Runaway Electron Confinement during Rapid Shutdown of Diverted DIII-D Discharges

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Outline

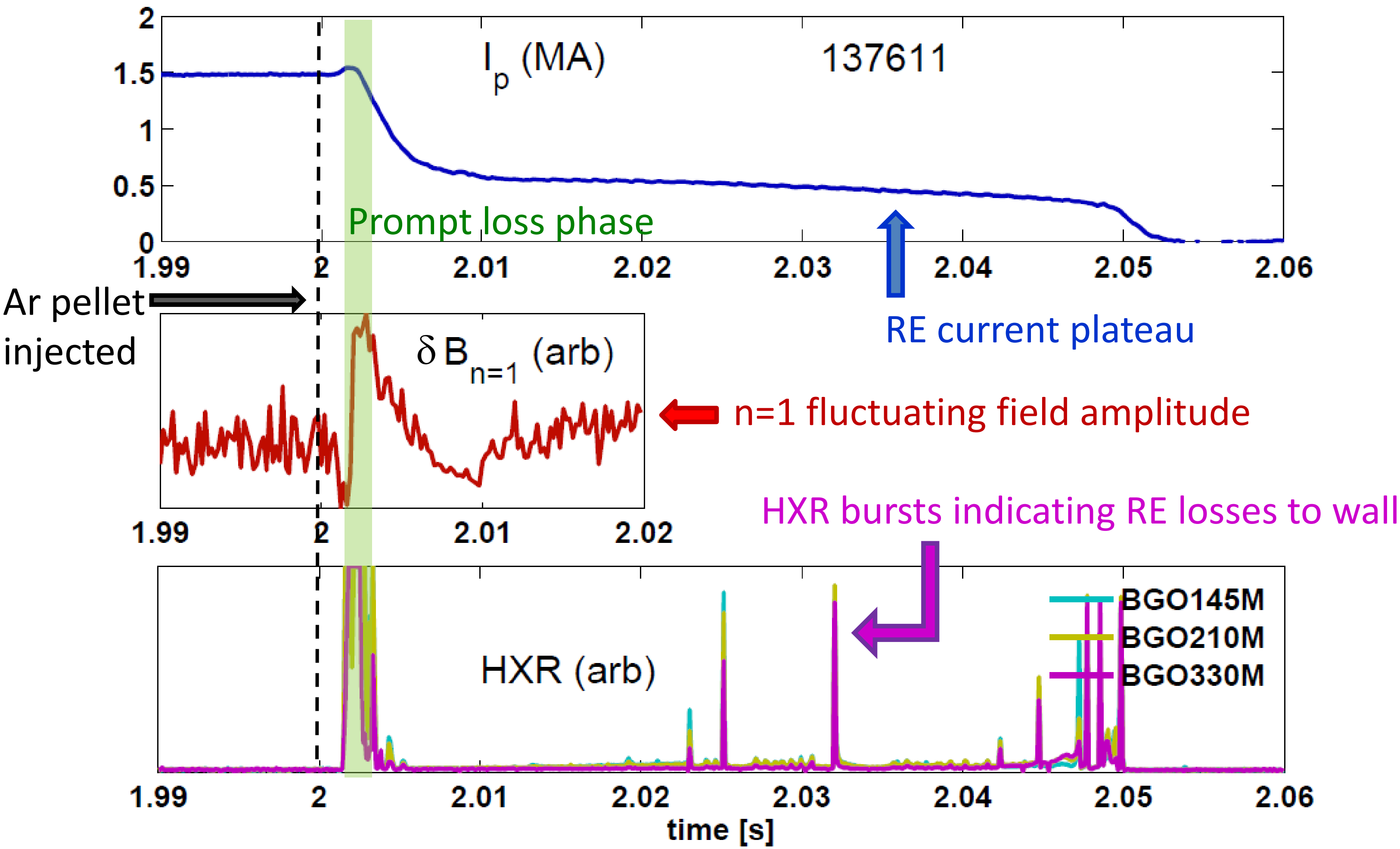
1) DIII-D RE experiments with diverted target plasmas

2) GATO linear stability analysis of early TQ phase triggered by Ar-pellet injection

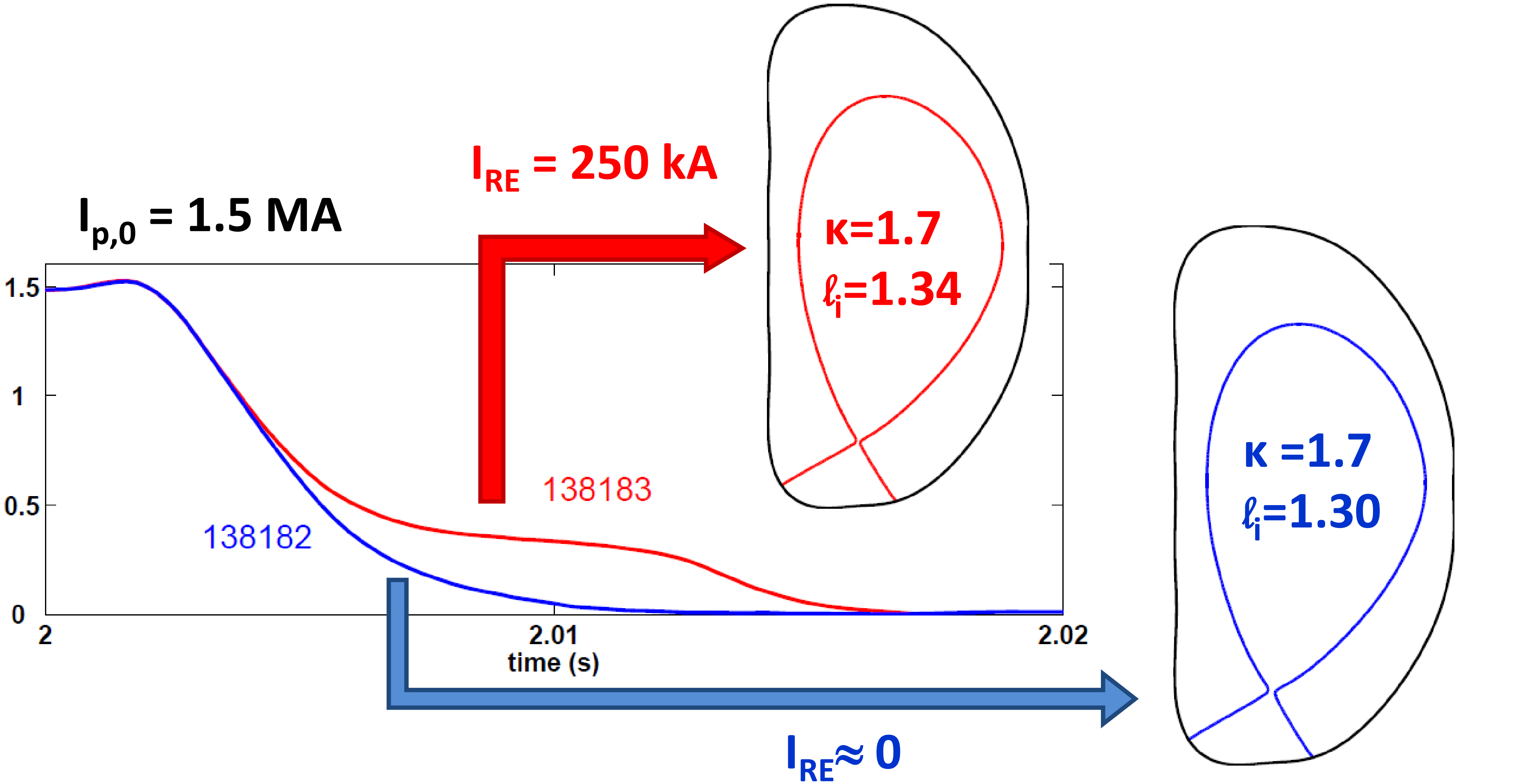
3) NIMROD nonlinear simulations with simplified Ar pellet model

