Velocity Space Studies of Fast-ion Transport During a Sawtooth Crash

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Special thanks to the entire DIII-D team

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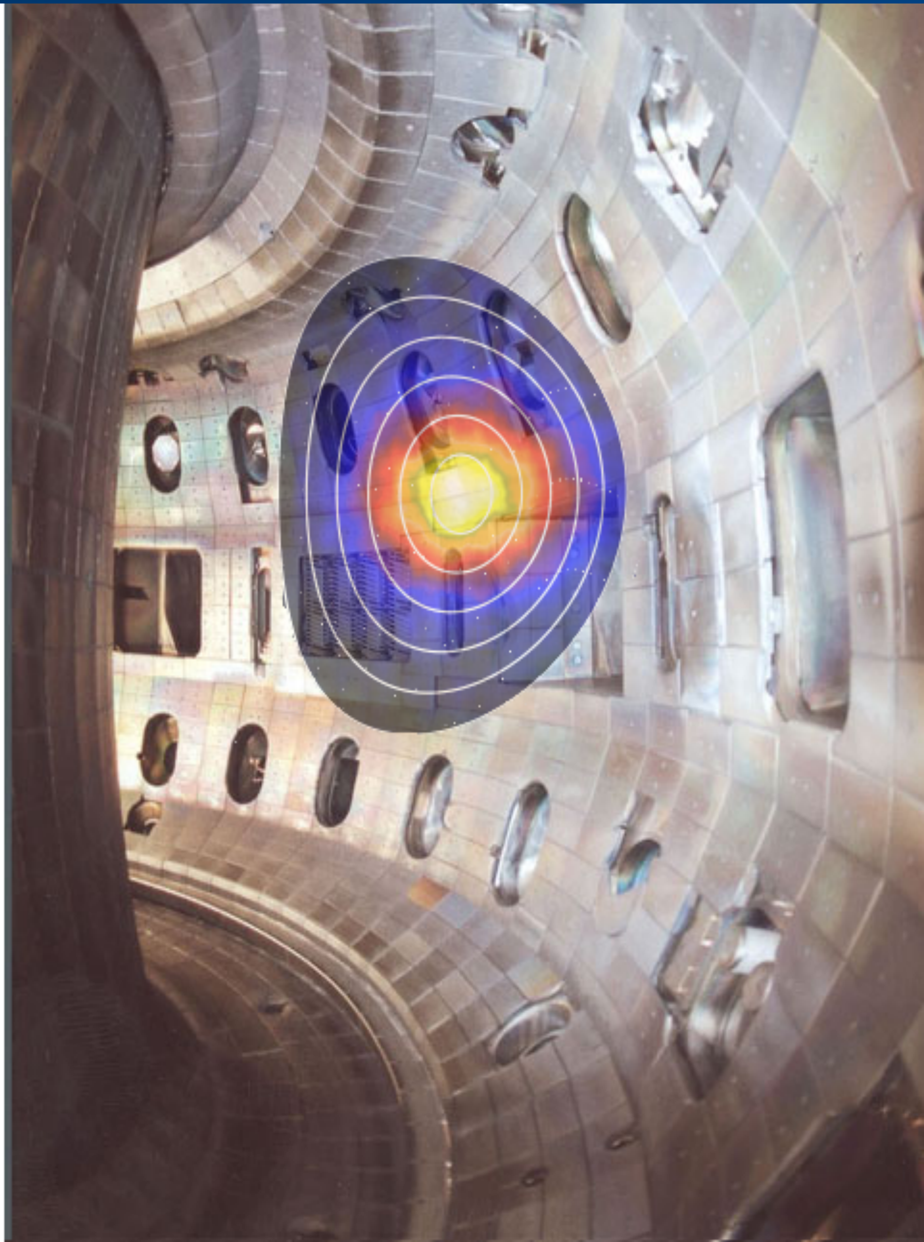
San Diego, CA

April 8th 2011



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Sawtooth-Induced Fast-ion Transport is Not News

1987-1995

(general investigations on superthermal ion populations)

JET – beam D, ICRF heated minority ions, fusion products of D-D reactions

DIII-D – beam D

TFTR – fusion-produced T

1995-2010

(studies began dissecting fast-ion velocity space)

TFTR – trapped and passing D-T alphas

TEXTOR – pitch resolved beam H

DIII-D Introduces Capabilities to Resolve Fast-ion Velocity Space

- **Revisit sawteeth for validation of transport models and build confidence in basic understanding of energetic ion dynamics**

- **New fast-ion deuterium-alpha (FIDA) system added during 2009-2010 campaign to complement previous systems**

  – The systems weight velocity-space differently providing reasonable discernment of different fast-ion populations

Outline

- Experimental setup and results: measured velocity-space dependence of fast-ion transport at a sawtooth crash

- Theory: drift-kinetic simulation of sawtooth-induced fast-ion transport and analytic treatment of particle drifts

- Summary

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Outline

- **Experimental setup and results: measured velocity-space dependence of fast-ion transport at a sawtooth crash**
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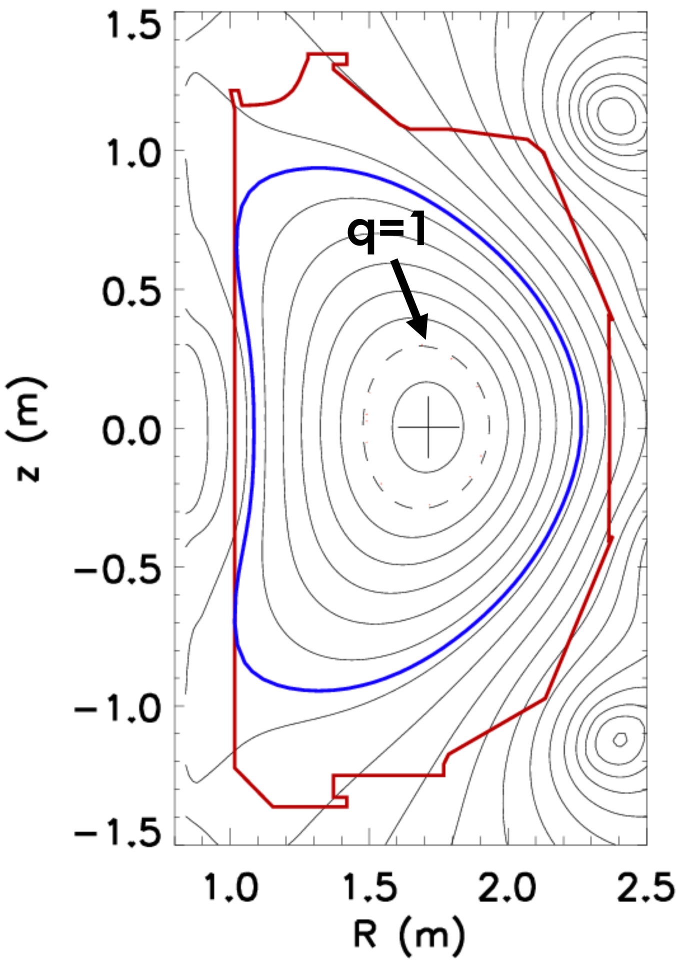
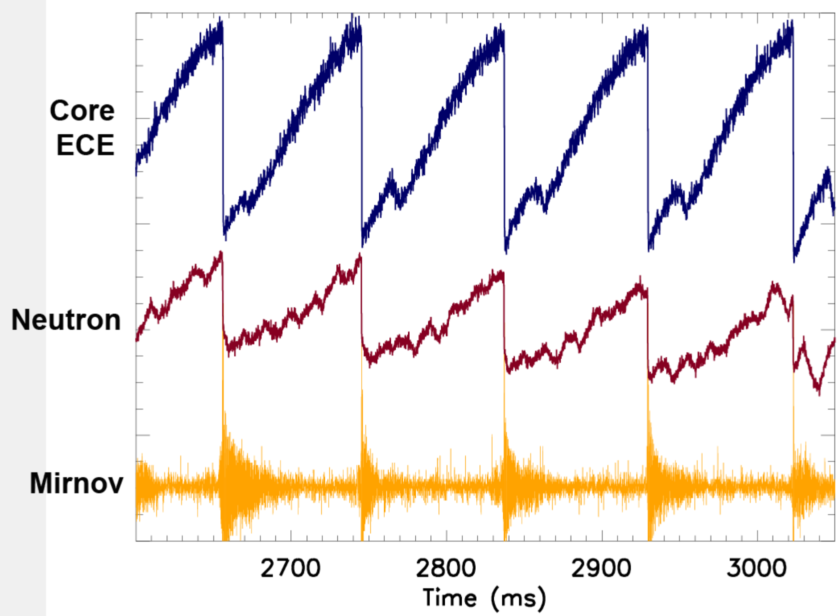
Low-n_e L-mode Discharge With Uniform Sawteeth



