Fusion Reactor Technology 2
(459.761, 3 Credits)

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Non-linear Plasma Activity

- **MARFE (Multi-faceted Asymmetric Radiation From the Edge)**

MARFE: AN EDGE PLASMA PHENOMENON

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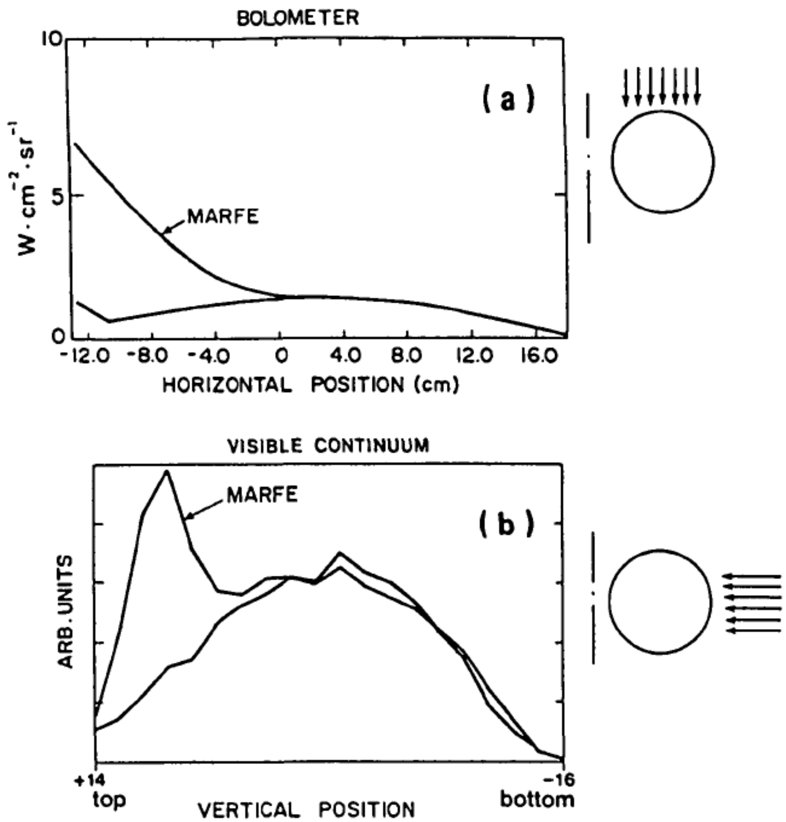
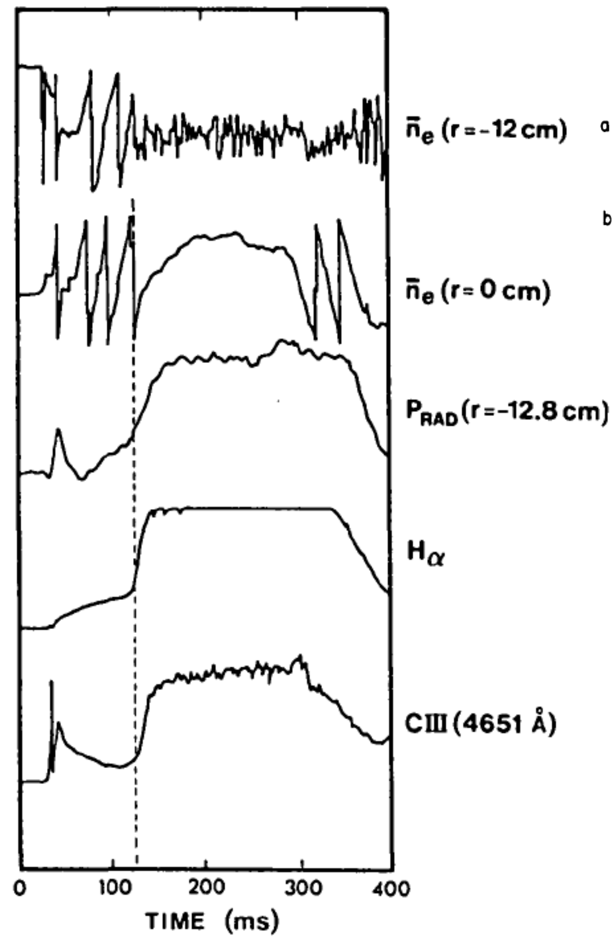
ABSTRACT. A tokamak edge phenomenon, dubbed the 'marfe' (for multifaceted asymmetric radiation from the edge), is described. This phenomenon, observed in medium- to high-density Alcator C discharges, is characterized by greatly increased radiation, density and density fluctuations, and decreased temperature in a relatively small volume at the inner major radius edge of the plasma. The marfe appears to be confined to minor radii greater than or of the order of that of the limiter. The affected region is typically above the midplane, extending poloidally for about 30° and toroidally for 360°. The temperature and density of the core plasma are unaffected by the marfe. A simple transport model is used to show that the marfe is the manifestation of a thermal instability, with impurity radiation being the main energy loss mechanism out of the marfe volume. A density threshold n_m for marfe onset is observed; n_m is found to be an increasing function of plasma current and a decreasing function of intrinsic low-Z impurity levels. Detailed observations from spectroscopy, bolometry, Langmuir probe measurements, interferometry and CO_2 scattering are presented.

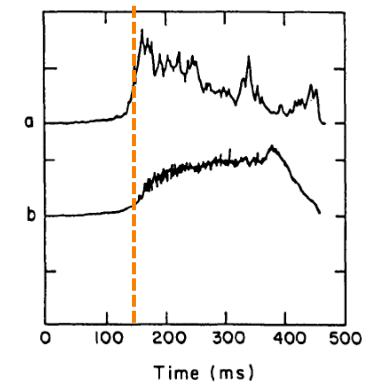
*B. Lipschultz et al, NF **24** 977 (1984)*

Non-linear Plasma Activity

- **MARFE (Multi-faceted Asymmetric Radiation From the Edge)**







high-frequency edge density fluctuations

*B. Lipschultz et al, NF **24** 977 (1984)*

Non-linear Plasma Activity

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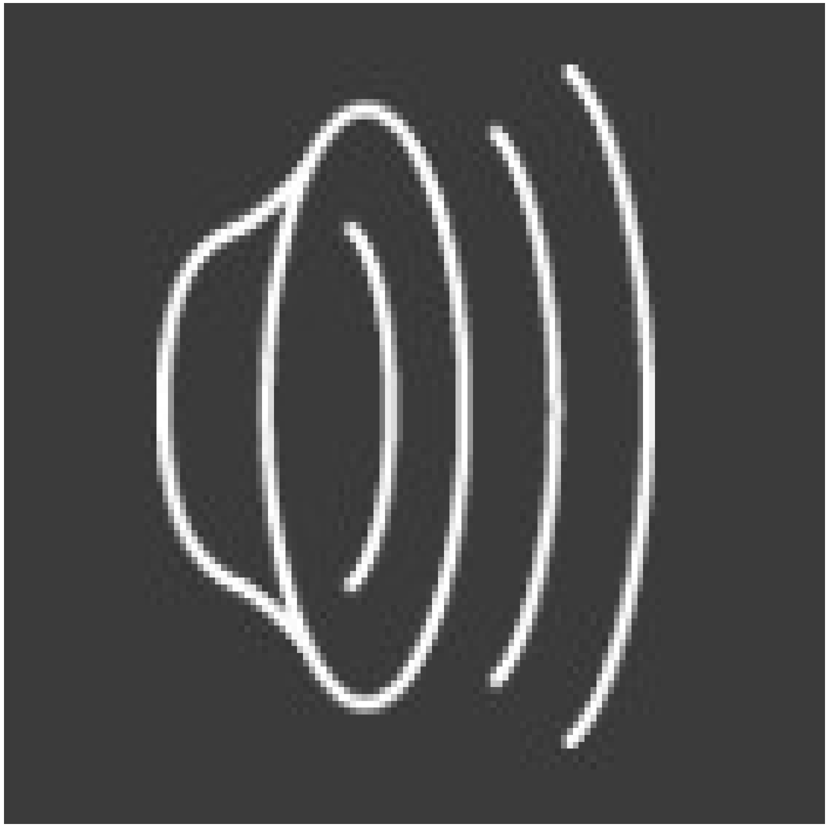

