High pedestal temperature experiments in JET and confined current filaments

Presented by

Emilia R. Solano

O2.020 30th EPS Meeting,

Sofia, Bulgaria

30/06/2009

High pedestal temperature experiments in JET and confined current filaments

E.R. Solano[1], P.J. Lomas[2], B. Alper[2], G. Xu[3], Y. Andrew[2], G. Arnoux[2], A. Boboc[2], L. Barrera[1], P. Belo[4], M.N.A. Beurskens[2], M. Brix[2], K. Crombe[5], E. de la Luna[1], S. Devaux[6], T. Eich[6], S. Gerasimov[2], C. Giroud[2], D. Harting[7], D. Howell[2], A. Huber[7], G. Kocsis[8], A. Korotkov[2], A. Lopez-Fraguas[1], M. F. F. Nave[4], C. Pérez Von Thun[6], E. Rachlew[9], F. Rimini[10], S. Saarelma[2], A. Sirinelli[2], L. Zabeo[2], D. Zarzoso[11] and JET EFDA contributors†.

JET-EFDA, Culham Science Centre, Abingdon, OX14 3DB, UK

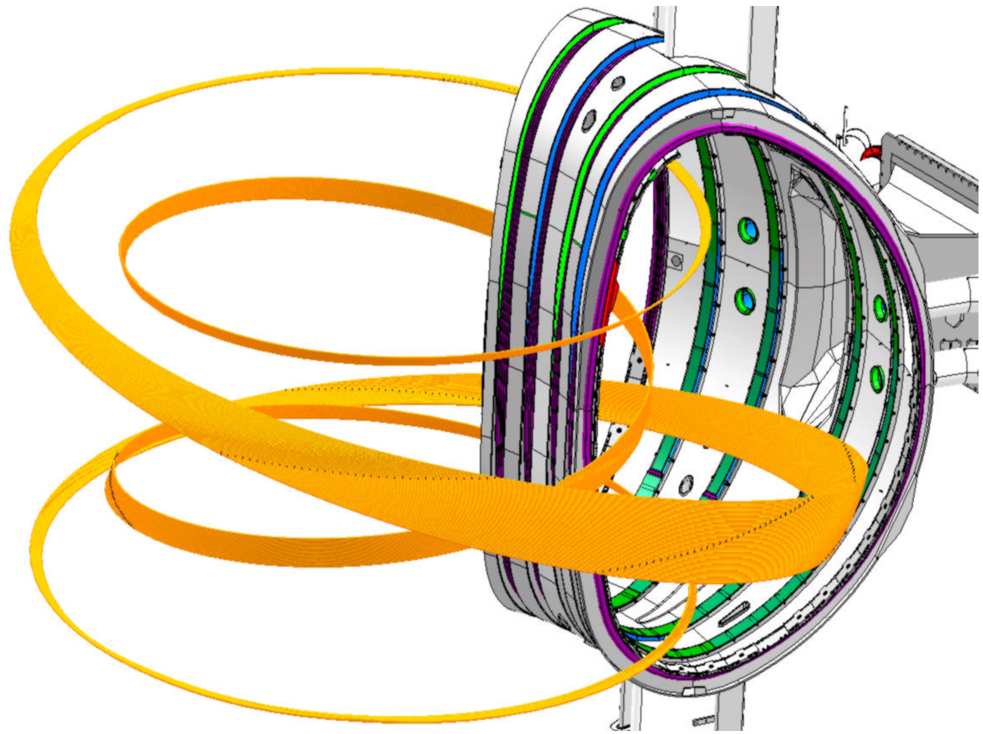
[1] Laboratorio Nacional de Fusión, Asociación EURATOM-CIEMAT, 28040, Madrid, Spain
[2] Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK
[3] Inst. of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, China
[4] Associação EURATOM/IST, Inst. de Plasmas e Fusão Nuclear, Av Rovisco Pais, 1049-001, Lisbon, Portugal
[5] Department of Applied Physics, Ghent University, Rozier 44, 9000 Gent, Belgium
[6] Max-Planck-Institut für Plasmaphysik, EURATOM-Assoziation, D-85748 Garching, Germany
[7] Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, EURATOM-Assoziation, TEC, D-52425 Jülich, Germany
[8] KFKI, Association EURATOM, P.O.Box 49, H-1525, Budapest, Hungary
[9] Association EURATOM-VR, Department of Physics, SCI, KTH, SE-10691 Stockholm, Sweden
[10] EFDA Close Support Unit, Culham Science Centre, Culham, OX14 3DB, UK
[11] Ecole Polytechnique, F-91128, Palaiseau Cedex, France

† See Appendix of F. Romanelli et al., Fusion Energy Conference 2008 (Proc. 22nd Int. FEC Geneva, 2008) IAEA, (2008)

Related presentations: P5.182, P5.171, P5.165

Outline

- Introduction: why study hotter plasmas?
- How to obtain them in a tokamak? Hot Ion H-mode
- Typical plasma behaviour and the Outer Mode
- Experimental evidence for Outer Mode as confined current filament
  - magnetics
  - fluctuations
- Consequences to energy outflux
- Theoretical considerations
- Summary



Why study hotter plasmas?

High $T_{e,ped}$ plasmas have:

low edge resistivity → high edge current density

Collisionality $\nu^* \sim n_e \frac{B_t}{I_p} \frac{1}{T_e^2}$ Electrical resistivity $\eta_e \sim \frac{1}{T_e^{3/2}}$

Low $T_{e,ped}$

expect ballooning mode (not stabilised by edge current), resistive modes, micro-tearing.

High $T_{e,ped}$

edge current stabilisation of ballooning mode;
expect peeling, kink
tearing, reconnection?

Are they different? Will ITER pedestals be different?

Experiment provided previously unexpected answer:
confined current filaments

How : Hot Ion H-mode

- The hot ion H-mode regime develops at low gas and recycling, with strong NBI heating.
  its is transient, usually terminated MHD
- Electron and Ion temperatures of order 3 keV (ITER-like) can be achieved in Hot Ion H-mode
- Between the L to H transition and the 1st ELM confinement is very good, H_{98}~1.4, rotation is fast, pedestal rises.
- Sometimes, **Outer Modes*** appear before 1st ELM (or in between 1^{st} few ELMs. A long OM can reduce confinement to H_{98}~1.

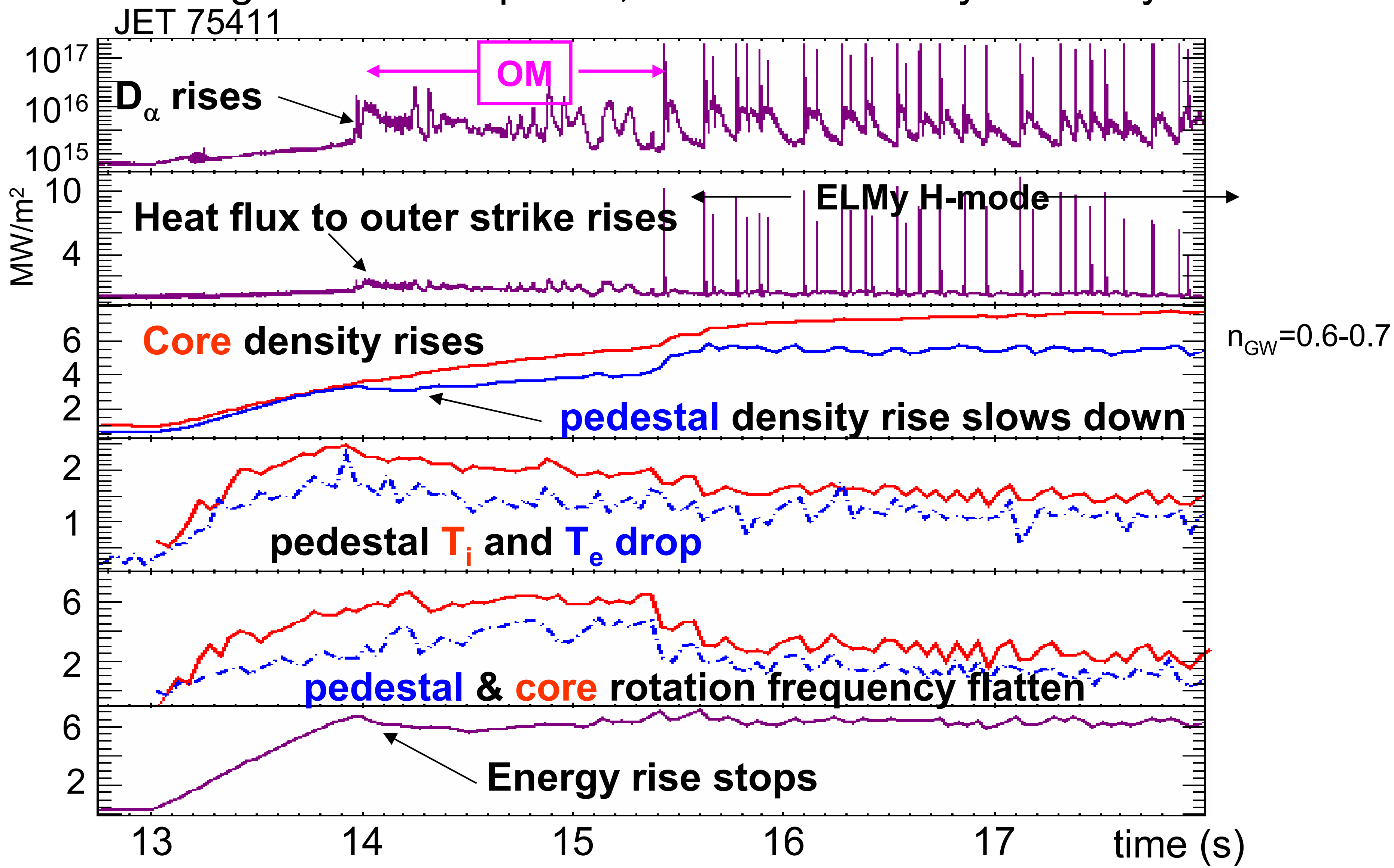
  OM: $T_{e,ped}$ stops rising.
- Searching for the reasons behind the failure to reach higher pedestal T_e, we studied the Outer Mode in more detail.

Most plasmas studied with OM had 2.5 MA, 2.7 T, 15 MW NBI, q_{95}~3.5
$T_{e,ped}$=1.8 keV achieved before OM.
Pulses without OM achieved $T_{e,ped}$= 2.8 keV before 1^{st} ELM.

