PEGASUS-III
Experiment

Identifying Beam-Driven Instabilities Responsible for Current Drive on PEGASUS-III

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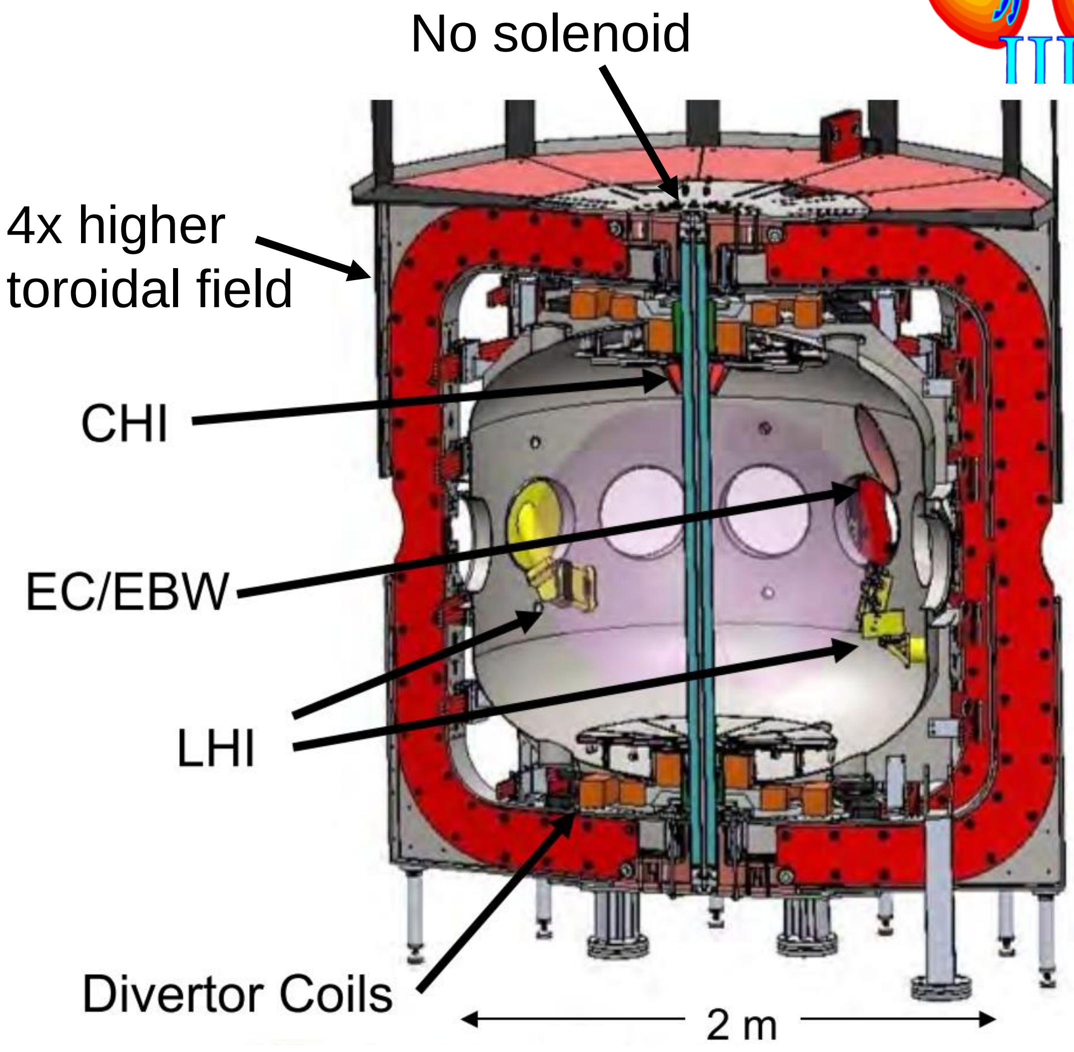
PEGASUS-III Will Explore Non-Solenoidal Current Drive Techniques At Higher Toroidal Field

- Goal: testing and projecting performance of non-solenoidal startup to fusion plant scale devices
- Understanding **physical mechanisms behind current drive** crucial to extrapolate performance

Parameter	PEGASUS	PEGASUS-III
$I_{p,\ target}$	225 kA	300 kA
$B_{T,max}$	0.15 T	0.58 T
B_T Flattop	25 ms	50-100 ms
A	1.15	1.18