4) Summary

Ar pellet injection into DIII-D discharges frequently produces RE current plateaus following disruption



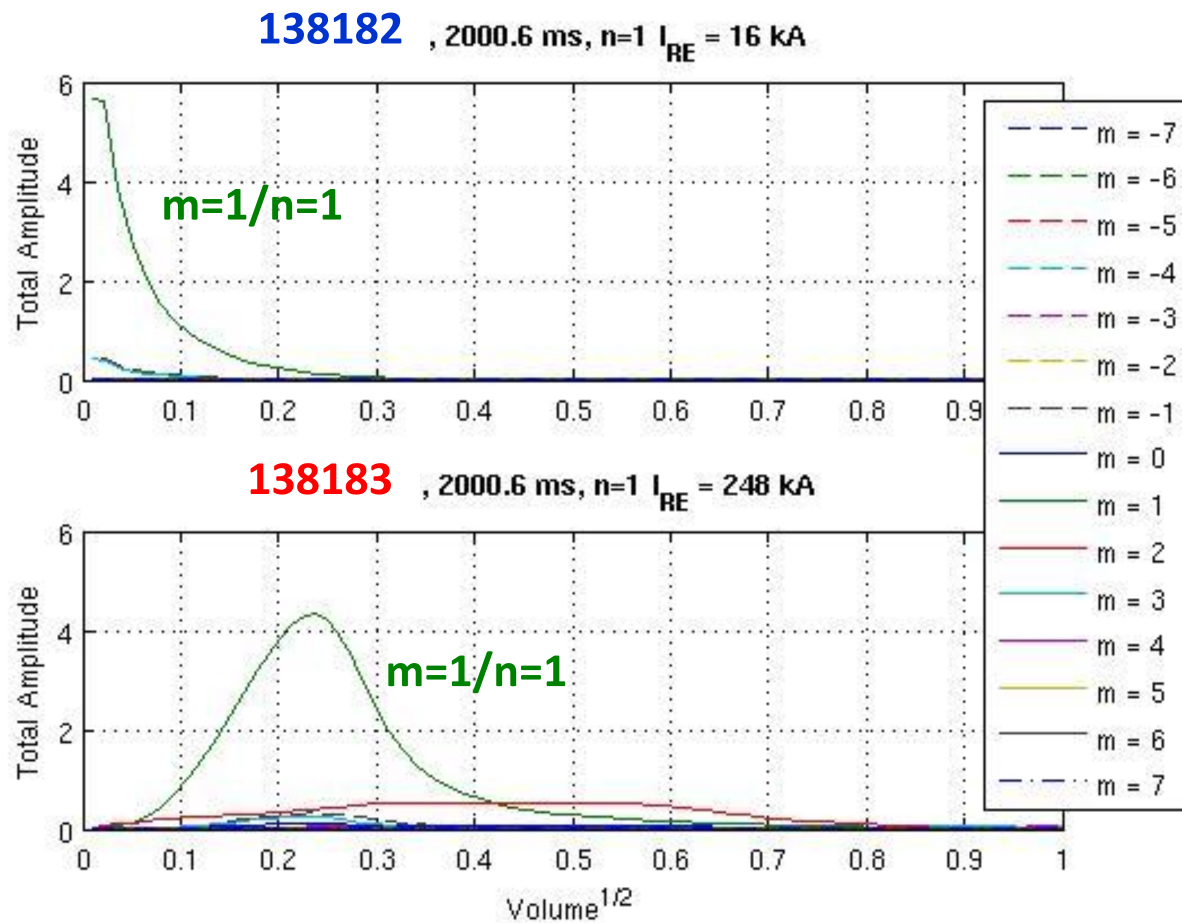
Appearance of RE plateaus for diverted plasma shapes is very unreliable on a shot-to-shot basis



GATO analysis reveals unstable linear mode structure shortly after Ar pellet injection

- Core-localized mode
  - Deconfine seed electrons from core, preventing REs ?
  - Low RE current

- Non-core-localized
  - Indicate remaining core-confinement?
  - High RE current

