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

ENEA Miniworkshop
Prospettive in Astrofisica del Plasma

Magnetic reconnection and electron acceleration in tokamaks: hints for astrophysical flares

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P. Buratti ENEA – Frascati
paolo.buratti@enea.it

Outline

Connect

a machine integrity issue
like the tokamak disruption

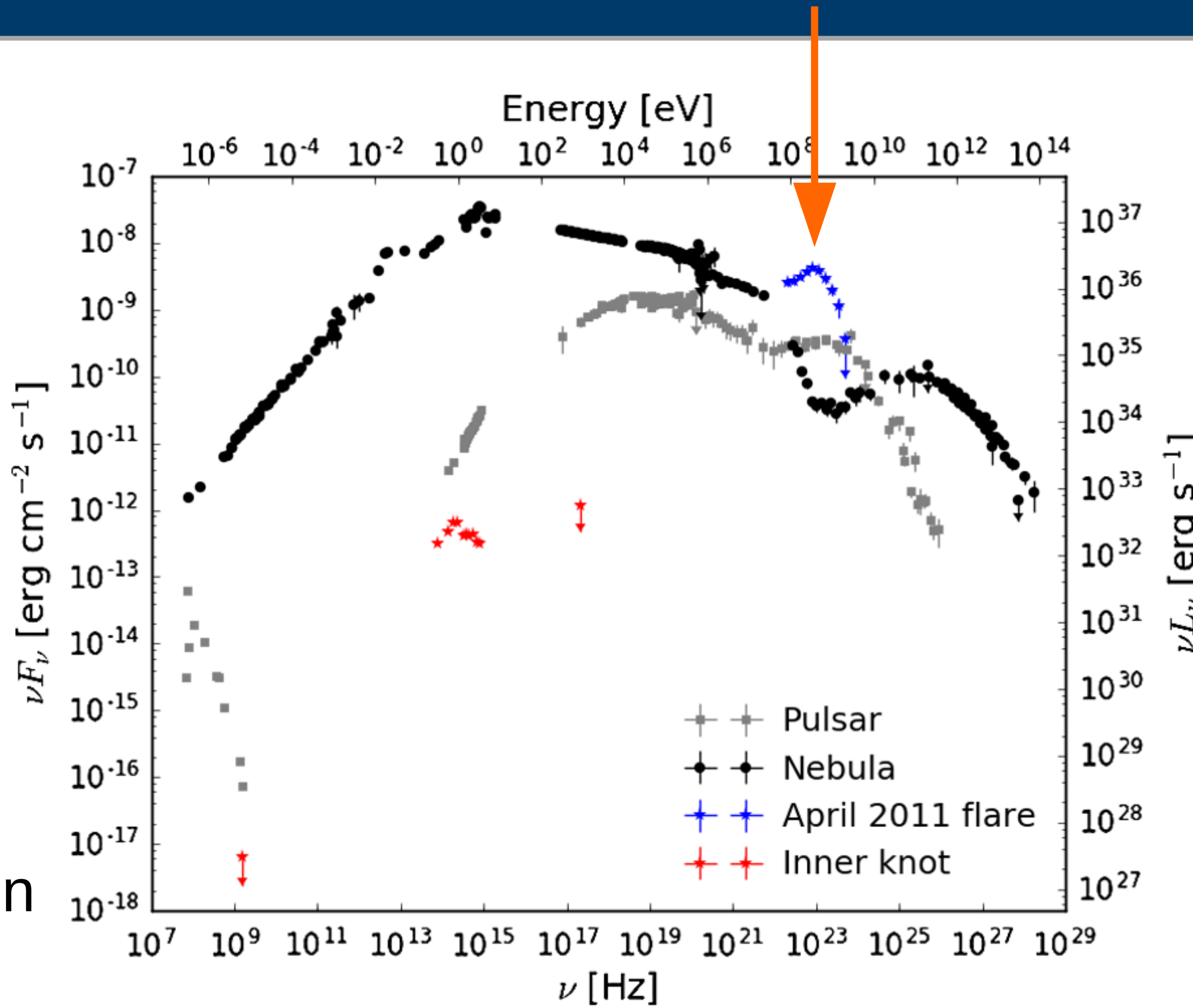
to

a fundamental phenomenon
like gamma-ray flares

Flares from the Crab Nebula