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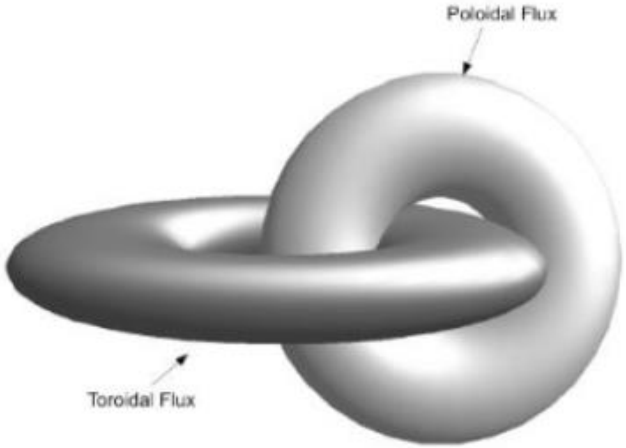
Helicity Injection Exploits Conservation Properties to Drive Current

- **Magnetic helicity** describes "interlinkedness" of flux in a volume
- In a tokamak, K_{plasma} results from linkage between $\Psi_{poloidal}$ and $\Psi_{toroidal}$

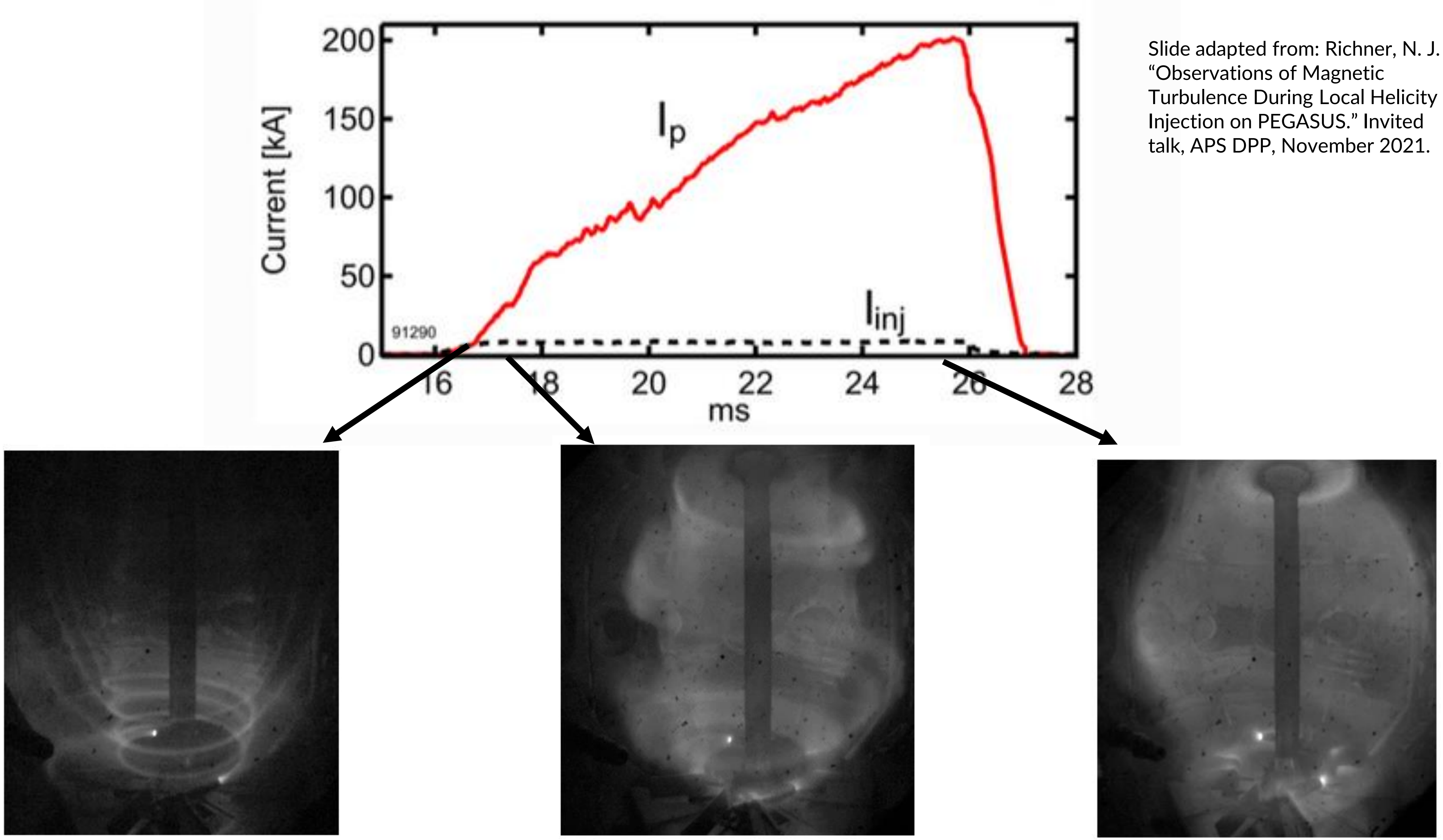
$$\boxed{\begin{array}{c} K = \int \vec{A} \cdot \vec{B} d\tau \\ \propto I_p \Psi_{tor} \end{array}}$$

