Frontiers in Energetic Particle Research in Fusion
(solved and unsolved EP problems)

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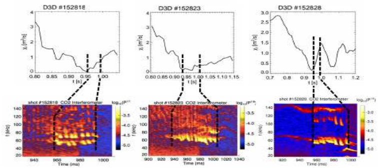

Chirping AE modes in DIII-D (& NSTX-U etc.) can be ***predicted*** *now by NOVA-K*

(V. Duarte et al., Nuclear Fusion letter'17)

1st AAPPS, Chengdu, China, Sept. 2017

Several priority topics are of major importance for burning plasmas

1. ***With fast ions (EP) required for burning self heated plasmas, Alfvénic eigenmode (AE) instabilities are hard to avoid***
   - ***Low**-f (*AEs) to subcyclotron frequency modes are **expected to be unstable in ITER** (Gorelenkov, Pinches, Toi, NF'14)*
2. *Deleterious effects on plasma confinement due to EPs (IAEA TCM'17, Princeton)*
3. *Ion Cyclotron Emission (ICE) could be important diagnostic tool for burning plasmas (BP, IAEA TCM'17, Princeton)*

- *can lead to significant losses up to 40% of EP ions in present day (PD) machines*
- *with linear AE theory mostly complete nonlinear studies should be in focus*
- *need to be understood for better planning of expensive reactor-size machines*
- *very attractive for BPs*
- *poorly understood for diagnostics*

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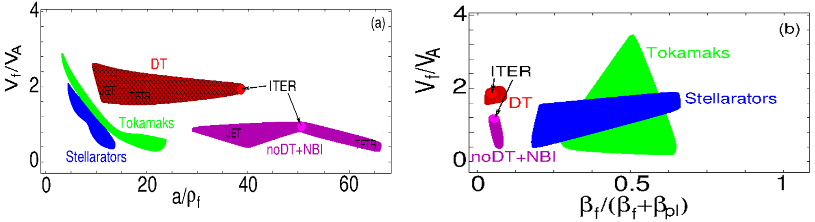
5. Summary and Possible directions for EP research

Parametrization of EP studies relates PD to future BP devices

Three parameters can be chosen for EP-relevant studies characterization:

$\mathbf{v_f/v_A}$ EP to Alfven speed ratio. minor to Larmor radius ratio $\mathbf{a}/\rho_\mathbf{f}$, and betas ratio $\beta_\mathbf{f}/\beta_\mathbf{pl}$.

- $a/\rho_f \sim n$ *(toroidal mode number)*
- v_f/v_A: *~ the fraction of resonant ions*
- β_f/β_{pl}: *~ available power for excitation*



Accessible parameter space is sufficiently broad to overlap most present day fusion devices with future BPs (Gorelenkov, Pinches, Toi, NF'14).

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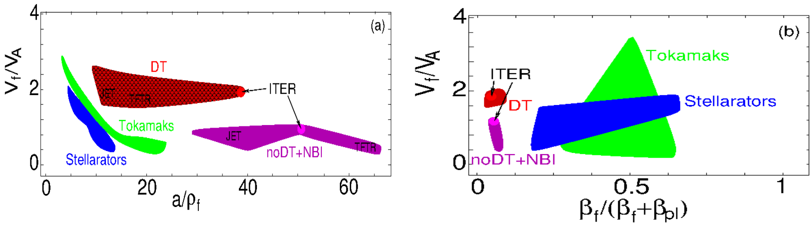

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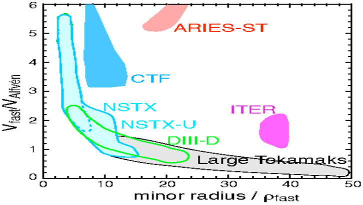
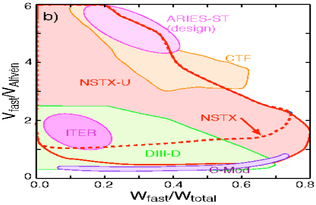
NSTX(-U), US specific studies

US fusion program with NSTX-U and DIII-D shows example of parameter space overlaps





DIII-D is closest to BP

BP overlaps with NSTX(-U) the most
W_f/W_{tot}: EP power ($\sim \beta_f$) for the drive

These maps help to focus EP research and direct it towards BPs.

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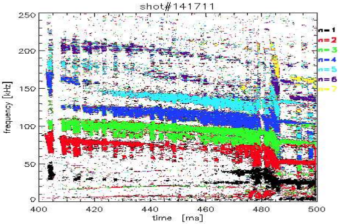
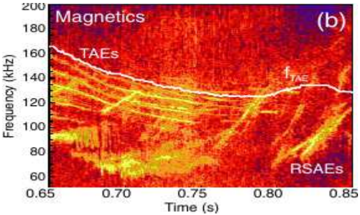
STs & conventional tokamaks regimes complement each other for (V&V)

mostly chirping (1-5msec) AEs in STs
(NSTX, Podesta, NF'16)



mostly steady state in conv. tokamaks
(ASDEX Upgrade - AUG, Garcia-Munoz'11)



1. Both **steady-state (AUG, DIII-D)** and **chirping** frequency (NSTX, MAST) regimes are required for BPs
   - Both regimes can have up to $\sim 40\%$ loss of fast ions in PD experiments
2. Initial value codes and reduced models are to be validated in both regimes
3. Developing reduced models: **steady state regimes** - ready; **chirping** regimes is not clear how to proceed.

