



ELM mitigation by externally induced ELMs - Physics and Prospects

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● ELM control techniques and application

Status quo

● Possible limits and open questions

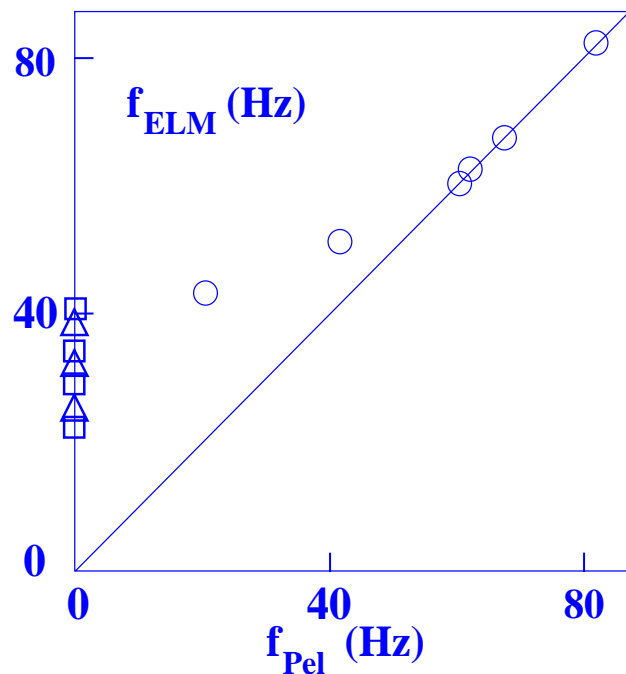
● ELM trigger threshold conditions

Physics

● Optimisation to the full potential

Prospects

Techniques imposing sufficient impact on the edge p and/or j profiles are able to trigger ELMs and to establish control of f_{ELM}
Pellet, magnetic triggering, I ramps,.....[not: supersonic gas jet]



ELM mitigation by keeping the relation

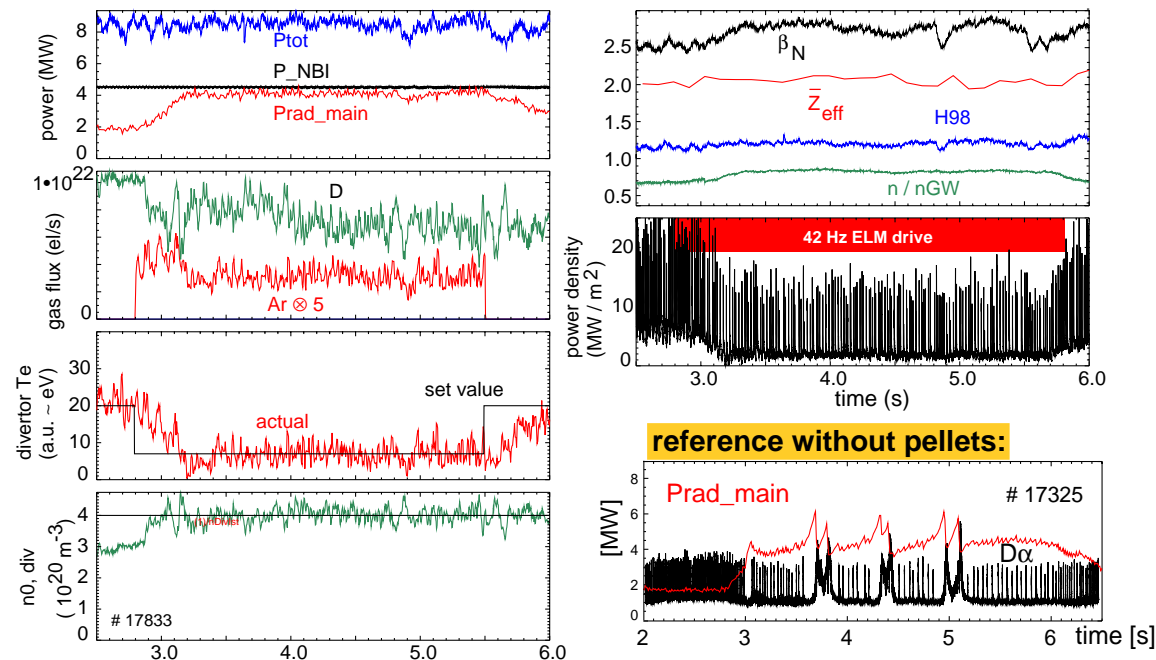
$$\Delta W_{\text{ELM}} \times f_{\text{ELM}} = 0.2 \times P_{\text{heat}}$$

$$f_{\text{ELM}} \uparrow \Rightarrow \Delta W_{\text{ELM}} \downarrow$$

"Direct approach"

"Indirect approach"

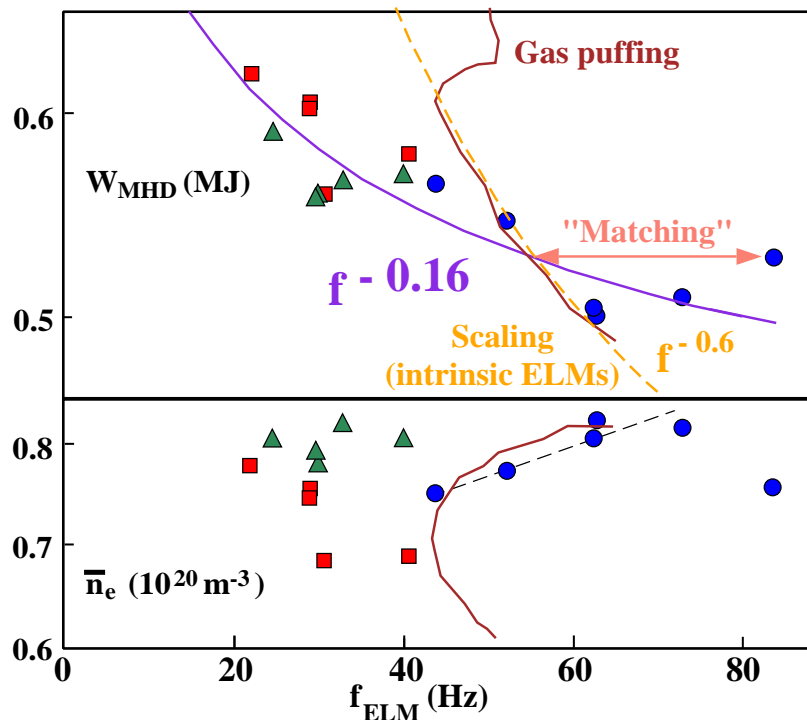
f_{ELM} control applied for scenario stabilisation
(Integrated exhaust control, Kallenbach I3.004)



