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Requirements for Runaway Electron Avoidance in ITER Disruption Mitigation Scenario by Shattered Pellet Injection

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Abstract

- Numerical modelling of Shattered Pellet Injection (SPI) assimilation using a new versatile 1.5D disruption simulator INDEX
- Comparison between injection of pure hydrogen pellets and that of neon mixed hydrogen ones regarding cooling time of q = 2 surface
- The amount of material that can be assimilated strongly depends on stored thermal energy of target plasmas parameters in ITER
- A specific difficulty for 15MA Hyd. L-mode can be resolved by using two-step (staggered) injection – hydrogen SPI followed by neon SPI
- Full spec 15MA DT H-mode operation is more favorable to raise the density with SPI but difficulties may arise if one loses the H-mode.

Introduction

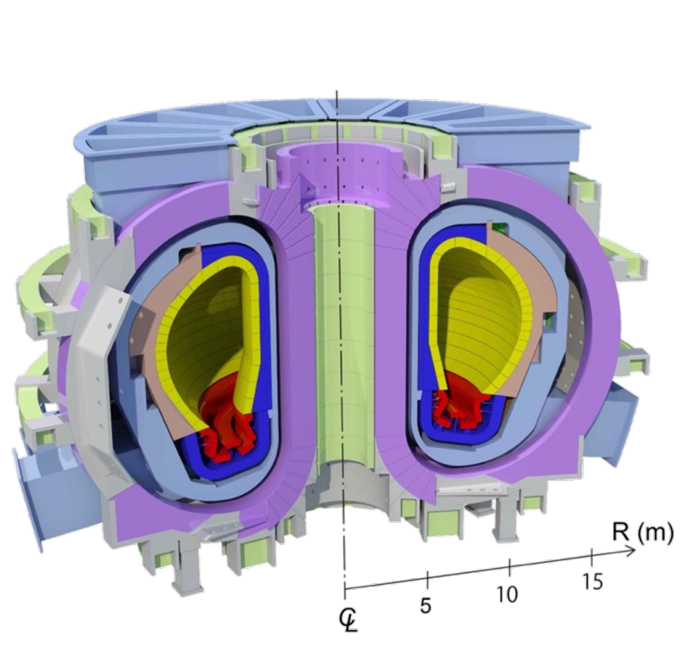
- Runaway Electron (RE) Avoidance may require rising the electron density by a factor 20-40 or more [1] but it is uncertain whether the plasma can assimilate such large amount of material.
- Baseline of ITER Disruption Mitigation System (DMS) has assumed assimilation of a small quantity of neon and a large quantity of hydrogen by means of Shattered Pellet Injection (SPI) [2].
- Current design offers significant injection capability (24 barrels) for RE avoidance, incl. redundancy and possibility to provide with different composition for the different phases of an ITER pulse.

