# Fast Particle Instabilities in Advanced Scenarii (Nonlinear Physics)

G. Vlad, S. Briguglio, G. Fogaccia and F. Zonca

Associazione Euratom-ENEA sulla Fusione,
C.R. Frascati, Rome, Italy

10th EFPW December 8-11, 2002, Vaalsbroek, The Netherlands

Electronic version:
http://fusfis.frascati.enea.it/~vlad/Miscellanea/Vlad_10thEFPW_02.pdf

# Motivations

- Fusion product & fast ion confinement in Burning Plasmas, as e.g. ITER, under steady state conditions (advanced scenarii)
- Study collective behaviors, such as those induced by Energetic Particle Modes (EPM)

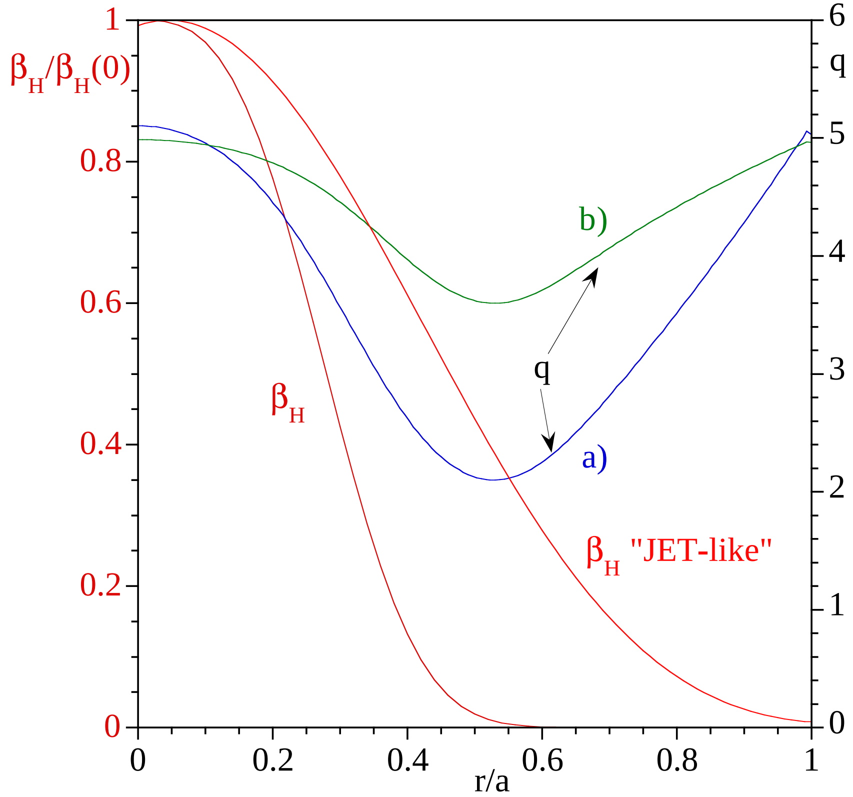
# Impact

- Choice of current profiles for Burning Plasmas in advanced regimes
- Choice of energy density profile of fast ions due to additional heating/current drive systems
- Consistency of reference scenarii in Burning Plasmas

# Outline

- Advanced scenarii: safety factor and energetic particle profile considered
- Linear theory predictions: unstable modes excited at different radial locations
- Nonlinear dynamics:
  - Numerical studies of EPM using 3D Hybrid MHD-Gyrokinetic simulations
  - Weak/Strong energetic particle drive
  - Fast particle transport: evidence of avalanches and redistribution within the minimum $q$ surface or degradation of confinement (depending on drive strenght and $q$ profile)
  - Possible experimental evidence of resonant EPM modes