#141182:
Bt = 1.9 T
Ip = 1.3 MA
$\beta = 0.003$
$q_{95} = 4.0$
$\langle T_e(0)^{precrash} \rangle = 3.7$ keV
$\langle n_e(0)^{precrash} \rangle = 3.4$‰$10^{19} m^{-3}$
$\langle P_{inj} \rangle = 3.2$ MW
$\langle E_{inj} \rangle = 75$ keV
$\langle T_{sawtooth} \rangle = 85$ ms
$\langle \Delta n/n \rangle = -0.15$

- NBI is the only auxiliary heating source
- No other MHD activity detected
  (such as tearing modes, fishbones, AEs)
- n_e, I_p, B_t held constant to generate repeatable sawteeth



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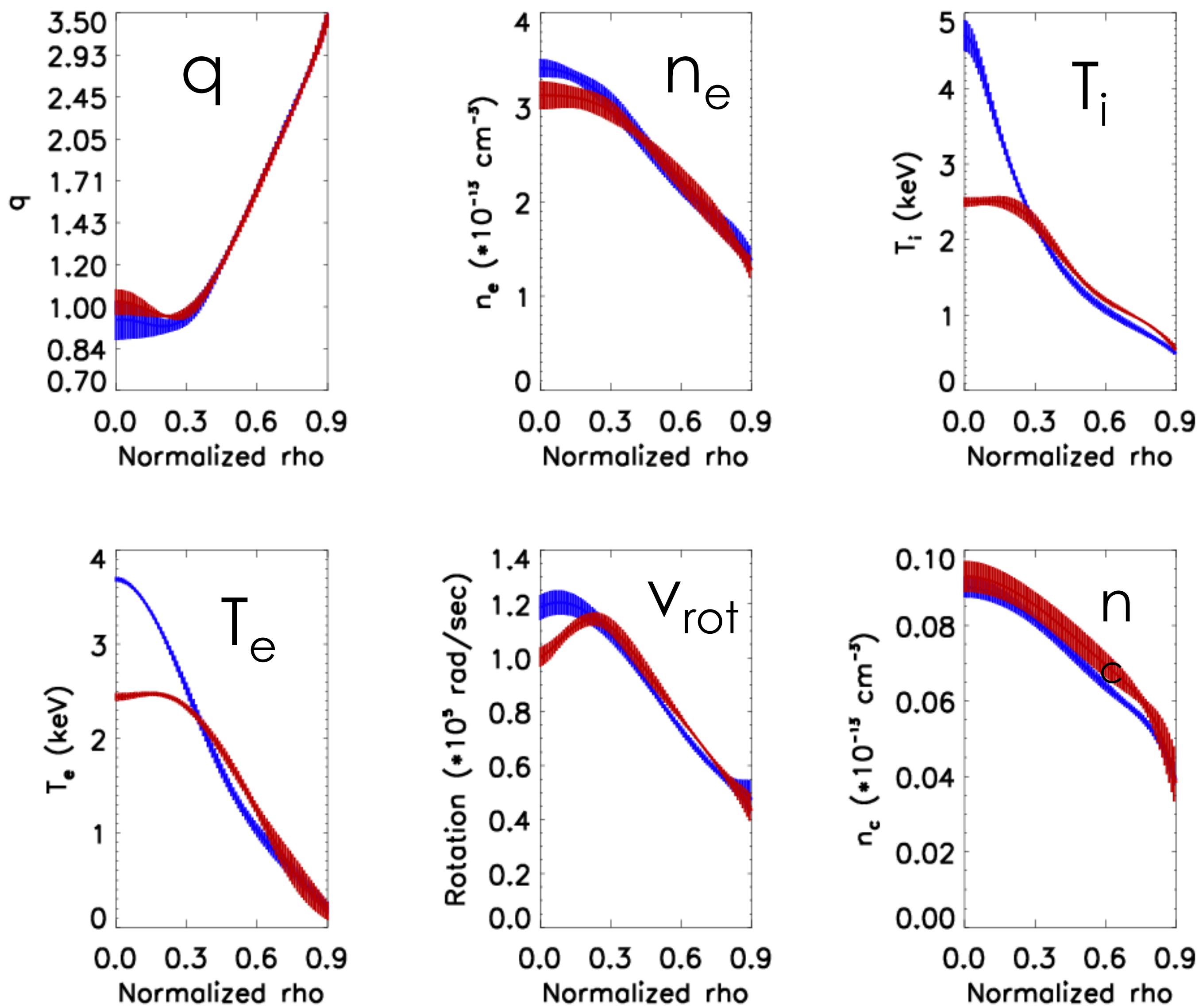
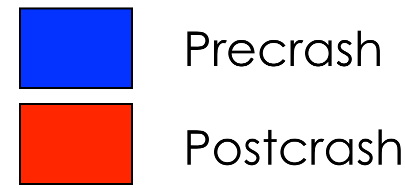
Clear Change in Many Plasma Profiles During a Crash





<u>141182</u>:

$\langle \Delta\, n_e(0)/n_e(0) \rangle = -0.10$

$\langle \Delta\, T_i(0)/T_i(0) \rangle = -0.47$

$\langle \Delta T_e(0)/T_e(0) \rangle = -0.34$

$\langle \Delta v_r(0)/v_r(0) \rangle = -0.15$

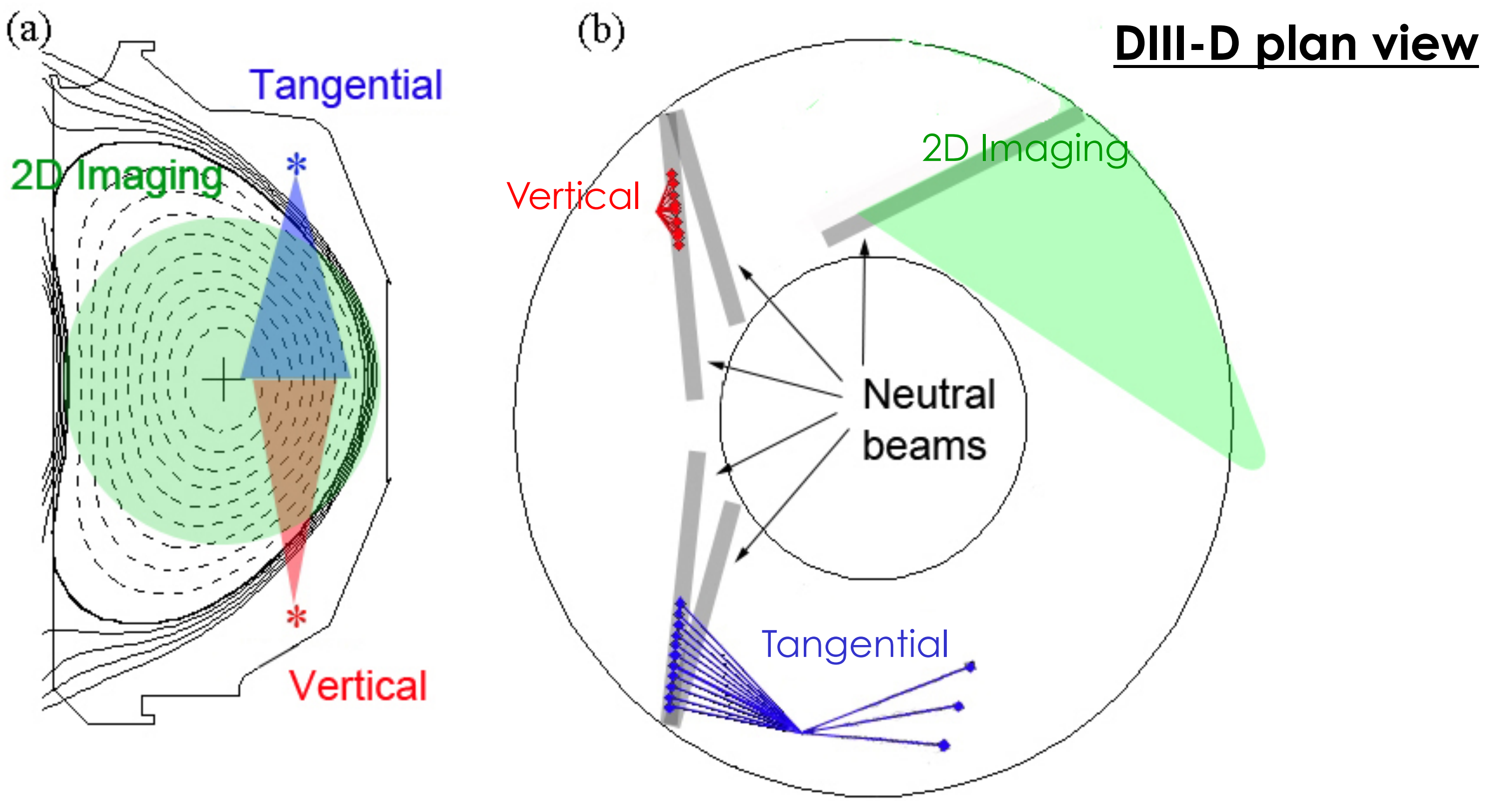
$\langle \Delta n_c(0)/n_c(0) \rangle = 0.03$

Employed FIDA Suite to Compare Different Parts of Velocity Space

Fast-ion deuterium-alpha (FIDA): spectroscopic-based diagnostic tool utilizing charge-exchange between injected D^0 and fast D^+ population to infer dynamics

- Each geometry provides unique instrumental weighting in phase space

<u>DIII-D poloidal plane</u>



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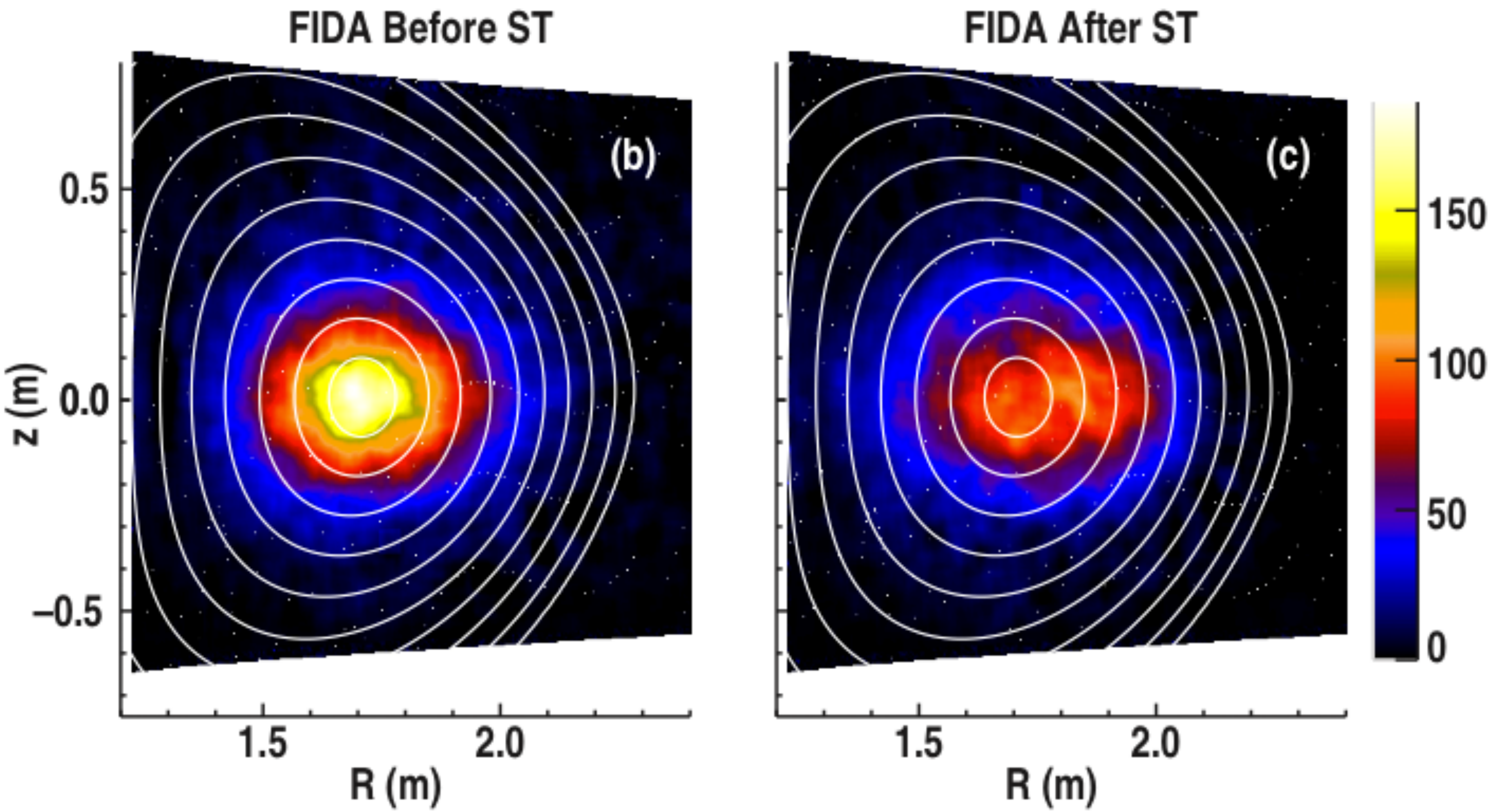
Fast-ion Profile Flattens at a Crash