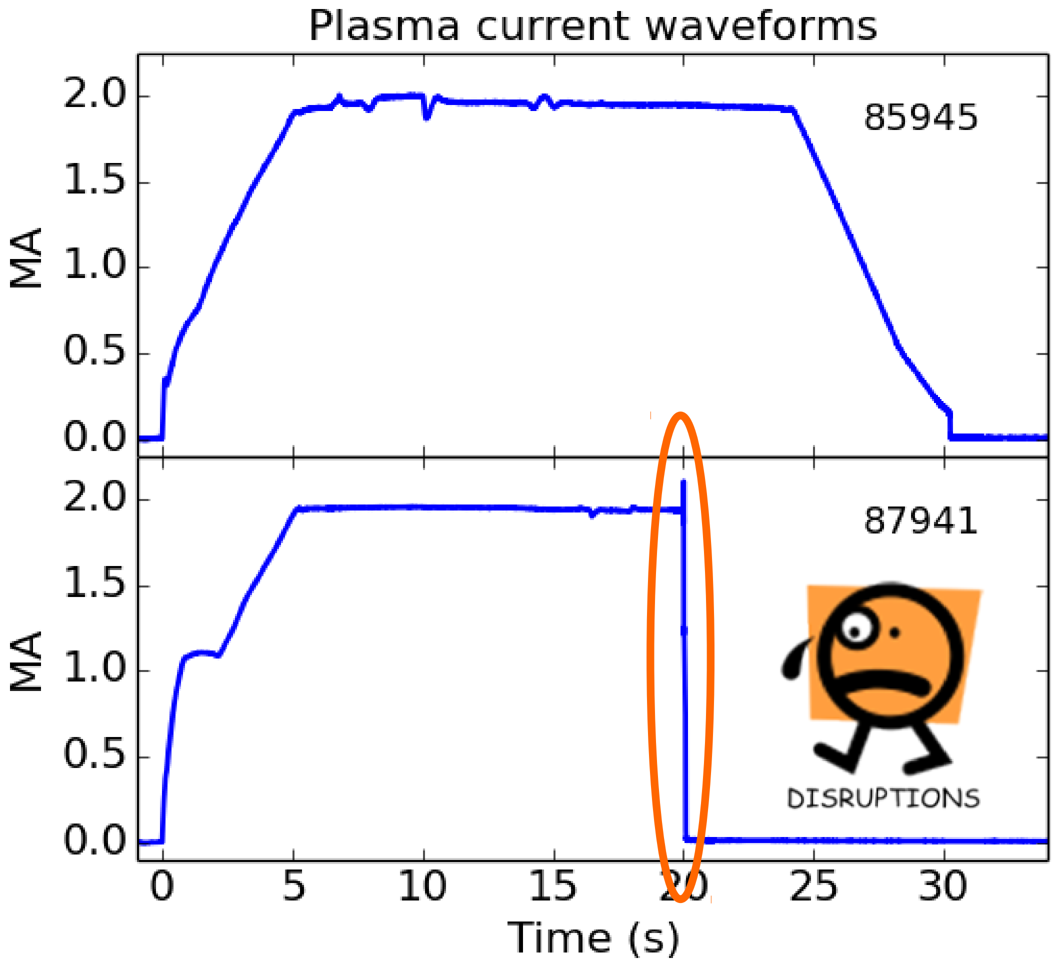
- 100 MeV – 1 Gev flares
- High luminosity
- 6 h growth

- Trigger
- Large E
- Macroscopic reconnection
- Minority acceleration



- Trigger, duration, energy partition: problems in common with sawtooth relaxations, ELMs, disruptions in tokamaks

The tokamak 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

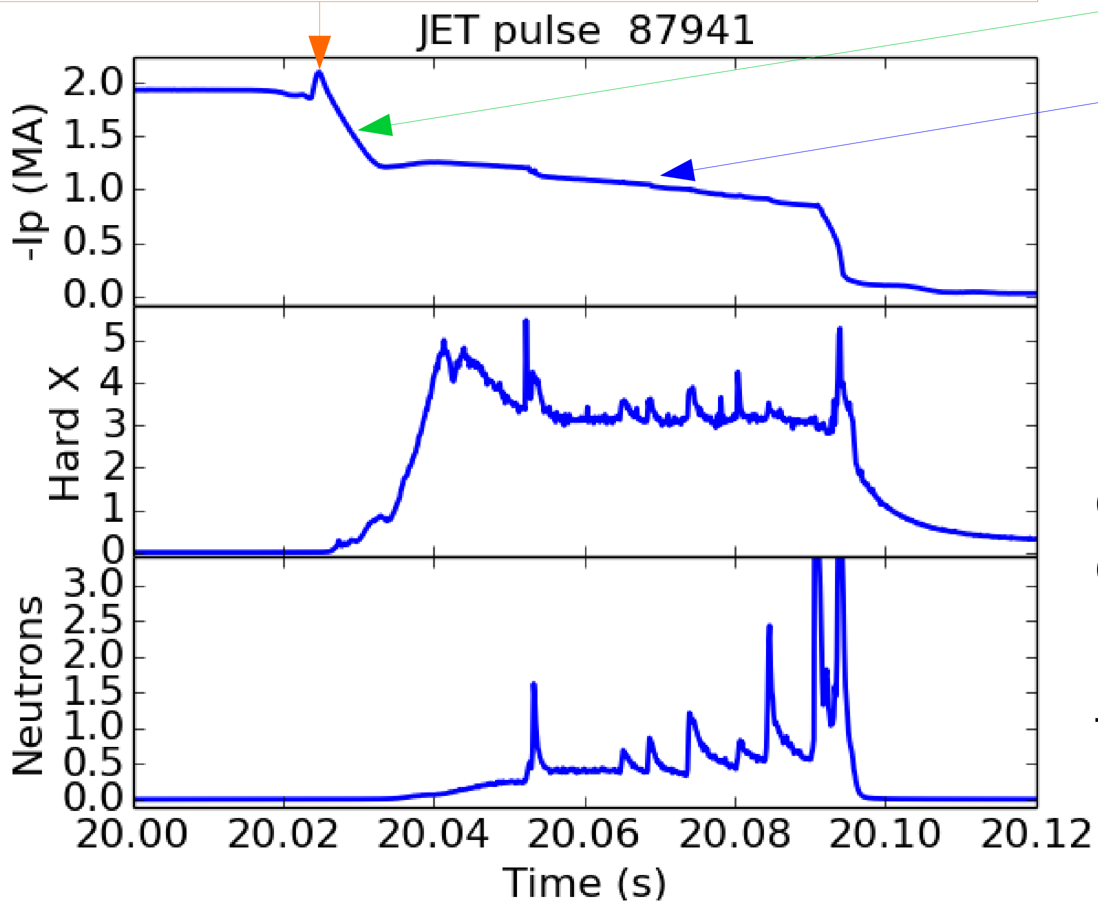
- High priority programs on mitigation (a machine integrity issue)
- Thermal and EM loads; relativistic electron beams

