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Instabilities, reconnection and particle acceleration in laboratory plasmas

ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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Outline

- Instabilities and particle acceleration in linear plasma machines
- Magnetic reconnection
- Runaway electrons in tokamaks

Early history (middle of the past century)

- A relatively simple (Z-pinch) device produced 10^8 neutrons in microsecond deuterium discharges (1954, Sherwood Project)
- Fine nuclear diagnostics revealed that fusion reaction were due to a small group of very fast deuterons: it was beam-target and not *thermo*nulear fusion.
- A big disappointment in the quest for controlled *thermo*nuclear energy
- But there were deuterons of at least 200 keV, with an applied voltage of about 10 keV.

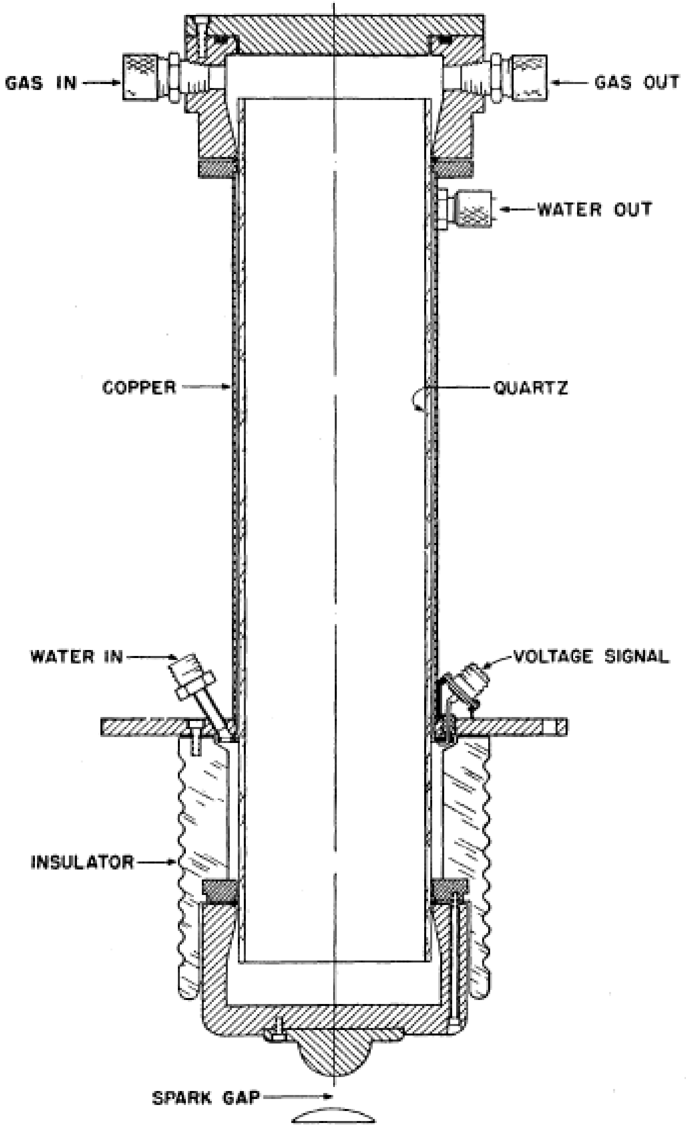


FIG. 4. Cross section of a pinch tube.

Read more: Anderson OA et al 1958 Pys Rev **110** 1375

Acceleration by the sausage instability

- Deuterons of at least 200 keV, with an applied voltage of about 10 keV: acceleration by some plasma effect.
- Acceleration occurred during the development of the sausage instability:
- Plasma is compressed by axial current and associated magnetic field (toroidal in jet language)
- Local necking enhances compression and grows.
- Acceleration details are not as simple as outlined in the figure.

