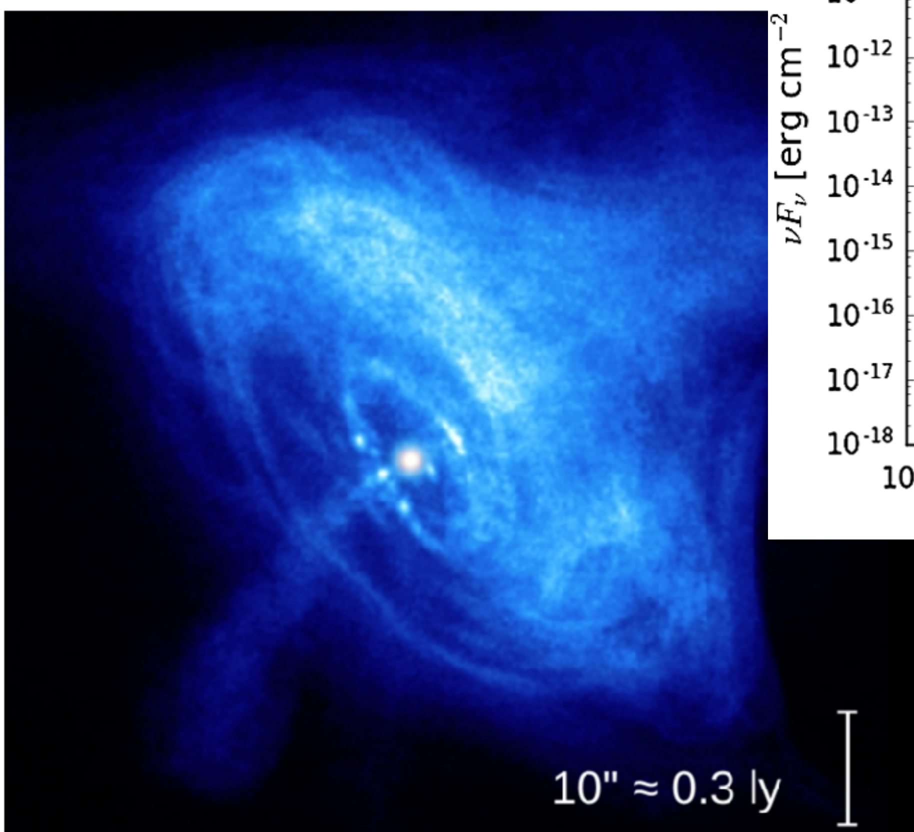
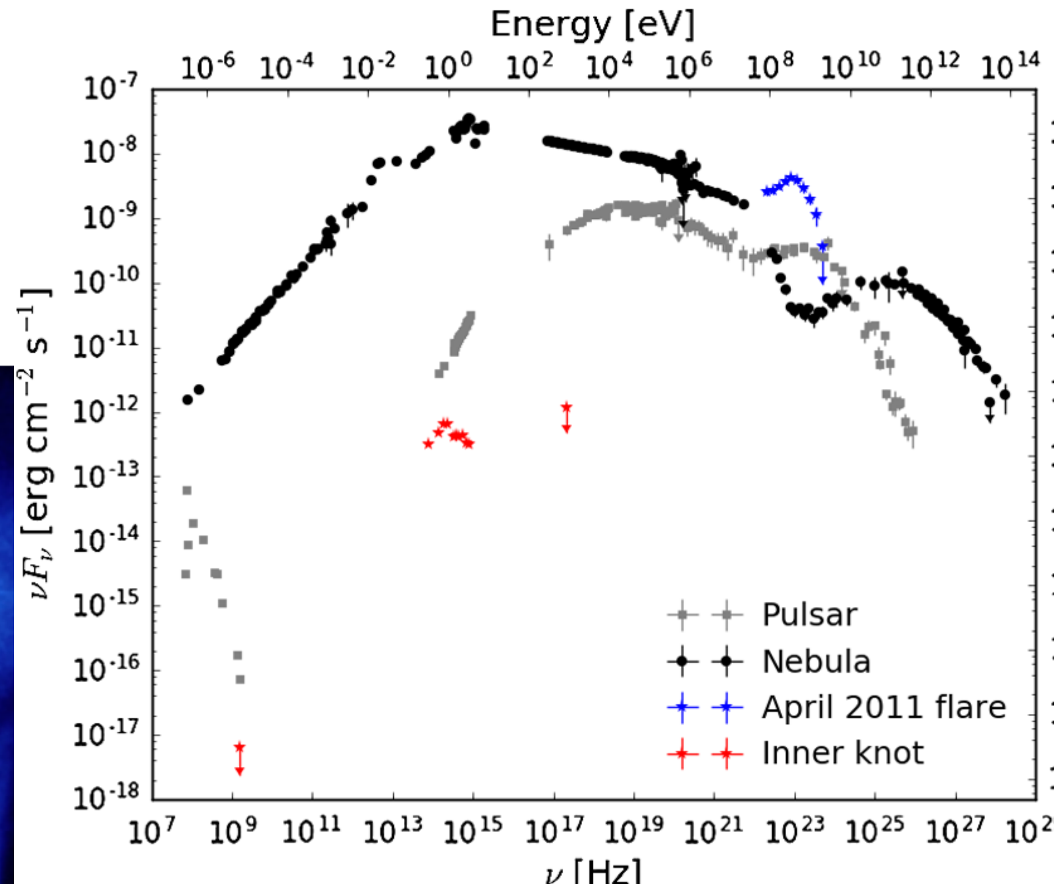
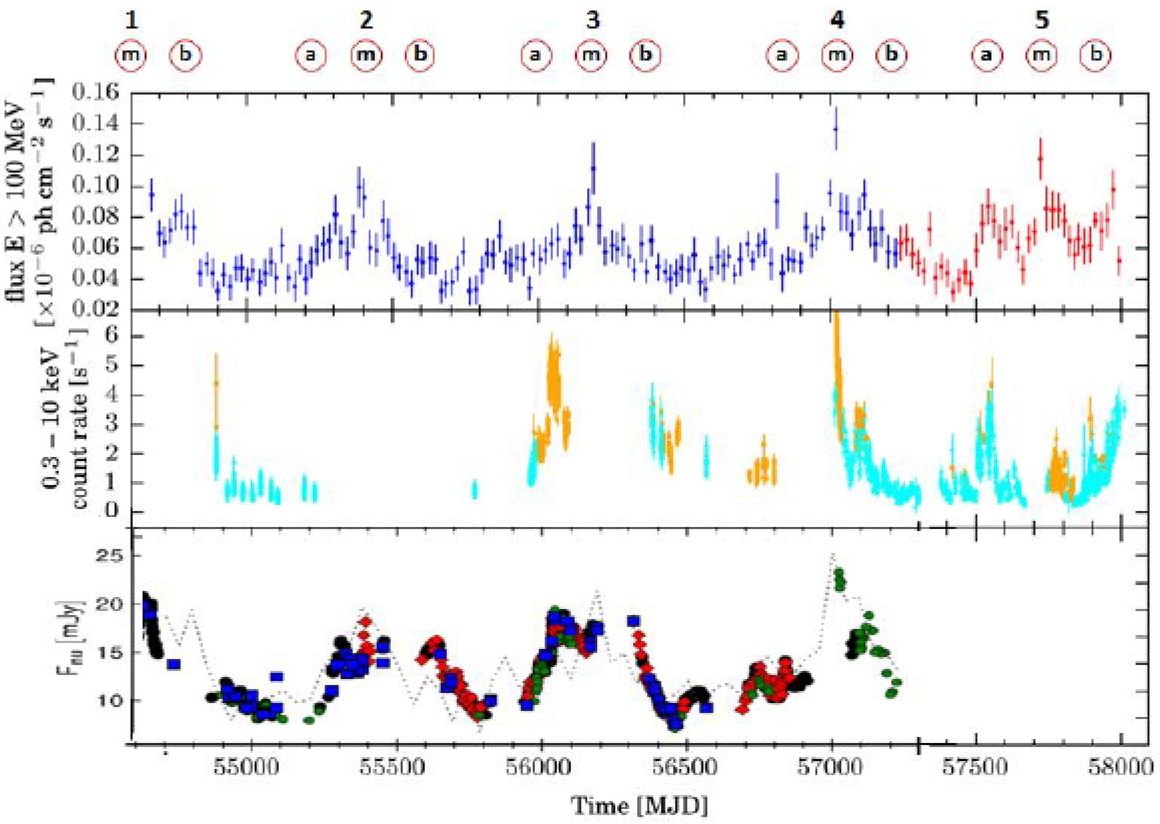
# 1. Flares from the Crab Nebula



