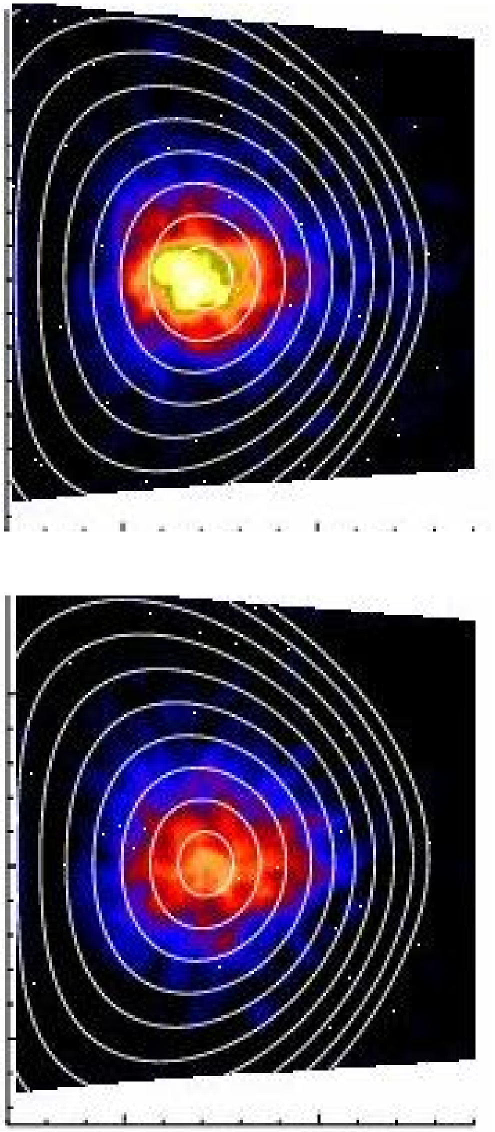
Using velocity-space resolution to determine the mechanism of fast-ion transport on DIII-D



Presented by C.M. Muscatello[a]

at the IAEA Technical Meeting on Energetic Particles in Magnetic Confinement Systems
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Motivation

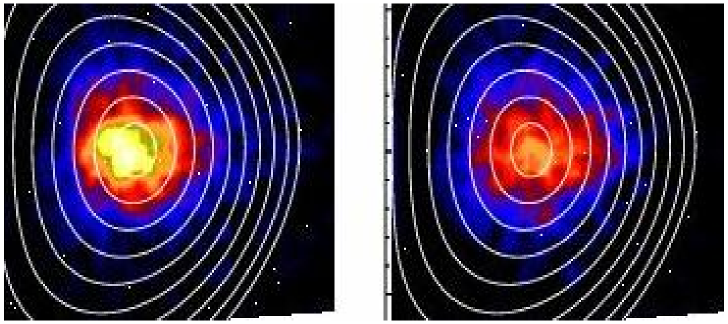
- Traditional measurements of energetic ion populations in tokamaks typically involve detection of fusion products
    - e.g. neutrons
    - broad phase space integration
    - lacks information on velocity distribution

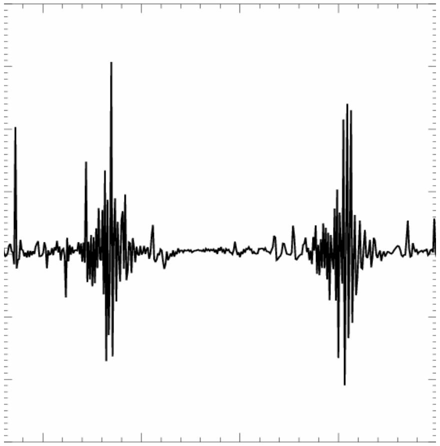
- Techniques such as CER, NPA, CTS, FILD provide phase-space localized and high temporally resolved measurements

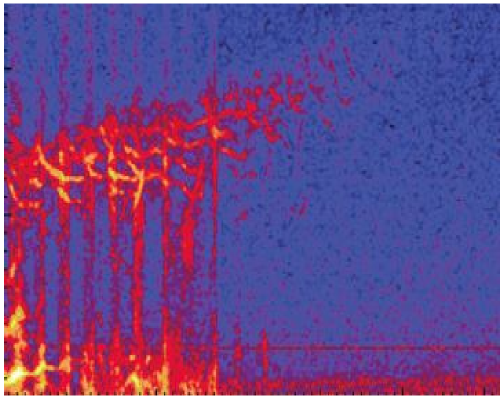
- Velocity-space discrimination of fast-ion signals provides
    - Information on source populations
    - Clues to transport mechanisms

Outline

- Introduction
  - Velocity-space resolving fast-ion diagnostics on DIII-D and phase-space maps
- Measurements of **confined** fast-ion population
  - internal redistribution of fast ions at a sawtooth crash
    - **moderate energy fast ions – transport by flux attachment**
    - **high energy fast ions – resonance**
- Measurements of **lost** fast-ion population
  - coherent losses of fast ions by off-axis fishbones and Alfvén eigenmodes
    - **resonant kicks into loss boundaries**
- Concluding remarks



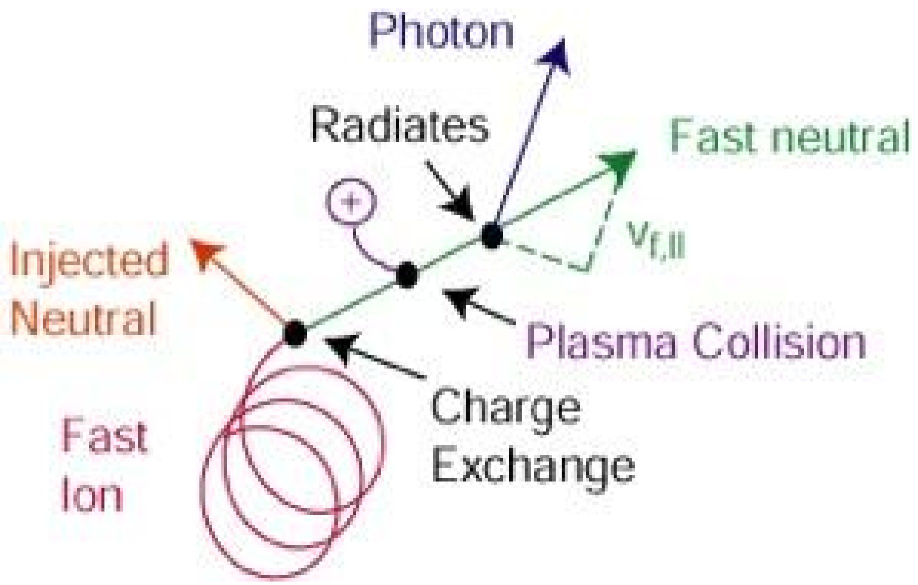




Introduction: velocity-space resolving diagnostics on DIII-D

FIDA used as active charge exchange yields confined fast-ion signal

- FIDA = fast-ion deuterium-alpha
- Neutral beam injection provides:
  - Source of particles, energy, and momentum
  - Diagnostic tool
- Energetic deuterium population created by NBI (sometimes ICRF too)
- As the **energetic ions** pass through the **neutral beam**, some charge-exchange with an **injected neutral** and a **fast "re-neutral"** is created
- **Re-neutrals** can become **atomically excited** and emit **light at the Dα wavelength λ_o=656.1nm**
- In the lab frame, wavelength of **photon** is Doppler-shifted
- **Goal of FIDA: measure Doppler shifted wings of Dα spectrum**



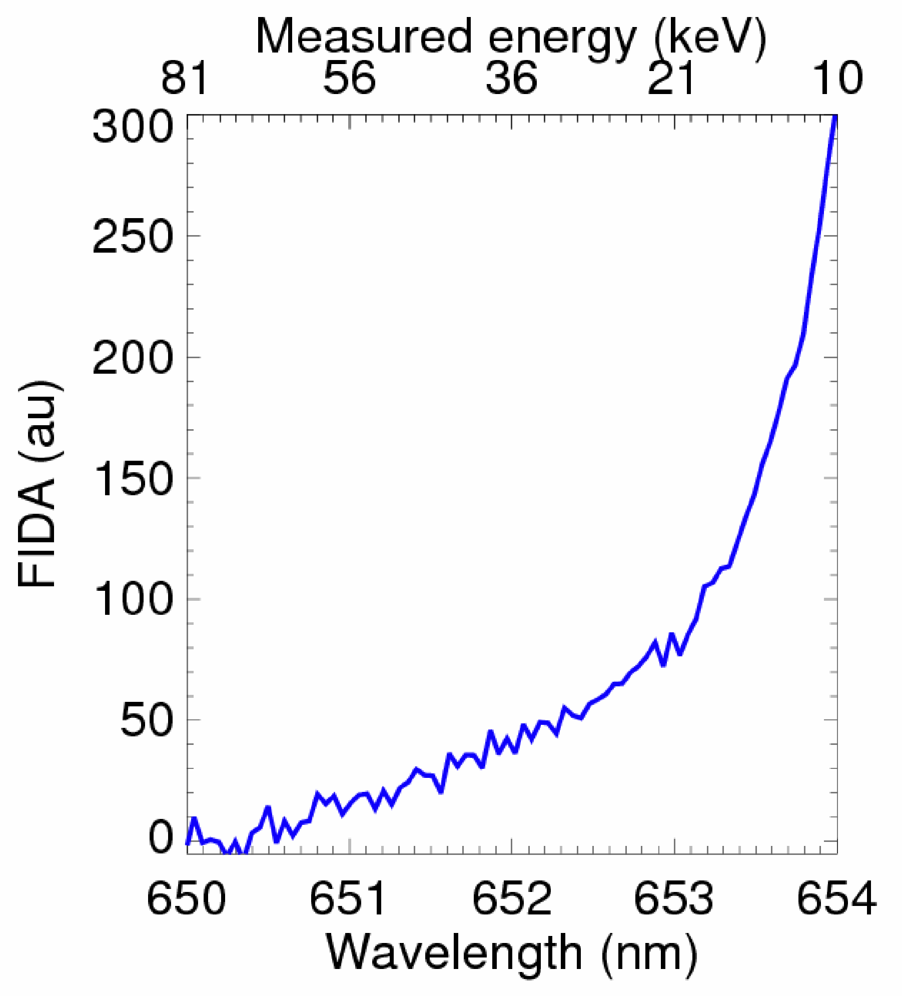
Heidbrink et al, Plasma Phys. Control. Fusion, **46** 1855 (2004).

FIDA approximates 1D measurement of distribution function

- FIDA involves measurement of Doppler shifted wings of Dα spectrum
- Each λ has an associated ***measured*** energy value, E_λ

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

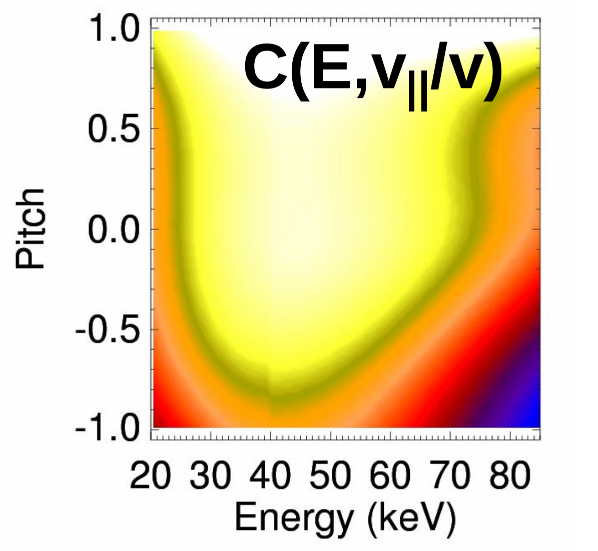
- **Particles with various different values of energy and pitch can produce a particular E_λ**



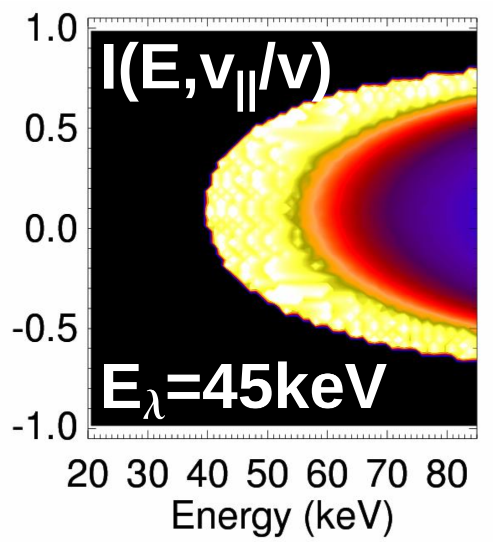
Interpreting FIDA signal as a velocity-space weight function

Goal: determine velocity-space contribution to a measured Doppler shift (E_λ)

→ convenient to represent the **measured** signal in velocity space
→ 3 main contributions to FIDA velocity-space weight function **$S(E,v_{||}/v)$**

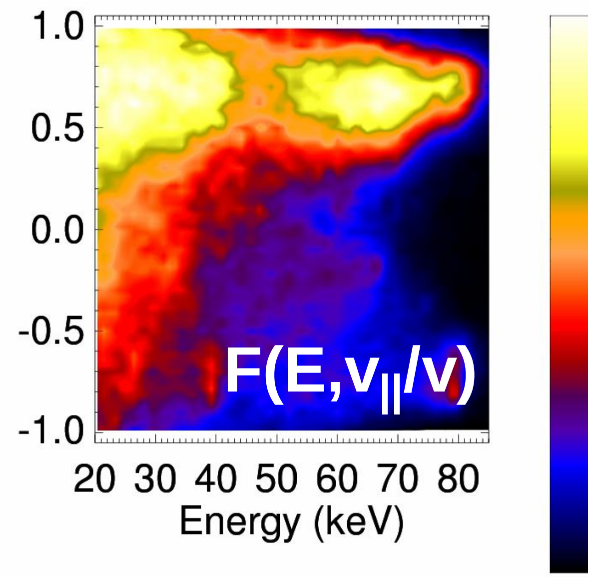


Charge-exchange weight



Instrument function

- **Spectral energy**
- **Sightline geometry**
- **Gyro weight**
- **Instrument resolution**

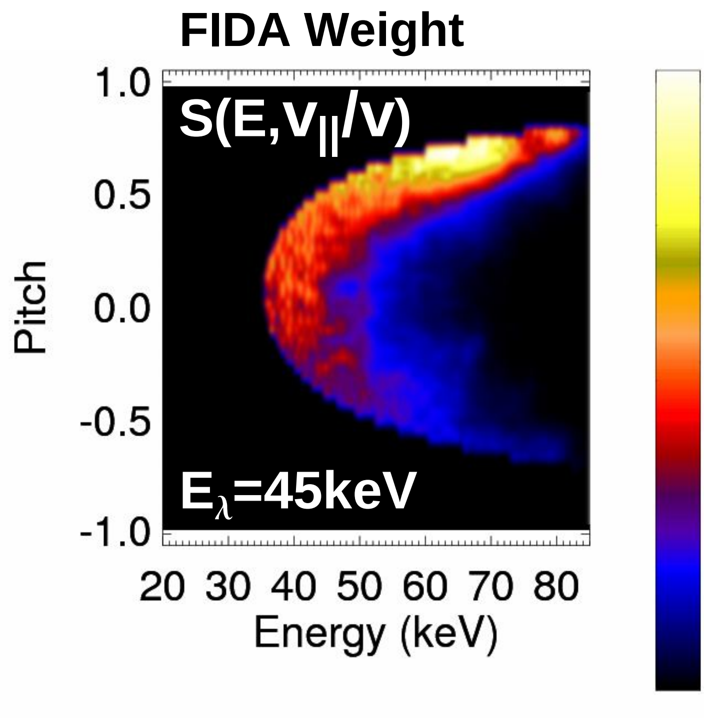


Modeled distribution function

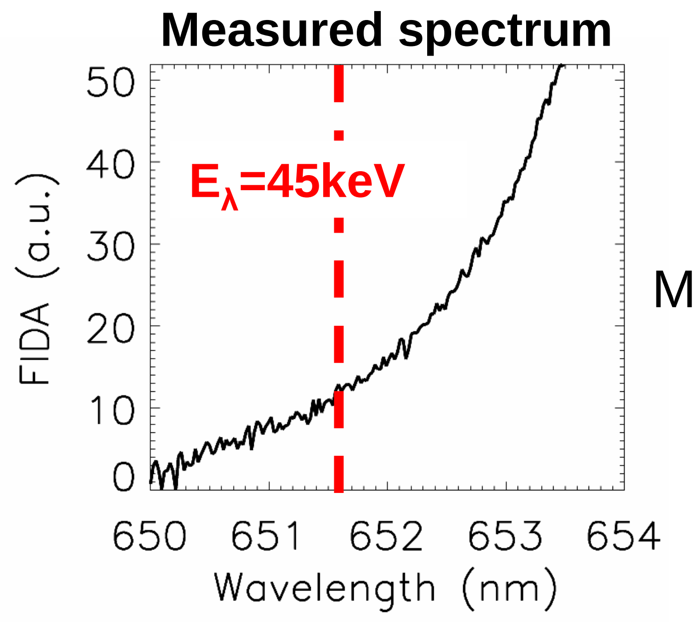
See Heidbrink et al Plasma Phys. Control. Fusion **49** (2007) 1457 for more details.

