EUROfusion

Disruption paths in high performance scenarios at JET with D, T, and DT plasmas

Edoardo Alessi
ISTP-CNR, Milano, Italy
IAEA-TM ID 33

JET

Consiglio Nazionale delle Ricerche

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Author’s list

ALESSI, Edoardo	Istituto per la Scienza e la Tecnologia dei Plasmi- CNR Milano Italy
BONALUMI, Luca	University of Milano-Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
BURATTI, Paolo	Università degli Studi di Roma “Tor Vergata”, Roma, Italy
GIOVANNOZZI, Edmondo	ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Italy
PUCELLA, Gianluca	ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Italy
SOZZI, Carlo	Istituto per la Scienza e Tecnologia dei Plasmi ISTP-CNR Milano Italy
BARUZZO, Matteo	ENEA, Fusion and Nuclear Safety Department, C.R. Frascati, Italy
CHALLIS, Clive	UKAEA, CCFE, Culham Science Centre, Abingdon, UK
DE LA LUNA, Elena	Laboratorio Nacional de Fusión, CIEMAT, Madrid, Spain
FRIGIONE, Domenico	Università degli Studi di Roma “Tor Vergata”, Roma, Italy
GARZOTTI, Luca	UKAEA, CCFE, Culham Science Centre, Abingdon, UK
HOBIRK, Joerg	Max-Planck-Institut für Plasmaphysik, Germany
JOFFRIN, Emmanuel	CEA, IRFM, St Paul Les Durance, France
KAPPATOU, Athina	Max-Planck-Institut für Plasmaphysik, Germany
LERCHE, Ernesto	Laboratory for Plasma Physics, ERM/KMS, Brussels, Belgium
MAGGI, Costanza	UKAEA, CCFE, Culham Science Centre, Abingdon, UK
MAILLOUX, Joelle	UKAEA, CCFE, Culham Science Centre, Abingdon, UK
NOWAK, Silvana	Istituto per la Scienza e la Tecnologia dei Plasmi- CNR Milano Italy
RIMINI, Fernanda	UKAEA, CCFE, Culham Science Centre, Abingdon, UK
VAN EESTER, Dirk	Laboratory for Plasma Physics, ERM/KMS, Brussels, Belgium

And JET contributors
See the author list of ‘*Overview of JET results for optimising ITER operation’* by J. Mailloux et al in *Nucl. Fusion* **62** 042026 (2022)

Contents

AIM: Survey of disruption paths found in high performance scenarios at JET with ITER-like Wall with different Isotope mix (D,T)

Present approach:

Introduction to most frequent disruptive paths:

- Overview of “a-posteriori” disruption rate in D,T, DT
- Incidence of disruption paths

Analysis of plasma profiles at the occurrence of given events

Attempt to describe effects of the Power balance in the disruption patterns

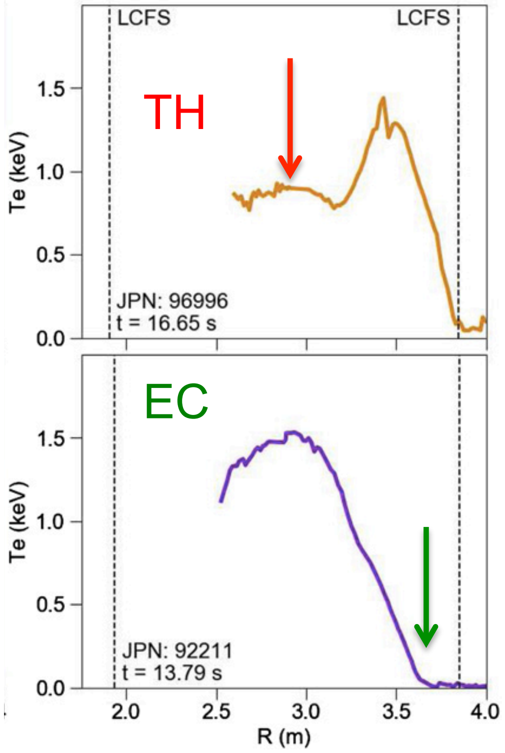
Incidence of disruption paths

- Majority of disruptions in JET-ILW follows two main paths
- Disruptions occur after events detectable from temperature profiles (see G.Pucella, this meeting)
  - Temperature Hollowing, **TH**

    strictly related with high Z impurities accumulating in the plasma core. The increased radiation loss deteriorates the electron temperature (T_e) profile leading to a local minimum at plasma axis
  - Edge Cooling, **EC**

    erosion of the edge T_e profile. It can be related to different causes:
    - Loss of density control
    - Sudden ingress of a large amount of impurities
    - Accumulation in the edge of mid/high Z-impurities
    - Operational issues (loss of additional heating and/or over-injection of gas)

- Incidence in D,T,DT experiments



From *G.Pucella, NF 2021*

Disruption paths in JET experiments (D)

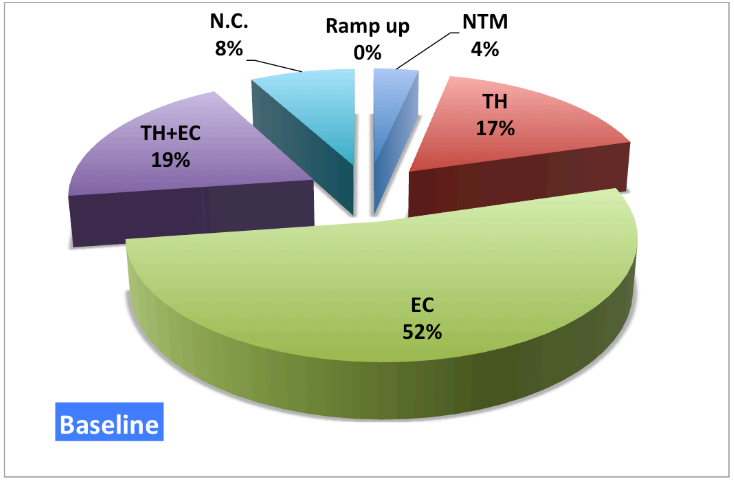
High performance experiments performed in Baseline (q_{95}~3, β_N~1.8; **BL**) and Hybrid (q_{95}~4, β_N~2-3; **Hyb**) scenarios [*L. Garzotti NF 2019*]

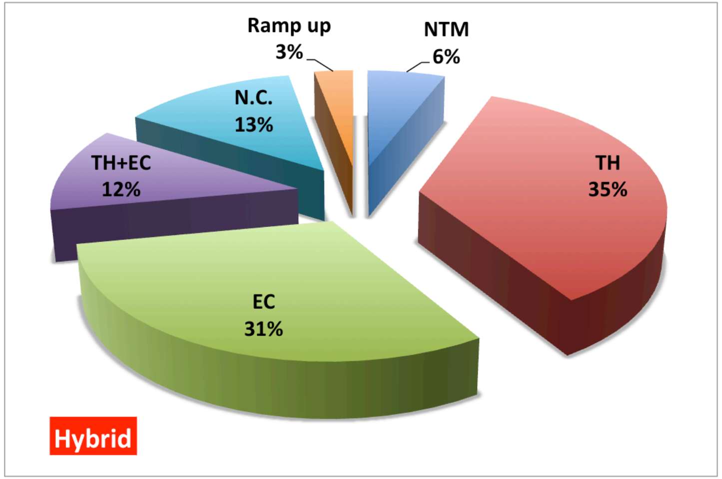
Mitigation actions are activated for alarm at **I_p>2MA** [*C.Sozzi IAEA-FEC 2020*].