**Applications in the context of different approaches can be beneficial
(e.g. ITB, improved H-mode)**

Open questions (I): what is the "price" of f_{ELM} control

It is not sufficient just to control f_{ELM} and hence ΔW_{ELM} ,
the "price" (= confinement loss) must be tolerable



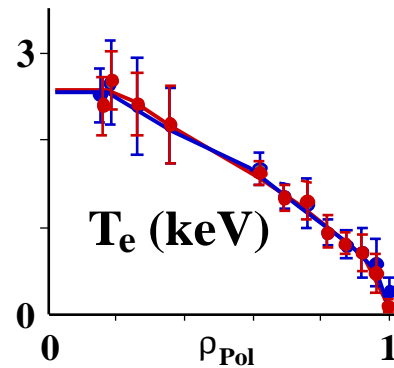
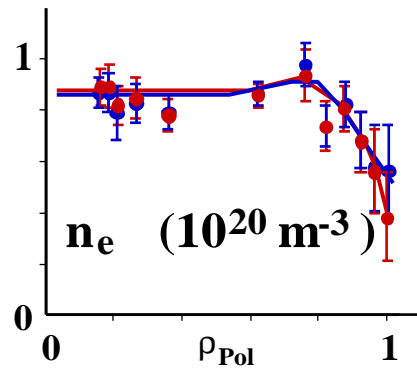
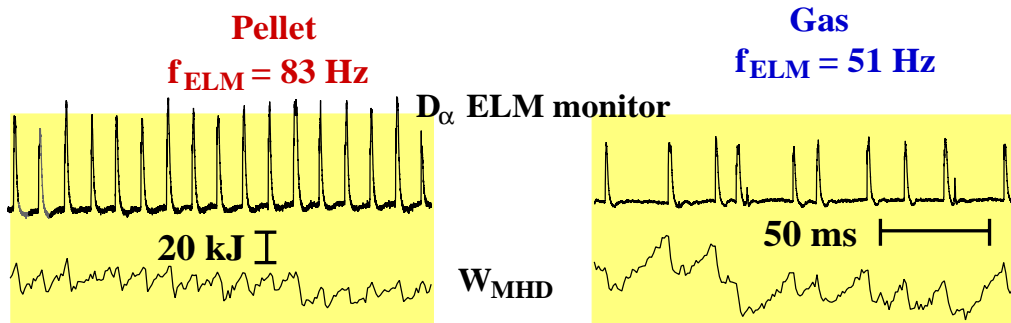
For the pellets
 $W_{\text{MHD}} \sim f_{\text{ELM}}^{-0.16}$
Due to convective losses?

For magnetic triggering
 $W_{\text{MHD}} \sim f_{\text{ELM}}^{-0.22 \pm 0.06}$

By change or due to same physics?

Can an optimised trigger tool (e.g. slow, small pellets)
improve the situation (reduce confinement losses)?

Open questions (II): what is special about triggered ELMs?



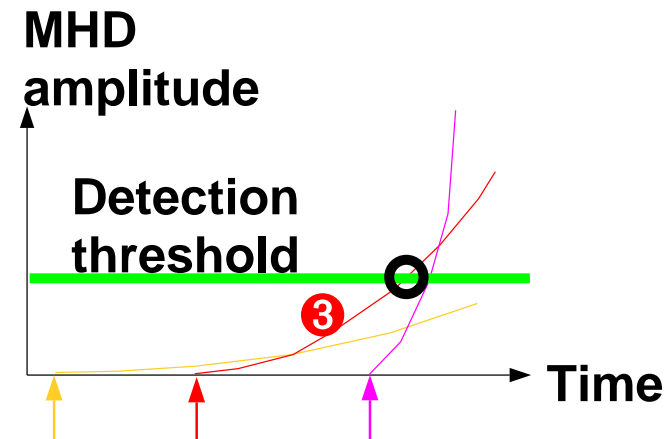
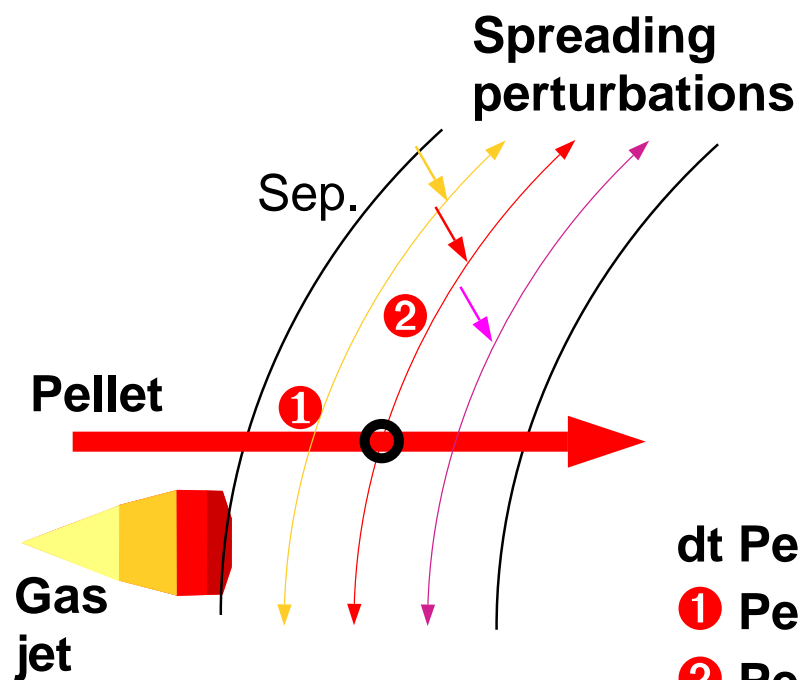
How can an ELM, triggered at approx. identical (n,T) plasma parameters be smaller than its initial counterpart?

