Fast particle physics on ASDEX Upgrade

Sibylle Günter

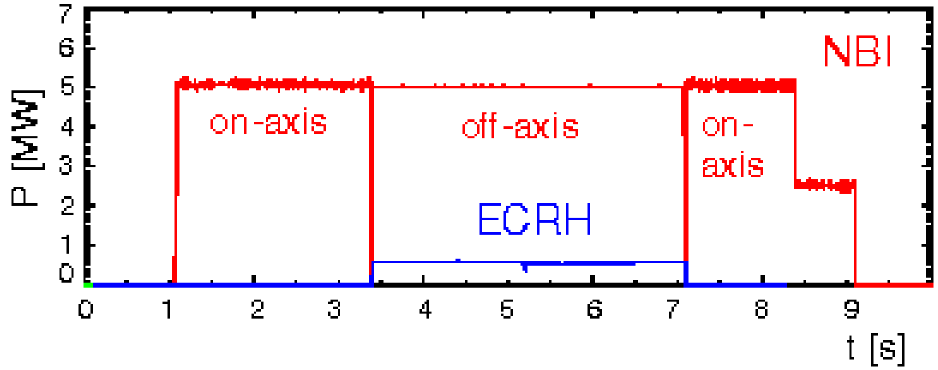
G. Conway[1], H.-U. Fahrbach[1], C. Forest[2], S. daGraca[3], M. Garcia Muñoz[1] T. Hauff[1], J. Hobirk[1],V. Igochine[1], F. Jenko[1], K. Lackner[1], P. Lauber[1], P. Mc Carthy[4], M. Maraschek[1], P. Martin[5], E. Poli[1], K. Sassenberg[4], E. Strumberger[1], H. Zohm[1], ASDEX Upgrade Team

- **Current profile modifications by NBI current drive**
- **Interaction of fast ions with MHD instabilities**

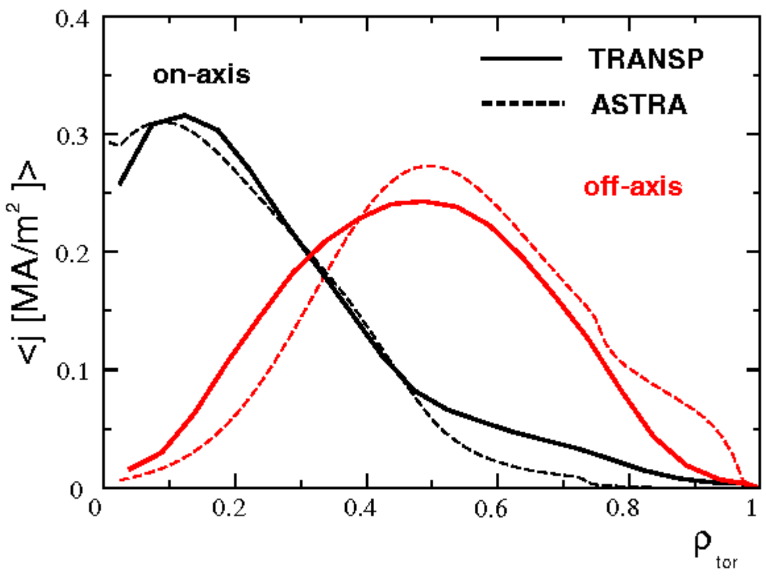
[1] Max-Planck Institut für Plasmaphysik, Garching, Germany, EURATOM Association
[2] Dept. of Physics, University of Wisconsin, Madison, Wisconsin, USA
[3] Centro de Fusão Nuclear, Associa cão EURATOM/IST, Instituto Superior Técnico, Lisboa, Portugal
[4] Physics Department, University College Cork, Cork, Ireland
[5] Consorzio RFX, EURATOM-ENEA per la fusione, Padova, Italy

NBI current drive experiments on ASDEX Upgrade

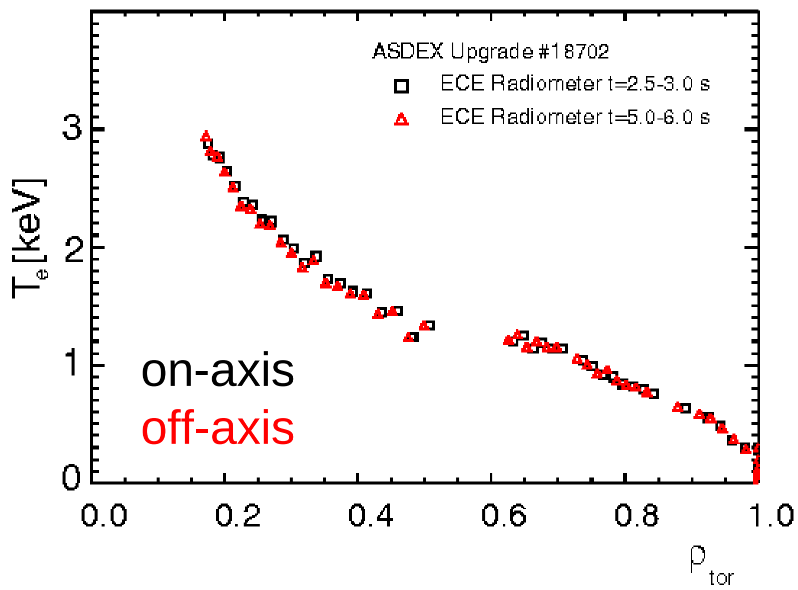
Switching experiments between on-and off-axis beams



Predicted NBI current profile

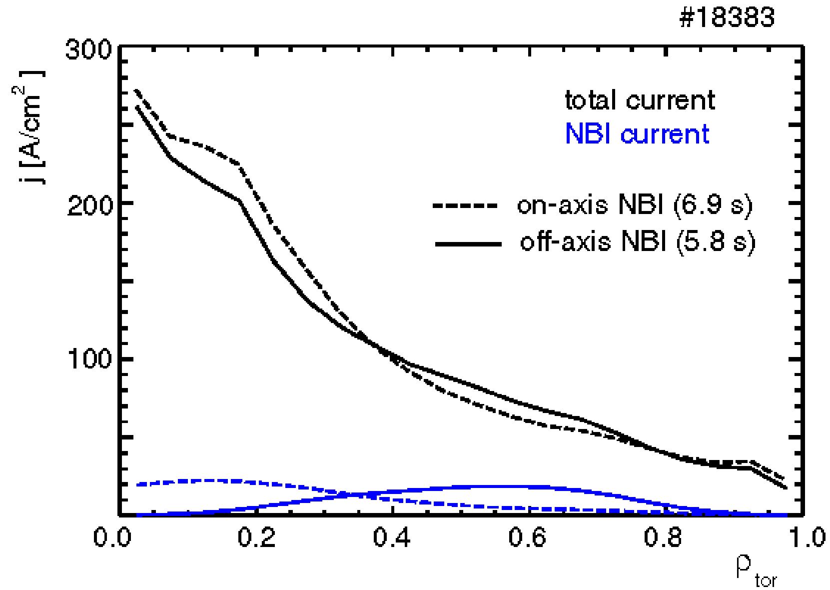


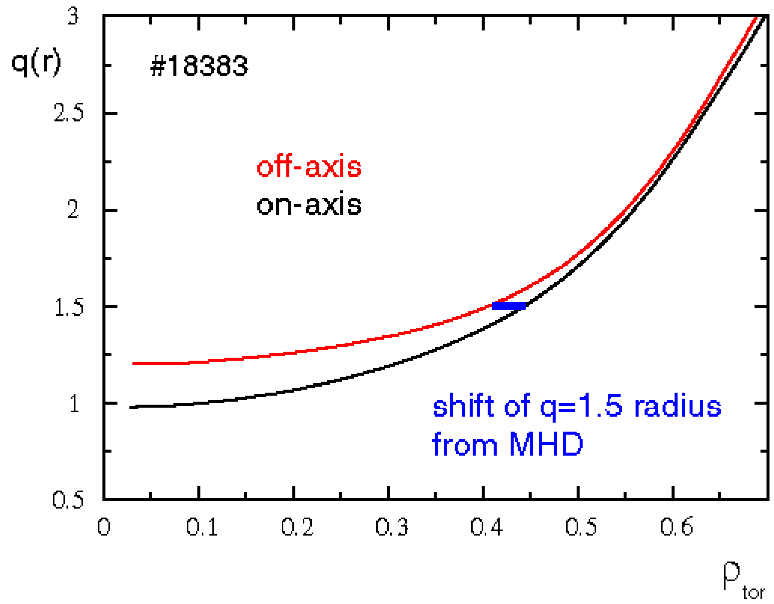
Adjustment of T_e profile (ECRH)



