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NSTX

# Energetic Particle Physics Research On NSTX


Nikolai Gorelenkov and Eric Fredrickson
for the NSTX research team


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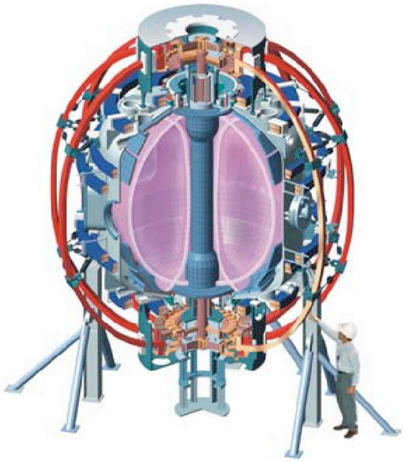

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# Research objectives and major milestones

## *Objectives of NSTX experiments are studies of:*

1. *instabilities driven by energetic particles (EP=beam ions) in presence of high beam and plasma $\beta$, low- R/a, high- $V_{EP}/V_A$ (unique parameter space):*
   - *thresholds for EP driven instabilities (ITPA, task mdc10: TAE damping rates)*
   - *effect of multiple modes on the transport of fast ions (mdc11: EP transport)*
   - *saturation and dynamic behaviour of mode amplitude (mdc11)*
   - *dependence of fast ion transport on mode amplitude (mdc11)*
2. *effects of these instabilities on (a) EP confinement; (b) plasma performance: current drive, plasma heating, transport etc.*
3. *advanced diagnostics: NPA, FIDA, CAE/ICE (ITER issue card)*

MILESTONES:

- *2007 Joule milestone: Measure, identify and characterize modes driven by super-Alfvénic ions*
- *2009 milestone: Study how j(r) is modified by super-Alfvénic ion driven modes.*

# Present and future plans build upon new discoveries in unique ST conditions

- Past research, linear physics, EP confinement, single mode effects:
  - new, high frequency ($\sim\omega_{ci}$) modes, CAEs/GAEs
    E. Fredrickson, et.al. Phys. Rev. Letter, v.87, p.145001-1 (2001)
  - new types of fishbones, bounce-frequency,
    E. Fredrickson et.al. Nucl. Fusion, v.43, p.1258 (2003).
  - tentative identification of BAAEs: new, beta Alfvén/acoustic eigenmodes in high $\beta$ plasma,
    Gorelenkov, Bulletin APS, v.51, p.183 (2006) paper NO1 10.
  - Alfvén cascades observation in NSTX in '06 at the same time as MAST,
    Fredrickson, submitted to PRL.
- Present research, multi-mode EP transport:
  - Initial studies of multiple mode driven EP transport
    Fredrickson, Nucl.Fusion v.46, p.S926 (2006)
    Medley, 21 Fusion Energy Conference, IAEA, Chengdu, 2006.
  - Three wave coupling effect in the presence of strong EP drive,
    N. Crocker, Phys. Rev. Letter, v.97, p.045002-1 (2006).
- Future research, AE effects on current drive, phase space engineering:
  - Interchange-type mode induced current redistribution via EP redistribution,
    J. Menard, et.al. Phys. Rev. Letter, v.97, p.095002-1 (2006).
  - may cause stochastic heating of thermal ions (energy channeling)
    Gates, Phys. Rev. Letter, v.87, p.205003-1 (2001)

# New Hardware Tools

FY07 (essential diagnostics are highlighted)