Measured FIDA signal is an integration of velocity-space

$$\mathbf{C}(E,v_{||}/v) \;\times\; \mathbf{I}(E,v_{||}/v) \;\times\; \mathbf{F}(E,v_{||}/v) \;\rightarrow$$



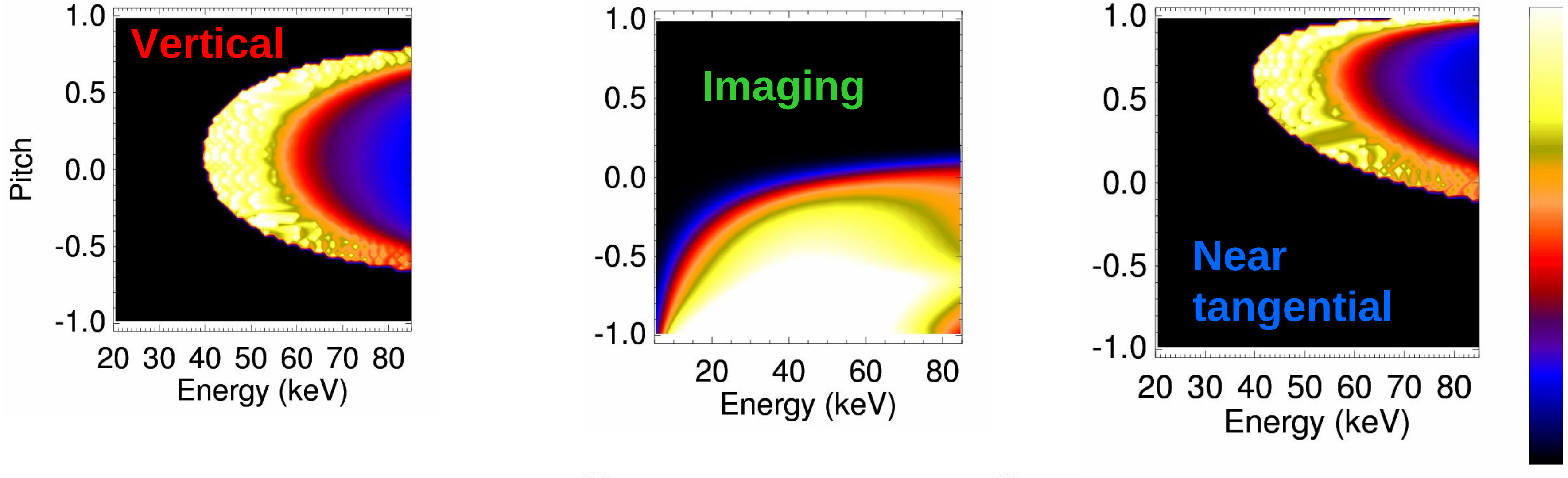
FIDA Weight



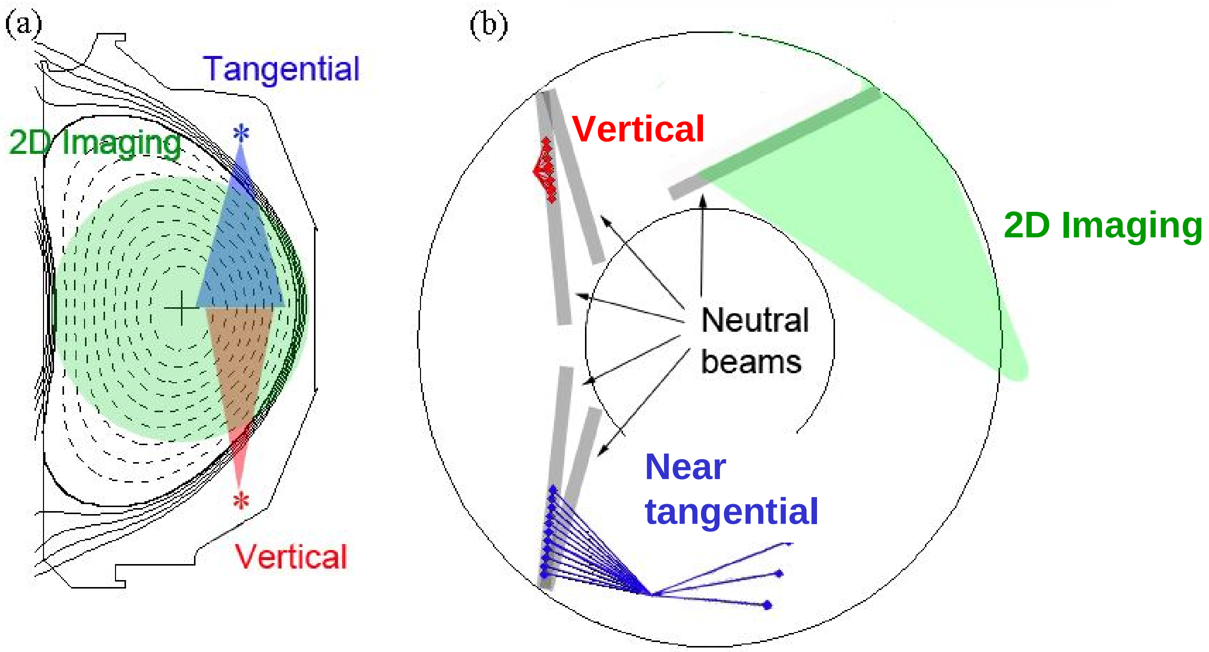
Measured spectrum

$$\text{Measured Signal} \propto \int\!\!\int \mathbf{S}(E,v_{||}/v)\, dE\, d(v_{||}/v)$$

3 FIDA installations on DIII-D measure different parts of velocity space



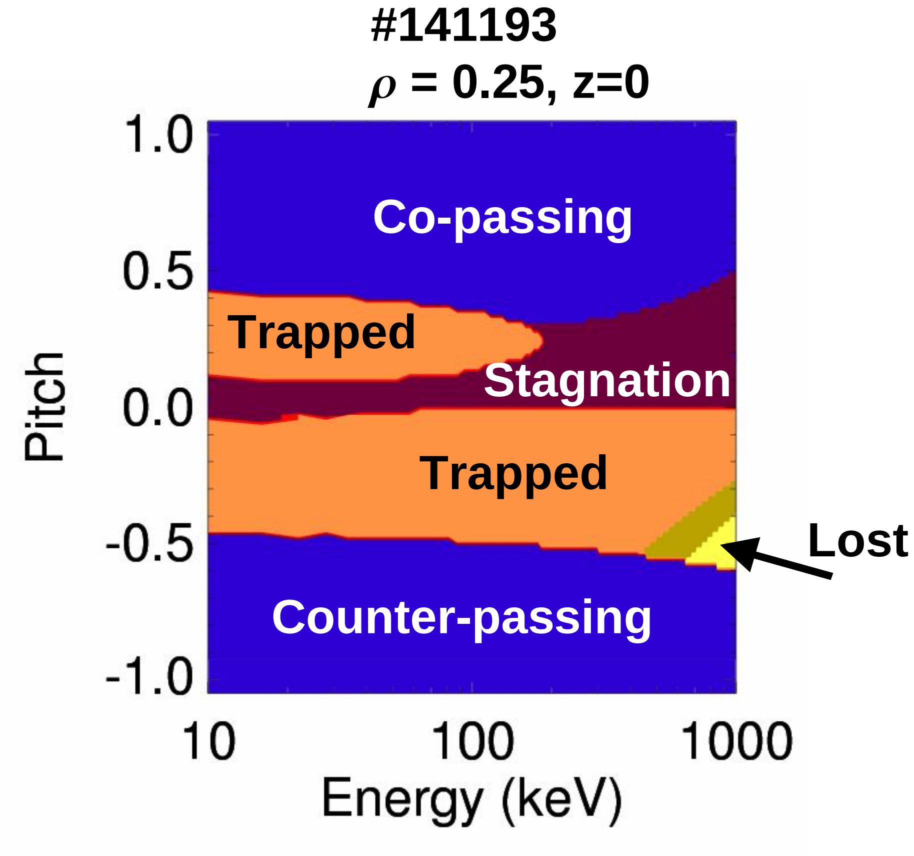
What orbits does each system detect?



Phase space mapping of orbits provided by guiding center code [1]

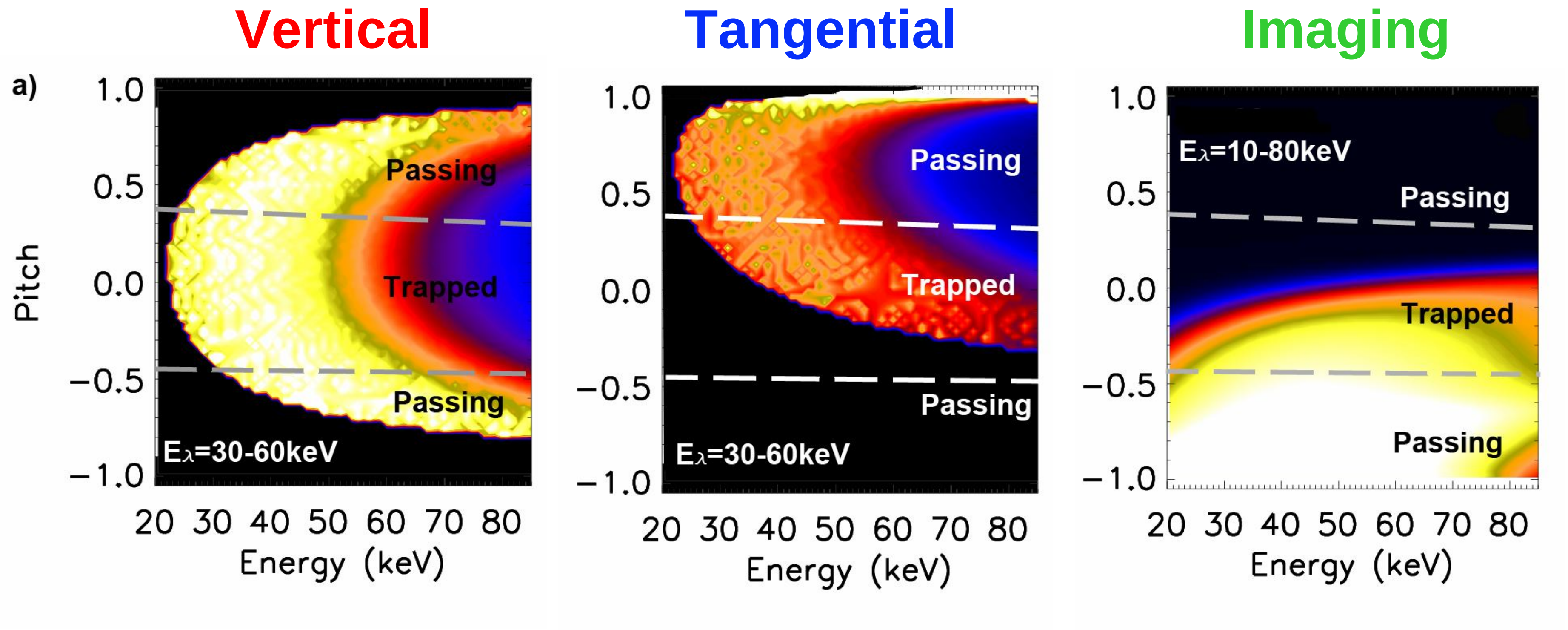
- Considering the constants of motions (μ, E, P_ζ), various orbital boundaries can be determined
  e.g. setting $v_{||} = 0$ *to find trapped/passing boundaries*

- In addition integration of orbits yields transit, bounce, and drift times



[1] Appendix of Van Zeeland et al, Physics of Plasmas 18 (2011) 056114.

3 FIDA installations on DIII-D measure different parts of velocity space



Predominantly measures trapped

Largely co-passing

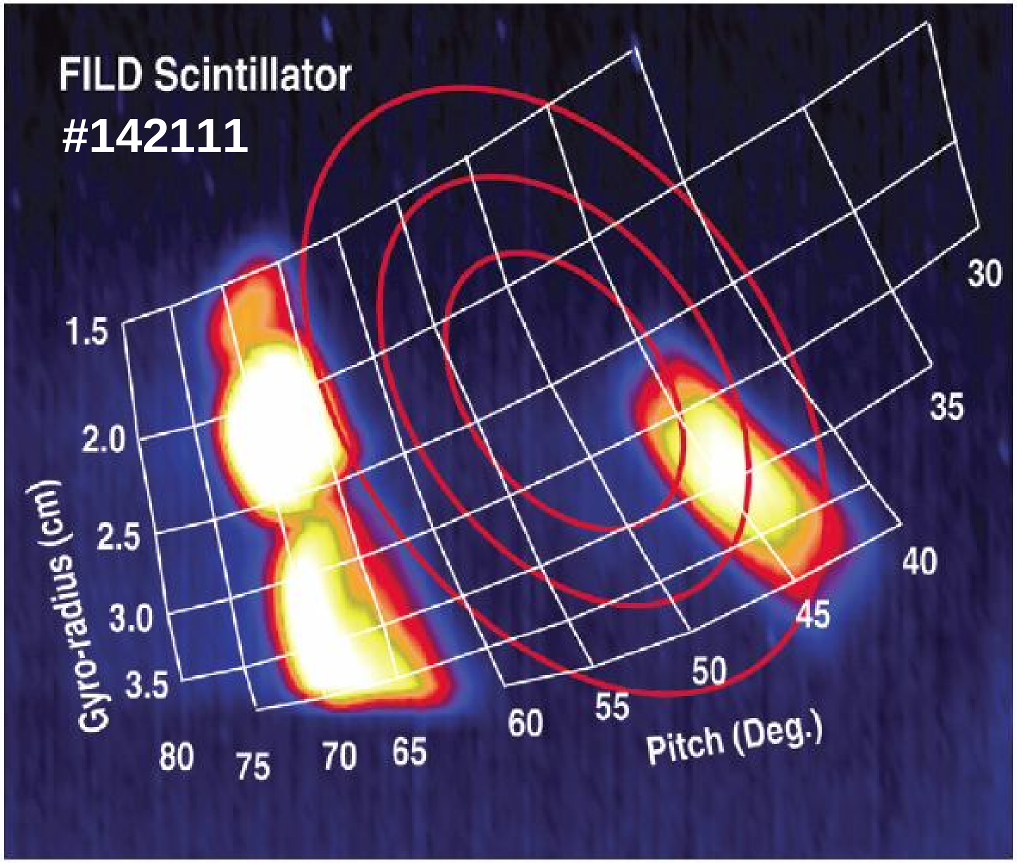
Majority counter-passing

Fast ion loss detector with velocity-space resolving capabilities

- Scintillator based lost detector with slit aperture discriminates particles in gyro-radius (energy) and pitch

- CCD Camera provides 2D image of scintillator face and velocity-space mapping constructed from equilibrium

- For high bandwidth measurements, PMT integrates central region of scintillator region of scintillator



Fisher R.K., et al Rev. Sci. Instrum. **81**, 10D307 (2010).

Measurements of confined fast-ion population

observations of fast-ion transport at a sawtooth crash

Theory predicts two regimes of fast-ion transport at a sawtooth crash

Transport by flux attachment

- Sufficiently low-energy ($E<E_{critical}$) fast ions are approximately attached to evolving flux surfaces [1]
- Leads to flattening of afflicted fast-ion density profile across sawtooth mixing radius

Transport by resonances

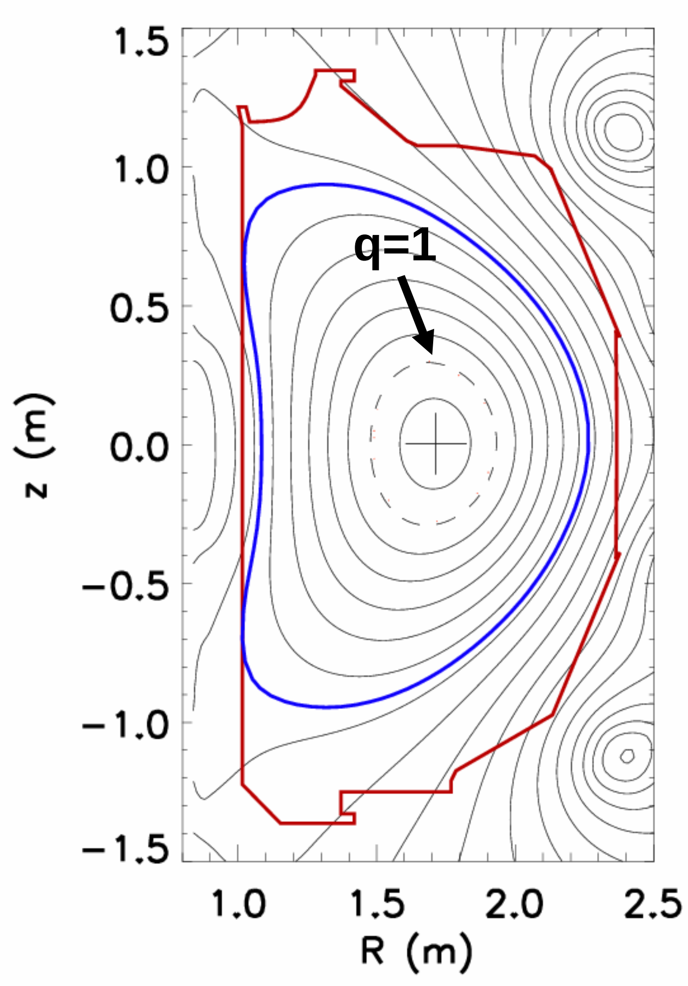
- Sufficiently high-energy ($E>E_{critical}$) fast ions may couple to the mode via the bounce-precession resonance condition $\omega + n\omega_{pr} - s\omega_b = 0$ [2,3]
- Resonant particles are transformed to large orbits leading to a plateau in the density profile at the resonance

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

[2] Kolesnichenko et al Phys Plasmas **5** (1998) 729.

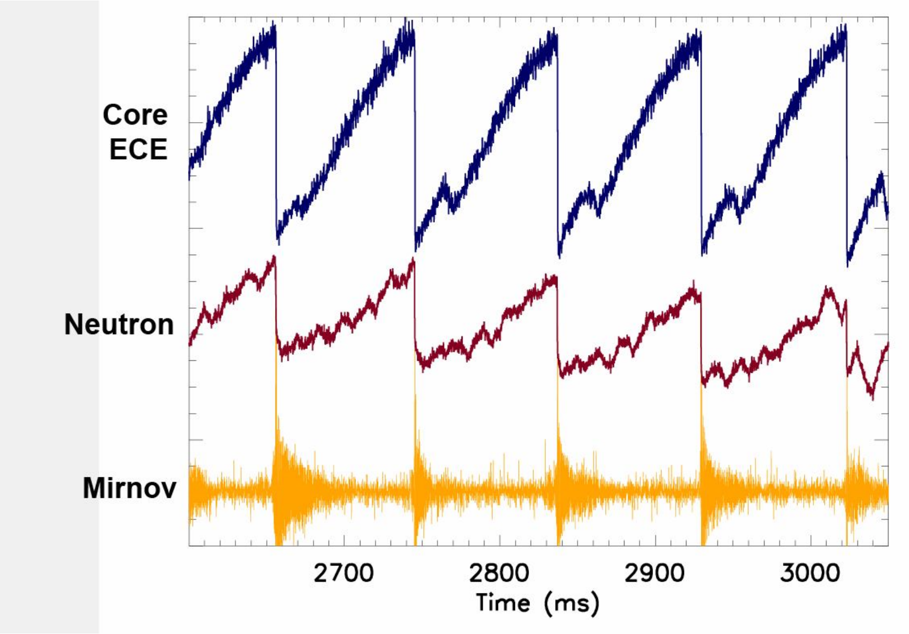
[3] R. B. White, The theory of toroidally confined plasmas, Imperial College Pr, 2006.

NBI in a low-n_e L-mode discharge with uniform sawteeth

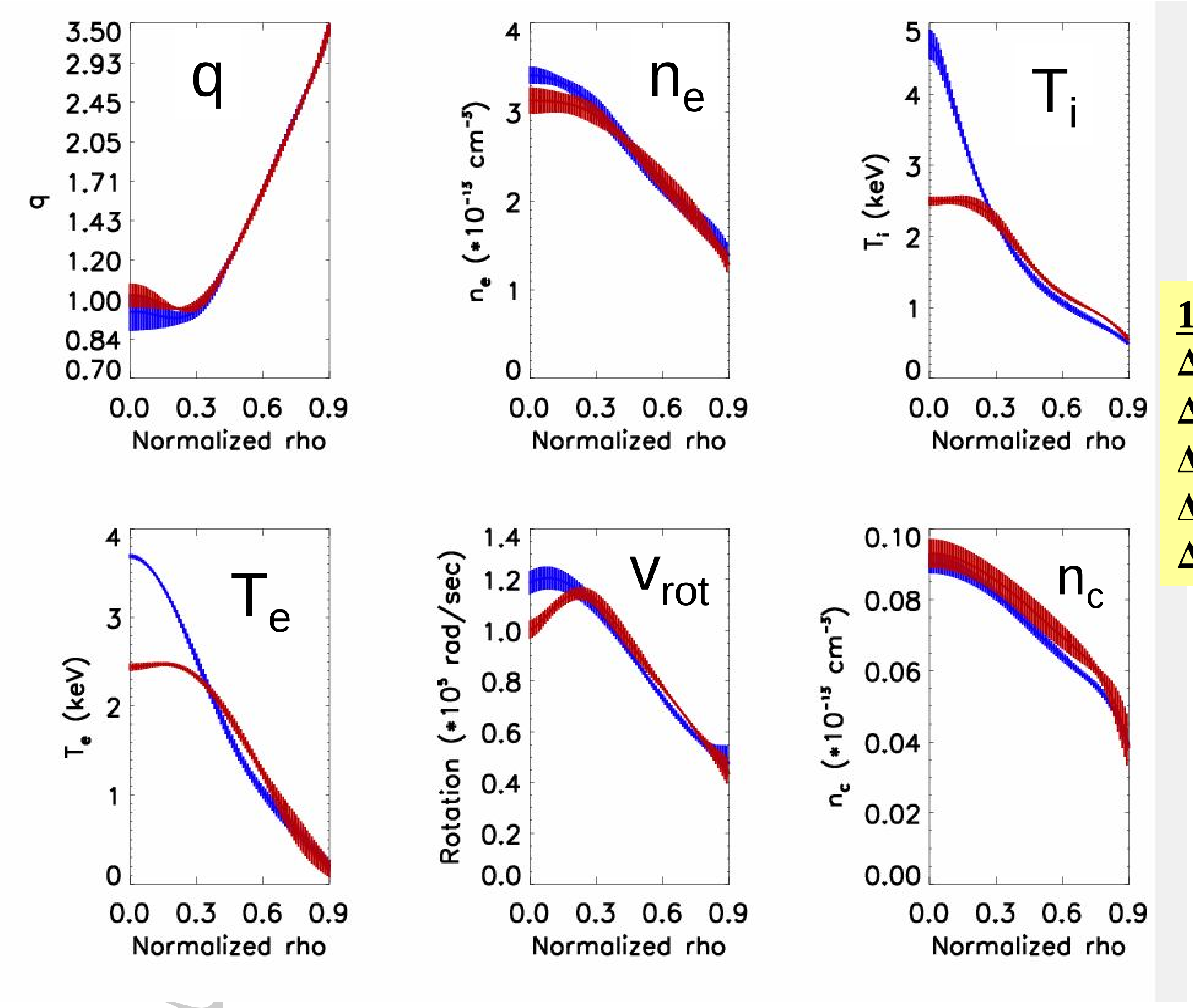


#141182:
Bt = 1.9T
Ip = 1.3MA
$\langle T_e(0)^{precrash} \rangle$ = 3.7 keV
$\langle n_e(0)^{precrash} \rangle = 3.4\times10^{19} m^{-3}$
$\langle P_{NBI} \rangle$ = 3.2MW
$\langle E_{NBI} \rangle$ = 75keV
$\langle T_{sawtooth} \rangle$ = 85ms
$\tau_{cr} = 50\mu s$
$\langle \Delta n/n \rangle = -0.15$