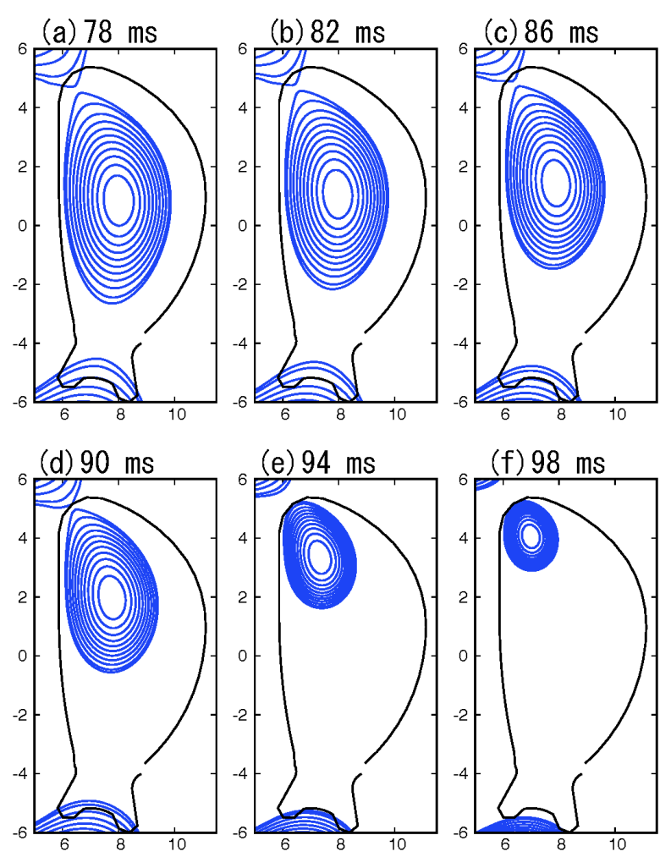
Key questions

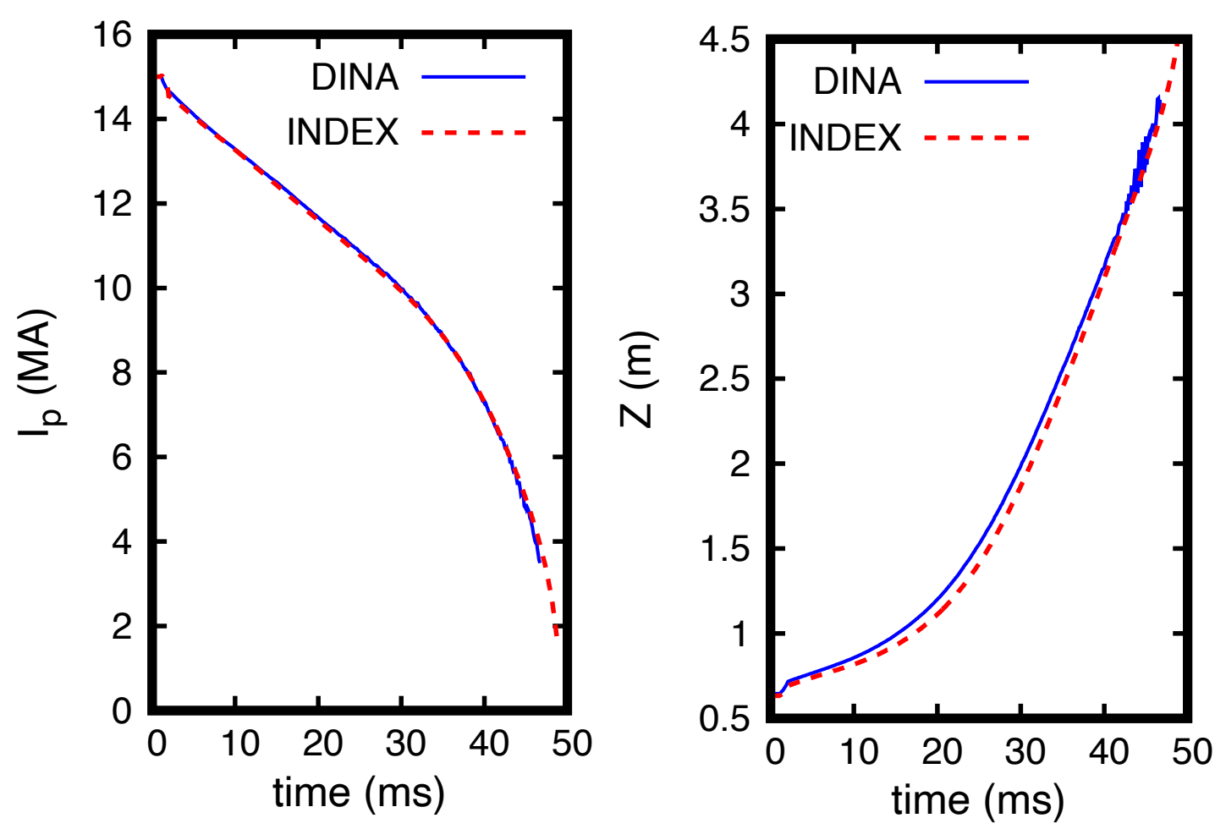
- How SPI injection parameters can be optimized for RE avoidance?
- How to match the requirements for different target plasmas?

A new versatile 1.5D disruption simulator INDEX

- Originally developed for VDE analysis of Japanese DEMO design
  - Coupling between 2D equilibrium, 1D current-diffusion, and external circuits
  - Benchmark for ITER upward VDE [3] against DINA [4]
- Extending the code capability to describe transport and actuators
  - Charge state of ion species resolved w/ OPEN-ADAS
  - SPI module based on NGS scaling [5] and statistical fragment size model [6]
- Present calculation describes density rise and electron cooling (radiation + dilution) due to particle source described with NGS scaling
  - Application of more refined model is a future subject