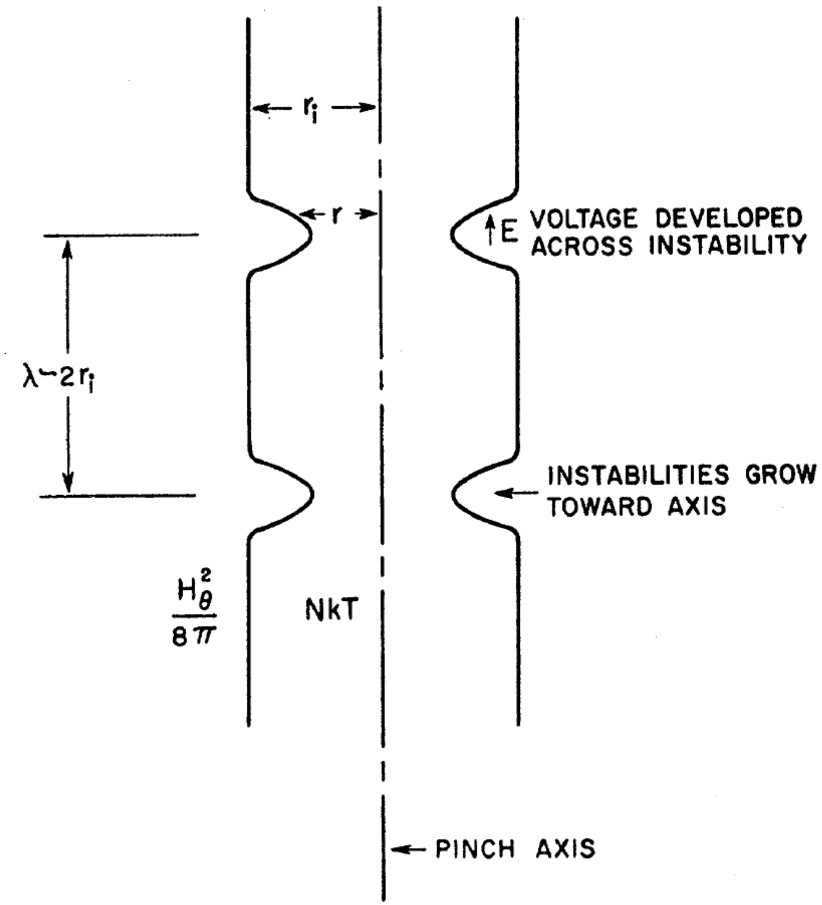


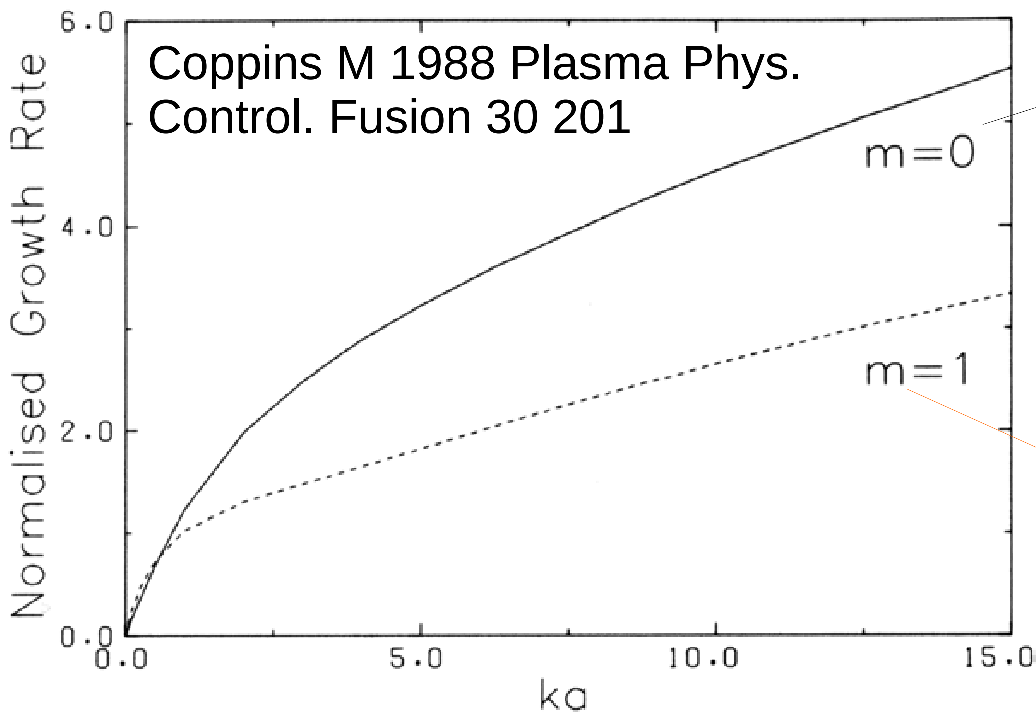
FIG. 13. Sausage instability with resulting electric field.

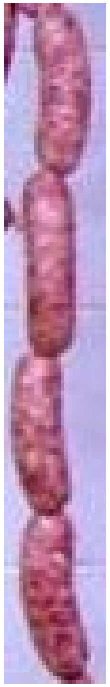
Acceleration by the sausage instability was found in many Z-pinch and jet experiments

Sausages (m=0) and kinks (m=1)

- Linear instability for uniform current density within the radius *a*
- The growth rate increases with wavenumber

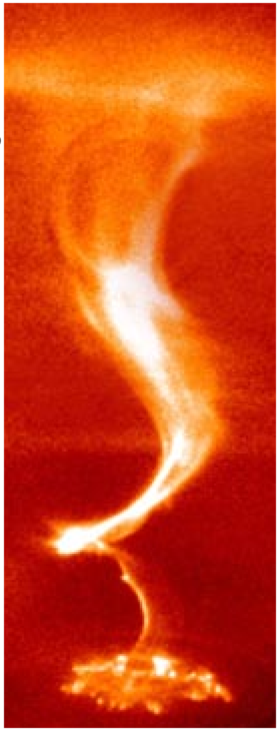
$$\gamma \approx \sqrt{\frac{k}{a}}\; c_{sound}$$





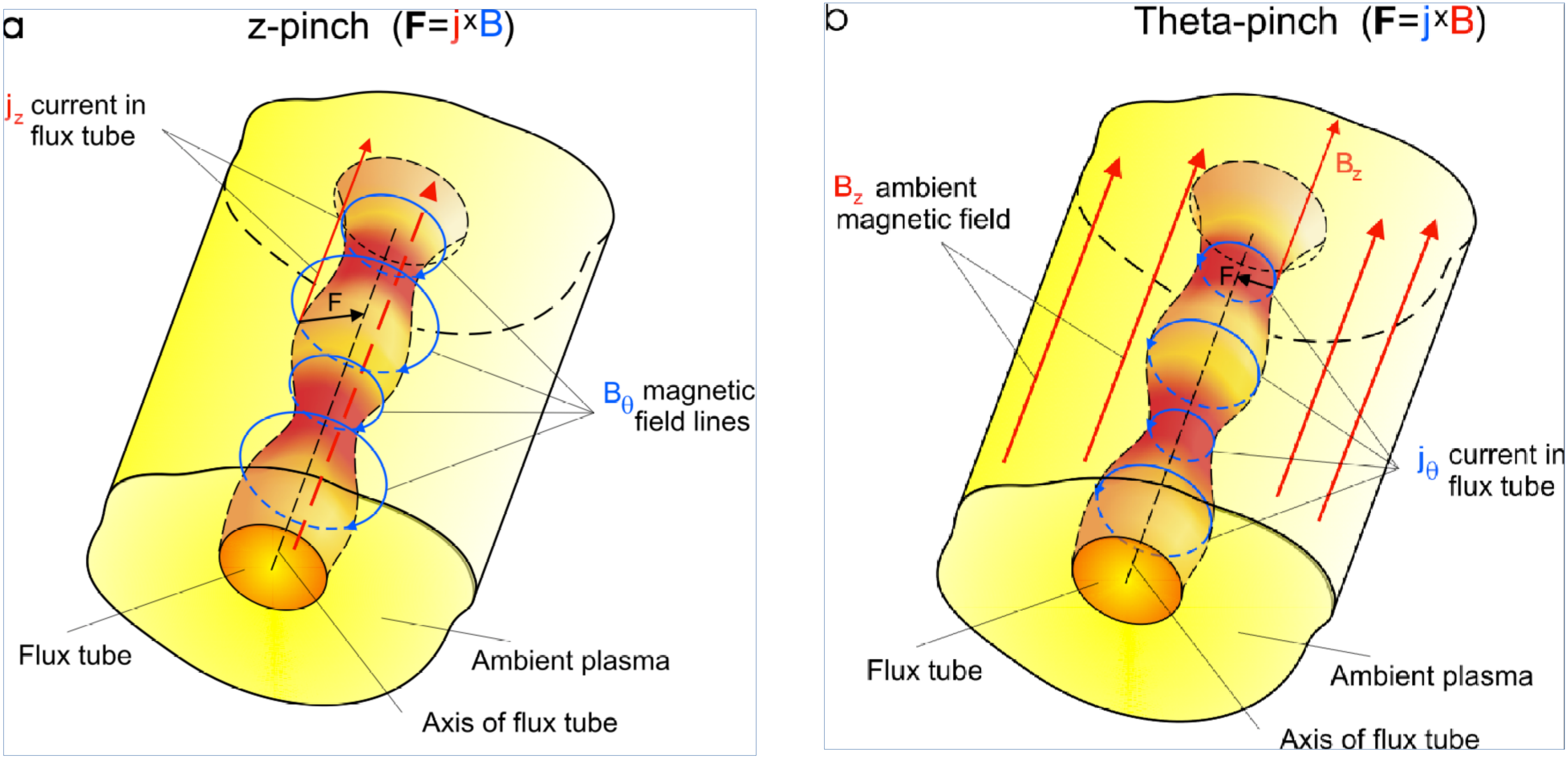
Kruskal M & Schwarzschild M 1954 Proc Roy Soc (London) **A223** 348

Hsu SC & Bellan PM 2003 Phys Rev Lett **90** 215002



- More peaked current density tends to stabilize
- Axial (z) magnetic field tends to stabilize.