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



Clear change in many plasma profiles during a crash



🟦 Precrash

🟥 Postcrash

<u>141182</u>:

$\Delta\ n_e(0)/n_e(0) = -0.10$

$\Delta\ T_i(0)/T_i(0) = -0.47$

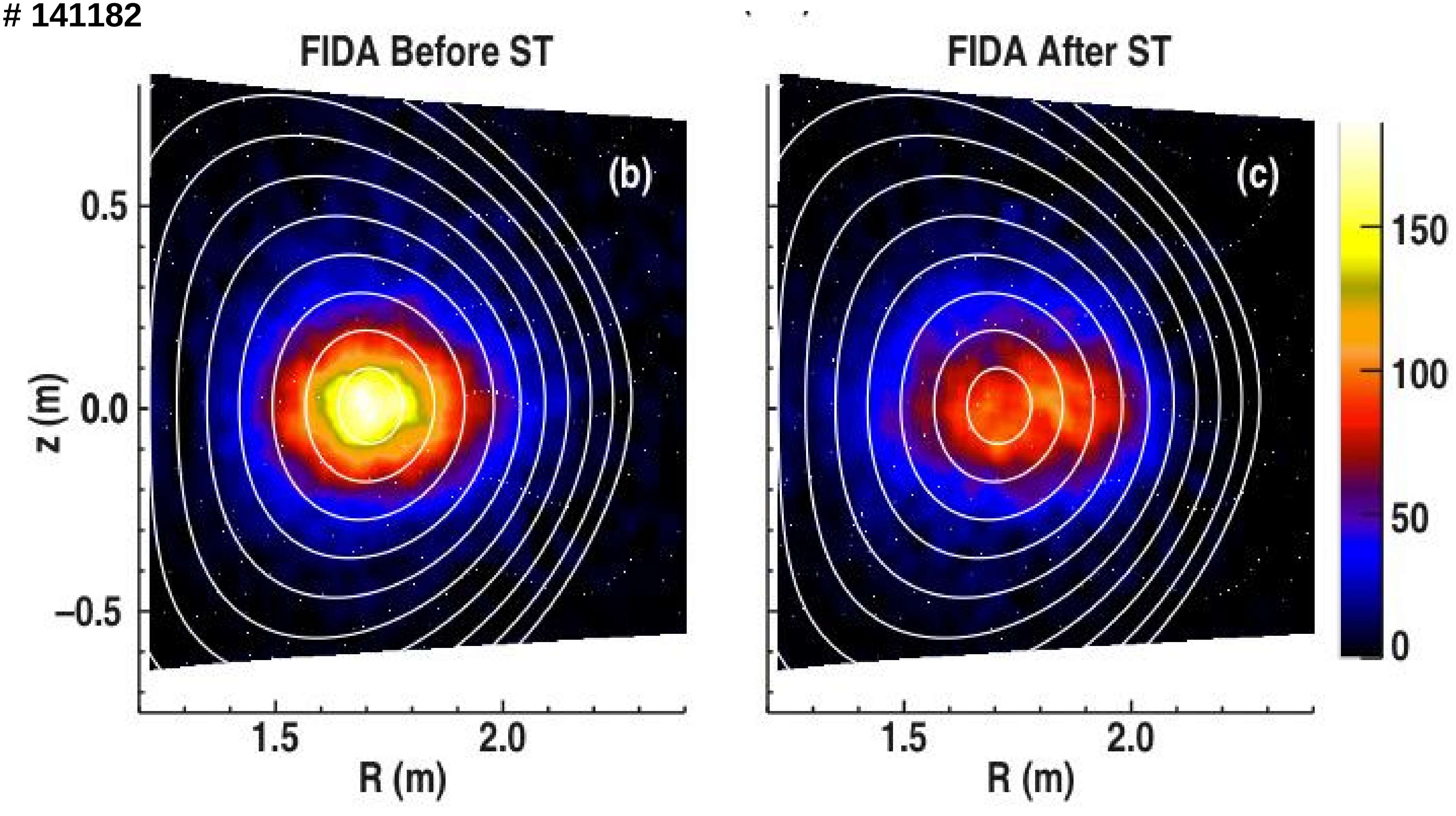
$\Delta T_e(0)/T_e(0) = -0.34$

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

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

Fast-ion profile flattens at a crash

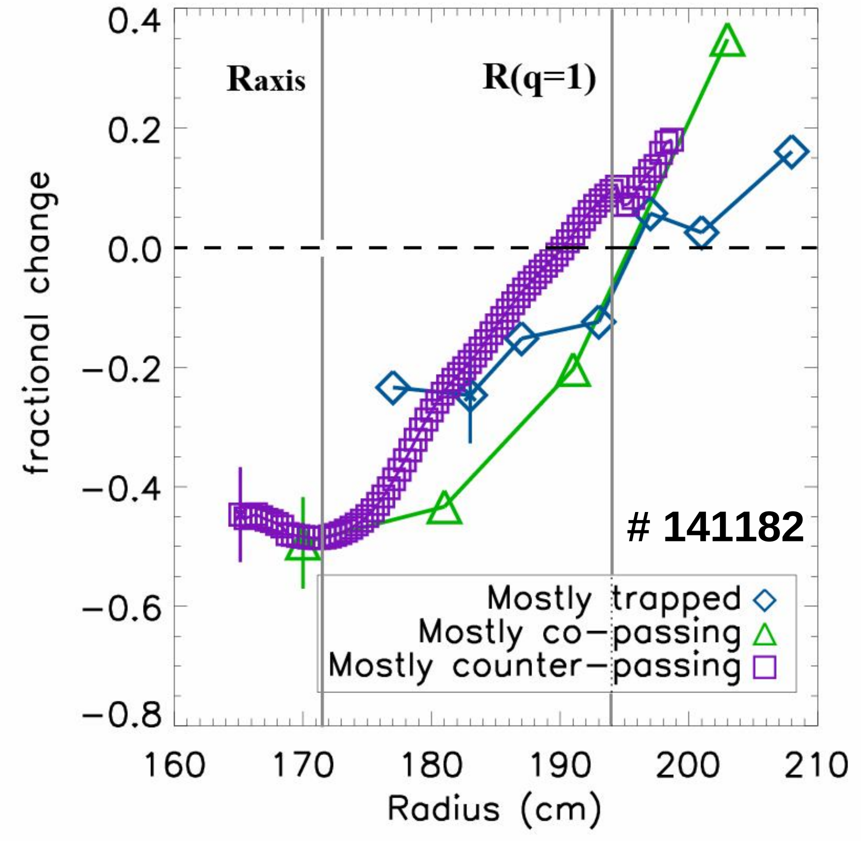
 # 141182



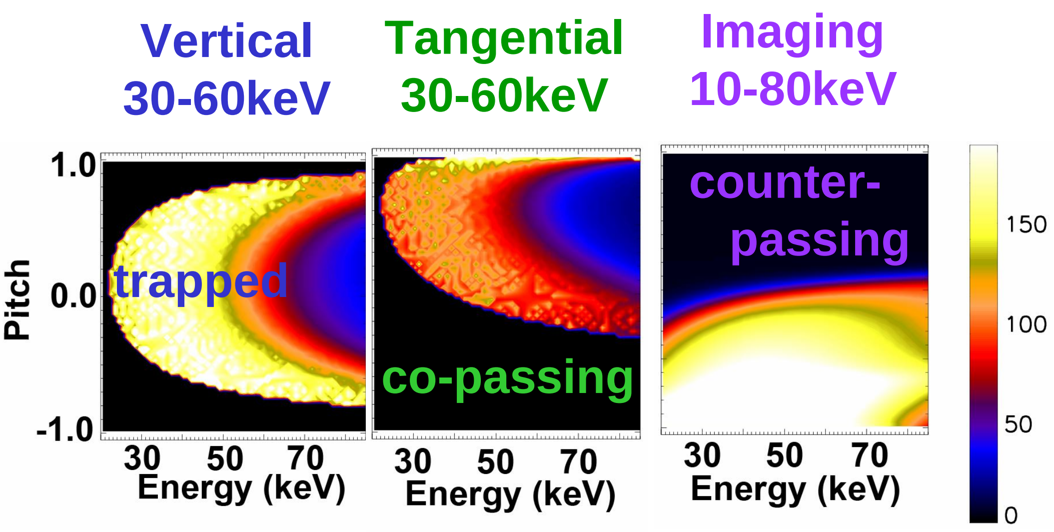
Van Zeeland et al, Nucl. Fusion **50** (2010) 084002.

Passing ions experience greatest internal redistribution

Changes in fast-ion density



Instrument weights



drop in density observed with co- & counter-passing fast-ions is double compared to trapped

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 = 1.86-2.05T

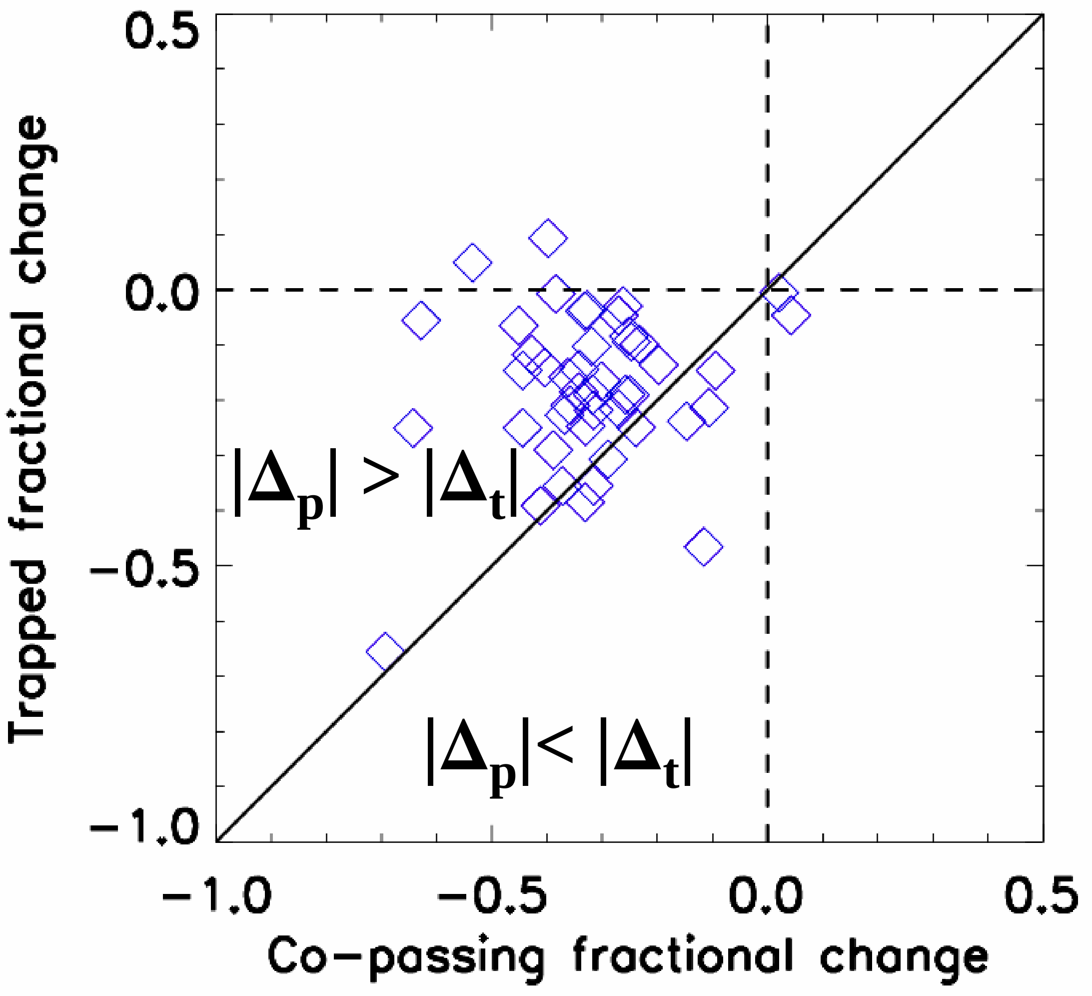
Ip = 1.16-1.34MA

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

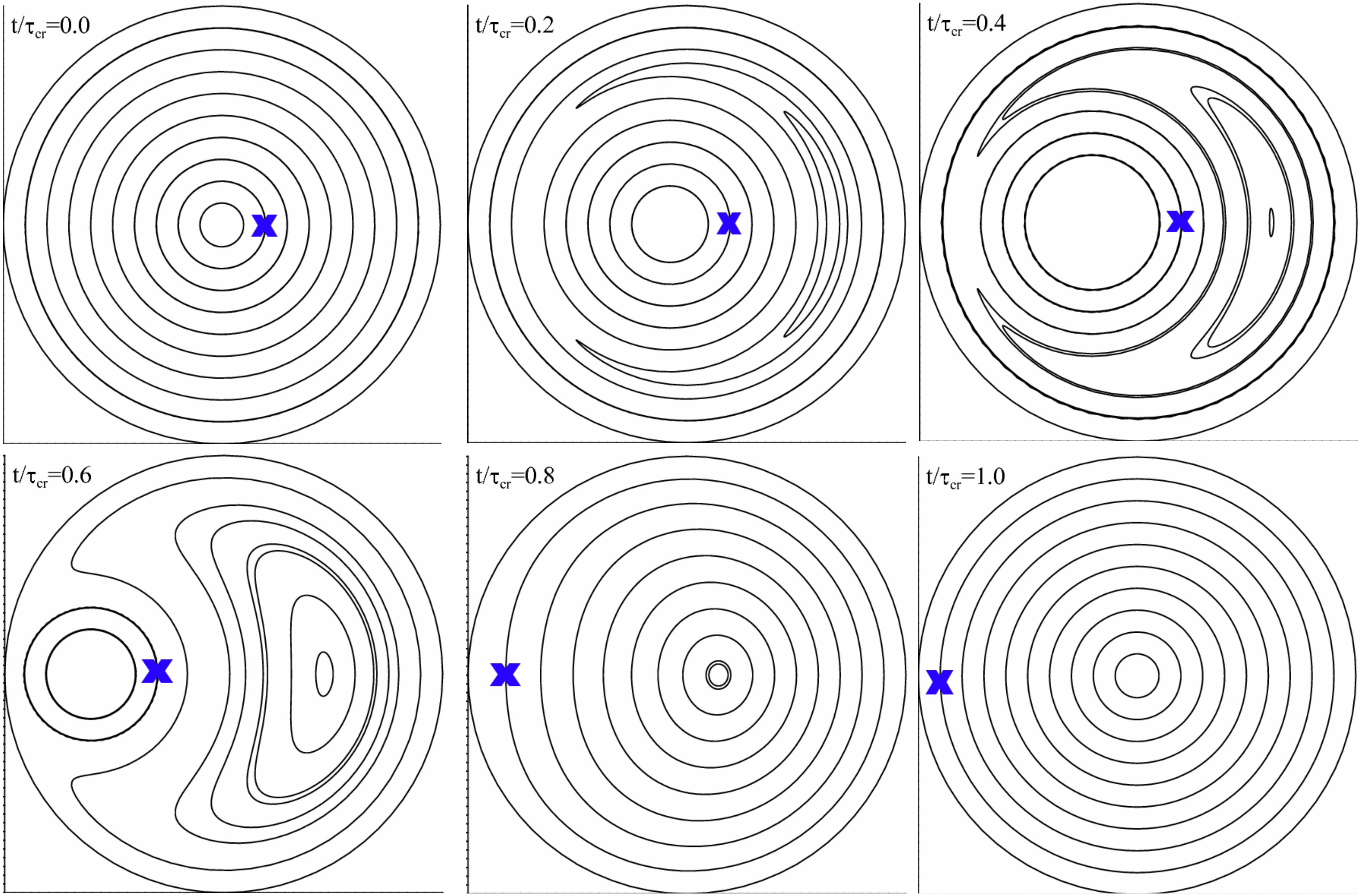
$\langle T_e(0)^{precrash} \rangle = 2 - 5$ keV

$\langle n_e(0)^{precrash} \rangle = 2 - 4\times10^{19}\mathrm{m}^{-3}$

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



Observed transport due to flux attachment…

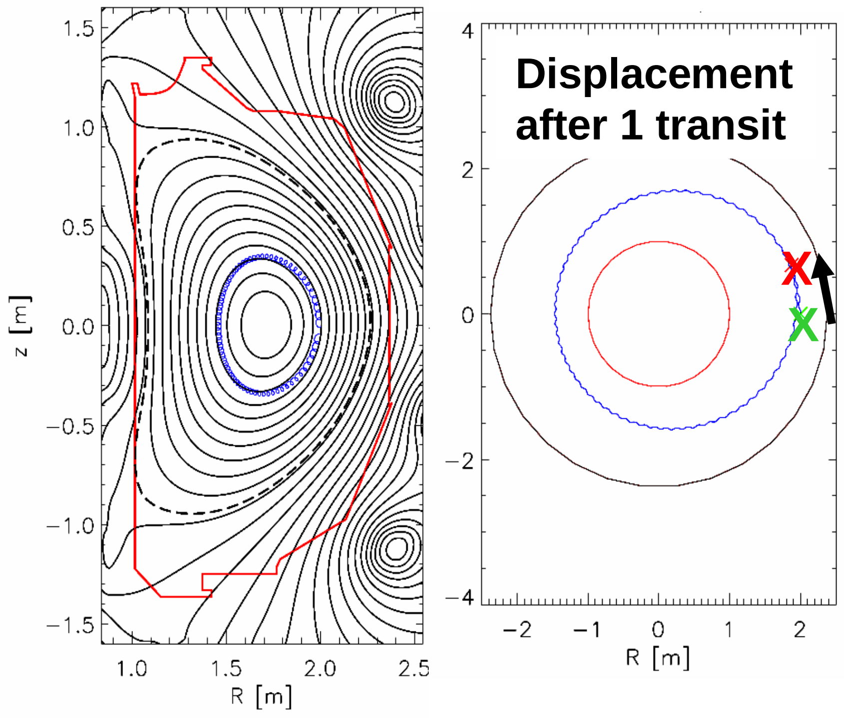


…but toroidal precession breaks flux attachment

Toroidal precession (drift) ≡ bounce/transit averaged toroidal motion due to ∇B and curvature drifts