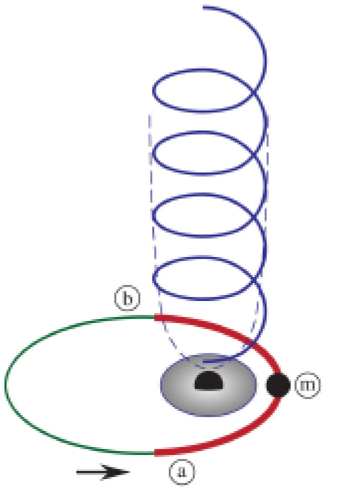




- 400 MeV photons
- 6 h growth

# 2. Blazar PG 1553+113 periodicity

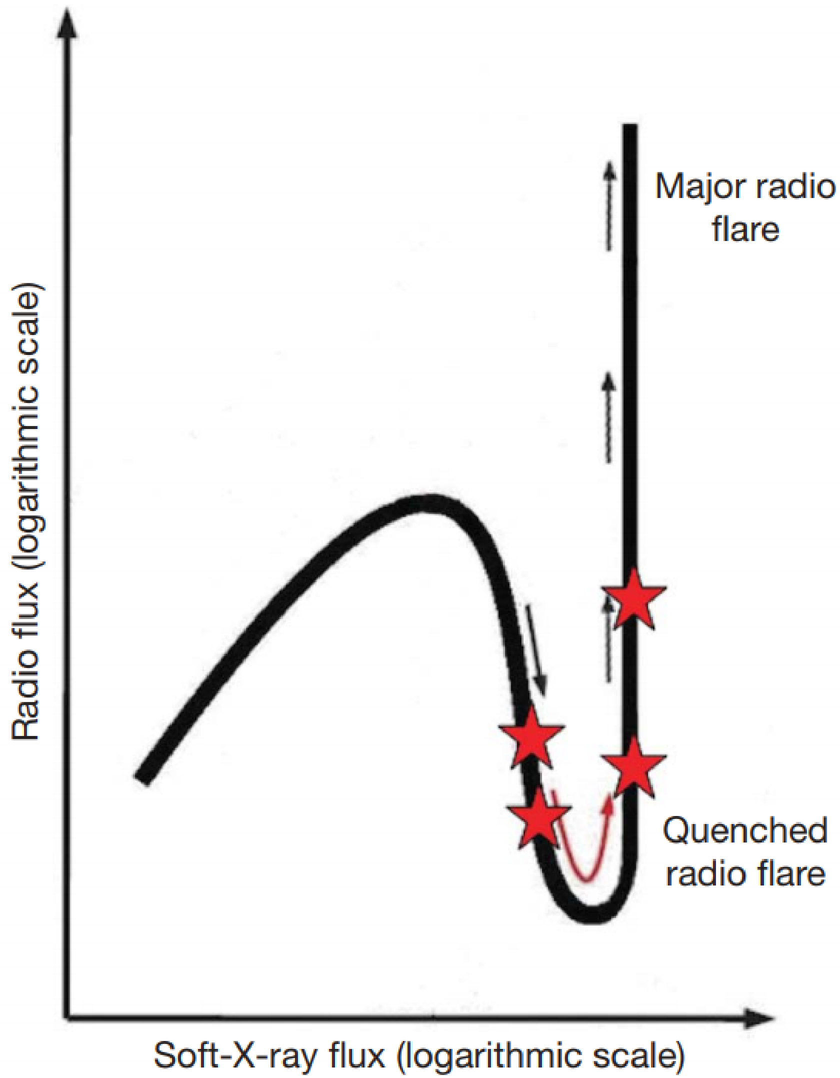



Tavani arxiv 2018




- Interpretation as a binary system of supermassive black holes

# 3. Cygnus X-3 radio and gamma flares




Tavani Nature 2009

- Quenched state with low hard-x and radio emission
- Ends with giant radio flare and gamma flare

Italian National Agency for New Technologies, Energy and Sustainable Economic Development

A DECADE OF AGILE: RESULTS, CHALLENGES AND PROSPECTS OF GAMMA-RAY ASTROPHYSICS

# Magnetic Reconnection and Electron Acceleration in Tokamaks as a Model for Astrophysical Flares

*December 12, 2017*

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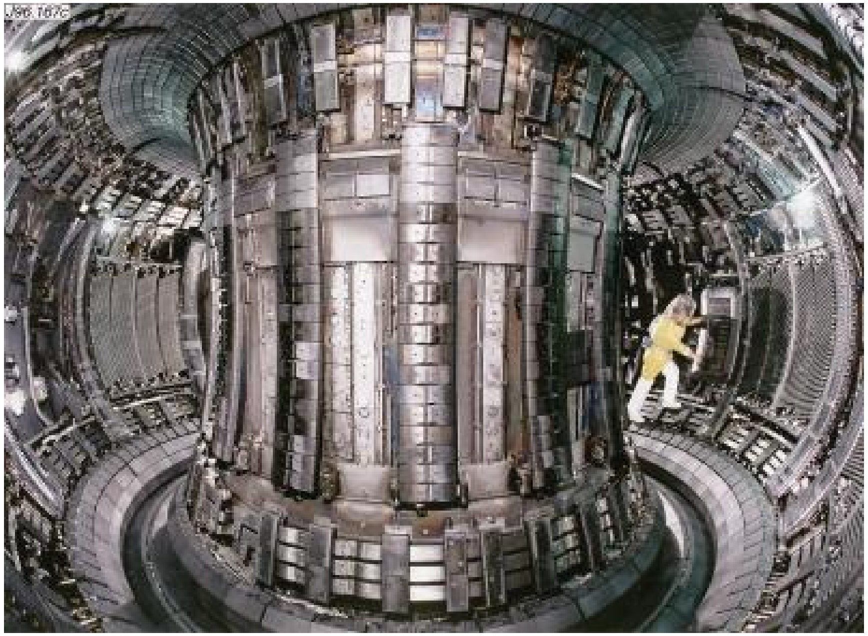
# Outline

