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On the possible injection schemes with the ITER SPI system

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EUROfusion

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Introduction (1/2)

- We will propose 2 « original » SPI schemes focused on the objective of avoiding RE beams in ITER
  - The compatibility of these schemes with other DMS objectives will not be addressed

- 2 main reasons why RE generation could be large in ITER:
  - 1) Strong hot tail due to high T_e [Paz-Soldan 2020]
  - 2) Enormous avalanche gain + small continuous seeds (Tritium β decay, Compton scattering of γ's from the activated wall)

Introduction (2/2)

- The current RE avoidance strategy is based on raising n_e by a large factor (~20-40) [Martín-Solís, NF 2017]
  - Hot tail generation assumed to be small

- **Scheme 1: Pure H_2 SPI before TQ** could be the best hope to raise n_e…
  - ...and to avoid hot tail generation thanks to pre-TQ dilution cooling
  - Impurity SPI would follow to trigger the TQ and radiate the energy

- !! But the validity of the current RE avoidance strategy for the Baseline 15 MA DT scenario is questioned by recent work !! [T. Fülöp, this conf.]

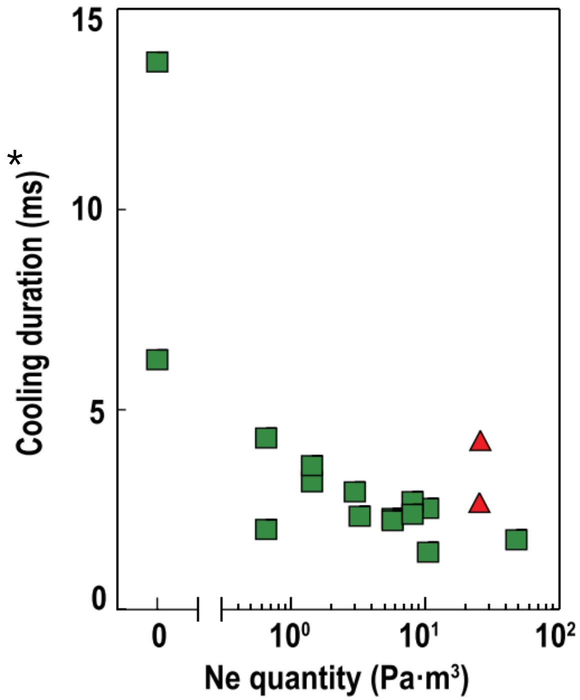
- An alternative idea to deal with the small seed + large avalanche issue: **Scheme 2: Post-TQ SPI to continuously deplete RE seeds**

Pure H_2 (or D_2) SPI before the TQ for fast plasma dilution

Experimental observations

- Pre-TQ (or ‘cooling’) phase is observed to be longer for pure D_2 SPI than for impurity SPI on several machines (DIII-D, JET, …)

D_2+Ne SPI in DIII-D



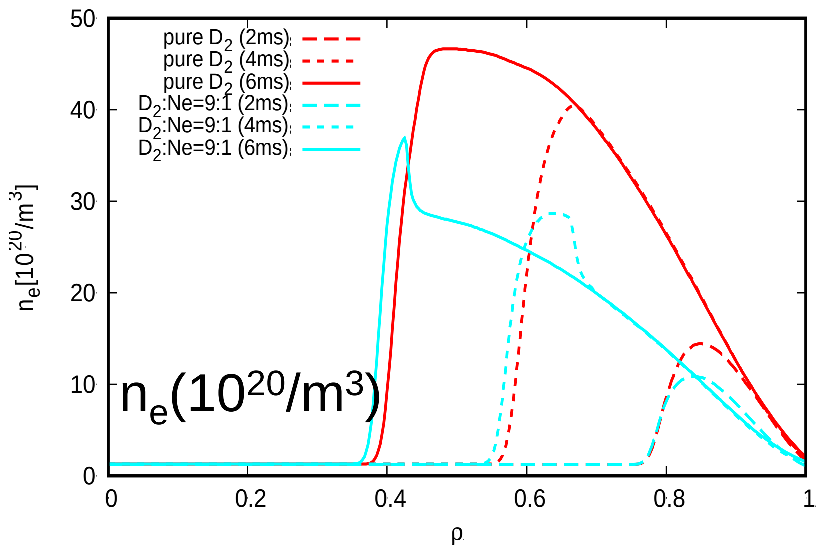
From D. Shiraki et al., Phys. Plasmas **23** 062516 (2016)

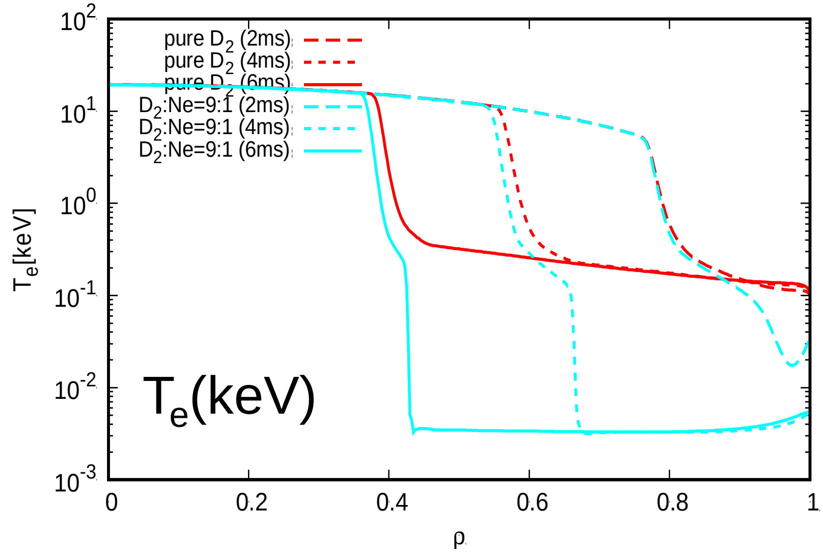
*Time between the arrival of initial pellet fragments and the I_p spike