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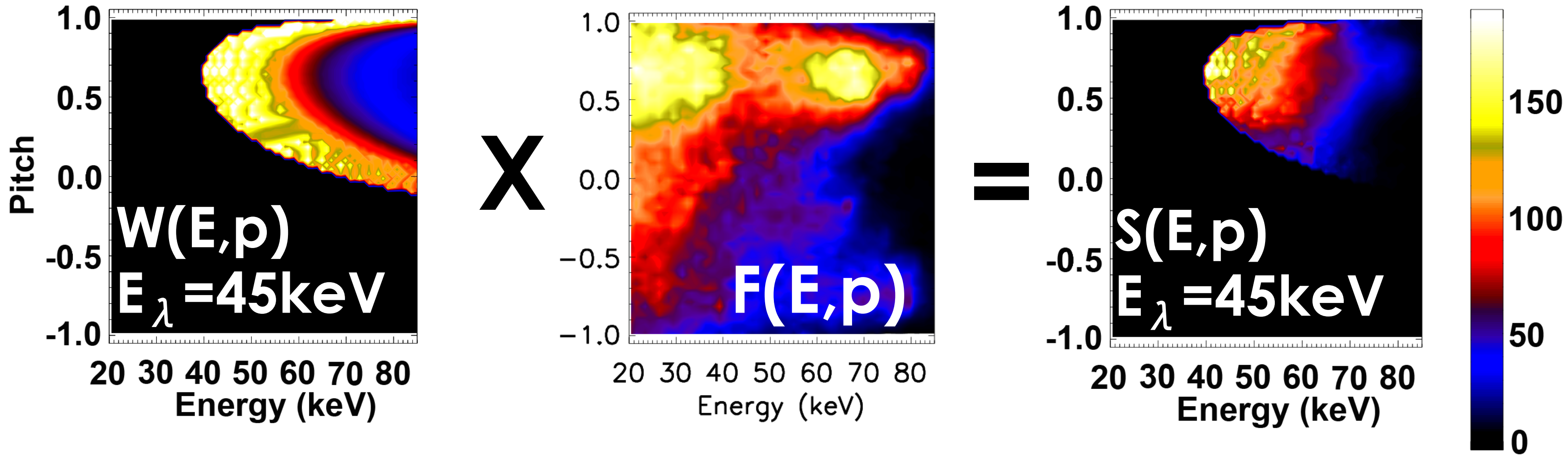
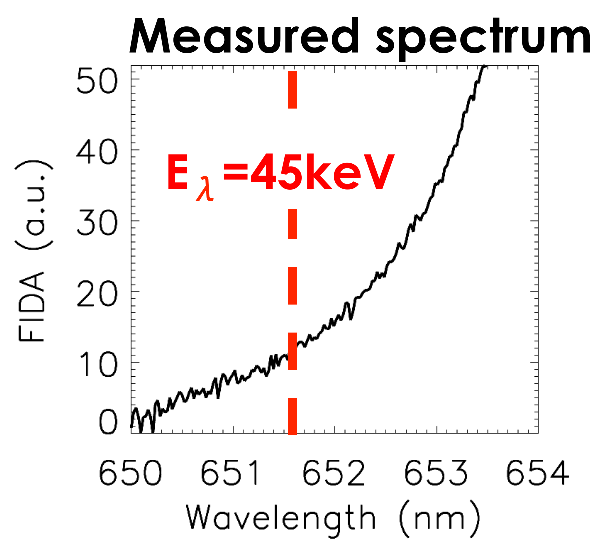
Van Zeeland et al, Nucl. Fusion **50** (2010) 084002

Interpreting FIDA Signal as a Velocity-space Weight Function

$$\text{Signal} \propto \iint W(E,p)*F(E,p)\, dE\, dp$$



E_λ: fast-ion energy component measured along line-of-sight



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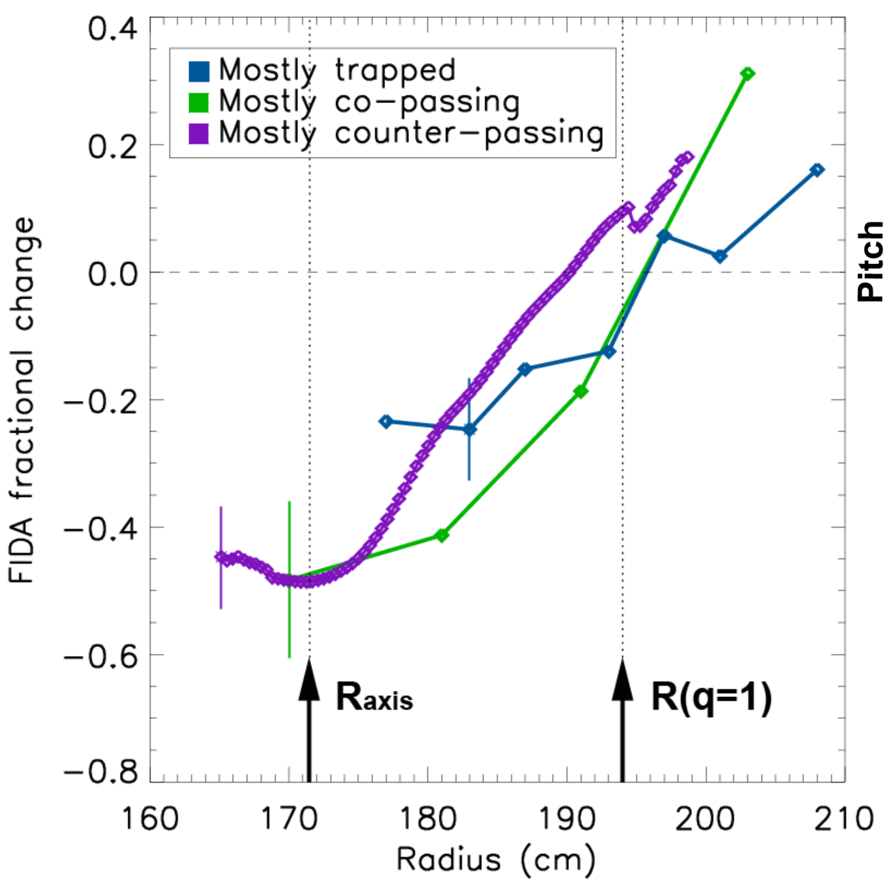
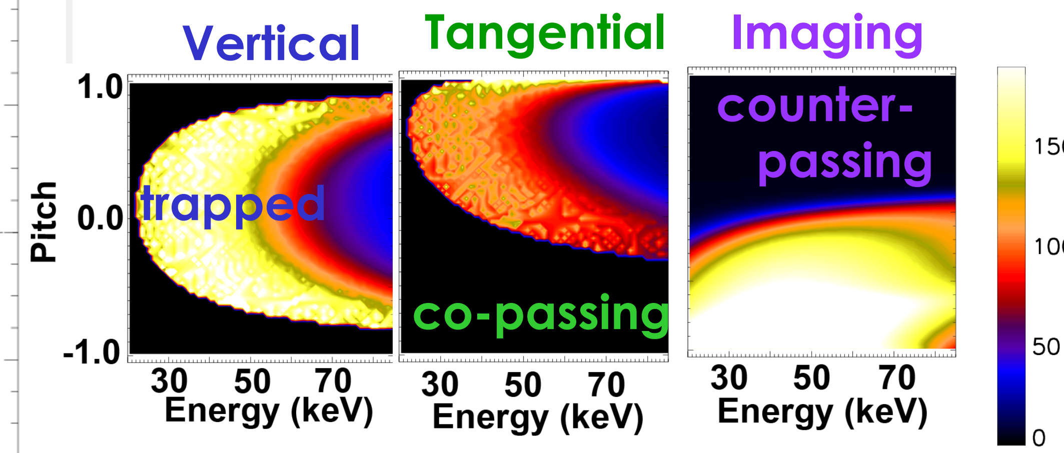
Passing Ions Experience Greatest Redistribution



