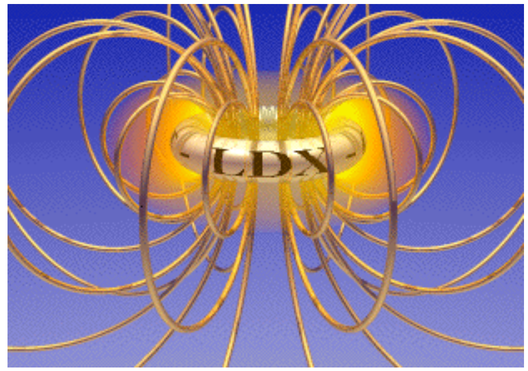

Overview of LDX Results

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Paper VP1.00020
Presented at the APS Meeting, Philadelphia, November 2, 2006

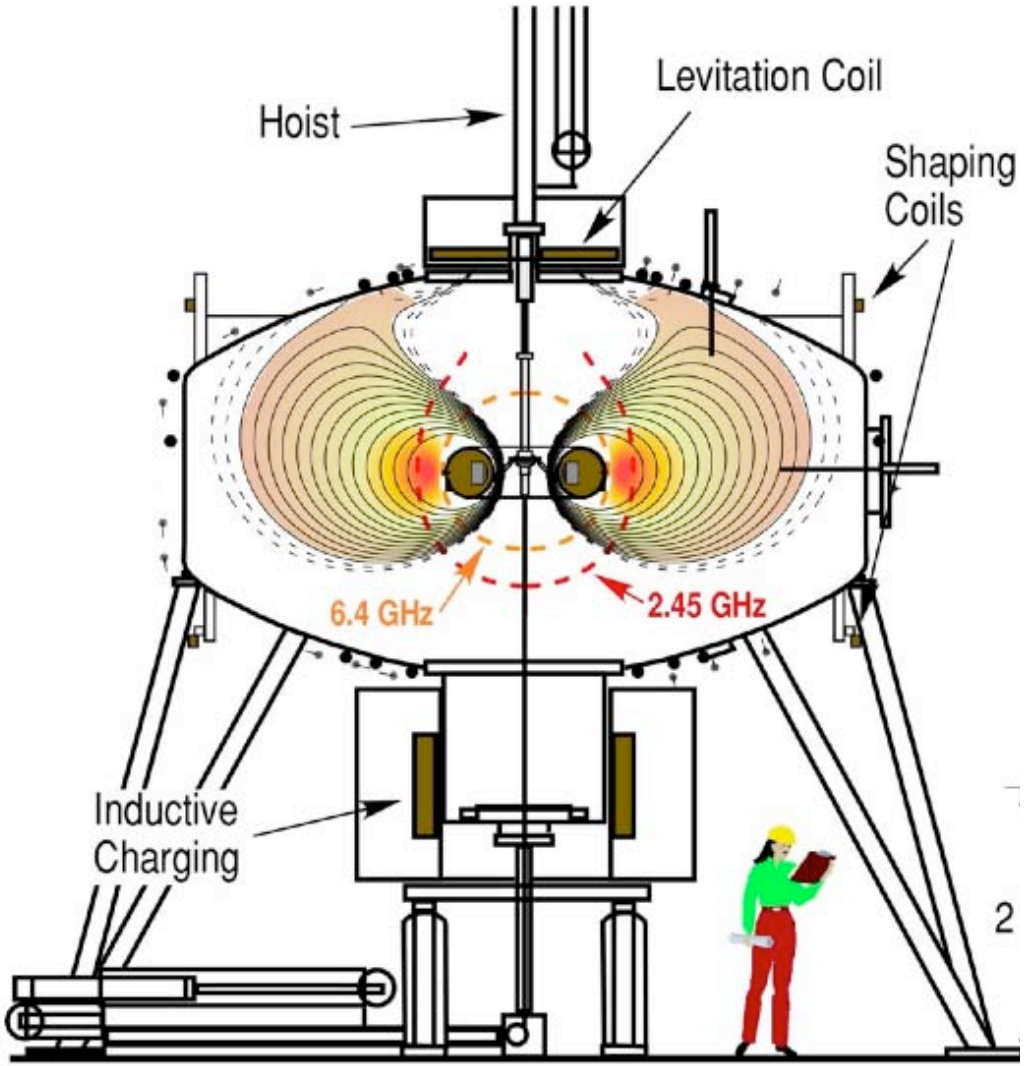
Outline of Poster

- Introduction to LDX
- MHD Equilibrium: High β results with ECRH
  - β_{max}~20% with P_{ECRH}~5 KW, $p_\perp / p_\parallel \approx 5$
- Hot electron interchange instability observed
  - Controlled by gas puffing affecting n_{eh}/n_i
- Low frequency drift modes
  - Controlled by gas puffing effecting grad(n_{eb})
- Power source implications
  - Ideal for advanced fuel DD reactor
- Future plans and conclusions

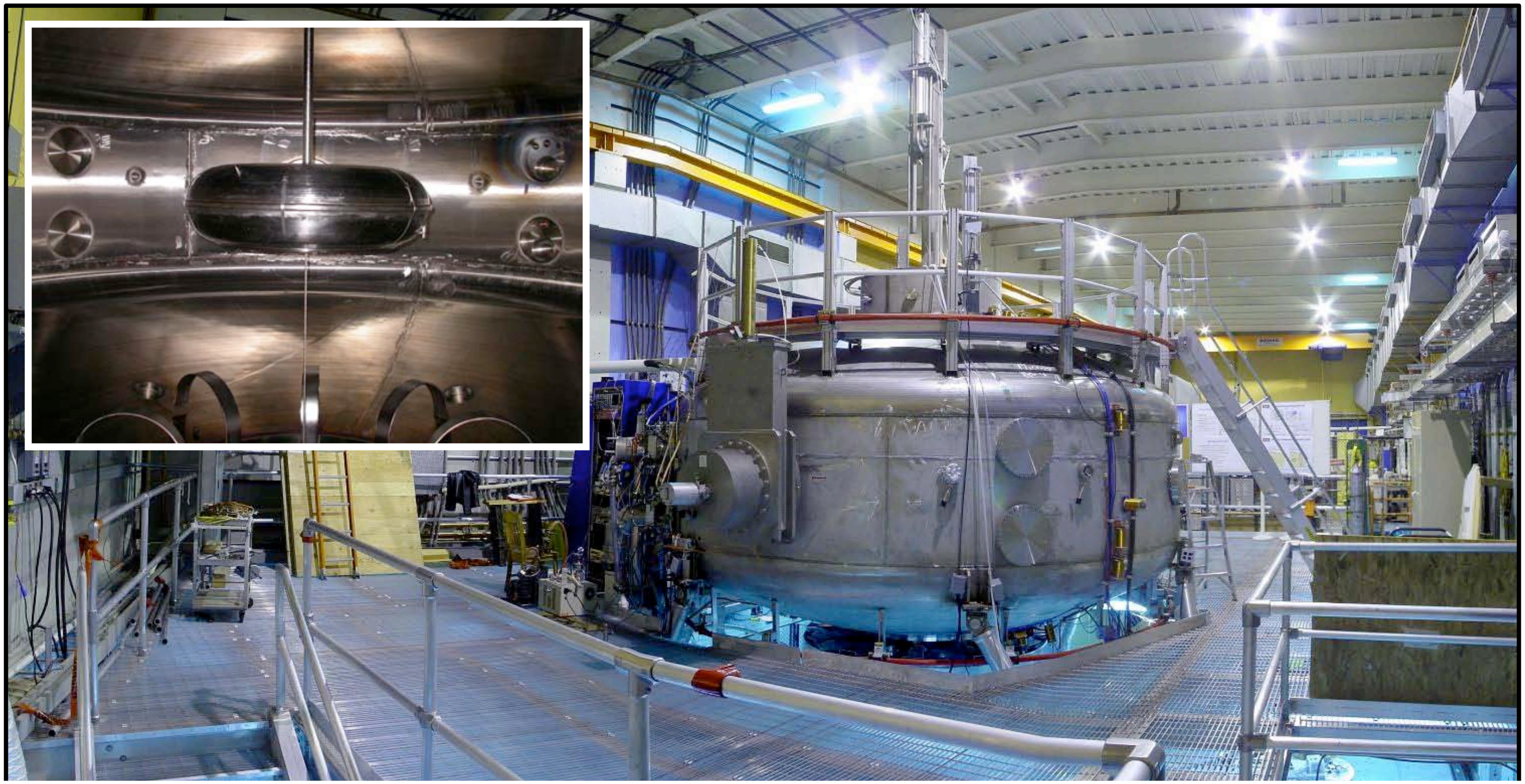
LDX Cross-Section/Operation

Supported Mode

1) Liquid Helium cools F-coil in charging station
2) Inductively charge F-coil (1 MA), C-coil discharges
3) Lift F-coil into position
4) Use ECRH (5 kW); create plasma
5) Run experiments safely for two hours
6) Lower F-coil back to re-charge or discharge into charging station