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



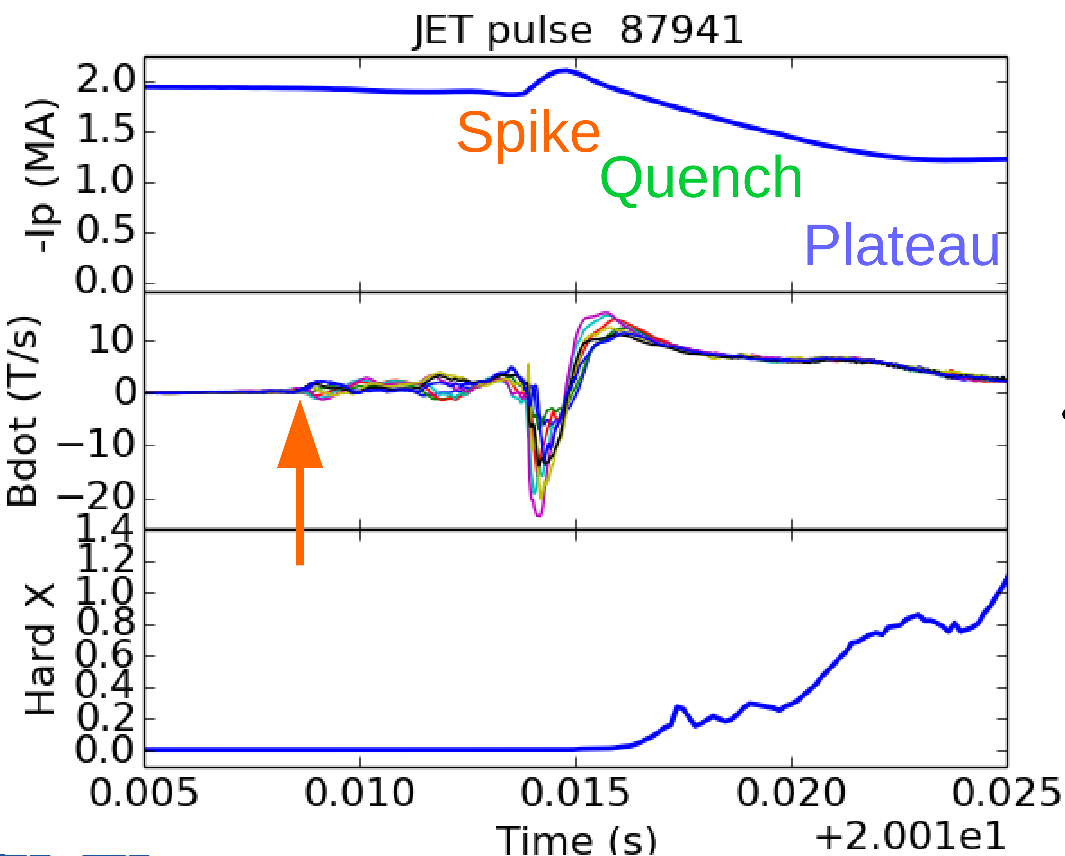
Hard x-ray from electron impacts on in-flight ions or on plasma-facing components

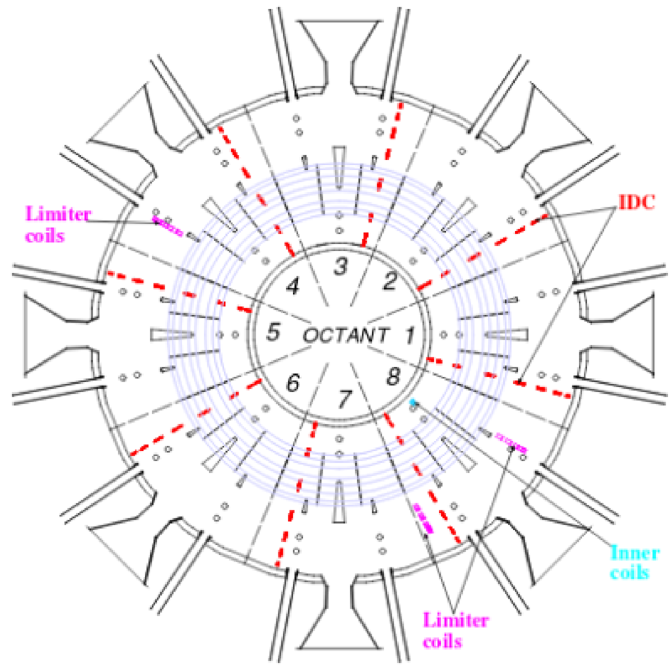
Rate of photoneutrons from impacts at some MeV

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

Axsisymmetry breaking

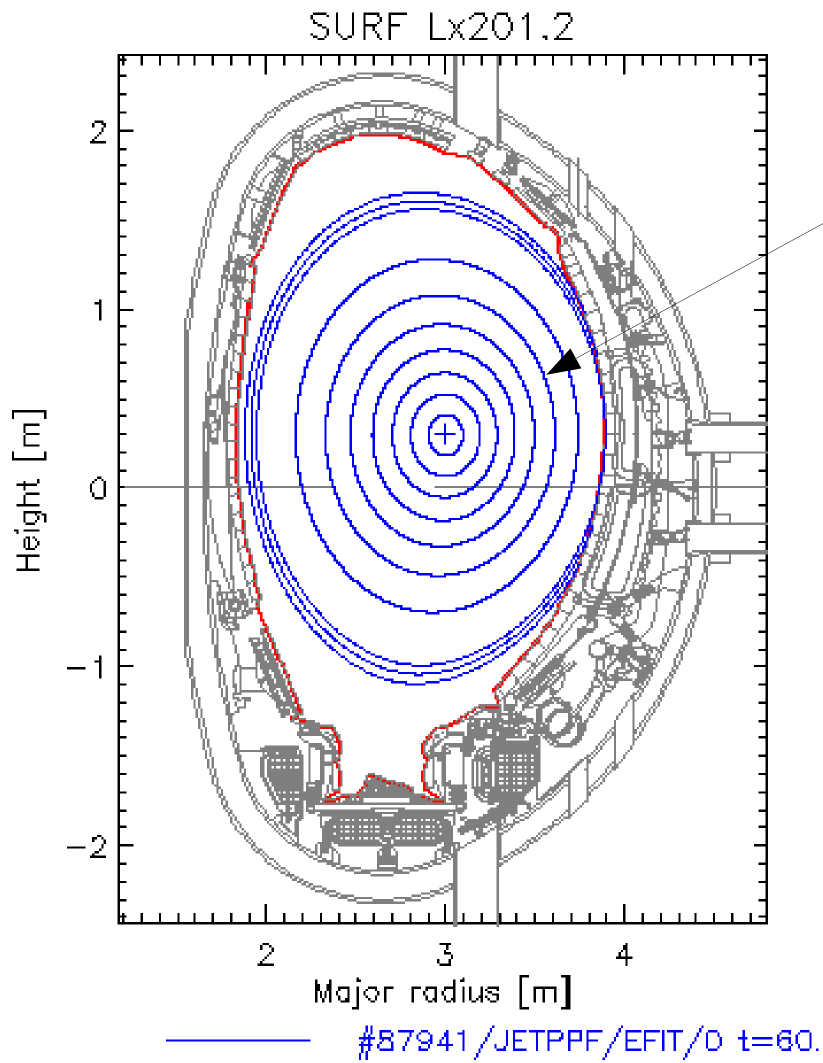
- In a laboratory we can go around the object
- 8 symmetric magnetic sensors (Internal Discrete Coils)





