EUROfusion

Real-time applications of Electron Cyclotron Emission interferometry for disruption avoidance at JET

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A. Peacock, L. Piron, S. Schmuck and JET contributors

JET CCFE CULHAM CENTRE FOR FUSION ENERGY EPFL Swiss Plasma Center

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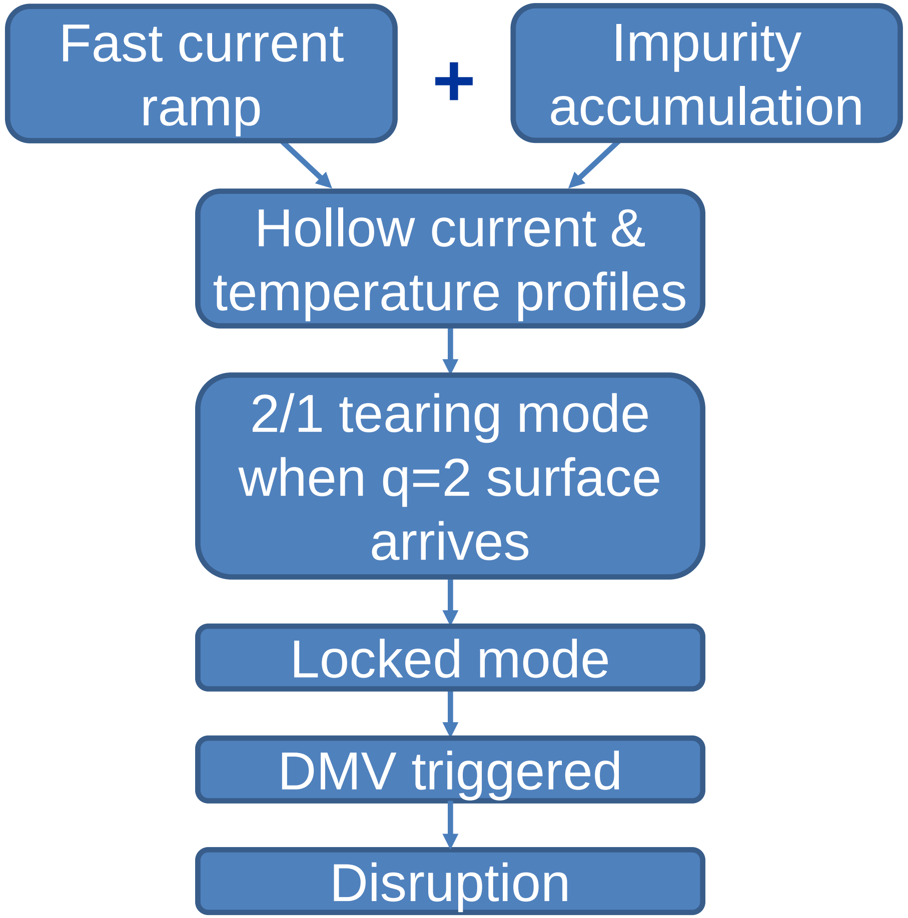
- **Motivation**
- Diagnostic

- First applications: plasma ramp-up
  - Peakedness metric definition
  - Application to experiments
- Future applications: plasma termination
  - Edge cooling metric definition
  - Tests on plasma terminations

- Conclusions

Motivation: T_e peaking related to disruptions

Typical sequence leading to disruptions during Ohmic ramp phase in high β_N D plasmas



Fast current ramp + Impurity accumulation

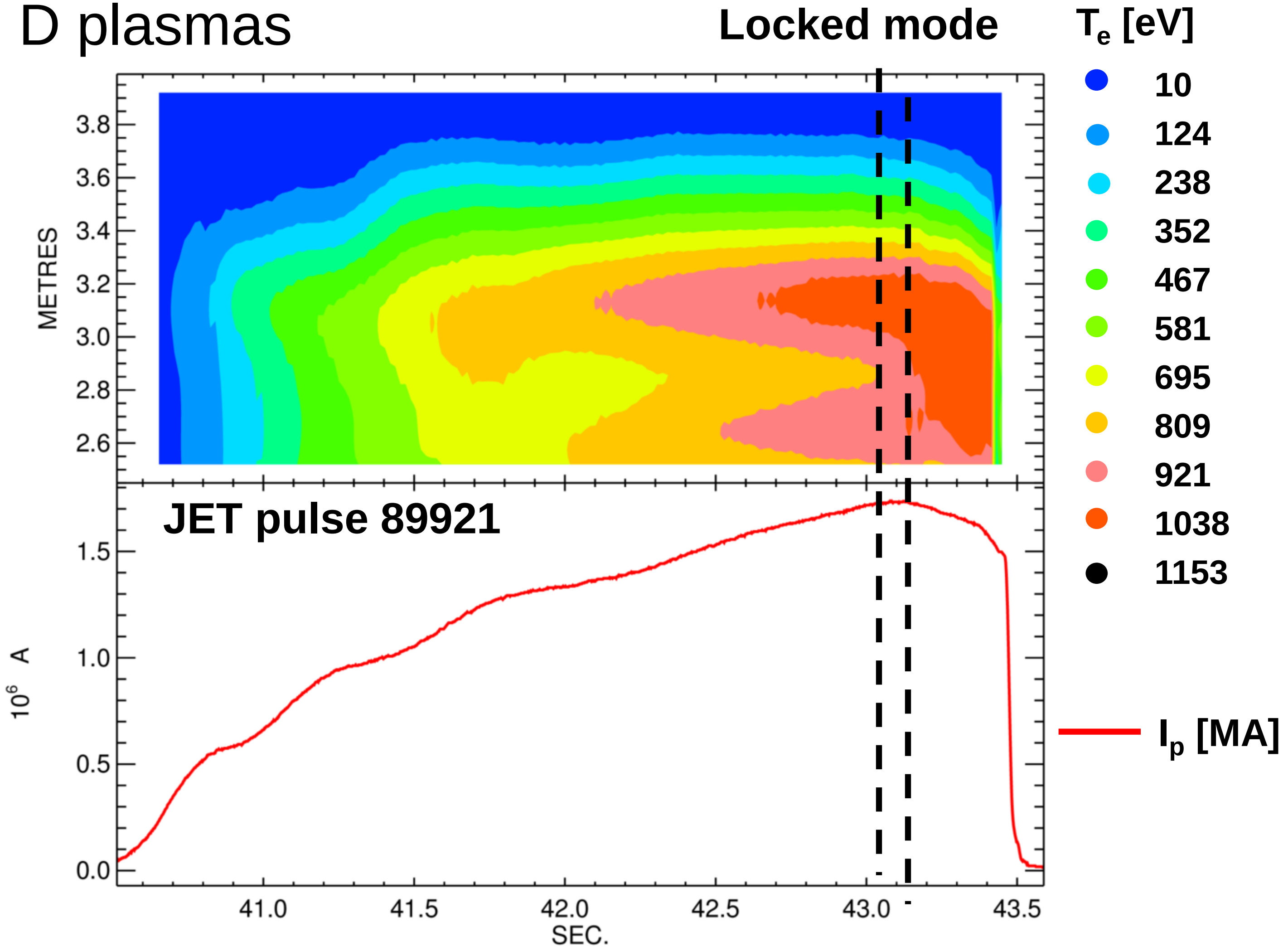
Hollow current & temperature profiles

2/1 tearing mode when q=2 surface arrives

Locked mode

DMV triggered

Disruption



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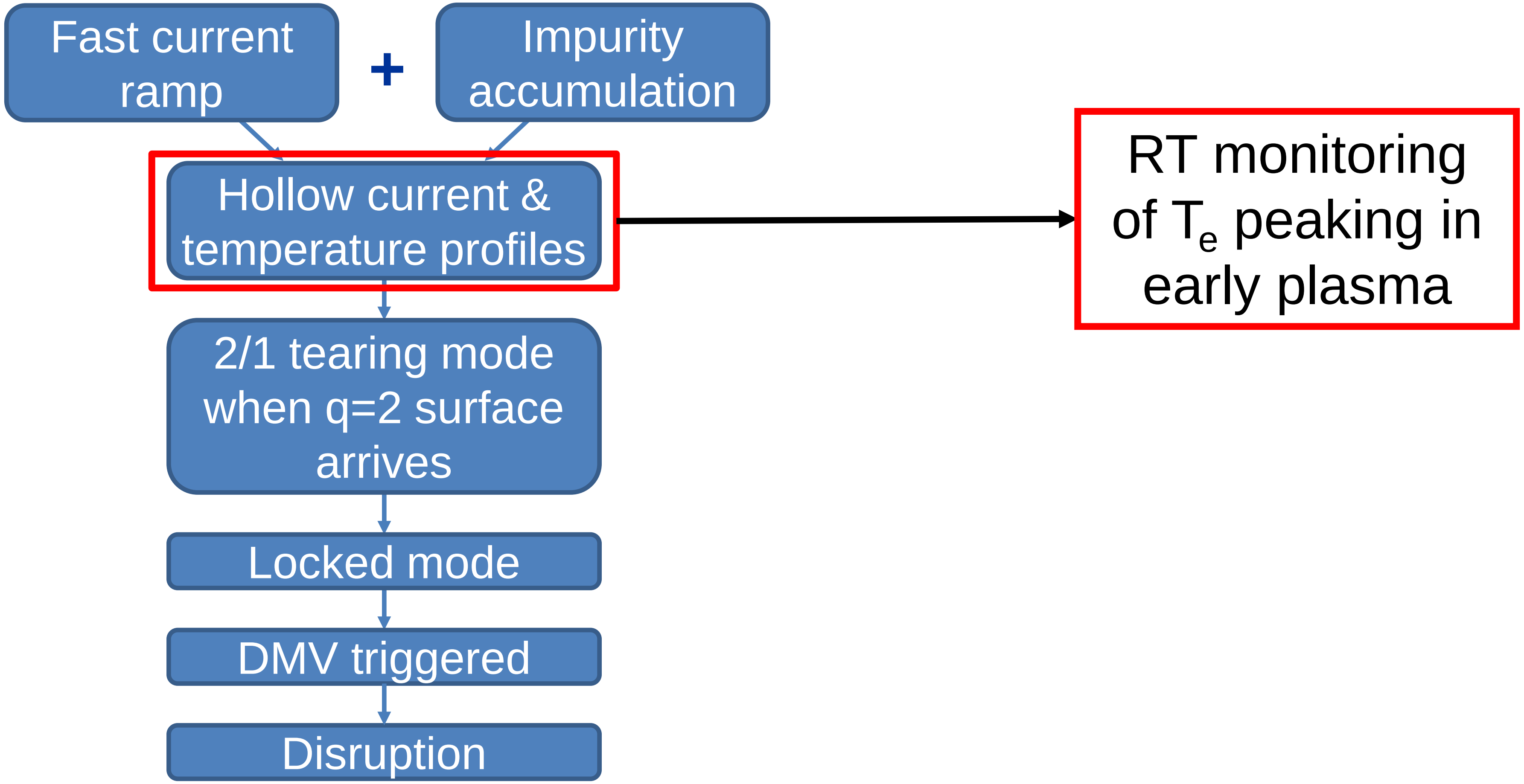

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RT monitoring of T_e peaking in early plasma

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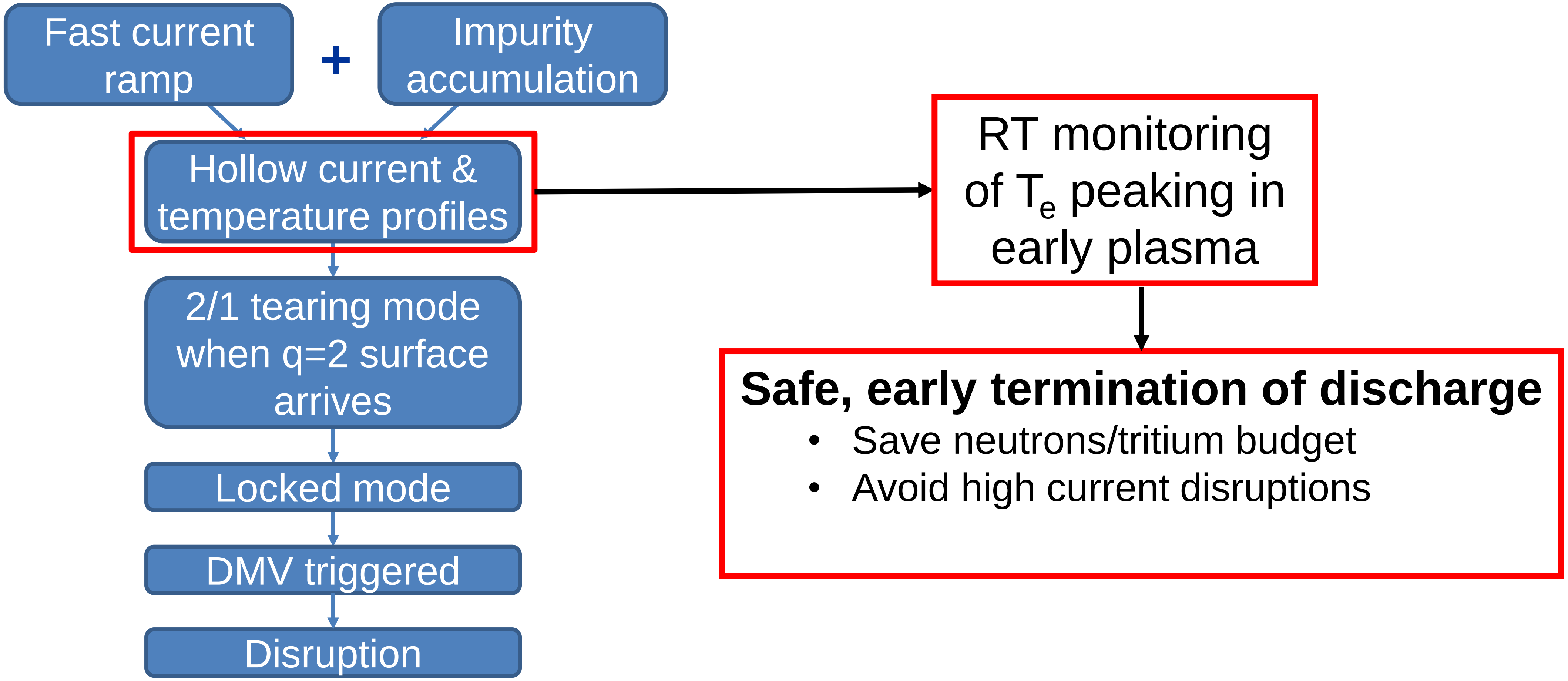

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RT monitoring of T_e peaking in early plasma

Safe, early termination of discharge

- Save neutrons/tritium budget
- Avoid high current disruptions

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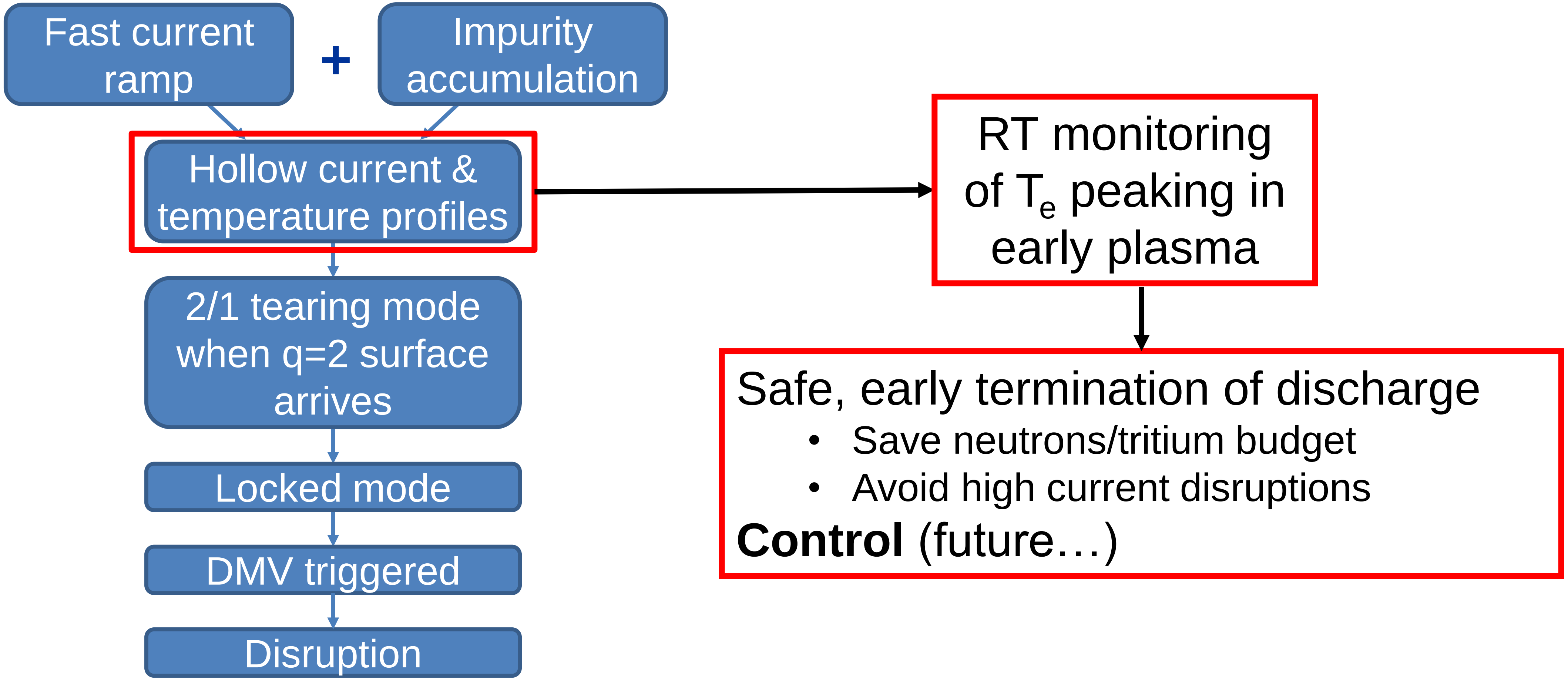

Fast current ramp

+

Impurity accumulation

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Disruption

RT monitoring of T_e peaking in early plasma

Safe, early termination of discharge

- Save neutrons/tritium budget
- Avoid high current disruptions

Control (future…)