Interpretation: cold front vs. 'lukewarm' front

Pure D_2 vs. **D_2:Ne = 9:1**

INDEX 1.5D simulations, ITER baseline 15 MA H-mode plasma
Single 28 mm pellet, V_p=200 m/s, N_{shards} = 300





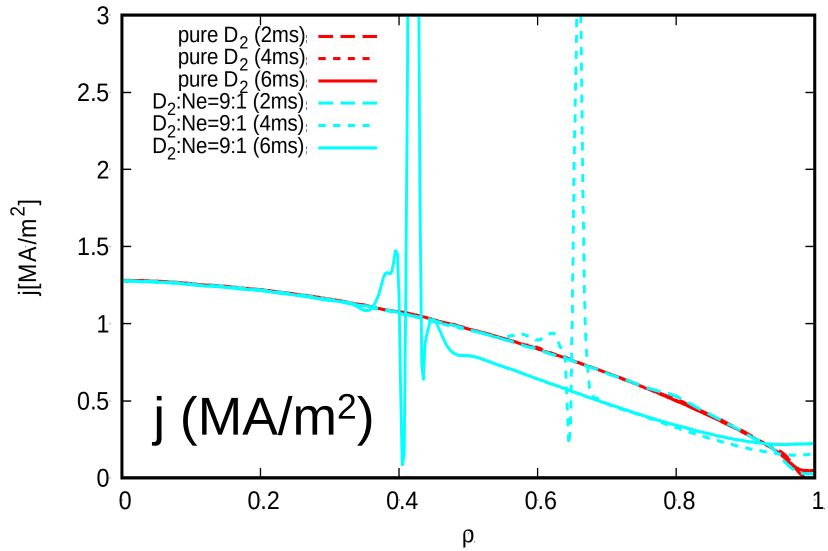
With pure D_2 SPI:

Only dilution cooling (no radiative collapse)

$\Rightarrow$ T_e remains > 100 eV

$\Rightarrow$ Resistive j decay time >> a/V_p

$\Rightarrow$ No modification of j profile



Interpretation: cold front vs. ‘lukewarm’ front

Pure D_2 vs. **D_2:Ne = 9:1**

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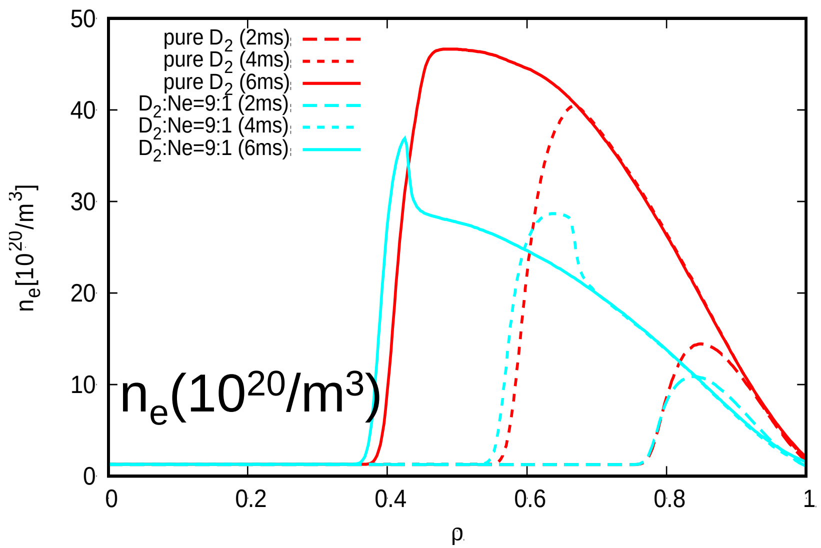
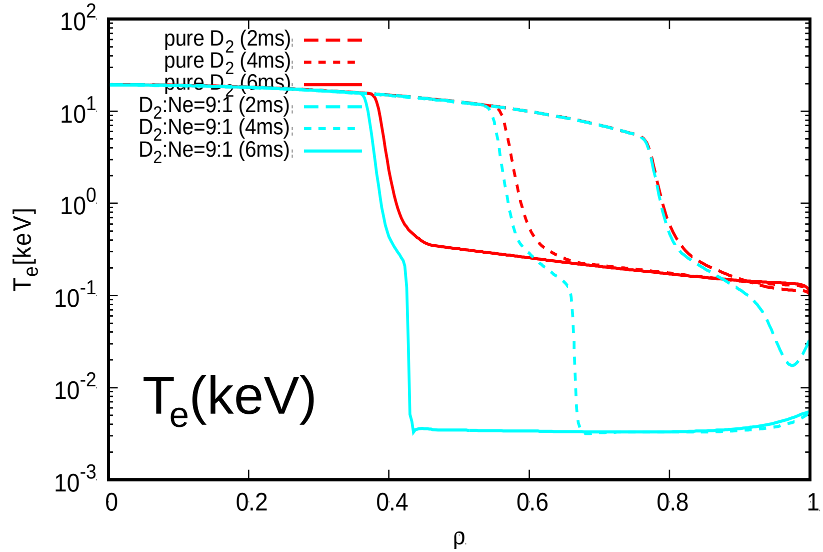
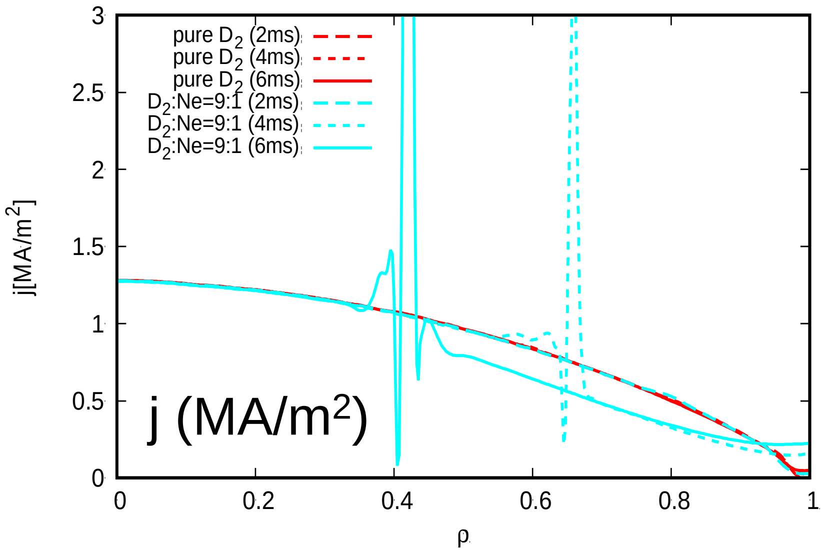