- Non-equal coil signals show broken symmetry onset

Consequences of broken symmetry



- Surface-filling field lines with axisymmetry (filled magnetic surfaces are nested tori)

- Volume-filling lines with broken symmetry (**surface breakup**)
- Alfvén waves redistribute the current density, hence the **current spike**: 3D reconnection
- Rapid loss of thermal energy via parallel transport, hence a **thermal quench**
- **Current quench** follows due to increased resistivity

Role of reconnection

- Magnetic reconnection acts as a switch

- Acceleration is acted by system electrodynamics, depending on the speed of current quench

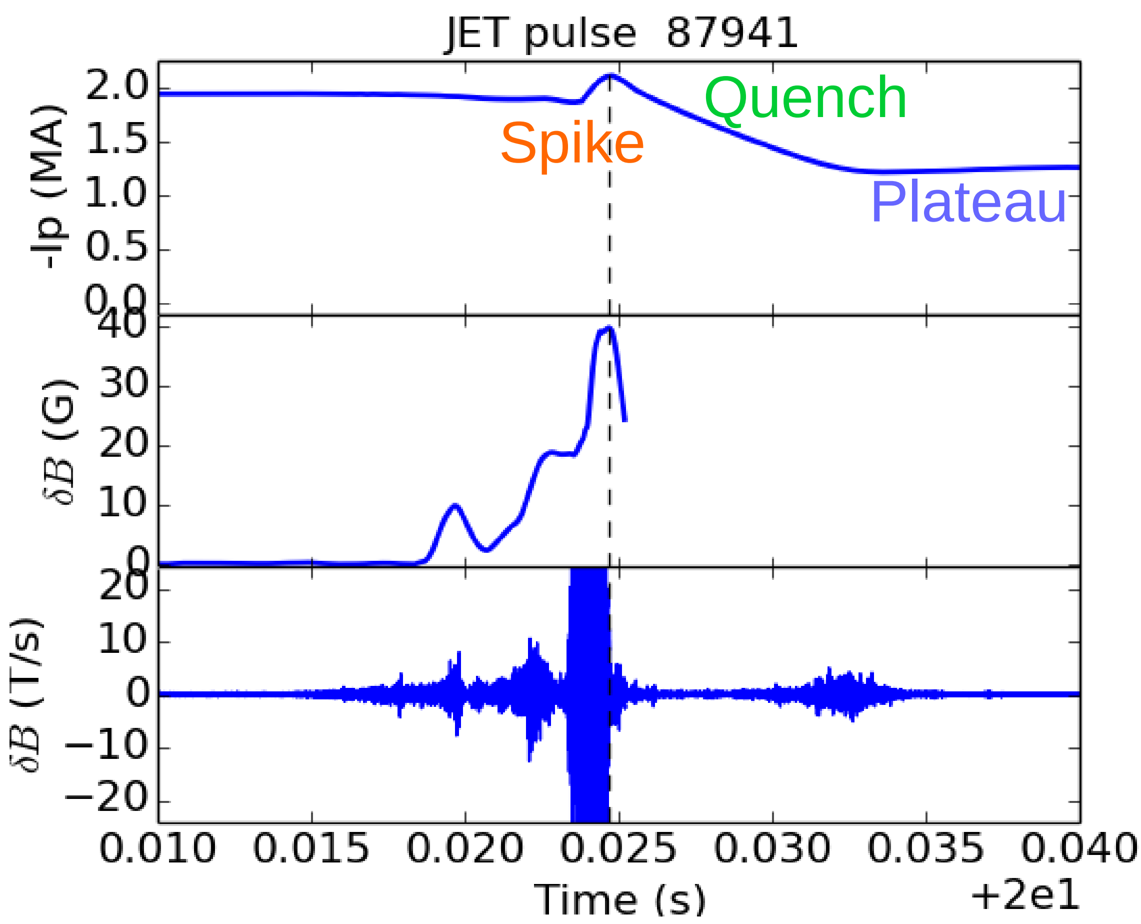
- The condition is

$$\frac{dI}{dt} \gg I_{Alfvén}\, \nu_{collision}$$

$$\nu_{collision} = 8\pi r_e^2 c\, n_e \ln\Lambda$$

- Can this be exported to astrophysics?
- Could reconnection produce charge starvation by expelling current carriers?