The Levitated Dipole Experiment (LDX)

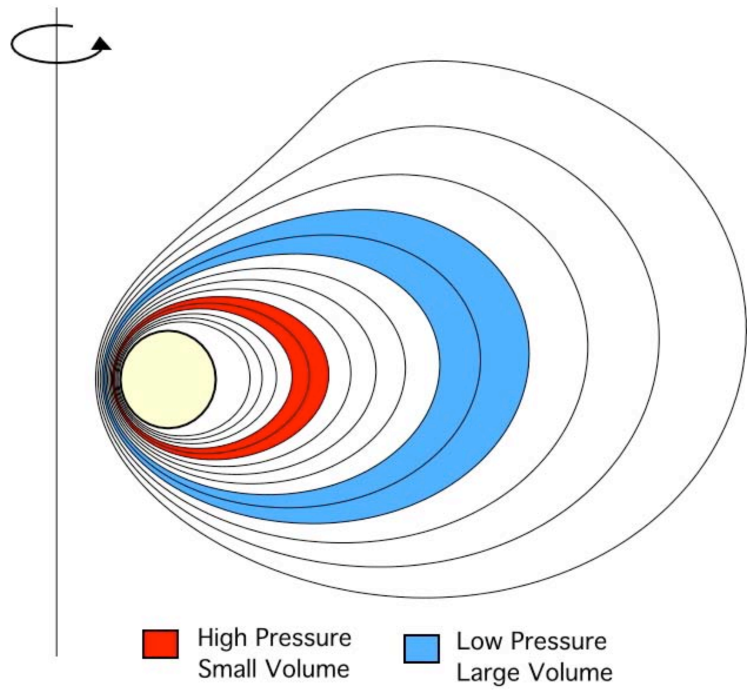


LDX utilizes 3 operating superconducting magnets

- Floating coil: (shown) Nb^3Sn (1.5 MA)
- Charging coil: NbTi (12 MJ, B_{max}=5.6T, 4.5K)
- Levitation coil: High Tc, BSSCO-2223 (20 kJ at 20K)

Ref: Garnier et al., to be published in Fusion Engineering and Design (2006).

Dipole Plasma Confinement



If $p_1 V_1^{\gamma} = p_2 V_2^{\gamma}$, then interchange does not change pressure profile.

For $\eta = \dfrac{d \ln T}{d \ln n} = \dfrac{2}{3}$, density and temperature profiles are also stationary.

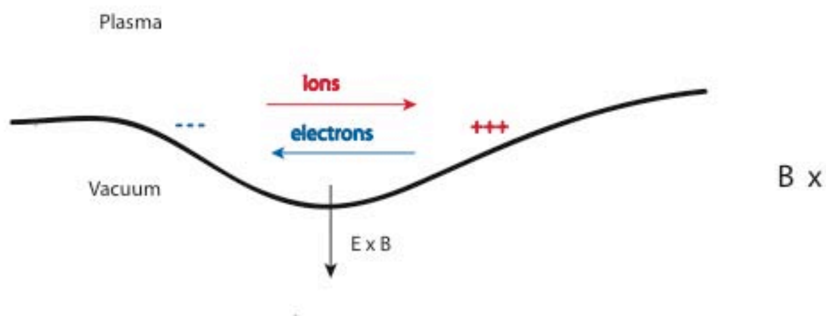
- Toroidal confinement without toroidal field
  - Stabilized by plasma compressibility
  - Shear free
- Poloidal field provided by internal coil
  - Steady-state w/o current drive
  - $J_{||} = 0$ ⇨no kink instability drive
  - No neoclassical effects
  - No TF or interlocking coils
  - ∇p constraint ⇨small plasma in large vacuum vessel
  - Convective flows transport particles w/o energy transport

Dipole Stability Results from Compressibility

- No compressibility:

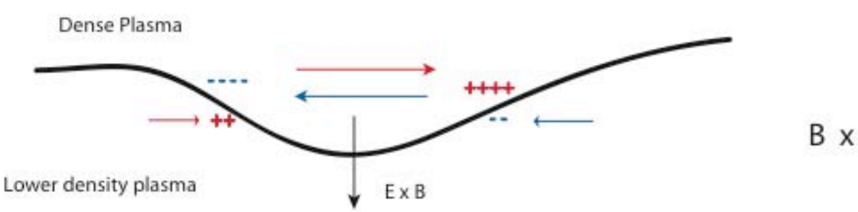
"bad" κ & ∇B drifts causes charge separation ⇨

V_{ExB} increases perturbation



- With compressibility: as plasma moves downwards pressure decreases. For critical gradient there is no charge buildup

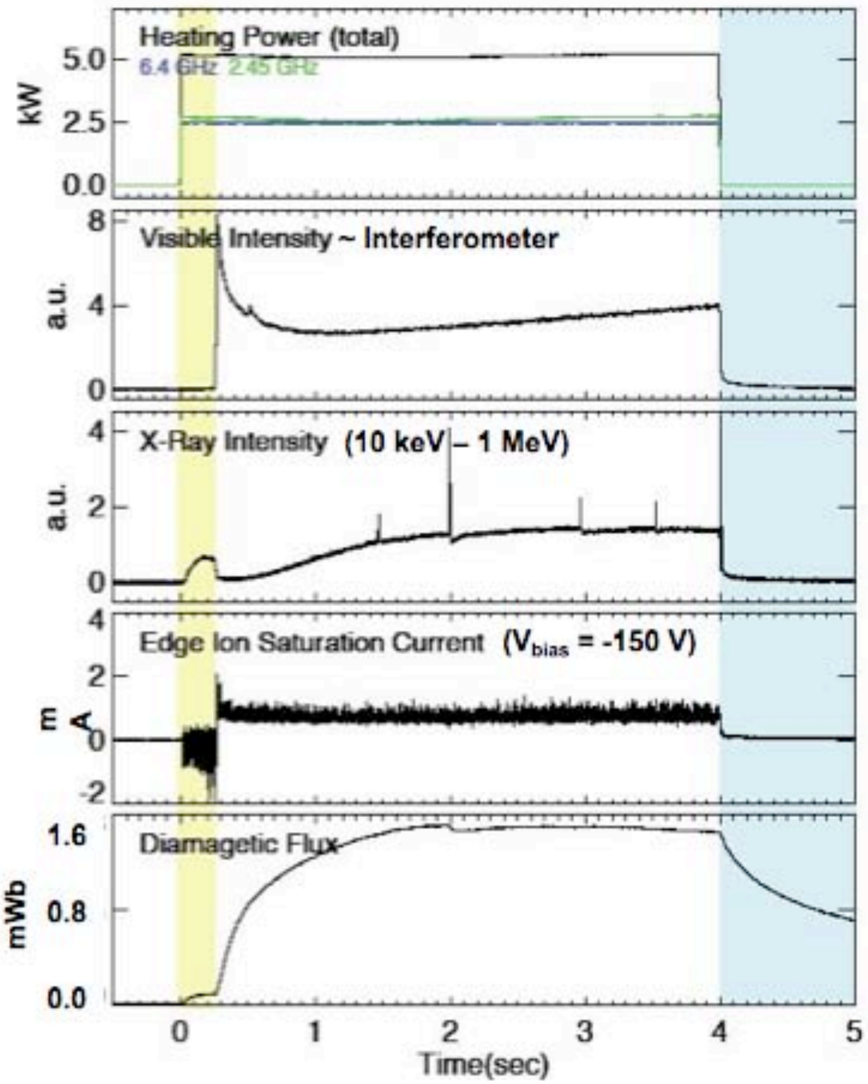
Density gradient.
Compressibility: Density decreases as plasma moved downward.