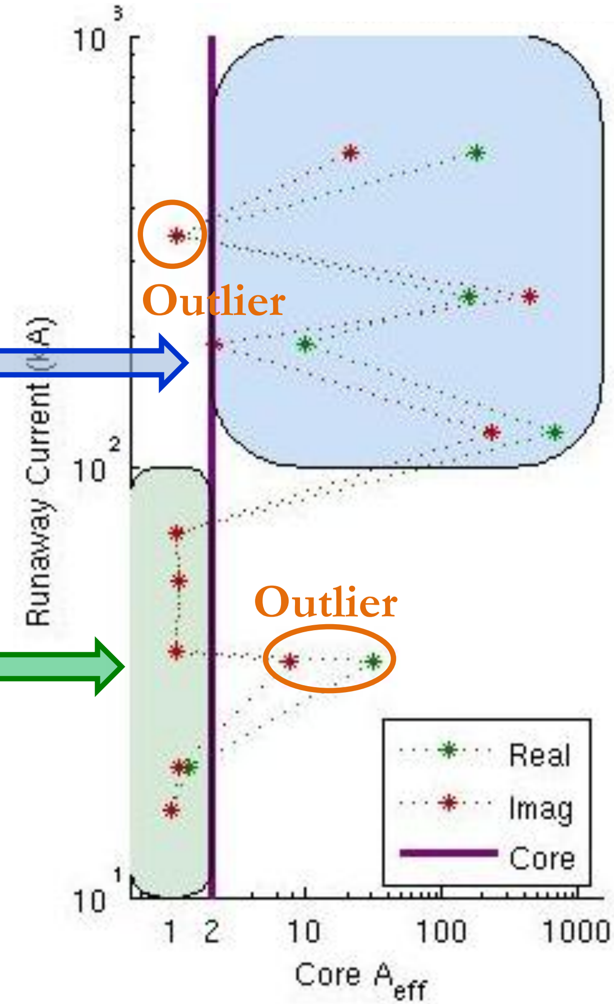


GATO results separate high/low RE current discharges based on location of instability peak

Runaway Current vs. Core localization of n=1 mode:

$$A_{eff}(m) \equiv \frac{A_{max}(m)}{A_{core}(m)}$$

- **Non-core-peaked n=1 mode**
  - **Many REs, high current**
  - **Effective good core confinement of REs**
- **Core peaked n=1 mode**
  - **Few REs, low current**
  - **Effective core deconfinement of REs**

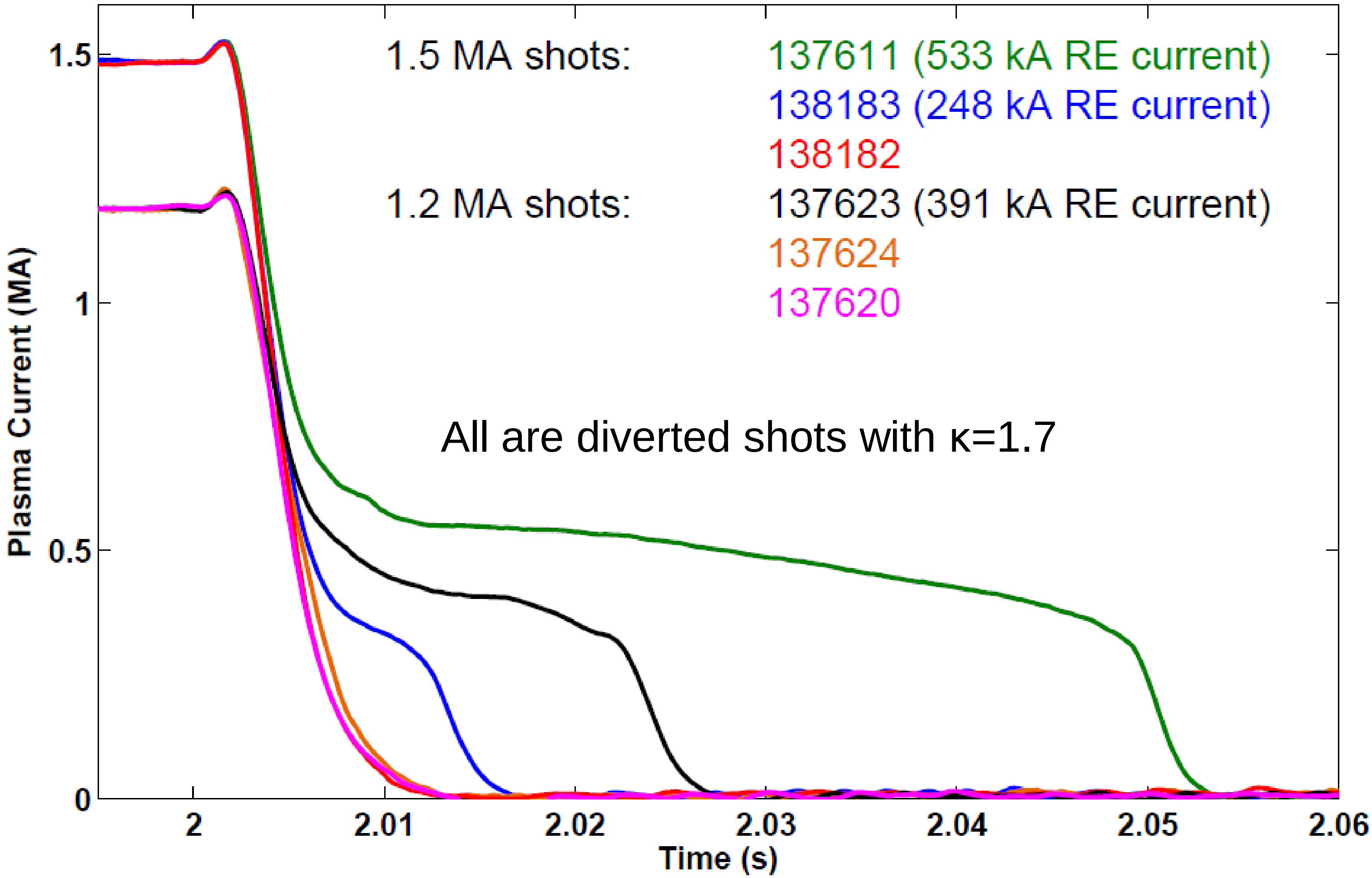


Is core/edge peaking of modes due to target equilibrium or pellet differences?

