Predictive modeling in Energetic Particle Reserch

presented by N. N. Gorelenkov, PPPL

in preparations for 5 year Theory Research Plan

collaborations:
strategic with IFS, Irvine, DIII-D, Colorado, NSTX-U, JET...

Work supported by US DoE

for Predictive modeling

- To plan operating regimes in BPs against *AEs/other instabilities (XPs are too expensive, minimize the risk)
  - new regimes with **self-sustained** plasma heating
  - need accurate predictions of AE instabilities (how accurate?ITER?)
- Existing/developing approaches (list may not be complete)
  - initial value codes, US, Europe, Japan (validations?)
  - **hybrid** theory/guiding center modeling (ORBIT, HAGIS)
  - 2D QL (theory, IFS/PPPL)
  - *crit. grad. model (**CGM** or 1.5D) & stiff transport model (GA) (linear tools are validated within ITPA)*
- In this talk we present predictive relaxation models
  - some specific examples rely on CGM
  - need further validation (collisionality scan XP?)

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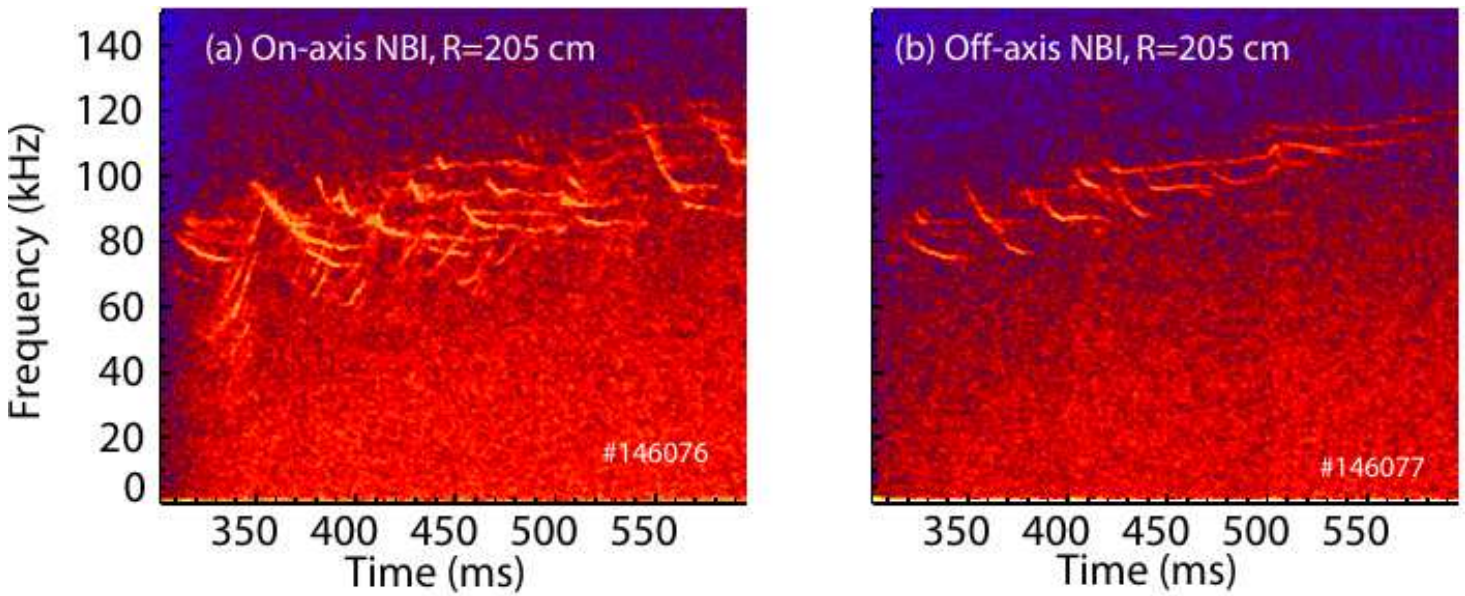
need to address burning plasmas with nonvirulent AEs

- DIII-D data are available for validations.
- equilibrium change time scale, $\sim 20 - 100 msec$
  - opposite to fast chirping time scale $\sim 1 - 5 msec$.



- DIII-D on-, off-, axis slow evolving plasmas
- strong neutron signal drops are seen at on-axis NBI

What is predictive modeling?

Prediction (Terry, TTF, PoP'08):

use of a code, outside of its previously validated domain, to foretell the state of a physical system: PD $\rightarrow$ BP.