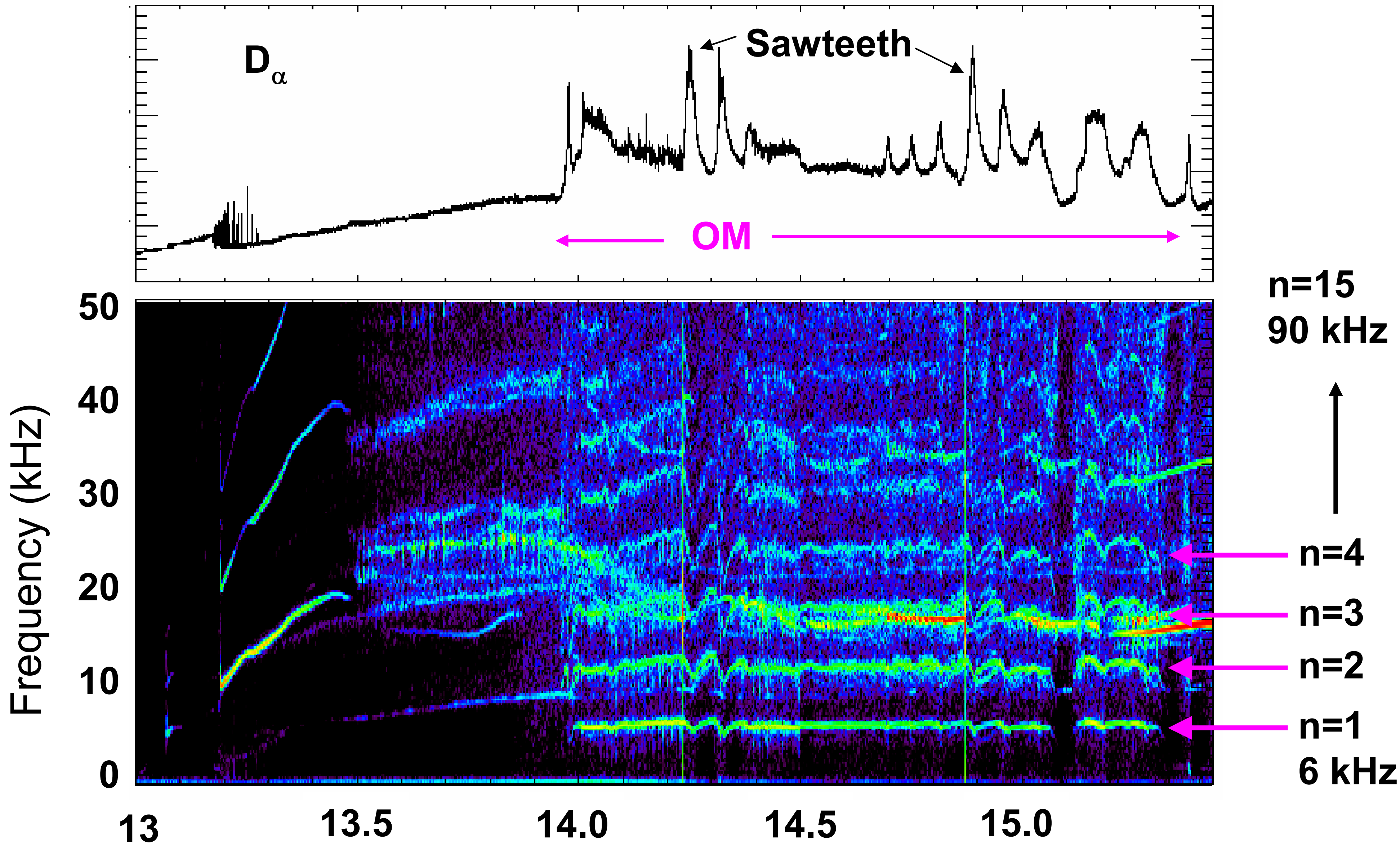
G.T.A. Huysmans et al, Nucl. Fusion 38, 179 (1998)

The Outer Mode: global effects on plasma

- In hot ion regime Outer Mode (MHD mode) reduces confinement
- OM produces longer ELM-free phase, in this case delays ELM by 1 s.

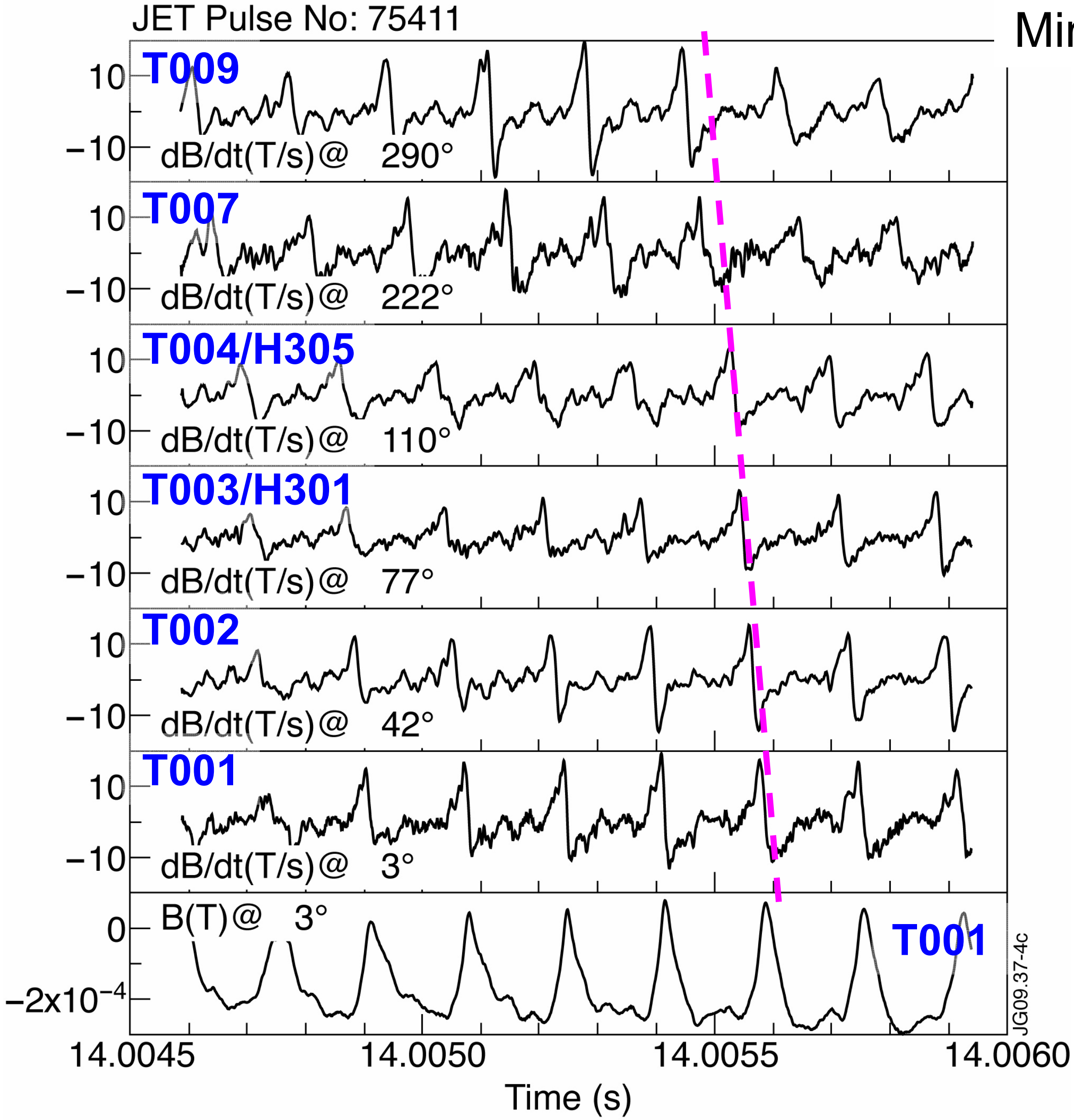


Spectrum of MHD signals: multiple harmonics

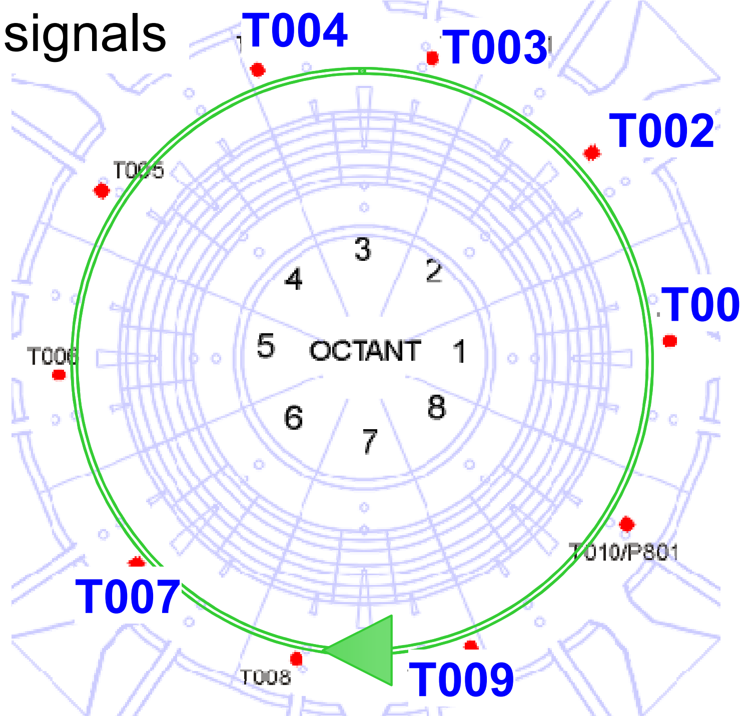


so many harmonics: due to toroidally localised structure ?

Toroidally localised dB/dt and B(t)



Mirnov signals

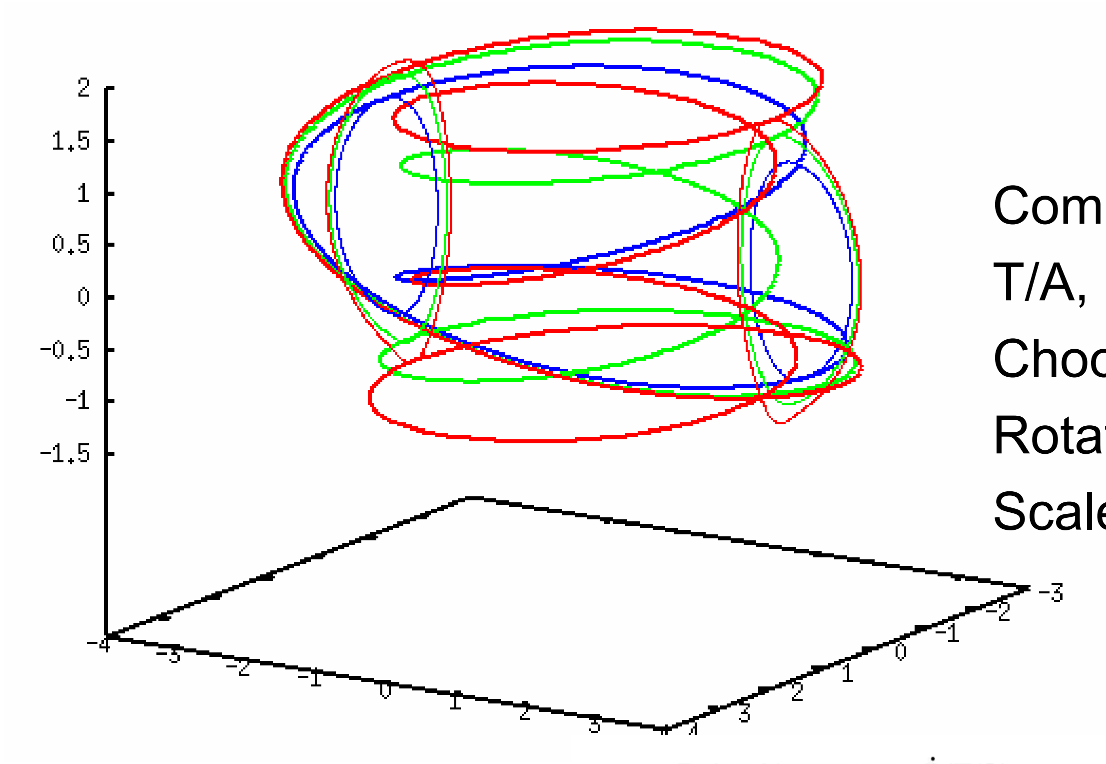


Localised current structure, propagating toroidally at 6 kHz.

