Microstability Properties of the Local Minimum $|B|$ Regime in Pegasus

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A local **minimum** \( |B| \) **region**, or “magnetic well,” was recently observed in the **low-aspect-ratio Pegasus device** in high-\( \beta \) scenarios with strong edge current peaking [1]. The \( \nabla B \) **reversal** within the magnetic well alters magnetic drifts and particle orbits associated with instabilities. Here, we report on the microstability properties of the magnetic well region with calculations from the **GENE gyrokinetic code** [2].


[2] F. Jenko and the GENE Development Team,  
http://genecode.org/
Outline

• Background
  – Reduced neoclassical transport with ST paramagnetism
  – Drift wave stabilization and improved fast-ion confinement with diamagnetic well

• Pegasus minimum $|B|$ regime
  – $\beta_t \approx 100\%$ operation with HFS local helicity injection
  – Diamagnetic well with net-paramagnetism

• Microstability properties of Pegasus min-$|B|$ regime
  – GENE gyrokinetic simulations
  – Two tearing-parity modes with on- and off-midplane peaking
  – Particle, ion heat, and electron heat transport

• Discussion, plans, and summary
  – Probe measurements
Enhanced confinement with ST paramagnetism

- STs are strongly paramagnetic due to large helical pitch and $J_p$
  - $\beta_p \sim 0.3$ ($< 1$ is paramagnetic)

- Omnipotence in bad curv. region from paramagnetic $|B| \approx |B|(\psi)$
  - Reduced neoclassical transport due to vanishing banana orbit width

Y-K. M. Peng and D. Strickler, NF 1986

D. R. Smith, APS-DPP 2017
Enhanced confinement with diamagnetic $|B|$ well

- At high $\beta$, plasma digs a diamagnetic $|B|$ well
  - Gyromotion is diamagnetic
- Drift wave stabilization
  - $\nabla B$ reversal in magnetic drift
- Improved fast ion confinement
  - Expanded parameter space for:
    - fast ion trapping
    - co-and counter- fast ion confinement
- Reduced neoclassical transport
  - Smaller trapped particle fraction

D. R. Smith, APS-DPP 2017

J. Rome and Y-K. M. Peng, NF 1979
Drift wave stabilization with $\nabla B$ reversal

Toroidal ITG dispersion relation*

\[
\omega^2 \frac{T_i}{T_e} - 2\omega_d \omega + \frac{2\omega_d \omega_{*T}}{\text{key term}} - 7\omega_d^2 = 0
\]

with $\omega_d = \vec{k} \cdot \vec{v}_d$, $\vec{v}_d = \frac{v_d^2 + \mu B \nabla B}{\Omega} \frac{B^2}{B^2}$, and $\omega_{*T} = -k_\theta \rho_i \frac{v_{ti}}{L_T}$.

Typically $B(R) \propto 1/R$ with $\text{sgn}(\omega_d) = \text{sgn}(\omega_{*T})$ on LFS. ITG instability ($\text{Im}(\omega) > 0$) exists if $\nabla T_i$ $(L_T)$ is sufficiently large (small).

$\nabla B$ reversal on LFS gives $\text{sgn}(\omega_d) = -\text{sgn}(\omega_{*T})$ and all modes are strictly stable.

* neglect $k_\parallel$, assume $\omega \gg \omega_d$, and let $\nabla n \to 0$
HFS LHI enables $\beta_t \approx 100\%$ regime in Pegasus

- Enhanced stability at low $A$ (1.21) and high $\kappa$ (2.6) in Pegasus
- Local helicity injection (LHI) with high field side (HFS) injectors
  - Reconnection ion heating ($T_{i0} > T_{e0}$)
  - Suppression of low-m tearing modes
  - Edge current peaking with low $l_i$ (0.22)
- Kinetic-constrained equilibria

D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

Edge current peaking
High $\beta_t$ at high $aI_p/B_{t0}$ ($I_N$) in Pegasus

- Sykes-Troyon scaling
  - $\beta_{t,max} \propto aI_p/B_{t0}$
  - Normalized current: $I_N \equiv aI_p/B_{t0}$
  - Normalized beta: $\beta_N \equiv \beta_{t,max}/I_N$
    - Higher $\beta_N$ accessible at lower $A$ and/or higher $\kappa$

