Fast particles in tokamak plasmas

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Thanks to many contributors, especially Simon Pinches and Jon Graves

Outline

- Particle orbits in tokamaks
- Sources of energetic particles
- Measuring fast ions
- Interaction of energetic particles with instabilities
  - Resonant interaction of fast ions with Alfven instabilities
  - Effect of fast ions on instabilities in thermal plasma
- Redistribution and loss of fast ions
  - Losses from instabilities and 3d fields
  - Effects on driven current
- Controlling and utilising fast ions

Why do we care about fast ions?

- Loss of bulk plasma heating
  - Unacceptable for an efficient power plant
  - May lead to ignition problems
- Damage to first wall
  - Can only tolerate fast ion losses of a few % in a reactor

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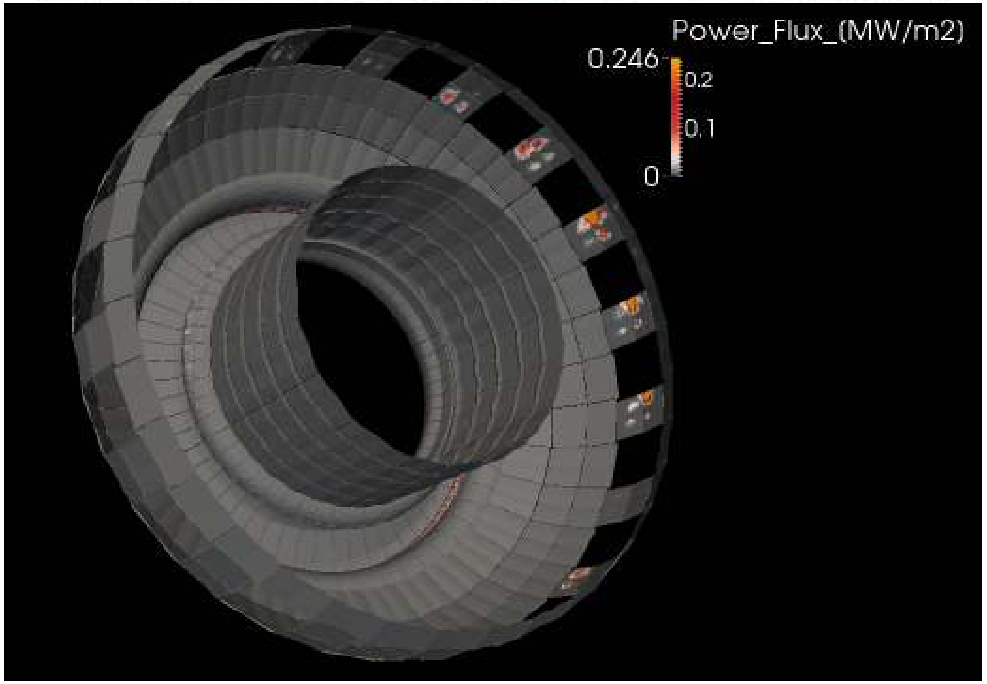

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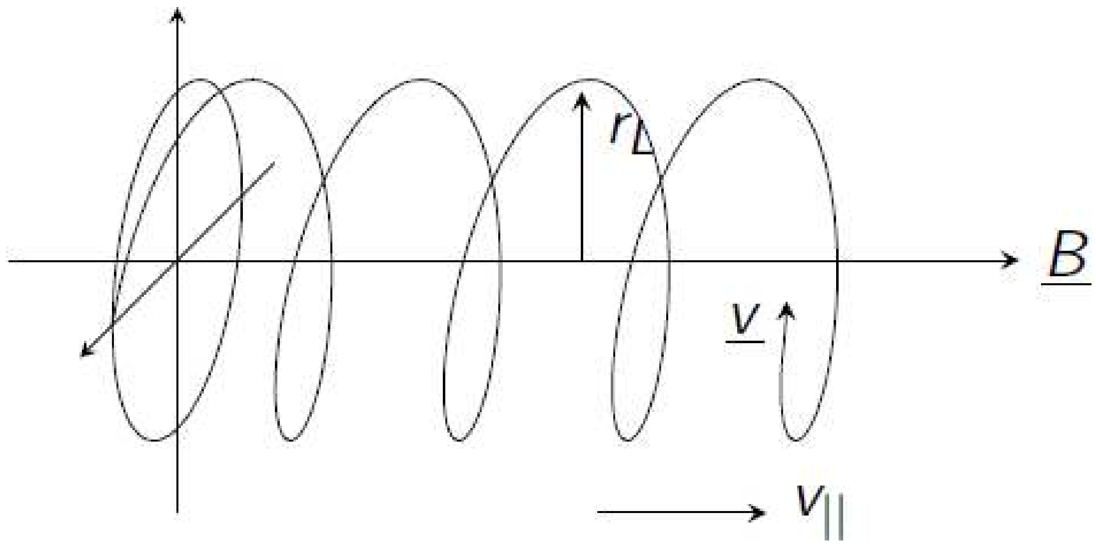
Motion in a magnetic field

In magnetic fields, charged particles follow helical paths



Particles are free to move along magnetic fields, but are constrained in the perpendicular direction by the Lorentz force:

$$\boxed{\underline{F} = q\underline{v} \times \underline{B}}$$

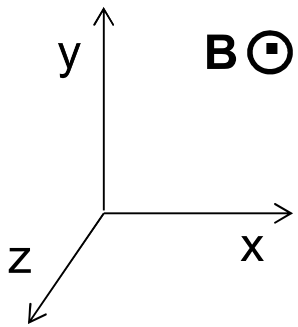
Particle motion

- The equation of motion of a particle of mass, M, charge, e, velocity, **v**, in an electric field, **E**, and a magnetic field, **B**, is

$$M\frac{d\boldsymbol{v}}{dt} = e(\boldsymbol{E} + \boldsymbol{v} \times \boldsymbol{B})$$

- In the presence of uniform E-field and no B-field the ions accelerate in direction of **E**, whilst the electrons accelerate in opposite direction to **E**

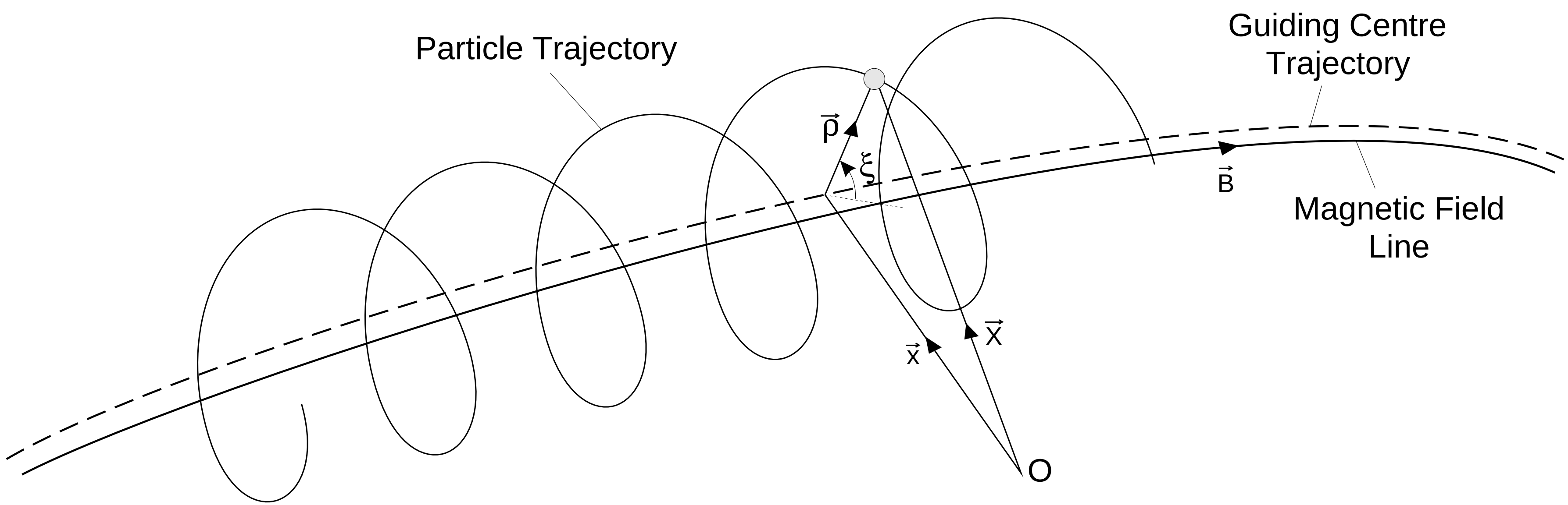
Particle Motion II



- In a uniform B-field and no E-field…
- $m\frac{dv_z}{dt} = 0 \quad m\frac{dv_x}{dt} = ev_yB \quad m\frac{dv_y}{dt} = ev_xB$
- Taking derivatives…
- $\frac{d^2v_x}{dt^2} = \frac{eB}{m}\frac{dv_y}{dt} = -\left(\frac{eB}{m}\right)^2 v_x; \frac{d^2v_y}{dt^2} = -\frac{eB}{m}\frac{dv_x}{dt} = -\left(\frac{eB}{m}\right)^2 v_y$
- This is the simple harmonic oscillator equation
- Integrating gives…
- $x = x_0 + \frac{v_\perp}{\Omega_c}\sin(\Omega_c t + \text{⍰})$; $y = y_0 + \frac{v_\perp}{\Omega_c}\cos(\Omega_c t + \phi)$
- Which describes circular motion about (x_0, y_0) with frequency $\Omega_c = {}^{eB}/_{m}$ and "Larmor radius", $\rho = {}^{v_\perp}/_{\Omega_c}$

Particle Motion III

- "Cyclotron frequency": $\Omega_c = \frac{eB}{M}$
- "Larmor radius": $\rho = \frac{Mv_\perp}{eB}$



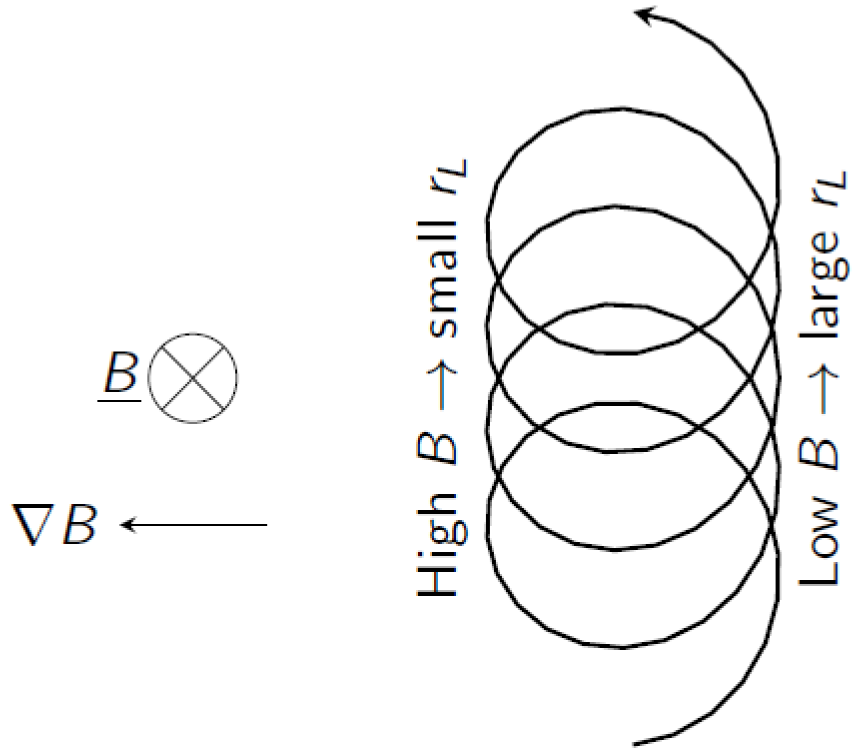
Adiabatic Invariants

- If a system performs periodic oscillations, invariants of the motion can be found
- The first adiabatic invariant (ie the periodicity remains the same in the presence of a perturbation) is the magnetic moment

$$\mu = \frac{Mv_\perp^2}{2B}$$

∇B Drifts

- In a tokamak, the magnetic field is not uniform
- The B-field is stronger near the centre than the outside, producing a particle drift in the direction perpendicular to the magnetic field and it gradient

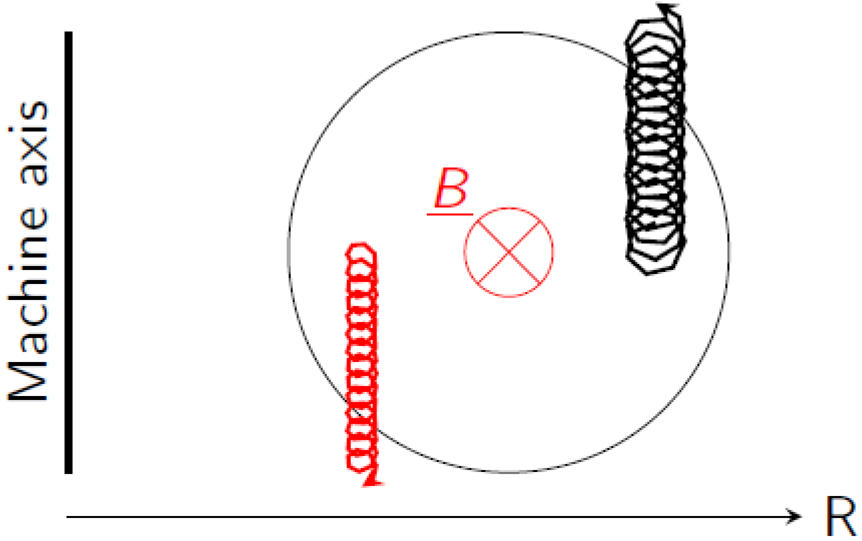


∇B Drifts II

- The ∇B drift is given by

$$v_{\nabla B} = \frac{1}{2}\frac{Mv_{\perp}^{2}}{eB}\frac{\mathbf{B}\times\nabla B}{B^{2}}$$

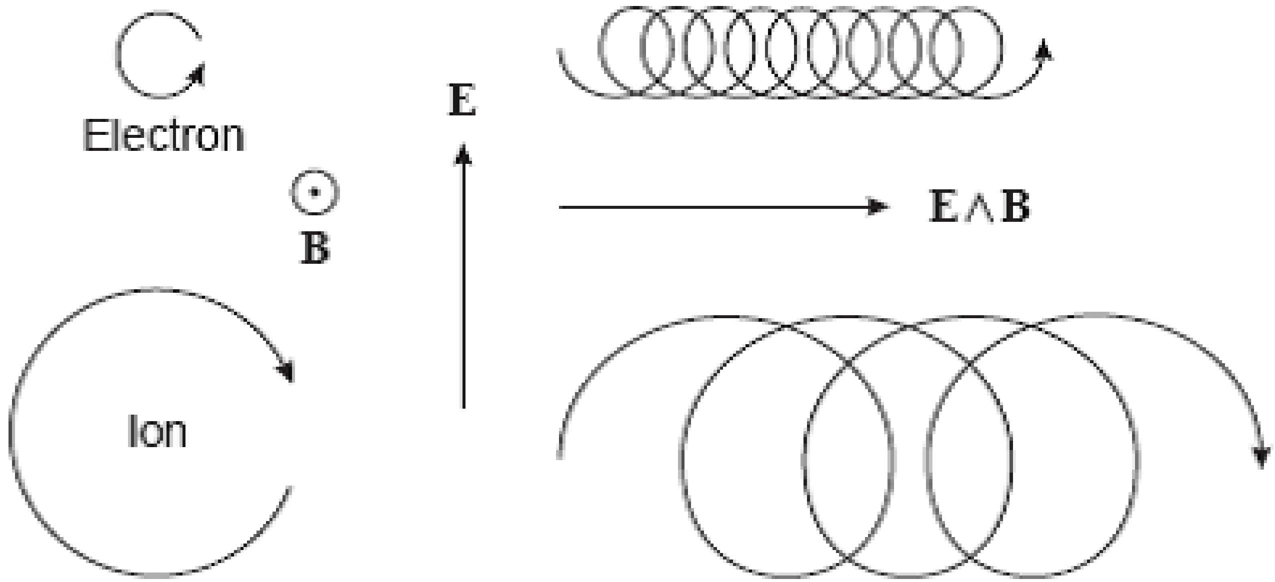
- It depends on charge, so ions and electrons separate



- Charge separation creates a vertical electric field

ExB drifts

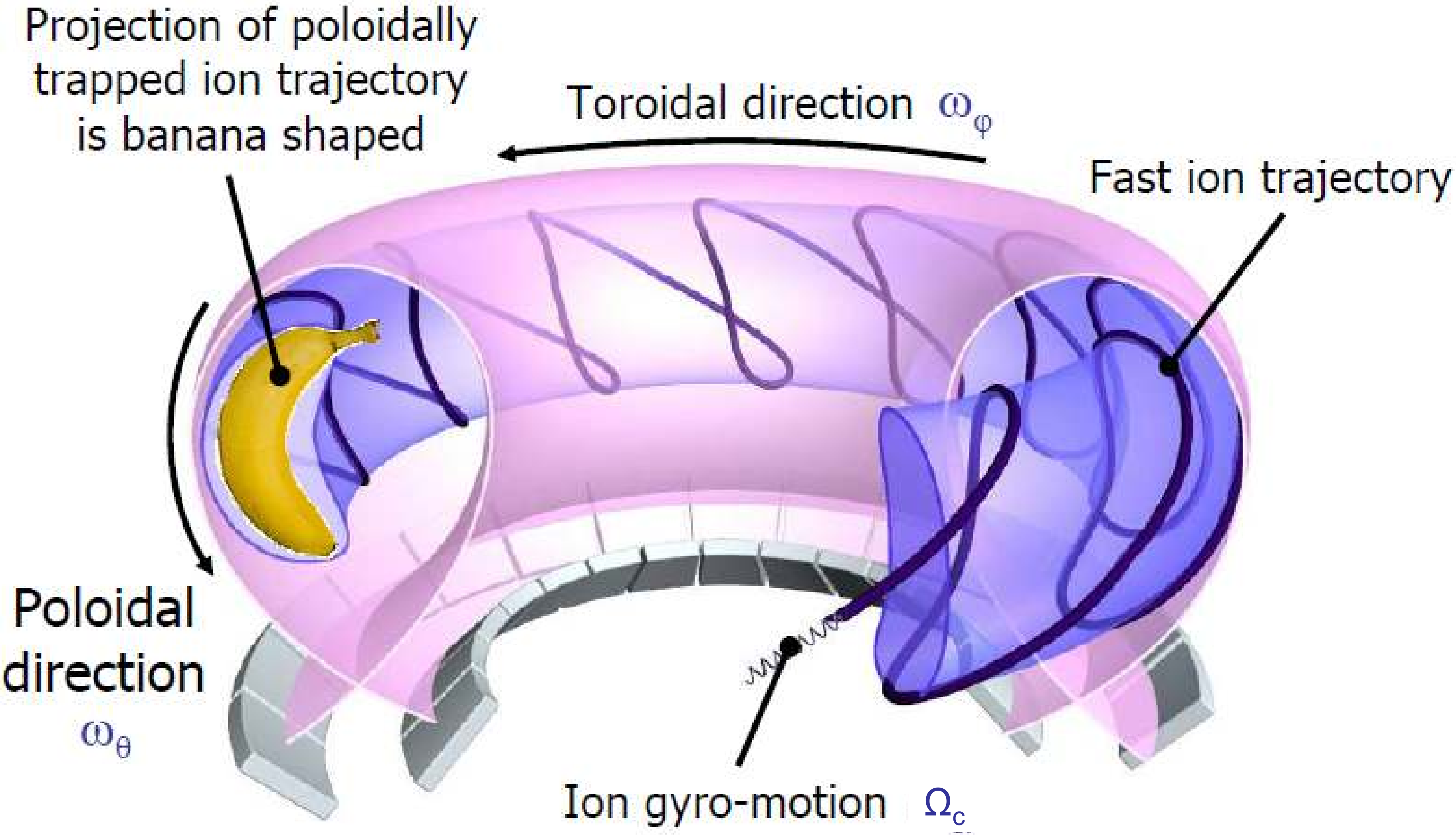
- The electric field accelerates (decelerates) positive ions when moving in the same (opposite) direction as the E-field
- As velocity increase, the Larmor radius increases, resulting in a drift of the guiding centre



Particle Trapping

- To conserve magnetic moment, as particles move to region of higher B-field, their perpendicular velocity increases
- To conserve energy, the parallel velocity decreases and in some cases reaches zero and the particle is reflected – these are called ‘trapped’ particles
- Trapped particles bounce back and forth between mirror points, all the while experiencing ∇B drift from their surface, earning their trajectory the name “banana orbits”