Co-rotating magnetic blip
Co-current (excess current)

nearby low current or distant higher current ?

Plotting field lines



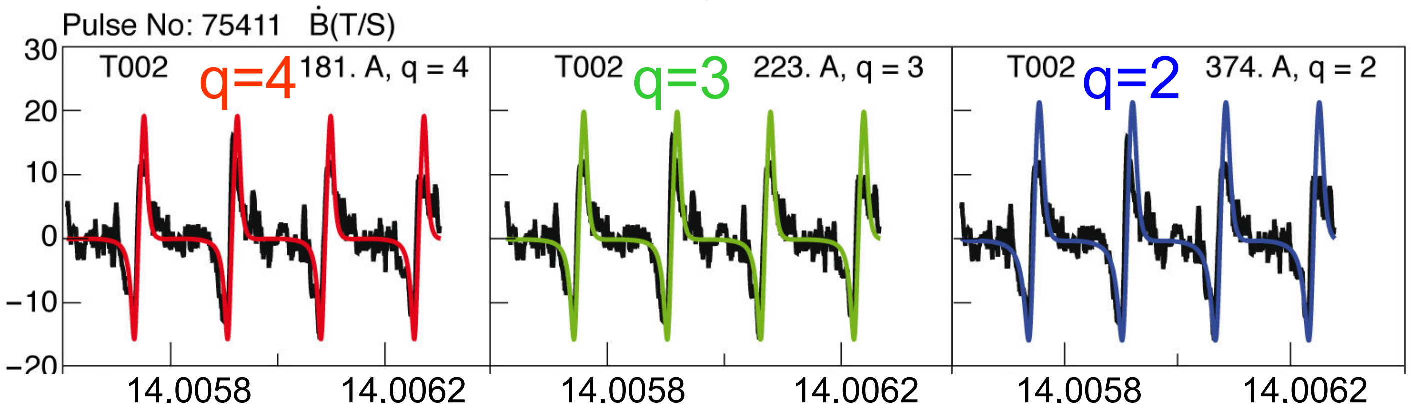
Plot of q=4, q=3, and q=2 field lines and flux surfaces.

Compute signal from each current filament, T/A, in one rotation period.

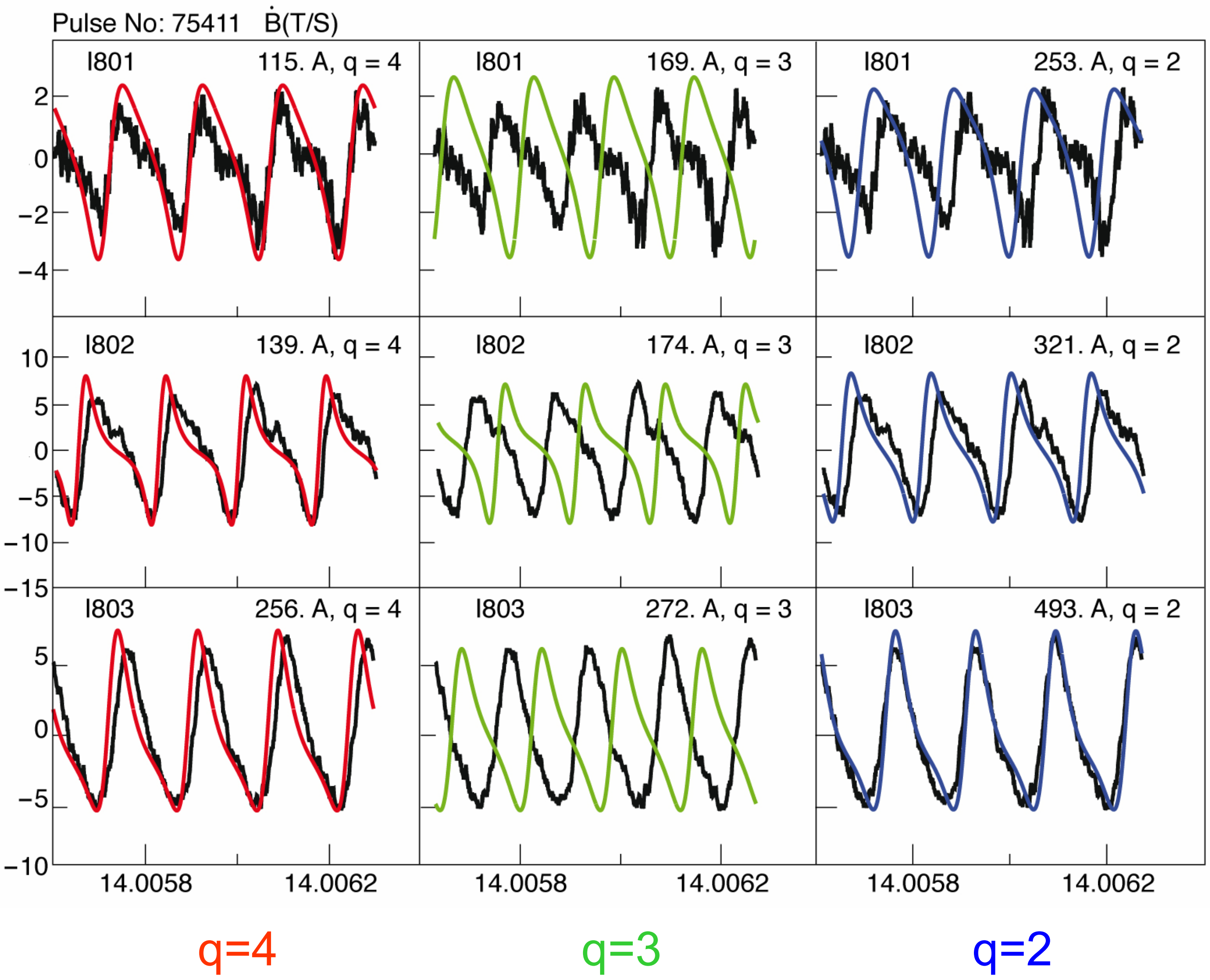
Choose phase to match one coil.

Rotate filament at correct frequency.

Scale filament current to fit data.



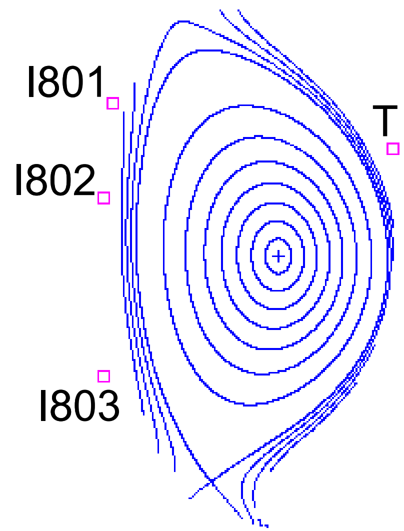
Bdot generated from 100-500 A current filament, co-rotating, co-current



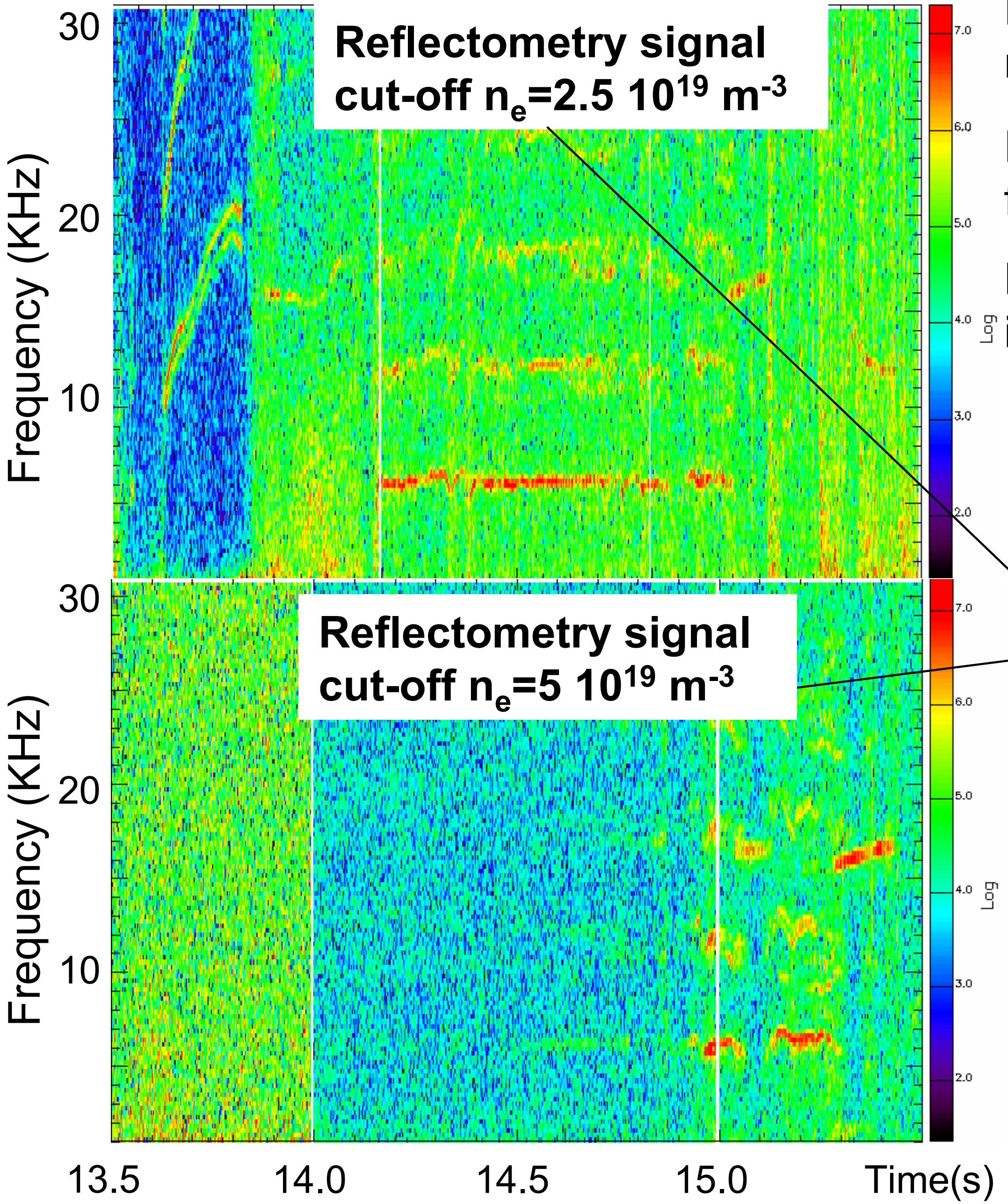
Inboard data compatible with q=4, or *even* q

The actual amount of current in the ribbon needed to match measurement depends sensitively on plasma details.