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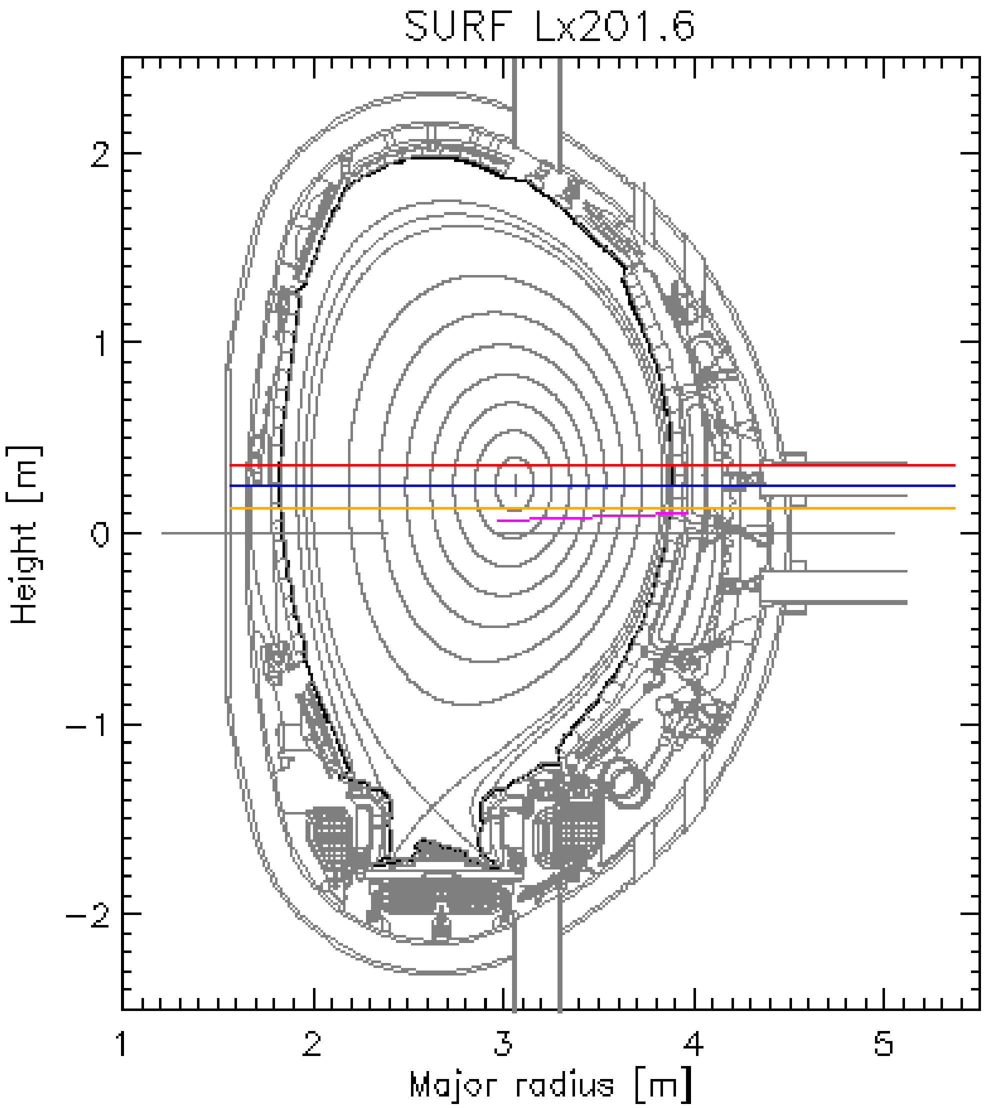
ECE interferometers at JET

JET ECE interferometers

[*S. Schmuck, RSI, 2016*]

- Absolutely calibrated T_e profiles covering [2.5 3.9] m
- Time resolution ~60 Hz (~16 ms/profile)
- X-mode and O-mode polarizations on two LOS.
- Used for ECE radiometer calibration



ECE interferometer X-mode (60 Hz)

ECE radiometer (5-200 kHz)

ECE interferometer O-mode (60 Hz)

High resolution Thomson scattering (30 Hz)

ECE interferometers at JET

JET ECE interferometers

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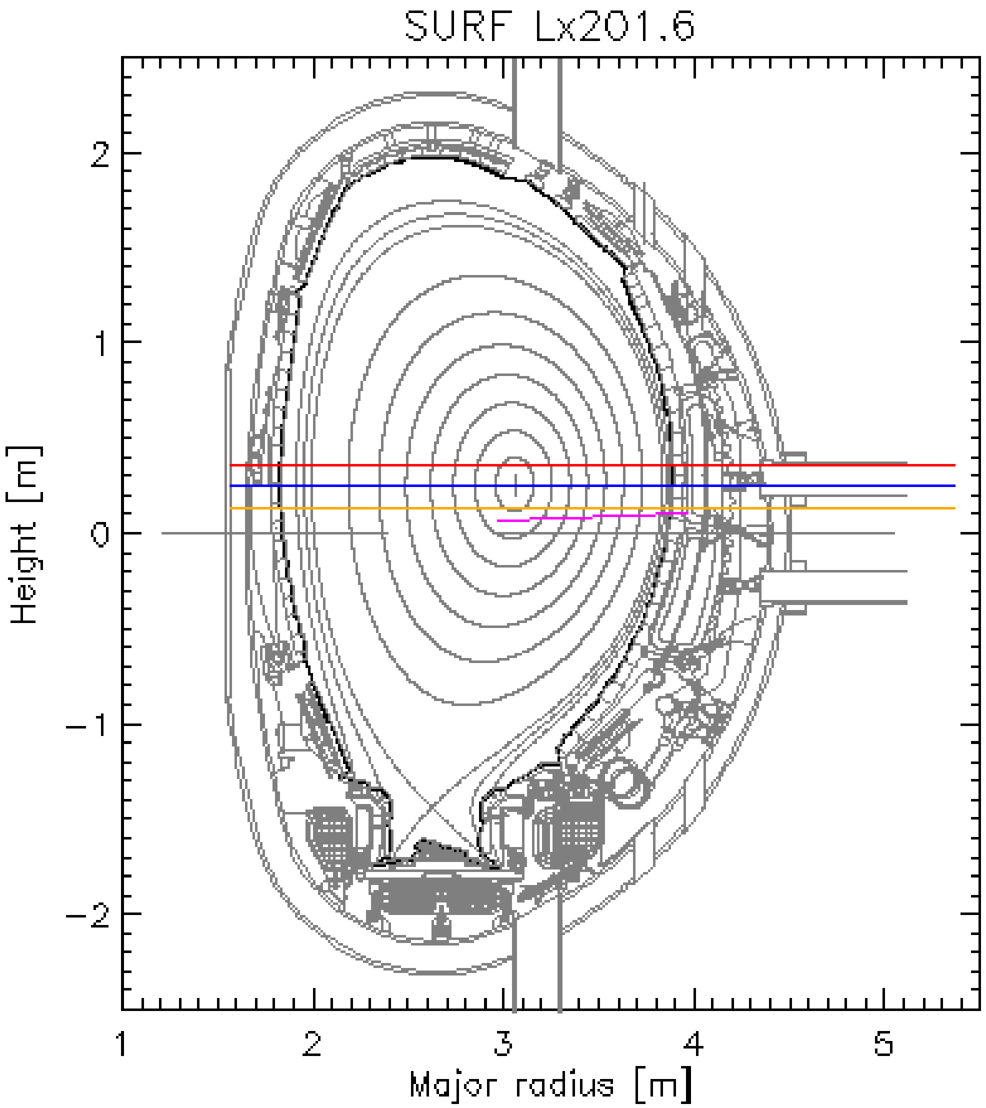
- Time resolution ~60 Hz (~16 ms/profile)
- X-mode and O-mode polarizations on two LOS.
- Used for ECE radiometer calibration

Data now available in real time

- Approx: $\boldsymbol{B_{approx} = B_{tor}}$



ECE interferometer X-mode (60 Hz)

ECE radiometer (5-200 kHz)

ECE interferometer O-mode (60 Hz)

High resolution Thomson scattering (30 Hz)

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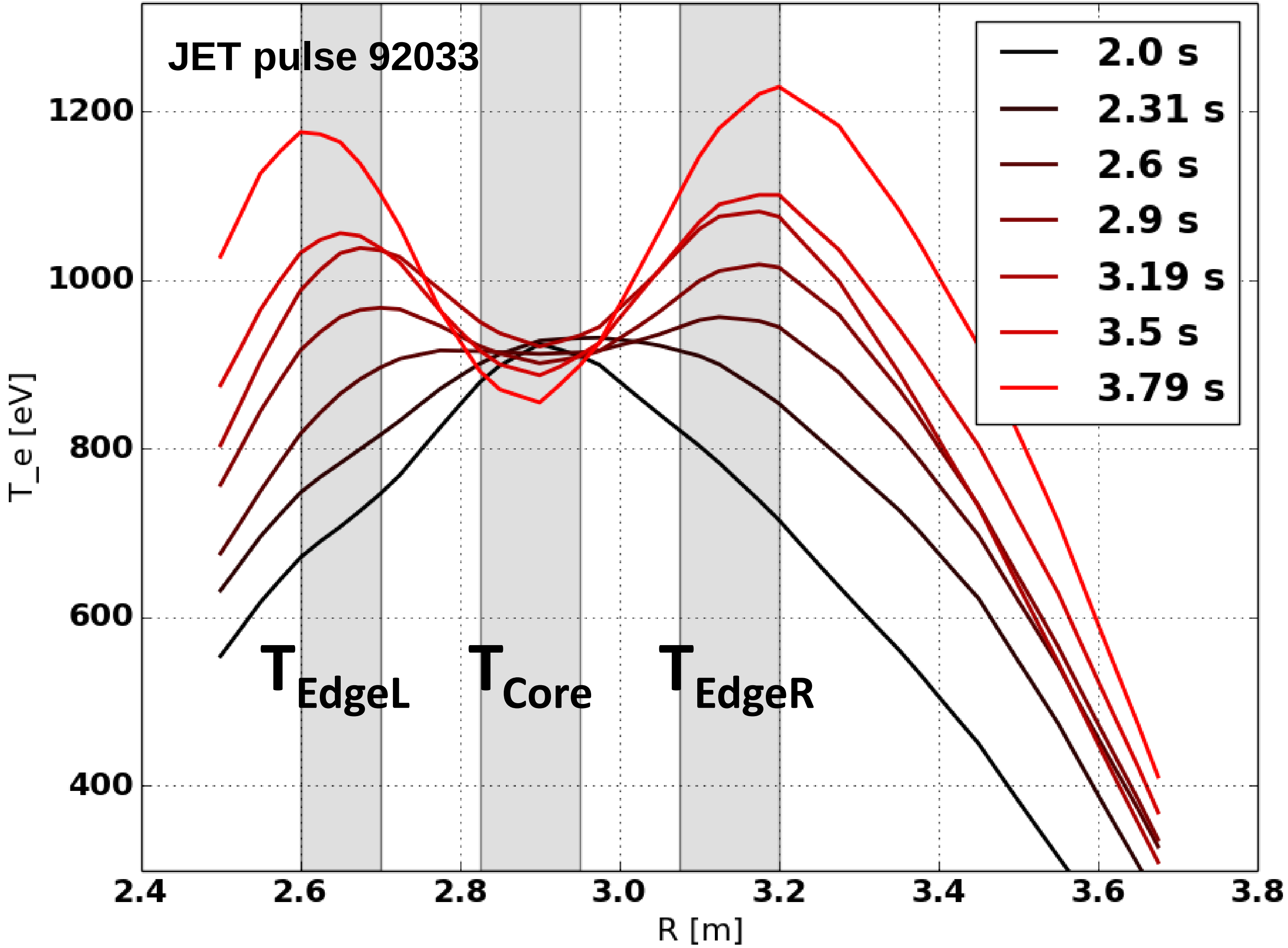
Monitor T_e peaking: a simple, robust metric



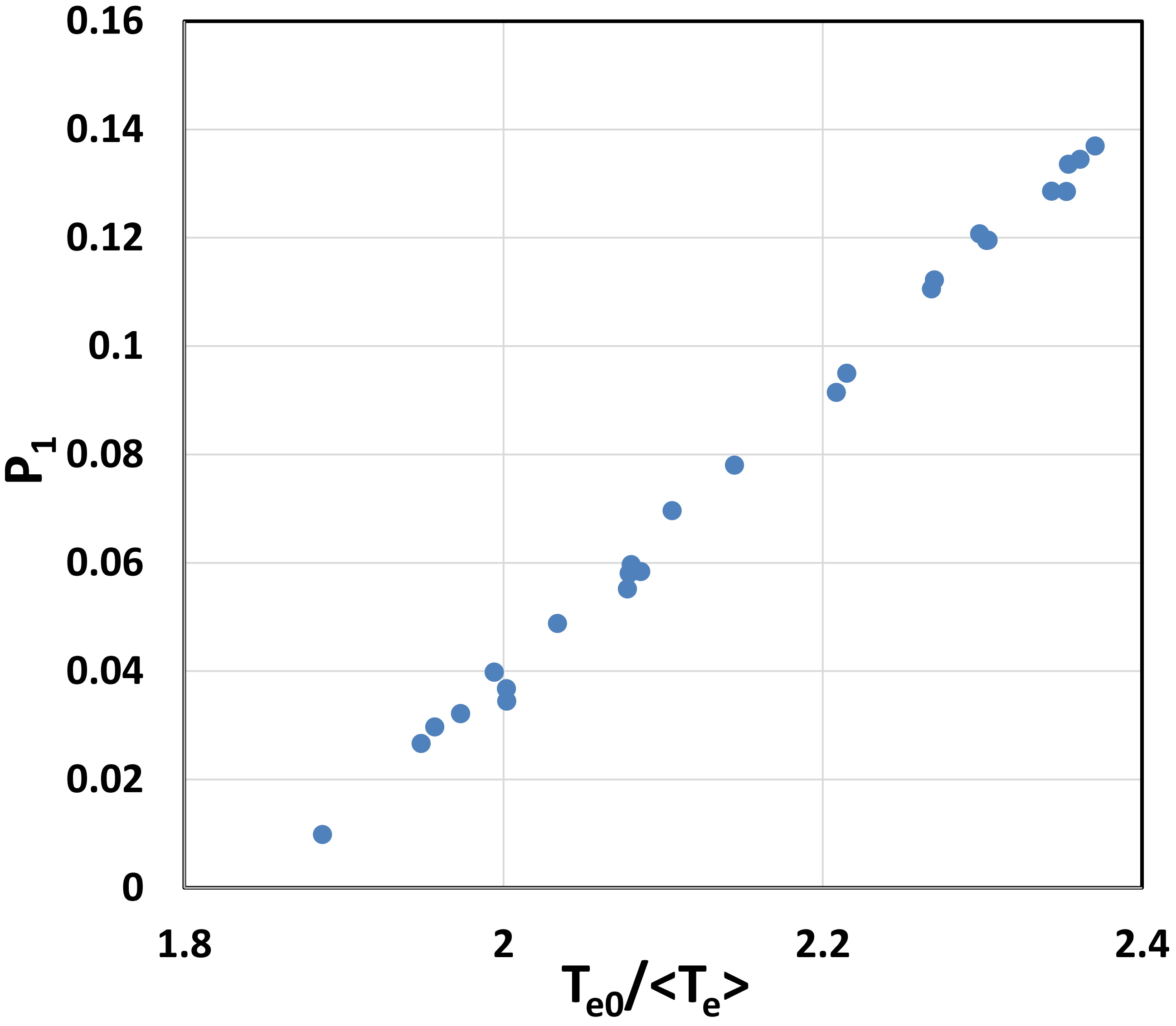
$$T_{Edge} = (T_{EdgeL} + T_{EdgeR})/2$$

