PLANNED MHD STABILITY STUDIES IN THE UPGRADED COMPACT AUBURN TORSATRON (CAT)

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- **Current-driven instabilities and disruptions will be experimentally investigated in current-carrying stellarator plasmas**
- **Results will lead to better understanding of how much bootstrap current can be accommodated in compact stellarator configurations.**
- **Studies will be carried out with ohmic current in a flexible, university-scale torsatron.**

MOTIVATION FOR STELLARATOR DISRUPTION STUDIES

- **A major focus of the US stellarator program is the exploration of high β, low aspect ratio stellarators with quasi-axisymmetric (QA) and quasi-omnigeneous (QO) configurations for improved confinement.**

- **Unlike W7-X, these advanced compact configurations generally cannot be optimized for high performance with minimal pressure-driven currents (Pfirsch-Schlüter and bootstrap).**

  - **In contrast to QH and QO, bootstrap current in QA configuration is comparable to that in tokamak.**

  - **The bootstrap current may be exploited in the QA stellarator to reduce the required external rotational transform, thus simplifying the coil design in low aspect ratio experiment (NCSX).**

- **Current-driven MHD instabilities and disruptions triggered by finite bootstrap and Pfirsch-Schlüter current may limit the β in compact configurations, as well as in more conventional high β stellarators such as LHD.**

It must be demonstrated that current-carrying compact stellarators can be made resistant to serious disruptions during all phases of the discharge including both start-up and high β operation with fully-developed bootstrap profiles.

- **Only if disruptions can be eliminated or controlled will the compact stellarator be seen as a significant advancement in toroidal magnetic confinement.**

- **Earlier studies on the JIPP T-2 and W7-A show evidence of tearing modes, but major disruptions are suppressed if the vacuum rotational transform $\iota_V(a) \geq 0.14$. Stellarator operation with current-carrying discharges free of external kinks at $q_{edge} \leq 2$ demonstrated.**

- **Current-carrying plasmas in the L-2 and Cleo stellarators show evidence of double tearing modes in discharges with non-monotonic rotational transform profiles.**

- **Recent disruption studies on W7-AS**

- **Studies on CAT will extend our understanding of the stellarator disruption (stability boundaries, severity of disruption) to compact configurations with moderate shear, similar to NCSX.**

  - **Flexibility of CAT configuration provided by two independent sets of helical field windings.**

  - **CAT experiments are comparable in scale to MHD stability studies on the Columbia University High-Beta Tokamak (HBT-EP).**

PLAN OF UPGRADE

1. **Increase magnetic field from B = 0.1 T to 0.5 T.**
   - **10 motor generators (each 1 MW) donated by MIT and University of Wisconsin.**
   - **Existing magnet coil supports to be strengthened.**

2. **RF plasma generation by non-resonant ICRF (5-10 MHz) using Nagoya Type-III antenna.**
   - **Efficient over range of magnetic field (in contrast to ECH):** $\omega \leq \omega_{ci}$
   - **Successfully proved in CHS low field, high-β studies.**
   - **Fast wave mode conversion electron heating to raise β will be explored.**

3. **Addition of ohmic transformer and equilibrium field system.**
   - **OH solenoid and coils to be installed.**
   - **OH solenoid powered by capacitor banks.**
   - **EF to use existing spare vertical field coil set.**

CAT → CAT-Upgrade

	CAT	CAT-Upgrade
Major Radius	0.53 m	0.53
Minor Radius	0.17 m	0.17 m
Avg. Plasma Radius	0.11 m	0.11 m
B_O	0.1 T	0.5 T
Electron Density	8×10^{16} m^{-3}	5×10^{18} m^{-3}
Electron Temperature	5-10 eV	100-200 eV (ISS-95)
Ion Temperature	0.25 eV	< 50 eV
Plasma Current	0	25 kA
Edge Transform ι(a)	0.15 – 0.7	0.15 – 0.7 (vac); 0-0.5 (w/ OH)
Input Power	2 kW (ECH)	200 kW (ICRF); 50 kW (OH)
β (%)	0	0.5
Pulse duration	120 s	0.4 s; 0.1 s w/ OH