- Linear GATO runs begin with EFIT reconstructed **after** pellet injection, finds unstable modes at start of thermal quench
  - -Differences in target plasma equilibrium or variations in pellet size/ablation rate could contribute to GATO results

- Nonlinear NIMROD simulations are carried out starting from EFIT reconstructed **before** pellet injection
  - -NIMROD includes Ar-pellet deposition model, which is simplistic, but invariant over the set of simulations
  - -Only difference between two NIMROD cases is target equilibrium
  - -NIMROD also includes RE orbit-following model to calculate RE confinement as nonlinear instabilities evolve

Six shots are chosen for NIMROD simulations

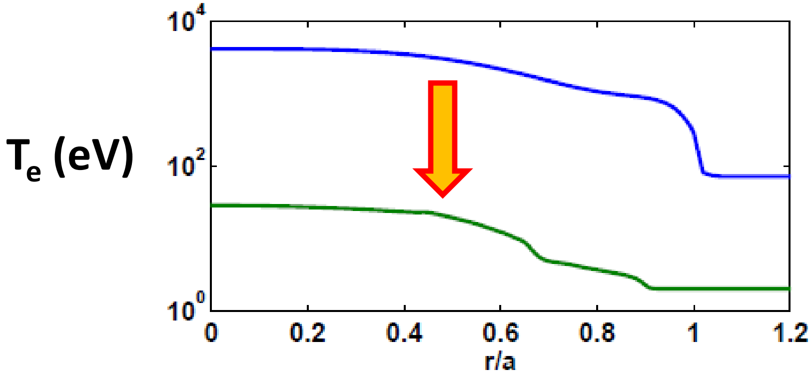


Equilibrium correlations with DIII-D RE measured current for these six shots

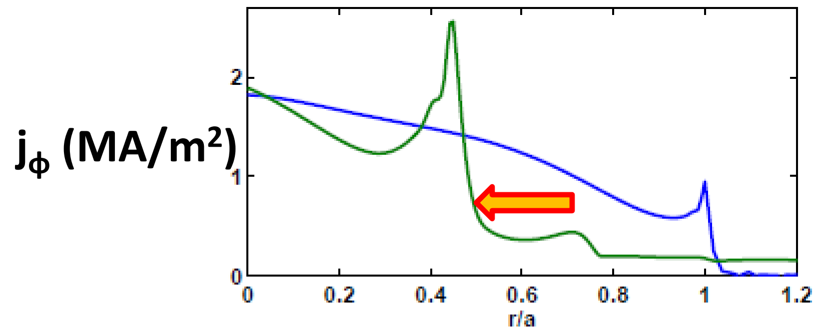
shot	137623	137624	138183	138182	137611	137620	
Ip0	1.19E+06	1.19E+06	1.48E+06	1.47E+06	1.46E+06	1.18E+06	
I_RE	3.91E+05	3.49E+04	2.48E+05	1.60E+04	5.33E+05	2.00E+04	
I_RE/Ip0	3.29E-01	2.94E-02	1.67E-01	1.09E-02	3.65E-01	1.69E-02	Correlation with I_RE/Ip0
psi_q=2	0.562	0.528	0.569	0.548	0.596	0.469	0.742705
j0/j50%	2.69E+00	2.68E+00	2.05E+00	2.32E+00	1.74E+00	2.32E+00	-0.36075
Ip_q<2	7.32E+05	6.32E+05	8.53E+05	7.93E+05	9.43E+05	5.76E+05	0.646166
Ip_q<2/Ip0	**0.616**	**0.533**	**0.576**	**0.538**	**0.645**	**0.487**	**0.947574**
rho_q=2	0.696	0.673	0.720	0.698	0.751	0.637	0.717773
dj/drho_q=2	1.77E+06	1.22E+06	1.82E+06	6.39E+05	2.46E+06	1.89E+06	0.710424
q95	3.730	3.800	3.260	3.170	3.210	3.620	-0.13553
q0	0.860	0.847	0.834	0.752	1.049	1.037	0.337314
li	1.436	1.396	1.344	1.297	1.337	1.167	0.518384
j0	2.16E+06	2.17E+06	2.26E+06	2.48E+06	1.82E+06	1.77E+06	-0.29596
j_q=2	7.30E+05	7.87E+05	1.03E+06	1.05E+06	9.06E+05	8.23E+05	-0.22539
(rho/j) (dj/drho) q=2	1.68E+00	1.04E+00	1.27E+00	4.23E-01	2.04E+00	1.46E+00	0.796378
j0/jq=2	2.96E+00	2.76E+00	2.19E+00	2.35E+00	2.01E+00	2.16E+00	0.028818