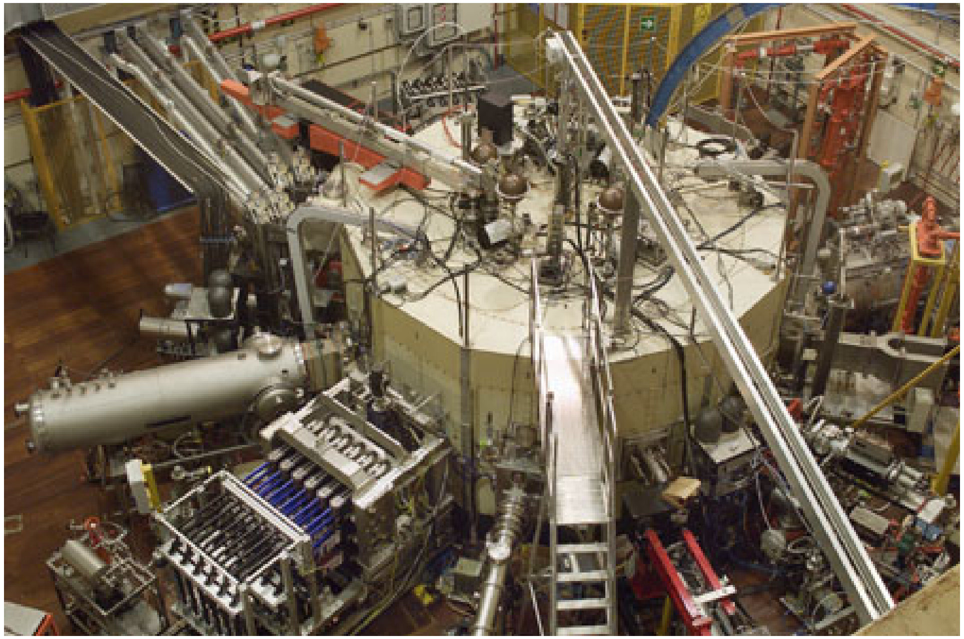
- Tokamak plasma
- Plasma disruptions
- Electron acceleration
- Simulations

# Tokamaks

- Electron temperature 1 – 10 keV
- Electron number density 2 – 20 E19 $m^{-3}$
- Major radius 1 – 3 m
- Lundquist number $10^6$ – $10^8$



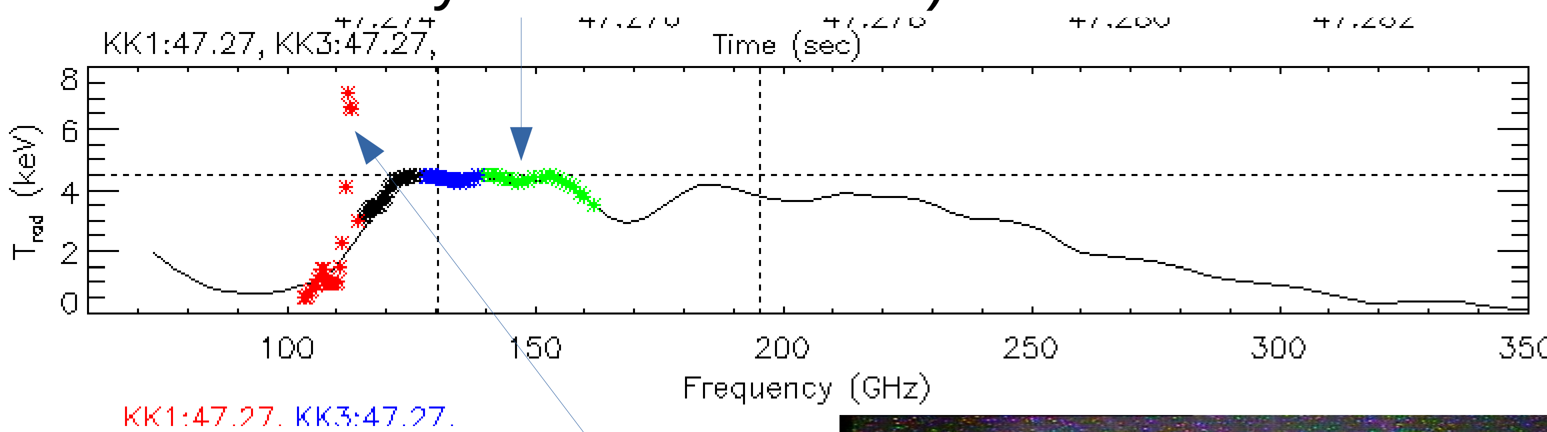
Inside JET tokamak
Culham - UK



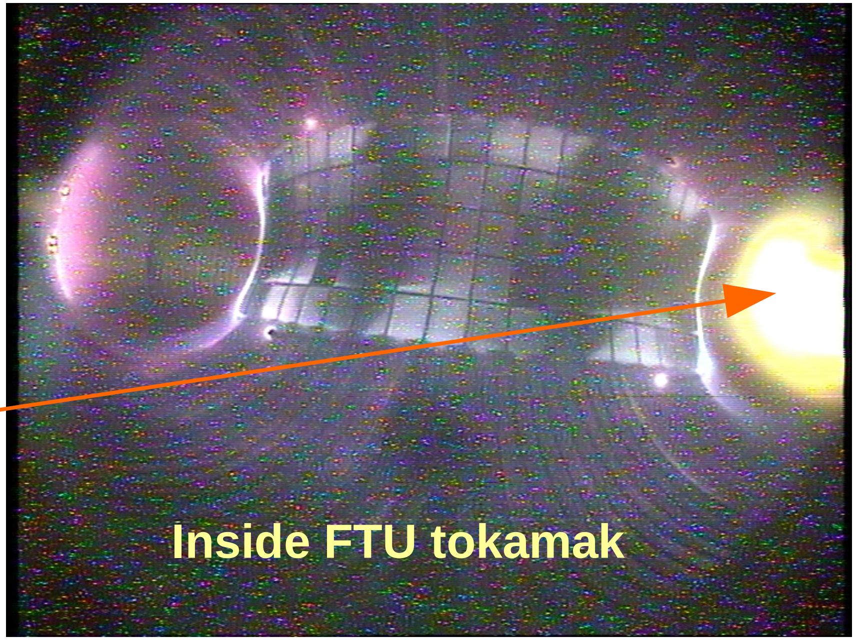
Outside FTU tokamak
Frascati

# Synchrotron radiation

- Thermal electrons: blackbody emission at low harmonics (named electron cyclotron emission)