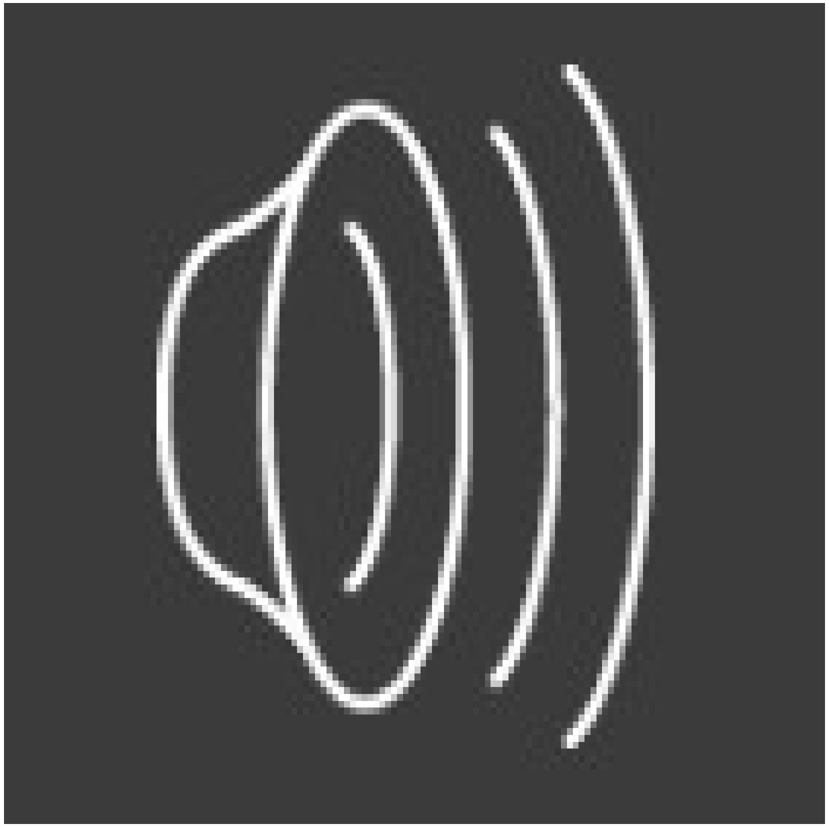

Shots selected by Dr. Y. M. Jeon (NFRI)

Non-linear Plasma Activity

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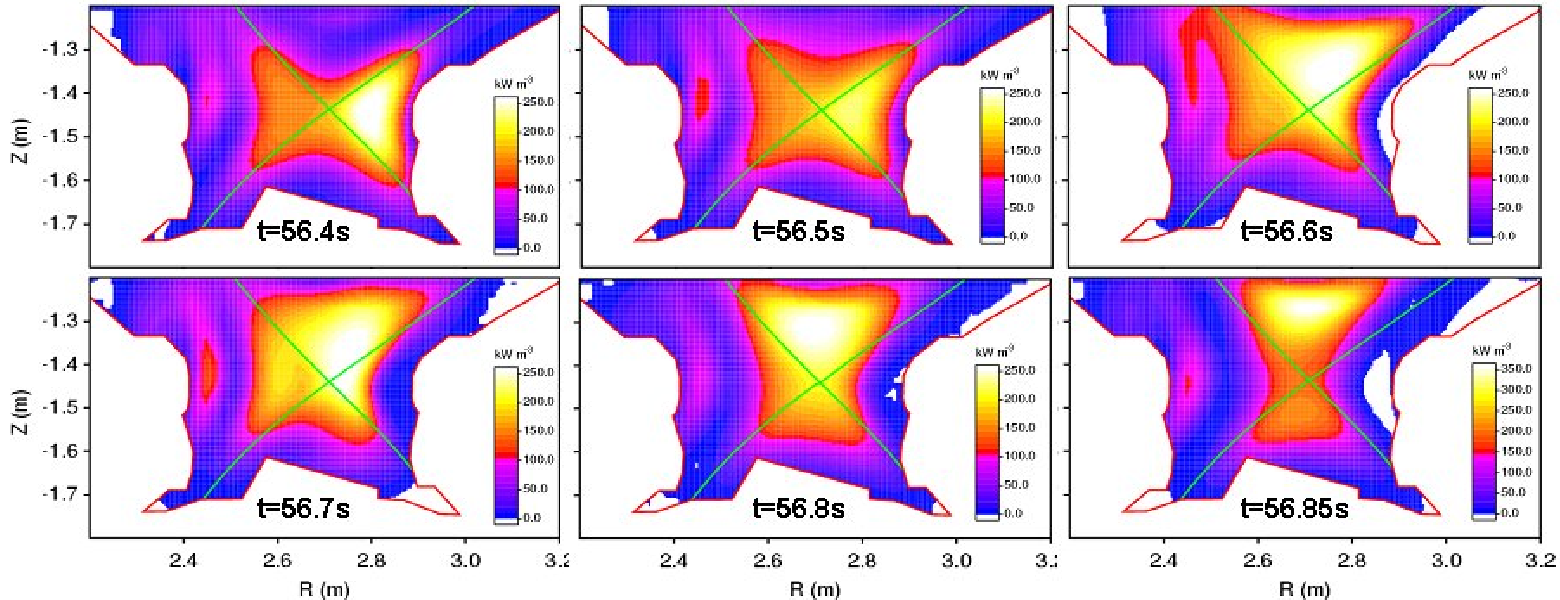
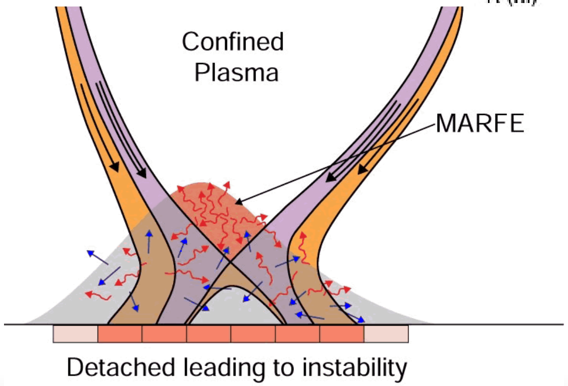
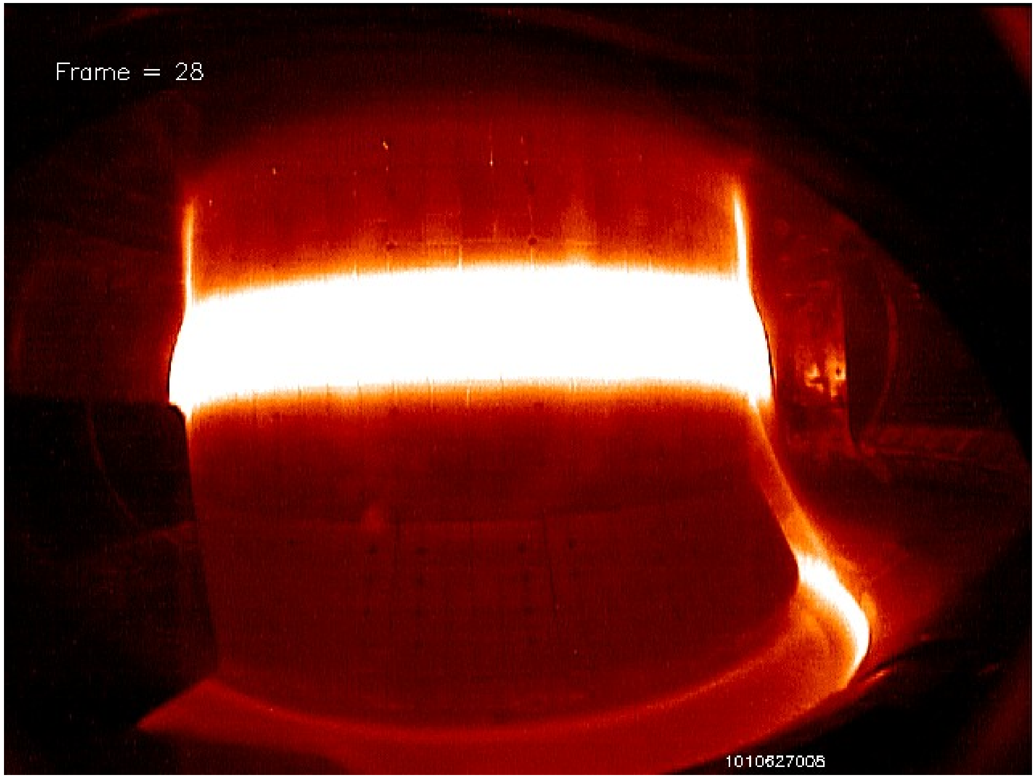