- Local helicity injection (LHI): biased cathode produces beam of electrons that spirals around vessel and relaxes into tokamak-like configuration
- Plasma current sustained by LHI proportional to injector properties, field at injector location:

$$I_p = \frac{A_p V_{LHI}}{2\pi R_0 < \eta >} \approx \frac{V_{inj} A_{inj}}{2\pi R_0 < \eta >} \frac{B_{inj}}{B_0}$$



Relaxation Takes Plasma From LHI Startup To High Current Tokamak State



Slide adapted from: Richner, N. J. “Observations of Magnetic Turbulence During Local Helicity Injection on PEGASUS.” Invited talk, APS DPP, November 2021.

$I_p \approx N_{turns} I_{inj}$ $I_p \gtrsim N_{turns} I_{inj}$ $I_p \gg N_{turns} I_{inj}$

Exploring Physical Mechanisms for LHI Current Drive

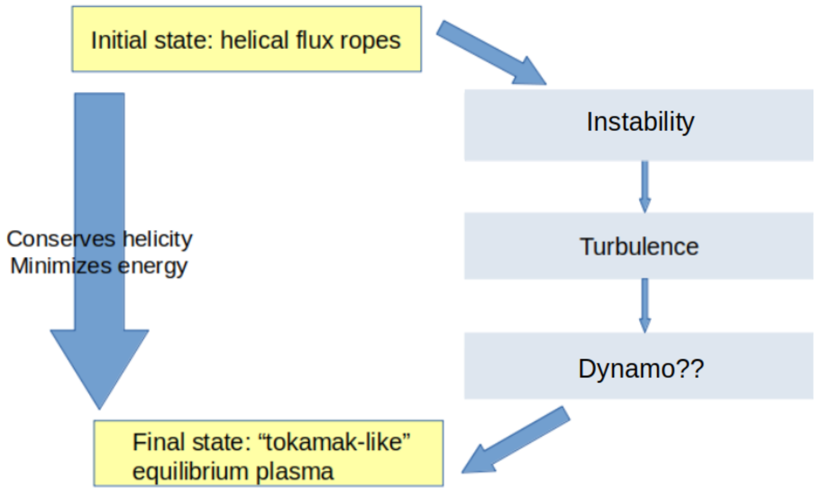
- Global limits for Ip are well understood
  - Helicity balance

$$I_p = \frac{A_p V_{LHI}}{2\pi R_0 < \eta >} \approx \frac{V_{inj} A_{inj}}{2\pi R_0 < \eta >} \frac{B_{inj}}{B_0}$$

  - Taylor limit: Ip limited by edge $J_{||}/B$

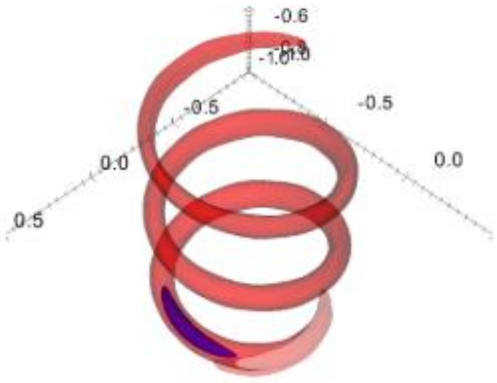
$$I_p \leq \frac{\Psi_{tor} I_{inj}}{2\pi R_{inj} B_{p,inj} w}$$

- Understanding **physical processes behind current drive** crucial to extrapolate LHI performance to fusion-relevant parameter spaces