# 1 Advanced-scenario profiles



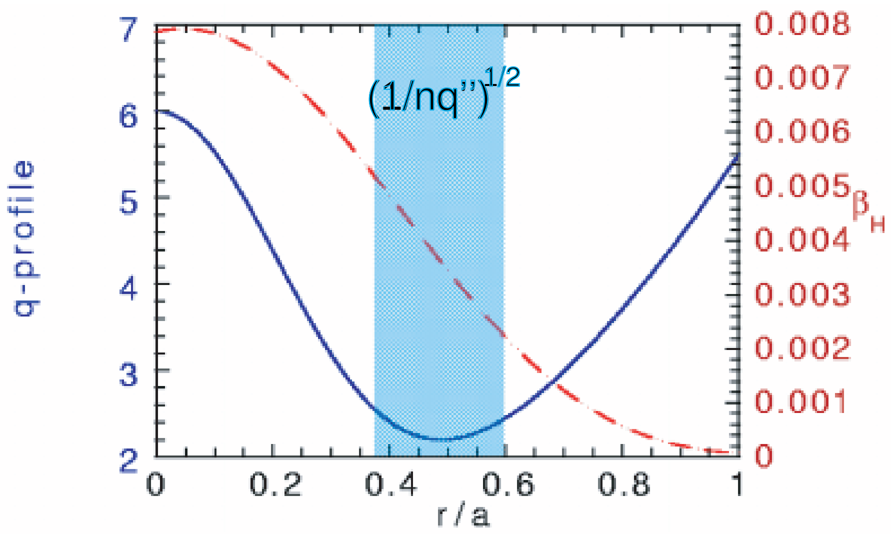
Two different reversed shear $q$-profiles considered:

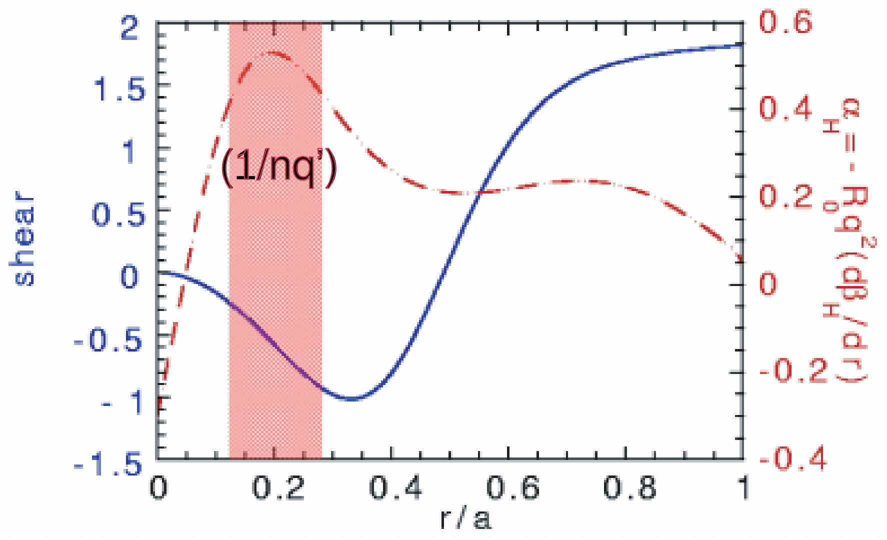
- hollow $q$-profile
- shallow $q$-profile

Energetic particle pressure profiles considered (shown in figure, red):

- peaked profile, peaking factor $\beta_{H0}/\langle\beta_H\rangle \approx 8$
- “JET-like” profile $\beta_{H0}/\langle\beta_H\rangle \approx 3.7$