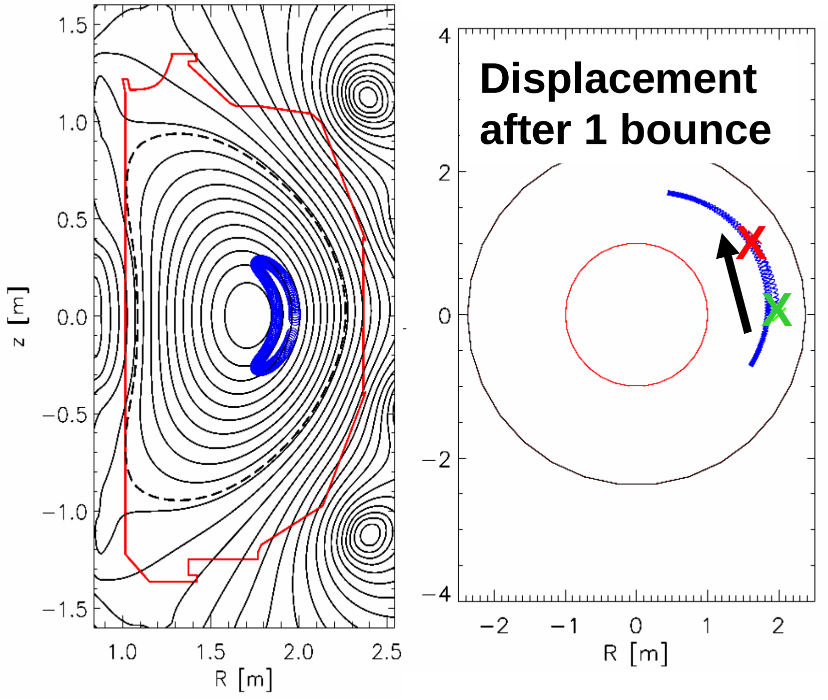
Passing

1 poloidal transit



Trapped

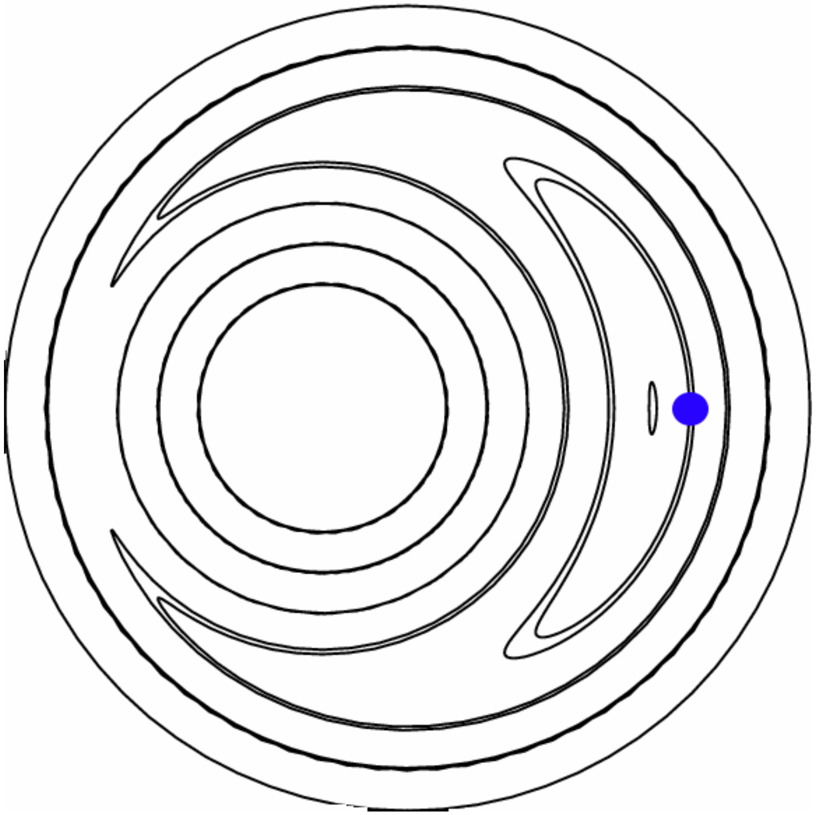
1 poloidal bounce



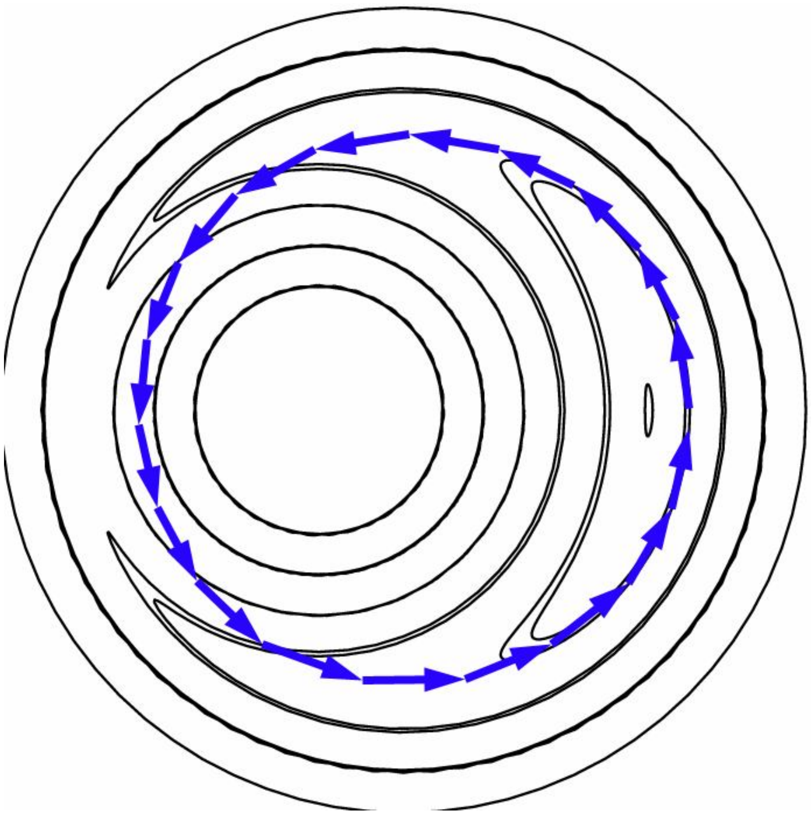
Particle with strong toroidal precession drifts off evolving perturbed flux surface

- “Untwisted” cylindrical representation so that 1/1 mode is straight longitudinally down cylinder
- Arrows/dot indicate direction of **bounce/transit-average motion**

Well-passing particle with negligible precession



Trapped particle with strong precession



In reality, most particles are somewhere in the middle

Comparison of characteristic timescales yields transport conditions

- **Toroidal precession** (τ_{pr})
  - Period of 1 precession

Conditions for strong transport

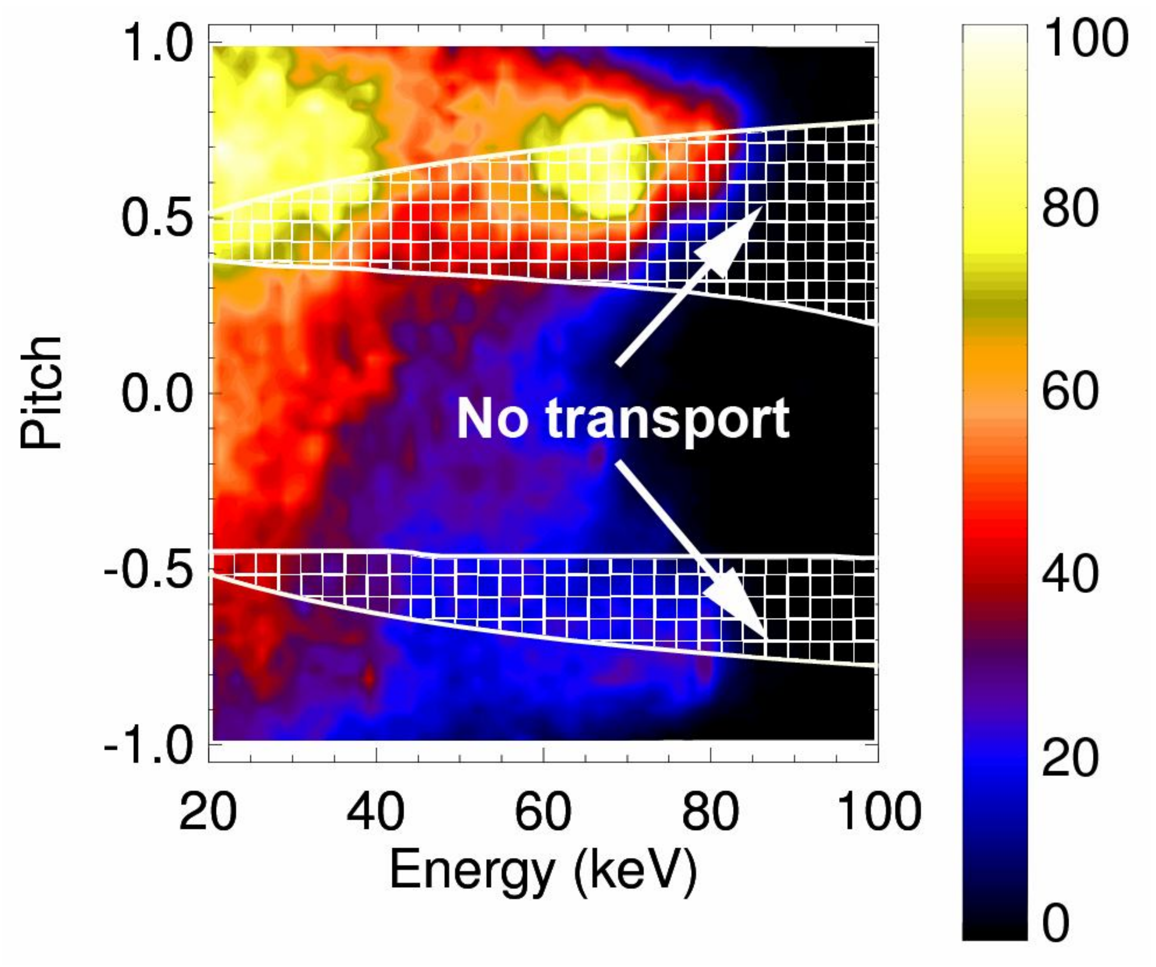
Passing: $\tau_{\psi} << \tau_{pr}$

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

- **Longitudinal time** (τ_{ψ})
  - Period about **perturbed** flux surface
  - Passing particles only

- **Crash time** (τ_{cr})
  - Characteristic time of rearrangement of flux surfaces
  - Sufficiently slow crash → frozen-in condition breaks

Timescale comparison can be recast in terms of energy and pitch



- Classical slowing-down fast-ion distribution function calculated by TRANSP

  - The equalities

    $\tau_{\psi} = \tau_{pr}$ and $\tau_{cr} = \tau_{pr}$ are re-expressed as a function f(**E**,**$v_{||}$/v**) → **E_{crit}** [1]

- **No transport expected for regions where E > E_{crit} (hatched)**

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

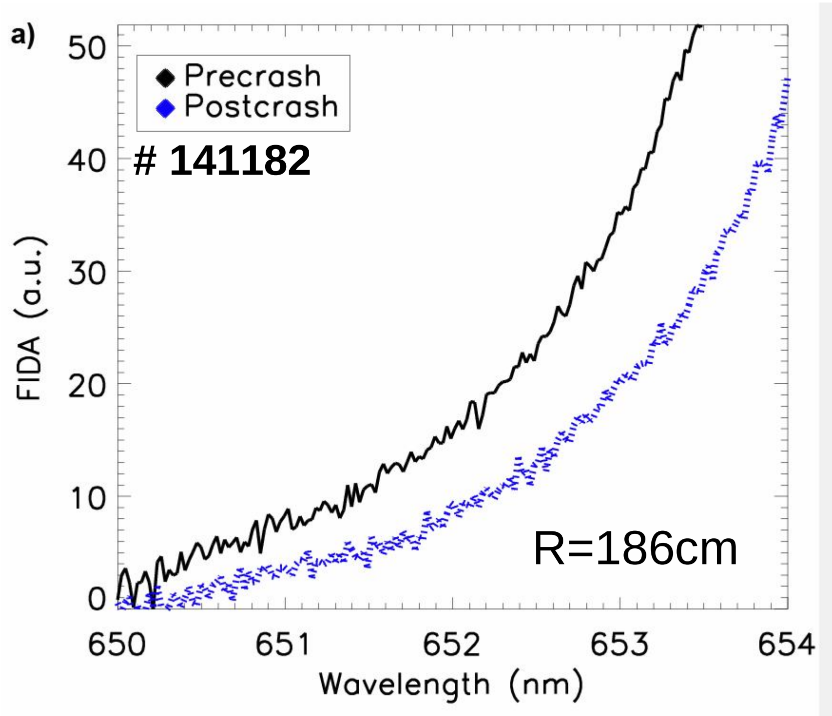
Transport dependence on velocity space parameters observed in FIDA spectra

Co-passing energy spectrum

- Ions in the entire spectral range are redistributed

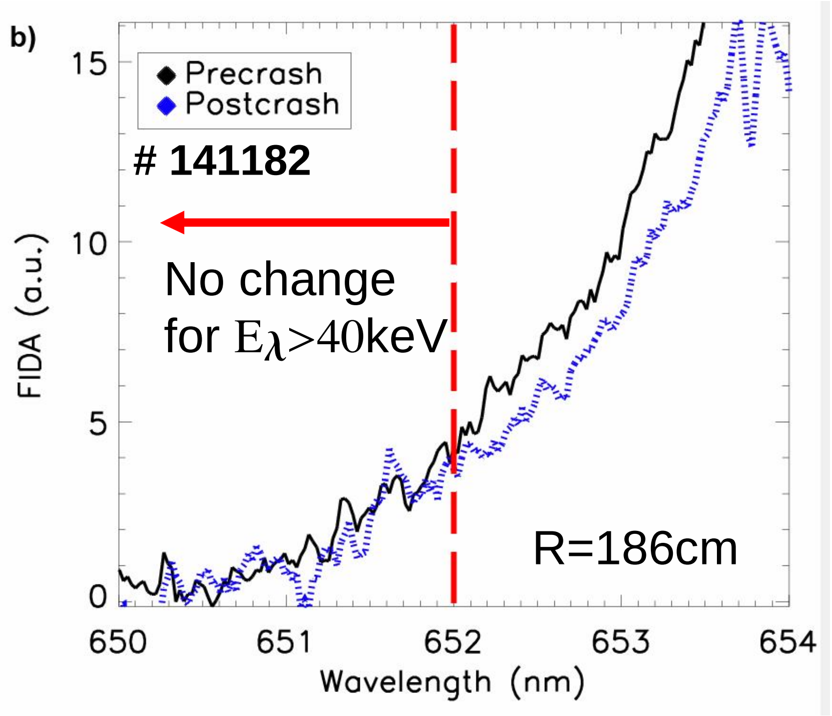
Trapped energy spectrum

- Change in the spectrum observed only for $E_{\lambda} \lesssim 40$keV



 # 141182

R=186cm



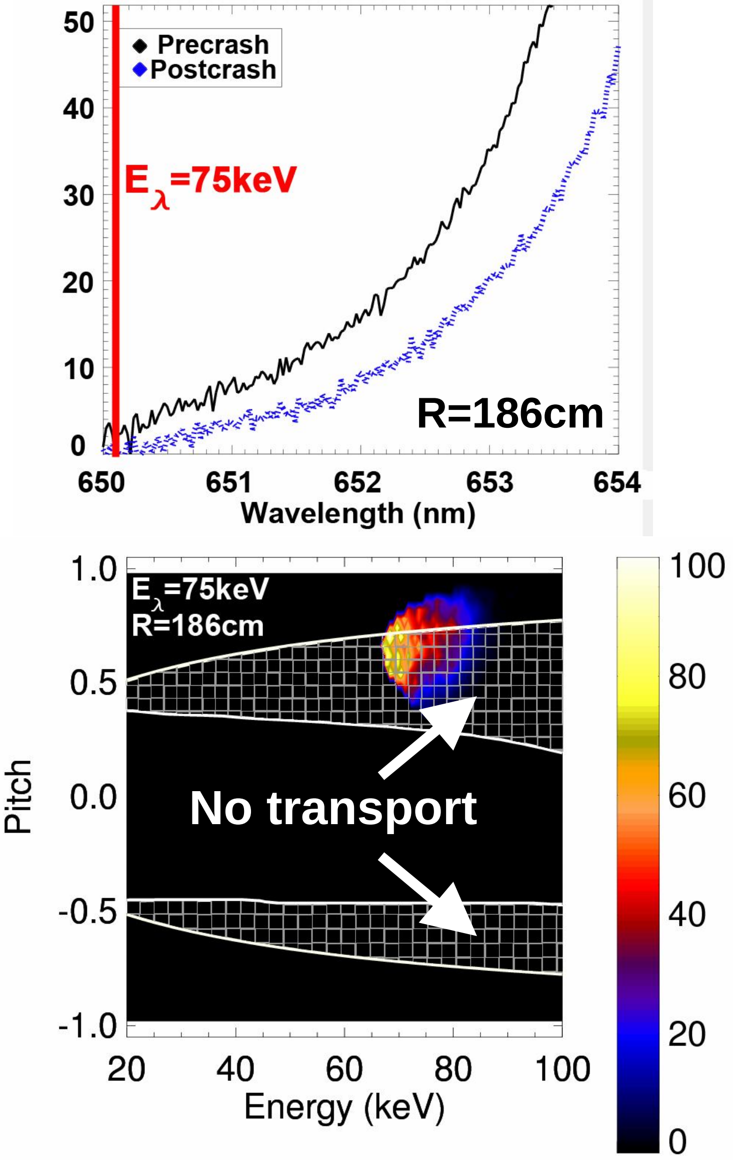
 # 141182

No change for $E_{\lambda}>40$keV

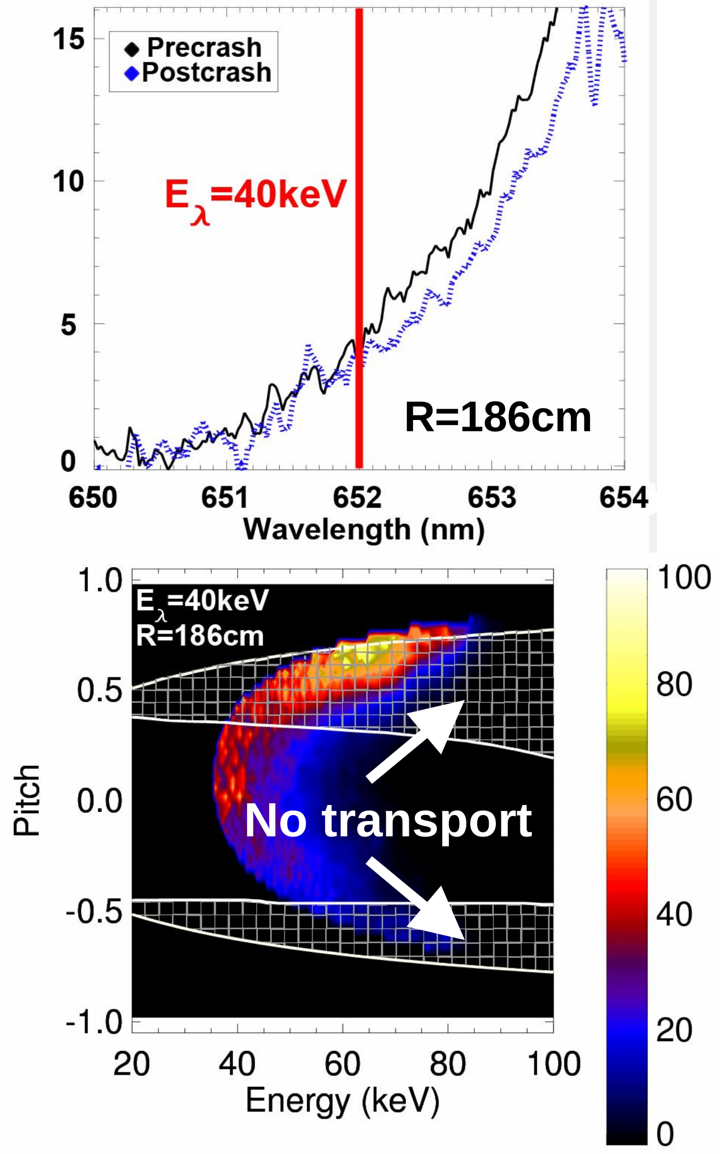
R=186cm

Different transport observed by FIDA systems can be explained by E_{crit}

Tangential FIDA



Vertical FIDA



Simulation produces results consistent with observed transport difference between passing and trapped

Drift kinetic code [1] employs Kadomtsev crash model to solve f(**v**,**x**,t)