How is the ELM triggered?
(measure required localisation and strenght of perturbation)

How does the ELM evolve?
(compare dynamics and extention)

Better knowledge could allow to tailor the optimum trigger tool

Where does the perturbation finally cause the ELM?
(ELM: first component detected in Mirnov coils)

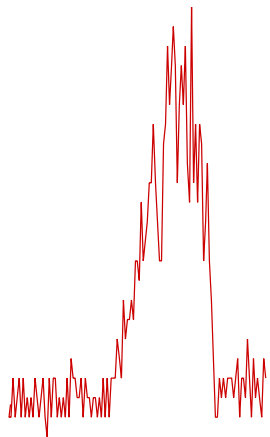


$dt_{\text{Pellet @ separatrix}} - \text{ELM onset detected} =$

- ① Pellet time of flight to seed position +
- ② Perturbation spread time to trigger position +
- ③ ELM growth time to detection threshold

**ELM onset delay composed from intrinsic component and
time of flight : determine trigger location by v-scan**

D_α pellet monitor



0.1 ms

D. McNeill, J. Nucl. Mater.
162-164 (1989) 476.

$$D_\alpha(t) \longrightarrow dN/dt(t)$$

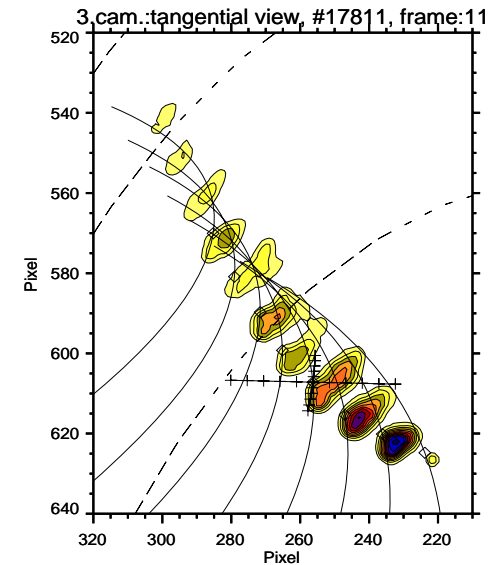
$$dN/dr(r)$$

"Perturbation"

More & details:
S. Kalvin
P2.078
K. Gal
P2.098

$$\vec{r}(t)$$

3D pellet tracking



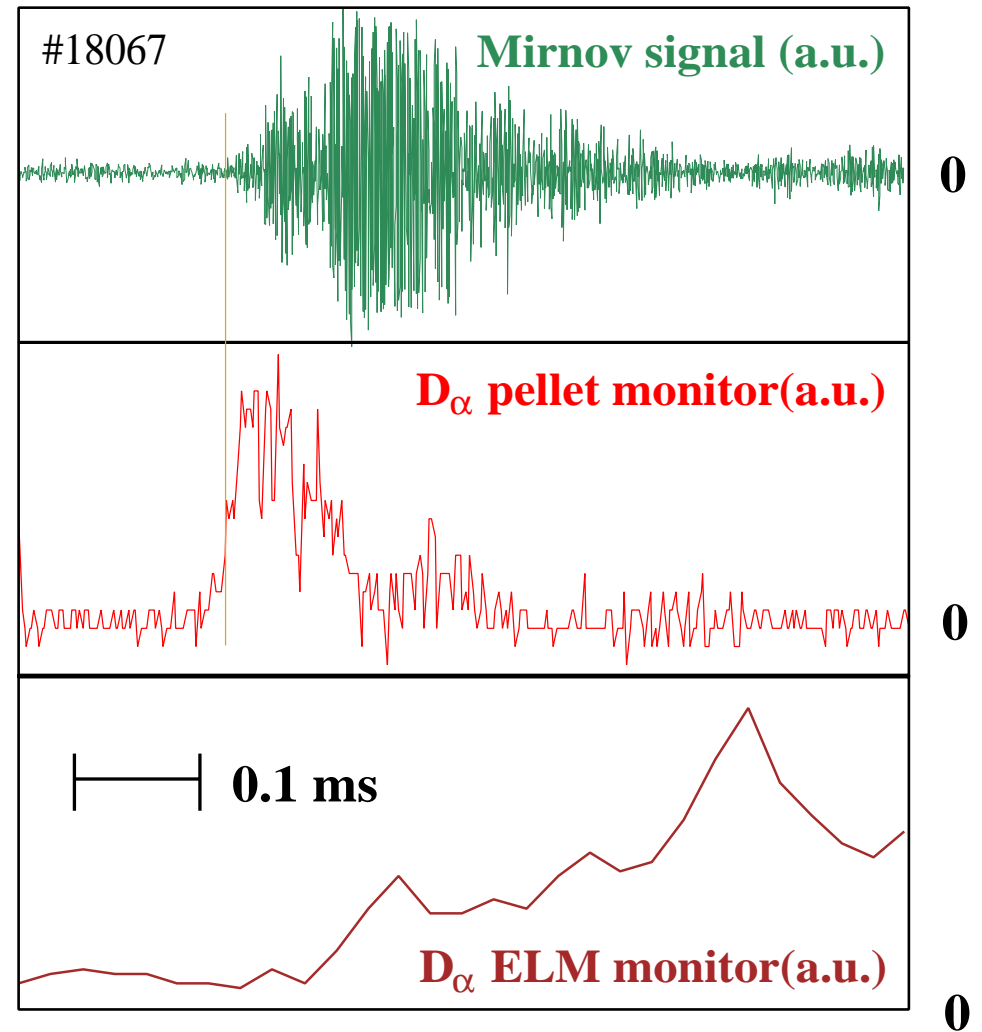
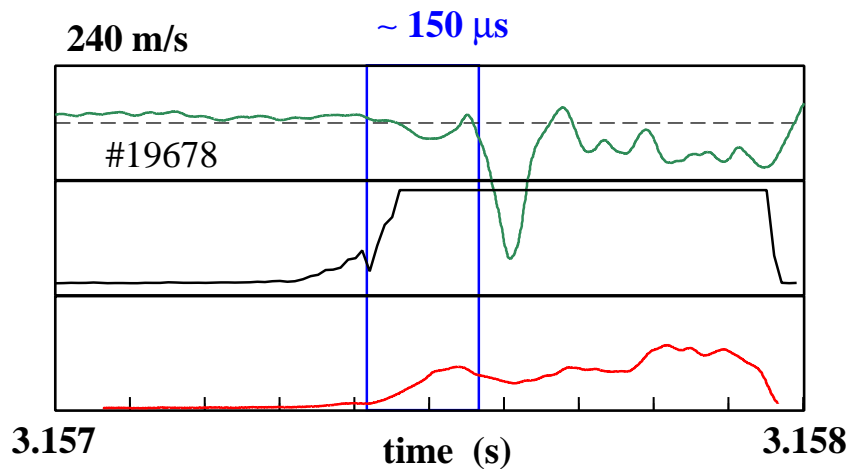
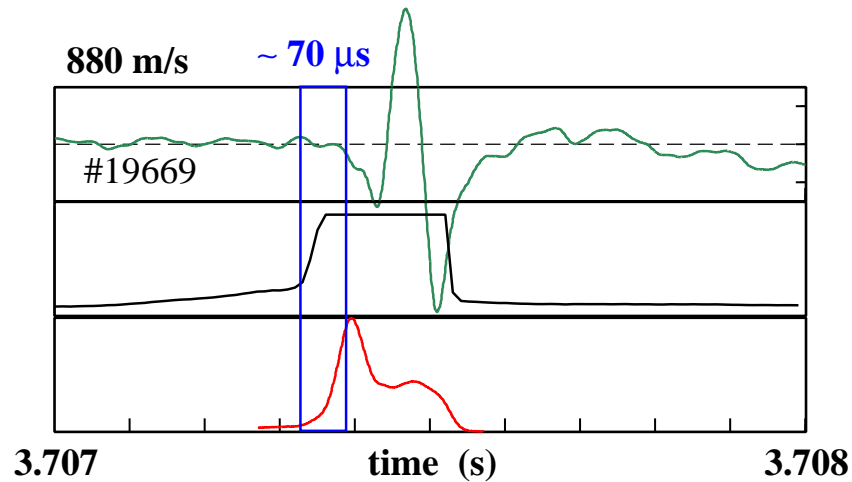
$$\Delta t_{\text{Pellet-ELM}} = dt_{\text{intrinsic}}(dN/dr, r, \dots) + \frac{r_{\text{seed}}(dN/dr) - r_{\text{Sep.}}}{\langle V_{\text{Pel.}} \rangle}$$

