Cryogenic Pellet Ablation Physics and Integrated Modelling of Shattered Pellet Injection

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Background

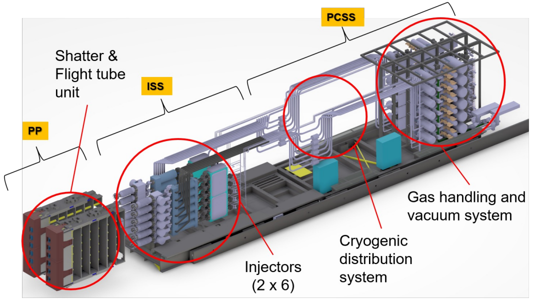
- The baseline of the ITER Disruption Mitigation System (DMS) has assumed the assimilation of a small quantity of neon and a large quantity of hydrogen by means of Shattered Pellet Injection (SPI)
  - Runaway Electron (RE) avoidance may require rising the electron density by a factor 20-40 or more [Martin-Solis+, NF2017]

    → it is uncertain whether the plasma can assimilate such large amounts of material.
  - ITER DMS offers significant material injection capabilities up to 24 pellets (D=28.5 mm, L/D = 2 → about 2 x 10^{24} atoms for H) from three different toroidal locations. A mixture of neon with 5 % molar ratio is about 4.8 x 10^{22} atoms.
  - It also offers flexibility and redundancy to inject the pellet along different poloidal chords, to prepare the backup for injection failure, and to test different pellet sizes, shattering angles, and composition, **depending on target plasmas and operation phase.**

✧ Full spec 15MA DT (nuclear) H-mode : W_{th} = 367 MJ
✧ 15MA (non-nuclear) Hydrogen L-mode : W_{th} = 36 MJ
✧ Other low I_p H-mode scenarios (7.5MA He, 5MA Hyd.): W_{th} up to 50MJ

Scope of this work

- DMS design specification needs to be validated through experiment and modelling data defining requirements on SPI injection parameters (injected mass and timing, fragment size, velocity, velocity dispersion)



[Lehnen+, AAPPS-DPP2020; Luce+ IAEA-FEC2020]

[Gebhart+, NF2021]

- This talk summarizes the recent modelling efforts to address these above requirements with emphasizes place on:
    - Validation of the Neutral Gas Shielding (NGS) type ablation rates
    - NGS-based integrated simulations of pre-TQ SPI for RE avoidance
    - Impact of plasmoid drift on the SPI assimilation and implications to ITER

Validation of the Neutral Gas Shielding (NGS) type ablation rates

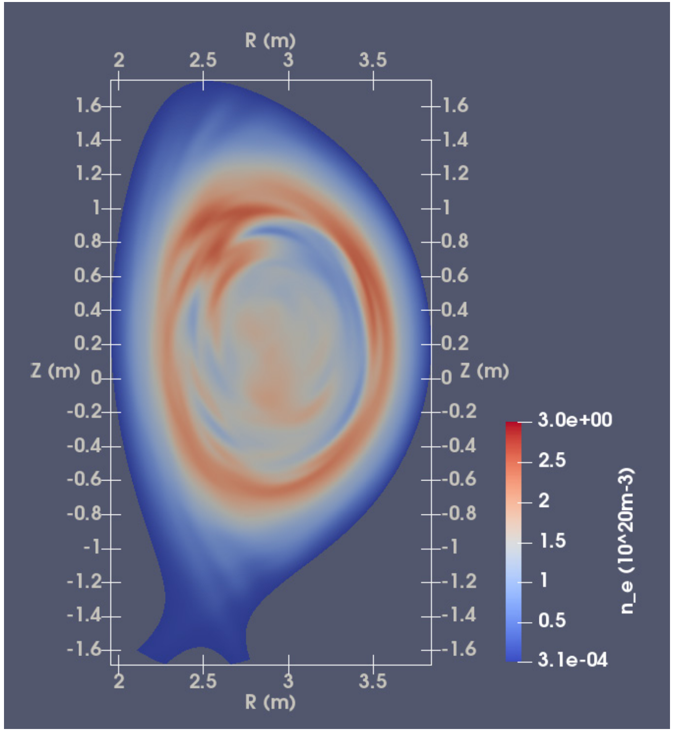
NGS model – a physical basis of the current SPI simulations

- While ITER DMS Task Force has applied different types of the SPI simulations such as
  - 3D MHD simulations: JOREK, M3D-C1, NIMROD
  - 1D transport simulations: INDEX
  - 1D RE simulations: DREAM
- These codes rely on the similar SPI source model based on Neutral Gas Shielding (NGS) type scaling expression.
  - For D2/Ne composite pellets [Parks TSDW2017]

$$\frac{dN_{\mathrm{mix}}}{dt} = \frac{C\lambda(X)}{f_W(1-X)+X} n_e^{1/3} T_e^{5/3} r_p^{4/3}$$

- X: molar ratio
- $\lambda(X)$: fit function
- f_W: mass ratio

[Hu+ NF2018]



Validation of NGS model for hydrogenic pellets

[Baylor+ NF1997]

- This simple scaling has been demonstrated to well capture experimental trends of non-shattered hydrogen pellet penetration into ohmic tokamaks

For linear n_e and T_e profiles:

$$\frac{\lambda_p}{a} = 0.079 m_{\mathrm{pel}}^{5/27} V_p^{1/3} n_{e0}^{-1/9} T_{e0}^{-5/9}$$