In last High performance D experimental campaign (2018-2020):

- BL: 390 pulses, overall **disruption rate** ~31% (21% DMV fired)
- Hyb: 422 pulses, overall **disruption rate** ~19% (2% DMV fired)

Incidence **of disruption paths**: TH and EC are the dominant events (~80-90%)





Disruptions in T, DT experiments

- T, DT experiments in main scenarios performed at fixed Flat Top I_p levels:
  - 2.3MA for Hybrid scenario (T: 12 pulses, 11 disruptions -1 DMV fired; DT: 32 pulses, 15 disruptions -2 DMV fired)
  - 3MA and 3.5MA for Baseline scenario (T: 8 pulses, 8 disruptions –all DMV fired; DT: 23 pulses, 13 disruptions -11 DMV fired)

Reduced dataset:

Isotope	Hybrid scenario	Baseline scenario
D	13, 4 (124)	39, 34 (150)
T	5, 0 (9)	4, 4 (4)
DT	10, 1 (23)	9, 9 (12)

Disruptions, DMV firings (Pulses)

- Discharges lasting >2s in main performance phase: FT with additional heating >20MW;
- *Disruptions at high Plasma current:*
  $I_{p,dis} > 0.6 * I_{p,FT}$
- Considering D experiments with same $I_{p,FT}$ of T, DT campaigns

Disruption paths in T, DT

Disruption paths in this dataset ($I_{p,dis}$>0.6*$I_{p,FT}$) have larger incidence (close to 100%) of TH, EC events (or a combination of both).
Each of the two scenarios in T, DT is mainly characterized by a different type of disruption:

- in *Baseline* T and DT, **EC** disruptions have larger incidence
- In *Hybrid* DT, disruptions occur after a **TH** in the *ramp-down phase*

Incidence of TH,EC events before disruption

Event Incidence #	D Hyb	D BL	T Hyb	T BL	DT Hyb	DT BL
TH	11	20	4	0	9	0
EC	6	31	1	4	3	9

Kinetic profiles

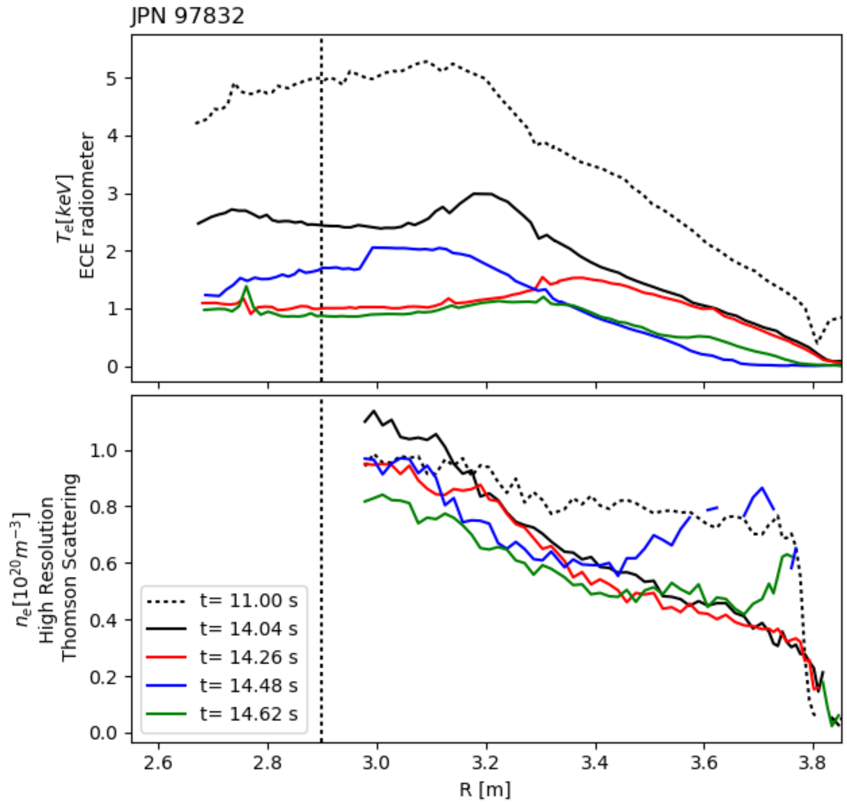
T_e profile from heterodyne radiometer

n_e profile from High resolution Thomson scattering

A case with TH followed by EC triggering a 2/1 mode and disrupting

Profiles shown at:

- **Flat top**
- **Before** (last) **TH** event and in termination
- **Temperature Hollowing**
- **Edge Cooling**
  - At the edge: erosion of T_e and increase of n_e
- **Before disruption**



Parameters from Temperature profile

Study kinetic profiles by looking at <u>volume averaged quantities</u> within:

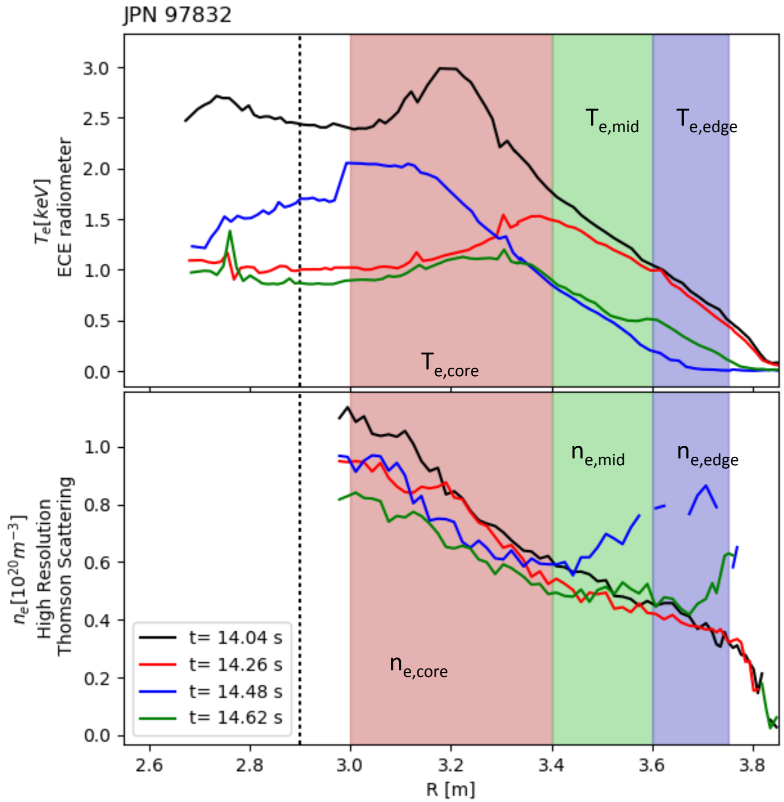
- Core: 3. -3.4m
- mid radius: 3.4-3.6m
- Edge: 3.6-3.75m

Temperature Hollowing events for $$TH = \frac{5 < T_e >_{mid}}{< T_e >_{core}}$$ >4

Edge cooling events for $$EC = \frac{< T_e >_{mid}}{< T_e >_{edge}}$$ >4

Temperature peaking $$TP = \frac{3 < T_e >_{core}}{< T_e >_{core} + < T_e >_{mid} + < T_e >_{edge}}$$

-> relation with other similar parameters used in literature [*Alessi EPS 2018, Challis NF 2020*]



Parameters from density profile

Study kinetic profiles by looking at volume averaged quantities within:

- Core: 3. -3.4m
- mid radius: 3.4-3.6m
- Edge: 3.6-3.75m

Density peaking (DP):

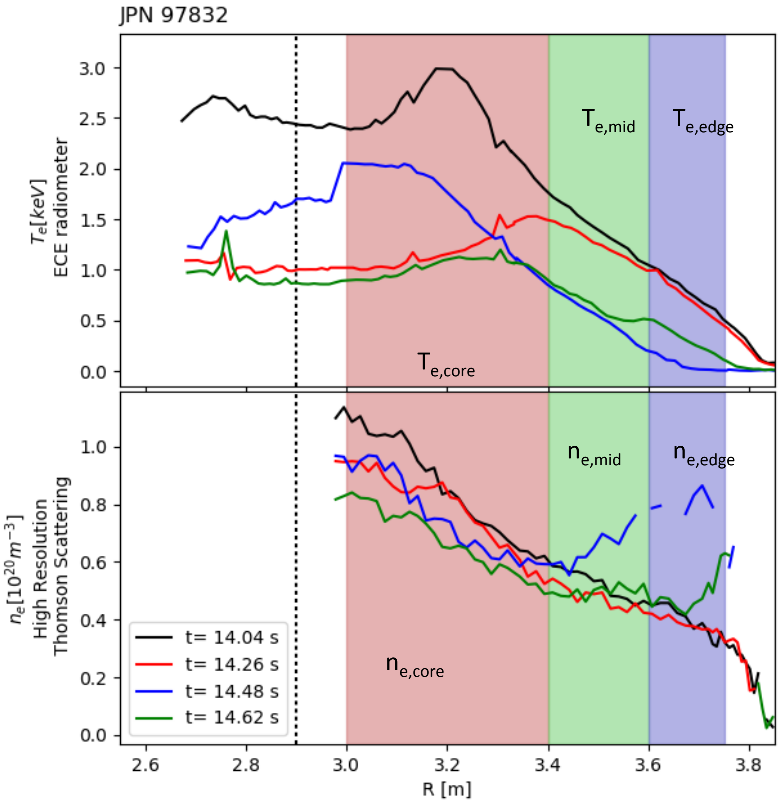
$$DP = \frac{<n_e>_{core} - <n_e>_{edge}}{<n_e>_{mid}}$$