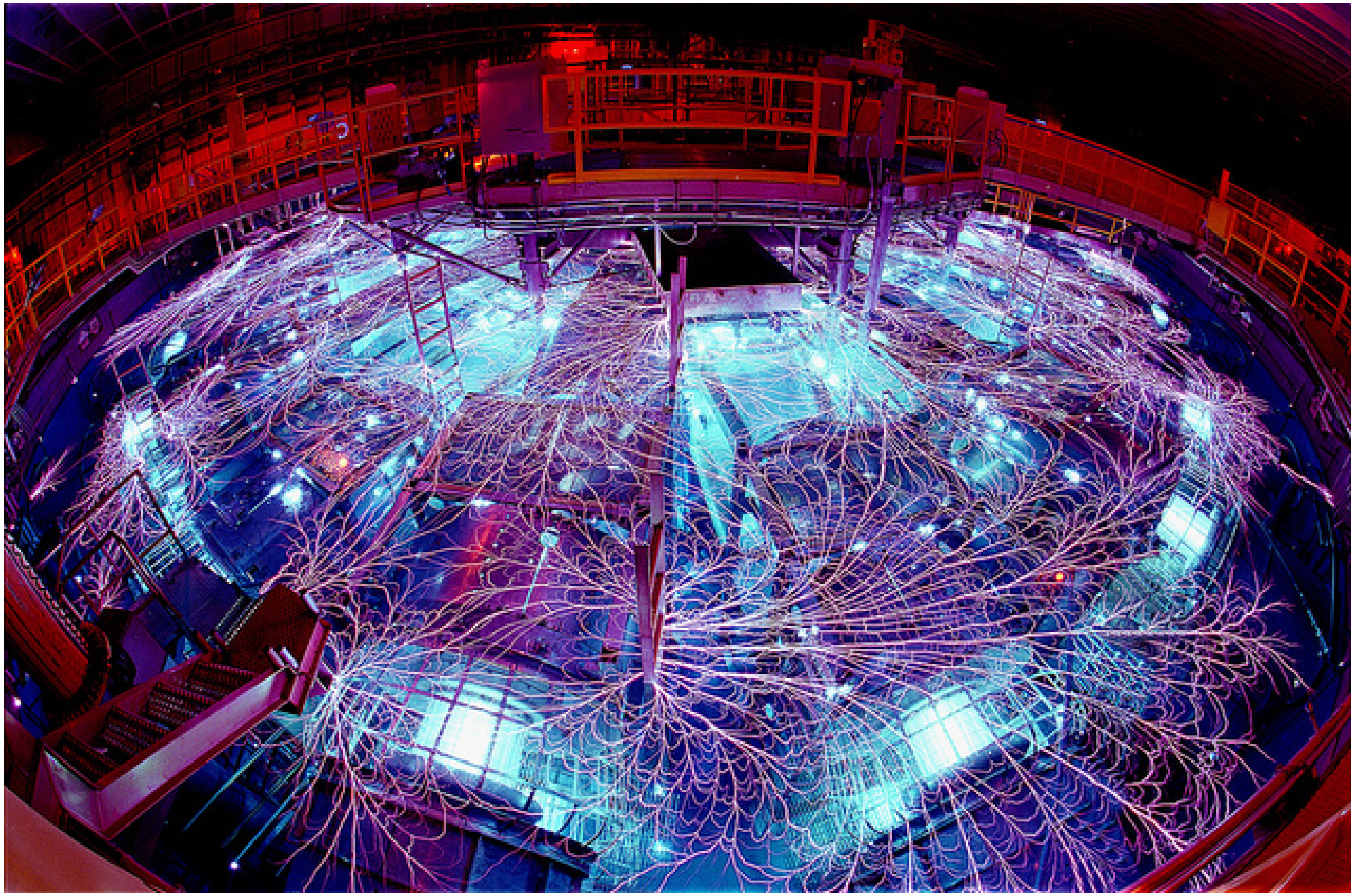
Sausages



Larger radial pinch force in neck regions.

http://inspirehep.net/record/1217817/plots

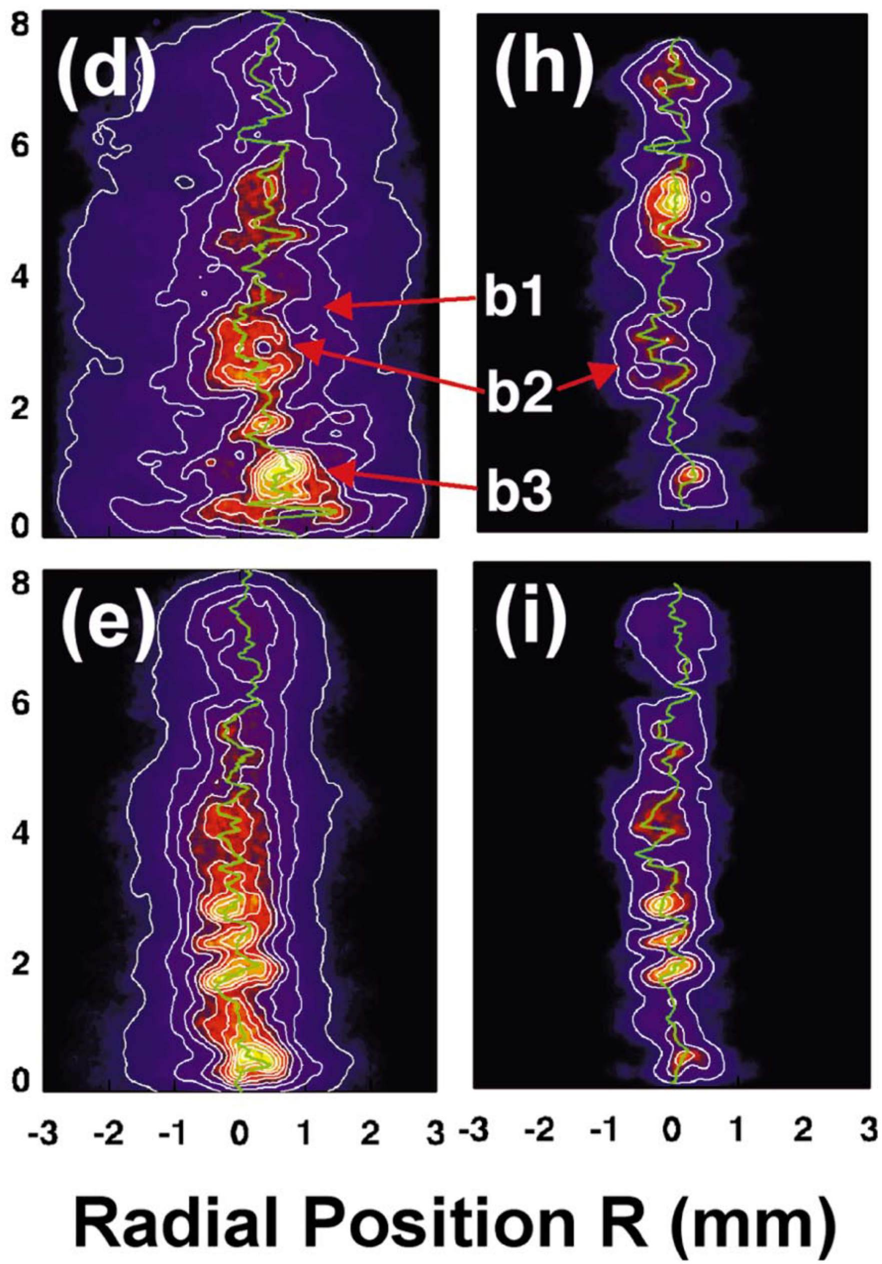
The most powerful Z-pinch (1)



- 20 MA in wire array (tungsten, carbon, solid D)
- Evaporation and pinch compression
- X-ray pressure sufficient to compress matter

Read more: http://www.sandia.gov/z-machine/

The most powerful Z-pinch (2)