Sequence of event is common to all NIMROD simulations of Ar pellet injection

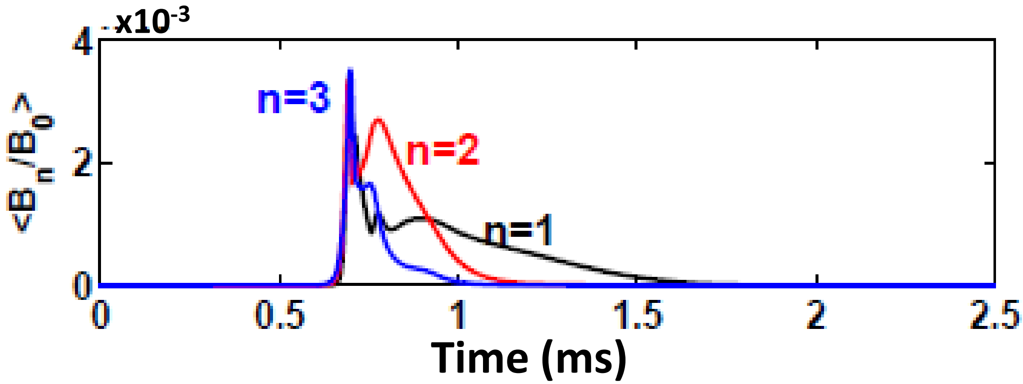
Deposited Ar rapidly cools plasma



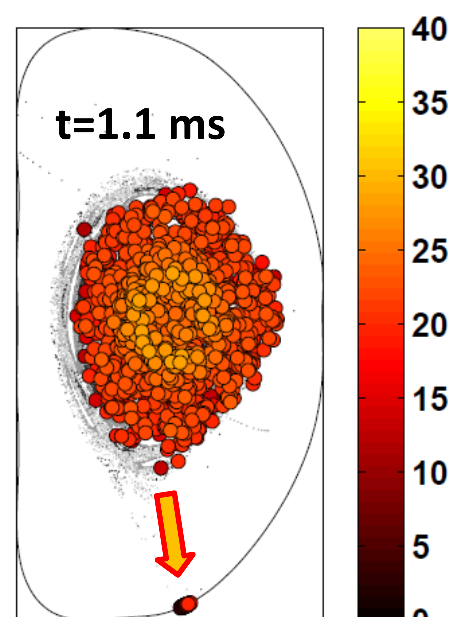
Current profile contracts



MHD instabilities appear



Stochastic fields lead to RE losses



Escaping REs strike outer divertor

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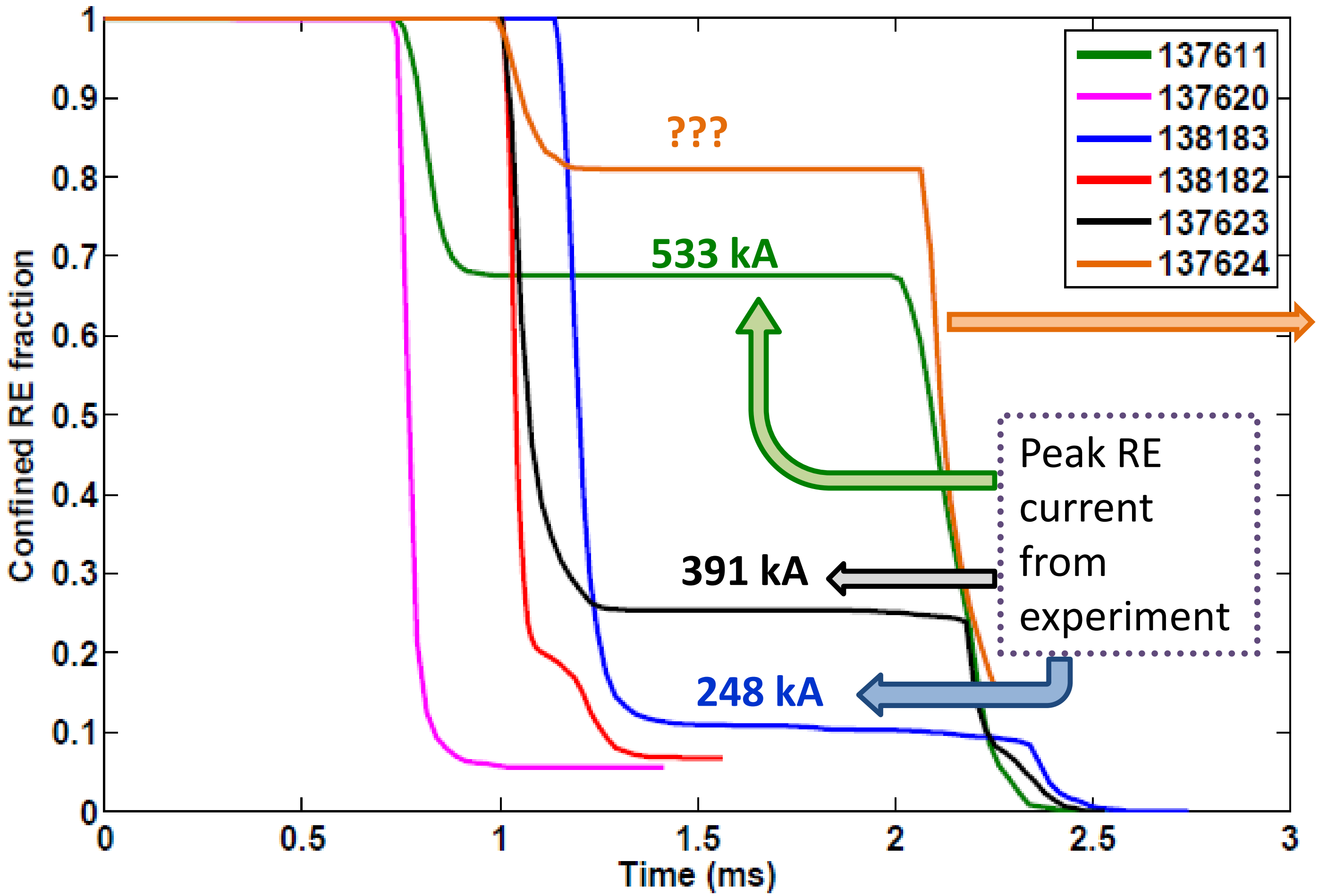
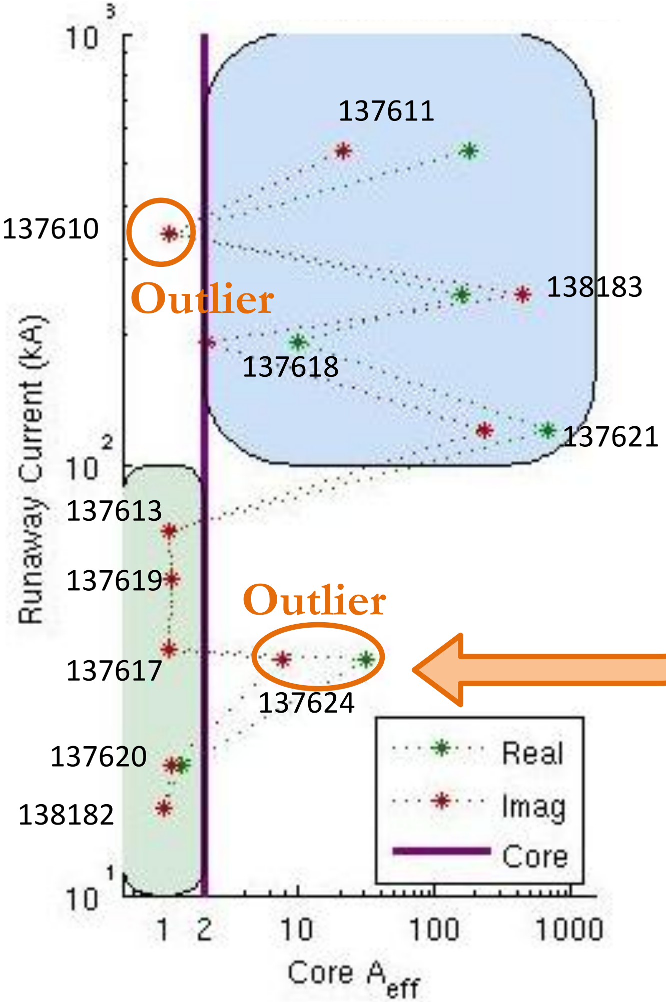
Fraction of REs lost due to MHD varies considerably between the simulations



