Pellets, etc.
(JOREK at ITER)

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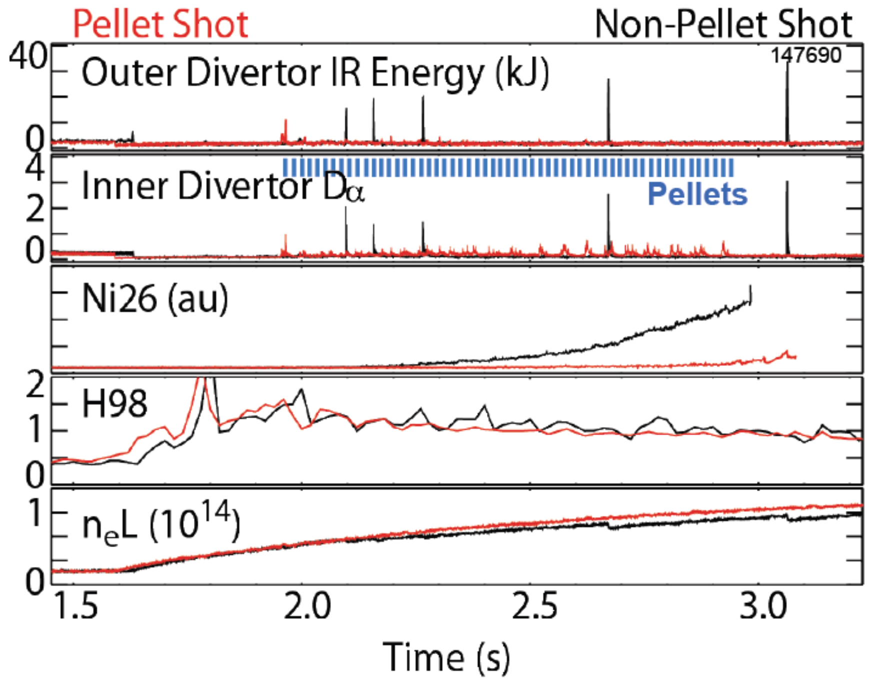
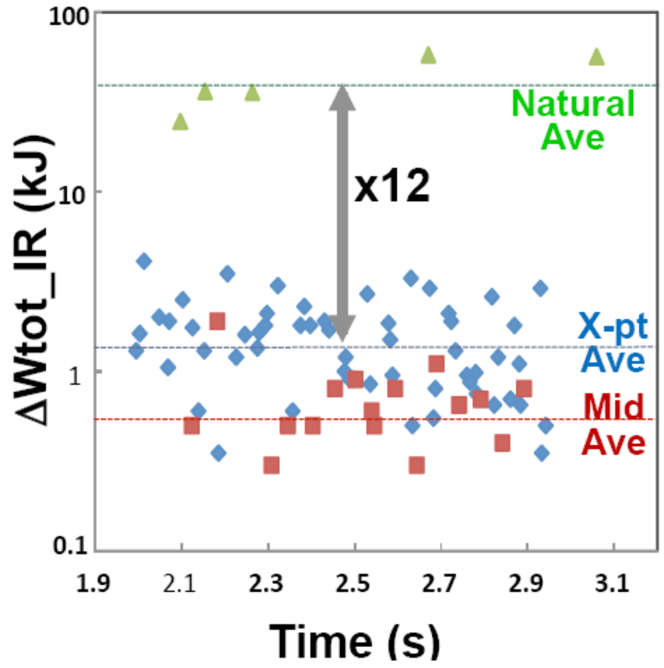
ELM control: Pellet triggered ELMs

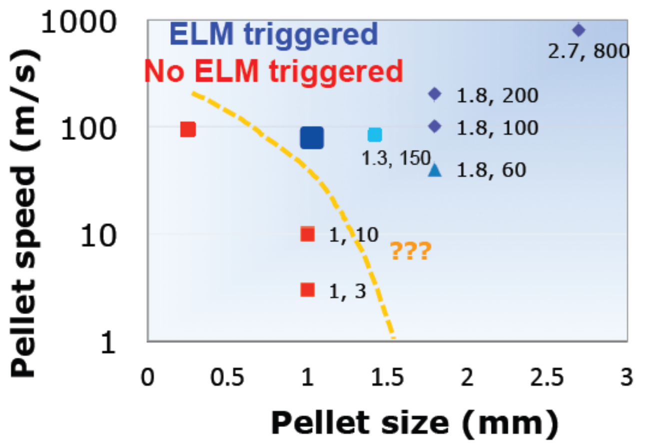
- Pellet pacemaking is one of the ELM c foreseen in ITER
  - Injecting a pellet triggers an ELM
  - forcing an increased ELM frequency leads to smaller ELMs



DIII-D, Baylor, IAEA2012



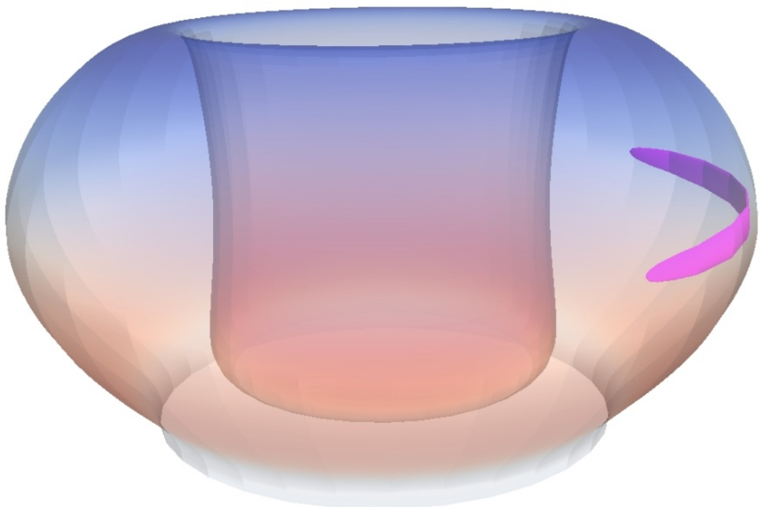
DIII-D Pellet Parameters



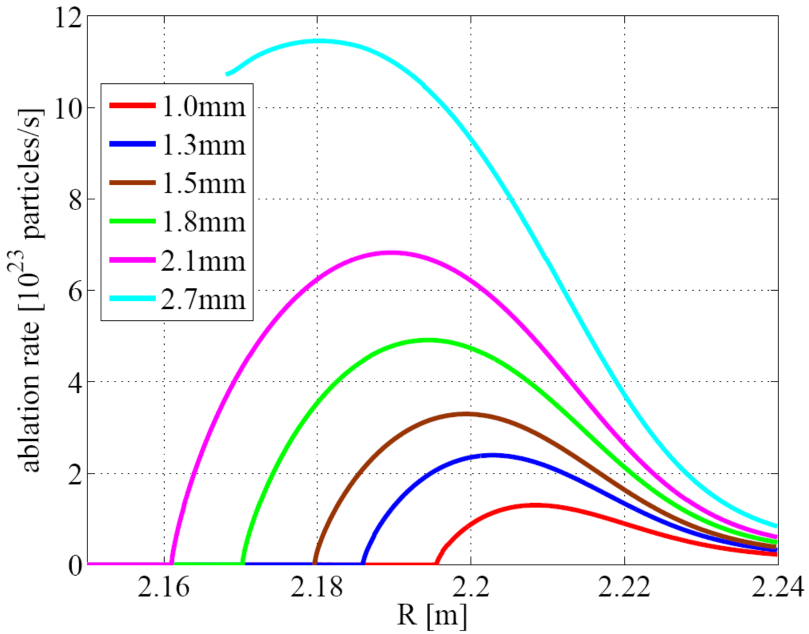
Pellet triggered ELMs

- Pellets are modelled as a moving density source:
  - Ablation rate function of local plasma parameters
  - Fixed pellet velocity (100-300 m/s)
  - Simulated pellets much larger than physical pellet
    - with same number of particles