# 2 Linear theory predictions



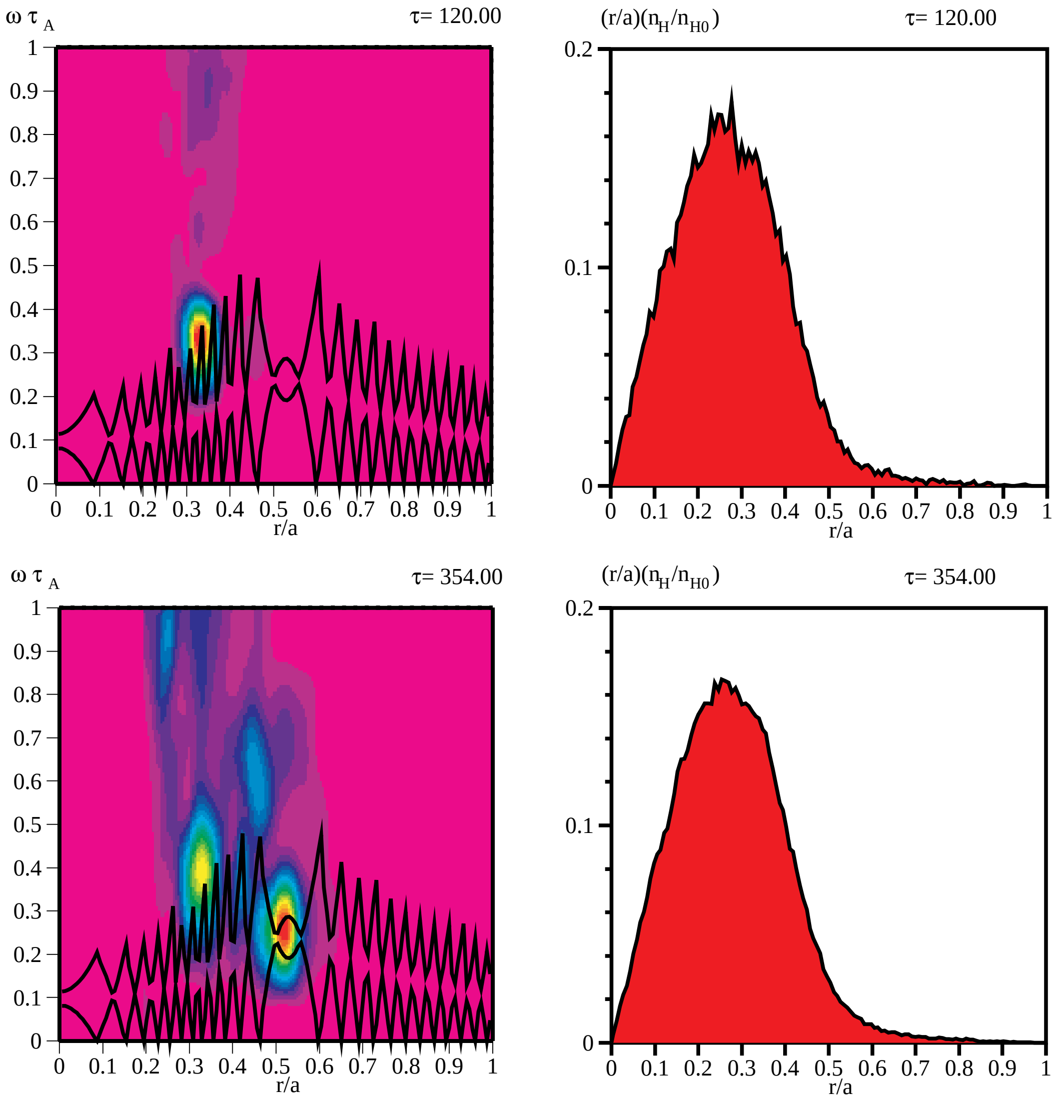


- Natural gap in the Alfvén continuum appears at $q_{min}$ (Berk et al., PRL 2001) $\Longrightarrow$ EPM Gap Modes
- Strong resonant excitation of EPMs should occur at $r/a \approx 0.2$, where the drive ($\alpha_H$) is maximum (Chen, 1994)