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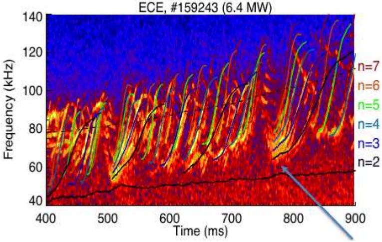
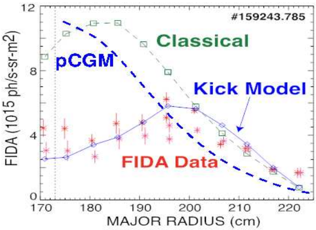
Recent FIDA challenged reduced models in detailed comparisons

- Detailed analysis using Fast Ion D_α (FIDA) signal reveals inversed radial profile due to AEs *(Collins et al. PRL'16, Heidbrink et al. PoP'17)*
- Initial value MEGA simulates similar DIII-D cases well, requiring ~1 month to run! *(Todo et al, NF'16)*.



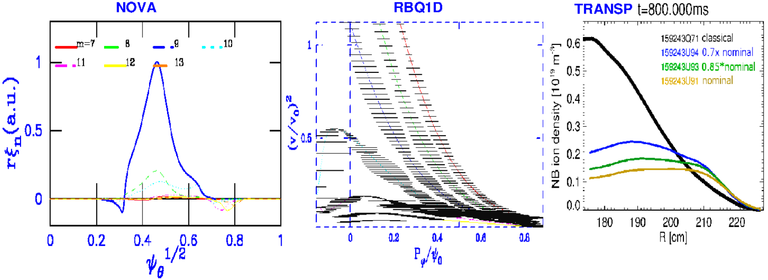


Earlier developed perturbative Critical Gradient Model (reduced Quasi-Linear) does not reproduce hollow EP profiles, and underestimates the neutron deficit by the factor of 2.

Need velocity space resolution such as in shown Kick Model *(Podesta et al., PPCF'14)* ⇒ *to be addressed by Resonance Broadened QL (true QL model, Berk et al., PoP'96; Gorelenkov, IAEA'17).*

Initial RBQ application in predictive mode

MHD RSAE structure Broadened resonances EP relaxation:



Broadening is defined by RSAE amplitude $\delta B_\theta/B = 7\times10^{-3}$, $f = 84kHz$, *Collins, PRL'16*.

The choice of this RSAE is critical to understand the EP transport leading to hollow EP pressure profiles in DIII-D.

Nominal predicted amplitudes times $0.85\delta B_\theta/B$ give good agreement with neutron deficit.

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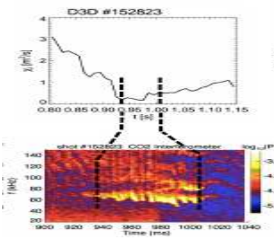
Building RBQ code requires the identification of these regimes

PPPL/IFS/SPU collaboration:

(V.Duarte et al. NF'17 letter, TTF'17, IAEA'17 invited talks)

a correlation emerged between the turbulence driven pitch $\rightarrow$ angle scattering and AE frequency chirping in DIII-D, TFTR, NSTX

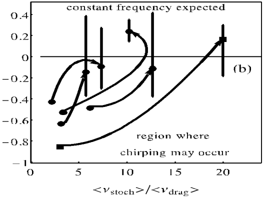


New criterion for chirping modes is implemented in NOVA-K $\sim (\boldsymbol{E}_{TAE} \cdot \boldsymbol{v}_{dr})\, \nu_{drag}^{-4}$: $\rightarrow$

i) > 0 then fixed frequency wave is likely;

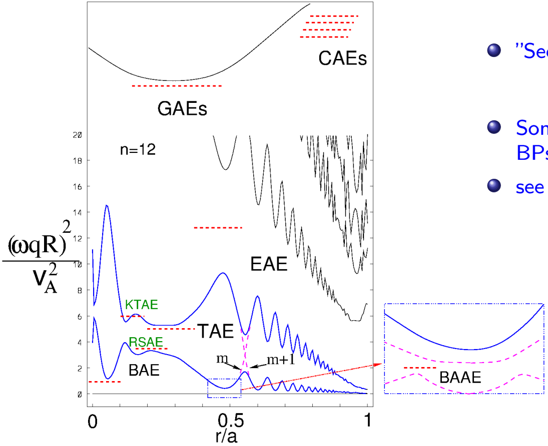
ii) < 0 chirping wave is likely;

The criterion is able to quantitatively explain observations if turbulent diffusion boosts pitch-angle scattering from collisional level.



Chirping criterion is available in NOVA-K and needed for (RBQ) applications.