In bad curvature pressure gradient is limited to $-\frac{d\ln p}{d\ln V} < \gamma \qquad V = \oint dl/B$

Typical High Beta Discharge

- High beta maintained in quasi-steady state
- Plasma diagnostics:
  - External magnetic flux loops, pick-up coils and hall sensors
  - X-ray detectors
  - Visible diode array
  - Fixed & swept Langmuir
  - Interferometer
- HEI observed during three distinct intervals
  1. Unstable plasmas
  2. High beta plasmas
  3. Afterglow plasmas



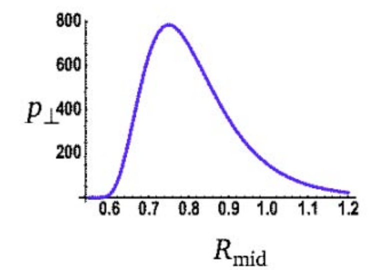
Magnetic Equilibrium Reconstruction

- Equilibrium reconstruction demonstrate that plasmas with high local beta are created in LDX
- X-ray images show the fast electrons to be localized at the ECRH resonance. The fast electrons are anisotropic.
- Anisotropic equilibria are well fit to magnetic measurements. The equilibria have pressure gradients that exceed the usual MHD instability limits.
- New magnetic diagnostics will be installed closer to the plasma to distinguish more details of the pressure profile.

Magnetic Reconstruction

- Use pressure model from [Connor,Hastie, PF**19**,(1976)],
  $p_{||}(\psi,B) = p_0(\psi)(B_0(\psi)/B)^{2p}$ and $p_\perp(\psi,B) = (1+2p)\ p_{||}(\psi,B)$
  p is a constant $p = 1/2\ (p_\perp / p_{||} - 1)$ and 0 subscript is for midplane.

- Parallel momentum balance gives $J_\phi = \frac{B\times\nabla p_\perp}{B^2} + (p_{||} - p_\perp)\frac{B\times\kappa}{B^2}$
- Use 26 magnetic measurements to reconstruct profile
- Pressure model: $p_0(\psi) = p_{peak}\frac{(\psi - \psi_{fcoil})}{(\psi_{peak} - \psi_{fcoil})}(\psi/\psi_{peak})^{4g}$
  optimize the fit varying p_{peak}, ψ_{peak} & *g*.

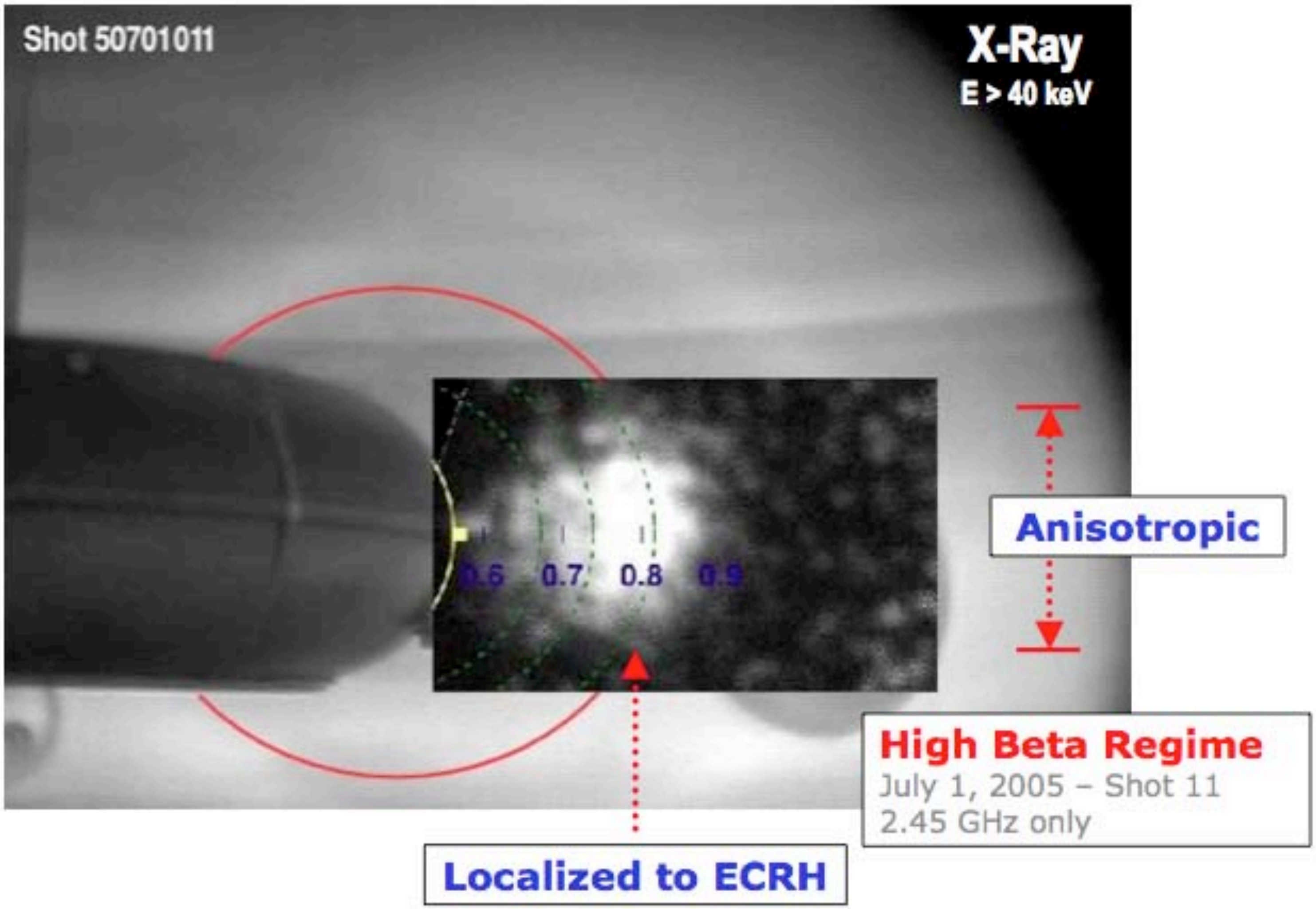


- We can obtain ψ_{peak} from X-ray measurements and find this yields best fits.

Anisotropic Interchange Stability

- Anisotropic momentum balance: $\frac{\partial p_{||}}{\partial B} = \frac{p_{||} - p_{\perp}}{B}$ $\frac{\partial p_{\perp}}{\partial B} = \frac{c + 2p_{\perp}}{B}$
- A convenient form for pressure is [Connor,Hastie, PF19,(1976)]:
  $p_{||}(\psi,B) = p_0(\psi)(B_0(\psi)/B)^{2p}$ and $p_{\perp}(\psi,B) = (1+2p)p_{||}(\psi,B)$
  $B_0(\psi)$ is the magnetic field on the outer midplane
- Defining $V_p = \oint d\ell / B^{(1+2p)}$ and $\hat{\gamma} = \frac{5}{3}\,\frac{1+(4/5)p}{1+(4/3)p}$ the interchange stability requirement becomes [Simakov, Hastie, Catto Ph.P 7 (2000)]
  $$-\frac{d\ln p_0}{d\psi} < \hat{\gamma}\frac{d\ln V}{d\psi} + 2p\frac{d\ln B_0}{d\psi}$$
- For p=0 (isotropic pressure) obtain: $-\frac{d\ln p_0}{d\psi} < \gamma\frac{d\ln V_0}{d\psi}$ $V_0 = \oint d\ell / B$
- For $p \neq 0$ find requirement: $-\frac{d\ln p_0}{d\psi} < \hat{\gamma}\,\frac{d\ln V_p}{d\psi} + 2p\frac{d\ln B_0}{d\psi}$
  ∴ Evaluating RHS for p=2 critical gradient increases 3%. Anisotropy does not significantly change stability limit.