Off-axis NBI current drive on ASDEX Upgrade

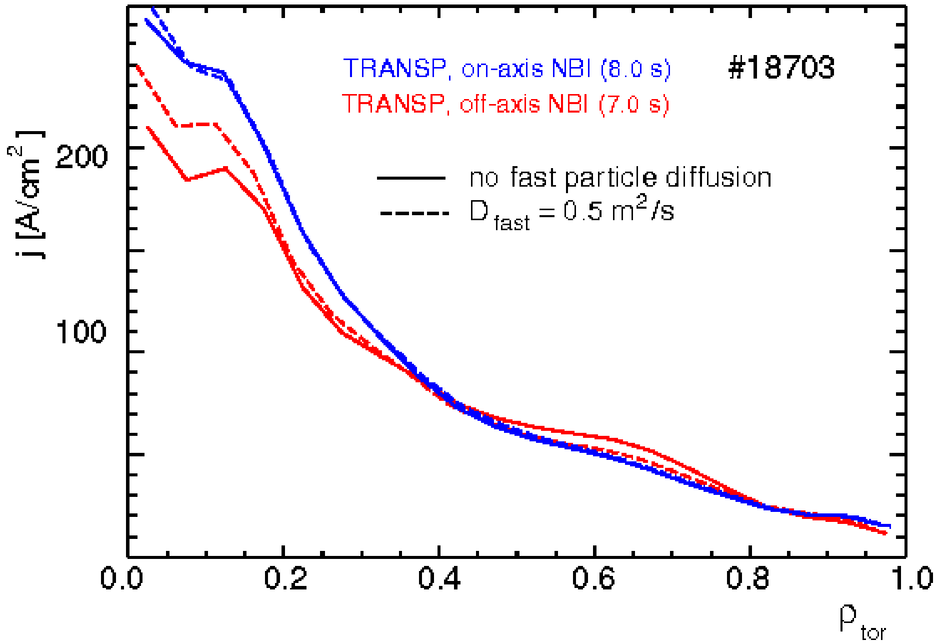
Current profile modification as predicted by TRANSP for moderate heating power: up to 5 MW for high triangularity (δ ~0.4) and below for lower triangularity

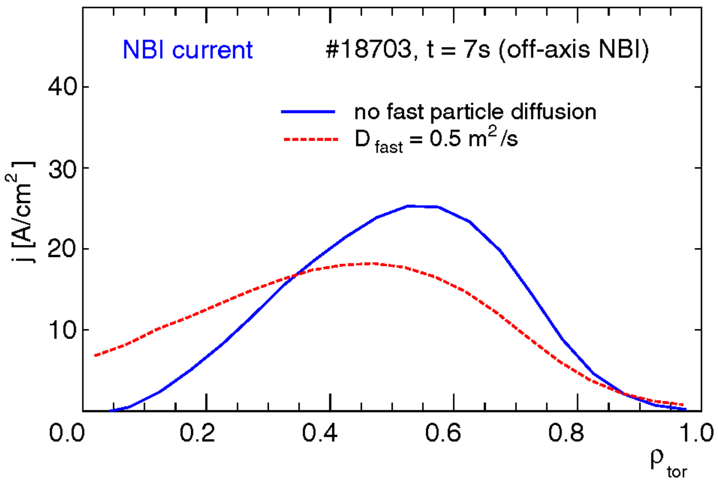




Strongly reduced current profile modification for larger heating power

Agreement with theory only if diffusion of fast particles assumed (D_{fast} ~ 0.5 m^2/s)

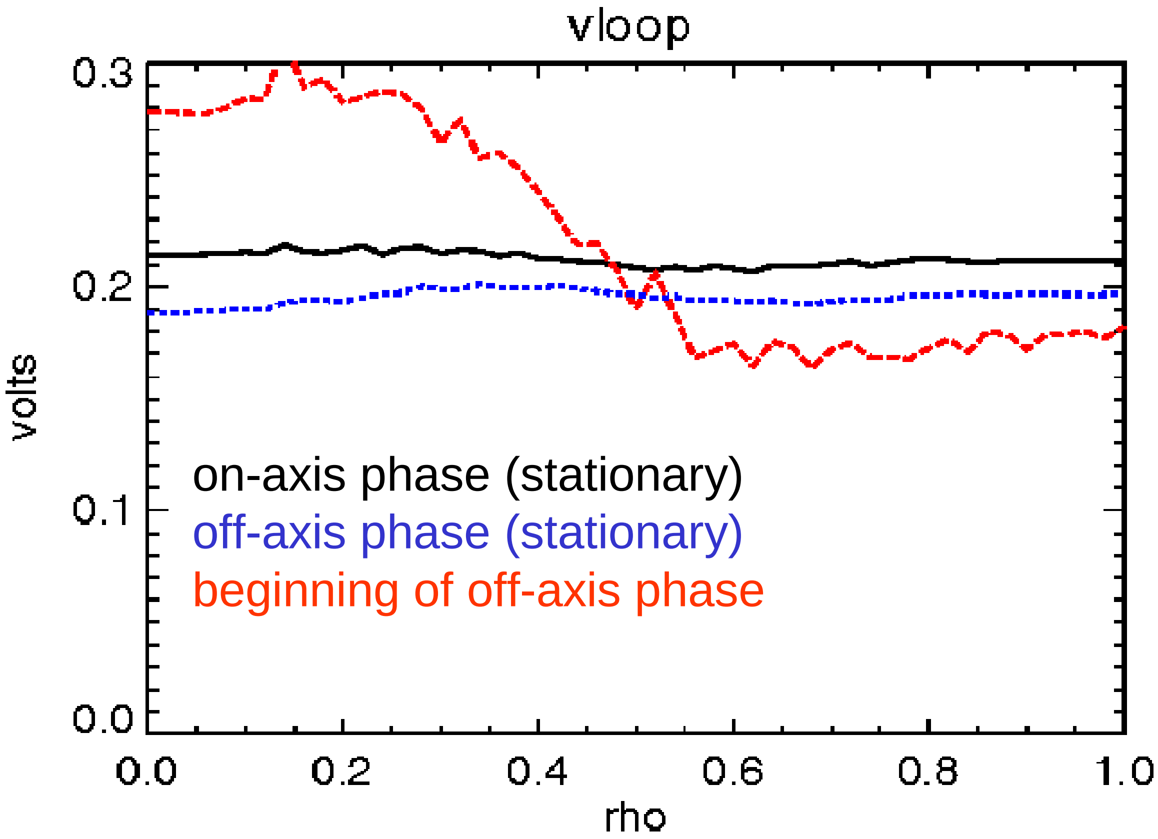




no effect for on-axis current drive, but off-axis CD strongly affected

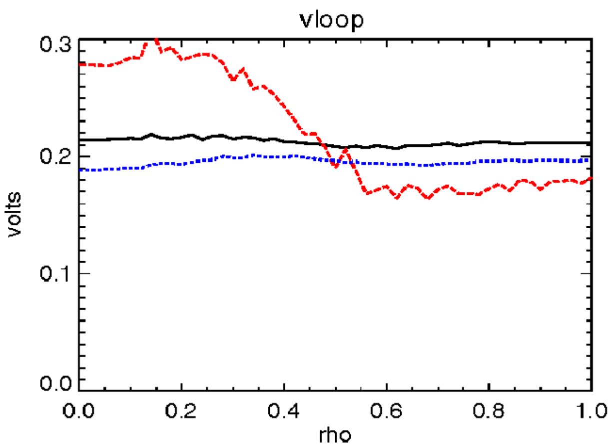
Radial profile of loop voltage

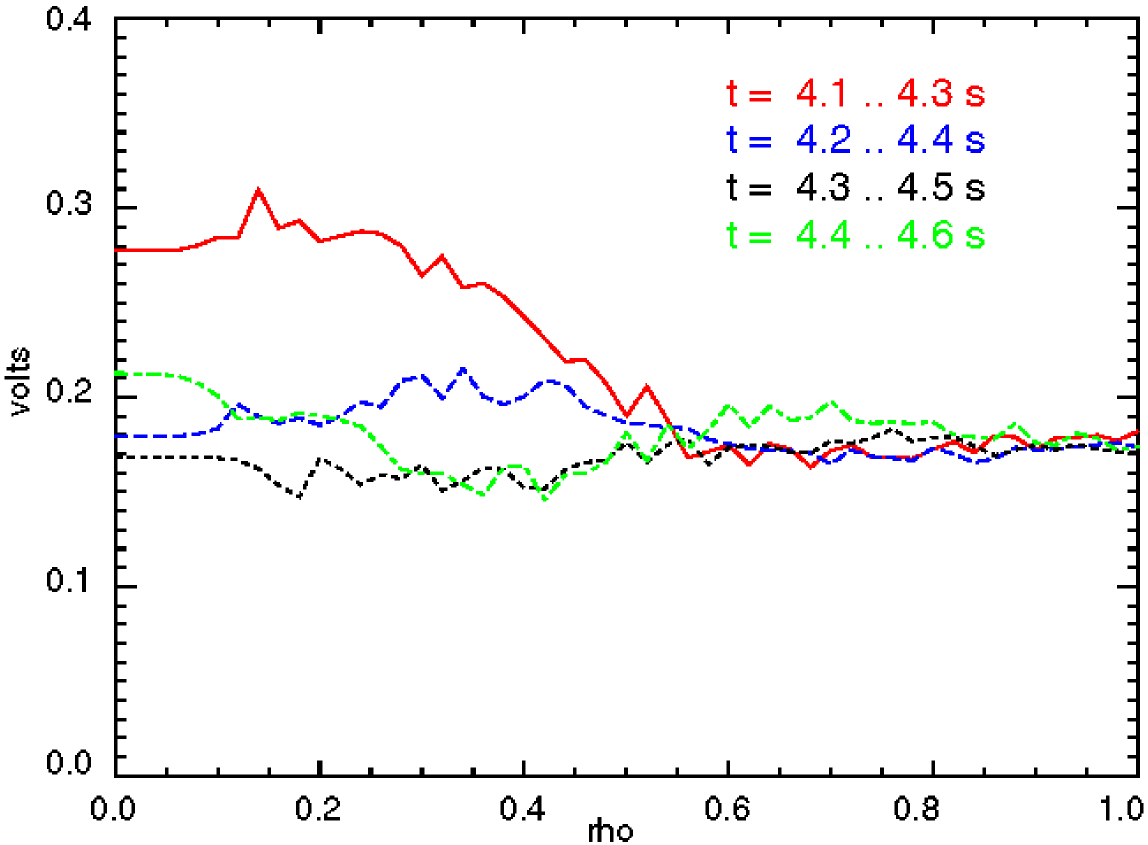
see P.J. McCarthy et al., TH/P3-7



Even in discharges with very small modification of current profile, the loop voltage profile changes as expected immediately after switching from on- to off-axis beams