Topology and relative phase, as observed by inboard coils, is not so sensitive.



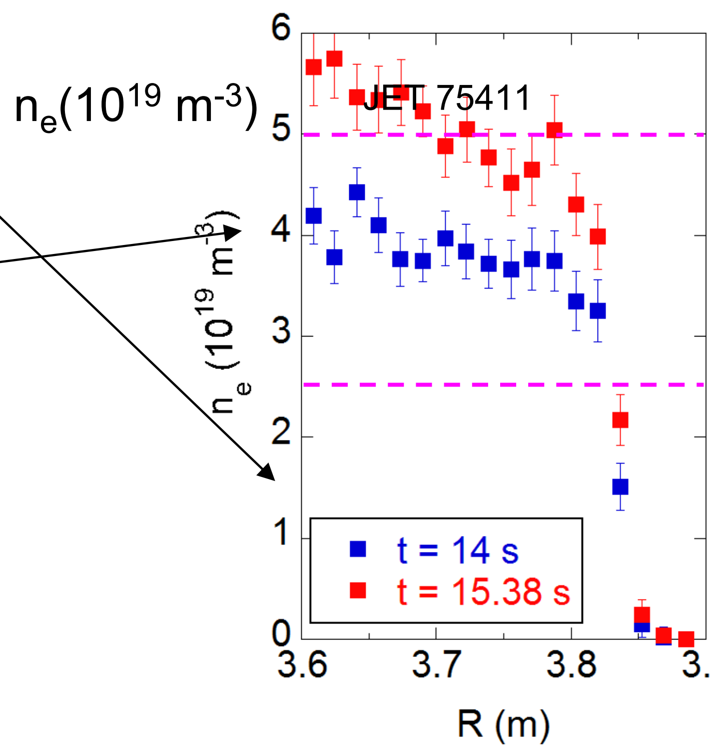
Fluctuation Measurements



Reflectometry strongest signal moves to high n_e channels as n_e rises: top of pedestal ?

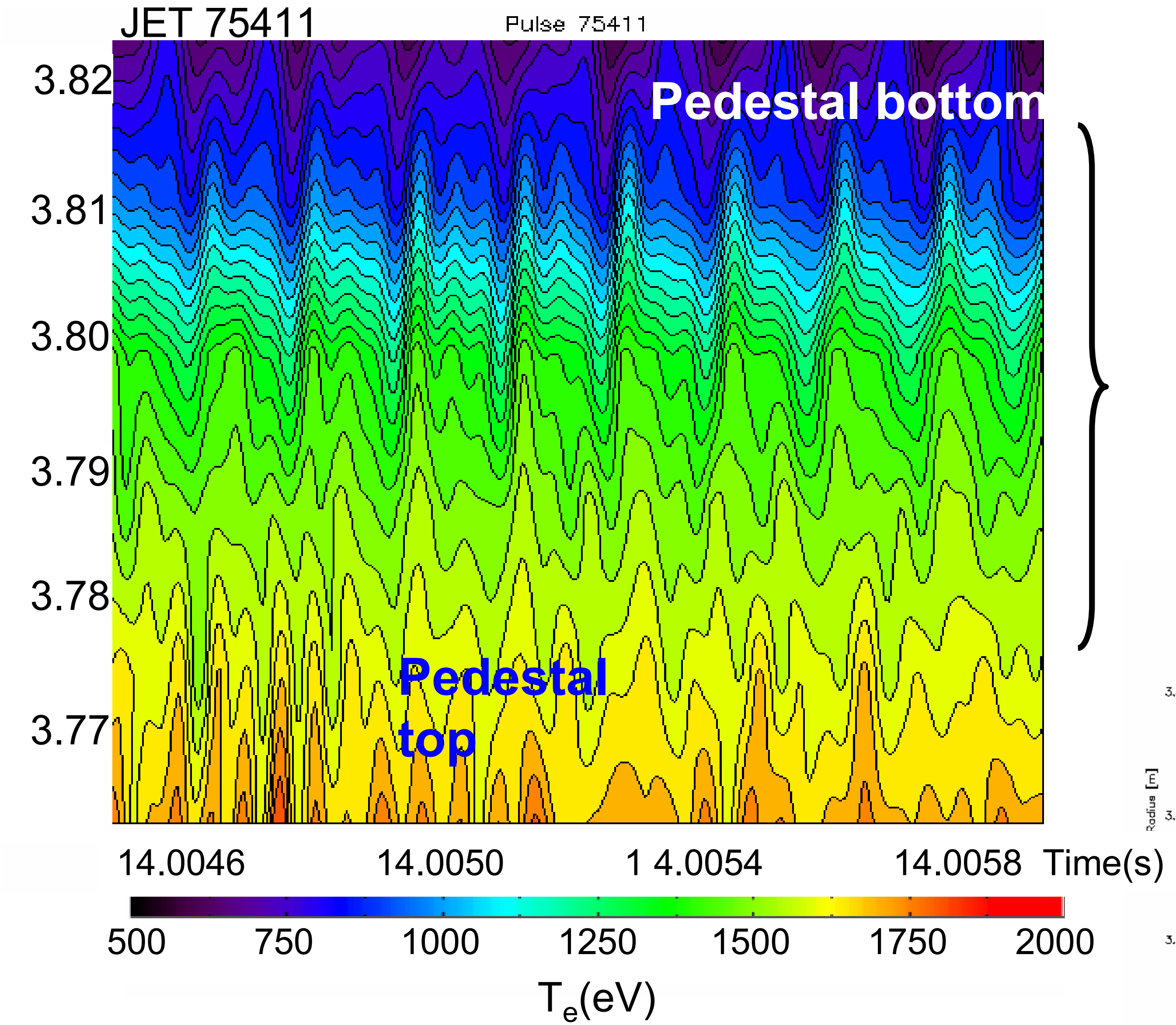
Reflectometry and ECE more sensitive to fluctuations in gradient region.

Mode with multiple harmonics seen in SXR, interferometer, Langmuir Probes, D_α



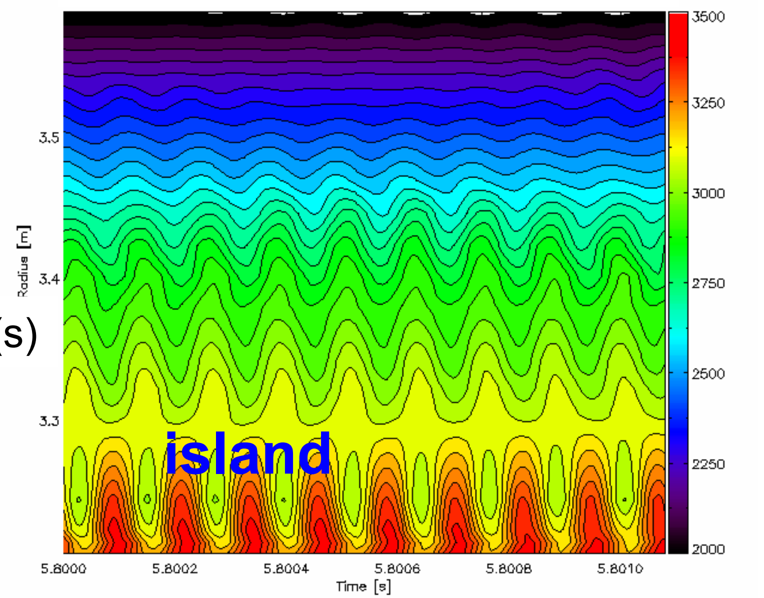
ECE fluctuations: not a tearing mode

see P5.171



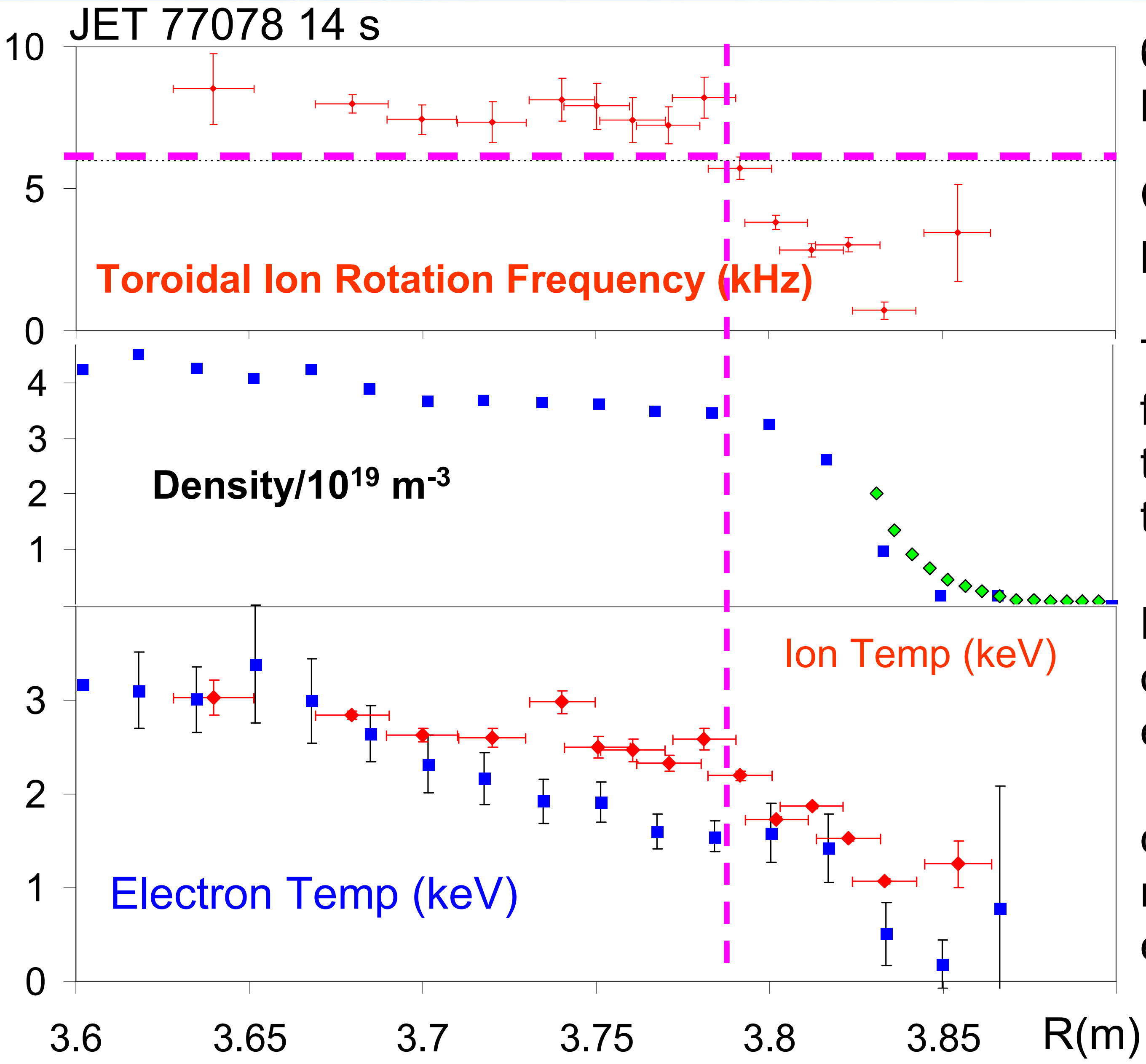
Contours of $T_{e,ECE}$ show no evidence of islands (tearing) in the outboard gradient region.