Non-linear Plasma Activity

- **MARFE (Multi-faceted Asymmetric Radiation From the Edge)**



HW. Why showing a belt shape rather than following B field lines?

M. Greenwald, "Density Limits in Toroidal Plasmas", APS (2001)

Non-linear Plasma Activity

- **MARFE**

- First observed in medium- to high-density in ALCATOR-C discharges

  J. L. Terry et al, Bull. Am. Phys. Soc. ***26*** *886 (1981)*

- Characterised by a toroidal ring of a dense moderately cold plasma,

  located at the periphery of a plasma column on its inner contour

- Edge impurity radiation is both in/out and up/down asymmetric,

  before and during a MARFE.

- Relatively small MARFE region emits a large fraction of the total

  radiated power.

- Easily observed due to its intense light radiation:

  High plasma density: ion density increased by a factor of up to ten

  comparable with the central

  density of the main plasma

  Low temperature: temperature dropped by 50% or so

  several eVs

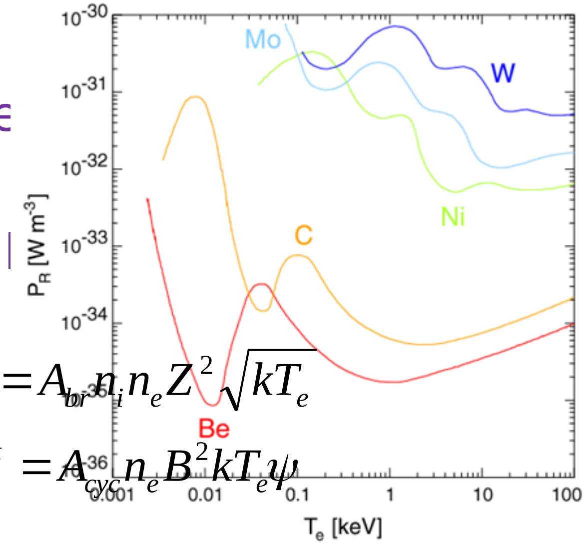
Non-linear Plasma Activity

- **MARFE**

- Thermal-radiation instability observed in the
  at high densities near the density limit:
  Temperature decreases (due to radiation of I
  → radiation increases

$$P_{line} = n_{19}\bar{n}_{19}^{*} A/\hat{T}_e^{\alpha} \quad (\alpha > 0)$$

↑ density of radiating elements

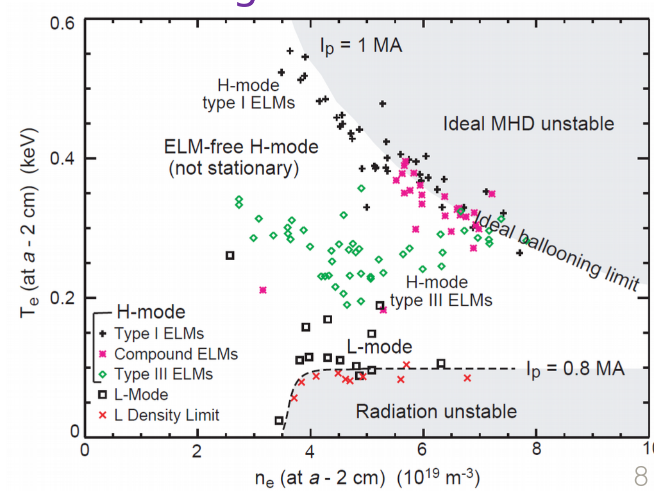


$$P_{br} = A_{br} n_i n_e Z^2 \sqrt{kT_e}$$

$$P_{cyc}^{net} = A_{cyc} n_e B^2 kT_e \psi$$

The emissivity of most of the important impurities (mainly carbon from the wall materials) reach maxima at temperature in the range of 10 – 200 eV.

→ temperature continuously decreases
→ plasma pressure along the magnetic field increases plasma density
→ radiation further enhanced
→ a region of cold plasma (MARFE) formed
→ (sometimes) L-mode disruption



Non-linear Plasma Activity

- **MARFE**

- Edge plasma ‘compresses’ MARFE cold plasma (plasma flows into the MARFE, increasing the density) along magnetic field lines to maintain pressure balance and feeds the energy for the subsequent re-radiation: radiative condensation
- MARFE forms on closed flux surfaces inside the main plasma on a poloidal location where the temperature has a minimum: in a cylindrical limiter tokamak at the high-field side near the inner wall and in a divertor tokamak near the X-point.
- Outcome: not always the loss of H-mode confinement

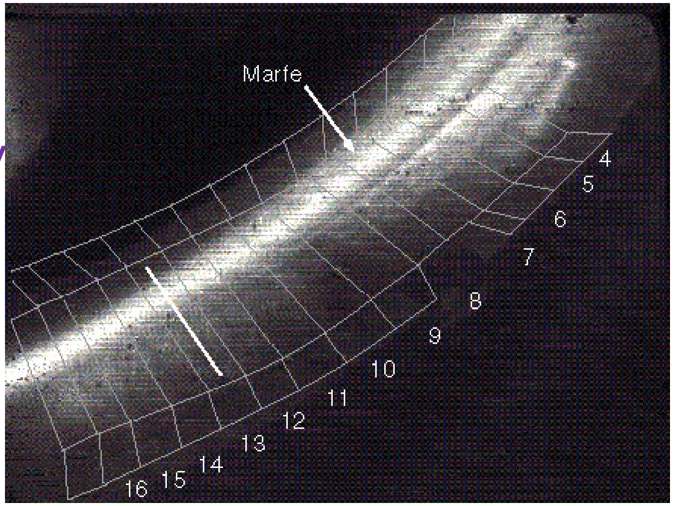
Non-linear Plasma Activity

- **MARFE: measurements**

- Discovered by the observation of an increased localised impurity emission from the MARFE edge by bolometry and visible spectroscopy
- Also detected by the bremsstrahlung from the high-density core of the MARFE in ASDEX Upgrade.

The temperature in the MAFRE centre can drop below 1 eV so that the plasma recombines by three-body recombination ($e+e+D^{+} \rightarrow D_{0}+e$).

The three-body recombination in MARFE was detected by the characteristic Balmer spectrum near the series limit.