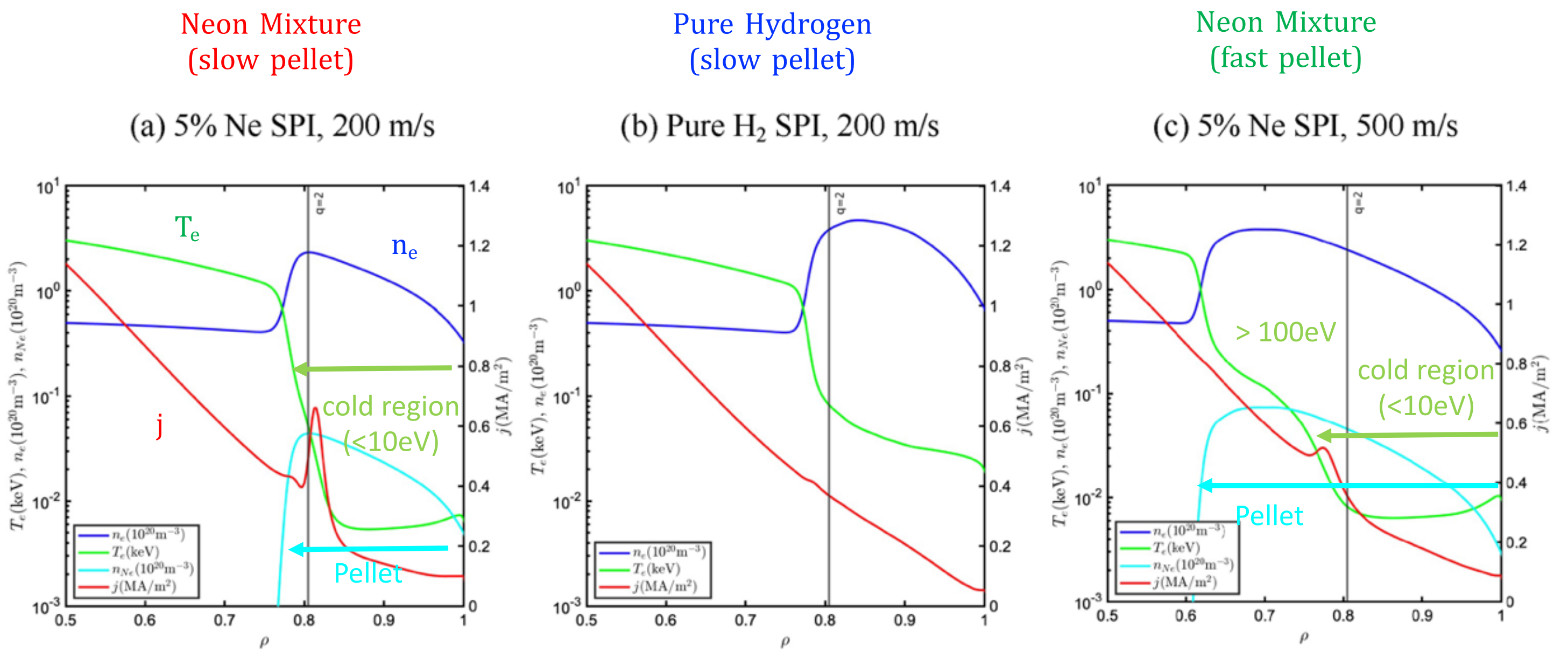






A comparison of pure H and Ne mixed pellets

- A mixture of neon may lead to an immediate TQ when pellet shard crosses q = 2 rational surface
  - Mixed pellet cools T_e down to 10 eV → destabilizing current perturbation
  - Pure hydrogen pellet or increasing injection velocity suppressing or decreasing perturbation → longer TQ time and possibility of direct core fueling by pellets
  - Large shard sizes have a merit to allow deep penetration



Profiles after SPI with the 15MA Hydrogen L-mode scenario: (a) The pellet shards penetrate simultaneously with the radiative cold front with 5% neon mixed SPI at V_p = 200 m/s. (b) No current perturbation is observed for pure hydrogen SPI at the same velocity. (c) The penetration of neon is separated from that of the cold front.