$$= \langle dt_{\text{onset}} \rangle + \frac{\langle r_{\text{seed}} \rangle - r_{\text{Sep.}}}{V_{\text{Pel.}}} + \underbrace{\delta \text{ intr. } (dN/dr, r, \dots) + \delta r_{\text{seed}}}_{\text{a lot of physics, still hidden in the error bar}}$$

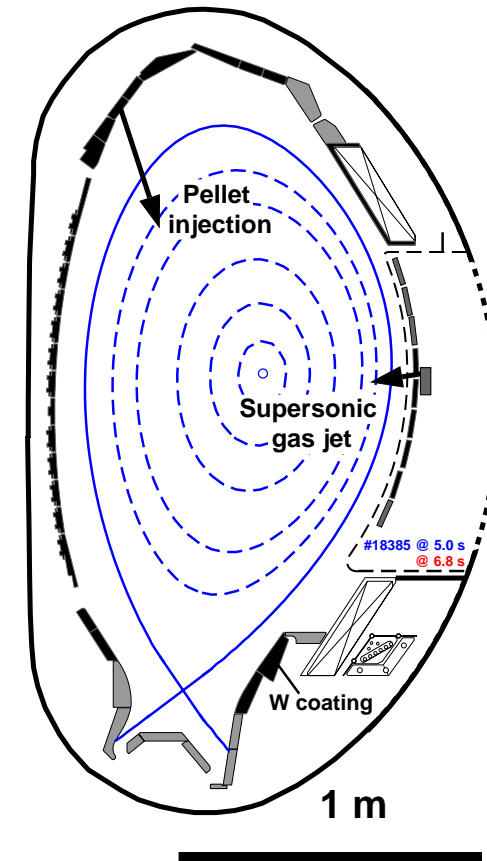
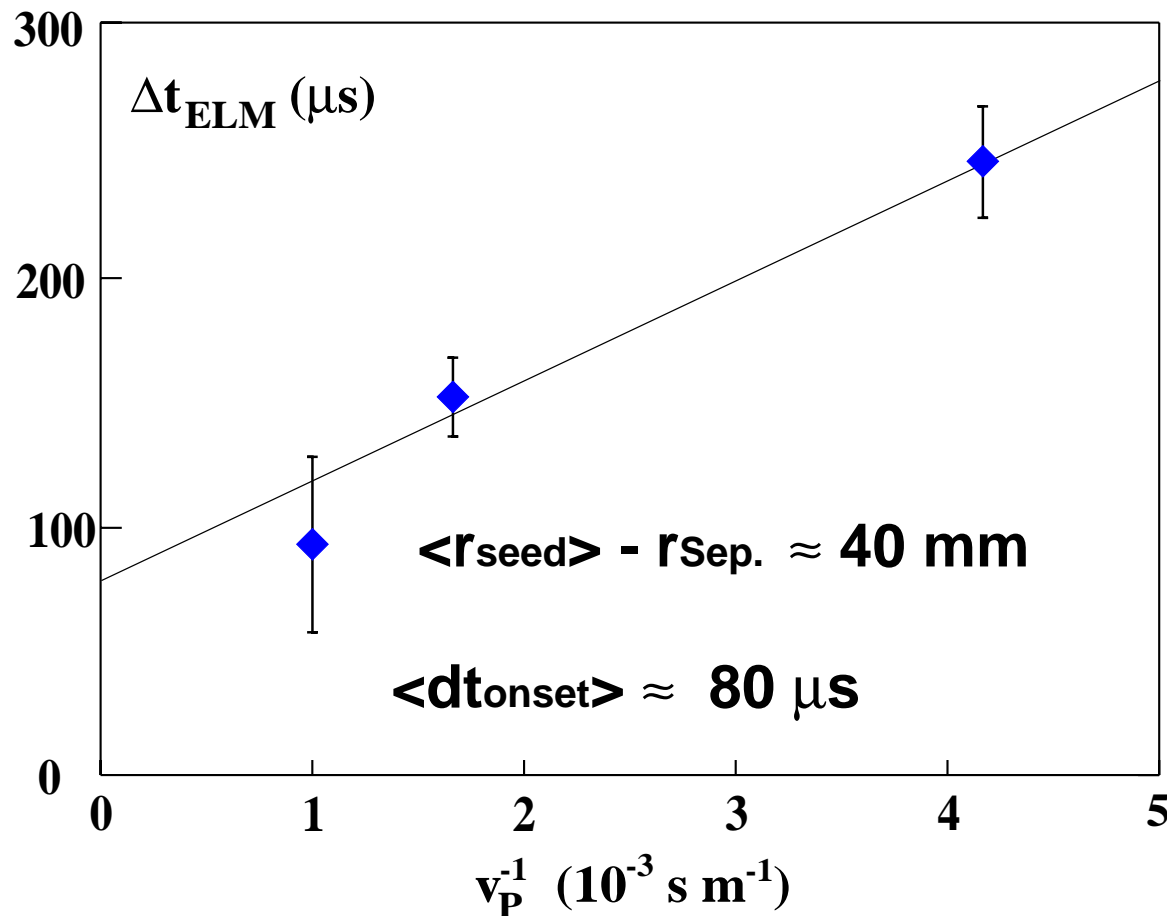
This presentation