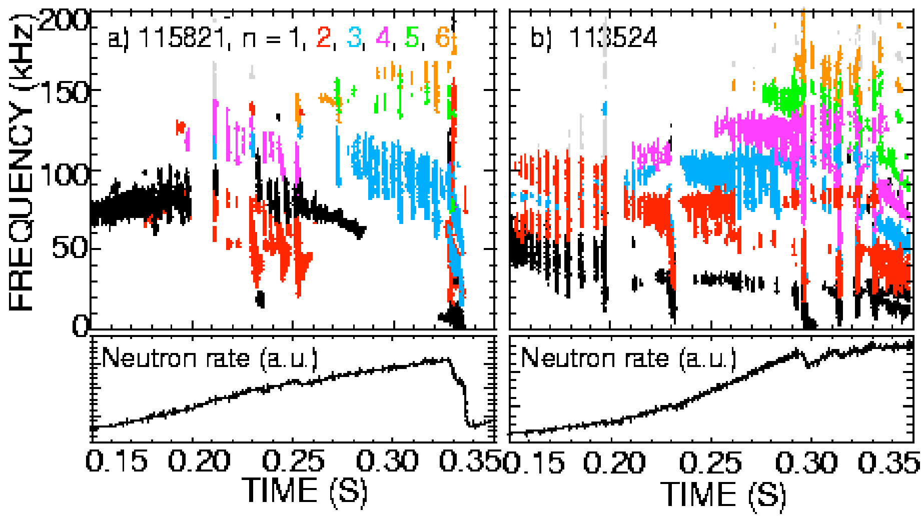
- Additional reflectometers (3 => 6 channels)
  - max density increased from 3.1 to 5.3 x $10^{13}$)
- Fast profile reflectometer (<50 kHz)
  - High resolution eigenmode structures for lower frequency modes
- Fast NPA, vertical scan, ssNPA
- Soft x-ray cameras (with impurity doping to improve sensitivity)
- Additional Firetip channels (<250 kHz), mode amplitude and structure
- n=3 non-resonant plasma braking, eliminate complexity of sheared rotation
- Faraday cups to measure fast ion losses

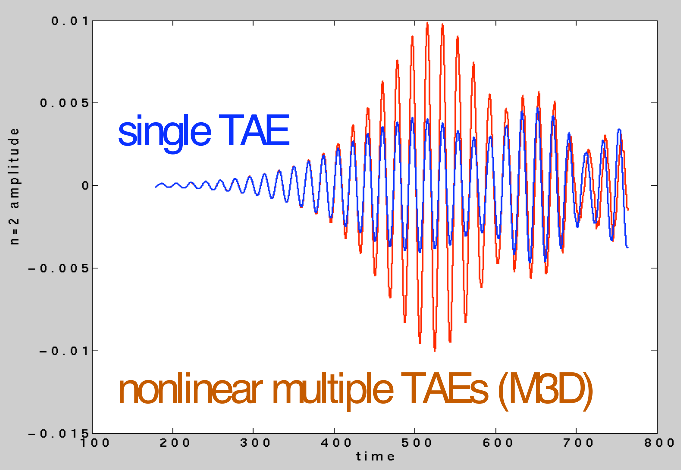
FY08 and FY09

- FIDA (Fast Ion D-Alpha, '08).
- Faster profile reflectometer
- Faster Firetip ($\approx$ 2-3 MHz bandwidth)

# Main objective at present: EP transport induced by multiple modes

- Phase-space islands overlap with multiple modes should lead to large EP redistribution.
- Overlap triggers "avalanche" where multiple modes are destabilized.
- Relevant to small $\rho^*$ regime

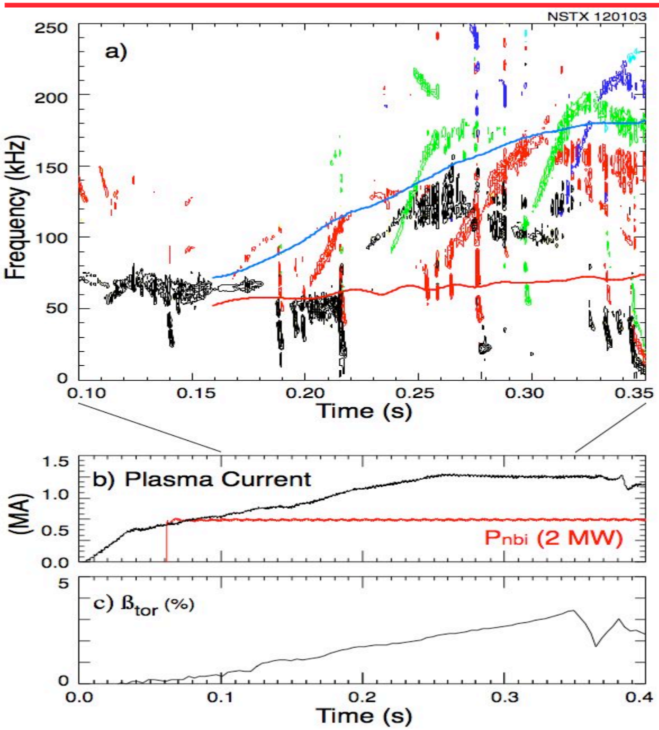



Experiments will provide (1st priority for '07):