→ However, the ablation rate for H_2 + Ne has not been measured experimentally

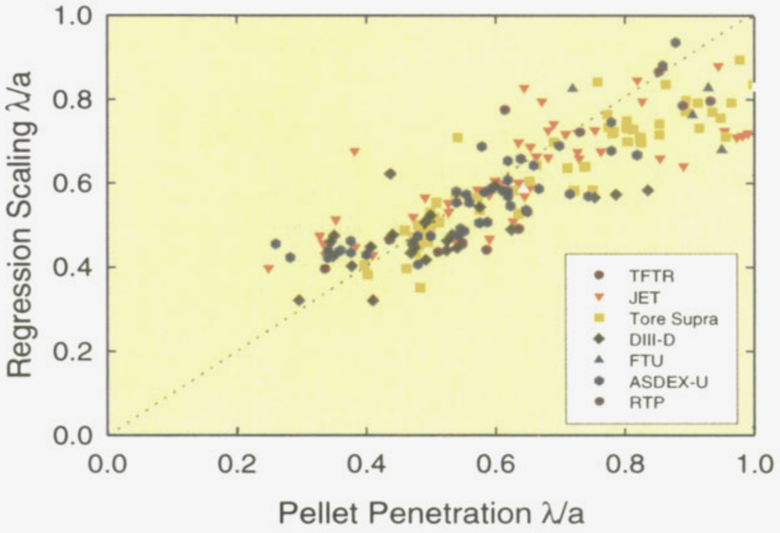


FIG. 3. Comparison of penetration depth with scaling using regression analysis for the IPADBASE database.

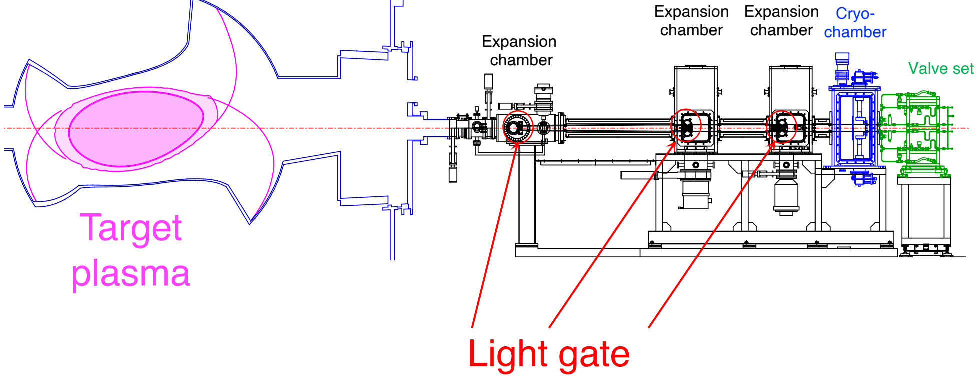
Non-shattered pellet injection experiment for ablation model validation

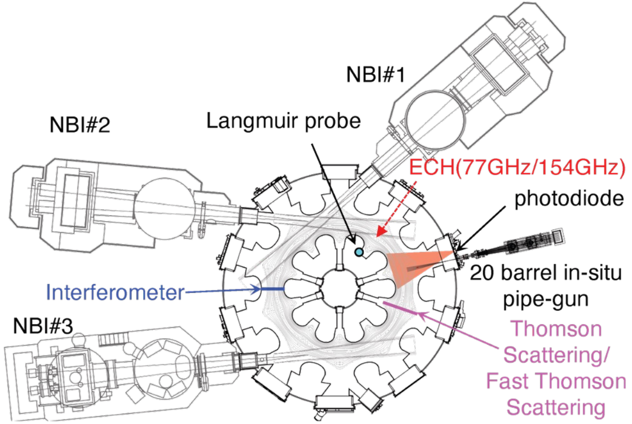
- Large Helical Device (LHD) heliotron provides a good platform to validate the pellet ablation model

- 1 of 20 barrels of the pipe-gun injector is adopted for Ne-mixed pellets (5%/10%/100%)
  - 3 mm diameter/length (10^{21} atoms)
  - Nominal speed: 1100 m/s for pure H_2

- Well diagnosed experiments
  - Ablation light measurement without disruptions (thermal quench radiation)
  - Spatially resolved pre- and post-injection Thomson Scattering profiles

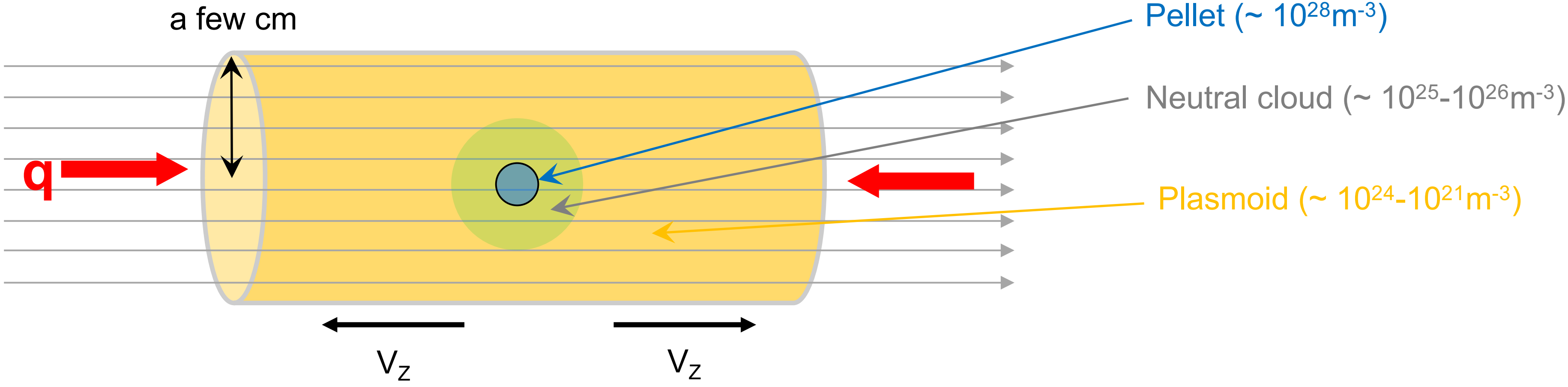
[Sakamoto+ RSI2013]