Greenwald Fraction (GF)
To neglect I_p as variable in the analysis

$$GF = \frac{\bar{n}_{e,l}}{n_{Greenwald}}$$

From an expression of the line averaged density:

$$\bar{n}_{e,l} = 0.53 <n_e>_{core} + 0.27 <n_e>_{mid} + 0.2 <n_e>_{edge}$$



Example of a disruption path

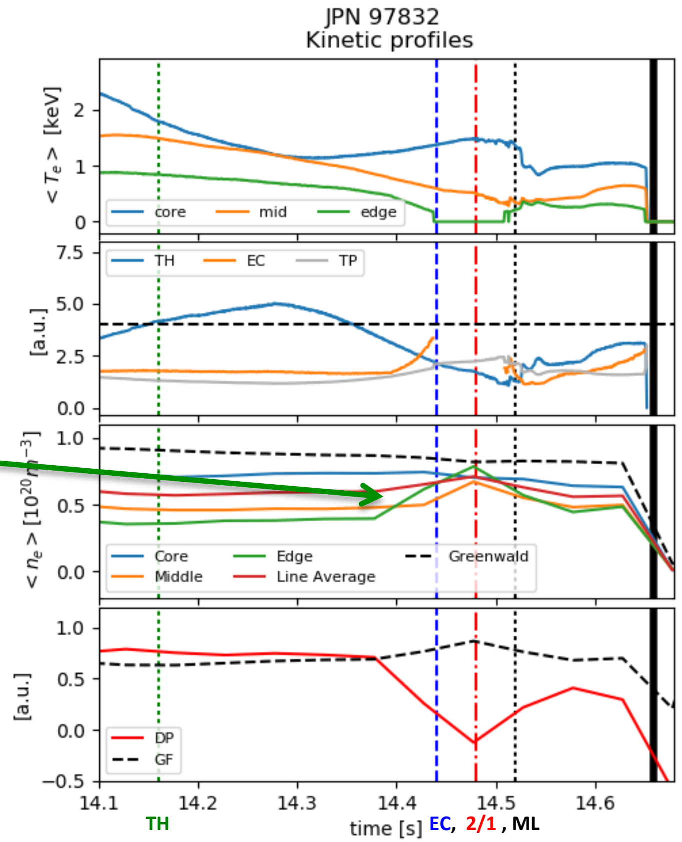
Termination phase
3 TH events -> EC -> 2/1 onset **-> locking**
-> Profiles relaxation -> disruption induced by DMV

Highlights:
At TH, peaked density profile (see bottom, DP).

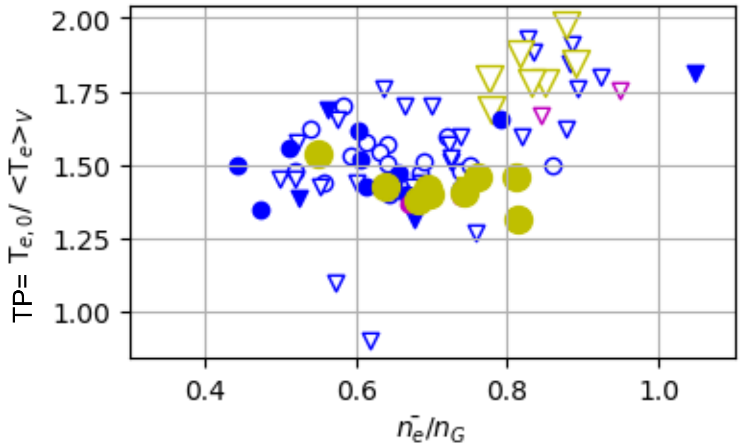
Before EC, GF ↑ DP ↓ => $n_{e,edge}$ ↑.

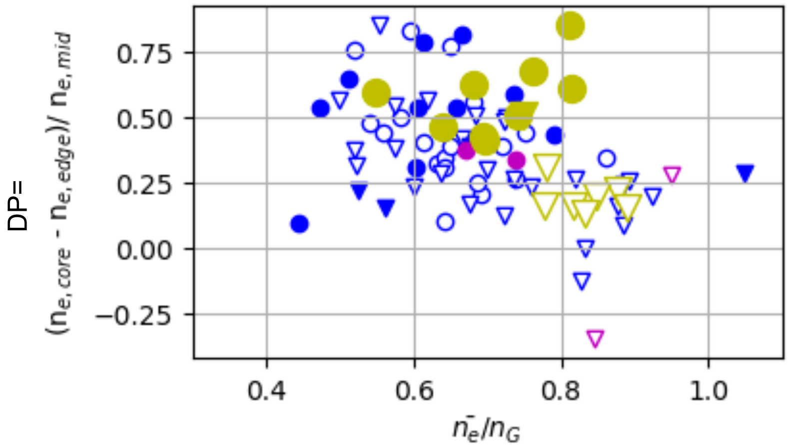
Rotating 2/1 mode is triggered at max GF (min DP)

How general is such a picture?



Profiles at events





Hybrid: solid markers; Baseline: open markers. D, T, DT **Triangles: EC event, Circles: TH event**

Baseline:

TH event

EC event

D **T** **DT**

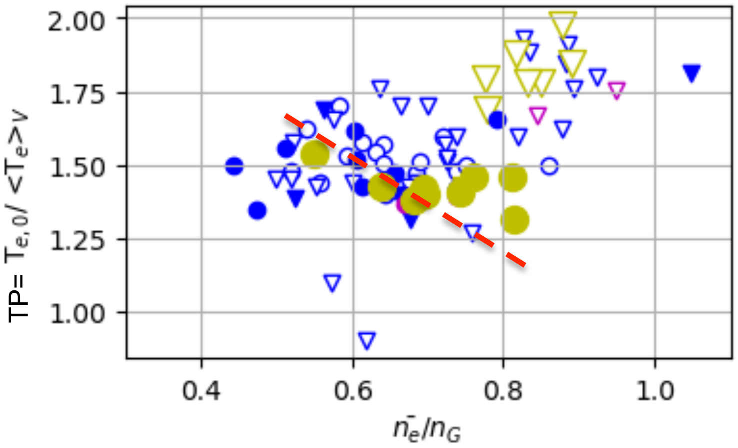
Hybrid:

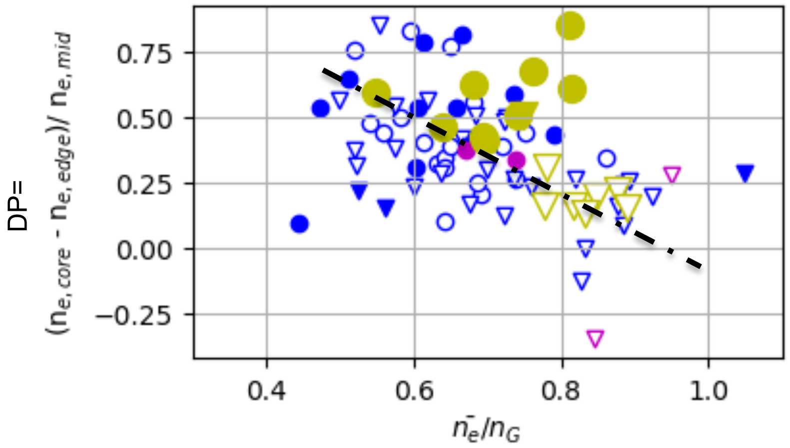
TH event

EC event

D **T** **DT**

Profiles at events





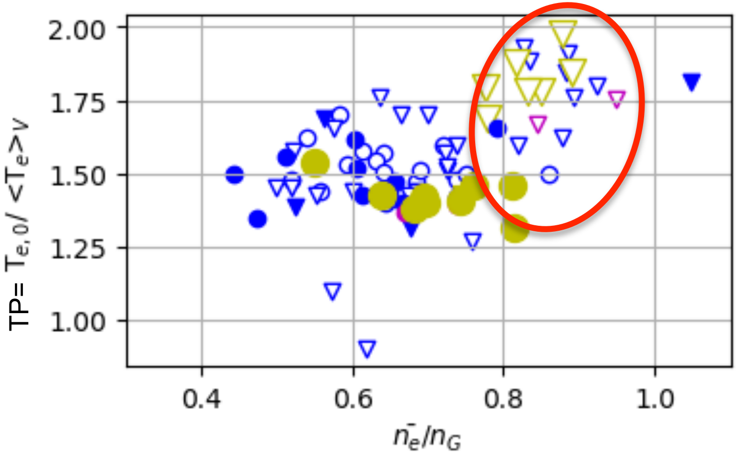
Hybrid: solid markers; Baseline: open markers. D, T, DT **Triangles: EC event, Circles: TH event**

