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Physics of Energetic Ions in Tokamaks

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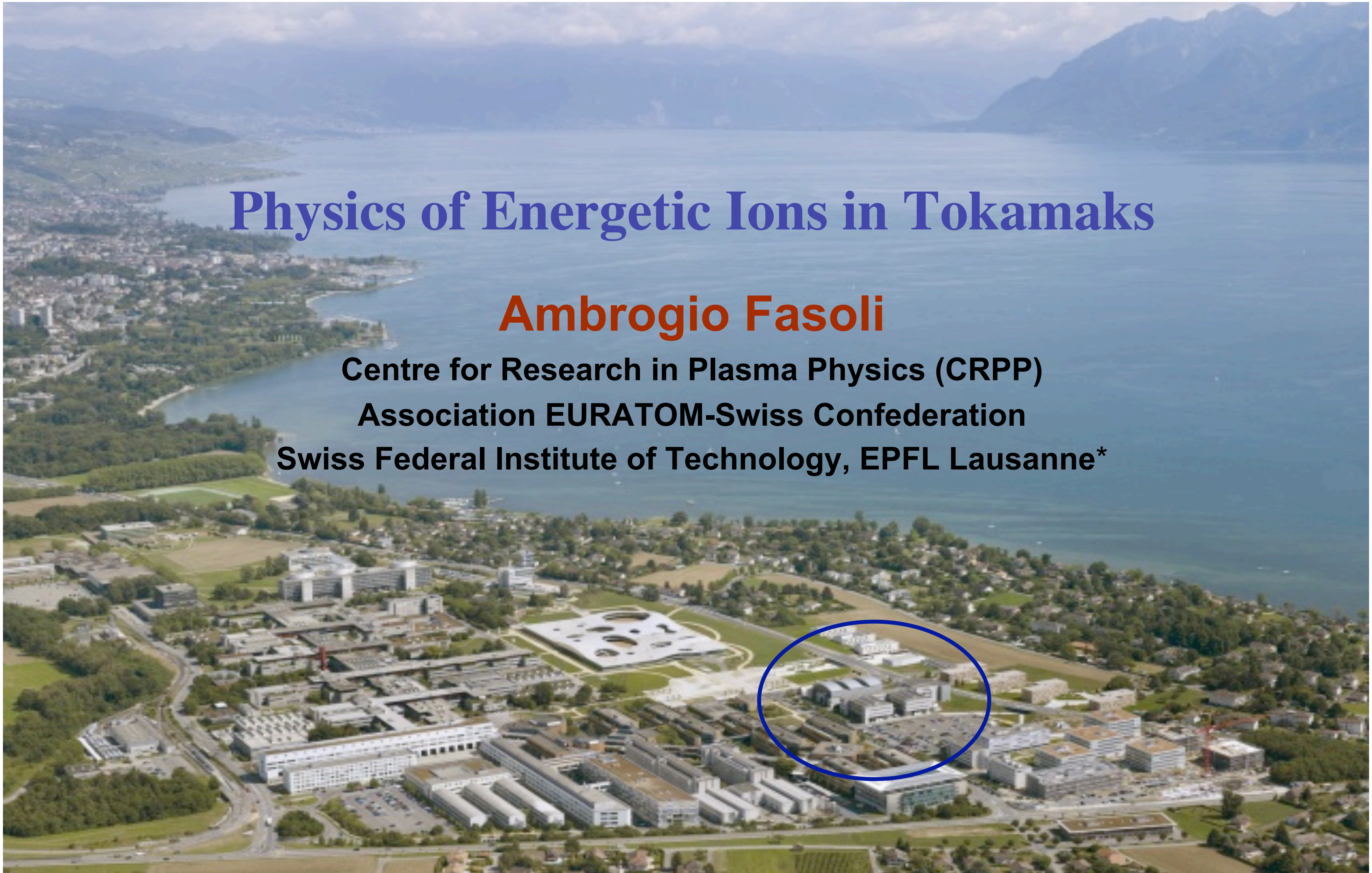

Physics of Energetic Ions in Tokamaks

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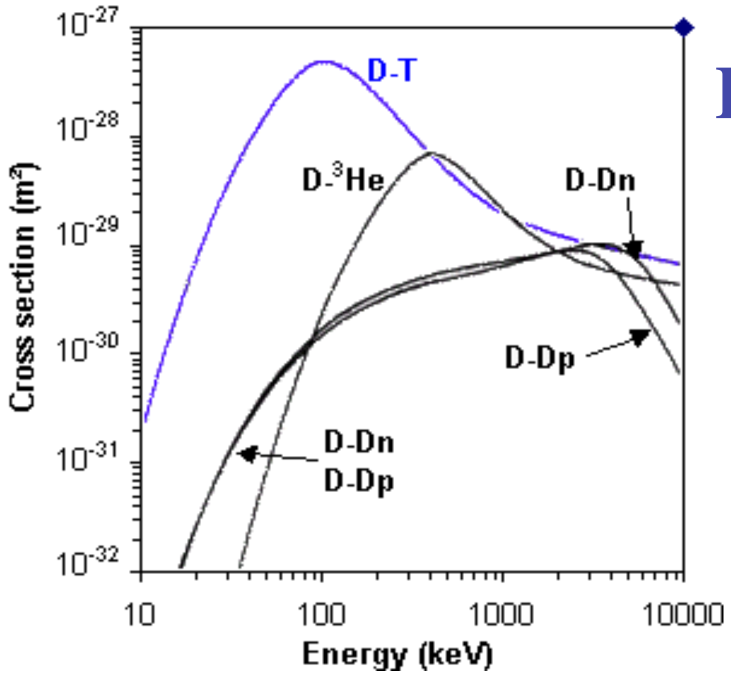
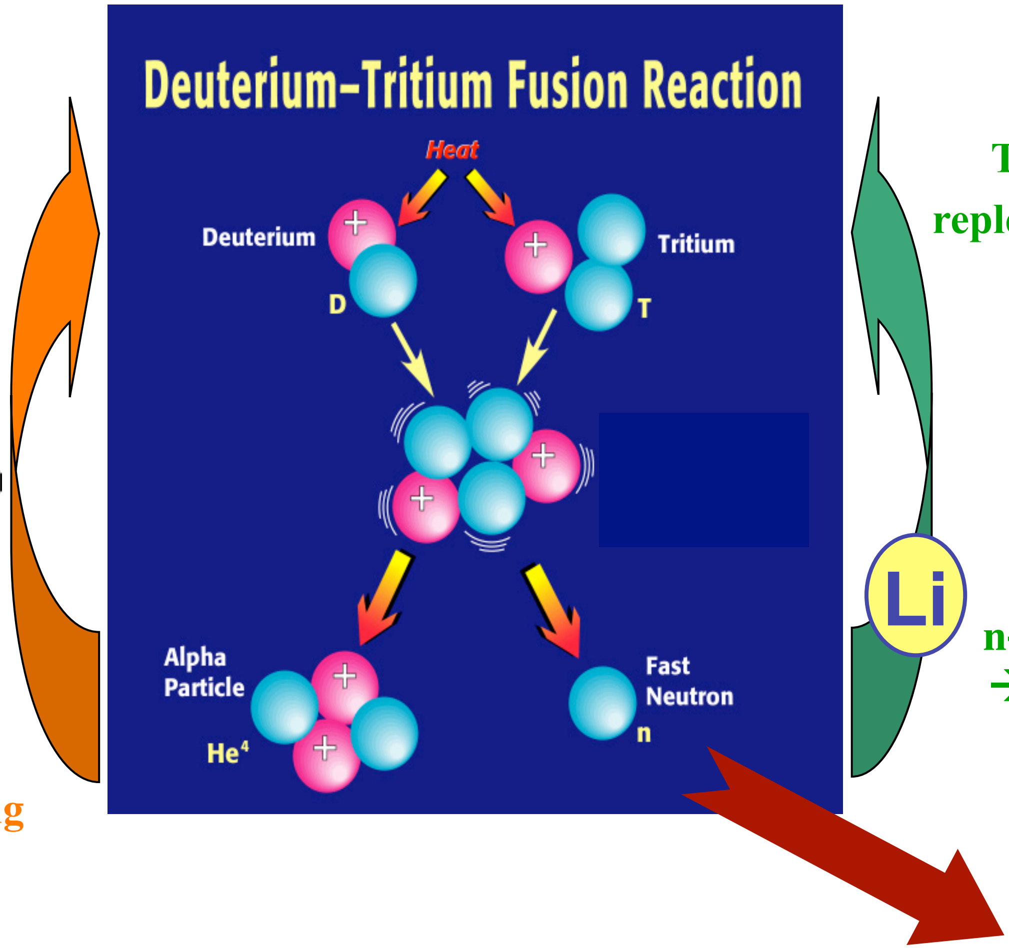
Fusion reactions



$D+T \rightarrow {}^{4}He\,(3.5MeV) + n(14MeV)$



Tritium replenishment

$n+Li^{6(7)} \rightarrow$
$\rightarrow He^{4}+T\ (+n)$

Plasma self-heating

Energy for electricity

Definition of a burning plasma

– Fusion power density $\equiv P_{fusion} = \frac{1}{4} n^2 \langle\sigma v\rangle E_{fusion}$ $(n_D = n_T = n/2)$

– α power density $\equiv P_\alpha = 0.2\, P_{fusion}$

– Thermal energy $W \equiv 3nT$

– Energy balance

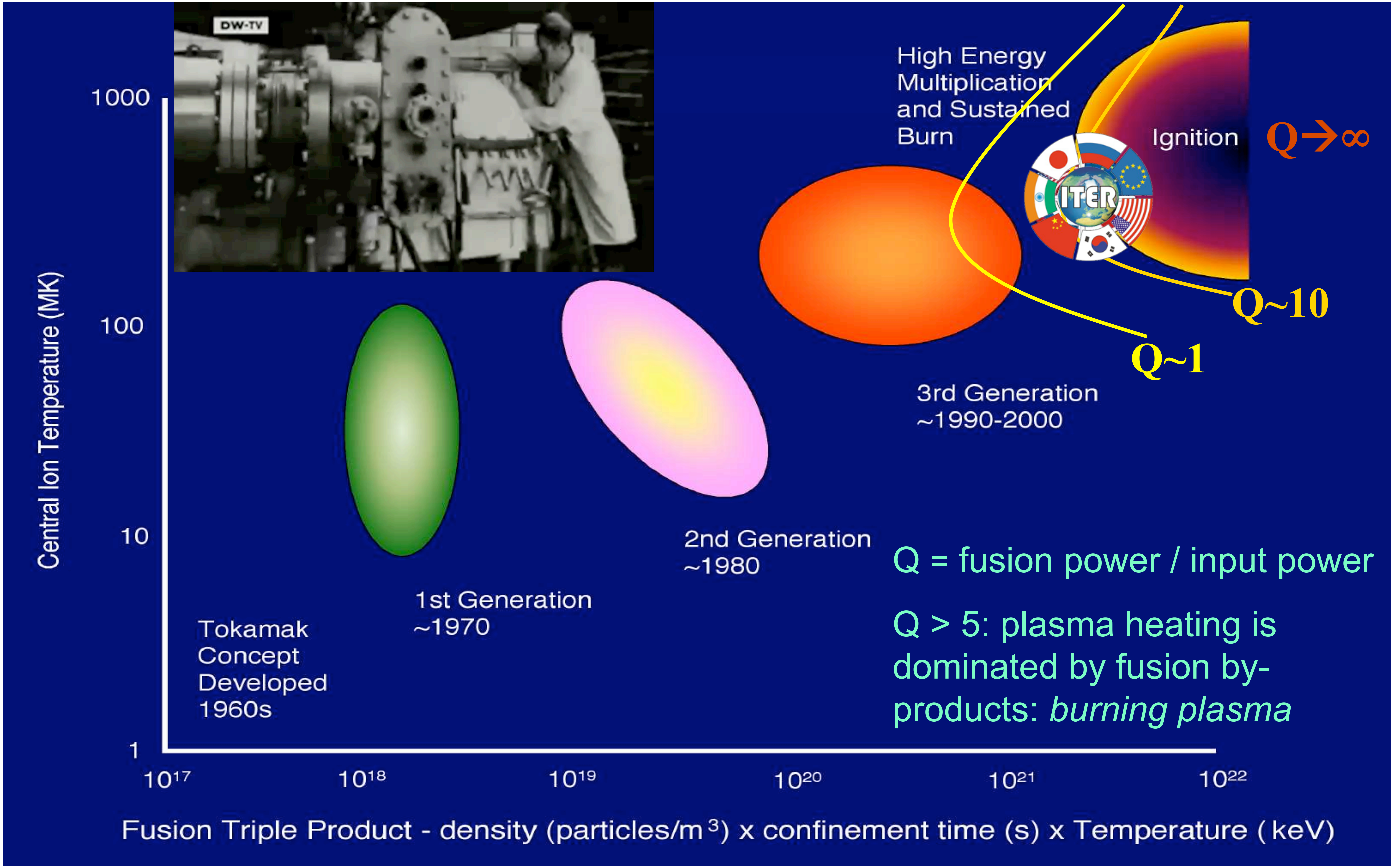
$$\frac{dW}{dt} = \underbrace{P_\alpha}_{\alpha\text{-heating}} + \underbrace{P_{heat}/V}_{\text{ext. heating}} - \underbrace{W/\tau_E}_{\text{losses}}$$

– Fusion energy gain: $Q \equiv P_{fusion}/P_{heat} = 5\, P_\alpha / P_{heat}$

– α heating fraction: $f_\alpha \equiv P_\alpha/(P_\alpha + P_{heat}) = Q/(Q+5)$

$Q=1$	$f_\alpha=17\%$ *breakeven*	
$Q=5$	$f_\alpha=50\%$	
$Q=10$	$f_\alpha=67\%$	*burning plasma*
$Q=\infty$	$f_\alpha=100\%$ *ignition*	

Progress in magnetic fusion



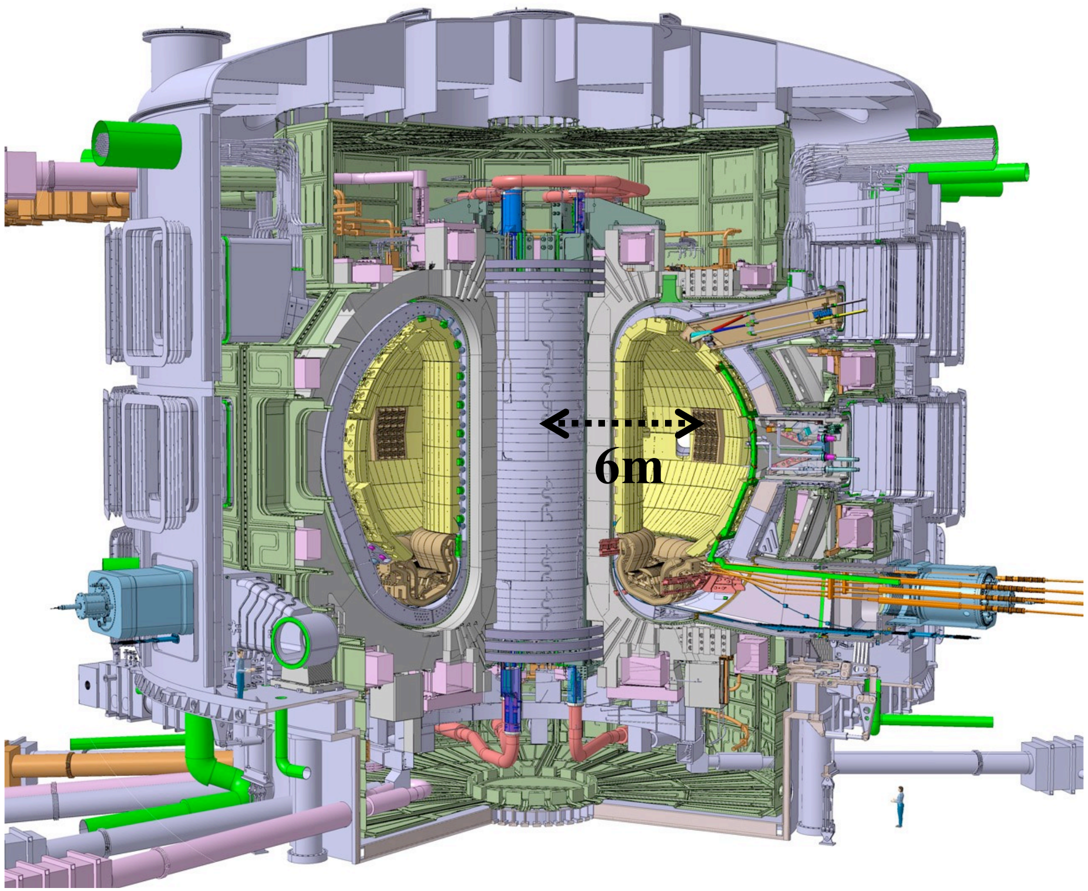
ITER

Demonstration of the scientific and technological feasibility of fusion energy for peaceful purposes

The first ever burning plasma

$Q \geq 10$

$P_{fusion} \geq$ 500MW for ~500s



$R \sim 6m$; $B \sim 5T$; $I_{plasma} \sim 15MA$

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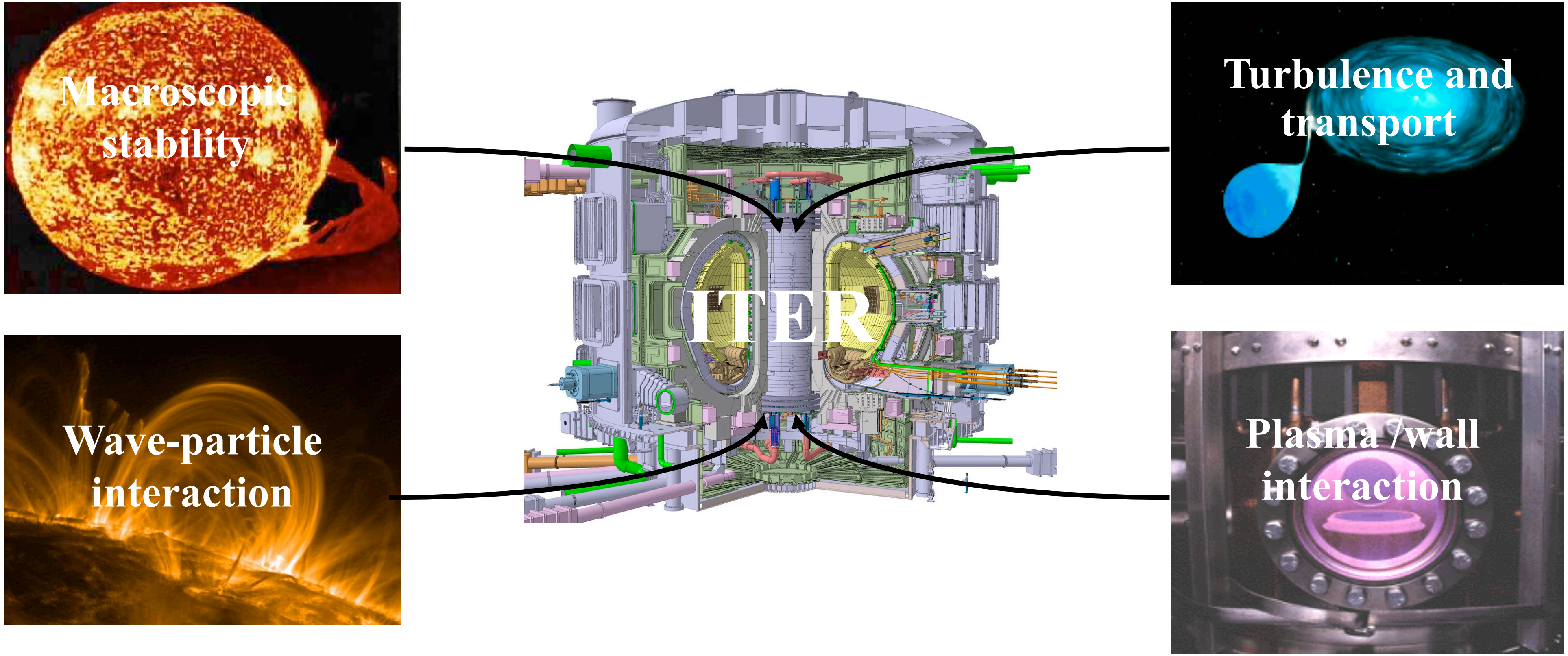
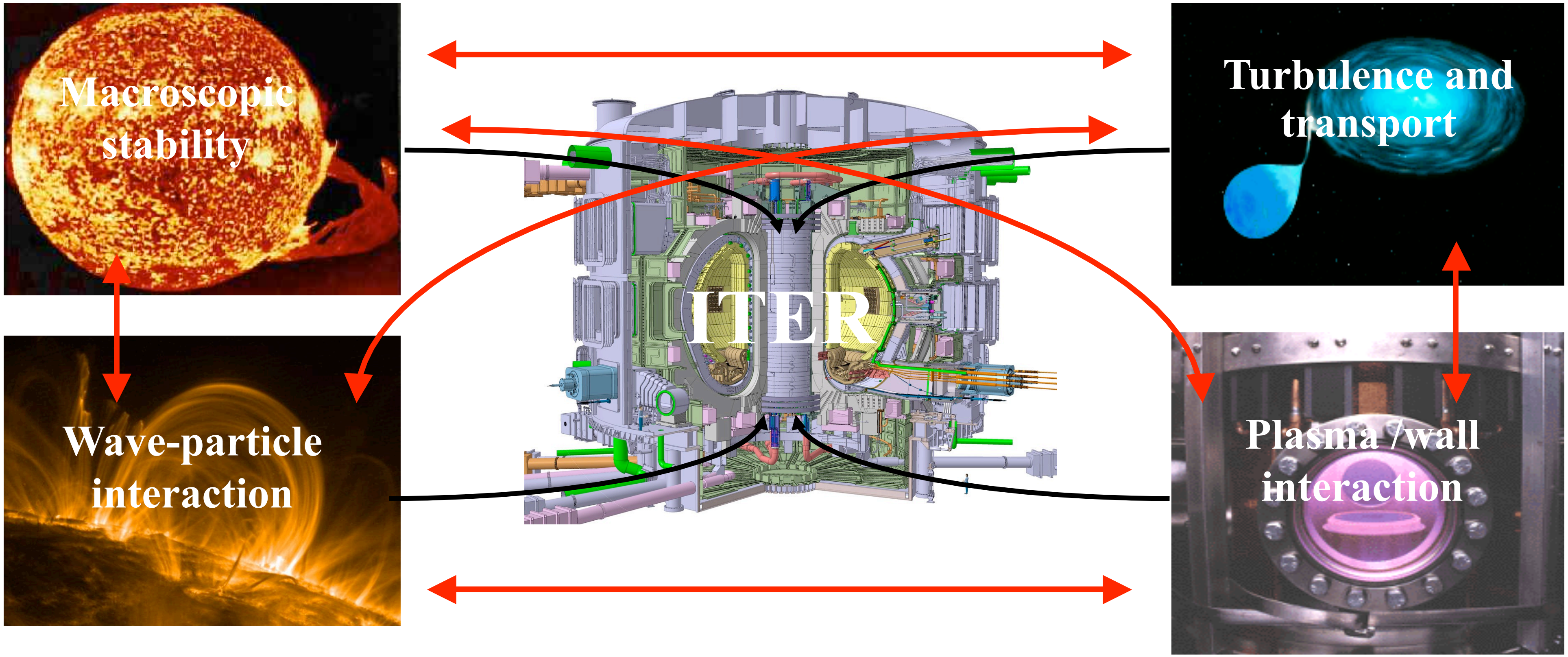
Progress in key physics areas is leading to next step burning plasma experiment



Burning plasmas are complex systems in which all elements are coupled via the α's

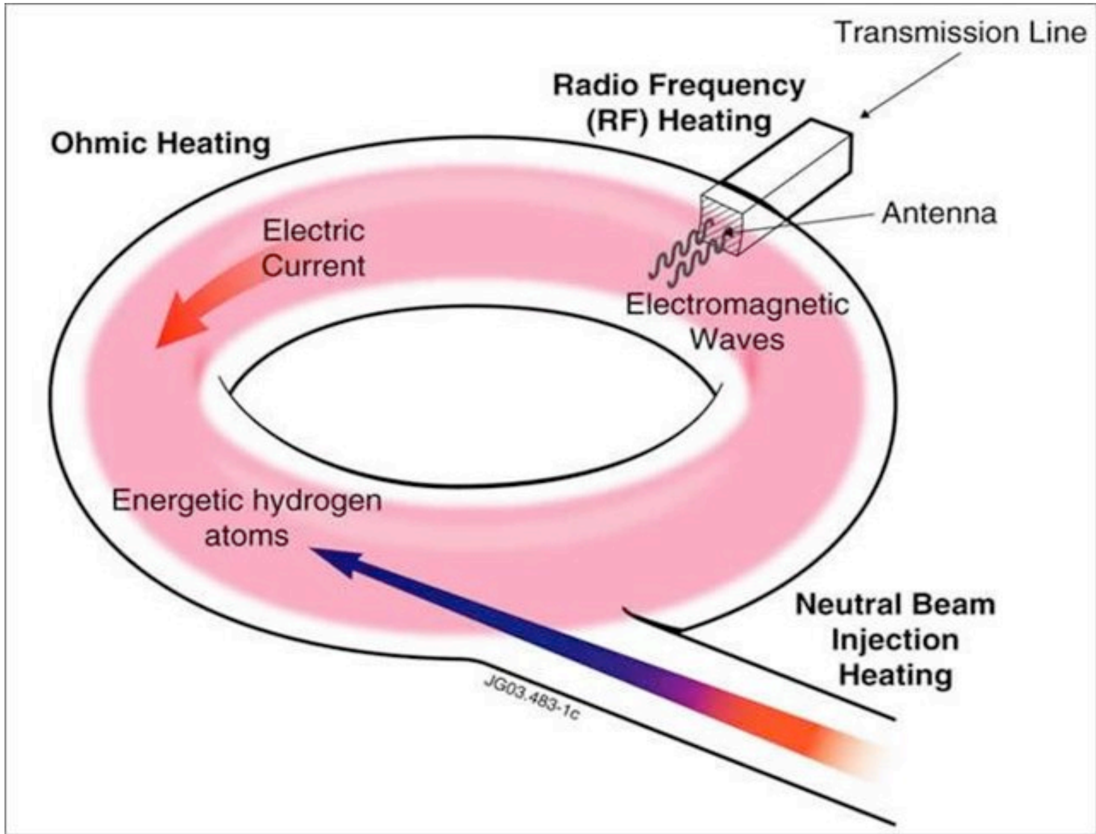


- The coupling of these elements makes extrapolations from weakly self-heated plasmas difficult and may lead to new phenomena
- A fundamental building block of burning plasma physics is the physics of energetic ions and the implications on self-heating