With Ne+D_2 SPI:

Radiative collapse in cold front

- ⇒ T_e goes down to a few eV
- ⇒ Resistive j decay time < a/V_p
- ⇒ Modification of j profile
- ⇒ Likely to trigger an early TQ



Testing pure D_2 SPI with JOREK 3D non-linear MHD simulations

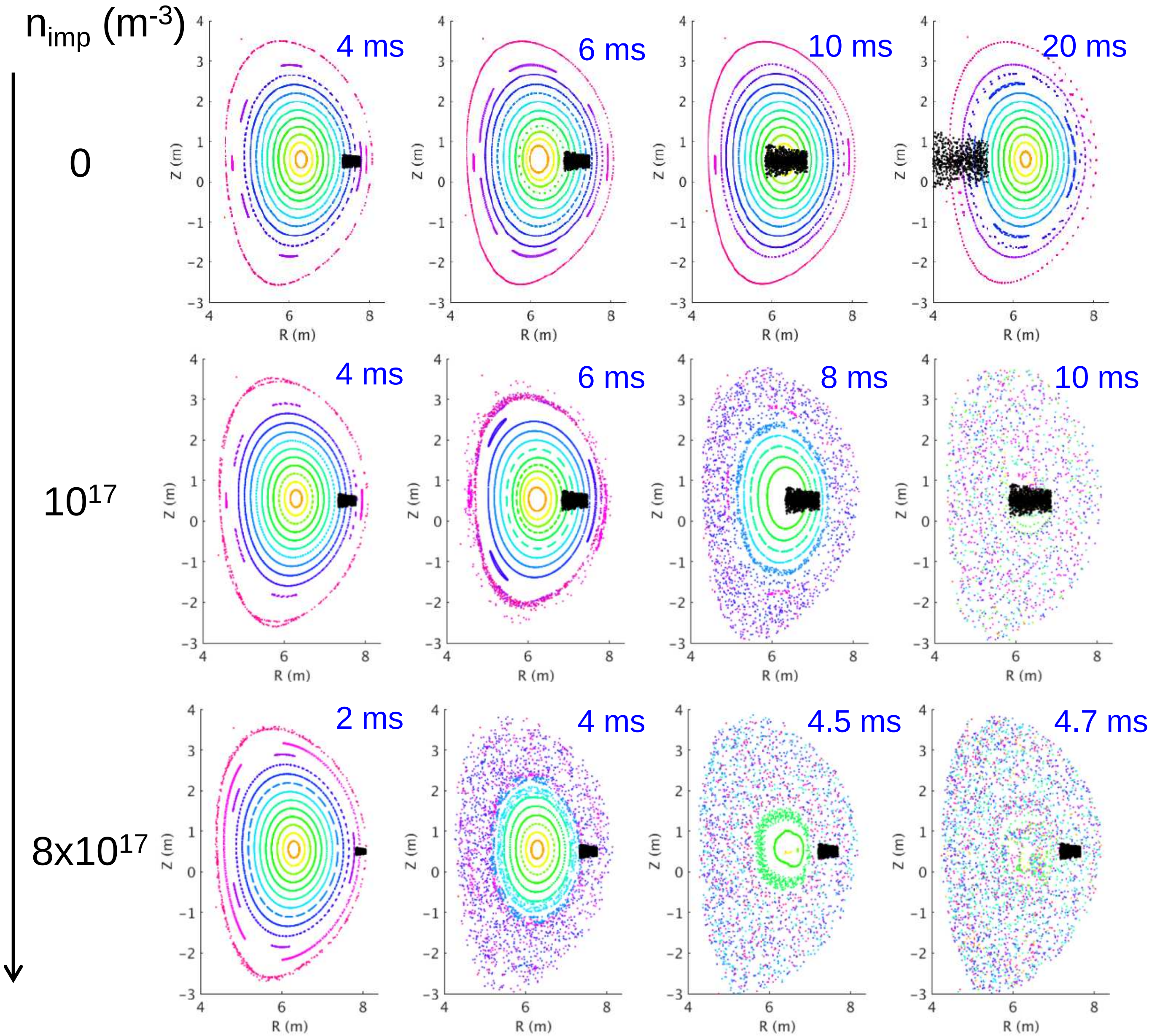
⇒ Experimental and early modelling results suggest that with pure H_2 (or D_2) SPI, shards may have the time to reach the plasma core and dilute the whole plasma before triggering a TQ

- What about the effect of:
  - Background impurities in the target plasma?
    - Lukewarm front → cold front?
  - Toroidal localization of ablation clouds?
    - Enhances MHD modes?

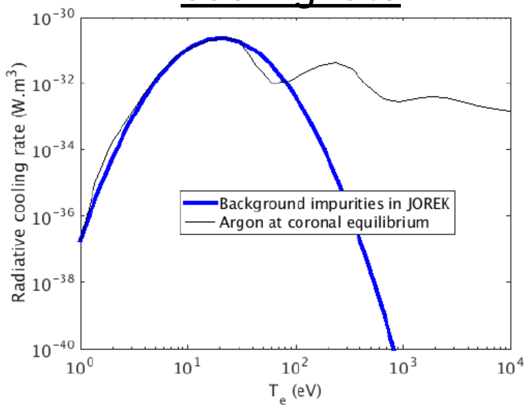
⇒ JOREK simulations

- Target plasma = 15 MA L-mode
- Injection of a 28 mm D_2 pellet with V_p=200 m/s, N_{shards}=1000

Shards can travel across the plasma without causing an MHD crash… below a certain background impurity density