$$N' = 4.12 \times 10^{16} \cdot r_p^{1.33} \cdot n_e^{0.33} \cdot T_e^{1.64}$$

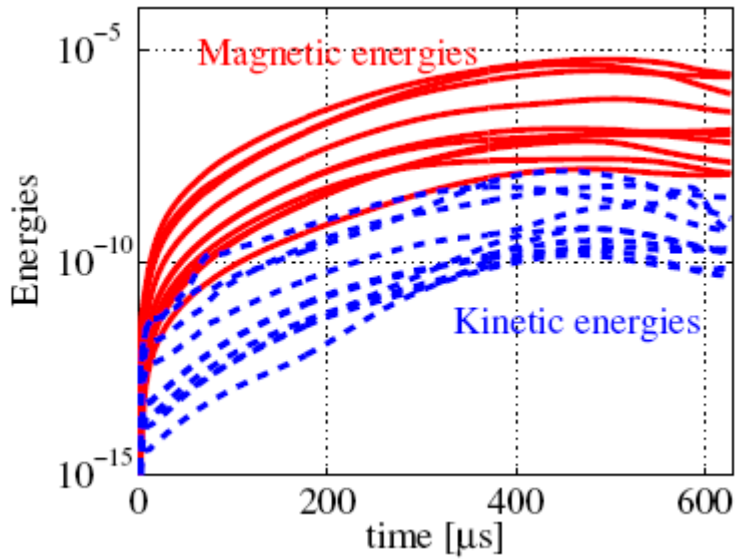


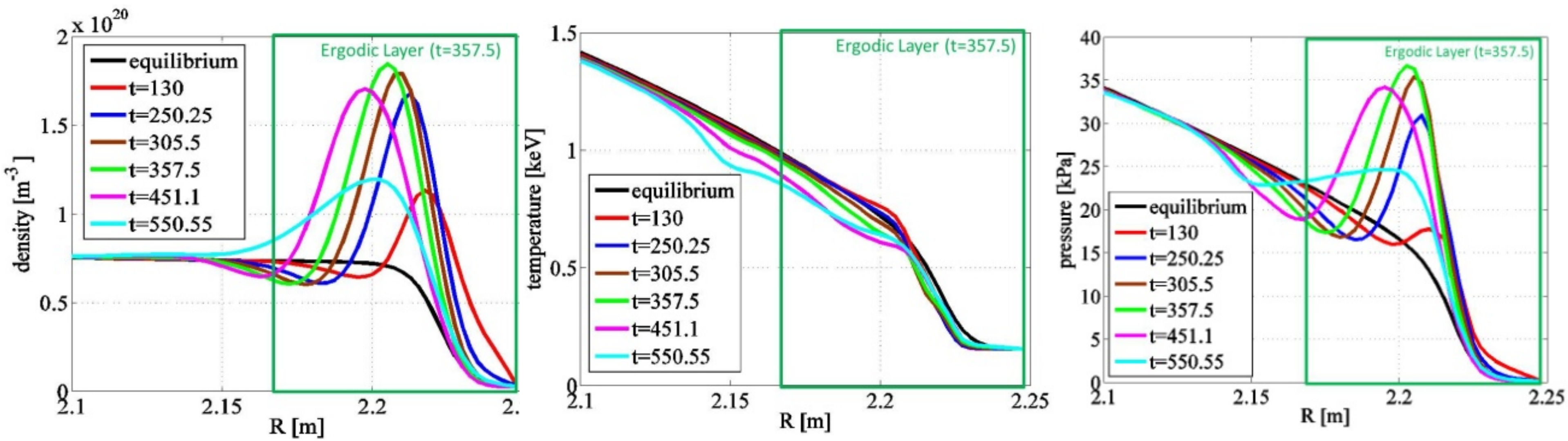
toroidal : 60 degrees
poloidal : 5x radial size



Profile Evolution

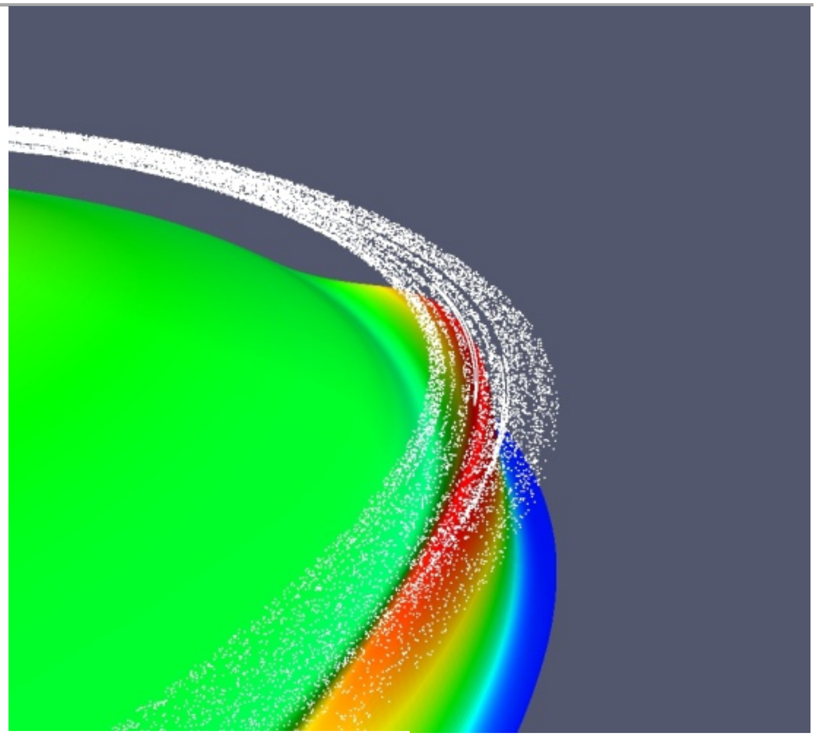
- Pellet injection leads to perturbations in magnetic and kinetic energies
- Pellet injection is adiabatic
  - Initial temperature cooling due to density rise is reheated by large parallel heat conduction
  - Yields large local pressure perturbation spreading along the fieldlines with the local sound speed
  - Large pressure perturbations can trigger MHD instabilities (ballooning modes)

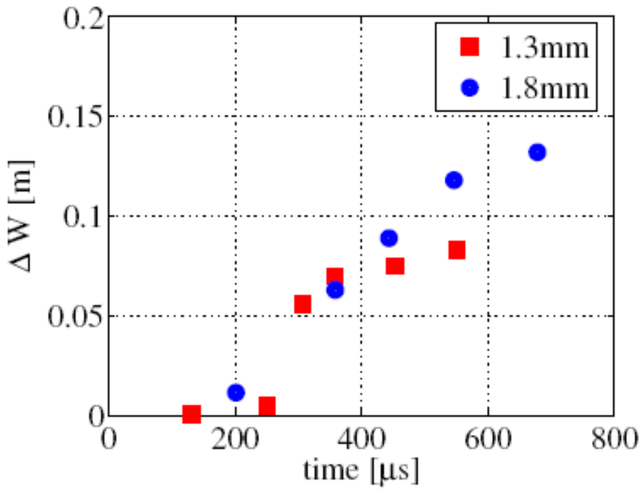


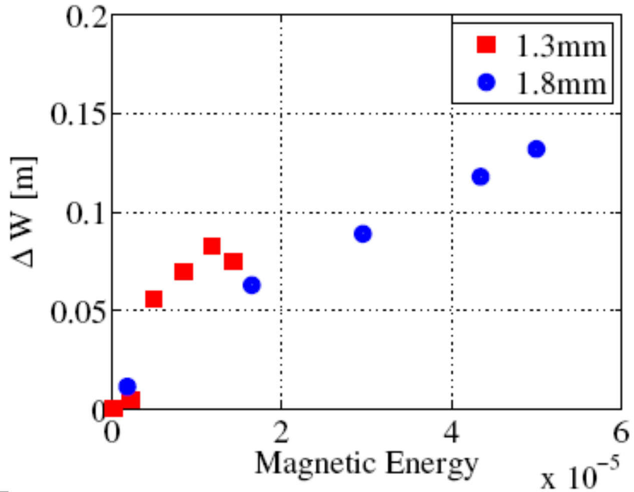


Ergodic layer

- MHD perturbation due to pellet injection leads to an ergodisation of the edge magnetic field
  - Heating of the pellet could can come from a larger area than just the pellet position
  - Consequence for ablation models?