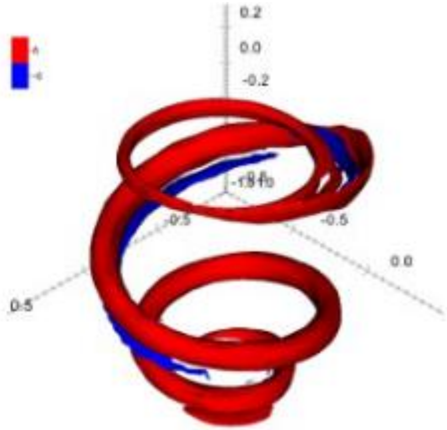


Simulations Predict a Relaxation Mechanism Based On Global Instability

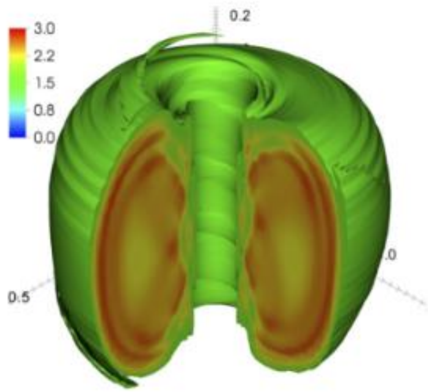
- NIMROD simulations model relaxation during LHI on PEGASUS (O'Bryan, J. B., & Sovinec, C. R. (2014). "Simulated flux-rope evolution during non-inductive startup in Pegasus." *Plasma Physics and Controlled Fusion*, 56(6).)
- Injected electron beams modeled as **flux ropes**
- Adjacent passes of flux rope reconnect and release current rings, which diffuse into tokamak-like plasma
- Simulations suggest a mechanism for poloidal flux development: the **dynamo**



initial current path

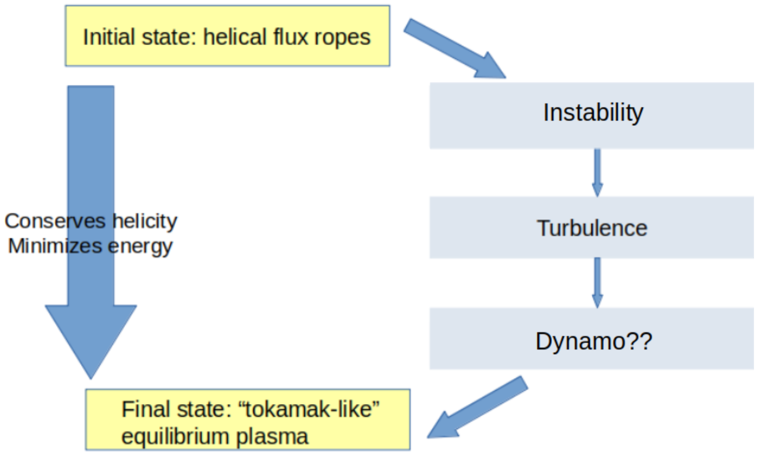


early ring formation



tokamak-like axisymmetric plasma

Dynamo Effects Generate Large-Scale Fields and Flows



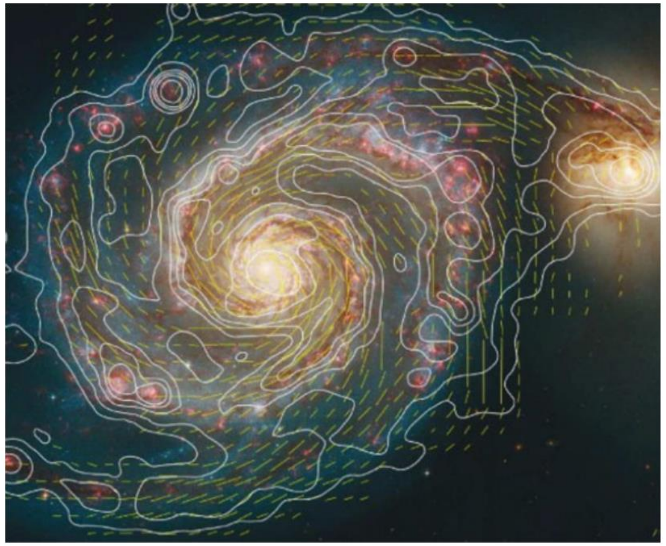


Image source: Rincon, F. (2019). Dynamo theories. Journal of Plasma Physics, 85(4). https://doi.org/10.1017/s0022377819000539

- Astrophysical dynamos convert kinetic energy to magnetic energy (flow-dominated)
  - Earth's magnetosphere
  - Galaxy-scale magnetic fields
- Lab plasma dynamos tend to be magnetically dominated
  - Dynamo current drive effects studied in depth on MST