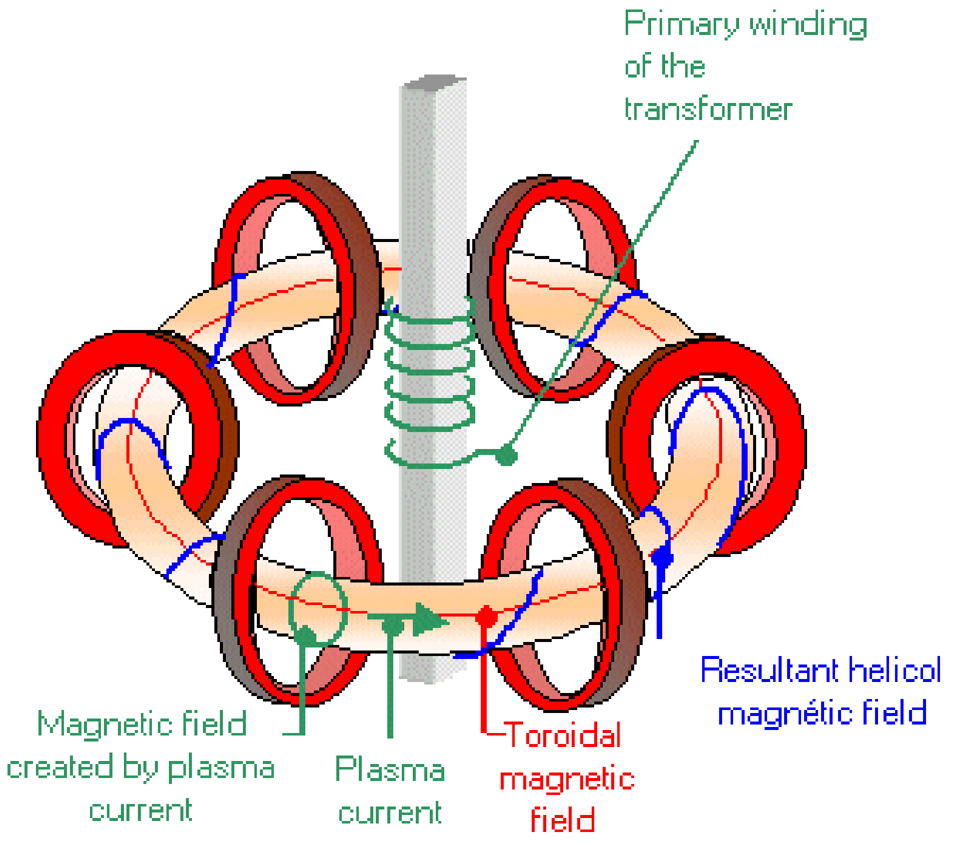



- Suprathermal electrons:
  - suprathermal emission at low harmonics
  - Beamed synchrotron emission at high harmonic (visible)



# Tokamak fields (1)

- Like a bent screw pinch
- Imposed toroidal field $B_T$ 2 – 8 T
- Mainly toroidal current
- Self (poloidal) field $B_P < 0.1\ B_T$ : winding much slower than in the figure
- Self-field energy is available for impulsive acceleration

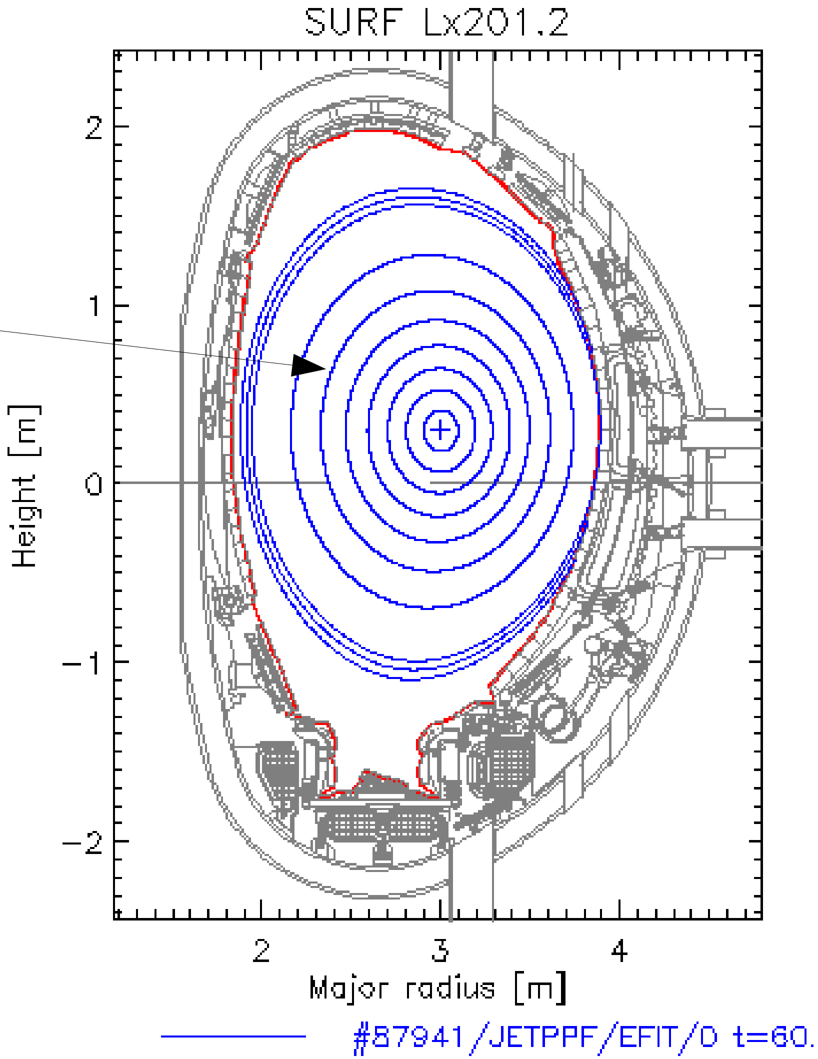



- Electron energy *runaway* if electric force beats friction
- Note that kinks wind around toroidal direction: this is the analogue to jets axial direction.