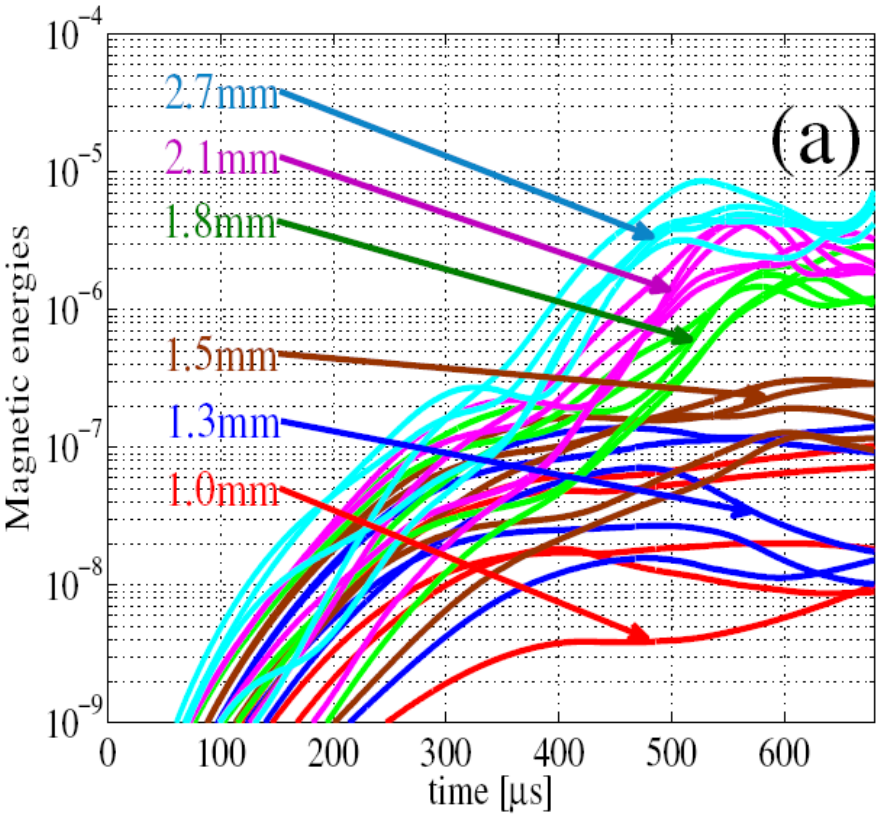


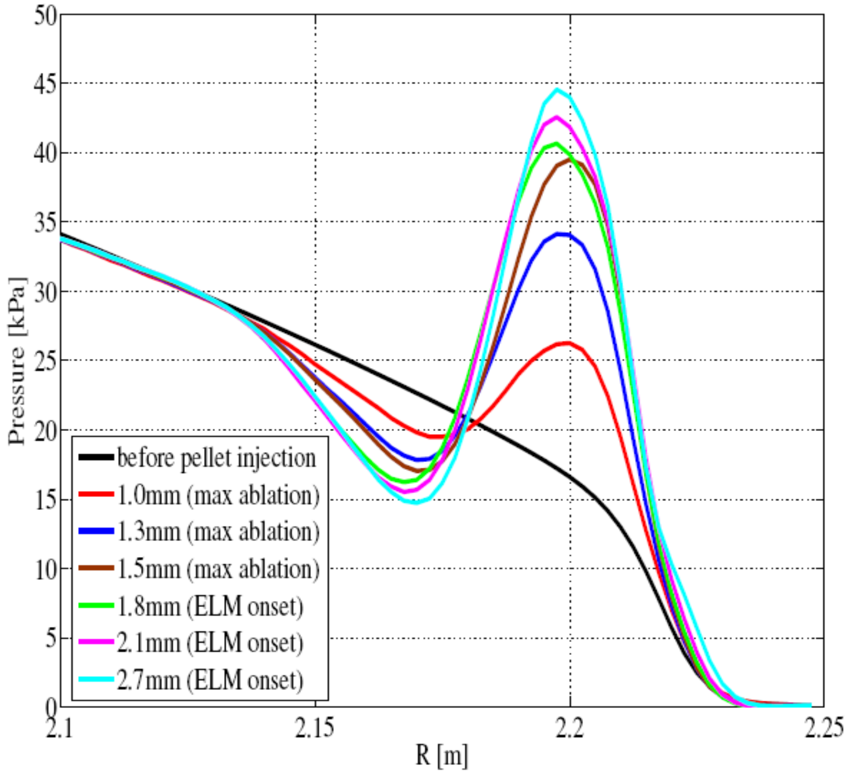




Critical Pellet Size

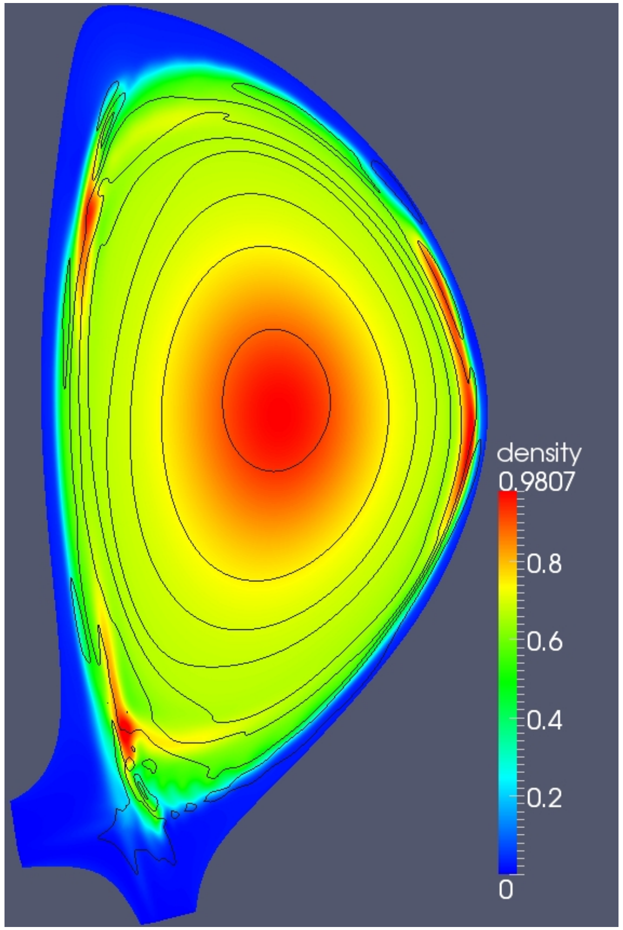
- JOREK simulation show a minimum pellet size is needed to trigger an ELM
  - Critical pressure perturbation



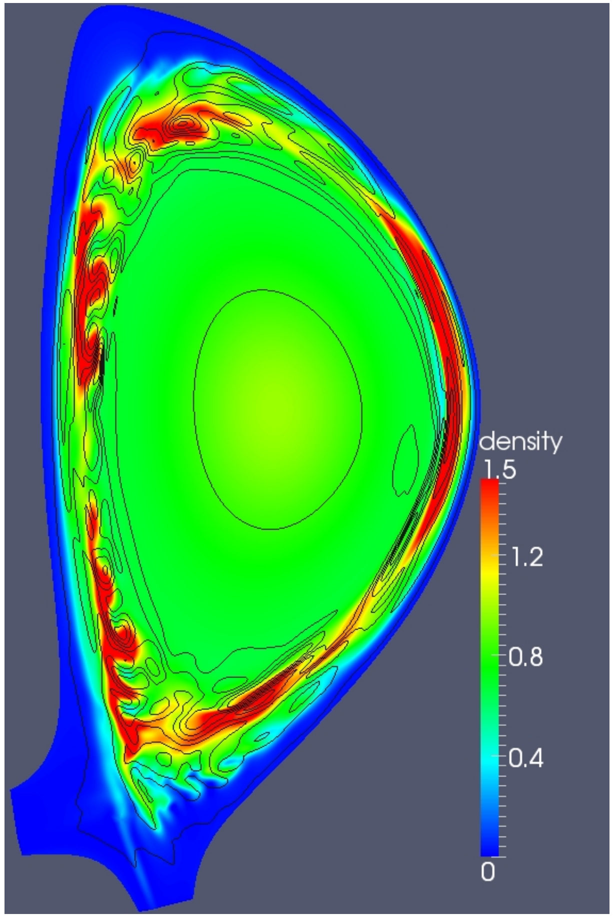


Density Perturbation due to ELM onset

1.0mm midplane (stable)

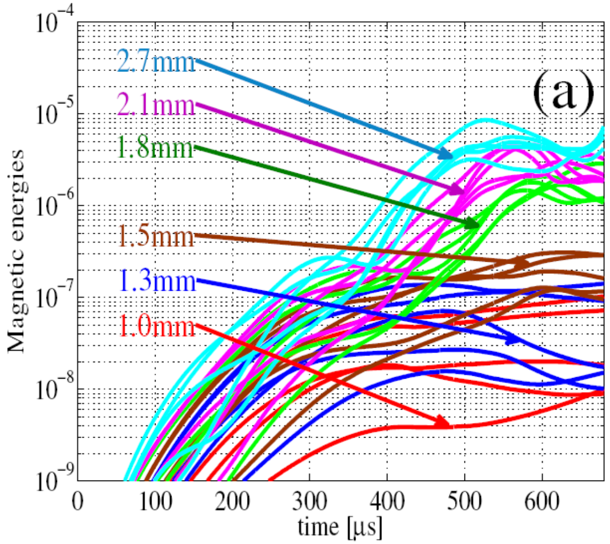


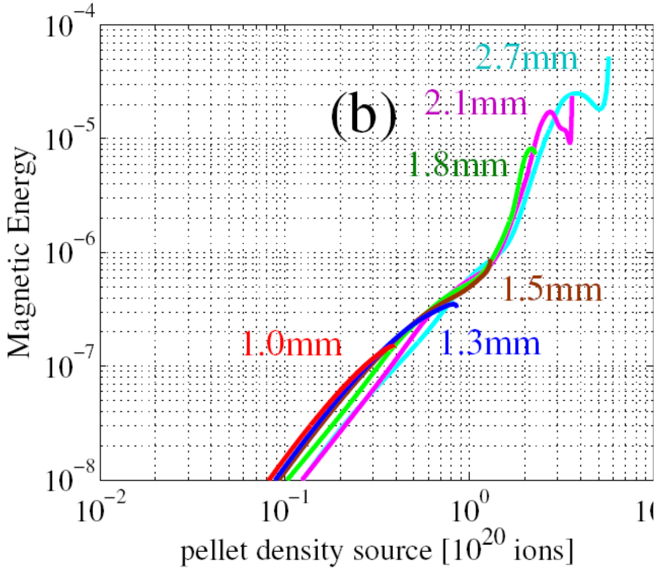
2.1mm midplane (ELM)