Neutral Gas / Plasma Shielding (NGPS) model for H_2 + Ne mixed pellets

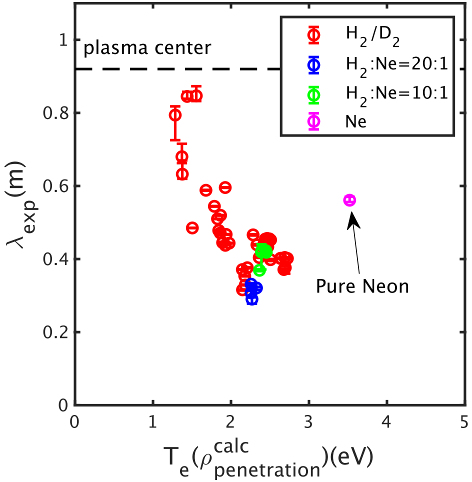
- The NGPS model provides more realistic description including plasmoid shielding (incl. electrostatic sheath) and Maxwellian (kinetic) ambient electron fluxes.
  - NGS and NGPS model provides the ablation rate of the same accuracy [Garzotti NF1997]
  - More free parameters to reproduce the cloud temperature [Rozhansky PPR2005]
  - NGPS code for H_2 + Ne mixed pellets developed recently [Matsuyama PoP2022]



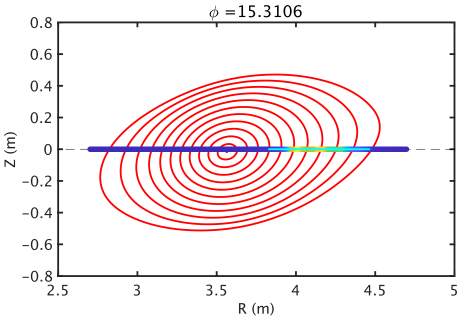
Pure neon injection

- Even the pellet velocity becomes a half (~500 m/s), the pellet can penetrate deeper into high T_e location
- T_e at pellet burn-out position shows ablation rate of pure neon smaller than hydrogen pellet one
  - High electron stopping power (~Z)
  - Elastic scattering (~Z^2) [Parks NF1994; Fontanilla NF2019]
- NGPS has well reproduced the experimental penetration

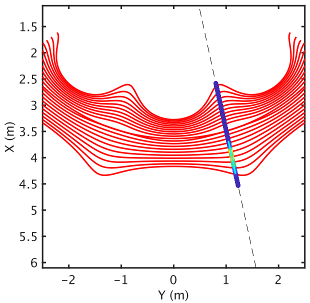
[Matsuyama, in preparation]



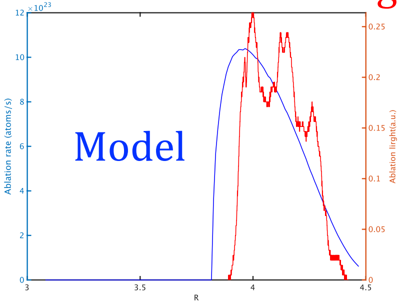
On poloidal plane



On midplane



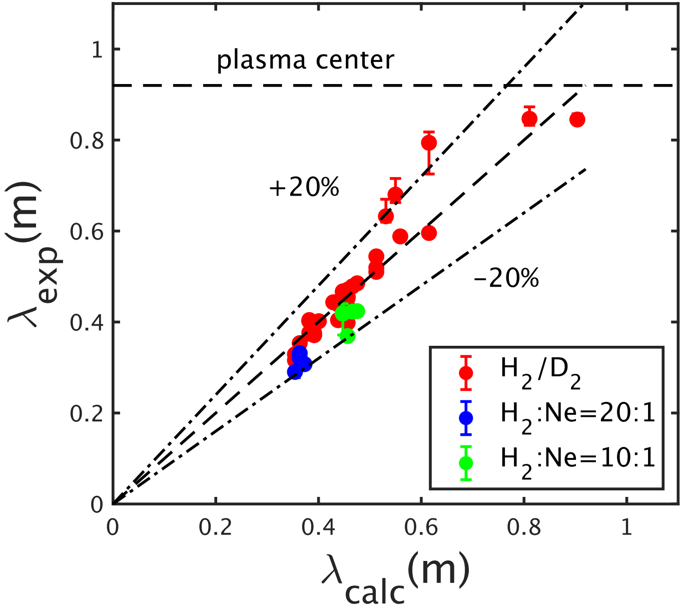
Ablation light



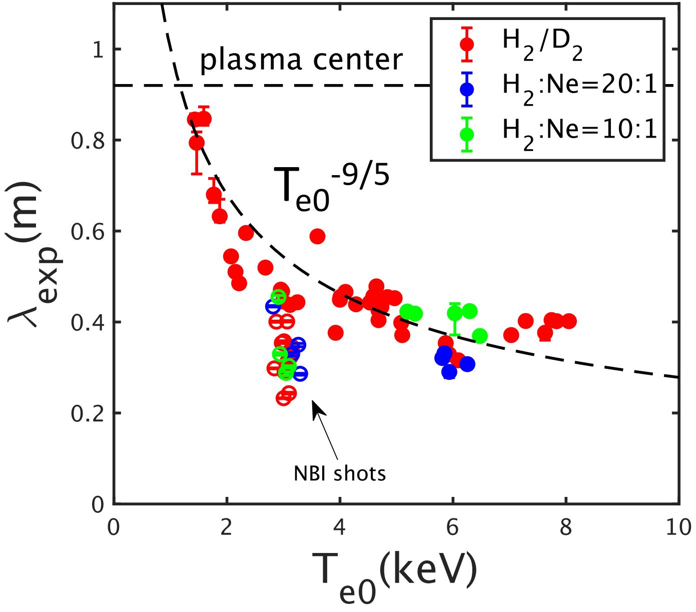
H_2 + Ne mixed pellet ablation validation

[Matsuyama, in preparation]