Local current drive source vanishes within milliseconds

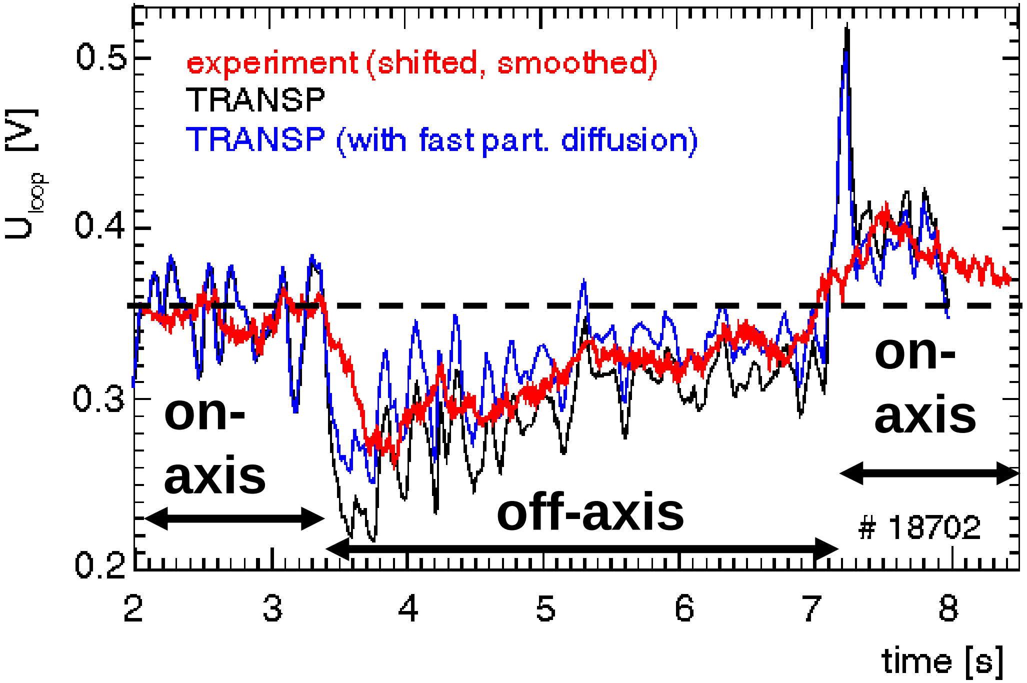




Within 100 ms (<< current redistribution time) loop voltage profile becomes flat again! Consistent with redistribution of fast particles

Total current drive efficiency as predicted by theory

Loop voltage at plasma edge agrees with TRANSP with and without fast particle redistribution



Fast particle redistribution:

- does not change the total current drive efficiency significantly
- needed to explain the off-axis current drive results
- would not be measurable for on-axis NBI

Reasons for missing current profile modification?

Fast ion redistribution by Alfvén waves?

- no Alfvén waves observed
- $v_b < v_A$, no difference between experiments with full beam energy ($v_b > v_A/3$) and reduced beam energy ($v_b < v_A/3$)
- no dependence on q-profile, monotonic q-profile

Current redistribution by MHD?

- only (1,1) activity observed
- no influence of q_a/q=1 surface (q_a varied between 3.9 and 6.2)

Fast ion redistribution, correlated to intensity of thermal transport

Increase in heating power (independent of radial location and pitch angle reduces CD)

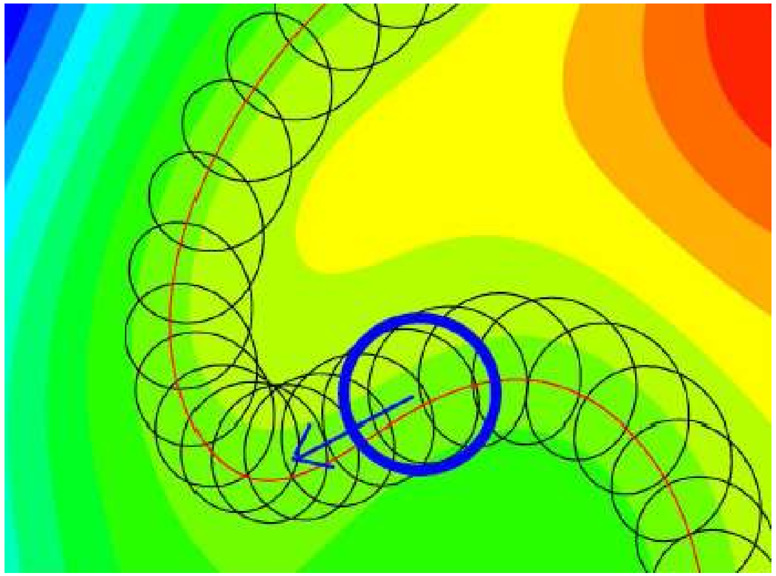
Redistribution of fast ions by background turbulence?

• usual argument against turbulence affecting fast particles:
gyro-averaging of perturbations

• but additional effect: finite gyro-radii increase correlation length

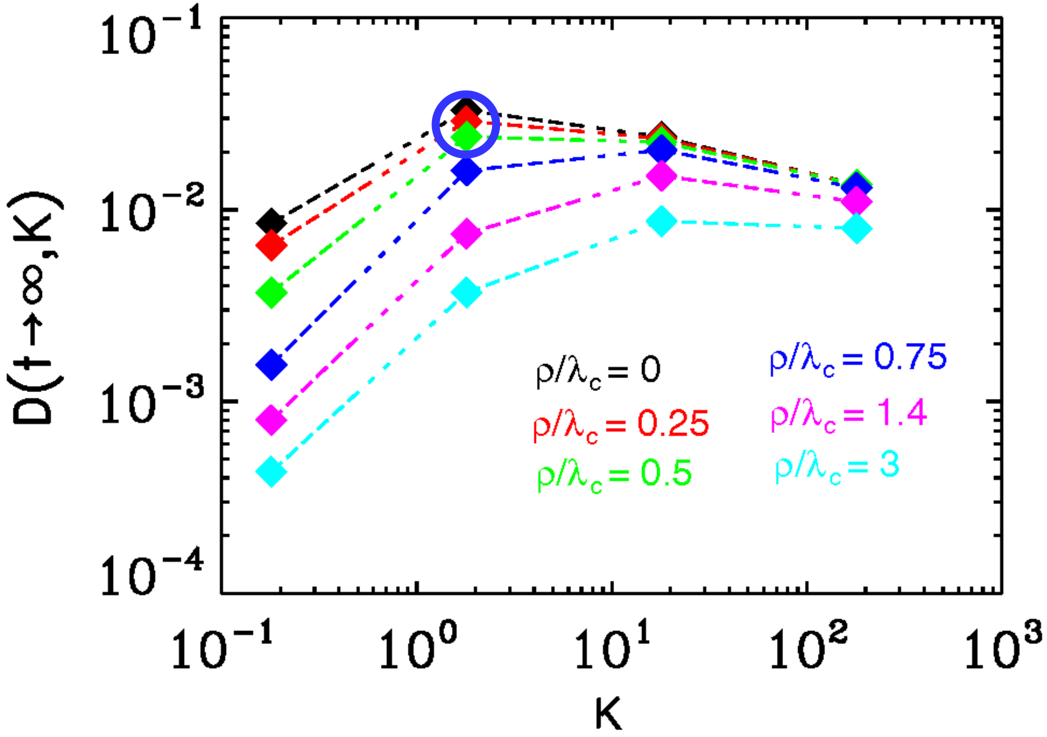
Motion of test particles in (test) turbulent electrostatic field:

$$\phi(\vec{x},t) = \sum_{i=1}^{N} A_i \sin(\vec{k}_i \vec{x} + \omega_i t + \varphi_i)$$



Full Lorentz dynamics and gyrokinetics

Redistribution of fast ions by background turbulence?



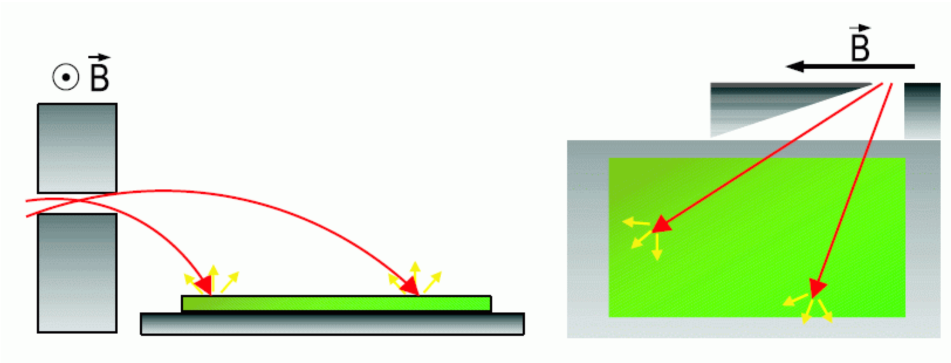
Realistic parameters for fusion plasmas:
$K = 1 \ldots 3$
$\rho/\lambda_c = 0.2 \ldots 1$

significant diffusion of fast ions in background turbulence!