Anisotropic Fast Electrons Localized to ECRH Resonance



Anisotropy Significantly Changes Pressure Profile Height

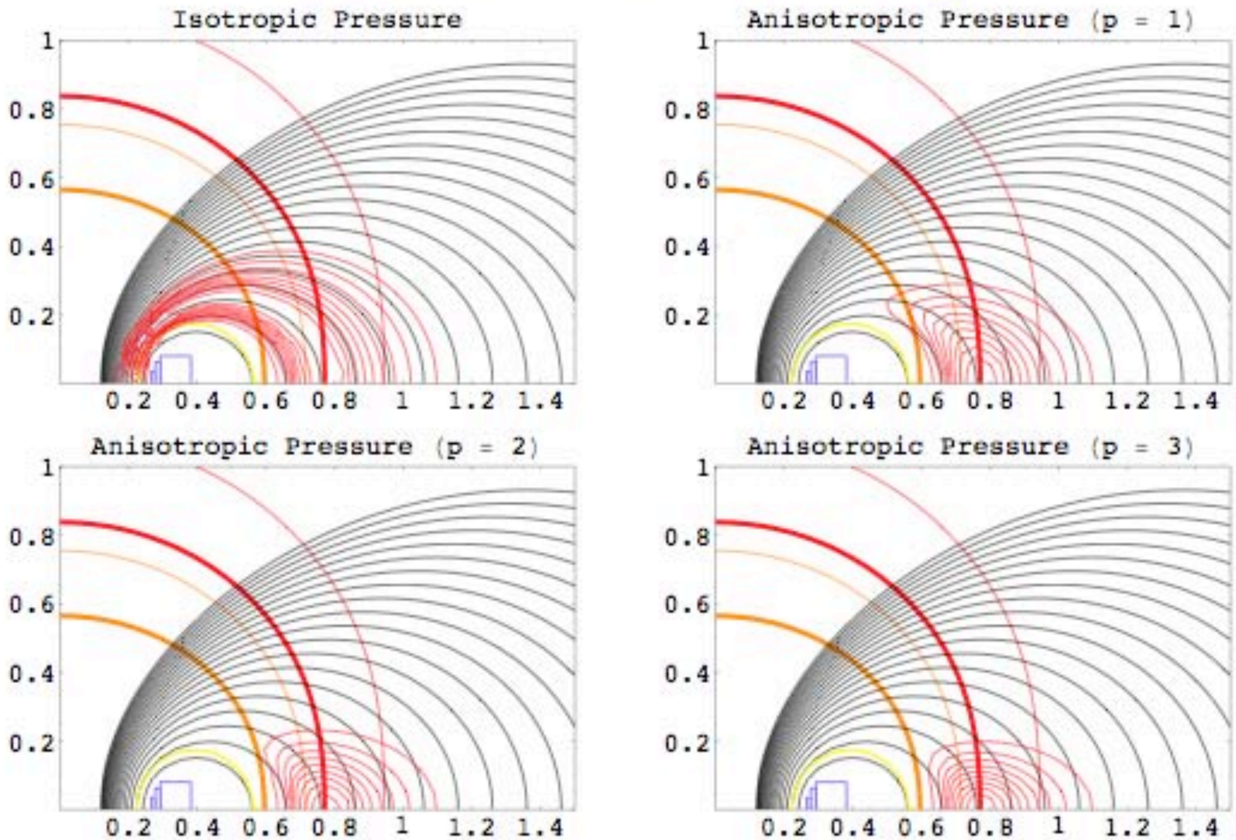
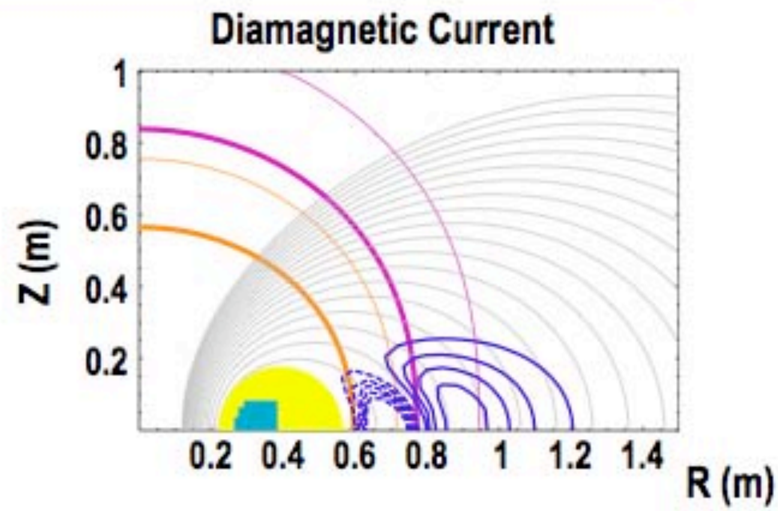


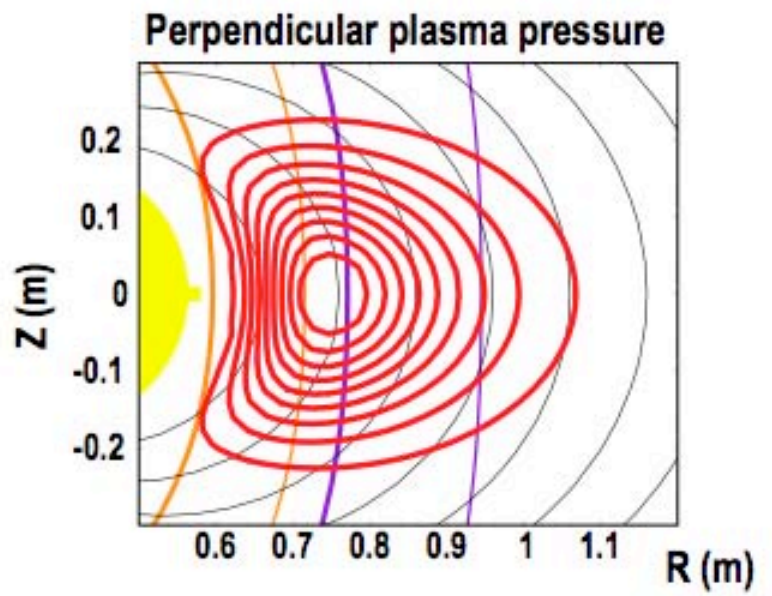
Figure 1: Example anisotropic pressure profiles with $G(\psi)$ defined with $g = 4$ and ψ_0 located at $r = 0.77$ m. The anisotropy parameter was $p = 0$, 1, 2, and 3.

Anisotropic Magnetics Reconstruction

- Shot 50513029
- Fixed from imaging
  - R_{peak} = 0.75 m
  - $p_{\perp} / p_{\parallel} = 5$
- Magnetics fit
  - E_{total} = 330 J with 5 kW input
  - I_p = 3.4kA
  - β_{max} ~ 20%
- g=2.1*γ,

∇p exceeds MHD





Hot Electron Interchange Stability

- **Bulk plasma must satisfy MHD adiabaticity condition**

Rosenbluth and Longmire, (1957)

$$\delta\left(p_b V^\gamma\right) = 0$$

where $V = \oint \frac{d\ell}{B}$ or $-\frac{d\ln p_b}{d\ln V} < \gamma^{-1}$

- **Fast electron stability enhanced due to coupling of fast electrons to background ions**

Krall, (1966)

$$-\frac{d\ln n_{eh}}{d\ln V} < 1 + \frac{m_\perp^2}{24}\frac{\omega_{dh}}{\omega_{ci}}\frac{N_i}{N_{eh}}$$

HEI Appear Under Three Conditions

See poster VP1.00024, Ortiz et al

- Continuous Bursts:
  - Unstable plasmas, low beta, low-density
- Minor Relaxation:
  - Short, low-amplitude, remains at high **beta**
- Total Energy Collapse:
  - Intense, large-amplitude, rapid density & fast electron beta loss

Physics of Hot Electron Interchange (HEI) Mode

- Interchange instability driven by fast electrons
- HEI instability resonates with the drift motion of fast electrons. Causes a REAL frequency, $\omega \sim m\ \omega_d$
- Stable beyond the usual ideal MHD Limit
- As documented in low **beta** dipole experiment (CTX), HEI has the following characteristics:
  - Rapid outward transport with broad frequency spectrum
  - Dominated by low-m numbers
  - Broad global radial mode structure
  - Nonlinear frequency sweeping corresponds to radial propagation of "phase-space holes"