Other potential problems for EP transport in BP relevant regimes



- "See" of Alfvénic Eigenmodes plus ...
  - Fishbones (AE too), (E)GAMs ...
- Some should be prone to excitation in BPs (ITER)
- see sesssions today and thursday

Gorelenkov, Pinches, Toi, NF'14

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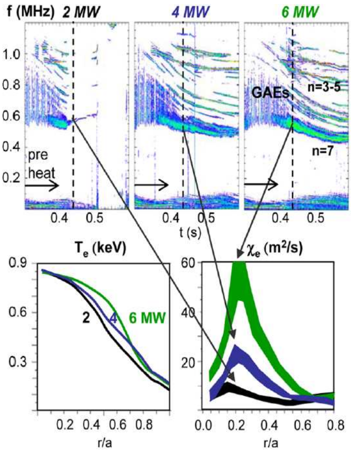
Full power NBI drove Global/Compressional AEs unstable. Did they affect T_e profile?

High-f modes on NSTX $0.5 - 1.1 MHz$

- T_e profiles are flattened with increased beam power
- attributed to enhanced e-transport
    - test particle ORBIT simulations using multiple GAEs explained possible temperature rollover *(Gorelenkov, NF'10)*
    - there is still no model in TRANSP to address this
    - power channeling is proposed *(Kolesnichenko etal., PRL10 and Belova, PRL'15)*



(Stutman et al., PRL'09)

Do we understand T_e flattening in STs (NSTX)
TRANSP often underpredicts e-heating.

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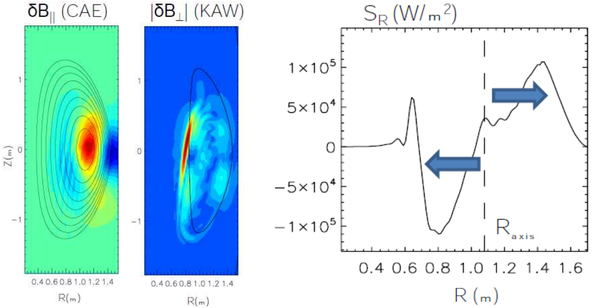
Power channeling can provide an explanation to reduced core plasma heating in NSTX

HYbrid MHD (HYM) demonstrates CAE to Kinetic Alfvén Waves (KAW) channeling for dissipation

Global & localized structures — Umov-Poynting vector indicates energy dissipation



(Belova et al., PRL'15)

- Energy flux is directed away the center towards KAW (edge) *(Chen, Hasegawa PRL'73,'74, Johnson, Cheng GRL'97)*.
- This mechanism is important for ICE, anomalous thermal ion heating (see below)

GAE/CAE driven effective e-transport could be a serious problem in STs.

Other toroidal plasma devices.

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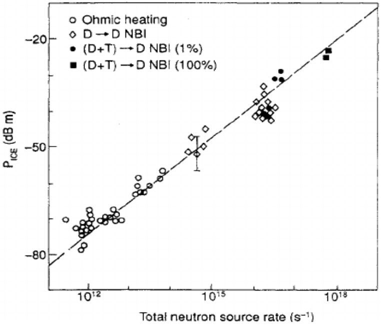
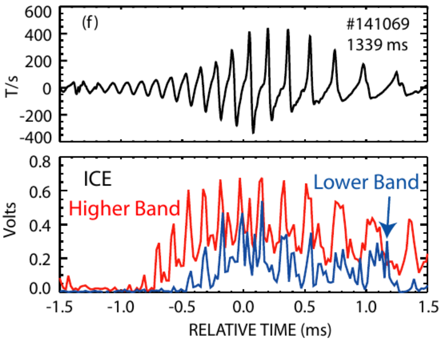
Complex ICE phenomenon promises important EP insights



Cottrell, NF'93

- ICE signal power is proportional to neutron source rate over 6 orders of magnitude
  - Ohmic to DD NBI to DT
  - It was not reproduced in other tokamaks (why?)
- Potential diagnostics is accessible in BP
- Linear physics is well understood *(Gorelenkov, New J. Phys.'16)*
- Nonlinear physics is being approached *(Carbajal et al., PRL.'17)*

Existing measurements point at ICE potential



(Heidbrink, PPCF'11)

- off-axis fishbones affect ICE
- ⇒ EP (drive source) redistribution to the edge (ICE location)
    - Lower Band Figure: ICE signals: deuterium cyclotron frequency at the plasma edge
    - Higher Band ICE: 2^{nd} and 3^{rd} harmonics.
- ⇒ better theory is needed for a proper interpretation measured
- ICE spectrum dependencies on plasma (&EP parameters) are complex *(Thome et al., IAEA TCM'17)*
- Some brakethrough is needed?

Potential directions

- AE transport of fast ions
  - Nonlinear regimes should be in focus both theoretically and experimentally
  - Initial value codes and reduced models are to be pursued
- Deleterious effects on EP and thermal plasma confinement
  - ST electron transport
  - Other effect could be non-deleterious: ion stochastic heating etc.
- ICE is important, partially (linearly) understood
  - Can we use it? in BPs? Phase-space engineering?