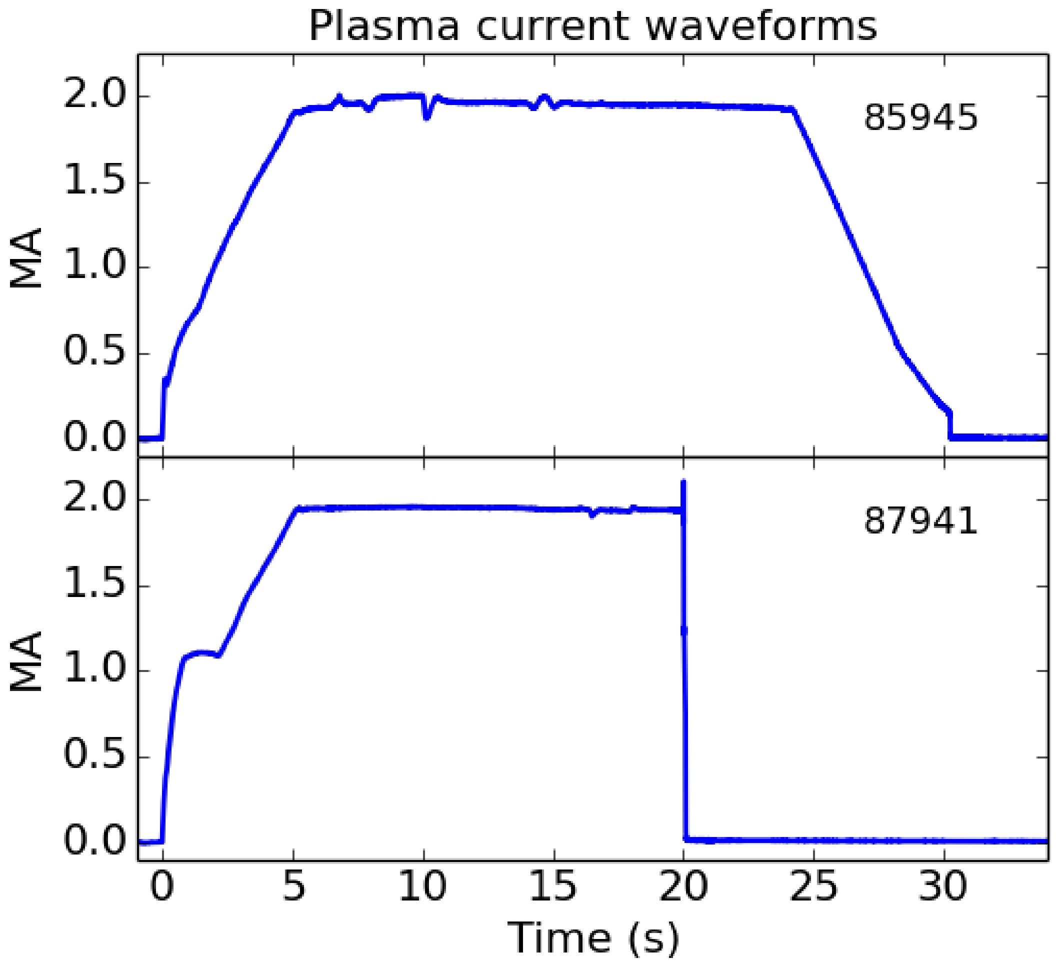
# Tokamak fields (2)

- Magnetic field lines are surface-filling in the ideal axisymmetric equilibrium
- Magnetic surfaces are nested tori
- Special surfaces with lines that close on themselves are analogous to neutral sheets in slab geometry.

- Field lines can be volume-filling in the presence of non-axisymmetric perturbations



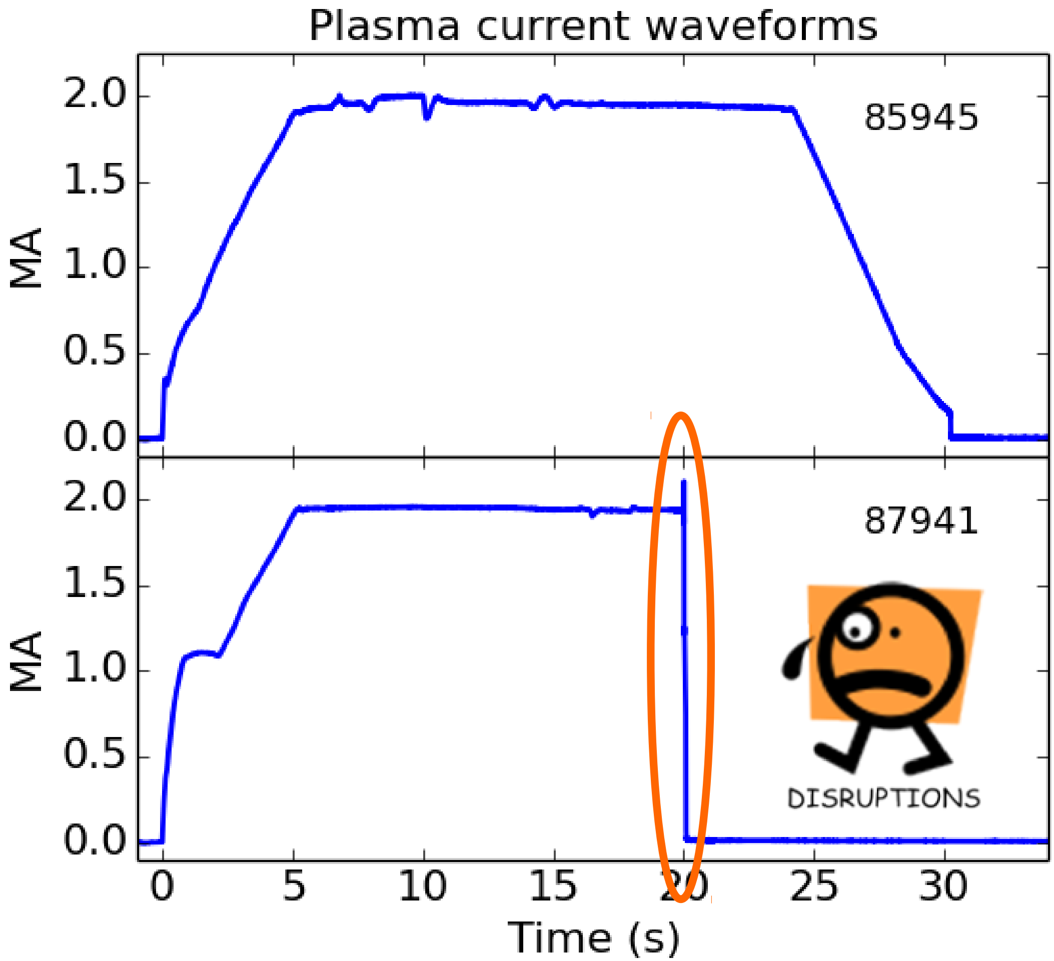
# The major disruption




- Typical plasma current evolution in JET:
  - 5 s rise
  - 20 s flat-top
  - 5 s termination