$$P_1 = (T_{Core} - T_{Edge})/T_{Edge}$$

P_1>0 when profile is peaked
P_1<0 when profile is hollow

Radial windows can be optimized for specific scenarios

P_1 correlates with T_e peaking

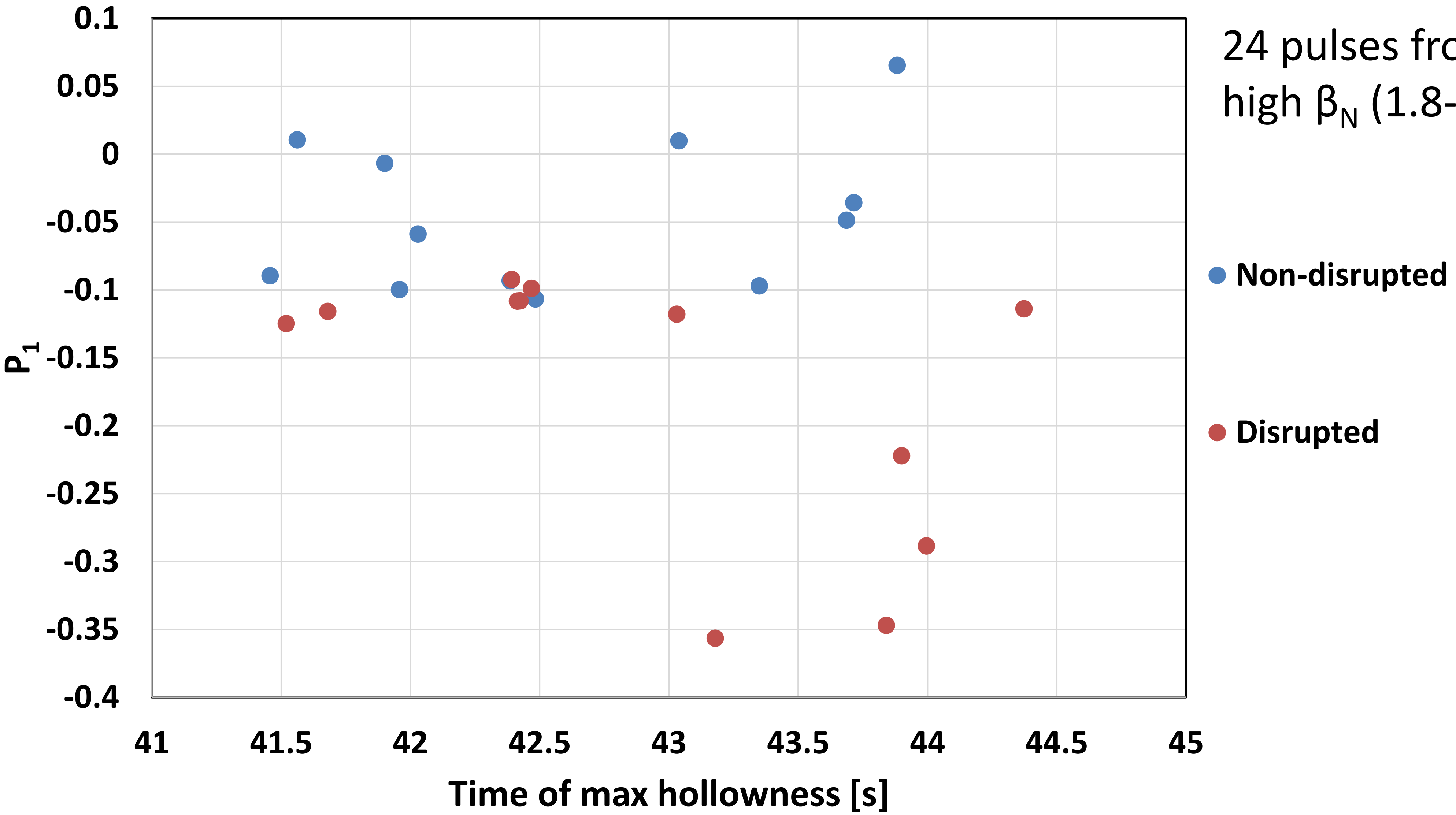


Discharges from 2015 M_{eff} scan

$B = 1.7$ T
$I_p = 1.4$ MA
$P_{NBI} = 6$ MW
$n_{el} = 5e19\ m^{-2}$

Quantities averaged over [1.5, 3.5] s

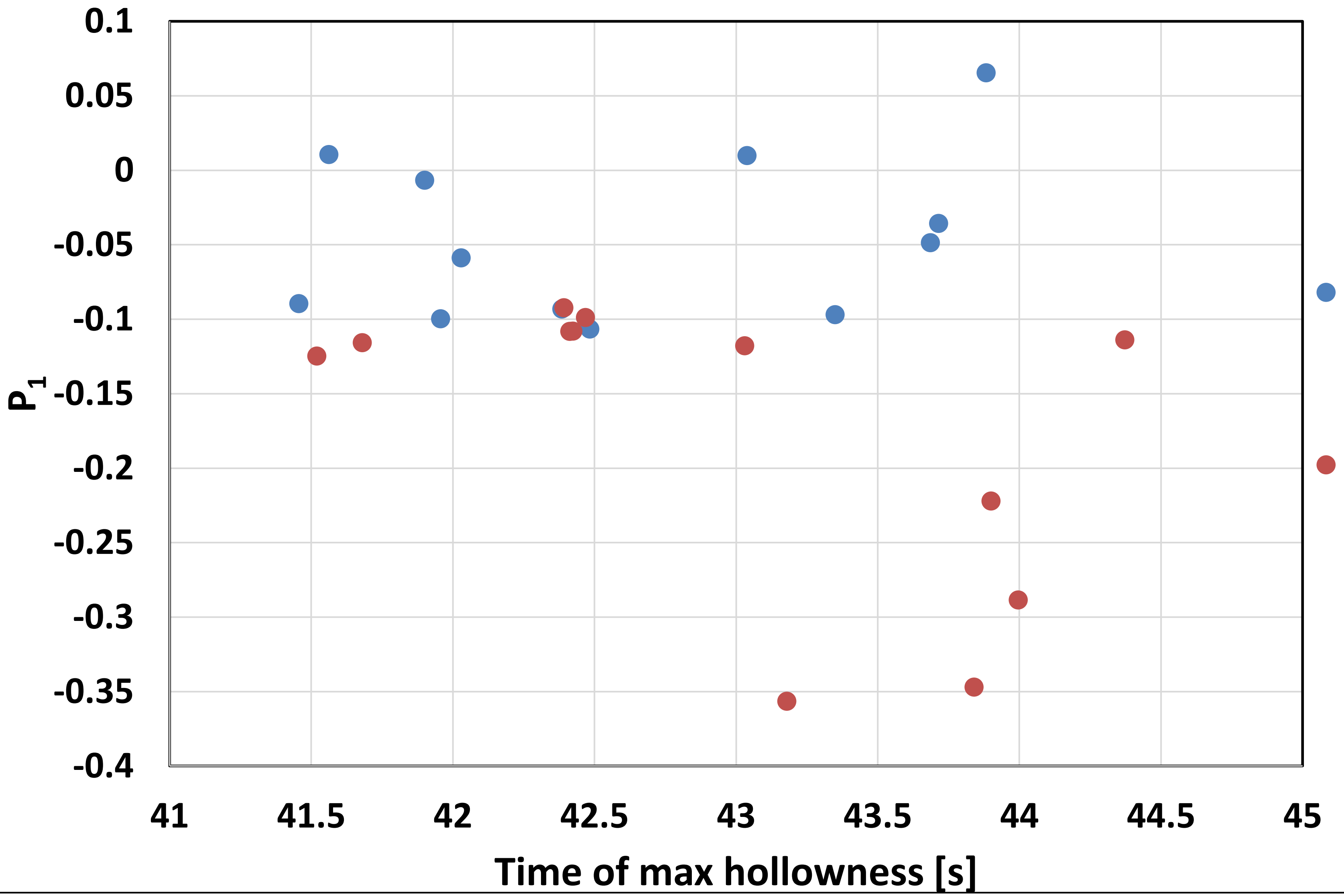
P_1 correlates with disruptions in ohmic ramp phase



24 pulses from 2016
high β_N (1.8-2.7) campaign

I_p=1.4-2.4 MA,
B_T=2.1-3.2 T,
H_{98}=0.81-1.2,
P_{NBI}=13-25 MW,
P_{ICRH} = 2-5 MW

P_1 correlates with disruptions in ohmic ramp phase



24 pulses from 2016
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P_{NBI}=13-25 MW,
P_{ICRH} = 2-5 MW

"Peakedness" (P1) is not an unequivocal identifier for disruptions, but is definitely correlated.
Useful metric to avoid disruptions.

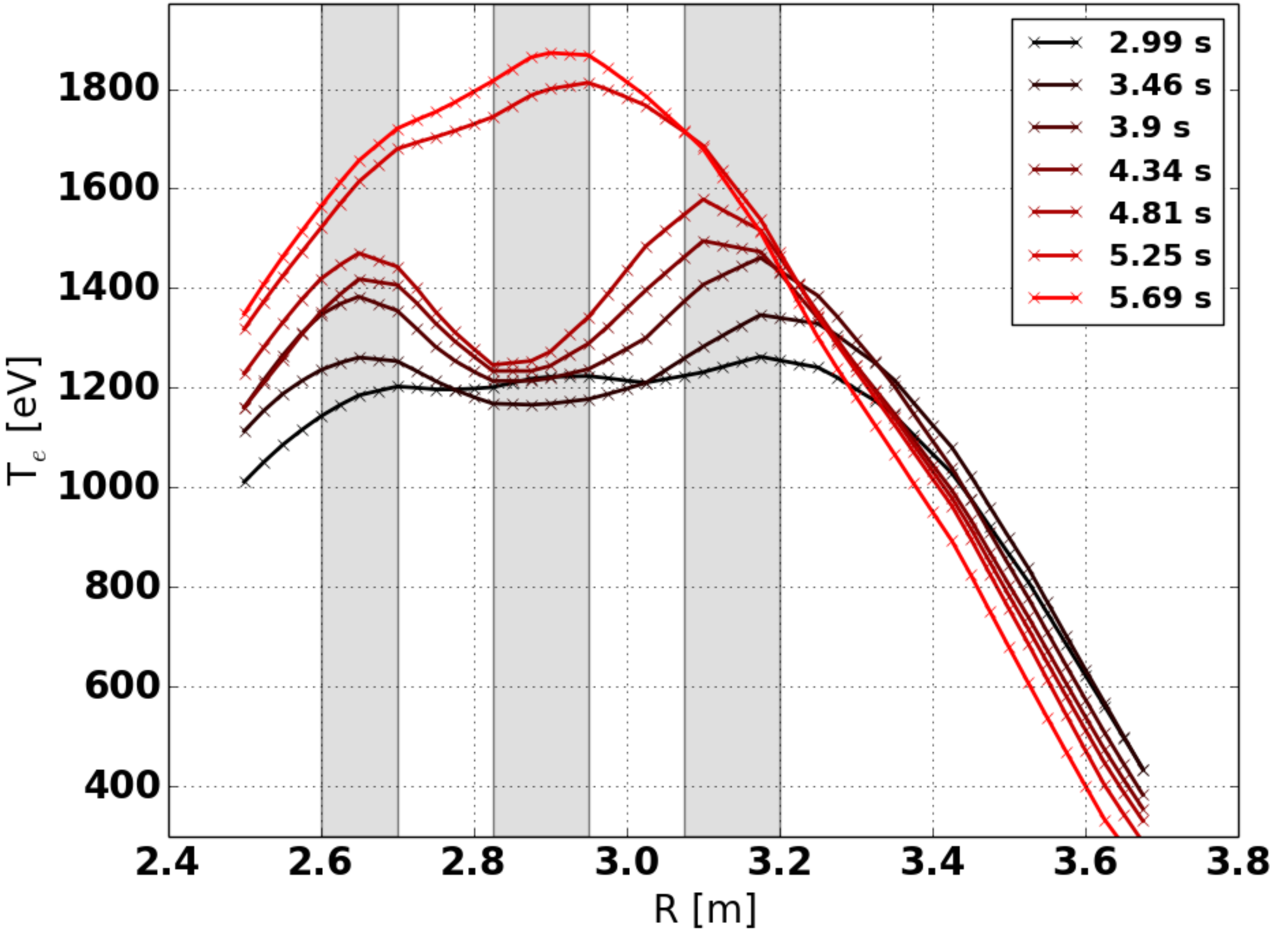
High β_N scenario ramp-up: disruption

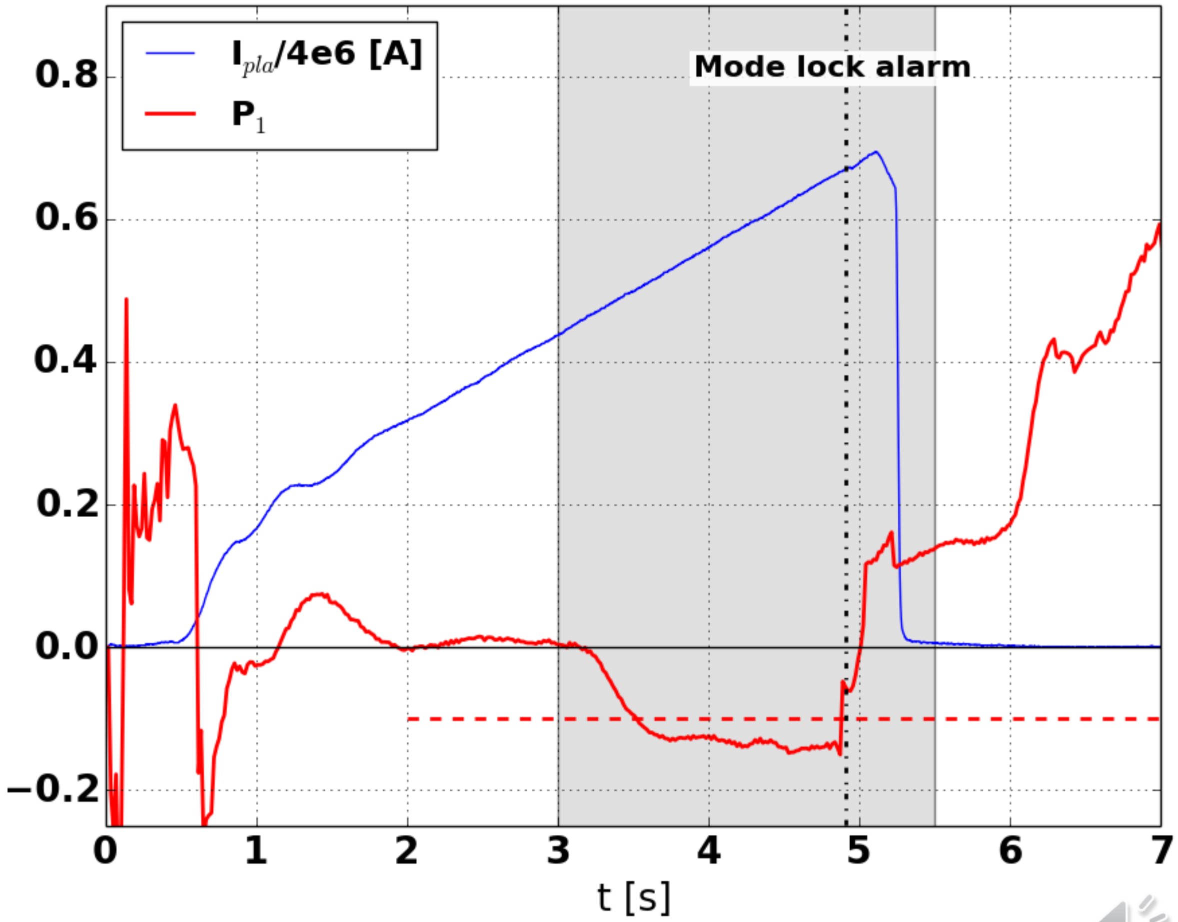
94065

I_p = 2.2 MA, B_T = 2.8 T

From 2016 high β_N disruptions, a controller is defined:

P_1<-0.1 for >20 ms in [3 5.5] s → Soft stop





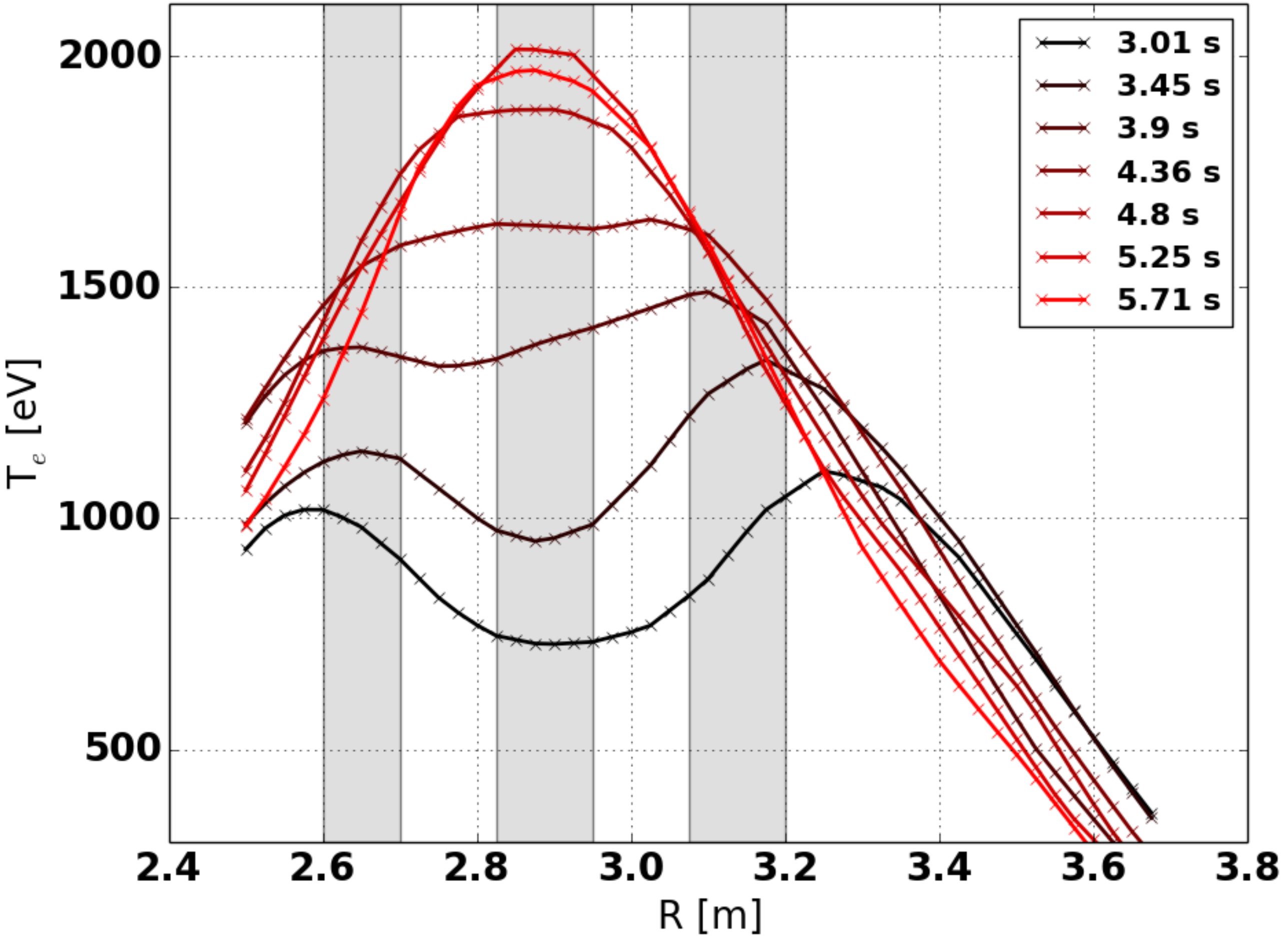
High β_N scenario ramp-up: safe termination

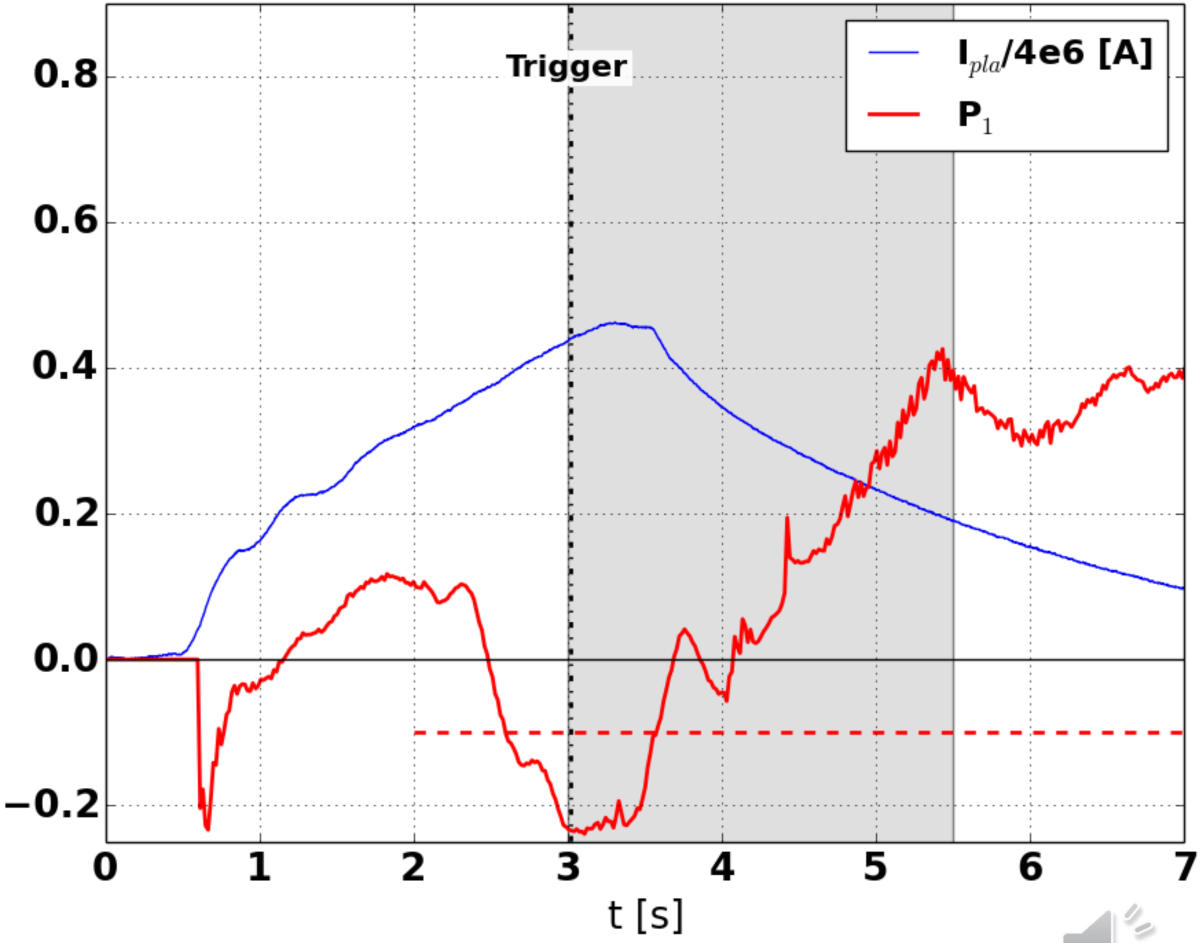
95252

I_p = 2.2 MA, B_T = 2.8 T

Applied from August 2019 (>150 pulses).