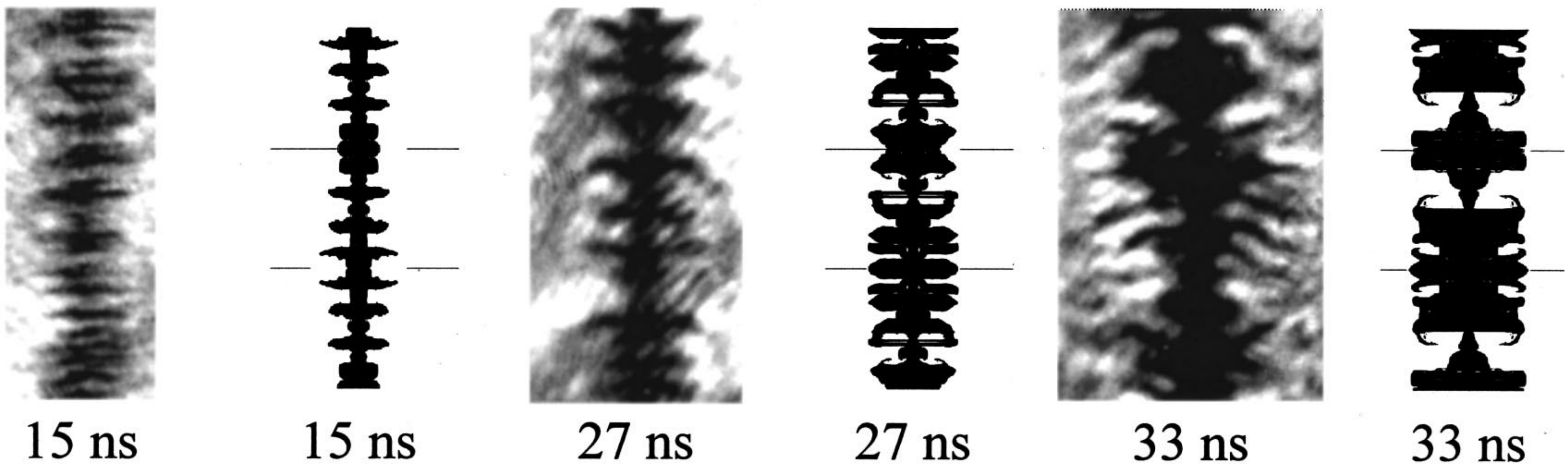


- X- ray pinhole camera data at different times (d), (e)
- Same with thicker filter (h), (I)
- Hot spots with clear m=0 sausage structure along the axis (vertical, 8 mm long)
- Weak m=1 kink deviation (horizontal)

From Cuneo ME et al (2005) Phys Rev E **71** 046406

Real and simulated sausages (1)

- Plasma from an exploding carbon fibre in MAGPIE (UK)
- A particular wavenumber dominates at each time

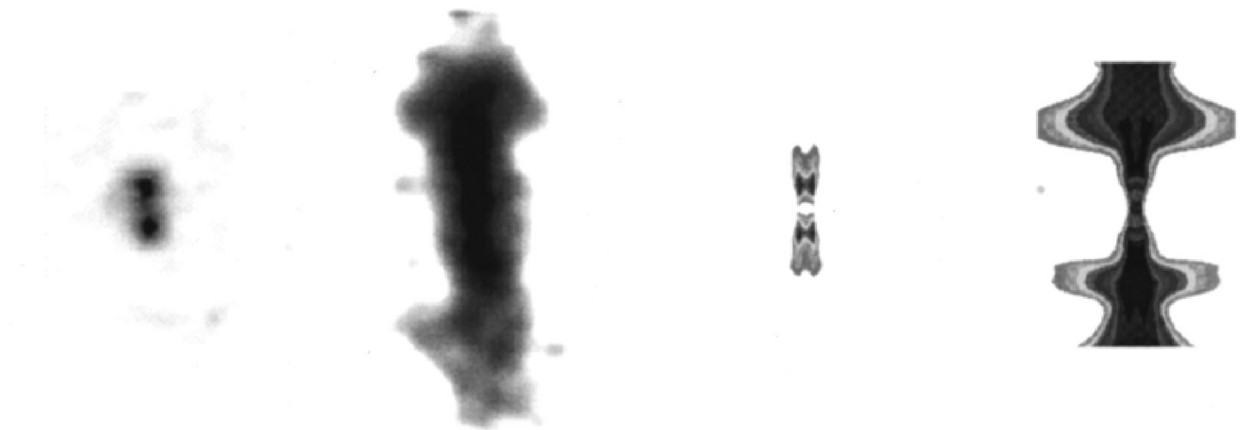


Real and simulated images generated by light deflection
Chittenden JP et al 1997 Phys. Plasmas **4** 4309

- 2D simulations reproduce this feature
- Multifluid (electrons, different ions, neutrals) resisitve MHD simulations in *r, z* geometry

Real and simulated sausages (2)

- Plasma from an exploding carbon fibre
- A particular wavenumber dominates at each time
- Bright spots of x-ray emission occur In the necking regions



10 μm Be filter | 1.5μm Poly-carbonate filter | 10 μm Be filter | 1.5μm Poly-carbonate filter

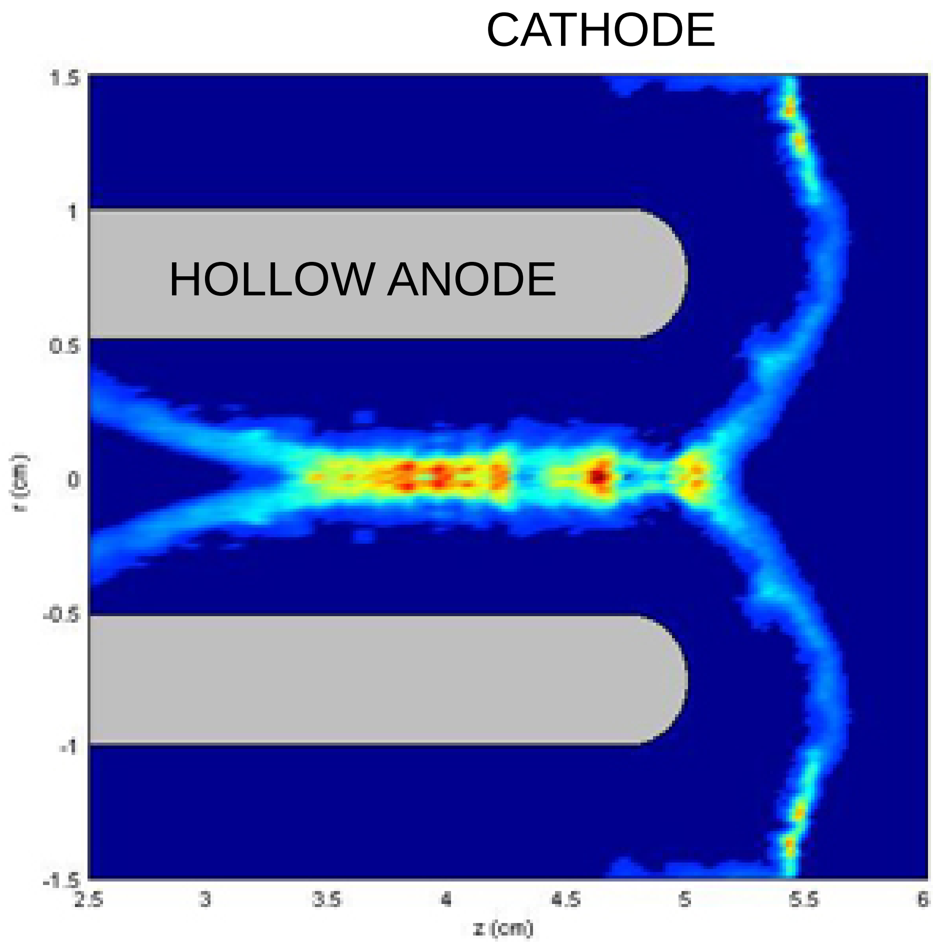
Experiment at t = 33 ns | Simulation at t = 33 ns