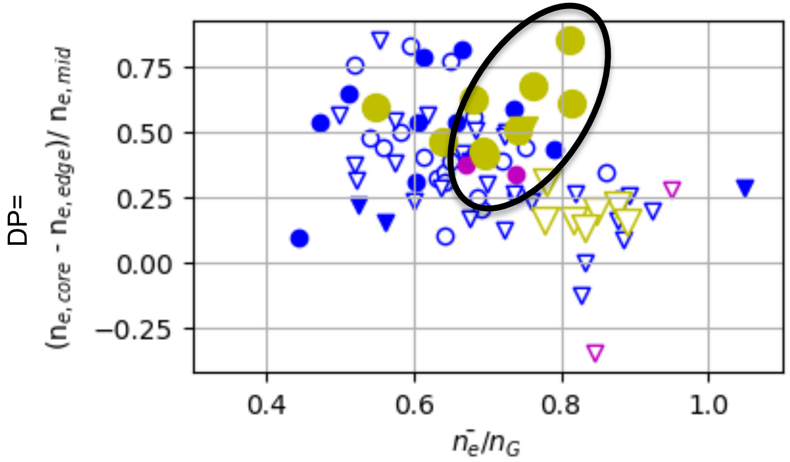
General relationships:

GF ↑ TP ↓

GF ↑ DP ↓

Profiles at events





Hybrid: solid markers; Baseline: open markers. D, T, DT **Triangles: EC event, Circles: TH event**

For a cluster of EC events (all Baseline in T, DT):

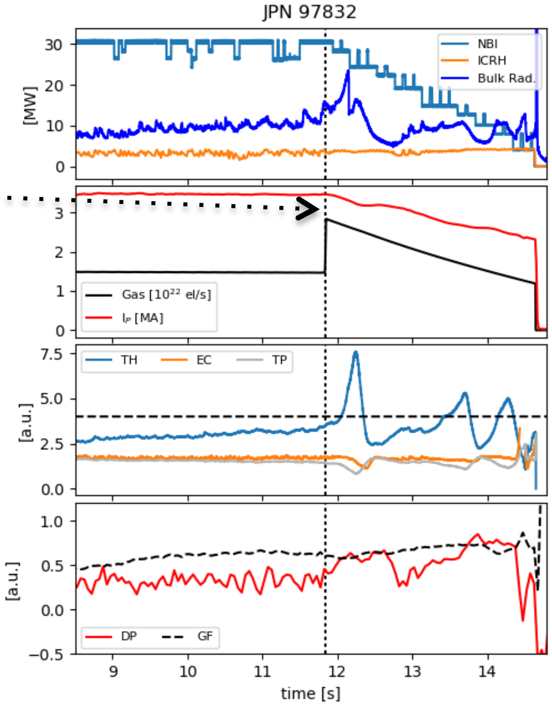
GF ↑ TP ↑

DT Hybrid TH events show a relationships:

GF ↑ DP ↑

Power Balance

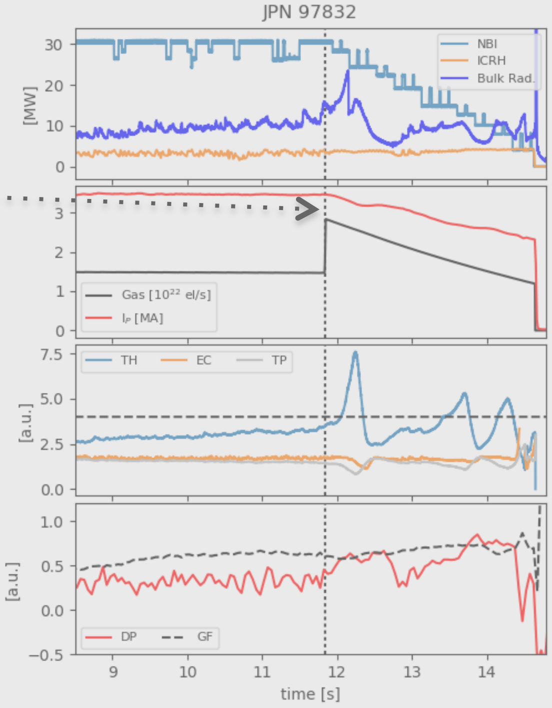
RT control system trigger a soft landing because of high radiation



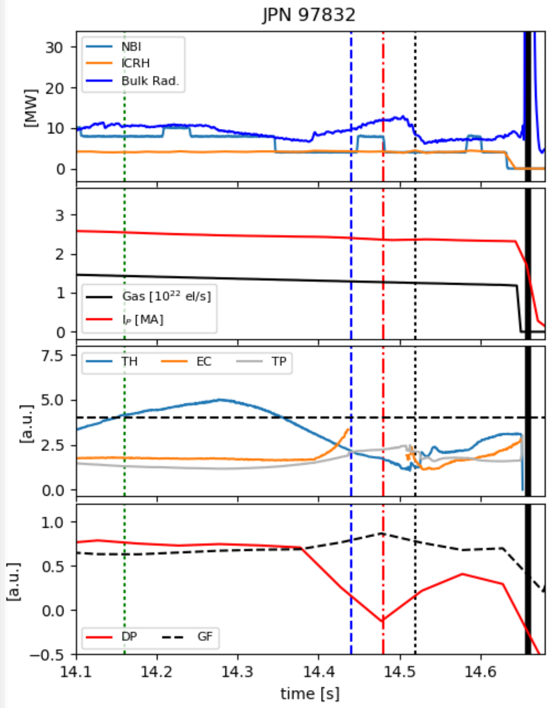
Discharge survives to three TH events in landing

Power Balance

RT control system trigger a soft landing because of high radiation



Three TH events in landing



radiation > additional heating
⇒ EC
⇒ Mode lock alarm fires DMV
⇒ Disruption

Power Balance

Attempt of taking into account how termination strategy interferes with the disruption path:

-> Pictures of Power balance and density levels at 3 times:

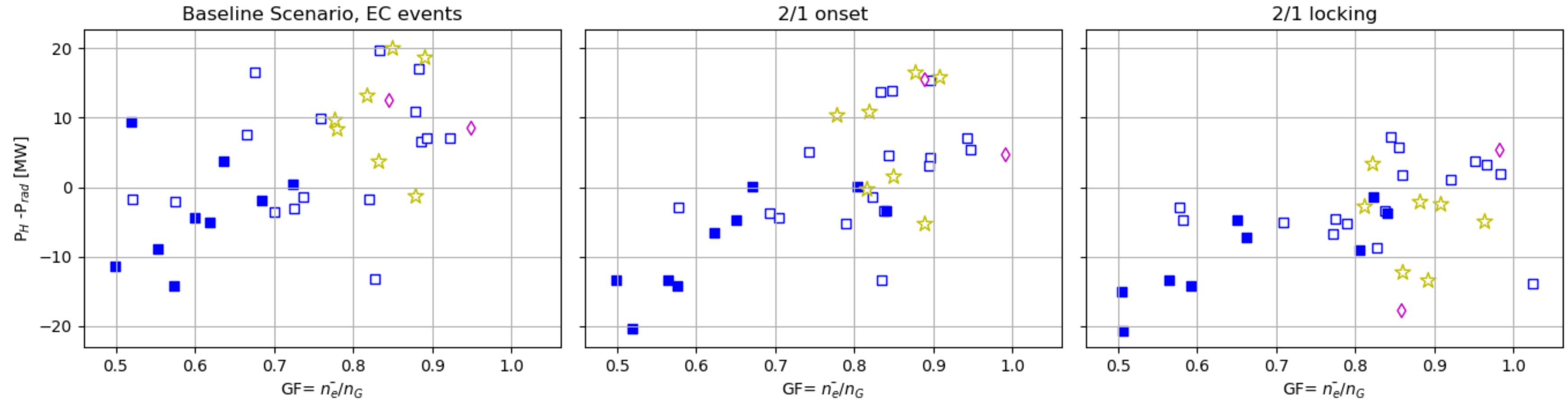
- Occurrence of a TH or a EC event
- 2/1 onset
- 2/1 Locking to wall

-> changes of characteristic timing with the power balance

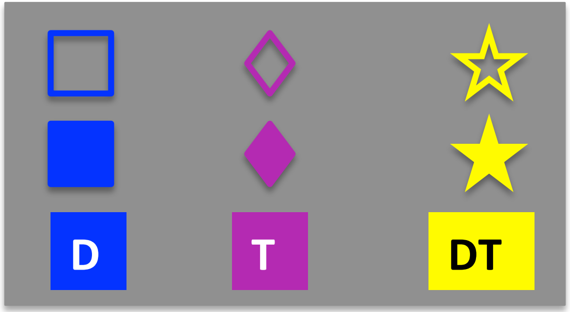
Most relevant Events for scenario:

- EC cases in Baseline
- TH cases in Hybrid

Power balance for EC cases in Baseline



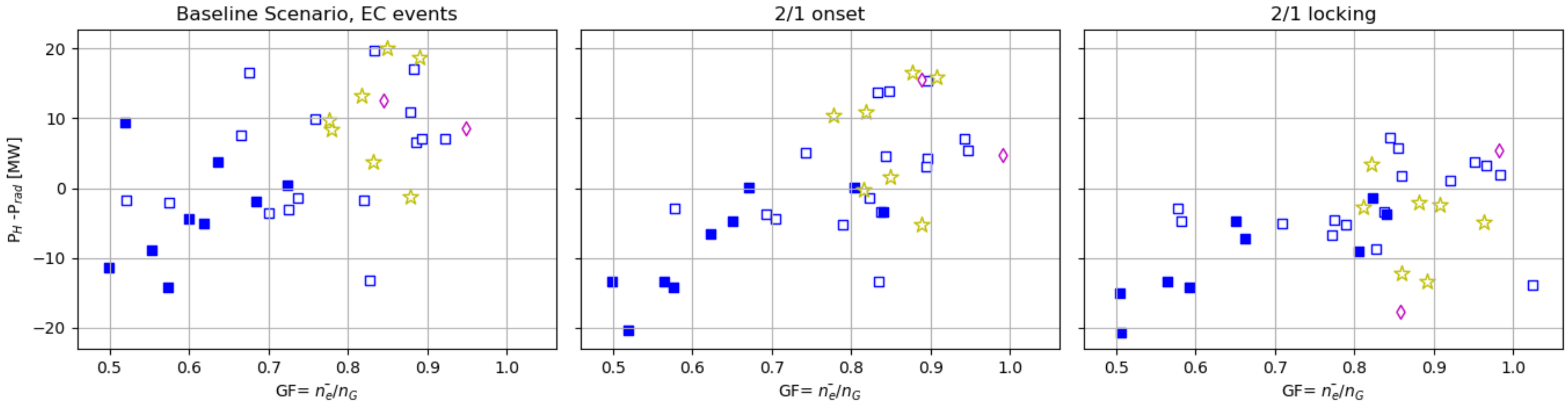
EC cases occurring after a TH are highlighted (solid markers). In this cases, EC typically occur for net radiation loss.
Power balance averaged 100ms before each event



Pure EC events

EC events following TH

Power balance for EC cases in Baseline

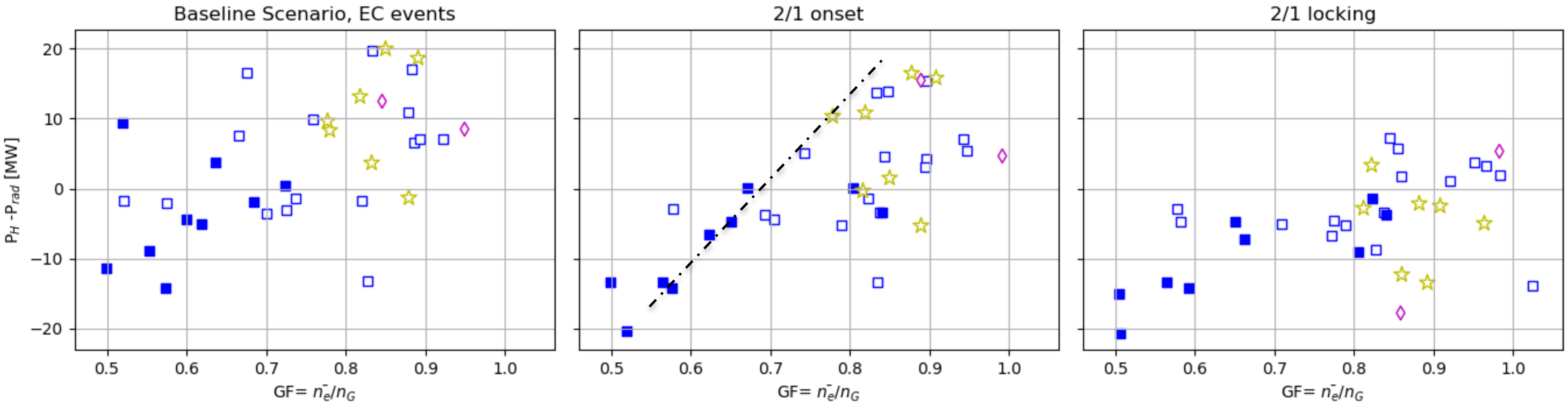


EC cases occurring after a TH are highlighted (solid markers). In this cases, EC typically occur for net radiation loss.

Sequence of events

Net heating power becomes negative before the locking of the 2/1 mode

Power balance for EC cases in Baseline



EC cases occurring after a TH are highlighted (solid markers). In this cases, EC typically occur for net radiation loss.

Notice Stable and unstable region for the 2/1 onset

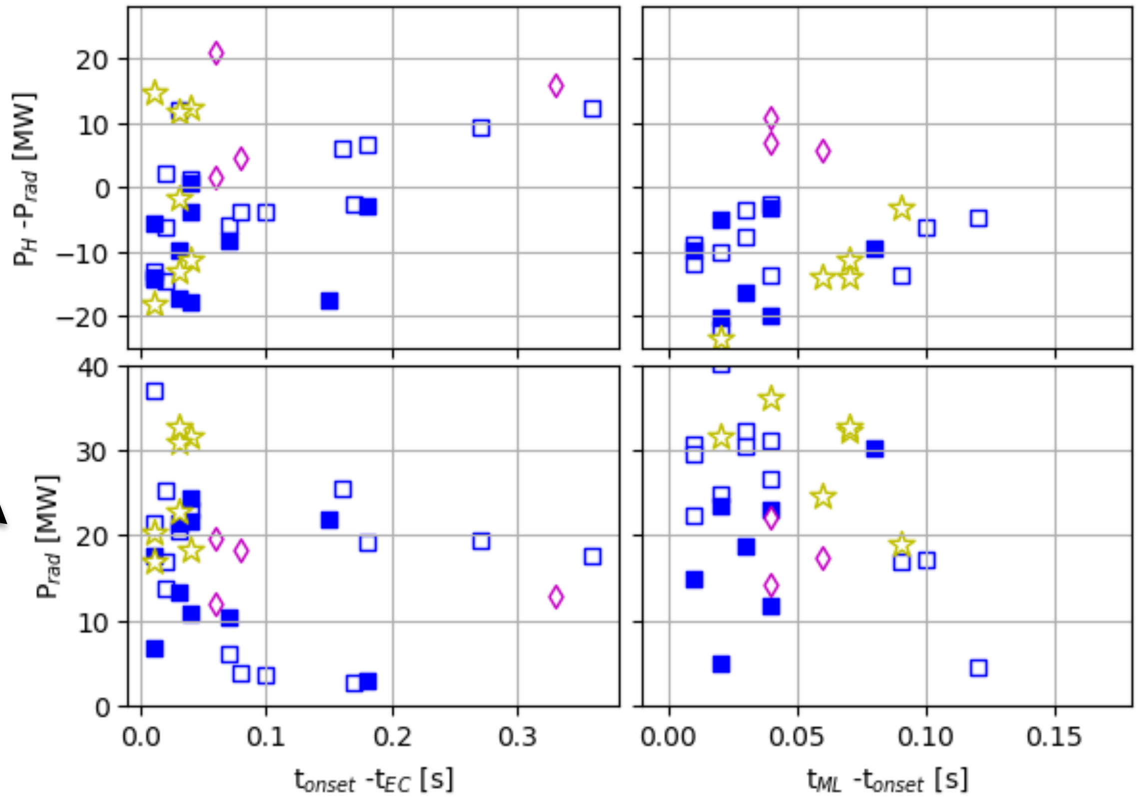
Threshold:

P_H-P_{Rad} ~ n_e => hint of localized radiation

Power balance between events

Effects of Power balance on timing
Average between events

- radiation increases from 2/1onset to locking



(powers evaluated by averaging between events)