# 3 Nonlinear dynamics of EPM using 3D Hybrid MHD-Gyrokinetic simulations

- Hybrid MHD-Gyrokinetic simulation Code (HMGC): nonlinear, initial value hybrid code in which the bulk plasma is described by $O(\epsilon^3)$, low-$\beta$, reduced MHD fluid equations and the energetic particle population is described by the nonlinear gyrokinetic equations
- Circular shifted flux surfaces
- isotropic Maxwellian with constant temperature for the initial energetic-particle distribution function
- flat bulk plasma density profile
- $\epsilon(\equiv a/R_0) = 0.1$, $\rho_{LH}/a = 0.01$, $v_{TH}/v_A = 1$, $m_H/m_i = 1$
- single toroidal mode number $n = 4$ considered (fluid nonlinearities neglected)

# 4 Weak energetic particle drive, hollow $q$ profile (**a**), $\beta_{H0} \approx 0.008$, $\beta_{H0}/\langle\beta_H\rangle \approx 8$



●Scalar potential fluctuation intensity in the $(r/a, \omega\tau_A)$ plane (left) during linear destabilization phase $(\tau/\tau_A = 120)$ and during fully nonlinear saturate phase $(\tau/\tau_A = 354)$. Shear Alfvén continuous spectrum is also shown

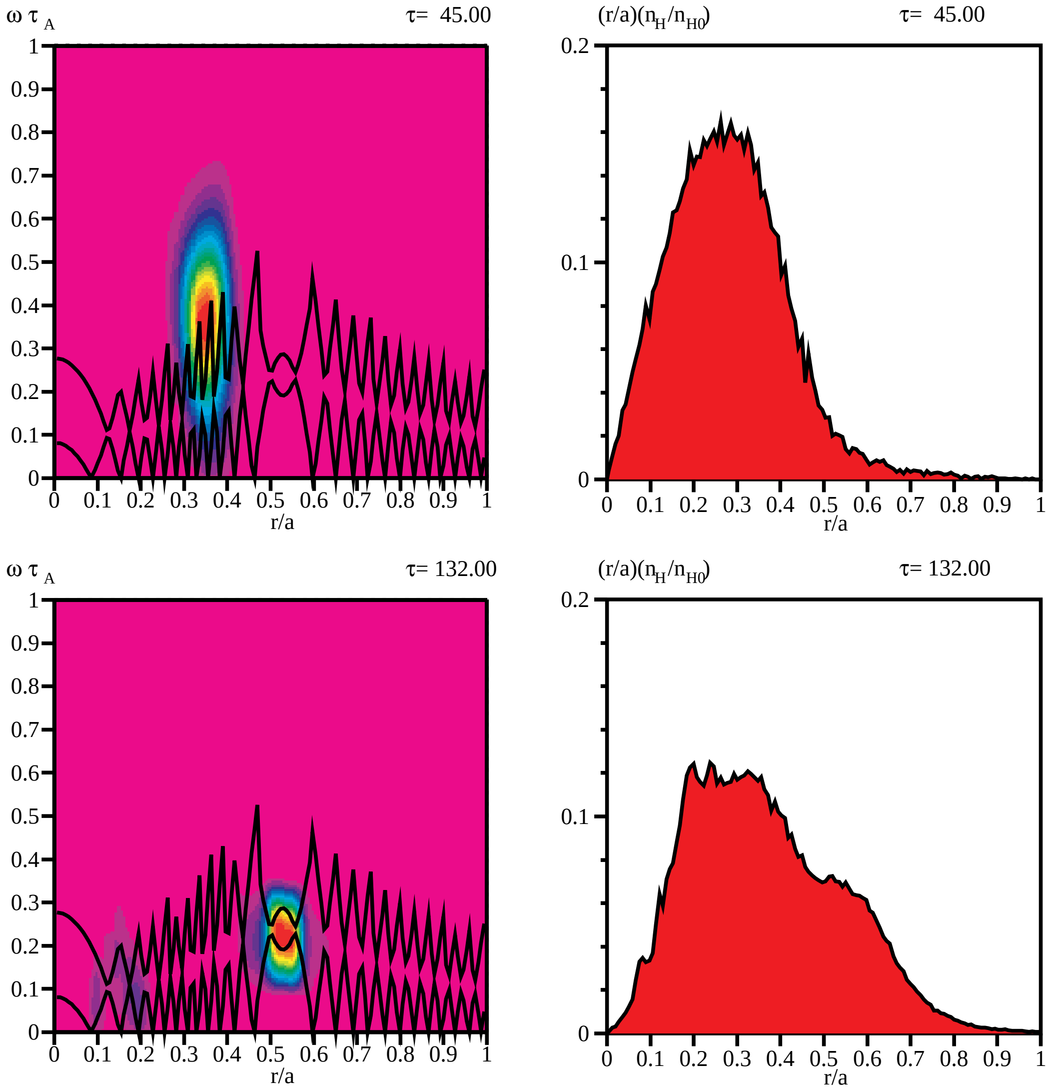
●Fast ion radial distribution $(r/a)(\beta_H/\beta_{H0})$ as a function of $r/a$ is shown (right)