- Simulations reproduce bright spots and their bifurcation

Chittenden JP et al 1997 Phys. Plasmas **4** 4309
For a complete review on Z-pinches see:
Haines MG 2011 Plasma Phys. Control. Fusion **53** 093001

Plasma Focus

- Ion beams, electron beams, neutrons
- Energies much larger than the applied voltage



Schmidt A et al 2012
Phys Rev Lett **109** 205003

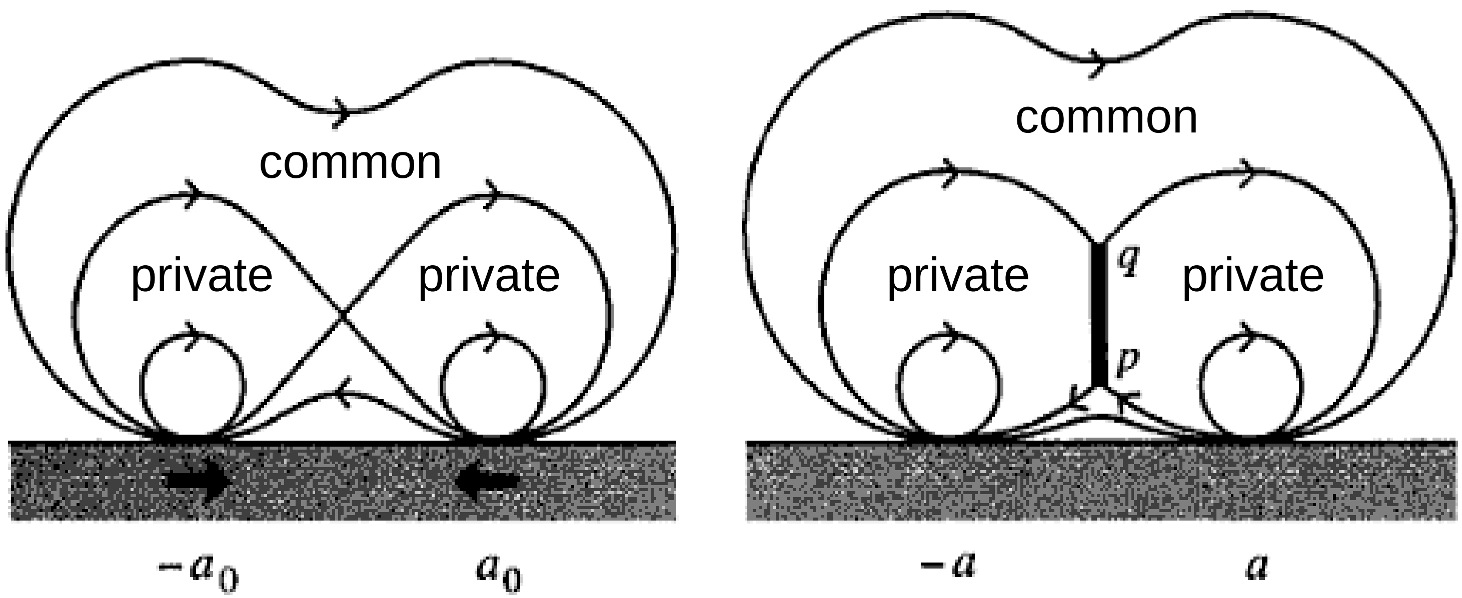
- Reproduced by fully kinetic PIC simulation

Part II
MAGNETIC RECONNECTION

Ideal plasma evolution

- Two attracting current filaments in *vacuum*: as they get closer, private regions shrink and disappear
- In an ideal (non dissipative) plasma private regions are conserved

Vacuum Plasma with diffusion time >> dynamic time

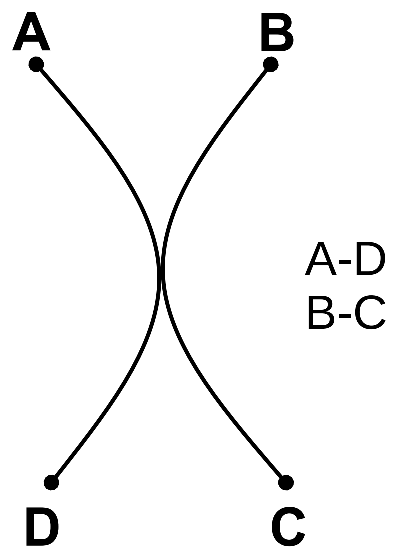


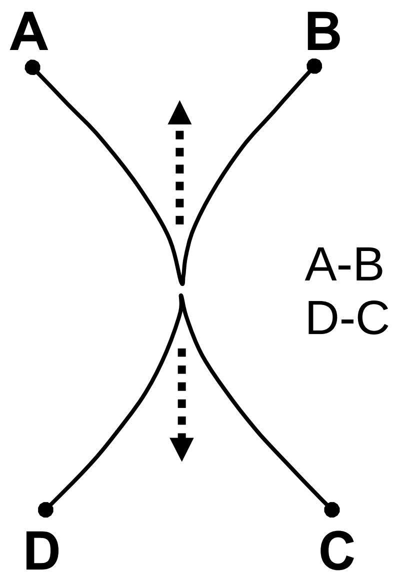
From Priest & Forbes *Magnetic reconnection* Cambridge 2000

- A current sheet is formed which counteracts attraction
- Non ideal effects are relevant inside the current sheet.

Magnetic reconnection

- Field lines topology is fragile in the current sheet
- A small local perturbation can globally change connection between plasma elements: tearing and *reconnection* of magnetic field lines.