Validation metrics?

losses $\delta\beta_\alpha/\beta_\alpha \sim 5\%$ (due to AE transport) may have strong wall heat load constraints in ITER.

loss boundary is sharp in T in steady-state as $\beta_\alpha \sim T_i^{5/2}$.

$T \rightarrow \beta_\alpha? \rightarrow T$ What are the reasonable error bars?

Predictive power of nonlinear/QL, stiff, CGM, other models is to be demonstrated via validations (P.Terry et.al., Phys. Plasmas'08).

ITPA is the venue: example - linear computations benchmarks: $\partial\beta/\partial r_{cr}$, distr.func., FOW/FLR;

***nonlocal effects** are key: cont., rad, coll dampings?*

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Initial value codes

Variety of approaches:

- *GK, GF, hybrid MHD, PIC & continuum codes, theories*
- Validation is a serious test given this variety
  (G.-Y. Fu, DOE Joule milestone FY14)
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Crit. grad. (CGM); stiff transport; hybrid - theory + NOVA/ORBIT

Stiff transport - GA, UCSD

- *Mostly local computations by GYRO*
- Validation for a drive and dominant dampings needed
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Crit. grad. model - PPPL, IFS

- *Full eigenvalue computations*
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  - *Are they important for predictive modeling? pessimistic?*

Hybrid modeling: TAEs & theory & guiding center orbits (LIGKA+HAGIS is similar)

- *use NOVA and*
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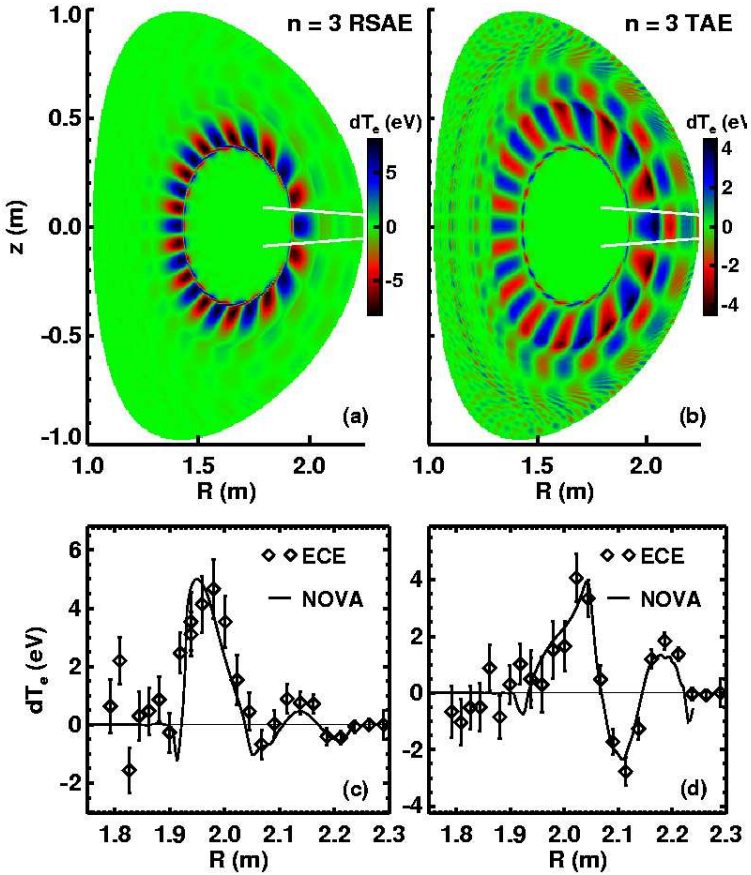

M. Van Zeeland, et.al.PRL06

DIII-D $*AE$ validation XP:

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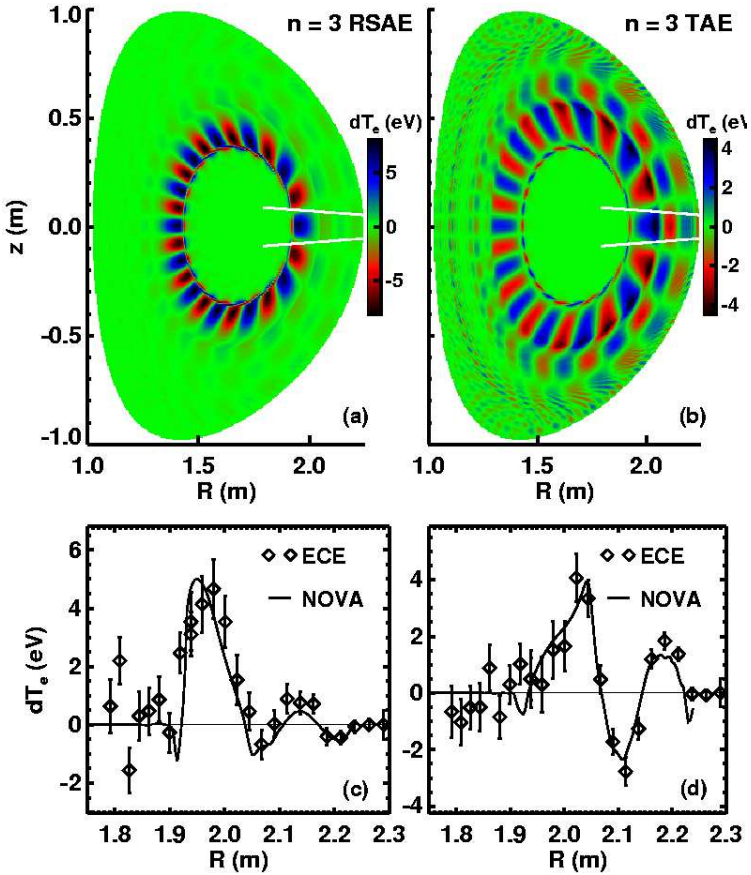

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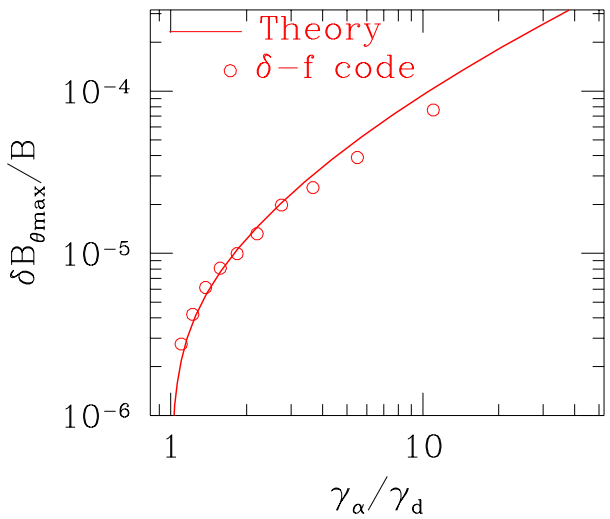
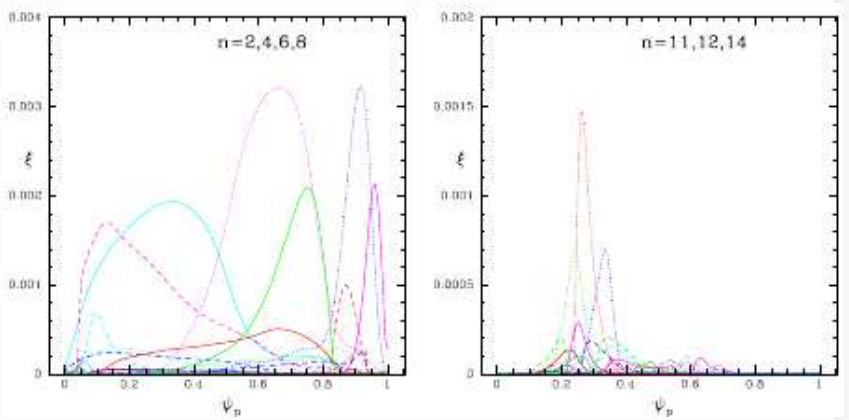
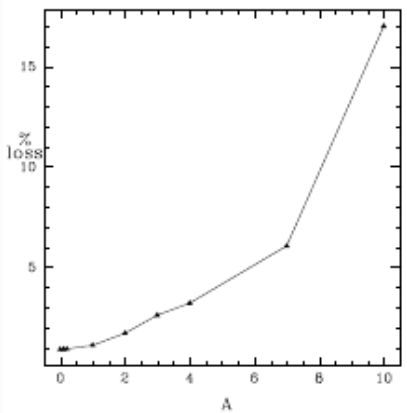


Can predict EP redistribution in ITER - consistent with CGM; *(N.Gorelenkov, R. White, PPCF'13)*