- Major disruption event: very rapid drop of plasma current

# The major disruption




- Typical plasma current evolution in JET:
  - 5 s rise
  - 20 s flat-top
  - 5 s landing

- Major disruption event: very rapid drop of plasma current

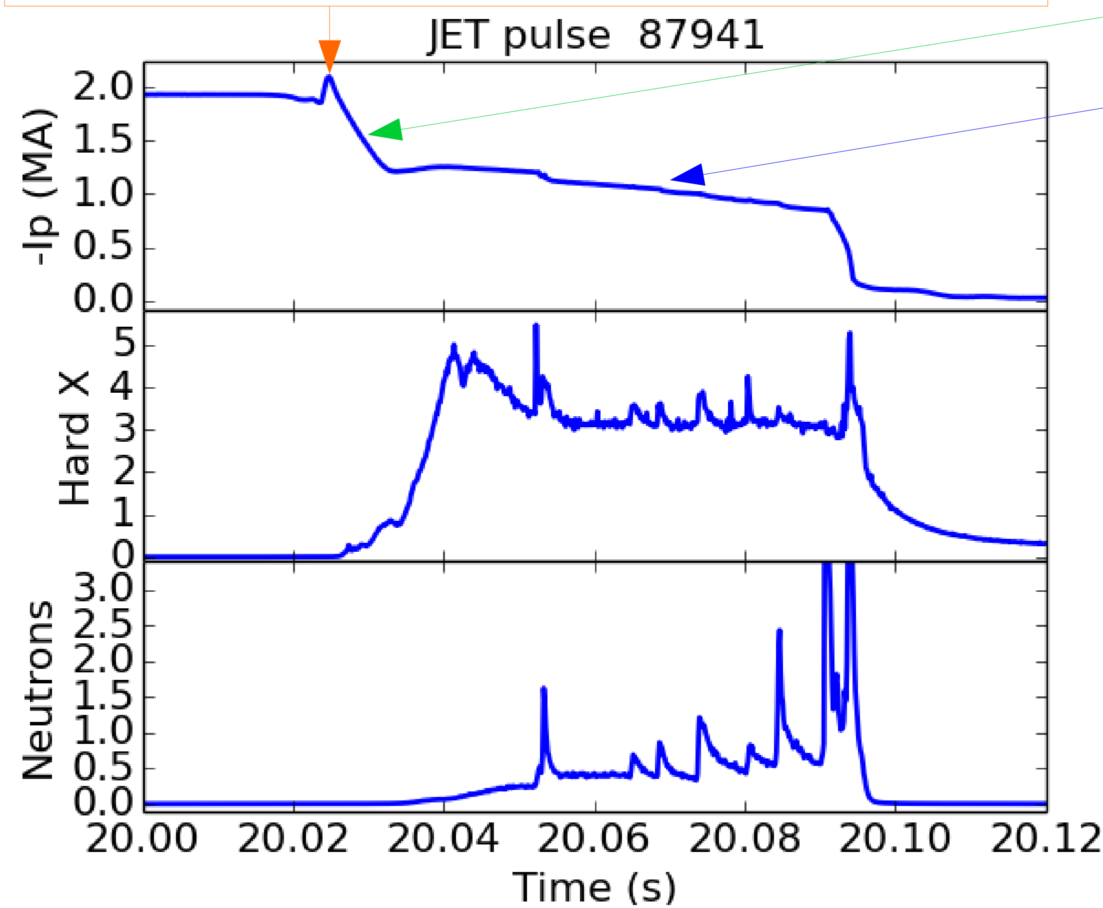
- High priority programs on electromagnetic and thermal loads mitigation (a machine integrity issue)
- Some aspects are of broader interest