NIMROD finds best RE confinement for no-RE-plateau shot !☹

NIMROD outlier was also outlier in the GATO analysis

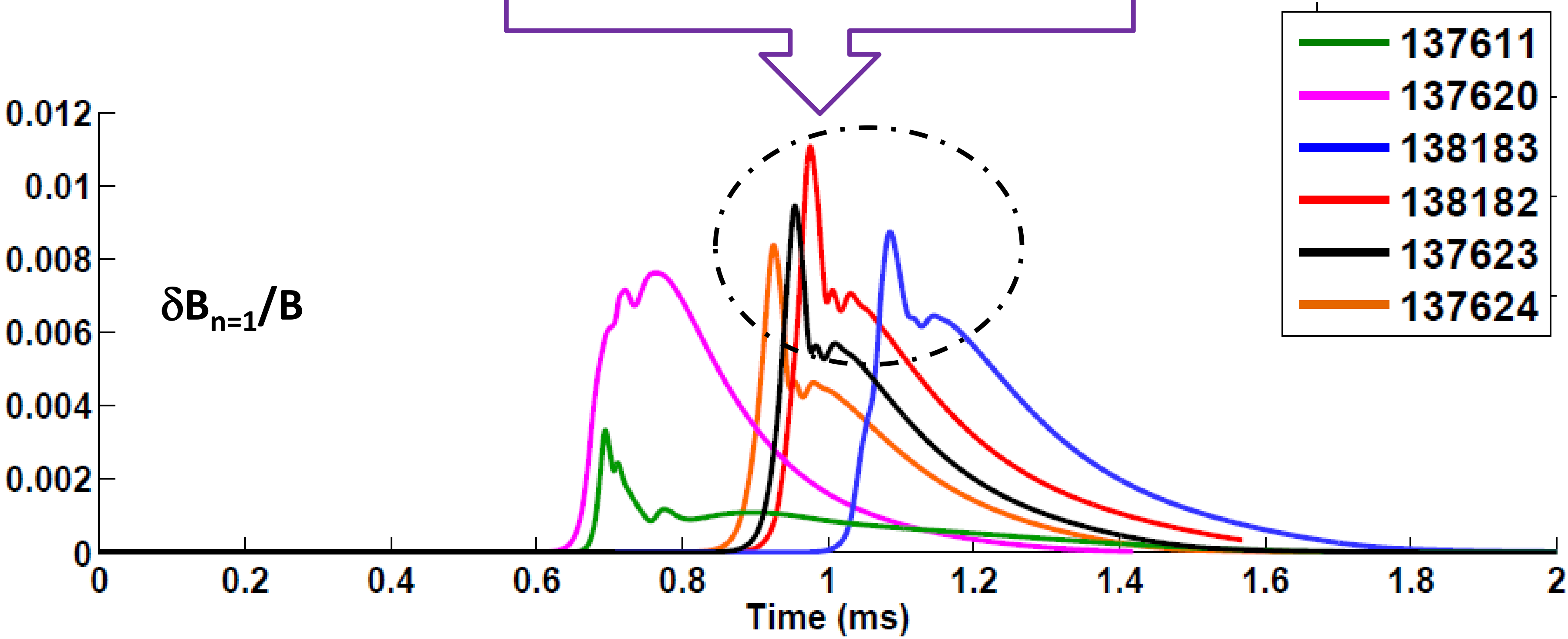


Shot 137624: Linear unstable eigenfunction more like high-RE shots, yet still didn't produce RE current plateau

Alternate explanation for lack of runaways in this shot ?

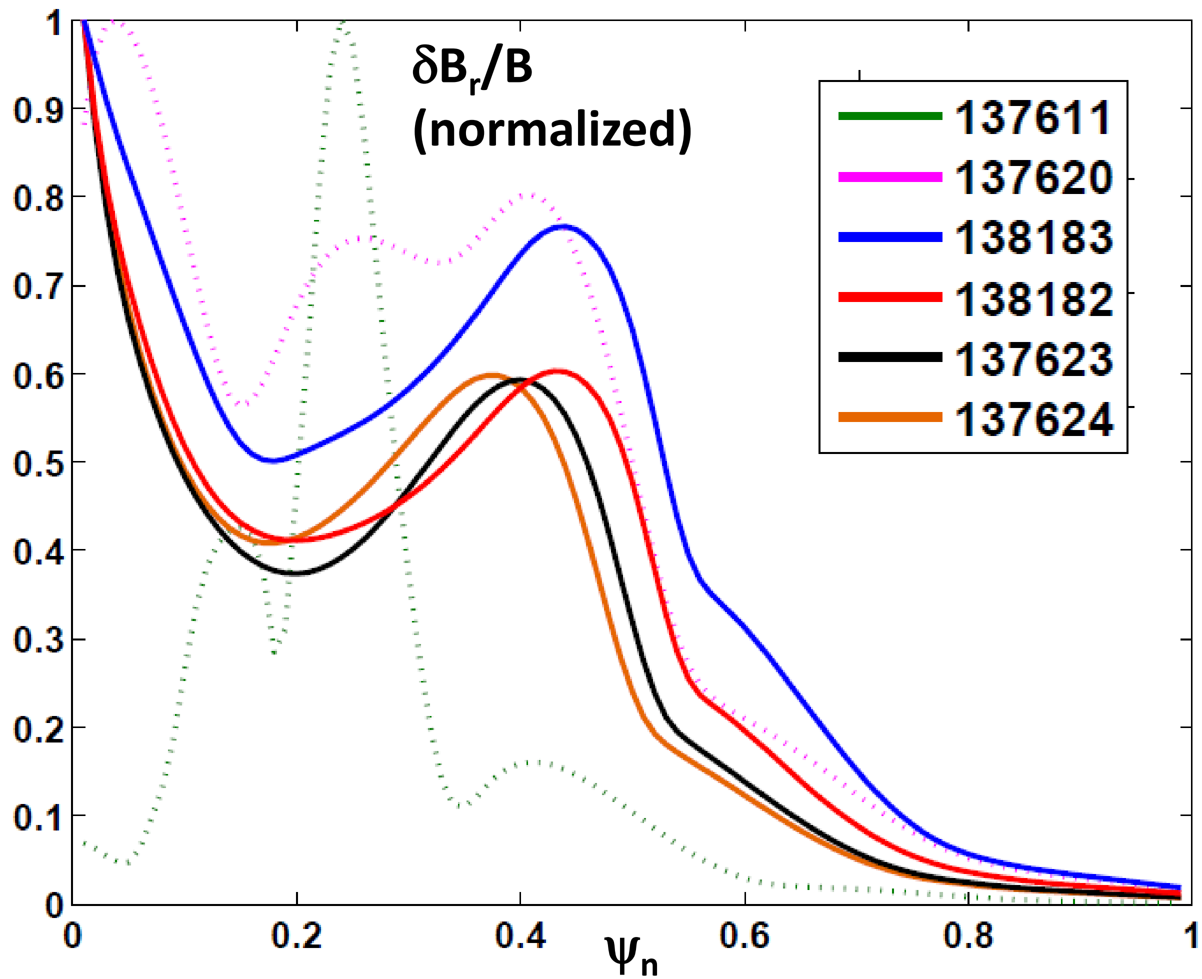
Time evolution of n=1 mode shows strong similarities in several simulations