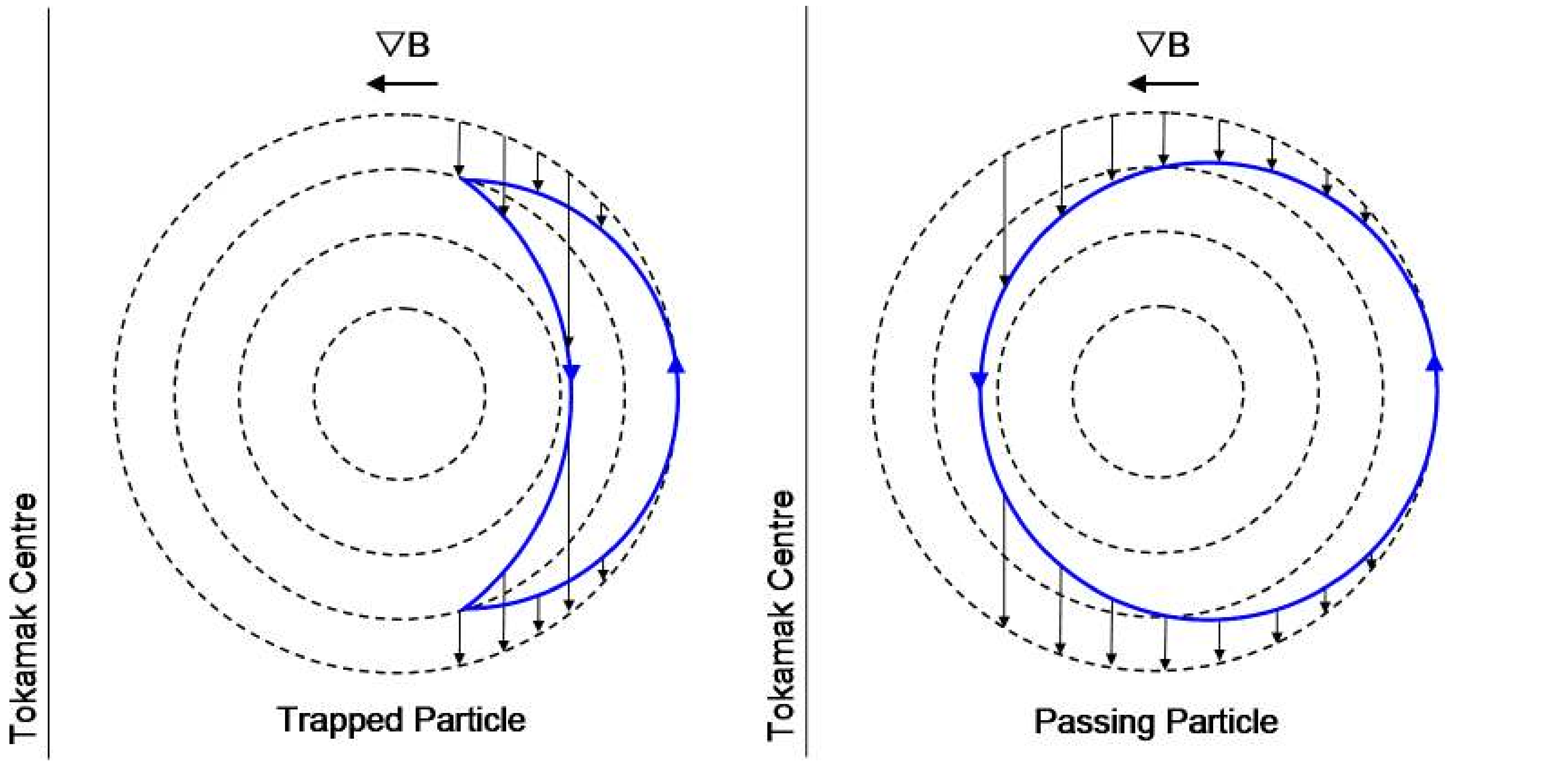
Banana Orbits



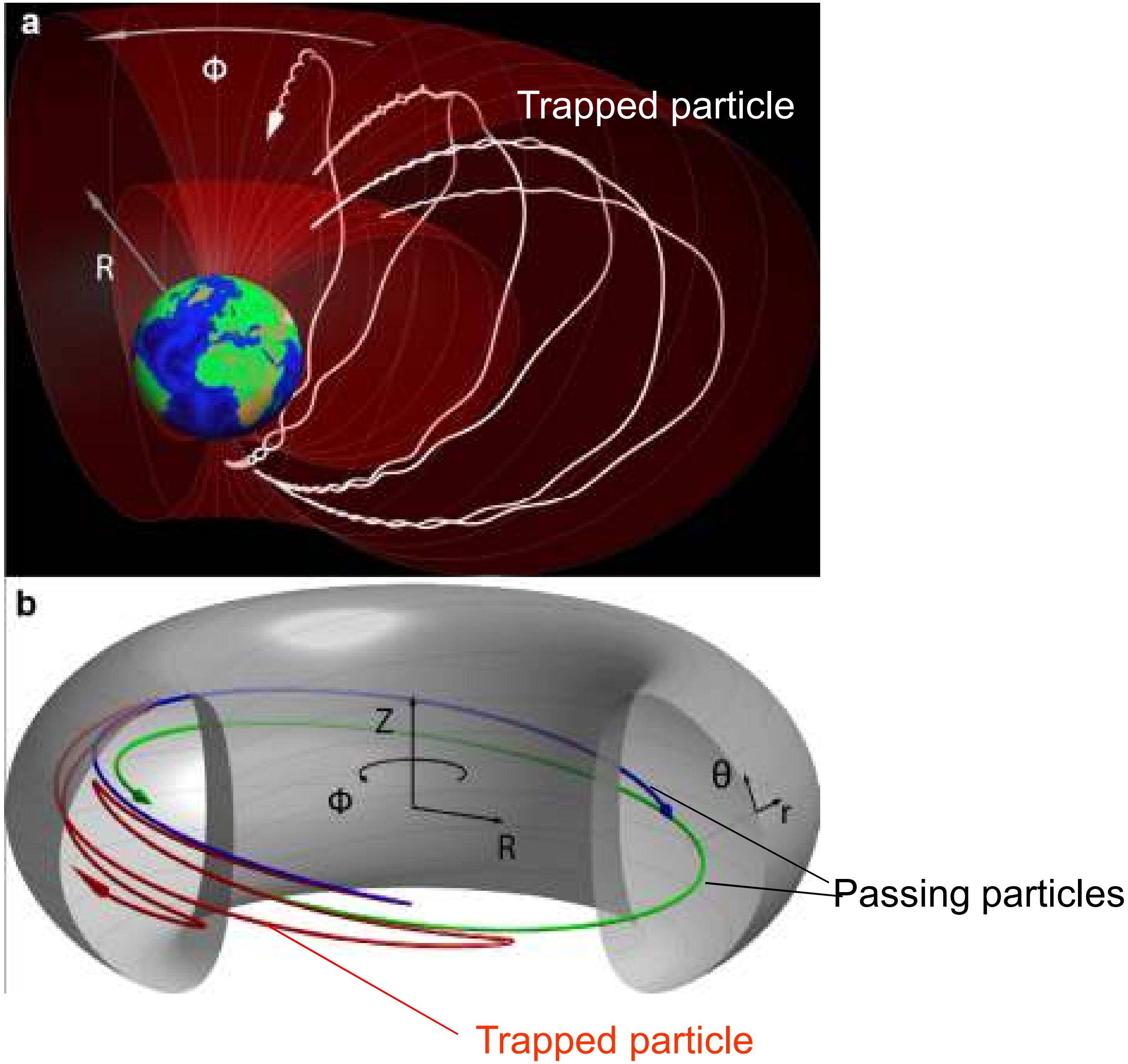
Various natural frequencies associated with particle motion

Particle Orbits

- All particles experience vertical ∇B drift but don't go anywhere!



Particle orbits in magnetic geometry

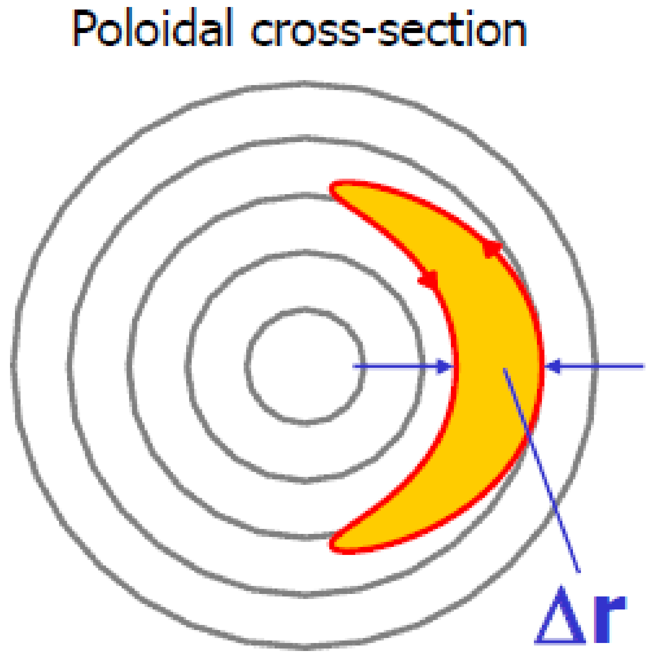


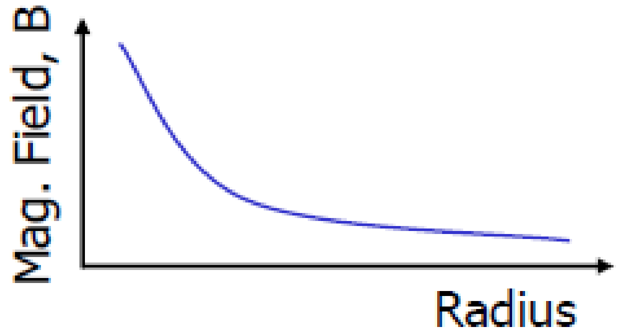
In a tokamak,
two kinds of confined particles exist:
-trapped
-passing

Source: Graves,
Nature Commun. 2012

Confinement of fast ions

- **Require orbit width less than minor radius**
  - $\Delta r << a \Rightarrow$ *Build big devices*
  - $\Delta r = mv_{||}/eB_\theta$
    $= 2\pi a\, mv_{||}/(e\mu_0 I_p)$
  - $\Rightarrow I_p > 1.5$ MA
  - $\Rightarrow$ *Build with high current!*





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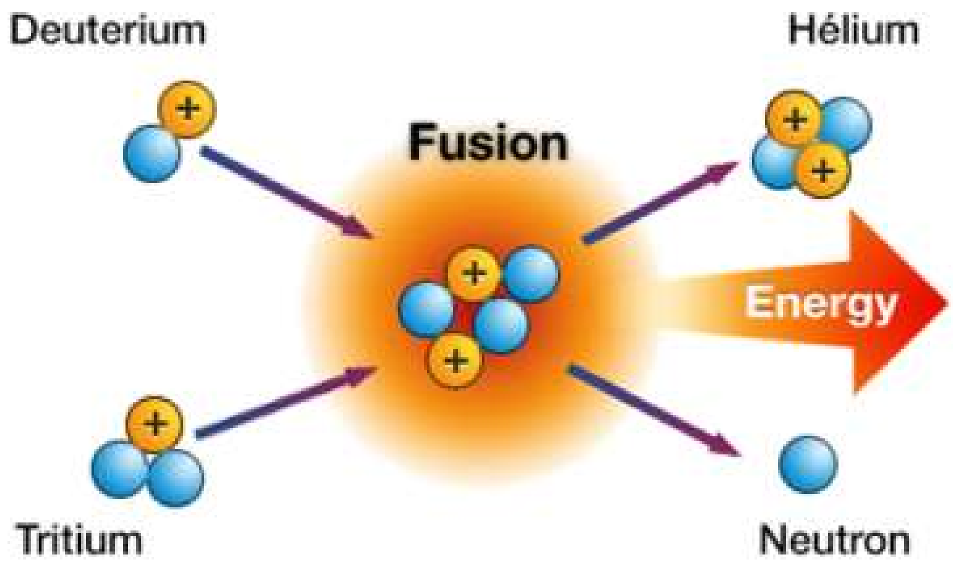
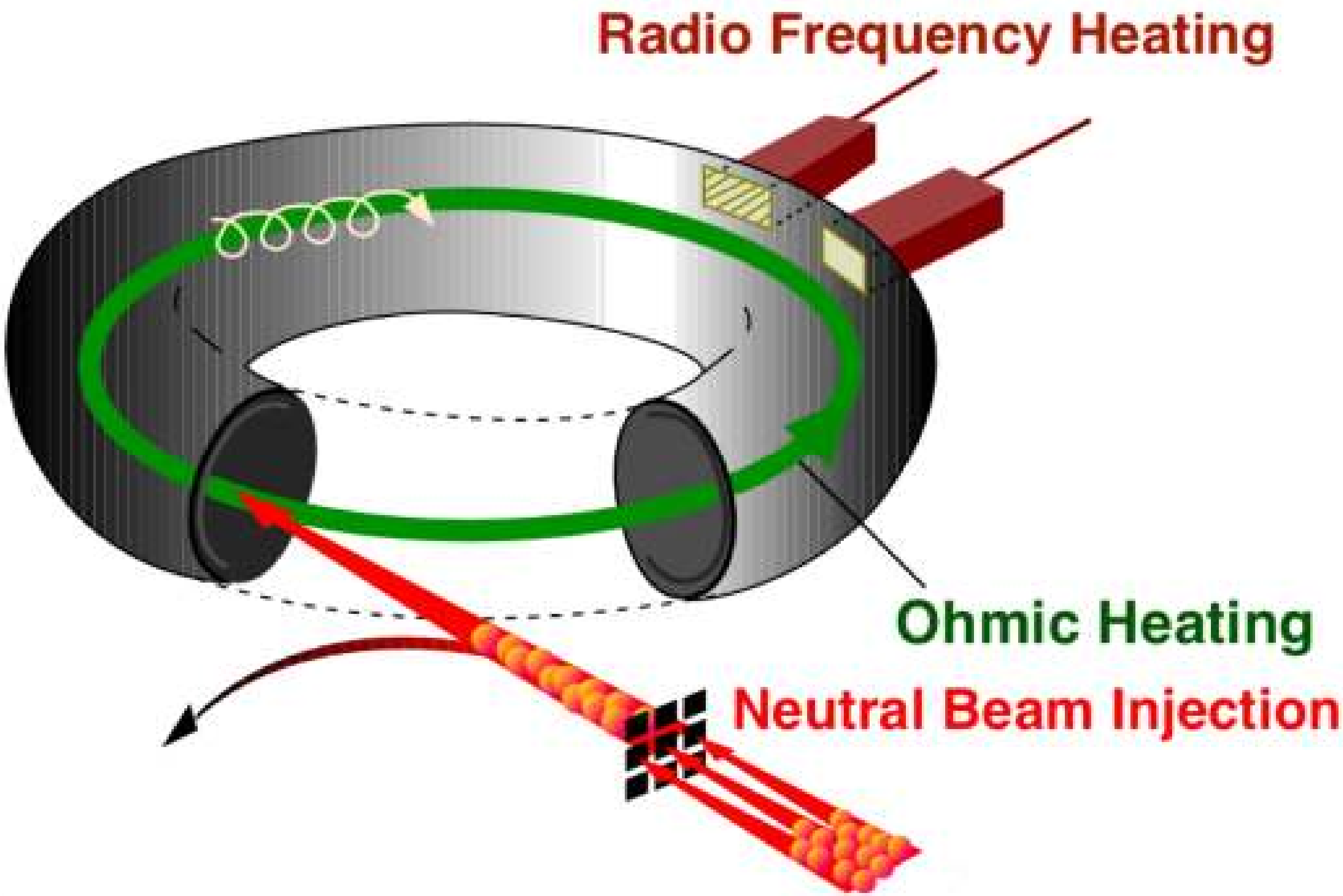
Thermonuclear Fusion

- In a burning plasma, the primary source of fast particles is from the fusion reactions directly, which produce 3.52MeV alpha particles



Heating the plasma

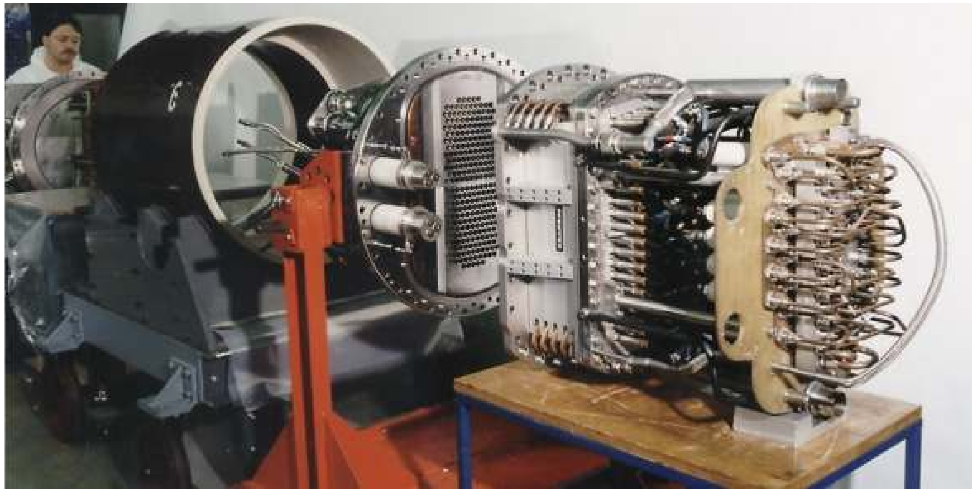
- However we need to heat the plasma to hot enough temperatures to maximise the reaction rate



Neutral Beam Injection

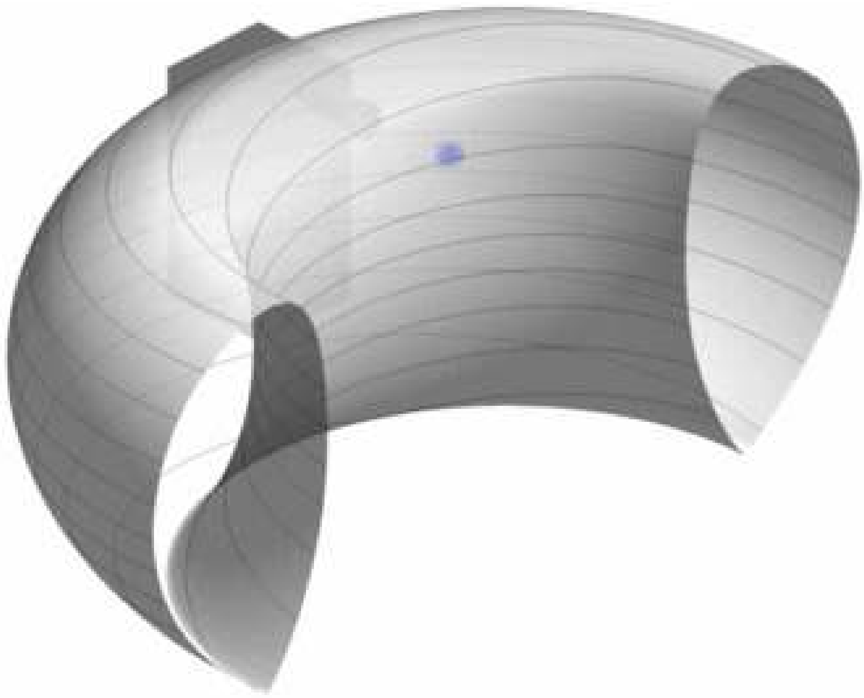
- Energetic neutral particles are fired in a beam into the plasma, carrying a large uni-directional kinetic energy
- In the plasma, beam atoms lose electrons due to collisions, i.e. they get ionised and captured by the B-field
- These new ions are much faster than average plasma particles. Ion-ion, ion-electron and electron-electron collisions mean the group velocity of beam atoms increases mean velocity of bulk plasma
- In JET, the neutral particles are ~120keV and total up to 30MW. In ITER they will be up to 1MeV

Neutral Beam Injector

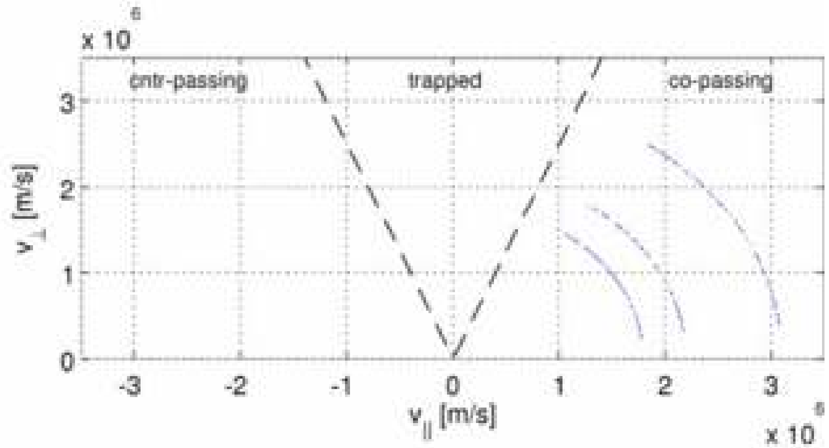


NBI Fast particles

- Simulation of fast ions born due to NBI:



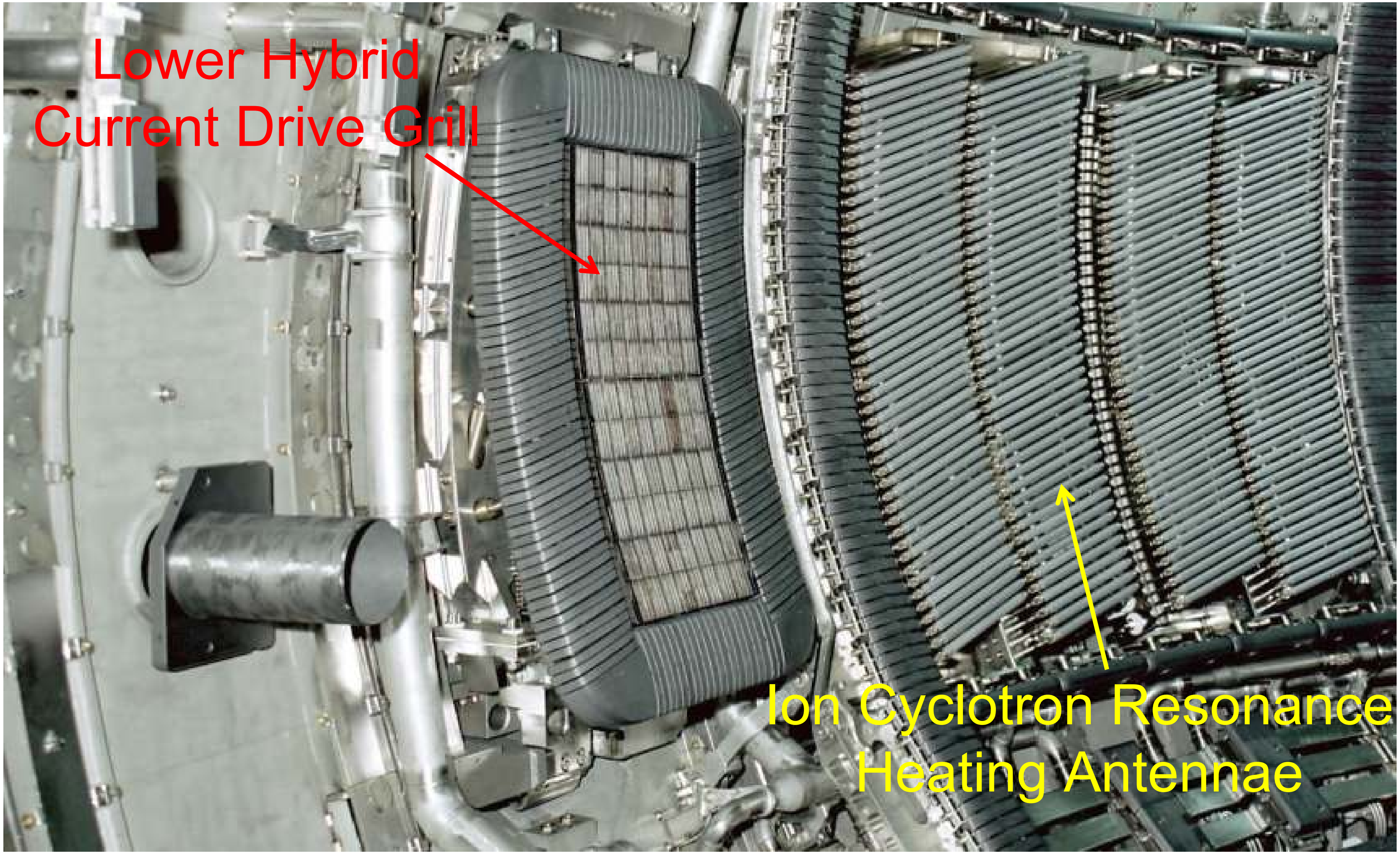
Mattia Albergante



Radio Frequency Heating

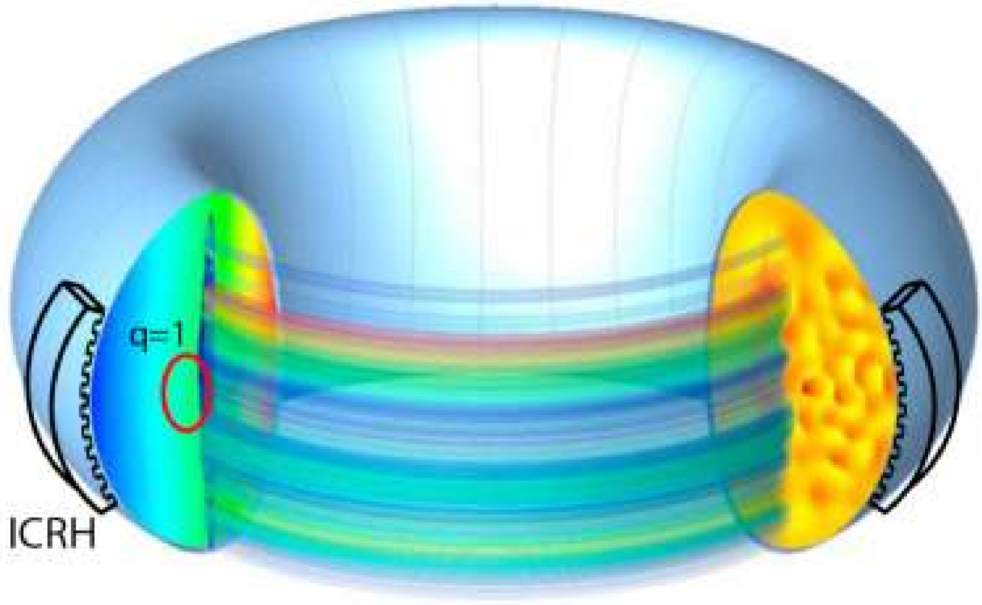
- Plasmas can host sound, electrostatic, magnetic and electromagnetic waves.
- Depending on local parameters, plasma waves can propagate, get dumped (absorbed), be reflected or even converted to different plasma waves
- Wave absorption is extremely efficient if the wave frequency is resonant with some of the fundamental oscillations of the medium
- Get effective absorption at ion/electron cyclotron resonance layers, which are largely determined by magnetic field (remember $\Omega_c = \frac{eB}{M}$)