a lot of physics, still hidden in the error bar

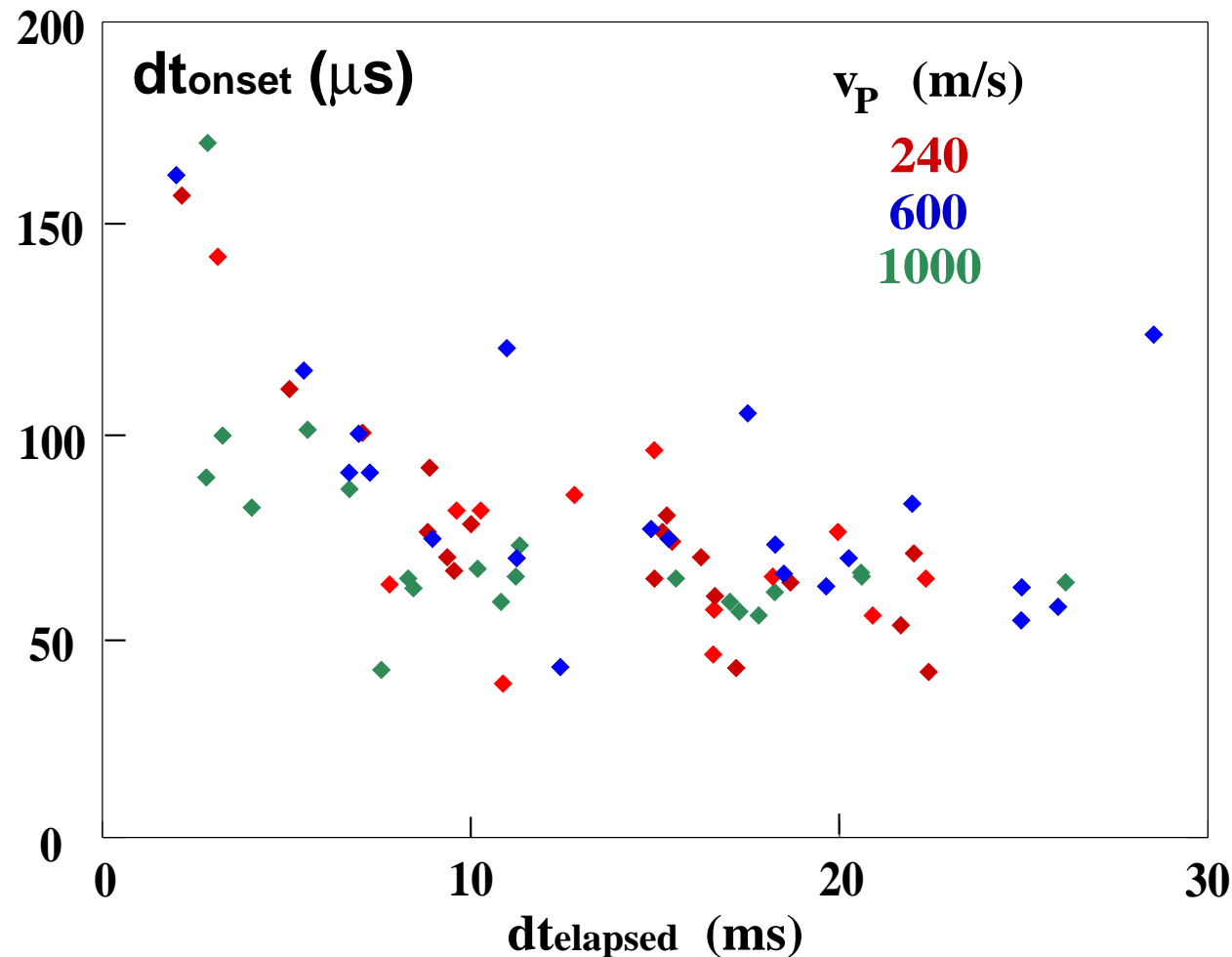
Detection of ELM and ablation onset with very high precision required



Result from pellet velocity scan (may be modified slightly after more refined analysis)

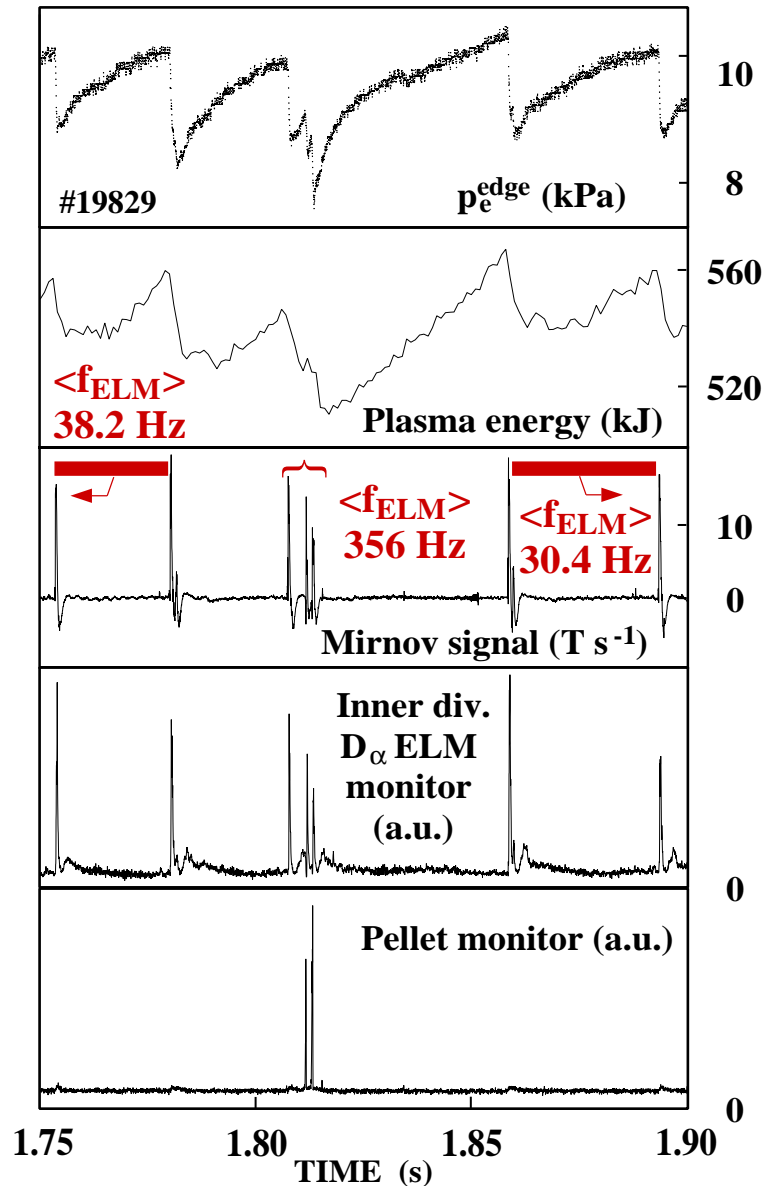


Perturbative ($f_{pe1} = 6 \text{ Hz} \ll f_{ELM}^0 \approx 40 \text{ Hz}$) triggering
Statistical variation of $dt_{elapsed}$ since previous intrinsic ELM