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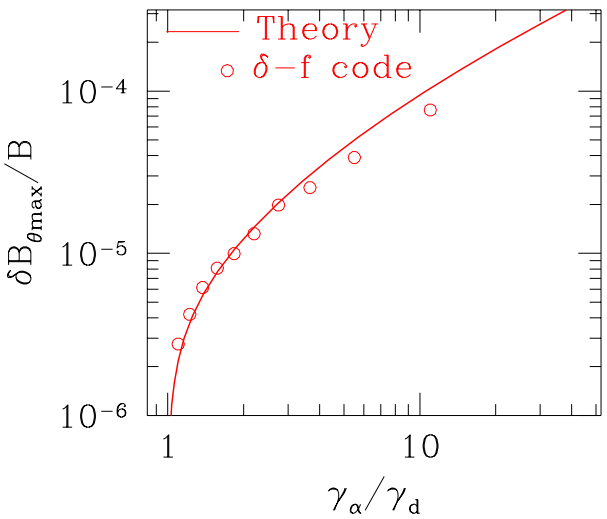

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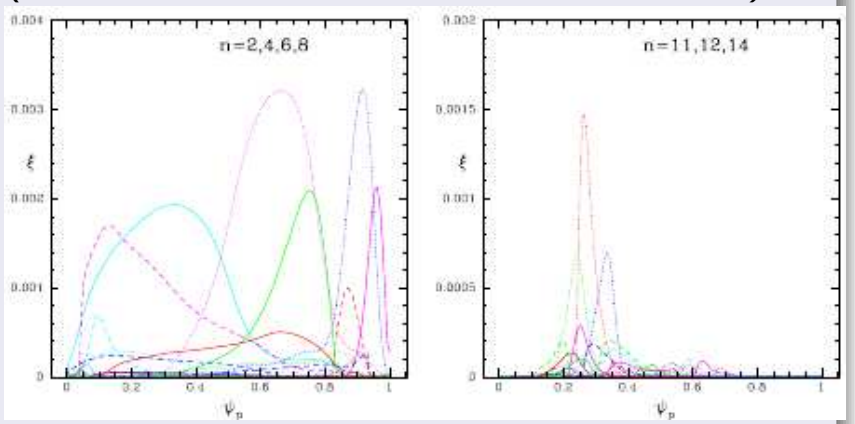
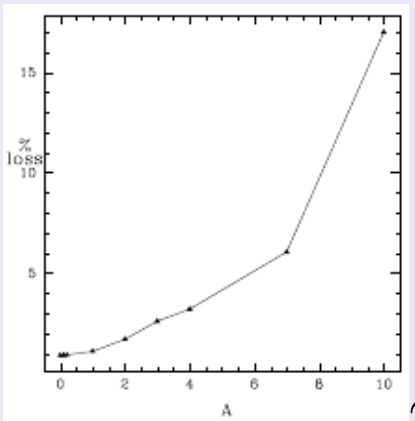




$\sim 1\%$ loss

Outline

1.5D (&2D), crit.grad.model implementation (K.Ghantous et.al.PoP'12)

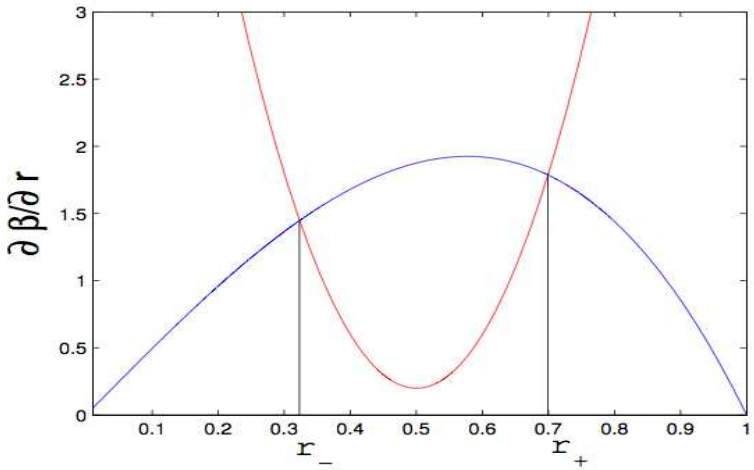
Employ linear code for critical EP gradient against *AEs