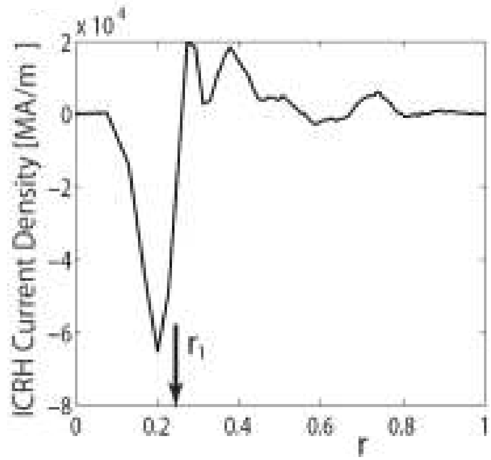
Radio Frequency Antennae

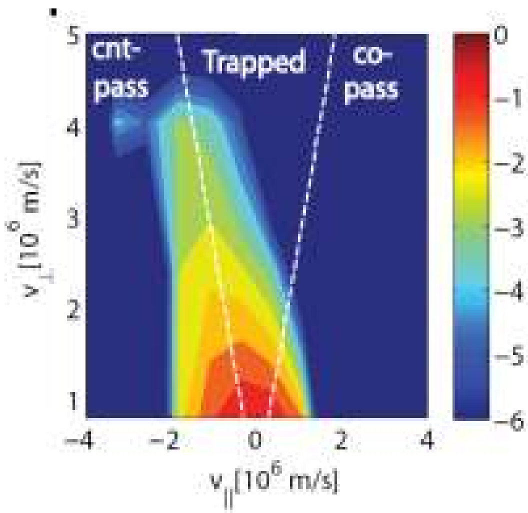


ICRH Fast Particles

- Simulation of fast ions born due to ion cyclotron resonance heating:







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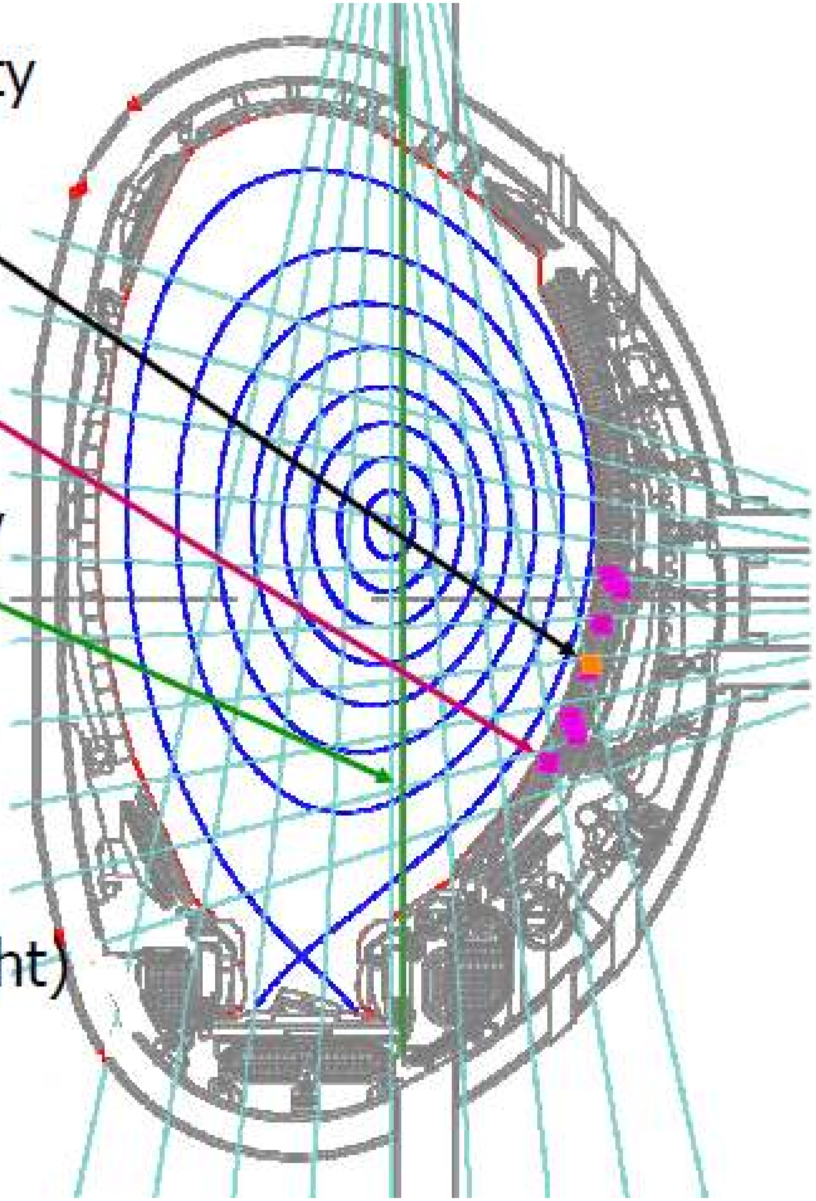
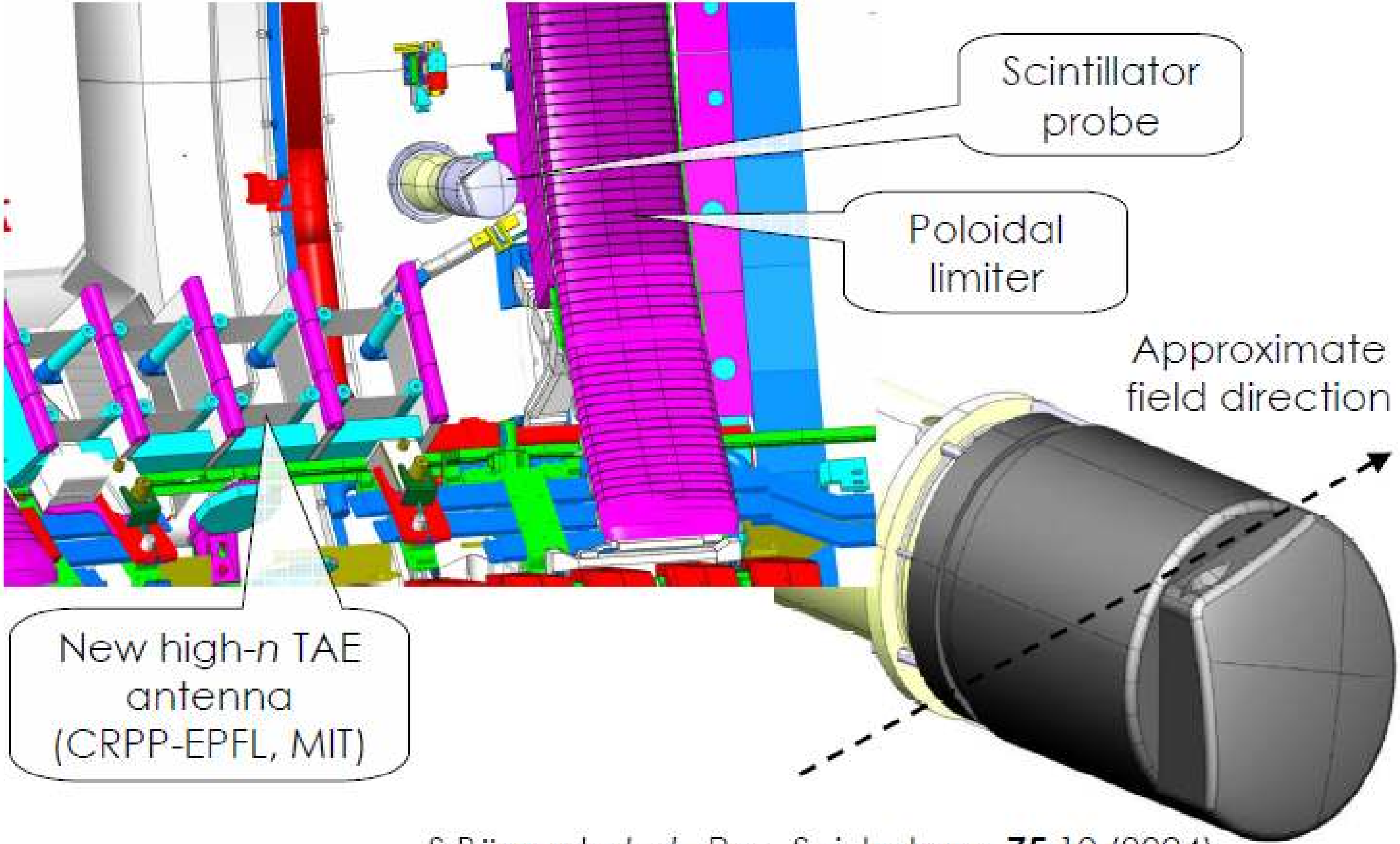
JET fast ion diagnostics

- **Scintillator probe** provides velocity distribution of lost fast ions
- **Faraday cups** give spatial and energy distribution of lost ions
- **Neutral Particle Analyser** energy distribution of confined fast ions
- **γ-ray tomography** (19 channels) and **γ-ray spectroscopy** (2 lines of sight) for energy distribution



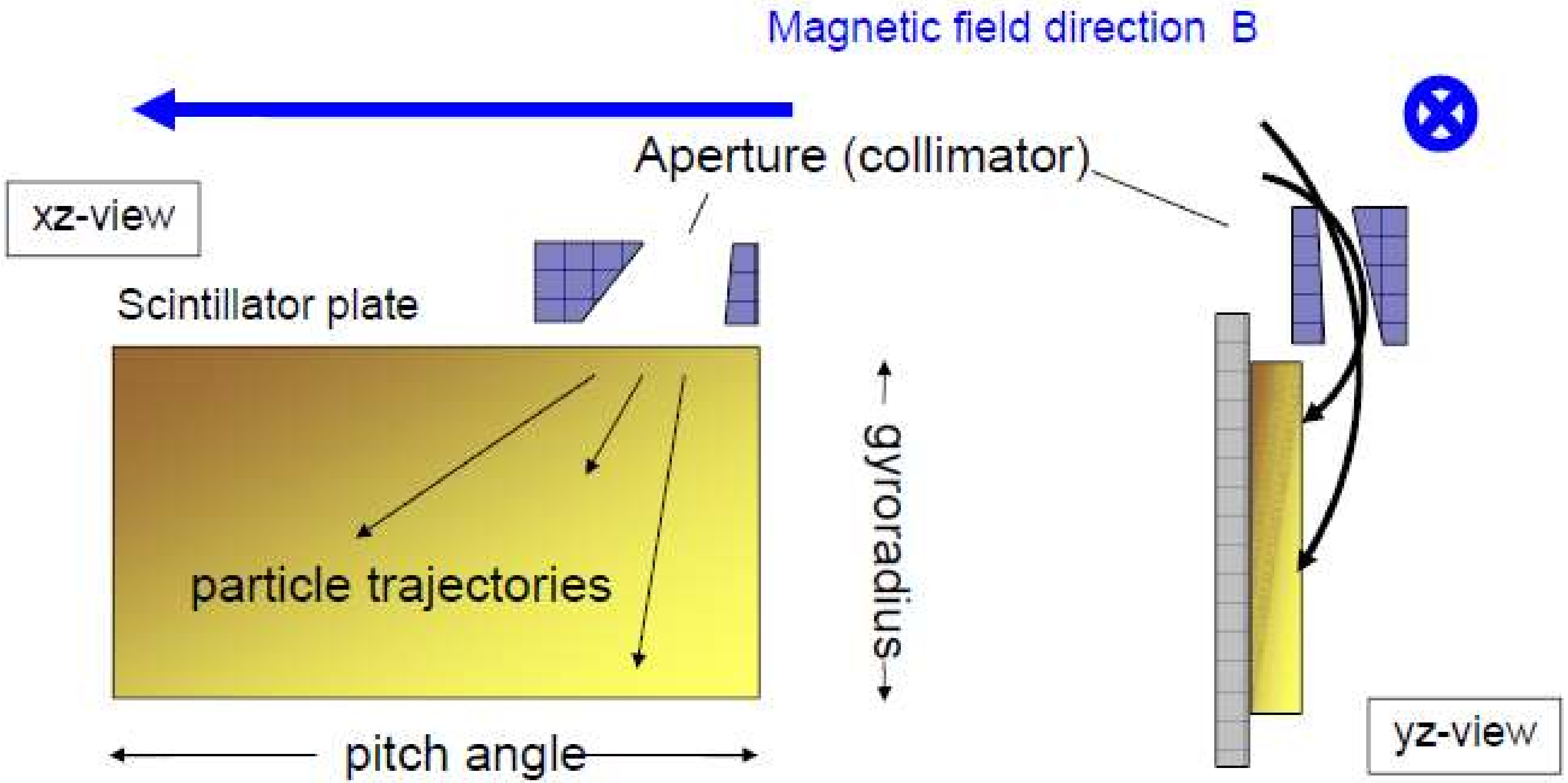
Example: Scintillator Probe



S Bäumel *et al.*, Rev. Sci. Instrum. **75** 10 (2004)

Example: Scintillator Probe

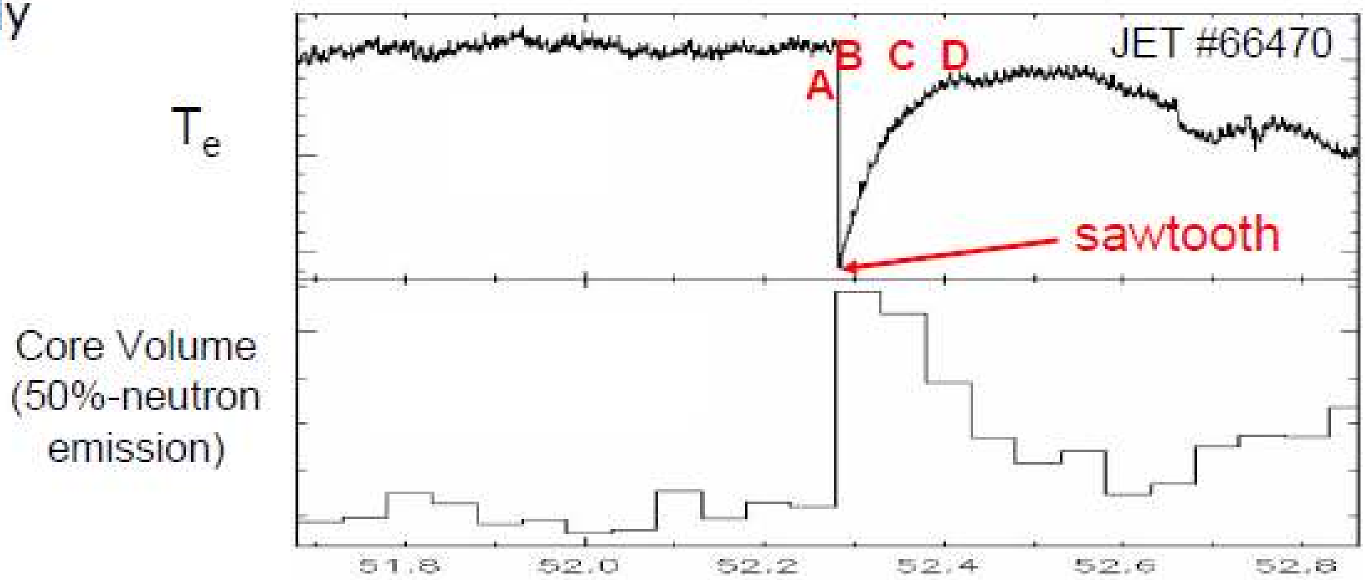
Probe head collimator and magnetic field form a magnetic spectrometer

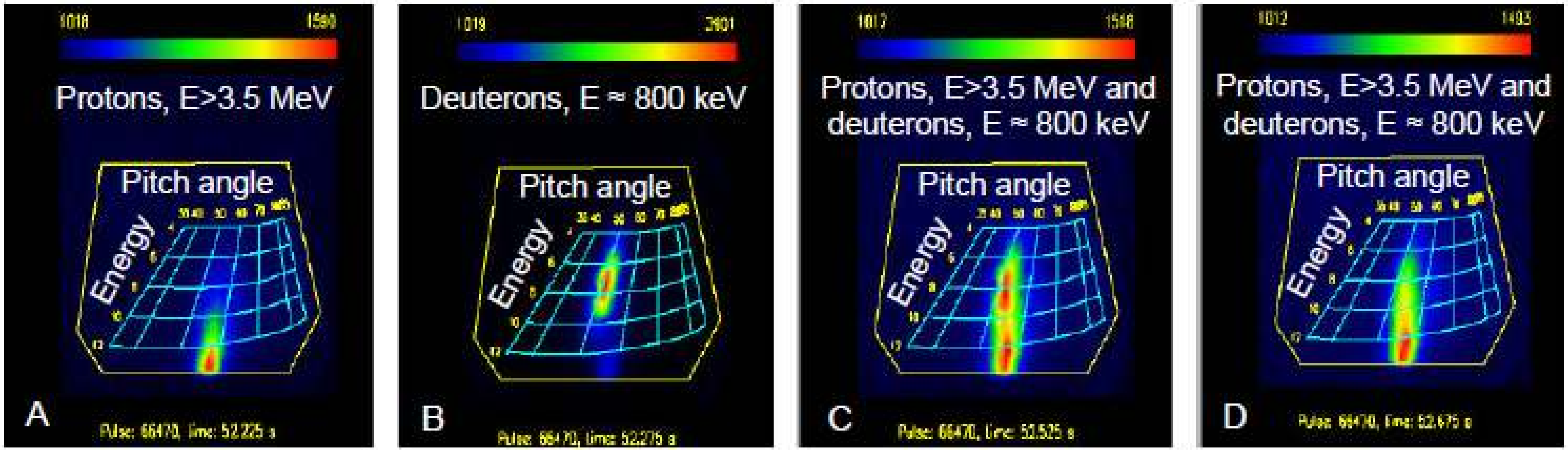


Scintillator probe converts pitch-angle / energy distribution into 2D picture

Measuring losses during sawteeth

V. Kiptily

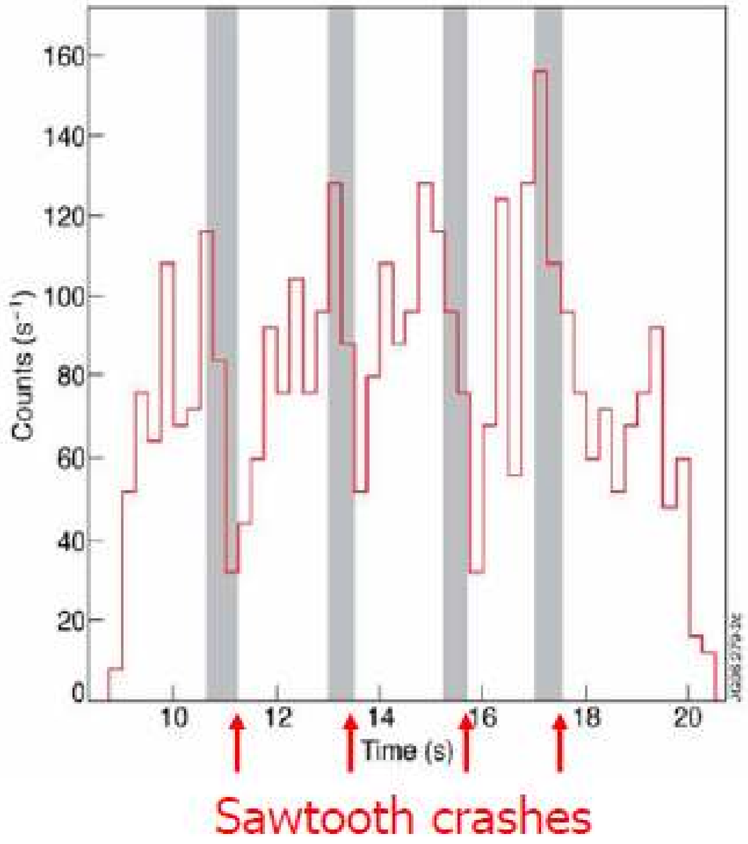




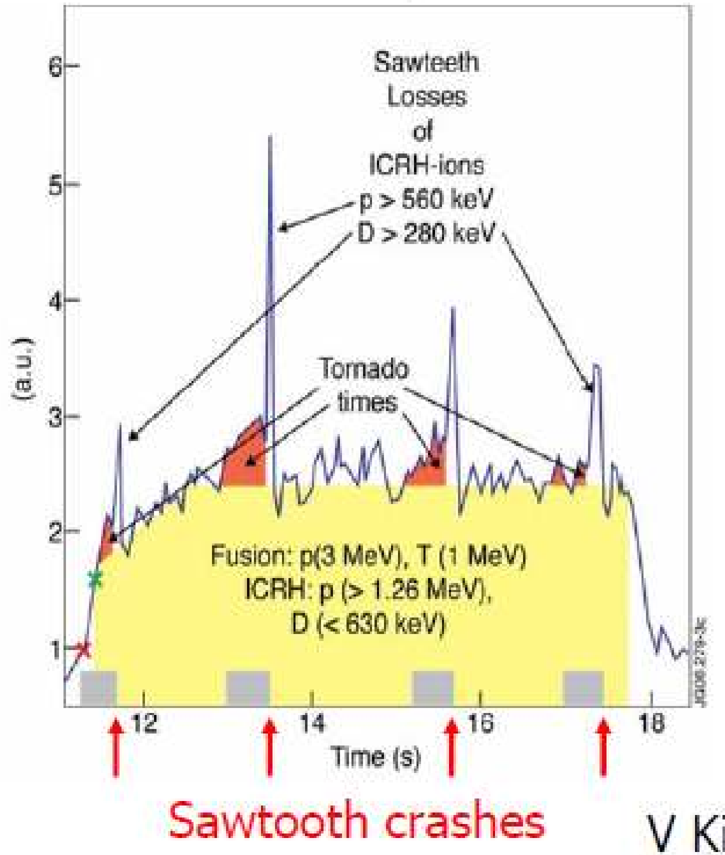
Tornado Modes causing losses

- Tornado modes (TAEs within q=1) redistribute fast ions, which then leads to sawtooth crashes

3.1-MeV γ-ray emission from $^{12}C(d,p\gamma)^{13}C$;
Deuterons with E>500 keV



Scintillator probe



V Kiptily

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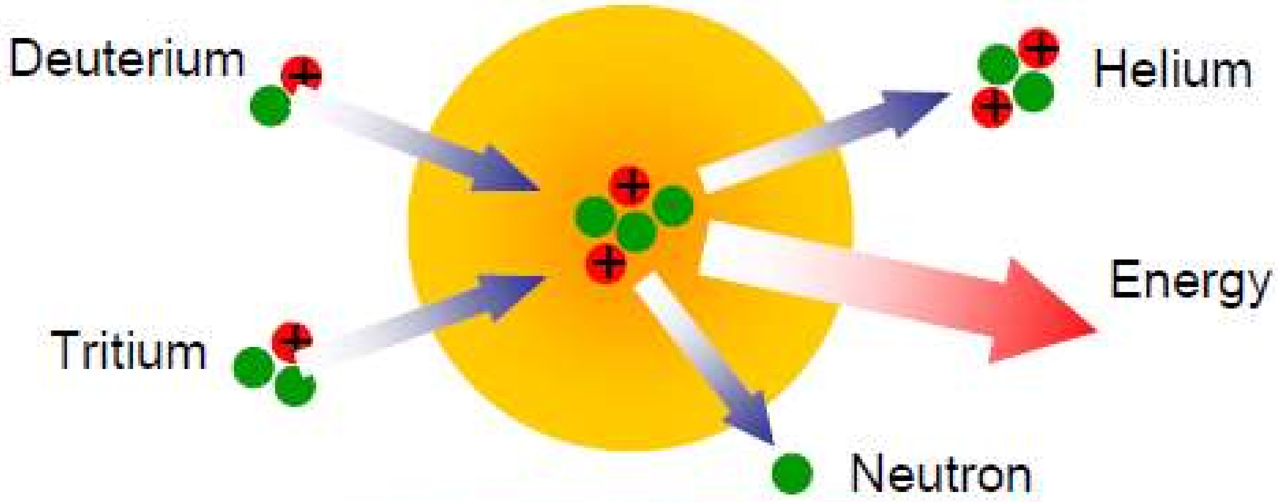
Burning Plasmas