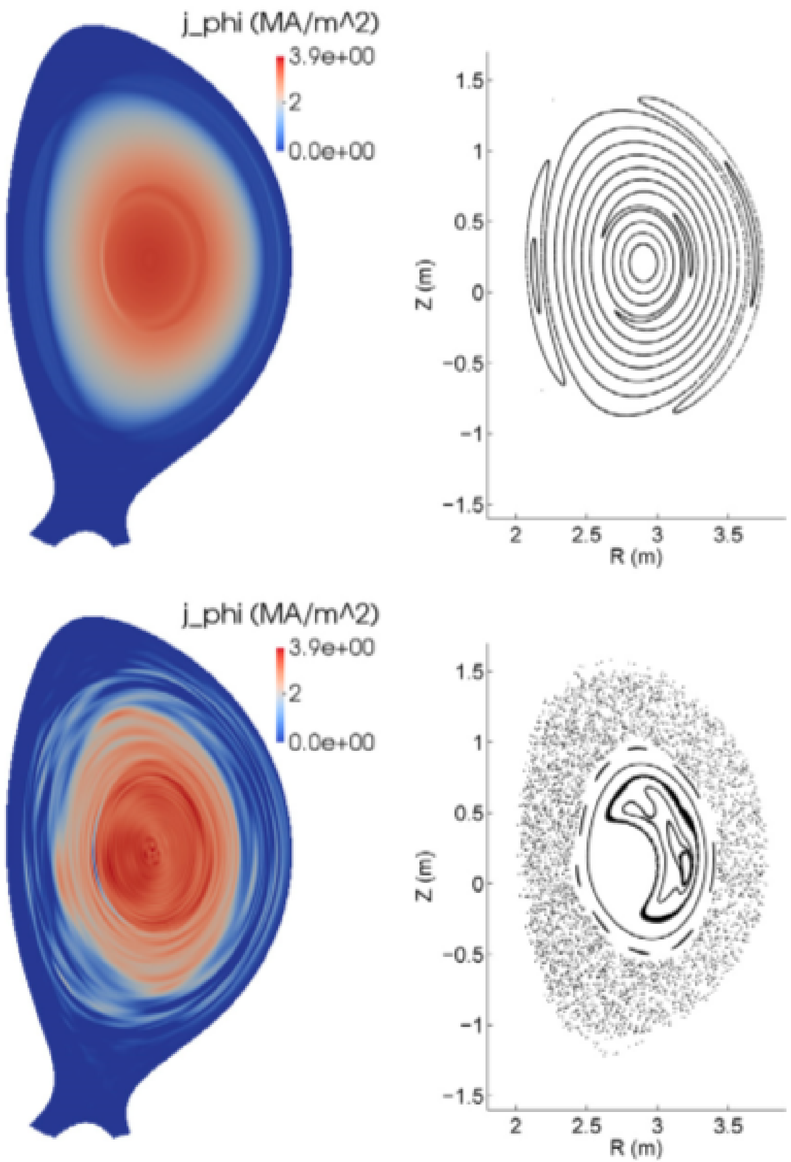
Rapid magnetic fluctuations



- Symmetry breaking deformation with simple structure
- Fast fluctuations with more complex structure

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

Simulations



- Non-linear 3D codes such as JOREK (Nardon E. et al 2017 Plasma Phys. Control. Fusion 59 014006) capture the main structural features
- But underestimate the current spike and magnetic fluctuations
- Present-day 3D codes can not resolve the involved times (alfvénic) and lengths (collisionless skin depth)

Mean field theory

- 2D equations with surface breakup effects lumped in an extra term (related to helicity transport) in Ohm law

$$\vec{E} \cdot \vec{B} = \eta \vec{j} \cdot \vec{B} - \vec{\nabla} \cdot \left(\lambda \vec{\nabla} \frac{j_{\|}}{B} \right)$$

A.H. Boozer
Nucl. Fusion
58 (2018) 036006

- Large λ leads to current density flattening
- It will decrease with increasing Alfvén time along the volume-crossing length
- It will be zero where magnetic surfaces are intact
- A boundary between intact and broken surfaces will develop a current sheet
- Build a toy model for λ based on magnetic island concepts and on observed fast fluctuations

Other threads

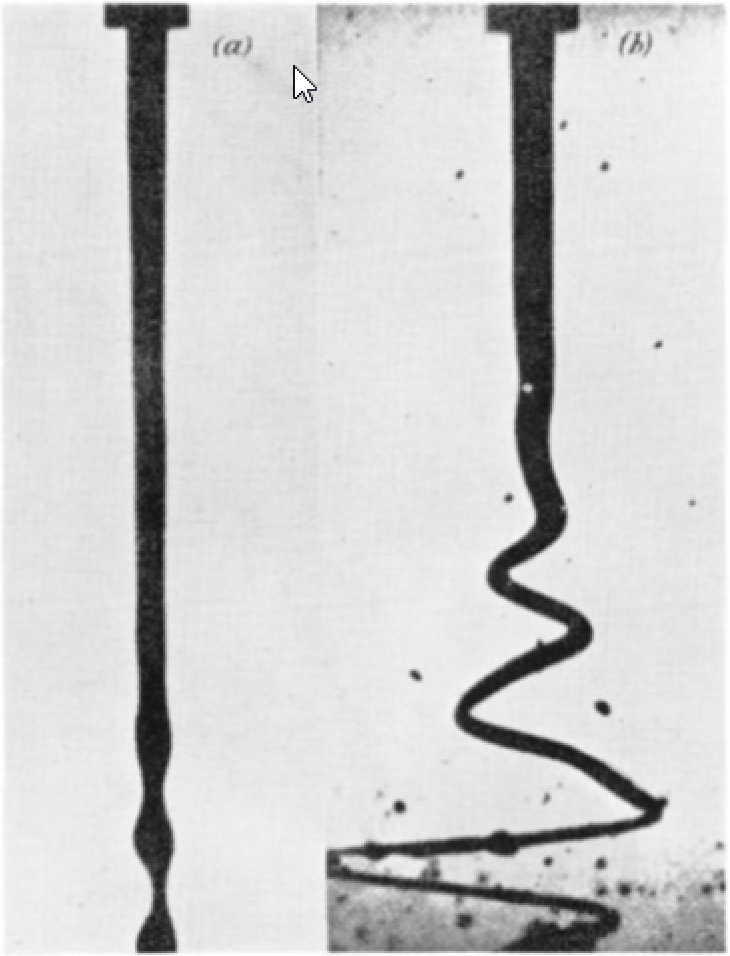
- Monoenergetic distributions tailored by collisional pitch angle scattering + synchrotron radiation
- Pitch angle scattering via anomalous Doppler instability
- Advanced synchrotron emission calculations (including plasma dispersion) and comparison with FTU data
- Radiation reaction and Ohm law