Kubo-number: $K = v_{E\times B}\tau_c / \lambda_c$

so far simple geometry (drift motion perpendicular to constant magnetic field) and perturbation field, and tracer particles only, but GENE calculations on the way

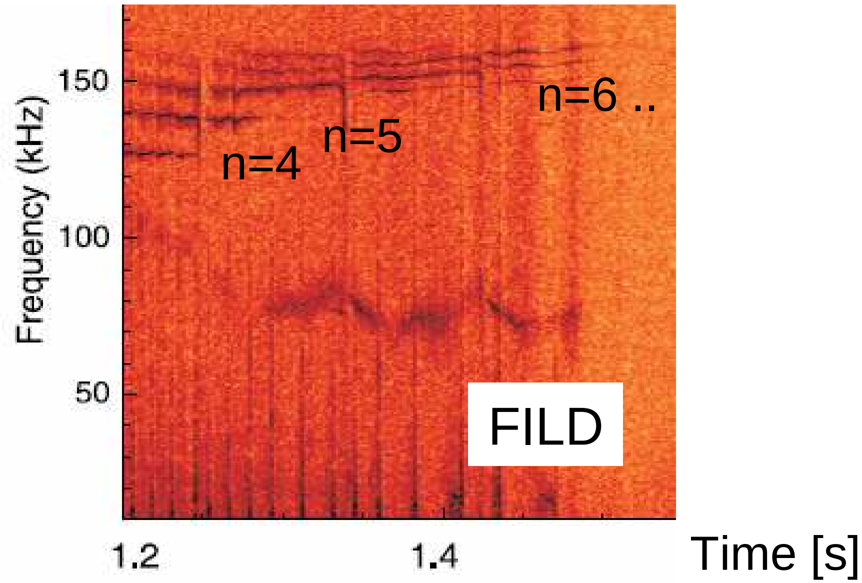
New diagnostics: Fast particle loss detector

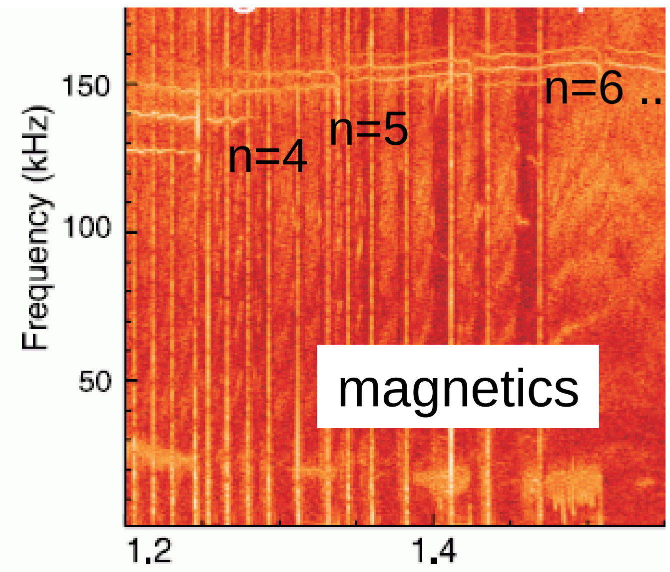


energy and pitch angle resolved measurements

very high time resolution ⇒ phase resolved measurements possible

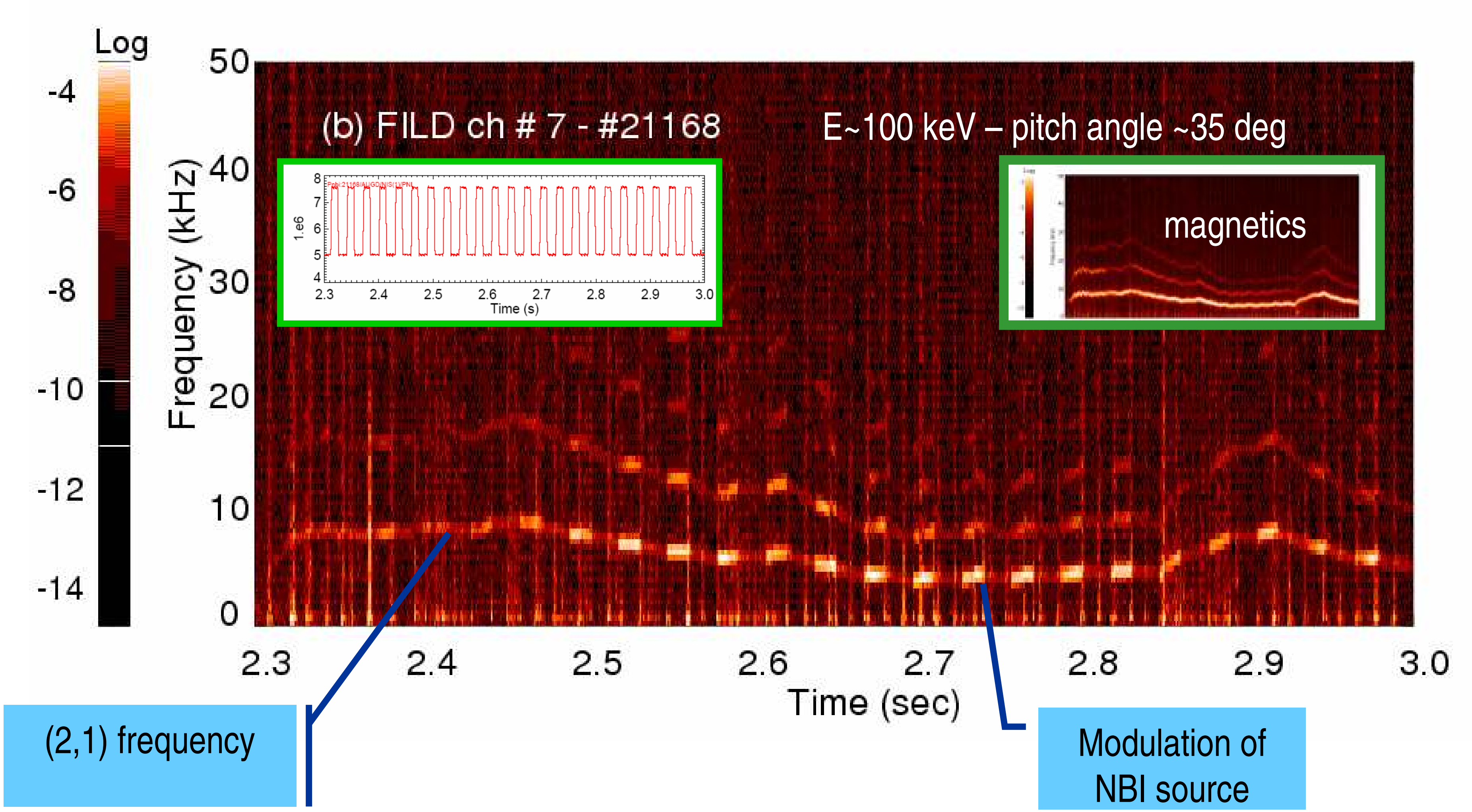
fast particle expulsion by (and in phase with) TAE modes





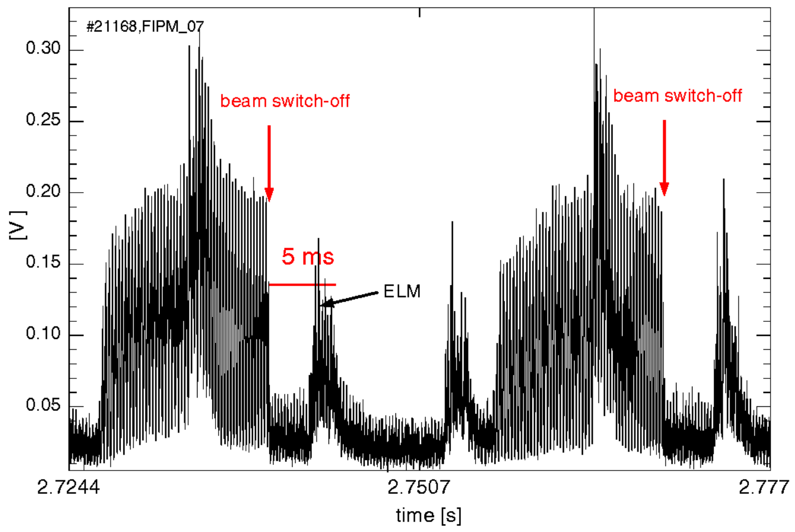
Losses caused by large (2,1) magnetic islands