*U. Wenzel et al, Plasma Phys. Control. Fusion **44** L57 (2002)*

Non-linear Plasma Activity

- **Snakes**

VOLUME 59, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1987

Persistent Density Perturbations at Rational-q Surfaces Following Pellet Injection in the Joint European Torus

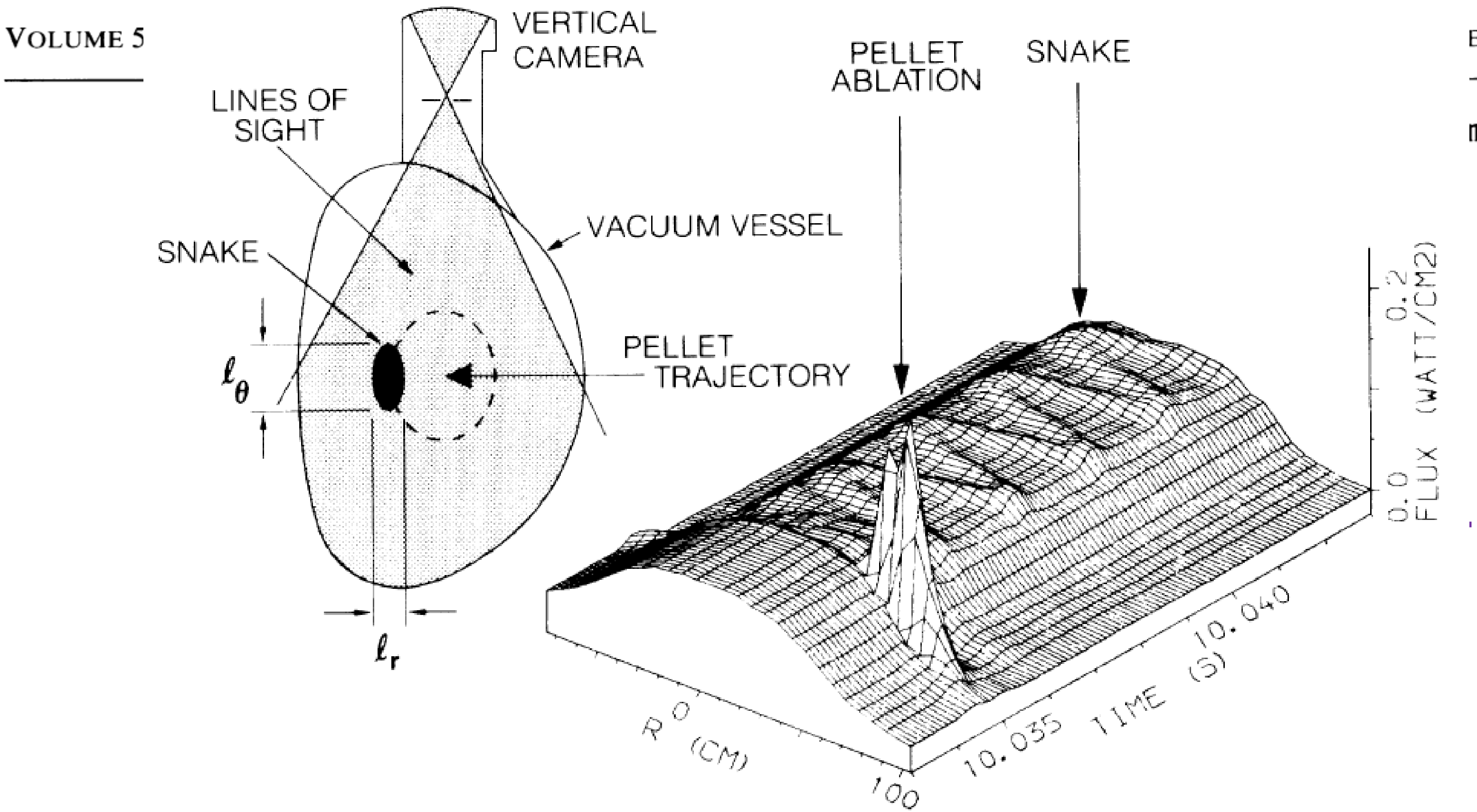
A. Weller,[a] A. D. Cheetham, A. W. Edwards, R. D. Gill, A. Gondhalekar, R. S. Granetz,[b] J. Snipes, and J. A. Wesson
JET Joint Undertaking, Abingdon, Oxon OX14 3EA, United Kingdom
(Received 9 February 1987)

In the Joint European Torus the ablation of injected pellets produces a striking resonance effect when the pellets reach surfaces with q values 1 and $\frac{3}{2}$. Subsequently, structures with mode numbers $m=1, n=1$ and $m=3, n=2$ are observed with the soft-x-ray cameras for up to 2 s as compact snakelike perturbations. These structures, which persist through several sawtooth collapses, give information on the radii of the $q=1$ and $q=\frac{3}{2}$ surfaces and the q-profile evolution. The observations can be explained by the formation of magnetic islands.

PACS numbers: 52.55.Fa, 52.30.−q

Non-linear Plasma Activity

- **Snakes**



Contour plot showing the snake-like perturbation of soft X-ray emission (by vertical cameras) following the injection of a deuterium pellet

Non-linear Plasma Activity

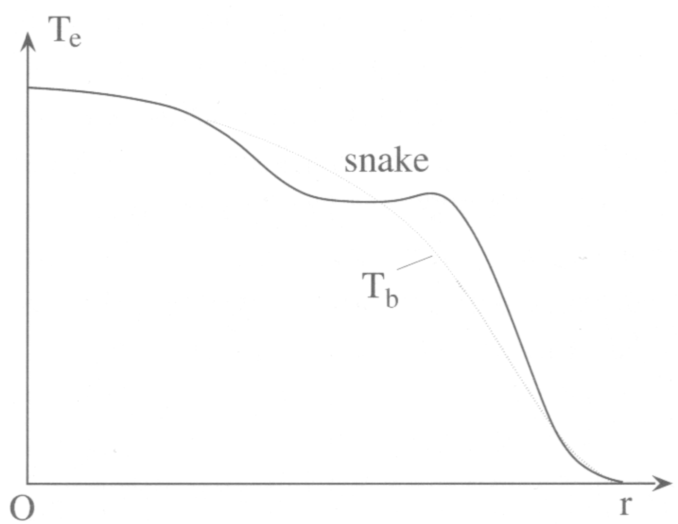
- **Snakes**

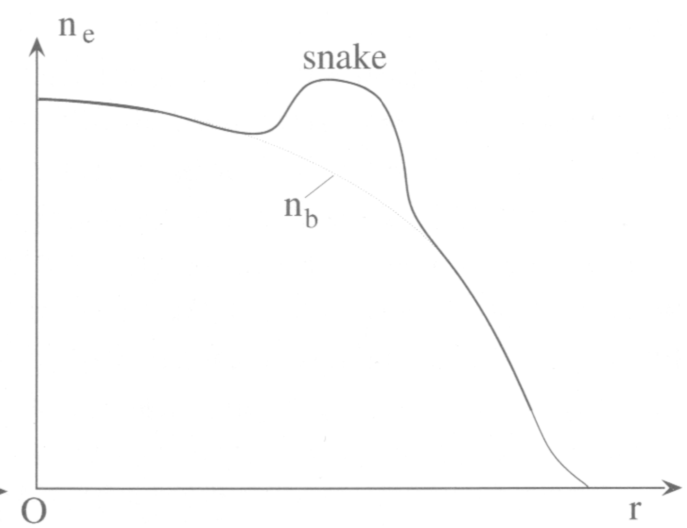
- First observed in JET: a rope-like filament observed in the soft-X-ray emission following the injection of a D_2 pellet
- A relatively cool, high density structure with typical poloidal and radial dimensions of $l_\theta \sim 25$ cm and $l_r \sim 17$ cm that forms on the $q = 1$ surface and which rotates about the minor axis
- While $q = 1$ is the preferred value, similar structures can occur on the $q = 3/2$ surface.
- Surviving for ~ 2 s regardless of frequent disturbances from sawtooth oscillations
- Pellet penetration needs to be inside the $q = 1$ surface to form the snakes.

Non-linear Plasma Activity

- **Snakes**

- Density and temperature of a typical snake:
  Δn = 3x10^{19} m^{-3}, n_b = 6x10^{19} m^{-3}, ΔT_e = -140 eV, T_b = 1200 eV
  (b : background values)
  total number of particles in the snake ~ 1% of the pellet particles
- Following an initial large drop attributed to the energy required to ionize the pellet atoms, T_e within the snake quickly rises to within 10% or so of the ambient plasma temperature.