Experiment/Modeling benchmark



Trends against T_e



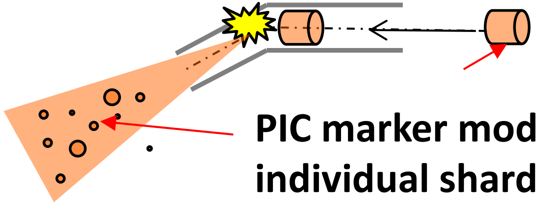
→ Application of NGS/NGPS type model to ITER DMS-like H_2+Ne mixed pellets works well (except the cases where over-ablation by fast ions become significant)

NGS-based integrated simulations of pre-TQ SPI for RE avoidance

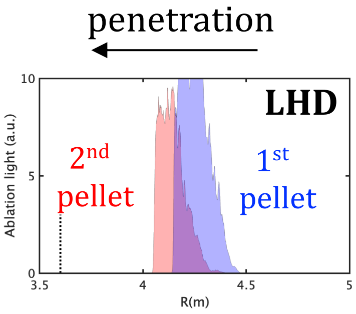
NGS-based 1D transport modeling of SPI assimilation in ITER plasmas

[Matsuyama+ IAEA-FEC2020]

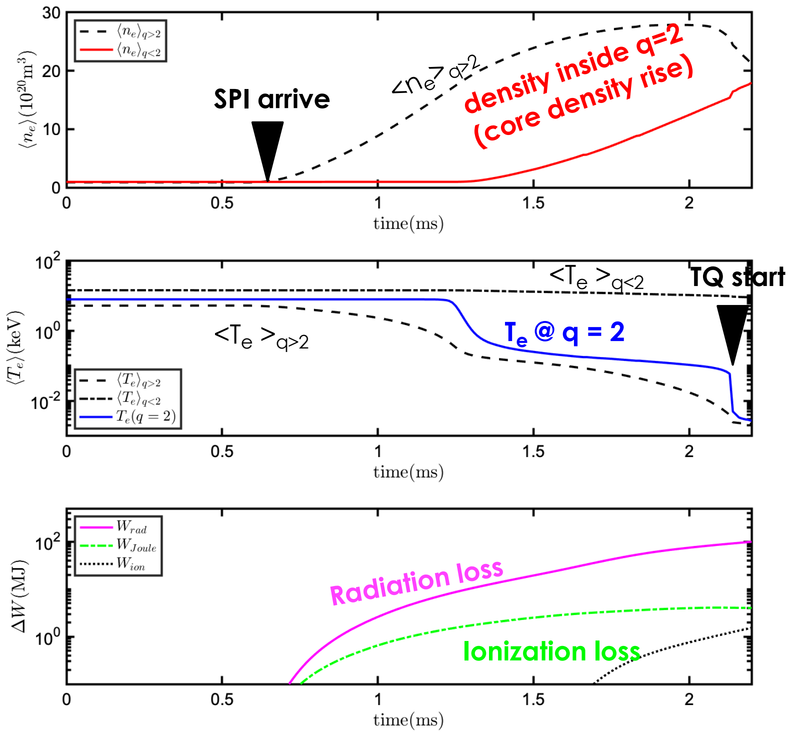
- **INDEX code:** in-house transport code suitably designed for disruption modeling (TQ, CQ, VDEs, etc…) [Matsuyama+, JPS Conf. 2017]
- **Assumption:**
  - Pellet ablation rates follow the NGS model
  - Ablated materials instantaneously homogenize over the flux surface
  - Collective behavior accounted by PIC marker model of pellet shards: vanguard shards allow next shards to penetrate deeper



PIC marker model for individual shards



ITER 15 MA DT H-mode scenario (CORSICA)
V_p = 500 m/s ± 20%, $X_{H2}:X_{Ne}$ = 0.95 : 0.05

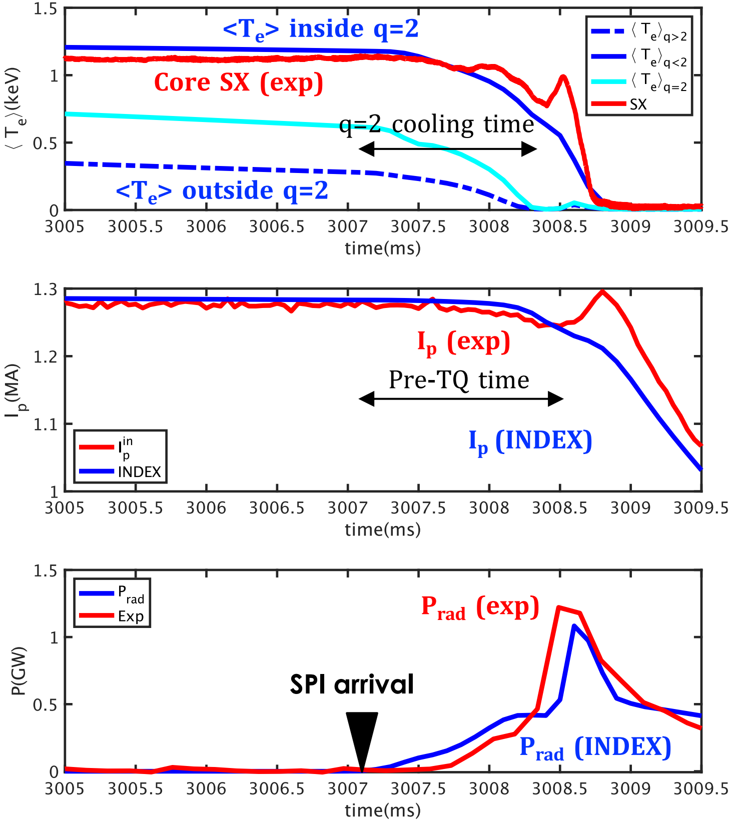


Modeling/Experiment benchmark between INDEX and DIII-D data

[Matsuyama & Shiraki]

- Global match of the experimental data with NGS-based model has been shown using 0D KPRAD analysis [Shiraki+, Previous meeting]