Dynamos Can Drive Field-Parallel Current

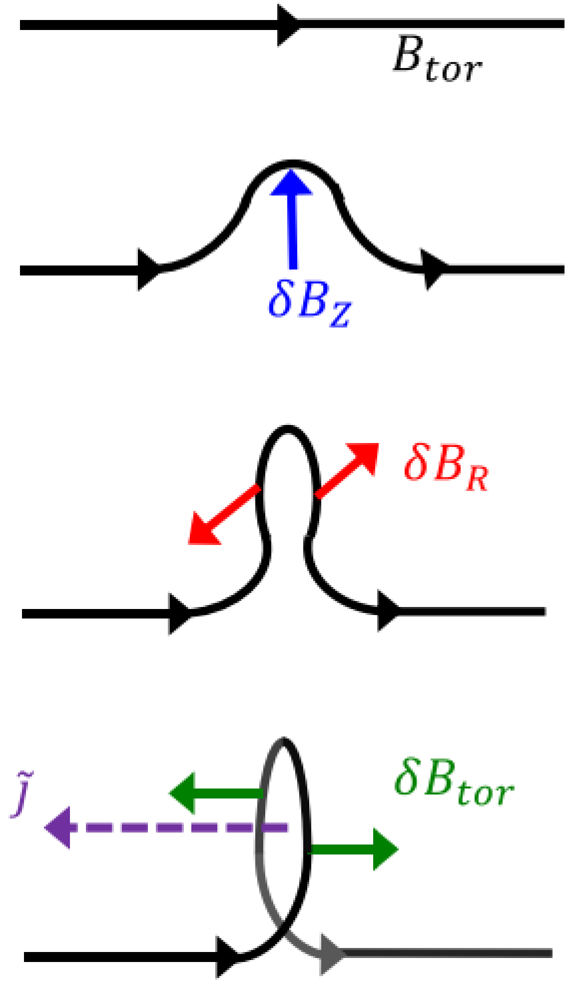


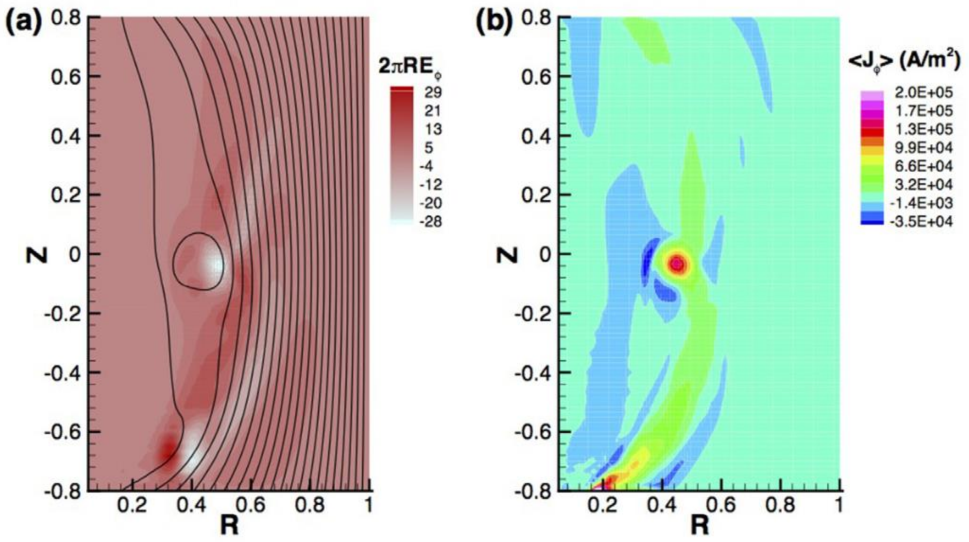
Image source: Richner, N. J. "Observations of Magnetic Turbulence During Local Helicity Injection on PEGASUS." Invited talk, APS DPP, November 2021.

- Lab dynamos typically involve fluctuation in magnetic field and another field quantity
- Example: in MHD dynamo, perpendicular velocity and magnetic fluctuations drive parallel current

$$\overline{\mathbf{E}} + \langle \widetilde{\mathbf{v}} \times \widetilde{\mathbf{B}} \rangle = \eta \overline{\mathbf{j}}$$

- Phase difference of fluctuations affects amount of current driven and its direction
- Dynamo activity must be considered statistically

Simulations Predict a Dynamo Mechanism Based On Global-Scale Instability on PEGASUS



Dynamo activity during an early ring formation event

a) Contours of induced EMF from MHD fluctuations

b) Toroidally averaged poloidal current density

Source: O'Bryan, J. B., & Sovinec, C. R. (2014). "Simulated flux-rope evolution during non-inductive startup in Pegasus." *Plasma Physics and Controlled Fusion*, 56(6).

Simulation predicted dynamo drive from flux-rope scale fluctuations from an **island coalescence instability**

$\tilde{v}$: slight rotation of flux rope
$\tilde{B}$: inherently asymmetric field of flux rope

$$\overline{\mathbf{E}} + \langle \widetilde{\mathbf{v}} \times \widetilde{\mathbf{B}} \rangle = \eta \overline{\mathbf{j}}$$