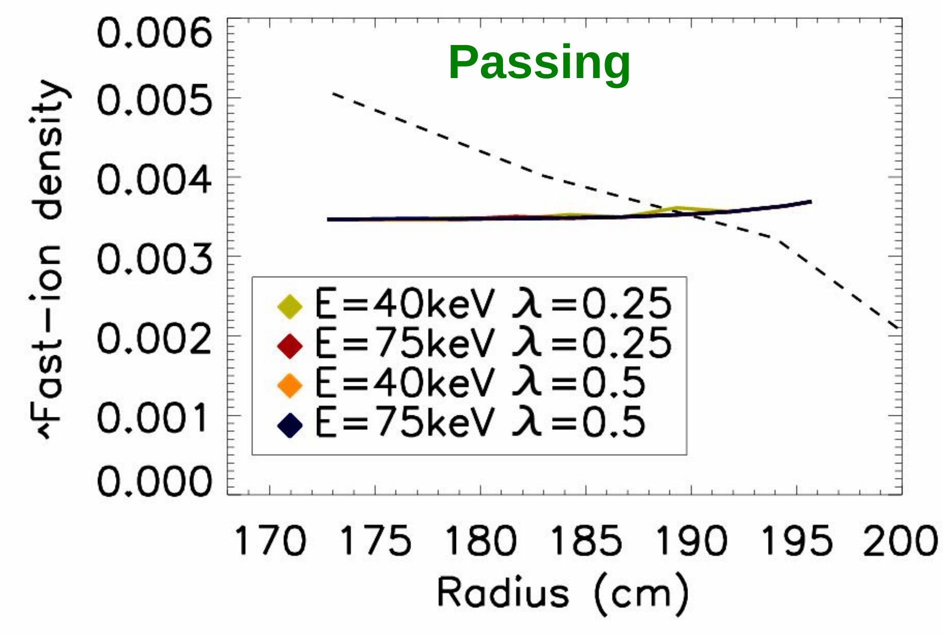
$$\partial f/\partial t = (-\mathbf{v}_{||}^{0} - \mathbf{v}_{||}^{1} - \mathbf{v}_{D} - \mathbf{v}_{E})\cdot\partial f/\partial \mathbf{x} - e(\mathbf{v}\cdot\mathbf{E}(\mathbf{x},t))\partial f/\partial \mathcal{E}$$

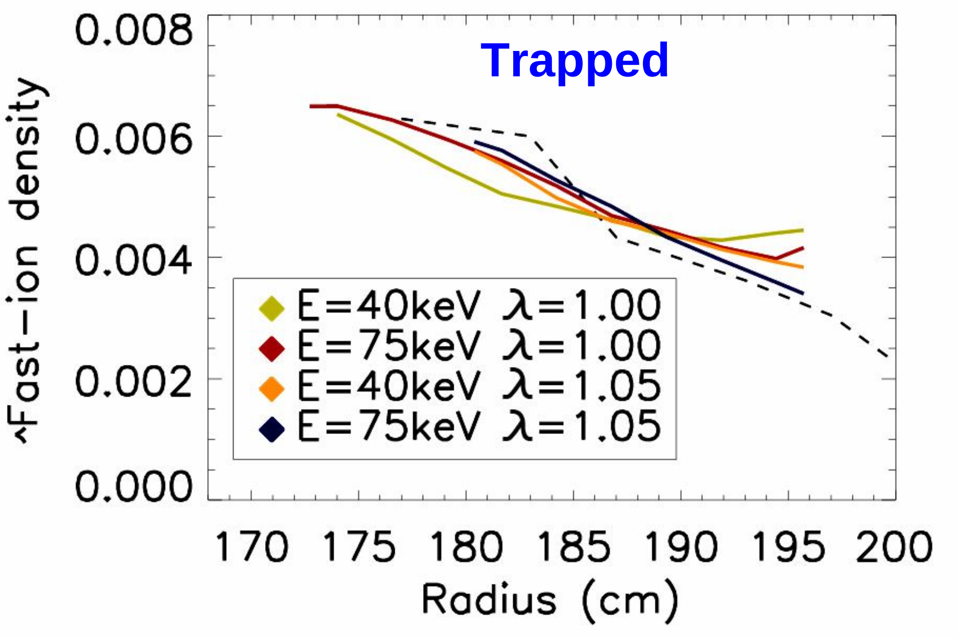
$\mathbf{v}_{||}^{0}$ – v along unperturbed flux surfaces

$\mathbf{v}_{||}^{1}$ – v along perturbed flux surfaces

$\mathbf{v}_{D}$ – toroidal drift

$\mathbf{v}_{E}$ – **E** X **B** drift due to perturbation

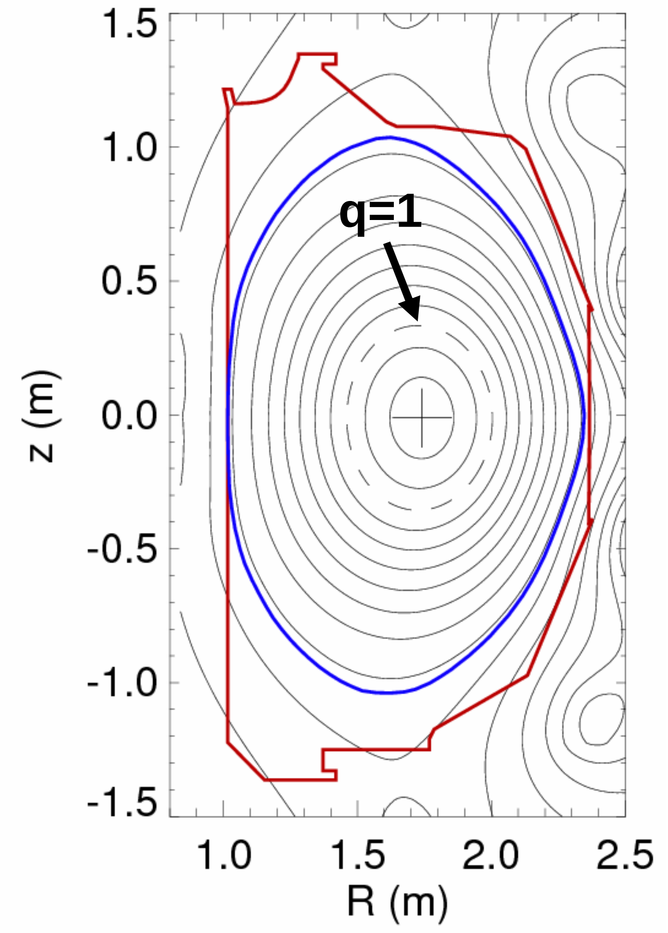




[1] Kolesnichenko et al Phys. Plasmas **4** (1997) 2544.

…but the story changes in ICRF-heated plasmas...

ICRF injected into low density L-mode discharge with uniform sawteeth



#141193:

Bt = 1.9T

Ip = 1.15MA

$\langle T_e(0)^{precrash} \rangle$ = 4.5 keV

$\langle n_e(0)^{precrash} \rangle$ = $5.0\times10^{19}m^{-3}$

$\langle P_{NBI} \rangle$ = 1.2MW

$\langle P_{ICRF} \rangle$ = 1.6MW

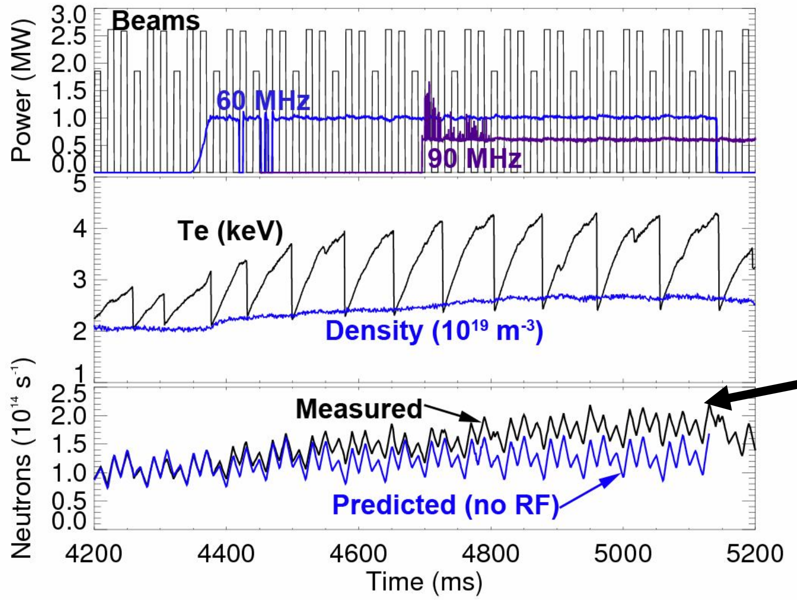
$\langle T_{sawtooth} \rangle$ = 83ms

τ_{cr} = 150μs

- **Equivalent ½ source NBI & 2 freq. (60+90MHz) fast wave provide auxiliary heating**

- No other MHD activity detected (such as tearing modes, fishbones, AEs)

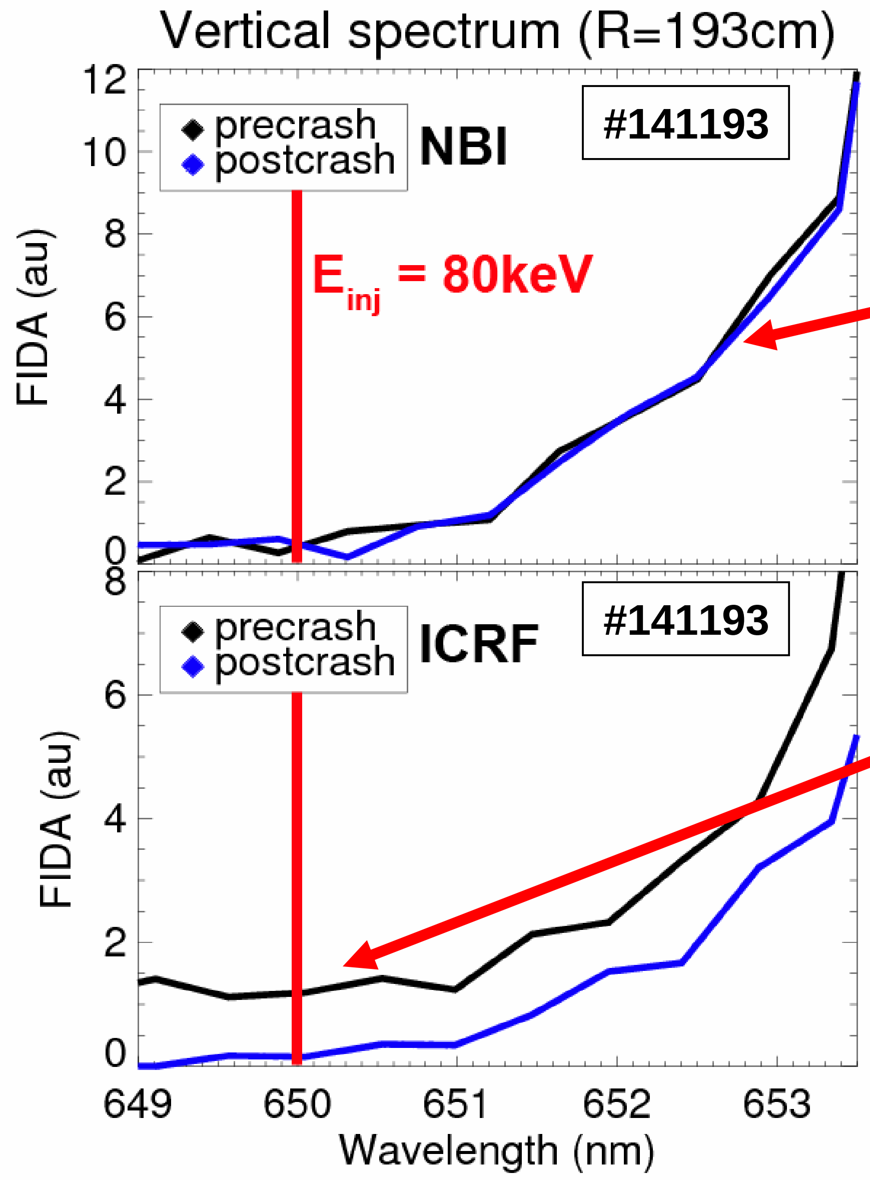
- n_e, Ip, Bt held constant to generate repeatable sawteeth



Fast-ion acceleration evidenced by enhanced neutron rate

DIII-D
NATIONAL FUSION FACILITY

Transport of trapped ions larger in ICRF heated plasma



NBI
No changes observed at a crash

ICRF
FW creates fast-ion tail observed by FIDA

Redistribution over entire measured bandwidth up to and exceeding NBI injection energy!

Sawtooth crash affects ICRF-accelerated trapped ions strongly

- Fast-wave → Off-axis peak observed in trapped fast-ion signal [1] ("hot spot") [2]

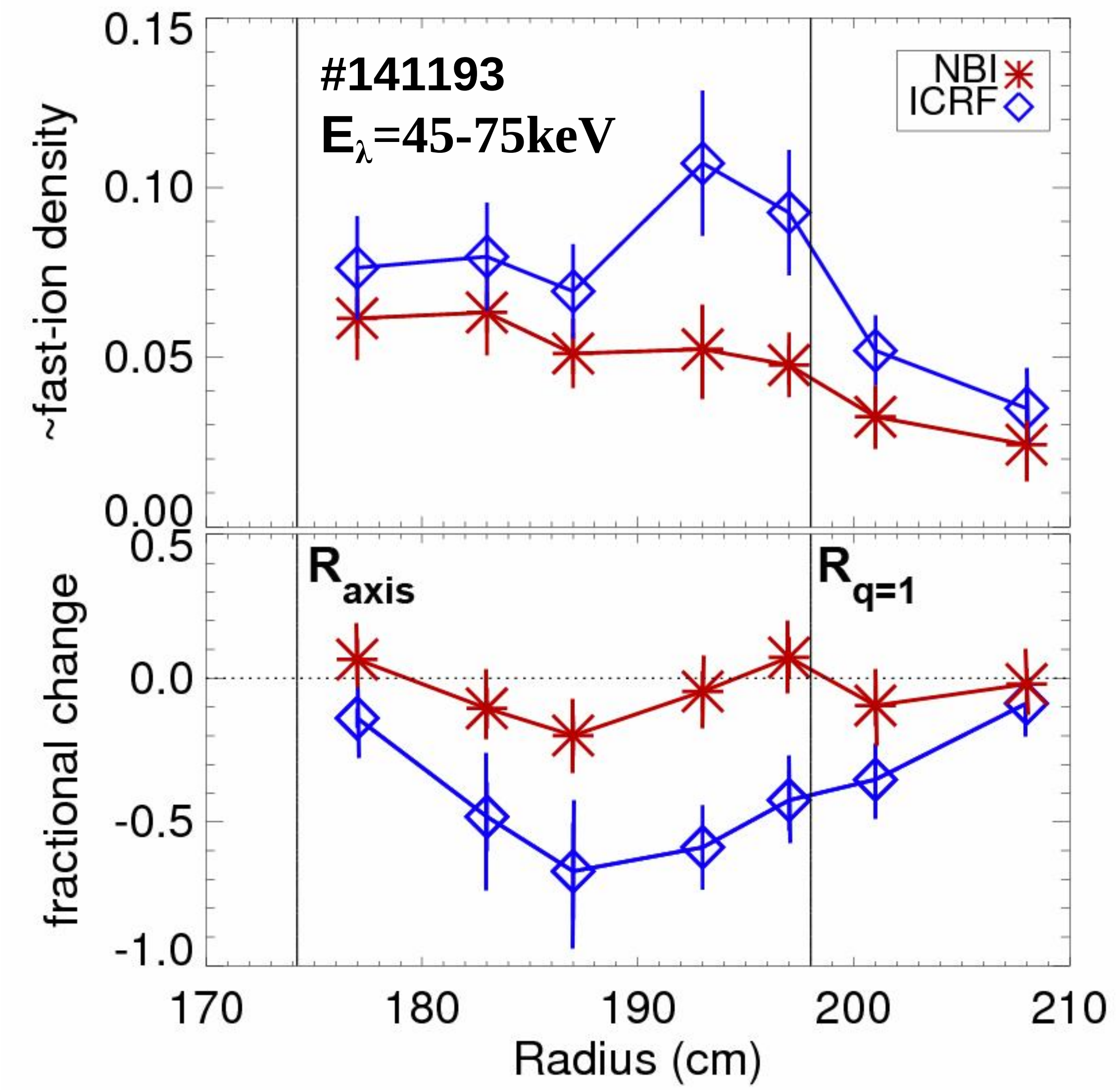
- Sawtooth crash during ICRF phase leads to different transport characteristics compared to NBI-only phase

NBI

- **no transport observed for this equilibrium (also longer crash time compared to 141182)**

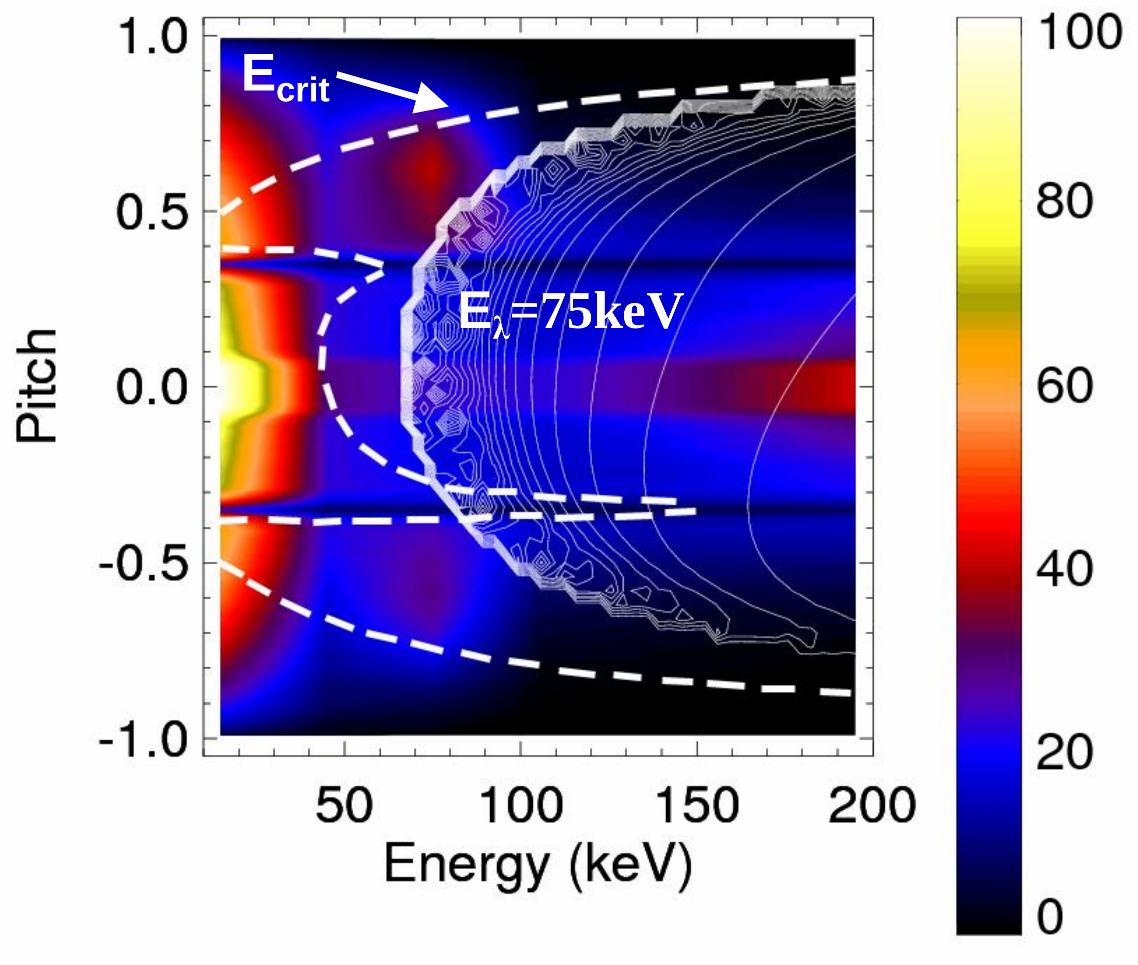
ICRF

- **~50% reduction in signal of off-axis "hot spot" fast ions**



[1] Heidbrink, et al., Plasma Physics and Controlled Fusion 49 (2007) 1457.
[2] Jarvis, et al., Nuclear Fusion 36 (1996) 1513.