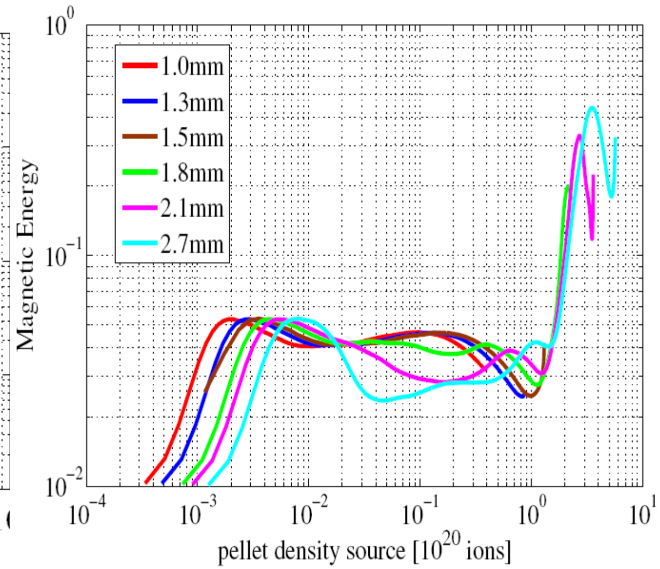


ELM Onset Criterion

- Pellet injection leads to a magnetic perturbation
- ELM trigger leads to an additional increase in magnetic energy
  - How to distinguish an ELM trigger?
  - Deviation from quadratic dependence of magnetic energy with particle source
  - Change in relative amplitude of low and high-n toroidal harmonics

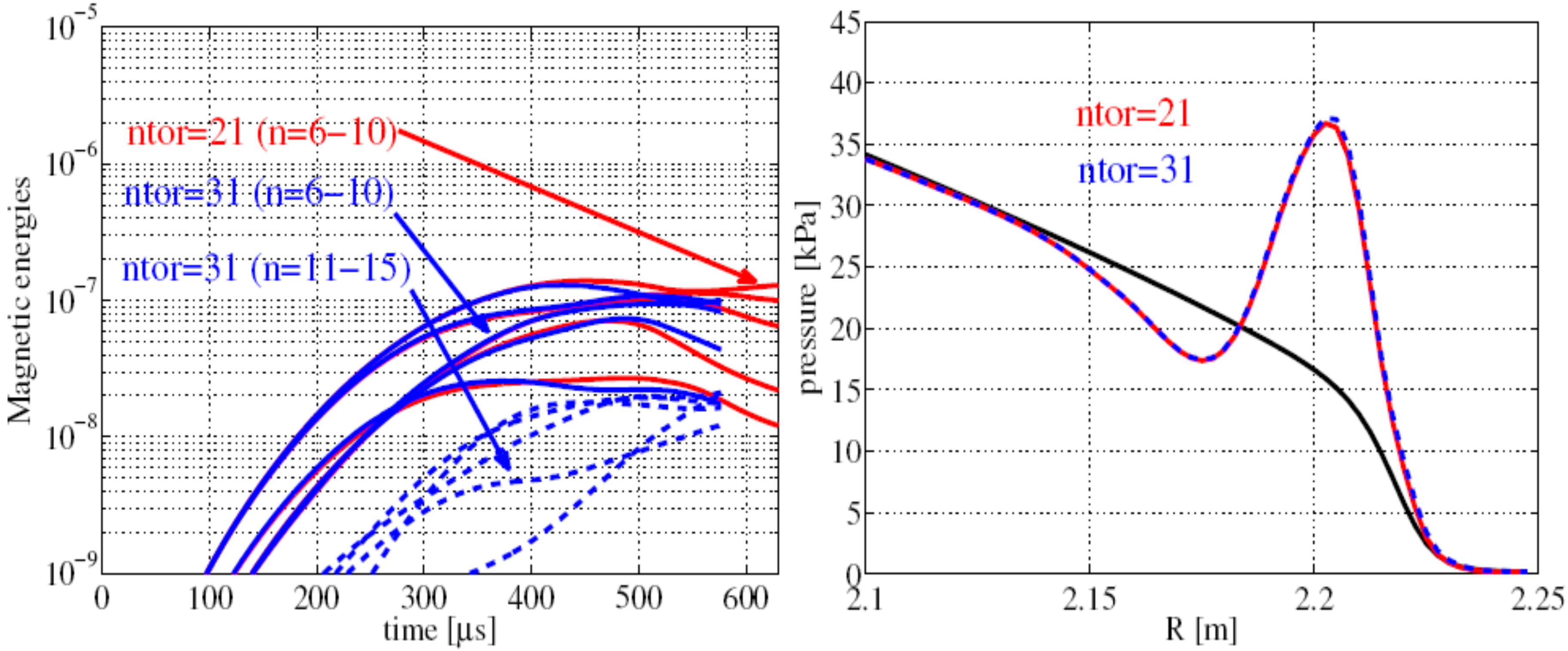






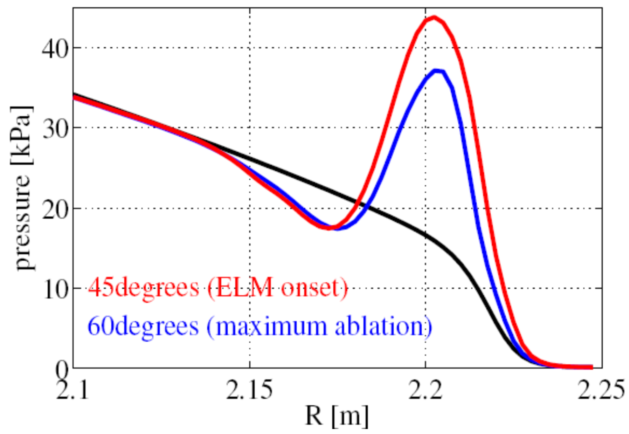
Toroidal Resolution

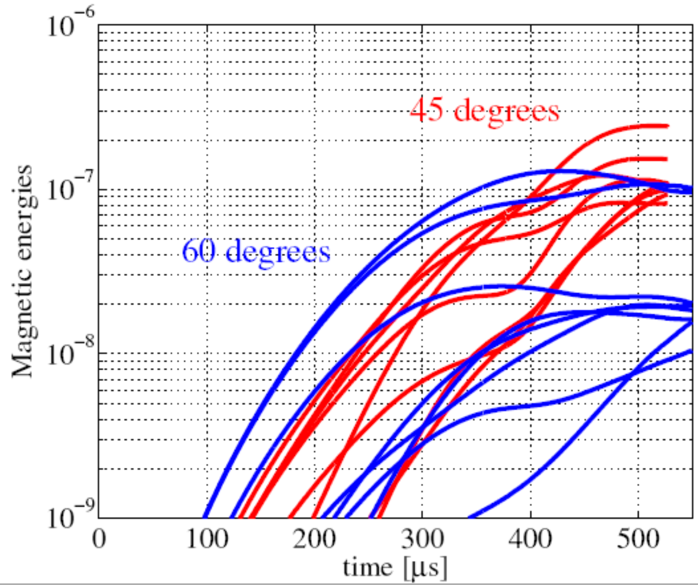
- For large toroidal pellet size (60deg), resolution ntor=21 seems sufficient:
  - Comparison ntor=21 to ntor=31

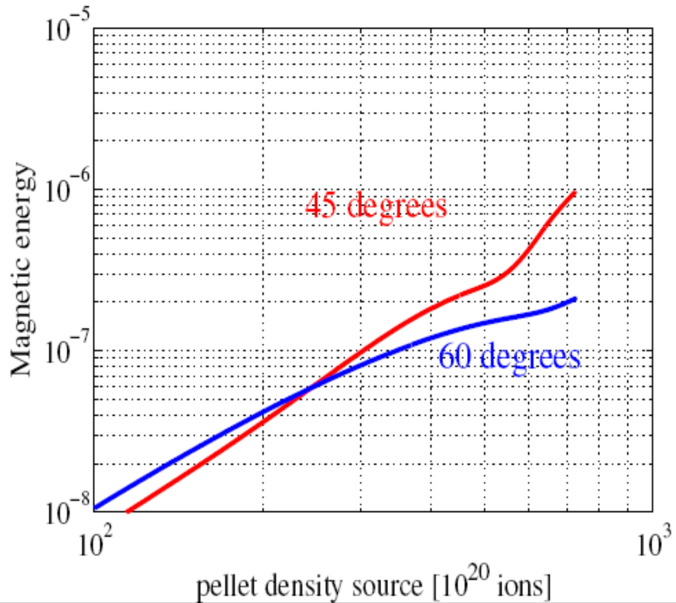


Toroidal pellet size

- Reducing the pellet toroidal extension leads to larger pressure perturbation
  - Current estimates minimum pellet size are an over-estimate
  - 3D FE simulations will be really useful