Energetic ions from additional heating

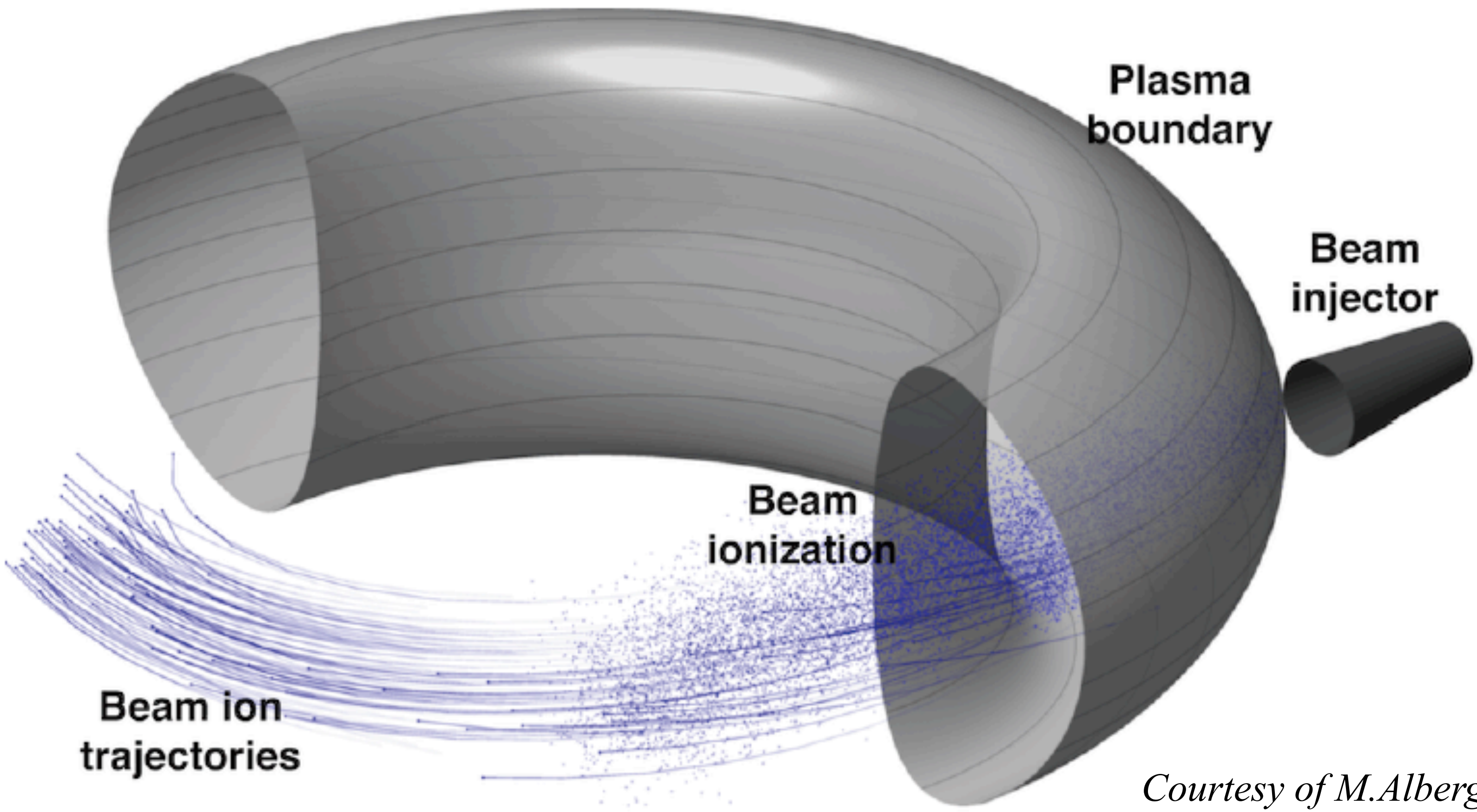
- Burning plasma regime is reached using external heating and current drive
  - *Electron cyclotron heating*
  - Ion cyclotron heating
  - Neutral beam heating

Based on creation of ~MeV ions, then thermalised by collisions



Energetic ions from Neutral Beam Injection

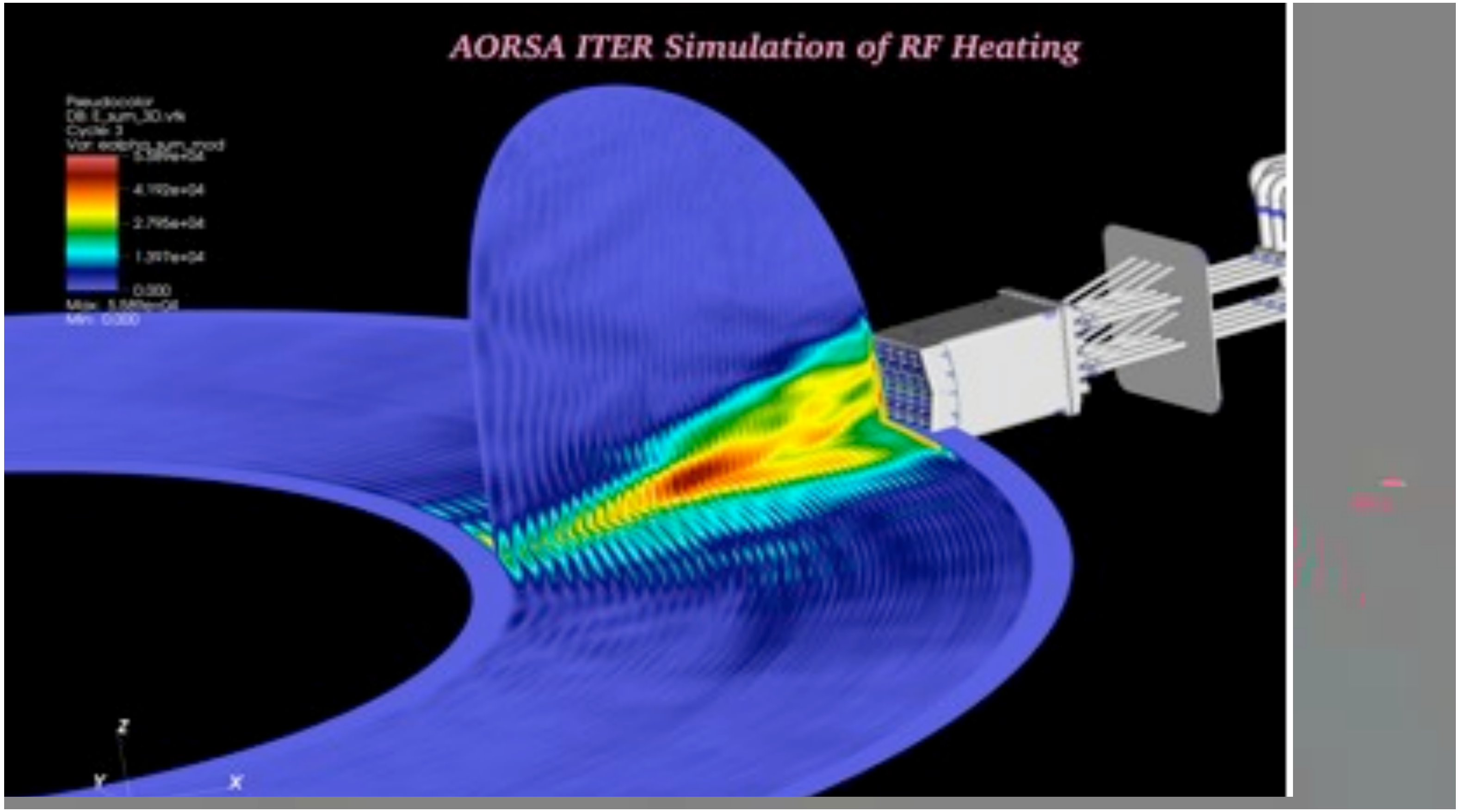
- Ions at ~100keV in present devices, ~1MeV in ITER
- Injection geometry determines orbits. If tangential, mostly passing orbits



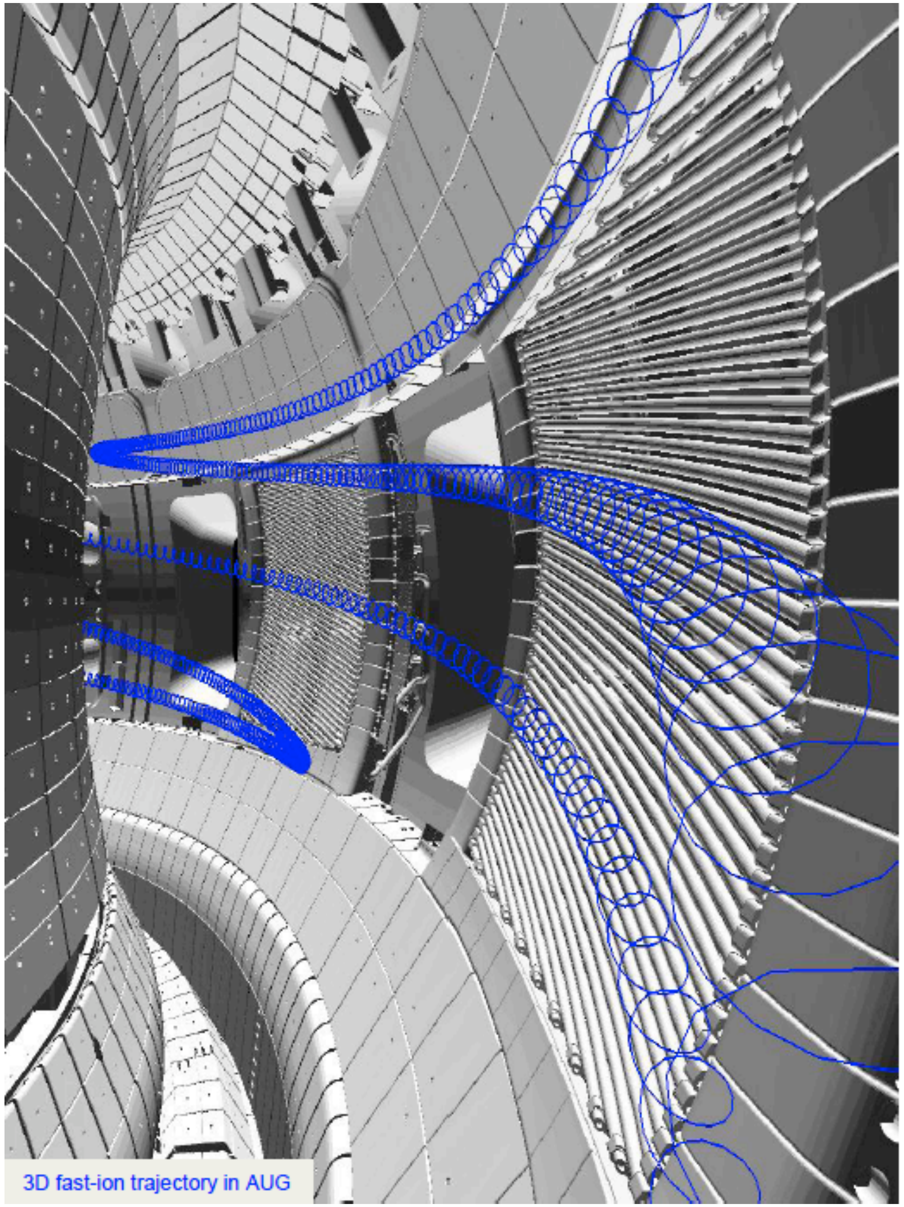
Courtesy of M.Albergante

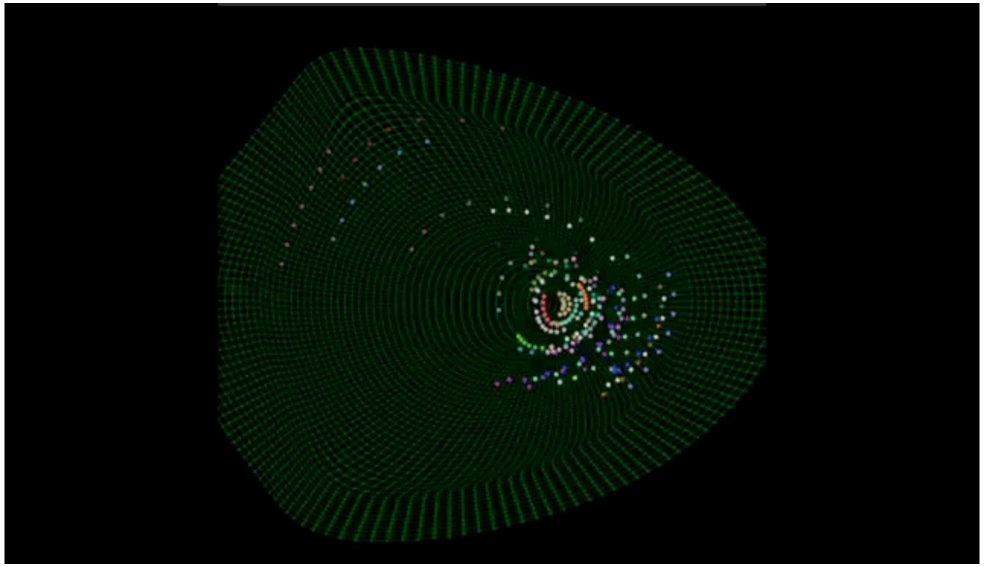
Energetic ions from Ion Cyclotron Heating

- Wave fields at $\omega \sim \omega_{ci}$ give enegy to perpendicular motion of minority ions
  - Strongly anisotropic distribution function
  - Mostly trapped orbits



Energetic ion orbits in tokamaks





GPU-NUBEAM DIII-D Simulation

Sources of fast ions

Fast ion parameters in contemporary experiments compared with projected ITER values.

Tokamak	TFTR	JET	JT-60U	JET	ITER
Fast ion Source	Alpha Fusion	Alpha Fusion	Deuterium Co NBI	Alpha ICRF tail	Alpha Fusion
τ_S (s)	0.5	1.0	0.085	0.4	0.8
δ/a^{a}	0.3	0.36	0.34	0.35	0.05
$P_f(0)$ (MW m^{-3})	0.28	0.12	0.12	0.5	0.55
$n_f(0)/n_e(0)$ (%)	0.3	0.44	2	1.5	0.85
$\beta_f(0)$ (%)	0.26	0.7	0.6	3	1.2
$\langle\beta_f\rangle$ (%)	0.03	0.12	0.15	0.3	0.3
max $\lvert R\nabla\beta_f\rvert$ (%)	2.0	3.5	6	5	3.8
$v_f(0)/v_A(0)$	1.6	1.6	1.9	1.3	1.9

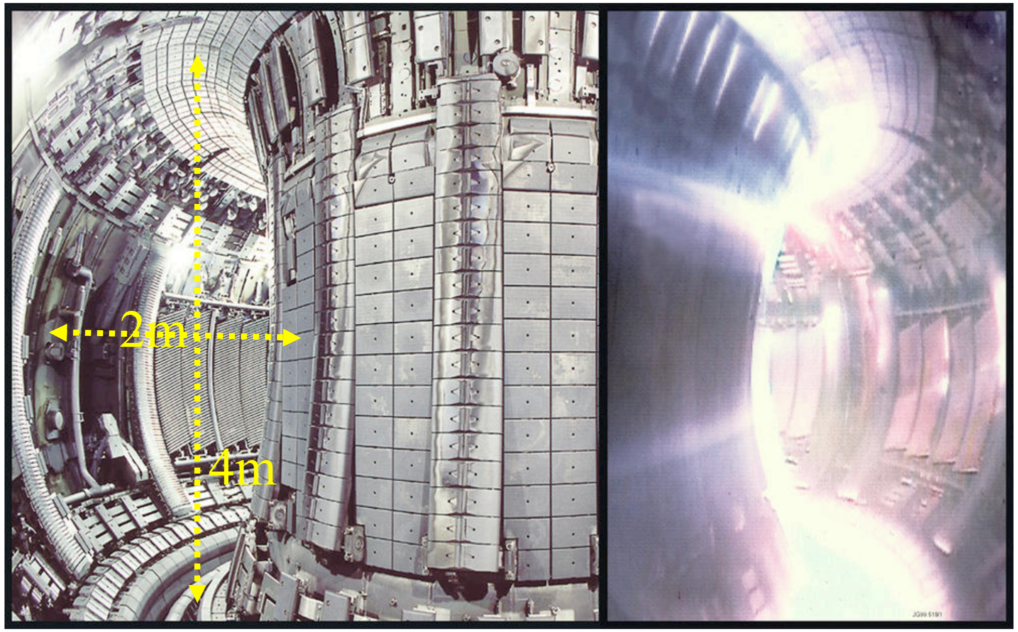
[a] Orbit shift from magnetic flux surface for banana particles: $\delta = q\rho_f\sqrt{R/r}$.

A.Fasoli et al., NF (2007)

- Main differences between existing devices and ITER
  - Orbits: anisotropy, size relative to machine size: $\rho^*_{fast} >> \rho^*_{fast,ITER}$
  - Slowing down relative to confinement time $\tau_S/\tau_E >> \tau_S/\tau_{E,ITER}$

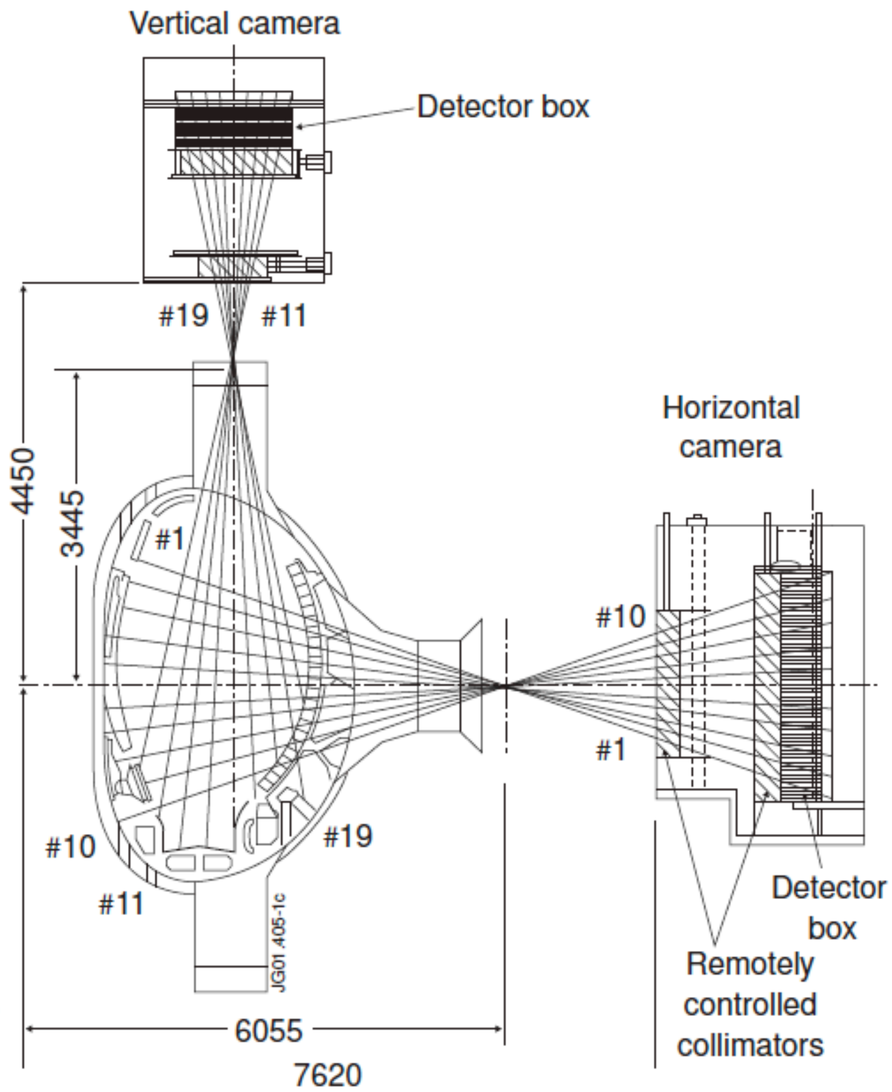
Measurement of confined energetic ions
Neutron / γ ray emission profiles

The JET tokamak



R~3m; $B_T \leq 4T$; $I_p \leq 4MA$; D, H, He, D-T

Detectors:
- NE213 liquid scintillators (2.5 & 14 MeV)
- Bicron-418 plastic scintillators (14 MeV)
- CsI(Tl) photo-diodes (hard X-rays and γ-rays)

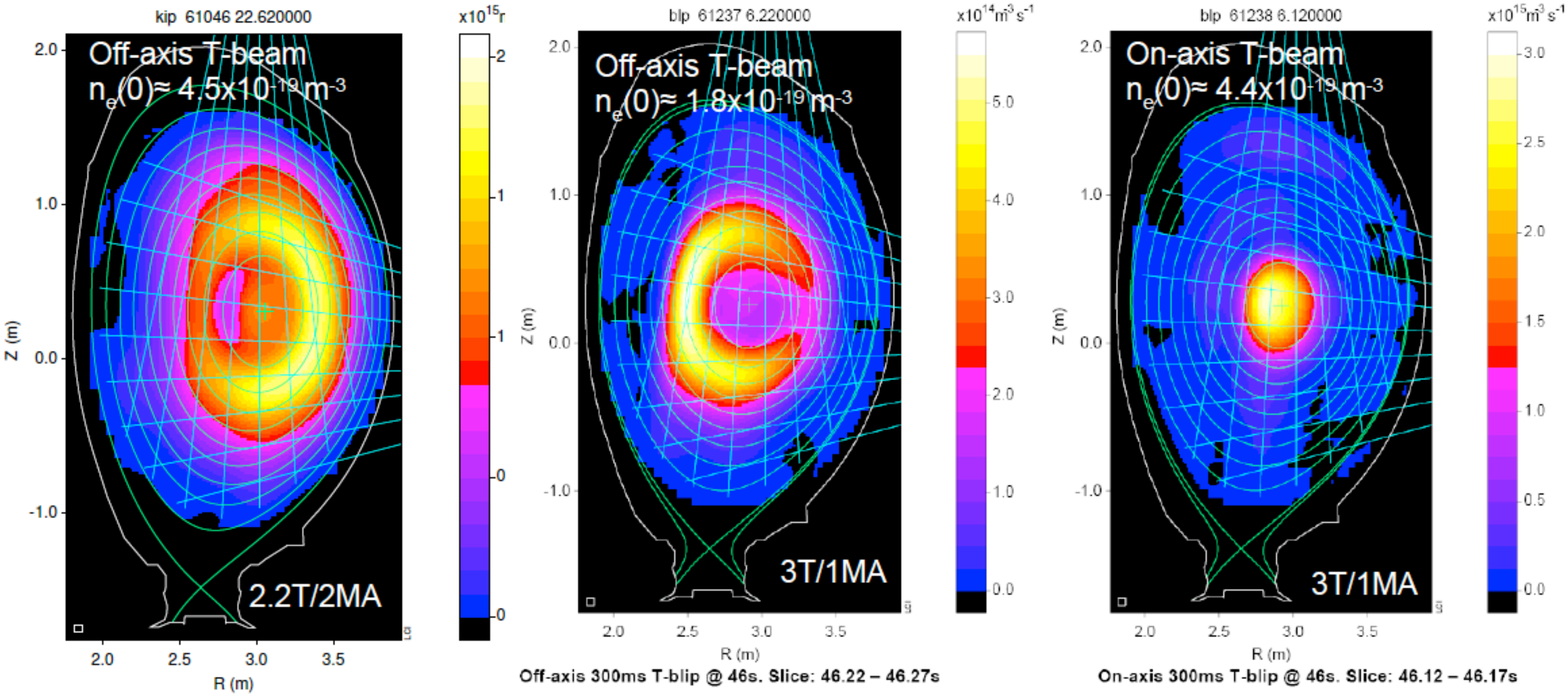


EUROPEAN FUSION DEVELOPMENT AGREEMENT

Courtesy of V.Kiptily

Evidence for fast ions in JET - NBI
Neutron emission profiles in trace-T experiments

14-MeV neutron profile measurements in the monotonic current discharges with T-NBI blips