PLANNED STABILITY STUDIES ON CAT

- **Add ohmic current to RF-generated target plasmas**
  - **$P_{OH} < P_{RF}$**
  - **Current profile may be varied over magnetic skin time scale (5 ms) by current ramping & current reversal.**
  - **Diagnose stability with Mirnov loops and SX diode array**
- **Measure rotational transform profile to compare with cylindrical and 3-D stability theory**
  - **Motional Stark Effect (MSE) with LIF on low current hydrogen beam (under development by F. Levinton, [Rev. Sci. Instrum. 70 810 (1999)] for field line pitch measurements in low field ($B \leq 0.5$ T) devices)**
- **Investigate current stability in presence of controlled magnetic islands**
  - **Amplitude and phase of island controlled by resonant coils as in previous studies on CAT.**
  - **No close-fitting conducting wall in CAT to provide wall stabilization.**
- **3-D ideal stability will be modeled with the Terpsichore code in collaboration with A. Cooper of Lausanne and A. Reiman of PPPL.**

STABILITY OF CURRENT-CARRYING STELLARATOR PLASMAS

Toroidal plasma current in tokamaks and stellarators is a source of free energy for MHD instabilities.

Free potential energy of ideal and tearing modes:

$$\delta W = -4\pi^2 R_o \int_0^b r\,dr \left[\left(\frac{d\psi}{dr} \right)^2 + \frac{m^2}{r^2}\psi^2 + \left(\frac{mr}{m\iota(r) - n} \right) \frac{\mu_o R_o}{B_o} \frac{dj}{dr} \psi^2 \right]; \qquad \psi = ir B_r \text{ (perturbed helical flux function)}$$

Euler equation of free energy integral [K. Matsuoka et al., Nucl. Fusion **17**, 1123 (1977)]:

$$\frac{1}{r}\frac{d}{dr}\left(r \frac{d\psi}{dr} \right) - \frac{m^2}{r^2}\psi - \left(\frac{mr}{m\iota(r) - n} \right) \frac{\mu_o R_o}{B_o} \frac{dj}{dr} \psi = 0$$