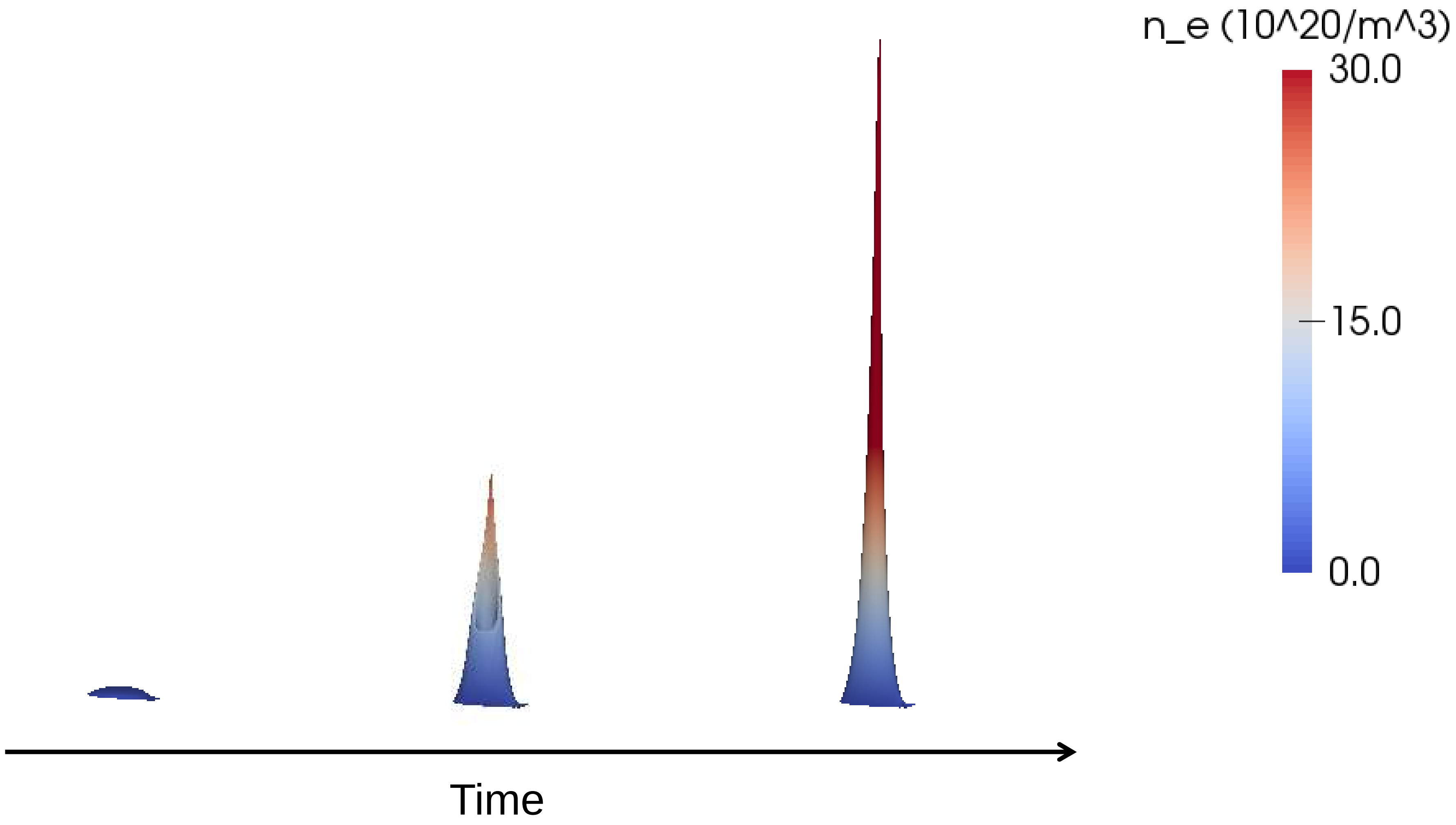


Background impurity cooling rate



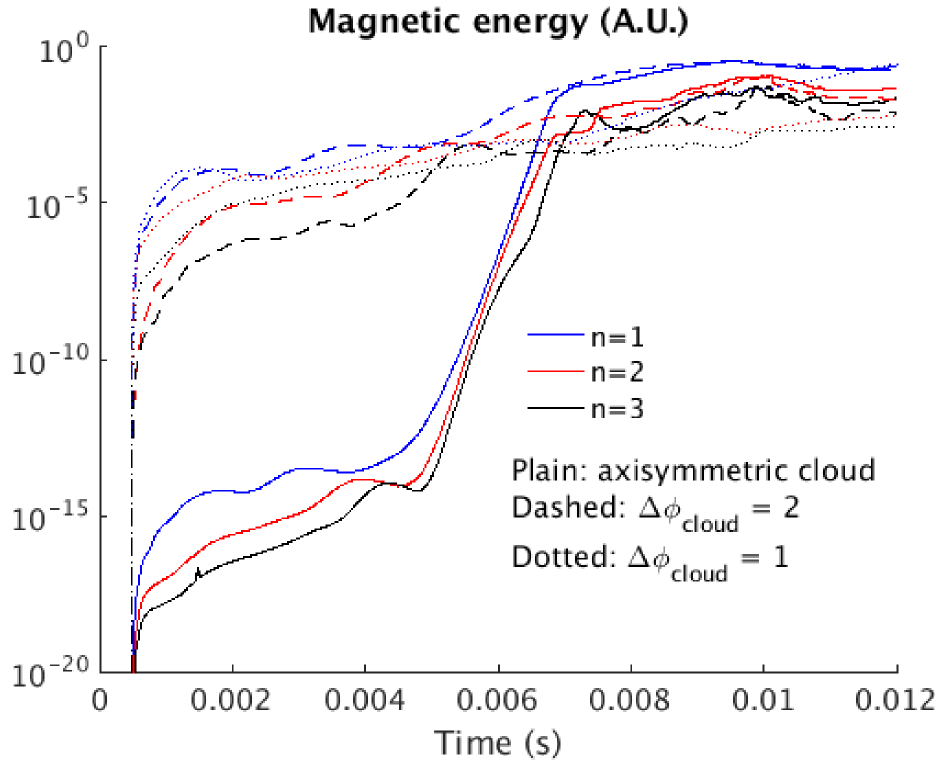
⇒ Motivates further studies with a more realistic description of background impurities