CRPP EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET

Courtesy of V.Kiptily

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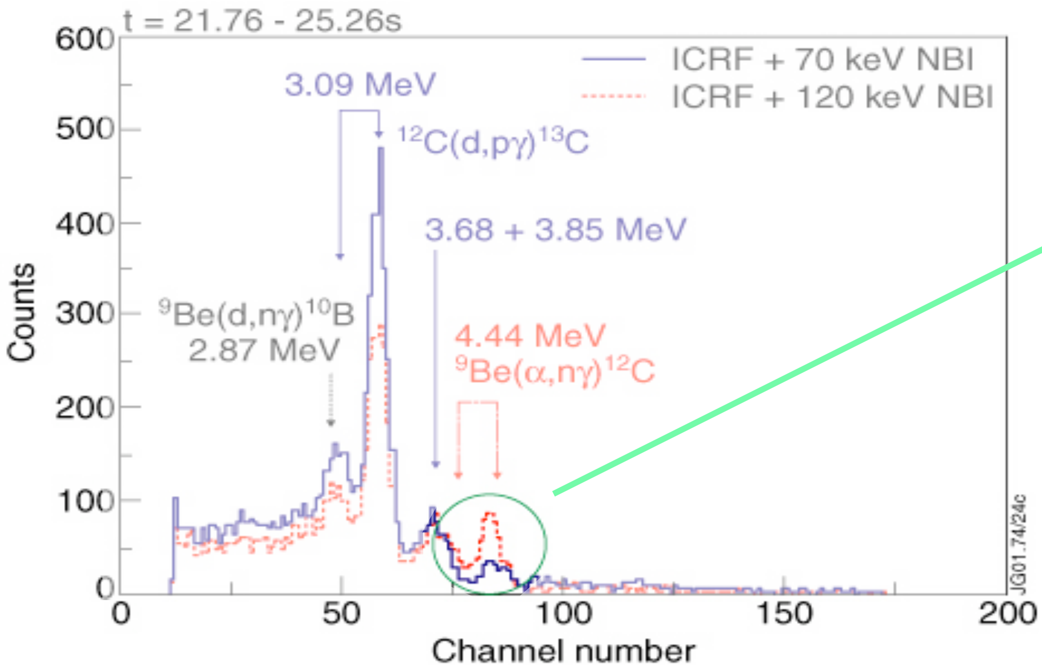
Evidence for fast ions in JET – ICRH γ-rays spectrum

Ex.: ^{4}He acceleration by ICRH at $f_{ICRH}=3f_{ci}(^4He)$

γ-ray emission spectrum

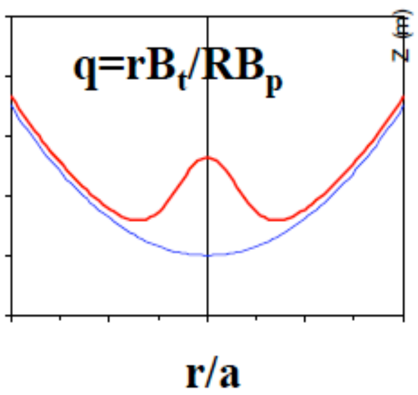


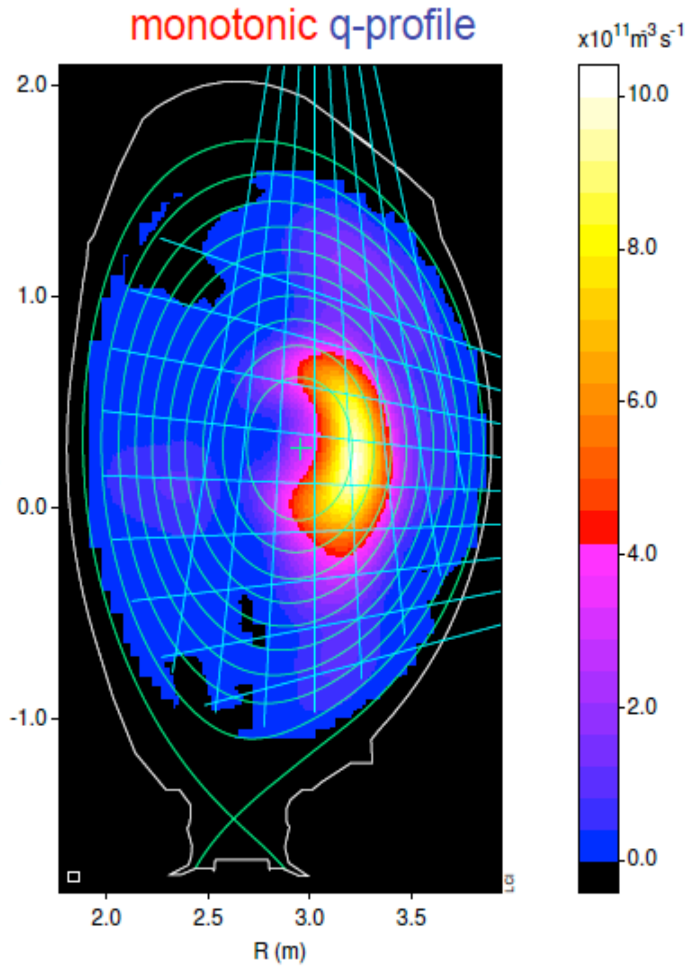
signal from reaction $^9Be(\alpha,n\gamma)^{12}C$

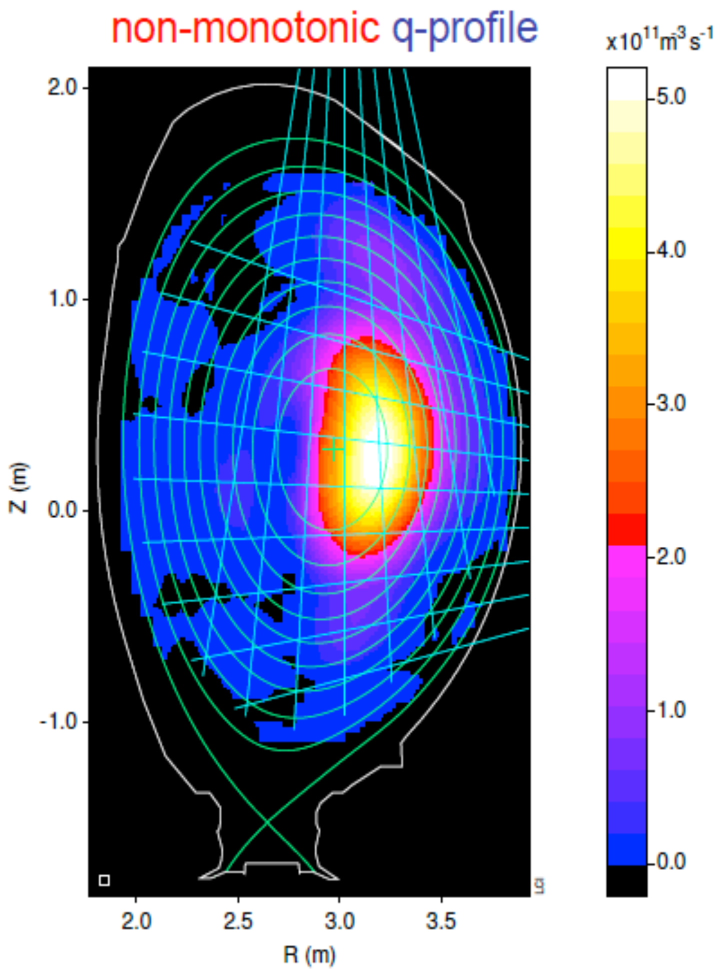
→signature of ^{4}He ions with E_α>~2MeV

Evidence for fast ions in JET – ICRH γ-rays profile

Ex.: ^{4}He acceleration by ICRH at $f_{ICRH}=3f_{ci}(^4He)$

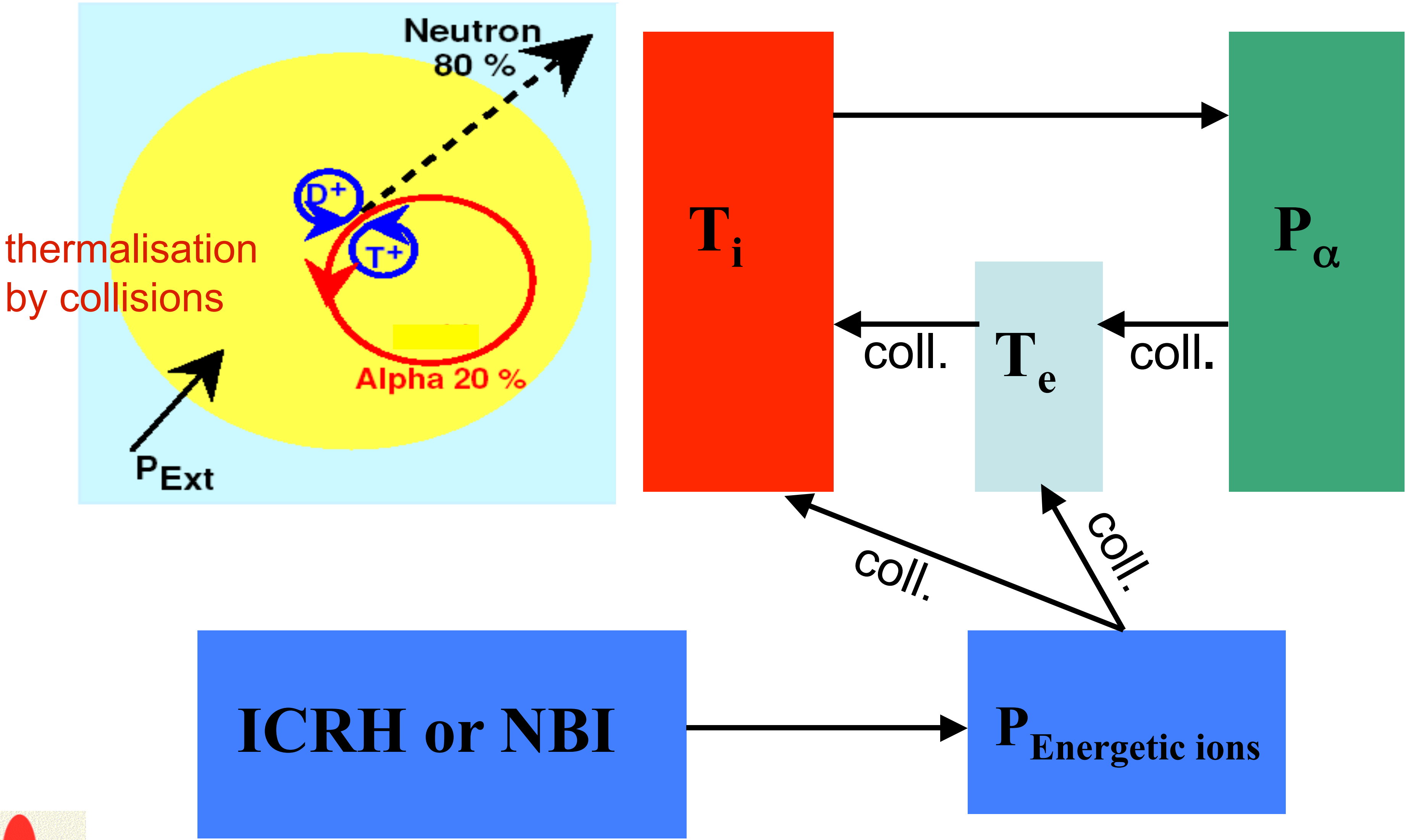






Kiptily et al NF **45** (2005) L21

External heating and self-heating

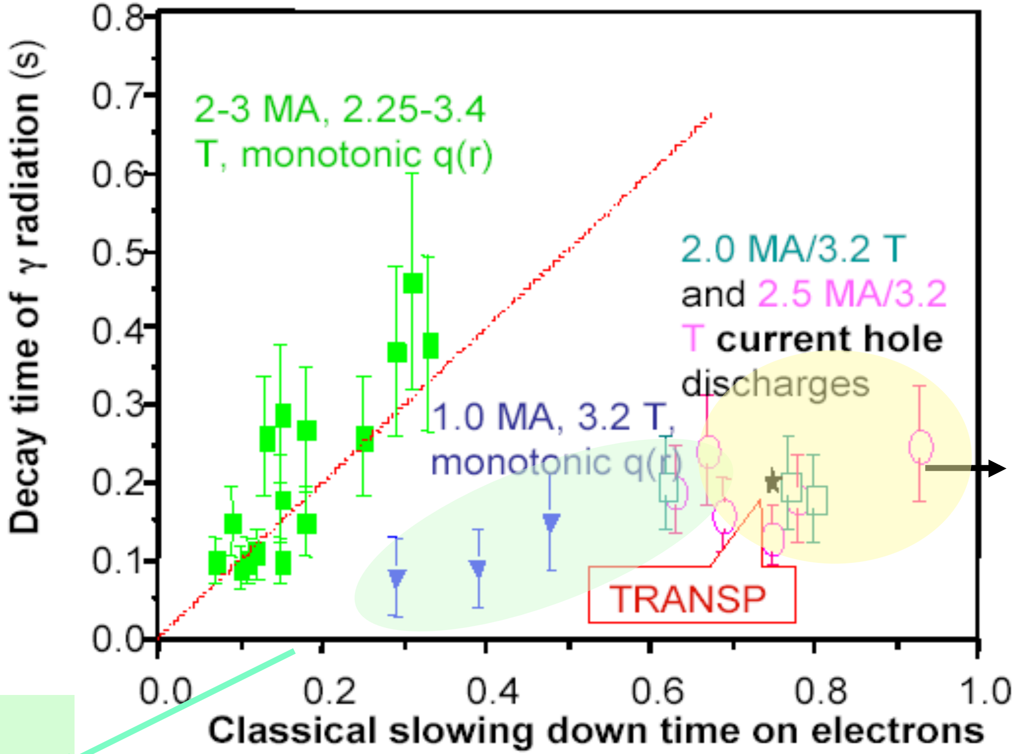


External heating and self-heating

- To reach and sustain burning plasma regime, energetic ions must be well confined

Self-heating: collisional slowing down

- JET trace T experiments: γ-ray spectroscopy
  → direct observation of collisional slowing down (unless plasma current is too small)

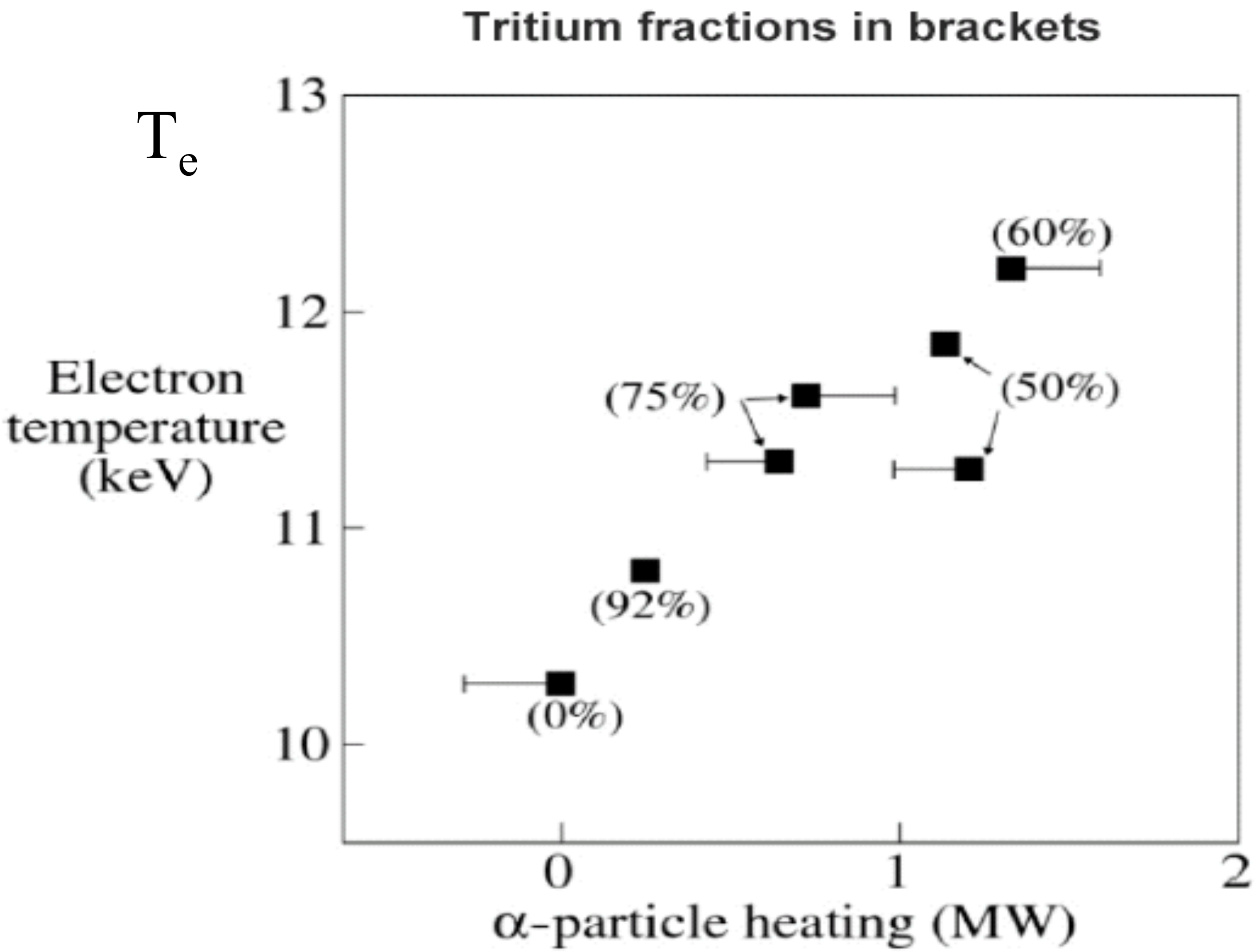


Current profile not apt to confine α's

Too low current

Self-heating: α electron heating

- Electron heating in D-T ($Q \lesssim 1$) on JET



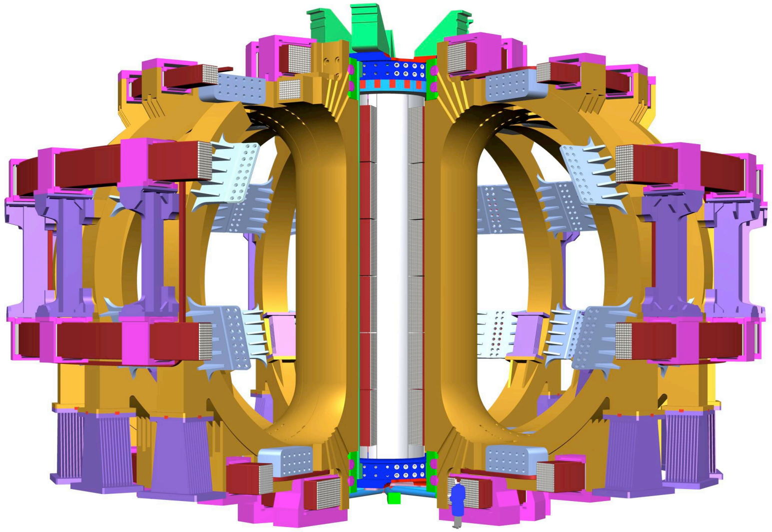
P R Thomas et al, PRL (1998)

External heating and self-heating

- To reach and sustain burning plasma regime, energetic ions must be well confined

- Need to understand and possibly minimize redistribution and loss mechanisms
  - Magnetic field imperfections (ripple and externally applied perturbations)
  - Low frequency MHD instabilities
  - Turbulence
  - Resonant interaction with Alfvén waves

Ripple losses



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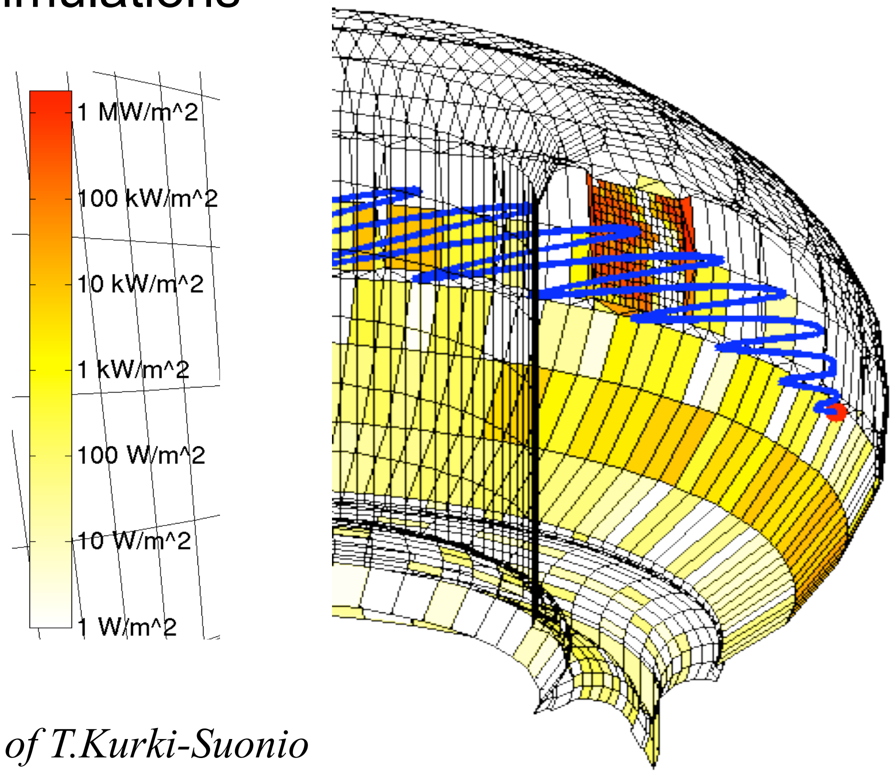
- 18 toroidal field coils
  - Significant B-field ripple
  - Orbits can be calculated and power deposited on walls can be evaluated in Monte Carlo simulations

ASCOT code



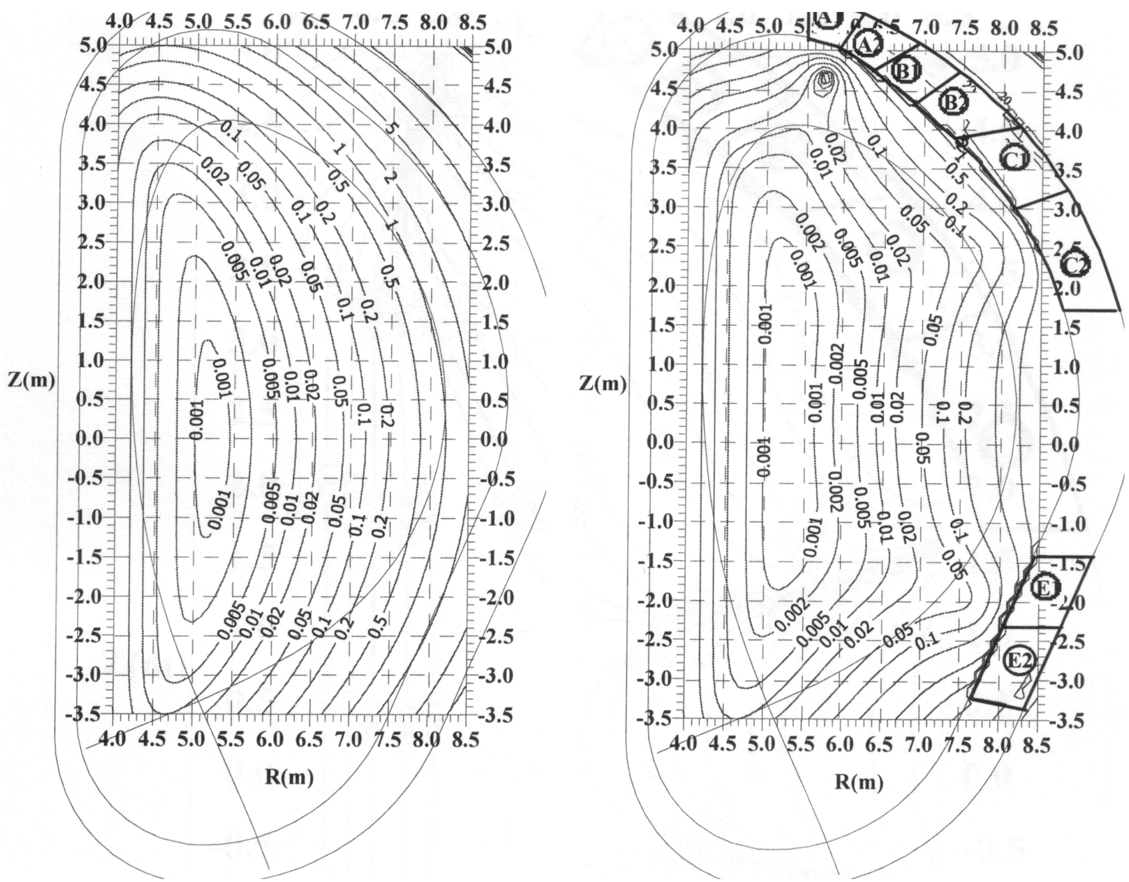
Courtesy of T.Kurki-Suonio

Ripple losses - mitigation

ITER

- How can magnetic ripple be reduced?