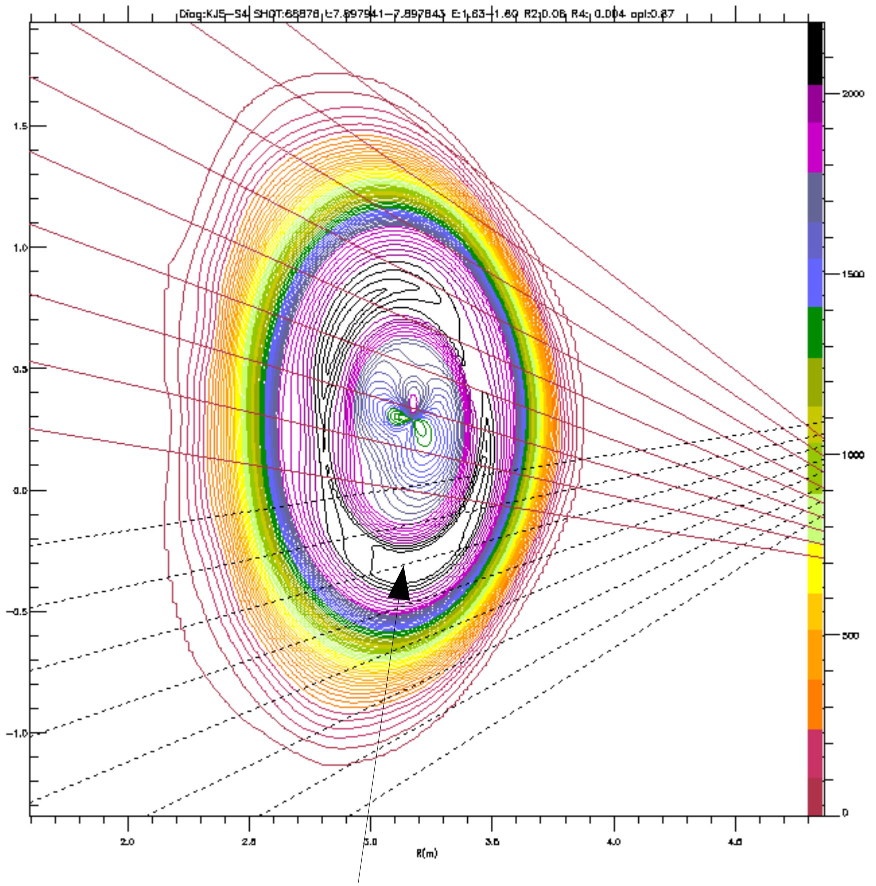


- Large electric fields and magnetic tension forces can develop
- Layer physics can include: resistivity, electron inertia, pressure anisotropy, Hall effect, pair creation, radiation pressure and radiation drag.

See refs in ftp://geosp-server.aquila.infn.it/isss/Corso2012/Buratti.pdf

Reconnection at different scales

- Colliding laser-formed plasma bubbles (1 mm) Dong QL et al 2012 Phys Rev Lett **108** 215001
- Tearing instabilities or forced reconnection in magnetically confined plasmas (1 m)
- Magnetic islands in magnetotail (10^3 km)
  Chen LJ et al 2008 Nature Physics **4** 19
- In solar wind (>390 Earth radii)
  Phan TD et al 2006 Nature **439** 175
- In solar flares (50000 km)
  Su Y et al 2013 Nature Physics **9** 489
- Anomalous cosmic rays from Voyager
  Drake JF et al 2010 ApJ **709** 963
- Pulsars, Jets, GRB

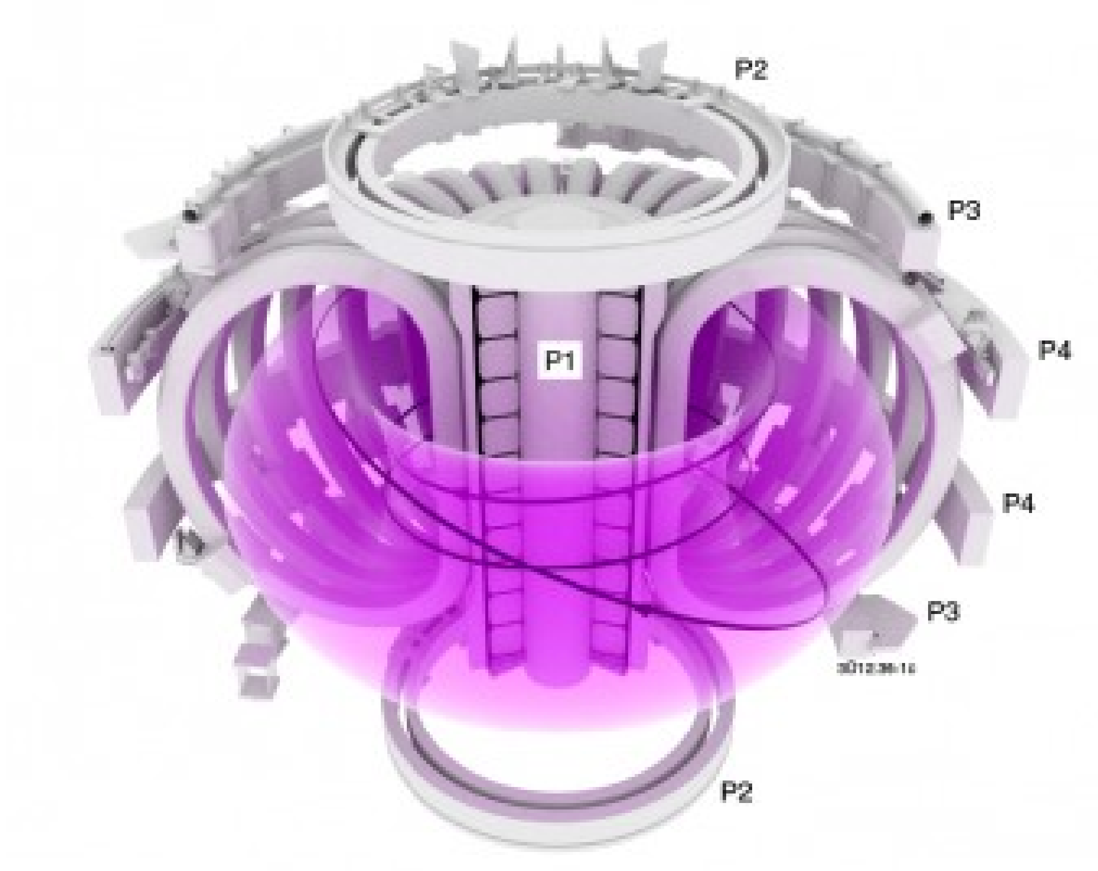


Magnetic islands formed by field line tearing and reconnection as seen in x-ray maps of plasmas in the Joint European Torus

Part III
RUNAWAYS

Tokamak machines

- Toroidal chamber (1 – 3 m major radius)
- Strong imposed toroidal magnetic field (some Tesla)
- Imposed toroidal electric field (fraction of V/m)
- Toroidal current flowing in the plasma (MA)



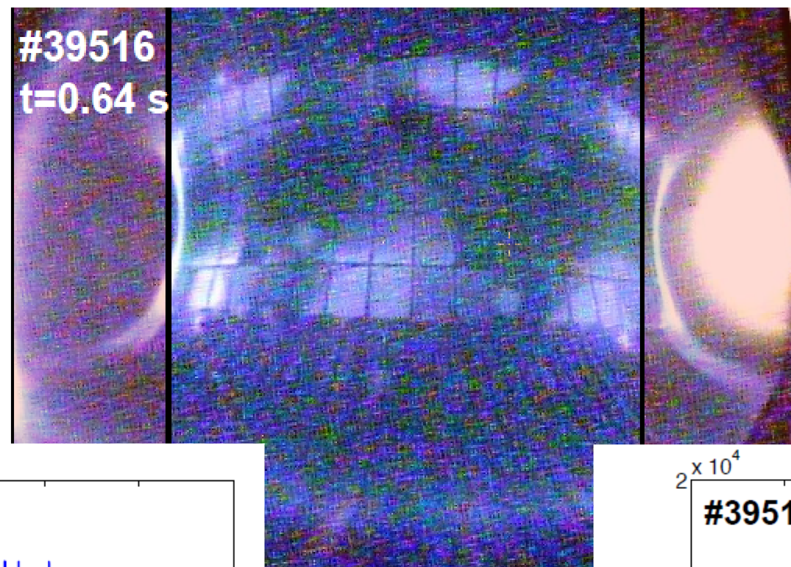
Runaway electrons

- The Coulomb collision frequency decreases with increasing velocity (as v^{-3}).
- There is a critical speed above which electrons run away, i.e. are freely accelerated by the ambient electric field (Dreicer effect)
- A runaway electron can knock on a thermal electron and bring it above the critical velocity (avalanche)
- Runaway electrons running in a torus gain a few eV or a few tens of eV per turn, but the number of turns can be huge
- A beam of relativistic electrons is formed if the plasma density is small or if the toroidal electric field is sufficiently large.
- The beam is nearly unidirectional.