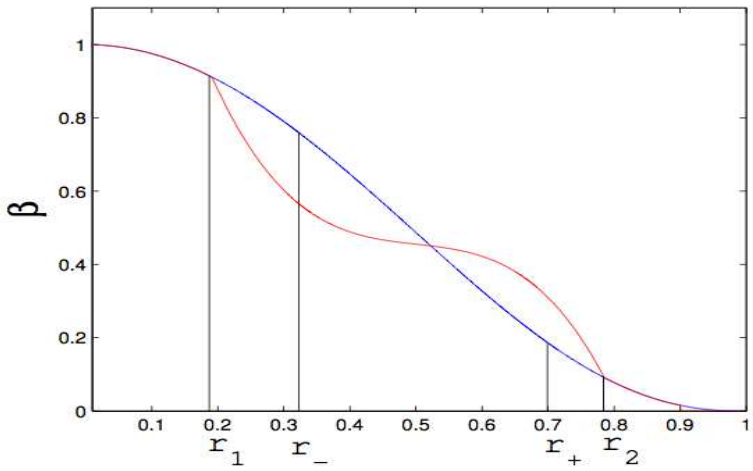
- large number of unstable localized modes $\rightarrow$ QL connection
- fast EP diffusion in velocity/phase island
- fixed background dampings, plasma profiles
- make use of comput. of critical gradient $\partial\beta_{EP}/\partial r$
  - "improve" linear calculations with accurate evaluation of the growth/damping rates (use NOVA-K)
  - 1.5D produces analyt. expressions to keep the parametric dependence when the codes can not be run
- integrate critical EP beta to compute (i) relaxed profiles; (ii) losses;
- too optimistic? can account for distrib. in a simple form *[Kolesnichenko, NF'80]*, i.e. simple resonance $v_{\|} \sim v_A$ ($\rightarrow$ 0.5D)

EP critical gradient from *AE instabilities

$$\frac{\partial \beta_{EPcr}}{\partial r} = -\frac{\gamma_{iL} + \gamma_{ecoll} + \gamma_{rad}}{\gamma'_{EP}},\ \gamma'_{EP} = \gamma_{EP}/(\partial \beta_{EP}/\partial r)$$

Three damping mechanisms are often dominant in DIII-D, ITER...:
ion Landau, electron collisional, radiative $\rightarrow$ essentially nonlocal!! $\Rightarrow$1.5D, 2D should rely on global codes stability analysis.





Use particle conservation law $\int_0^a r(\beta_{EP} - \beta_{EPrelax})\,dr = 0$ to compute **profile broadening** and EP losses.

limit $|\beta'_{EP}| \leq |\beta'_{EPcrit}|$ result in the relaxed EP profile $r_{\pm} \rightarrow r_{1,2}$

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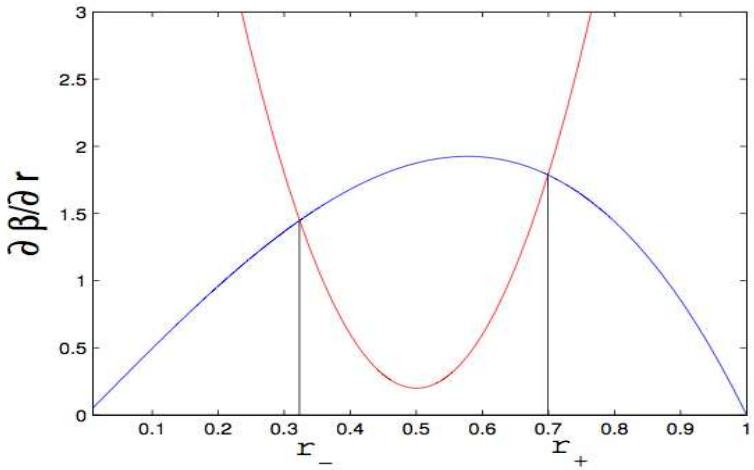

