Scenario preparation for the observation of alpha-driven instabilities and transport of alpha particles in JET DT plasmas

R. Dumont, D. Keeling, M. Fitzgerald, S. Sharapov, M. Baruzzo, P. Bonofiglo, C. Challis, M. Dreval, C. Giroud, J. Eriksson, J. Ferreira, N. Fil, J. Garcia, L. Giacomelli, V. Goloborodko, E. Joffrin, S. Hacquin, N. Hawkes, T. Johnson, Y. Kazakov, V. Kiptily, E. Lerche, M. Lennholm, J. Mailloux, F. Nabais, M. Nocente, L. Piron, M. Poradziński, P. Puglia, E. Solano, R. A. Tinguely, S. Vartanian, H. Weisen, and JET contributors

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Experimental team encompasses wide range of competences

R. Dumont[1], D. Keeling[2], M. Fitzgerald[2], S. Sharapov[2], M. Baruzzo[3], P. Bonofiglo[4], C. Challis[2], M. Dreval[5], C. Giroud[2], J. Eriksson[6], J. Ferreira[7], N. Fil[2], J. Garcia[1], L. Giacomelli[8], V. Goloborodko[9], E. Joffrin[1], S. Hacquin[1], N. Hawkes[2], T. Johnson[10], Y. Kazakov[11], V. Kiptily[2], E. Lerche[11], M. Lennholm[2], J. Mailloux[2], F. Nabais[7], M. Nocente[8], L. Piron[3], M. Poradziński[12], P. Puglia[13], E. Solano[14], R. A. Tinguely[15], S. Vartanian[1], H. Weisen[13], and JET contributors*

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France

[2]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK

[3]Consorzio RFX, corso Stati Uniti 4, 35127 Padova, Italy

[4]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA

[5]Institute of Plasma Physics, NSC KIPT, Kharkov, Ukraine

[6]Dept of Physics and Astronomy, Uppsala University, SE-75119 Uppsala, Sweden

[7]Instituto de Plasmas e Fusão Nuclear, IST, Universidade de Lisboa, Portugal

[8]University of Milano-Bicocca, piazza della Scienza 3, 20126 Milano, Italy

[9]Kyiv Institute for Nuclear Research, Prospekt Nauky 47, Kyiv 03680, Ukraine

[10]Fusion Plasma Physics, EES, KTH, SE-10044 Stockholm, Sweden

[11]LPP-ERM/KMS, Ass. EUROFUSION-Belgian State, TEC partner, Brussels, Belgium

[12]Institute of Plasma Physics and Laser Microfusion, Hery 23, 01-497 Warsaw, Poland

[13]École Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland

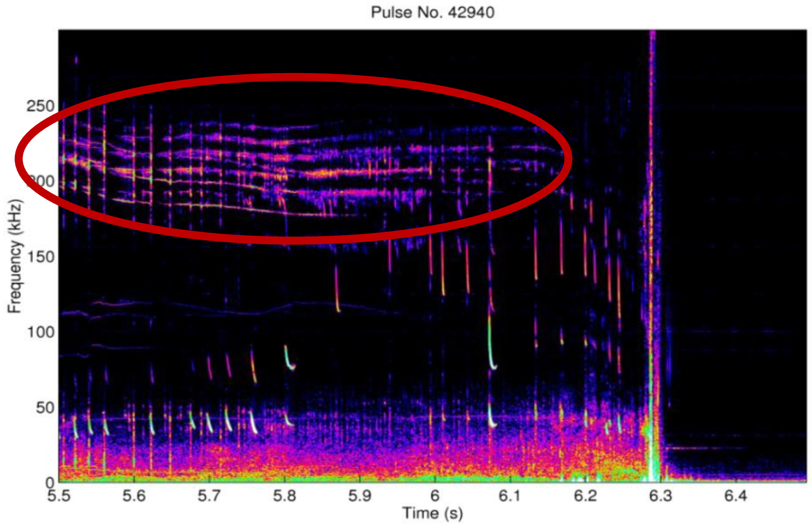
[14]Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain

[15]MIT PSFC, 175 Albany Street, Cambridge, MA 02139, USA

**See the author list of 'Overview of JET results for optimising ITER operation' by J. Mailloux et al to be published in Nuclear Fusion Special issue: Overview and Summary Papers from the 28th Fusion Energy Conference (Nice, France, 10-15 May 2021)*

JET is the only ongoing fusion device in which alpha effects can be studied experimentally

- TAEs (Toroidal Alfvén Eigenmodes) are instabilities excited by energetic ion radial pressure gradient, experience moderate damping by thermal plasma species
- α-driven TAEs may induce energetic ion transport / losses in burning plasmas (e.g. in ITER)
- TAEs observed in all plasmas with elevated q-profile ($q_0 > 1.5$) in JET DT plasmas (DTE1)
- Caveat: ICRH-accelerated ions always present, provided large TAE drive, dominating α-drive