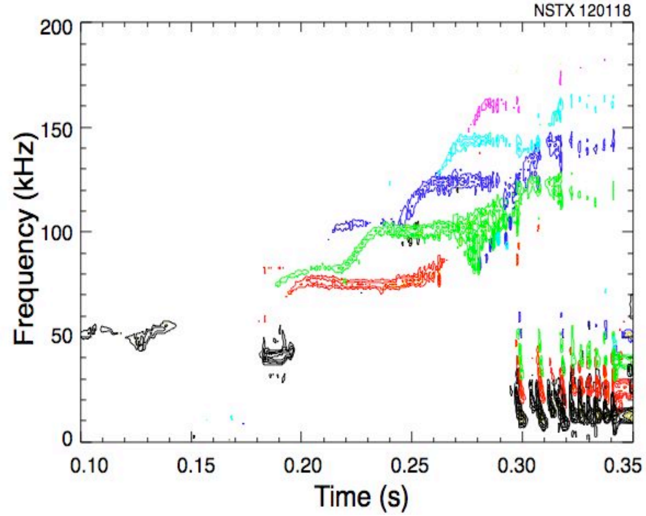
- Modes structure and amplitude.
- Excitation thresholds via power-scaling.
- Three wave coupling effects on fast ion confinement.
- EP profile measurements to verify predictive capabilities of codes like M3D and theory.

# Alfvén Cascades (RSAE) observed at low $\beta_e$ and verified on NSTX (also on MAST)

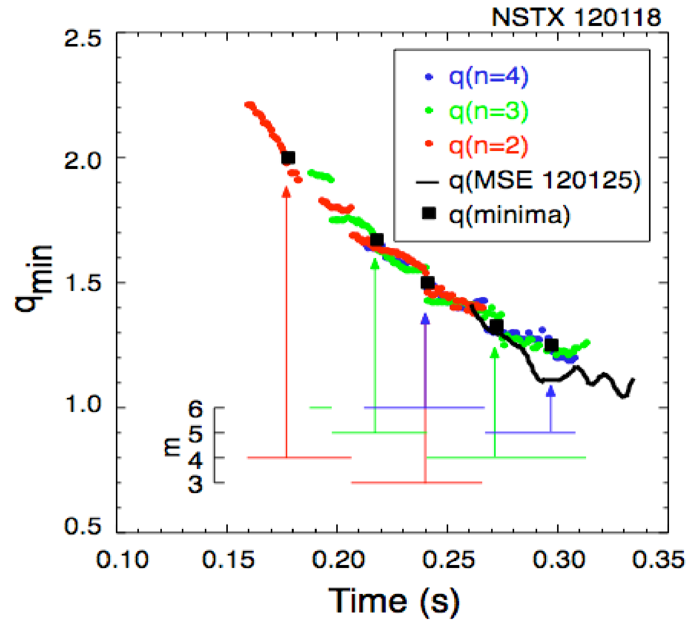



RSAE should exist for $\beta q_{min}^2 \ll 1/4\gamma$.
(merged into TAE gap)
(IFS-PPPL collaboration)

PAC19 question




Frequency chirp reveals evolution of $q_{min}$.



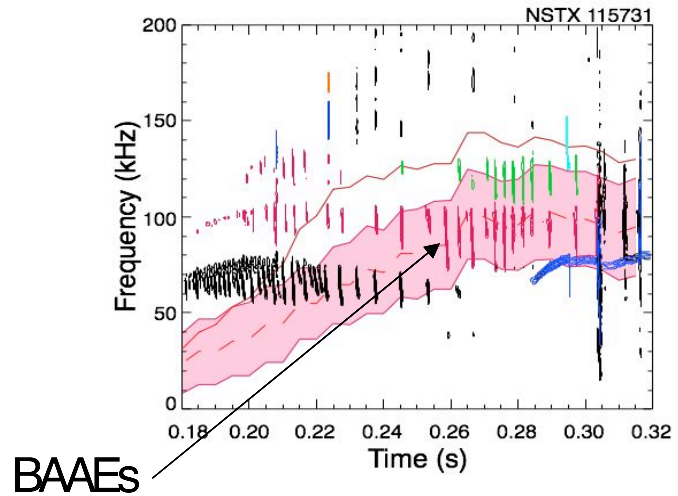

## Experiments will provide (1st priority for '07):

- Mode structure localization to $q_{min}$ by reflectometers.
- Evolution of mode structure at transition to TAE.
- Use RSAEs frequency for q reconstruction and verify MSE-constraints.
- Study effect of rotational shear by applying "non-resonant n=3 braking".
- Verify GAM/BAE coupling for Alfvén/acoustic.