Example of 2/1 island:



Confirms previous finding of Huysmans et al. NF 38, 179 (1998)

Where is the filament?



Plasma profiles at t=14 s, when OM just began.

6 kHz is at top of T_i pedestal, but in gradient region of v_{tor}

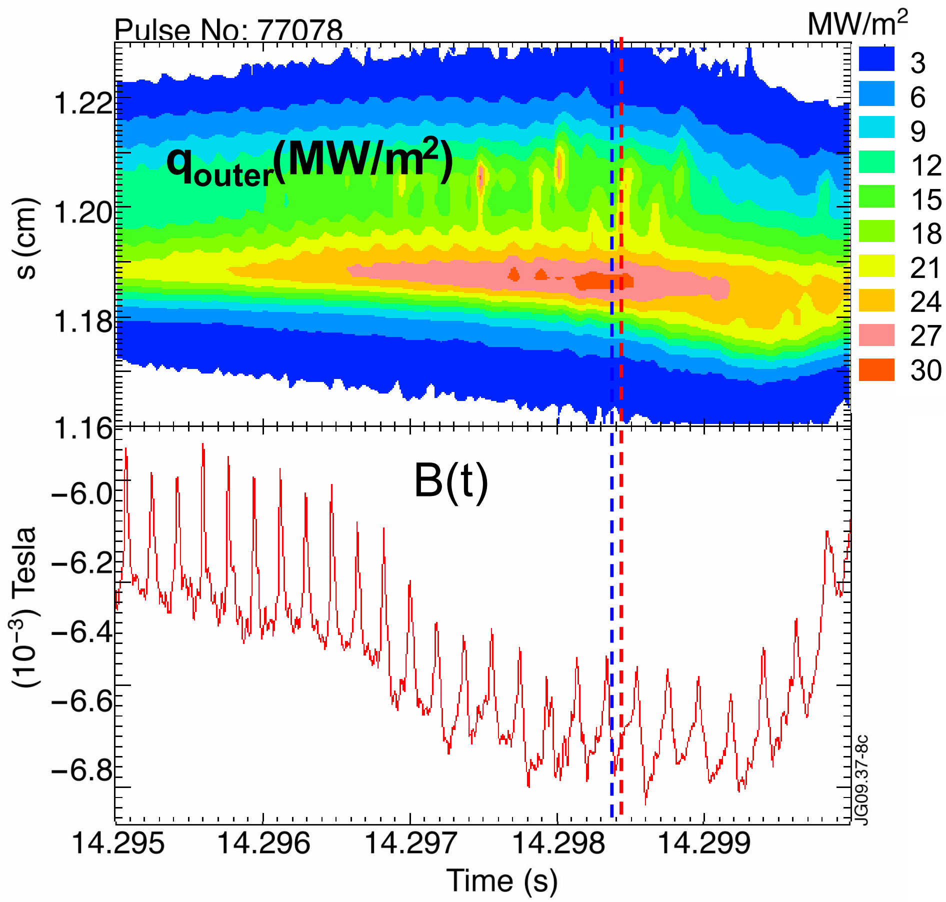
Confirmed in various different pulses and time-slices.

Therefore the q at the filament location is given by the position of the pedestal top.

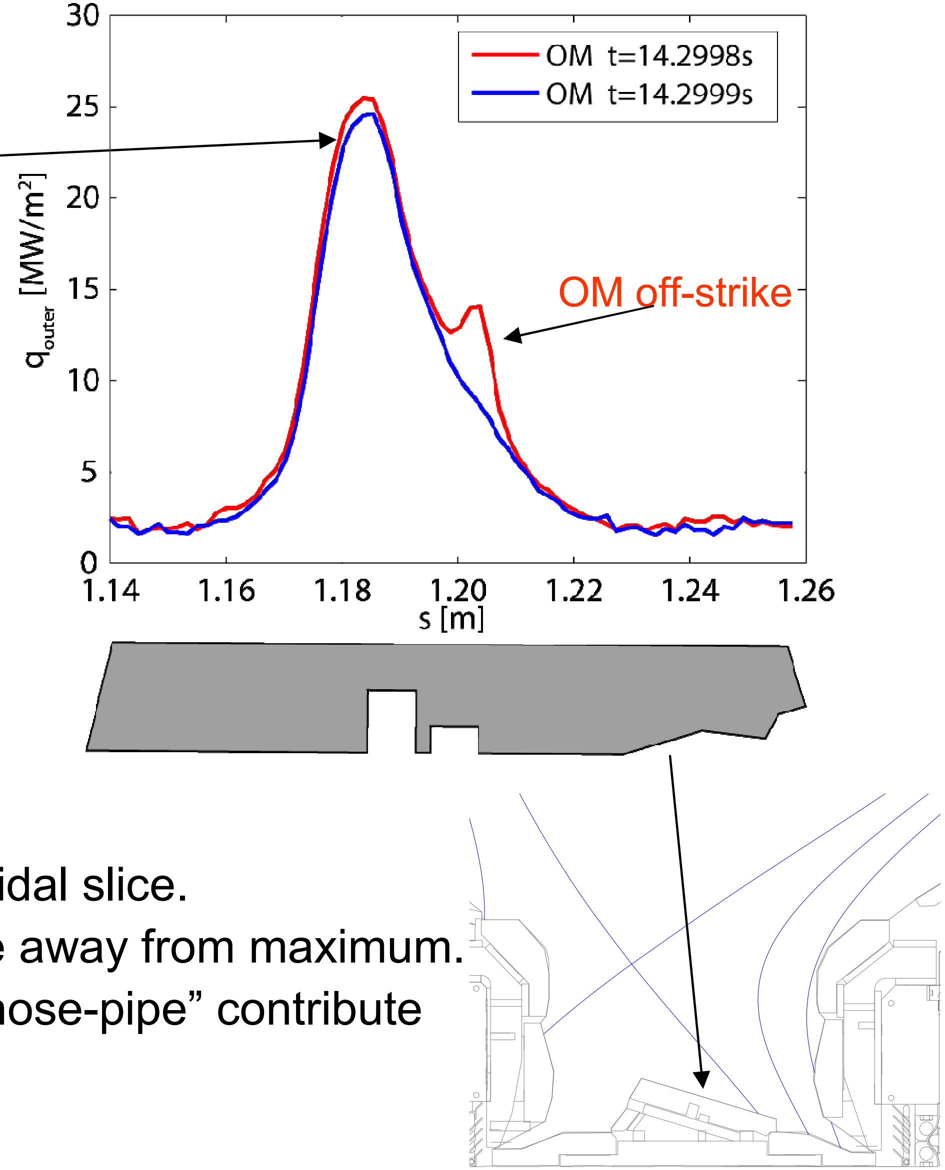
Plasma current ramp, up or down, can reduce or eliminate OM

q= 4 near mode location, need higher resolution equilibrium reconstruction

Impact at divertor target: IR measurements



Heat flux to outer divertor measured with infrared camera, 1 frame/38 μs

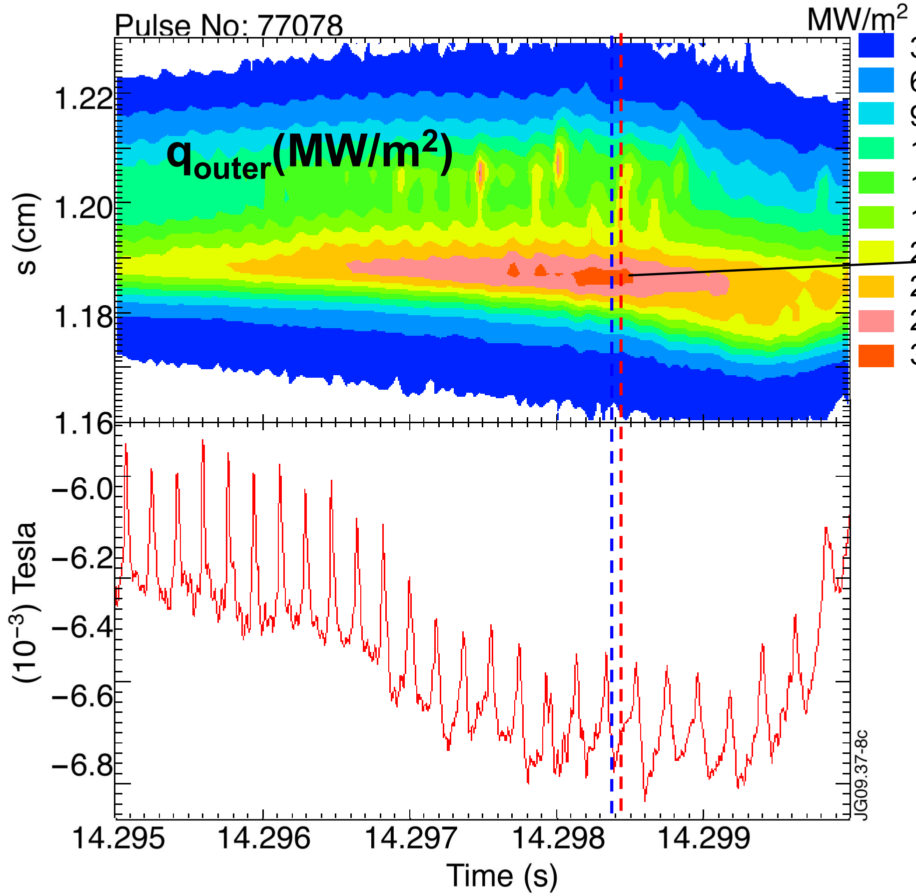


Geometry: plasma rotates, camera sees thin toroidal slice.