Observed “hot spot” ions mainly exceed E_{crit}



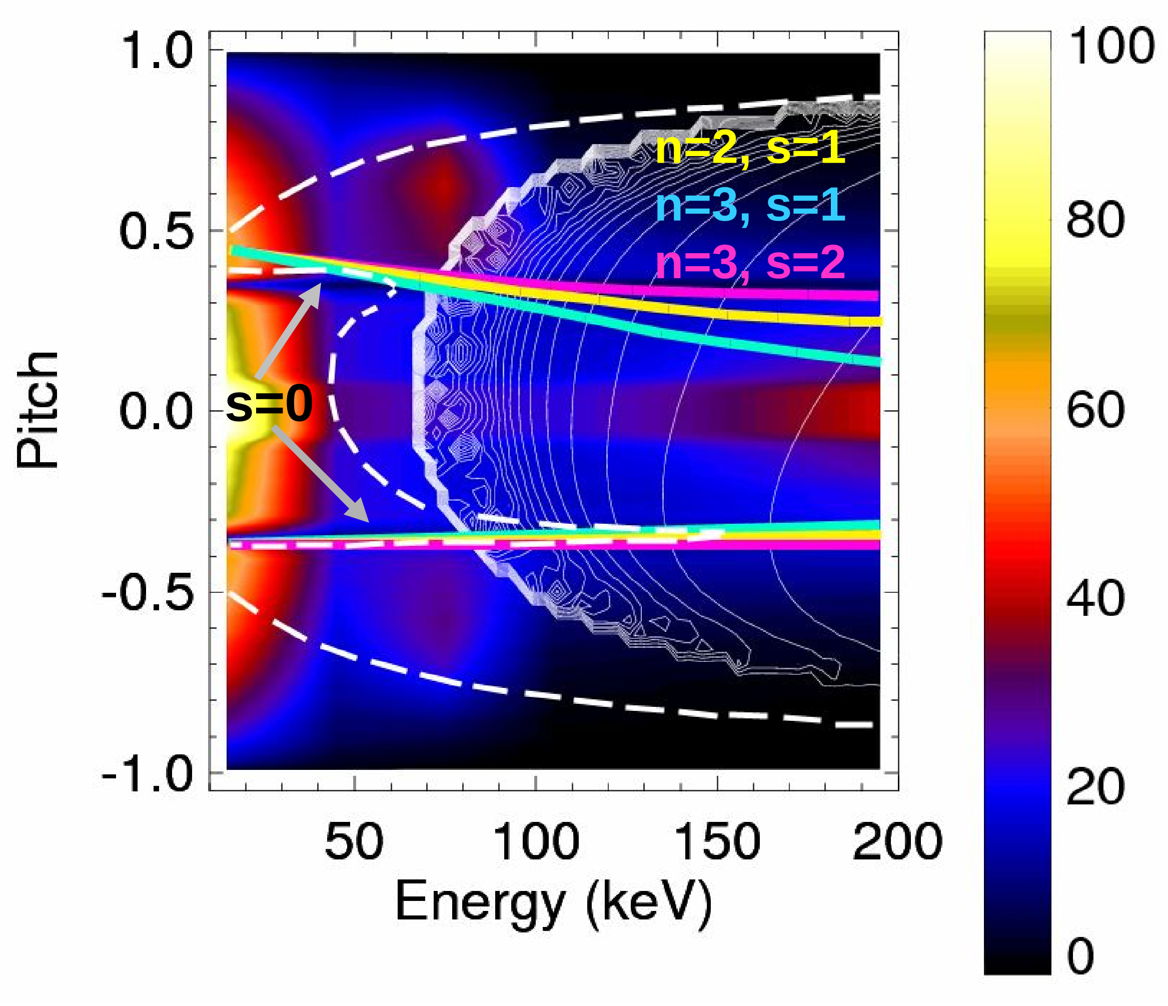
- CQL3D models distribution function during combined heating of 60+90MHz FW

- FW accelerates beam ions well above E_{inj} =75keV and E_{crit}

- But measured redistribution for E_{λ} > 75keV

- So why such large drop in trapped fast-ion density?

Resonances likely play key role in observed transport



- Applying ICRF populates region of phase space where bounce-precession resonances exist

$$\overset{\sim 0}{\cancel{\omega}} - n\omega_{pr} + s\omega_b = 0$$

- For the 1/1 internal kink during sawteeth

$$\omega \approx 0$$

Sawteeth redistribute confined energetic ions with a wide range of energies

- Experiments indicate that passing fast ions experience stronger internal transport than trapped in neutral beam heated plasmas
  - **Redistribution mechanism is shown to be consistent with flux attachment**
  - **But drifts tend to decouple the ion from an evolving flux surface and weaken its effective transport**

- Observations of enhanced internal transport of trapped fast ions in ICRF-heated plasmas
  - **Analysis indicates that resonant interactions between the 1/1 kink and fast ions are possible for particles in the trapped region of phase space with $E>E_{crit}$**

DIII-D
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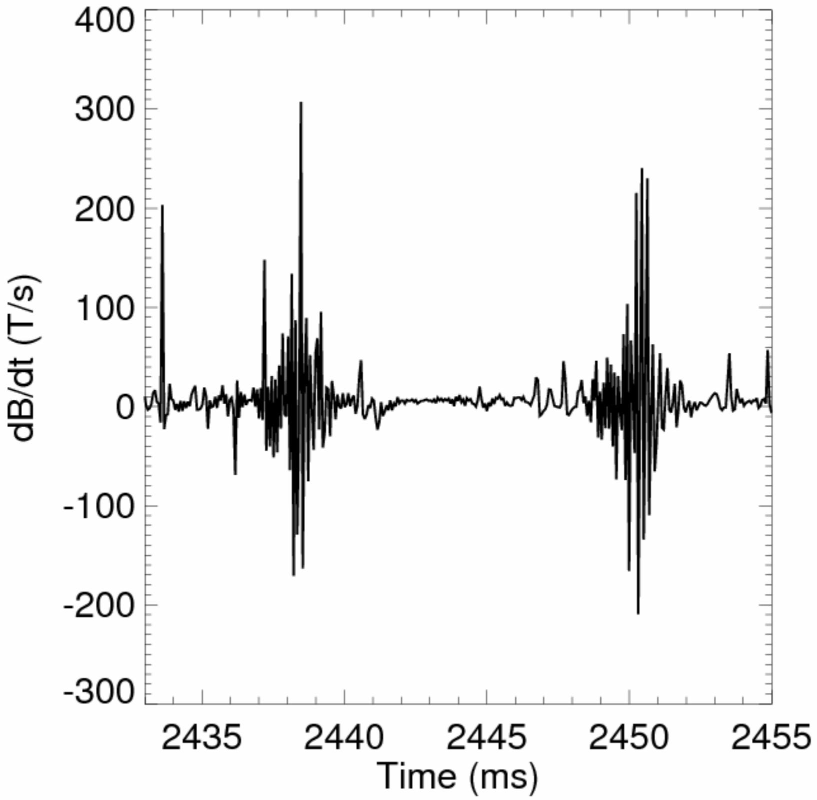
Measurements of lost fast-ion population

observations of fast-ion transport by off-axis fishbones and Alfvén eigenmodes

Fishbone-like instability observed with q>1

- Traditional fishbones observed as periodic bursts in magnetics with down-chirping frequency
  - → Internal kink structure (n=m=1)
  - → Observed to expel trapped fast ions with a definite phase w.r.t. the magnetic perturbation



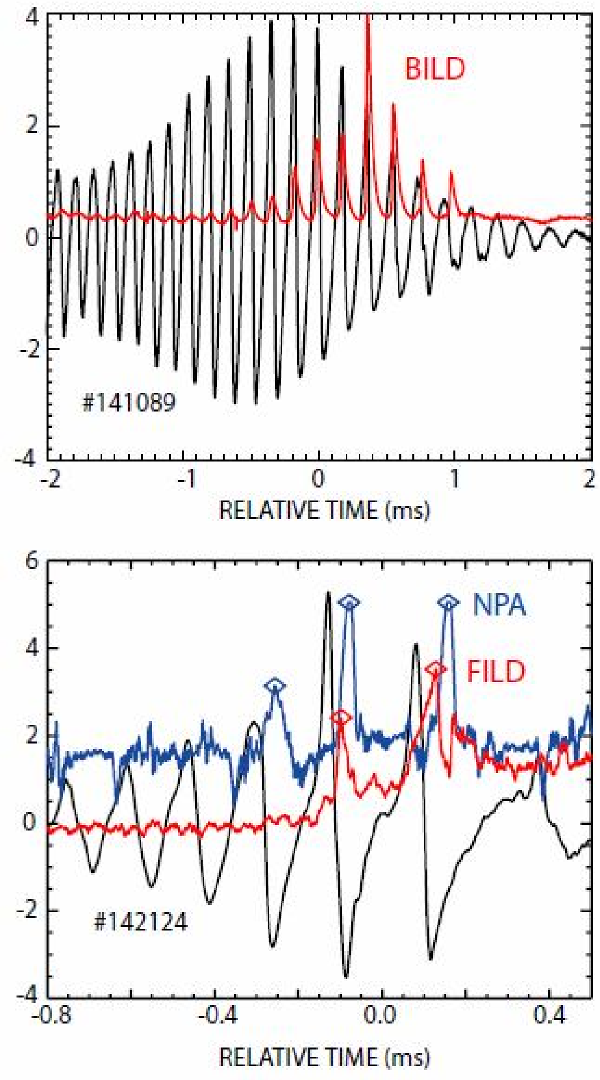
- Similar instability observed in plasmas with q>1
  - → Eigenmode situated around q=2 surface – "off-axis fishbones"
  - → Their presence in plasmas that are prone to resistive wall mode suggest they might be a branch of the external kink [1]

[1] Okabayashi M *et al* 2011 *Phys. Plasma* **18** 056112

q=2 fishbones observed to expel fast ions with fixed phase with respect to mode

- 7 independent fast-ion loss detectors observe beacon-like losses [1]

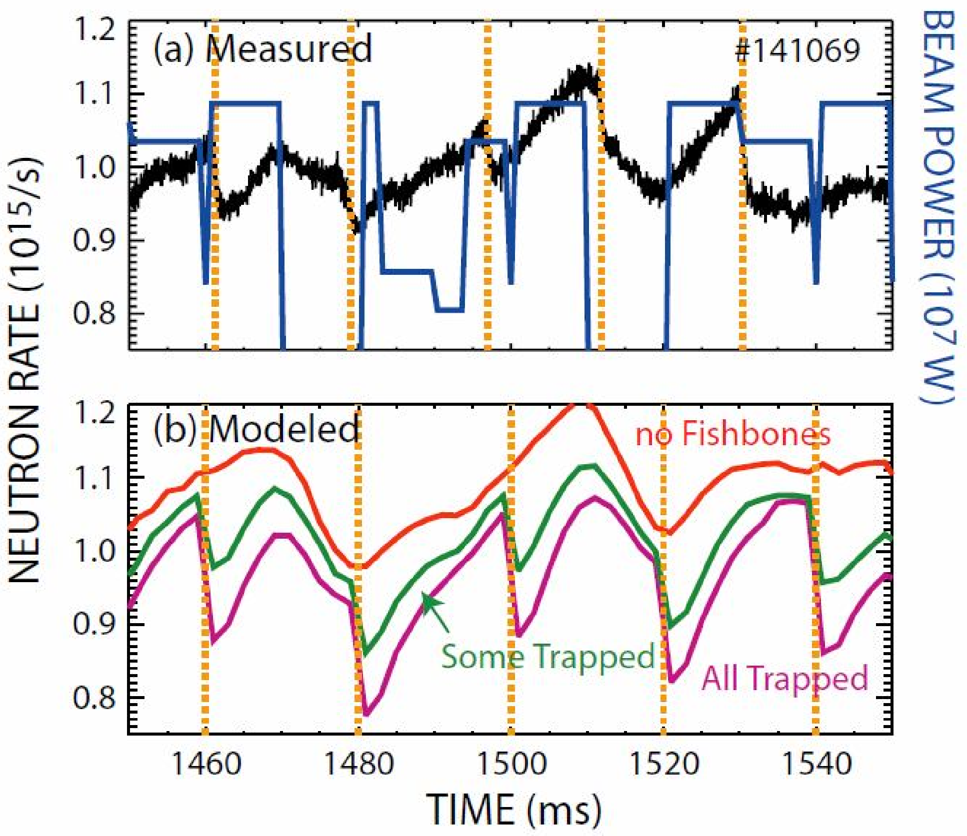
- Losses observed at fixed phase relative to mode
  - → mode-particle pumping theory: **E** x **B** drift of fast ions for a fixed phase of **E** [2]



[1] Heidbrink et al, Plasma Physics and Controlled Fusion, **53** (2011) 085028.
[2] White R B *et al* 1983 *Phys. Fluids* **26** 2958

Losses cause neutron rate to drop by almost 10%

- measured Δn/n ~ 10%
- TRANSP models fishbone-induced fast-ion losses
  - Expel all trapped with E>50keV → Δn/n = 18%
  - Expel deeply trapped with E>50keV → Δn/n = 11%



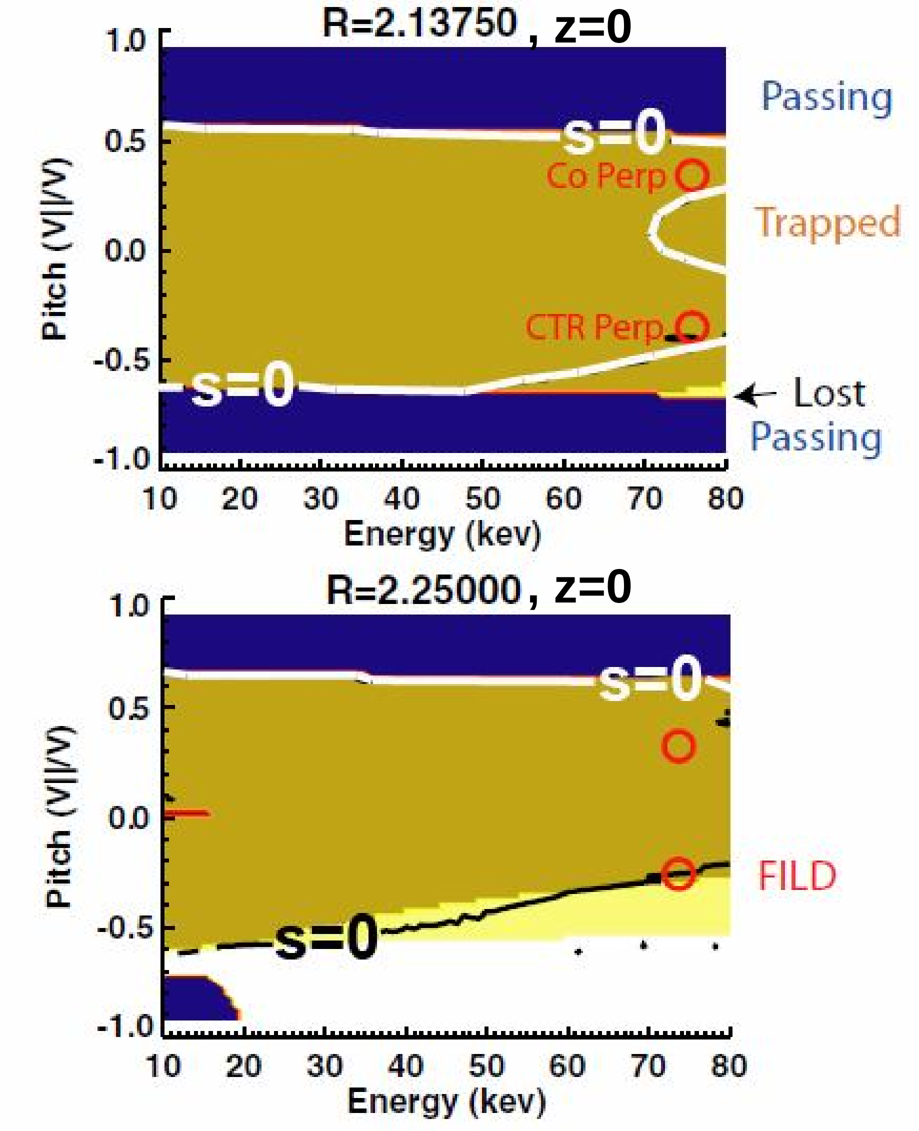
Heidbrink et al, Plasma Physics and Controlled Fusion, 53 (2011) 085028.

Fishbones expel fast ions via precession resonance

- Fishbones interact mainly with trapped energetic ions at the fundamental resonance (s=0)
  → precession resonance

$$\boxed{\omega - \omega_{pr} + \cancelto{0}{s}\omega_b = 0}$$

- Source of fast ions from NBI near resonances
  → ΔP_ζ → fast ions spread in pitch and intersect loss boundaries

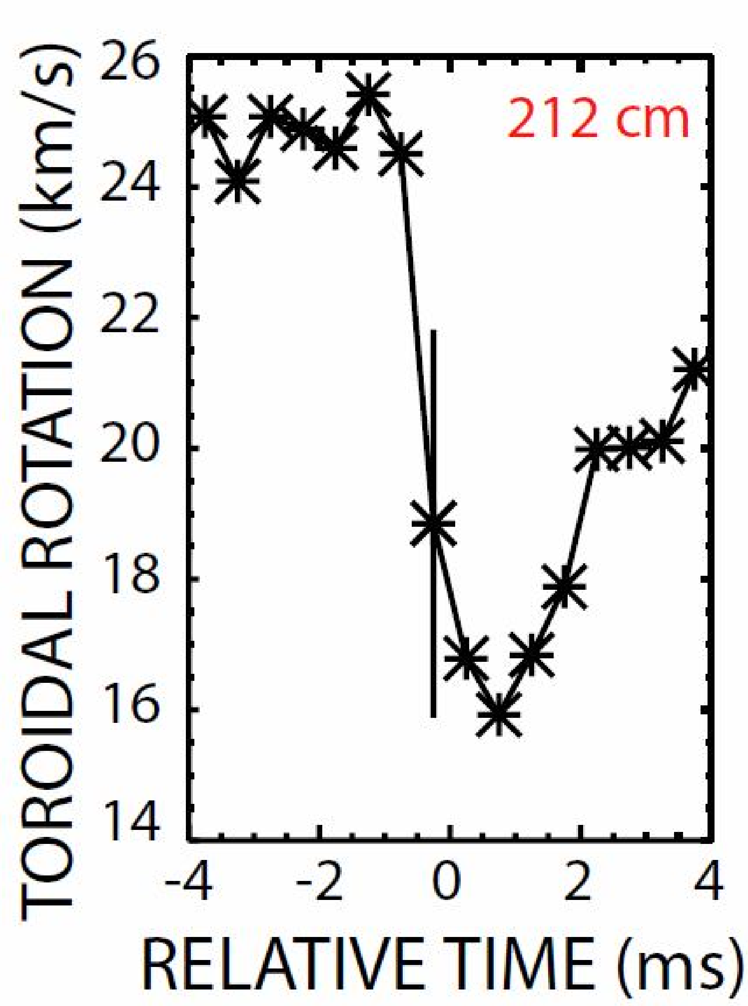


Heidbrink et al, Plasma Physics and Controlled Fusion, 53 (2011) 085028.

