On the possible injection schemes with the ITER SPI system


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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 $\beta$ decay, Compton scattering of $\gamma$’s from the activated wall)
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 $\text{H}_2$ (or $\text{D}_2$) SPI before the TQ for fast plasma dilution
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, …)

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

Interpretation:

cold front vs. ‘lukewarm’ front

**Pure D\textsubscript{2} vs. D\textsubscript{2}:Ne = 9:1**

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

With pure D\textsubscript{2} SPI:

Only dilution cooling (no radiative collapse)

\[ \Rightarrow T_e \text{ remains } > 100 \text{ eV} \]
\[ \Rightarrow \text{Resistive } j \text{ decay time } \gg a/V_p \]
\[ \Rightarrow \text{No modification of } j \text{ profile} \]
Interpretation:
cold front vs. ‘lukewarm’ front

**Pure D\(_2\) vs. D\(_2\):Ne = 9:1**
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Single 28 mm pellet, \(V_p=200\) m/s, \(N_{shards}=300\)

**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\textsubscript{2} SPI with JOREK 3D non-linear MHD simulations

⇒ Experimental and early modelling results suggest that with pure H\textsubscript{2} (or D\textsubscript{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\textsubscript{2} pellet with \( V_p = 200 \) m/s, \( N_{\text{shards}} = 1000 \)
Shards can travel across the plasma without causing an MHD crash... below a certain background impurity density.

\[ n_{\text{imp}} \left( m^{-3} \right) \]

- 0
- \(10^{17}\)
- \(8 \times 10^{17}\)

\[ 4 \text{ ms} \quad 6 \text{ ms} \quad 10 \text{ ms} \quad 20 \text{ ms} \]

Motivates further studies with a more realistic description of background impurities.
A dilution by a factor > 10 is obtained throughout the plasma.
Due to limited toroidal resolution in JOREK, ablation clouds toroidal extension $\Delta \phi_{\text{cloud}}$ is much larger than in reality.

A scan in $\Delta \phi_{\text{cloud}}$ shows that low-n mode excitation decreases with $\Delta \phi_{\text{cloud}}$.

Interpretation: low-n modes are primarily destabilized via a current profile modification, which is stronger for larger $\Delta \phi_{\text{cloud}}$.

Direct mode drive by helical cooling does not compensate.

$\Rightarrow$ JOREK predictions with artificially large $\Delta \phi_{\text{cloud}}$ probably overpredict low-n mode excitation, i.e. are « pessimistic ».
At low $n_{\text{imp}}$, 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 $\tau_e/\tau_{\text{TQ}}$.

- Electron collision time $\tau_e \sim T_e^{3/2}/n_e \sim D^{-5/2}$, where $D = \text{dilution factor}$
- TQ duration (radiative collapse) $\tau_{\text{TQ}} \sim 1/n_e \sim 1/D$

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

- Best way to raise $n_e$ (baseline RE avoidance strategy)
- Dilution cooling may suppress the risk of hot tail RE generation


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: REs travel across shards. When they do so, they lose an energy $\Delta E_{RE} = p\delta$, where $p$ = stopping power, $\delta$ = 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:** $E_{\text{gain/turn}}/E_{\text{loss/turn}} < 1$, where:
  - $E_{\text{gain/turn}} = eV_{\text{loop}}$
  - $E_{\text{loss/turn}} =$ energy lost per toroidal turn due to interaction with shards

- For many small shards: $E_{\text{loss/turn}} \approx \frac{V_s p}{2\pi r_\psi} \frac{dN_s}{dr_\psi}$
  - → **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: $E_{\text{loss/turn}} \approx \frac{V_s p}{2\pi r_\psi} \frac{2}{\pi r_s}$
  - → **Hydrogen:** need $r_s > 8.3$ mm
  - → **Neon or Argon:** need $r_s > 3.4$ mm

($p_{\text{H}_2}=38\text{MeV/m}$, $p_{\text{Ne/Ar}}=230\text{MeV/m}$; Assumptions: $V_{\text{loop}}=1.1\text{kV}$, $r_\psi=1\text{m}$)
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: \[
\frac{t_{stop}}{t_{pass}} \approx \frac{4\pi^2 R r_\psi E^0_{RE} \langle v_s \rangle}{c N_s V_s p} < 1
\]

(assuming \(E_{\text{gain/turn}}/E_{\text{loss/turn}} \ll 1\))

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

(Assumptions: \(R=6\text{m}, r_\psi=1\text{m}, E^0_{RE}=10\text{MeV}, \langle v_s \rangle=100\text{m/s}\))
For case of a few large shards, each shard needs to fully stop REs, otherwise they would re-accelerate between 2 shards.

**Stopping condition:**

\[ \frac{t_{\text{stop}}}{t_{\text{pass}}} \sim \frac{\pi^3 R E_{RE}^0 r_{\psi} v_s}{c V_s \rho} < 1 \]

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

→ **Hydrogen**: need \( r_s > 16 \text{ mm} \)

→ **Neon or Argon**: need \( r_s > 8.6 \text{ mm} \)

⇒ More stringent than braking condition

(Assumptions: \( R=6\text{ m} \), \( r_{\psi}=1\text{ m} \), \( E_{RE}^0=10\text{ MeV} \), \( v_s=100\text{ m/s} \))
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: $\Delta E_{RE} = eV_{\text{loop}} - p\delta$, where $\delta$ = 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

REs 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
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):

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

Comparison to shard heat of vaporization → Upper limit on $\Delta t_{\text{gap}}$ → Lower limit on injection rate

(Input numbers:
- $j_{\text{RE} \text{seed}} \sim 0.1 \text{A/m}^2$ [Boozer PPCF 2019; Martín-Solís NF 2017]
- $\tau_{\text{e-fold}} \sim 2\text{ms}$ ($\Delta \psi_{\text{e-fold}}=2.3\text{V.s}$ [Boozer PPCF 2019] and $V_{\text{loop}}=1.1\text{kV}$))
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)...
Injection rate required to penetrate and stop RE seeds
(Unit = equivalent # of 28 mm pellets over 100 ms)

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<thead>
<tr>
<th></th>
<th>H</th>
<th>Ne</th>
<th>Ar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Many small shards, continuous</td>
<td>60</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Many small shards, repeated</td>
<td>100</td>
<td>18</td>
<td>18</td>
</tr>
<tr>
<td>A few large shards</td>
<td>30</td>
<td>6</td>
<td>6</td>
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</tbody>
</table>

(Tolerable amount of assimilated material
(Unit = equivalent # of 28 mm pellets)

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<tr>
<th></th>
<th>H</th>
<th>Ne</th>
<th>Ar</th>
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<tbody>
<tr>
<td>5-10</td>
<td>0.03</td>
<td>0.01</td>
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(Main assumptions: $E_{RE}^0=10\,\text{MeV}$, $v_s=100\,\text{m/s}$)

- 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 ($T_e \sim 5\,\text{eV}$)
  - 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’)