# Zoom on the major disruption

Current spike in dt << diffusion time: an indication of magnetic reconnection

Rapid current quench and strong electric field

Current “plateau” carried by relativistic electrons



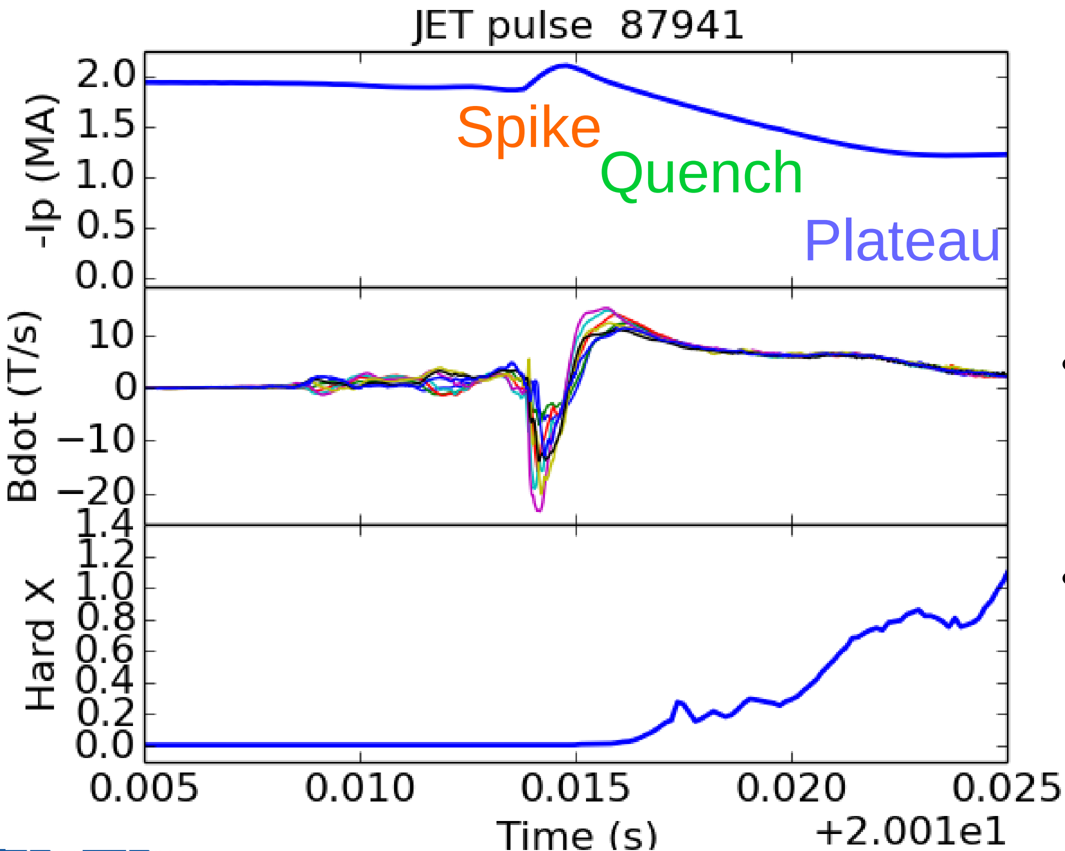

Hard x-ray from electron impacts on in-flight ions or plasma facing components

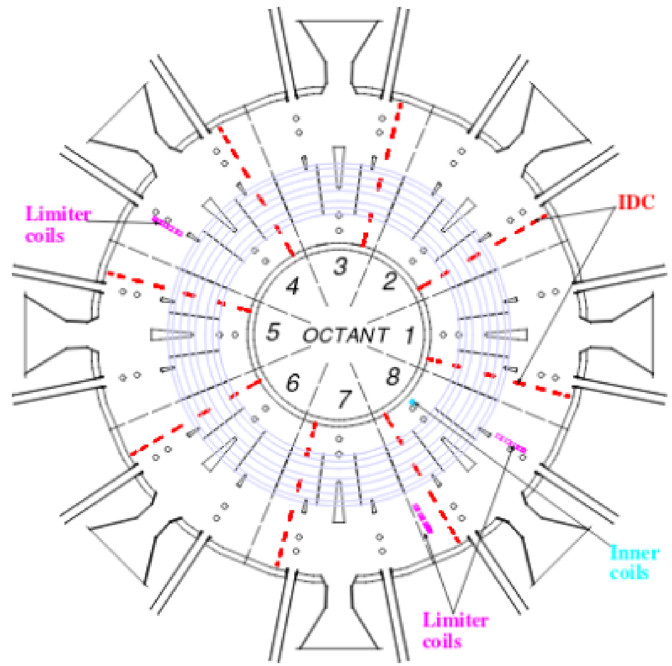
Rate of photoneutrons from impacts at some MeV

- Tokamak disruptions are a laboratory for magnetic reconnection and particle acceleration

# Axsisymmetry breaking

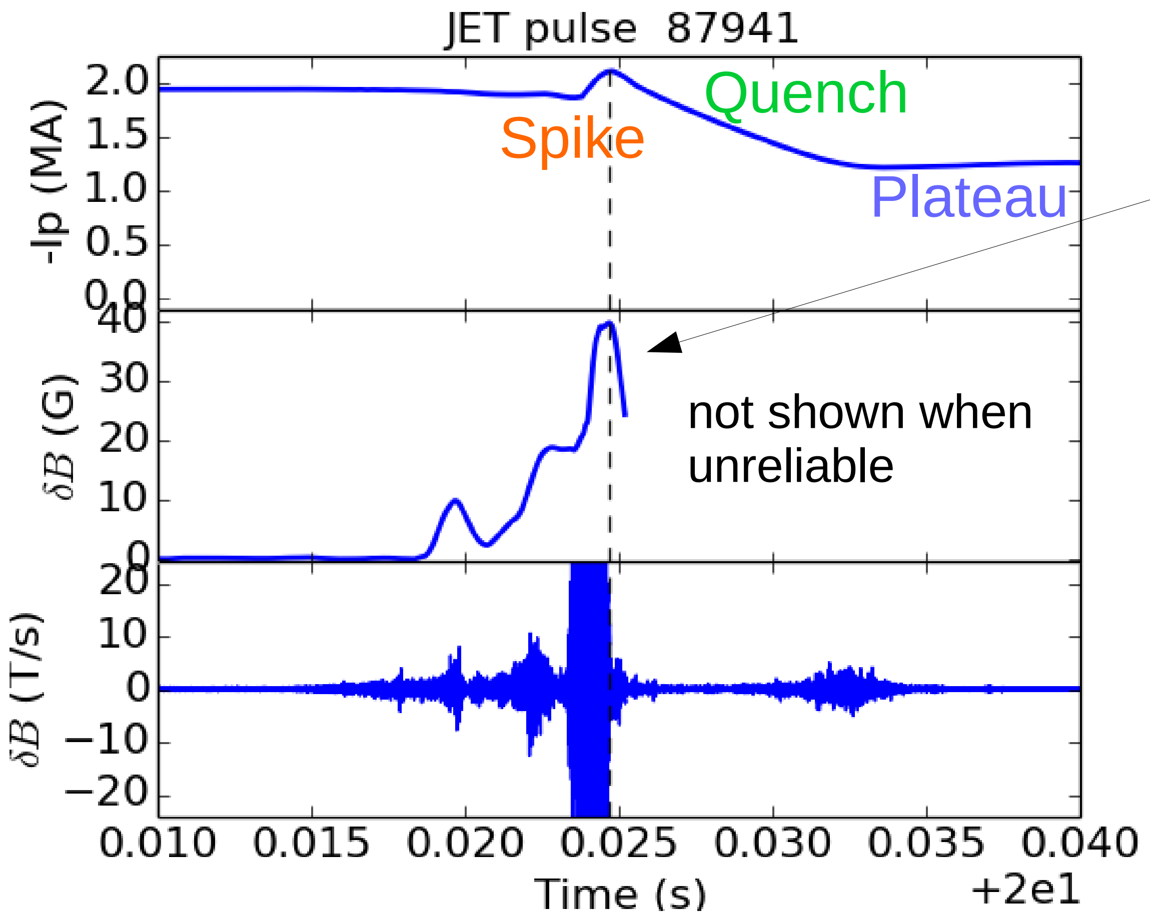
- In a laboratory we can go around the object
- 8 magnetic sensors around the torus are used to detect breaking of axisymmetry




- Differing coil signals show symmetry broken by a global (n=1) deformation
- Rapid growth during the current spike (some underestimate due to insuficient bandwidth)