- New physics element in burning plasmas:
  - Plasma is self-heated by fusion alpha particles



$v_{Ti} \ll v_A < v_\alpha \ll v_{Te}$

ITER parameters

$v_{Ti} = 0.9\times10^6$ m/s

$v_A = 8\times10^6$ m/s

$v_\alpha = 12\times10^6$ m/s

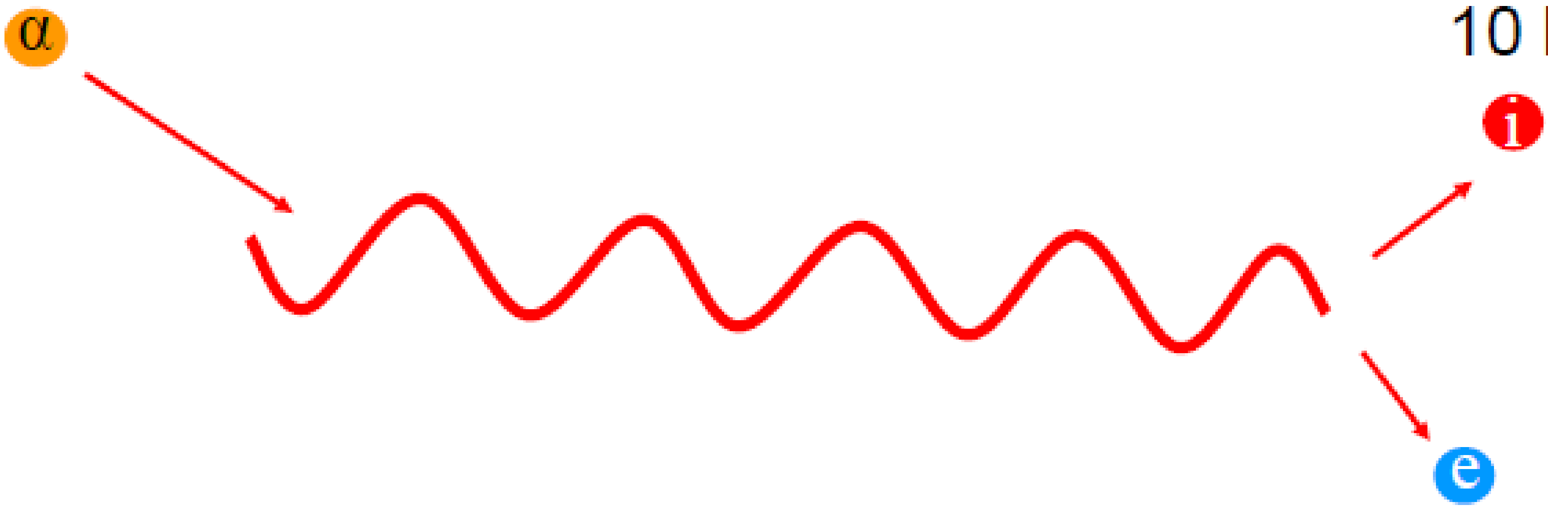
$v_{Te} = 59\times10^6$ m/s

Alfven waves and alphas

Alfvén wave is *very* weakly damped by background plasma

3.5 MeV

10 keV

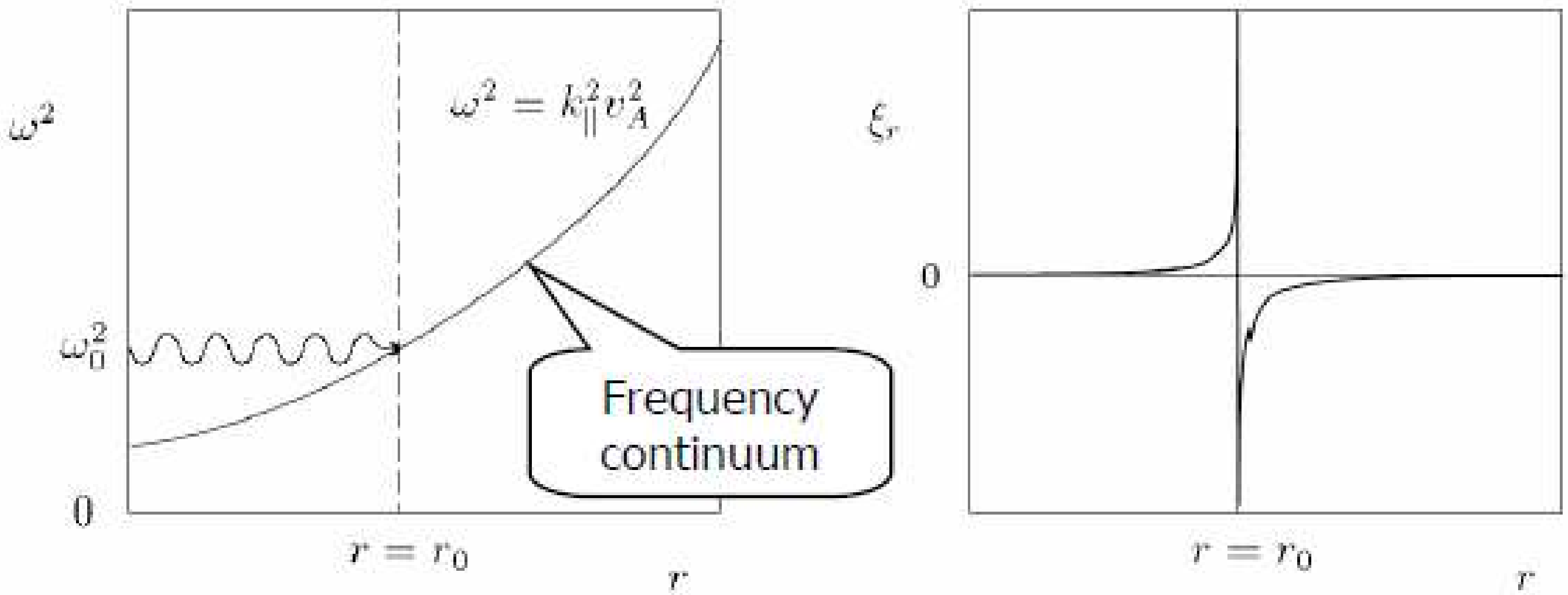


10 keV

Fusion products (αs) interact with Alfvén waves *much* better than thermal plasma

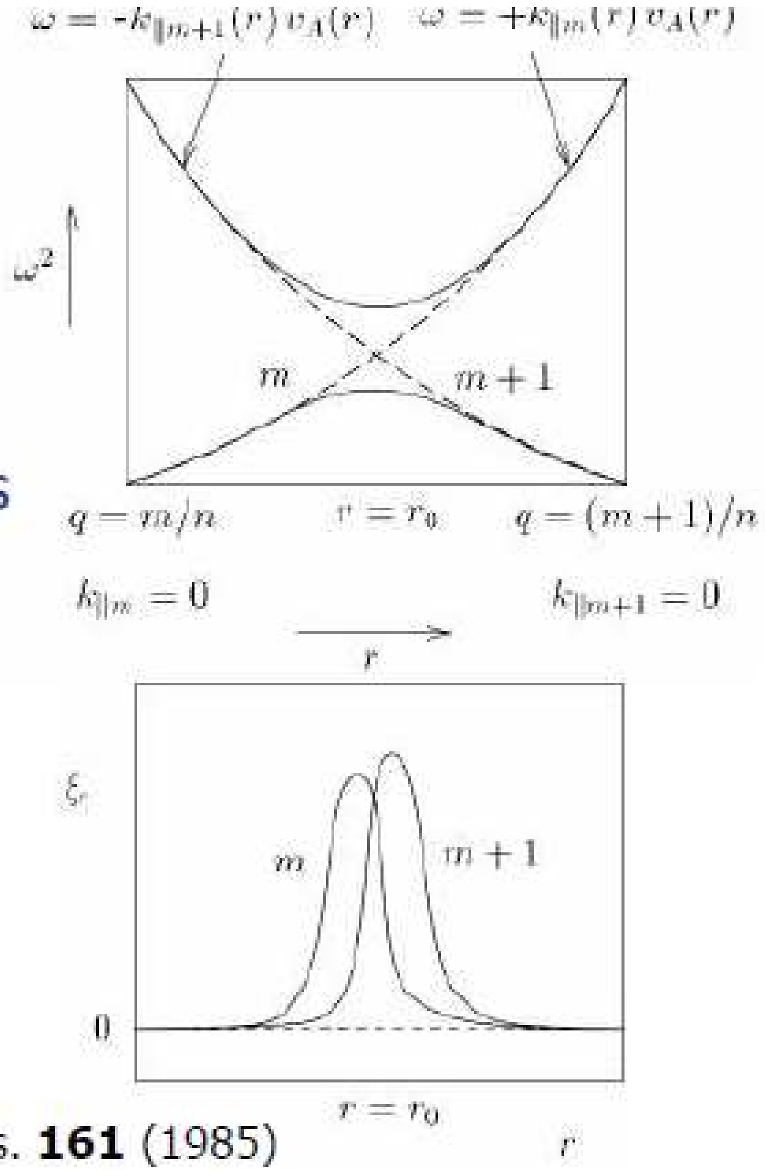
Alfven Waves

- Analogous to waves on a string
  - $v_A = B/\sqrt{(\mu_0 m_i n_i)}$
  - $\omega^2 = \omega_A^2(r) \equiv k_\parallel^2 v_A^2(r)$
  - Form continuum of waves in inhomogeneous plasma
  - Damped due to phase mixing with neighbouring waves



Alfven Waves in a Tokamak

- Tokamak plasma:
  - Fourier decomposition:
    - $A \sim \exp[i(n\phi - m\theta - \omega t)]$
  - $B \approx B_0 R_0 / R \approx B_0 (1 - r/R_0 \cos\theta)$
  - Neighbouring poloidal harmonics couple due to toroidicity
  - Gaps in frequency continuum
  - Toroidal Alfvén Eigenmodes (TAE) exist in frequency gap
    - Weakly damped
  - $f_{TAE} \sim v_A/(2qR)$

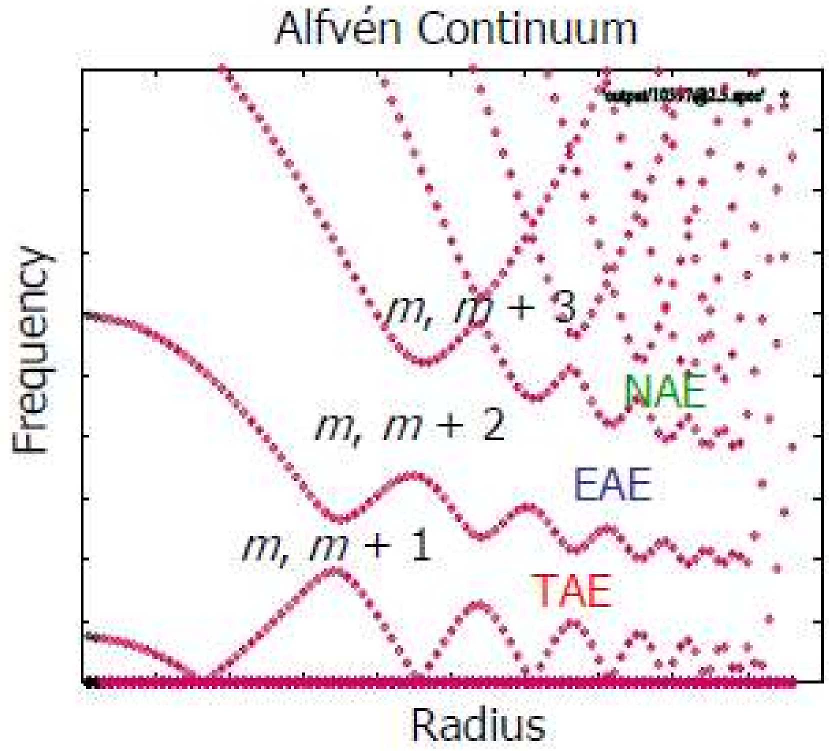


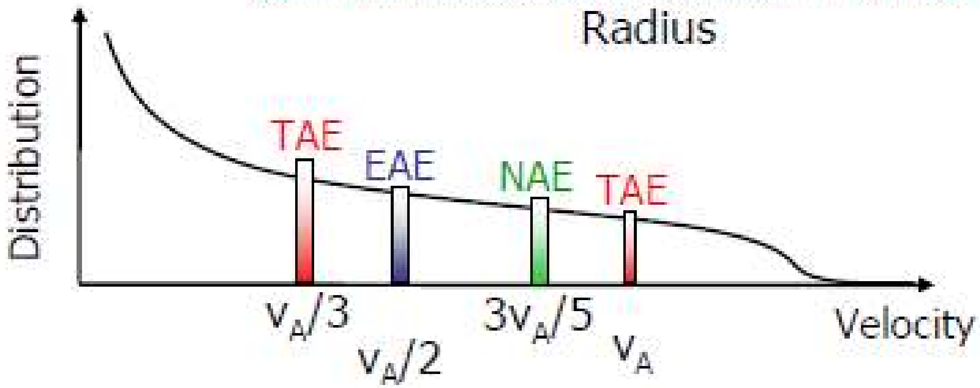
C. Z. Cheng, Liu Chen and M. S. Chance, Ann. Phys. **161** (1985)

- Exist in frequency gaps
- Comprise of two primary harmonics, m and $m + L$
  - **Wave-particle resonance condition:**
    $\omega - n\,\omega_{\phi} + (m \pm 1)\,\omega_{\theta} = 0$

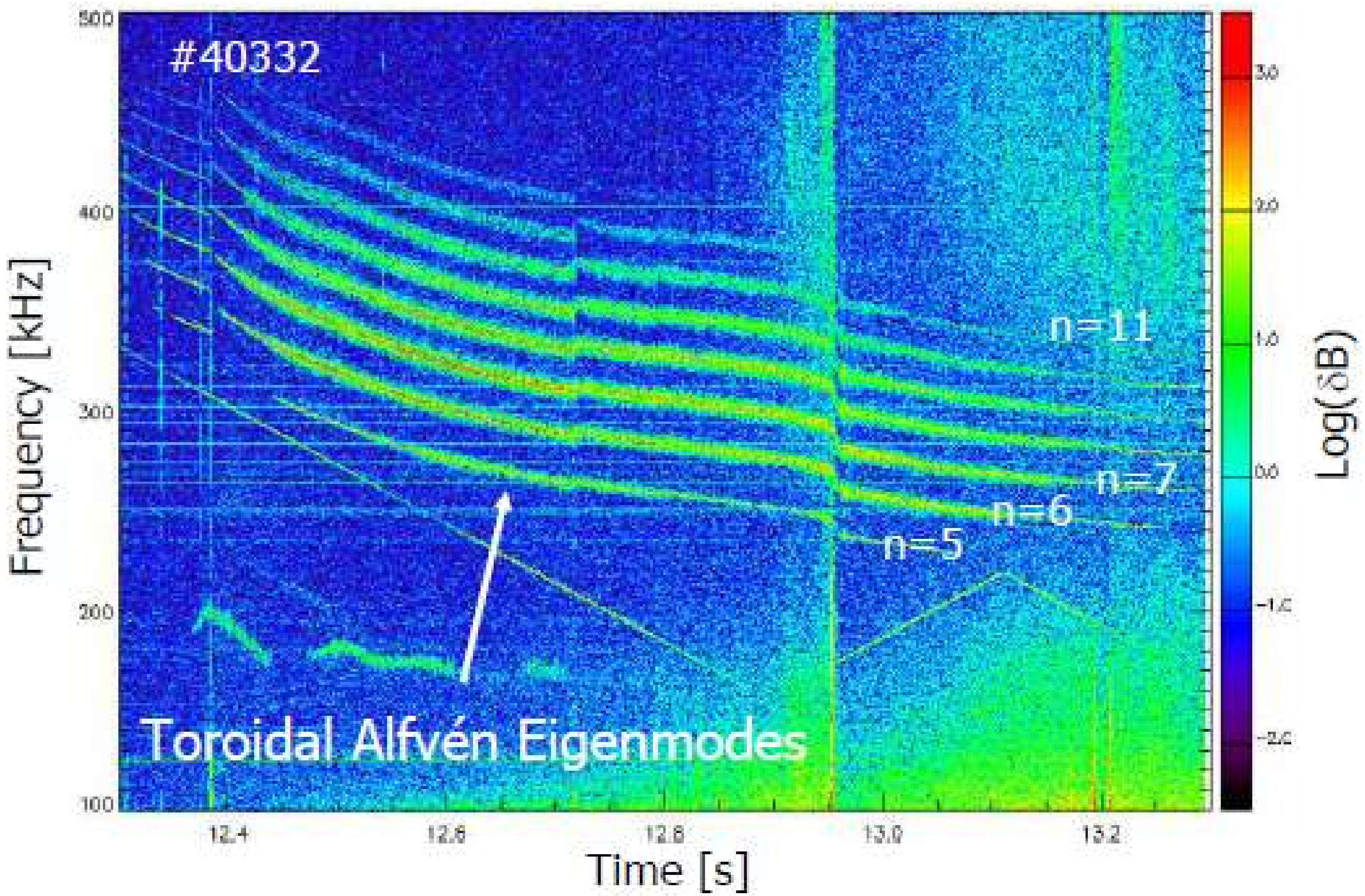
$$\boxed{\mathbf{v}_{||} = \pm \mathbf{L}/(2 \pm \mathbf{L})\, \mathbf{v}_A}$$

  - **TAE**: L = 1
  - **EAE**: L = 2
  - **NAE**: L = 3





Example: TAE driven by ICRH in JET

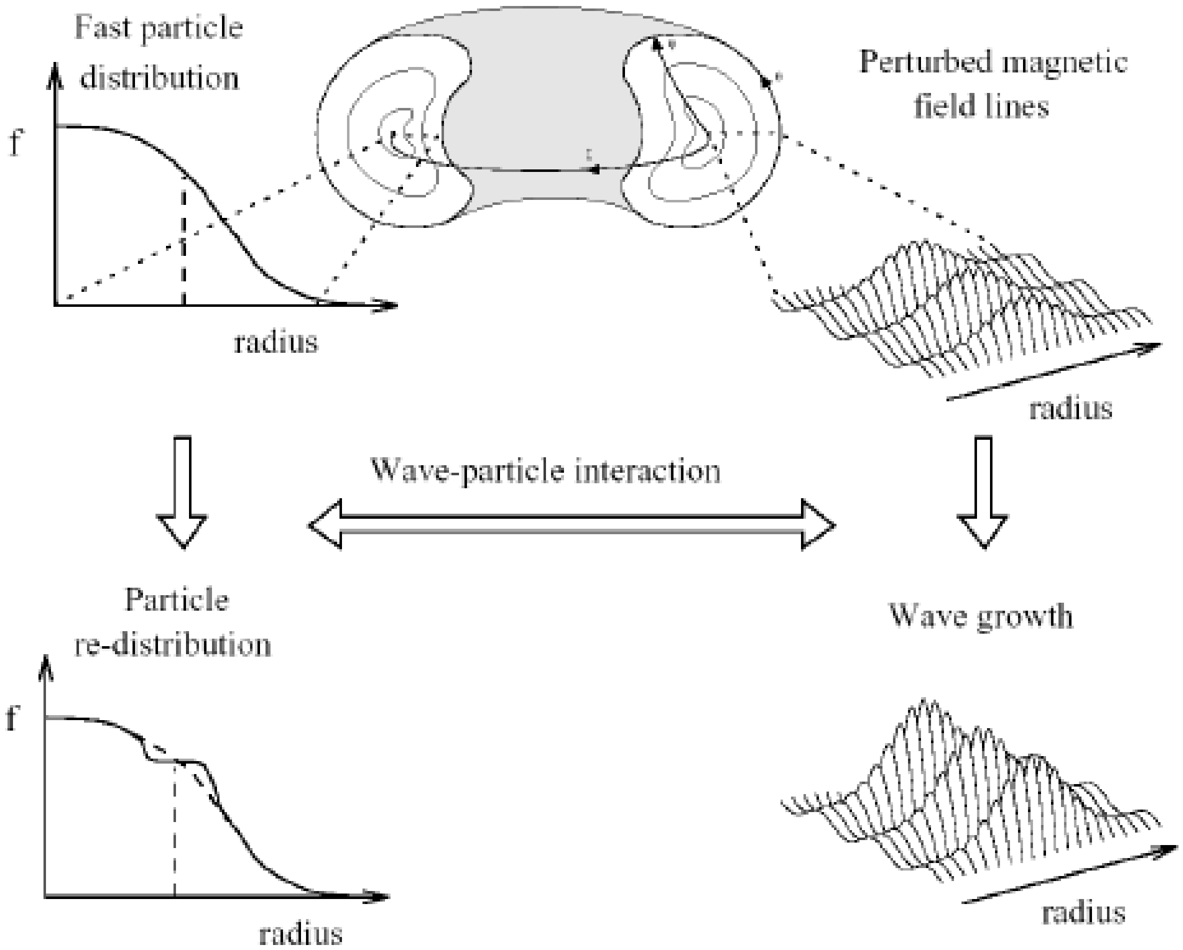


- TAE have constant amplitude and fine frequency splitting

$\Rightarrow$ **Nonlinear effect**

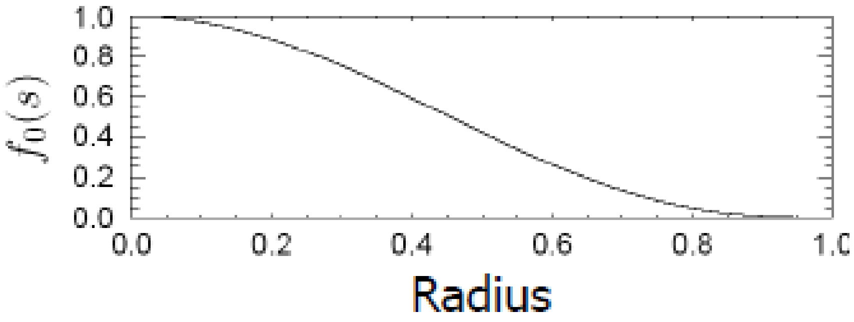
Wave-Particle Interaction

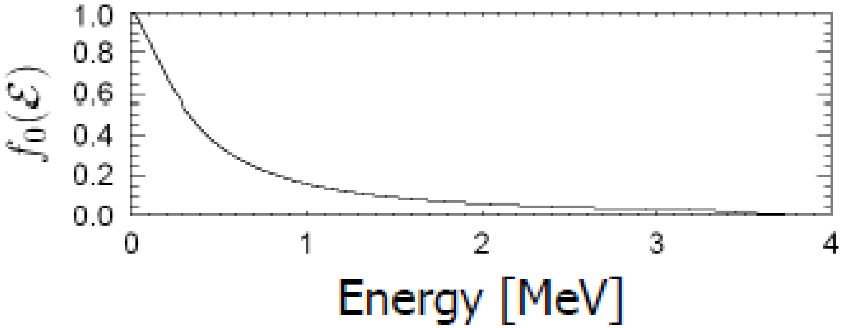
- **Linearly unstable AE grows and saturates**
  - Nonlinear wave-particle interaction
  - Wave redistributes fast ions and removes drive