Non-linear Plasma Activity

- **Snakes**

- Cool deuterium atoms supplied are swept outwards by the radial plasma motion until reaching a cool channel, C of the $q = 1$ surface (bottom of the sawtooth oscillation), where if the collapse phase of the sawtooth oscillation has just occurred or a tearing mode occurs.
- Ionization of the deuterium atoms as they cross C absorbs considerable energy and results in the large temperature drop. Equilibrium will require a nearly constant pressure and therefore initially, when C is relatively cool, it will become appreciable denser than its surroundings.
- Further progress to a fully developed snake depends on the transport of more particles into C and the maintenance of a temperature depression.

HW. What is the impurity snake?

Non-linear Plasma Activity

- **Snakes**

- Snake at the q = 2 surface near the location of the ITB foot can cause the colla the ITB for a moderately peaked ion pressure profile.

A Becoulet et al, Nucl. Fusion 40 1113 (2000)

Non-linear Plasma Activity

- **Snakes**

with sawtooth oscillations of the q 1 region and understanding them is potentially important for a burning plasma like the International Thermonuclear Experimental Reactor where the q ¼ 1 radius can be as large as half the minor radius. The standard model [3] to describe the snake formation is based on the physics of tearing modes and suggests that the localized cooling of the q ¼ 1 surface is responsible for an increase of the local plasma resistivity, which in turn causes a drop in the current density that leads to the formation of a magnetic island with poloidal and toroidal harmonics m ¼ 1, n ¼ 1. This island is assumed to trap the excess ions from the pellet and form the snake. Snakes have been a common feature in every major tokamak fusion experiment as well as in spherical tori and reversed field pinches. A second type, produced by an accumulation of impurity ions rather than the deuterium ions from injected fueling pellets, is also observed. Impurity snakes probably appeared first in ‘‘type O’’ discharges in Doublet-III [4] and laser-blow-off experiments in the Princeton Large Torus [5]; later examples include the Joint European Torus [2] and the Axially Symmetric Divertor Experiment [6]. Both types of snakes possess surprisingly good MHD stability and particle confinement, since they can survive tens to hundreds of sawtooth cycles.

PRL_110_13_065006-Delga

Non-linear Plasma Activity

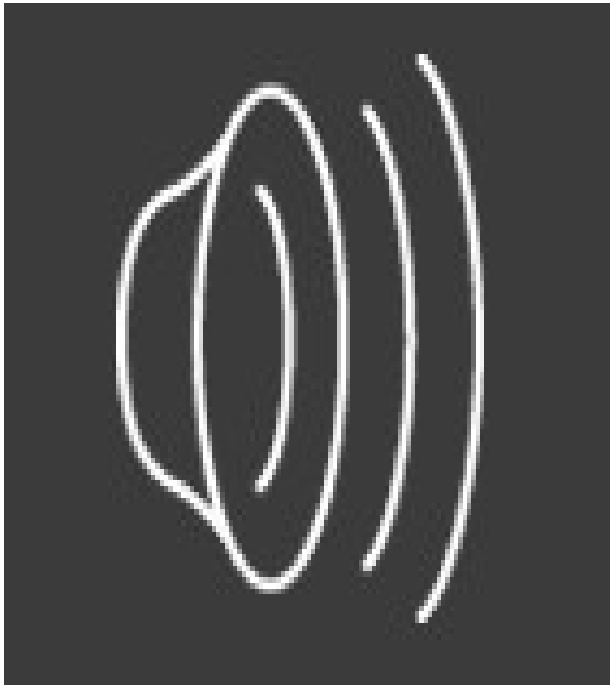
- **Snakes: application to diagnostics**

- Acting as a sort of probe for studying of the position of the q = 1 surface during a sawtooth cycle
- Angular velocity of the snake about the minor axis providing a diagnostic of ion temperature, radial electric field (E_r)

$$E_r = v_\phi B_\theta - v_\theta B_\phi + p_i' / e n_e$$

Non-linear Plasma Activity

- **Disruptions**



Non-linear Plasma Activity

- **Disruptions**

- Disruptions are fast (~1 ms) global instabilities that may arise in magnetic confinement fusion devices that use plasma current for confinement such as tokamak, ST, etc.

- Termination of confinement, uncontrolled loss of thermal and magnetic energy

  - shift of the plasma column

  - heat load damage to plasma facing components (PFCs)

  - large mechanical stresses from **J**x**B** forces during current quench (large negative voltage spike in the transformer)   - rapid cooling of the plasma

  - Highly efficient conversion of poloidal magnetic energy into "runaway" electrons through avalanche amplification,

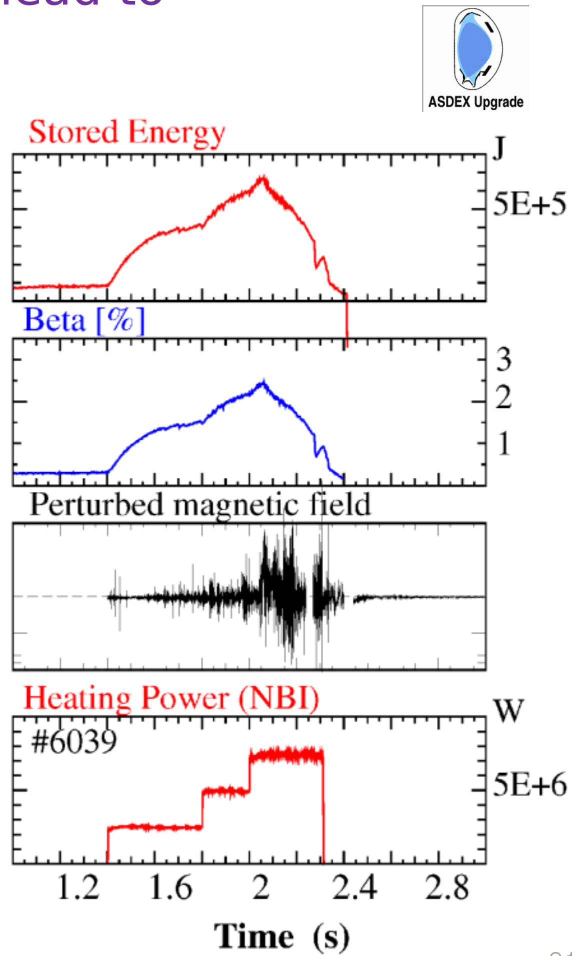
    resulting in a > 5 MA of relativistic electron beam

Non-linear Plasma Activity

- **Disruptions**

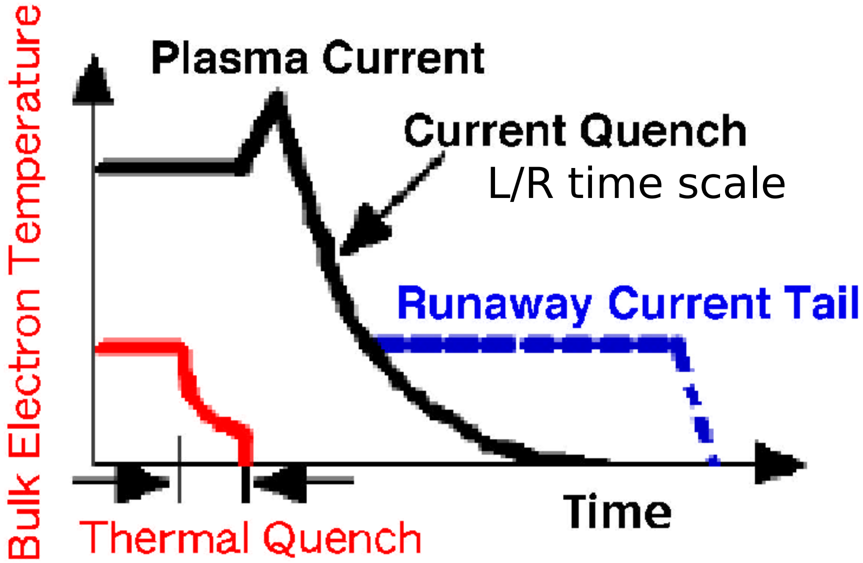
- Several classes of "triggering" instabilities lead to this "final" ideal instability
  - Beta / pressure limits
  - Radiative limits
  - Vertical position instability (Vertical Displacement Event (VDE))

- Disruptions in KSTAR
  - VDE (#2265)
  - low-*q* (#2271-3)
  - density limit (#2277, #5321)



Non-linear Plasma Activity

- **Disruptions**



- Thermal quench:
  Rapid loss of plasma thermal energy, global MHD activity

- Current quench:
  Resistive current decays due to lowered plasma temperature, loss of confining poloidal field

Why positive spike on the plasma current immediately after the thermal quench?