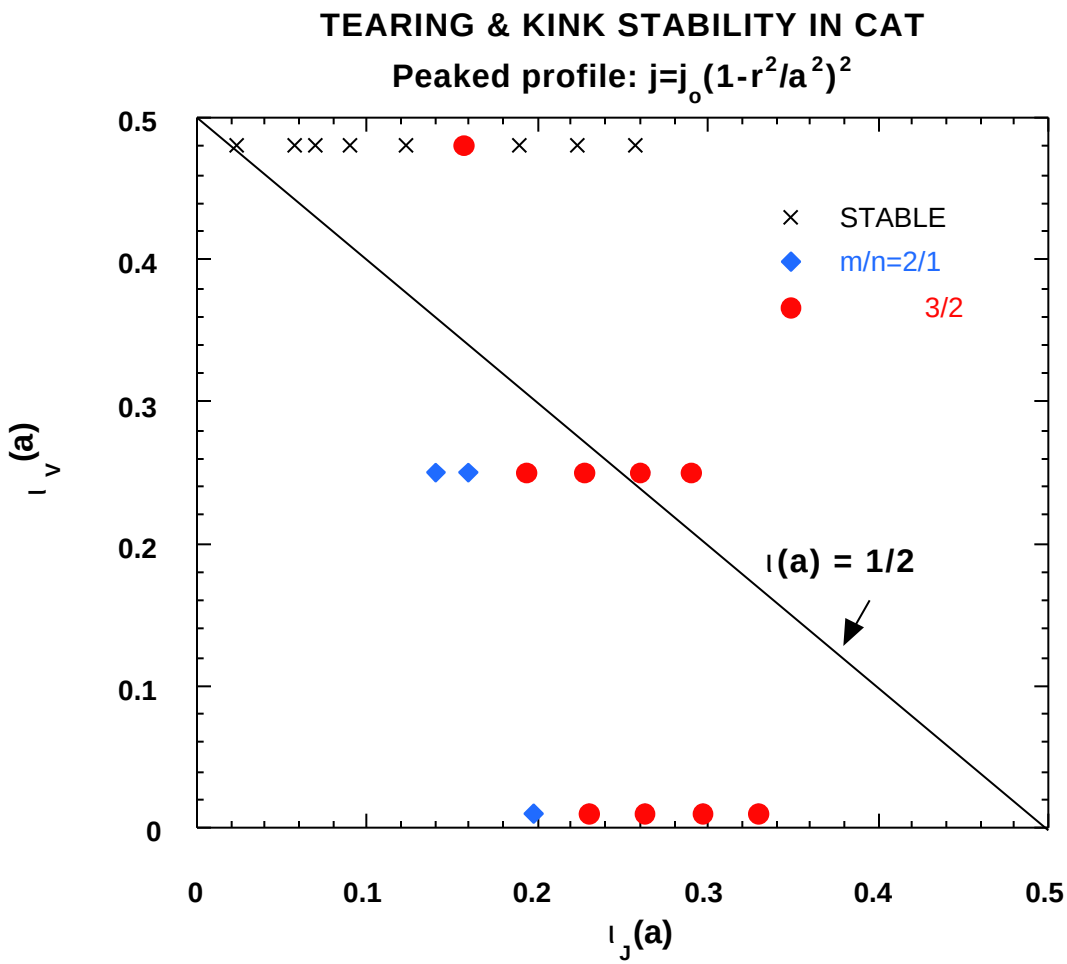
Tearing modes

From the solution of ψ(r), we calculate the stability parameter Δ′ :

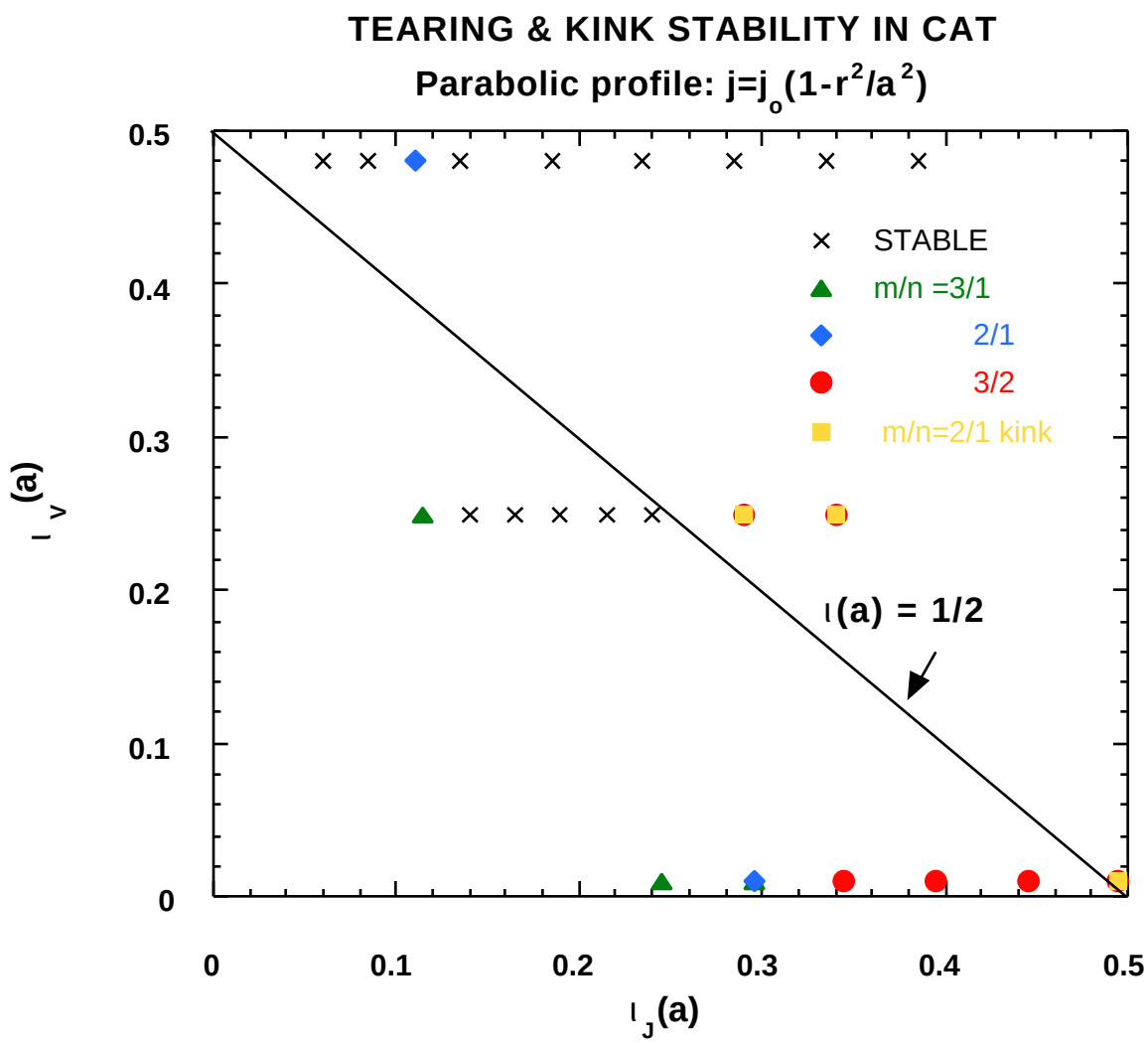
$$\Delta'(w) = \frac{1}{\psi(r_s)} \left[\frac{d\psi(r_s + \varepsilon)}{dr} - \frac{d\psi(r_s - \varepsilon)}{dr} \right]_{\varepsilon \to 0}$$