When triggered, always led to safe termination (11/145)





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- **Future applications: plasma termination**
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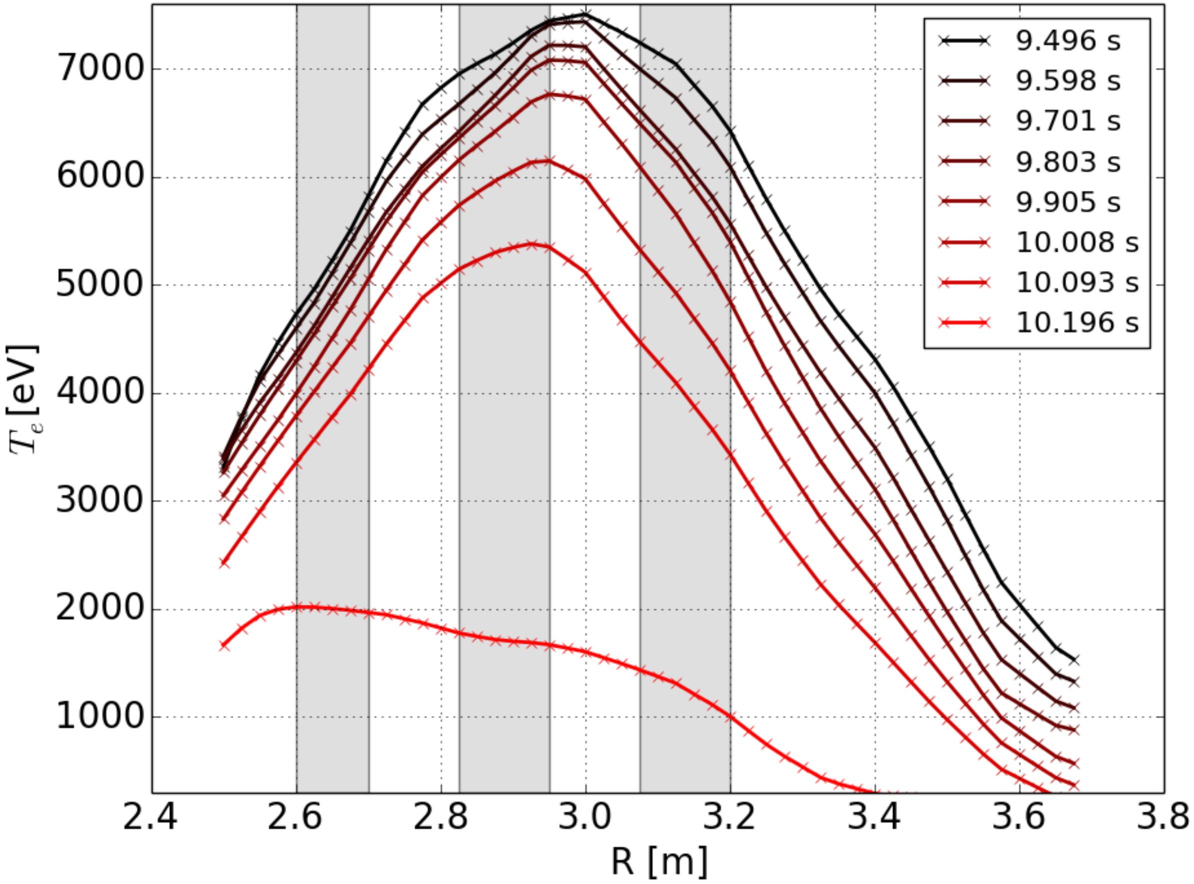
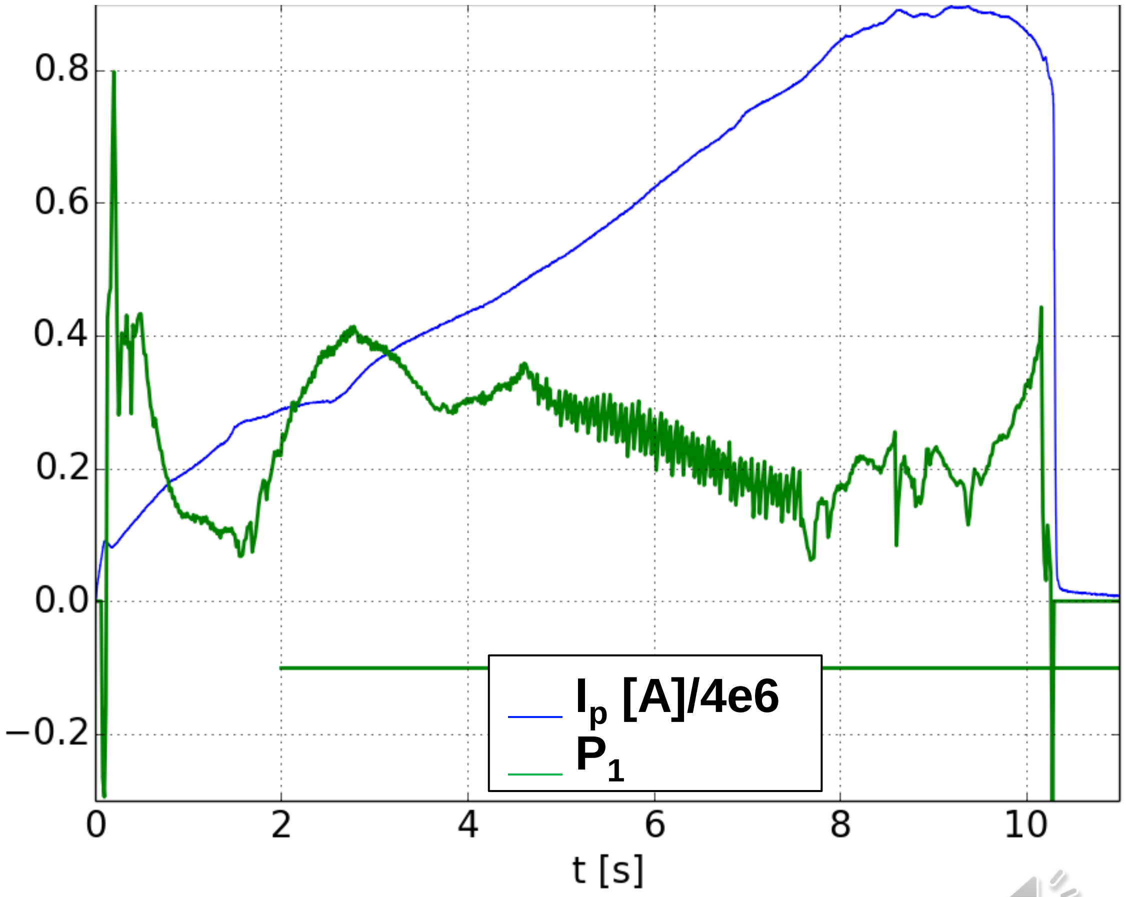
Outer core logarithmic gradient as metric for edge cooling

96483

I_p = 3.5 MA, B_T = 3.3 T

Example: disruption preceded by edge cooling and no core hollowing





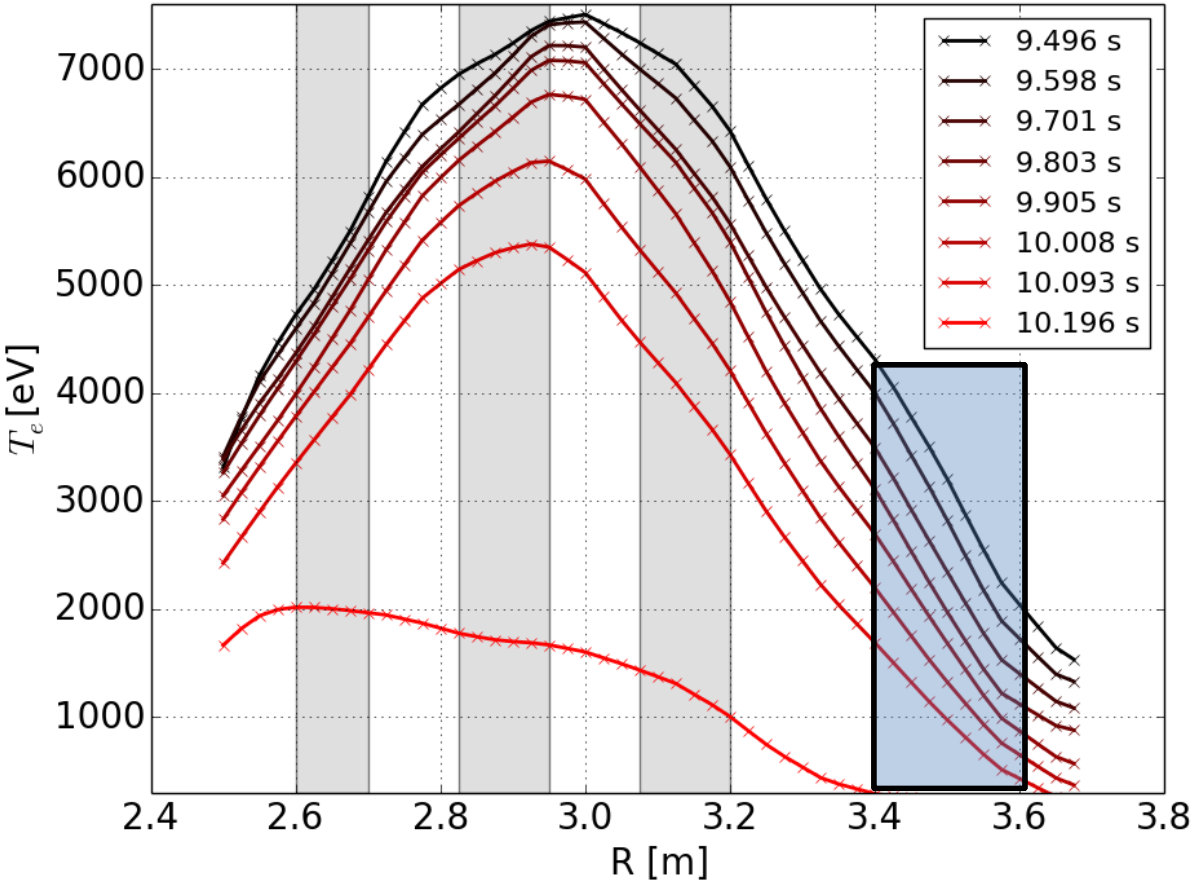
Other applications: metric for edge cooling

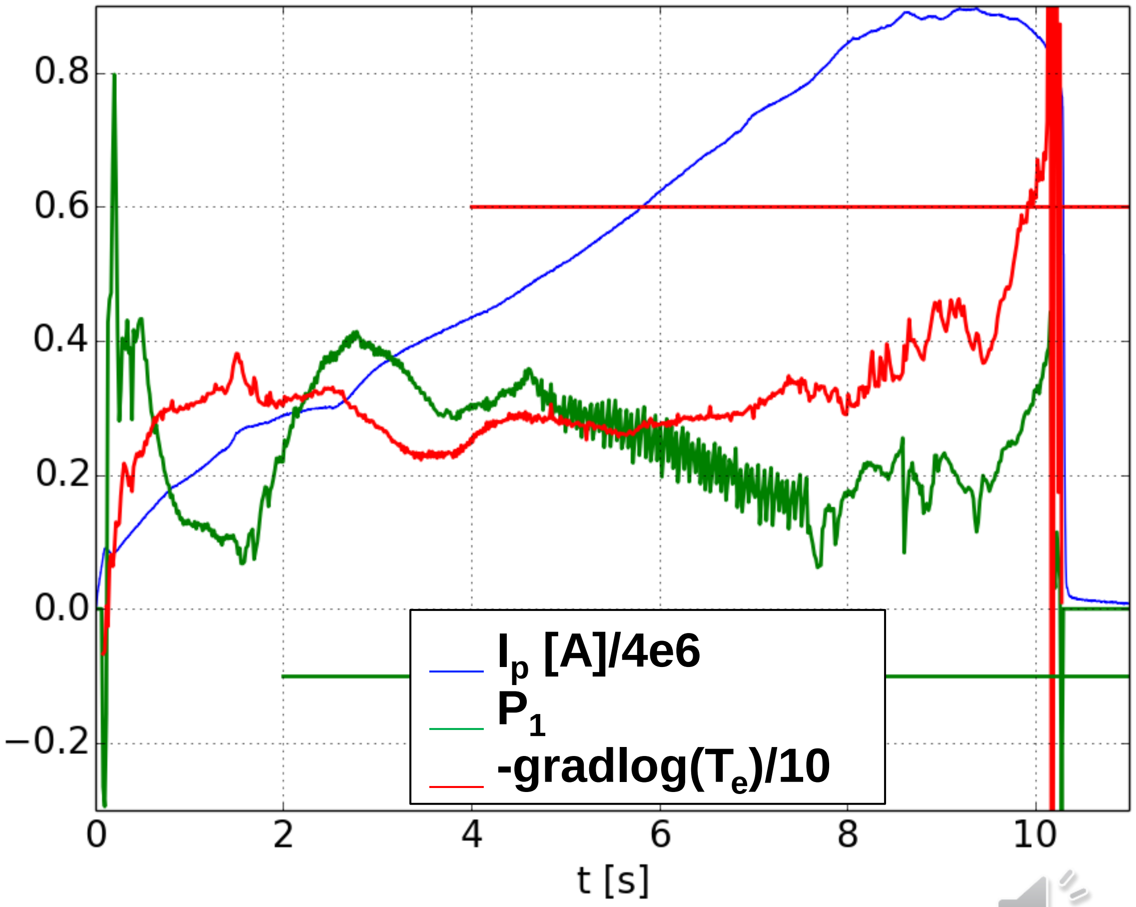
96483

$I_p = 3.5$ MA, $B_T = 3.3$ T

$$\frac{1}{T_e(R_{out})}\frac{dT_e}{dR}(R_{out})$$

$$R_{out} = 3.5\ m$$





Other applications: plasma terminations

P1 and outer core gradient were compared to the existing alarms used at JET in plasma terminations.

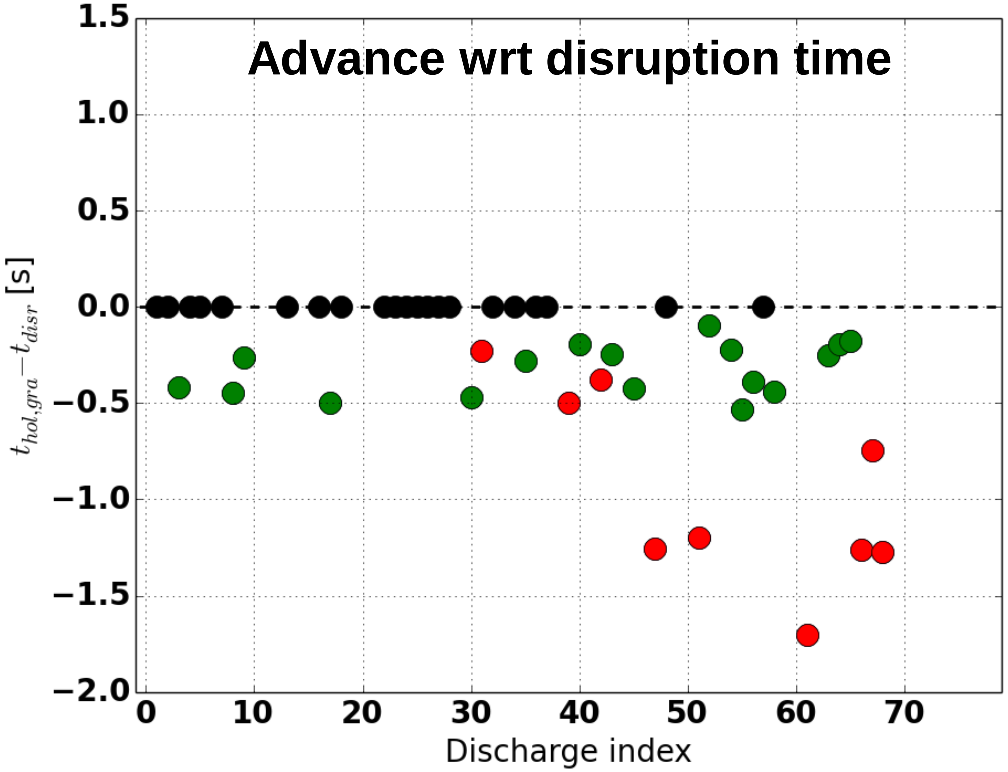
They identify most disruptions with variable advance.

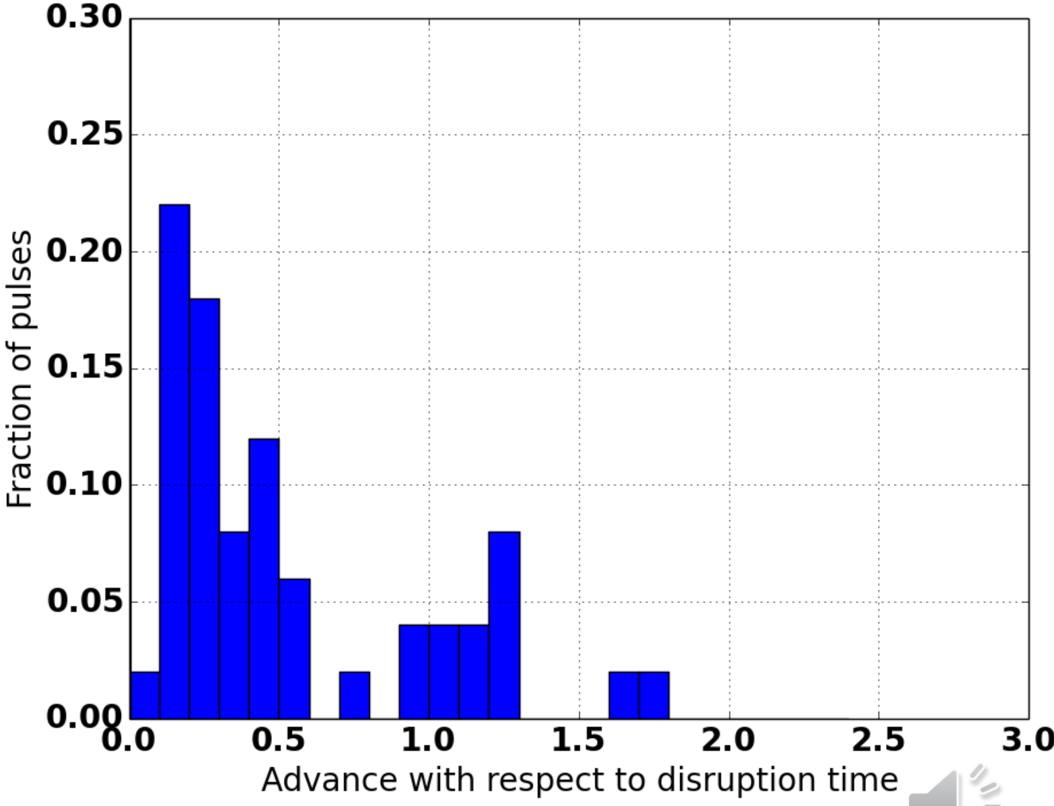
69 pulses from JET baseline experiments (2019-2020)

🟢 **Gradient**

🔴 **Hollowness**

⚫ **False negatives**





Other applications: plasma terminations

P1 and outer core gradient were compared to the existing alarms used at JET in plasma terminations.

