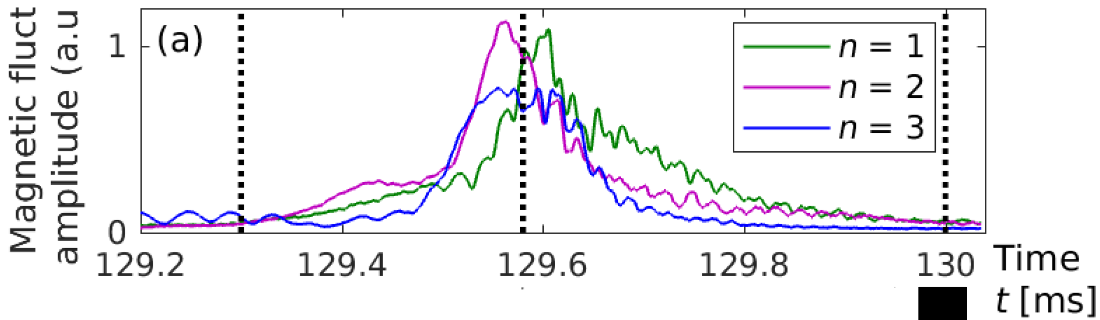


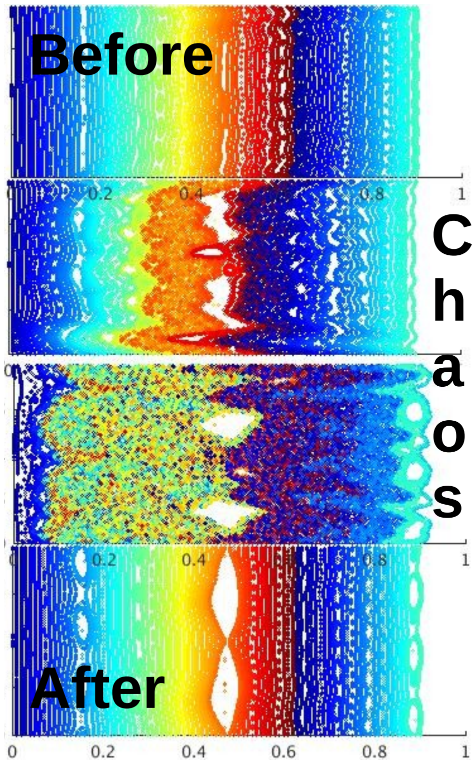
- Island decay time:
  $\tau_{resistive} \sim 1$ ms
- Island formation to be clarified:
  $\tau_{island} \sim 0.2$ ms < $\tau_{resistive}$
  Reducing dissipation by 1/2 gives similar (or larger) islands.

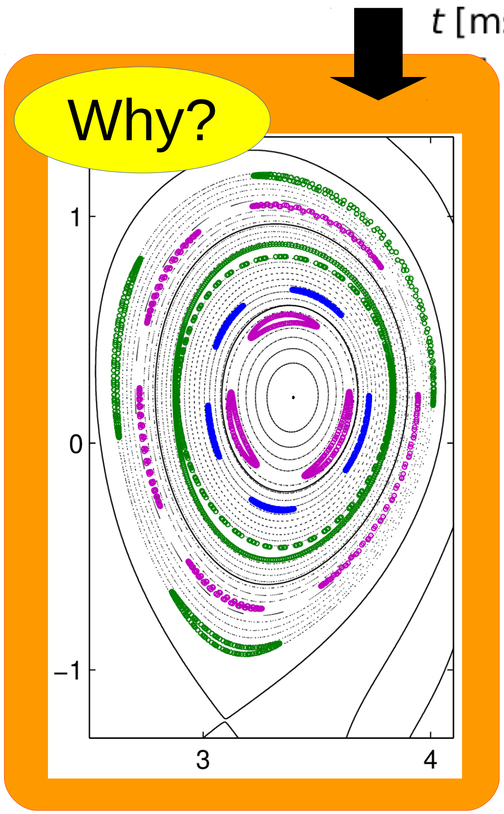
Tentative conclusion:

► Phenomenon seems to be physical within realm of resistive MHD (not a numerical artifact).

Discussion: Open questions & relevance







To be examined:

- How can 50 kHz Alfvén waves reconnect ***B*** field?
- Analyze combined effect of chaotic ***B*** & ***δE×B*** on EPs, bulk (… & vice versa).
- Experimental check?

Relevance:

- May explain enhanced electron transport observed during ALEs in JT-60U exp.

Ishikawa et al, *Nucl. Fusion* **45** (2005) 1474.

- May also be relevant for space plasmas; e.g. "flux transfer events (FTE)" in magnetopause.