- No conclusions regarding α-driven TAEs could be drawn from JET DTE1 data [Sharapov NF 1999], unlike from successful TFTR experiments [Budny NF 1992, Spong NF 1995, Nazikian PRL 1997]

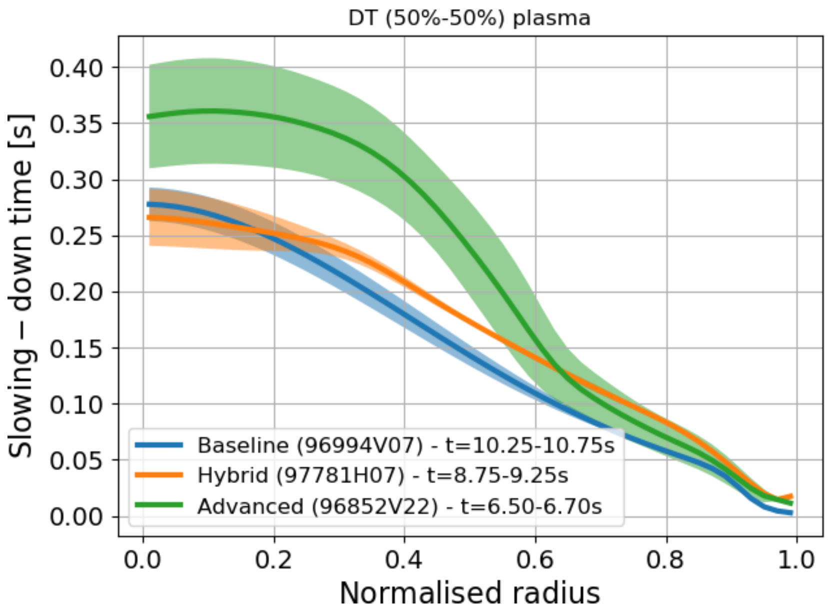
Dedicated advanced scenario under development for the study of alpha-driven instabilities in JET

- α-driven TAE growth / damping rate is given by

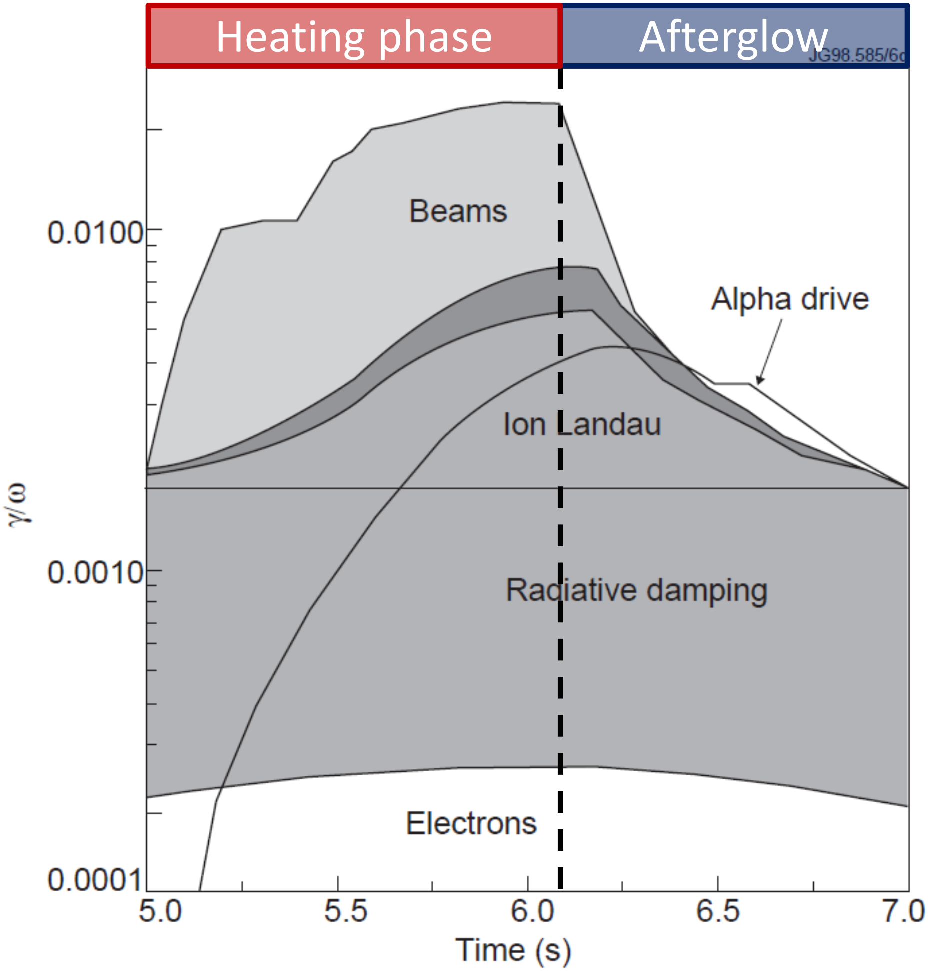
$$\gamma \equiv \gamma_\alpha - \gamma_d = -Cq^2\beta_\alpha\left(1 - \frac{\omega_\alpha^\star}{\omega}\right)F(v_\alpha/v_A) - \gamma_d$$