Slowing of toroidal rotation observed at a burst

- Non-ambipolar particle losses evidenced by drop in toroidal rotation at a burst

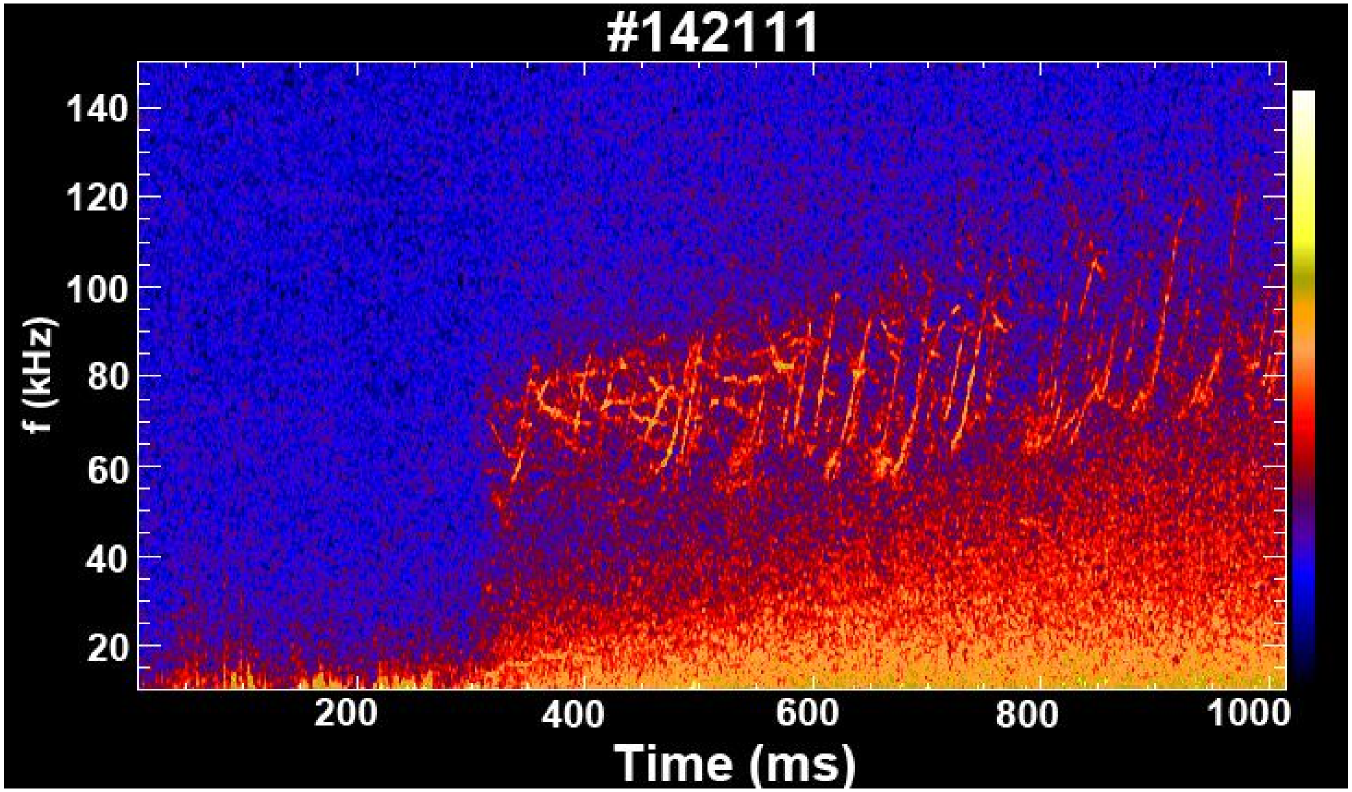
- Loss of fast ions from plasma negatively charges the depleted region
  - → changes E_r
  - → but must maintain radial force balance
  - → changes toroidal rotation



Heidbrink et al, Plasma Physics and Controlled Fusion, 53 (2011) 085028.

NBI injection during current ramp excites Alfvén eigenmodes

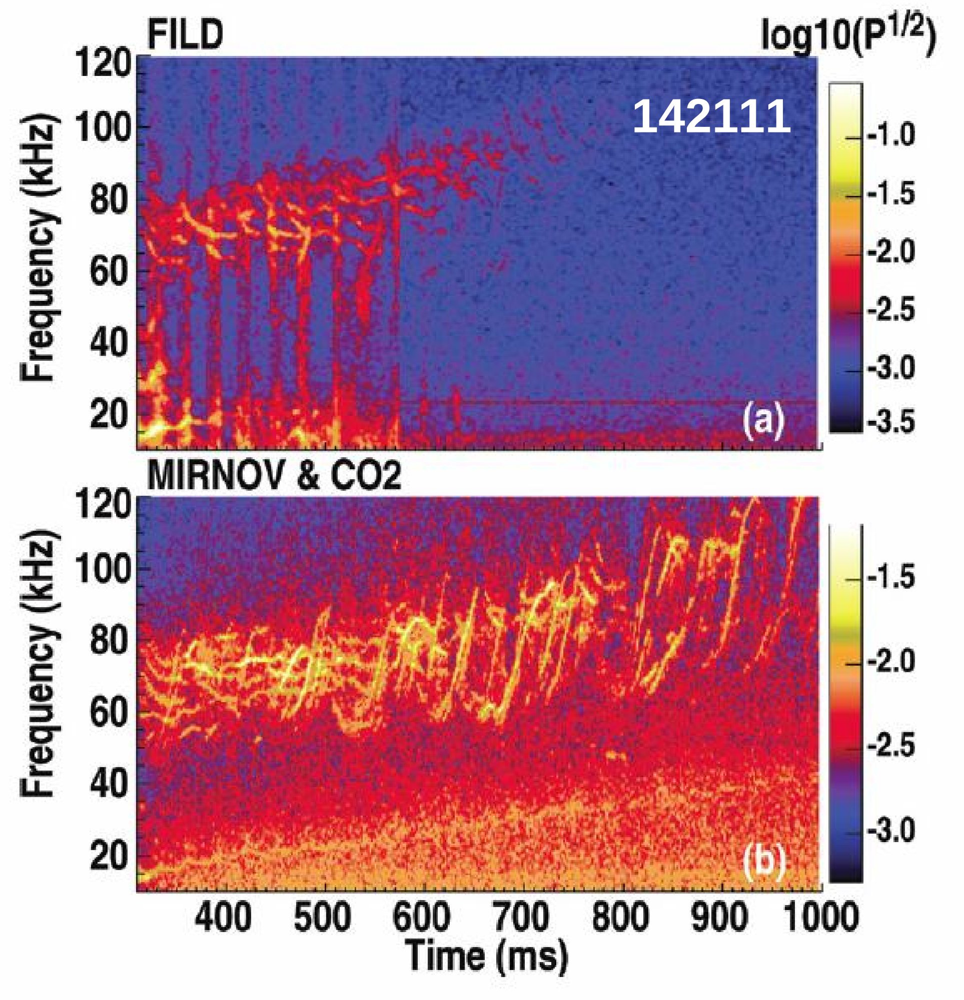
- AEs are regularly observed in neutral beam injected plasmas during the current ramp phase of the discharge
- Most common modes observed on DIII-D consist of reverse-shear AE (RSAE) and toroidicity-induced AE (TAE)



Coherent loss measurements during strong AE activity

- FIELD measures strong signals due to RSAE and TAE early in the discharge [1,2]

What induces these losses and can we synthetically reproduce them?



[1] Van Zeeland et al, Physics of Plasmas, **18** (2011) 056114.
[2] Pace et al, Plasma Phys. Control. Fusion **53** (2011) 062001.

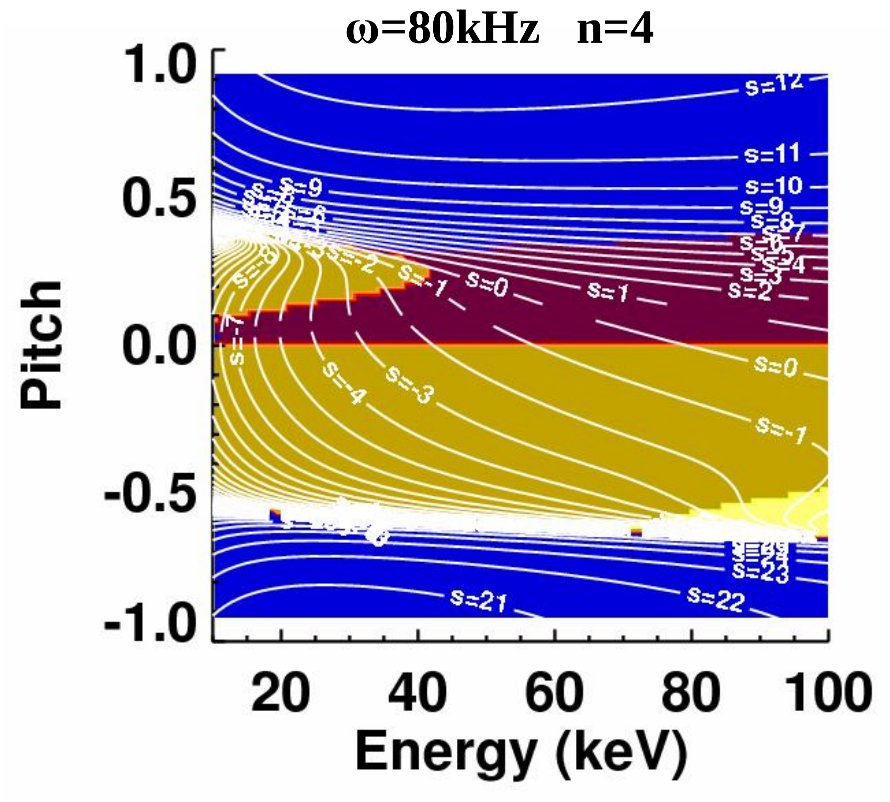
Resonances play key role in observed transport of fast ions during AE activity

- AE span large range of frequencies and toroidal mode numbers

  → $\omega - n\omega_{pr} + s\omega_b = 0$ with no general simplifications like sawteeth and fishbones

- Zoo of resonances throughout all of velocity space

- Counter-going fast ions situated near resonance spread out in pitch and can enter loss region



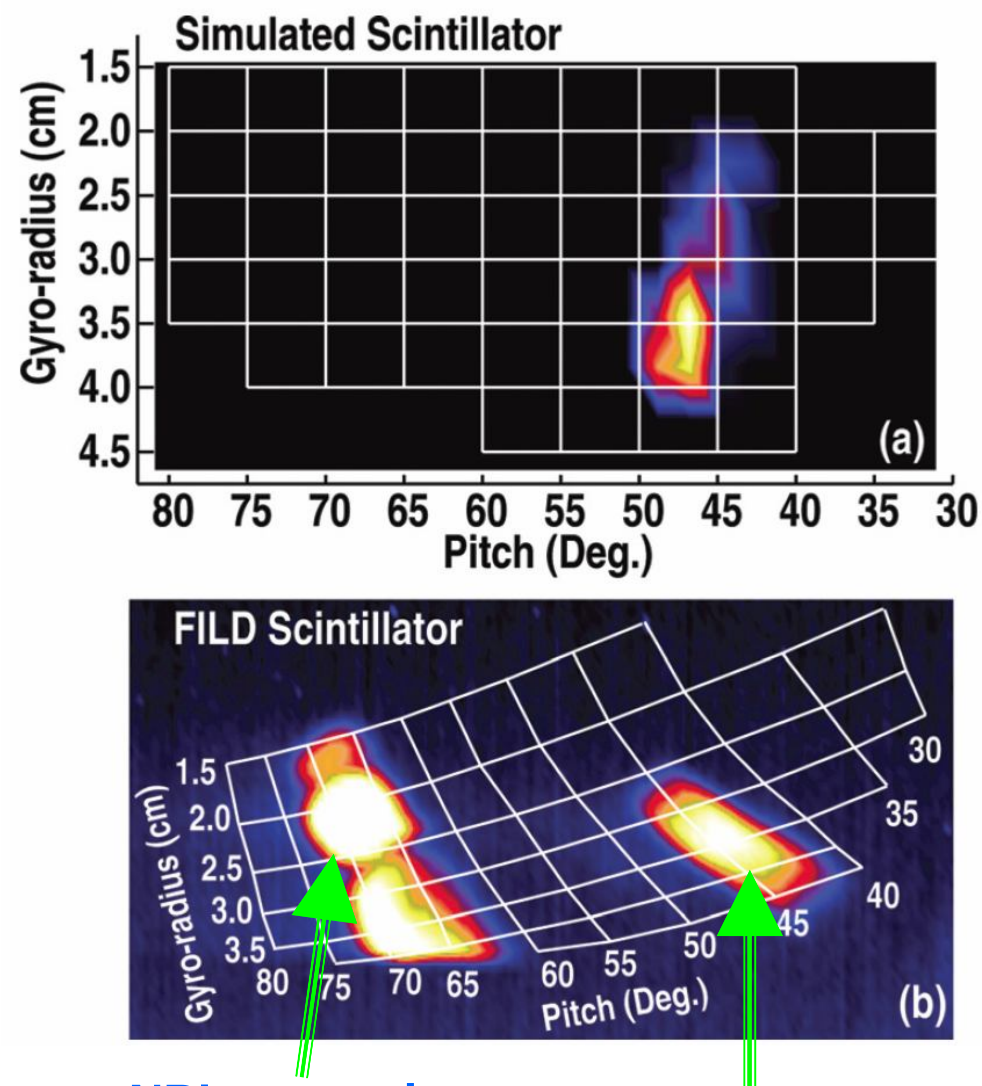
Van Zeeland et al, Physics of Plasmas, **18** (2011) 056114.

Modeling yields good agreement with measurement

Can predicted eigenfunctions (with similarities to experimental ones) reproduce measured losses?

- To model losses…
    - TRANSP calculates beam distribution function
    - NOVA models eigenfunctions
    - ORBIT models particle orbits in equilibrium field + NOVA wavefileds

→ Produces results similar to experiment



NBI prompt losses

AE-induced losses

Van Zeeland et al, Physics of Plasmas, **18** (2011) 056114.

Summary

➢ Interrogation of fast-ion phase space is an essential tool for determining transport mechanisms

➢ Wave-particle resonances are responsible for many observed transport phenomena

- Interaction between *confined* fast ions and instabilities well suited for diagnostic like FIDA *e.g. sawteeth cause large internal redistribution of energetic ions*
- Velocity-space discrimination of *lost* fast ions provided by diagnostic like FILD *e.g. off-axis fishbones and AE cause large measurable losses to the wall*

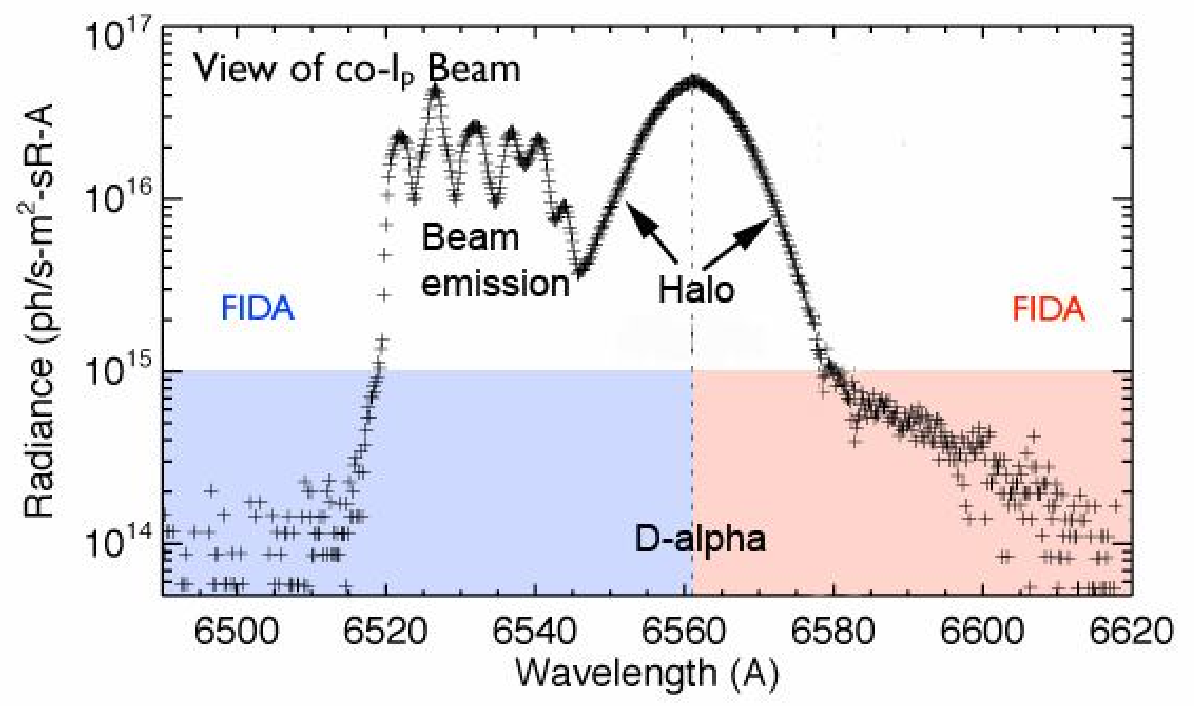
➢ Provide us with confidence in theoretical models for extrapolation to ITER (see Van Zeeland poster P2.12)

FIDA measurement involves extraction of fast-ion feature from active Dα spectrum

Several features of active D-alpha spectrum:

1. Halo & main ion – CX between injected neutrals and surrounding thermal ions
2. Beam emission – emission from excited injected neutrals
3. FIDA – CX between injected neutrals and fast ions

   – max $\Delta\lambda$ depends on fast-ion source



Grierson et al, submitted to Nuclear Fusion.

Light is Doppler shifted depending on ion velocity

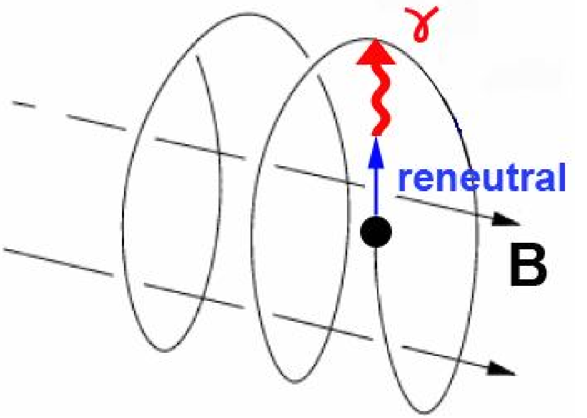
The *measured* wavelength λ of the emitted photon is Doppler-shifted due to the large velocity of the fast ion and subsequent reneutral

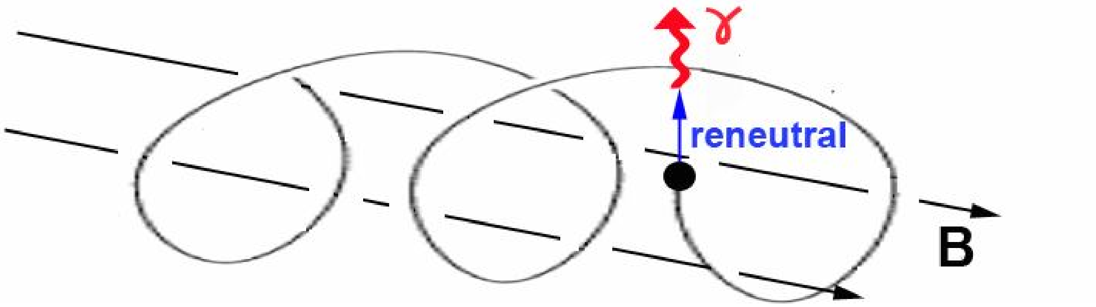
$v_{||}/v = 0.3$
E=80keV → $E_\perp$ = 73keV

λ=650.3nm

$v_{||}/v = 0.8$
E=80keV → $E_\perp$ = 29keV

λ= 652.4nm





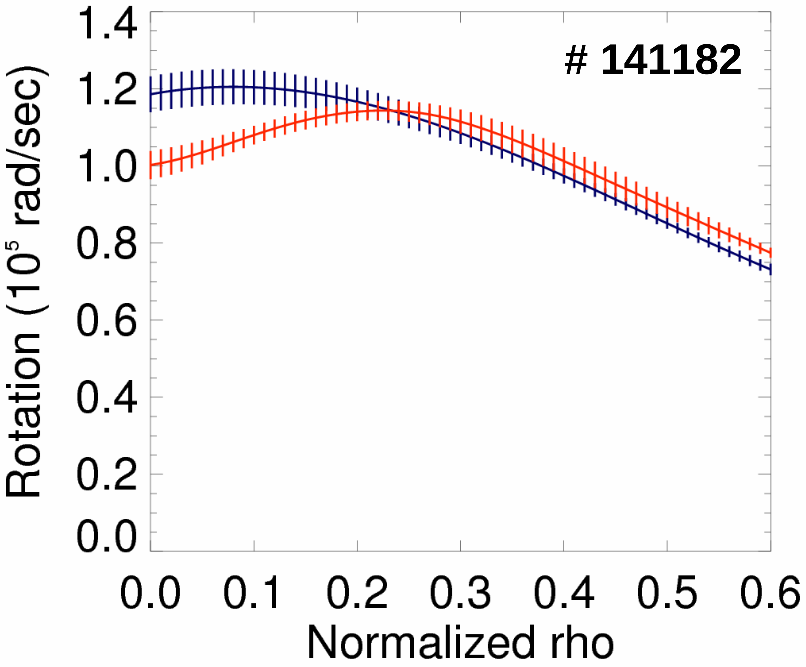
So…

- Particles with **same** E and pitch can produce **different** Doppler shifts
- Particles with **different** E and pitch can produce **similar** Doppler shifts

How can we represent this in phase space?