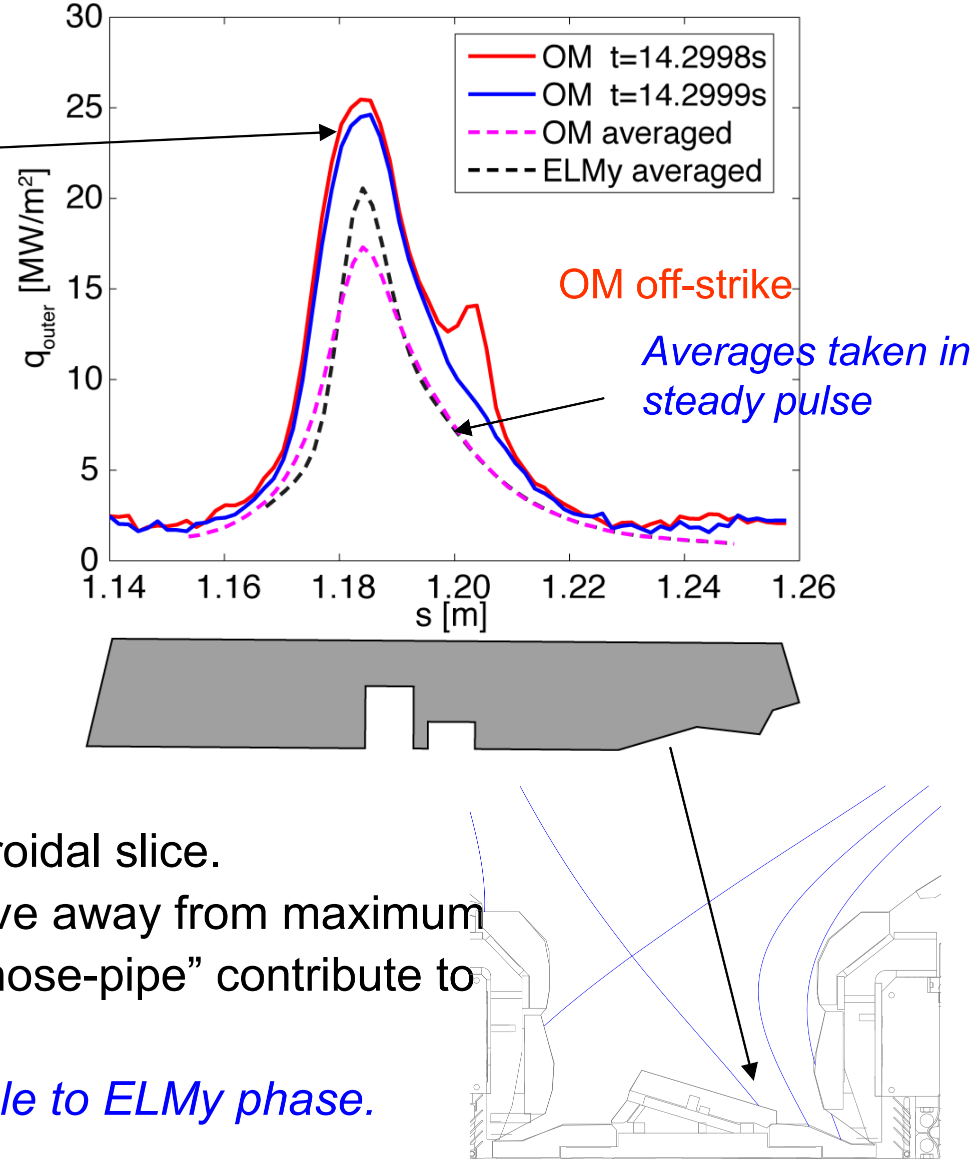
Periodically (1/6 kHz), bursts of 1-3 MW/m^2 arrive away from maximum.

Both, overall transport increase and a localised “hose-pipe” contribute to heat flux on to target.

Impact at divertor target: IR measurements



Heat flux to outer divertor measured with infrared camera, 1 frame/38 μs



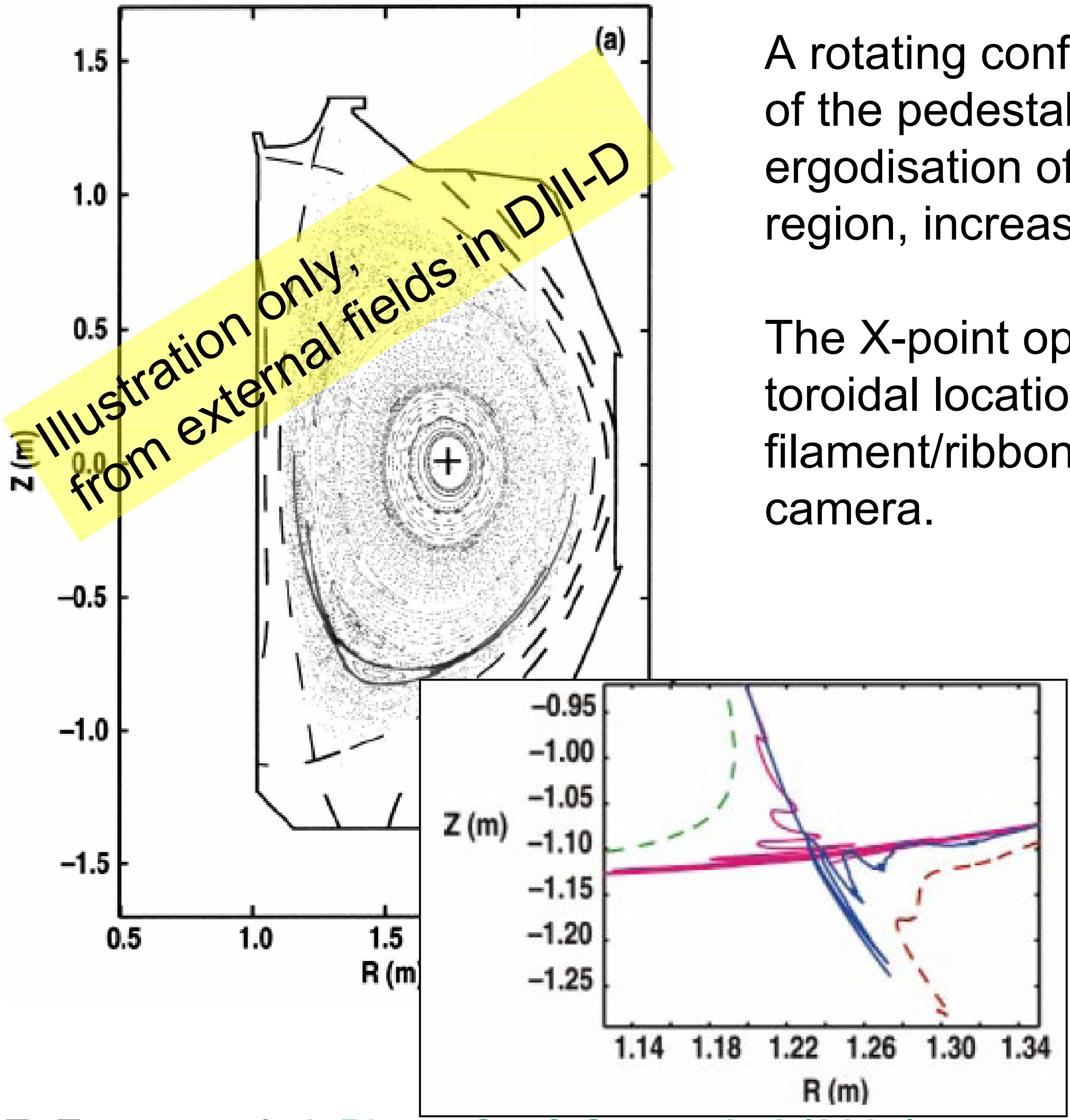
Geometry: plasma rotates, camera sees thin toroidal slice.

Periodically (1/6 kHz), bursts of 1-3 MW/m^2 arrive away from maximum.

Both, strong overall transport, and a localised "hose-pipe" contribute to heat flux on to target.

During steady OM, heat flux to target comparable to ELMy phase.

How? Ergodisation & homoclinic tangles?



A rotating confined even filament at the top of the pedestal may produce partial ergodisation of field lines in the pedestal region, increasing overall heat flux.

The X-point opens up, probably at the toroidal location just under the current filament/ribbon, periodically viewed by IR camera.

A particular flux tube (ribbon-like?) can escape through the broken X-point (or elsewhere?) and reach the divertor tile, producing intermittent heat flux away from strike position.

T. E. Evans et al, J. Phys.: Conf. Ser. **7, 174 (2005)**.

OM theory-based model?

- Observation: OM is a confined current filament at top of the pedestal
- Theory of “current-vortices” studied by Petviashvili and co-workers (90’s).
- Combining equations for v and B, an equation is derived for the localised strength of generalised vorticity. A closed current filament might be similar to a smoke ring, an open one to a tornado.

2 types of stationary vortex solutions,

$$(\vec{v}+\vec{B}/\sqrt{\mu_0\rho}) \quad \text{and} \quad (\vec{v}-\vec{B}/\sqrt{\mu_0\rho})$$

Vorticity growth/decay for rotating filament would be given by balance between velocity and local magnetic field, depends on n_e.

Tantalising.

In our plasmas shear of $V_{toroidal}$ is comparable to $j_{toroidal}$

Further theory development needed.

Vorticity is a very economic way of describing real phenomena.