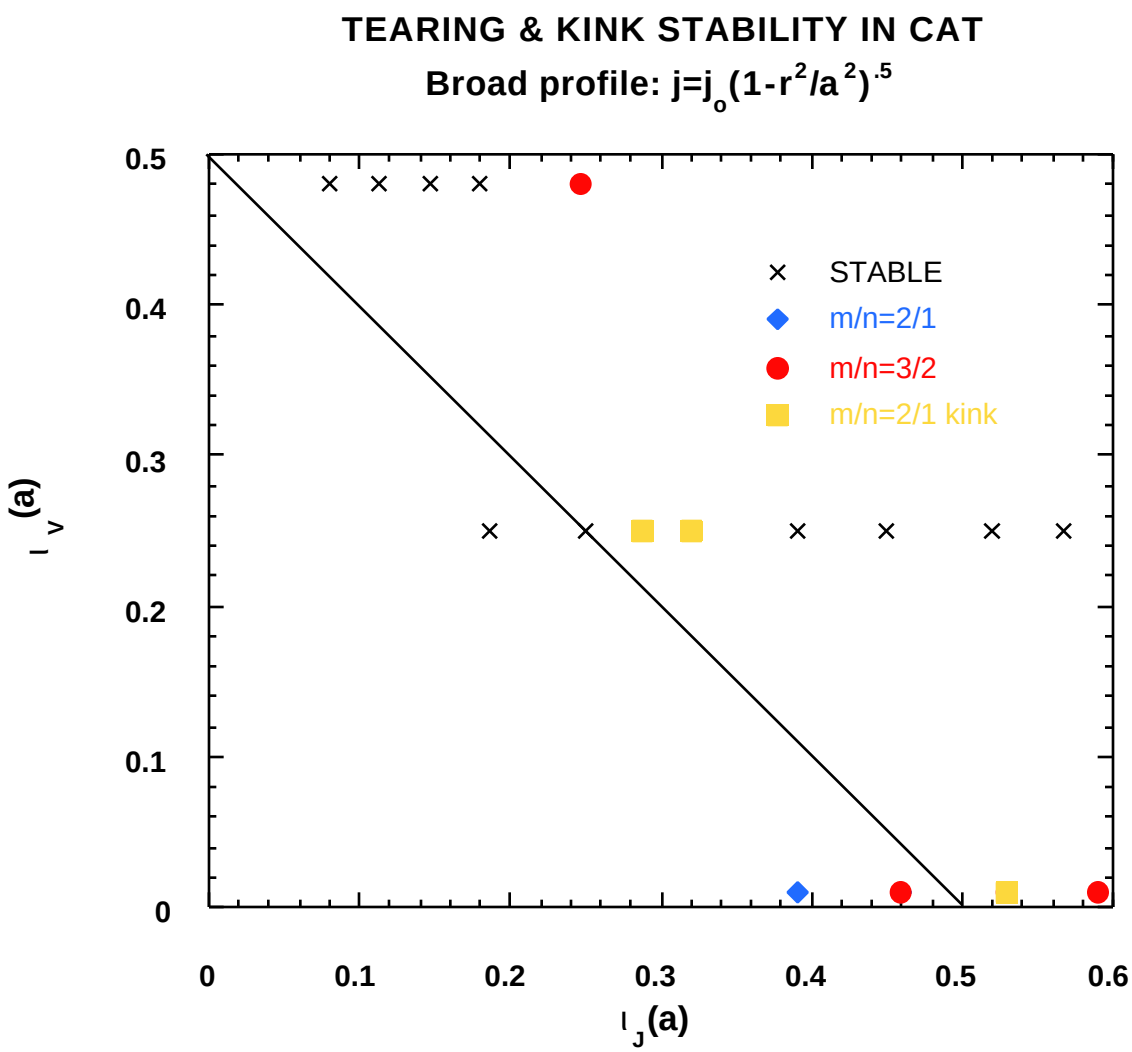
• **Kink modes**

Ideal stability calculated from the criteria of Newcomb [Ann. Phys. **10**, 232 (1960)]:
ψ(r) has a root at 0 < r < b.



- Region between $\iota_V(a)$ = 0.25 to 0.5 accessible in CAT.
- Peaked profiles can be made unstable to tearing modes.


TEARING & KINK STABILITY IN CAT
Parabolic profile: j=j_o(1-r^2/a^2)
STABLE
m/n =3/1
2/1
3/2
m/n=2/1 kink
ι(a) = 1/2
ι_V(a)
ι_J(a)
0
0.1
0.2
0.3
0.4
0.5


TEARING & KINK STABILITY IN CAT
Broad profile: j=j_o(1-r^2/a^2)^.5
STABLE
m/n=2/1
m/n=3/2
m/n=2/1 kink
l_V(a)
l_J(a)
0
0.1
0.2
0.3
0.4
0.5
0.6

Magnetic islands have a strong effect on the equilibrium and stability of stellarator plasmas.

- **Static islands may play a similar role in stellarator disruptions as locked modes do in low density tokamak disruptions.**

- **Their influence in these MHD stability studies on CAT may be very important since the rotational transform will vary significantly during the discharge.**

- **Previous studies on CAT have demonstrated the ability to greatly reduce the size of vacuum magnetic islands with low current error-correction coils in which the phase and magnitude of the correction field is controllable.**

- **We plan to extend these techniques as necessary to the MHD stability experiments on CAT.**

CONCLUSIONS

- **CAT Upgrade will contribute to understanding of MHD stability of current-carrying stellarator plasmas, and will specifically address the issue of stellarator disruptivity.**

- **The studies will be carried in a flexible magnetic configuration making use of the multiple coil set of CAT to change the rotational transform, as well as trim coils for magnetic island control.**

- **Plasma generation by non-resonant ICRF also adds flexibility to the experiment.**
  - **Allows operation over a range of magnetic field**
  - **Ohmic power does not dominate the power balance.**