High **Beta** Control with Gas Puffing

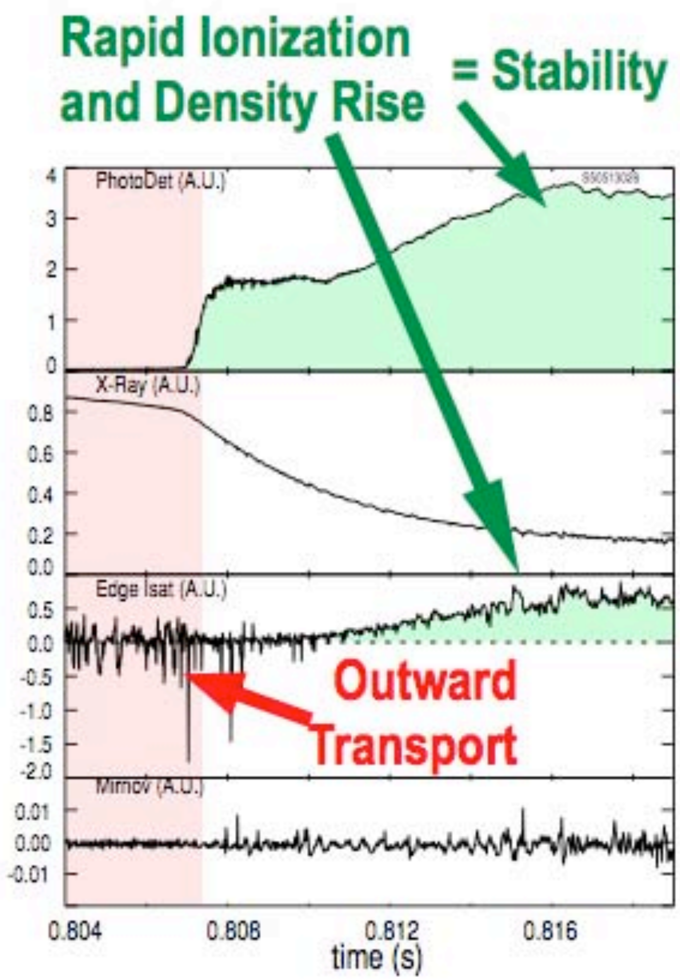
- With sufficient neutral gas pressure, plasma enters high **beta** regime

- With insufficient neutral gas pressure, the plasma will become unstable (sometimes violently)

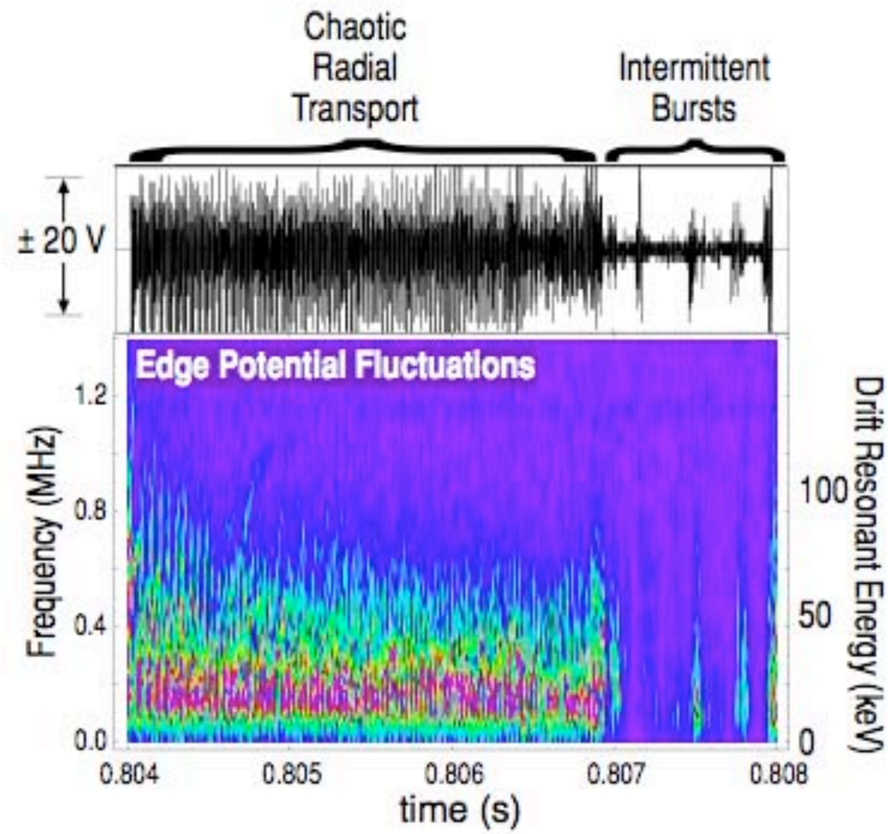
- A hysteresis in the observed thresholds implies the bifurcation of the low density unstable and stable high **beta** regimes

- Consistent with theory of the Hot Electron Interchange (HEI) instability

High-β Plasma Begins Upon HEI Stabilization



In unstable regime, quasi-continuous HEI instability prevents plasma build-up ...

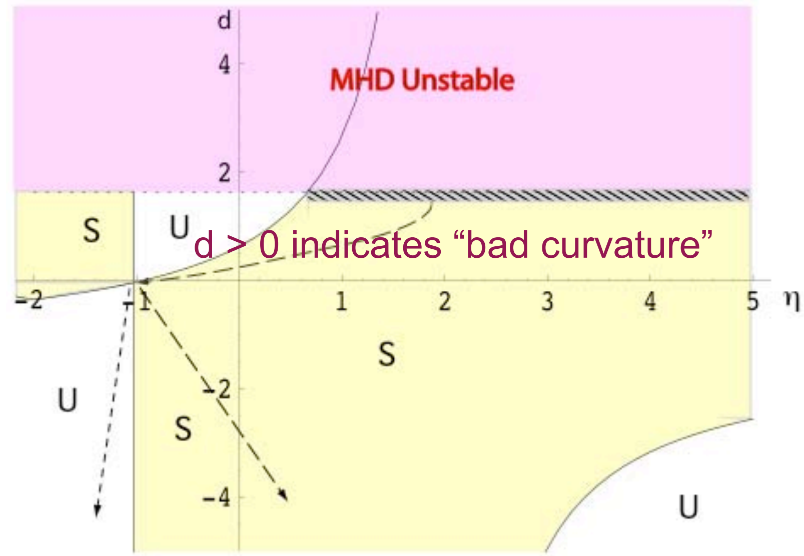


Plasma can be unstable to drift frequency mode

- Entropy mode properties [1]
  - Plasma beyond pressure peak stable for $\eta > 2/3$
  - Frequency $\omega \sim \omega_* \sim \omega_d$

    ω increases with ∇n_e and T_b
  - Instability will relax plasma towards d=5/3, η=2/3.

  i.e. it tends to steepen ∇n_e
- Stability in good curvature region depends on sign of ∇n_e
- Mode appears at both high and low collisionality [2].
- Electrostatic "entropy" mode persists at high β [3].
- Linear theory not always relevant to real plasmas



$$\eta = d\ln T / d\ln n_e$$

$$d = -d\ln p / d\ln V = \omega_{*i}(1+\eta)/\overline{\omega_d}$$

$$V = \oint dl/B$$

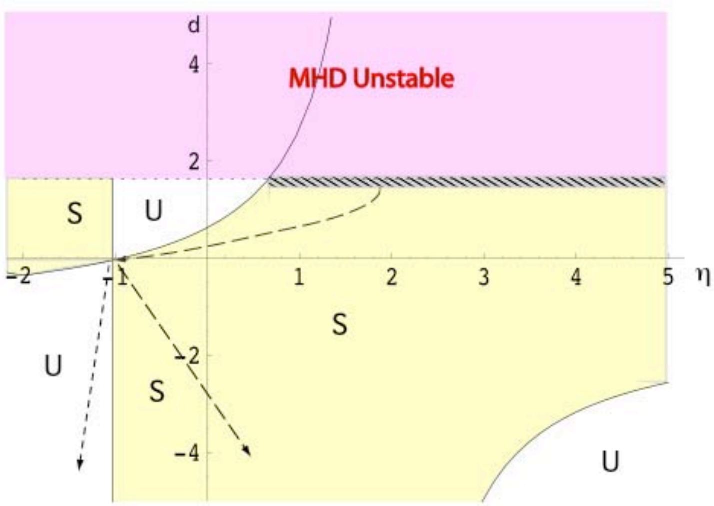
Some references:

1. Kesner, PoP **7**, (2000) 3837.
2. Kesner, Hastie, Phys Plasma **9**, (2002), 4414
3. Simakov, Catto et al, PoP **9**, (2002), 201

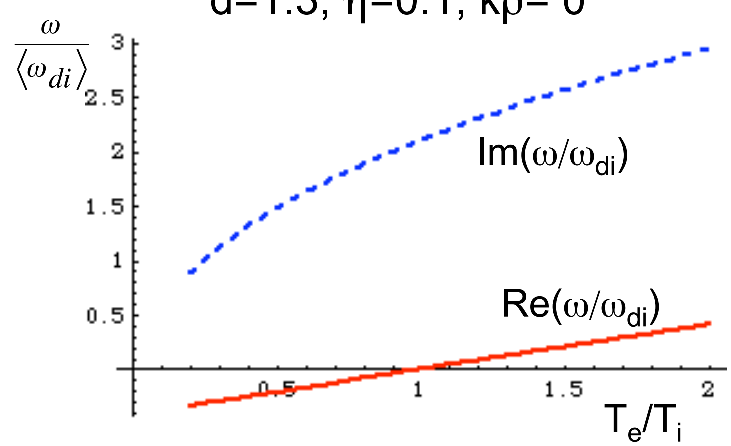
Plasma can be unstable to drift frequency mode

- Entropy mode is a drift frequency, flute mode.
- Dispersion Relation $\hat{\omega} = \omega / \langle \omega_{di} \rangle$, $d = -\frac{d \ln p}{d \ln V} = (1+\eta) \frac{\omega_{*i}}{\langle \omega_{di} \rangle}$, $\eta = \frac{d \ln T}{d \ln n}$

$$\hat{\omega}^2 \left(\frac{d \ln p}{d \ln V} + \frac{5}{3}\right) + \frac{5\hat{\omega}}{3}\left(\frac{T_e}{T_i} - 1\right) \left(\frac{d \ln p / d \ln V}{1+\eta} + 1 \right) + \frac{5}{9}\frac{T_e}{T_i} \left(\frac{d \ln p}{d \ln V} \frac{3\eta - 7}{\eta + 1} - 5 \right) = 0$$



d=1.3, η=0.1, kρ= 0

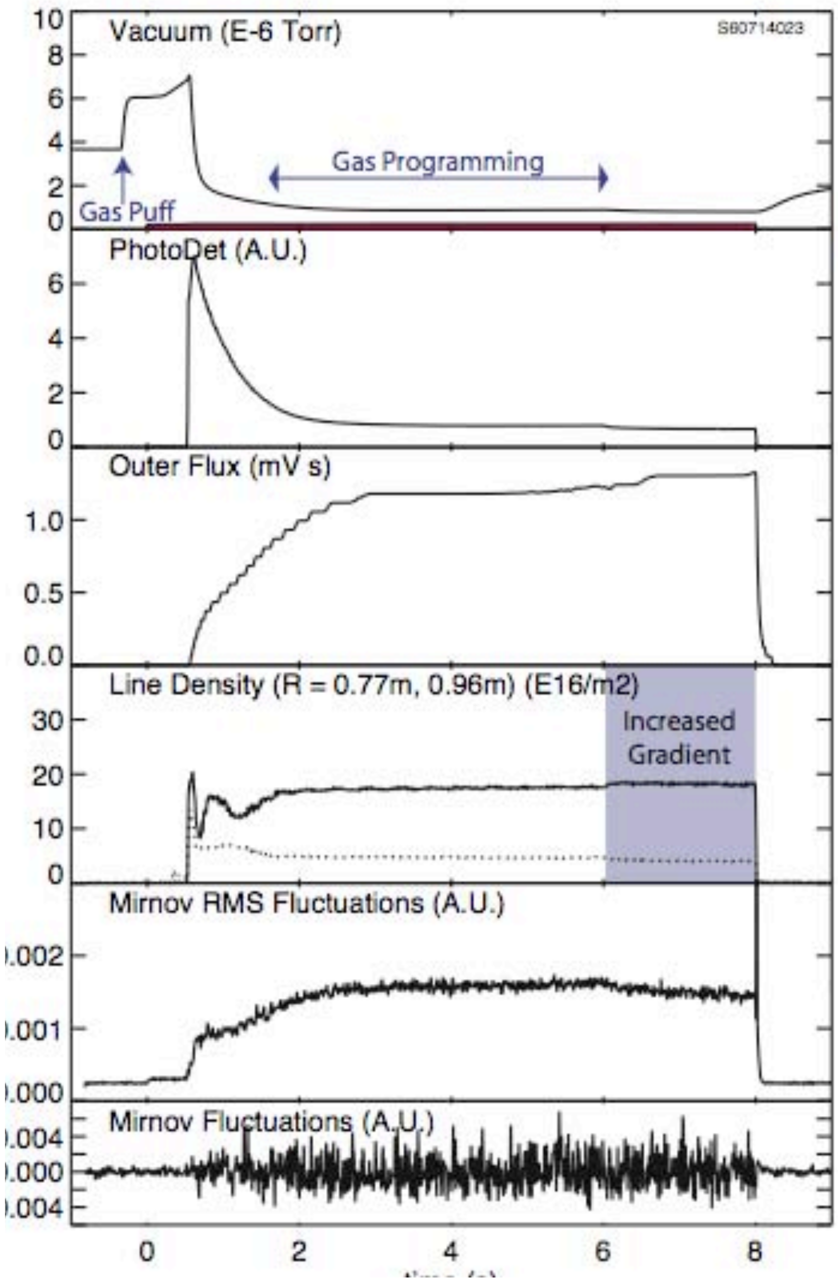


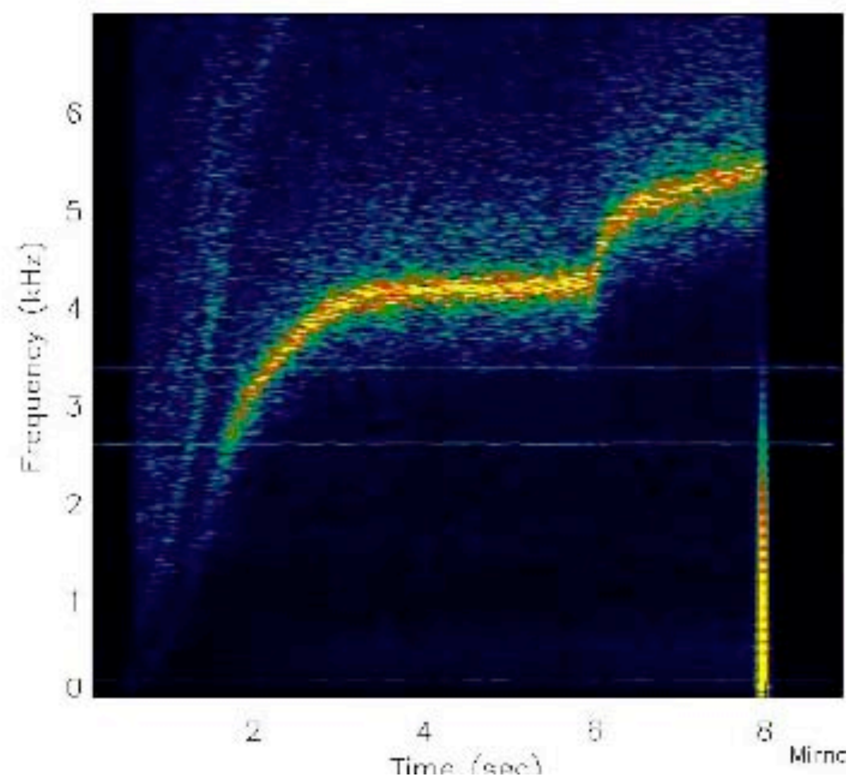
Real frequency is introduced for $T_e < T_i$