Fast Particle Energy Release

- **Collective instabilities**
  - Fast particle gradients act as source of free energy
    - Non-Maxwellian distribution
  - $\gamma \sim \omega\, \partial f/\partial E - n\, \partial f/\partial P_\phi$
  - Negative radial gradient
    $\Rightarrow$ *Drive (n>0)*
  - Negative energy gradient
    $\Rightarrow$ *Damping*





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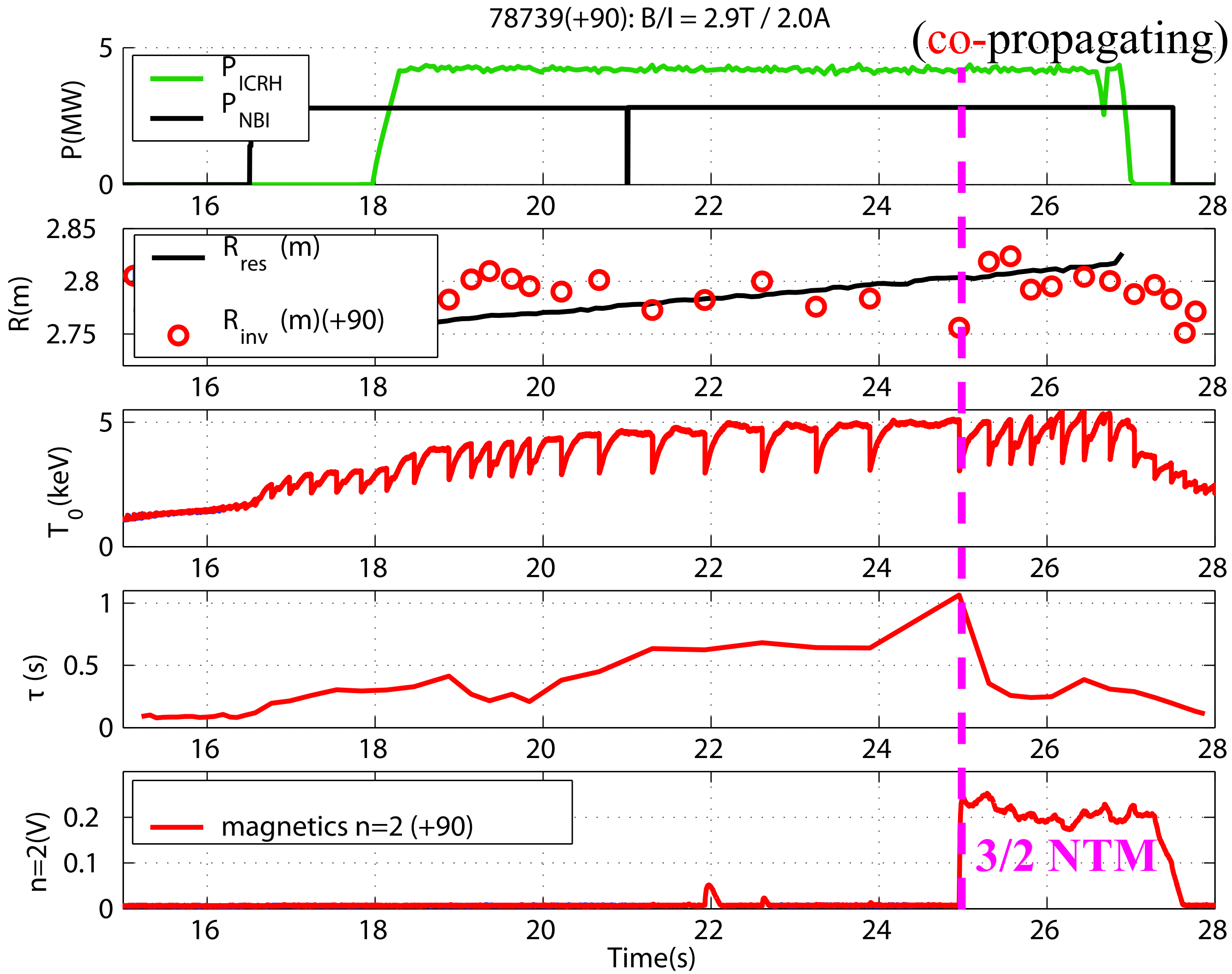
Effect of ICRH on sawteeth

- Fast ion populations inside q=1 leads to very long sawtooth period, which increases likelihood of triggering NTMs

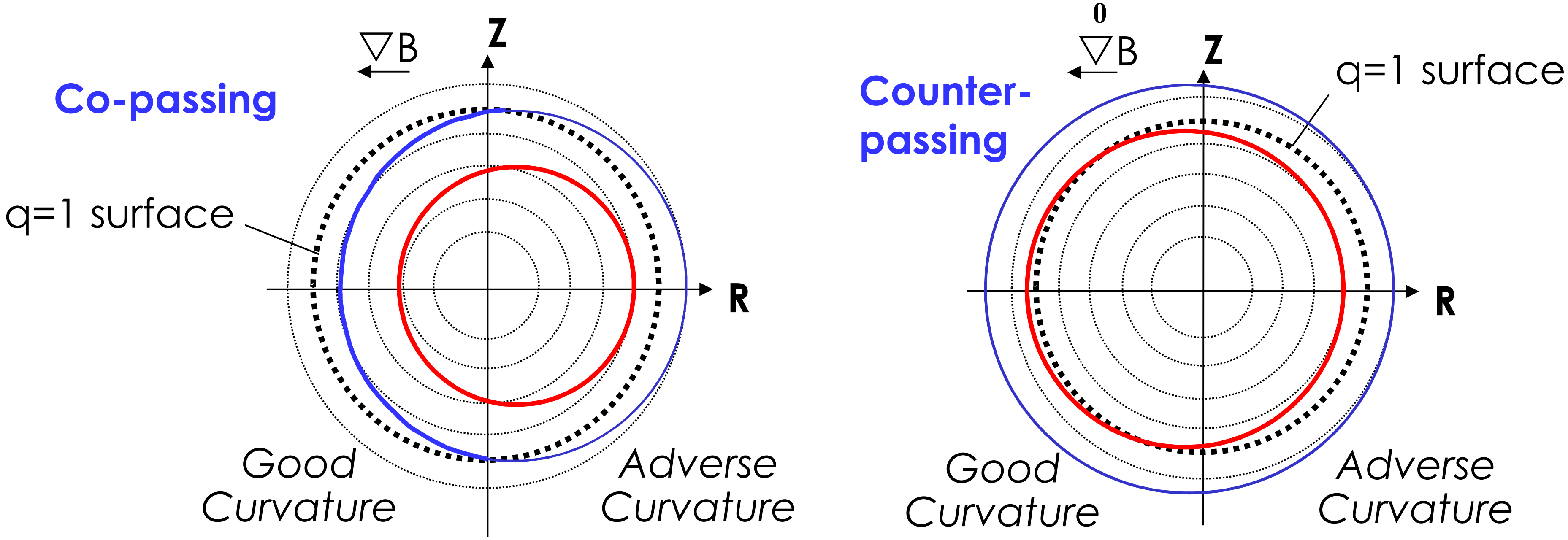


L-mode
β_N=0.8

Graves et al, Nucl Fusion 2010; Nature Comms 2012

Passing Particle Stabilisation Mechanism

δW has a term dependent upon curvature: $$\delta W \sim -\int_0^{r_1} \left(\xi\cdot\nabla\langle P_h\rangle\right)\left(\xi\cdot\kappa\right)dr$$



Co-pass, $\langle P_h\rangle'\|_{r_1} < 0 \rightarrow$ stabilising	Ctr-pass, $\langle P_h\rangle'\|_{r1} < 0 \rightarrow$ destabilising
Co-pass, $\langle P_h\rangle'\|_{r1} > 0 \rightarrow$ destabilising	Ctr-pass, $\langle P_h\rangle'\|_{r1} > 0 \rightarrow$ stabilising

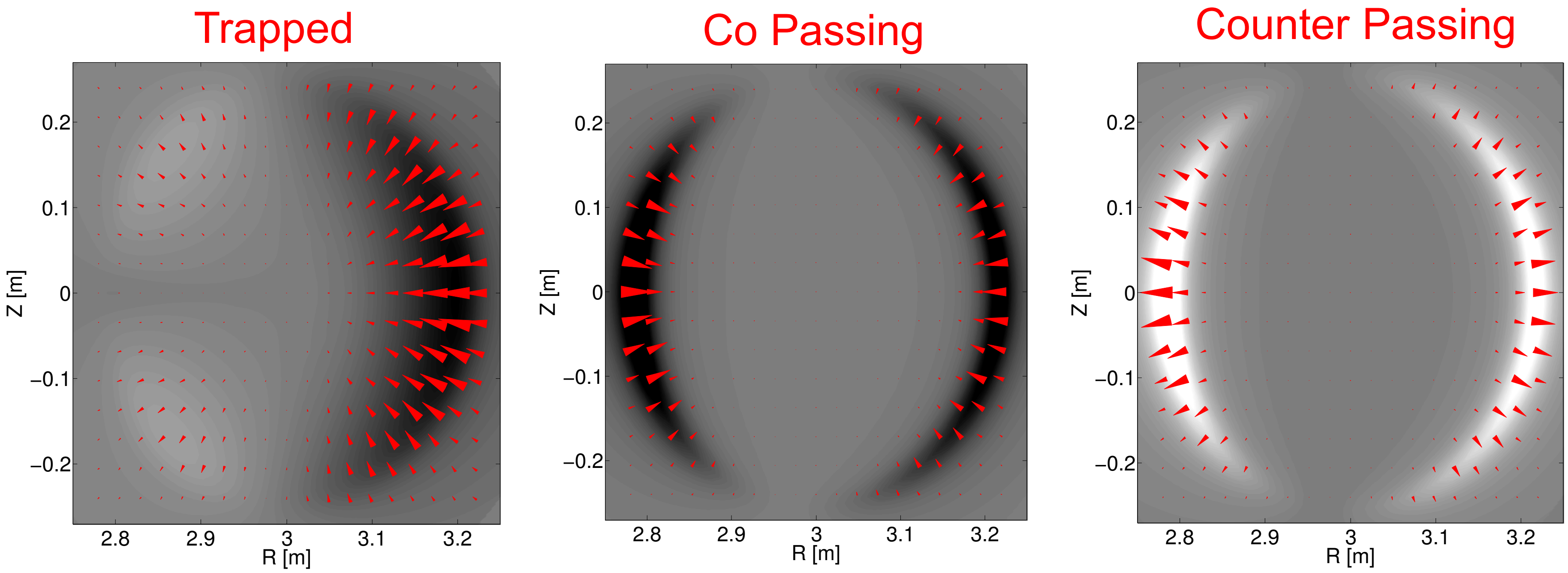
Graves, Phys Rev Lett, 2004

Effect of Passing Energetic Ions

- Highly localised outward pointing force (destabilisation) on both sides of the torus for a case with:

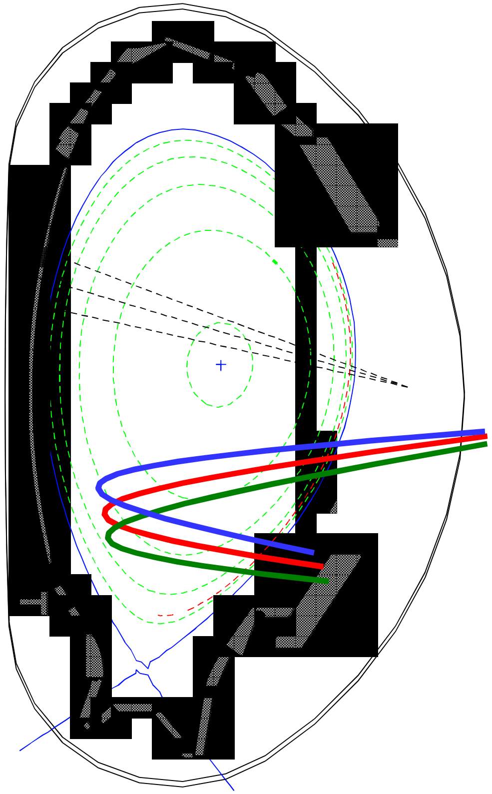
$$F_h(v_{\|}^{+}) < F_h(v_{\|}^{-}) \text{ and } \nabla F_h|_{r_1} < 0$$

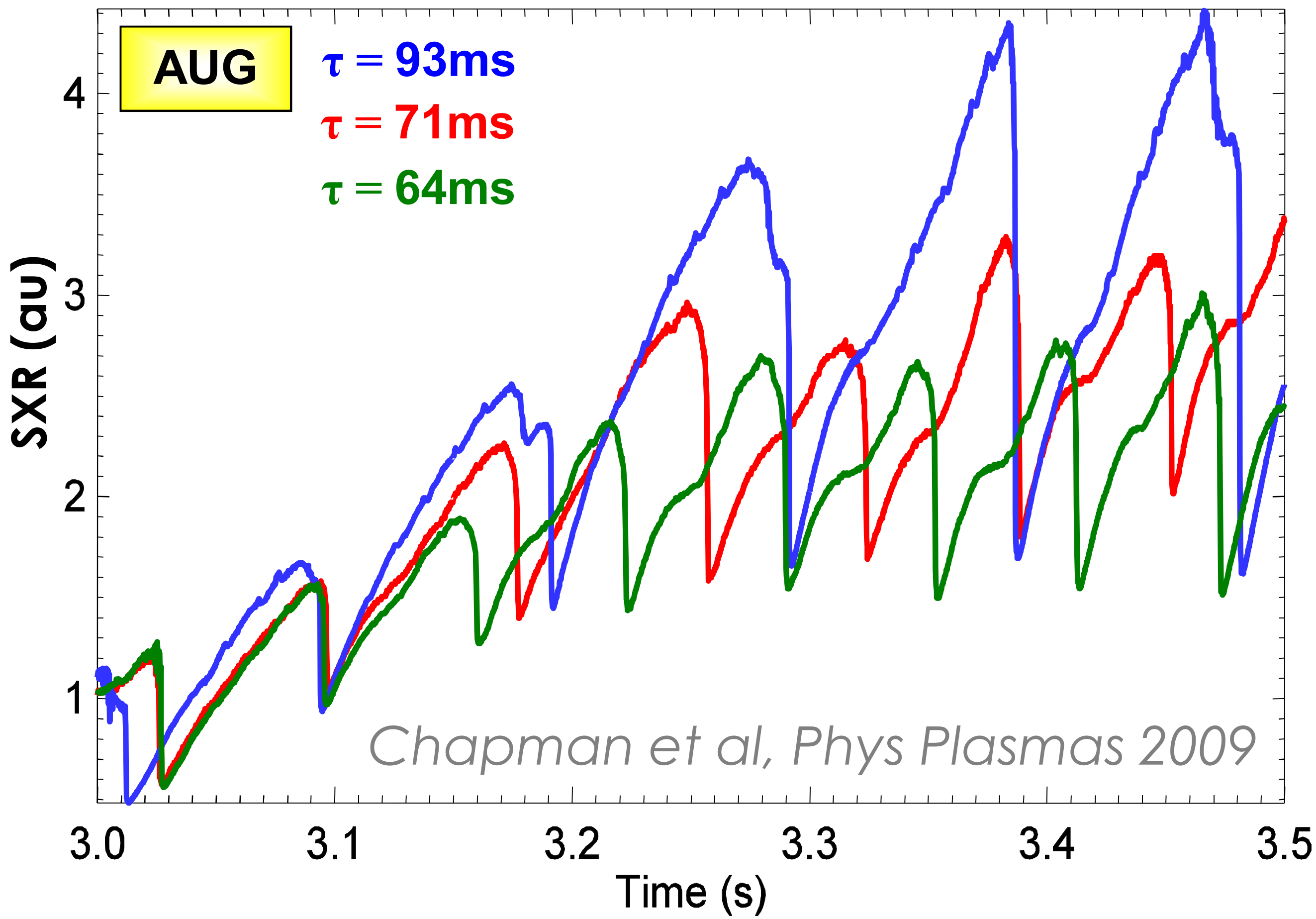
- Obtain an inward pointing force (stabilisation) if one of the two conditions above are reversed
- Effect increases with orbit width



Off-axis NBI Effects in ASDEX Upgrade

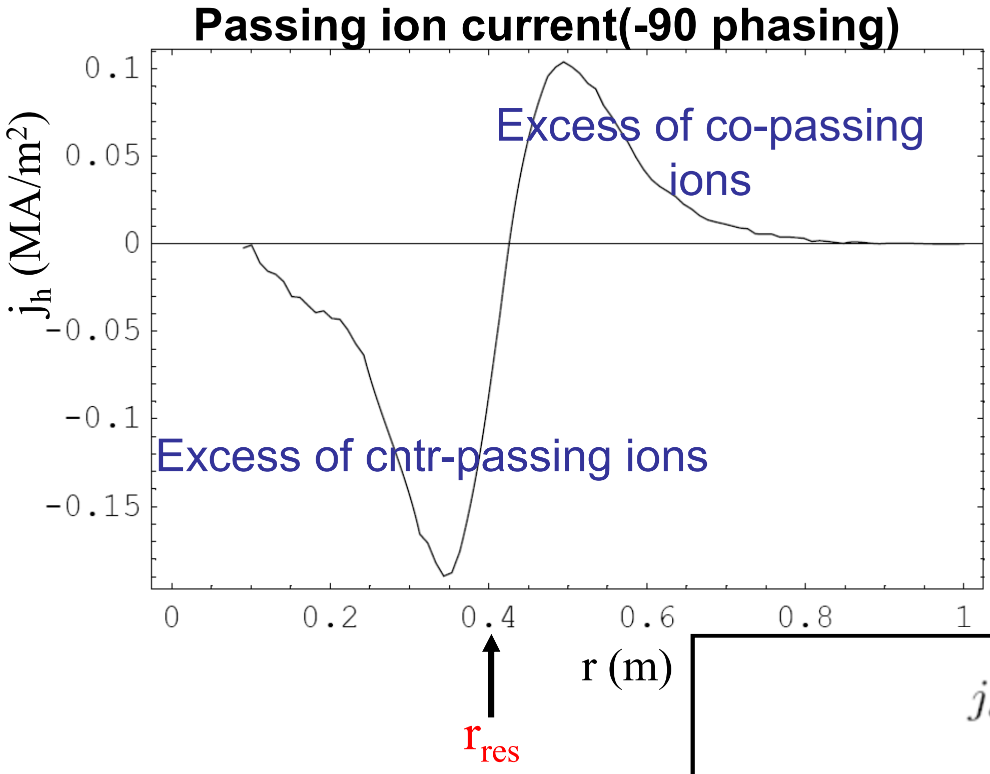
- Off-axis NBI affects sawtooth behaviour
  - As f_h moves further outside q=1, τ_s decreases by ~50%
  - Modelling again shows passing ions dominate over NBCD





Asymmetric F_h in toroidally propagating ICRF Waves

- Theory extended for toroidally propagating ICRF waves
- Parallel velocity asymmetry in F_h seen e.g. in the ICRH current from SELFO



$$j_\phi(r) \approx eZ_h \int dv^3 \sum_\sigma v_\parallel F_h$$

Graves et al, PRL, 2009

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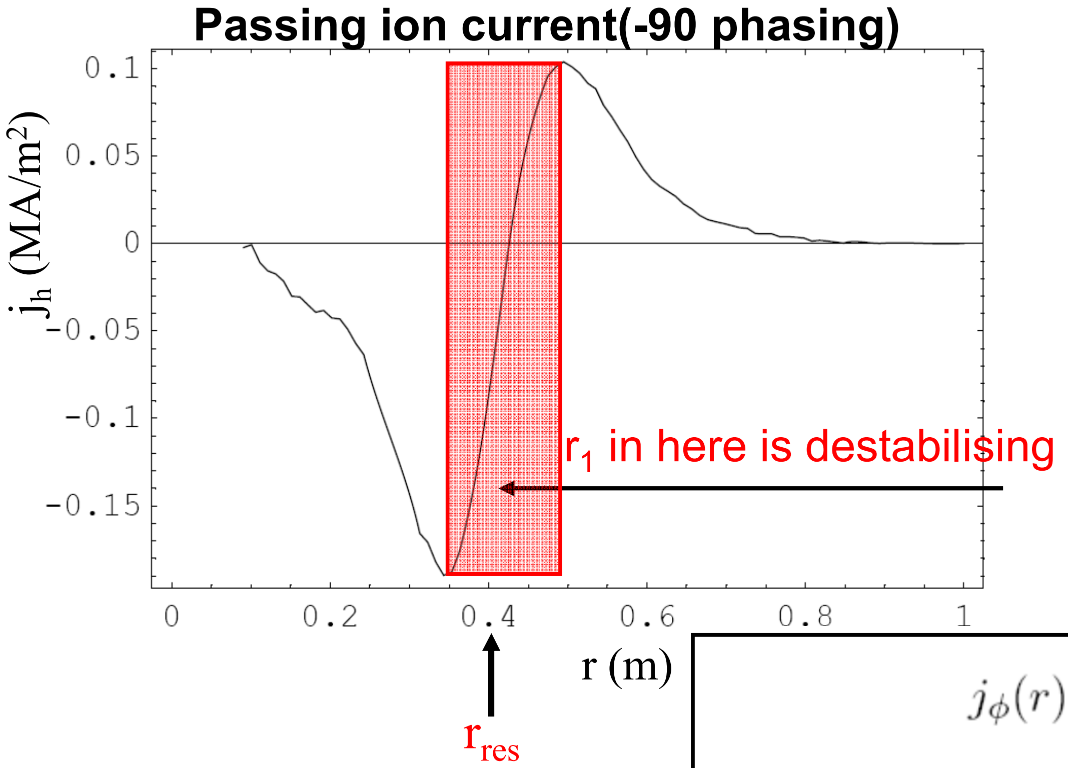

$$j_\phi(r) \approx eZ_h \int dv^3 \sum_\sigma v_\parallel F_h$$

$$\delta W \propto -\int dv^3 \sum_\sigma \left(\frac{v_\perp^2}{2} + v_\parallel^2\right) \Delta_r \frac{\partial F_h}{\partial r}\bigg|_{r_1} \sim -T_h \frac{dj_\phi}{dr}\bigg|_{r_1}$$

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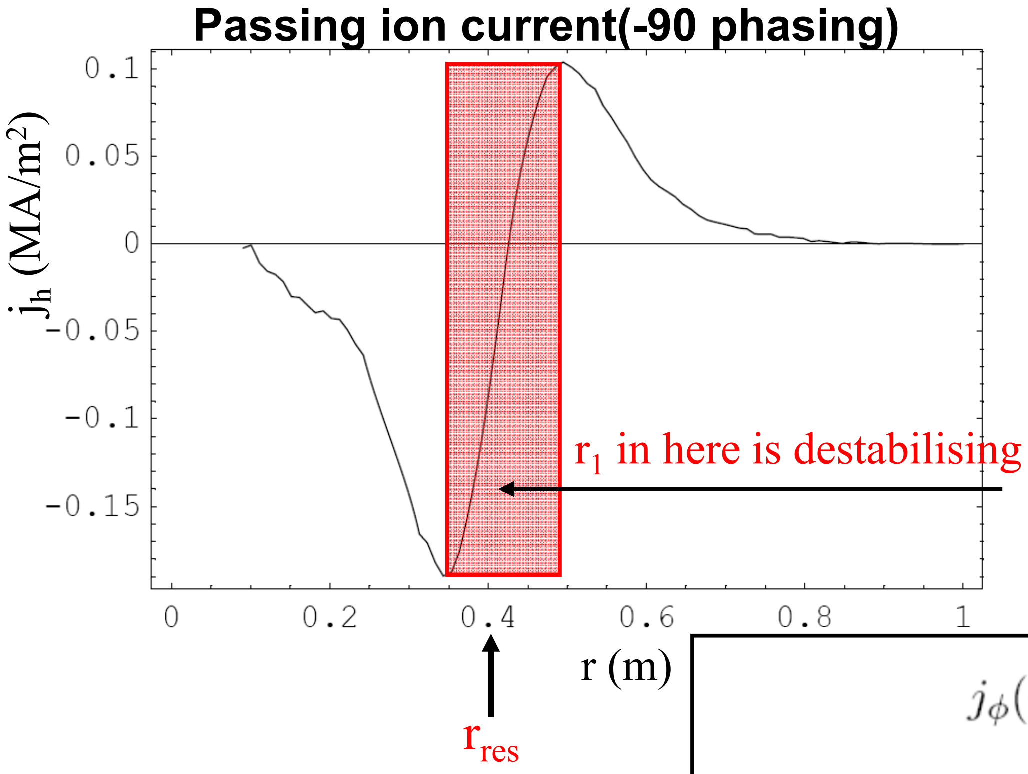