A dilution by a factor > 10 is obtained throughout the plasma



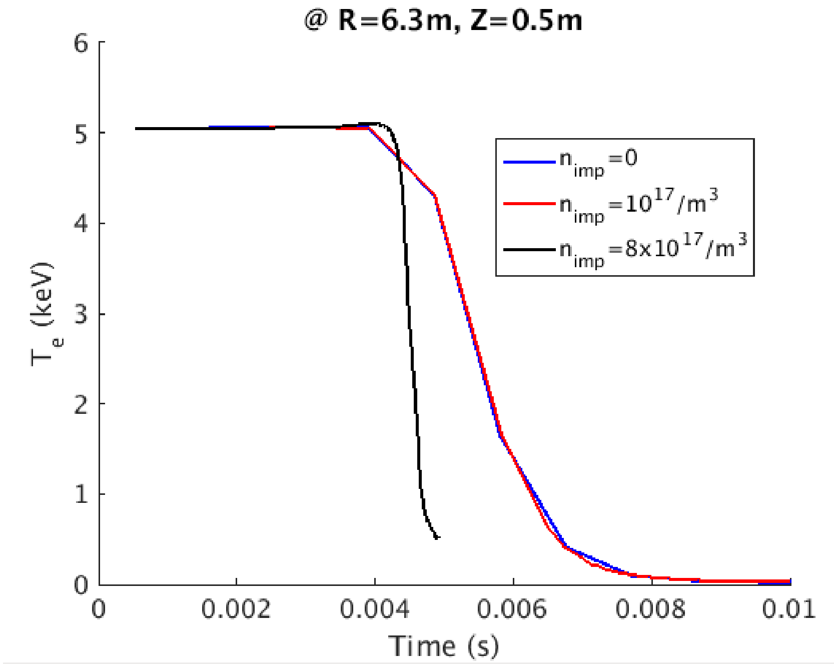
Effect of the toroidal localization of ablation clouds

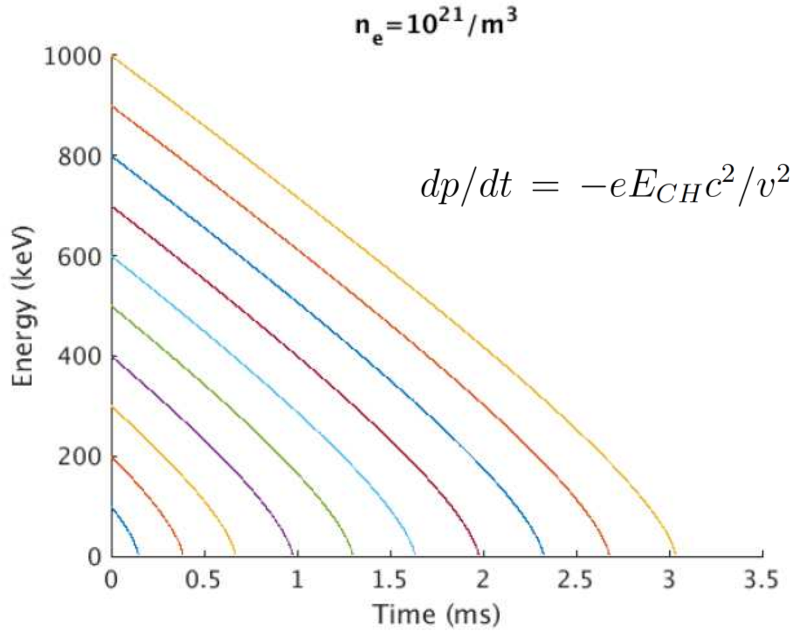
- Due to limited toroidal resolution in JOREK, ablation clouds toroidal extension $\Delta\varphi_{cloud}$ is much larger than in reality
- A scan in $\Delta\varphi_{cloud}$ shows that low-n mode excitation decreases with $\Delta\varphi_{cloud}$
- Interpretation: low-n modes are primarily destabilized via a current profile modification, which is stronger for larger $\Delta\varphi_{cloud}$
  - Direct mode drive by helical cooling does not compensate



⇒ JOREK predictions with artificially large $\Delta\varphi_{cloud}$ probably overpredict low-n mode excitation, i.e. are « pessimistic »

Effect on hot tail generation





- At low n_{imp}, dilution cooling in the core takes place on a multi-ms timescale, allowing the electron distribution to remain Maxwellian
- Hot tail generation during the TQ is very sensitive to τ_e/τ_{TQ}
  - Electron collision time $\tau_e \sim T_e^{3/2}/n_e \sim D^{-5/2}$, where D = dilution factor
  - TQ duration (radiative collapse) $\tau_{TQ} \sim 1/n_e \sim 1/D$

$\Rightarrow$ $\tau_e/\tau_{TQ} \sim D^{-3/2}$, i.e. dilution may dramatically reduce hot tail generation

Pre-TQ pure H_2 (or D_2) SPI: Summary and outlook

- JOREK simulations suggest that plasma can be diluted by a large factor (>10) all the way to the core without triggering a global MHD crash, provided n_{imp} is low enough
  - Best way to raise n_e (baseline RE avoidance strategy)
  - Dilution cooling may suppress the risk of hot tail RE generation

- For more detail: http://arxiv.org/abs/2006.16020

- Motivates more detailed studies, and in particular:
  - More accurate modelling of background impurities
  - Assessment of the effect of pre-existing islands
  - Validation against present experiments
  - Assessment of compatibility with other DMS objectives

Post-TQ SPI
to deplete RE seeds

Principle and required conditions for success

Principle: REs travel across shards. When they do so, they lose an energy $\Delta E_{RE} = p\delta$, where p = stopping power, δ = distance travelled across shard.

⇒ Try to use this effect to deplete small RE seeds before they avalanche

Since seeds are continuously produced, need repeated or continuous injection.