- Key parameters to maximise TAE drive (γ_α):
  - High α-pressure + large pressure gradient
    - Large P_{add}, T_i (increase fusion yield), T_e (increase slowing-down time) → Low n_e, low I_p (still large enough for alpha confinement)
  - Elevated q-profile

- Optimal conditions for TAE excitation not naturally fulfilled by parameters of baseline or hybrid steady-state scenarios in JET DT plasmas [Garcia, EX1-989]
  → dedicated development of an advanced scenario for JET-ILW [Mailloux, OV1-1080]

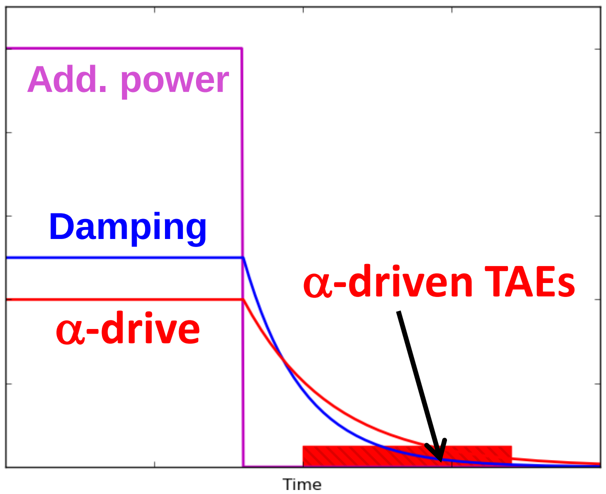


Observation of alpha-driven TAEs in JET requires afterglow phase in the pulse



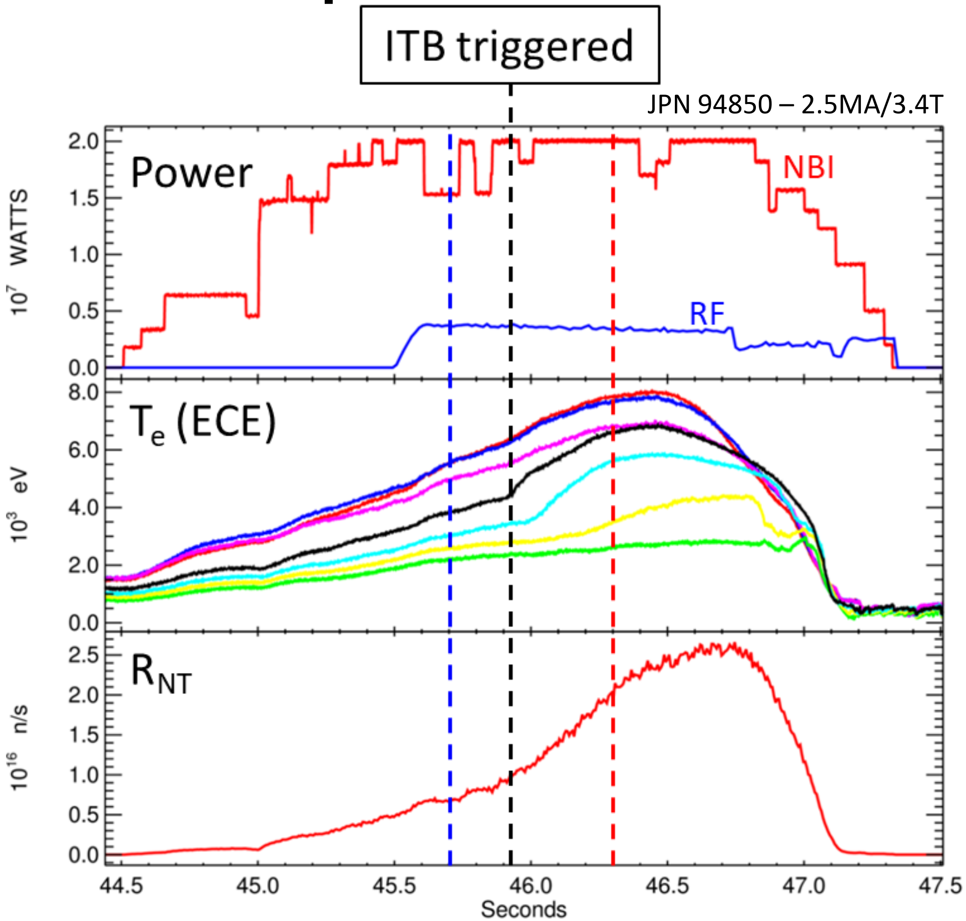
JET DT pulse 41723 – CASTOR-K, MISHKA
[Sharapov NF 1999]