Quasi-coherent low frequency mode

- Under good vacuum conditions $p_0 < 10^{-6}$, quasi-coherent low frequency activity observed: $f < 10$ kHz
- Mode seen on Mirnov, edge probes, photodiodes, interferometer.
- Gas fueling can change frequency or stabilize mode
  - Cutoff fueling ⇨mode frequency rises
  - Sufficient fueling ⇨quasi-coherent mode disappears
    - Gas fueling tends to flatten the density gradient as seen in 60 GHz μ–wave interferometer array.
- Mirnov array indicates toroidal mode # m=1

Low Frequency Fluctuations Modified by Density Gradient





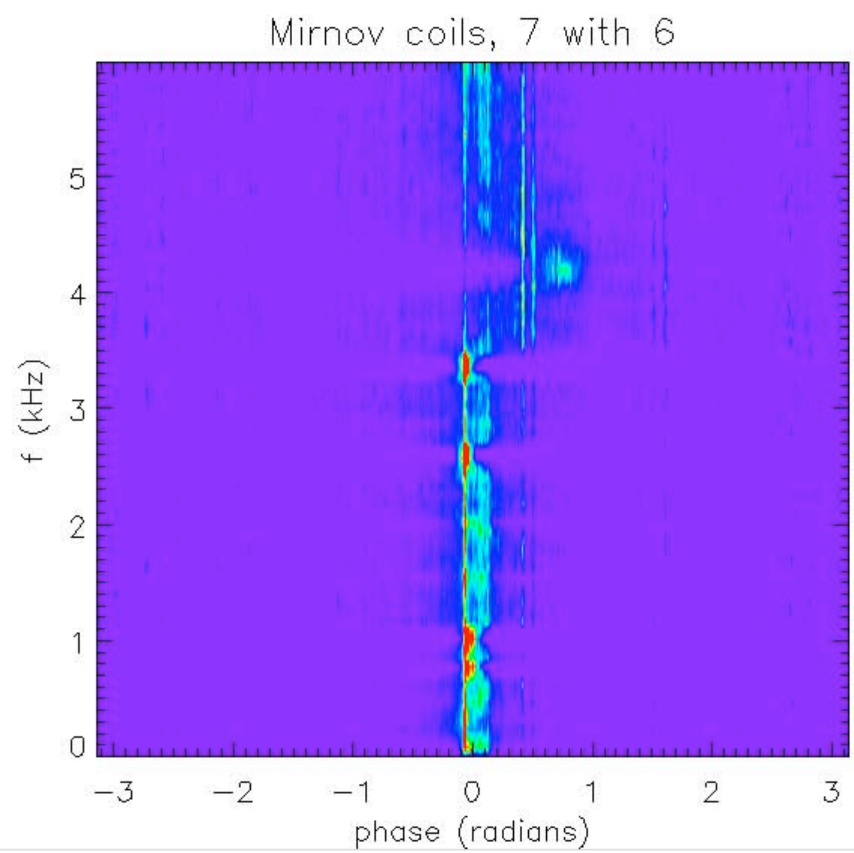
Mode appears to be m=1

Use 8 Mirnov coils separated by 45 degrees

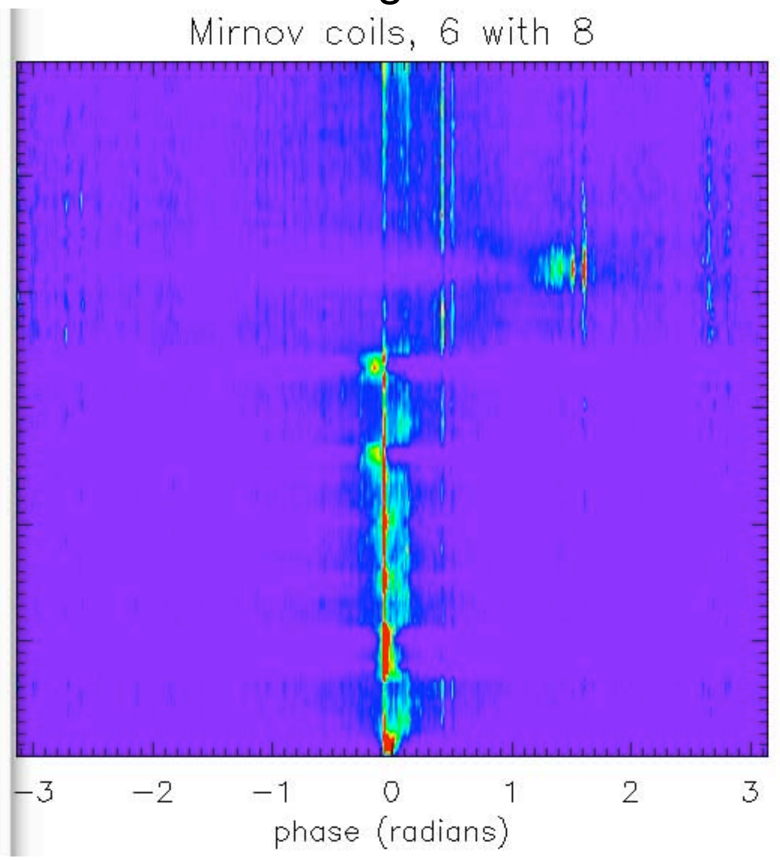
Ref: Beall, Kim, Powers, J App Phys 6 (82) 3933.