Required conditions for success:

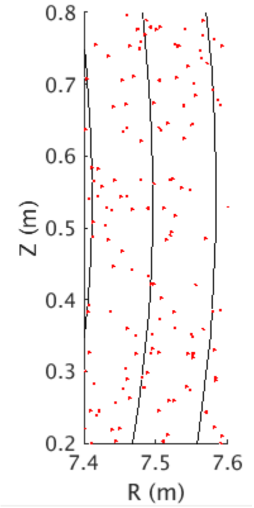
1) Shards should be able to stop RE seeds

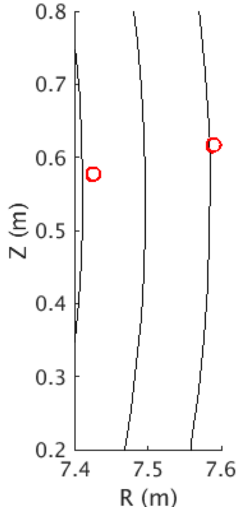
2) Shards should be able to penetrate

3) Additional assimilated material should not make the CQ too short

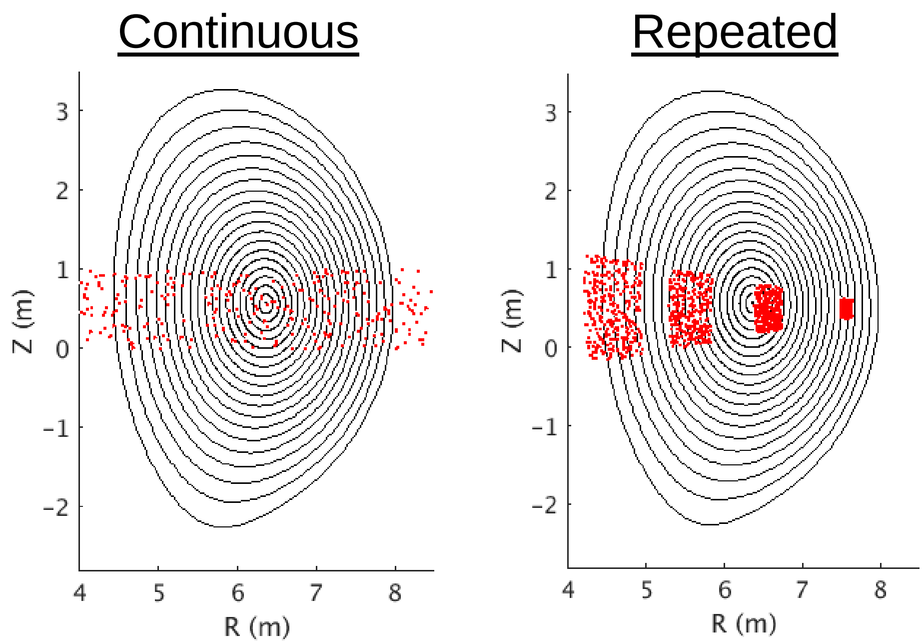
Design choices

- Many small shards or a few large shards?





- Continuous passage of small shards vs. discrete passages of large shards



- Continuous or repeated injection?
  - Note: « Few large shards » case assimilated to shard by shard injection at given freq.

- Pellet material?
  - Hydrogen → lower stopping power p but less risk to make CQ too fast
  - Neon or Argon → larger p but more risk to make CQ too fast

Can shards brake REs? Analytical estimates

- **Braking condition**: $E_{gain/turn}/E_{loss/turn} < 1$, where:
  - $E_{gain/turn} = eV_{loop}$
  - $E_{loss/turn}$ = energy lost per toroidal turn due to interaction with shards
- For many small shards: $$E_{loss/turn} \simeq \frac{V_s p}{2\pi r_\psi} \frac{dN_s}{dr_\psi}$$

  → Hydrogen: need more than 5.3 large (28mm) pellet/meter
  → Neon or Argon: need more than 0.9 pellet/meter
- For a few large shards: $$E_{loss/turn} \simeq \frac{V_s p}{2\pi r_\psi} \frac{2}{\pi r_s}$$

  → Hydrogen: need $r_s > 8.3$ mm
  → Neon or Argon: need $r_s > 3.4$ mm

(p_{H2}=38MeV/m, $p_{Ne/Ar}$=230MeV/m; Assumptions: V_{loop}=1.1kV, r_Ψ=1m)

Can shards fully stop REs?
Analytical estimates

- For case of repeated injections with many small shards, each injection needs to fully stop REs, otherwise they would re-accelerate between 2 injections

- **Stopping condition**: $\frac{t_{stop}}{t_{pass}} \simeq \frac{4\pi^2 R r_\psi E^0_{RE} \langle v_s \rangle}{c N_s V_s p} < 1$

  (assuming $E_{gain/turn}/E_{loss/turn} << 1$)

→ Hydrogen: need more than 5 large (28mm) pellet / injection
→ Neon or Argon: need more than 0.9 pellet / injection

(Assumptions: R=6m, r_ψ=1m, E_{RE}^0=10MeV, $\langle v_s \rangle$=100m/s)

Can shards fully stop REs?
Analytical estimates

- For case of a few large shards, each shard needs to fully stop REs, otherwise they would re-accelerate between 2 shards

- **Stopping condition:** $\frac{t_{stop}}{t_{pass}} \simeq \frac{\pi^3 R E_{RE}^0 r_\psi v_s}{c V_s p} < 1$

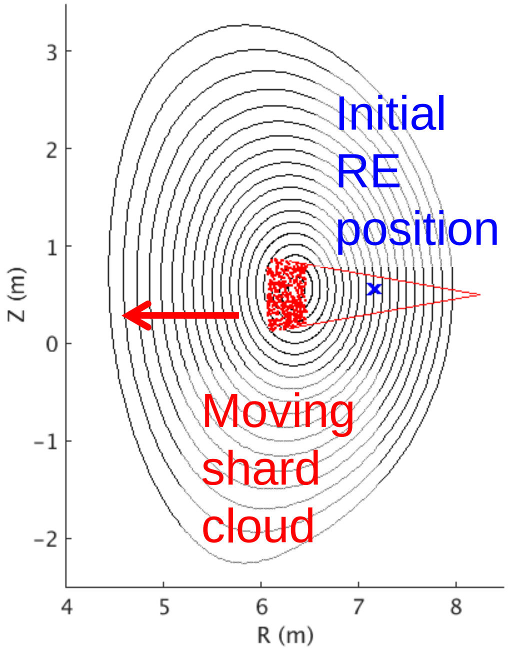
(assuming $E_{gain/turn}/E_{loss/turn} << 1$)