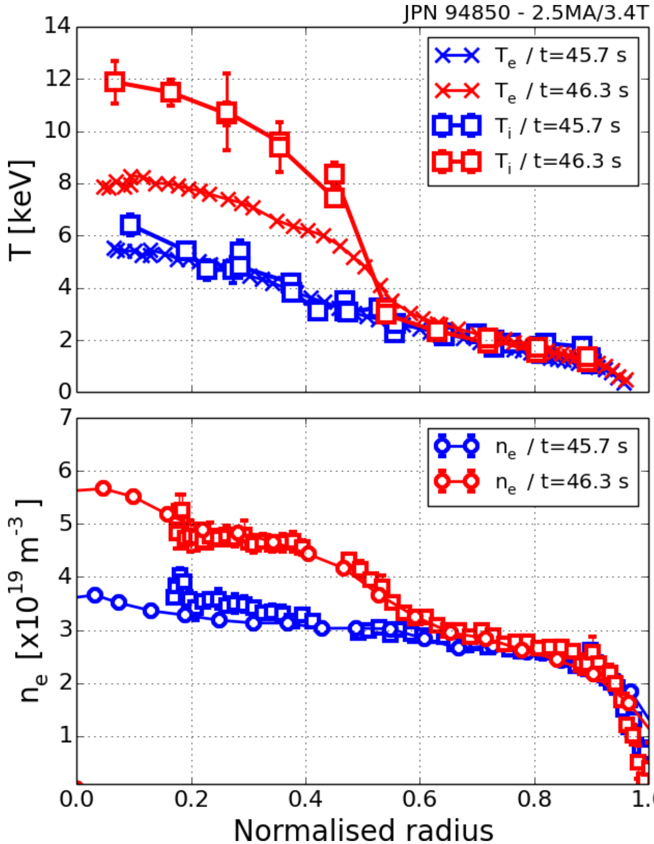
- TAEs very stable during main heating phase
  - Beam + th. damping ~1-2%
  - Alpha drive ~0.1-0.2%
- α-driven TAEs may be observed only during afterglow phase



- No ICRH before afterglow period in DT plasmas
- ICRH used in D plasmas to develop scenario & probe TAE stability