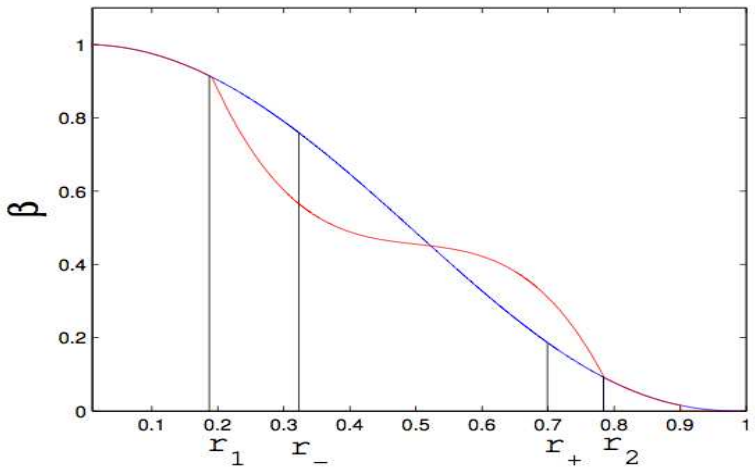

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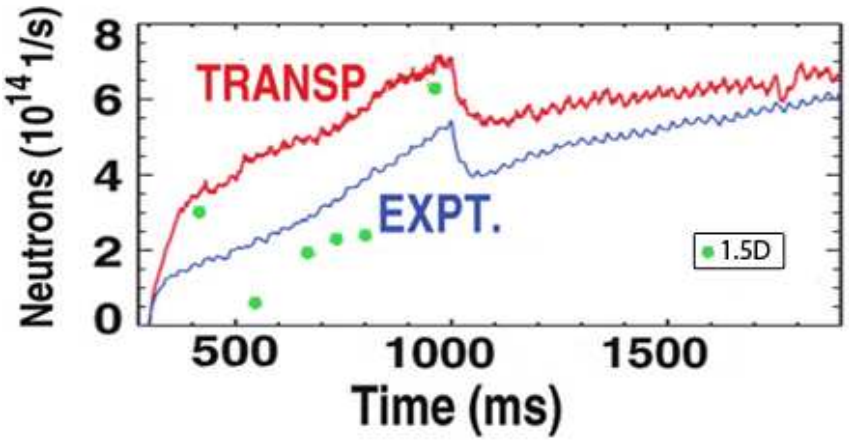
1.5D (CGM); 2D model; hybrid; how should we reduce the problem?

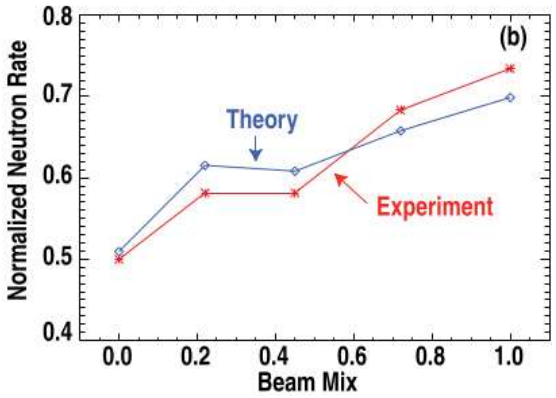
model	diffus.mechanism	accuracy	Valid.	readiness
crit. gradient	crit.thresh.	approx.	+ (-)	+
GYRO stiff transp.	crit.thresh.?	approx.	-	+/-
2D QL complete	QL diffusion	good	-	-
hybrid: theory/ORBIT	diffusion	good	+/-	+
initial value codes	diffusion	good	+/-	-

Outline

Approximate agreement can be claimed



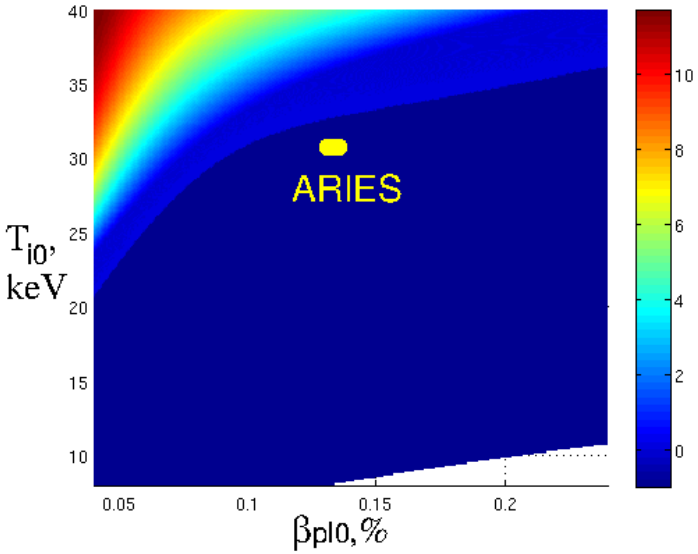
(K. Ghantous et al. Phys. Plasmas'12)



(W.W. Heidbrink et al. Nucl. Fusion'13)

Outline

Example of projections to BPs readily made



- Stability diagram: $\beta_{pl}(0)$, $T_i(0)$
  - plasma source of alphas
  - CGM normalized to NOVA
- predict the loss level, width of the benign region to stable
  - $R_0 = 5.5m$, $a = 1.4m$, $10MA$, $B_0 = 6T$. $T_i = 35keV$, $T_e = 40keV$. $\beta_\alpha = 3.5\%$, $\beta_{pl} = 20\%$.
  - error bars?