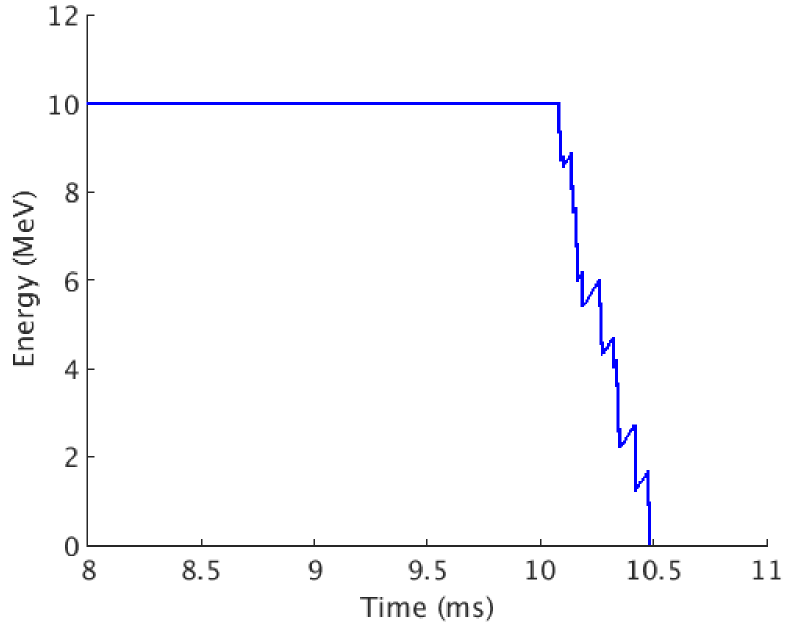
→ Hydrogen: need $r_s > 16$ mm
→ Neon or Argon: need $r_s > 8.6$ mm

⇒ More stringent than braking condition

(Assumptions: R=6m, r_ψ=1m, E_{RE}^0=10MeV, v_s=100m/s)

Numerical simulations are consistent with, but less optimistic than analytical estimates

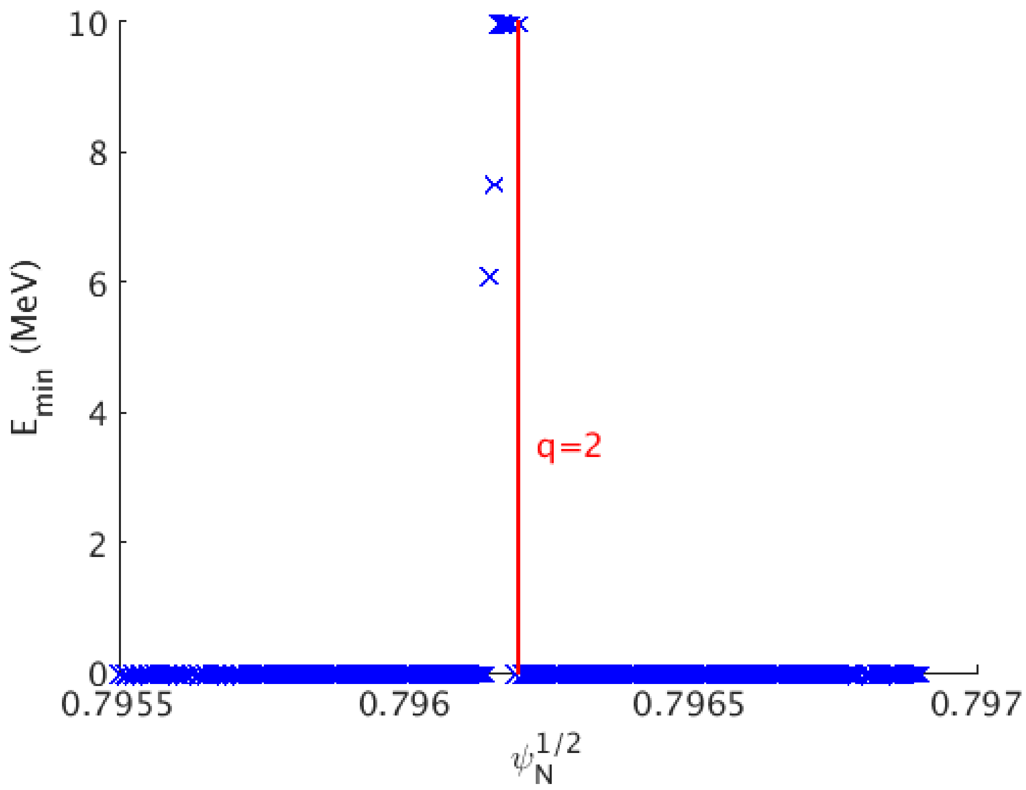




- Model:
  - REs assumed to follow field lines and tracked by steps of 1 toroidal turn
  - RE energy evolved at each turn: $\Delta E_{RE} = eV_{loop} - p\delta$, where δ = distance travelled across shards (calculated from position of shards at current time)
    - E_{RE} saturated at 10 MeV

⇒ Trends from analytical estimates confirmed, but less optimistic results due to realistic equilibrium geometry

Effect of rational surfaces is very limited in the absence of islands



- REEs perform a large number of toroidal turns over the passage of shards

⇒ Magnetic shear makes the effect of rational q surfaces very localized

- The presence of islands could be a concern
- Another possible concern is the vertical plasma motion

Can shards penetrate?