ICRH used to reveal and tune ITBs at relatively moderate levels of NBI power

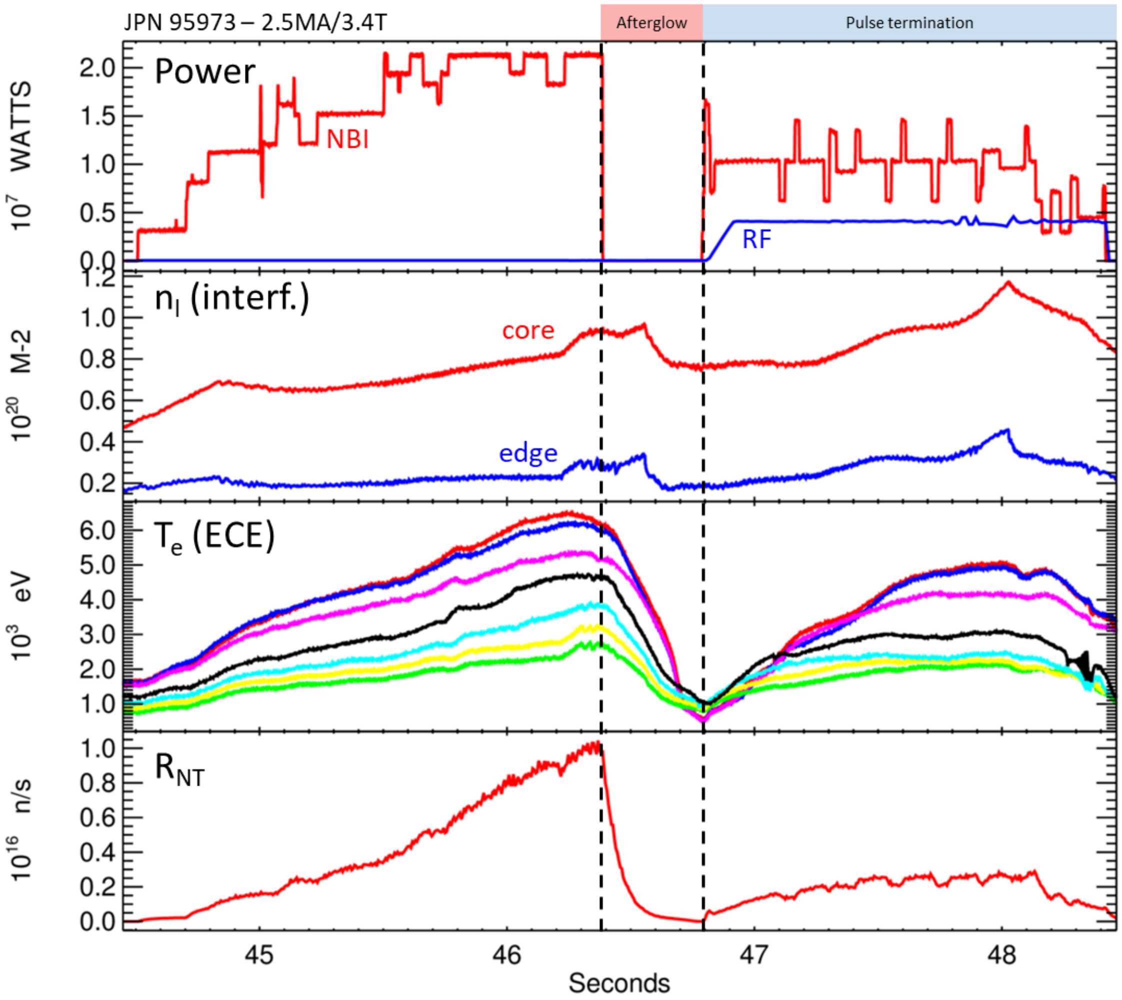




- Pulse 94850: ITB triggered with NBI+ICRH - R_{NT}=2.6x10^{16}/s with P_{tot}=(20+3.8)MW
- No sign of shear reversal in most pulses. ITB triggered upon q=2 surface entering plasma
- Scenario development and ITB tuning done with ~20MW NBI power + ~4MW ICRH, then applied to NBI-only pulses at higher NBI power levels (> 24MW)

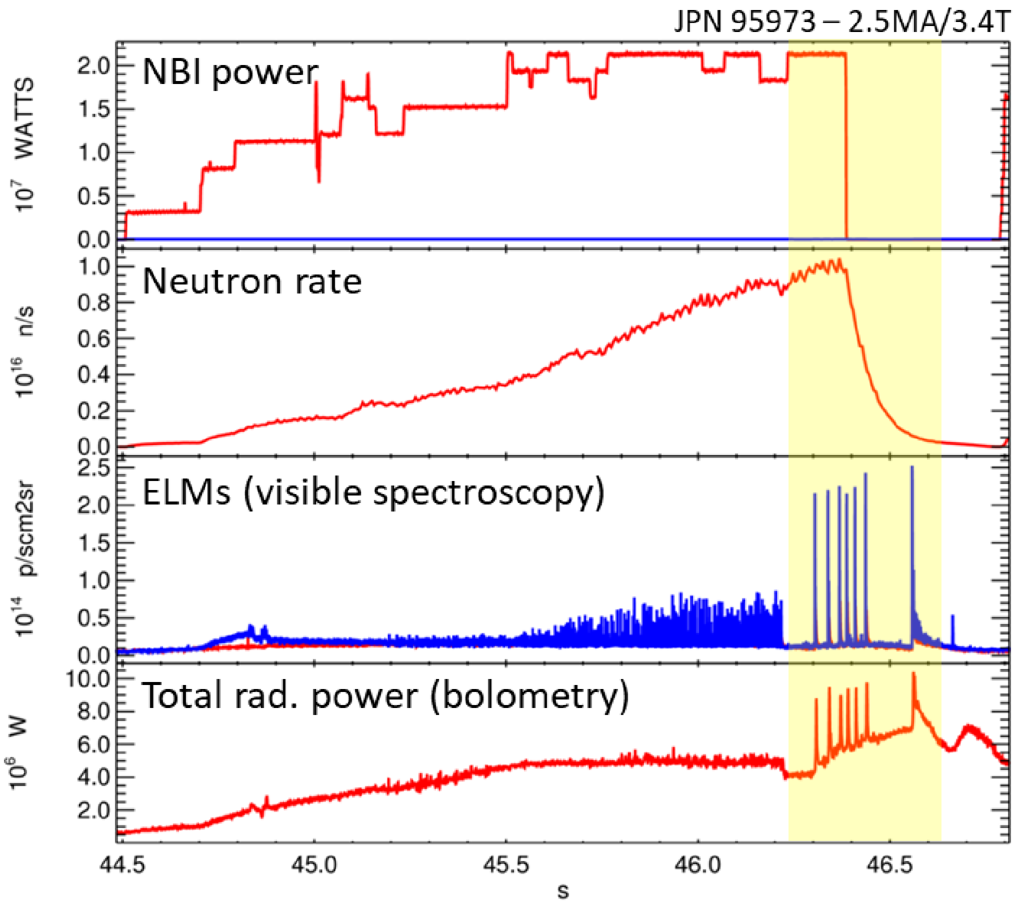
JET CCFE CULHAM CENTRE FOR FUSION ENERGY cea

Afterglow successfully triggered by bespoke real-time control scheme



- Pulse 95973 set up to trigger afterglow when
  - Neutron rate large enough (> $8x10^{15}/s$)
  - dR_{NT}/dt low (< $1x10^{13}/s^2$)
- First successful demonstration, although just above threshold (limited NBI power)
- RF power applied to ensure safe pulse termination (requirement for DTE2)
- Neutron rate threshold can be used as dud detector (requirement for DTE2)