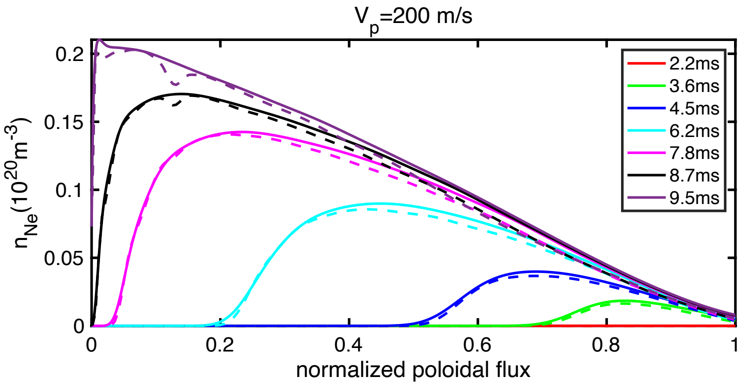
- The analysis has been extended to 1D INDEX simulation for 7 mm mixed SPI (93% neon: 7% D_2)
  - #160606 (Shiraki+, PoP2013)
  - V_p = 300 m/s
  - No current spike model included here
  - Good match of the TQ/CQ timescale is obtained with $N_{shard} = 10^3$, $\Delta t = \pm 0.5$ ms
  - Observed $t_{pre\text{-}TQ}$ comparable to simulated cooling time of q = 2 surface



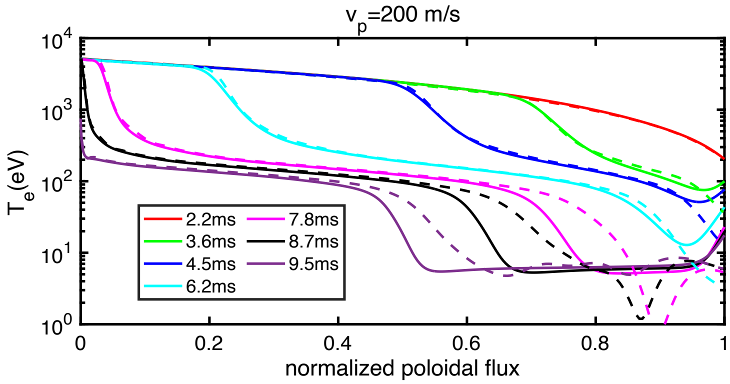
Cold front dynamics during SPI penetration

[Matsuyama, Hu+, submitted to PPCF]

- Careful code-code comparison between JOREK axisymmetric run and INDEX
  - 28.5 mm ITER DMS pellet (5% neon) into ITER 15 MA Hydrogen L-mode
  - Reasonable match of the SPI assimilation including profiles!



- Movement of 10 eV cold front – connected to current profile perturbation
  - Contrary to MGI, the cold front follows behind the SPI plume
  - Two-stage cooling nature of H_2/Ne:
    1) Fast dilution
    2) Radiative cooling to 10 eV range



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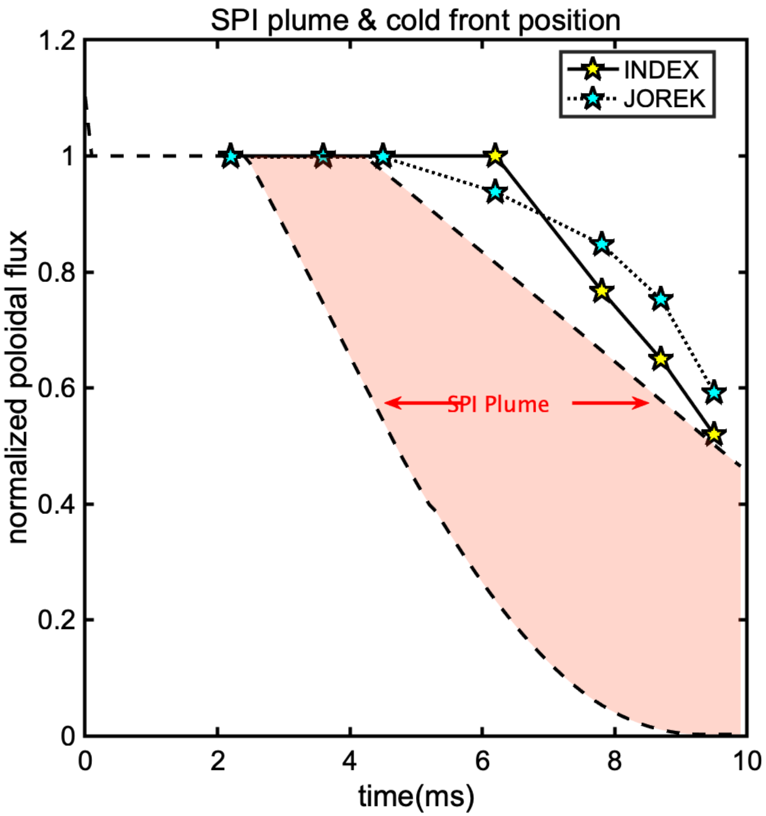