Instrument weights



$\text{pitch} \equiv V_{||}/V$

$$\text{fractional change} \equiv \frac{\langle\text{postcrash}\rangle - \langle\text{precrash}\rangle}{\langle\text{precrash}\rangle}$$

- ~ 50% reduction in the core co- & counter-***passing*** fast-ion signal
- ~25% reduction in the central-most ***trapped*** fast-ion signal

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Stronger Passing-ion Transport is a *General* Trend Under Many Conditions

- Database of 30+ shots
- Various plasma shapes and conditions
- Fractional change database of FIDA signals for mostly trapped ions and co-passing ions

Parameter regimes

Bt = 1.86-2.05 T

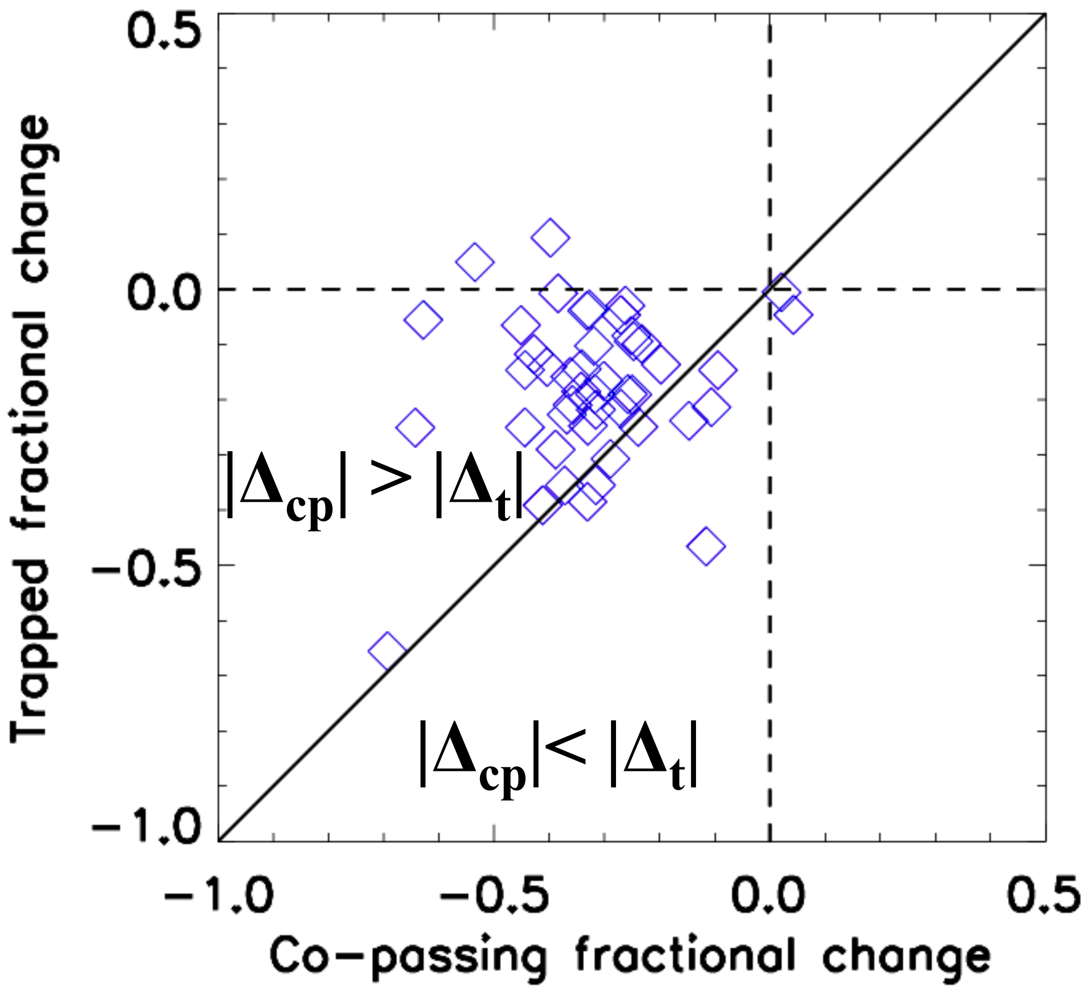
Ip = 1.16-1.34 MA

$\langle \Delta T_e(0)/T_e(0) \rangle = 0.21\text{-}0.37$

$\langle T_e(0)^{precrash} \rangle = 2 - 5$ keV

$\langle n_e(0)^{precrash} \rangle = 2 - 4‰10^{19} m^{-3}$

$\langle T_{sawtooth} \rangle = 48\text{-}108$ ms



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Outline

- The DIII-D FIDA suite incorporates 3 systems which weight velocity-space differently. Experiments indicate that passing fast ions experience stronger sawtooth-induced transport than trapped ions
- **Theory: drift-kinetic simulation of sawtooth-induced fast-ion transport and analytic treatment of particle drifts**
- Summary

Numerical Simulation Solves Bounce/Transit-averaged Drift-kinetic Equation

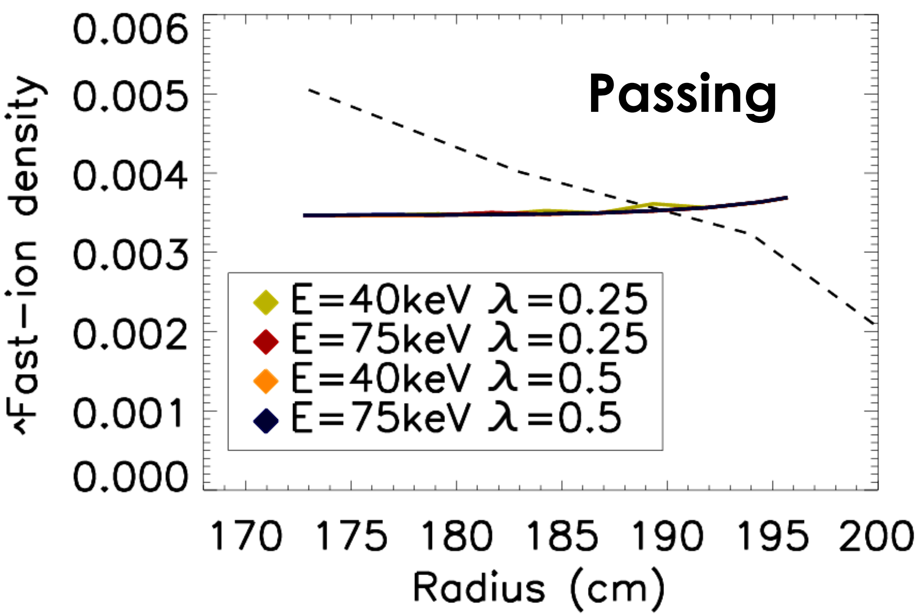
- OFSEF[1] code employs Kadomtsev sawtooth crash model to evolve the fields and solves the following kinetic equation