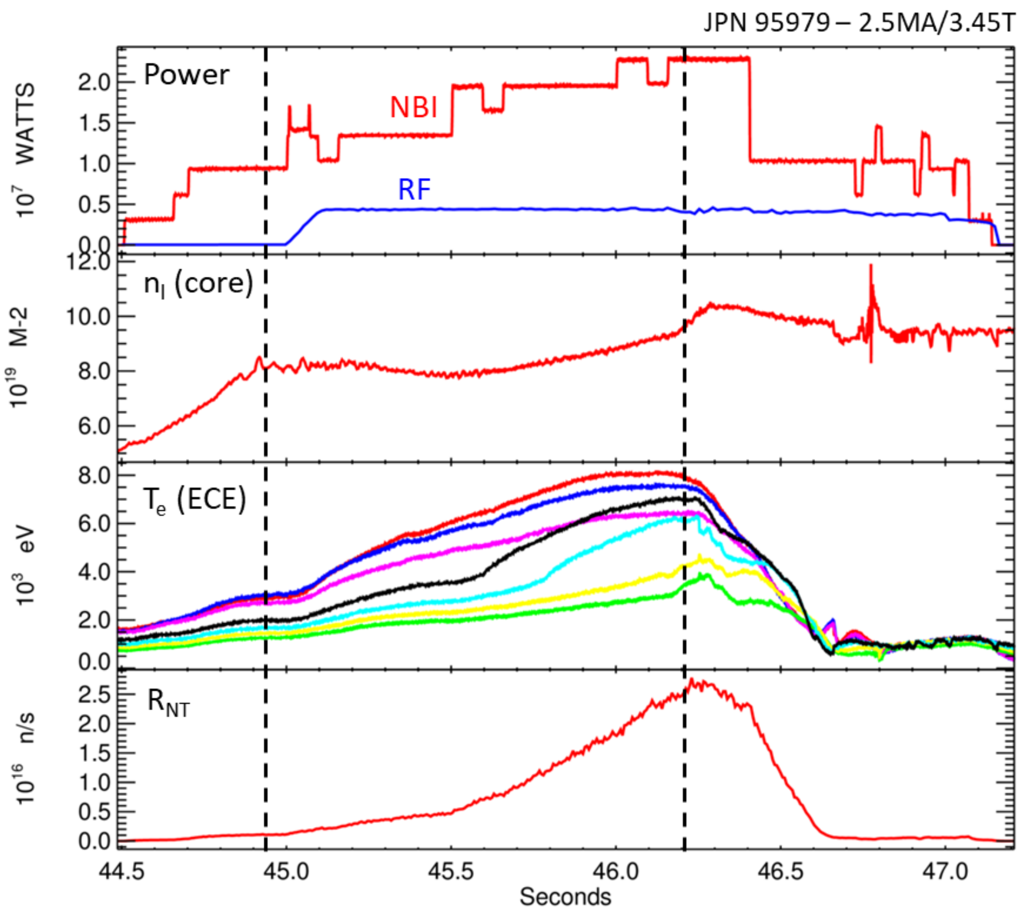
ELM control achieved in advanced scenario

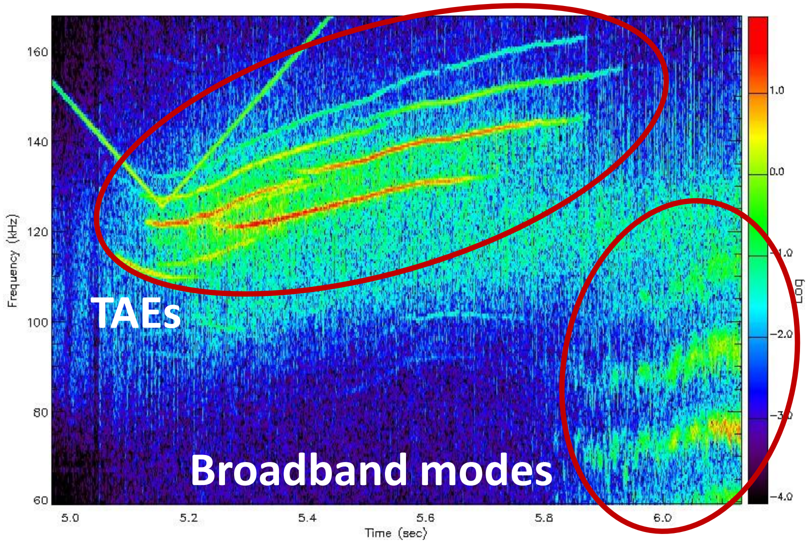


- Pulse 95973: ELM-free/type-I ELMs period before peak performance
- In this example, radiation peaking induces power ramp-down just following afterglow
- ITB beneficial for performance → ELM control needed
- ELM pacing by D pellets (~1.4mm, ~30Hz-45Hz) effective
- Last sessions much less affected by ELM issues compared to previous sessions, despite larger NBI power
- H pellets successfully tested → usable during T campaign (although H minority concentration increase can make ICRH use difficult)