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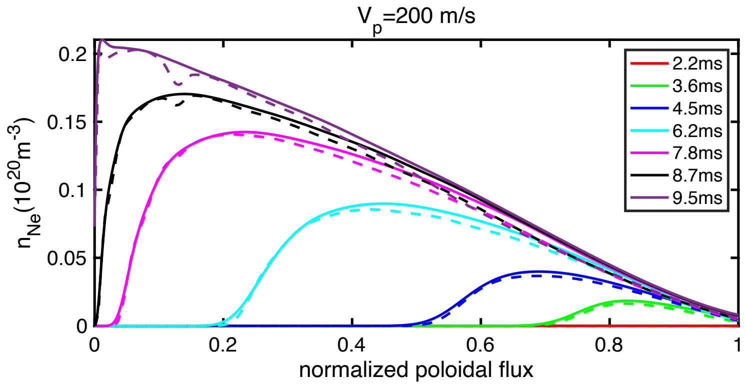
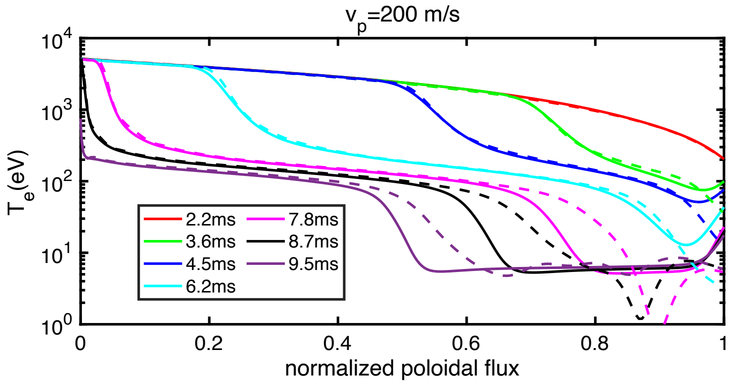
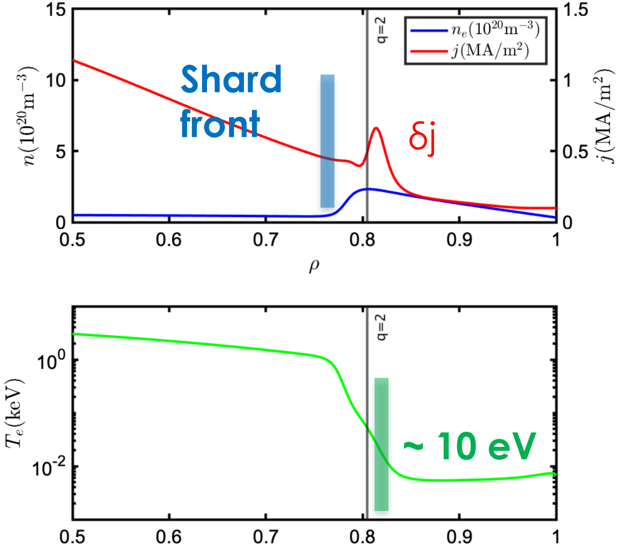


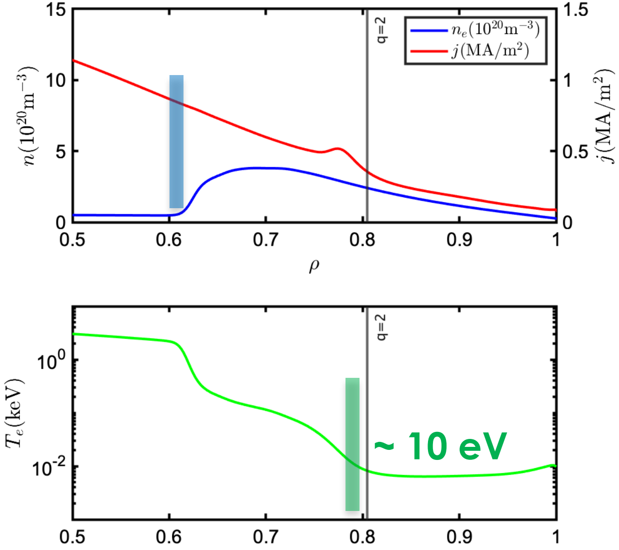


Comparison of cold front dynamics for different pellet compositions

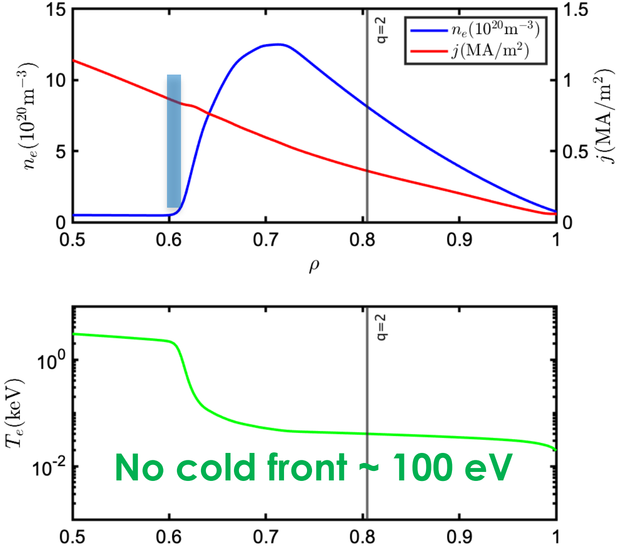
[Matsuyama+ IAEA-FEC2020]



5% Ne mixed SPI 200m/s



5% Ne mixed SPI 500m/s



Pure H_2 SPI 200m/s

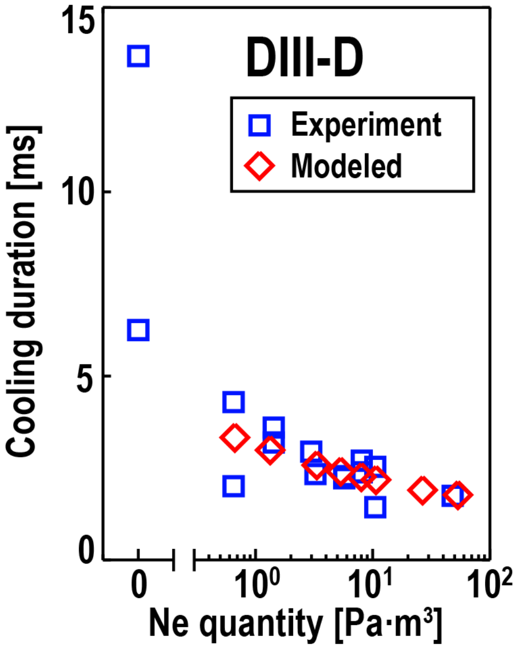
ITER 15MA Hydrogen L-mode n_e : Electron density j: plasma current density T_e: electron temperature

➔ Pure H_2 SPI not leading immediate TQ and being useful for maximizing density rise?