●Two dominant modes are observed: (1) a resonant EPM at the radial position of max drive $(r/a \approx 0.3)$, and (2) an EPM gap mode near the $q_{min}$ $(r/a \approx 0.5)$ with a weaker growth rate (modes coexist asymptotically in time)

●Energetic particle radial distribution almost unchanged

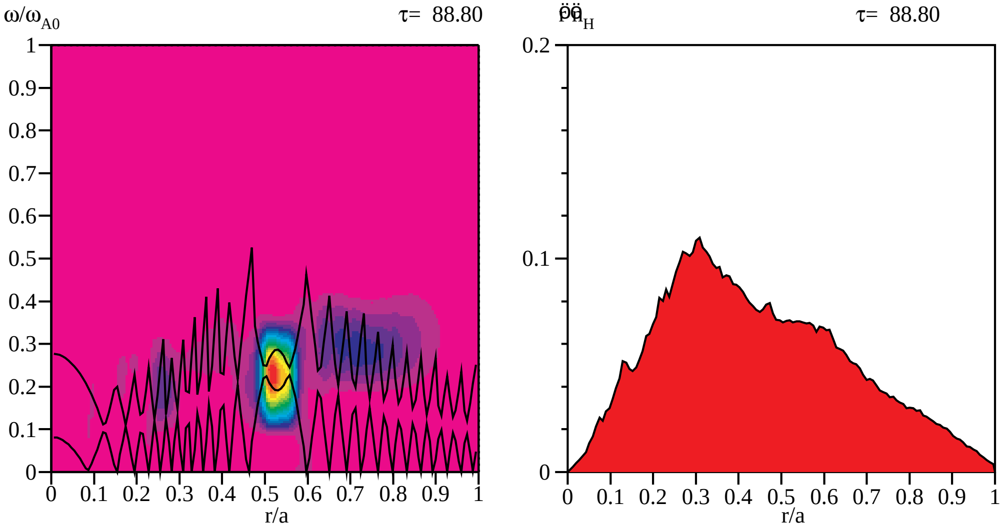
(Simulation case: n4_JET_32.mov)