JET CCFE CULHAM CENTRE FOR FUSION ENERGY cea

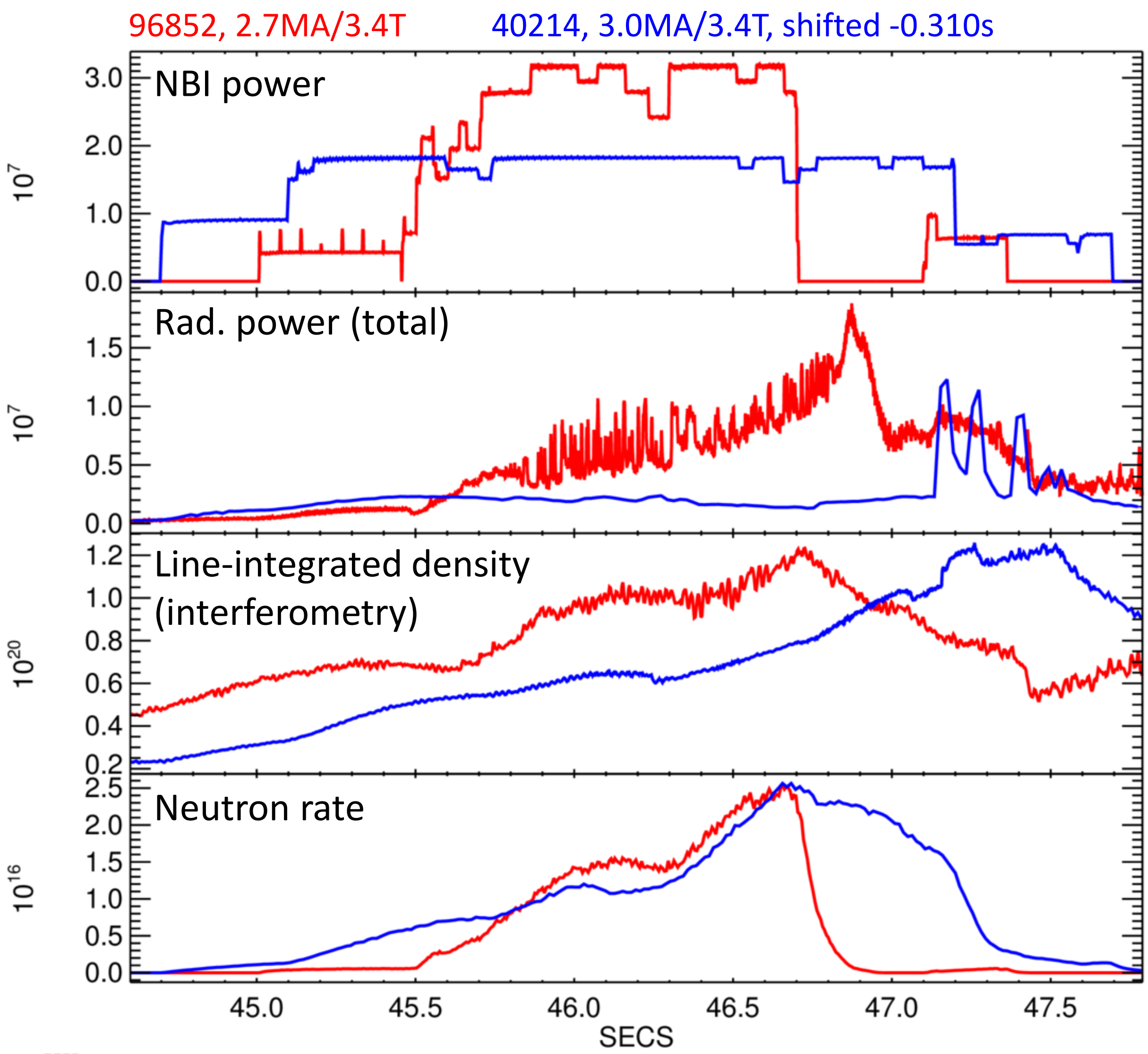
Core TAEs observed during RF-powered ITBs