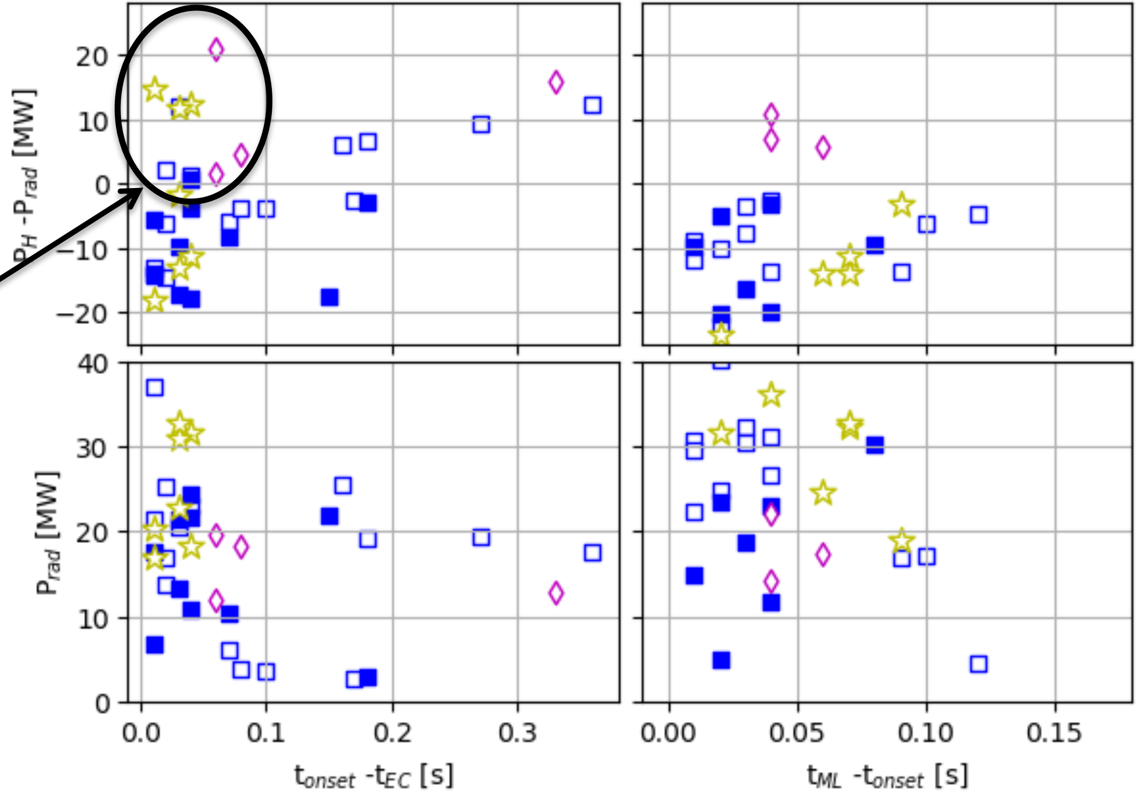
Power balance between events

Effects of Power balance on timing
Average between events

- radiation increases from 2/1onset to locking

- In T, DT Power heating seems less effective

(powers evaluated by averaging between events)

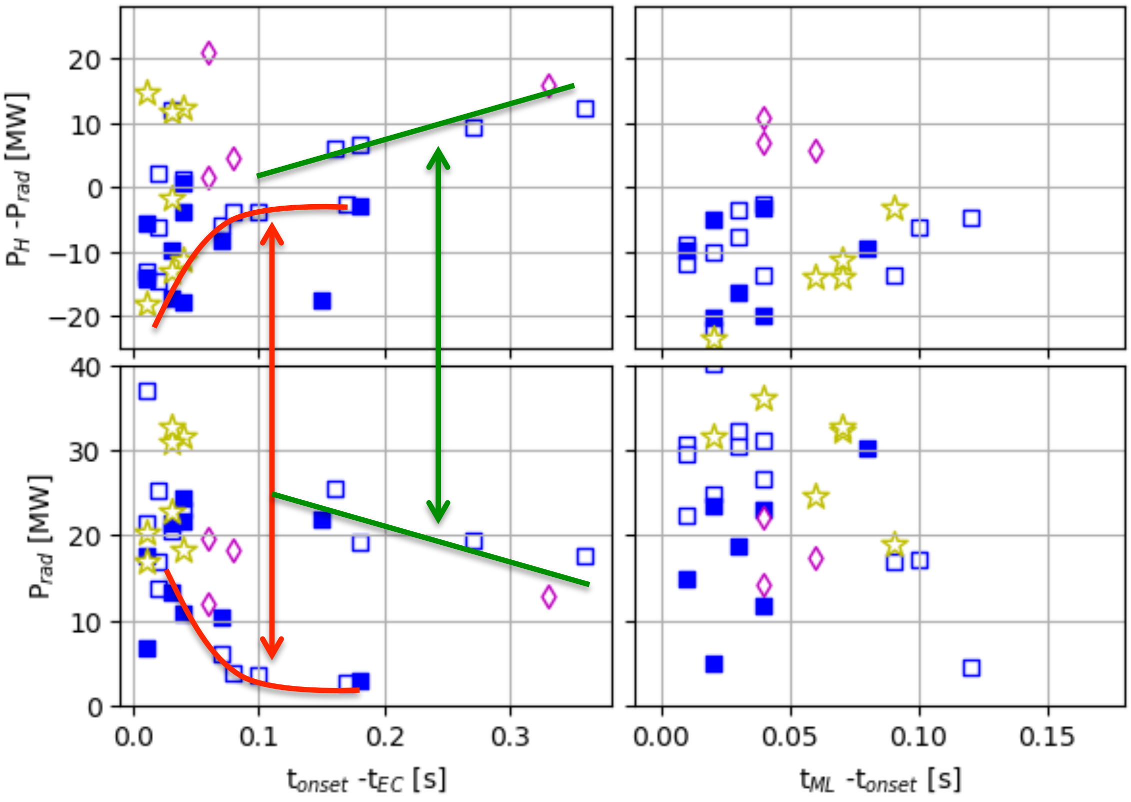


Power balance between events

Effects of Power balance on timing
Average between events

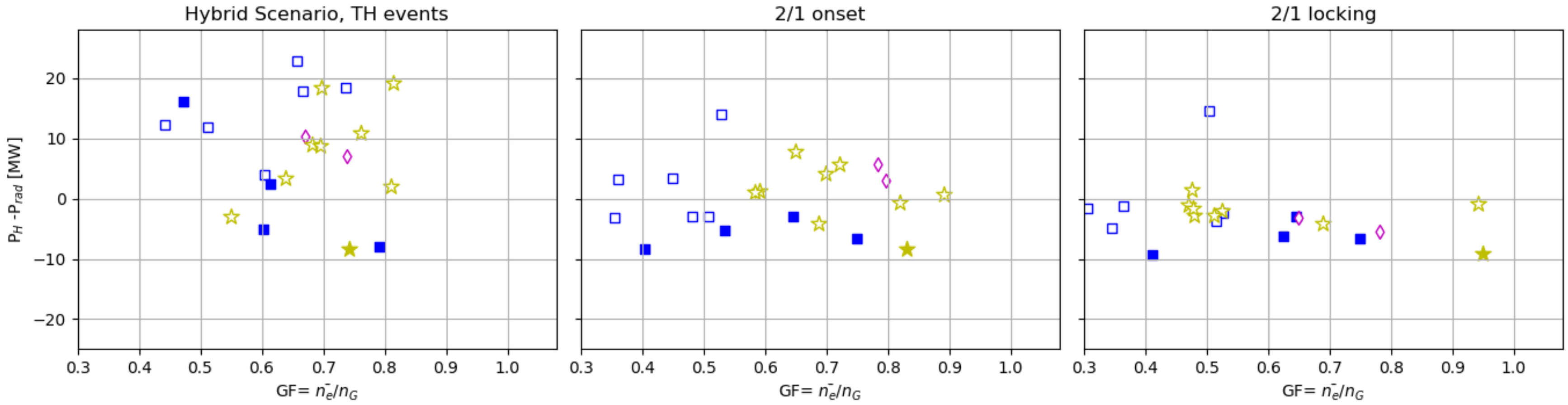
- In cases without heating, timing at 2/1 onset depend on the average P_{Rad}

- A population of mild radiated power sensitive to heating power

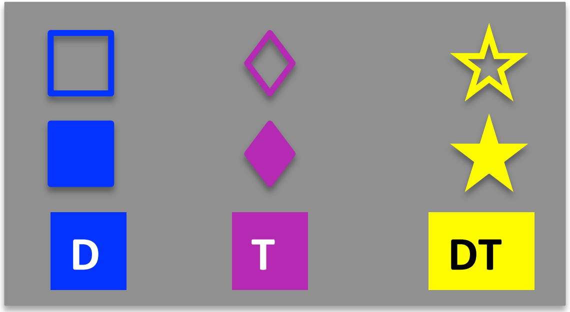


(powers evaluated by averaging between events)