Slides in reserve

Plasma macroscopic instabilities

Mercury column with 300 A

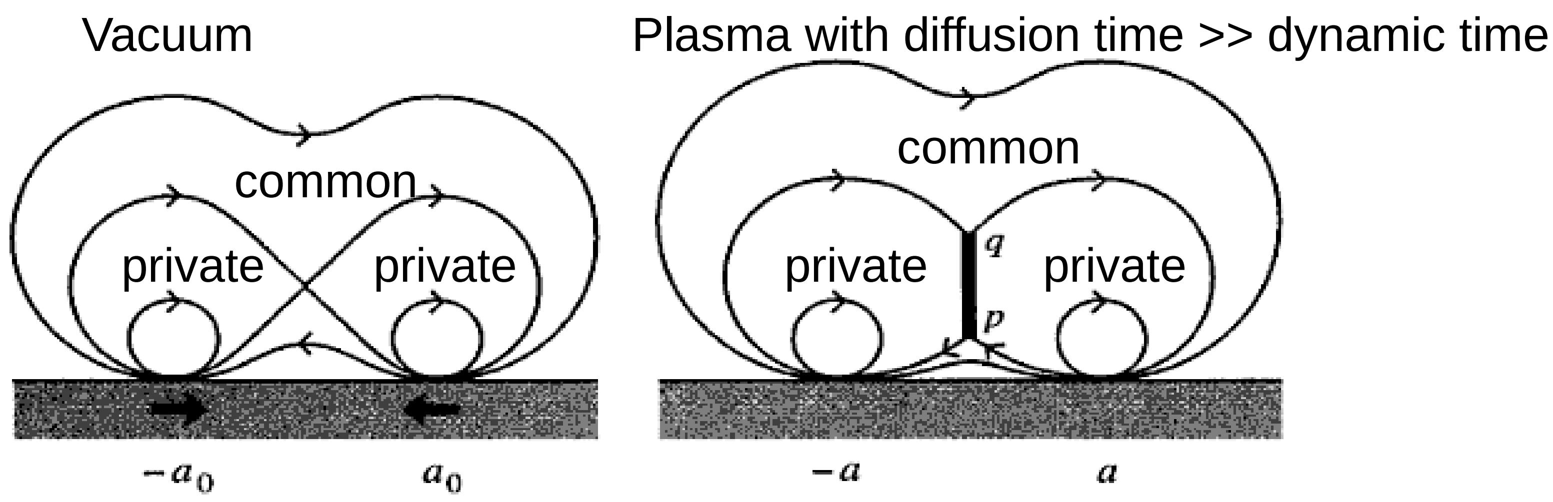
DATTNER, A., LEHNERT, B., and LUNDQUIST, S., 1958, Geneva, **31**, 325.