  → Ferritic inserts



TF only | TF with ferritic inserts

A.Fasoli et al., NF (2007)

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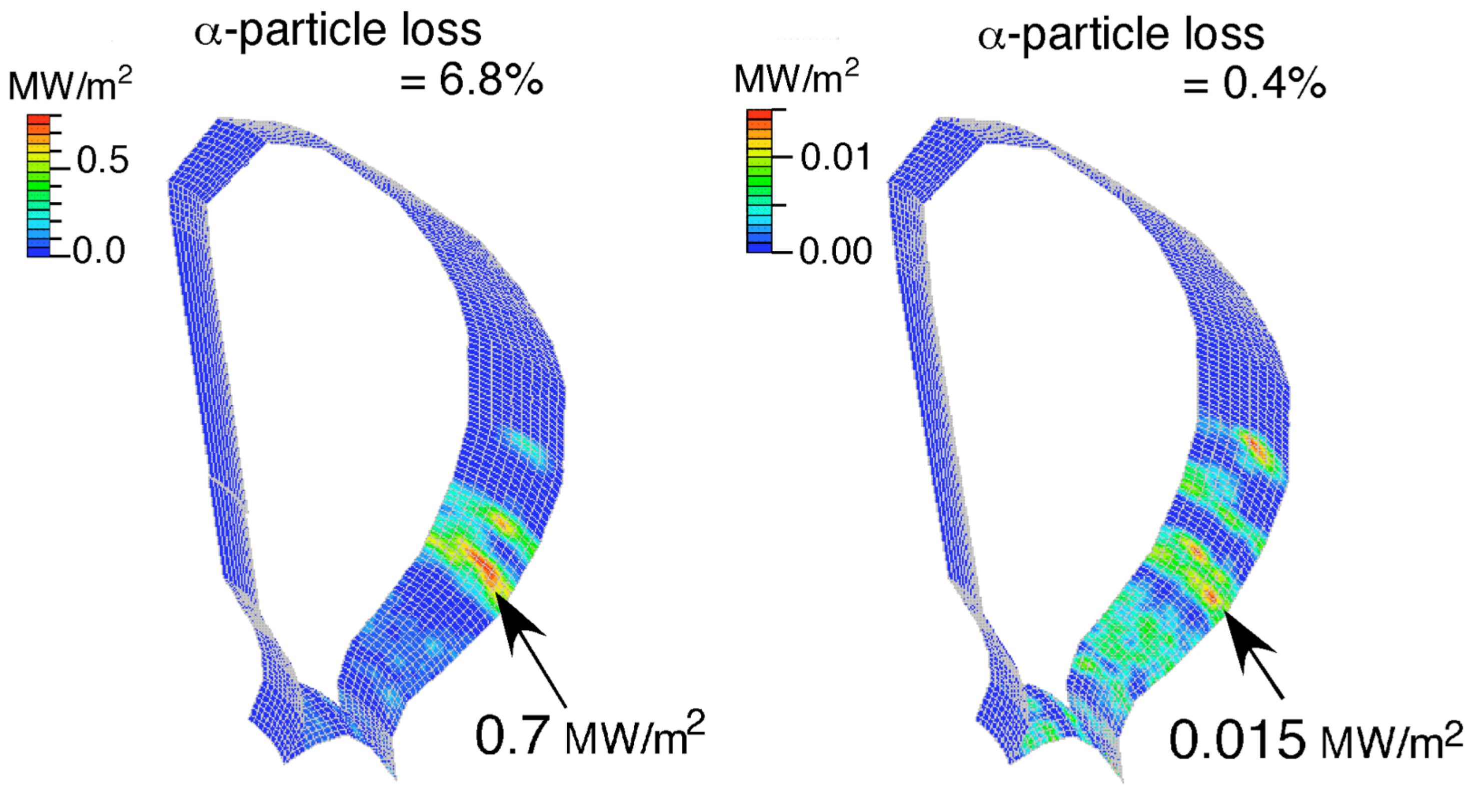
Ripple losses - mitigation

ITER

- How can magnetic ripple be reduced?

  → Ferritic inserts



A.Fasoli et al., NF (2007)

TF only　　　　TF with ferritic inserts

Ripple losses – effect of test blanket modules

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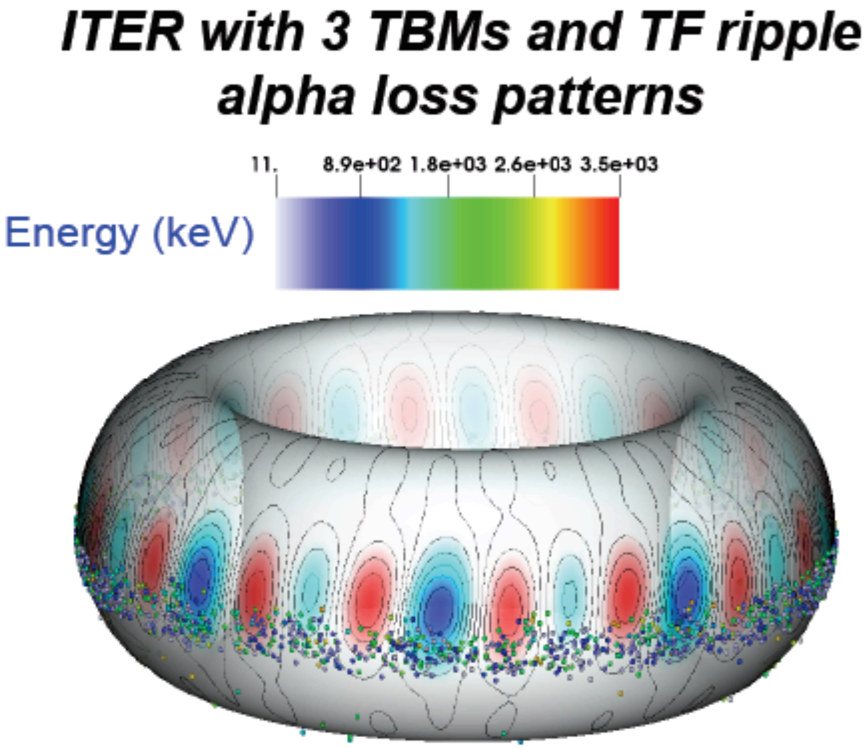
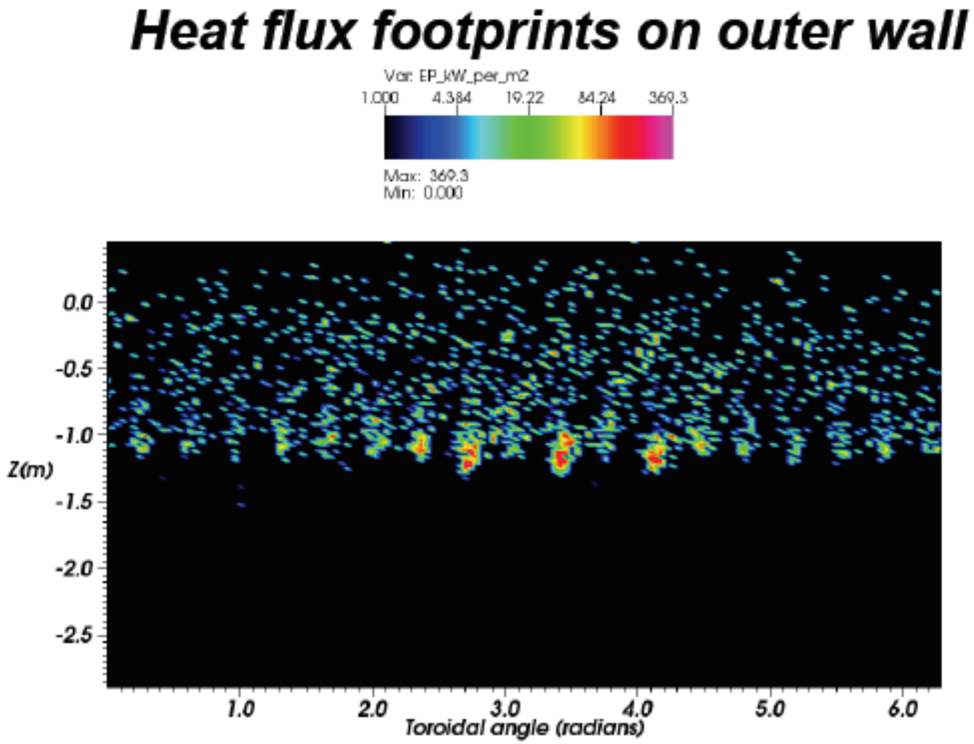
- Additional problems: test blanket modules perturbing B locally





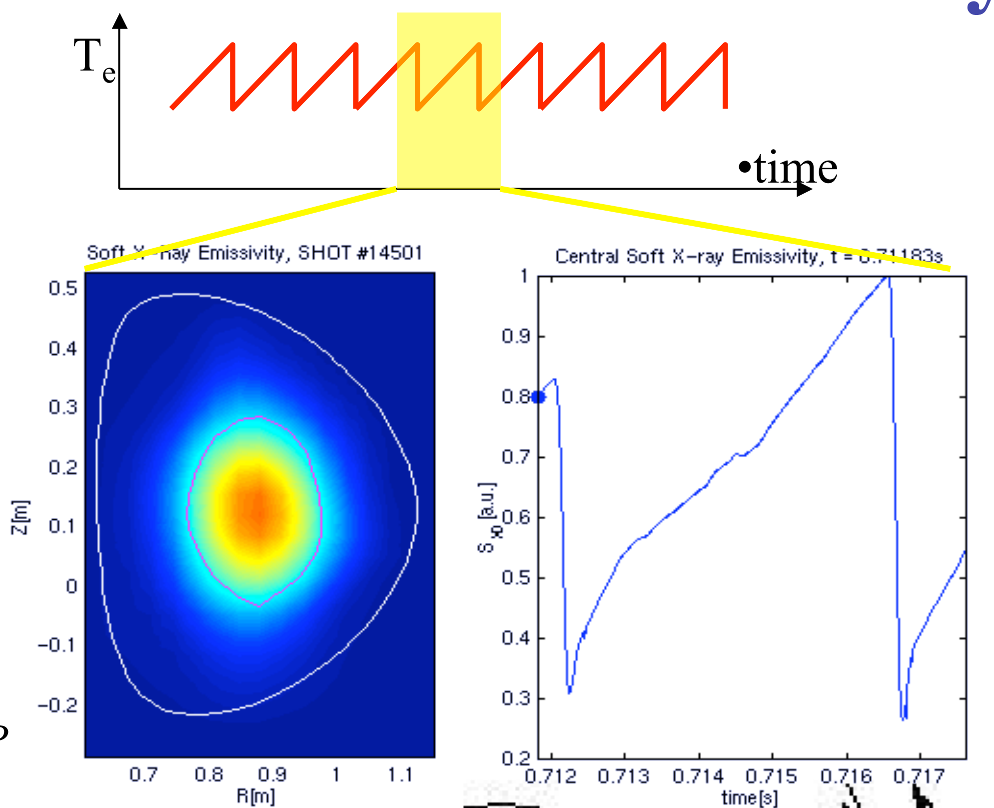
- Loss levels are acceptable

Courtesy of D.Spong

- Numerical tools are ready to address orbit losses in the presence of other possible perturbations (e.g. coils for ELM control)

Low frequency MHD - the sawtooth instability

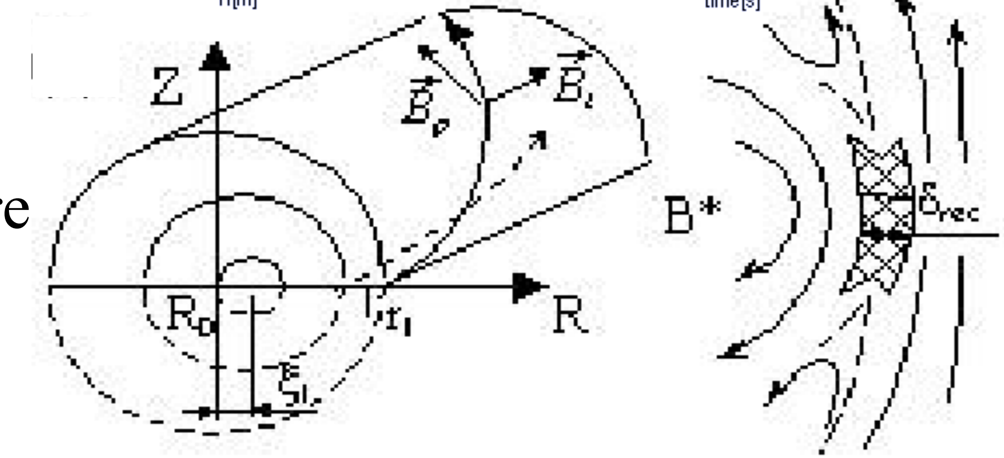
- Sudden, very fast losses of energy and particles in core
- Ex.: X-ray emissivity ($\sim T_e$, n) evolution in TCV



Courtesy of I.Furno, CRPP

→local breaking of magnetic structure

→redistribution of energetic ions



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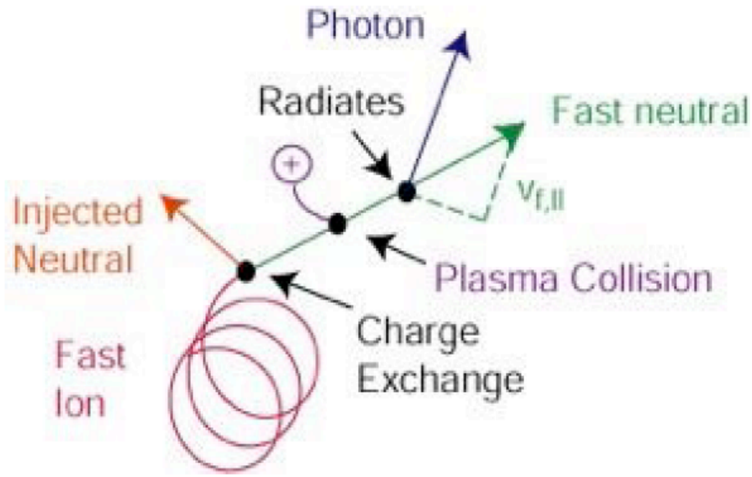
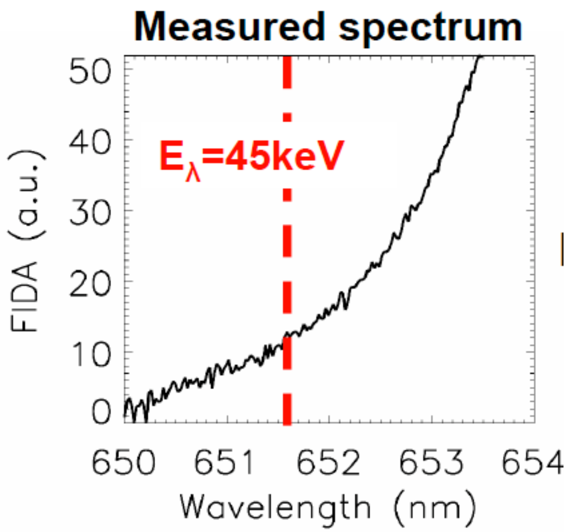
Low frequency MHD - the sawtooth instability

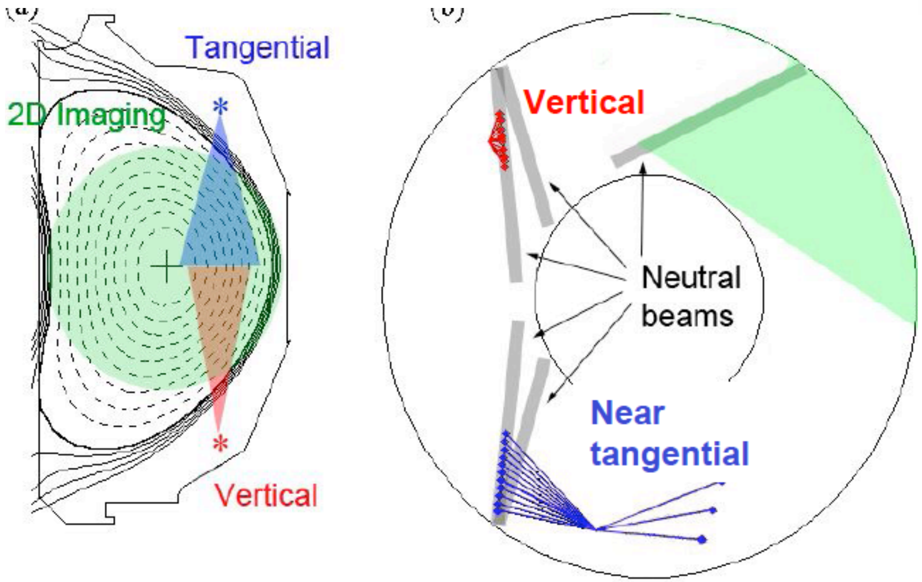
How to measure internal redistribution?

→ **Fast ion Dα**





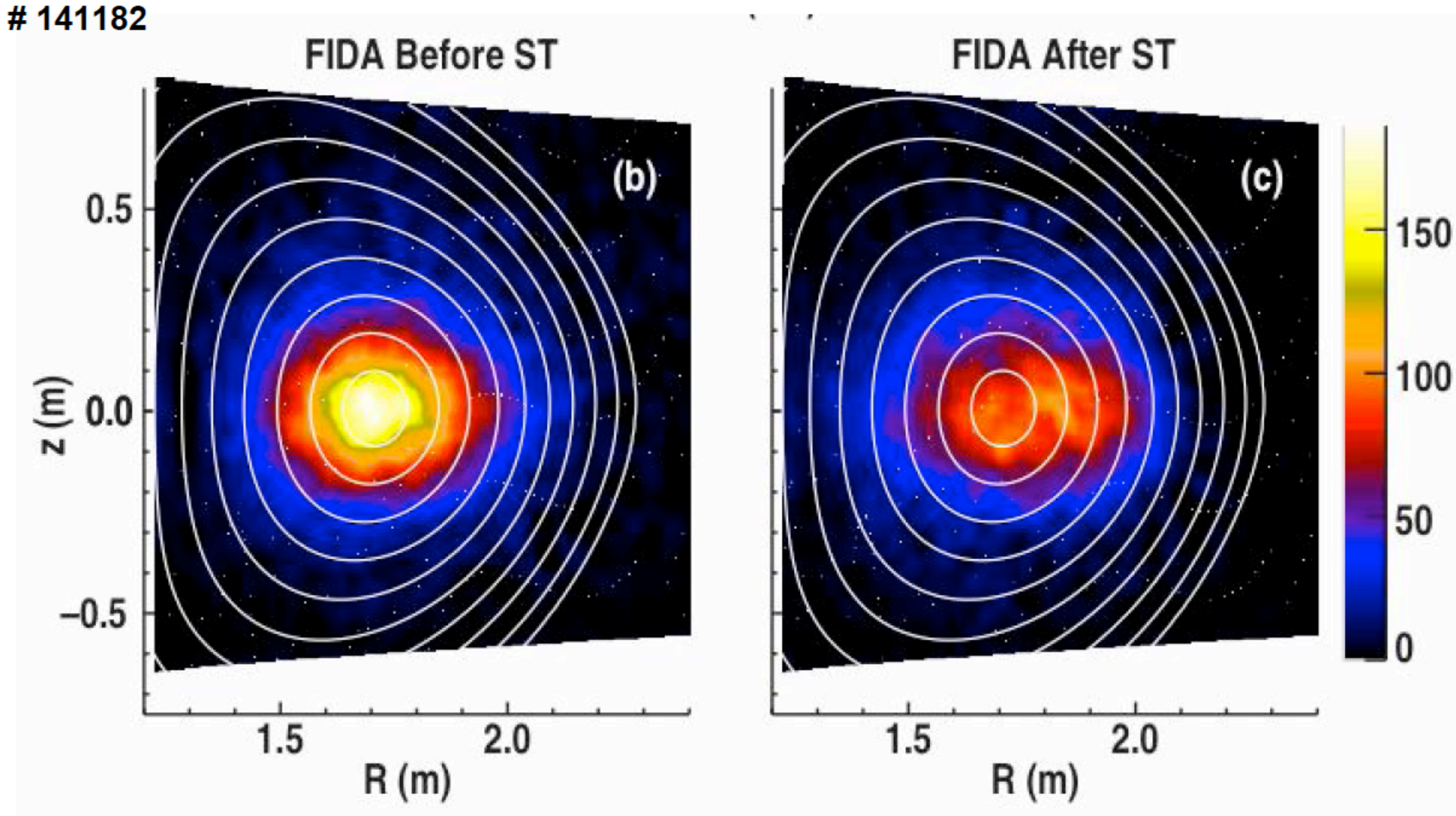
2D imaging



Courtesy of W.Heidbrink and C.M.Muscatello

Low frequency MHD - the sawtooth instability

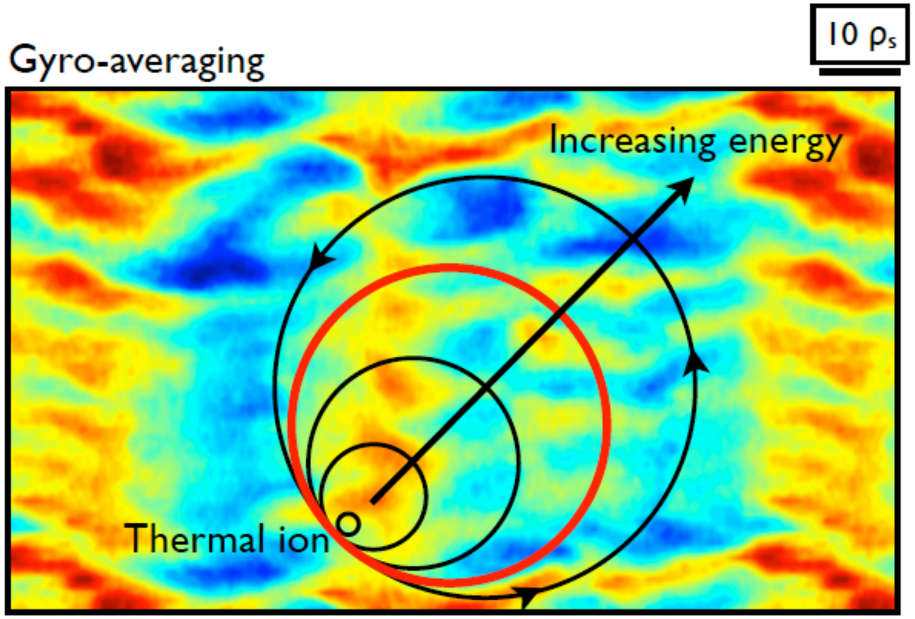
Redistribution measured by Fast ion Dα



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

Energetic ion interaction with turbulence

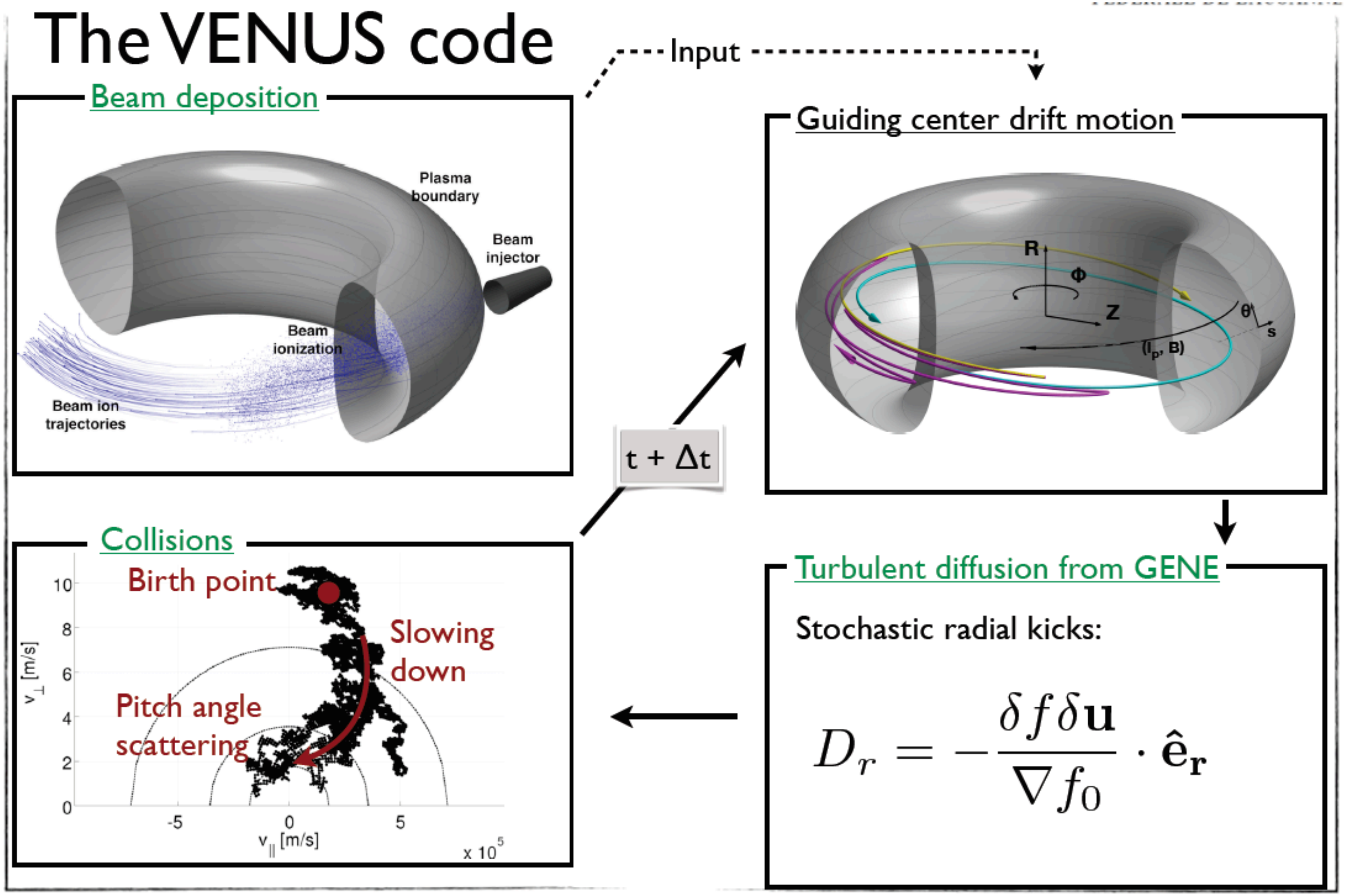
- Large energetic ion orbits are expected to average out the effect of turbulence



Courtesy of M.Albergante

- Are there conditions in which turbulent transport of energetic ions is significant?
- Experimental evidence of some anomalous cases exists
  - Deficit of energetic ions in DIII-D; Asdex-U anomalous NBI current drive profile
- Key parameters are $E_{\text{energetic ions}}/T_{\text{plasma}}$, and the slowing down time

Fast ion interaction with turbulence Modelling

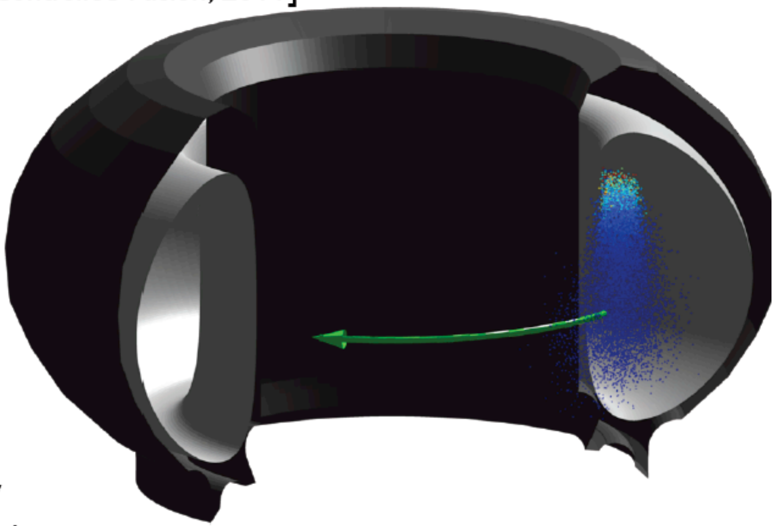


Courtesy of M.Albergante

Fast ion physics interaction with turbulence
Conclusions of modelling

- Present devices (modest values of $E_{\text{energetic ions}}/T_{\text{plasma}}$)
  - Some anomalous transport of NBI ions, hence anomalous heating and current drive
- ITER
  - Negligible effect for NBI ions and for α's
- DEMO ?