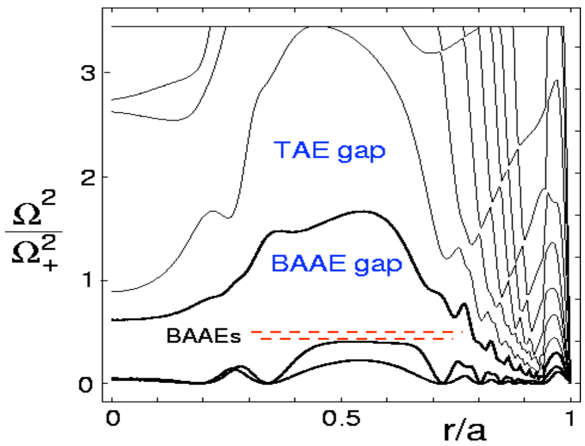
# Tentative identification of $\beta$-induced Alfvén-Acoustic Eigenmodes (BAAE) in unique ST conditions at high beam and plasma $\beta$

- EP driven modes are often seen at frequencies much lower than expected for TAE.
- Couples two fundamental MHD branches - new.
- Joint studies with JET (low density, high EP pressure plasmas).

NSTX BAAEs, f=103kHz




NOVA on BAAE gap in NSTX



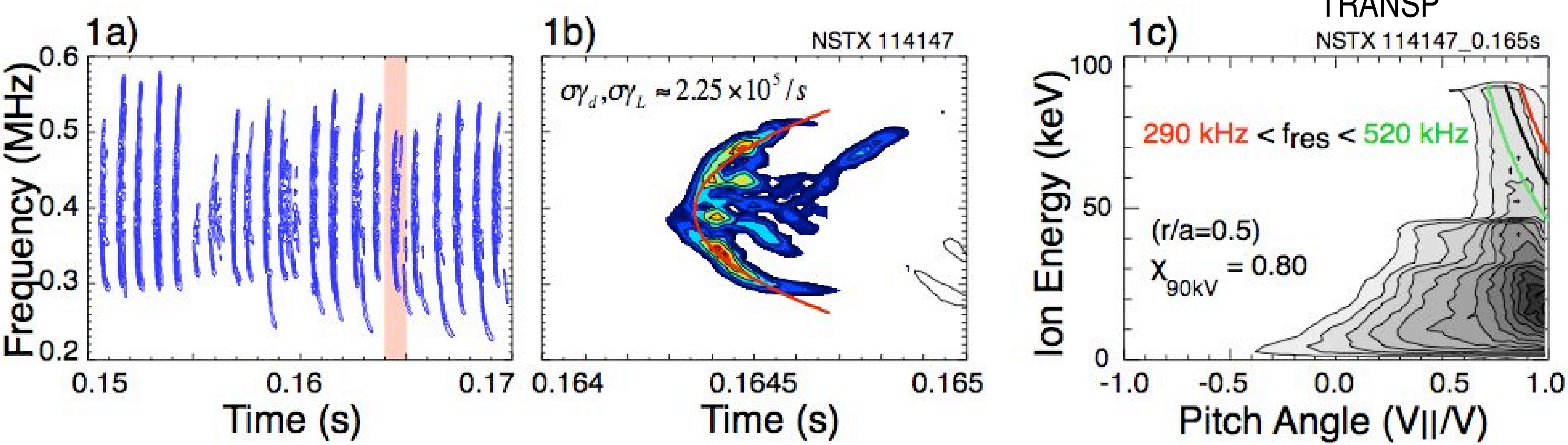

IFS-PPPL collaboration

Experiments will provide (2nd priority for '07):

- BAAE radial structure: is it localized to $q_{min}$?
- Unfold effects of plasma rotation by applying n=3 braking.
- Measure fast ion redistribution to assess effects on their confinement.