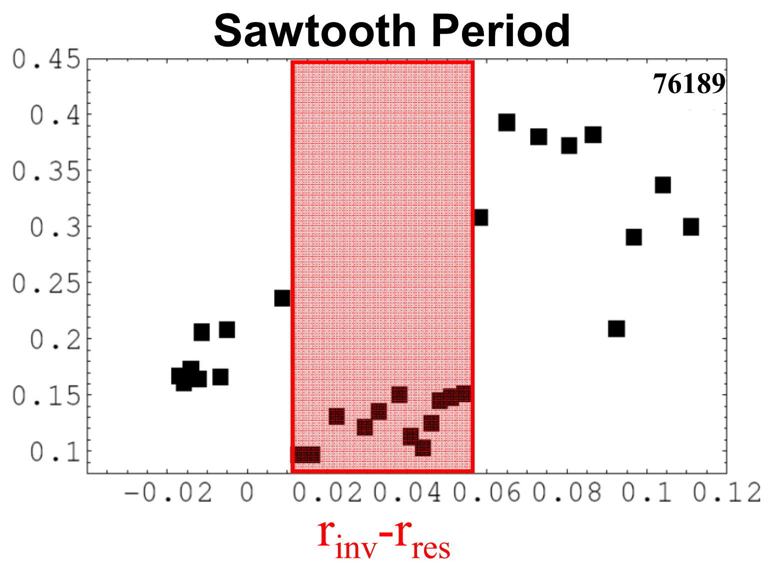

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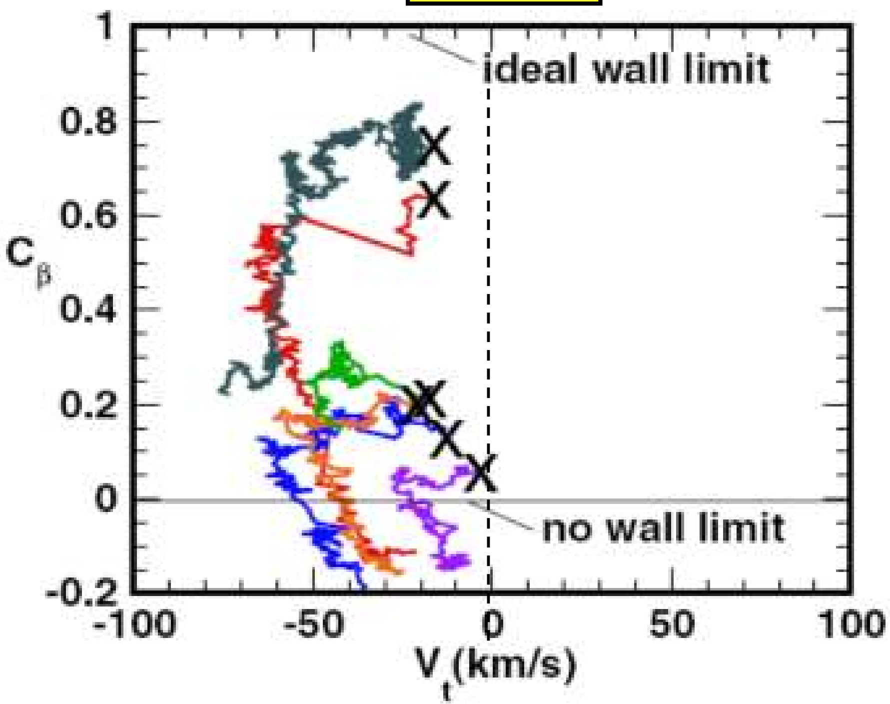
Graves et al, PRL, 2009

Passive stabilisation of RWM at low rotation

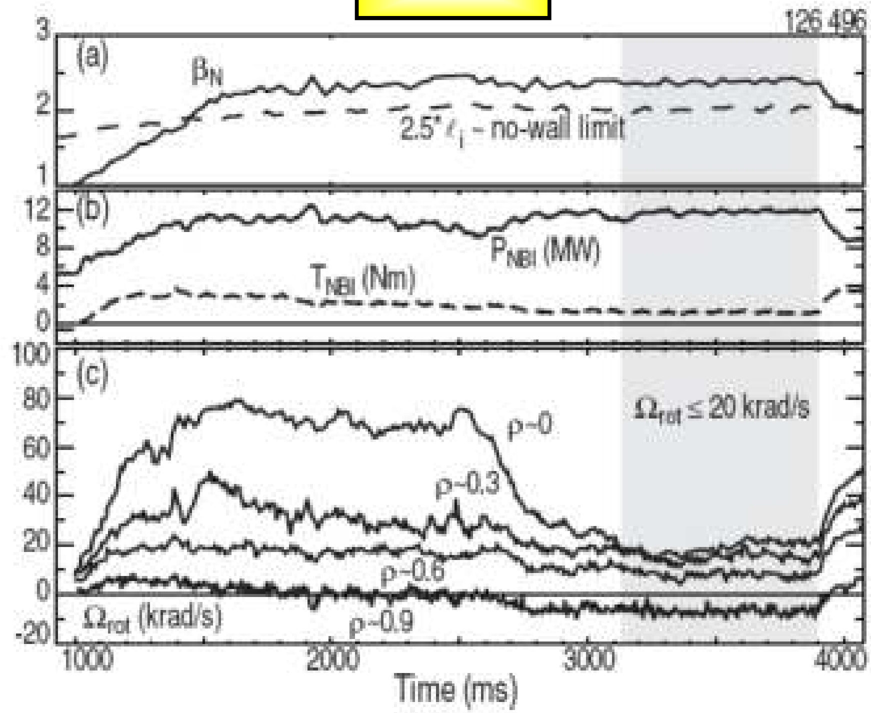
- Previous experiments explained RWM stability by rotation damping
- Recently DIII-D, JT-60U & NSTX operated with $\beta > \beta^{\infty}$ despite low v_{ϕ}

JT-60U



Takechi et al, PRL, 98, 055002

DIII-D



Reimerdes et al, PRL, 98, 055001

Kinetic Damping of RWM

- Why do resonances occur?
  - Change in mode energy has a term:

$$\delta W_K \sim \sum_{l=-\infty}^{\infty} \frac{\omega - \omega_{E\times B} - n\omega_*}{\omega - \omega_{E\times B} - n\langle\dot{\phi}\rangle - l\langle\dot{\theta}\rangle}$$

  - When denominator tends to zero, get a large contribution to δW_K
  - Resonance can occur in very different frequency regimes:

Transit Frequency	$\omega_t \sim (v_{th} / R)$
Bounce Frequency	$\omega_b \sim \sqrt{r/R}\,(v_{th} / R)$
Precession Drift Frequency	$\omega_d \sim \rho_L / r\,(v_{th} / R)$

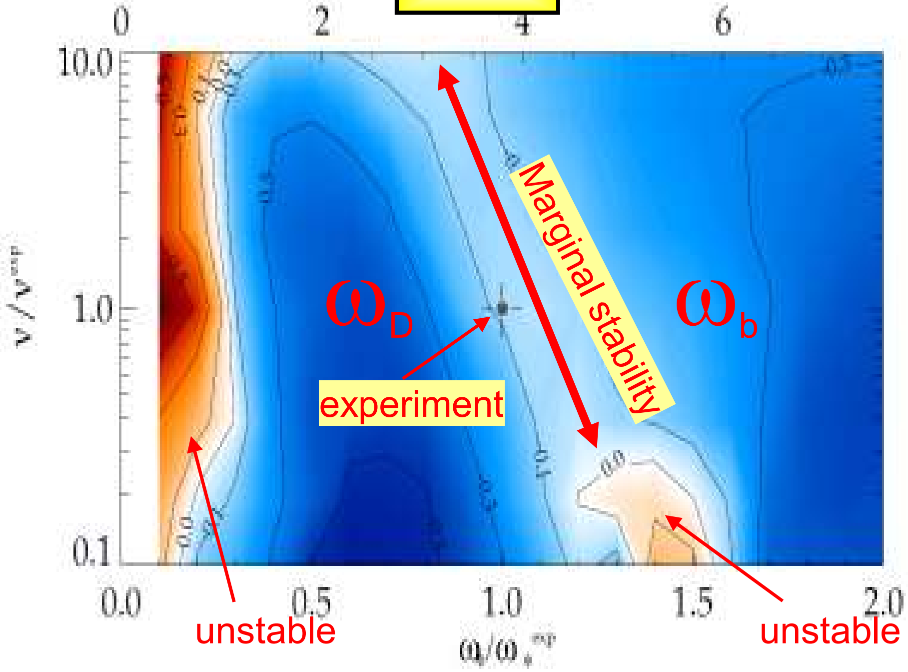
$$\omega_d << \omega_b < \omega_t$$

Kinetic Damping of RWM

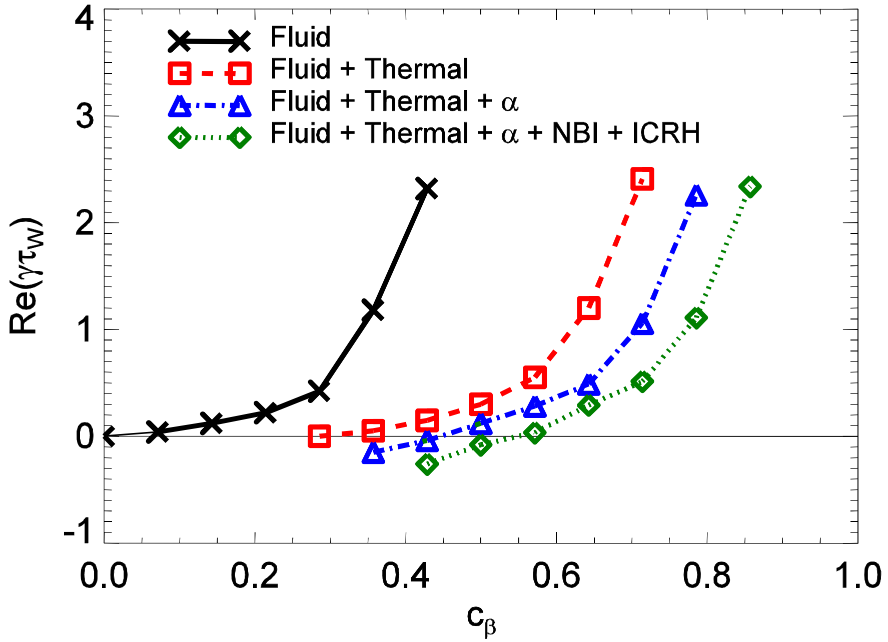
- Stability depends on rotation influence of resonance with ω_b or ω_d
- Destabilisation between precession drift resonance at low V_φ, bounce resonance at high V_φ

$$\delta W_K \sim \sum_{l=-\infty}^{\infty} \frac{\omega - \omega_{E\times B} - n\omega_*}{\omega - \omega_{E\times B} - n\langle\dot{\phi}\rangle - l\langle\dot{\theta}\rangle}$$

NSTX



ITER



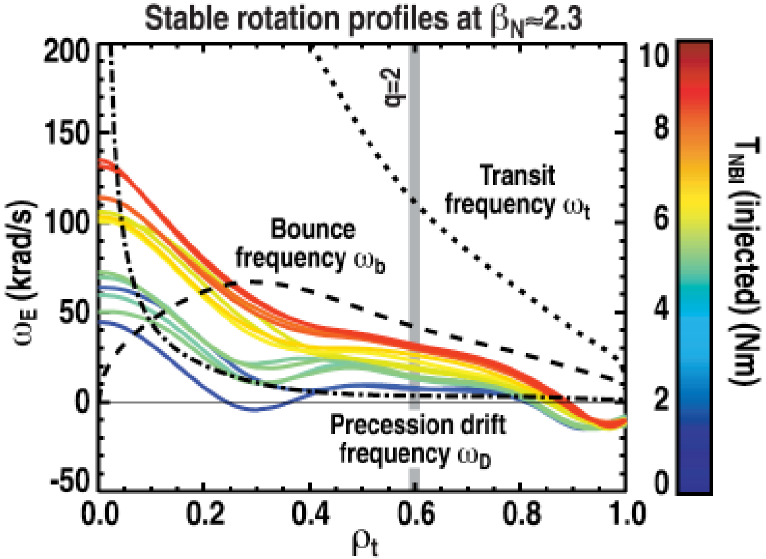
NSTX

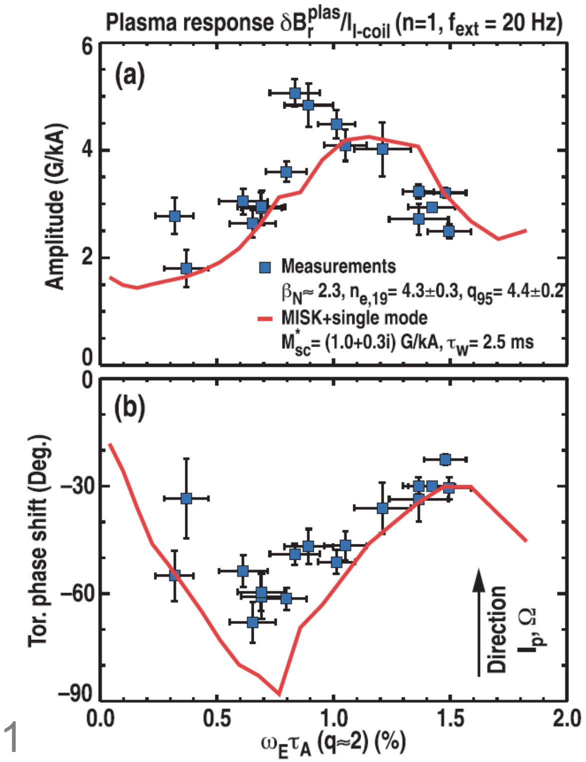
Berkery et al, Phys Rev Lett, 2010

Chapman et al, Phys Plasmas, 2012

Kinetic damping of RWM in DIII-D

- RFA measured in DIII-D by varying the rotation profile agrees with MISK simulations including kinetic effects, though only qualitatively, due to approximations in the code
- Improved stability at very low rotation suggests that it may not be an RWM that leads to previously measured low-rotation thresholds in DIII-D and JT-60U!





H. Reimerdes et al, PRL 2011, APS 2008 PO3.00011

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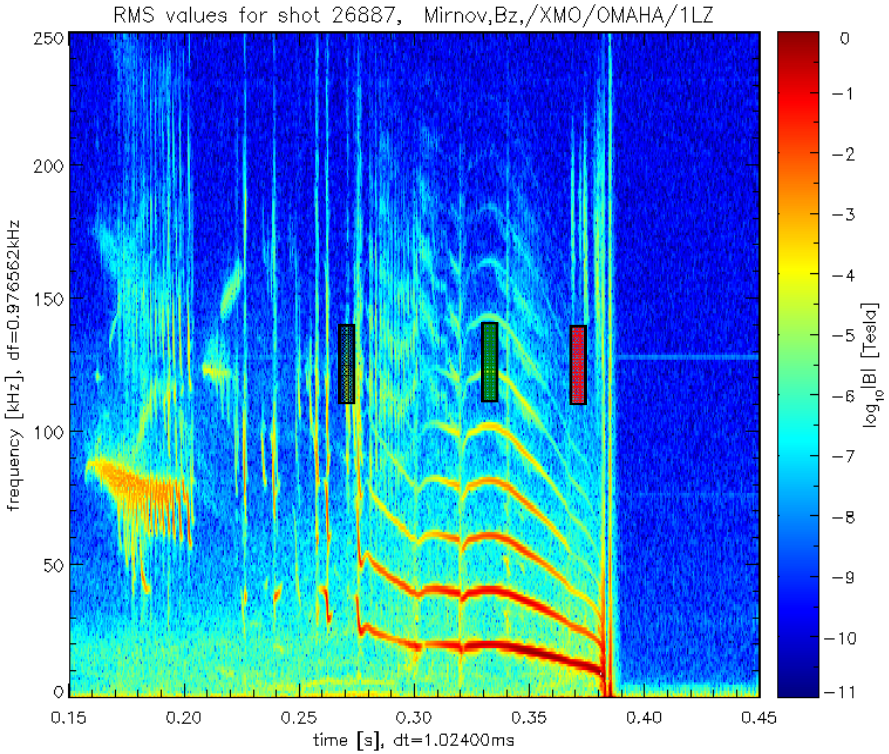
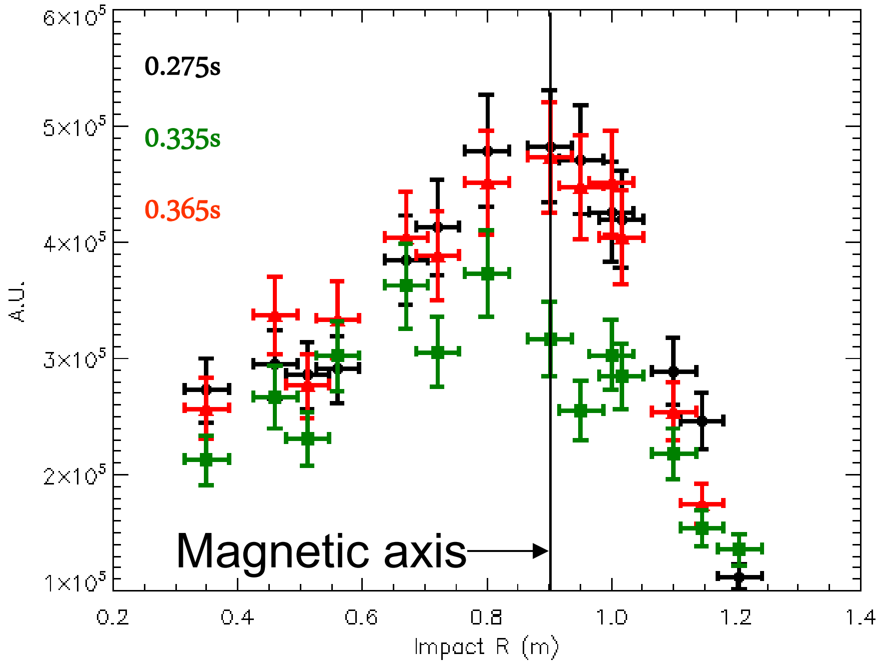
Redistribution due to helical modes

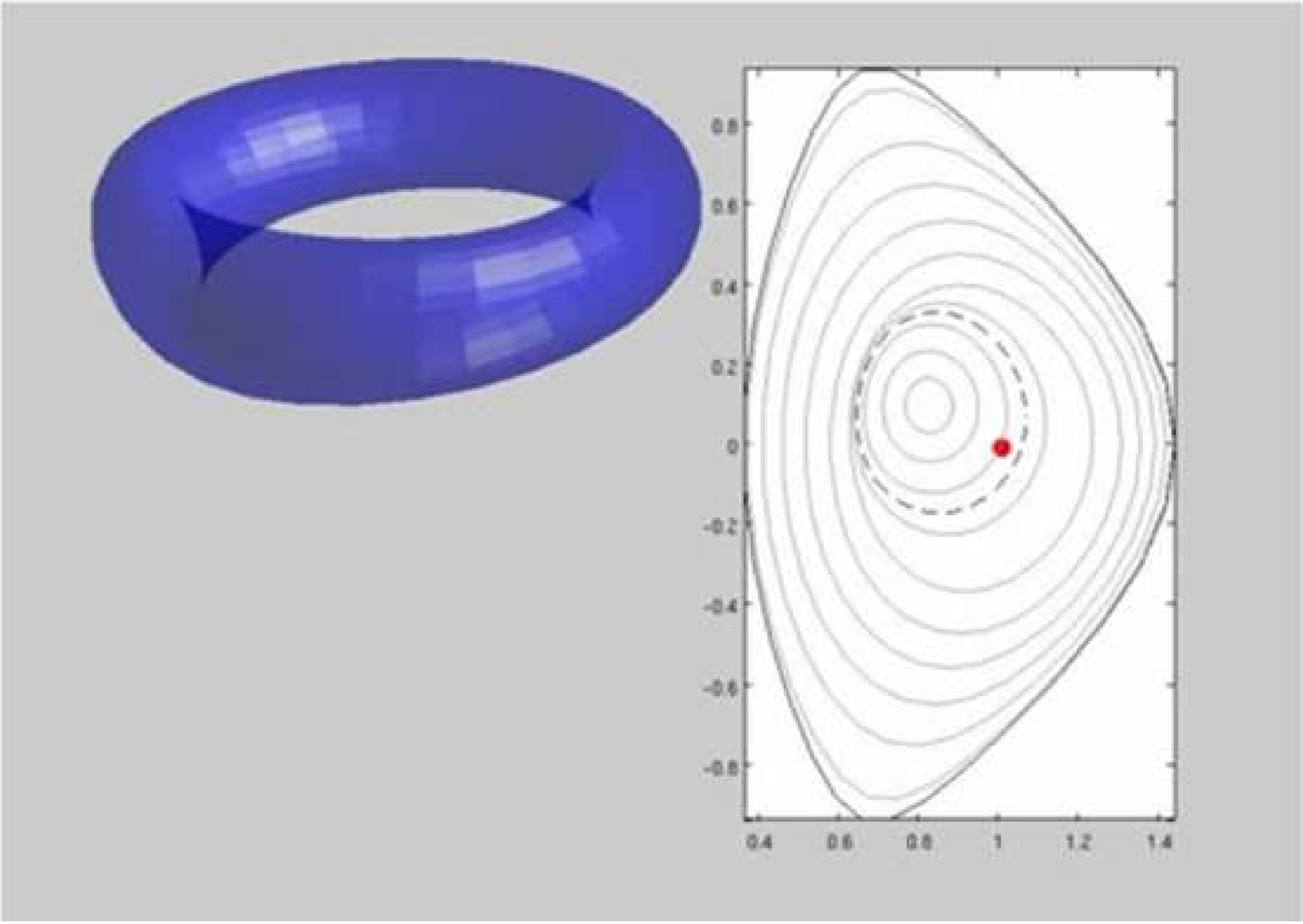
- Fast ion redistribution follows q-profile evolution
  - As q_{min} approaches unity, LLM appears and fast ions are expelled from the plasma core (fast ions distribution represented by neutron emissivity)
  - As q_{min} drops through unity, internal mode growth drops (alternatively, helical core amplitude decreases) and fast ions confined once more