→ Predicts dynamo current drive associated with n=1 mode on the order of 1E4 Hz

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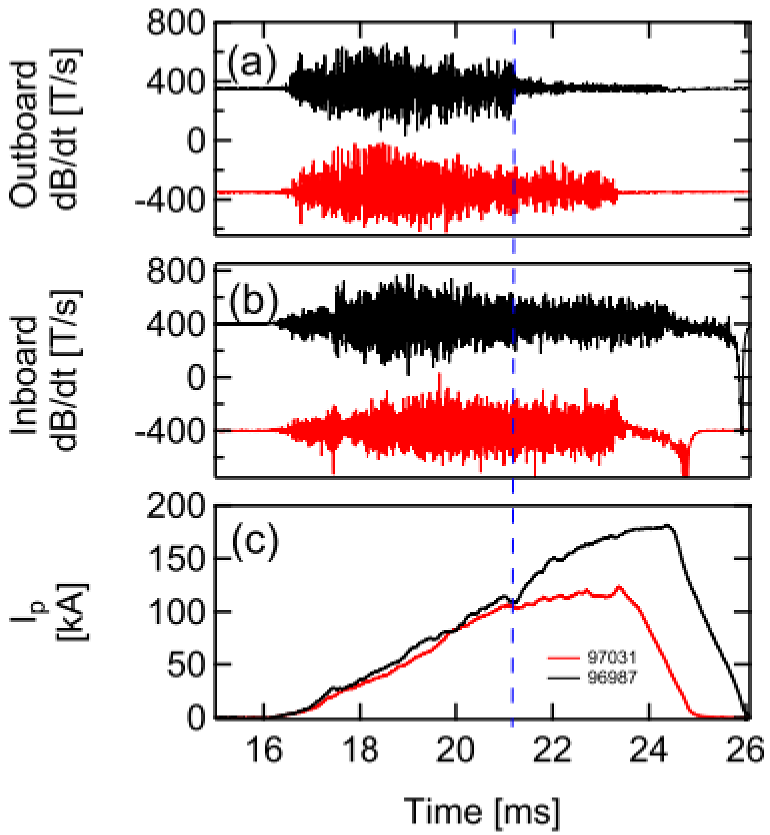
Observation of n=1 Mode During LHI Shows Global Modes Can't Fully Explain Current Drive

Observation: High-amplitude n=1 kink mode at 20 – 50 kHz dominates in a large parameter space

- Kink mode could result from island coalescence instability
- Suggested n=1 mode would be primary current drive mechanism, until...

A mode with n=1 activity reduced by ~10x ("**reduced MHD mode**") was discovered on PEGASUS for HFS injection

- Kink reduction event corresponds to ~50% current drive *increase*
- High frequency fluctuations inside edge suddenly increase→ related to current drive?
- Motivated experiments to characterize magnetic turbulence and its relationship to current drive on PEGASUS



Source: Perry, J. M. et al. (2018). "Initiation and sustainment of tokamak plasmas with local helicity injection as the majority current drive." *Nuclear Fusion*, 58(9).

LHI Generates Broadband Turbulence That Obeys Power Laws

- Turbulence characterized by uniform transfer ("**cascade**") of energy to smaller scales at constant rate down to dissipation

- Helicity injected along with energy, but cascades up to system scale—develops large scale structures

- Turbulence in magnetized plasmas often **Alfvénic:** travels along field lines w/ $\tilde{B}$ and $\tilde{v}$ perpendicular to direction of propagation

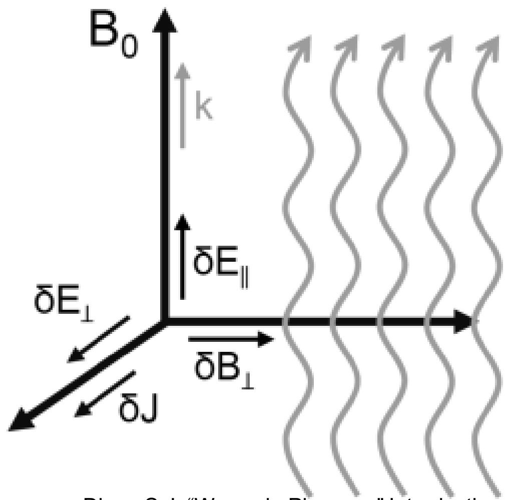
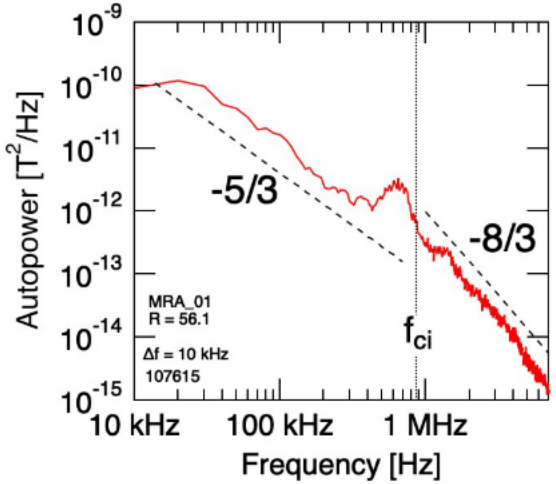


Image source: Diem, S.J. "Waves in Plasmas." Introduction to Fusion and Plasma Physics Course lecture slides, SULI, 16 June 2020.