For 5<t<6s,

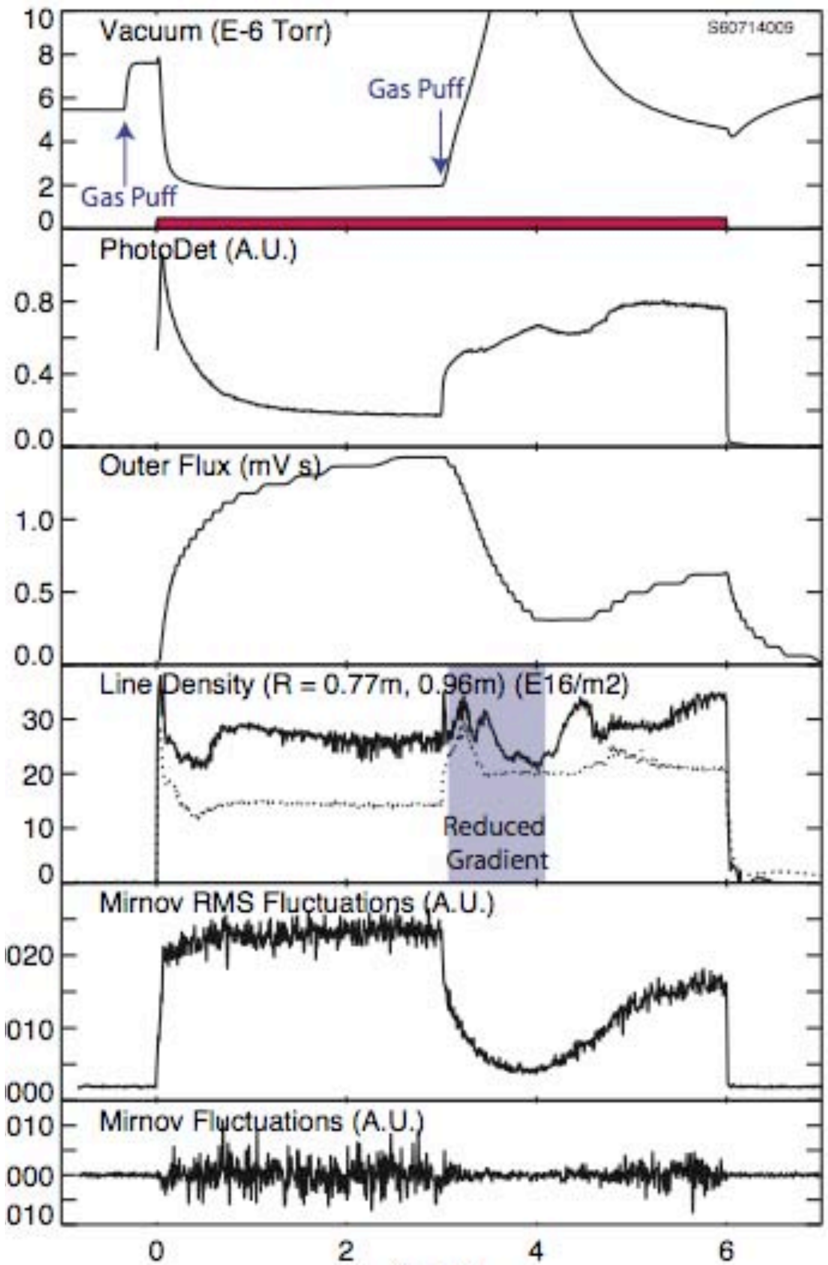
coil separation 45 deg

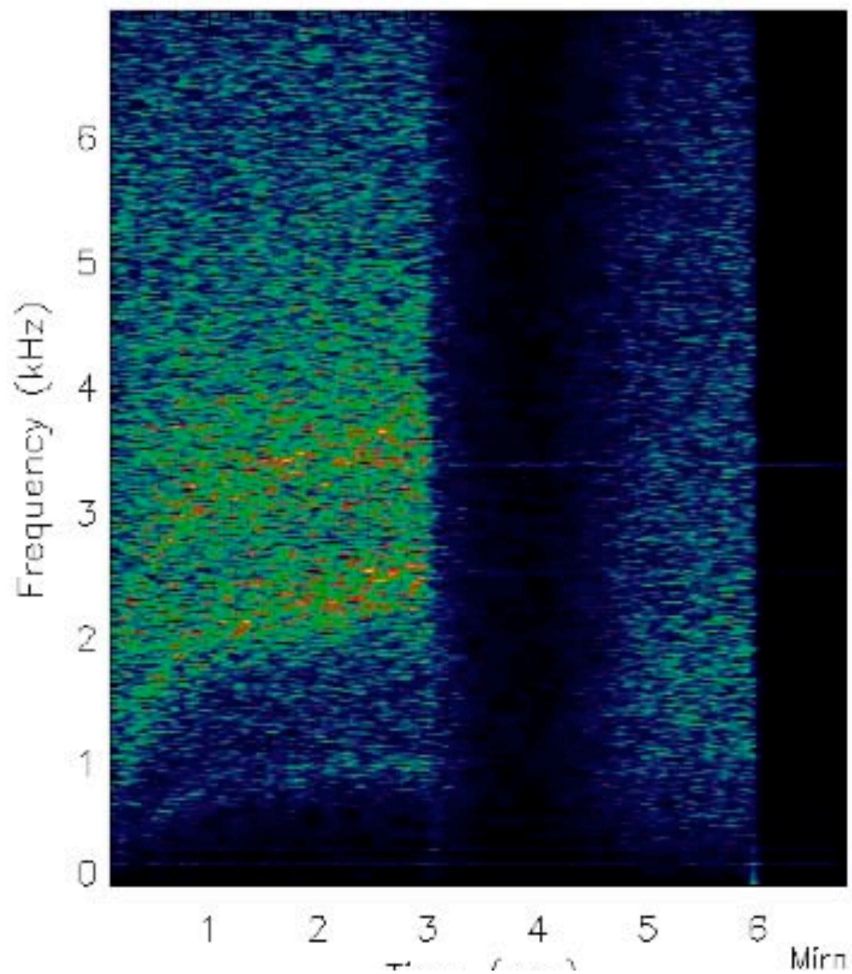


90 deg



Fluctuations Suppressed wit Flat Gradient





Requirements for "Ideal" fusion power source

- MHD does not destroy confinement (no disruptions)
- Intrinsically Steady State
- High β for economic field utilization
- High τ_E necessary for ignition
  - Ignition in small device
  - Advanced fuels (D-D, D-^{3}He)
- Low τ_P for ash removal
- Low divertor heat load - want plasma outside of coils for flux expansion
- Circular, non-interlocking coils

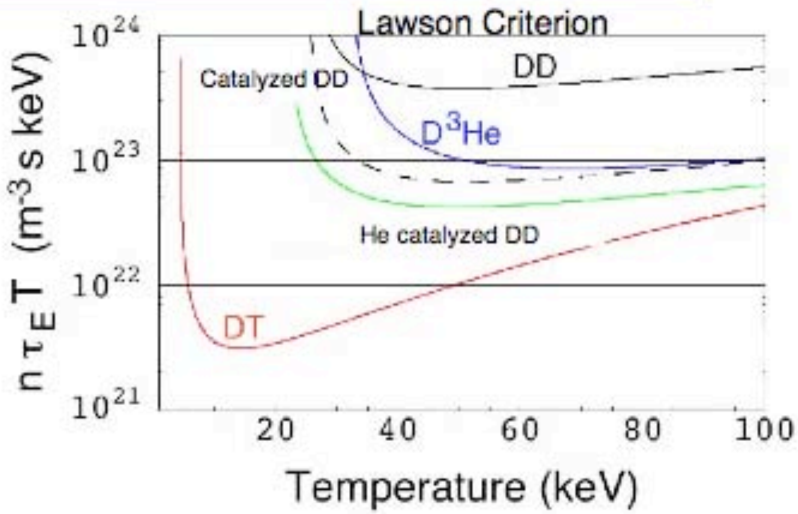
Levitated dipole may fulfill these requirements if the physics and technology does not produce show-stopper.

Fusion reactions of primary interest

$$D + T \rightarrow \ ^4He(3.5\ MeV) + n(14.1\ MeV)$$
$$D + \ ^3He \rightarrow \ ^4He(3.6\ MeV) + p(14.7\ MeV)$$
$$D + D \xrightarrow{50\%} \ ^3He(0.82\ MeV) + n(2.45\ MeV)$$
$$D + D \xrightarrow{50\%} T(1.01\ MeV) + p(3.02\ MeV)$$

- D-T: Highest fusion x-section
  - Must breed tritium
  - 14.1 MeV neutrons (a) Damage and activate structure
    (b) Necessitate a massive shield
- D-^{3}He: Lower x-section, reduced neutron flux
  - ^{3}He source requires lunar mining
- D-D: Smallest x-section - Ignition requires decoupling of particle and energy confinement [Ref: Nevins, JFE **17** (1998) 25.]
  - Plentiful fuel source
  - Can eliminate energetic energetic neutrons if we can eliminate tritium
  - Fusion products mostly charged particles - eliminate blanket and shield
    - **high power/volume**

Helium Catalyzed D-D (self fueled D-^{3}He cycle)



- Primary D-D reaction produces 3.65 MeV plus T & ^{3}He.
- Permit the ^{3}He to burn.
  - D-^{3}He produces 18.3 MeV.
- Remove T and re inject the ^{3}He decay product (T -> ^{3}He + e^-).
  - Some T will fuse (4 to 6%) before removal, (during slowing down).
- This produces 22 MeV per DD fusion with 94% of power in charged particles (along with a 2.45 MeV neutron)
  - Surface heating -> thin walled vessel with high power density
  - 2.45 MeV neutron produces little structural damage

Ref: Sawan et al, Fus Eng and Design **61-62** (2002), 561.

Kesner et al., Nuc Fus **44** (2004) 193.

Next Step: Levitation

- Fast electron losses to supports eliminated
  - Pitch angle scattering reduce anisotropy, not beta
  - Anisotropy driven modes relax plasma without losses
- Bulk plasma confinement also improved
  - Stable fast electron fraction with lower neutral gas fueling ?
- Radial transport driven profiles
  - Single peaked, broader (more stable) profiles

➡ **Expectation of improved stability and confinement**

  - Contrast with supported operation will further understanding of unstable/high-β regime bifurcation.

Conclusions and Future Plans

- LDX is novel in both physics and technology
  - Only superconducting experiment in US program
- LDX began operation on 2004: Observe 3 operating regimes
  - In high n_e regime β~20%, T_{eh}~50 KeV.
  - Observe MHD events (HEI limits).
  - Multiple frequency ECRH provides profile control.
  - Can operate with magnetic separatrix
    Shaping coil permits variation of flux expansion.
- Levitation experiments planned for late fall
  - Will eliminate pitch-angle scatter as loss mechanism
  - Expect substantial increase in plasma parameters
  - 10.5 GHz to be brought on line
    - Later 18 and 28 GHz