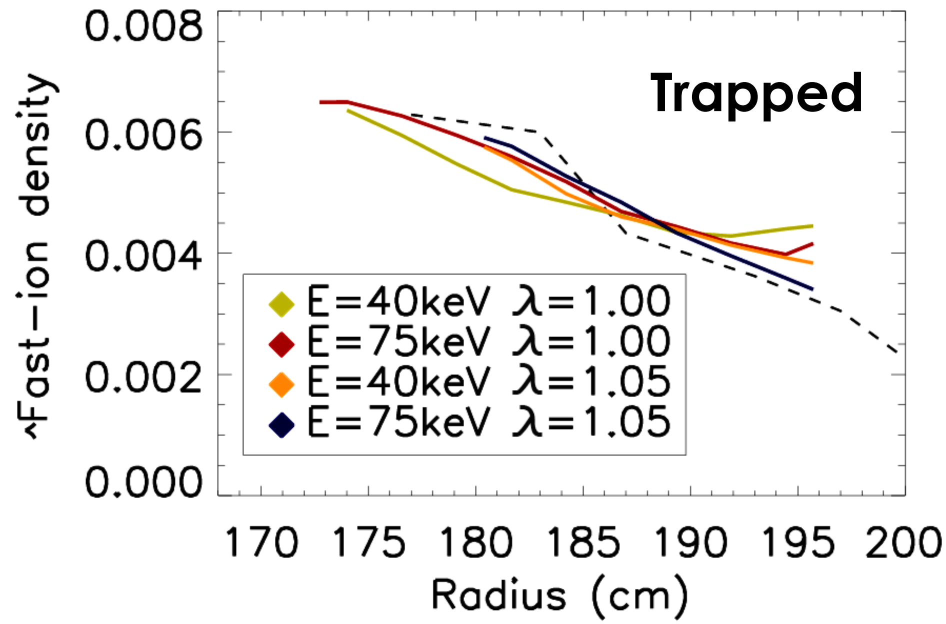
$$\partial f/\partial t = (-\mathbf{v}_{||}^{0} - \mathbf{v}_{D} - \mathbf{v}_{||}^{1} - \mathbf{v}_{E})\cdot\partial f/\partial \mathbf{x} - e(\mathbf{v}\cdot\mathbf{E}(\mathbf{x},t))\partial f/\partial \mathcal{E}$$

f – fast-ion distribution function
$\mathbf{v}_{||}^{0}$ – velocity along unperturbed flux surfaces
$\mathbf{v}_{D}$ – toroidal drift velocity
$\mathbf{v}_{||}^{1}$ – velocity along perturbed flux surfaces
$\mathbf{v}_{E}$ – **E** X **B** drift due to evolving perturbation
$\mathcal{E}$ – fast-ion energy

[1] Kolesnichenko et al Phys. Plasmas **4** (1997) 2544.

General Feature of the Simulation Shows that Passing Ions are More Readily Redistributed than Trapped Ions





$$\lambda \equiv \mu B_o / E$$

- Passing particle transport is insensitive to different energies and pitches

- Trapped particle transport depends on energy and pitch
- Smaller values of E and smaller values of λ produce flattest postcrash profiles

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Fast-ion Transport at a Crash is Driven by E X B Drift

- Underlying perturbation δ **B** takes on helical n=m=1 mode structure
- Assuming ideal conditions (except for thin layer) electric field (**E**= -**u** X **B**) generated by bulk plasma motion (**u**)
- Cross-field transport during crash driven by **E**X**B** drift and fast ions frozen to flux surfaces move with them
- However, some types of orbits are more prone to flux attachment than others....

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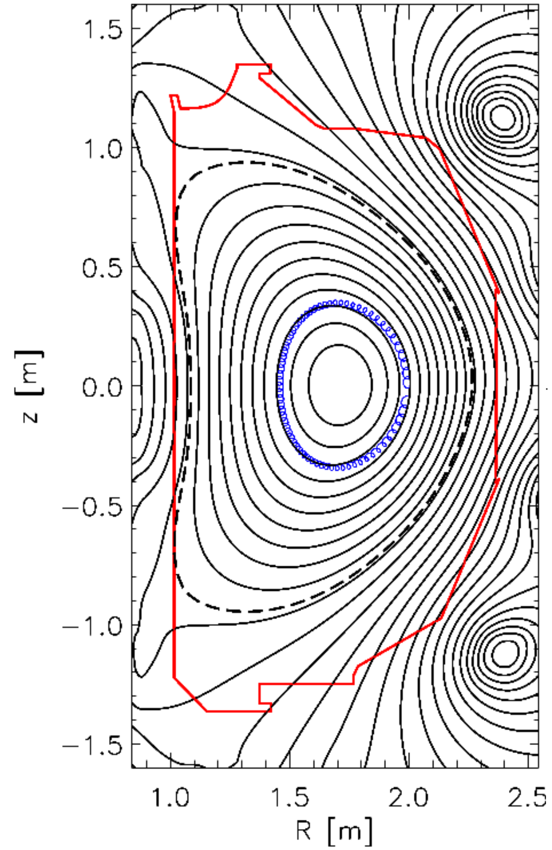
Potential for Transport of *Passing* Ions Depends on Parallel and Drift Motions

τ_Ψ – **longitudinal time** – *transit-averaged* period along a *perturbed* flux surface

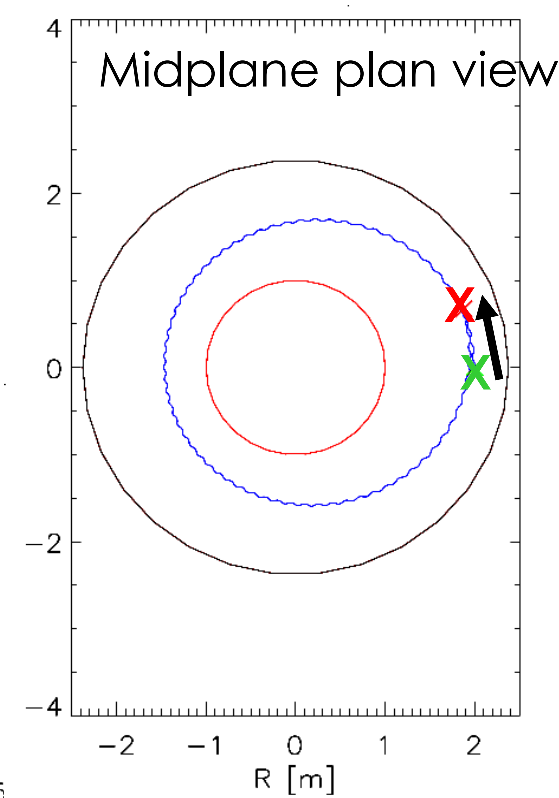
τ_{pr} – **toroidal precession time** – *transit-averaged* toroidal period