Sausage instability

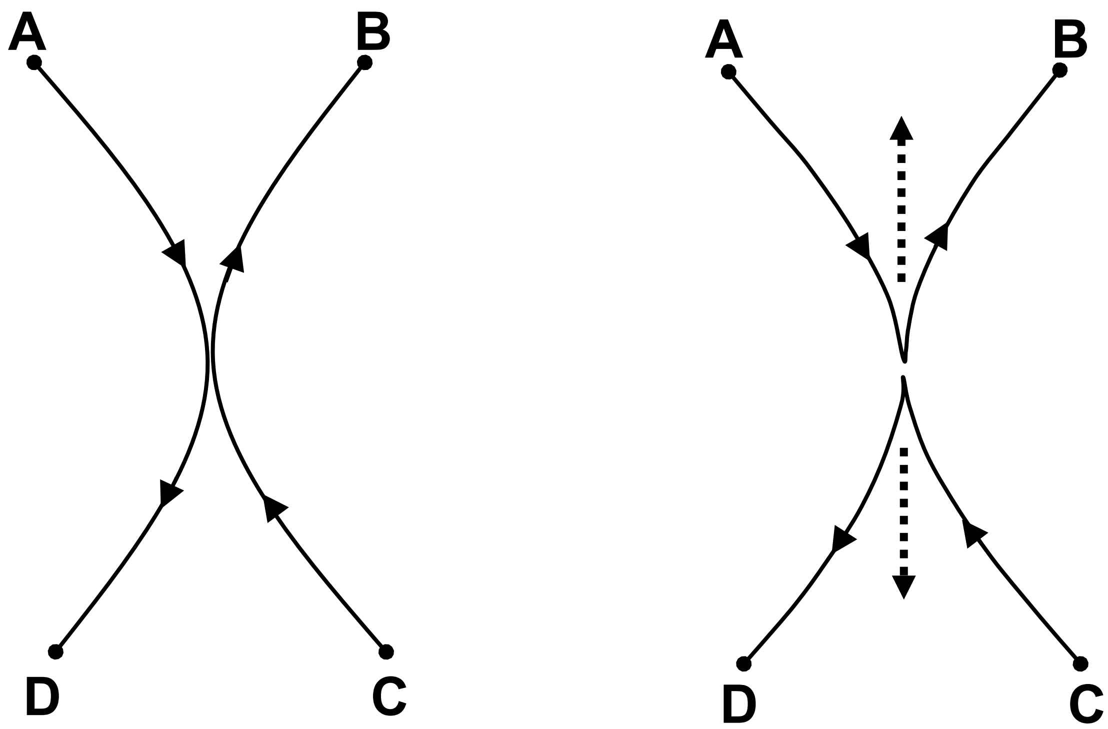
Kink instability

Magnetic reconnection 1



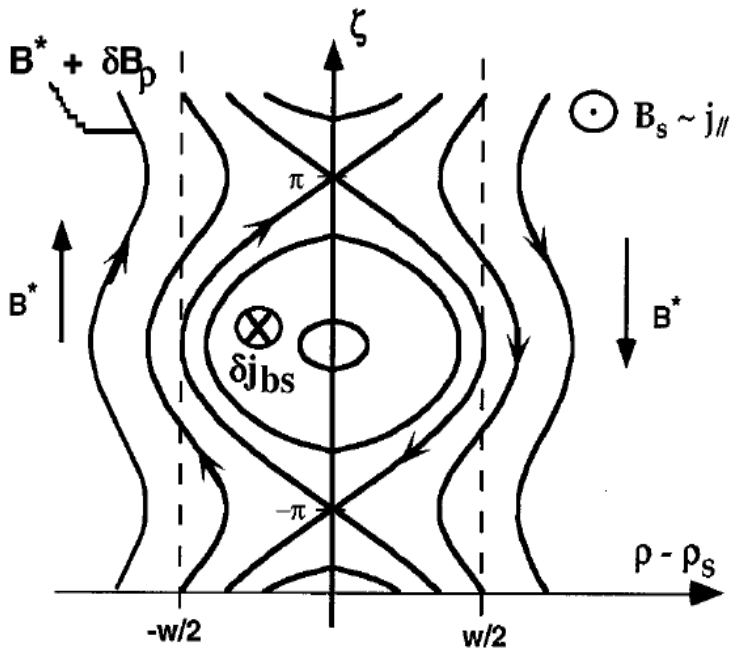
- Two wires with common (encircling both) and private field lines
- Conservation of connection: private regions can not be mixed
- Private regions shrink and disappear as the wires get closer in vacuum
- A conductive plasma reacts by forming a current sheet that preserves private regions from mixing.