Thermal quench → current profile flattened → l_i reduced
→ total plasma inductance reduced → I_p increase for flux conservation

Non-linear Plasma Activity

- **Disruptions**

- By necessity, burning plasmas for fusion energy production will have high thermal and magnetic energy densities, making the problem of disruption damage much more severe than on present confinement experiments.
- End-of-lifetime damage will occur to internal components of burning plasma devices as a result of the uncontrolled loss of thermal and magnetic energy associated with disruptions.

1. Heat load damage to plasma-facing surfaces.
2. Large mechanical stresses from **J**x**B** forces during current quench.
3. Highly efficient conversion of poloidal magnetic energy into "runaway" electrons (E_{Φ} induced to sustain poloidal magentic flux) through avalanche amplification if $E_{\Phi} > E_{Dreiser}$ (Rosenbluth et al.), resulting in a > 5 MA of relativistic electron beam.

- As a consequence, disruptions drive up cost and decrease flexibility for design choices of next-step burning plasma experiments.

Non-linear Plasma Activity

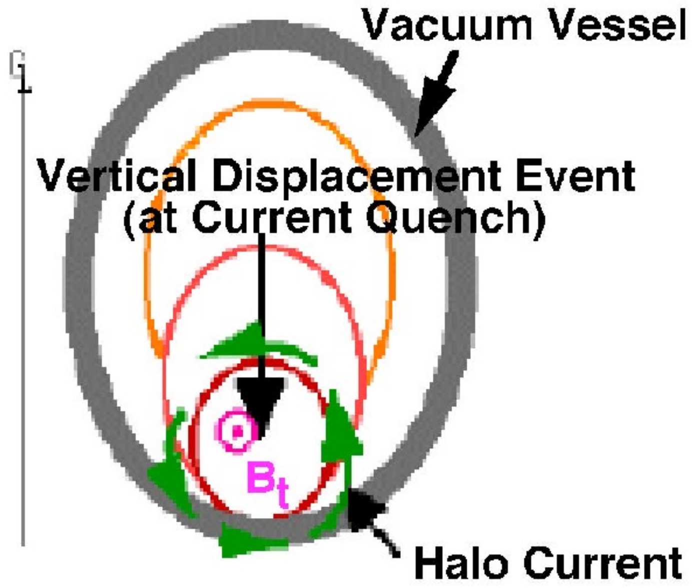
- **Disruptions**

- Halo current:

Induced to sustain magnetic flux

Can reach ~50% of plasma current before disruption

EM force induced by Halo Current x $\mathbf{B_t}$



Non-linear Plasma Activity

- **Disruptions**

- Divertor target thermal loading illustrates the severity of disruption damage for burning plasma devices.
- Extrapolate damage threshold in poloidal divertor tokamak:
  - Stored thermal energy W_{th} ($\sim 3nkTV$) is “lost” in MHD/conduction time scale t_{TQ}
  - Divertor impulse heating onto divertor wetted area, $A_{divertor}$

    W_{th} / $A_{divertor}$ / $t_{TQ}^{1/2} \rightarrow \Delta T_{divertor\ plates}$

Ex) Expected heat loads in thermal quench time ~0.5 ms:

Device	W_{th} (MJ)	$A_{divertor}$ (m^2)	ΔT figure of merit ($MJm^{-2}s^{-1/2}$)
DIII-D	~ 1	2	~25
ITER	~ 300	25	~550

- Ablation limit of carbon / melt limit of tungsten: ~50 $MJm^{-2}s^{-1/2}$
- The power densities associated with a burning plasma disruption will easily surpass damage threshold for any divertor design.

Non-linear Plasma Activity

- **Disruptions**

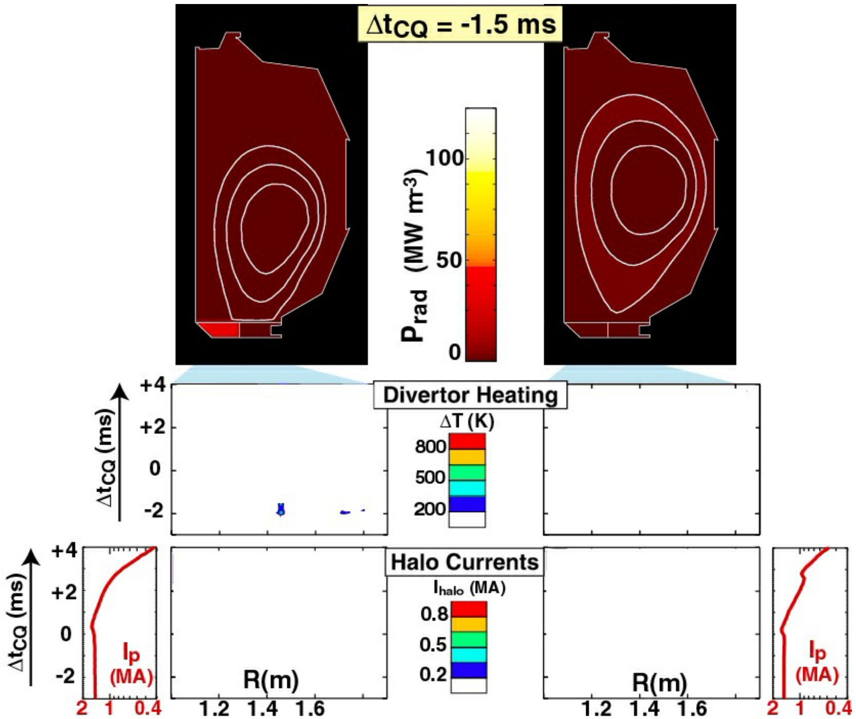
- Burning plasma experiments must develop a thorough strategy to deal with disruptions.

1. Plasma operations:
   Obtain needed performance away from known stability limits (e.g. keep plasma current and *n* within stable limits, close fitting conducting wall)
2. Disruption avoidance:
   Control of plasma pressure / current profiles (e.g. (2,1) NTM suppression)
3. Disruption detection:
   Reliably determine onset of triggering instability in real-time (e.g. neural network)
4. Disruption mitigation:
   Provide a rapid and safe emergency shutdown technique in order to alleviate damage to costly internal components

Non-linear Plasma Activity

- **Disruption Mitigation**
  - Killer pellet injection: fast conversion of thermal energy to the radiation energy. Ex) SPI (Shattered Pellet Injection) in ITER
  - MGI (Massive Gas Injection): H, He, Ne, Ar, Kr, Xe, etc.
  - RMP to reduce runaway electrons