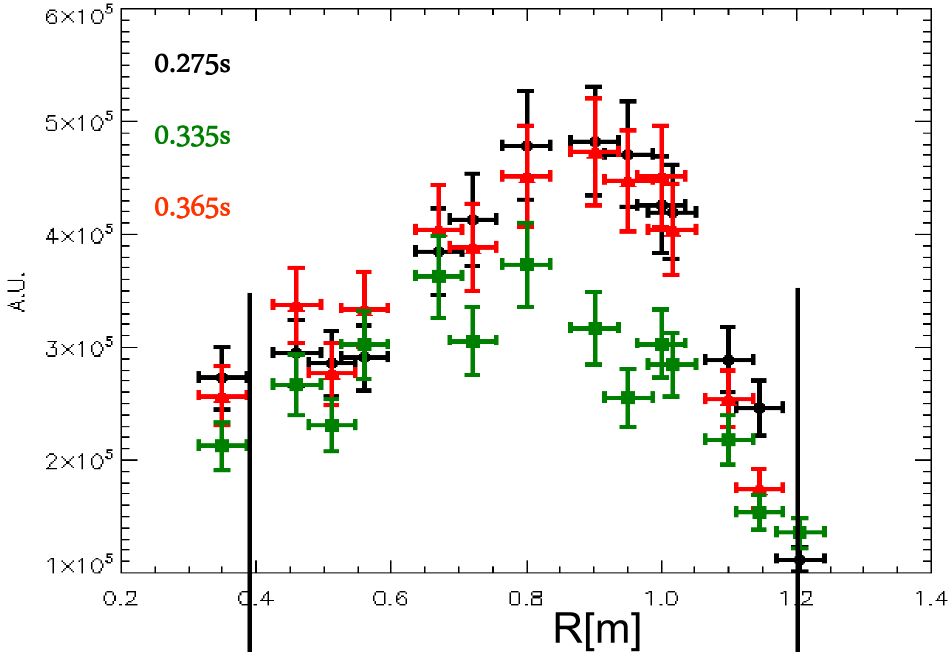


Redistribution due to helical modes

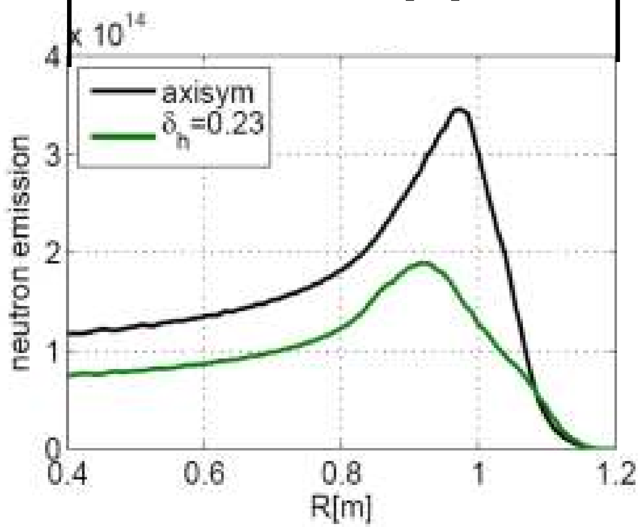
- Saturated n=1 mode leads to exotic particle orbits



Redistribution due to helical modes



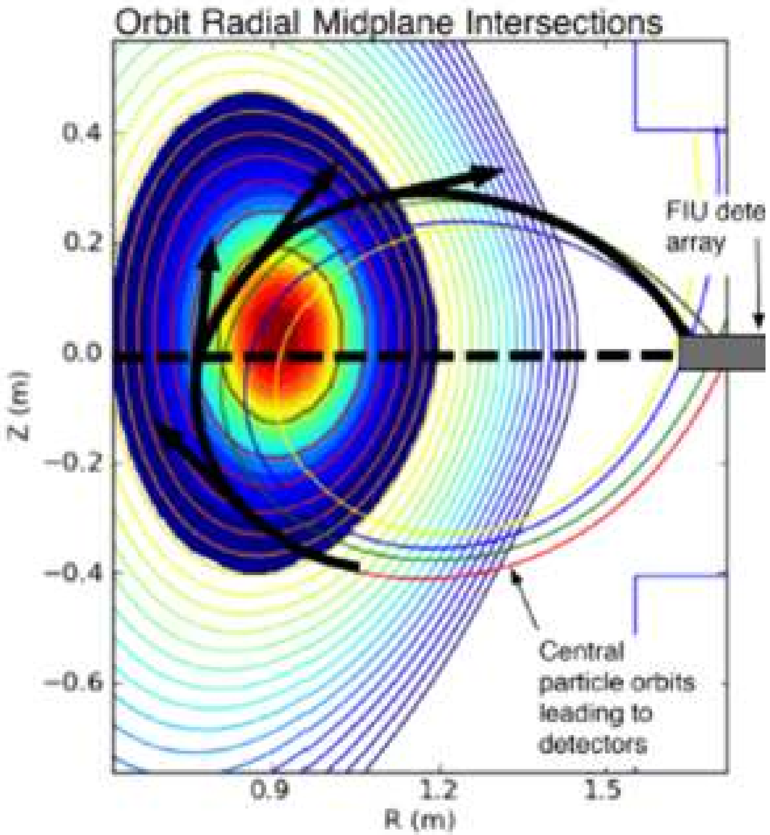
MAST neutron camera data

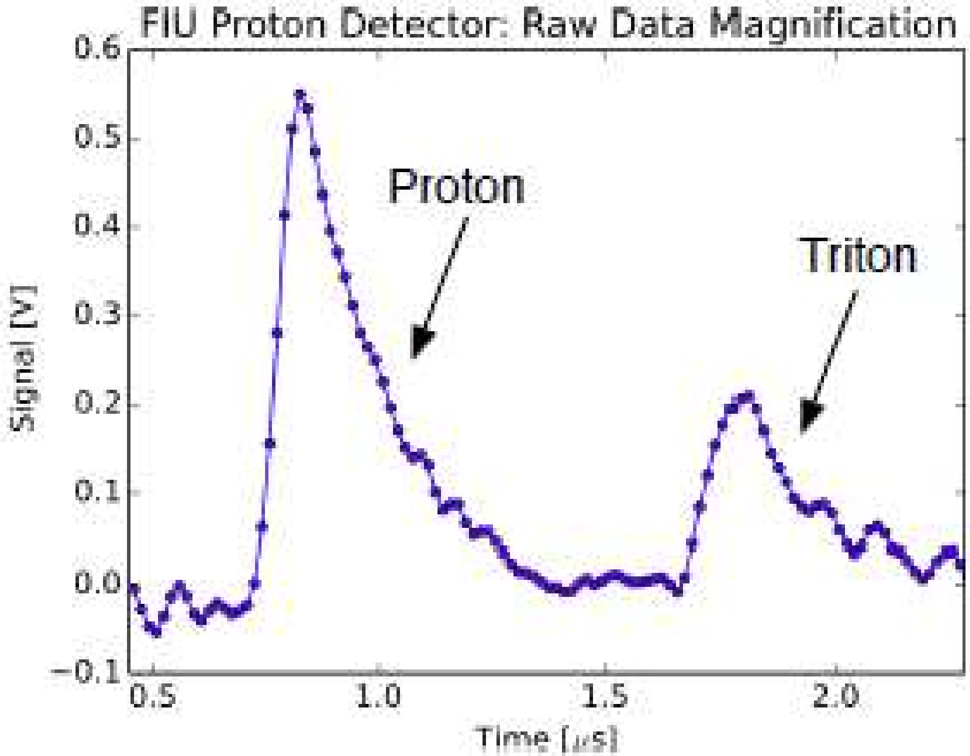


SCENIC modelling
(virtual diagnostic)

Fusion proton/triton measurements

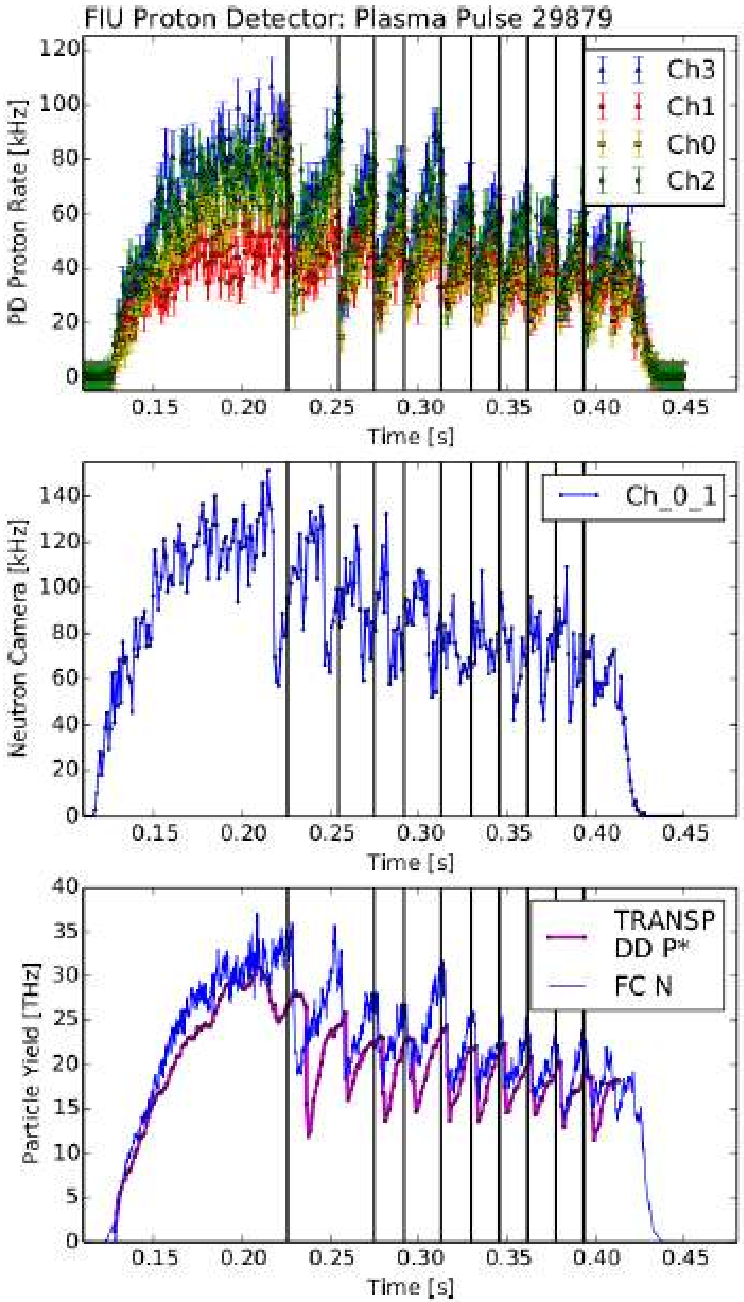
- Four channels detect particles at different angles, corresponding to birth positions in midplane; moved radially between shots
- Raw data consist of ~100ns pulses produced by individual 3.0 MeV protons & 1.0 MeV tritons





RV Perez et al, HTPD, 2014

Proton losses due to sawteeth

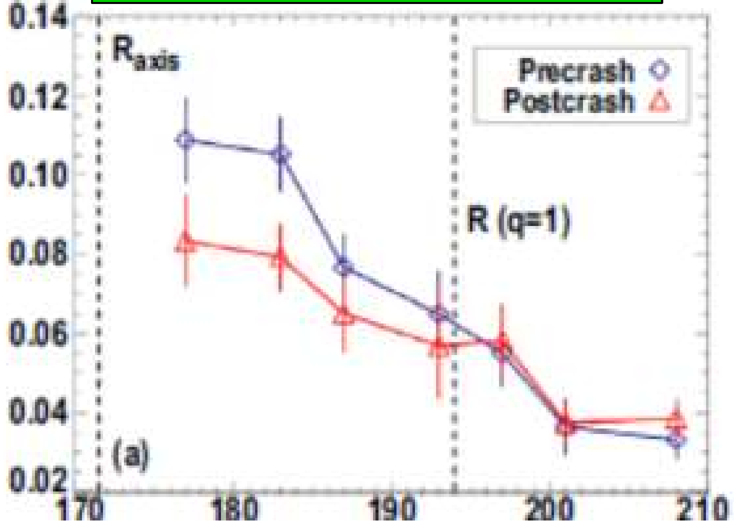


- First DD fusion proton data obtained with Proton detector up to 200kHz with 1ms time resolution
- Effect of sawteeth on fusion rate in sync with neutron camera and fission chamber data

RV Perez et al, HTPD, 2014

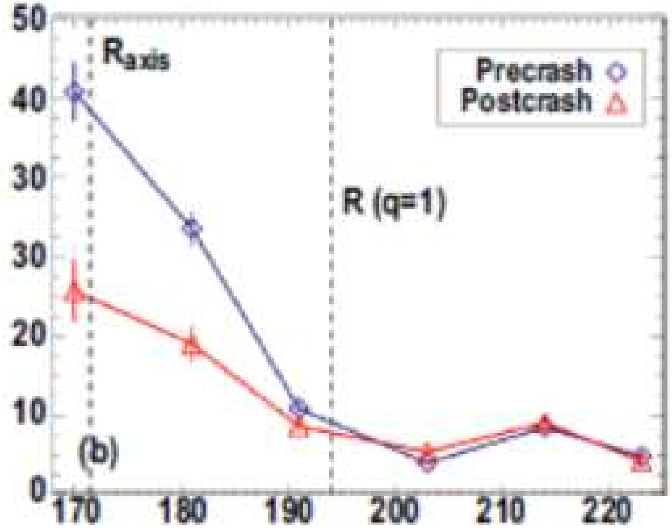
Redistribution due to sawteeth

Trapped ions (vert FIDA)

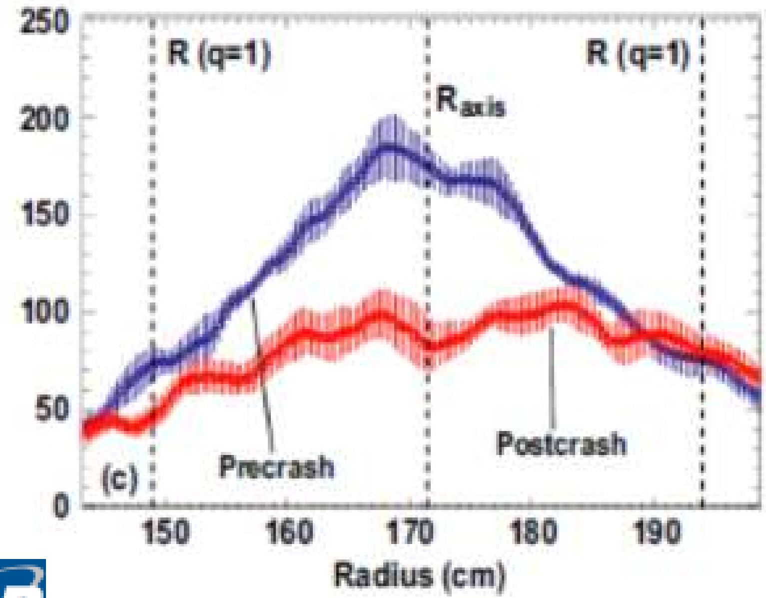


- Fast ions transported radially outwards by sawtooth crash
- Passing fast ions more affected than trapped fast ions

Co-passing ions (tang FIDA)



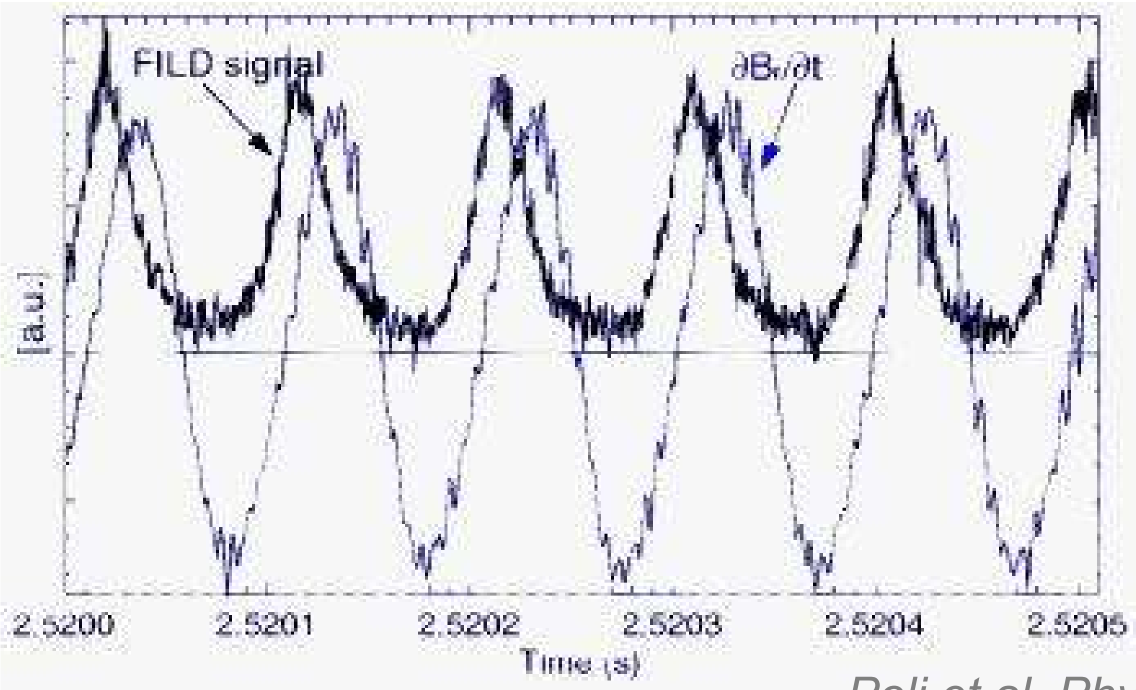
Counter-passing ions (FIDA imaging)



CM Muscatello et al, PPCF 2012

Losses due to NTMs

- NTMs also lead to enhanced fast ion losses
- Fast ions losses modulated at mode frequency
  - Losses of passing particles caused by drift island formation
  - Losses of trapped particles due to stochastic diffusion
- Insignificant change in wall loads predicted in ITER



IPP

Poli et al, Phys. Plasmas 2008

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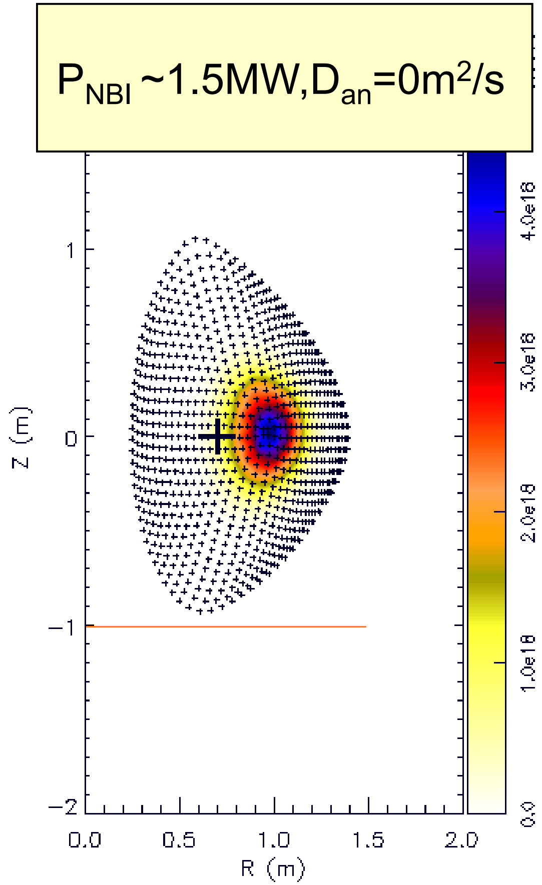
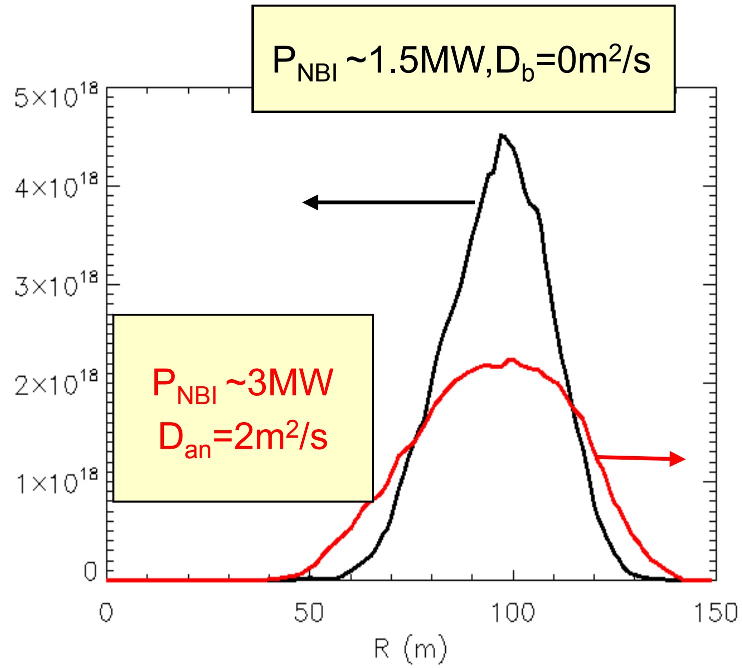
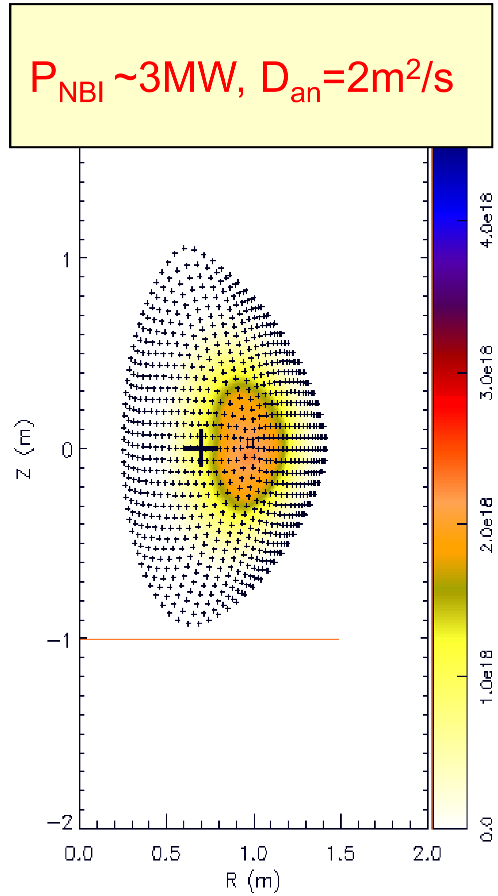
Impact of FI redistribution (on axis NBI)