"DEMO will be 8.5m major radius with a toroidal field of 6T, [...] whose density will be similar to the ITER density. DEMO is expected to be a high temperature device" [Ward, *Plasma Physics and Controlled Fusion*, 2011]

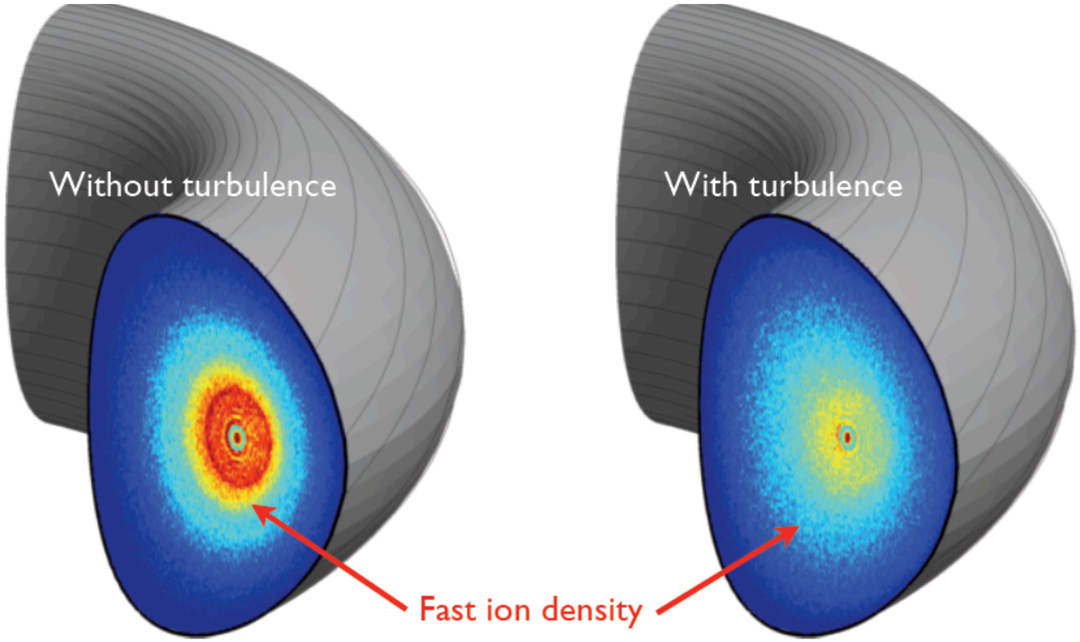


Same density as ITER's
Peak temperature of 50 keV
Neutral beam injection at 1.5 MeV
On-axis, co-current, with E_{nbi}/T_e ratio
- 35, same as ITER

Courtesy of M.Albergante

Fast ion physics interaction with turbulence
Conclusions of modelling

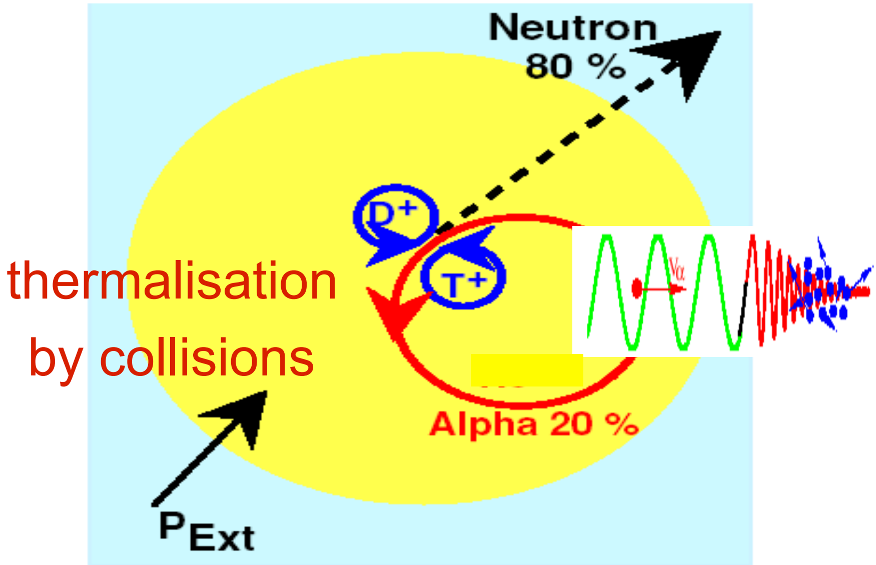
- Present devices (large values of $E_{\text{energetic ions}}/T_{\text{plasma}}$)
  - Some anomalous transport of NBI ions, hence anomalous heating and current drive
- ITER
  - Negligible effect for NBI ions and for α's
- DEMO
  - NBI ions are redistributed

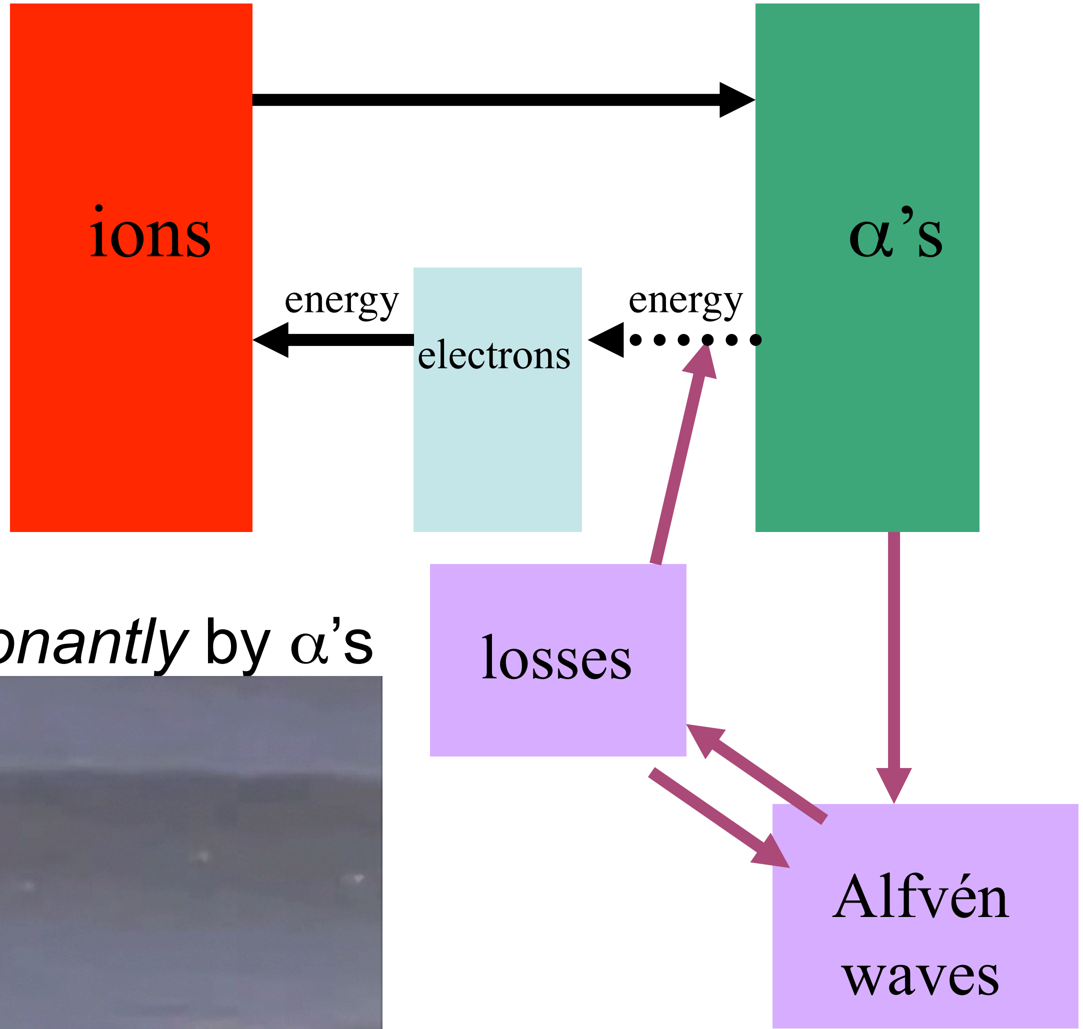


Particle losses do not change: they are negligible
Particles are moved from core to mid-radius

Courtesy of M.Albergante

Resonant interaction with waves and self-heating



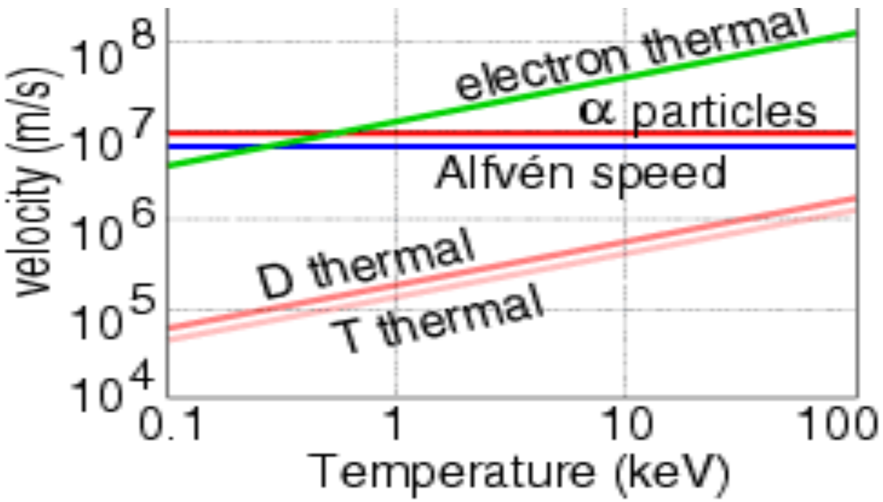


• Alfvén waves can be driven *resonantly* by α's

Alfvén waves and Eigenmodes

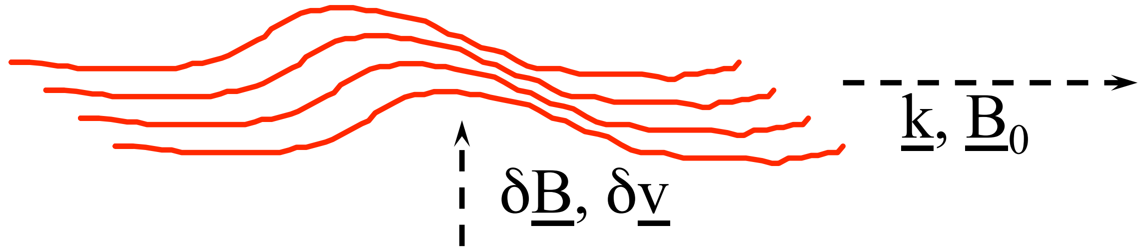
Typical velocities in a tokamak

B=4T; n=10^{20}m^{-3}



- α's resonate with Alfvén Waves
- Alfvén Waves are driven unstable if
  - → sufficient 'free'energy ∇p_α
  - → α drive > plasma damping

– B-field and plasma frozen together; field lines are strings with tension and inertia → Alfvén wave propagation



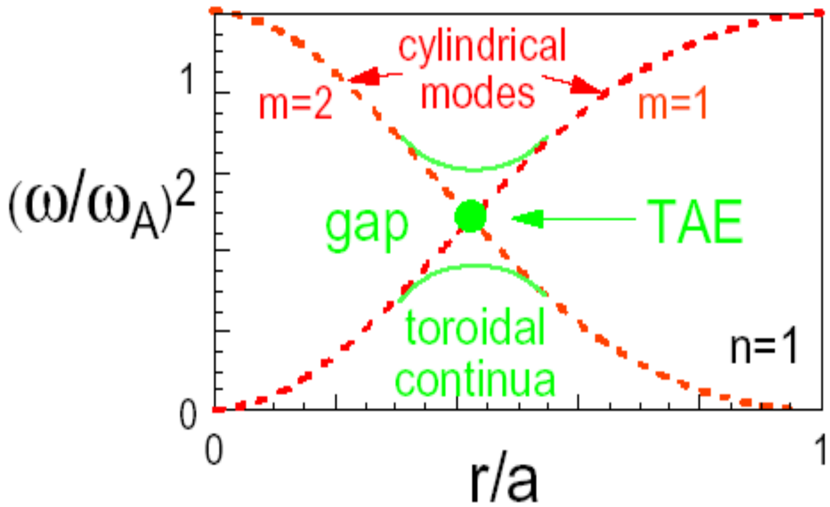
In tokamaks: weakly damped Alfvén Eigenmodes (AEs)

Alfvén waves in nonuniform plasma

– Cylinder: Alfvén 'continuum'

$$\omega^2(r)=k_{||}^2(r)v_A^2(r)$$

- No globally propagating wave
  - small scales → strong damping



– Torus: Fourier $\phi \sim e^{i(m\theta - n\varphi - \omega t)}$

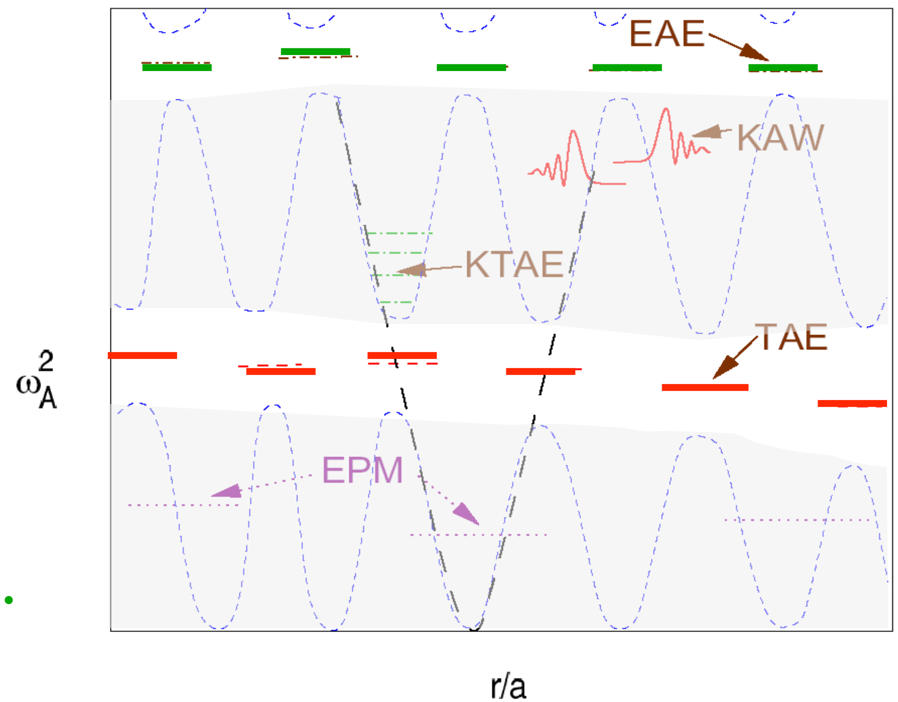
$k_{||}= 1/R\ (n- m/q(r));\ q(r) = rB_z/RB_\theta$

Coupling of toroidal harmonics

→gaps in continuum spectrum

→weakly damped eigenmodes

Toroidal AEs, Elliptical AEs,...



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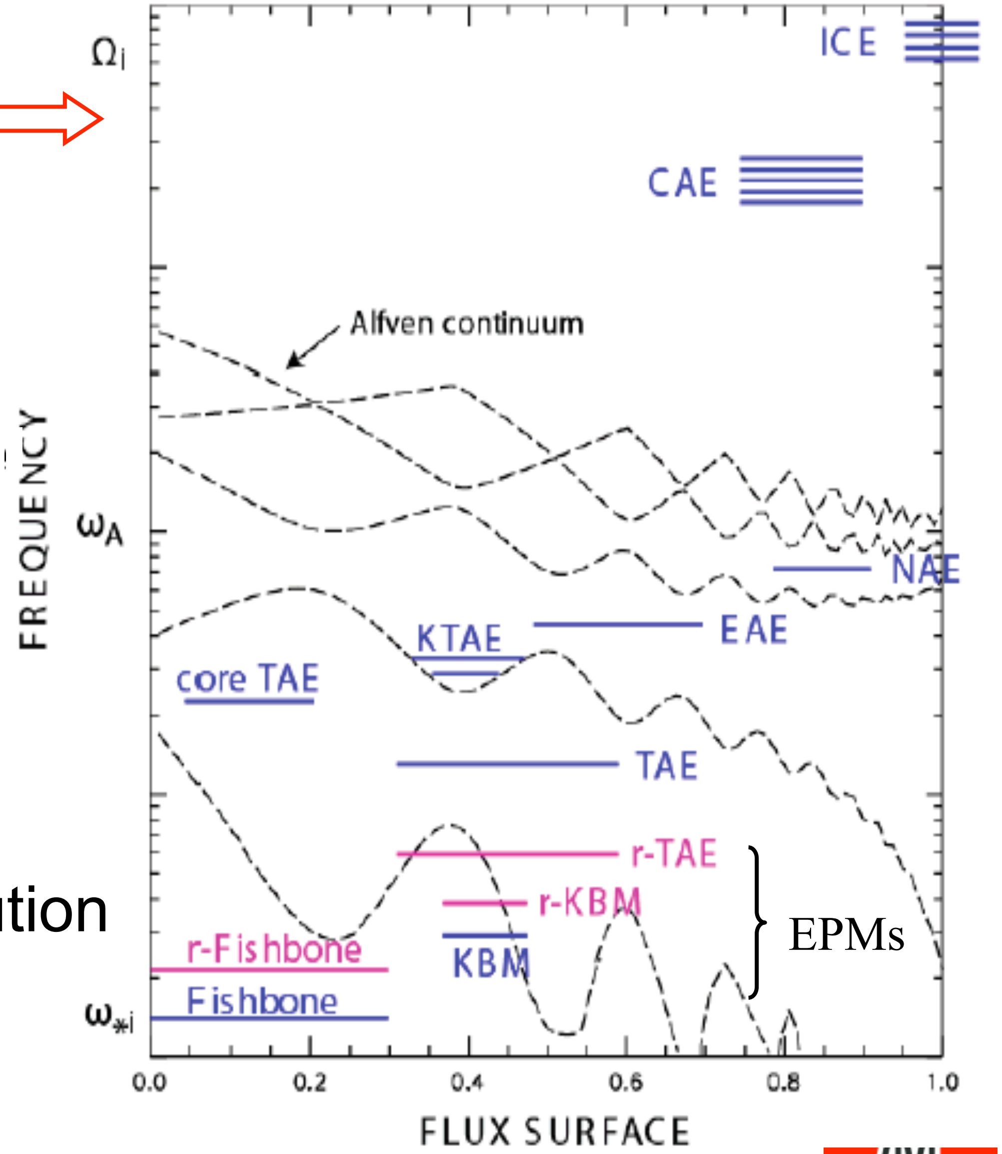
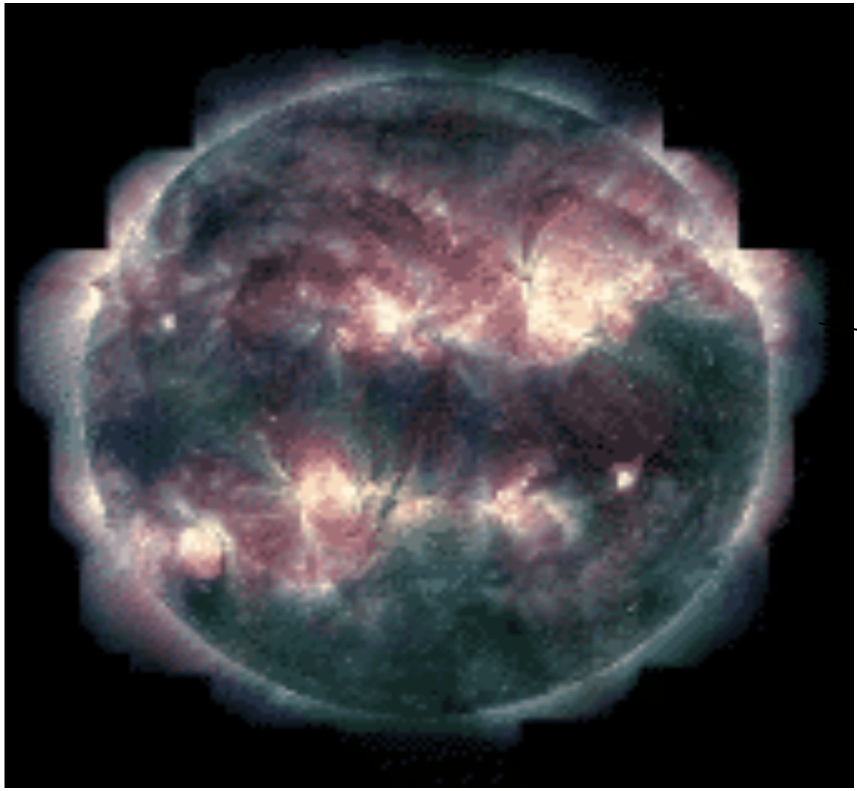
Alfvén Waves and Eigenmodes

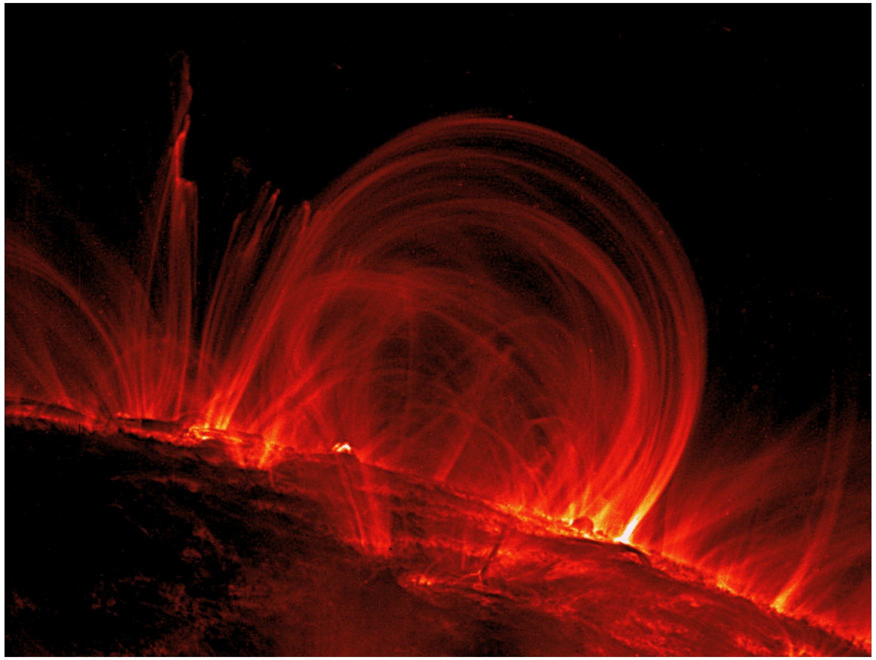
- *Zoo* of Alfvén Eigenmodes (AEs)



- Questions
  - Linear stability
  - Nonlinear interactions: redistribution and losses

Alfvén waves exist also in space plasmas
E.g. coronal loops





Courtesy of NASA

A.J.C.Belien et al., PRL ('96)