    for CGM $\sim 50\% \Rightarrow \sim 10\%$ in T_i

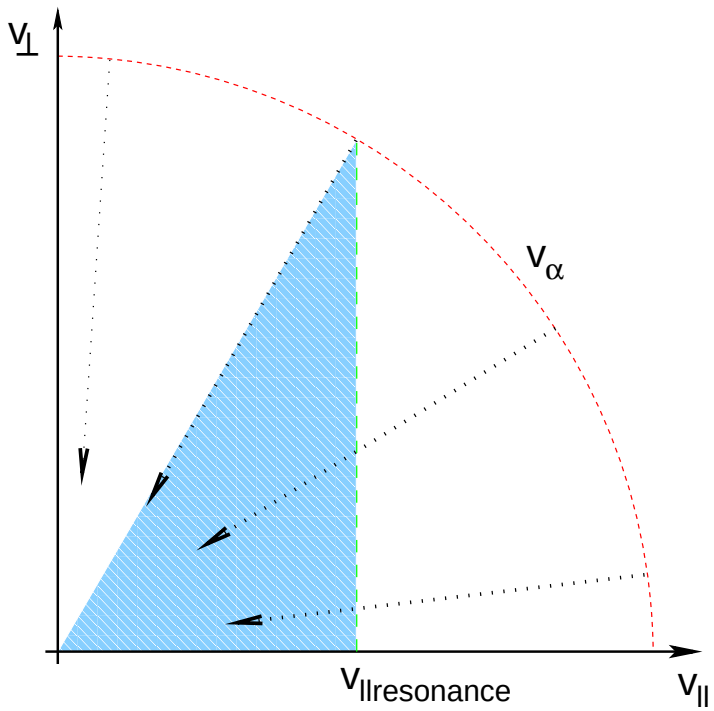
    MEGA - factor of 2 (50%?) accuracy?

- α's sl. down d.f., ion Land., radiative*, trapp.electron collisional dampings (C. Kessel, submitted)

Summary and status

- 1.5D critical gradient model is ready for applications
  - offers rather limited accuracy
- 2D QL model promises to be accurate but maybe challenging numerically
  - multiple modes/resonances to track
  - need to be in the focus
- CSEP work is important to highlight but should be presented separately
- Hybrid models can be used for predictive modeling ORBIT+ NOVA
- Most of the models need validations
  - ITPA should take leading role in benchmarks
  - single, multi - mode (cyclone like) comparisons are to be developed and documented

How much EP/alphas are affected?



Ya. I. Kolesnichenko, NF'80

- expected max effect from instabilities with $v_{\|} = v_A \sim$ shaded area
- $\Rightarrow$ address EP transport in a regime when $*AE$ modes are not virulent
- fraction of effected alpha power $P_{\alpha res} = P_{\alpha}\left(v_{\alpha 0} - v_{\|}\right) v_{\|}/v_{\alpha 0}^2 \leq 25\%$
- 0.5D part of the QL model

too optimistic? sideband resonances ignored: $v_{\|} = v_A/(1 \pm 2l...)$!!!
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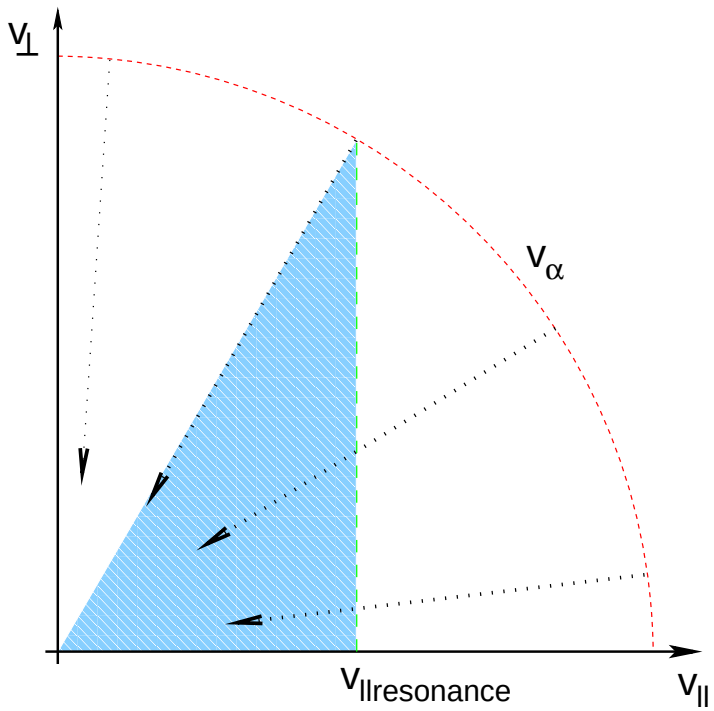