Strong transport:

$$\tau_\Psi \ll \tau_{pr}$$



Above: 1 poloidal transit



Above: toroidal distance traveled in 1 poloidal period

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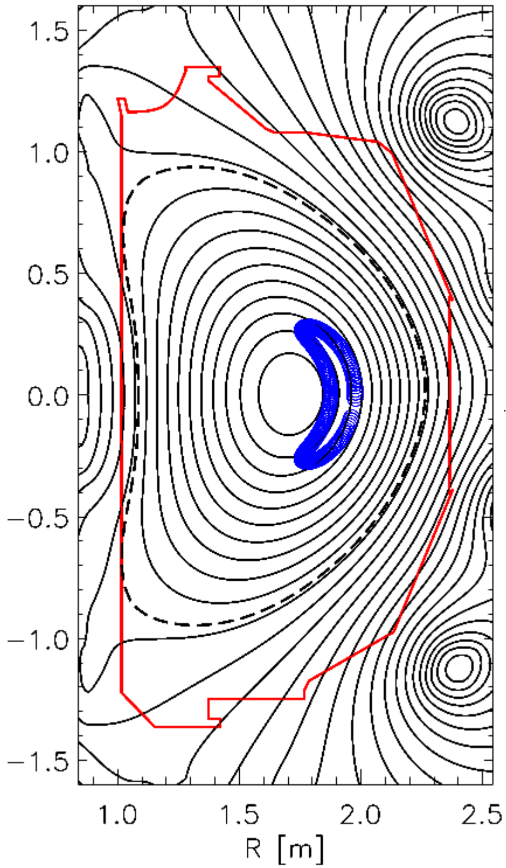
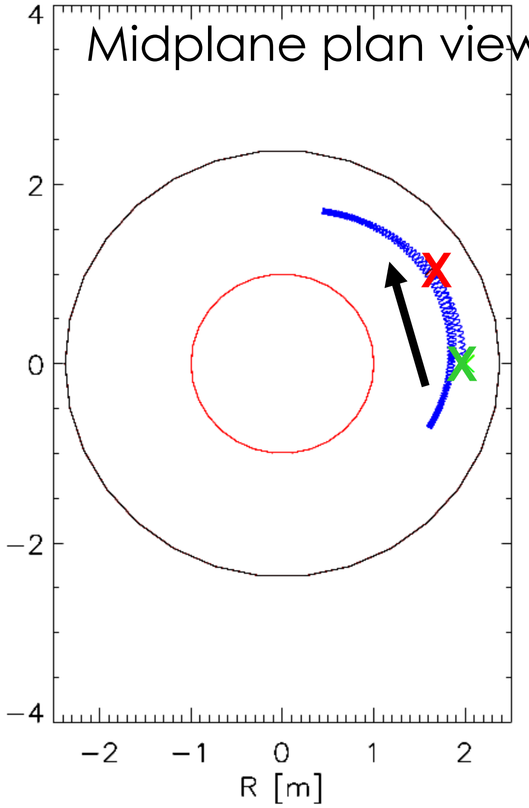
Potential for Transport of *Trapped* Ions Depends on Crash Time and Drift Motions

τ_{cr} – **crash time** – presumably synonymous with the reconnection time

τ_{pr} – **toroidal precession time** – *bounce-averaged* toroidal period



<u>Above</u>: 1 poloidal bounce



<u>Above</u>: toroidal distance traveled in 1 poloidal period

Strong transport:

$$\tau_{cr} << \tau_{pr}$$

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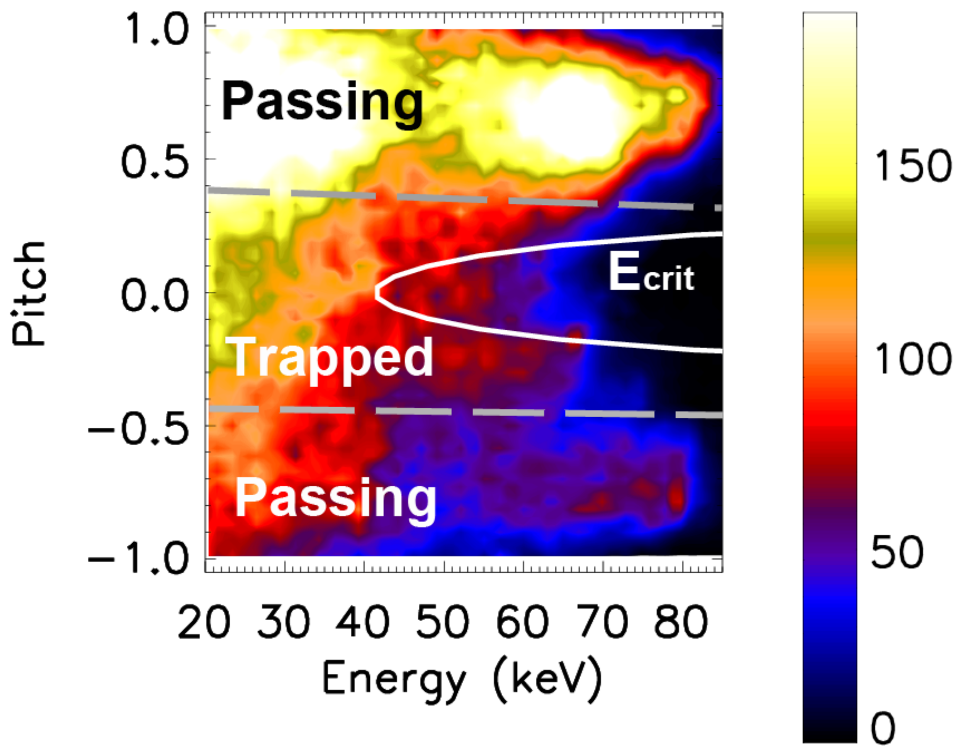
Timescale Comparison can be Recast in Terms of Energy and Pitch

Criteria for **strong** redistribution of fast-ions

- Passing: $\tau_{\Psi} \ll \tau_{pr} \rightarrow E \ll E(\chi)_{crit,passing}$
- Trapped: $\tau_{cr} \ll \tau_{pr} \rightarrow E \ll E(\chi)_{crit,trapped}$

Pitch:
$\chi \equiv V_{\|}/V$



- Classical slowing-down fast-ion distribution function calculated by TRANSP
- Trapped/passing boundaries (dashed) calculated by g.c. orbit code (Van Zeeland)
- Analytic E_{crit} (solid) calculated for trapped and passing regions
  $E_{crit}^{trapped}$ **≈ 40 keV**
  $E_{crit}^{passing}$ **≈ 200 keV**

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Kolesnichenko *et al* 1997 Phys. Plasmas **4** 2544-2554.