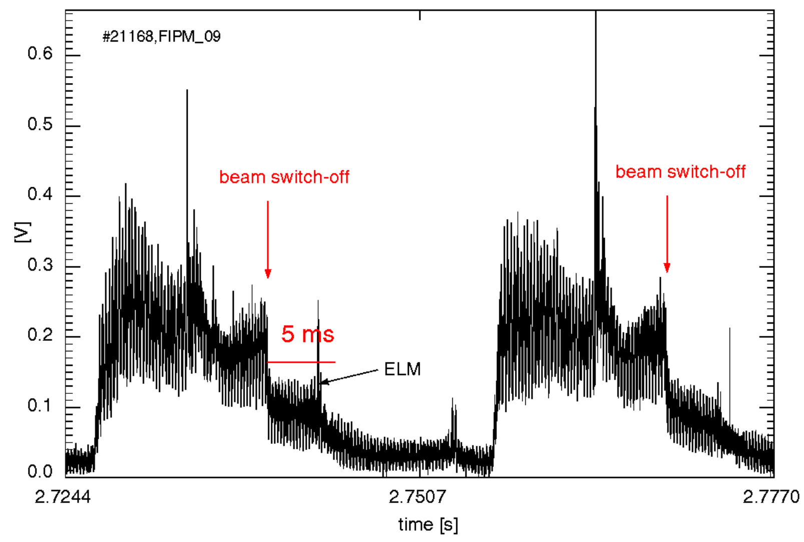
Passing as well as trapped particles expelled in phase with magnetic islands



Observed losses consistent with modeling (pitch angle, energy, response times)

Response of fast particle losses on switch on- and off-experiments





Response within microseconds (immdediate losses for particles deposited on HFS, well passing)

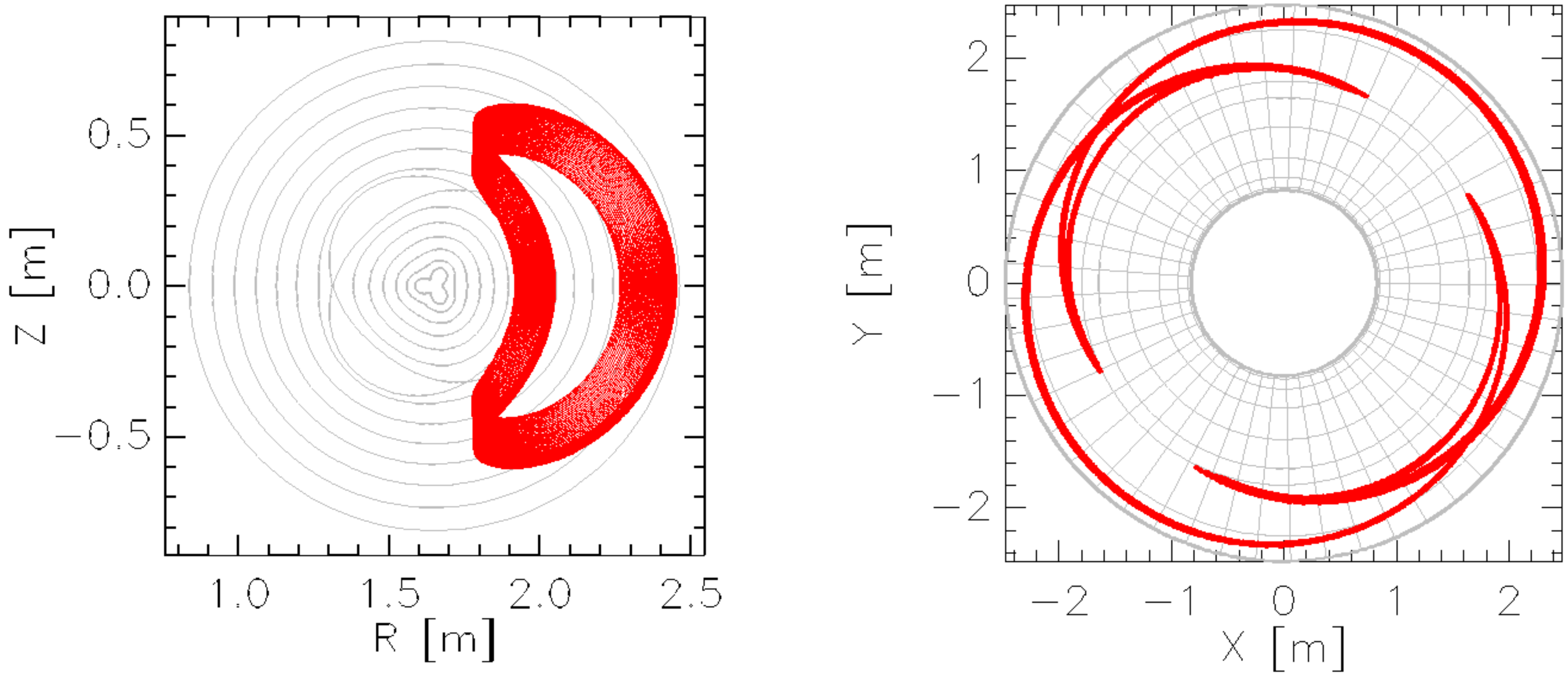
Response within milliseconds (diffusive losses for particles deposited on LFS)

Simulation of particle orbits in 3d equilibrium (Orbit, Gourdon):

drift islands

orbit stochastization

Losses of trapped particles caused by (3,2) NTMs



Fixed phase relation for ICRH heated particles:

- n=2 symmetry of the particle orbits, fixed phase relation between island and particles possible
- $\langle v_{||} B_r \rangle \neq 0$ responsible for outward drift

Discrepancies between calculated and measured TAE damping rates

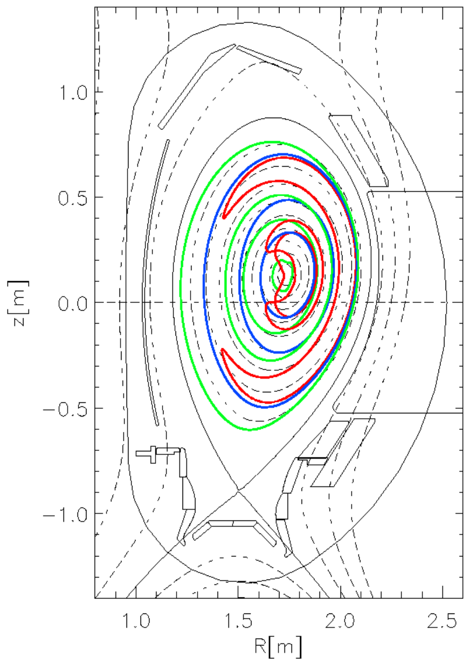
• JET: large discrepancies between measured and calculated damping rates for TAE modes (except for PENN model?)

• too small damping rates from all hybrid MHD- fast particle codes

• gyrokinetic PENN code: very large radiative damping, strongly dependent on the plasma shape, stable TAE modes in ITER divertor plasmas?

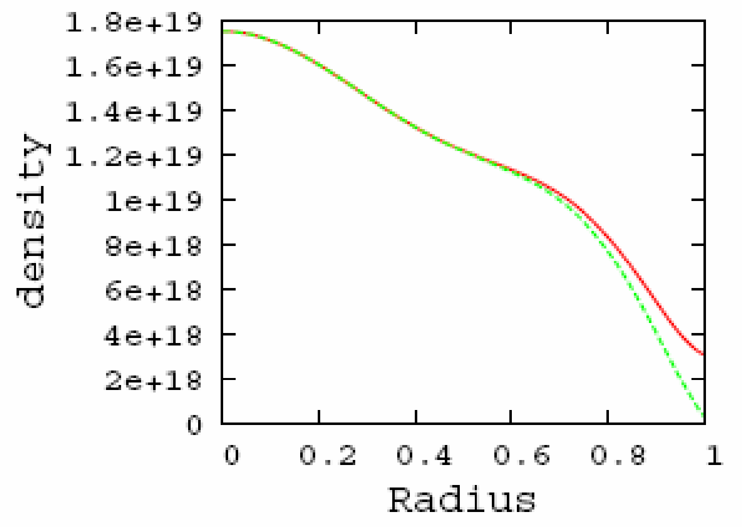
New code development: LIGKA

• fully gyrokinetic (radiative damping)
• non-perturbative (energetic particle modes)
• realistic tokamak geometry
• realistic particle orbits
• successfully benchmarked



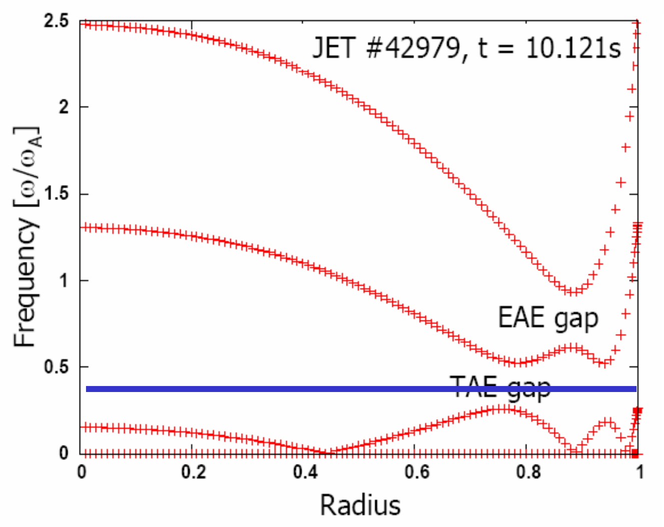
Large damping rates from theory for closed gaps only