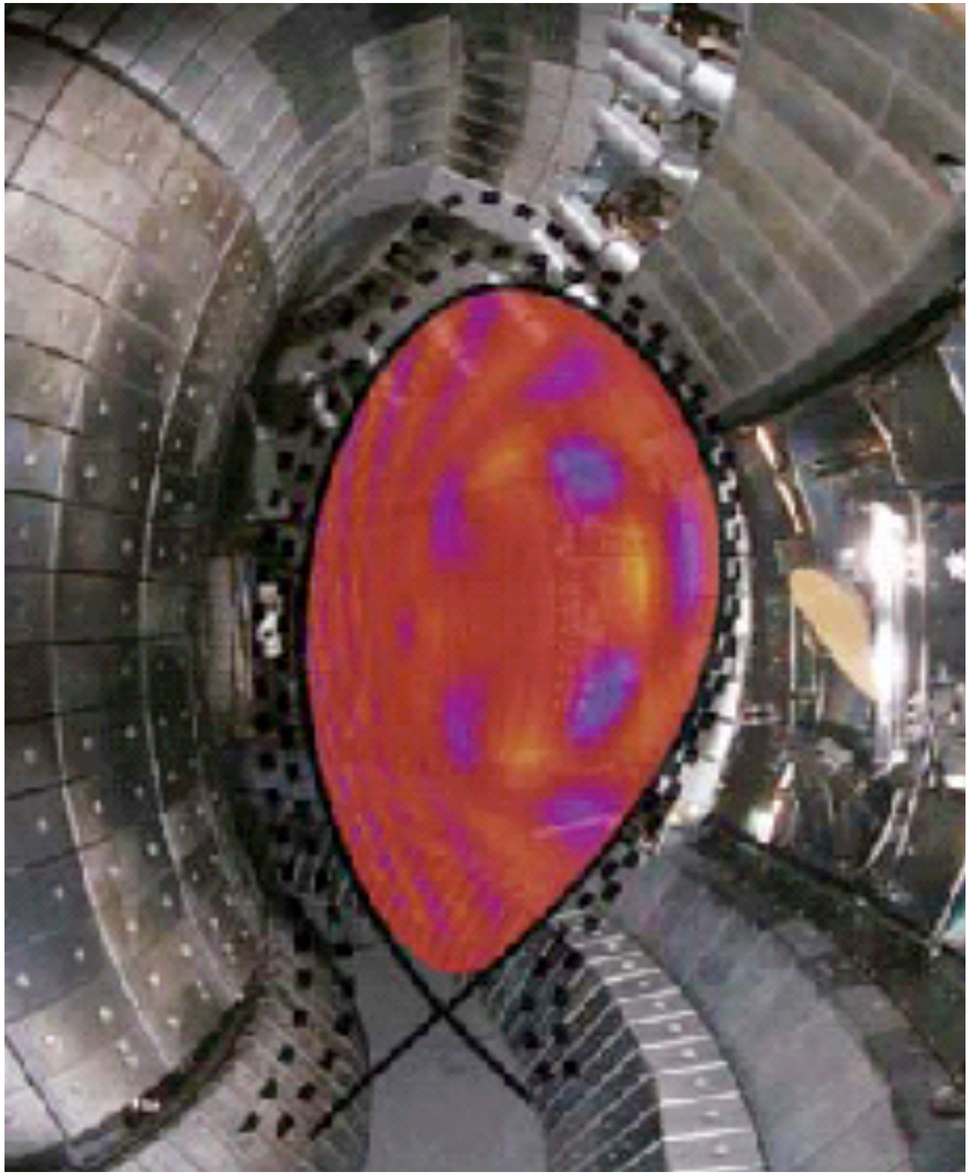
- From remote observations of frequencies

  → information on B-field and density inside loop

Ex. of TAE calculated structure

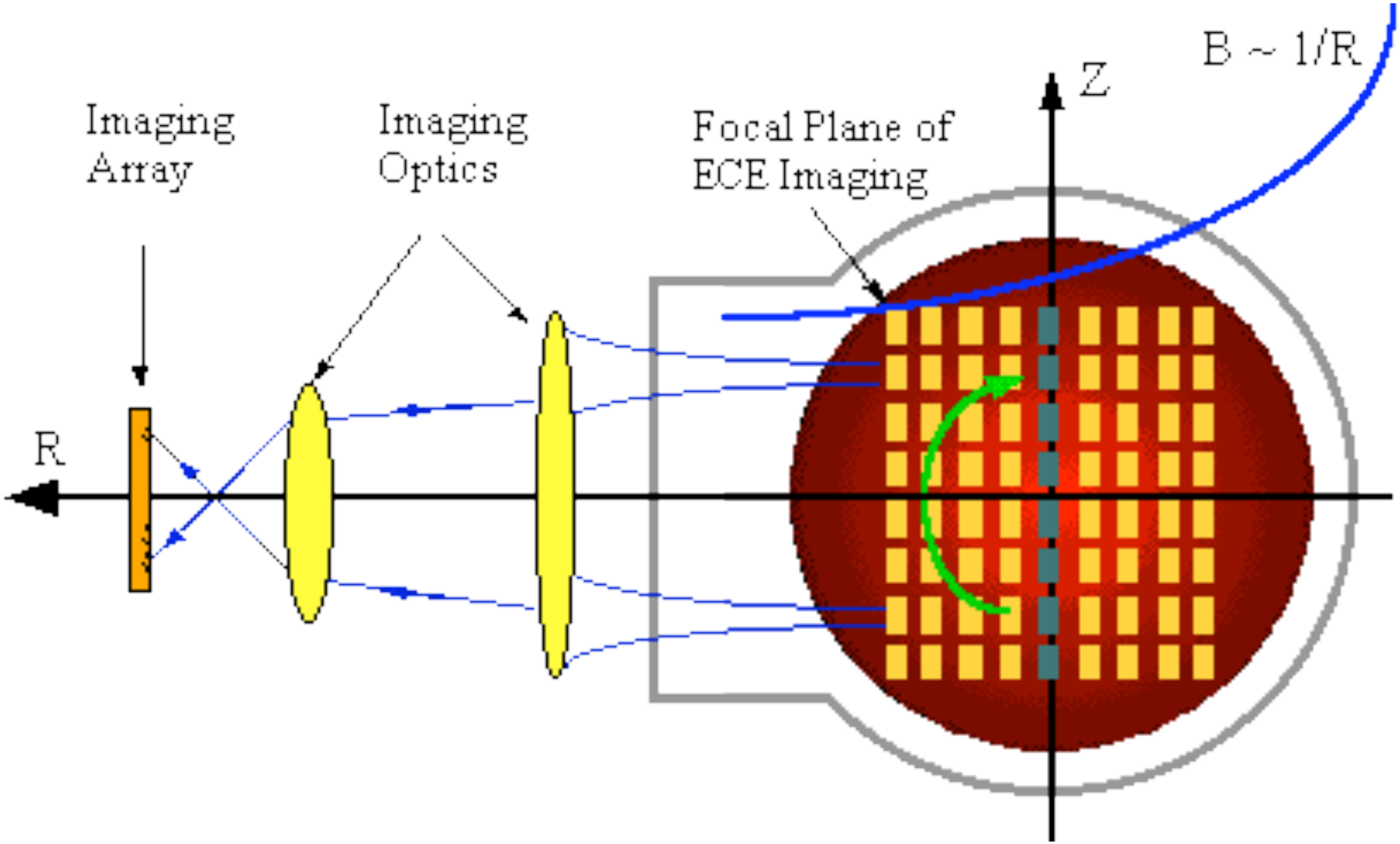
LIGKA code

Asdex-Upgrade



Courtesy of P.Lauber

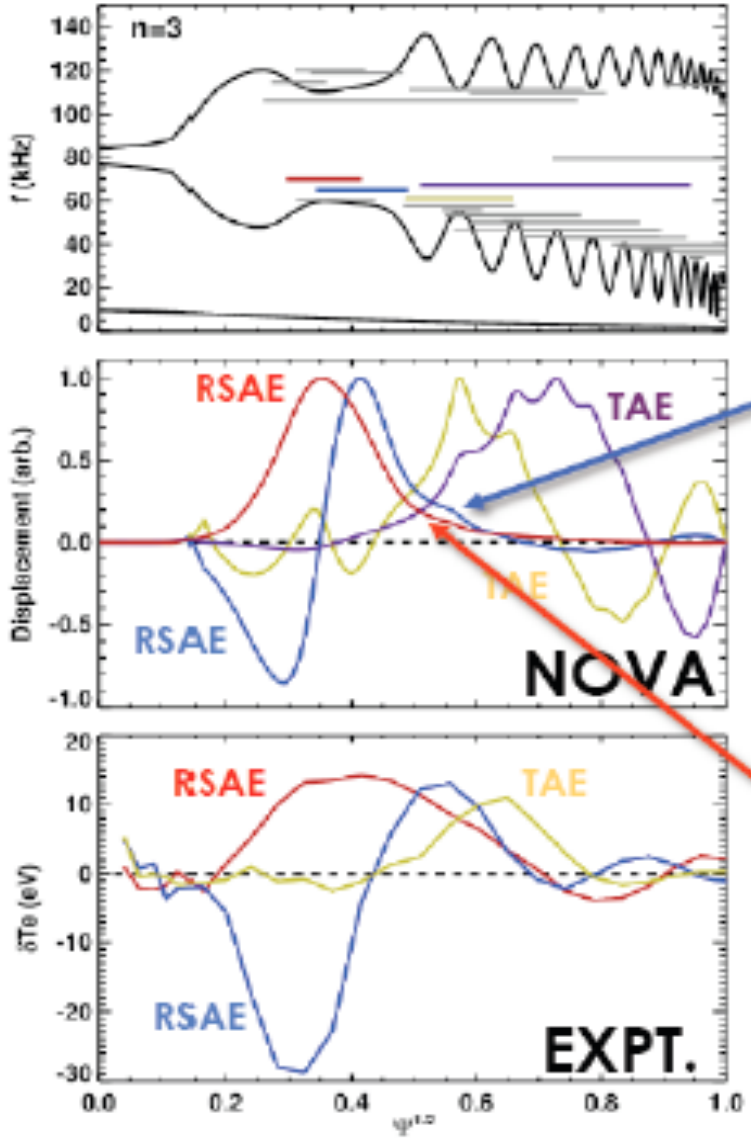
2D measurements of AEs
E.g. via Electron Cyclotron Emission imaging

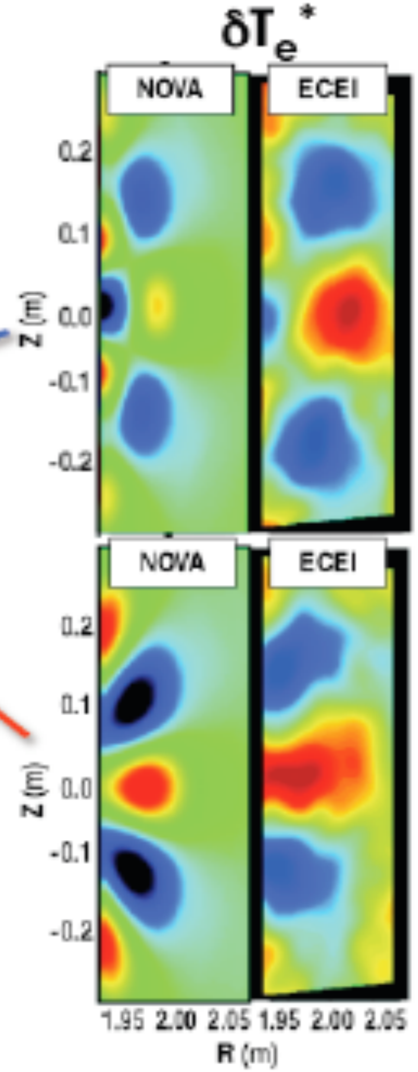


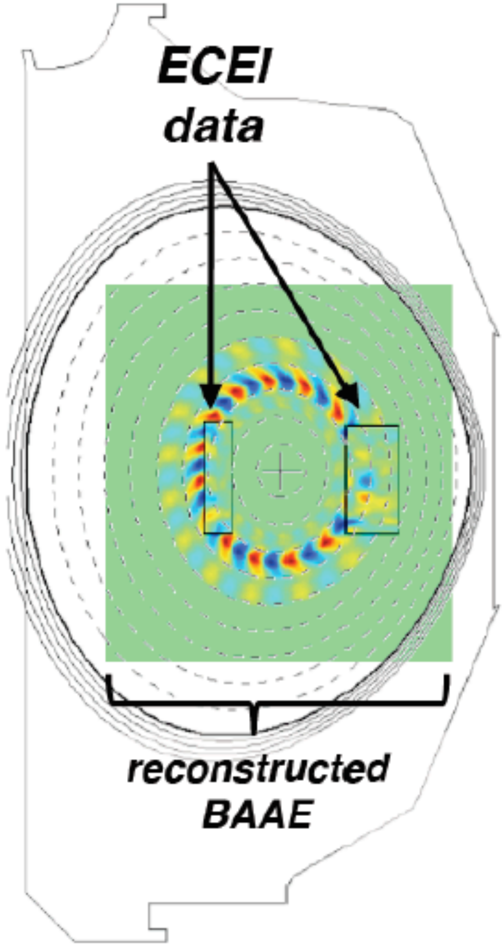
Courtesy of B.J.Tobias

2D measurements of AEs by ECEI in DIII-D

UNSTABLE MODES IN COLOR







B.J.Tobias et al., PRL (2011)

AE instability drive

- Fast particle drive $$\gamma = \int \left[\omega \frac{dF}{dE} - const \times n \frac{dp_{fast}}{dr} \right] F_{resonance}(v, v_A)\, dv$$

- Unstable AEs ←→ sufficient dp_{fast}/dr **&** proximity to resonance

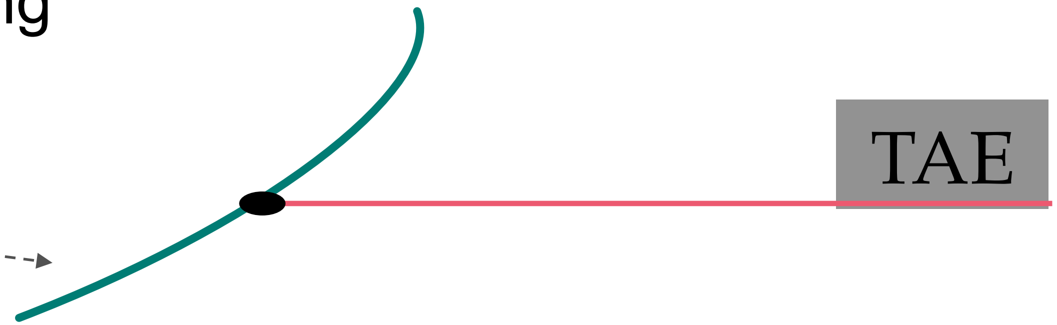
- Resonance: passing $v_{||} = v_A$ ($v_A/3$, $v_A/5$, …)

  trapped -bounce frequency $|v| = v_A/2(R/r)^{1/2}$
  -precession frequency $|v| = v_A/2qk_\theta\rho_L$

AE damping mechanisms

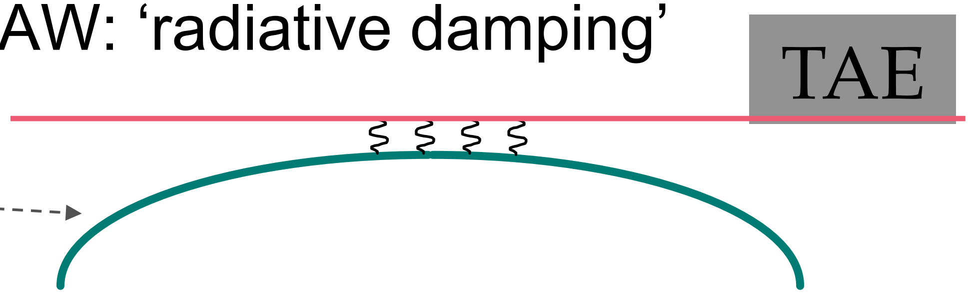
- Direct ion, electron Landau
  - $v_{th\|\ i,e} \sim v_{Alfvén}$ (or $v_{Alfvén}/3$)
- Mode conversion
  - Directly to shear AW (fluid theory) or to kinetic AW (kinetic theory): ‘continuum damping’
    - large γ/ω up to ~ 5-10 %

$$\boxed{\omega = k_{\|} v_A(r)}$$



  - Tunneling to shear AW or kAW: ‘radiative damping’

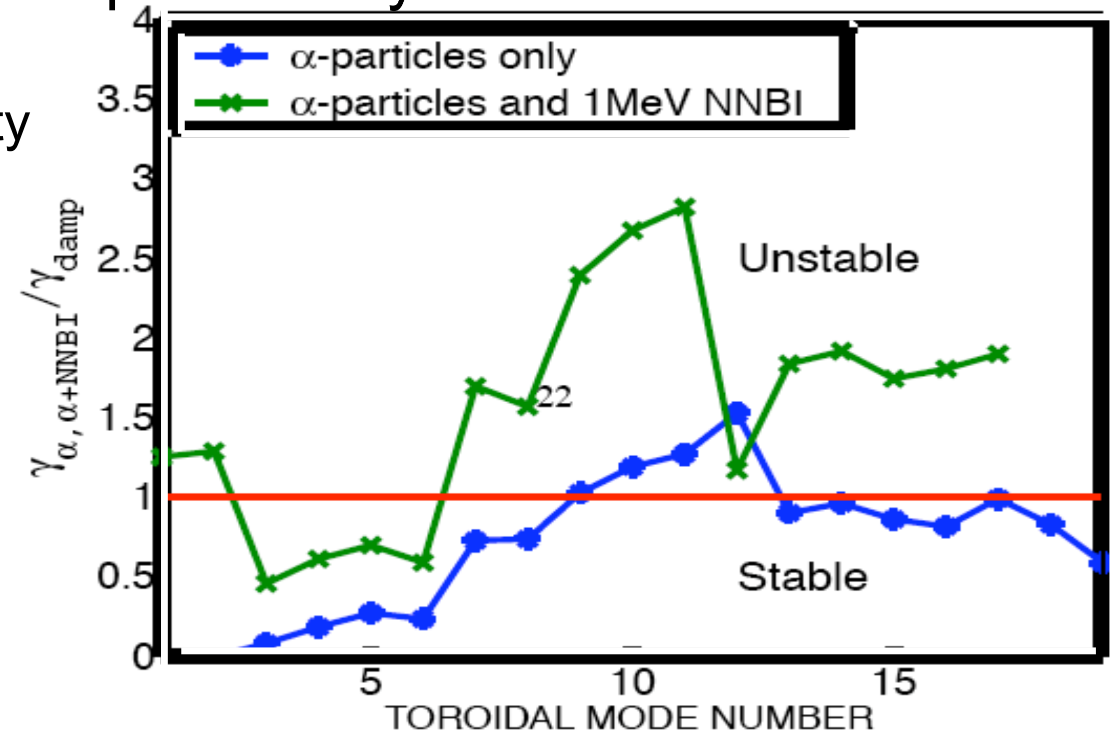
$$\boxed{\omega = k_{\|} v_A(r)}$$



- Collisional damping

AE linear stability: questions and status

- Most unstable modes in ITER scenarios?
- Parameters that control stability?
- Drive and damping mechanisms qualitatively understood
  - Ex. of predictions on TAE stability in ITER baseline scenario with $\beta_\alpha(0)$~1% (NOVA-K code)



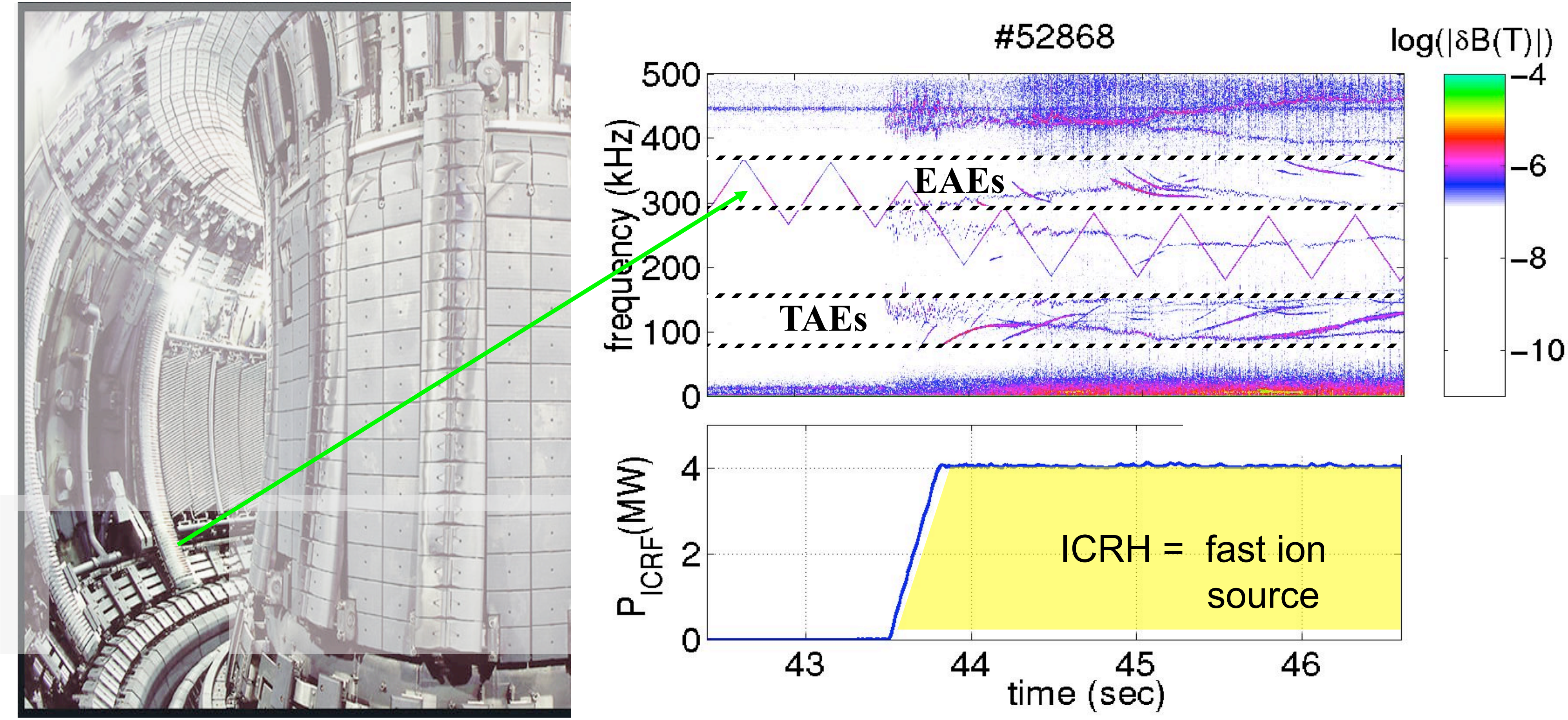
Courtesy of N.Gorelenkov

- But we need a quantitative assessment of stability limits, i.e. of drive and damping, in ITER relevant scenarios

Active and passive spectroscopy of AEs

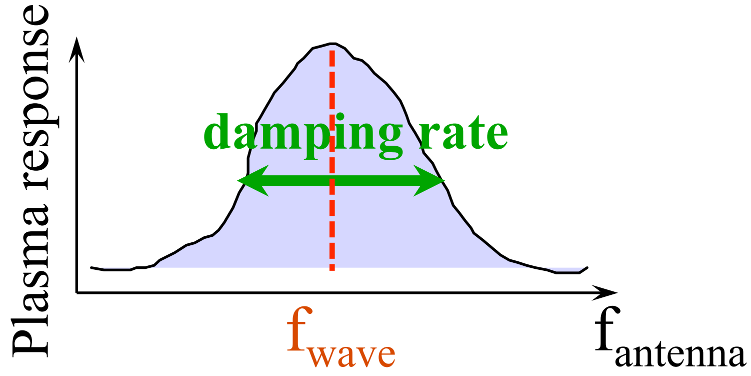
– Passive
  - Modes observed if destabilized by fast particles (NBI, ICRH, *fusion* α*'s*)

– Active
  - In-vessel antennas drive low amplitude perturbations
  - Plasma response measured on B-probes: global modes ← Resonances

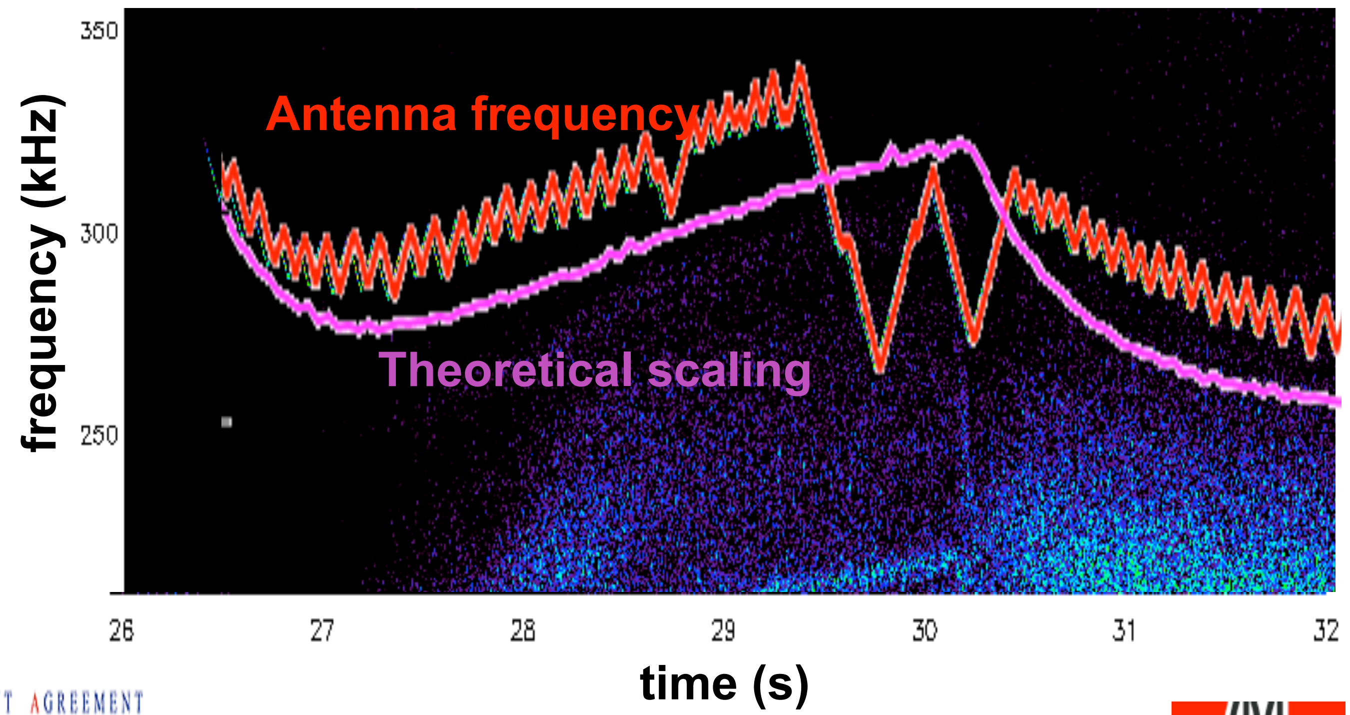


Measurement of Alfvén wave damping rate

- Alfvén Wave = resonance in plasma response to antenna signal
- Width of resonance → damping rate