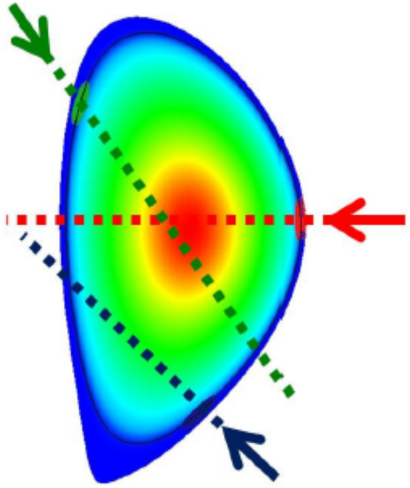


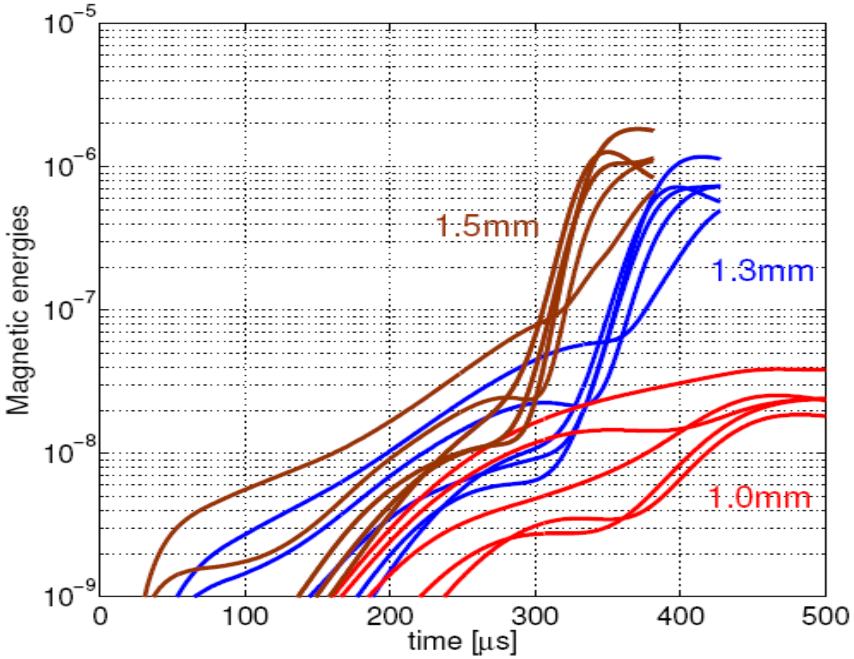


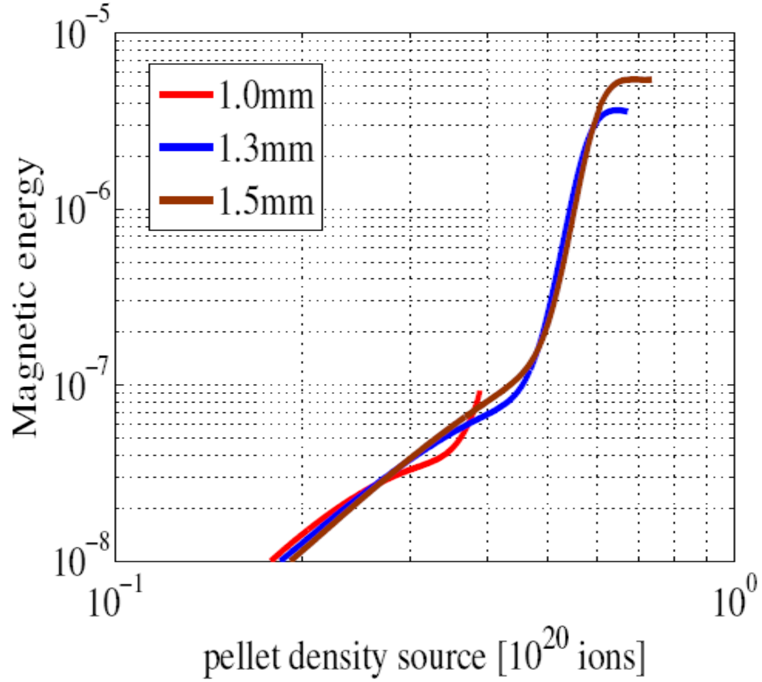


High Field Side Injection

- Critical pellet size significantly lower for high field side injection (compared to midplane)
  - Agrees with experiments (to be confirmed)
  - Critical pellet size <1.3mm^3

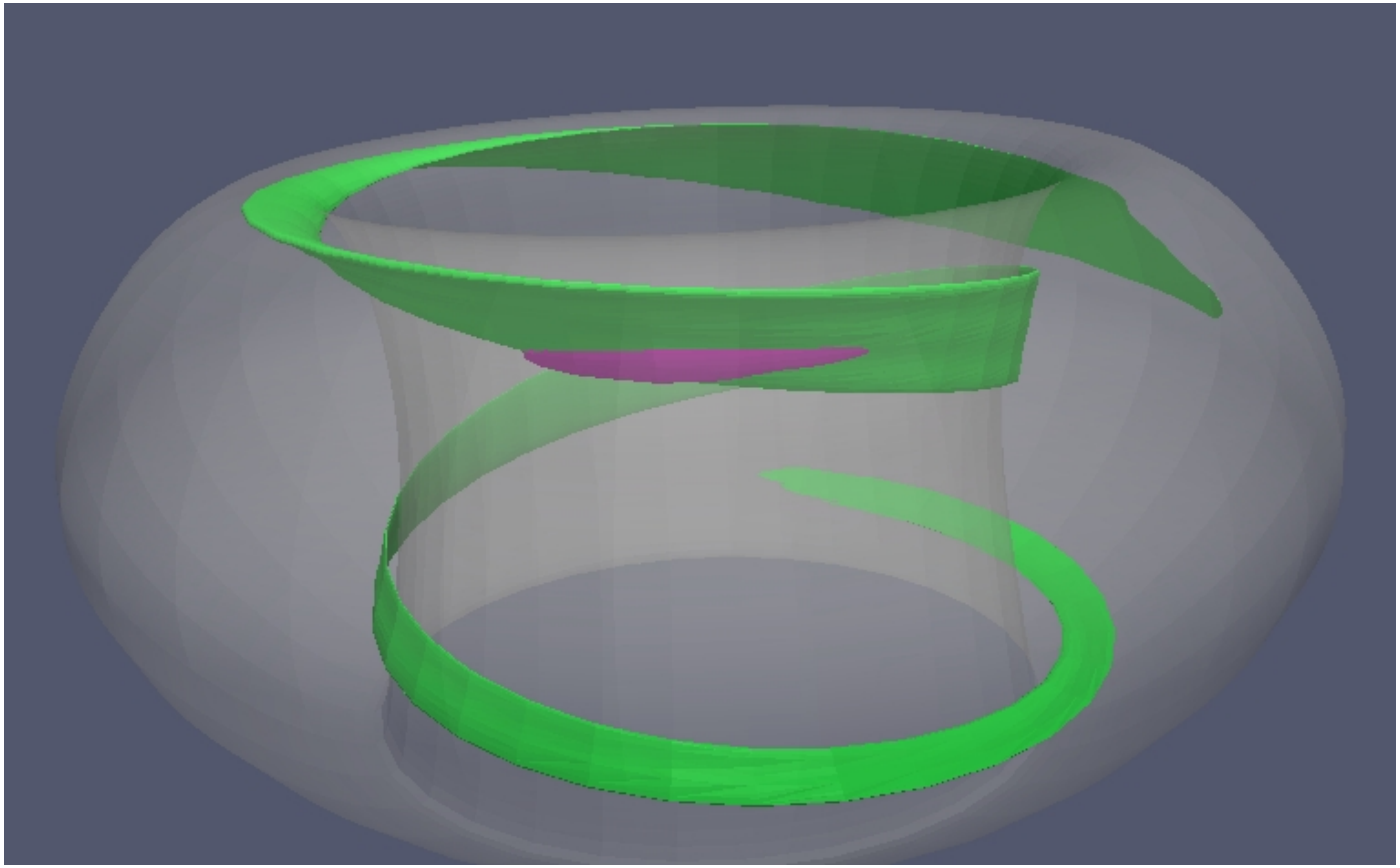






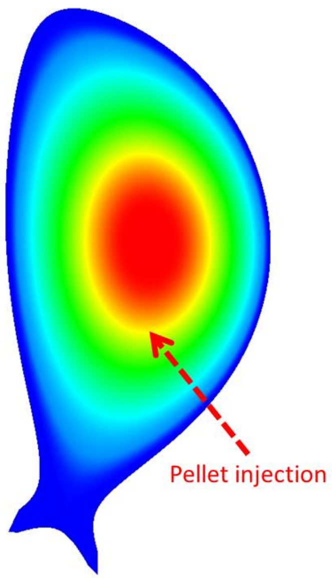
Pellet Cloud

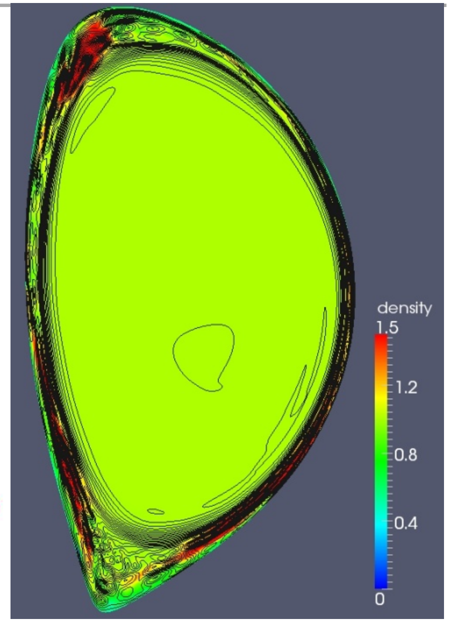
- High field side injection
  - At time of ELM onset