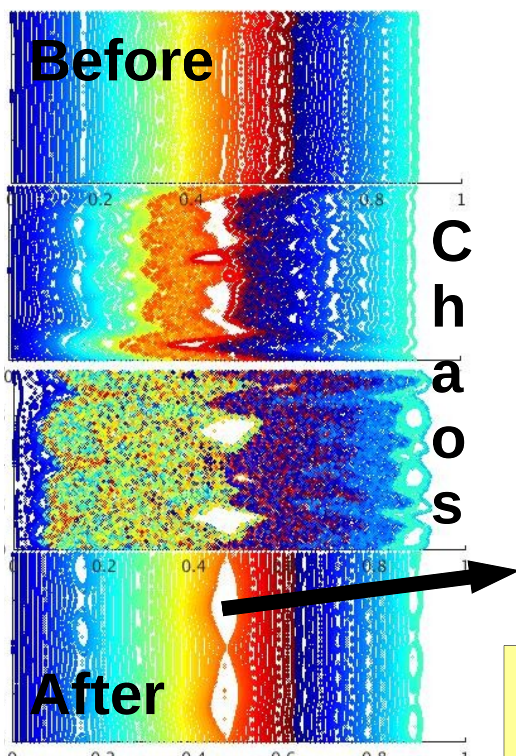
Uberoi, *J. Plasma Phys*. **62** (1999) 345.
Prikryl et al. *Ann. Geophys* **20** (2002) 161.

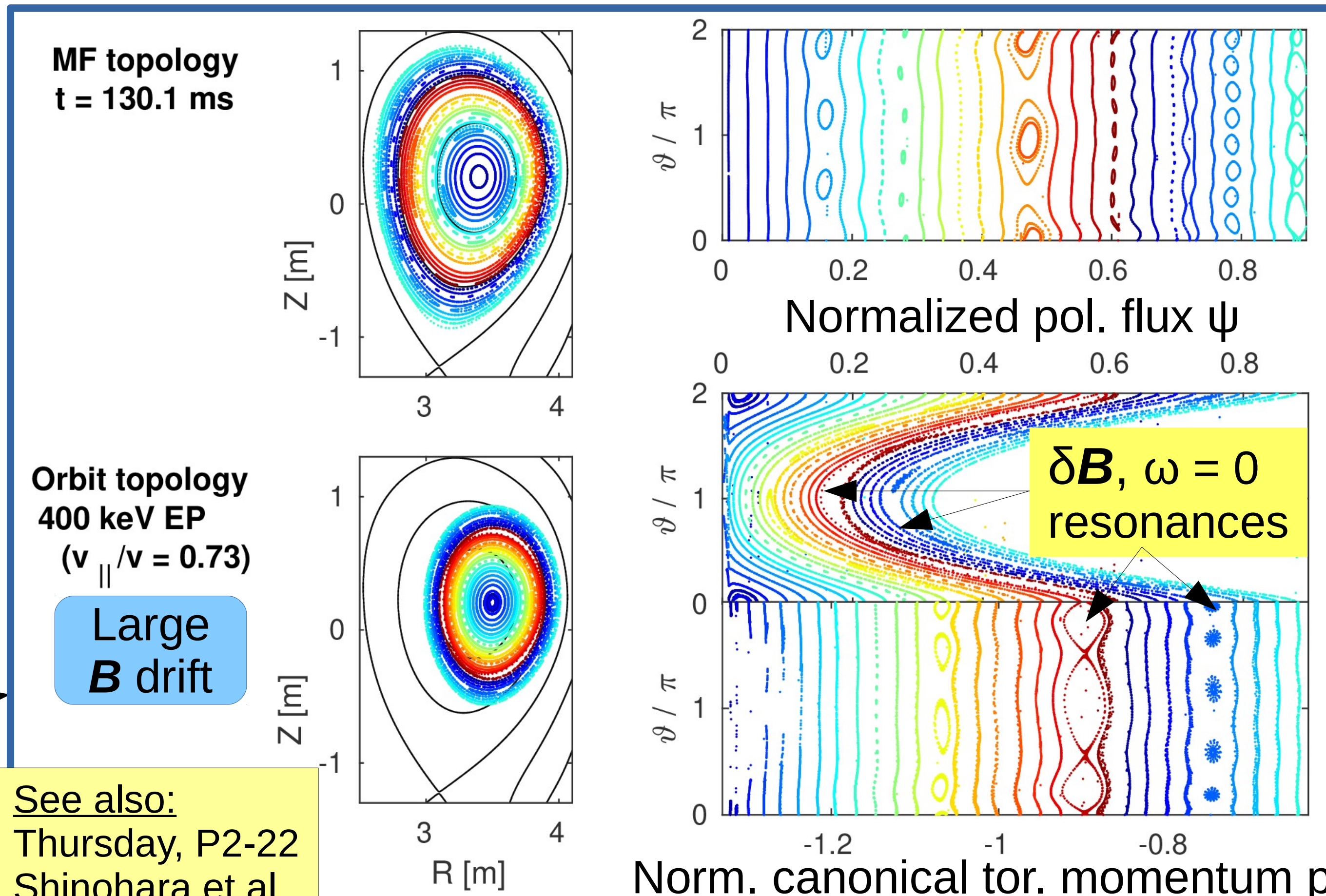
Question: **How can 50 kHz Alfvén waves reconnect *B* field?**

Educated guesses for parity mixing mechanisms:

(a) Chaotic *B* field effect:
Interference of large-amp. MHD waves with multiple helicities *m* / *n*.
→ Mixed-parity low-frequency beats?
→ Drive 3D reconnection at many locations?
→ Merging micro-islands?

(b) Collective NL interaction with EPs:
Interactions with both oscillating δ***E***×***B*** and quasi-steady δ***B*** causes phase space to be "reconnected" around resonances.
→ EP phase space islands are imprinted onto ***B*** field via EP current?





See also:
Thursday, P2-22
Shinohara et al.