Power balance for TH cases in Hybrid



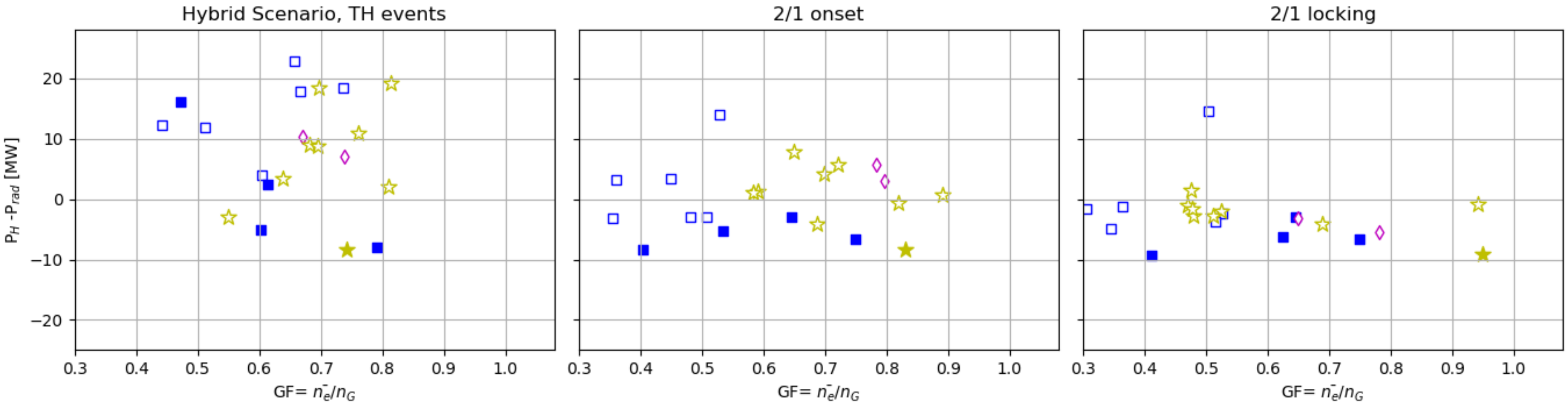
Same symbols as before but for TH events in Hybrids. Pure TH: open symbols, TH followed by EC before 2/1 onset: solid.



Pure TH events

An EC event occur before the 2/1 onset

Power balance for TH cases in Hybrid



Same symbols as before but for TH events in Hybrids. Pure TH: open symbols, TH followed by EC before 2/1 onset: solid.

Sequence of events →

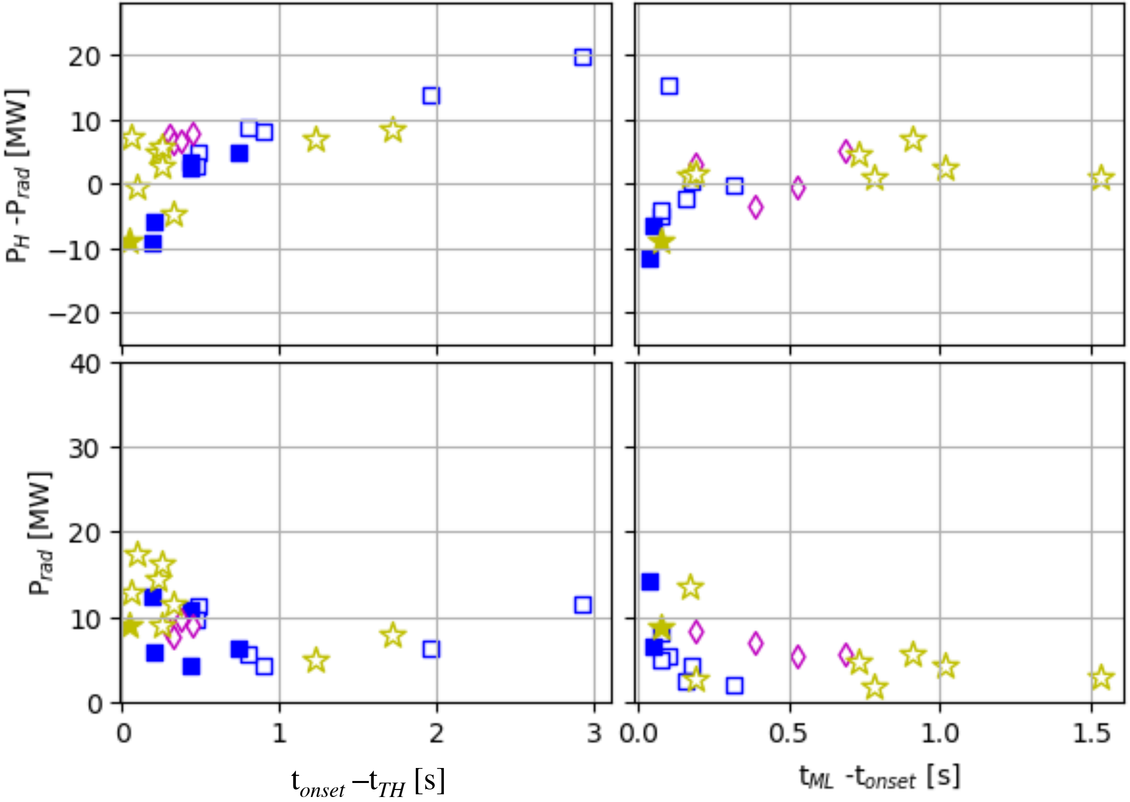
Mode locking happens when P_H-P_{Rad}<0

Power balance between events

Longer intervention times

D:

- Qualitative effect of additional power on delaying 2/1 onset



Power balance between events

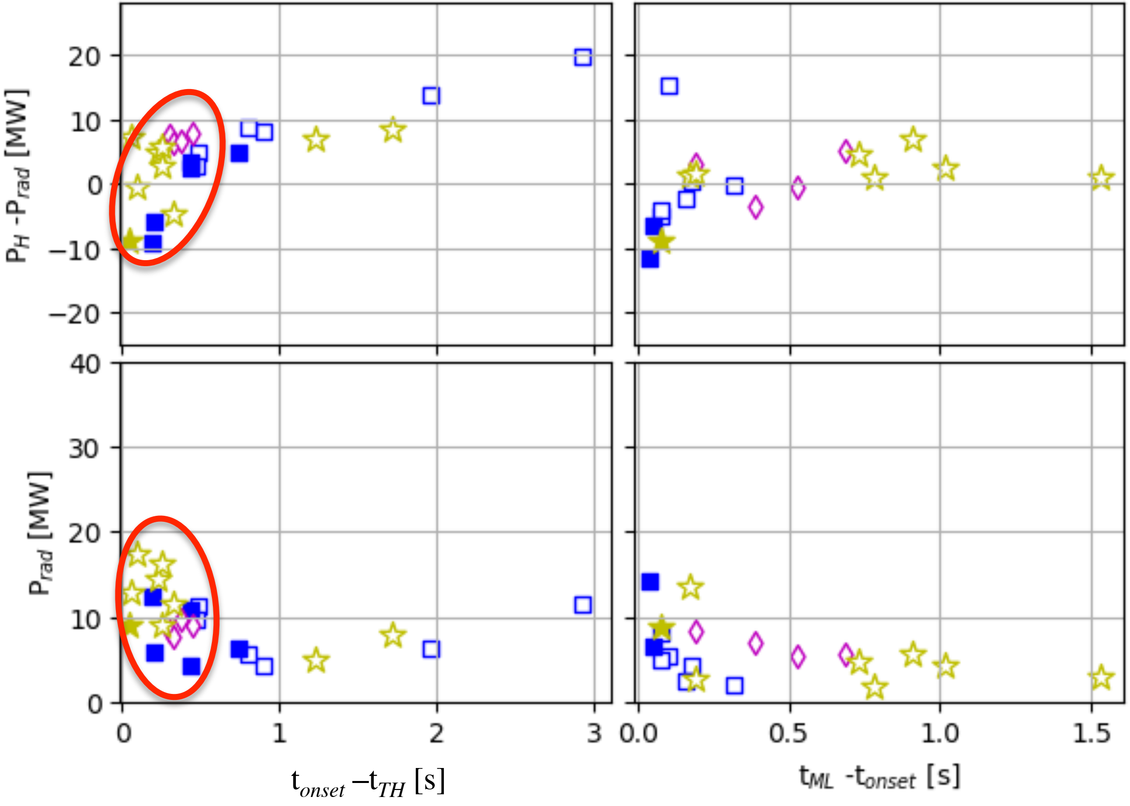
Longer intervention times

D:

- Qualitative effect of additional power on delaying 2/1 onset

T, DT:

- higher radiation losses
- Heating power less effective in delaying 2/1 onset



Power balance between events

Longer intervention times

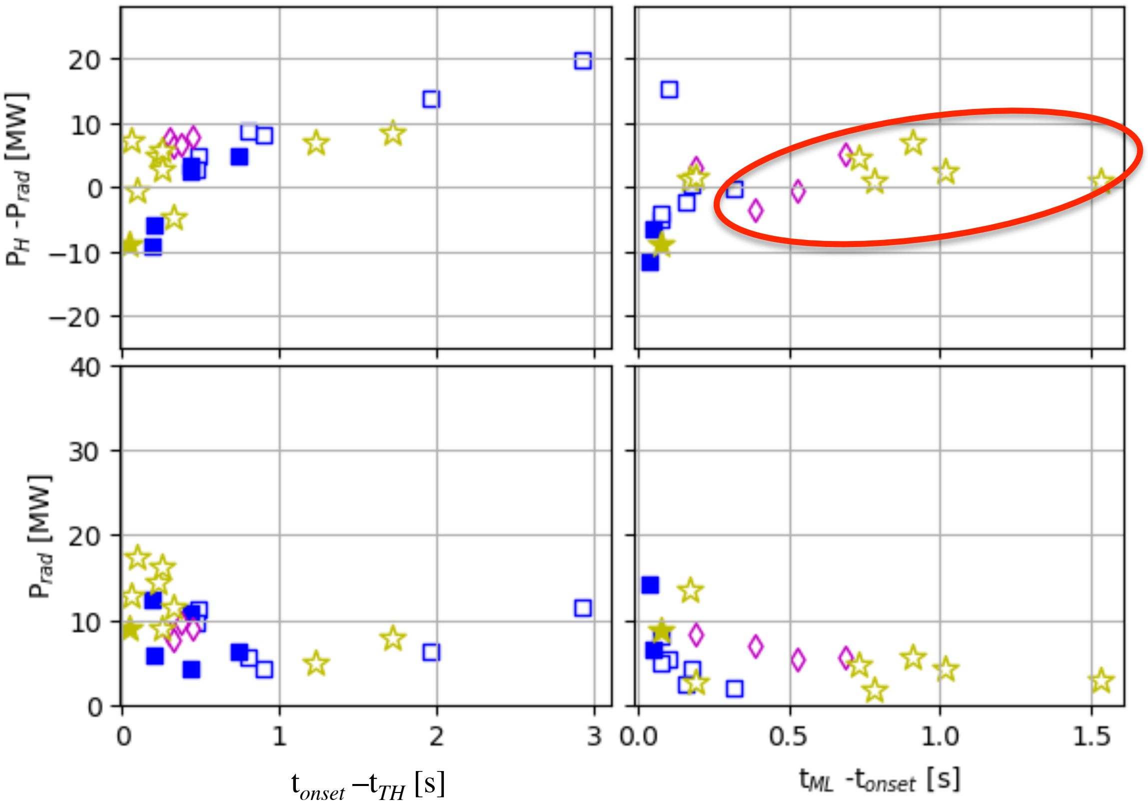
D:

- Qualitative effect of additional power on delaying 2/1 onset

T, DT:

- higher radiation losses
- Heating power less effective in delaying 2/1 onset
- More effective in delaying locking

It may depend on optimization of termination strategy.



Summary

Present observations are intended to provide a first insight on how disruptive phenomena at JET may change with the Isotope content [*C.Sozzi IAEA-FEC 2020*].

Limits in the present analysis are:

- A more complete picture would require adding information on the current density profiles, in particular at time of the 2/1 onset
- Power balance vs density shown considering “global” quantities.
  - Local estimates of radiated and heating power as well as of the density should provide better pictures and separation between different disruption paths
- Disruption rate and conditions can be affected by the RT control system
  - Detailed analysis to remove possible correlation between termination strategy and the relationships found between parameters

JET RT control system was updated [*L.Piron FED 2022*] for DT operation in JET with advanced algorithms for disruption avoidance and mitigation:

- A Temperature Hollowness detector [*M.Fontana FED 2021*] (saving disruptions in ramp-up)
- RT detector based on a Generative Topographic Mapping trained with input information on density, temperature and radiation profiles [*A. Pau NF 2019*] -> probability of disrupting
- RT bolometry tomography algorithm estimating the amount of radiation from different plasma regions [*D.Ferreira FED 2021*]

Summary

Disruptions in JET-ILW often follow a TH or a EC event, or a sequence of TH, EC.

Information from radiation and density profile are added to parameters taking into account the shape of T_e profile

Two main categories of EC can be identified:

- first category is characterized by high density (in particular at the ***plasma edge***), high radiation and by the peaking of the T_e profile;
- Second category usually occur after a TH event and is characterized by negative power balance.

In T, DT experiments:

- Disruptions are generally characterized by higher radiation, and shorter lag times from a TH/EC event to the onset of a 2/1 mode are observed
- In T, DT Hybrid scenario, disruptions follow the TH path in the landing phase, showing also a density peaking. Positive power balance after the 2/1 onset is seen to avoid locking for up to 1s.
- In T, DT Baseline scenario disruptions follow mainly the EC path -first category- with higher radiation and densities which resulted in reducing the available time for intervention.

Thank you for your attention

Disruption paths in T, DT

Disruption paths in this dataset ($I_{p,dis}$>0.6*$I_{p,FT}$) have larger incidence (close to 100%) of TH, EC events (or a combination of both).

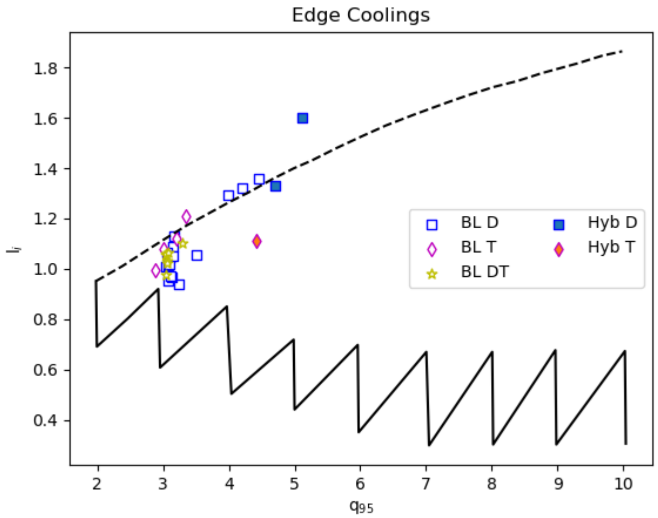
Each of the two scenarios in T, DT is mainly characterized by a different type of disruption:

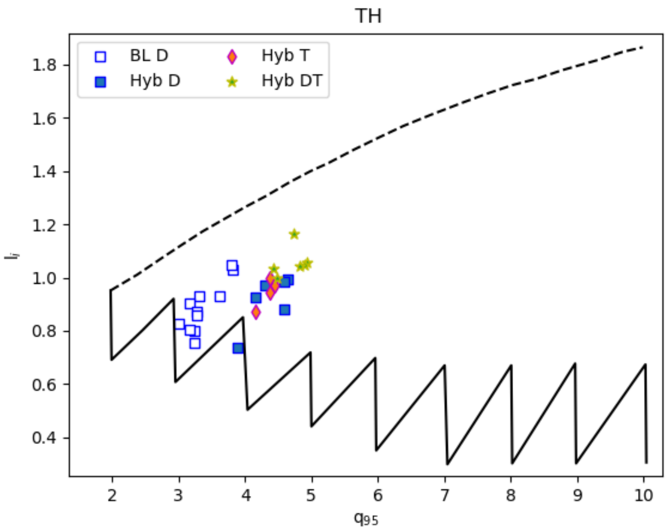
- in *Baseline* T and DT, **EC** disruptions have larger incidence
- In *Hybrid* DT, disruptions occur after a **TH** in the *ramp-down phase*

Incidence of TH,EC, TH+EC disruptions

DIsruptions #	D Hyb	D BL	T Hyb	T BL	DT Hyb	DT BL
TH	7	7	4	0	6	0
EC	2	18	1	4	0	9
TH + EC	4	13	0	0	3	0
Other Causes	0	1	0	0	1	0

2/1 onset conditions





2/1 onset after a TH event can be poorly predicted by the l_i. This is likely due to non-monotonic current density profiles, a condition in which the relationships between li and 2/1 stability is missing.

After EC, a set of cases is close to the limit related to shrinking of J inside the q=2 surface.

A second cluster is characterized by lower li values. This second cluster seem to be related with EC events found for higher $n_{e,l}/n_G$ and radiation asymmetry (ARP).