These 4 cases have $q_0<1$

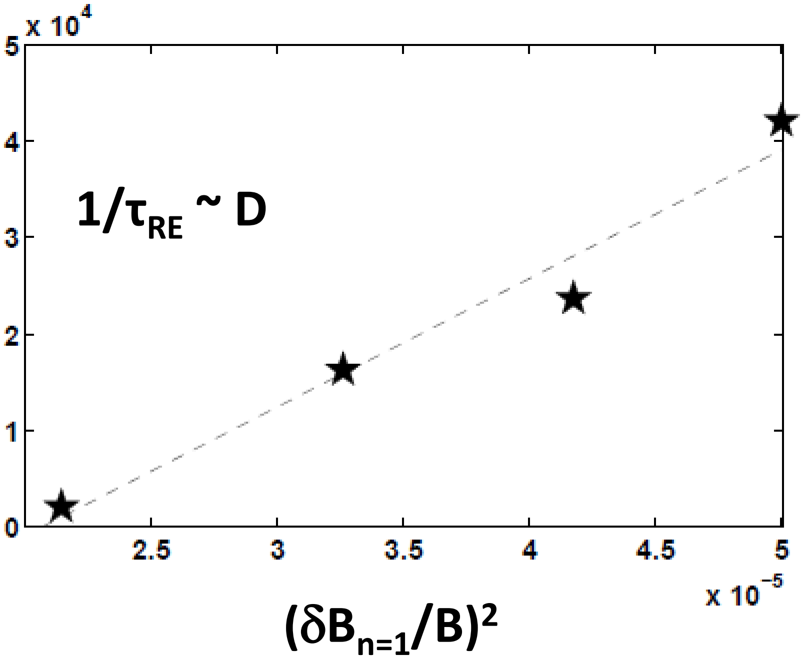


Radial profile of n=1 mode at first peak very similar for all $q_0<1$ simulations

Difference in mode structure does not appear to be the determining factor in different confinement results for these four simulations

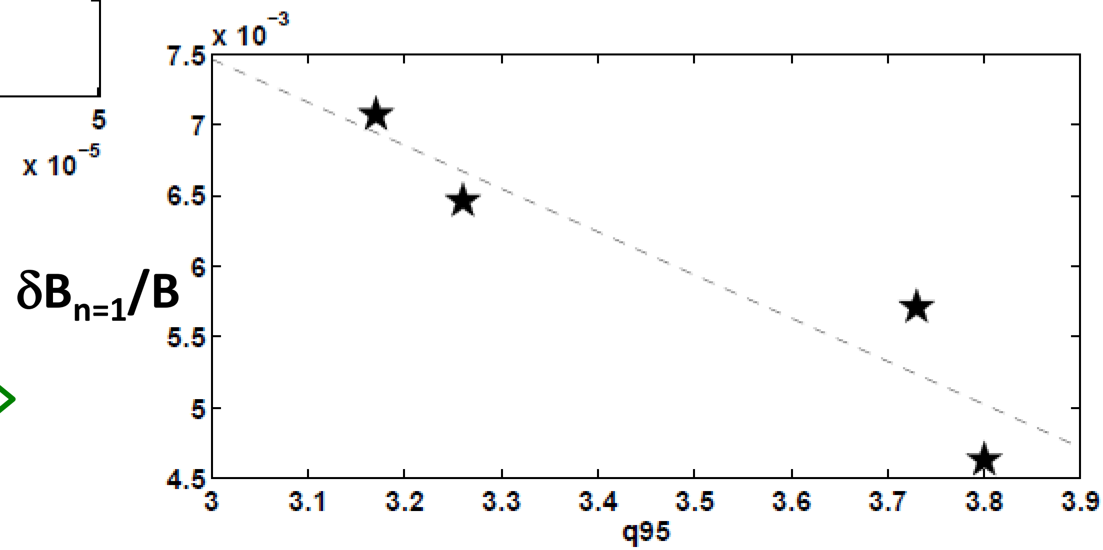


Amplitude of n=1 fluctuations appears to determine losses for q_0<1 simulations



Diffusion coefficient (maximum rate of RE loss) is proportional to square of fluctuating field amplitude at *last* local maximum.