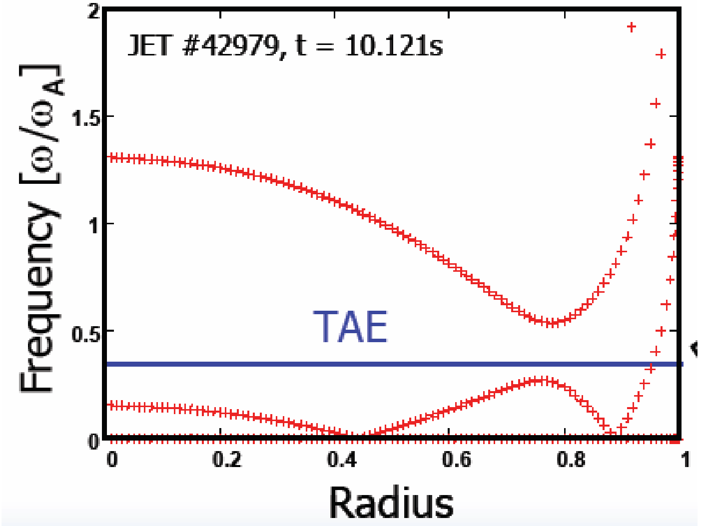
$v_A = B / \sqrt{\mu_0 \rho}$



experimental density profile

modified density profile

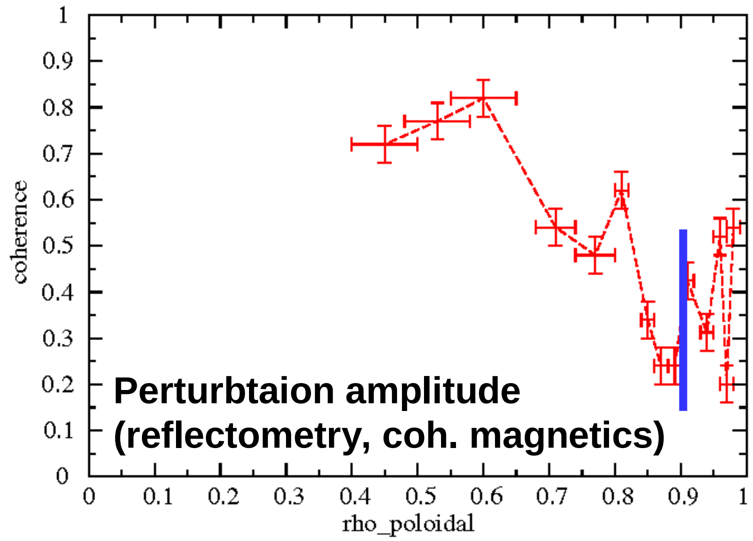


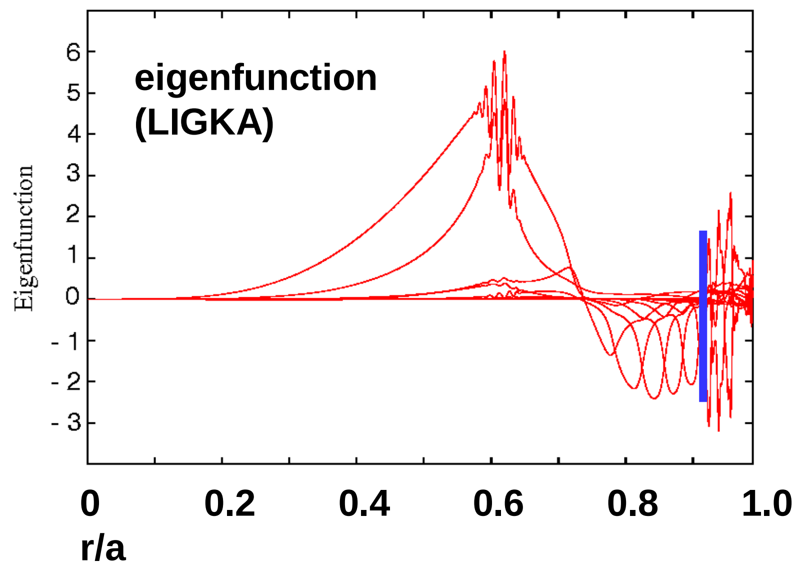


open TAE gap for experimental density profile

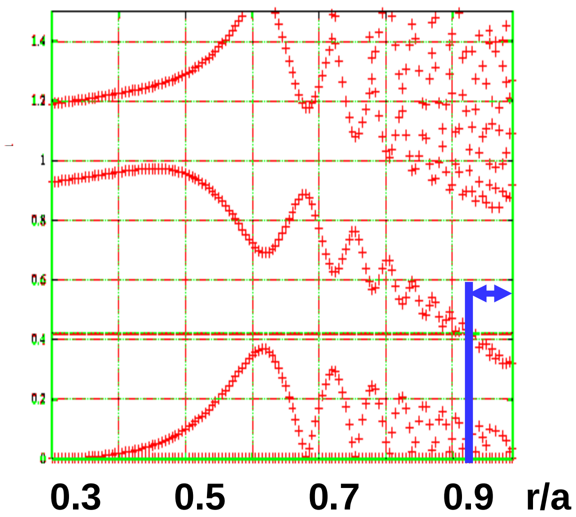
TAE gap closes modified density profile (within exp. error bars!)

For comparison between theory and experiment measurement of TAE eigenfunction beneficial





Alfvén continuum



- increase of TAE eigenfunction at plasma edge in gyrokinetic code for closed gap only

- significant amplitude for measured eigenfunction at the edge

= hint for closed gap in ASDEX Upgrade

Summary and Conclusions

NBI current drive

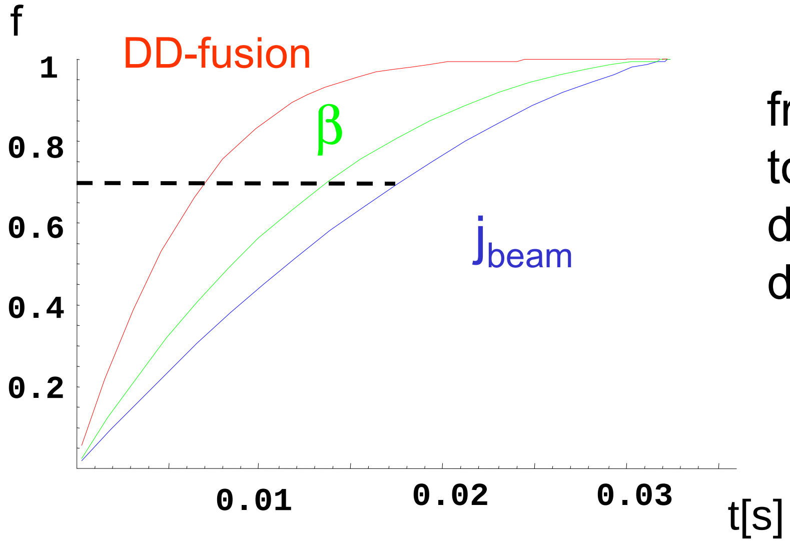
- total NBI current drive efficiency as expected from theory
- current profile modifications for moderate heating power/strong shaping only
- proposed reason: turbulent redistribution of fast ions

Interaction of fast particles with MHD modes

- new diagnostics: fast ion loss detector with high time resolution (< 1MHz)
- fast ion losses in phase with magnetic perturbation, in agreement with modelling
- TAE damping essentially by closed TAE gaps at the plasma edge

Note: Beam current is particularly susceptible to diffusion

Slowing down particles contribute substantially longer to beam current than to energy density or fusion rate



fractional contribution f of fast particles to DD-fusion, β, and beam current during first t seconds of their slowing down history

D-beam, E_{beam}=92keV,
T_e= 1keV, n=$5x10^{19}m^{-3}$

Are there inconsistencies with other experiments?

Slowing down of NBI ions is thought to be classical:

TFTR:

• NBI at r/a=0.5, 2 MW beams with 95 keV, no central heating
(nearly no radial diffusion of fast ions: $D < 0.05\ m^2/s$), Efthimion IAEA 1988

JET, TFTR:

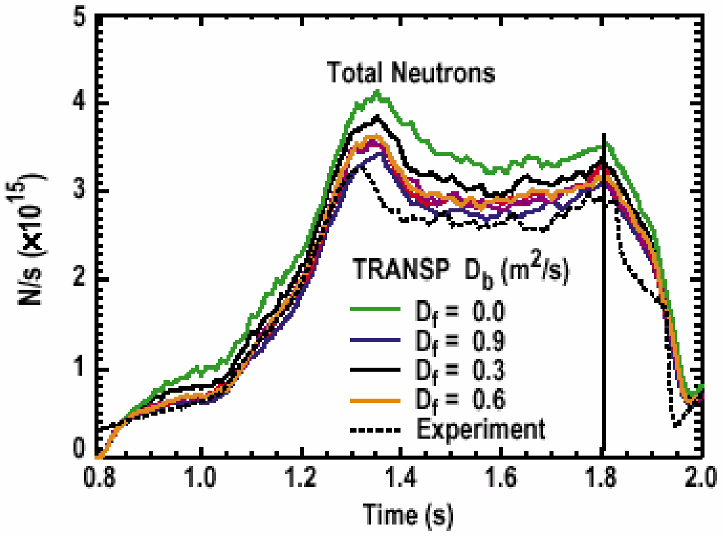
• Slowing down of 1 MeV tritons from d(d,p)t :

- in low temperature plasmas: classical slowing down
- for long slowing down time: $D \approx 0.1\ m^2/s$
  (Conroy EPS 1990, Scott IAEA 1991)

DIII-D:

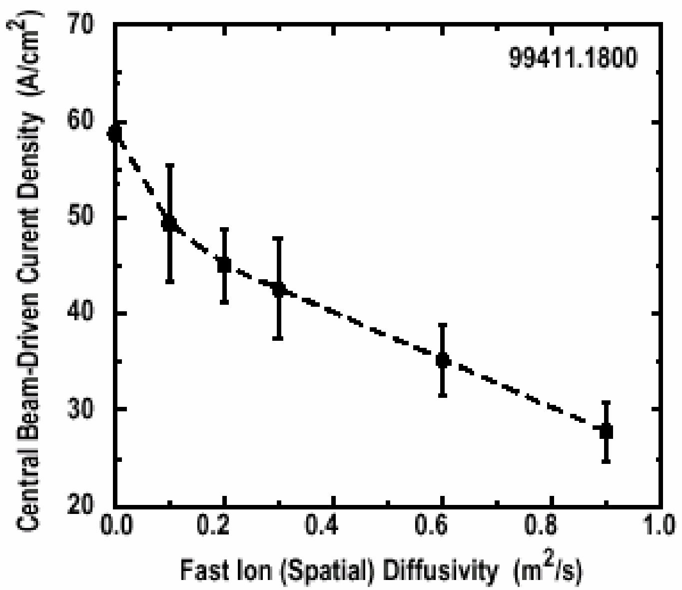
• anomalous fast ion redistribution needed to match stored energy and neutron rate for NBI heating in TRANSP simulations: $D \approx 0.9\ m^2/s$
(explanation: Alfvén waves)

Is slowing down of NBI ions always classical?



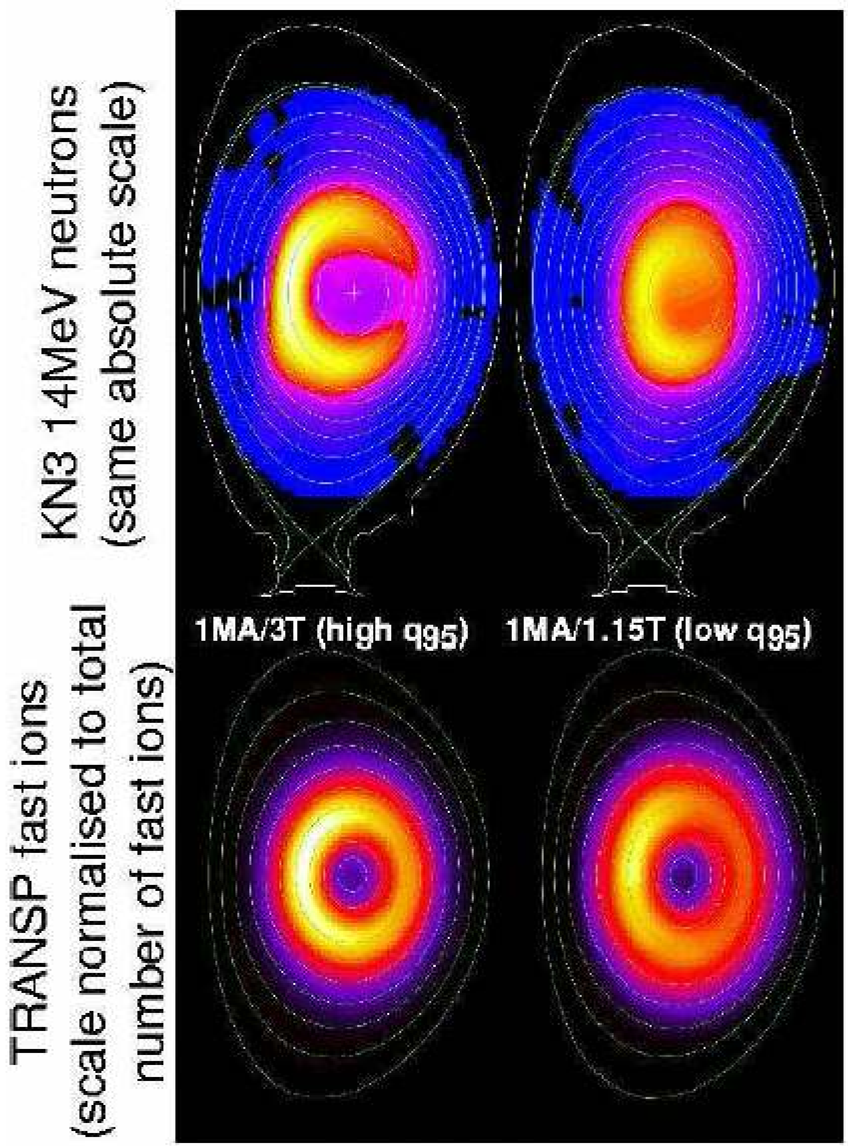
Anomalous fast particle redistribution needed to match the observed neutron rates at DIII-D (John et al., EPS 2001), explained by Alfvén waves

D_{fast} = 0.9 m^2/s would stronlgy reduce the beam current drive efficiency



Is slowing down of NBI ions always classical?

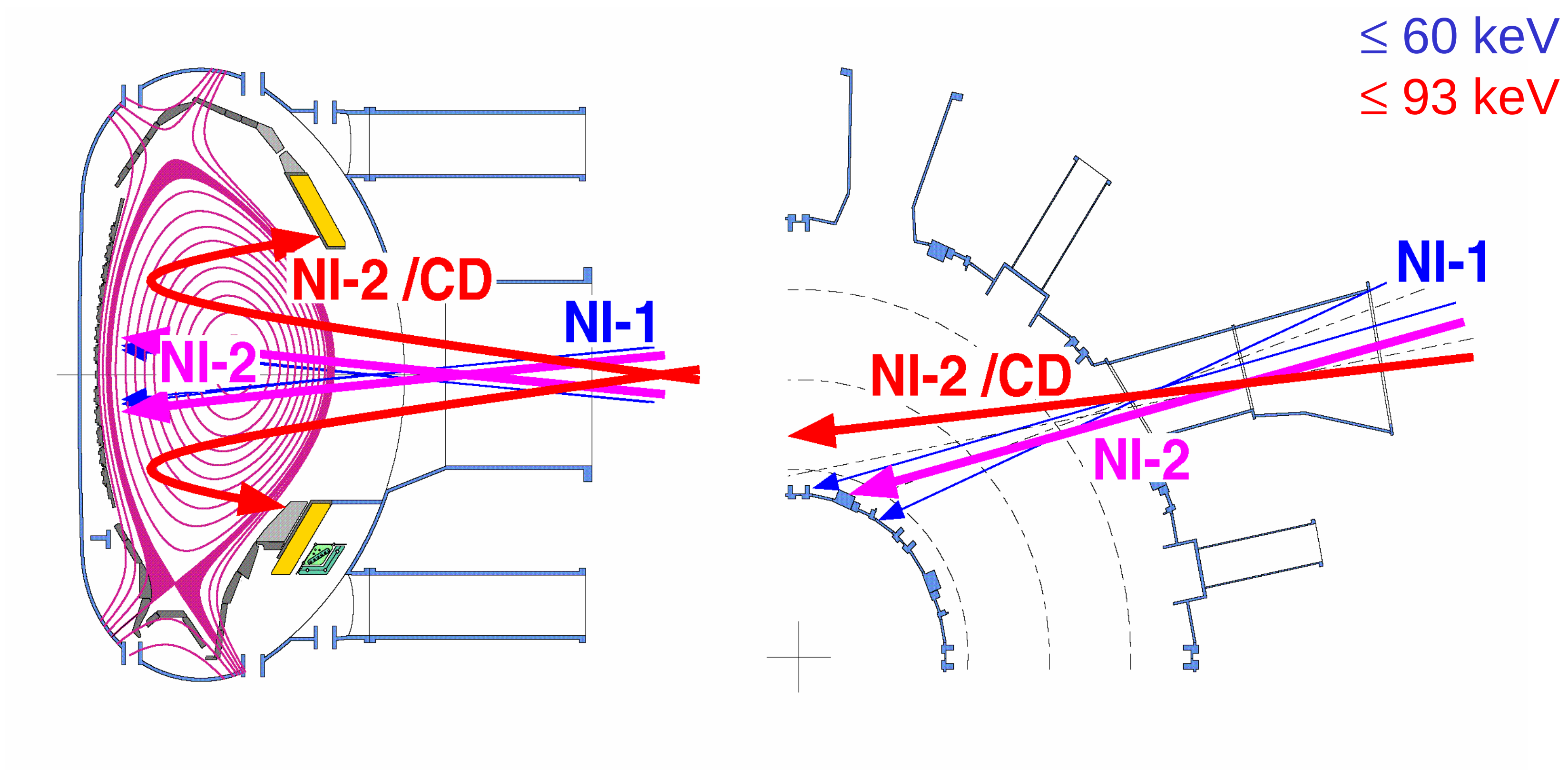
Challis, Hobirk 2004



Neutron rates for T beam into Ohmic JET discharges:

Anomalous fast ion transport for low magnetic field (no influence of MHD modes observed)

NBI current drive system on ASDEX Upgrade



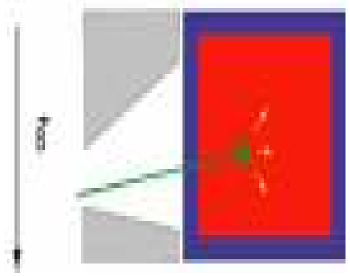
Re-direction of neutral beam injection system

- strong off-axis deposition by tilt of injection angle
- significant current drive at half radius expected