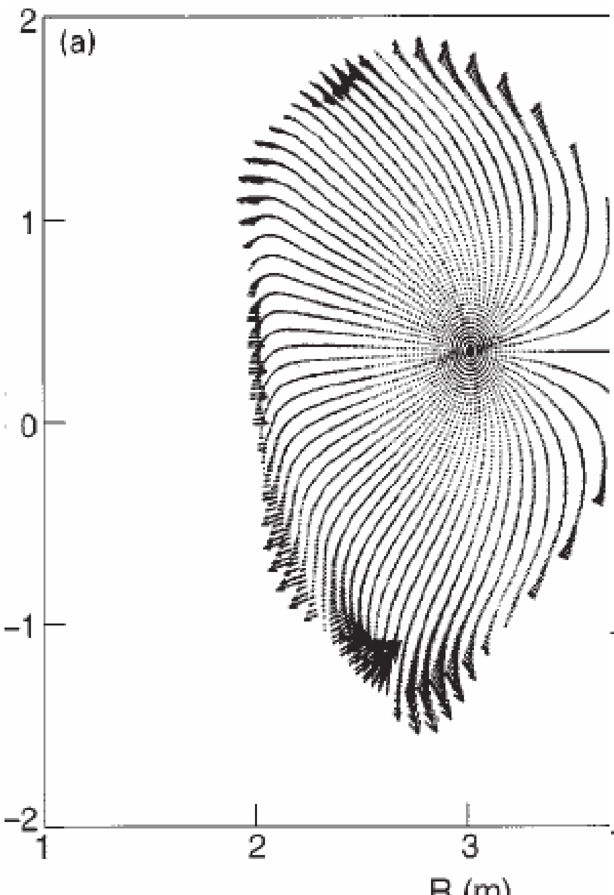
Summary

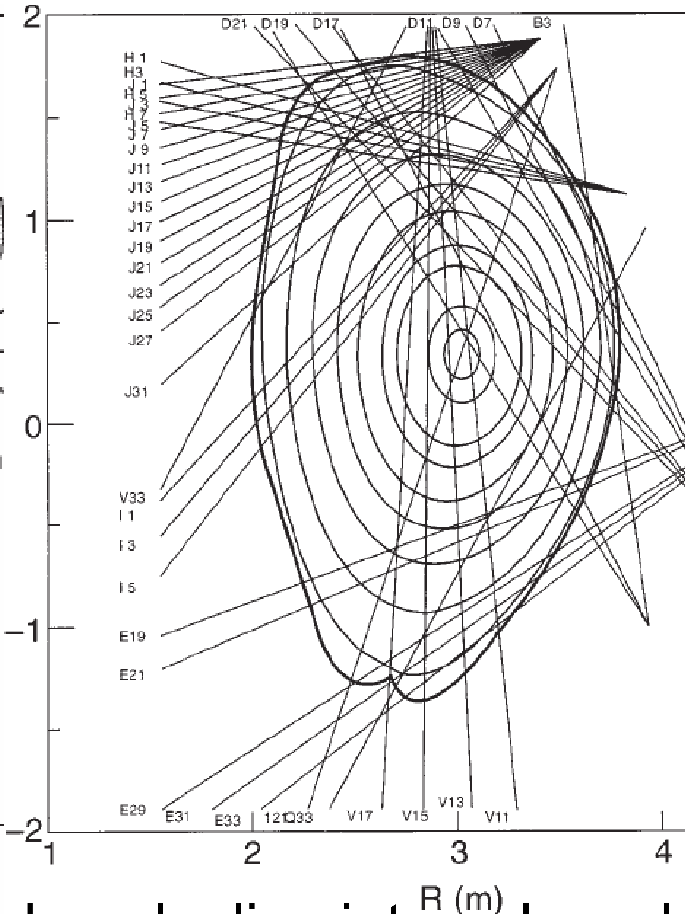
- In the hot ion H-mode regime, obtained with low gas puff & low recycling leads, obtain hot pedestal conditions: high T_e, T_i, V_{tor}
- In these conditions current filaments occurs spontaneously:

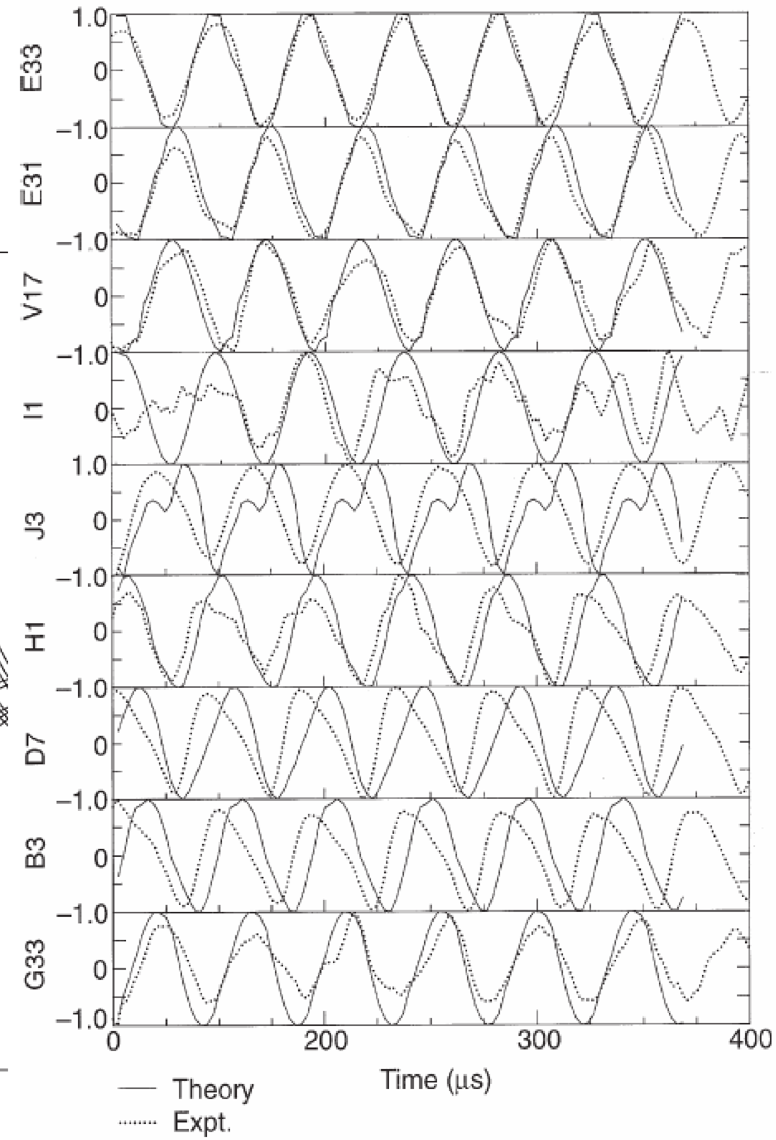
  confined current filament can be long-lived, delay ELM, and increase heat flux to the divertor targets. *Is this a QH-mode?*
- Magnetics proves existence, CX locates mode near pedestal top
- Fluctuation measurements: confirm mode, not tearing, so far can not localise it.
- If we can learn to control intensity and location of OM, we might control the pedestal and avoid ELMs: a desirable operating regime
- Theory points to singular solutions of MHD equations, akin to smoke rings or tornadoes.

Previous understanding of the OM

The Outer Mode was identified in JET as a low n ideal external kink, driven by the edge density.





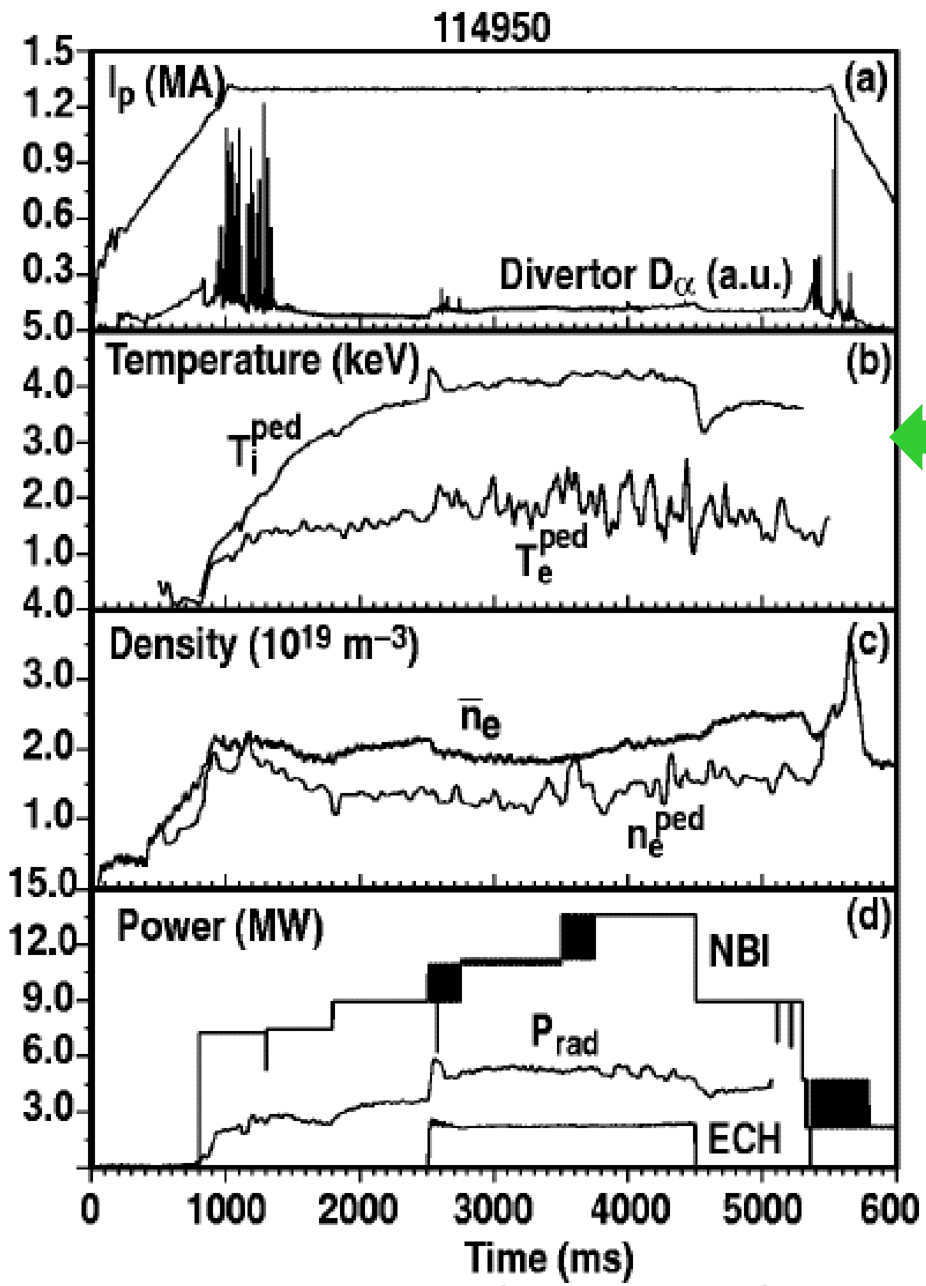


SXR data vs. calculated mode: line integral masked filaments?

G. Huysmans, Nucl. Fus. 38, (1998), p. 179

They are visible in magnetics.

DIII-D: QH-mode and EHO

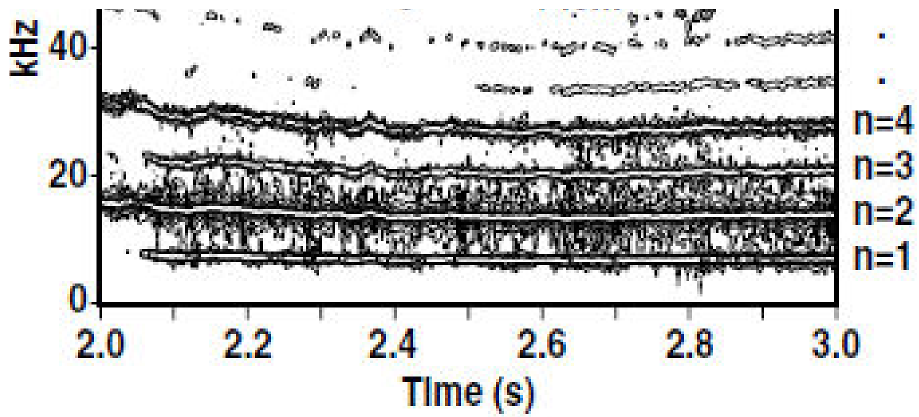


Acknowledgements: T Osborne, W Suttrop

QH-mode, previously observed with low density/fuelling, high pumping, cn-NBI.