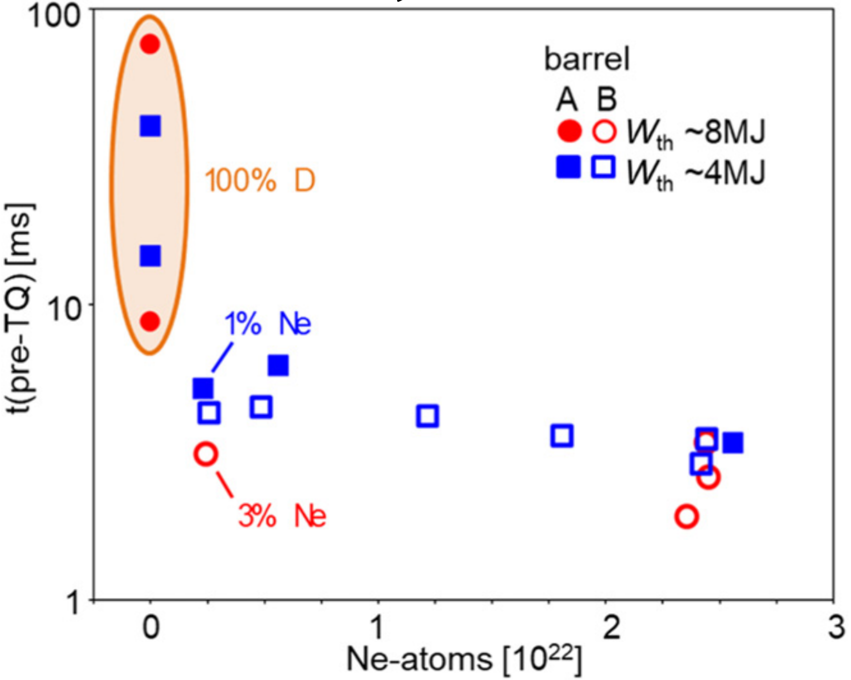
Long pre-TQ time observed experimentally

[Shiraki+ PoP2016; Jachmich+ NF2022]

DIII-D



JET



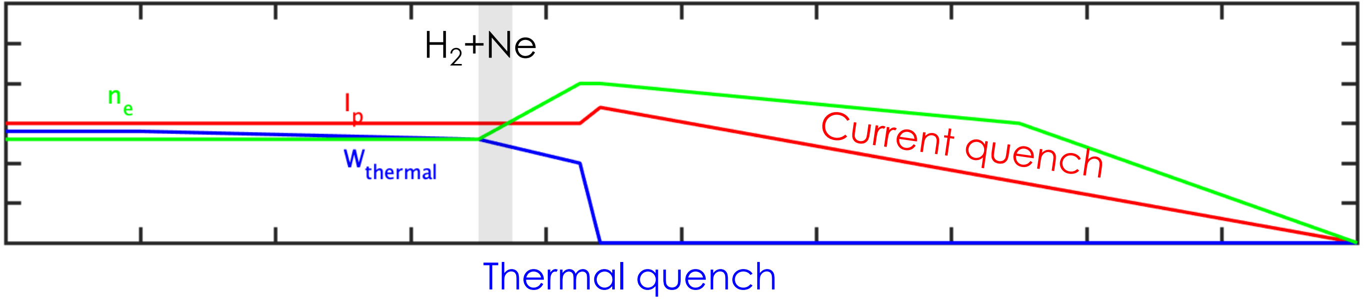
Effective injection scheme for RE avoidance

[Nardon+ NF2020]

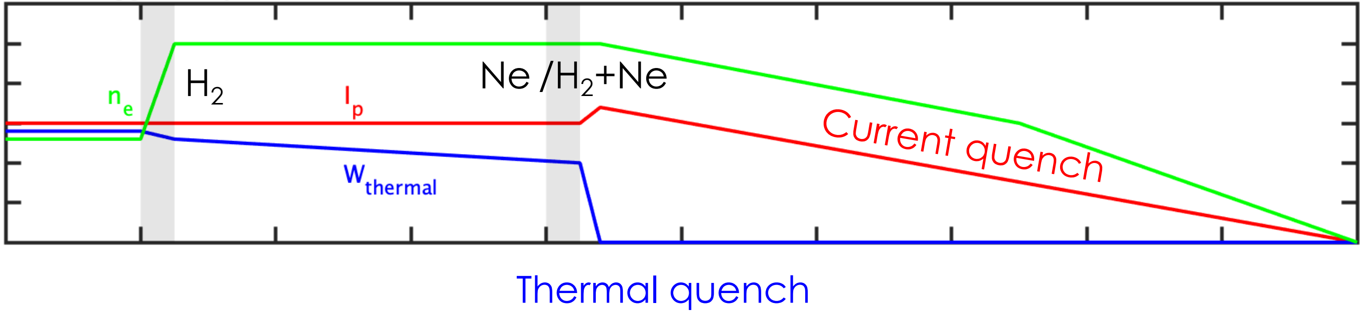
- **Pure hydrogenic SPI leads to long pre-TQ duration with high n_e**
  - Slowing down hot Maxwellian tails that can be a seed for runaway electrons

→ Motivation of the "staggered" injection.