Non-mitigated VDE



Neon gas jet injection triggered by control system

Non-linear Plasma Activity

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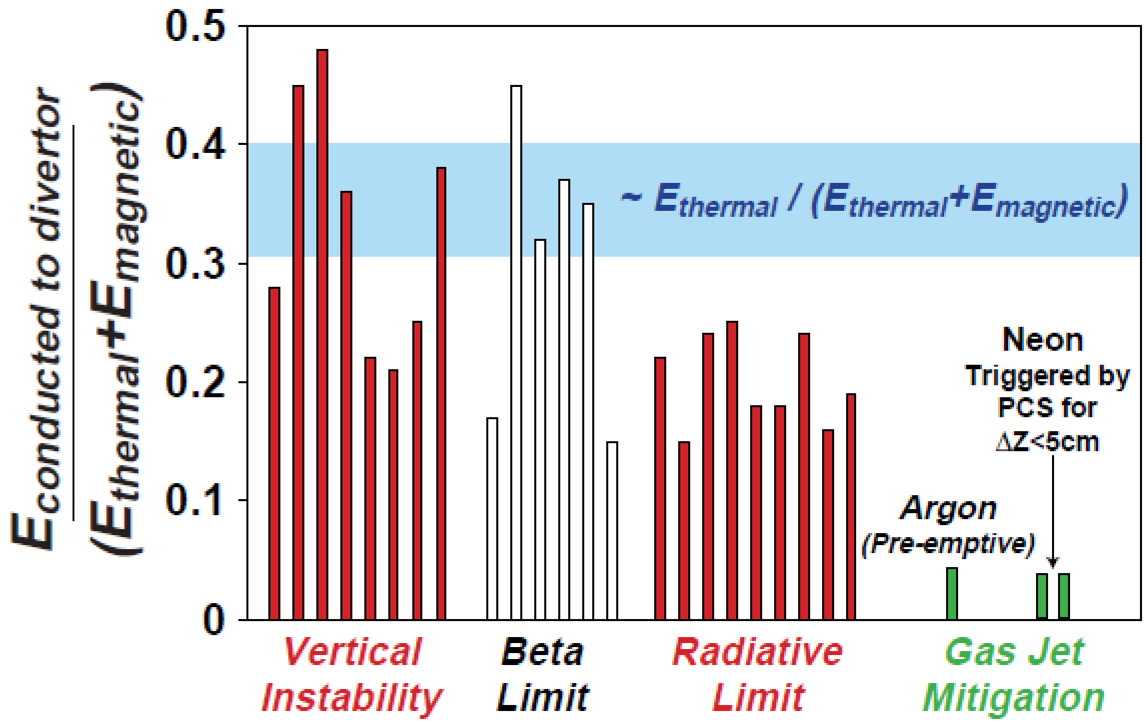
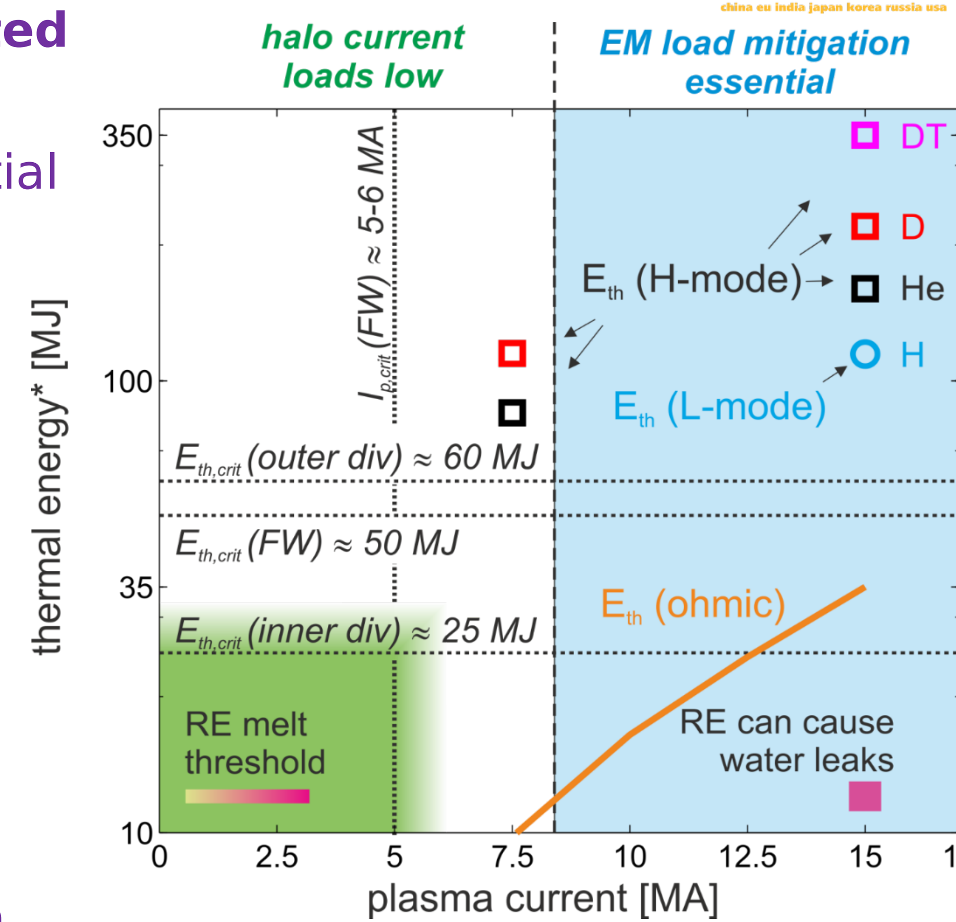