- When there are gaps between (clouds of) shards, the avalanche during gaps may lead to a large enough RE population to vaporize shards

- Energy into shard from REs (per unit volume):

$$\exp(\Delta t_{gap}/\tau_{e\text{-}fold}) \times (j_{RE}^{seed}/e) \times p \times 2a/v_s$$

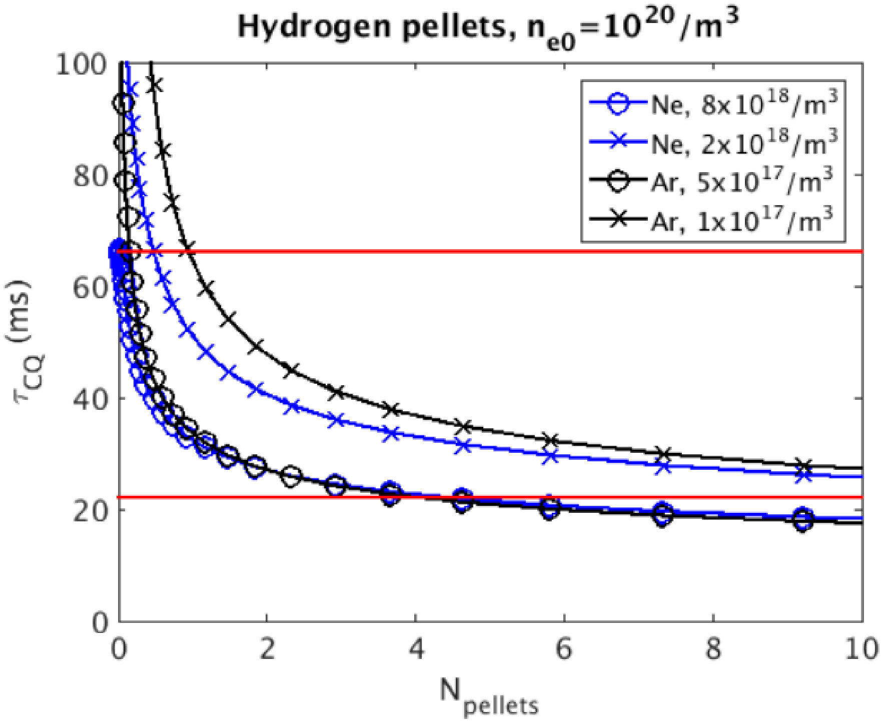
- Comparison to shard heat of vaporization → Upper limit on Δt_{gap} → Lower limit on injection rate

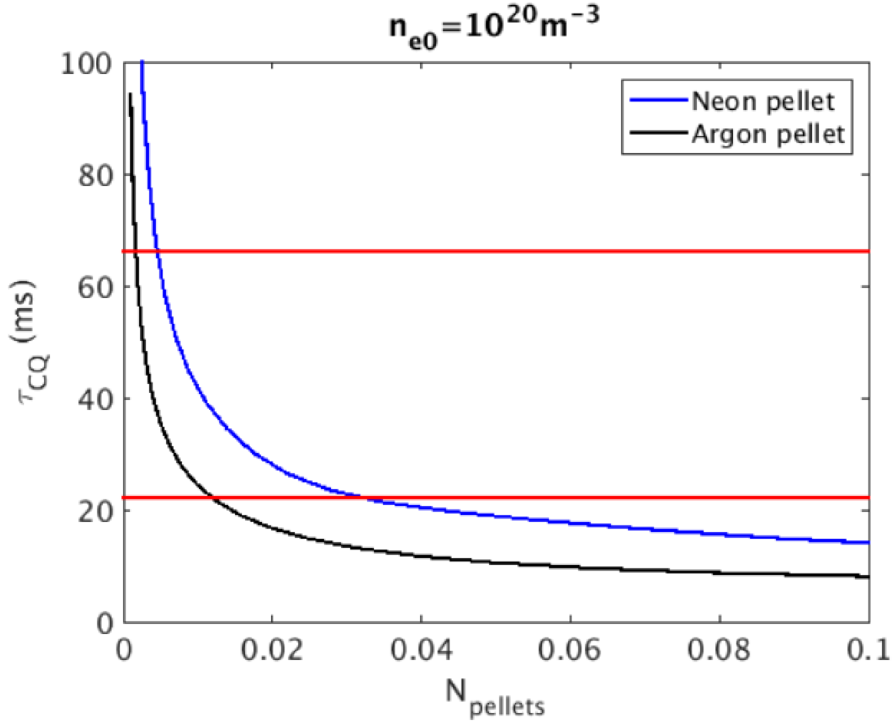
(Input numbers:

- $j_{RE}^{seed} \sim 0.1 A/m^2$ [Boozer PPCF 2019; Martín-Solís NF 2017]
- $\tau_{e\text{-}fold} \sim 2ms$ ($\Delta\psi_{e\text{-}fold}$=2.3V.s [Boozer PPCF 2019] and V_{loop}=1.1kV))

Consequences of material assimilation on CQ timescale?

Exponential CQ timescale vs. amount of assimilated material





- Estimate based on a simple 0D model, assuming balance between Ohmic heating and radiative losses
- Note: H (or D) radiation not considered but could shorten CQ drastically when injecting several H pellets (recombination)…

Summary and outlook

Injection rate required to penetrate and stop RE seeds

(Unit = equivalent # of 28 mm pellets over 100 ms)

	H	Ne	Ar
Many small shards, continuous	60	9	9
Many small shards, repeated	100	18	18
A few large shards	30	6	6

Tolerable amount of assimilated material

(Unit = equivalent # of 28 mm pellets)

H	Ne	Ar
5-10	0.03	0.01

(Main assumptions: E_{RE}^{0}=10MeV, v_s=100m/s)

- Pellet number appears prohibitive for H, but might be within DMS capabilities for Ne or Ar (up to 24 pellets of 28 mm)
- Ablation from thermal plasma would have to be extremely small
  - Need a model for ablation in the CQ plasma (T_e ~ 5 eV)
  - Experiments on SPI during CQ in present machines would be useful
- Look for better pellet material (i.e. with large stopping power, poor radiation at low T_e, small ablation rate, …)
- For more detail: paper on arXiv (lookup 'Nardon')