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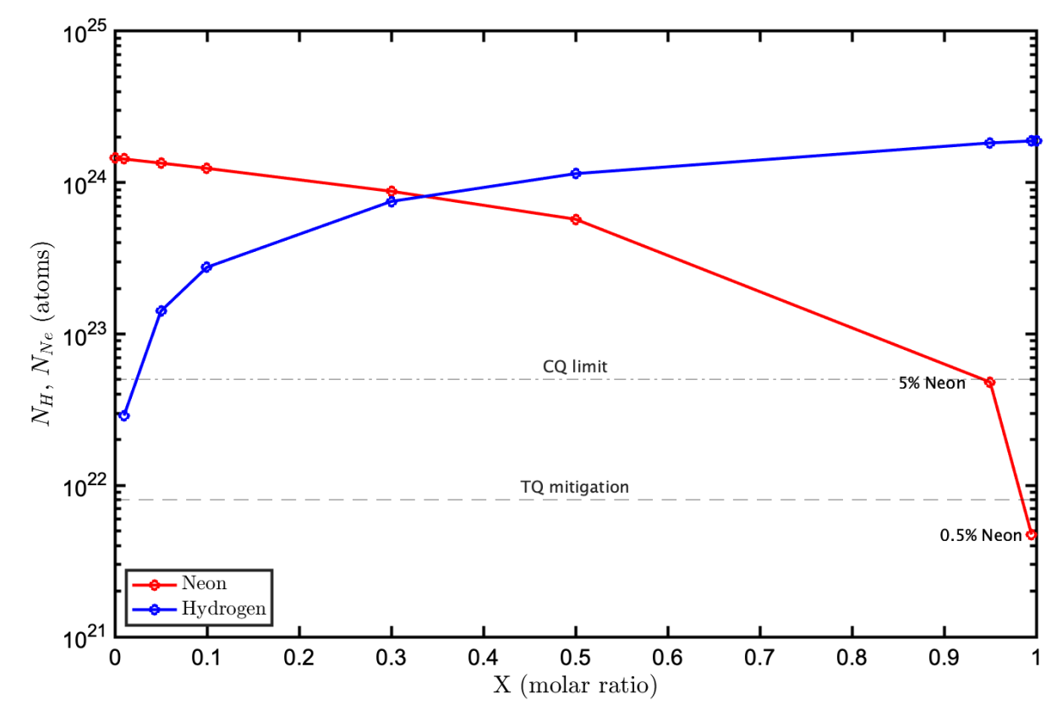
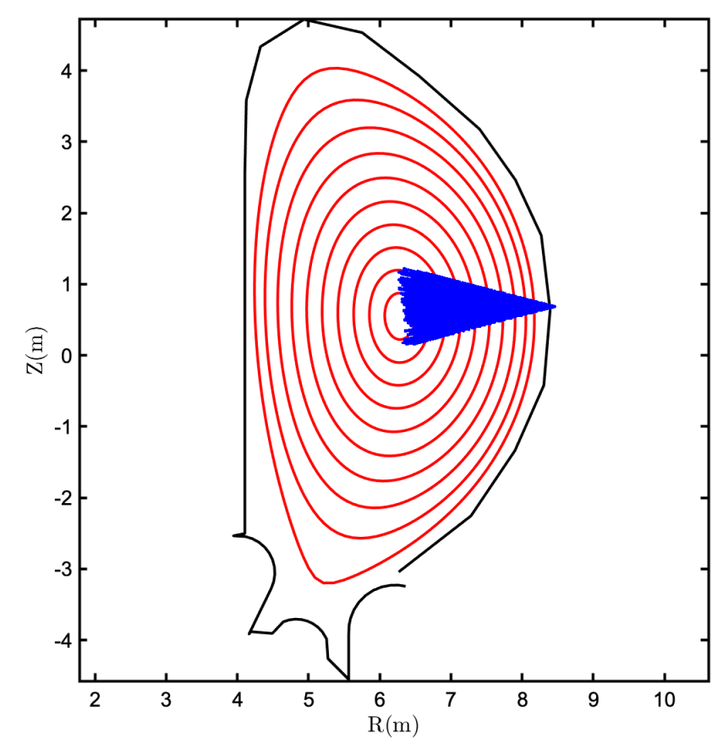
The work has been performed in collaboration with the ITER Disruption Mitigation Task Force. ITER is the Nuclear Facility INB no. 174. This paper explores physics processes during the plasma operation of the tokamak when disruption take place; nevertheless the nuclear operator is not constrained by the results presented here. The views and opinions expressed herein do not necessarily reflect those of the ITER organization.

Set up for ITER DMS simulations

- ITER nominal pellet size: D=28.5mm, L/D=2, corresponding to 2x10^{24}atoms
  - Required number of neon atoms for TQ load mitigation is unclear
  - Previous estimate of upper limit by CQ time: 5x10^{22} atoms = 5% molar ratio (without taking into account densities raised by hydrogen [2])
- Realistic ITER DMS geometry
- ITER reference scenarios from CORSICA data [7]
  - Full spec 15MA DT H-mode scenario: W_{th} = 367 MJ
  - 15 MA (non-nuclear) Hydrogen L-mode: W_{th} = 36 MJ
  - Other low I_p scenarios: 7.5MA H-mode (He), 5MA H-mode (Hyd.): W_{th} = 30-40 MJ
  - Intrinsic impurities (He, Be, W) → No visible impact here