# 5 Moderate drive, hollow $q$ profile (**a**), $\beta_{H0} \approx 0.022$, $\beta_{H0}/\langle\beta_H\rangle \approx 8$



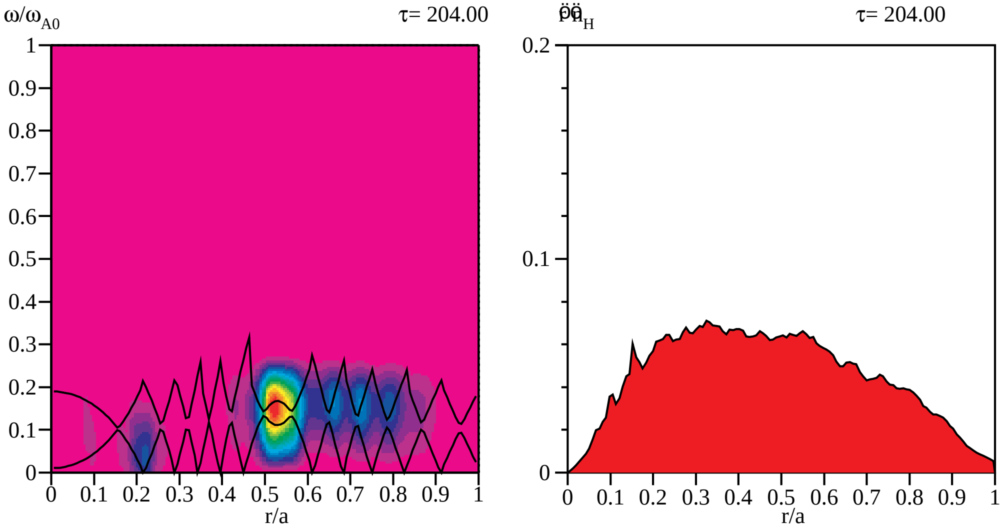
- Linear destabilization phase ($\tau/\tau_A = 45$) and fully nonlinear saturate phase ($\tau/\tau_A = 132$)
- (1) a resonant EPM at the radial position of max drive ($r/a \approx 0.3$) is observed during the linear phase which evolves in (2) an EPM gap mode near the $q_{min}$ ($r/a \approx 0.5$) in the fully nonlinear saturated phase
- Energetic particle radial distribution is modified: $q_{min}$ surface acts as a barrier
- Evidence of "avalanches": radial propagation of an unstable front
- see movie: n4_JET_7_avalanches.mov

# 6 Fast energetic particle transport



- Strong drive, hollow $q$ profile (a), $\beta_{H0} \approx 0.043$, $\beta_{H0}/\langle\beta_H\rangle \approx 8$
- Fully nonlinear saturate phase $(\tau/\tau_A = 88.8)$.
- The mode extends beyond the $q_{min}$ surface as well
- Energetic particle radial distribution is strongly modified

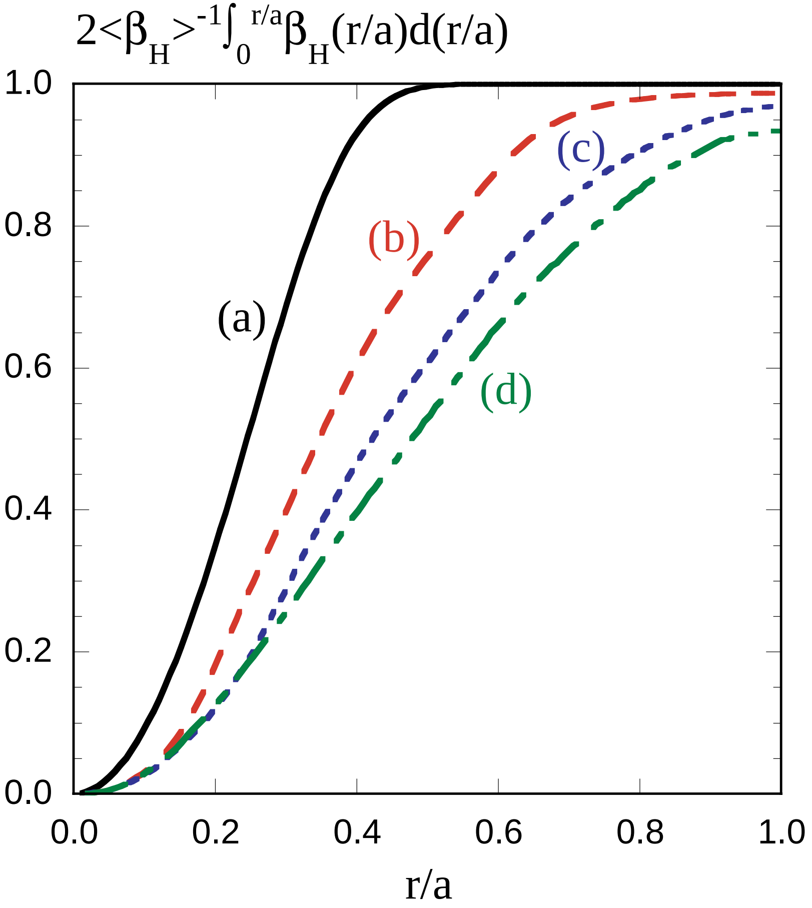
(Simulation case: n4_JET_19.mov)