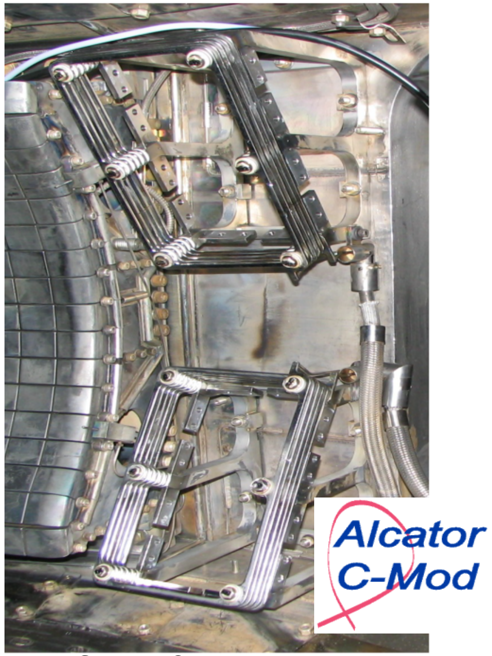
- Waves are tracked throughout plasma discharge



CRPP EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET EPFL

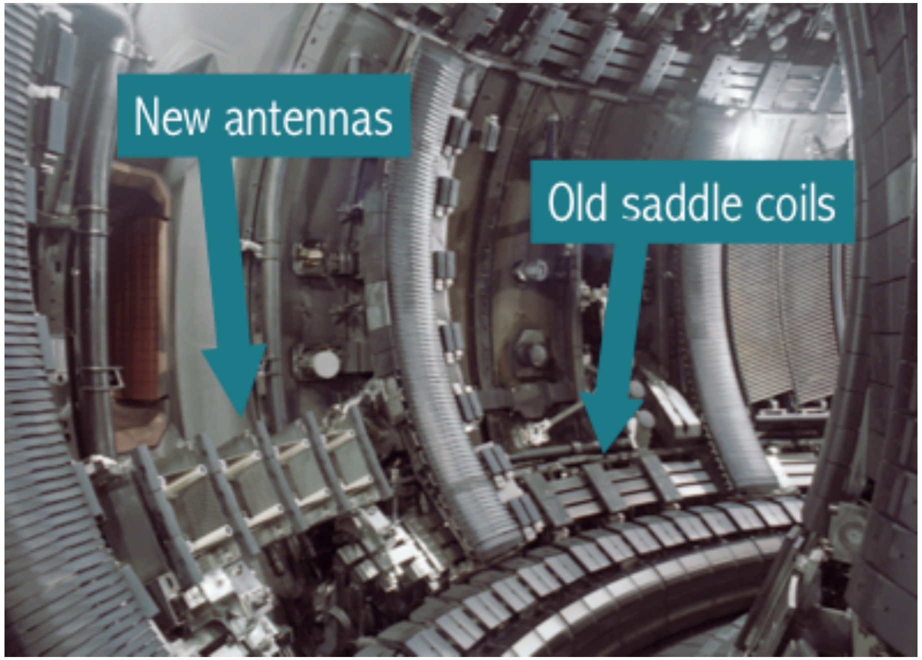
Alfvén Eigenmode Active Diagnostics

Aim: address physics of mode damping, identify modes most prone to instability in burning plasma scenarios, and parameters to control stability



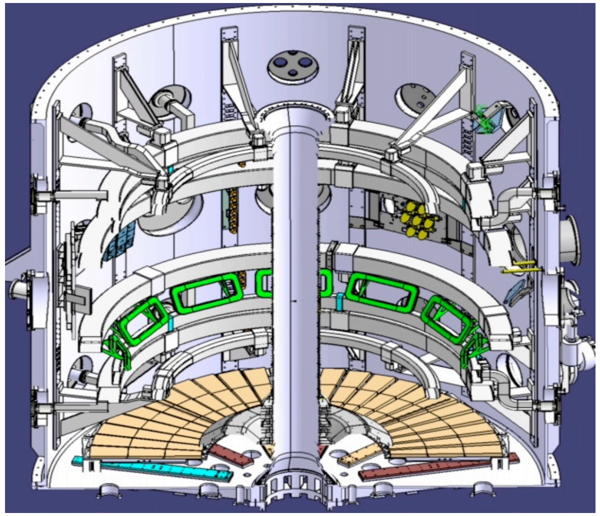
high field & density, $T_e \sim T_i$

EFDA EUROPEAN FUSION DEVELOPMENT AGREEMENT JET



ITER-relevance for size and shape scaling, scenarios

MAST



tight aspect ratio,
broad range of β

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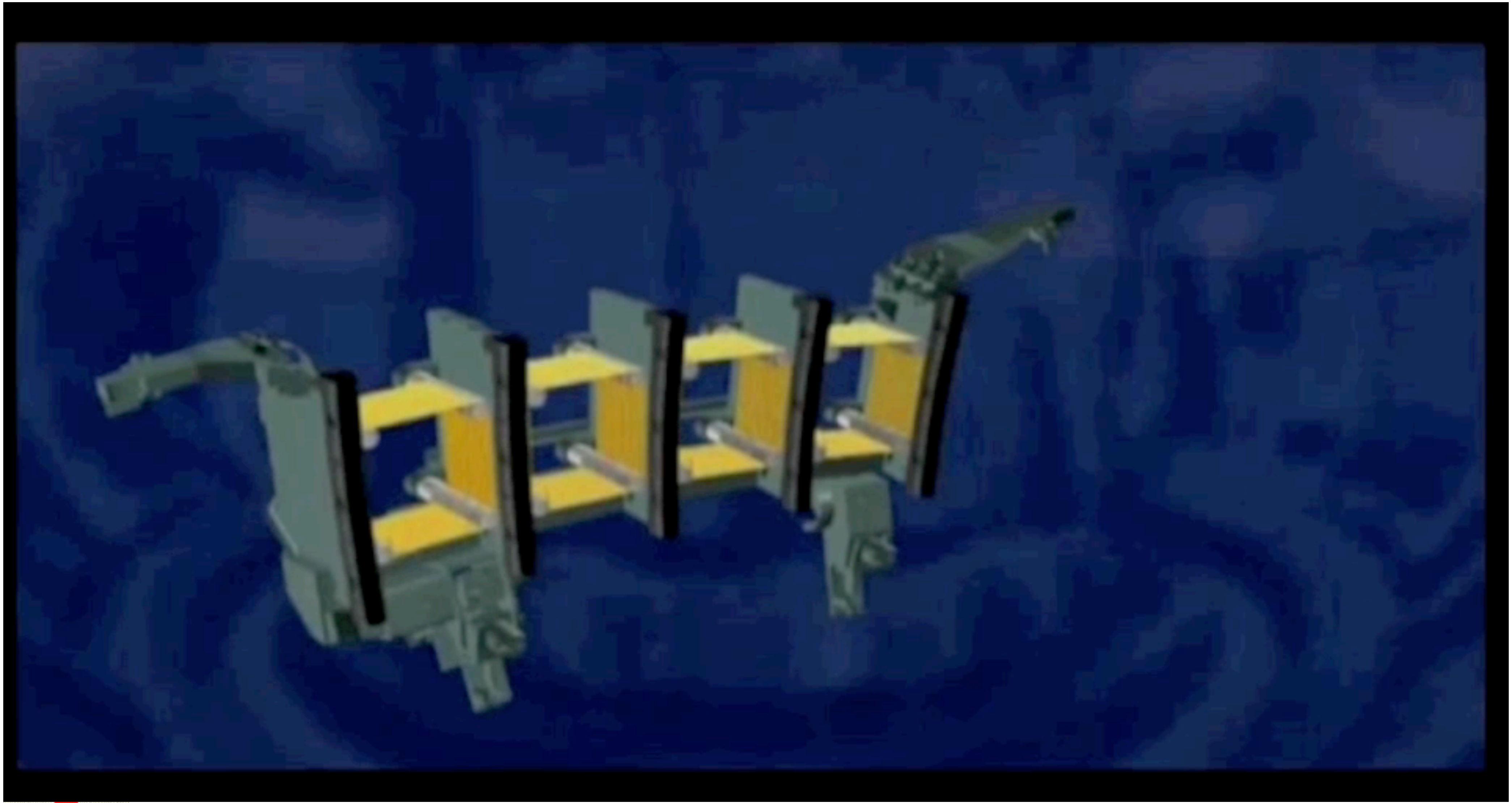
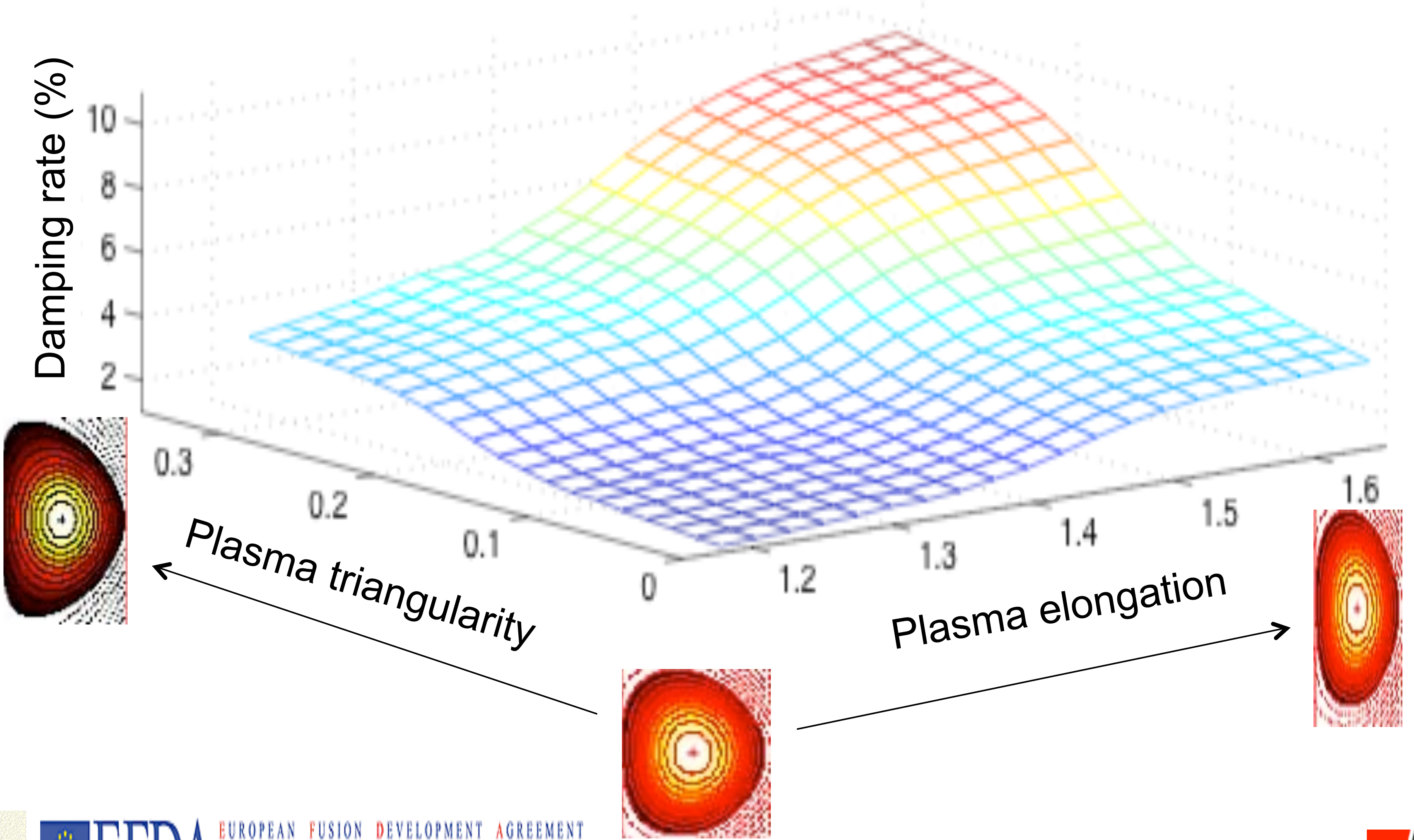
Fusion technology interlude
Remote handling of Alfvén wave antennas in JET



Ex. of result on Alfvén wave damping
Damping rates increase if plasma is shaped



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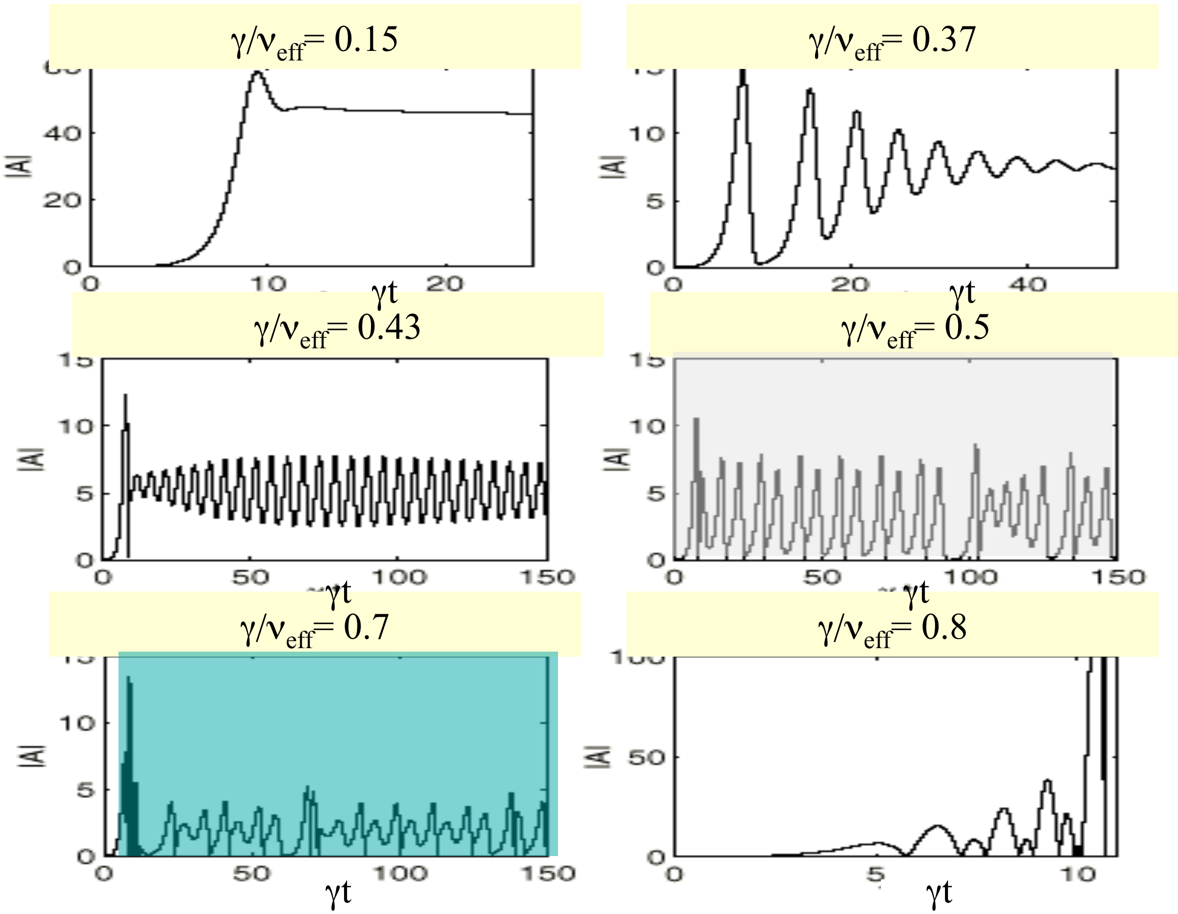
Nonlinear AE wave-particle interaction

- Wave flattens particle distribution: less drive, but relaxation processes ‘refresh’ distribution

$$\exp(-i\phi)\frac{dA}{dt} = \frac{\gamma}{\cos\phi}A - \frac{\gamma_L}{2}\int_0^{t/2}\tau^2 d\tau \int_0^{t-2\tau} d\tau_1 \exp\left[-\nu_{eff}^3\tau^2(2\tau/3+\tau_1)\right]A(t-\tau)A(t-\tau-\tau_1)A^*(t-2\tau-\tau_1)$$

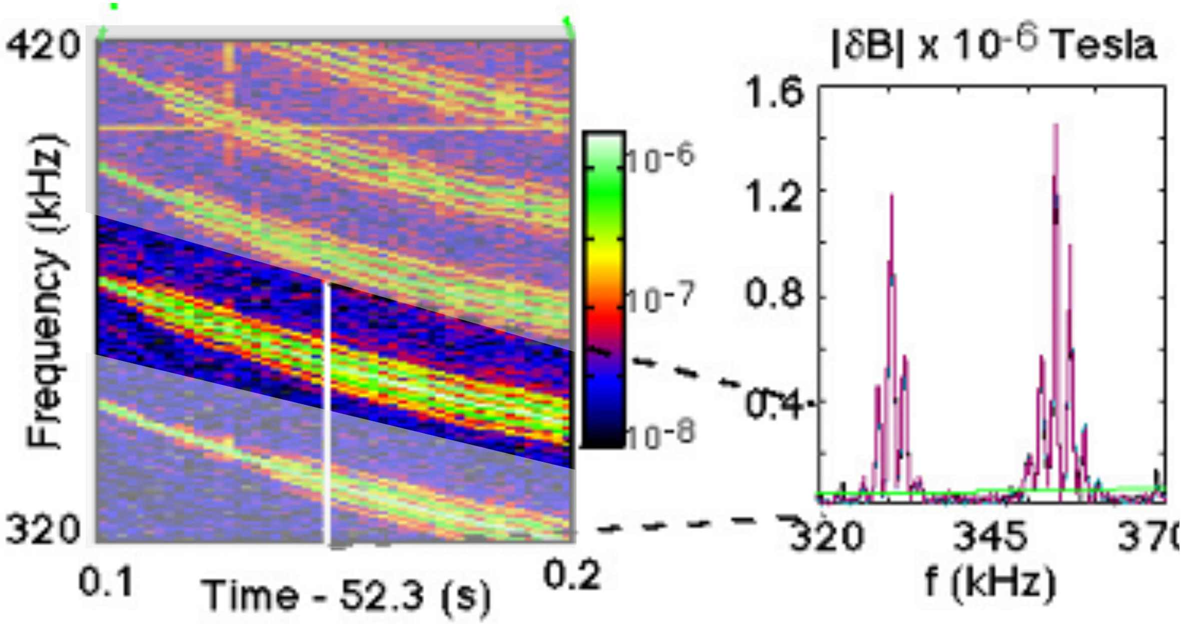
Amplitude evolution determined by

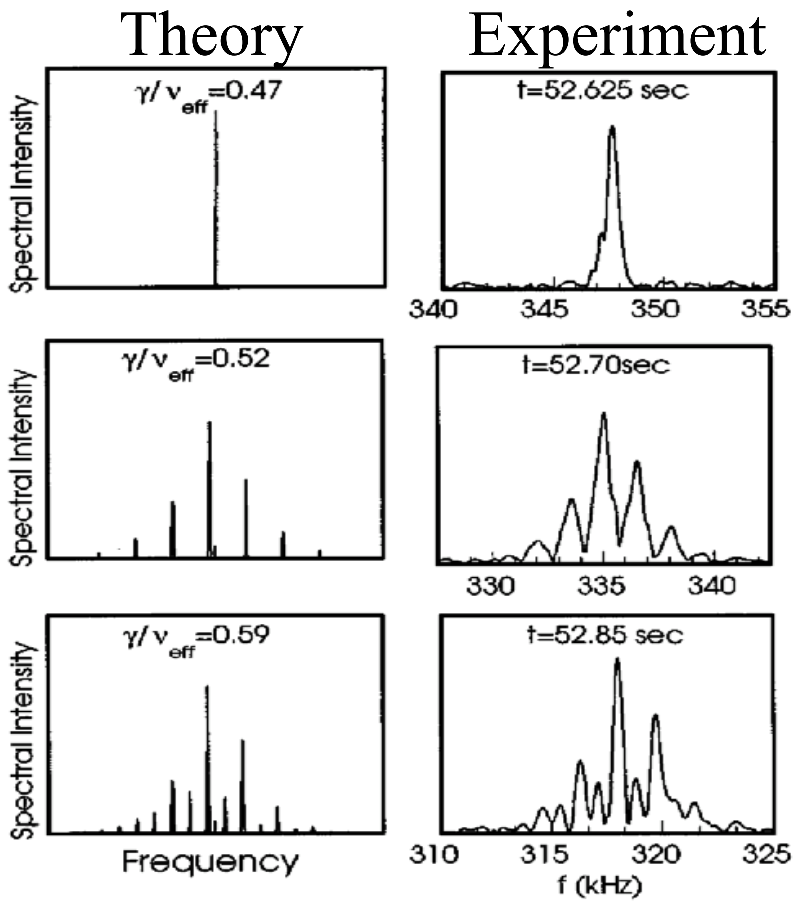
- $\gamma = \gamma_{\text{drive, linear}} - \gamma_{\text{damp}}$
- vs. coll. freq. ν_{eff}



Nonlinear AE wave-particle interaction →Fast ion phase space dynamics

- ‘Pitchfork’ splitting and period doubling
- Spectral features → γ and $\nu_{eff;}$ Ex.: ICRH driven n=7 TAE

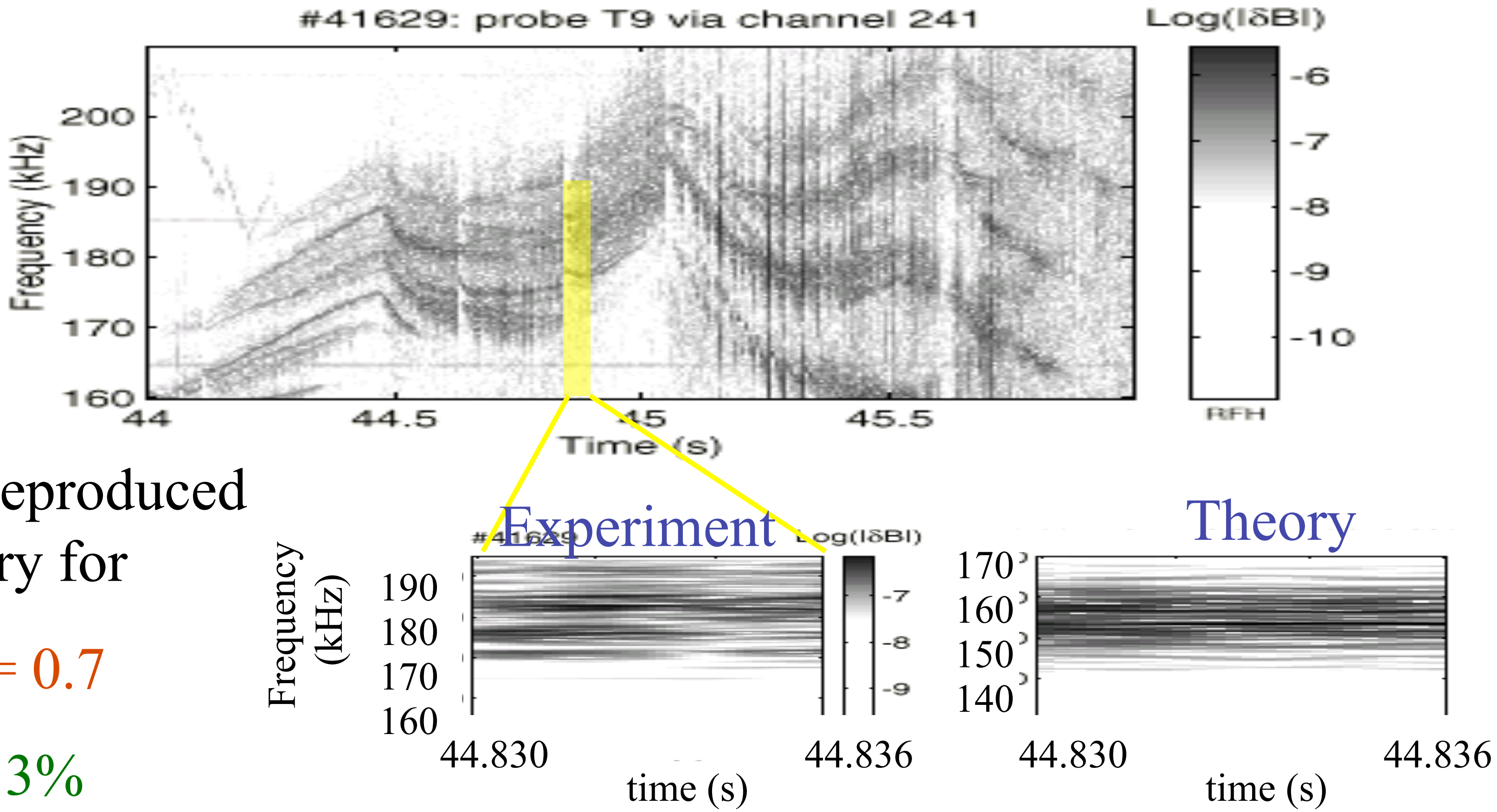




A.Fasoli et al., PRL (1998)