Source: Richner, N. J. "Observations of Magnetic Turbulence During Local Helicity Injection on PEGASUS." Invited talk, APS DPP, November 2021.

- Magnetic fluctuations measured on PEGASUS with a radial probe

- Measured LHI spectrum displays power law activity
  - MHD Alfvén waves at low frequencies (index = -5/3)
  - kinetic Alfvén waves at high frequencies (index = -8/3)

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Current is Driven Throughout the Alfvénic Cascade

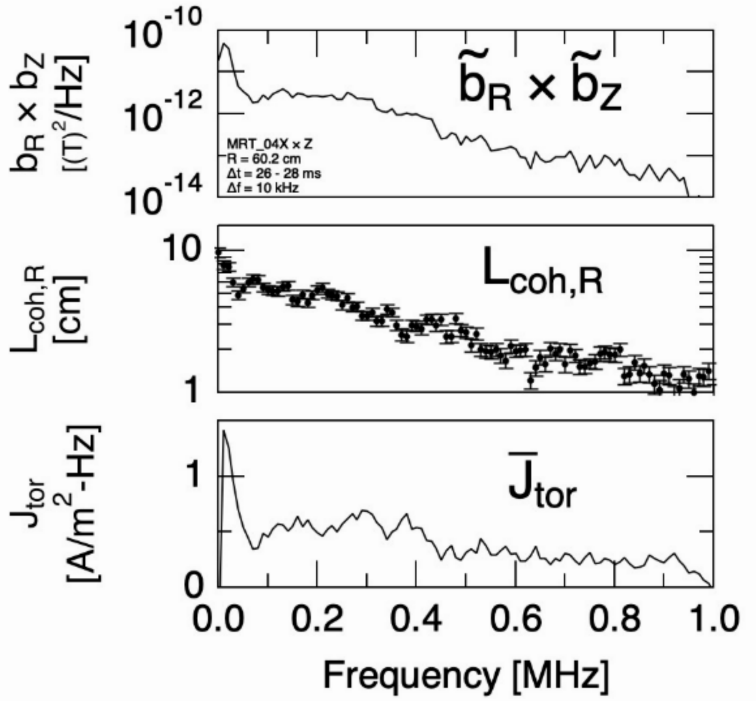
- Dynamo current can be estimated with the alpha dynamo model and Ampere's Law
- Correlations of fluctuations in b_z and b_r suggest current drive direction matches that of PEGASUS
- High frequency ($f >> f_{ci}$) fluctuations contain significant power and correlate with total Ip
- Dynamo-driven current density estimate ~ 400 kA/m^2; equilibrium reconstruction current ~ 250 – 600 kA/m^2

→ Broadband (including $f>>f_{ci}$) dynamo current drive may be a significant contributor to Ip on PEGASUS

Net coherent power

$$\bar{J}_{tor}(f) \approx 2\,\mathrm{sgn}(\theta_{RZ})\frac{\sqrt{\langle \tilde{b}_Z \tilde{b}_R \rangle}}{\mu_0 L_{coh,R}}$$

Co- vs. counter- drive



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Future Work & Planned Experiments

Characteristics of turbulence parallel to magnetic field

- Multiple probes spaced out along a field line
- **Parallel correlation length:** distance over which turbulence decorrelates from itself; may be related to scale of instabilities in LHI

Scaling of current drive mechanism up to power plant scale

- Measure amplitude of turbulence at high field (up to 0.6 T)
- Extrapolate turbulent behavior, instability performance
- Requires better understanding of instability

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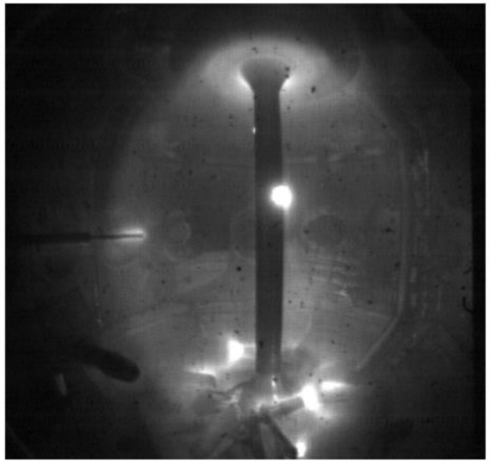
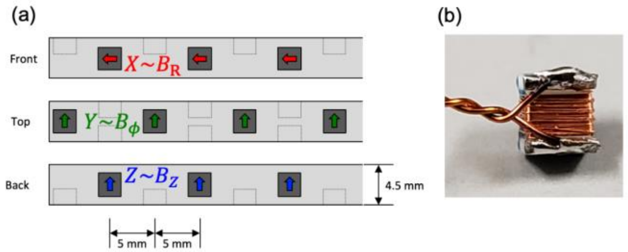
Existing Magnetic Turbulence Probes Can Be Adapted for New Experiments