Fast ion density profiles

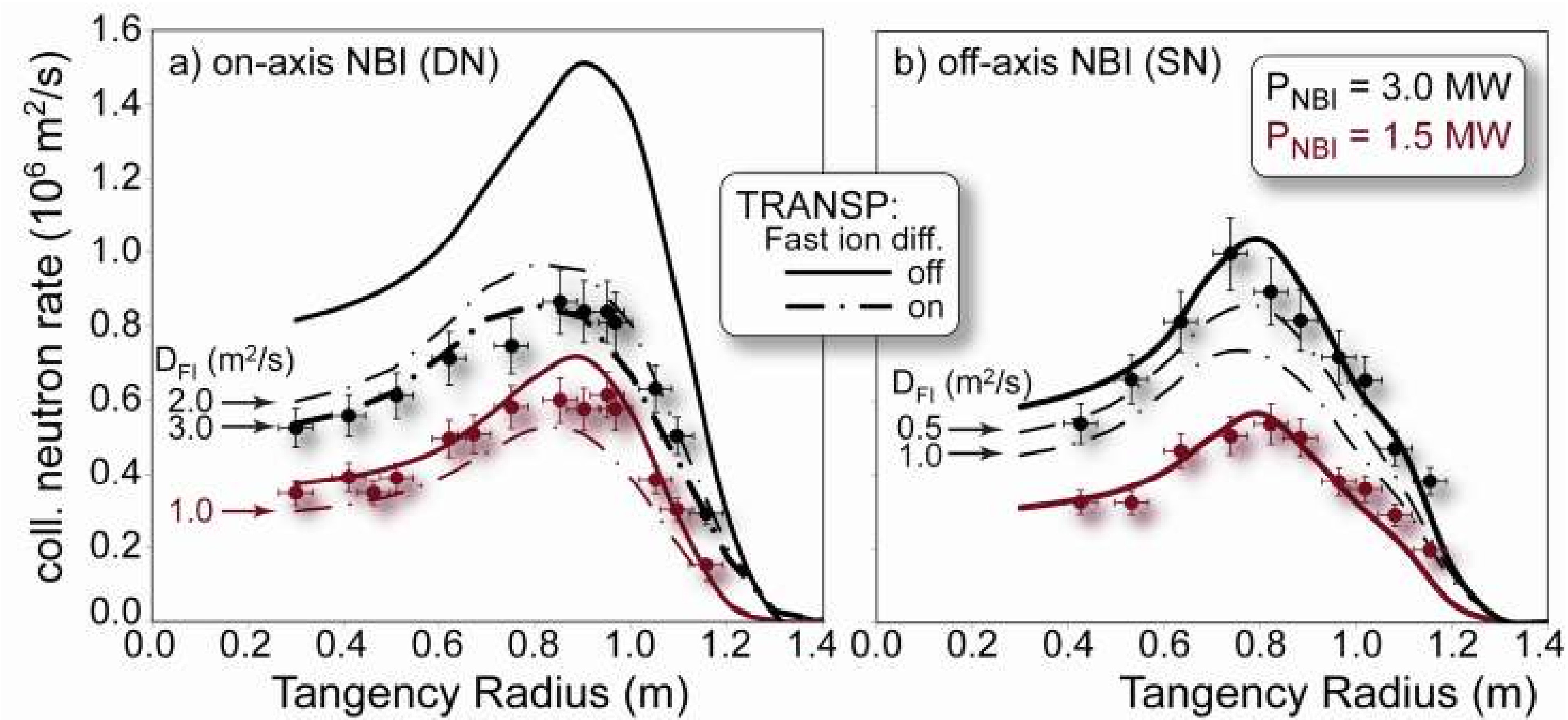


- Assuming ad hoc D_{an}, doubling beam power results in:
  - broader fast ion and current density profile
  - 50% increase in fast ion stored energy
  - reduced current drive efficiency by ~20%

Turnyanskiy et al, Nucl Fusion, 2013

Reduced redistribution for off-axis beams

- Doubling power from 1.5MW to 3MW for off-axis beam results in classical doubling of neutron emissivity
  - consistent with D_{an}<0.5m²/s



Turnyanskiy et al, Nucl Fusion, 2013

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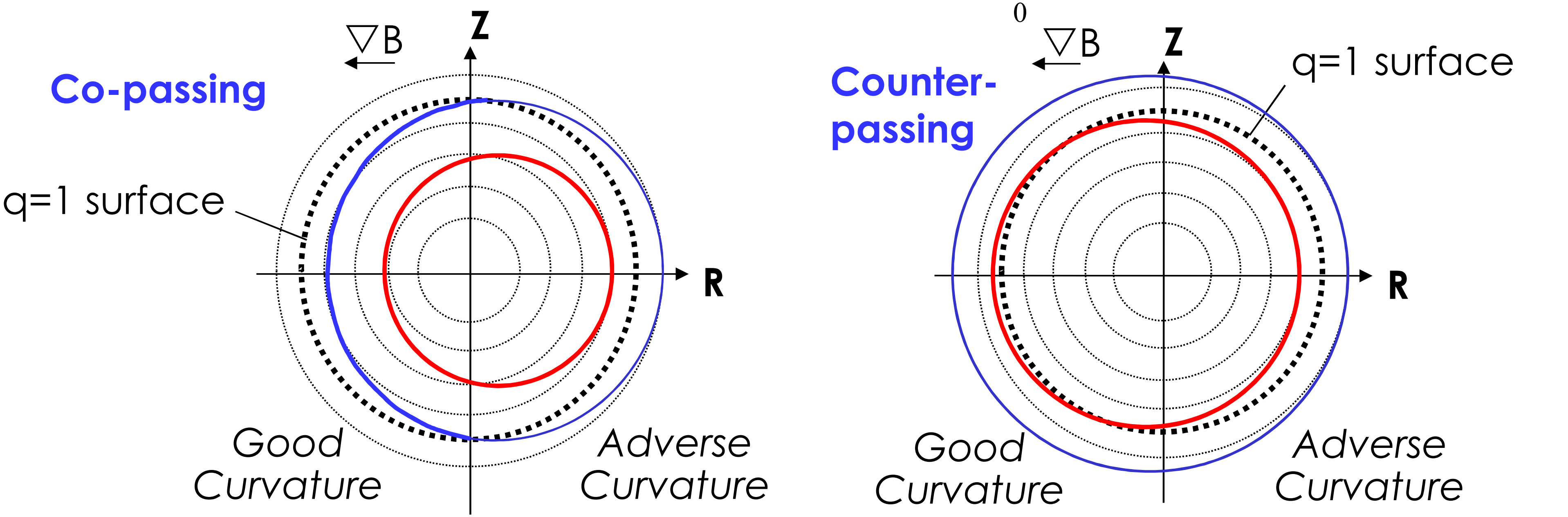
Reminder: Fast ion effect on sawteeth

δW has a term dependent upon curvature:
Graves, PRL, 2004

$$\delta W \sim -\int_0^{r_1} \left(\xi \cdot \nabla \langle P_h \rangle\right)\left(\xi \cdot \kappa\right) dr$$

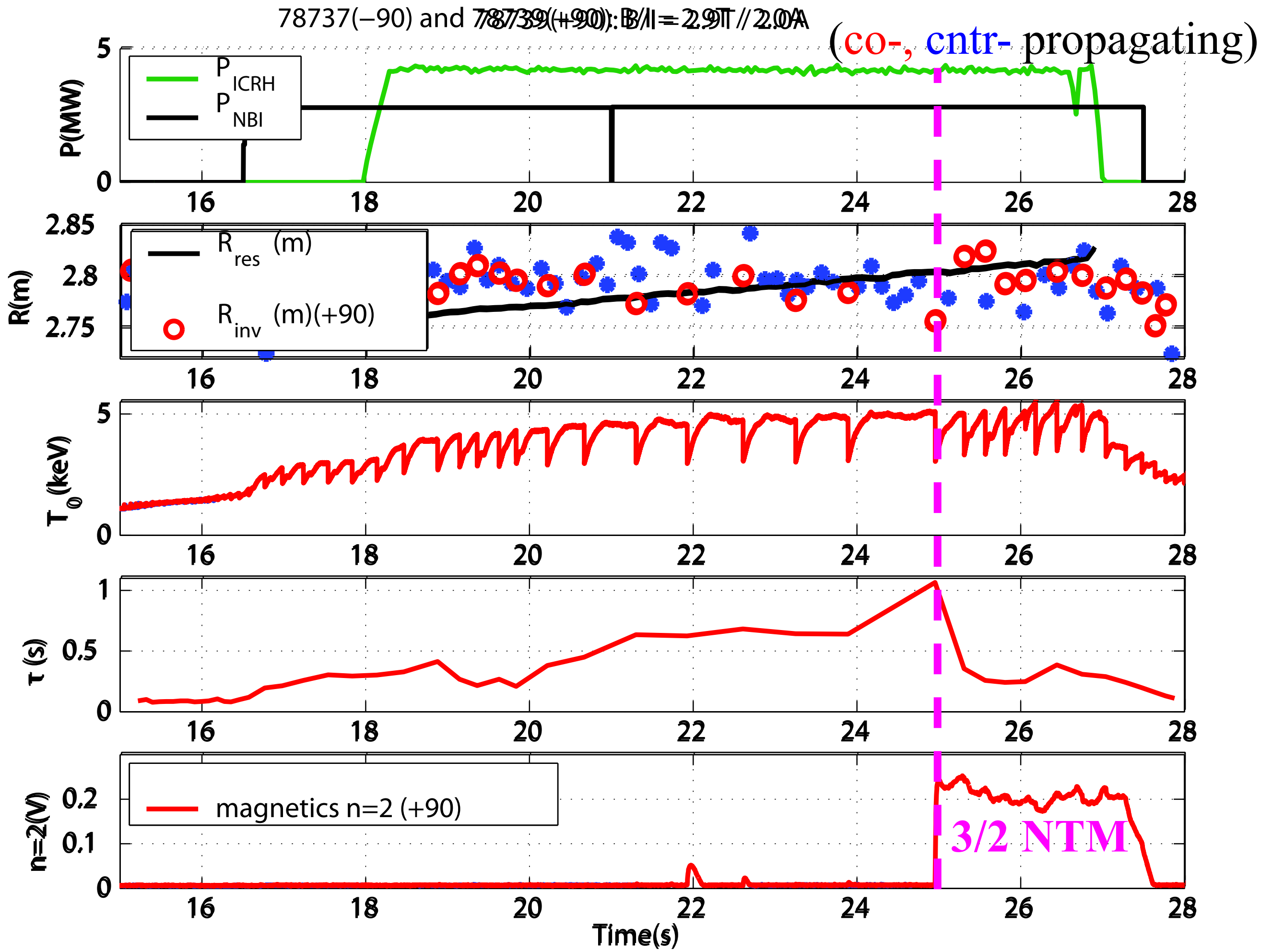


Co-pass, $\langle P_h \rangle'|_{r_1} < 0 \rightarrow$ stabilising	**Ctr-pass, $\langle P_h \rangle'|_{r1} < 0 \rightarrow$ destabilising**
Co-pass, $\langle P_h \rangle'|_{r1} > 0 \rightarrow$ destabilising	**Ctr-pass, $\langle P_h \rangle'|_{r1} > 0 \rightarrow$ stabilising**

- Increasing effective orbit width leads to large passing ion effect
  - Large thermal velocity (ITER NNBI, ICRH)
  - Large fraction of barely passing ions (JET NBI, ICRH)

ICRH Control in JET

- Control demonstrated with ^{3}He minority with negligible ICCD
  - Also shown in H-mode with higher P_{aux}



L-mode

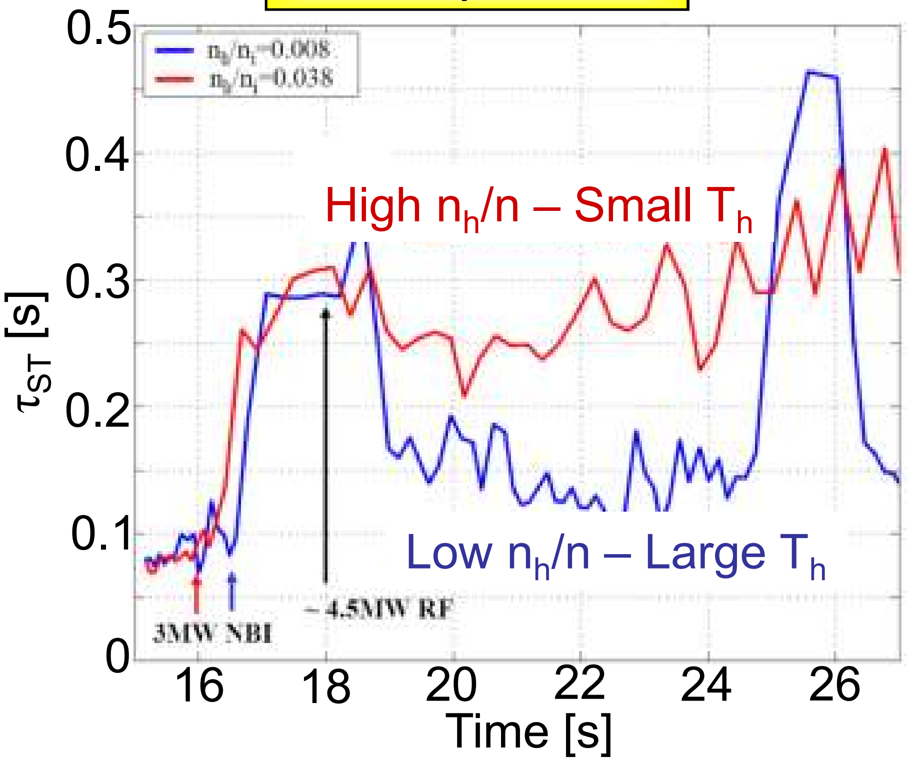
β_N=0.8

Graves et al, Nucl Fusion 2010; Nature Comms 2012

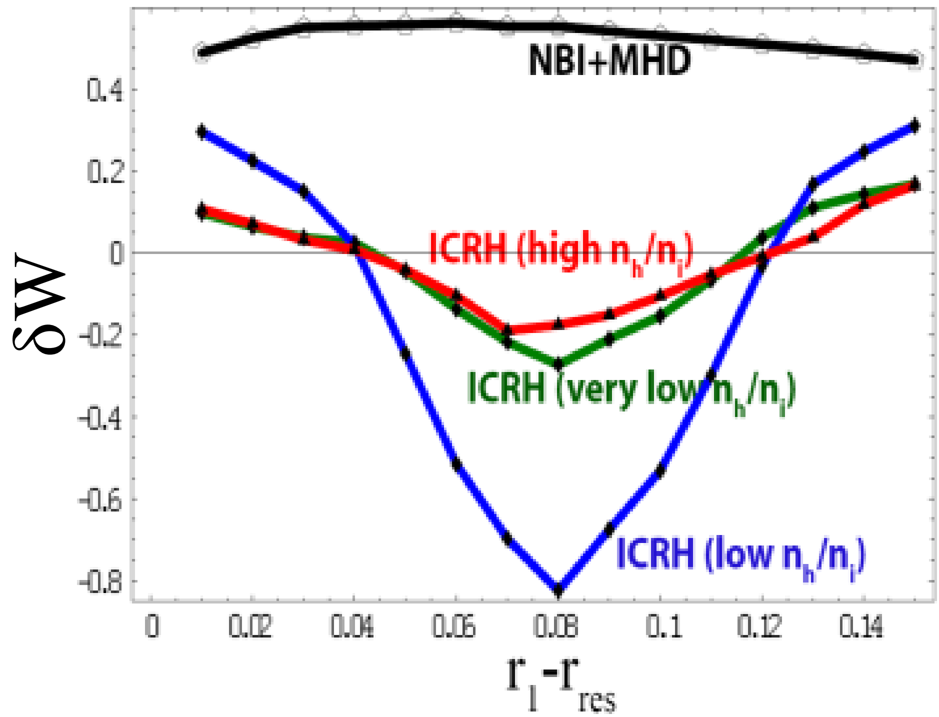
Verification of fast ion destabilisation

- Lower ^{3}He concentration → larger T_h → shorter τ_{ST}
  - Too much ^{3}He → tail energy too low
  - Too little ^{3}He → broader f_h, more losses

JET Experiment



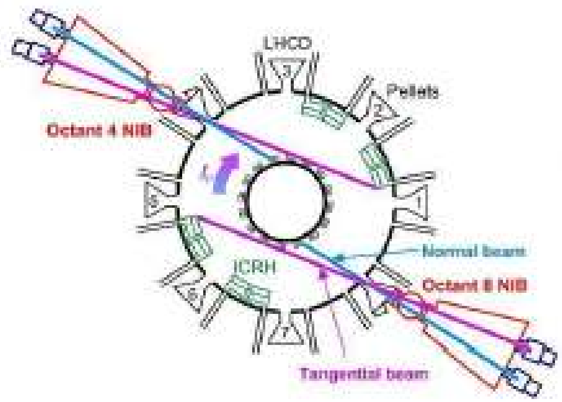
SELFO/HAGIS Modelling



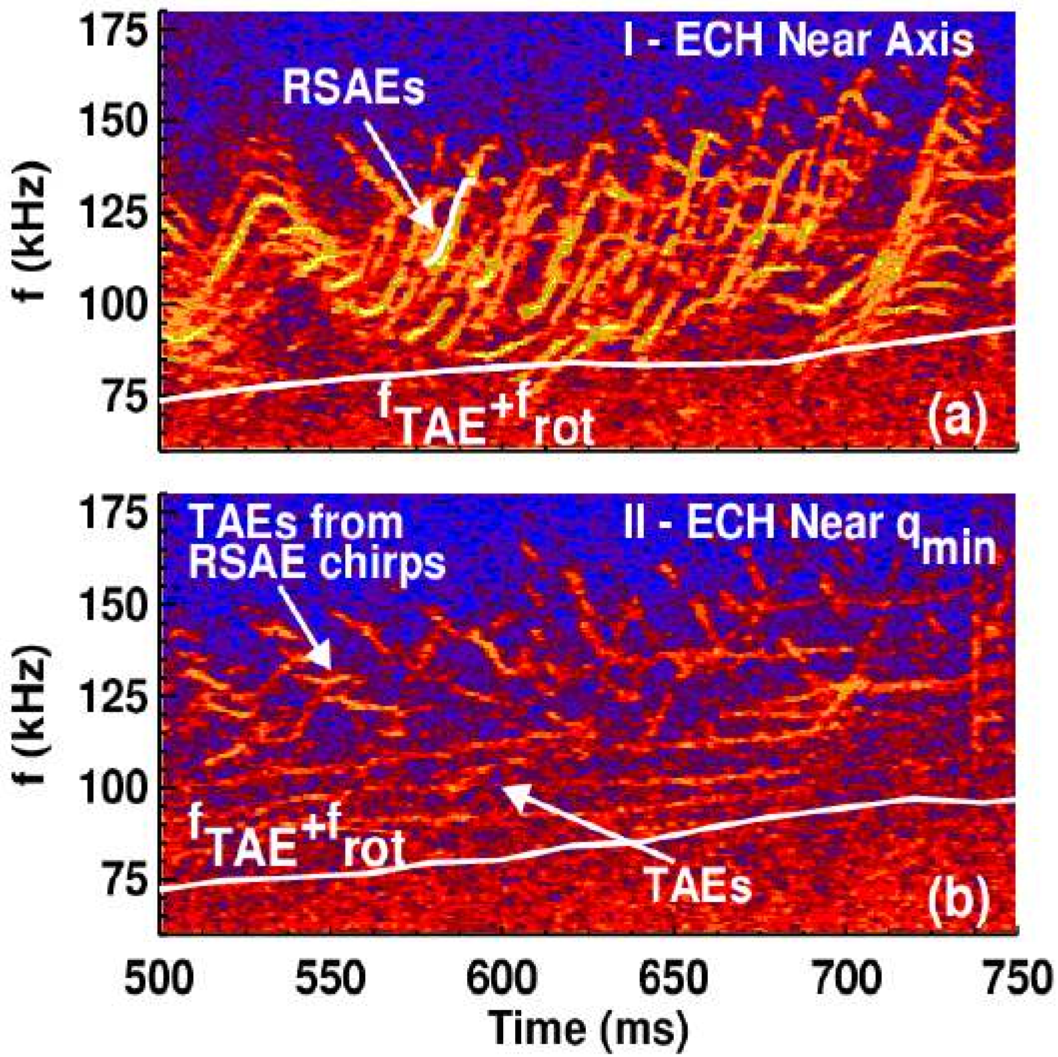
Graves et al, Nucl Fusion 2010

Control of AEs

- Affect stability/existence of Alfvén Waves
  - Plasma conditions: density, safety factor, beta, isotope mix (mass density), magnetic field, introduce flow (rotation)
  - Monitor with magnetics/antenna
- Tailor fast particle distribution
  - Alphas: Fuelling
  - NBI: Beam geometry, injection energy
  - ICRF: Resonance layer
  - Field topology: Ripple, 3D field coils, aspect ratio



Controlling AEs with ECRH



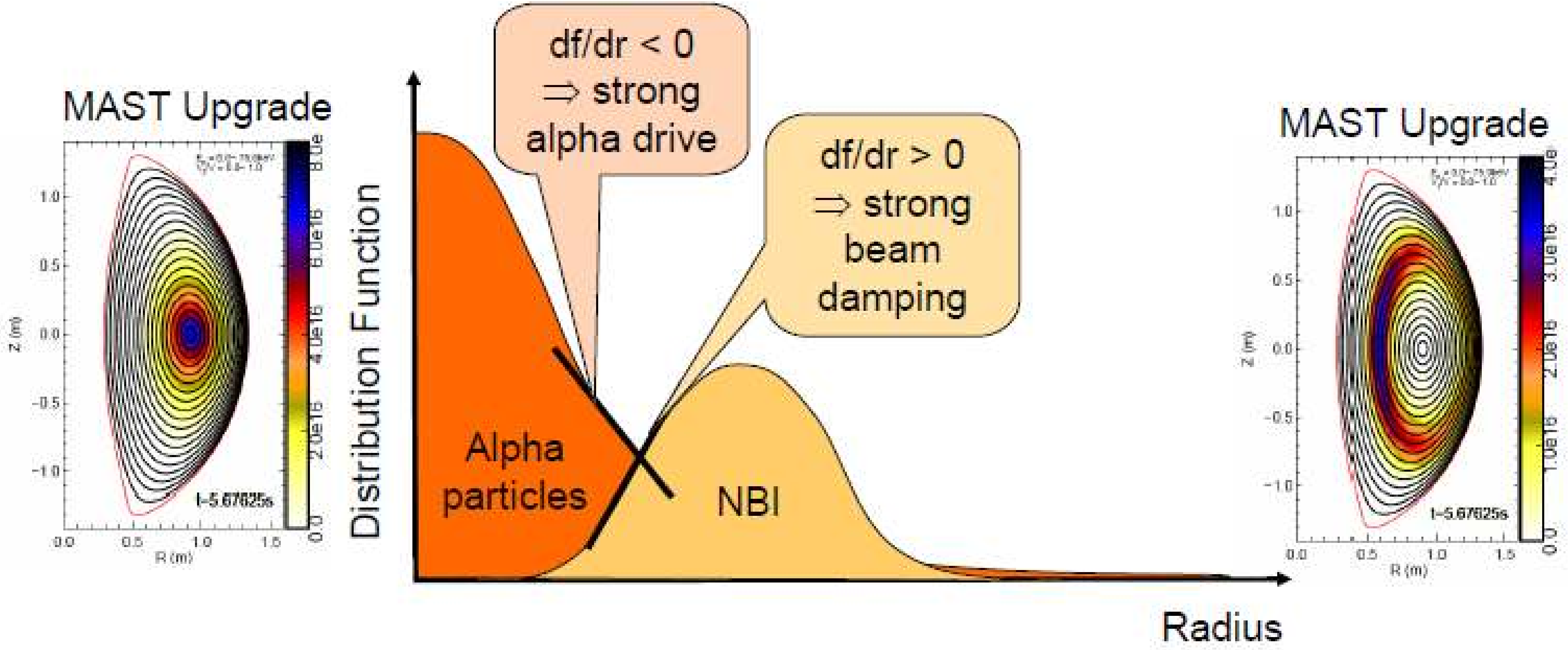
- Applying ECRH near radial position of AEs shown to suppress the modes

DIII-D
NATIONAL FUSION FACILITY

Van Zeeland et al, PPCF, 2008

Tailoring the fast ion distribution

- Alpha particles strongly peaked on-axis
- Use off-axis beams to change drive-damping balance?



Summary

- Our original concern was loss of heating and damage to the first wall. Is this a problem?
  - Physics of fast ion driven instabilities is well understood
  - Fast particles drive instabilities and are in turn redistributed and, in some cases, lost
  - Typically, saturation amplitudes and losses are low today
  - Burning plasmas may be a different story – more to do!
- How about effects on other MHD and current drive?
  - Theory and experiment agree that fast ions strongly influence other modes: sawteeth, RWMs, …
  - Fast ion driven modes can strongly influence current profile
- What are prospects for controlling AEs?
  - Tailoring distribution/plasma conditions, and ECRH

Problems Solving

Problem for you

- Determine the condition for the pitch angle at the midplane ($v_{||0}$ / $v_{\perp 0}$) for a particle to be in a trapped orbit
  - Hint: Use conservation of magnetic moment and energy to relate magnetic field at midplane and bounce point, then assume B~1/R