- Moderate drive, shallow $q$ profile (b), $\beta_{H0} \approx 0.02$, $\beta_{H0}/\langle\beta_H\rangle \approx 8$
- Fully nonlinear saturate phase $(\tau/\tau_A = 204)$.
- The mode extends beyond the $q_{min}$ surface as well
- Comparable radial redistribution, for shallow $q$ profile, even at moderate drive $(\beta_{H0} \approx 0.02)$

(Simulation case: n4_JET_11.mov)

# Fast ion radial redistribution within the minimum-$q$ surface and total losses ($\langle\beta_H\rangle = 2\int_0^1 (r/a)\beta_H d(r/a)$)



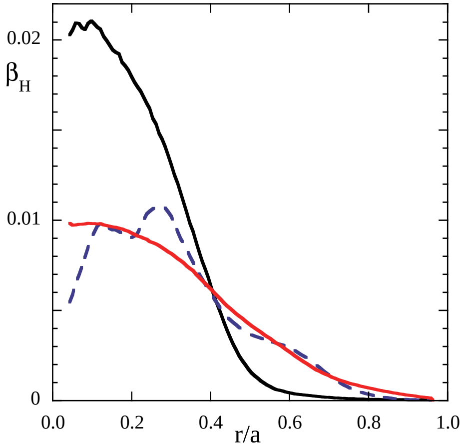
- ●(a) Equilibrium energetic particle distribution
- ●(b) hollow $q$-profile, moderate drive, $\beta_{H0} \approx 0.022$, 1.3% loss
- ●(c) hollow $q$-profile, strong drive, $\beta_{H0} \approx 0.043$, 3.1% loss
- ●(d) shallow $q$-profile, moderate drive, $\beta_{H0} \approx 0.02$, 6.6% loss

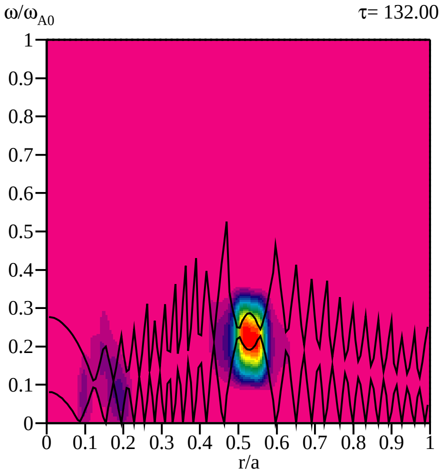
# 7 Possible experimental evidence of resonant EPM

Comparison between

- "moderate drive" case (hollow $q$ profile, $\langle\beta_H\rangle \approx 0.27\%$, $\beta_{H0}/\langle\beta_H\rangle \approx 8$ )
- a "JET-like" case (same $q$ profile and $\langle\beta_H\rangle$, but lower peaking factor $\beta_{H0}/\langle\beta_H\rangle \approx 3.7$)