Nonlinear AE wave-particle interaction
Chaotic regime

Larger γ/ν_{eff}: chaotic AE oscillations



broadening reproduced by theory for

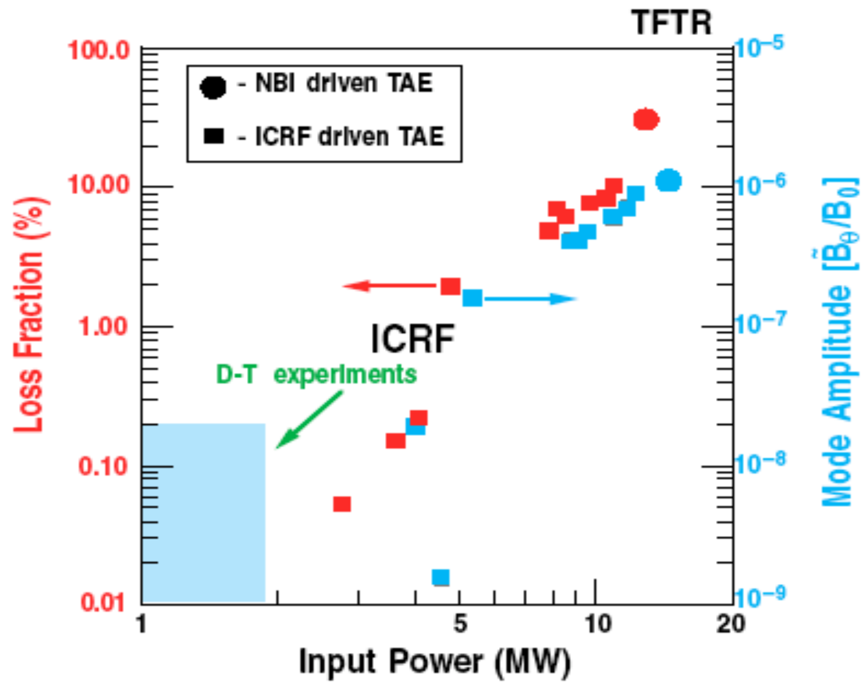
$\gamma/\nu_{eff} = 0.7$

$\gamma/\omega = 3\%$

R.F.Heeter et al., PRL (2000)

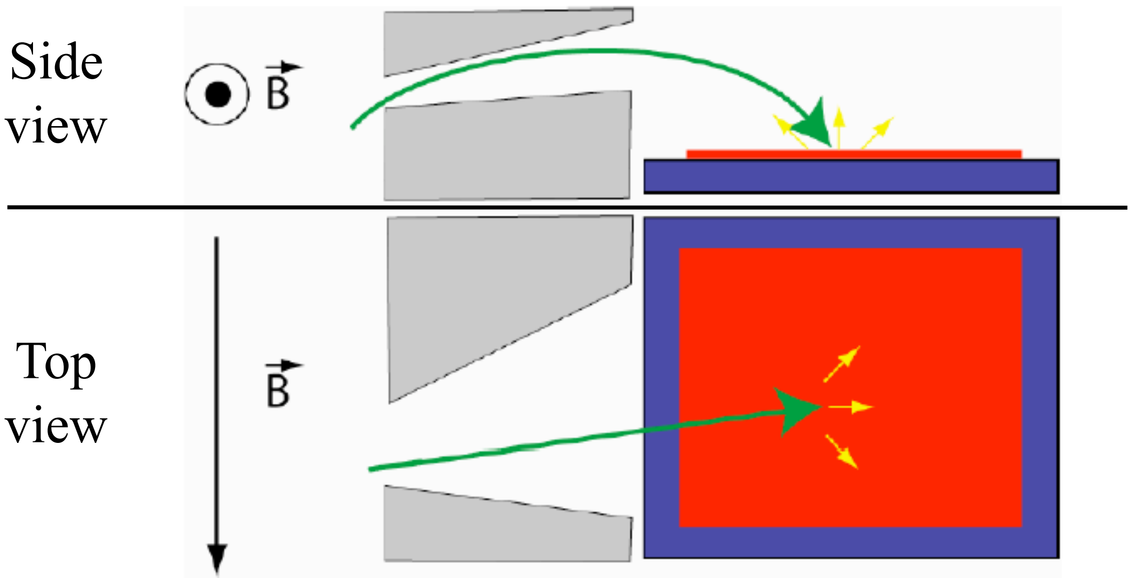
AE redistribution and losses
Questions and opportunities

- Limits to ITER operational scenarios?
  - ITER can withstand only ~5% of α losses
- Why were losses not observed in DT?
  - Q too low both in TFTR and JET
  - Losses clearly seen for other fast ions



- Good qualitative understanding of weakly nonlinear regimes
- First self-consistent models for ITER
  - Need validation from data on energetic ion redistribution

AE redistribution and losses
Measurement techniques - scintillator probe



- Gyromotion of fast ions
- Particle selection by slits
- Light emission by scintillator

Gyro-radius $\rho \propto \frac{mV_\perp}{ZB}$

Pitch-angle $\theta = \cos^{-1}\frac{V_{II}}{V}$

Species	ρ @B=3T
α(3.5 MeV)	9.0 cm
P(3.0 MeV)	8.3 cm
T(1.0 MeV)	8.3 cm

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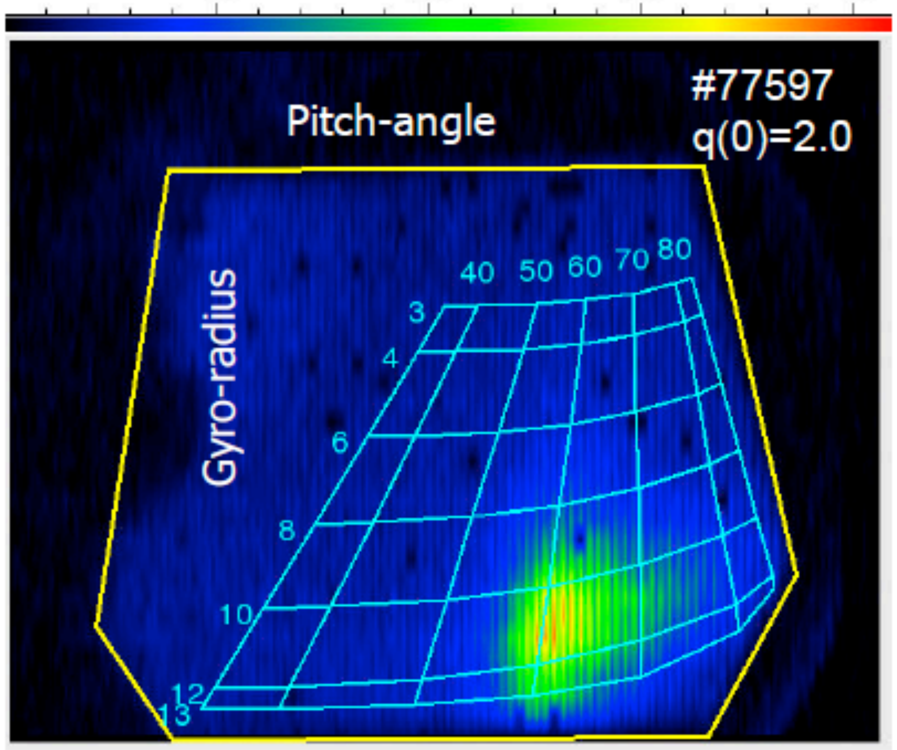
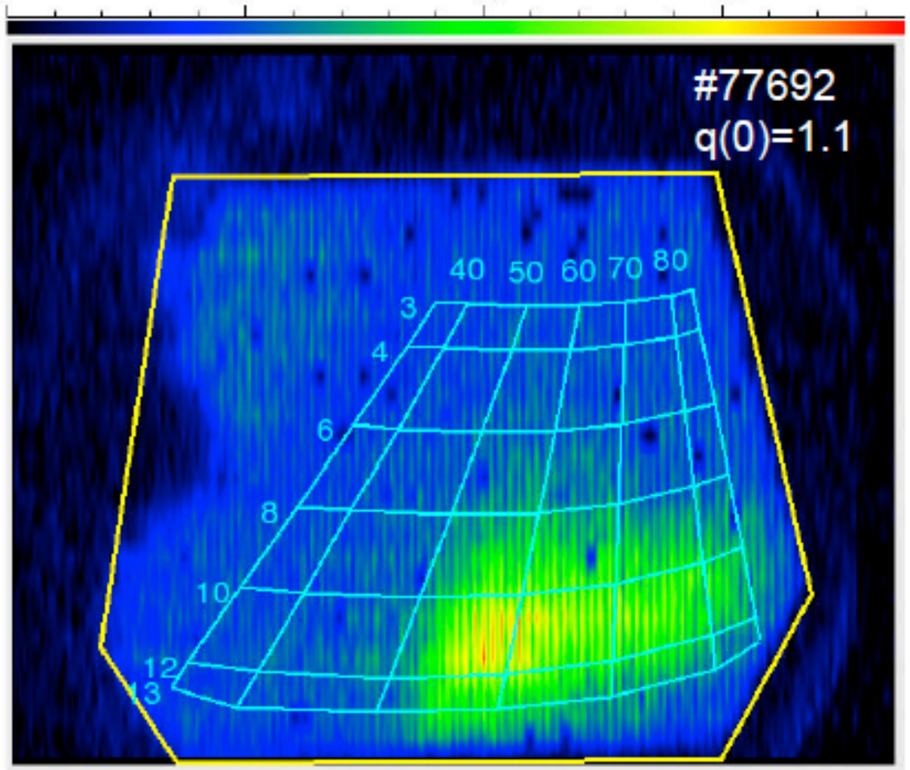
AE redistribution and losses
Measurement techniques - JET scintillator probe

AE redistribution and losses
JET scintillator probe – ex. data on first orbit losses

1-MeV tritons and 3-MeV protons

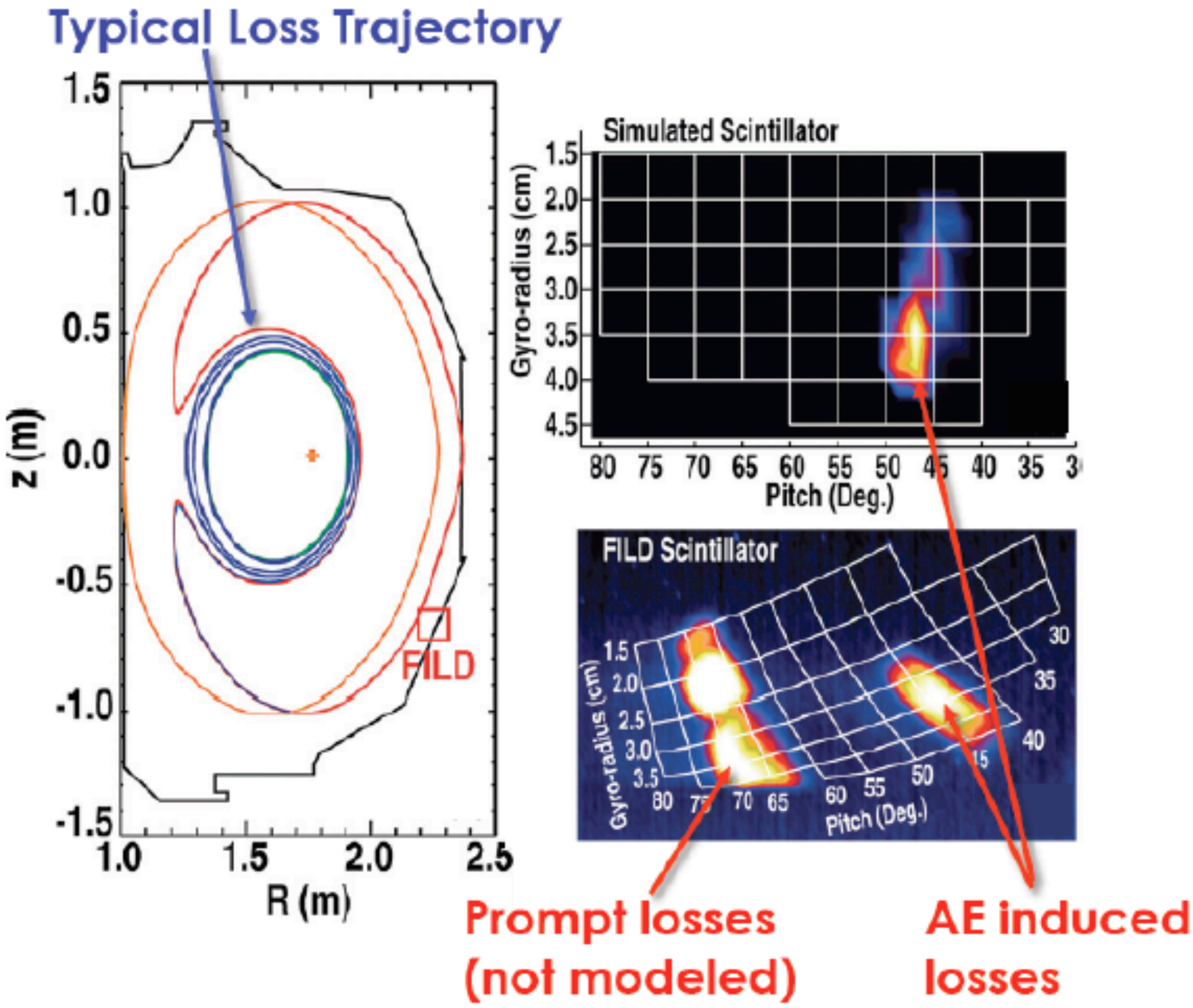


Discharge 2.7T / 1.8 MA



Discharge 2.7T / 2.5 MA

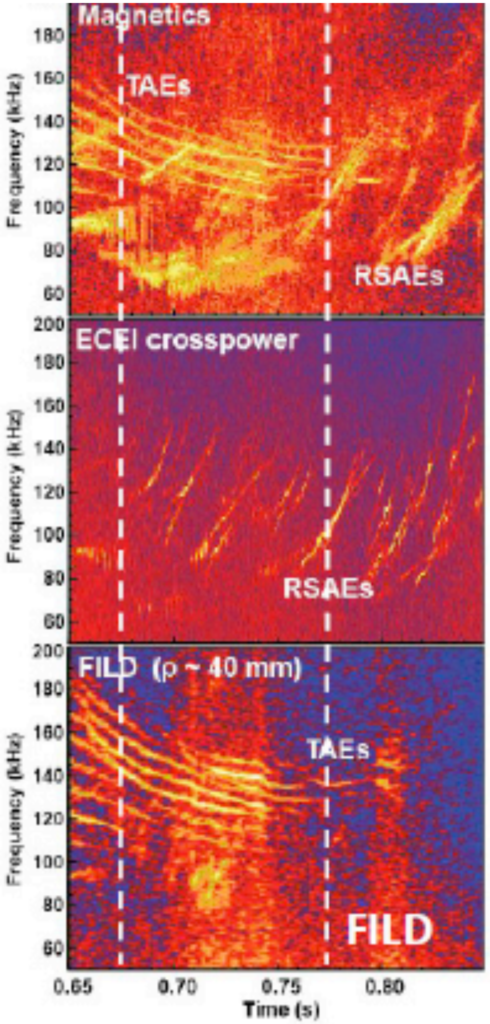
AE redistribution and losses
DIII-D scintillator probe – ex. data on AE losses

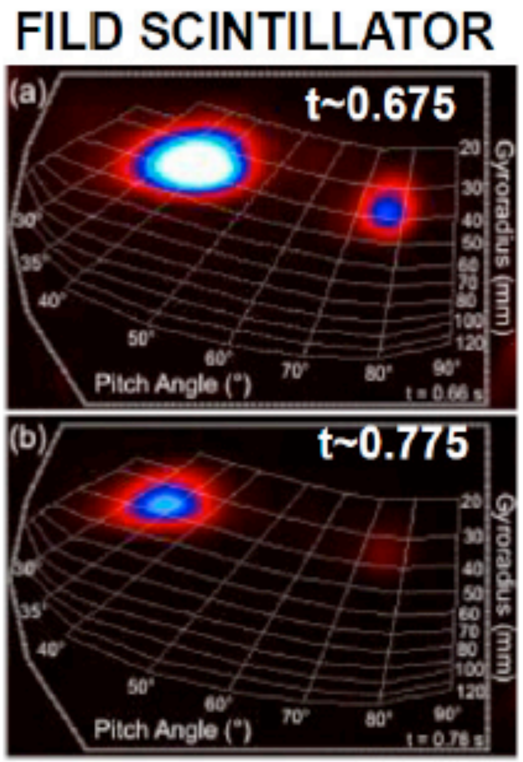


- Loss simulations follow particles from TRANSP distribution function in presence of NOVA eigenmodes
  - Amplitudes obtained from experiment
- Losses at FILD peak near injection energy (80 keV)
- Most common loss mechanism observed is transition of counter passing particles to trapped lost orbit

M.A. Van Zeeland, et al., Phys. Plasmas, 18, 056114(2011)

AE redistribution and losses
Asdex-U scintillator probe – ex. data on AE losses





- FILD spectrogram shows clear coherent losses from beam driven TAEs

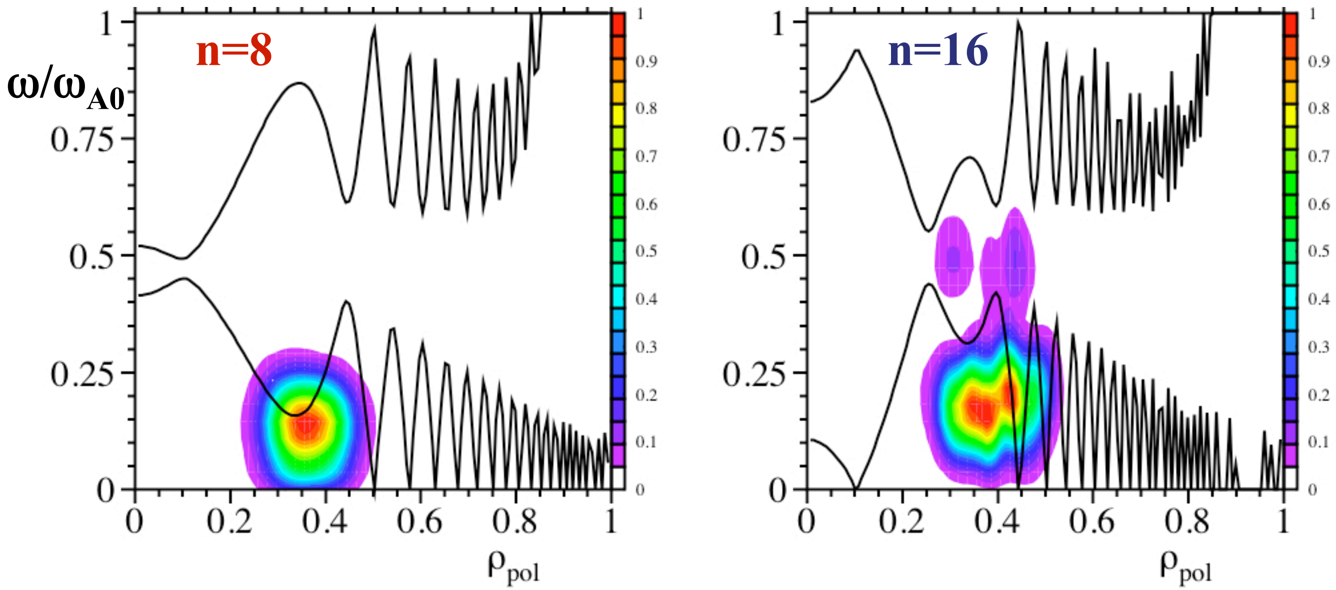
- FILD Scintillator indicates TAE induced losses appear near gyro-radius corresponding to injection energy

M .Garcia-Munoz et al., IAEA FEC, Daejeon, Korea (2010)
M. Garcia-Munoz et al., Nucl Fusion ***51*** *103013 (2011)*

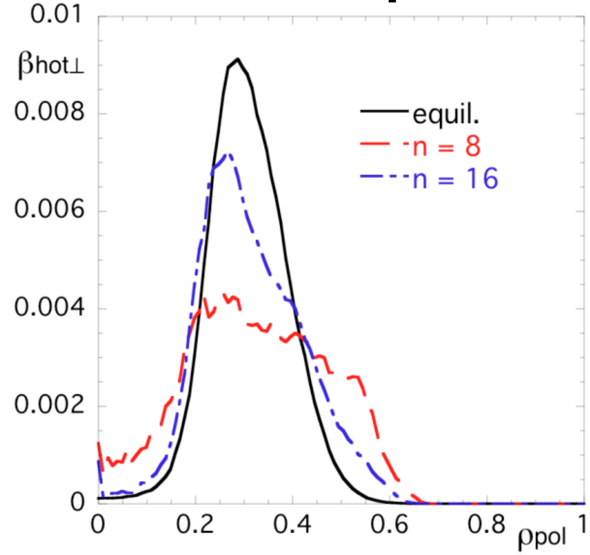
Energetic ions and burning plasma physics Example of self-consistent simulation

- H-mode scenario in FAST device
  - Spectrum of Alfvénic fluctuations similar to that expected in ITER
  - Hybrid MHD-gyrokinetic code *XHMGC*
  - Radial redistribution, with limited global losses, of ICRH created fast ions

Mode spectrum and radial structure

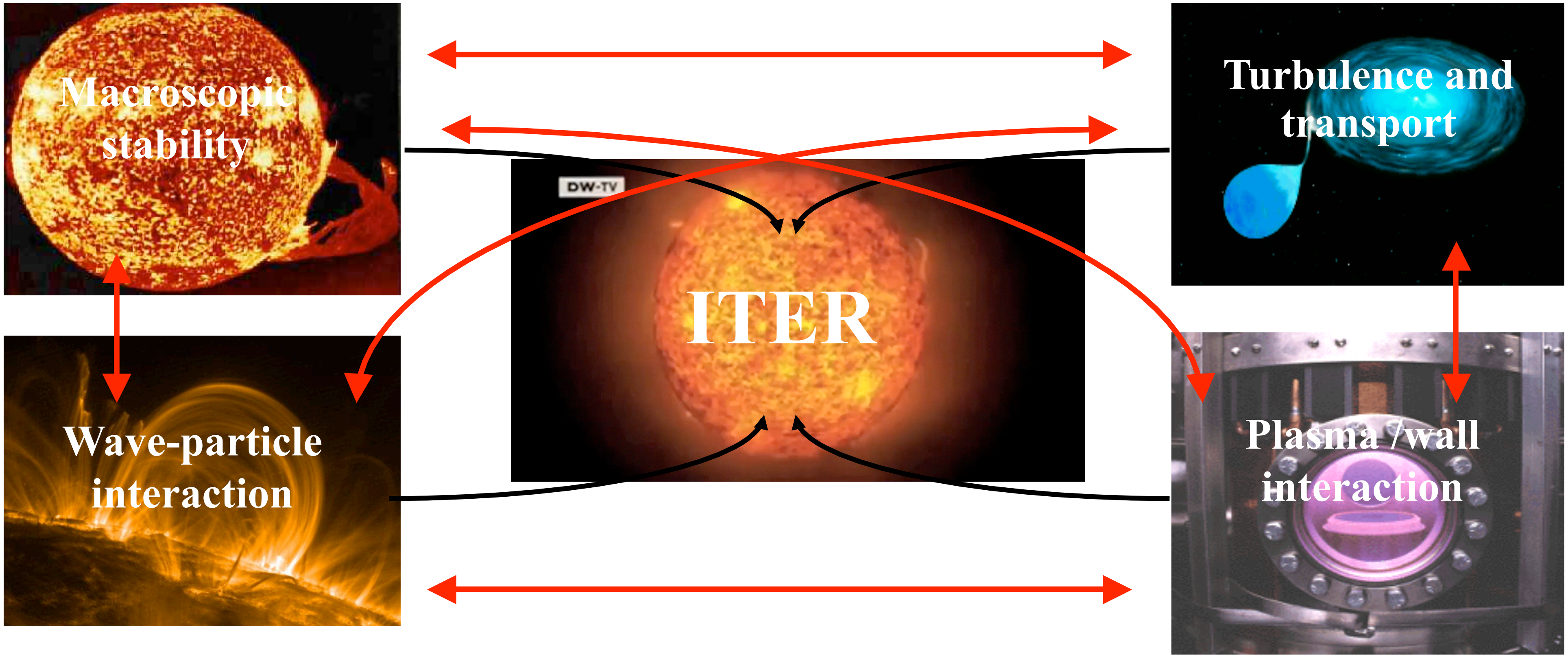


Fast ion radial profile



Courtesy of G.Vlad

Burning plasmas are self-organized systems in which all elements are coupled via energetic ions



- Progress is possible in today's weakly self-heated plasmas
- But to demonstrate the feasibility of fusion we need to produce and control actual burning plasmas, such as ITER