Probe Inserted into LHI Discharge



Magnetic probes built to measure magnetic fluctuations on PEGASUS (N. J. Richner)

- Features: frequency range up to MHz; variable insertion depth with a 40 cm throw; electrostatic and heat shielding
- Broadband array
- **Triple axis array**
  - 10 radially spaced, identical coil "triplets"
  - Co-located measurements of Br, Bz, and Bφ



Specifications for new probe system:

	bare minimum	desirable	aspirational
Dimensions	1 (radial)	3	3
Number of probes	2	3	4
Frequency range	2 MHz	5 MHz	10 MHz
Spatial resolution	<2 cm	<1 cm	< 5 mm
Max heating 10 ms	2500 K	1000 K	500 K

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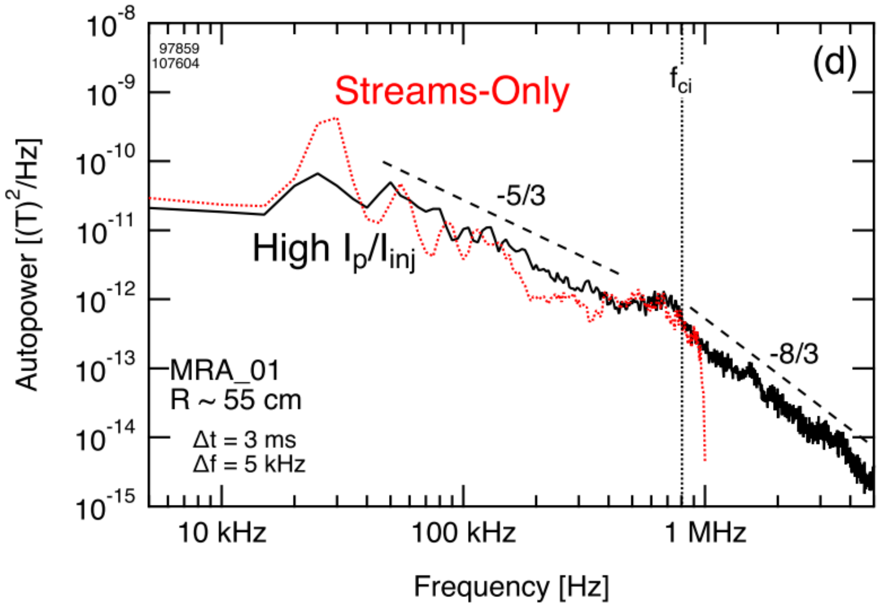
Future Work: Location and Type of Instability

- Evidence suggests that high-ω turbulence is generated by an injector or beam instability
  - Fluctuation amplitude increases with beam velocity
  - Streams-only discharges had similar spectra to relaxed discharges → turbulence comes from source other than reconnection/relaxation process
- Possible instability sources:
  - Super-Alfvénic, super-thermal beam electrons streaming into background plasma induce waves all along beam length
  - “Double-layer” plasma structure around injector electrode known to have own set of instabilities



Source: Richner, N. J. (2021). Characterization of Magnetic Activity During Local Helicity Injection. University of Wisconsin-Madison.

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Future Work: Instability Identification

- Modeling PEGASUS as monoenergetic beam incident on cold magnetized plasma, two possible instabilities:

$$D(\omega, k) = k^2c^2 - \omega^2 + \omega_{pe}^2\frac{\omega}{\omega + \omega_{ce}} + \omega_{pi}^2\frac{\omega}{\omega - \omega_{ci}} + \omega_{pb}^2\frac{\omega - kv_b}{\omega - kv_b + \omega_{ce}}$$

Electron beam ion cyclotron instability

Electron beam Alfvén wave instability (low ω, wave number limit)

- Modeling in kinetic regime (high k, ω limit) with different electron and ion temps predicts **kinetic Alfvén wave instability**

$$\omega^2 = k_{\parallel}^2 v_A^2 \left(\frac{k_{\perp}^2\rho_i^2}{1 - I_0(k_{\perp}^2\rho_i^2)\exp\left(-k_{\perp}^2\rho_i^2\right)} + \frac{T_e}{T_i}k_{\perp}^2\rho_i^2 \right)$$

- Calculating most unstable mode and growth rate as functions of parameter sweeps will enable instability ID