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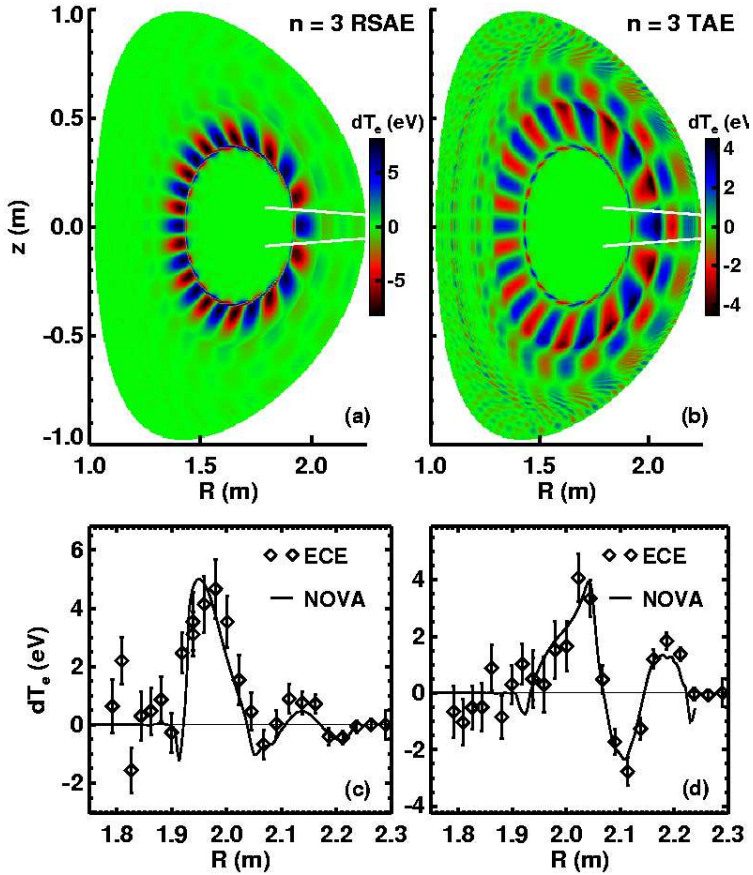

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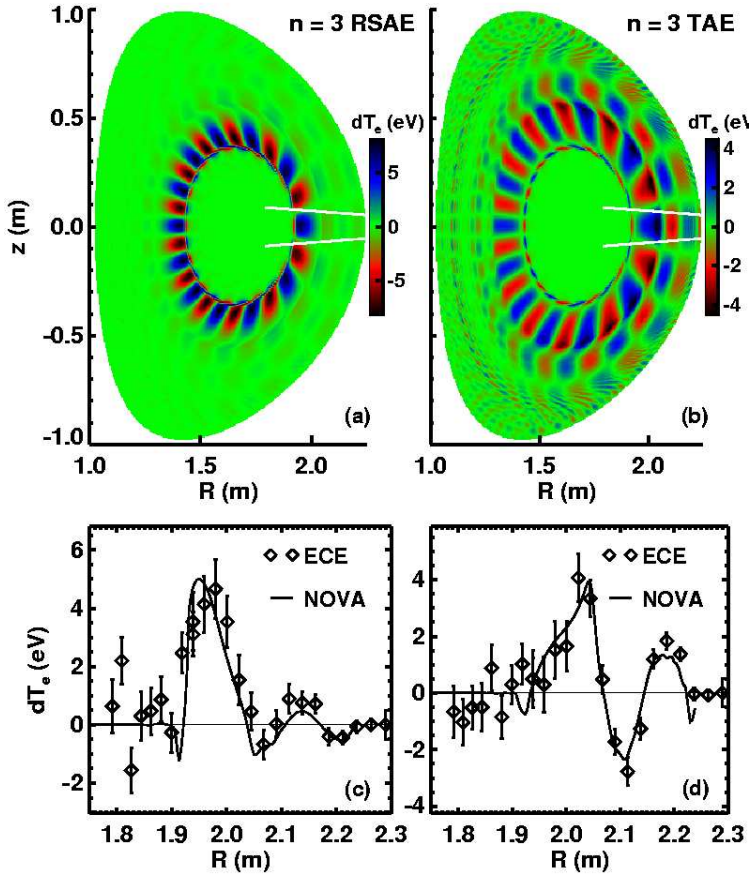

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DIII-D $*AE$ validation XP:

- TAE/RSAEs computations are validated
- growth/damping rates are consistent
  - predictions (NSTX, TFTR - TAEs, ITER)
- $\Rightarrow$ address EP transport in a regime when $*AE$ modes are not virulent [S. Sharapov, IAEA12]