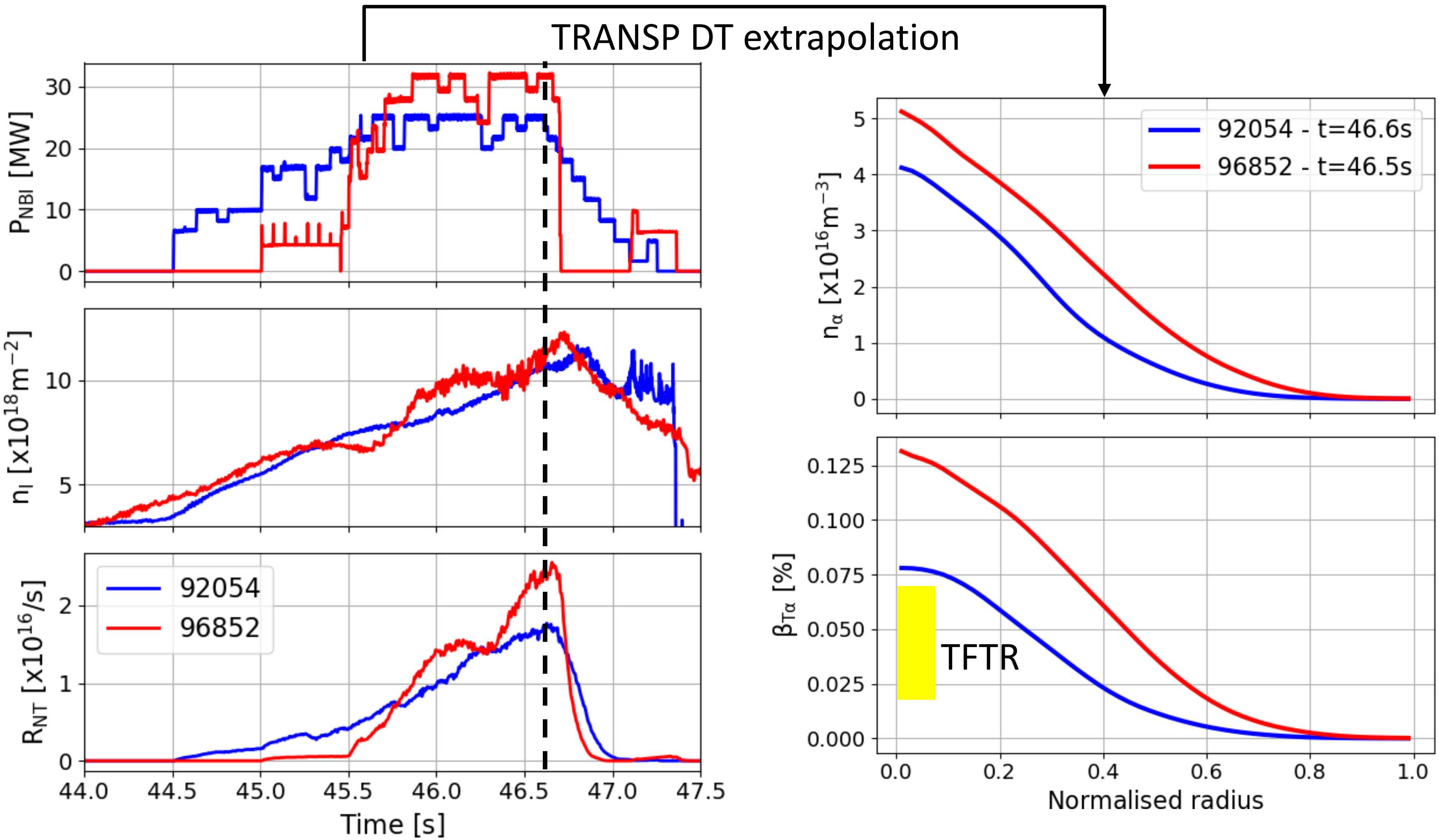
- Core TAEs n=3-7 seen during D(H) ICRH at 51MHz, damped by thermal/NBI ions as P_{NBI} increases
- Broadband modes 60-120kHz often seen in ITB pulses after TAEs disappear under study [Fil 2021]
- Alfvén cascades observed only during pulse termination (shear reversal)

Record pulse, performance comparable to reference C-wall pulse for alpha studies



- Pulse 96852: highest neutron rate obtained to date in JET-ILW with NBI only (R_{NT}=2.55x10^{16}/s)
- Good ITB obtained with NBI starting at 45.0s (differs from previous sessions)
- Performance similar to reference JET C-wall pulse for alpha studies
- Afterglow automatically triggered on R_{NT} rollover
- No ELM-free/type I ELM period seen (pacing pellets used)

Extrapolation to DT confirms significant progress in scenario developement



- Pulse 92054: former best NBI-only pulse for the study of alpha-driven instabilities [Dumont NF 2018]
- TRANSP DT simulation of 96852 very similar to CRONOS DT simulation of 92054 with extrapolated NBI power (31MW) [Garcia NF 2019]

Summary & prospects

- Main deliverable of development phase in D achieved: NBI-only pulses with good fusion performance in the presence of Internal Transport Barriers
- Core-localised TAEs in pulses with ICRH
- Pulses ready to be run in T and DT, include
  - ELM pacing by pellets
  - Real-time control-triggered afterglow
  - Gas injection with T-compatible modules
- Impossible to achieve 100% reproducibility in this scenario - included in strategy for DTE2 by allowing small changes in NBI switch-on time
- Data analysis ongoing, including fast ion transport/losses, MHD…
- Modelling effort ongoing
  - TRANSP modelling of best pulses, using refined equilibrium - extrapolations to DT
  - MHD stability analyses to evaluate damping mechanisms remaining during afterglow phase, and compare to alpha drive
- Experimental effort to couple TAE antenna power in these plasmas → probe stable modes [Tinguely, EX/P3-889]
- JET/TFTR comparisons included in DTE2 experimental plans