In co-NBI, usually very transient,
Greenfield PRL 86, 4544, (2001)
but recently reported to last 1 s
Burrell, PRL 102, 155003 (2009)

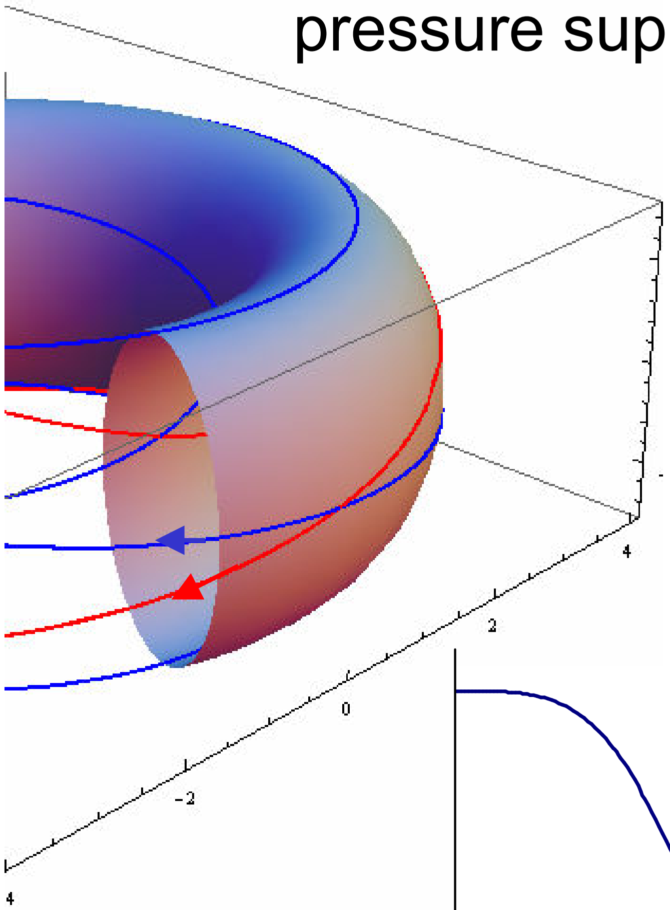
Details of EHO reported in
Burrell, Phys. Plasmas, 12, 056121 (2005)



The EHO of DIII-D, essential ingredient of the QH-mode, looks like the OM in JET.
AUG: *W. Suttrop et al NF 45 721-730, 2005*

Confined current filament in tokamak plasma

MHD equilibrium: background plasma pressure supported by electromagnetic force



$$\vec{F} = \vec{j}_{plasma} \times \vec{B} - \nabla p = 0$$

If ∇p has a flat spot, $\vec{j}_{plasma} \,//\, \vec{B}$

Extra current density added to a flux tube at $\nabla p = 0$ suffers no radial force

A closed current filament can remain in radial force balance at a flat spot of p: top or bottom of pedestal.

Similar to other MHD?

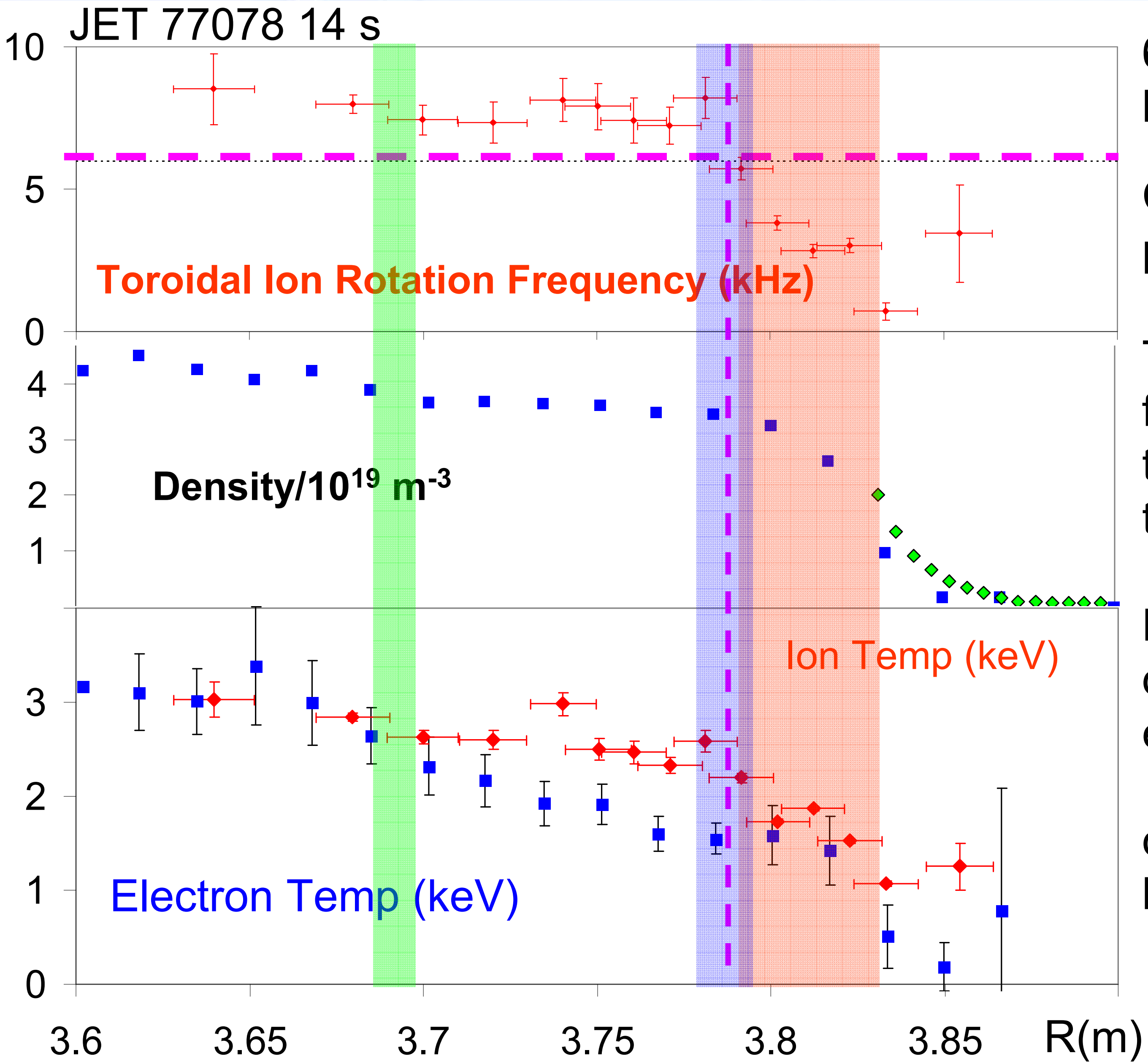
“Snakes” are typically a current density defect, not a current excess as we observe here.

They are otherwise very similar (T Hender, B Alper, D Howell, E Solano)

Palm tree modes are ELM postcursors, also have many harmonics, and are located in pedestal. Typically current defficit.

As shown before, the EHO is very similar to the OM.

Where is the filament?



Plasma profiles at t=14 s, when OM just began.

6 kHz is at top of T_i pedestal, but in gradient region of v_{tor}

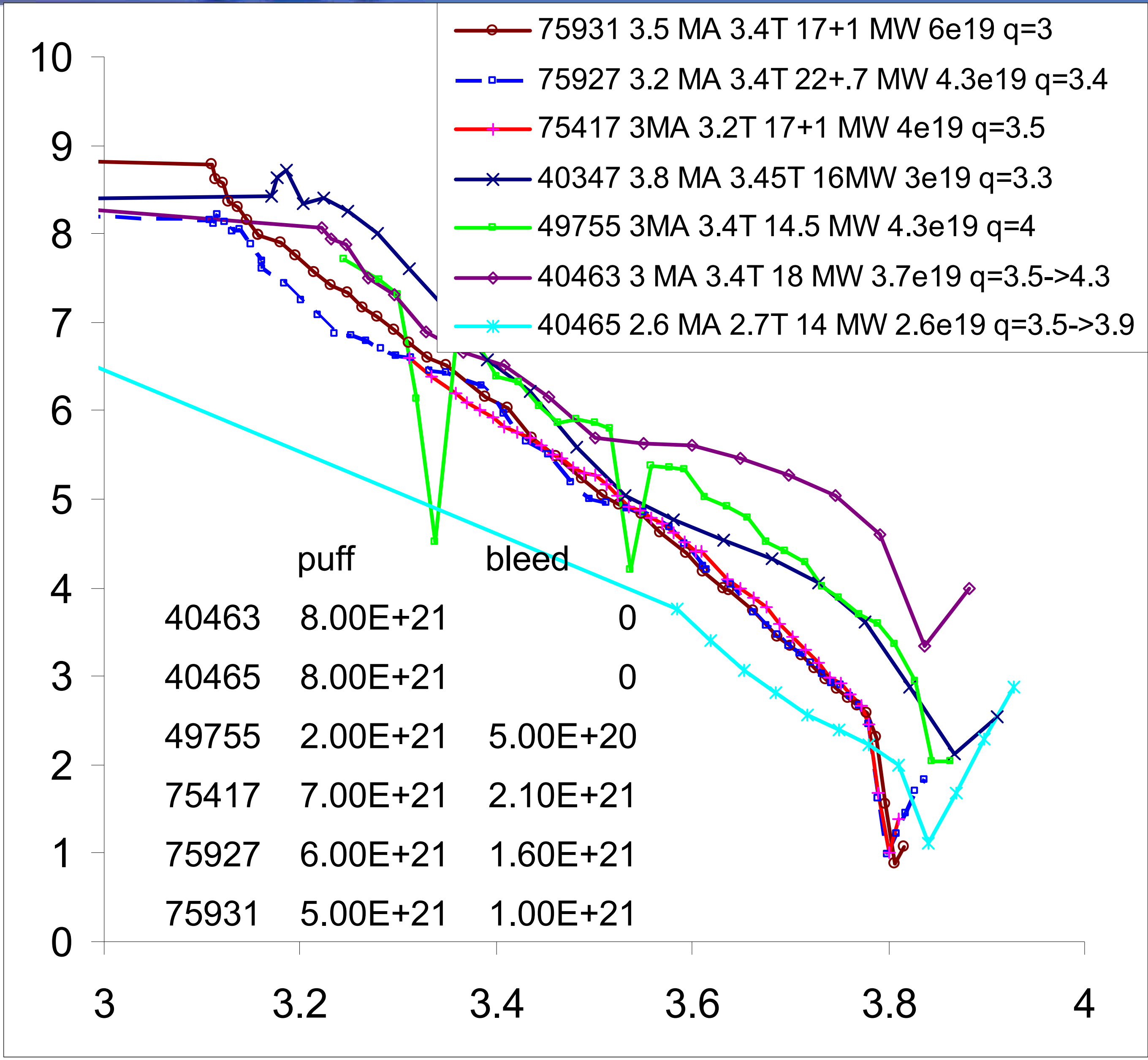
Confirmed in various different pulses and time-slices.

Therefore the q at the filament location is given by the position of the pedestal top.

Plasma current ramp, up or down, can reduce or eliminate OM

q of mode probably dictated by q at top of pedestal?

Reaching higher



Diagnostic improv. KG10 will provide density profiles in C27

Move strike to avoid layers?

Ip ramp down and q>3.5 can help achieve hotter pedestals