# Phase space engineering via HHFW: preliminary observations of Angelfish stabilization as predicted by theory

- Angelfish are identified as a form of hole-clumps in the phase space.
- Mode satisfies Doppler-shifted resonance condition for TRANSP calculated fast ion distribution.
- Growth rate estimates from slowing down distribution for the CAE is 0.04; from the frequency sweep 0.053.
- Engineering of fast-ion phase space can suppress deleterious instabilities.
- Potentially important tool for EP instability studies.



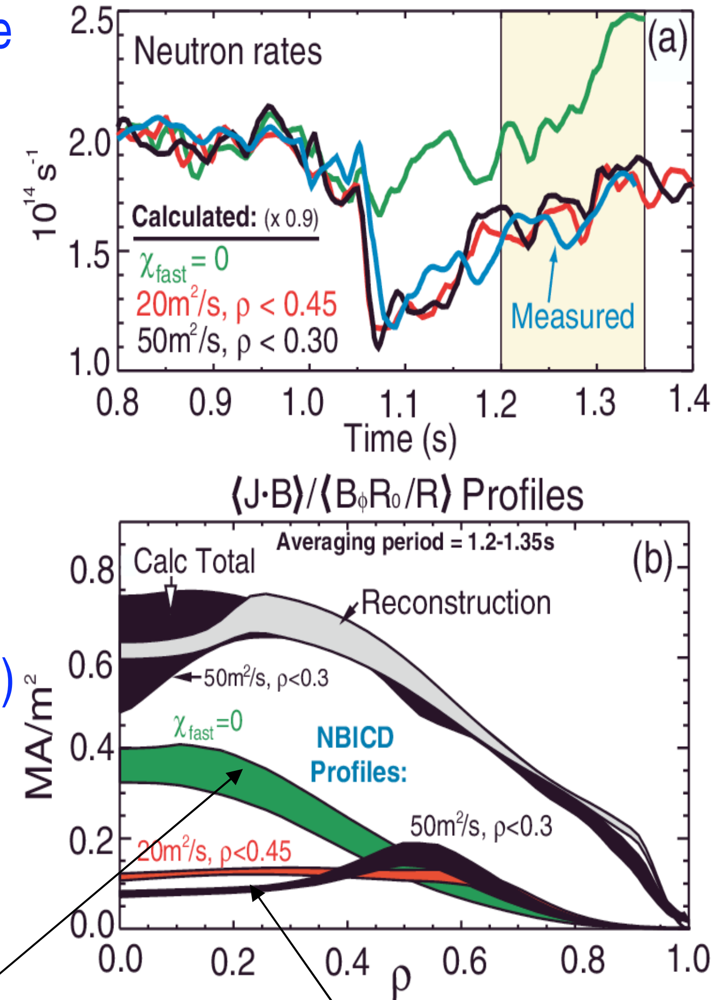

IFS-PPPL collaboration
H.Berk, 21st FEC, Chengdu, 2006

Experiments may provide (part of 2nd priority '07 and future plans)

- Mode amplitude and structure to identify CAE vs. GAE.
- RF power thresholds, *i.e.*, effective fast ion diffusivity, $\nu_{eff}$, to suppress chirps to validate theory, which predicts > 2 MW is sufficient to affect hole-clump frequency chirps.

# *AE effect on NBI current drive is in focus of future research: modeling technique is being developed

- Interchange mode has been identified to be responsible for NBI current drive profile broadening.
- Neutron rate, MSE q-profile constrain theory and TRANSP modeling of NBI current drive.
- Significant current redistribution is inferred.
- The same technique will be used for EP driven mode effects on NBI current drive.




Experiments will provide (initial study '07,'08, '09 milestone)

- Benchmark current drive models used in TRANSP
- NPA measurements of energy spectrum/pitch angle of redistributed ions.
- Extension to other instabilities.