Detection of runaway electrons

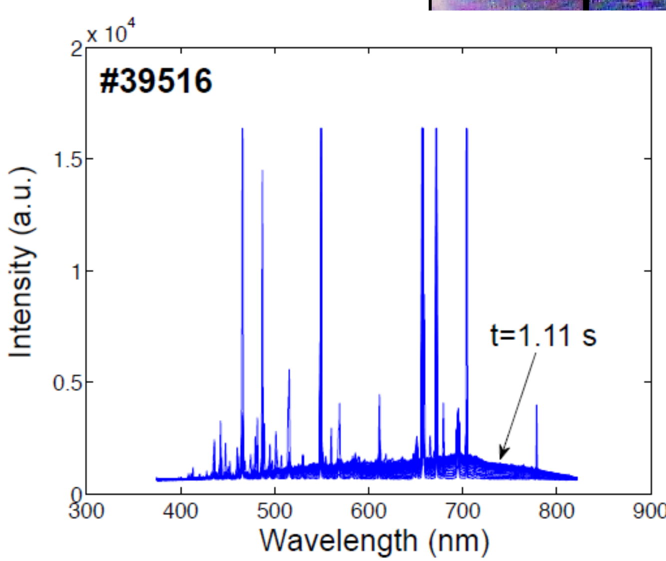
- Hard x-rays, gamma rays, photoneutrons are observed as runaways impact on plasma facing components
- Particularly interesting is the detection of in-flight runaways by synchrotron emission