Difference in passing/trapped redistribution also evidenced by change of V_{rot} profile

- $\Delta V_{rot}/V_{rot}$ ~ 15% observed in the core
- Possible explanation in terms of non-ambipolar transport:
  - Passing ions are strongly redistributed with electrons → no charge separation → no effect on rotation
  - Electron transport not followed by trapped fast ions → positively charges the core → ΔE_r → ΔV_{rot}



Flux attachment in terms of 3rd adiabatic invariant

$$J = \int [\, m\langle \mathbf{v} \rangle + q\mathbf{A}] \cdot d\mathbf{r}$$

Action integral associated with bounce-averaged periodic motion – toroidal precession

$$\frac{\int m\langle \mathbf{v} \rangle \cdot d\mathbf{r}}{\int q\mathbf{A} \cdot d\mathbf{r}} \approx \frac{m\, v_d\, 2\pi r}{q\, B\, \pi r^2}$$

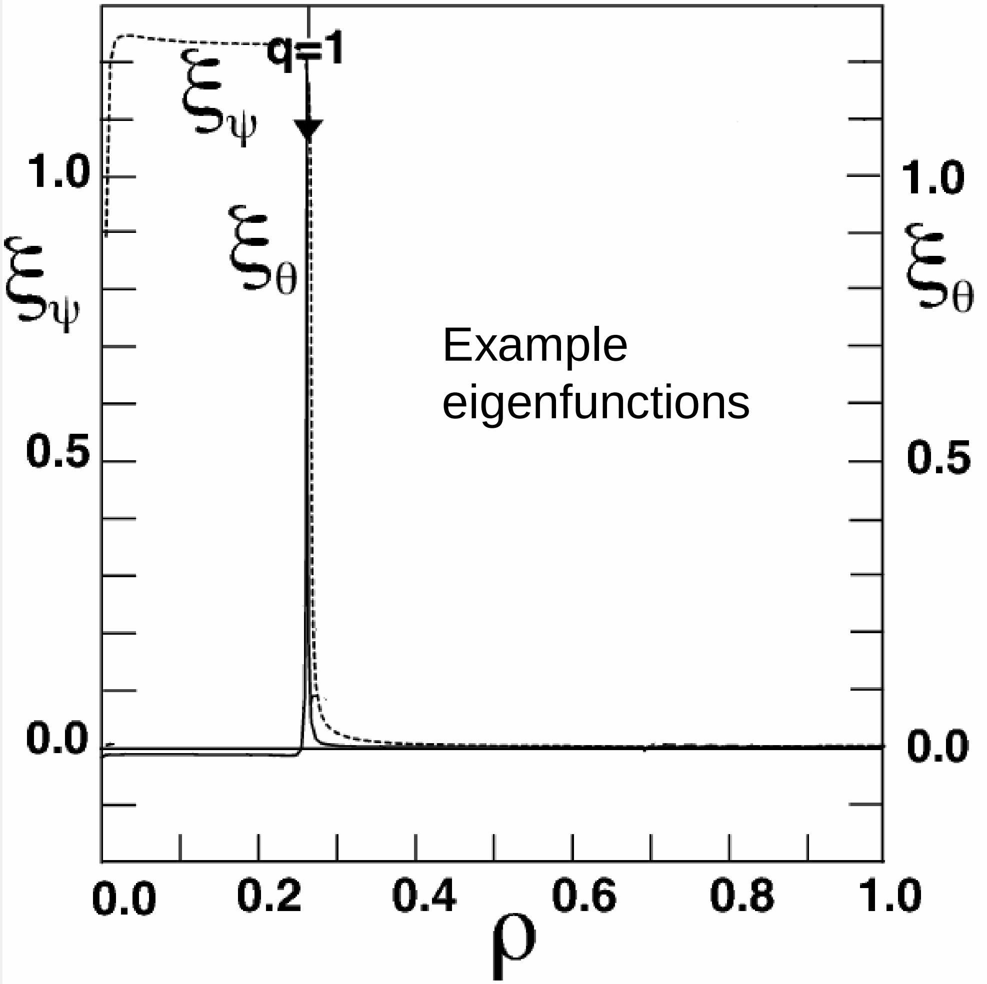
If J is conserved and …

- flux term >> drift term then particles attached to flux surface

- drift term >> flux term then particles decouple from flux surface

Kadomtsev crash model

- Hot core moves rigidly out → top-hat plasma displacement ξ_ψ eigenfunction
- Reconnection unites like-valued flux surfaces inside and outside q=1
- q resets to >1 following the crash

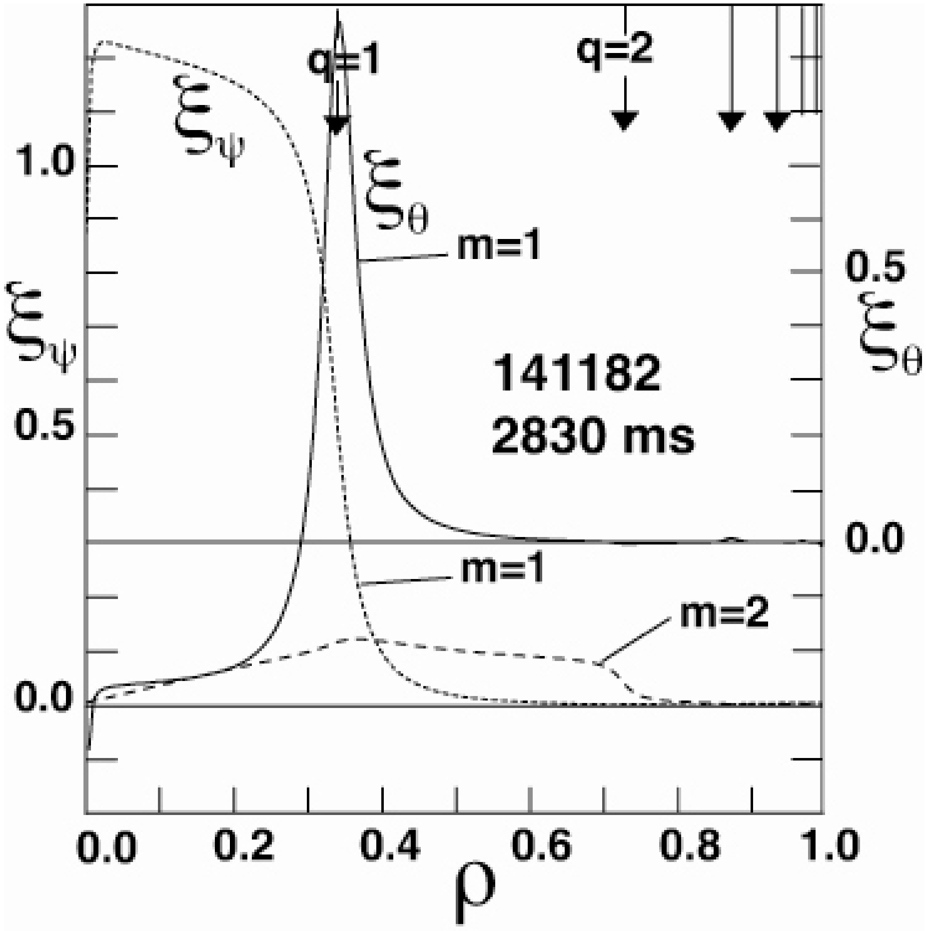


Example eigenfunctions

Kadomtsev-like eigenfunction is only a rough approximation to stability simulation results

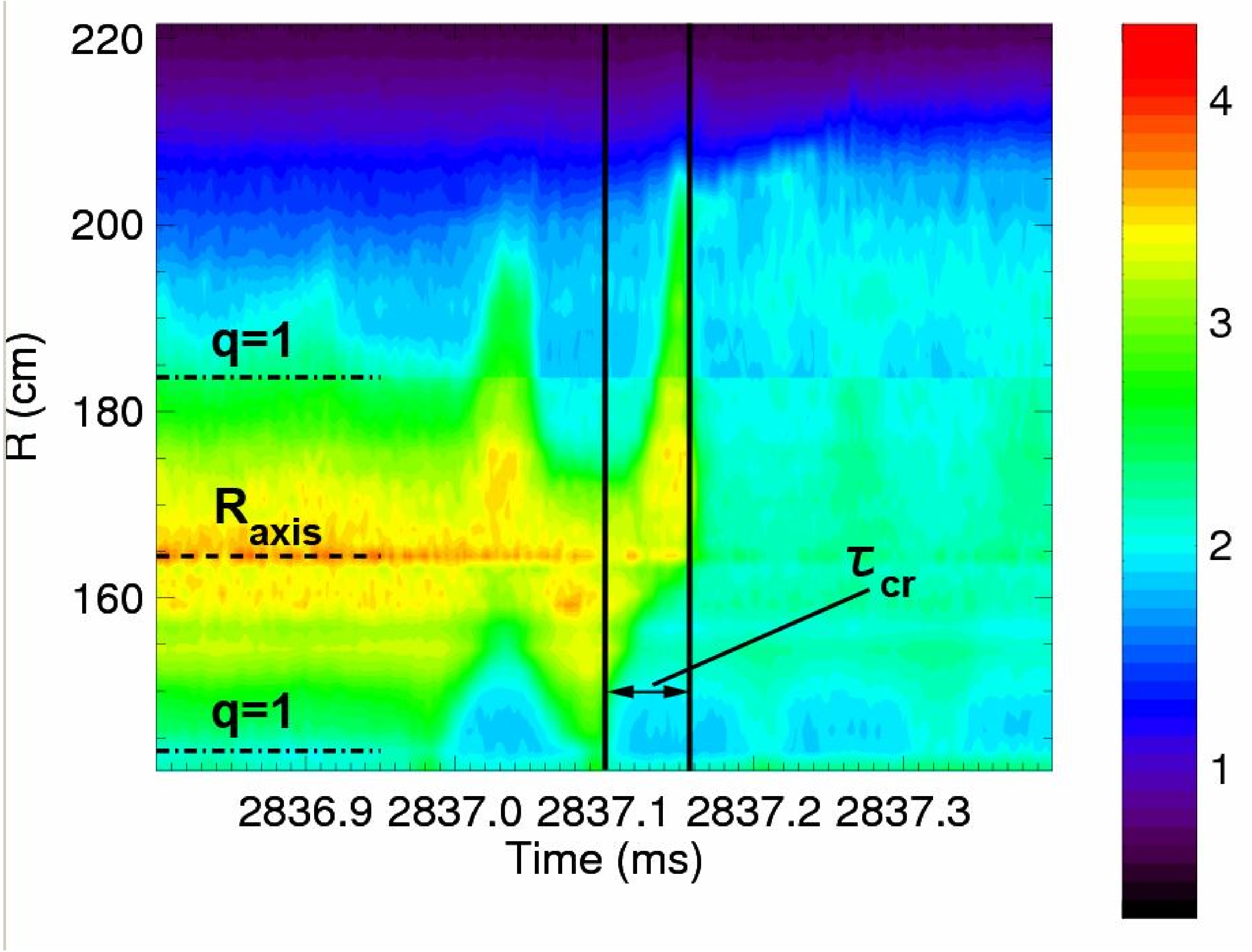
- GATO simulation indicates ξ_ψ eigenfunction is not quite top-hat

- The ξ_θ (poloidal return flow) eigenfunction is broadened presumably due to finite inertia



*Courtesy of Alan Turnbull

Crash time determined by time of expulsion of hot T_e core



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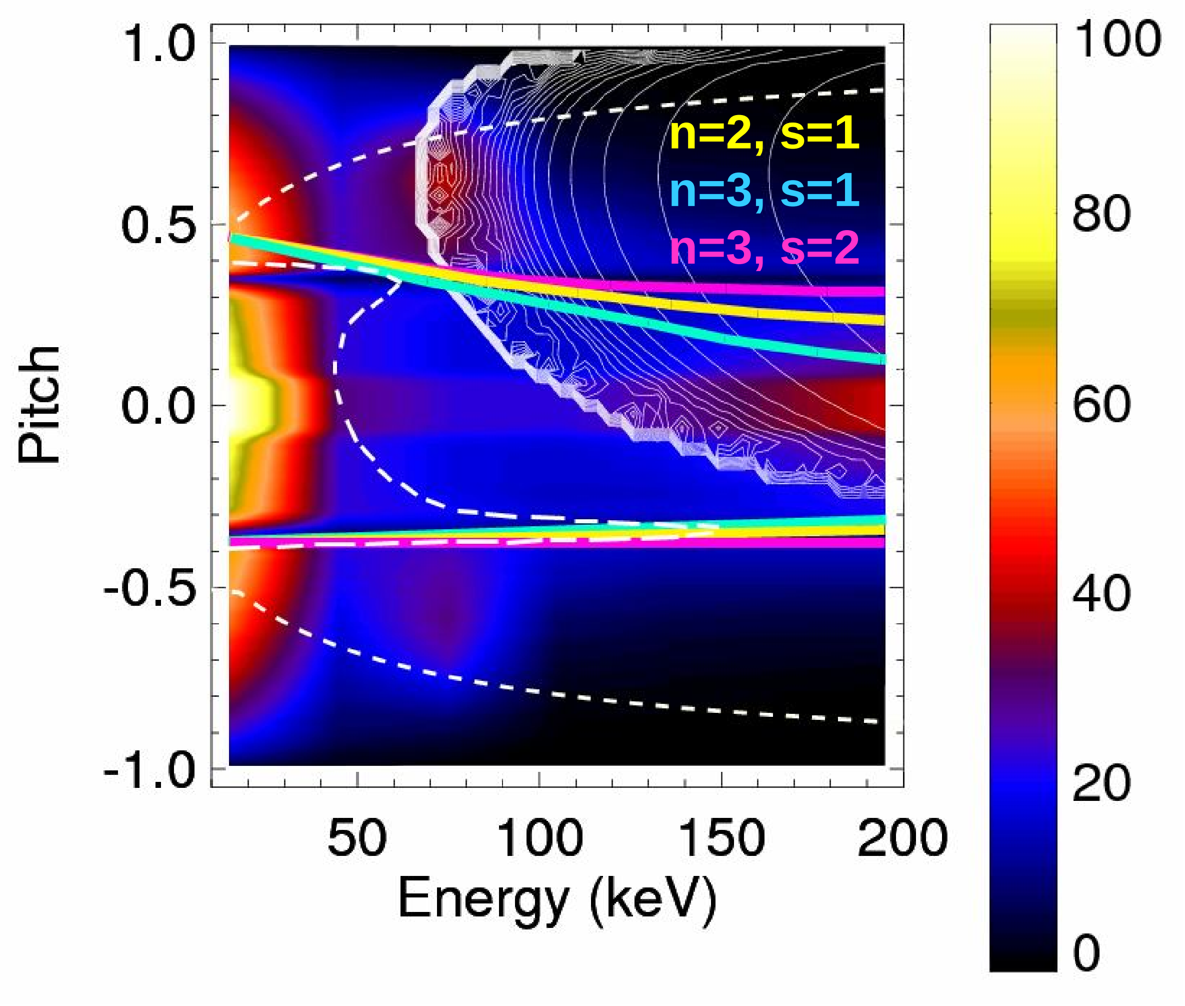
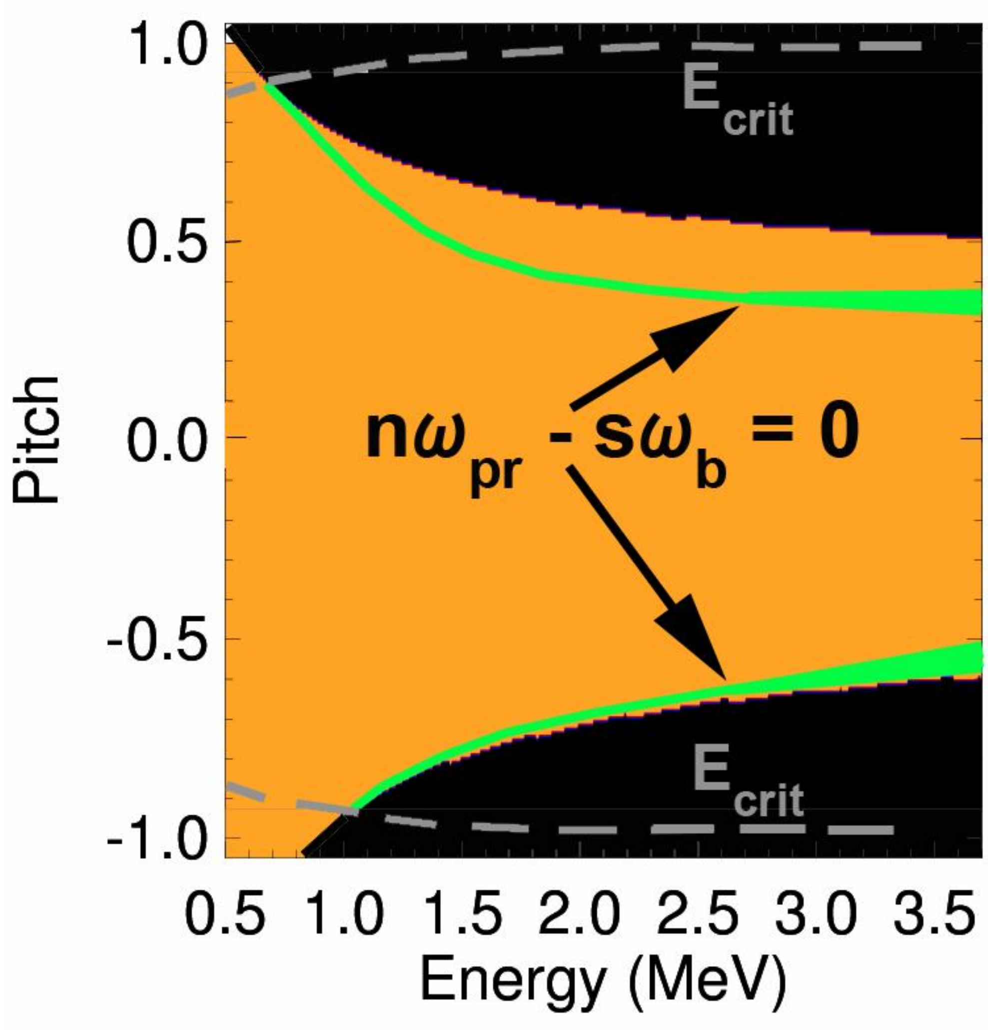
Anatomy of phase space orbit map elucidates possible transport mechanism



- Tangential FIDA weight is more skewed toward co-going ions
- Resonance curves intersect a weaker portion of weight function

  → no measured redistribution for high Doppler shifts

ITER alphas may experience minimal redistribution by sawteeth



- ITER scenario 2 (baseline scenario) EFIT

- Alpha orbit calculation suggests standard passing/trapped orbits

- $E>E_{crit}$ for vast majority of alphas

- For E ≤ 3.5MeV resonances overlap only narrow region of velocity space