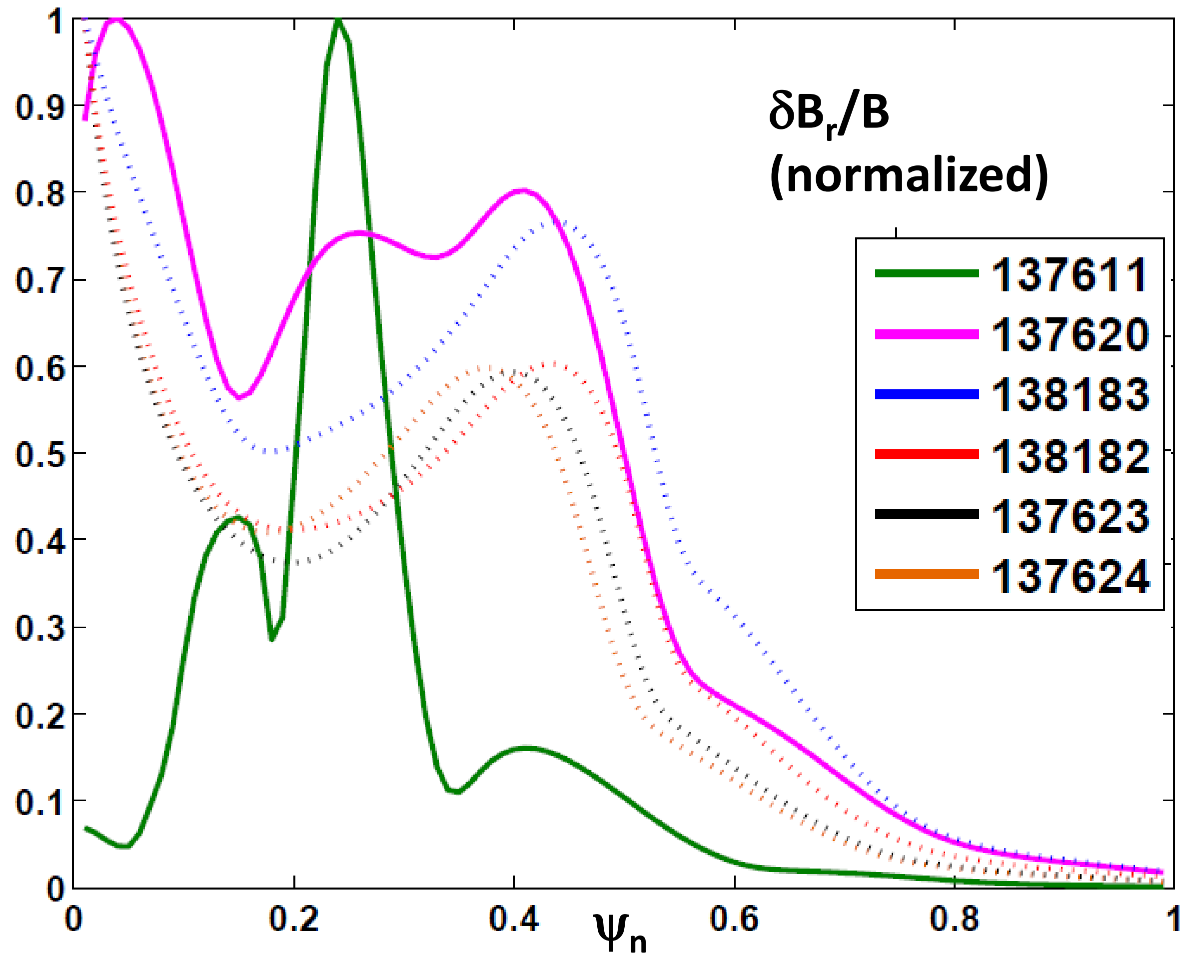
Larger fluctuating fields appear to be associated with lower q_{95}



Simulations with $q_0>1$ show very different mode structures

Case with good confinement is peaked off-axis, where as case with poor confinement is peaked on axis…

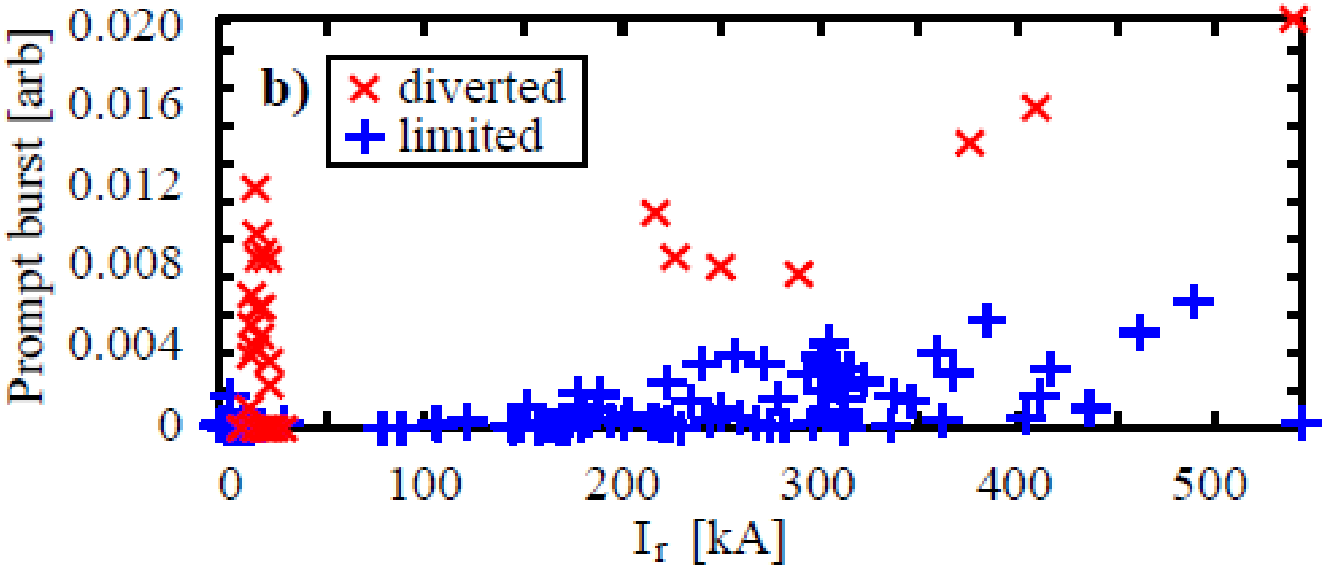
But, poor confinement case also has much higher amplitude; effect of mode structure is unclear



DIII-D tends to show higher prompt loss for higher RE current in diverted shots

Inconsistent with hypothesis that confinement is the primary determining factor in plateau current?

From A.N James



Variation in seed generation could be equally (or more) important. NIMROD does not yet model RE generation, but may need this capability to capture the whole story.

Summary

- Diverted DIII-D plasmas produce a wide range of RE plateau currents when terminated by Ar pellet injection
- GATO linear stability analysis suggests that radial structure of the unstable mode may play a role in RE confinement: on-axis peaked modes → poor confinement; off-axis peaked → good confinement
- NIMROD simulations of six DIII-D discharges predict a range of confined RE fractions, not in all cases consistent with DIII-D plateau currents
- Simulations with $q_0<1$ all have similar n=1 mode radial-profile and time evolution; amplitude predicts RE confinement well; q_{95} may play a role in determining amplitude
- Simulations with $q_0>1$ show different mode amplitudes and radial profiles; role of each factor is unclear.