# Rapid magnetic fluctuations

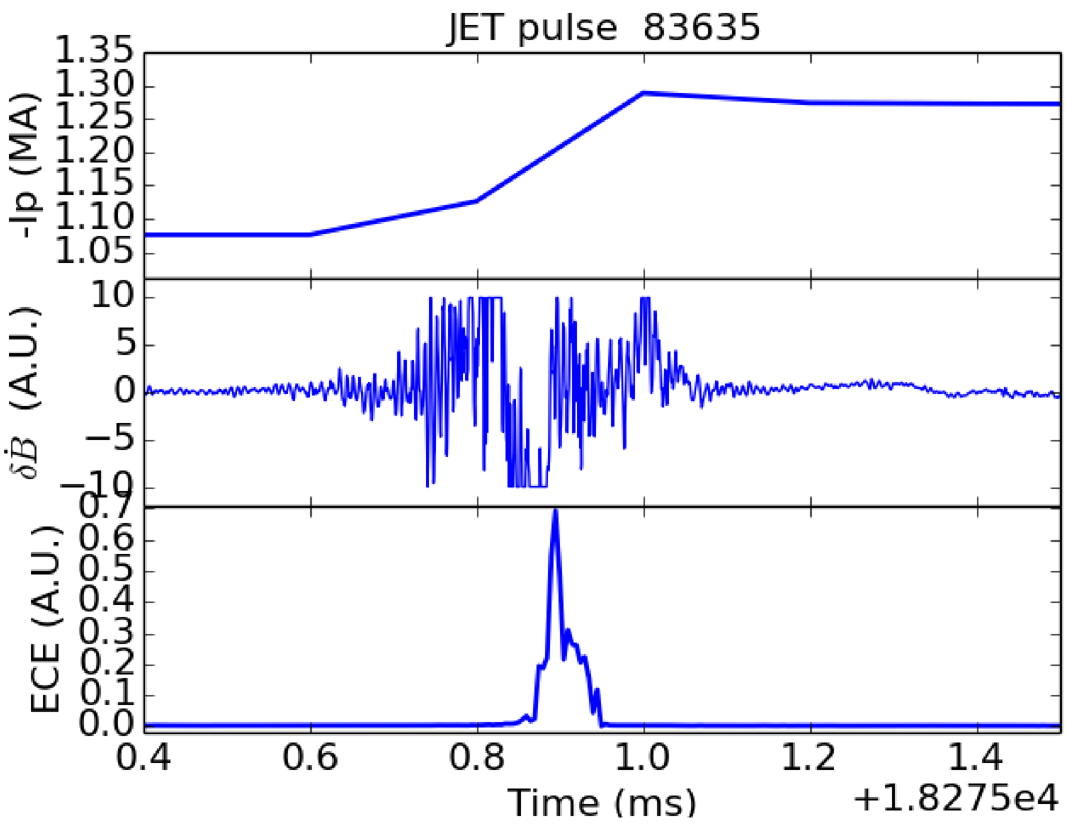



- Amplitude of symmetry breaking deformation from spatial Fourier analysis of integrated sensor signals
- Some problem from insufficient bandwidth

- Fluctuations revealed by a fast magnetic sensor
- out of scale during current spike

- Rapid, small-scale fluctuations on top of the global deformation
- In the ballpark of alfvénic transit time

# Acceleration during the current spike




- Current spike (not adequately sampled)
- Fast magnetic fluctuations
- Burst of suprathermal electon cyclotron emission

- Very rapid acceleration events during the current spike

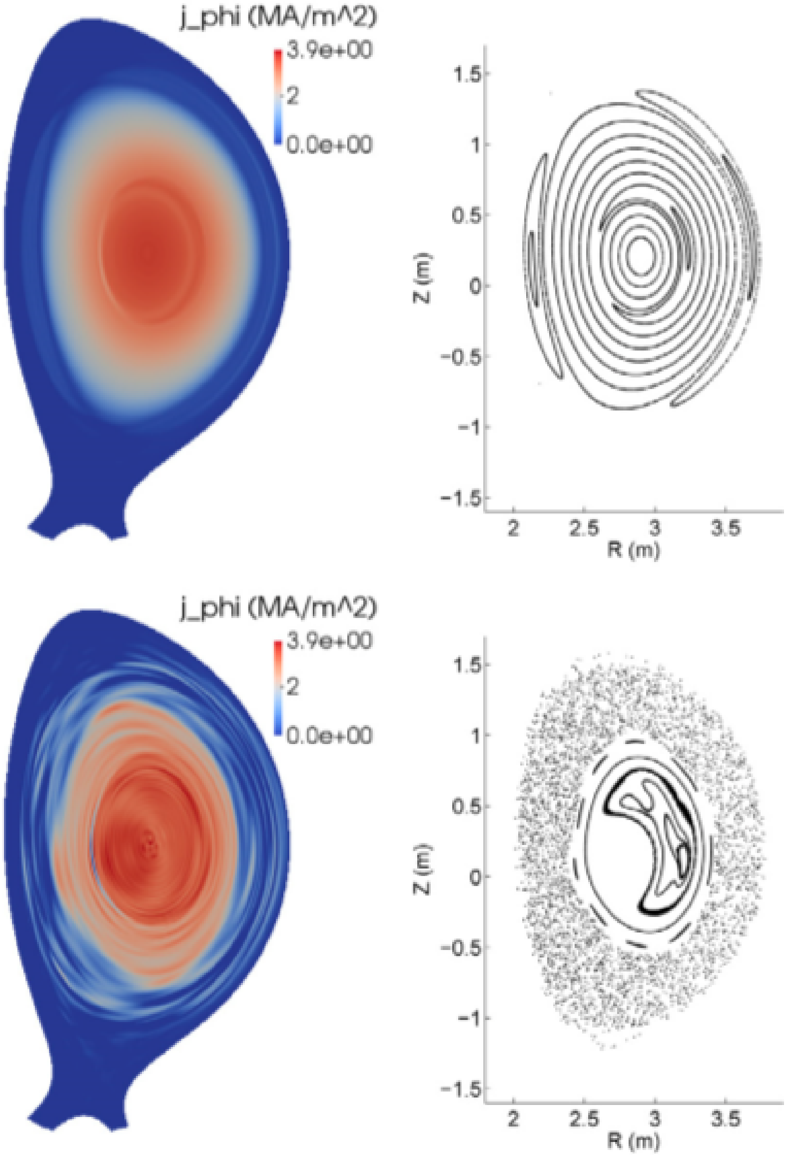
# Summary of observations

- Global deformation due to kink/tearing instability
- Current spike with
  - large magnetic fluctuations
  - plasma cooling
  - current density flattening
  - sporadic acceleration events (ECE spikes)
- Increase of plasma impedance and large-scale acceleration
- Substantial transfer of plasma current from a large number of low-energy electrons to a small number of relativistic electrons

- ECE spikes are also observed during the Edge Localized Modes, recursive instabilities that affect the plasma edge only (red dots in slide 4)

# Simulations

- Non-linear 3D codes such as JOREK (Nardon E. et al 2017 Plasma Phys. Control. Fusion 59 014006) find instabilities that give a multiplicity of island chains
- Magnetic surface breakup by islands interaction qualitatively reproduces current spike and magnetic fluctuations, but amplitudes are underestimated



# Unresolved phenomena

- Phenomena related to thin current sheets can not be resolved by present-day codes, in particular the plasmoid instability (Loureiro N.F. and Uzdensky D.A. 2016 Plasma Phys. Control. Fusion 58 014021) and 3D reconnection ensuing from boken symmetry (A.H. Boozer Nucl. Fusion 57 (2017) 056018)
- The latter involves current flattening via reconnection of volume-filling lines with different current density
- Current density is equalized by Alfvén waves
- The current spike follows from current flattening and magnetic helicity conservation
- If a region with intact magnetic surfaces persists, an intense current sheet forms at its boundary, which can explain acceleration events during the current spike.

# Summary

- Global instability
- Magnetic surfaces breakup
- Change of current profile
- Possibly macroscopic current sheets
- Increase of plasma impedance
- Acceleration of a minor population

- Rather than being a direct accelerator, magnetic reconnection acts as a switch