This seems to indicate forced ELM triggering soon after an intrinsic ELM causes a slower ELM growth rate but leaves r_{seed} at about the same position

Physics of ELM triggering: every pellet can trigger an ELM

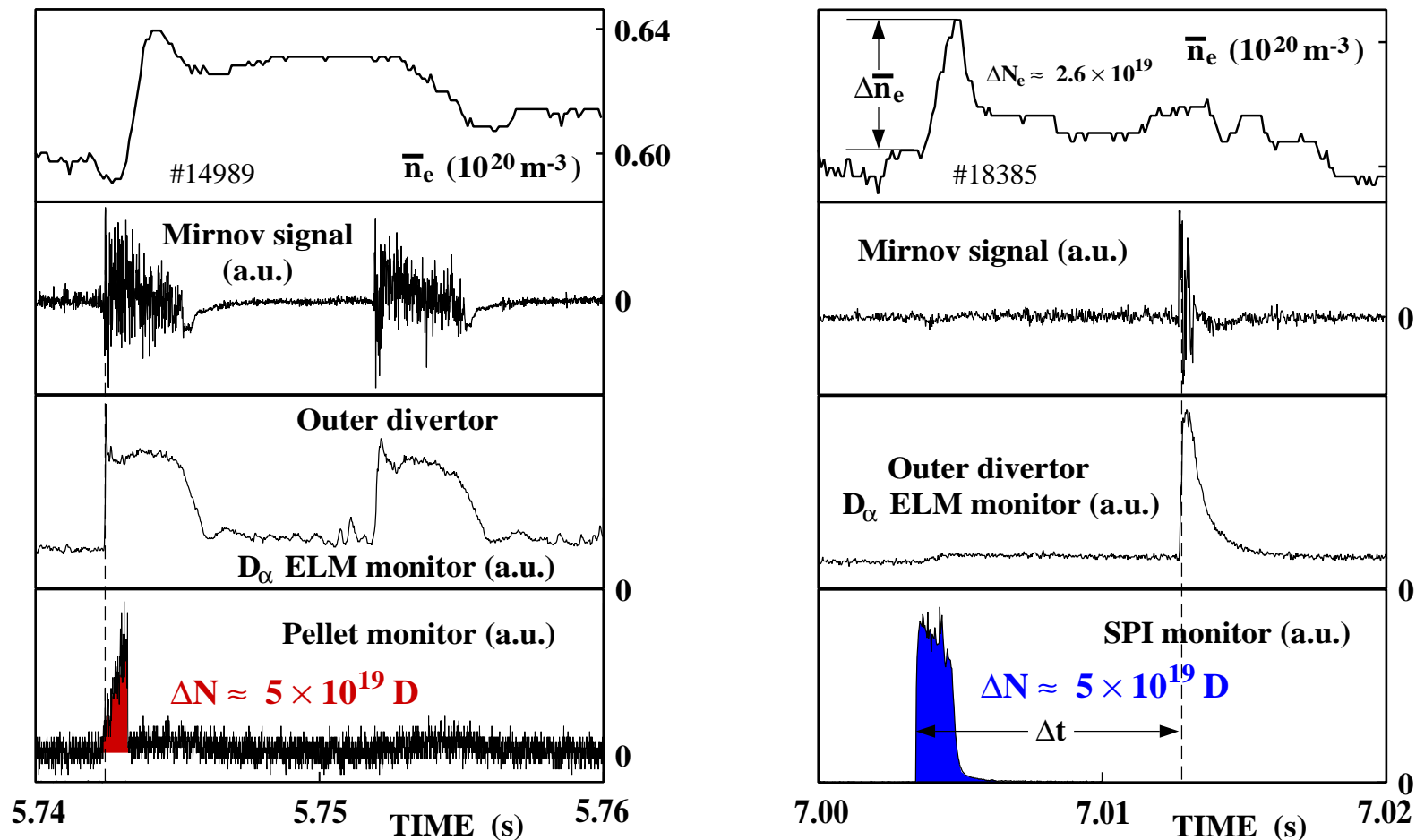


Even in cases $f_{Pel} \gg f_{ELM}$
(here accidentally by pellet fragments)
every pellet can trigger an ELM

Operational:
Significant enhancement beyond
intrinsic ELM frequency can be
achieved