They identify most disruptions with variable advance.

In several cases, earlier than current alarms

69 pulses from JET baseline experiments (2019-2020)

🟢 **Gradient**

🔴 **Hollowness**

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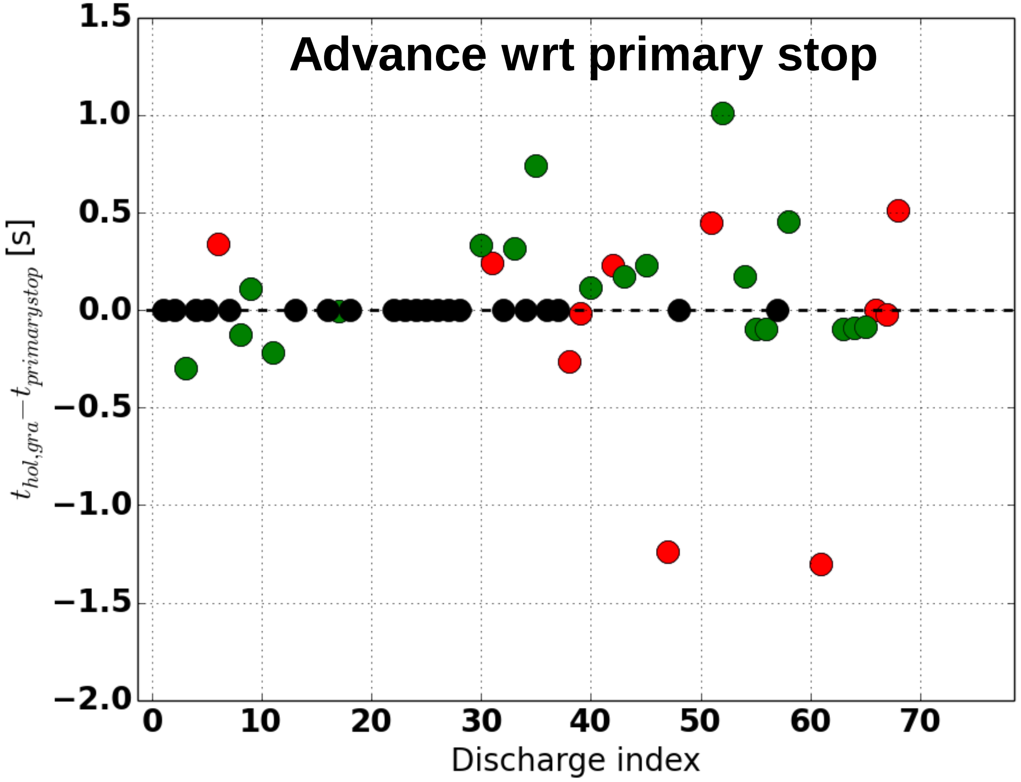
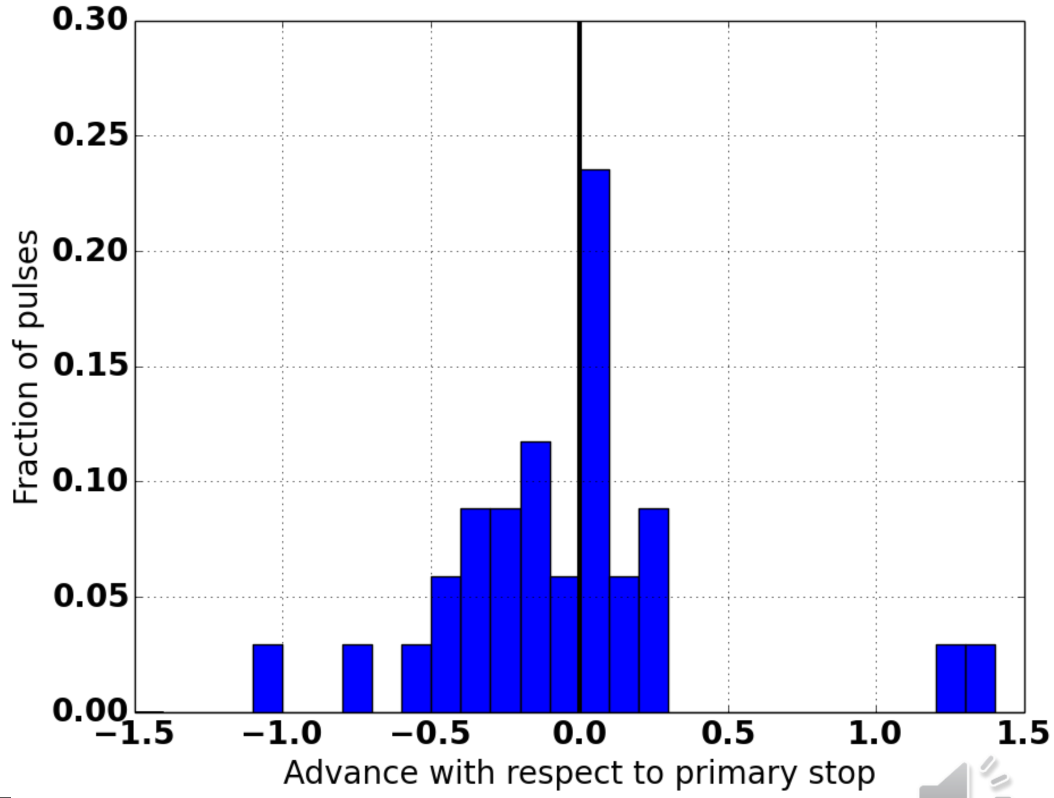




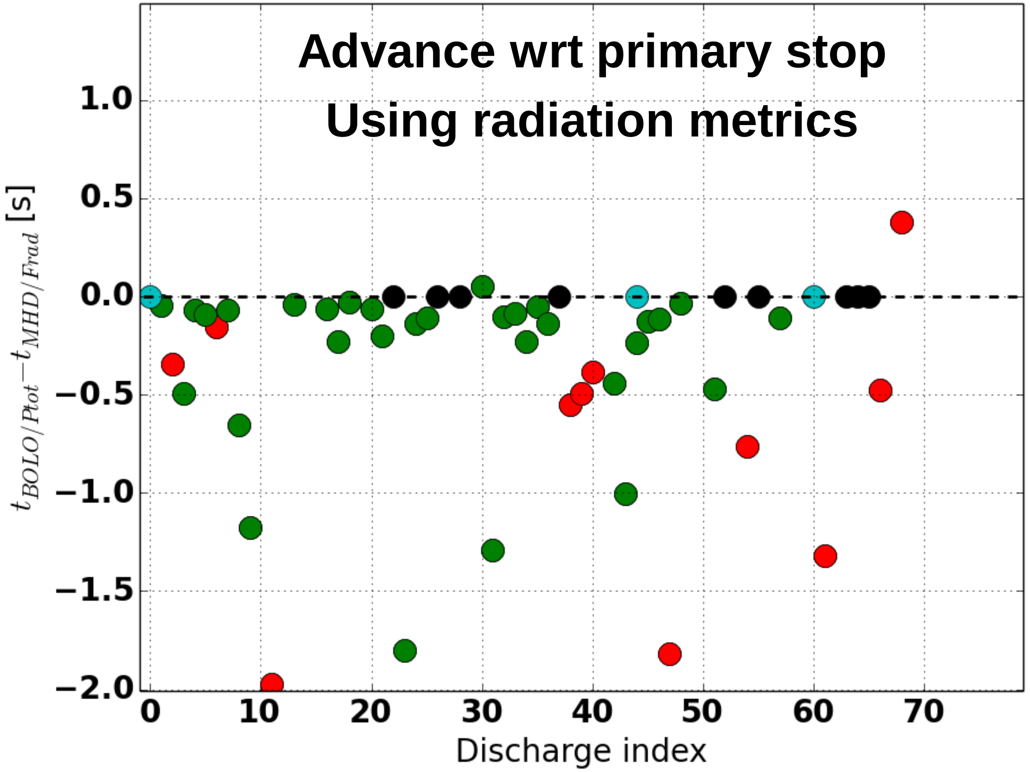
Future applications: combination with radiation metrics

Interesting results were obtained combining with radiation metrics based on bolometry tomographic inversion: $\mathbf{P_{rad,core}/(P_{RF}*P_1)}$ and $\mathbf{P_{rad,out}/P_{tot}}$

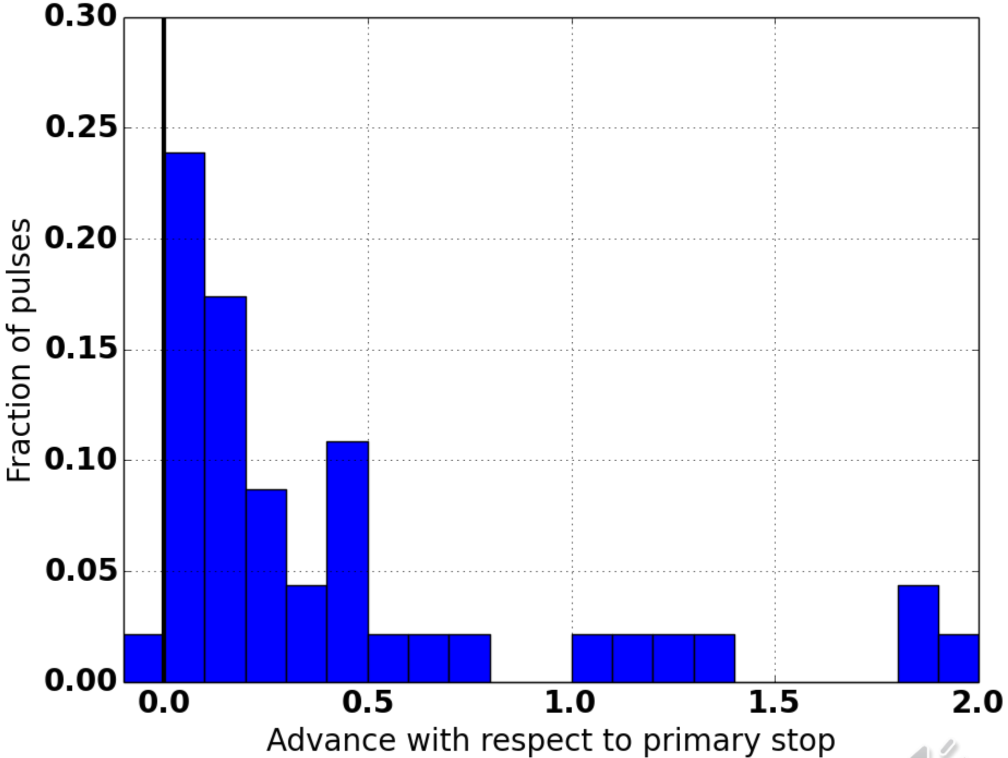
Very good advance with respect to existing alarms.

69 pulses from JET baseline experiments (2019-2020)

- 🟢 $P_{rad,out}/P_{tot}$
- 🔴 $P_{rad,core}/(P_{RF}*P_1)$
- ⚫ **False negatives**
- 🔵 **False positives**


Advance wrt primary stop

Using radiation metrics



Future applications: combination with radiation metrics

Interesting results were obtained combining with radiation metrics based on bolometry tomographic inversion: **$P_{rad,core}$ /(P_{RF}*P_1)** and **$P_{rad,out}$ /P_{tot}**

Very good advance with respect to existing alarms.

Particularly useful to separate core and edge radiation events

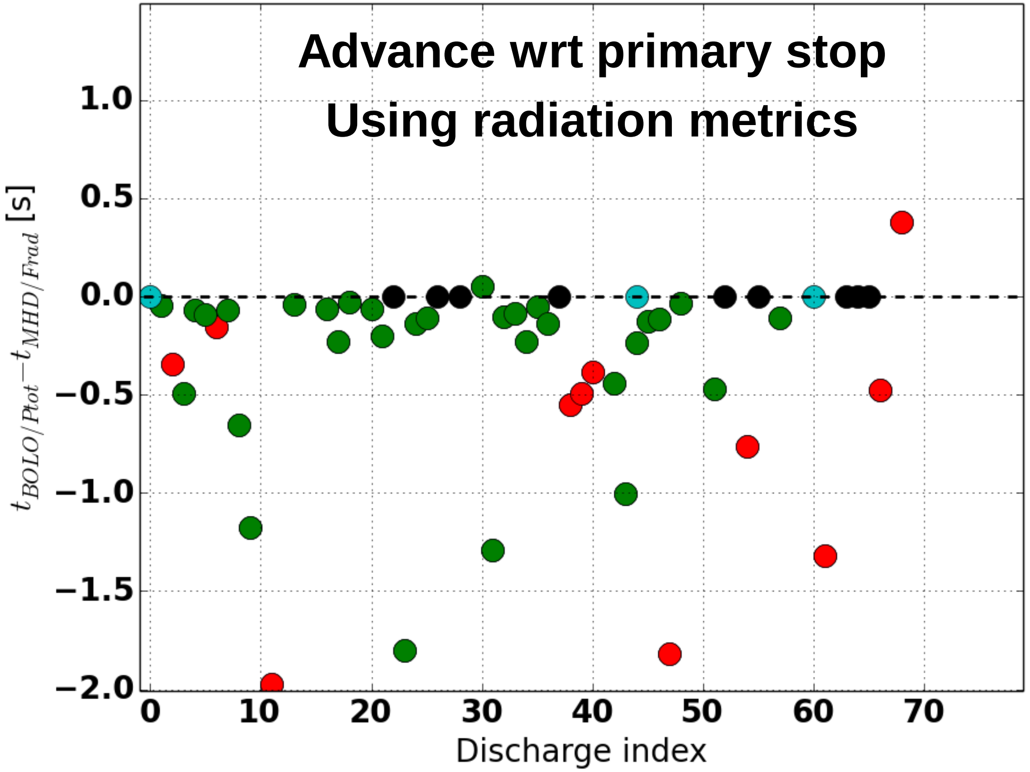
69 pulses from JET baseline experiments (2019-2020)