- $I_{TF}$ ramp-down to access high $I_N$
  - $I_N \propto I_p/I_{TF}$

D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

D. R. Smith, APS-DPP 2017
Diamagnetic well with net-paramagnetism in Pegasus

- Strong ST paramagnetism diminished by diamagnetic well
  - $\beta_p = 0.45$
- Magnetic well depth increases for higher $\beta_p$ or lower $B_t$

D.J. Schlossberg et al., PRL 2017
D.J. Schlossberg, Ph.D. Thesis 2017

D. R. Smith, APS-DPP 2017
Gyrokinetic simulations with \textit{GENE}

- \textit{GENE} evolves gyrokinetic equations in 5-dimensional phase space
  - Electromagnetic with $A_\parallel$ and/or $B_\parallel$
  - Local flux tube or nonlocal profiles
  - Linear/nonlinear initial value solver or linear eigenvalue solver (subdominant modes)
  - F. Jenko \textit{et al}, http://genecode.org/

Example \textit{GENE} simulation of finite-$\beta$ TEM turbulence at $A = 5.5$

M. J. Pueschel and F. Jenko, PoP 2010
Simulation parameters for Pegasus min-\(|B|\) regime

- **Flux tube**
  - \(\Psi_N = 0.6\) @ max \(\nabla B\) reversal
  - \(q = 3.5\) and \(\hat{s} = 0.55\)
- **Physics model**
  - \(\phi\) and \(A_{||}\)
  - \(m_e/m_d = 1/100\) (heavy electrons)
  - \(\nu_i^* = 0.07\)
  - \(\beta_e = 27\%\)
- **Species’ profiles**
  - \(a/L_n = a/L_{Ti} = a/L_{Te} = 3.15\)
  - \(T_e = T_i\)

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Linear eigenvalue solver indicates tearing-parity electron modes at $k_y \rho_i \sim 0.1$

Plots by GENE diagnostic tool
Preliminary nonlinear simulations indicate dominant electron electromagnetic heat flux

Longer run needed

Volume-averaged fluxes normalized to ion gyroBohm units

Large saturation value for electromagnetic component of electron heat flux $\approx O\left(10 \times Q_{i,gb}\right)$

Plots by GENE diagnostic tool

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Contour plots show microtearing-like eddies in $\phi$ with narrow $\Delta x$ and extended $\Delta y$

$L_x = 171\rho_i$ and $\Delta x/\rho_i = 0.67$  
$L_y = 628\rho_i$ and $k_y\rho_i = 0.01-0.32$

likely insufficient res.

Plots by GENE diagnostic tool

D. R. Smith, APS-DPP 2017
Particle and heat flux spectra show strong electromagnetic components at $k_y\rho_i \sim 0.1$

Plots by GENE diagnostic tool

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Particle flux due to low-k electrostatic component and ion magnetic flutter

Plots by GENE diagnostic tool

Cross-phase between perturbed fields

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Cross-phase and heat flux spectra indicate two modes are active.

- Both tearing parity and propagate in electron direction
- One mode generates particle and ion heat flux; the other mode generates electron heat flux
Modified equilibrium with monotonic $|B|$ shows larger growth rates

Slight RS and less edge current (cf. pg. 7)

Monotonic $|B|$ and $|B|'<0$ (cf. pg. 11)

Larger growth rates for unstable electron modes (cf. pg. 12)

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Discussion and plans

- Assess spectra, correlations, and mode structure of electric and magnetic fluctuations with probes
  - Core access
  - Configure for field-aligned or off-midplane measurements

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Summary

- ST paramagnetism and diamagnetic wells provide mechanisms for improved confinement
  - Drift wave stabilization with $\nabla B$ reversal
- Pegasus $\beta_t \approx 100\%$ regime exhibits diamagnetic well while remaining net-paramagnetic
  - Edge current peaking with HFS local helicity injection
  - D.J. Schlossberg et al., PRL 2017; D.J. Schlossberg, Ph.D. Thesis 2017
- GENE gyrokinetic simulations at min-$|B|$ region identify two tearing-parity modes at $k_y\rho_i \sim 0.1$
  - Tearing-parity modes linked to particle, ion, and electron heat flux
  - Subdominant mode with off-midplane peak
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