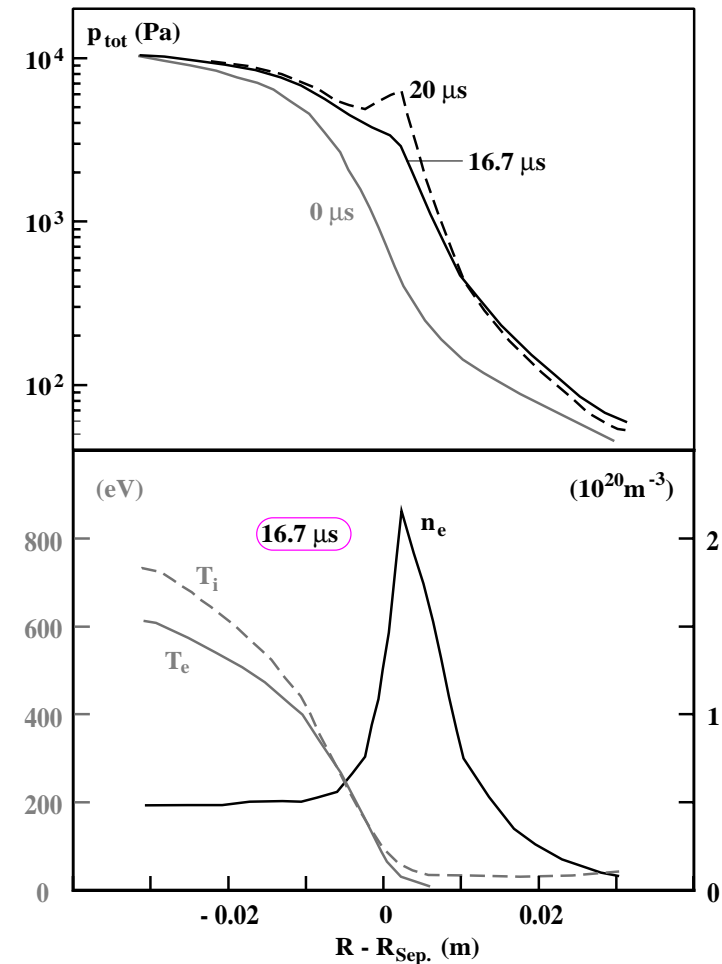
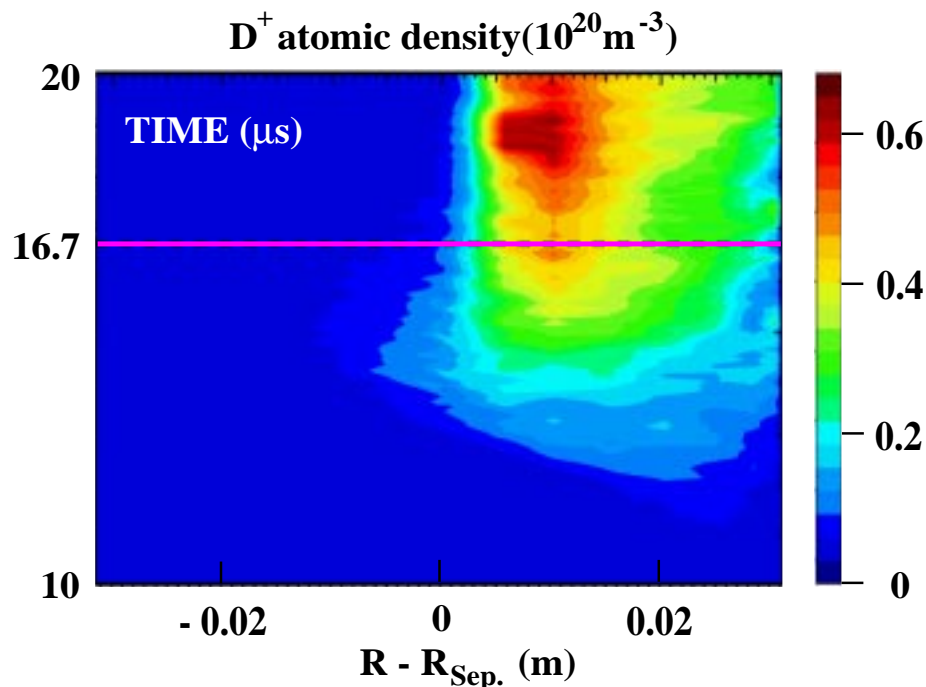
Physics:
The ELM is non-linearly unstable at
any time in the type-I regime

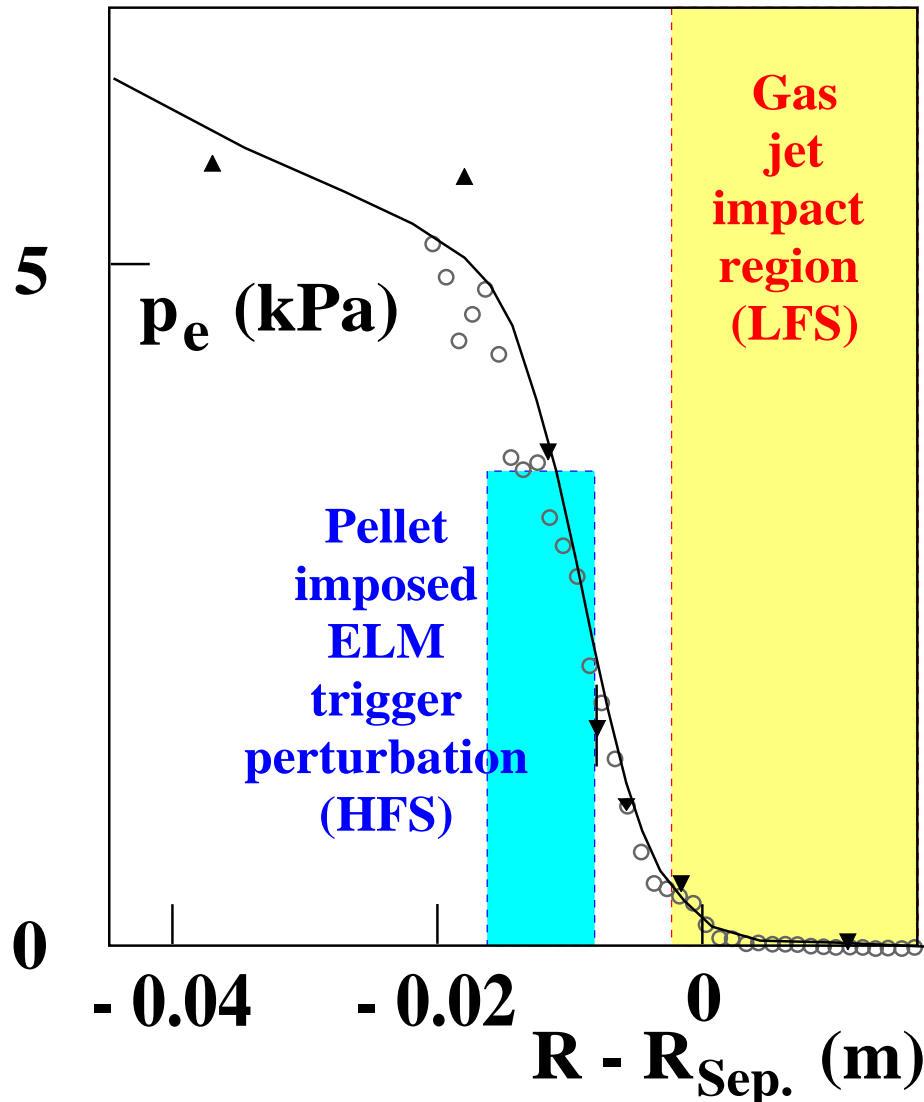
Very intense gas jet still fails to trigger prompt ELM
Particle amount already causes fuelling constraints (for pellet as well!)



Apart from minor fraction penetrating ~ cm in early phase, gas jet gets stuck in the vicinity of separatrix due to beam blocking

"Impact of a pulsed supersonic deuterium gas jet on the ELM behaviour in ASDEX Upgrade",
Plasma Phys. Contr. Fusion. vol. 47 (2005) issue 7.