Almost no difference in the Alfvén spectra and asymptotic pressure profiles



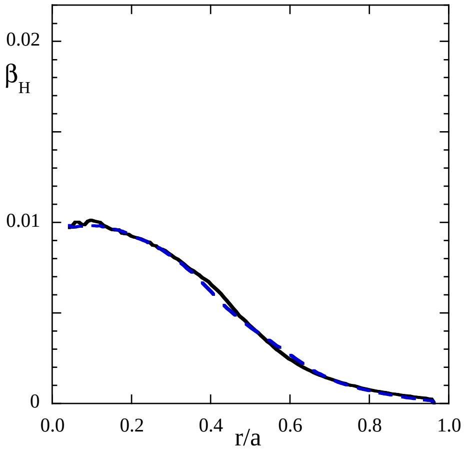


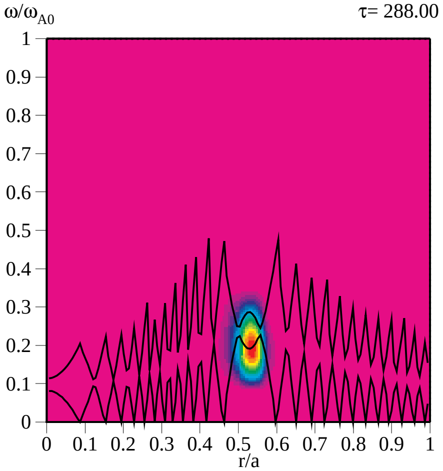
●peaking factor ≈ 8

●initial (black curve) and asymptotic (blue curve) pressure profile

●the "JET-like" profile (red) is also shown for comparison

(Simulation case: n4_JET_7_avalanches.mov)





●peaking factor ≈ 3.7 ("JET-like" case)

●initial (black curve) and asymptotic (blue curve) pressure profile

●internal resonant EPM is not excited

(Simulation case: n4_JET_33.mov)

- Nonlinear energetic particle (EP) redistribution takes place on a very short time scale, of the order of the inverse of the EPM growth rate (typically $\approx 100\tau_A$, $\tau_A = R_0/v_A$): too short to be experimentally observable!

- Discrepances between the EP deposition profile and the measured one (the measured profile being broader than the deposition one) can be the sign of the action of an internal resonant EPM

- A sequence of discharges with peaked EP deposition profile should give, as $\beta_{H0}$ decreases, the following phenomenology:
  - at high $\beta_{H0}$ (above the threshold $\beta_{H,th2}$ for which a strong internal resonant EPM is excited), a strong modification of the EP profile is observed as a consequence of the nonlinear dynamics (avalanches) and an EPM gap mode survives, asymptotically in time
  - as $\beta_{H0}$ is decreased below $\beta_{H,th2}$, the coexistence of an internal resonant EPM and of an EPM gap mode which does not produce any macroscopic modification of the EP profile should be observed
  - at low $\beta_{H0}$, below a second threshold $\beta_{H,th1}$, only a weak gap mode with no modification of the EP profile should be excited

# 8 Conclusions

- Resonant EPM are excited close to the radial position where the drive is maximum

- EPM gap modes are driven at $q_{min}$ and generally have a weaker growth rate

- For sufficiently high energetic particle drive, the evolution of the (stronger) resonant EPM and the (weaker) EPM gap mode can be strictly connected by rapid radial transport of the energetic particles

- Energetic particle internal "avalanche" barrier: the hollow $q$-profile is able to sustain higher energetic particle content within the $q_{min}$ surface in comparison with the shallow one

- Control parameters (besides $\beta'_H$, the obvious one), are $q''$, which reflects on the local mode width ($\propto 1/\sqrt{nq''}$), and $q_{min}$ itself, as the typical orbit size is proportional to $q$ and the energetic particle drive intensity ($\alpha_H$) scales as $q^2$

- A suggestion for experimentally revealing the effect of resonant EPM phenomenology has been proposed