classical j(r)

model j(r) consistent with measured neutron rate

J. Menard, et.al. Phys. Rev. Letter, v.97, p.095002-1 (2006).

# Strong theory supprot needing benchmarks in unique ST parameter space

## Supported theoretical tools under development

- Nova-Orbit – linear-quasilinear, hybrid MHD/kinetic
  - Fast ion losses during Avalanches, EPMs (resonance overlap)
  - Long standing conundrum (TFTR,DIII-D, etc.) on EP lossed with measured mode amplitudes to be addressed due to large FLR effect in ST
- NOVA-KN – linear, hybrid MHD/kinetic, nonperturbative code
  - Efficient calculations of linear physics of EPM like mode: ideal for strong driven modes like in NSTX (exploit high beam beta)
- M3D-k – fully nonlinear, hybrid kinetic
  - EPM/TAE/BAAE nonlinear selfconsistent for *multimode* (resonant overlap) simulations
- HYM – fully nonlinear, hybrid kinetic
  - Non-linear GAE/CAE simulations
  - Chirping frequency modes, Angelfish.
- HINST – linear ballooning, fully kinetic
  - KBM like modes with strong EP drive for potential applications in NCSX
  - BAAE kinetic nonperturbative (high beta) treatment to address Alfvén/acoustic coupling

'07 PPPL lead theory Joule milestone is to use predictive capabilities of TRANSP and NOVA-K codes for ITER TAE stability study.

# 2007 Experiments Address Near Term Research Objectives

## MHD Prioritized Experiments (from NSTX Forum – Dec 2006)

| Days | Experiment | ST devel. | ITER | physics |
|---|---|---|---|---|
| 3 days | Multi-mode beam loss power scan | x | x | x |
| | • Generation of *AE quiescent plasmas | x | | |
| | • Beam power scan of fast ion loss induced by multiple MHD modes | x | x | x |
| | Alfvén cascades on NSTX | x | x | x |
| 4.5 days | Beta-induced Alfvén-acoustic modes | x | x | x |
| | • Three-wave coupling effects on fast-ion loss | | x | x |
| | • Stabilization of CAE/GAE hole-clumps | | | x |
| | MHD-induced energetic particle redistribution - vsNPA | x | x | x |
| | RF beat wave excitation of *AE | | x | x |
| | Structure of Bounce-Resonance Fishbone-like Modes with n > 1 | | | x |
| | $\rho$ beam ion scan for NBI driven modes (NSTX & DIII-D) | x | x | x |
| | TAE hole-clumps | | x | x |
| | CAE/GAE stochastic thermal ion heating | x | x | x |
| | Ion power balance with modulated NBI | x | | x |

(Red highlight = addresses NSTX milestone)

# 2007 High Priority Experiments address Joule milestone and PAC recommendations

- EP redistribution induced by multiple MHD modes MDC11,ITER relevant, PAC19 question
  - Fast ion $\beta$ (beam power) scan to measure mode onset threshold
  - Documentation of multi-mode fast-ion transport regime
    - High spatial resolution eigenmode structure/amplitude measurements - determine "island overlap" condition
  - NPA scan to measure energy spectrum of redistributed fast ions
- Part II: Generation of *AE quiescent plasmas PAC-19 question
  - Data to benchmark TRANSP beam/bootstrap current calculations
  - Vertical NPA scan to document fast ion redistribution after mode onset.
- Alfvén cascades on NSTX - PAC-19 question
  - Verify that frequency sweeping modes are Alfvén Cascades with MSE q
  - High spatial resolution reflectometer data to show localization to $q_{min}$.
  - Show transition from GAM to TAE at frequency saturation
  - Document proposed $\beta$ dependence of frequency sweep range
  - Study physics of GAMs or BAEs

# 2007 Lower Priority experiments (results expected in piggy-back)

- Beta-induced Alfvén-acoustic modes
  - Some data potentially available from L-mode confinement experiments
- Three-wave coupling effects on fast-ion loss
  - Some data available from other L-mode experiments
- MHD-induced energetic particle redistribution - vsNPA
  - Intrinsic to Multi-mode beam loss XP
- HHFW stabilization of CAE/GAE hole-clumps
  - Planned as non-intrusive part of fast ion XPs - assuming Angelfish are present.
- RF beat wave excitation of *AE
  - Partly incorporated into other XPs as proof-of-principle and possibly as measure of mode linear damping rate
- $\rho_L$ ion scan for NBI driven modes (NSTX & DIII-D)
  - Some data expected from TF scan planned for Alfvén Cascade experiment
- CAE/GAE stochastic thermal ion heating
  - Preliminary measurements of HHFW antenna coupling to beam driven CAE/GAE hoped for in last week of campaign
  - Possibly some preliminary antenna loading measurements.