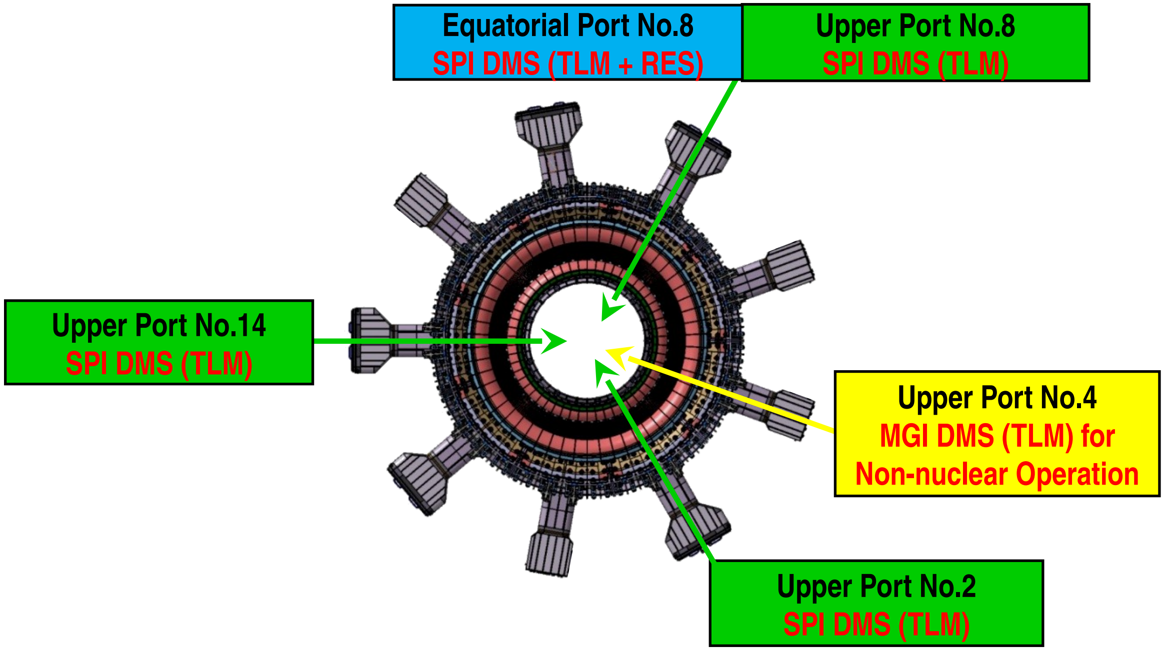
Non-linear Plasma Activity

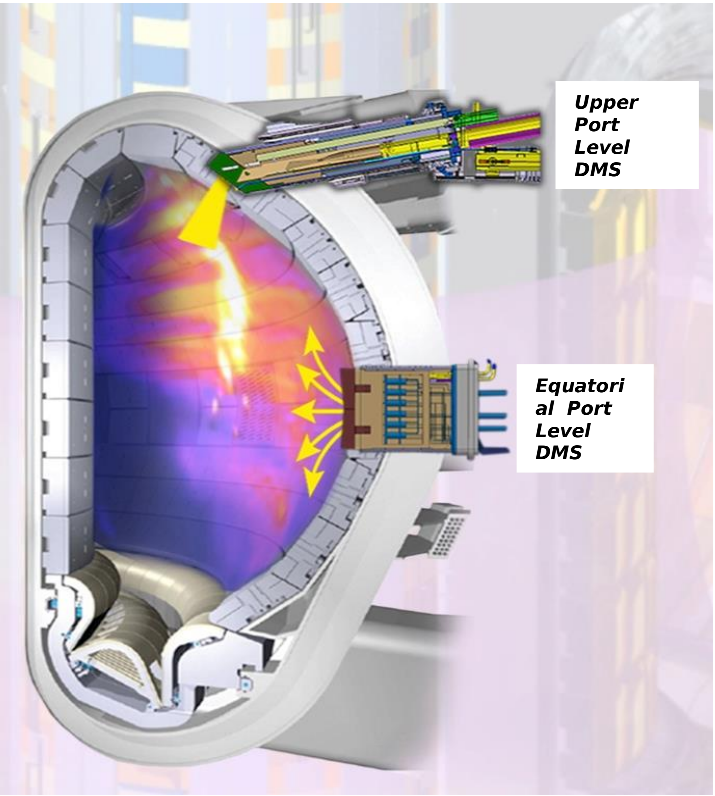
- **Quantitative analysis of thermal and EM loads for unmitigated disruptions in ITER:**
  - EM loads imply DMS essential above 8.4 MA
  - Green: operational space where no risk of melting of W-divertor
  - Magenta bars: risks associated with RE loss to FW
  - Orange line: W_{th} for ohmic plasmas
- **Extensive programme of disruption characterization, avoidance and mitigation throughout experimental phases**



SPI considered as primary DM technique in ITER

Disruption Mitigation System





Upper port level:

– Thermal and electromagnetic load mitigation
– Three locations with 120° distribution
– One addition MGI in UPP04 for non-nuclear operation (risk mitigation)

Equatorial port level:

– Thermal and electromagnetic load mitigation and runaway electron suppression

ITER_D_SQNH6Y

Disruption Mitigation System

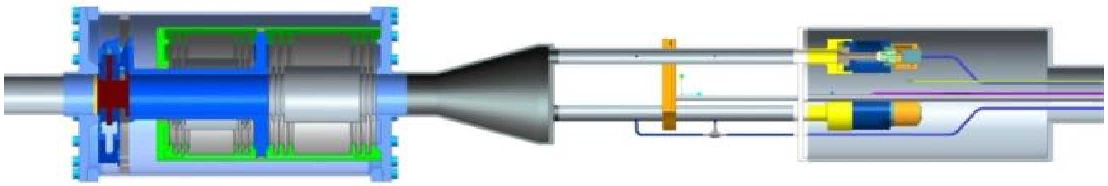
Injectors

Thermal load mitigation:
3 x 3 barrels in UPs, 1 x 3 barrels in EP

Runaway mitigation:
5 x 3 barrels in EP

Back-up:
1 x MGI inside port-plug

Pre-pulse configuration:
Shattered Pellet Injection / Massive Gas Injection
Ne, Ar and mixtures with D_2

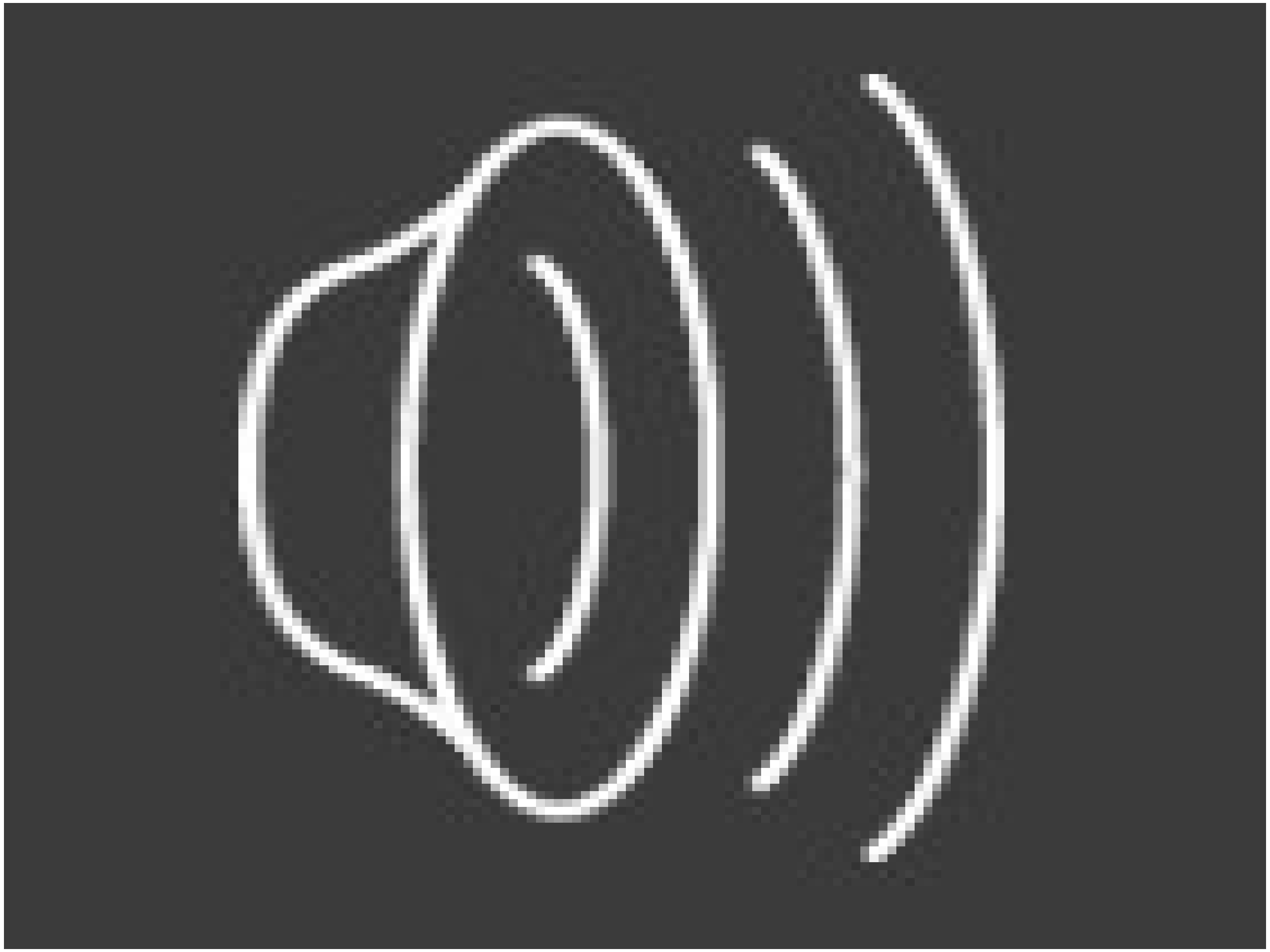


Timescales

Injector type/location	Delay [ms]	Injection efficiency [%]
MGI / Upper port cell	10 - 15	10
MGI / Upper port plug	2 - 3	20 – 40
SPI / Upper port cell	16 - 45	~100
SPI / Equatorial port cell	9 - 25	~100

ITER_D_SQNH6Y

Disruption



References

- *D. G. Whyte, "The Consequences of Disruptions for Burning Plasma Experiments", Plasma Physics Colloquium, Columbia University, 17 October 2003*