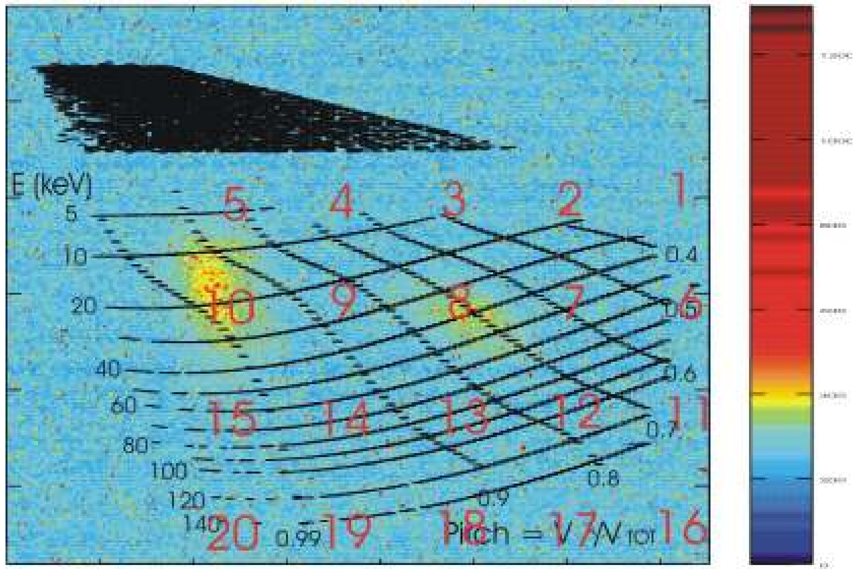
New diagnostic on AUG: fast ion loss detector

Energy Resolution.

Pitch Angle Resolution.



perp. energy



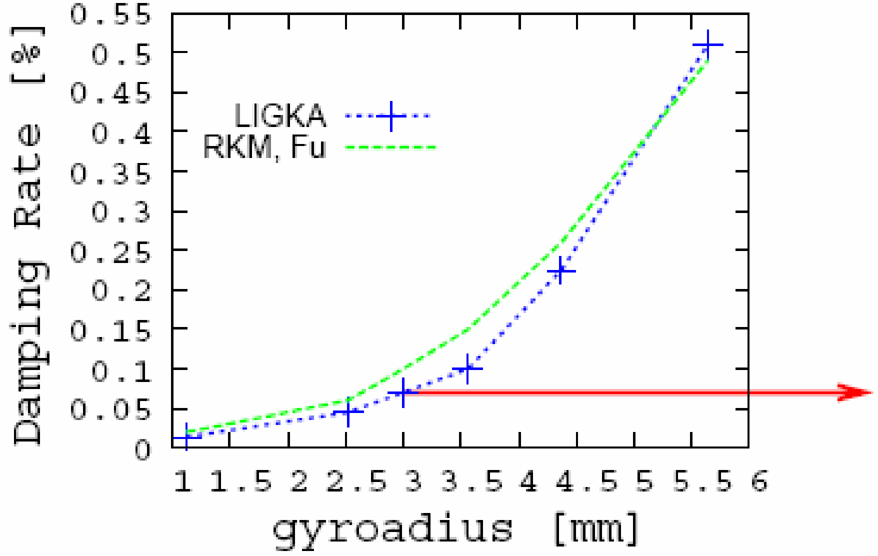
pitch angle

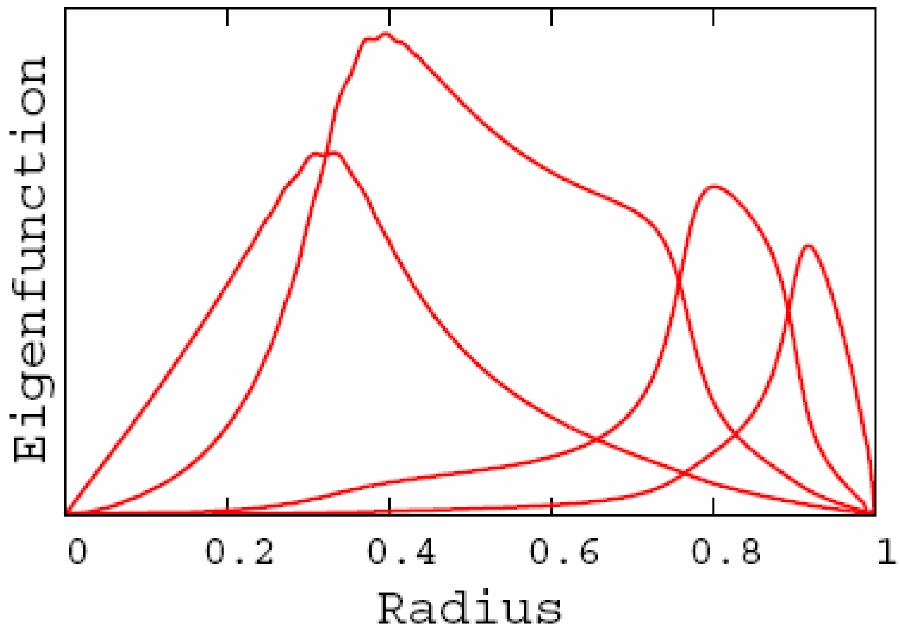
Particles with energies between 5 and 160 keV and pitch angles ($V_{\perp}/V_{tot}$) between 0.99 and 0.4

For realistic plasma parameters FLR effects small

Benchmark with Reduced Kinetic Model (G. Fu):

experimental values ($\varrho_i = 3$mm):
eigenmode structure starts to change compared to ideal case (perturbative treatment!)



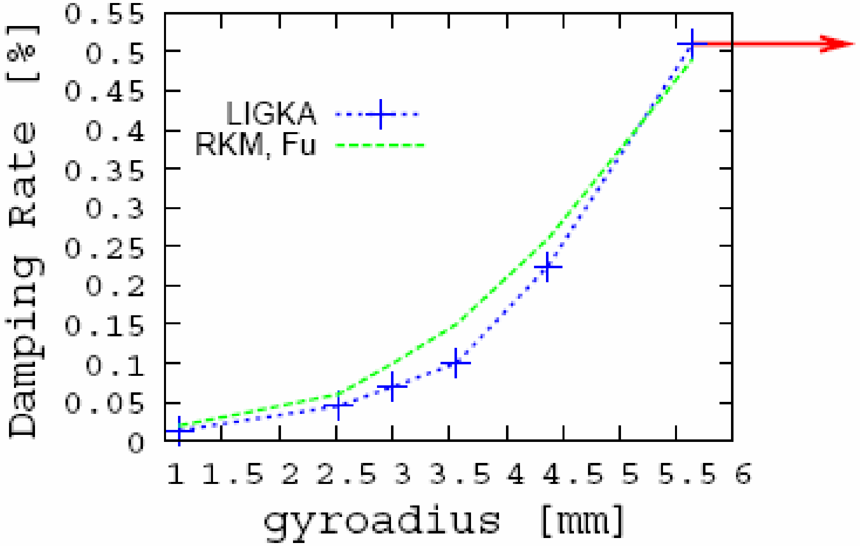


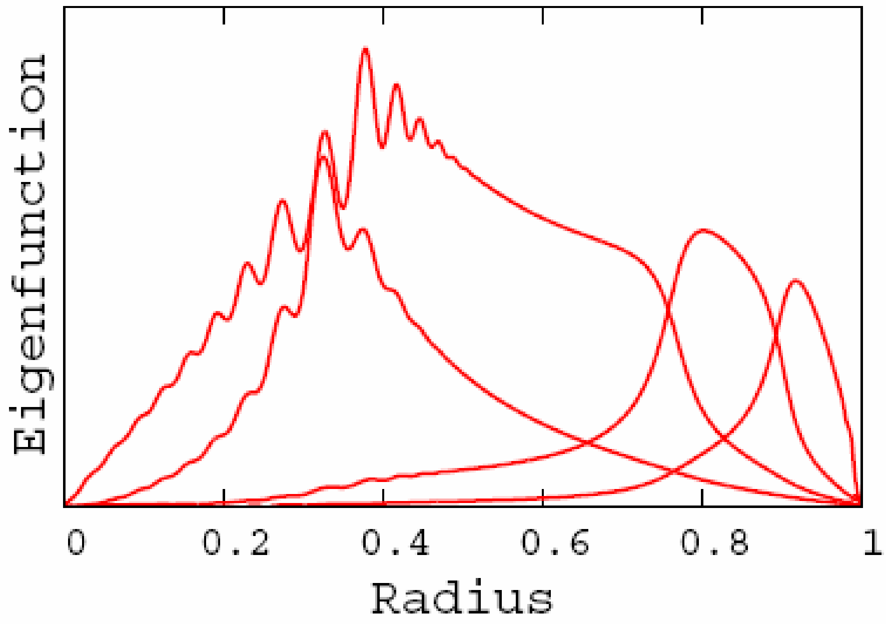
Influence of radiative damping

Artificial increase of FLR effects: benchmark successful

Benchmark with Reduced Kinetic Model (G. Fu):

Significant changes in the eigenfunction:





- NBI current drive can be used to replace inductive current (results consistent with theory, extrapolate well to ITER and DEMO)

BUT:

So far current profile modifications for very low heating power only

On the other hand:

Slowing down of NBI ions is thought to be local, usually concluded from :

- neutron rates
- heat deposition (mostly in low heat flux discharges)