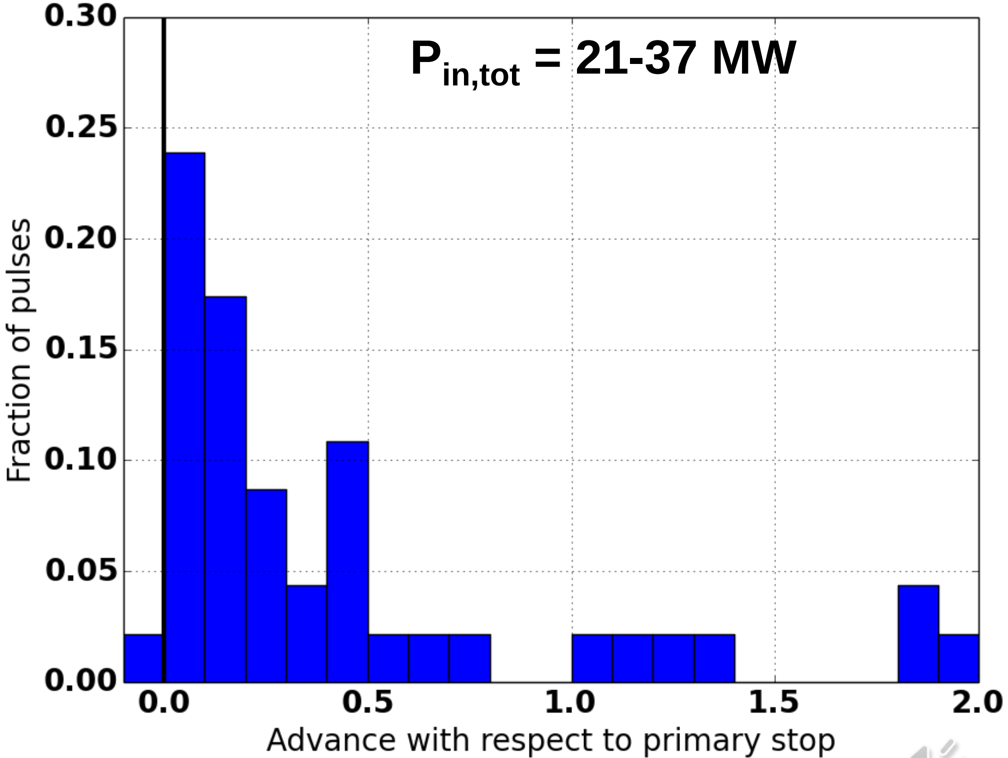
● **$P_{rad,out}$ /P_{tot}**

● **$P_{rad,core}$ /(P_{RF}*P_1)**

● **False negatives**

● **False positives**





Conclusions

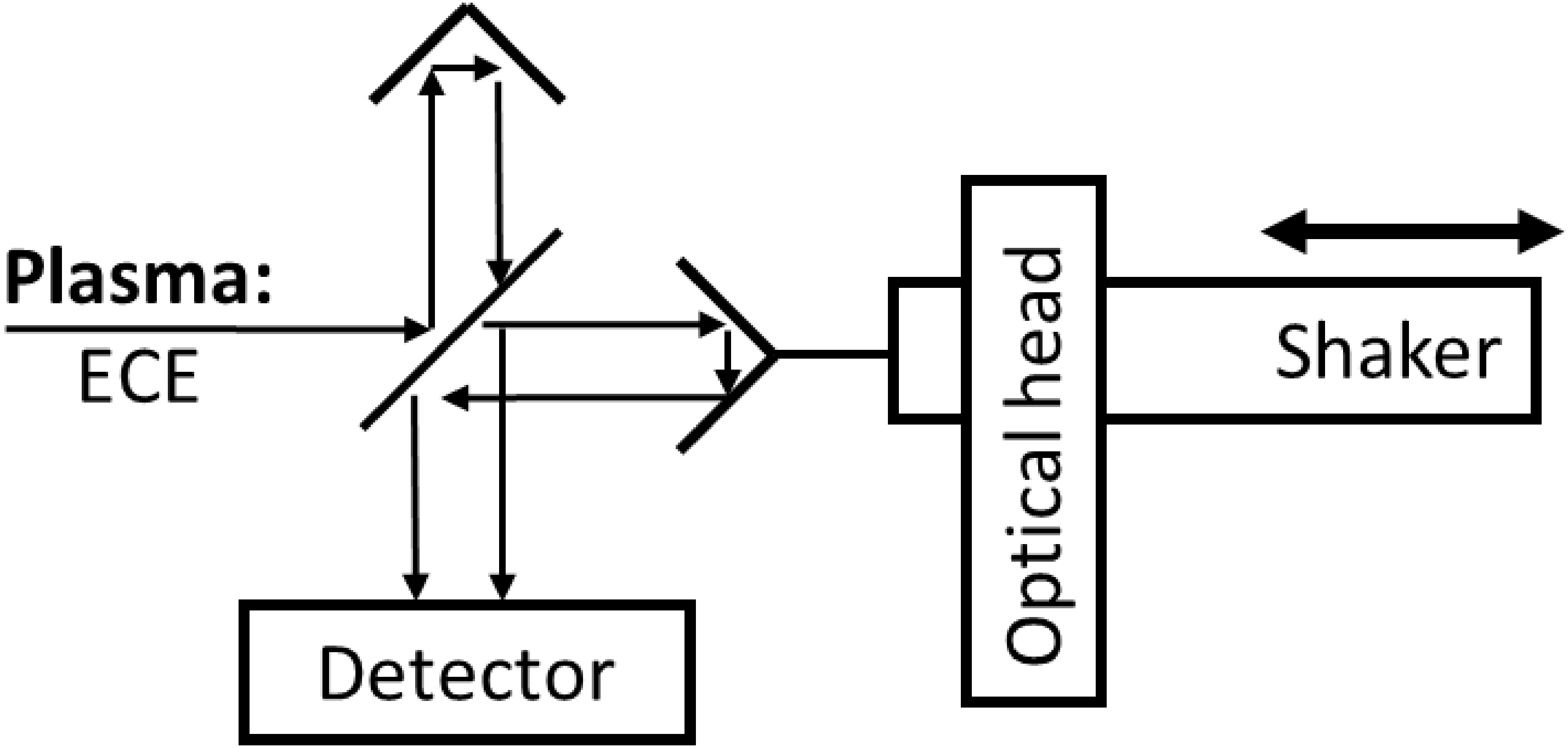
- **JET ECE X-mode interferometer now produces T_e profiles in real time**
  - First real-time application of ECE interferometers
  - Profiles every 16 ms, <1 ms for processing
  - Simple, robust definitions for peakedness and outer core gradient metrics

- **First application: hollowness detection in high β_N ramp-up**
  - Pre-emptively identify duds: avoid running bad pulses and avoid disruptions during current overshoot
  - Reliably employed in high β_N pulses since August 2019

- **Other applications: disruption avoidance in baseline scenario termination**
  - Peakedness gives substantial advance in certain cases. Promising in combination with bolometer tomography [*see also D. R. Ferreira talk at this conference*]

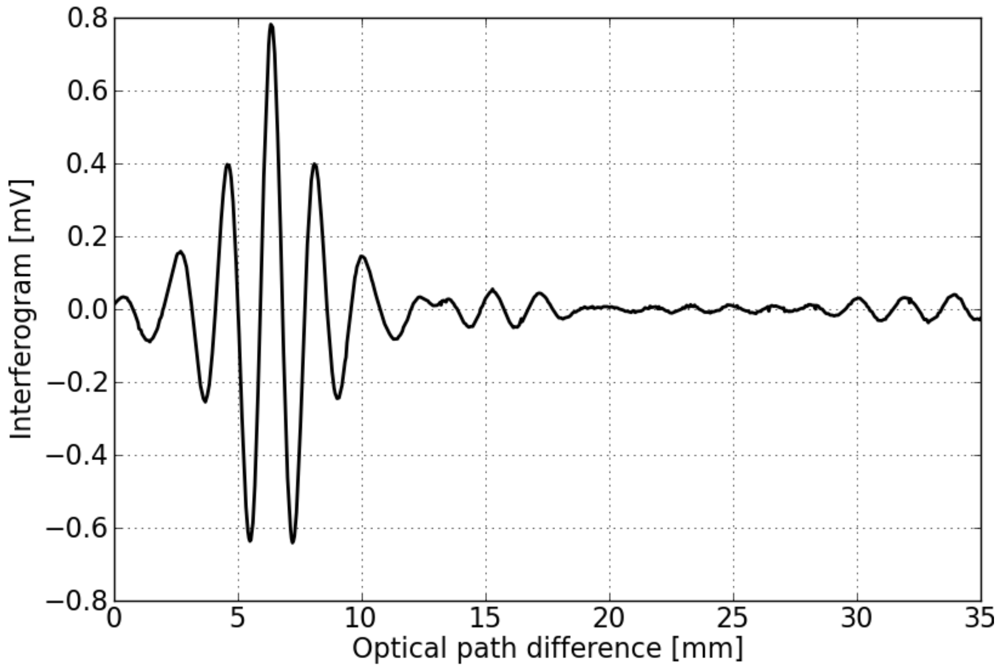
Back up slides

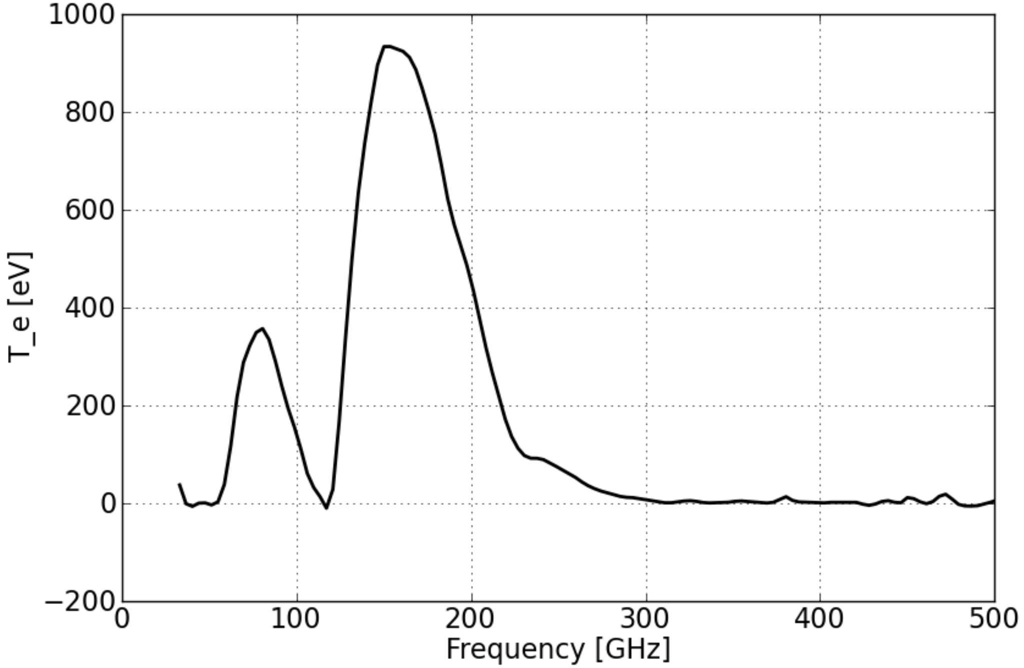
Interferometer schematics



Fourier transform of interferogram is $T_{rad}(f)$

$$\overbrace{V_R}^{\text{Raw interferogram}}(\underbrace{x_i}_{\text{Opt. path difference}}) = \overbrace{2A}^{\text{Amplification}} \overbrace{\int T_{Rad}(f)\underbrace{C_T(f)}_{\text{Calibration}}\cos\left(2\pi\frac{f}{c}x_i+\underbrace{\alpha}_{\text{Phase}}\right)\mathrm{d}f}^{\text{Fourier transform}} + \underbrace{B}_{\text{Background}}$$



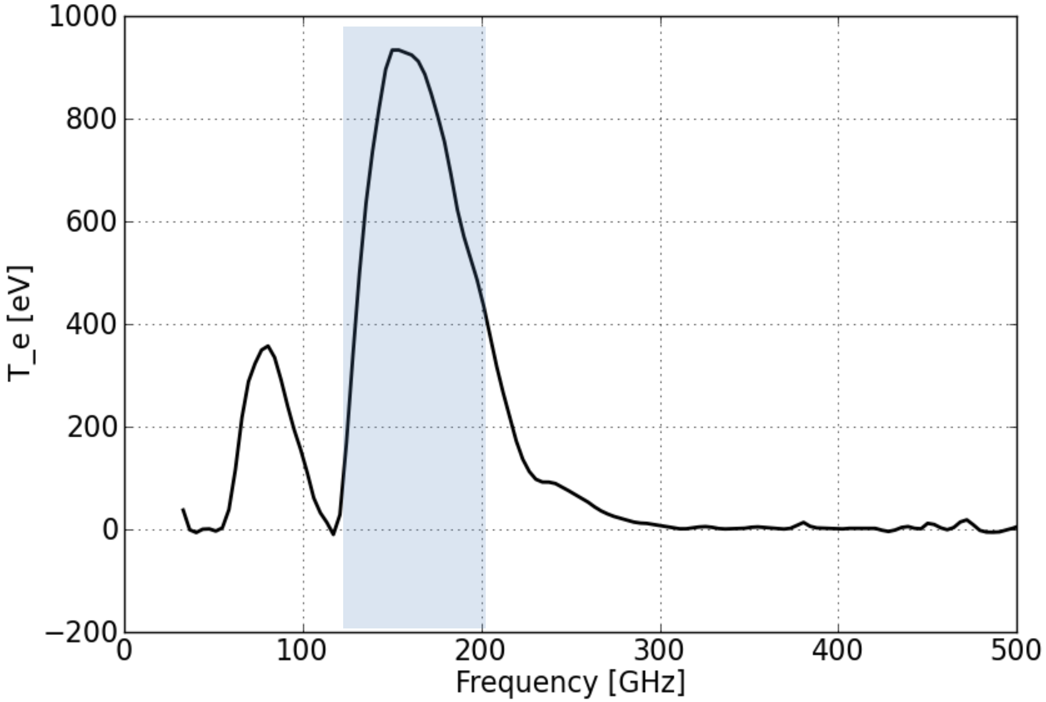


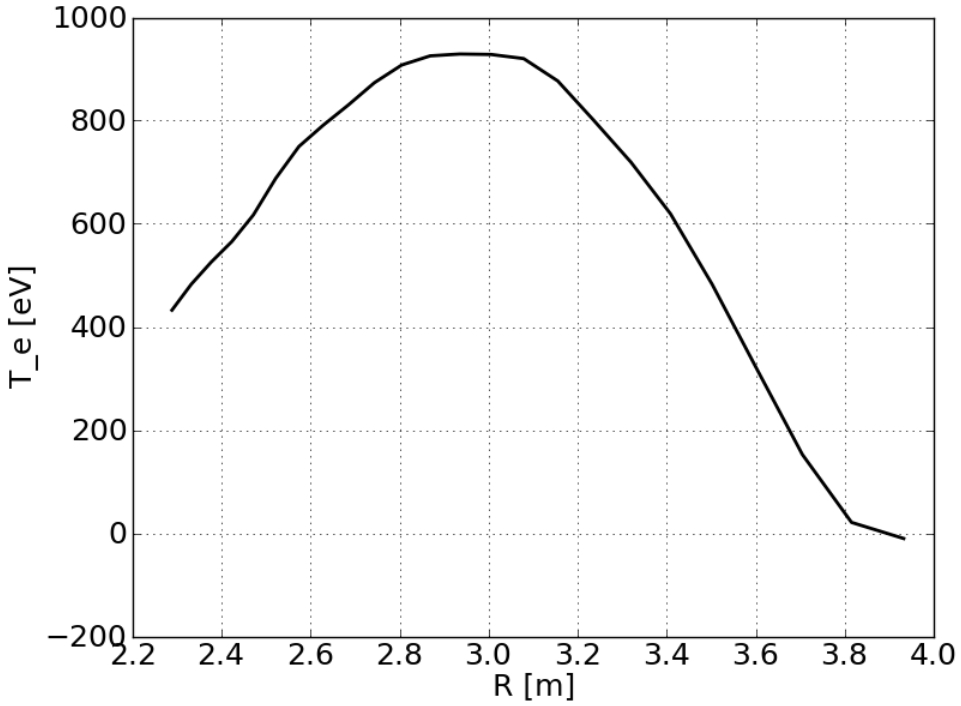
T_e profiles derive from magnetic reconstruction

$$f_{ECE} = \frac{eB}{2\pi me} \qquad B(R) = \sqrt{B^2{}_{tor}(R) + B^2_{pol}(R)}$$

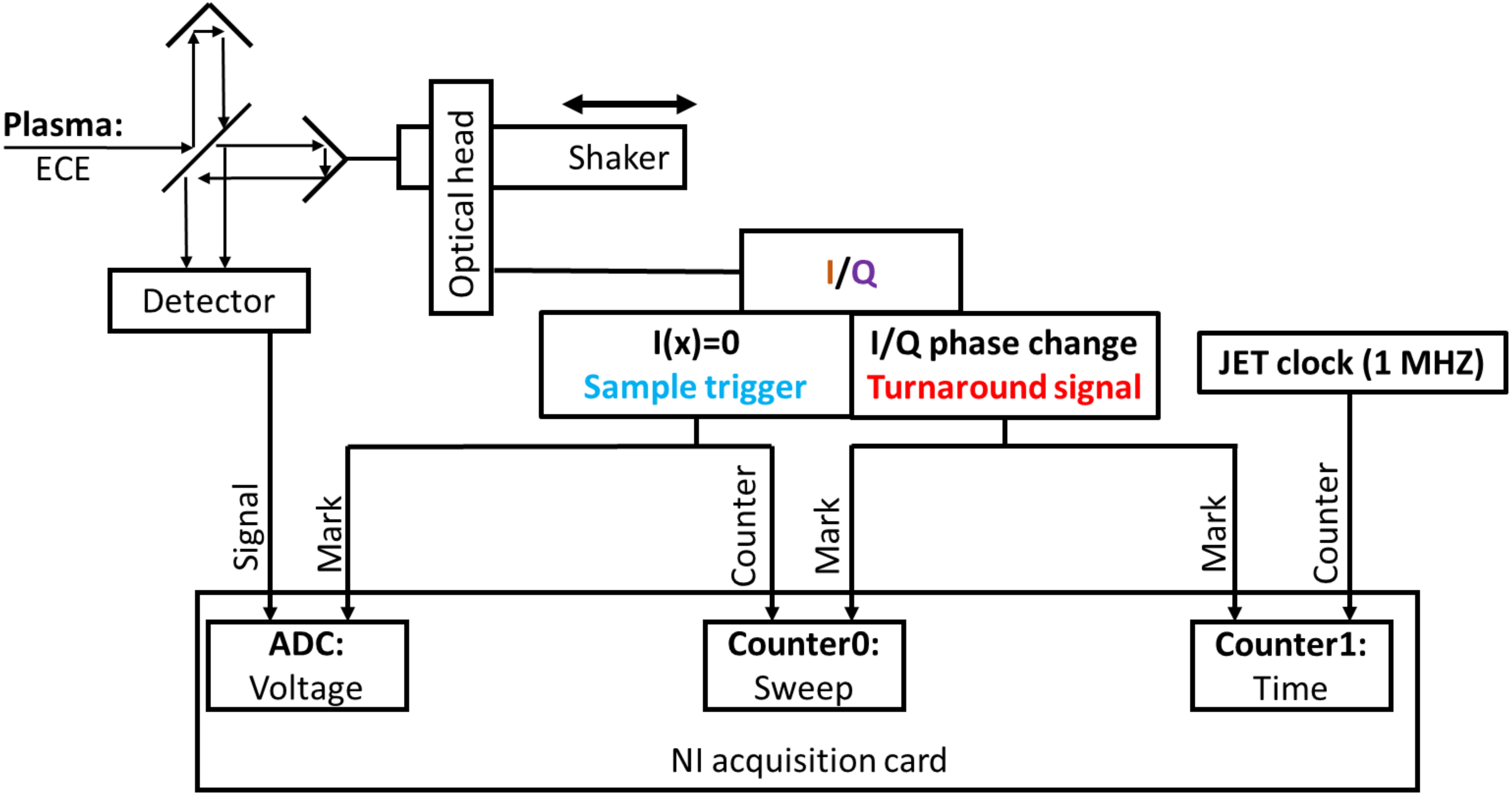
No individual channels:

Whole spectra are available for every interferogram



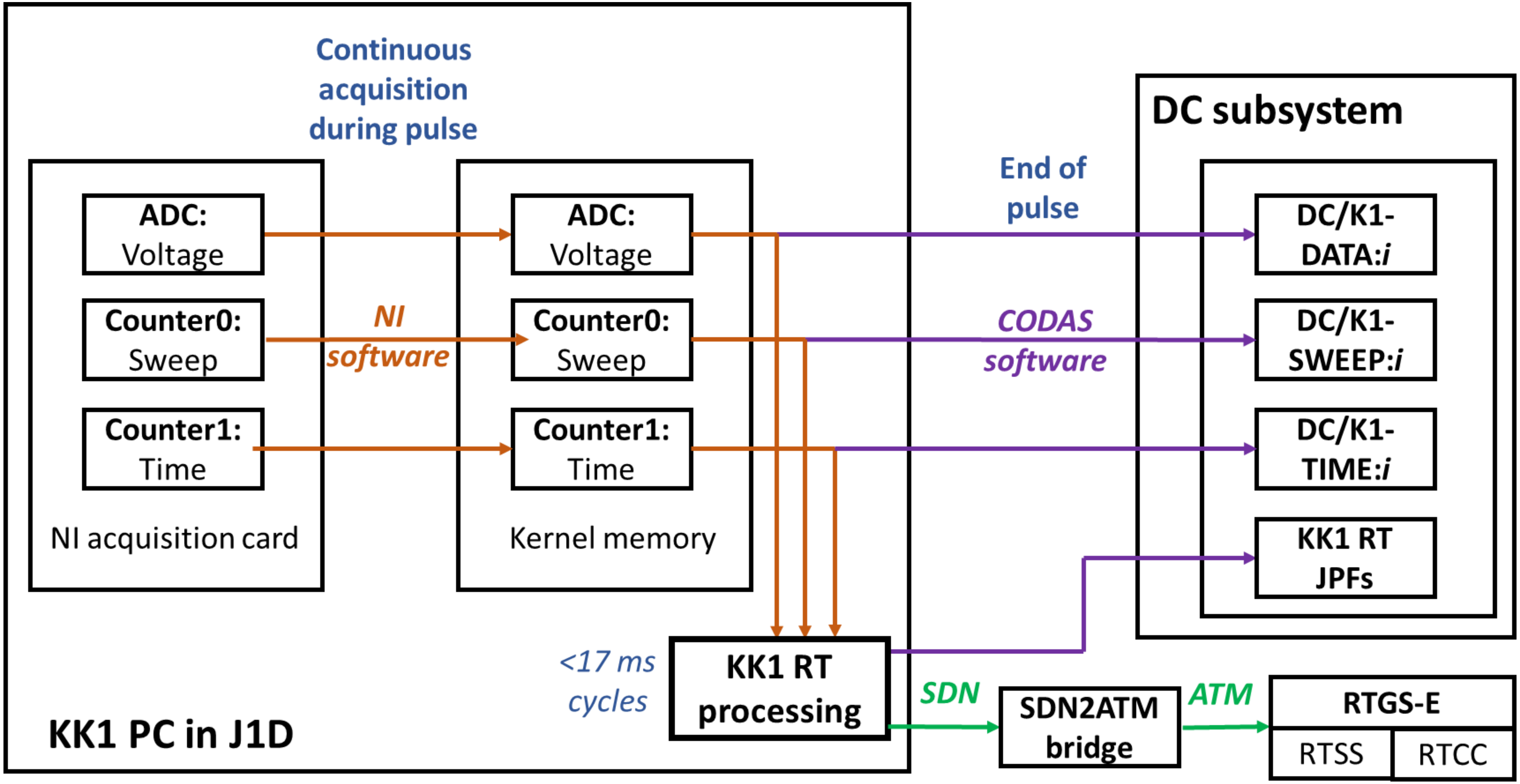


Interferometer acquisition architecture

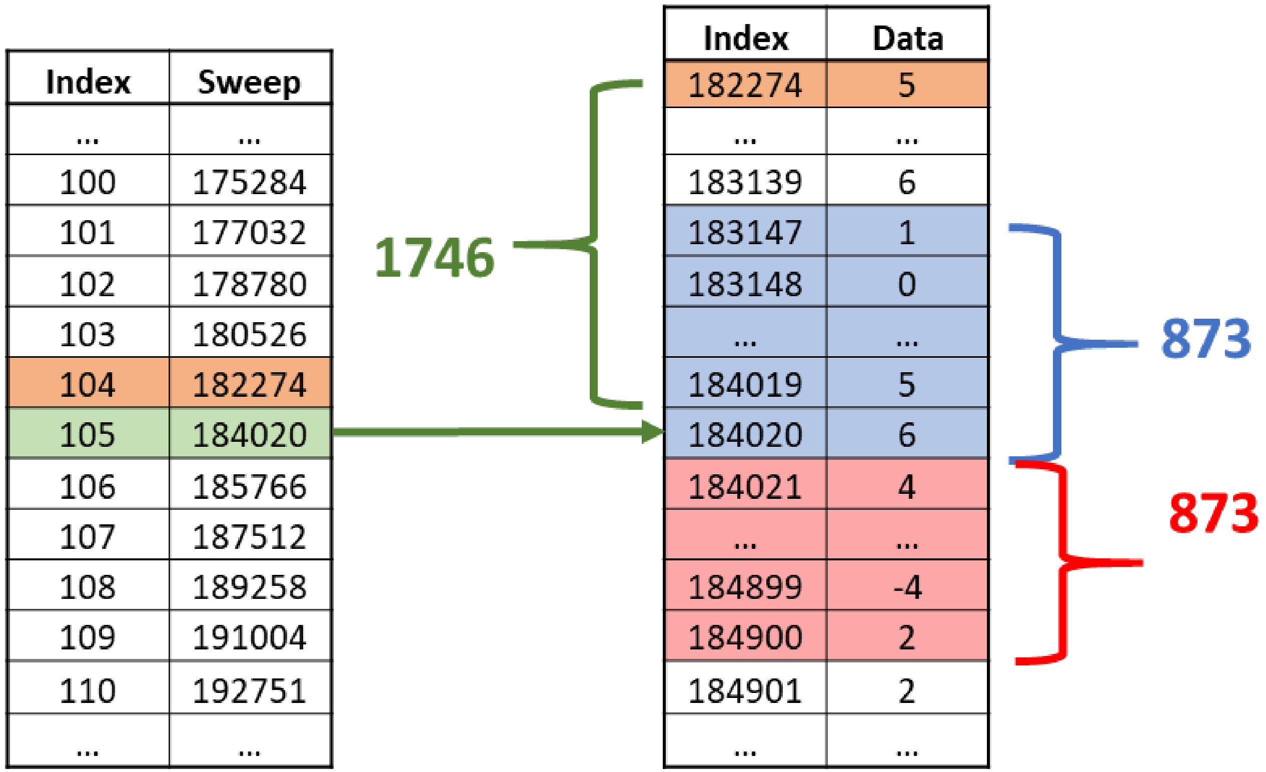


Swiss
Plasma
Center

System description

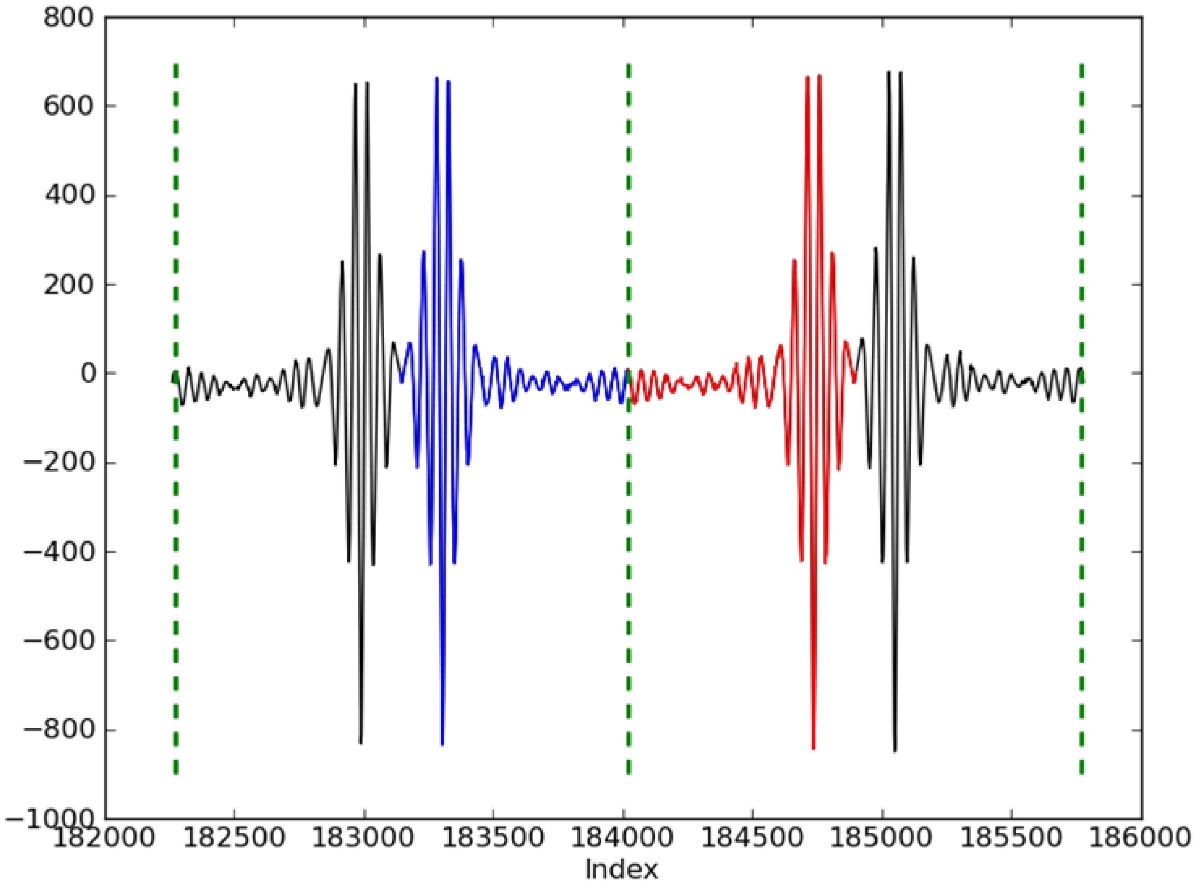


RT processing principle



Index	Sweep
...	...
100	175284
101	177032
102	178780
103	180526
104	182274
105	184020
106	185766
107	187512
108	189258
109	191004
110	192751
...	...

Index	Data
182274	5
...	...
183139	6
183147	1
183148	0
...	...
184019	5
184020	6
184021	4
...	...
184899	-4
184900	2
184901	2
...	...



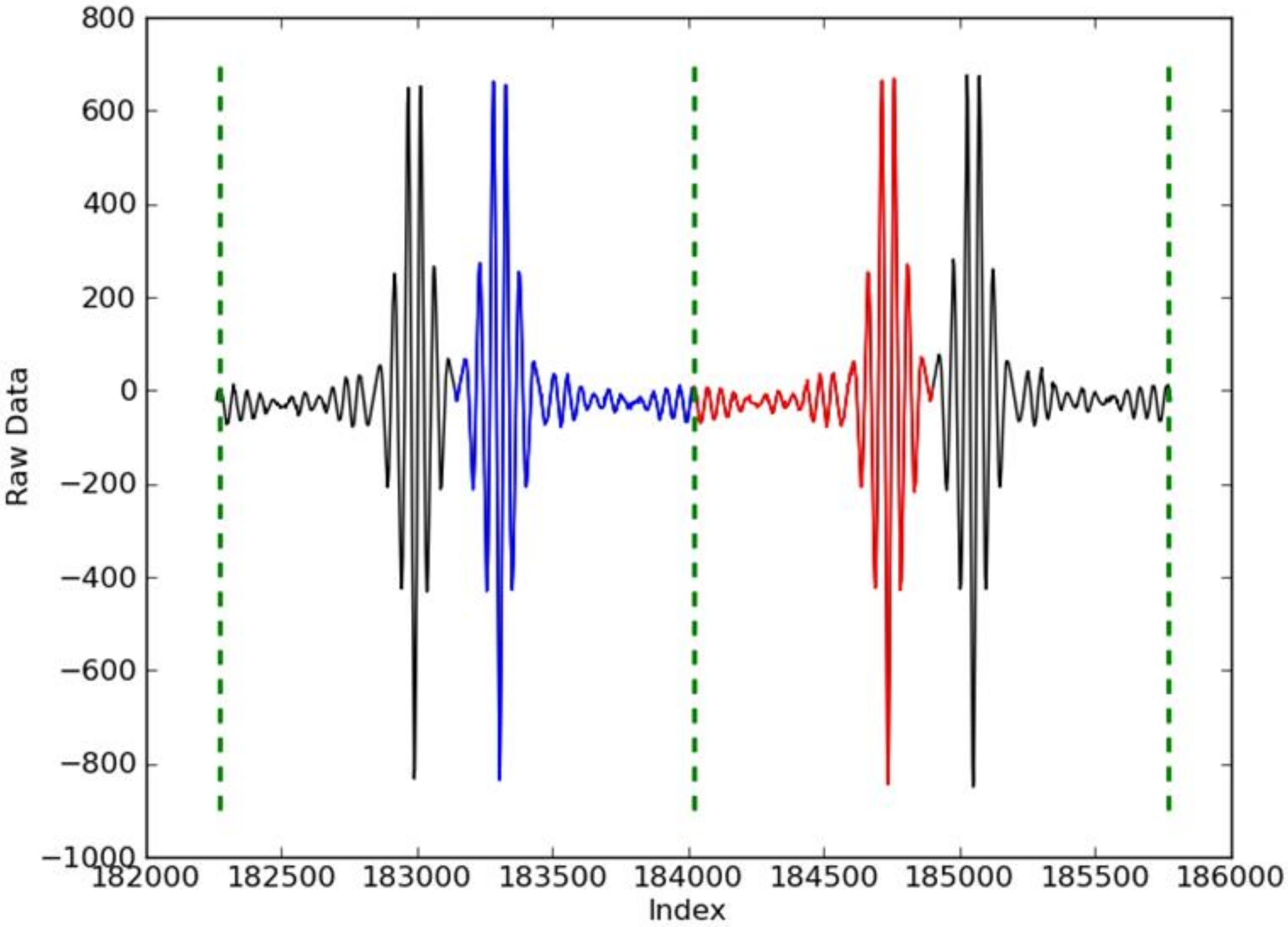
RT data processing: approximated B field

Each interferogram is isolated and processed separately.
~1 ms processing for each interferogram

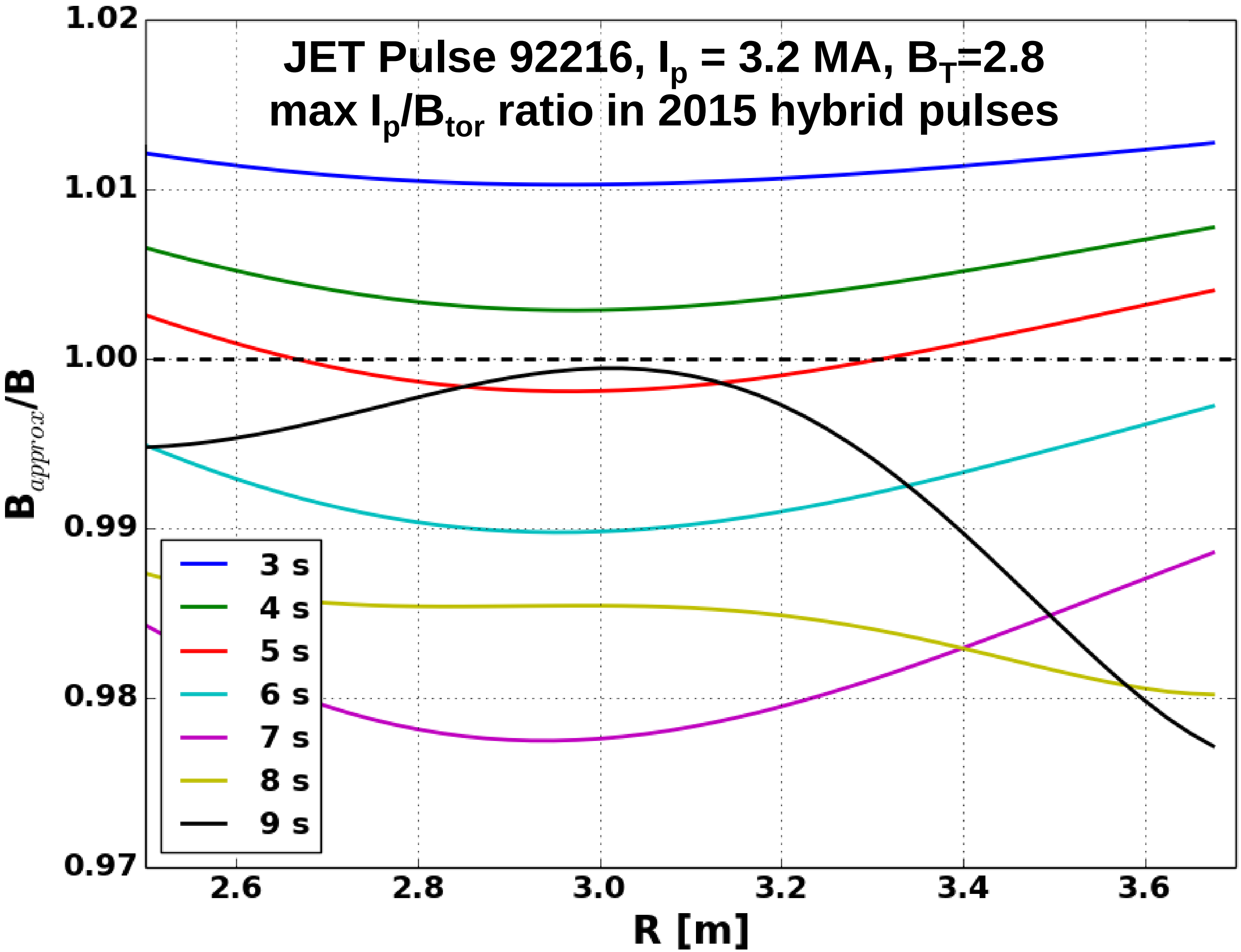
Approximation: $B_{approx} = B_{tor}$

Only $\mathbf{I_{tfc}}$ required as ext. input, no equilibrium reconstruction.