**ELM seed perturbation
imposed about 13 mm
inside separatrix**

$$dN/dt < 10^{23} \text{ D/s}$$

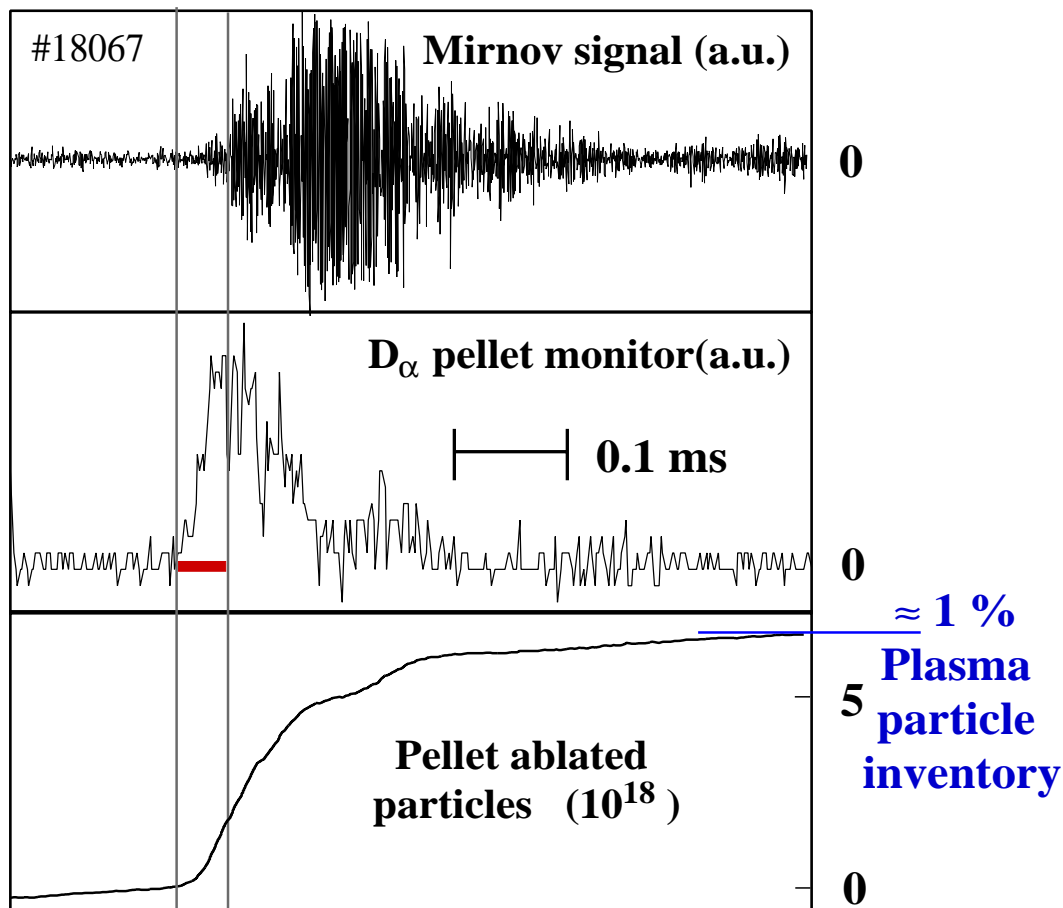
$$\text{Interaction time} \sim 10^{-5} \text{ s}$$

$$\text{Deposition volume} \sim 10^{-5} \text{ m}^3$$

More details:
Nucl. Fusion. 45 (2005) 502.

**Onset time $\approx 80 \mu\text{s}$
Time scale of the ion
expansion to LFS
Trigger at region of
unfavourable flux surface
curvature?**

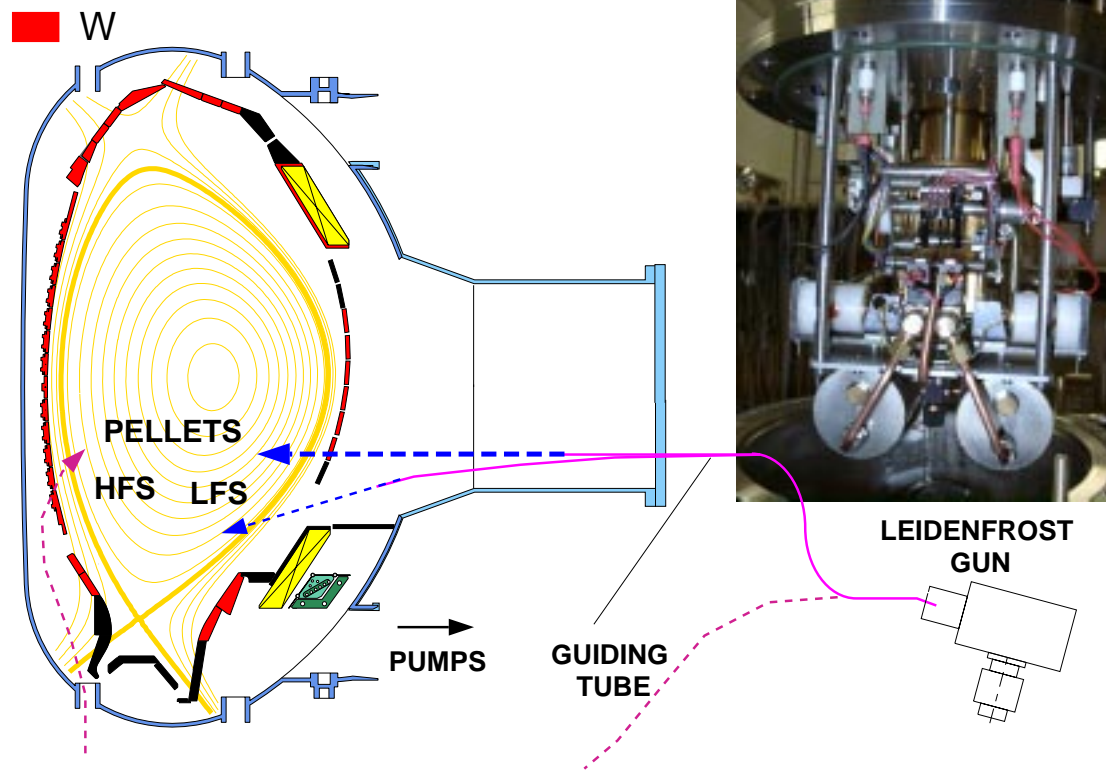
Unwanted side effects due to fuelling and deep penetration
Can be eliminated using much smaller pellets



Micro size pellets sufficient
(compensate smaller mass
by smaller velocity to keep
deposition constant)

fELM becomes smaller with
growing machine size
⇒ infrequent micropellets,
possibly non-cryogenic
light impurity

We are still (until July 2005) using our refuelling system for ELM control investigations, but soon (C2005/06) we will...



inject slower pellets

inject smaller pellets

**inject at higher rate
(143 Hz in testbed)**

**inject from different
locations**

This should allow for advanced operational features and improved physics related investigations