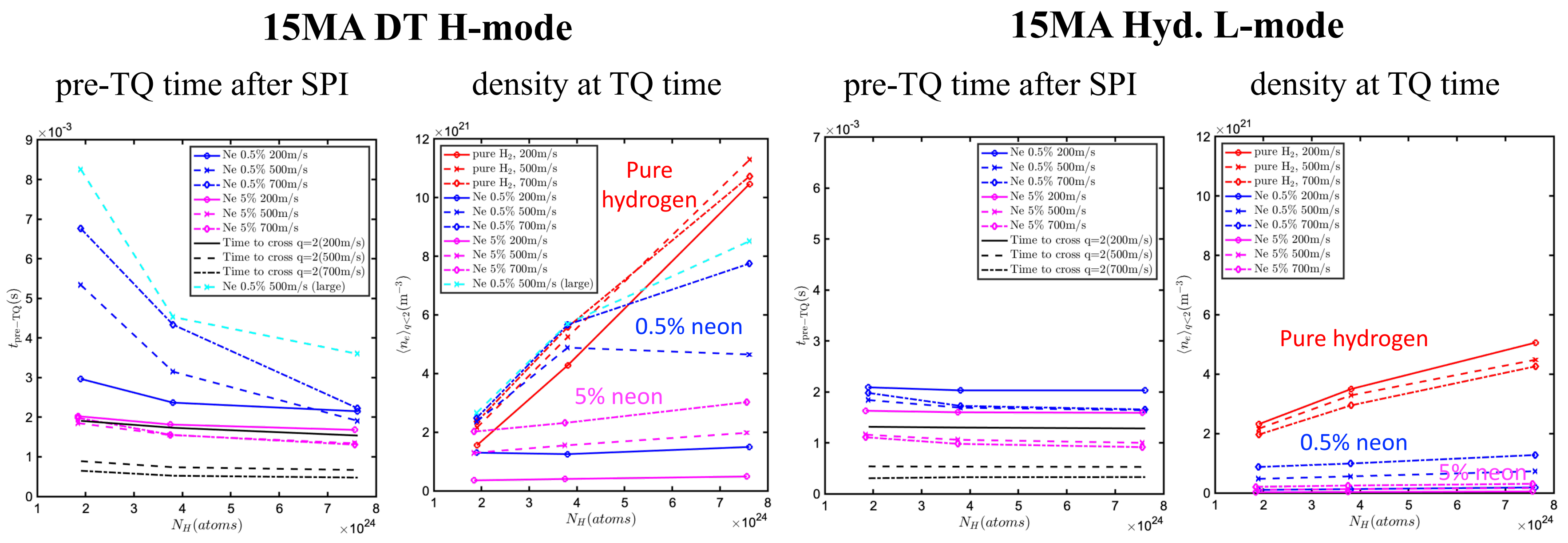




SPI param.	value
V_p	200,500,700
$\Delta V_p/V_p$	±0.2
N_{shard}	1000, 250
κ_p^{-1}	0.85, 1.35mm
θ_{div}	30 deg

Discussion: 15MA H-mode and L-mode

- 15MA DT H-mode with high W_{th} is favorable regarding density assimilation and is resilient to radiation by neon
  - Good density scaling up to a factor 2 below Rosenbluth density with optimistic assumption (100% assimilation without ExB drift or other loss mechanisms)
  - For neon mixed SPI, pre-TQ density rise is varied depending on the injection parameters (Composition, Velocity, Shard size) → room for optimization
- 15MA Hyd. L-mode with low W_{th} did not show any gain, other than pure hydrogen injection because small neon quantity leads to fast TQ ~ 1-2 ms.
  - Similar results in other low I_p scenarios



Pre-TQ time (Left) and core density rise inside q=2 surface (Right) as functions of injected hydrogen quantities with different pellet compositions (0%, 0.5%, 5% neon) and pellet velocities (200, 500, 700 m/s). For the 15MA DT H-mode scenario, the cyan symbols indicate the results obtained with large shard sizes (N_{shard}=250) with 0.5% neon mixed SPI at V_p = 500 m/s.

- Because of absence of steady-state source of RE seeds, RE avoidance in 15MA Hyd. L-mode could be achieved reliably with pure hydrogen SPI.
  - To be compatible with TQ and CQ load mitigation, disruption mitigation with two-step SPI (hydrogen SPI followed by neon SPI) is proposed. INDEX showed the assimilation efficiency of 2nd neon SPI is less than 10%. Assessment of TQ/CQ/VDE load is needed. See, more details in paper.
- RE avoidance in nuclear phase is still a major challenge (see, [8])
  - Massive deuterium injection may lead to recombination of hydrogen [9,10], resulting in the decrease of electron drag and significant avalanche.
  - Our work has focused favorable density assimilation of DT H-mode but this may in turn attract our attention to difficulties of the baseline for DT L-mode.

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