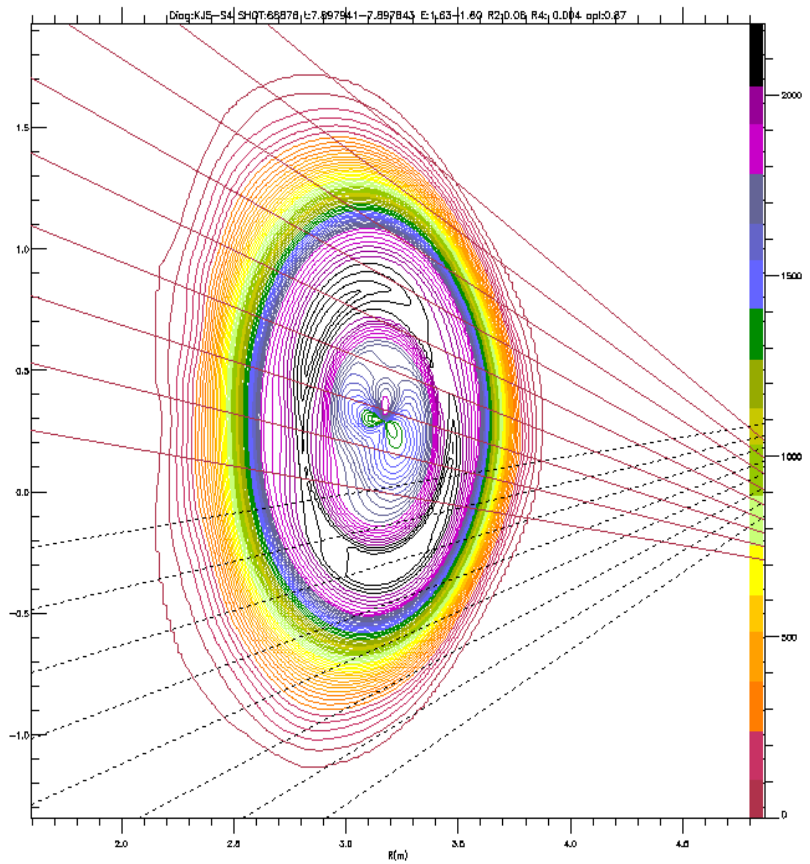
Magnetic reconnection 2



- From A-D & C-B to A-B & C-D
- Local event with global effects

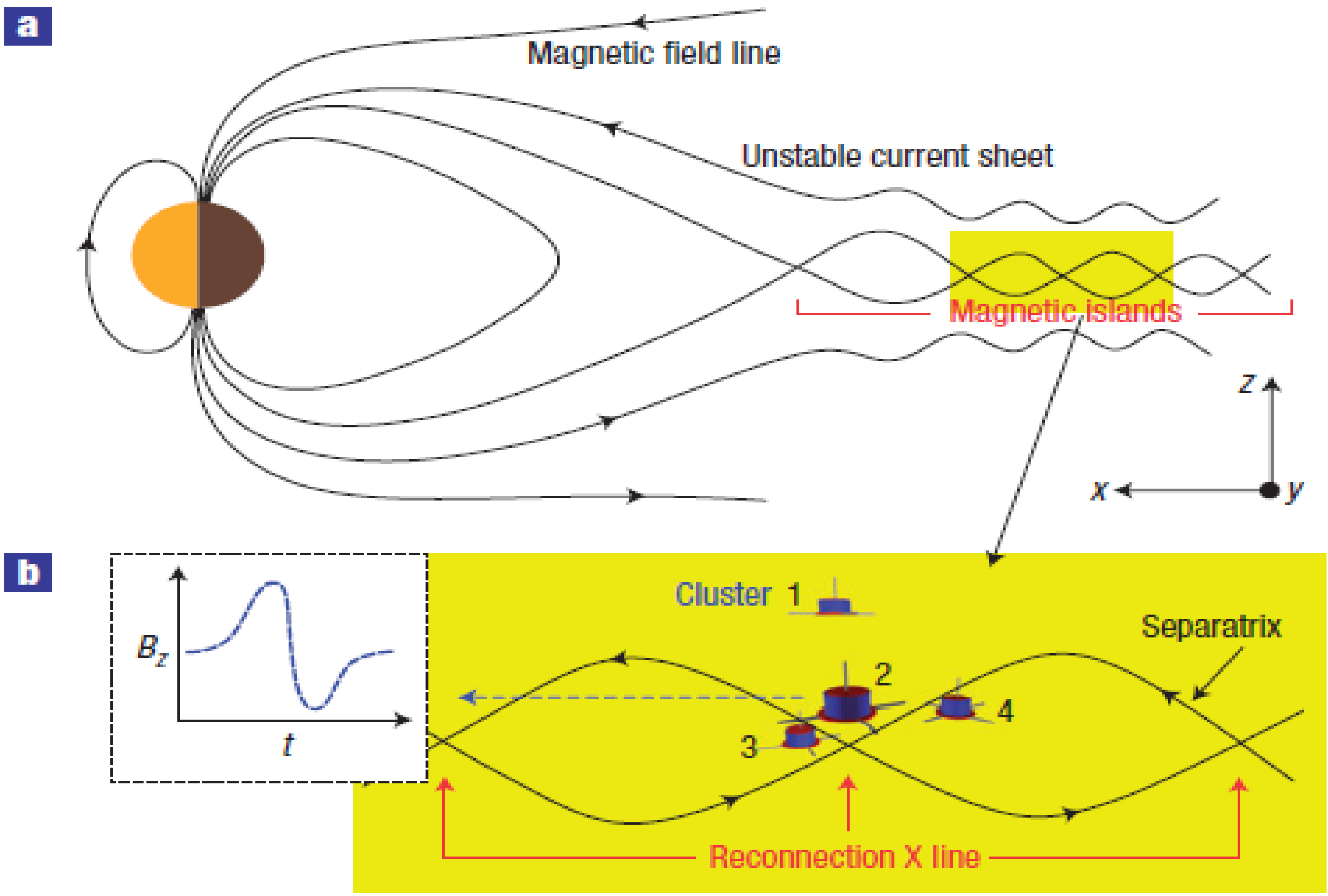
Magnetic islands 1





- Field lines are torn and reconnected
- Magnetic topology changes

Magnetic islands 2

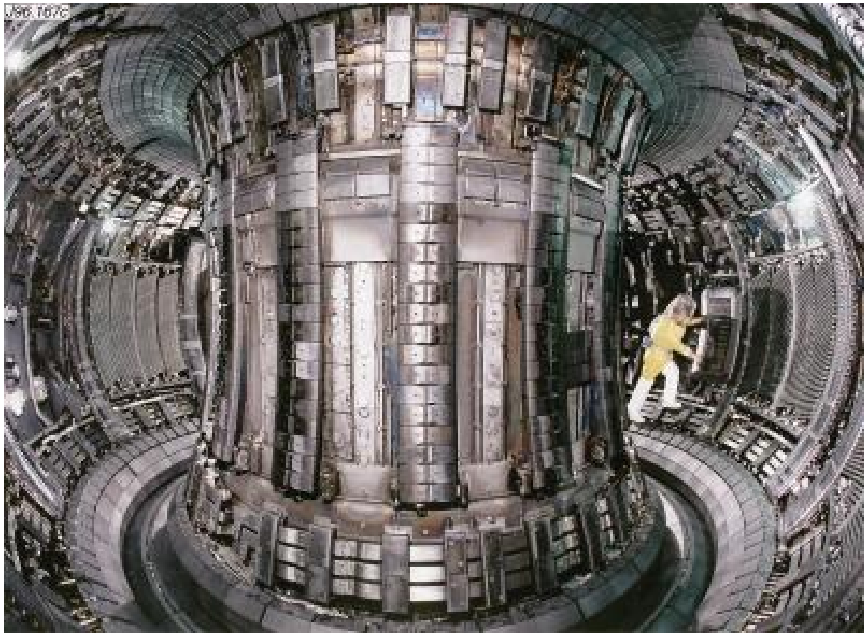


Chen, Nature Phys. 2007

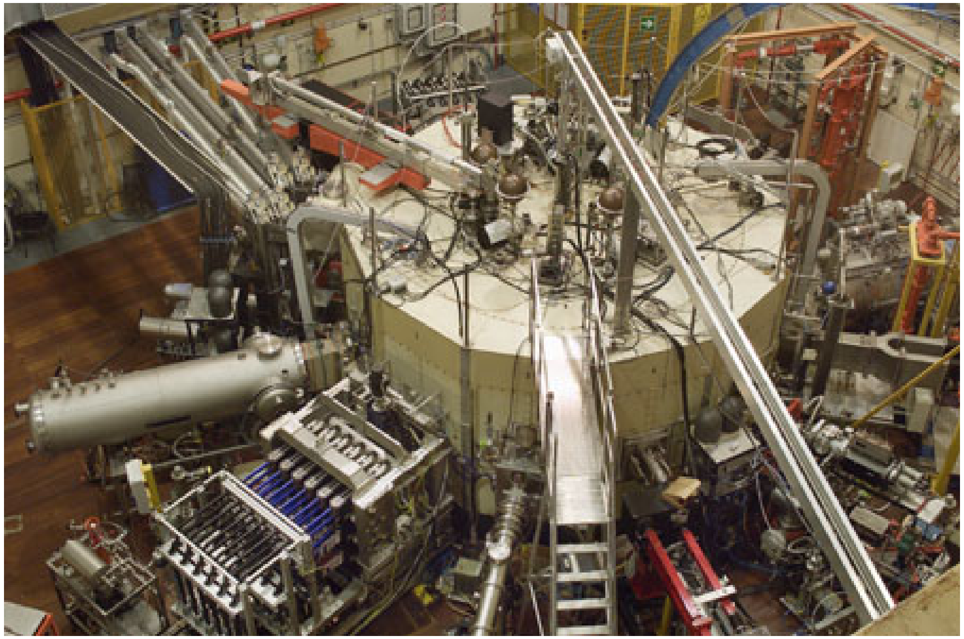
Figure 1 **Schematic diagrams of magnetic islands in the Earth's magnetotail.**

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