Best results are obtained for low I_p/B_{tor} pulses.
Interesting for current ramp phase



B field approximation: good results during current ramp



$$B_{approx} = B_{tor} = B_{tor,R_0}\frac{R_0}{R}$$

$$B_{tor,R_0} = \frac{\mu_0}{2\pi}\frac{I_{tfc}}{R_0}N_{turns}N_{coils}$$

$$0.97 < \frac{B_{approx}}{B} < 1.02$$

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Small shift due to magnetic field approximation

$$f_{ECE} = \frac{eB_{simple}}{2\pi m_e}$$

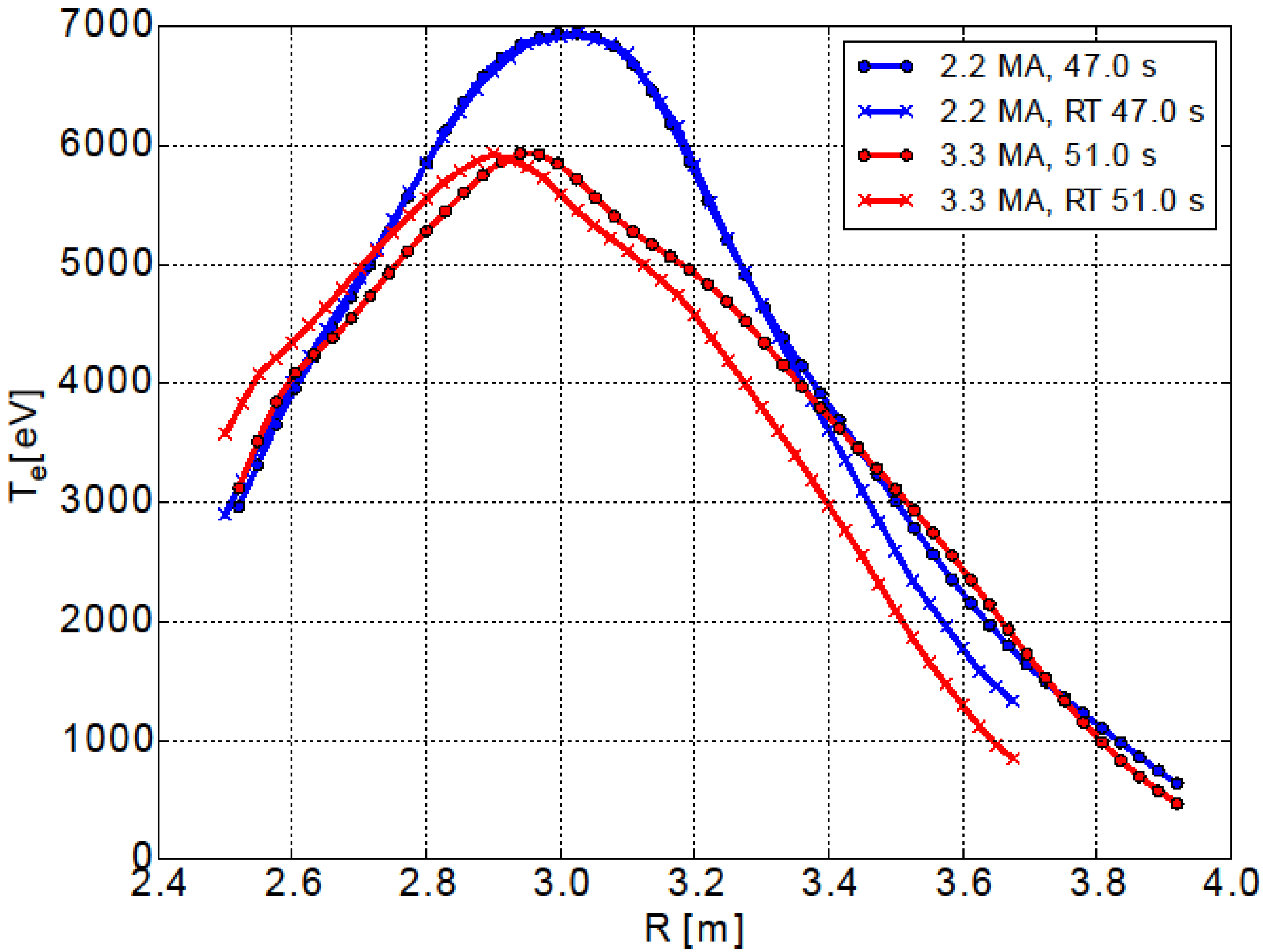
Agreement depends on I_p/B_{tor}

94945

I_p = 2.2 MA, B_T = 2.8 T
(<3 cm shift)

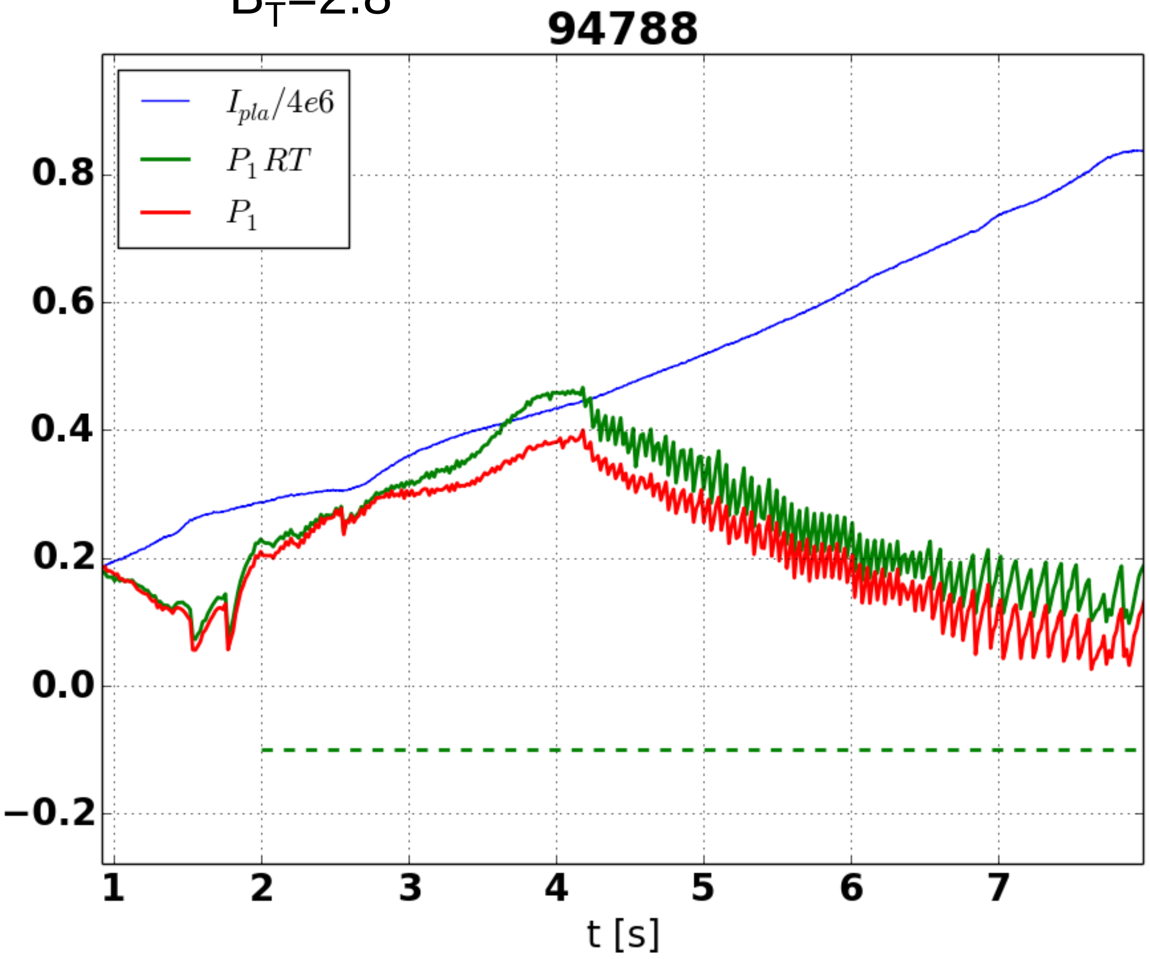
94788

I_p = 3.3 MA, B_T = 2.8 T
(5/15 cm core/LFS shift)

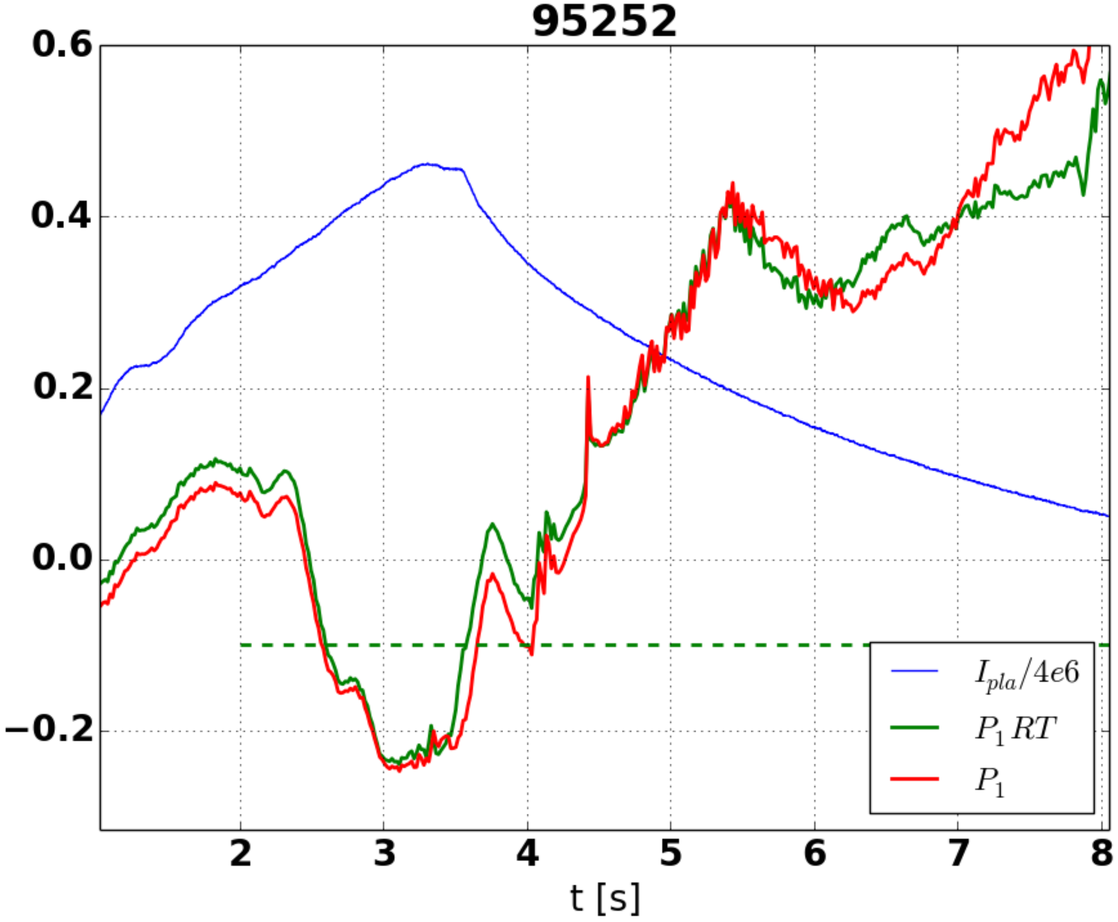


Small error between approximation and ppf

Pulse 94788
I_p 3.3 MA
B_T=2.8



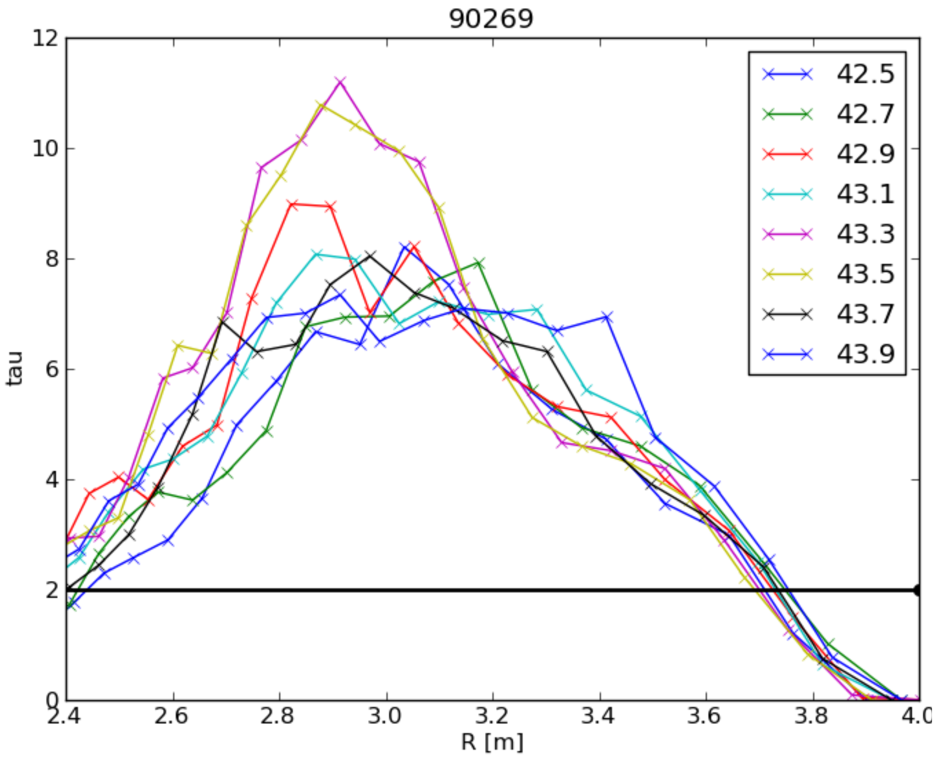
Pulse 95252
Ip 2.2MA Hybrid
B_T=2.8

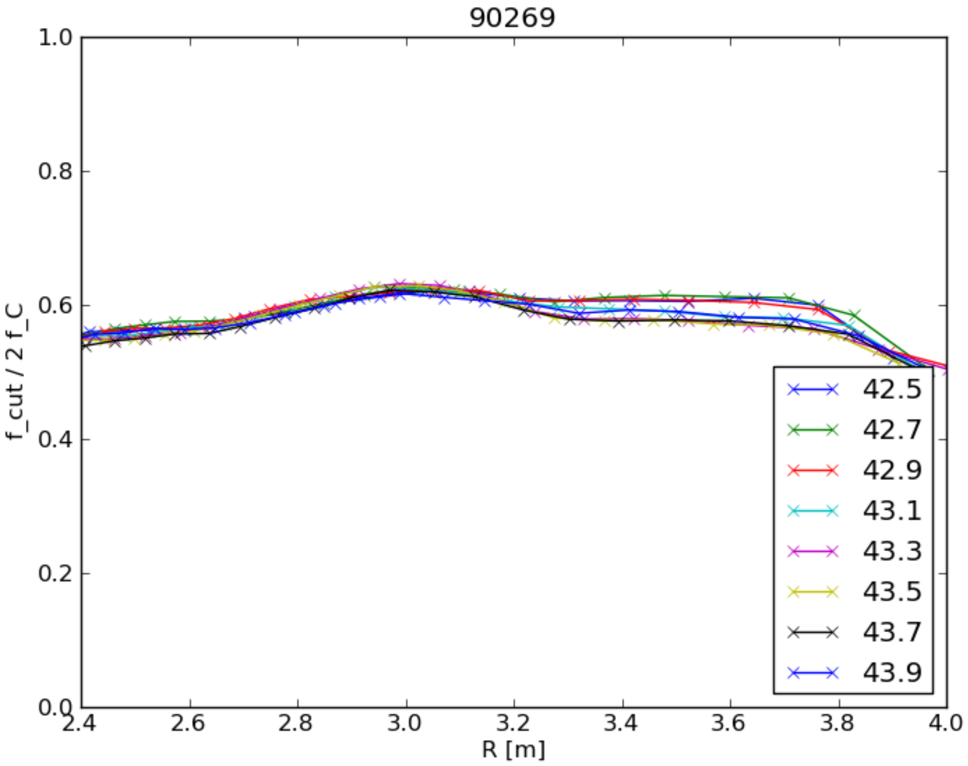


Cutoff/optical depth pose no problem in ramp

Optical depth (τ) > 2 is considered sufficient for $T_{rad} = T_e$

Issues may arise for high density phases before disruptions





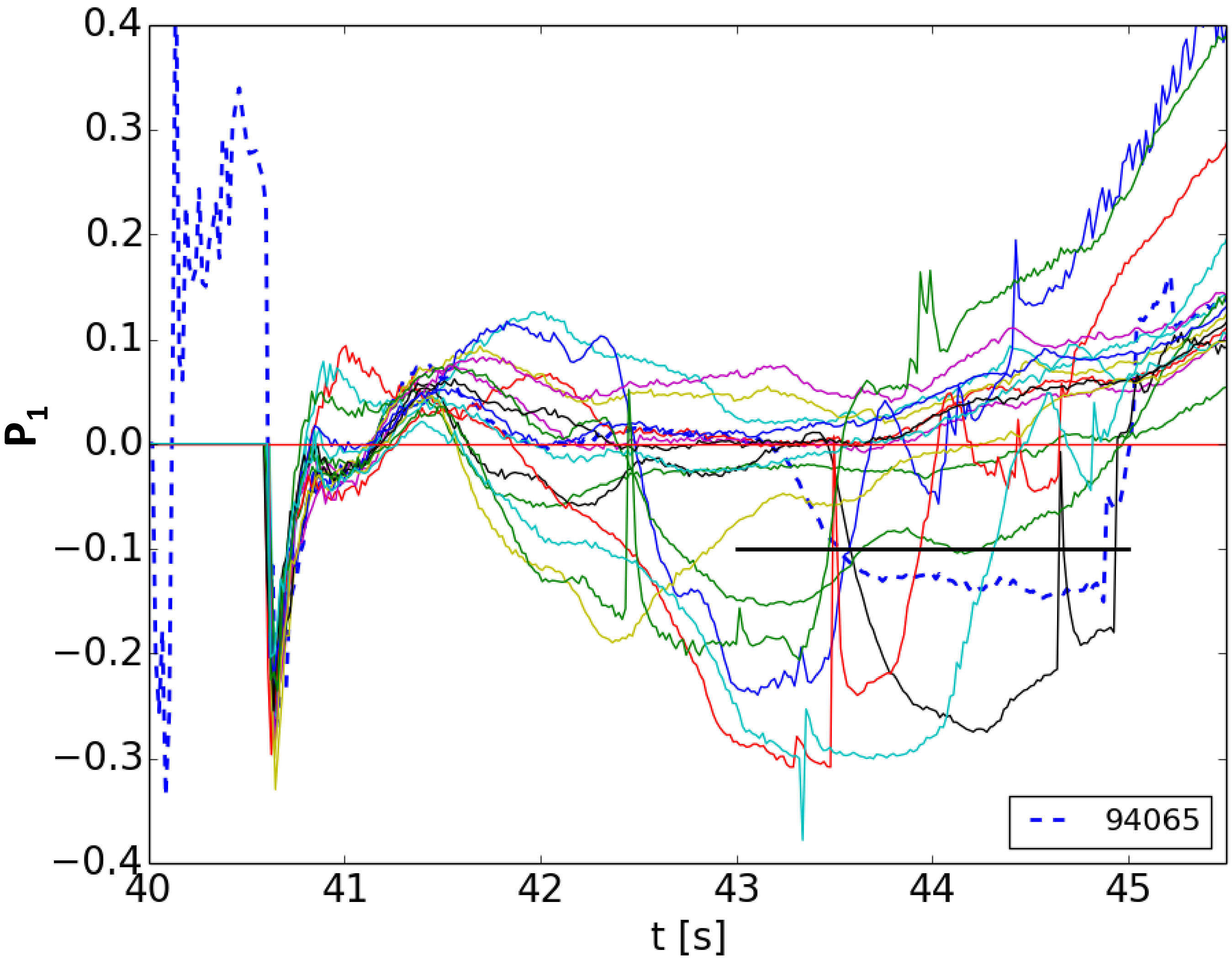
First applications: hybrid pulses ramp-up phase

Hybrid pulses at JET: improved confinement wrt IPB98(y,2) scaling

- High β_N
- Rely on wide low magnetic shear region in the plasma core at q=1
- q-profile optimized during current ramp-up phase
  - Often ending with a current overshoot
  - Sensitive to main ion mass [*C. D. Challis et al, Nuclear Fusion, 2020*]

- Sometime present hollow temperature profile during the current ramp-up as a consequence of impurity accumulation.
  - Can cause double tearing modes: terminated by mitigation system, but potential of high current disruptions (>3MA)

M18-02 tested the system with success



17/09 session:
6/16 pulses triggered protection

All landed safely

Not known if they would all have been disruptions.

Future applications: combination with radiation metrics

Interesting results were obtained using radiation metrics based on bolometry tomographic inversion: $\mathbf{P_{rad,core}/P_{tot}}$ and $\mathbf{P_{rad,out}/P_{tot}}$

Very good advance with respect to existing alarms.

53 pulses from JET baseline experiments (2019-2020)

🟢 $P_{rad,out}/P_{tot}$

🔴 $P_{rad,core}/P_{tot}$

⚫ **False negatives**

🔵 **False positives**