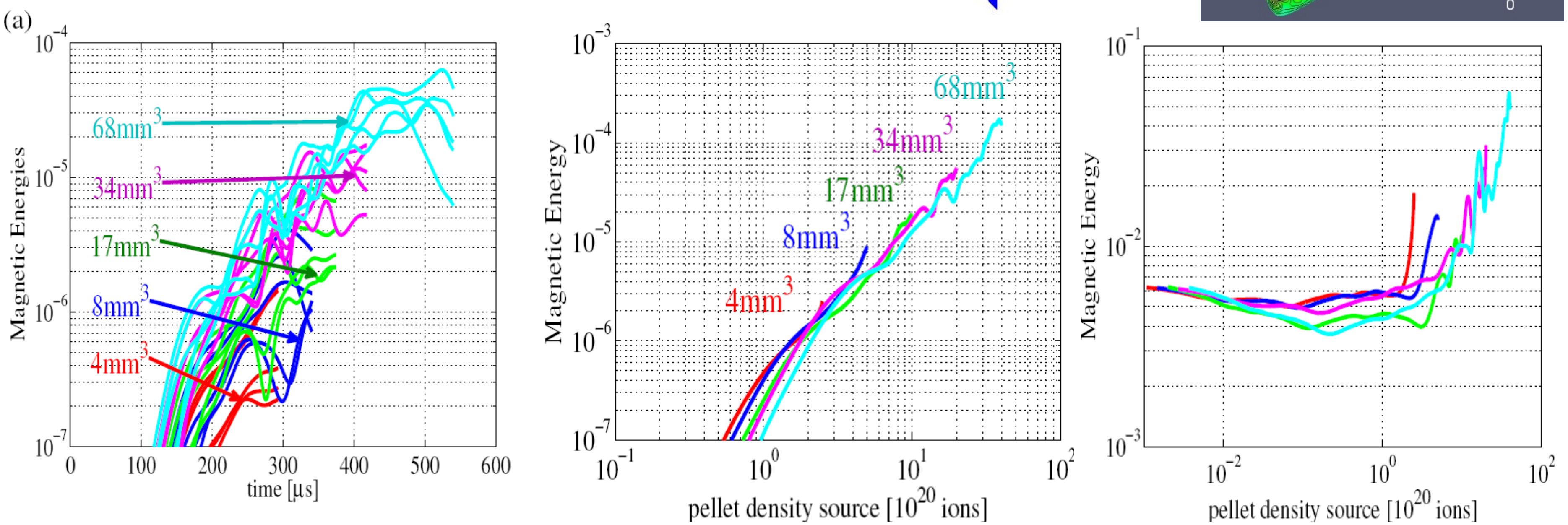


ITER Scenario

- ITER Q=10 15MA scenario
  - Pellet injected close to X-point
- ELM onset criterion not very clear
  - Critical pellet size ~34 mm^3







NEXT

- Pellet requirements for ELM trigger in ITER
  - Minimum pellet size
  - Optimum injection location
  - Energy losses (divertor)
  - Continue validation (JET, AUG)

- Pellet physics + MHD
  - Ergodicity influence on ablation profile
  - High field side injection, “inward ELMs”

- Increased toroidal resolution
  - 3D finite elements (BN)

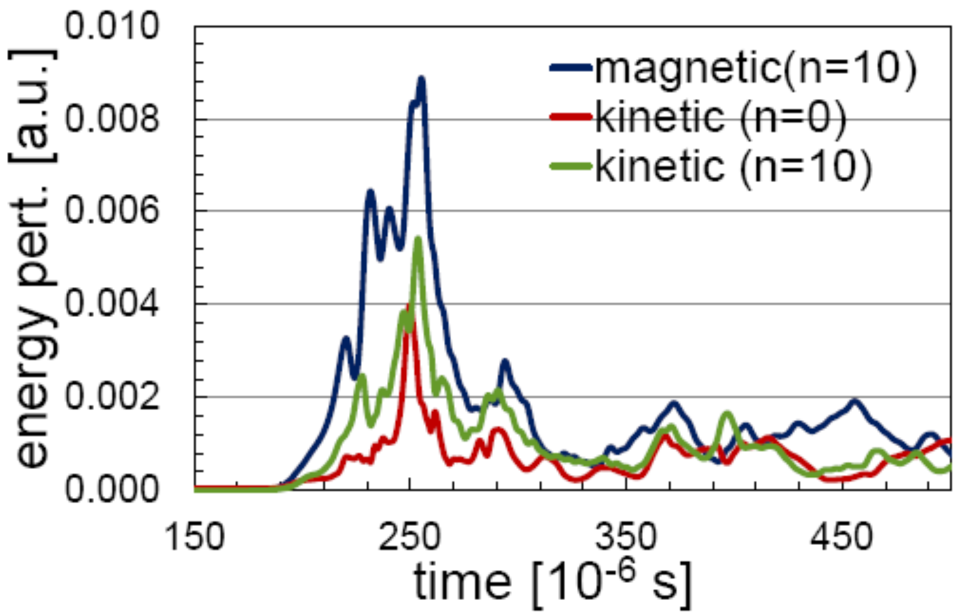
ELM Simulations in ITER

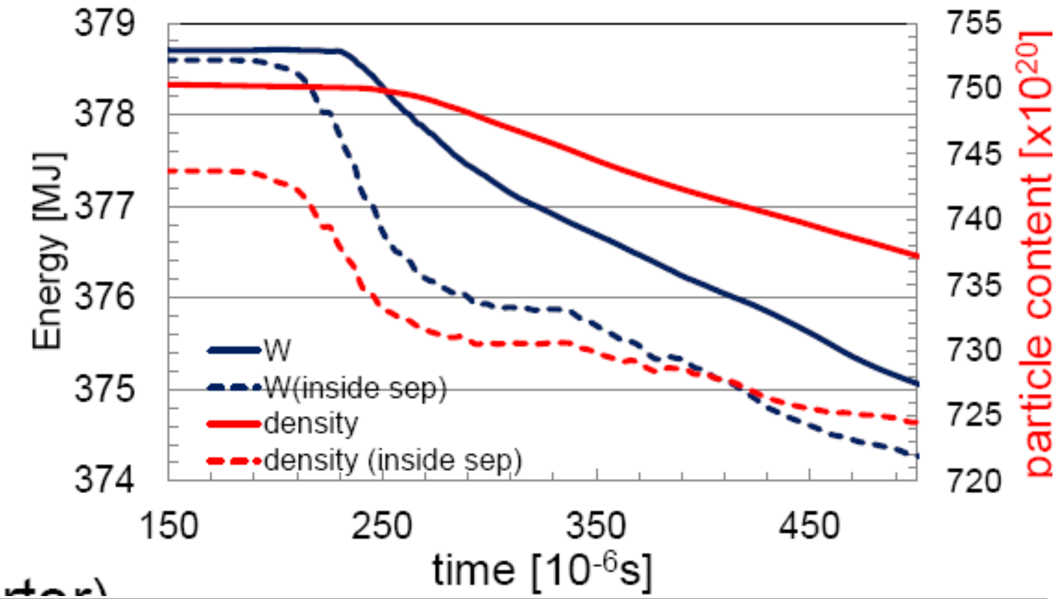
- ITER Q=10 scenario:

T_{ped} = 5.1keV, N_{ped} = 8.5x$10^{19}$$m^{-3}$
δ_{ped} = 4.5cm, W=378MJ

ELM size: 4 MJ, $\Delta W/W$=1%
$\Delta n/n$ = 2%

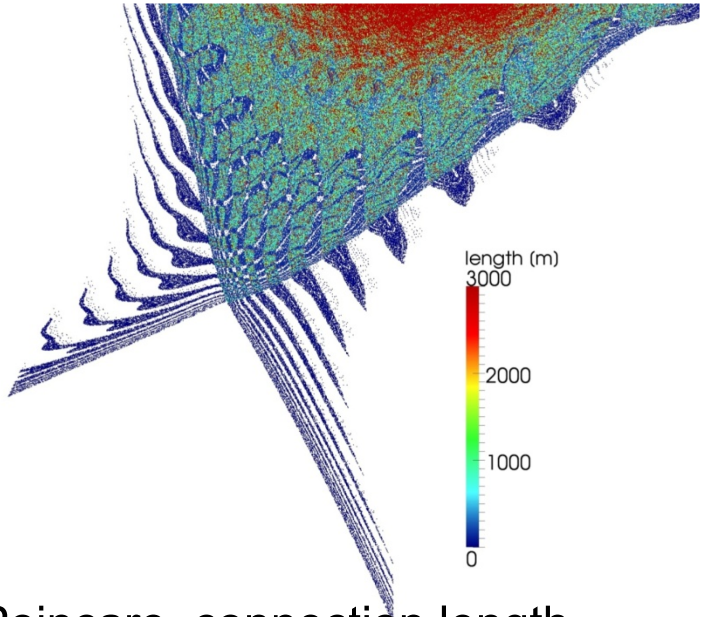
ELM affected depth ~12cm



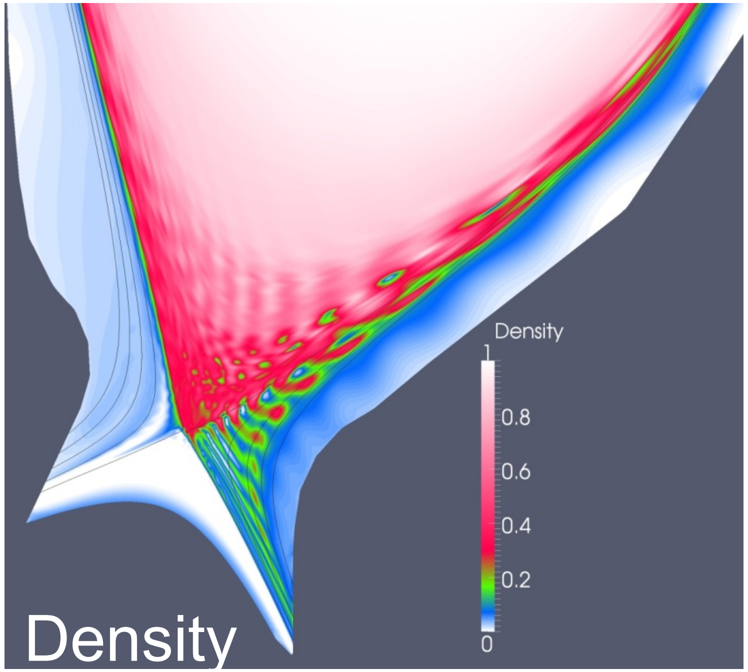


Homoclinic Tangles

- Large magnetic perturbation of ELM leads to Large homoclinic tangles
  - Both low field and high field side
  - Do not reach ITER first wall (only divertor)
  - Short field lines extend well into the plasma

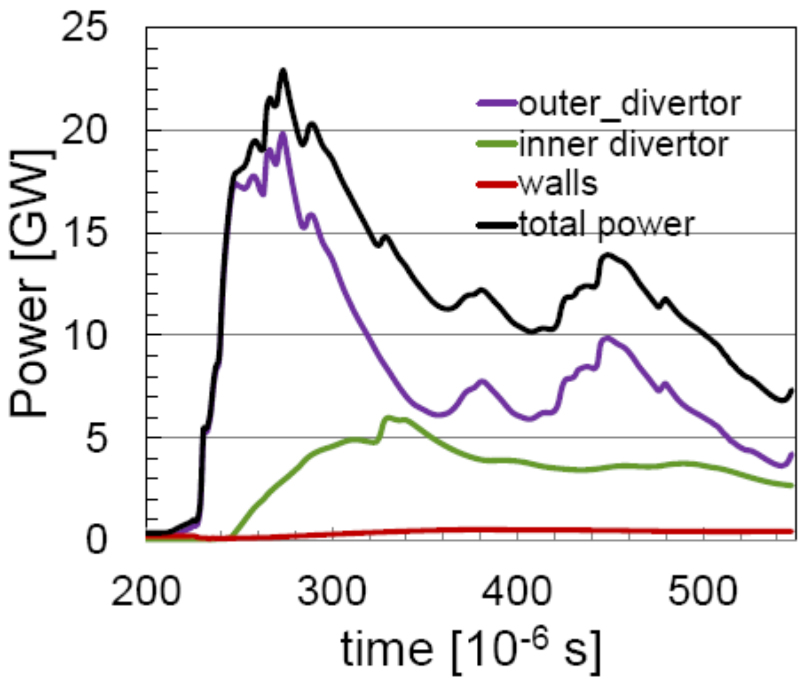


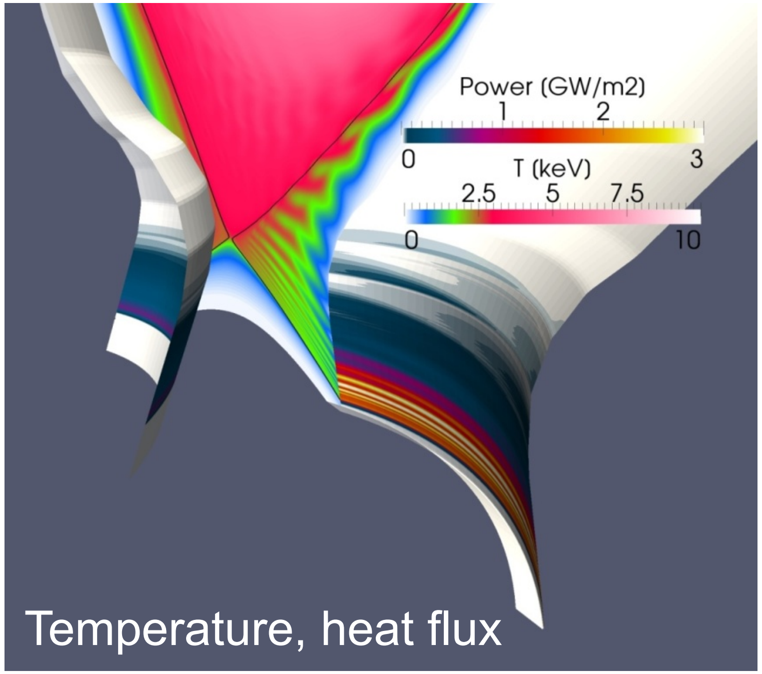
Poincare, connection length



ELM power deposition

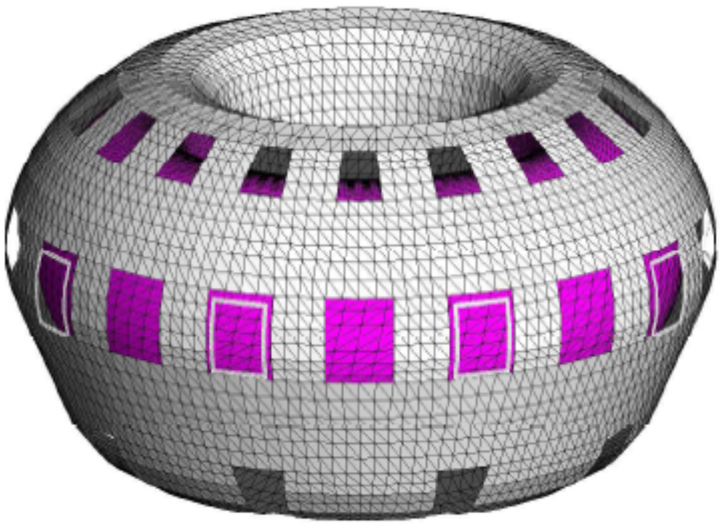
- Most power flows to the outer divertor
  - Opposite to observations in experiments
  - Small power load to first wall (consistent with earlier estimates)

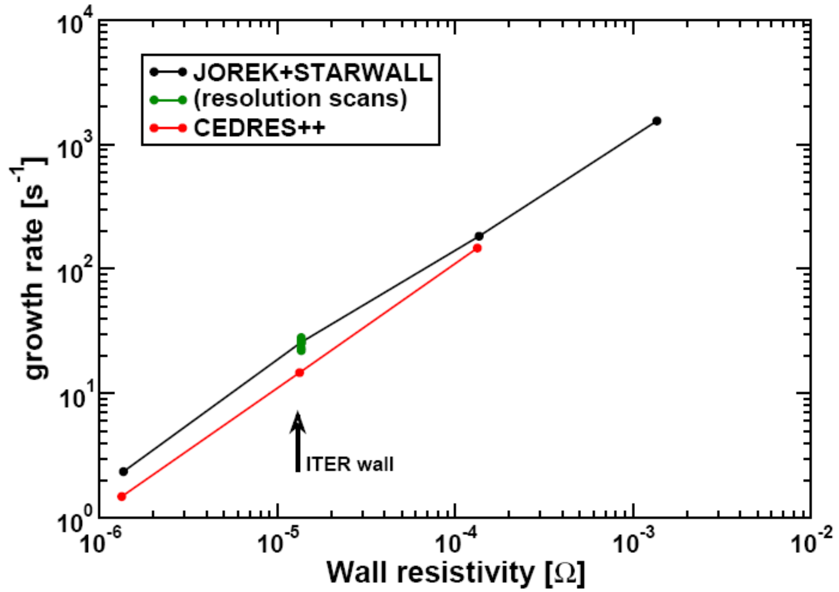




JOREK-STARWALL Coupling

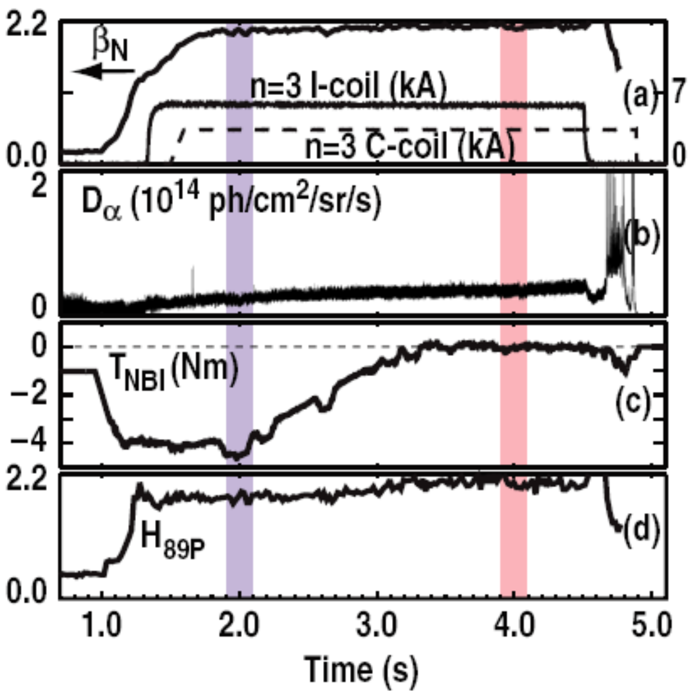
- Applications like **Disruptions, VDEs, RMPs** require that simulations include the interaction of the plasma with the resistive wall, magnetic field coils
  - Implemented through coupling with STARWALL code (M. Hoelzl, E. Nardon)
  - STARWALL solves the region outside the JOREK domain including the coils/ vessel. (once per simulation)
  - Provides boundary conditions for JOREK
  - First test look promising