Different Transport Observed by FIDA Systems can be Explained by E_{crit}

Mostly trapped

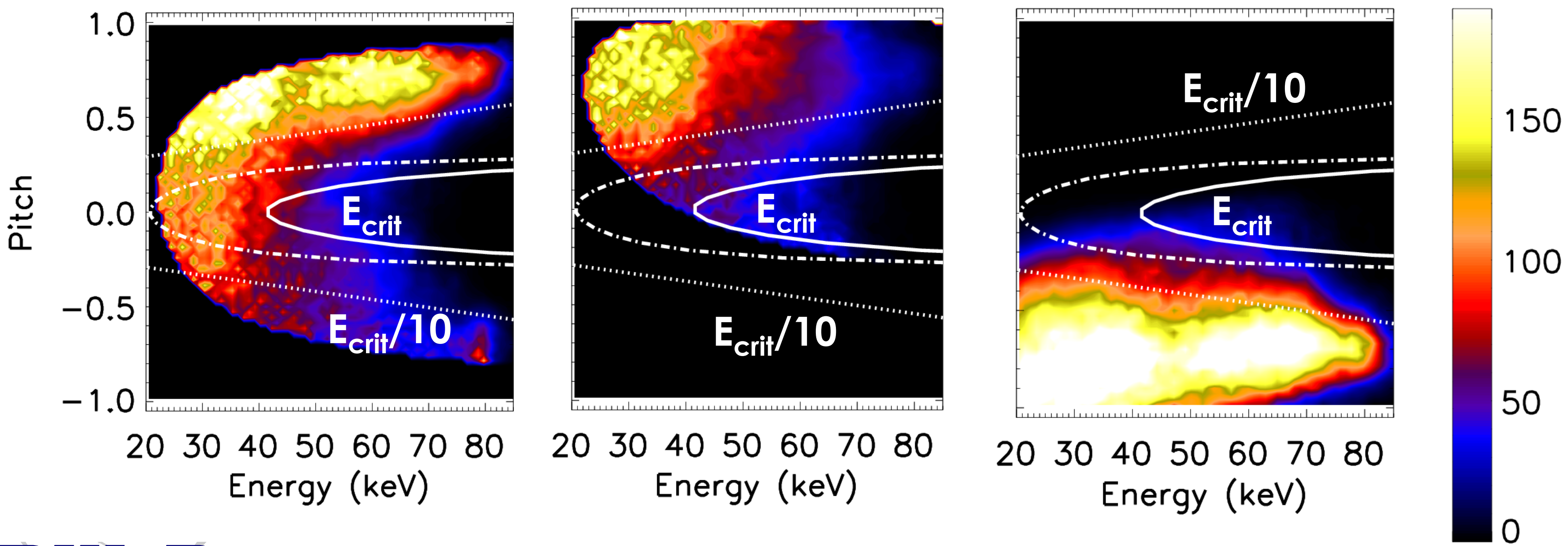
- Large fraction of detected particles do **not** satisfy $E \ll E_{crit} \approx 40$ keV
- Only moderate transport expected

Co-passing

- Almost all detected particles satisfy $E \ll E_{crit} \approx 200$ keV
- Large transport expected

Counter-passing

- Almost all detected particles satisfy $E \ll E_{crit} \approx 200$keV
- Large transport expected



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Evidence for E_{crit} Observed in FIDA Spectra

Co-passing spectrum

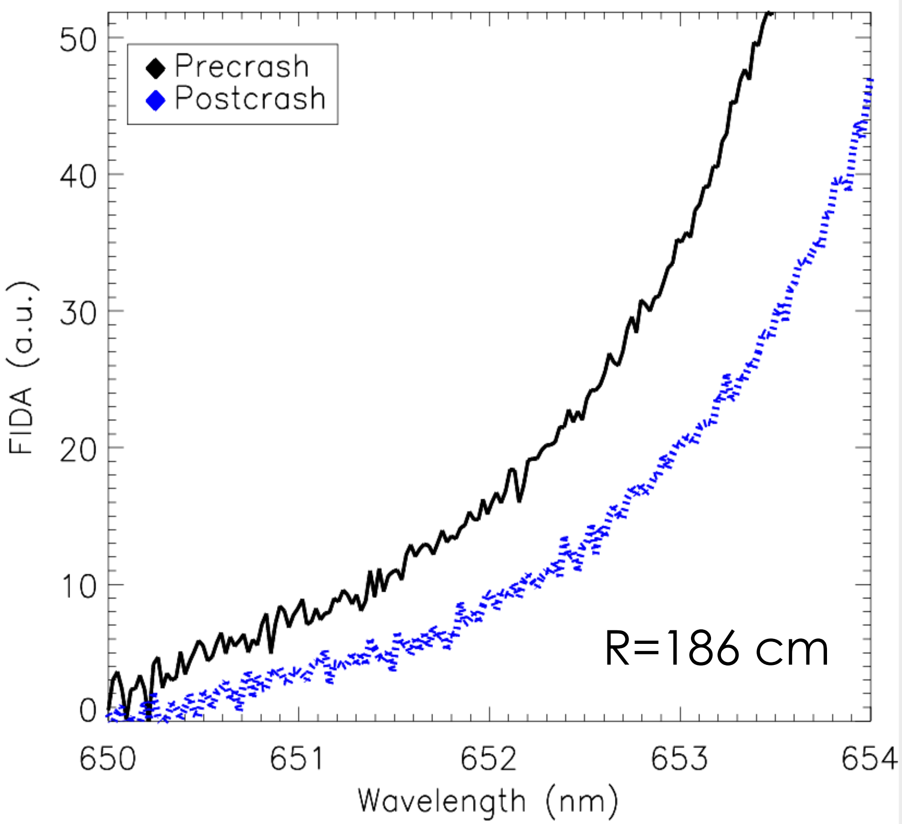
- Ions in the entire spectral range are redistributed

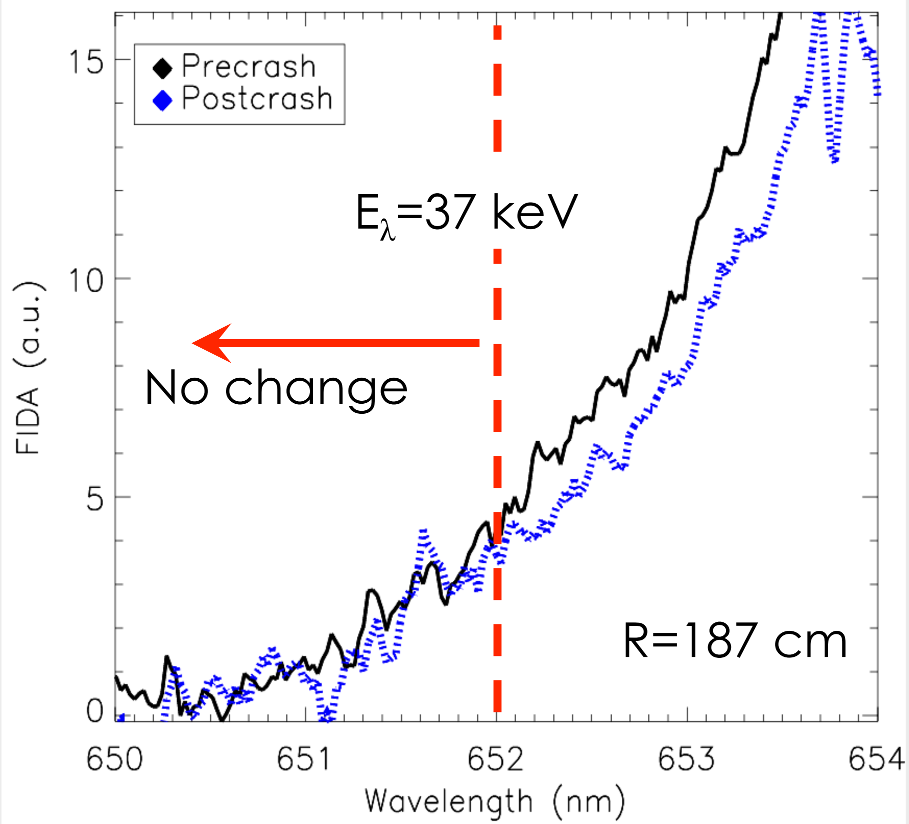
→ $E_{crit}^{passing} > E_{injection}$

Mostly-trapped spectrum

- Depletion in spectrum observed for $E_{\lambda} \lesssim 40$ keV

→ $E_{crit}^{trapped} < E_{injection}$





Summary

- The DIII-D FIDA suite incorporates 3 systems which weight velocity-space differently
- Experiments indicate that passing fast ions experience stronger transport than trapped
- Drift-kinetic simulation reproduces experimental observation of stronger passing fast-ion transport
- Mechanism differentiating trapped/passing transport: **Particle drifts and finite orbit width tend to decouple an ion from the evolving flux surfaces and weaken the effective transport**