Esposito B et al 2015 http://ocs.ciemat.es/EPS2015PAP/pdf/P4.113.pdf

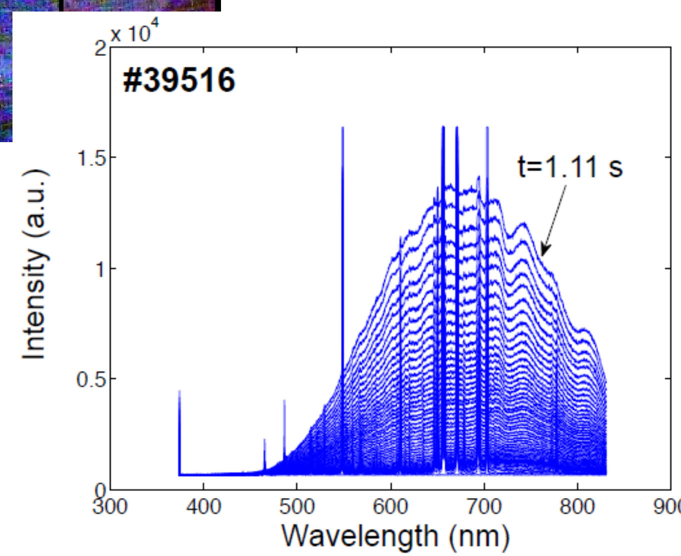


Visible light image and spectra from the Frascati Tokamak Upgrade

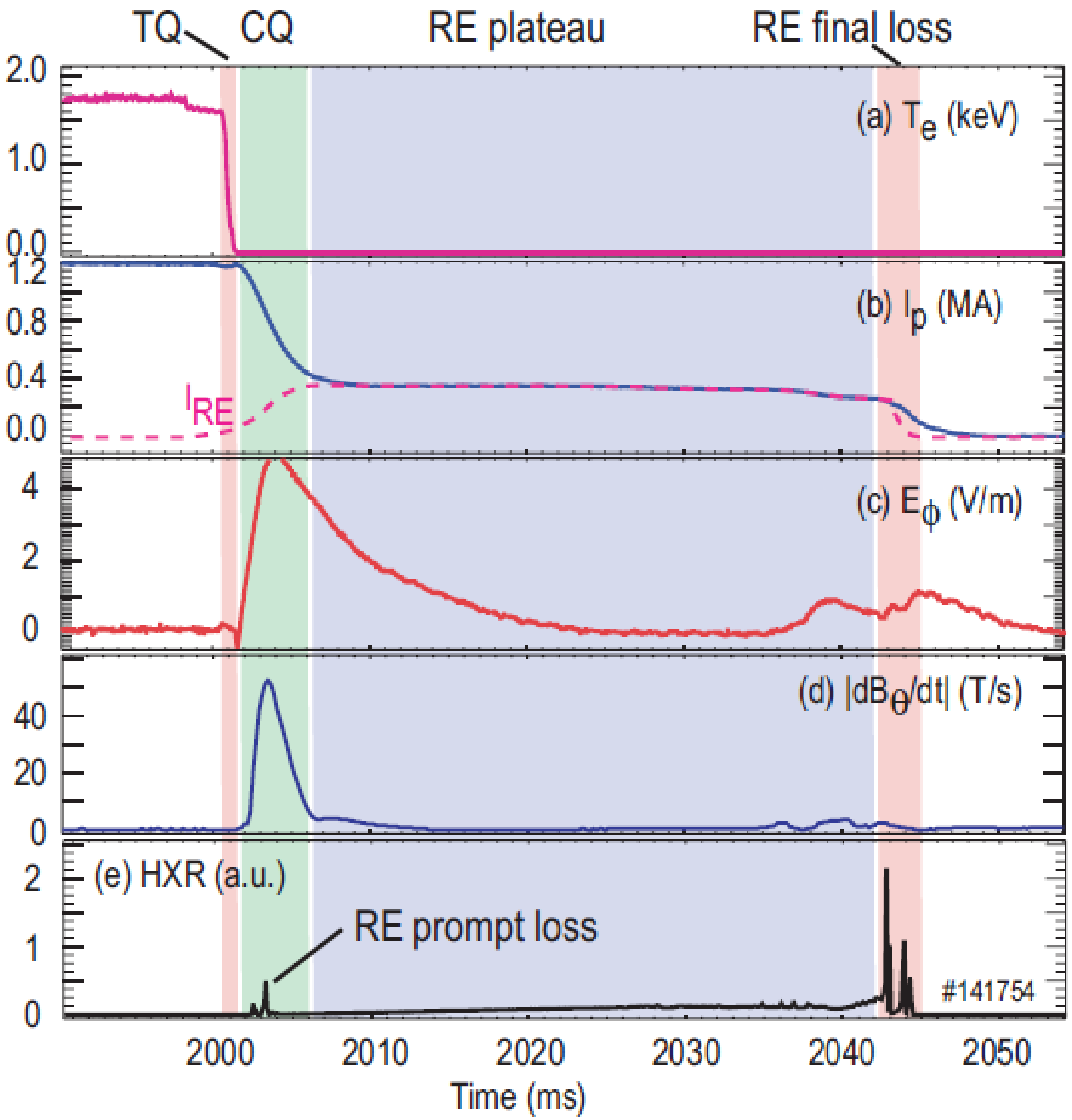
Backward view



Forward view



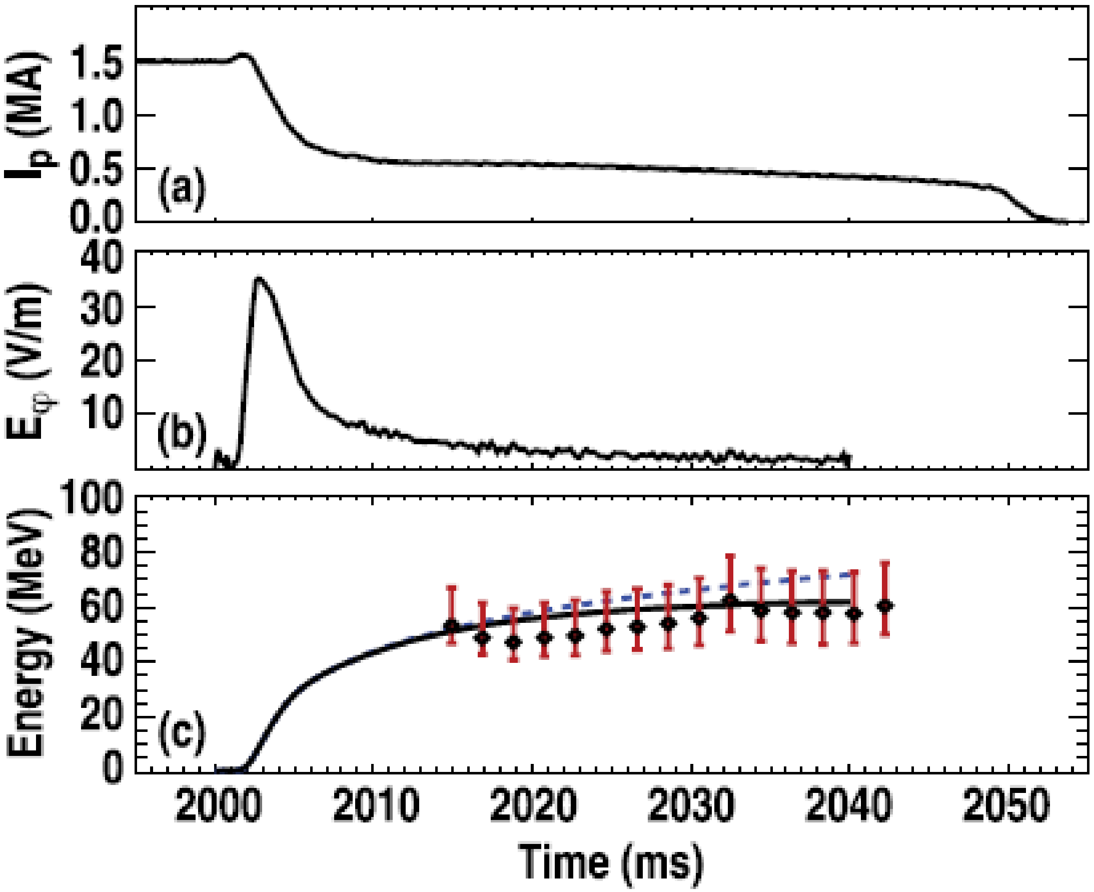
Tokamak disruptions (1)



Hollmann EM et al 2013 Nucl. Fusion **53** 083004

- Thermal quench due to magnetic reconnection
- Current quench due to increased resistivity
- Large electric field drives runaway electrons
- The current plateau after CQ is entirely carried by runaway electrons

Tokamak disruptions (2)



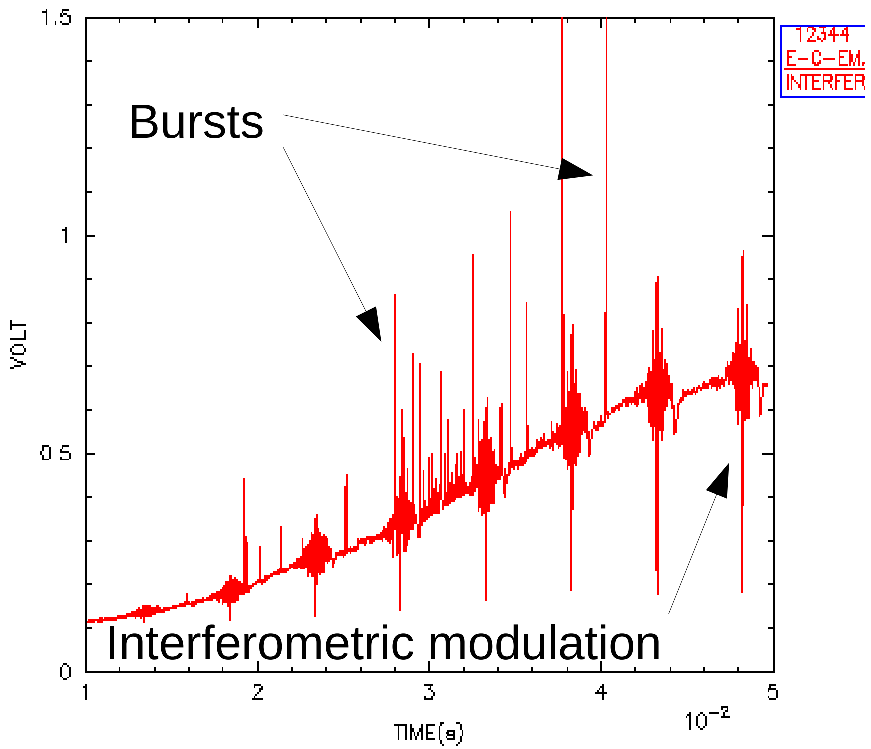
Yu JH et al 2013 Phys Plasmas **20** 042113

- Current quench and plateau as before
- Enhanced electric field
- Top energy of runaways as obtained from synchrotron emission
- Runaway energy is limited by synchrotron radiation itself.

Up to 25% of the initial magnetic energy can be transferred to relativistic electrons

Forster M et al 2012 Phys Plasmas **19** 052506

Runaways kinetic instabilities



- Synchrotron emission in the millimetric range from FTU
- Baseline radiation and its instrumental modulation increase smoothly
- **Bursts** are observed
- Bursts cannot be due to electron energy increase (for being very rapid)

- Most likely explanation by the anomalous Doppler effect:
- Runaways that are superluminal to some plasma wave can excite the wave and gain perpendicular momentum
- Synchrotron emission increases with perpendicular momentum

Nezlin MV 1976 Sov Phys Usp **19** 946
Freethy SJ et al 2015 Phys Rev Lett **114** 125004
Aleynikov P et al 2015 Nucl Fusion **55** 043014

Summary

- Linear machines have shown particle energies well above applied voltages
- The main cause has been identified as the sausage instability

- Magnetic reconnection can accelerate particles and reconfigure magnetic field topology

- Tokamak disruptions can produce relativistic runaway electrons
- Kinetic runaway instabilities can suddenly enhance synchrotron emission at constant energy