QH-mode

- One alternative for the control of the ELM energy losses is the so-called QH-mode
  - H-mode operating scenario without ELMs
  - saturated low-n external kink provides loss channel
    - Requires high bootstrap current (low collisionality)
    - Large flow shear at the boundary (possibly created by RMP)



DIII-D, Garofalo, NF2011

JOREK QH-mode Simulations

- Simulate QH-mode in DIII-D plasmas
  - Collaboration with DIII-D
  - ITER Monaco fellow: Feng Liu

- Challenging:
  - Requires free boundary, vacuum, resistive wall
  - Large flows/ rotation
  - (RMP driven flow at later stage)
  - Long time scales

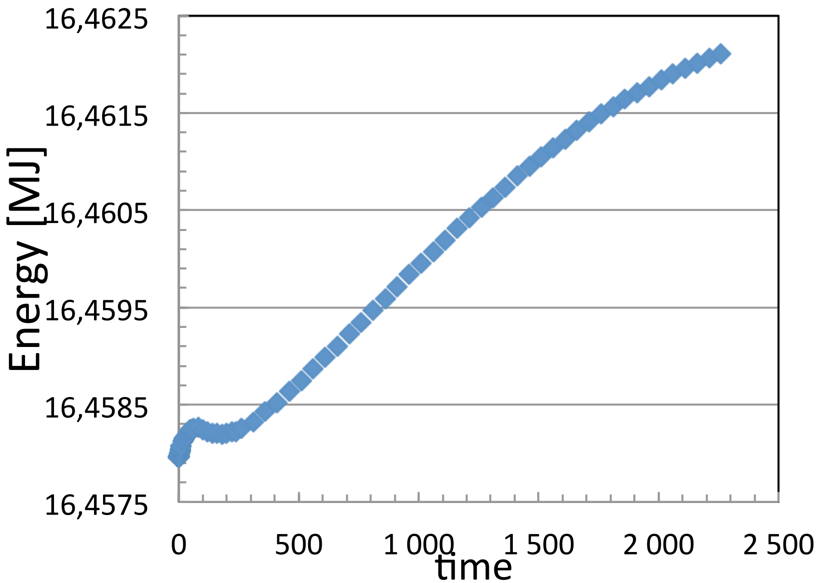
Energy Conservation

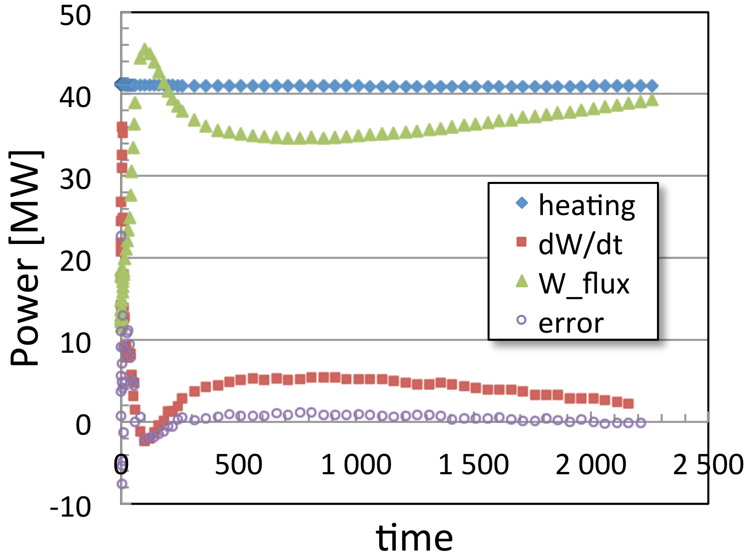
- Energy conservation:
  - Ideal MHD: $$\frac{\partial H}{\partial t} + \nabla \cdot \vec{U} = 0$$

$$H = \tfrac{1}{2}\rho v^2 + \frac{1}{\gamma - 1} p + \tfrac{1}{2} B^2$$

$$\vec{U} = \left(\tfrac{1}{2}\rho v^2 + \frac{\gamma}{\gamma - 1} p + \tfrac{1}{2} B^2 \right) \vec{v} - \vec{v} \cdot \vec{B}\vec{B}$$

- JET-like equilibrium:
  - Error < 1MW

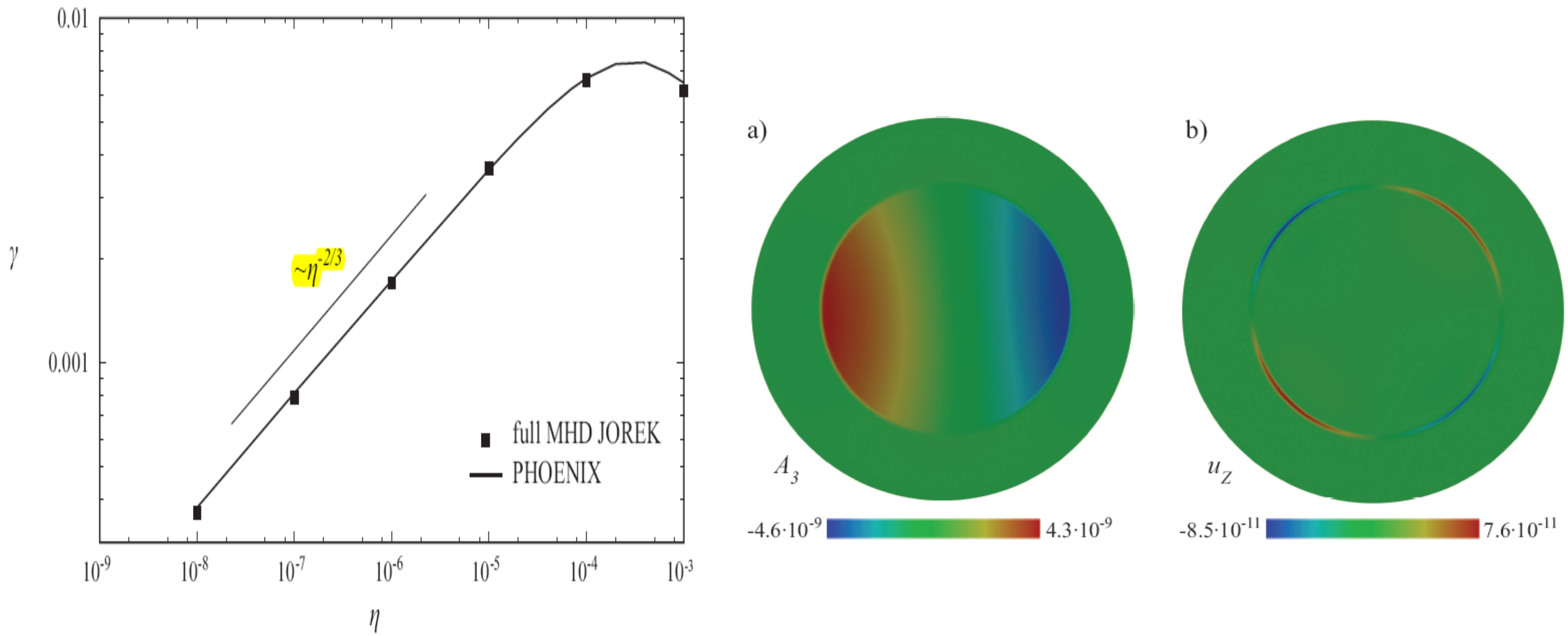




  - Error during ELMs can become large >50%
    - Need to find origin of problem

FULL MHD model

- Implementation full MHD model completed (W. Haverkort)
  - Using vector potential, parallel projection toroidal velocity eq.
  - Linear test cases successful
    - Internal kink, tearing modes, ballooning mode



Conclusion

- JOREK is actively used at ITER
  - pellet ELM trigger (for definition pellet injector requirements)
  - ELMs induced heat loads to ITER first wall
  - QH-mode, evaluation of relevance to ITER

- Other physics areas of ITER interest:
  - Disruptions, VDEs
    - Requires JOREK-STARWALL
    - Massive gas injection, runaway electrons
  - RMP
    - neoclassical toroidal viscosity (induced rotation)
    - neoclassical flow
    - application Gysela?
  - MHD+fast particles
  - Improved pellet simulations (3D FE)