(a) One–stage injection



(b) Staggered injection

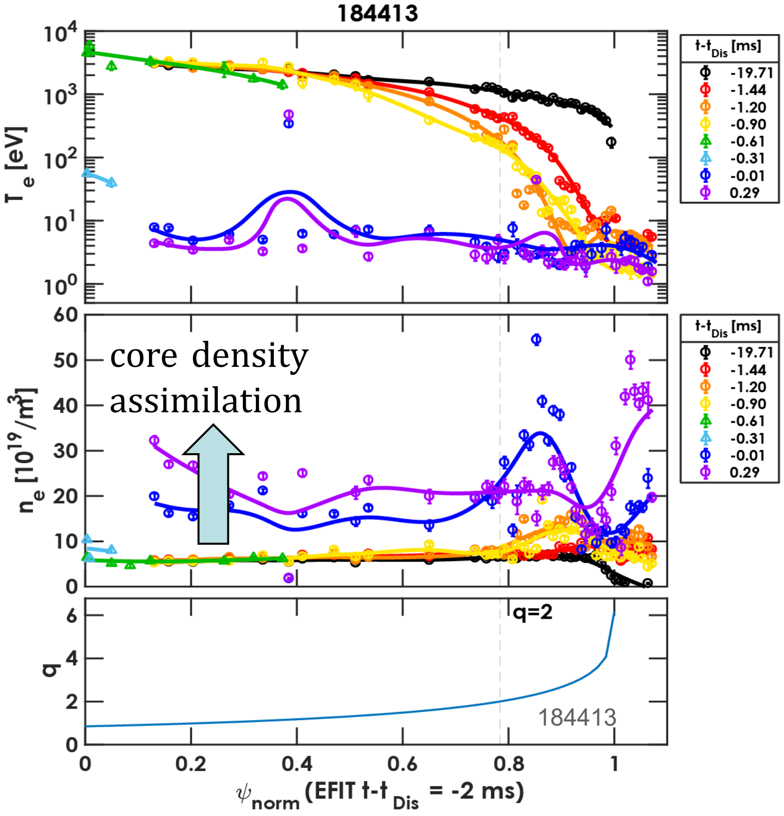


Impact of plasmoid drift on the SPI assimilation and implications to ITER

DIII-D Post-injection TS profiles

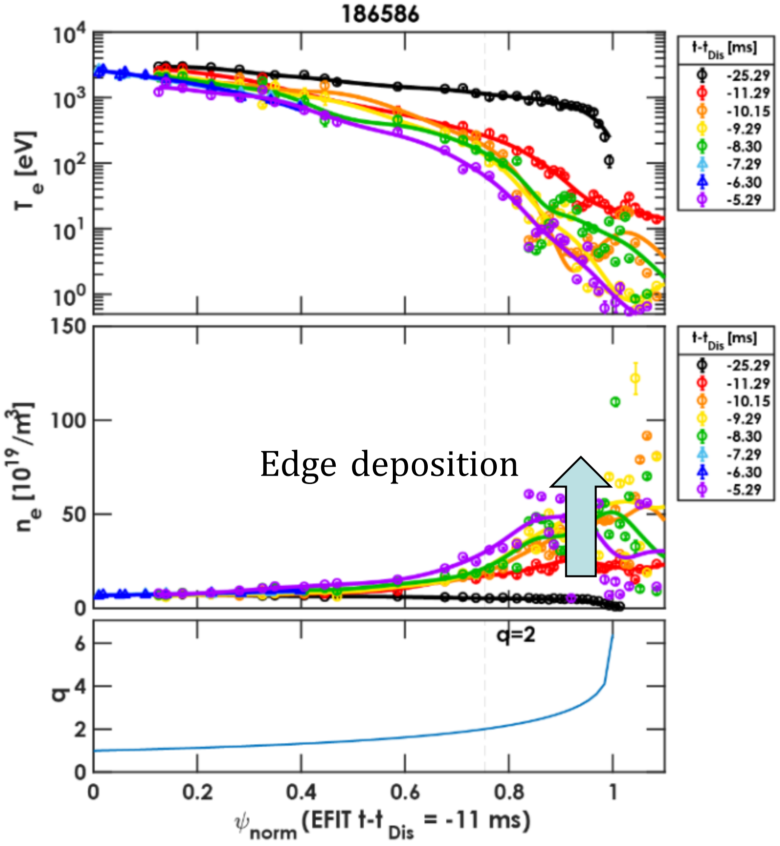
[Shiraki APS-DPP2021; Lvovskiy APS-DPP2022]

Ne mixed SPI



core density assimilation

Pure D_2 SPI

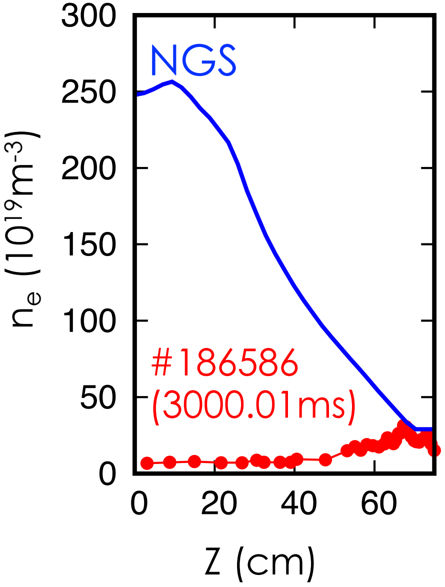


Edge deposition

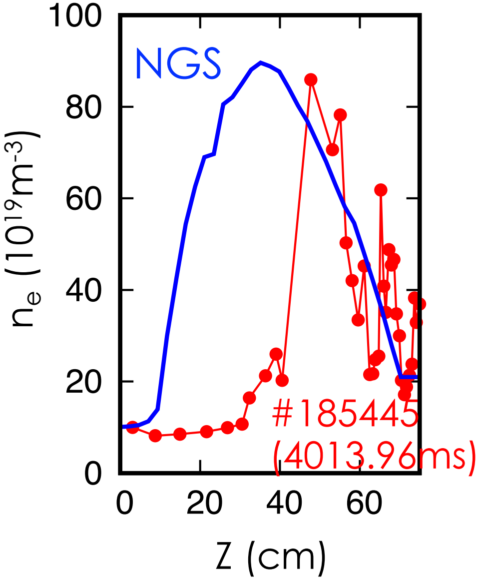
NGS-based simulation does not explain observed edge deposition

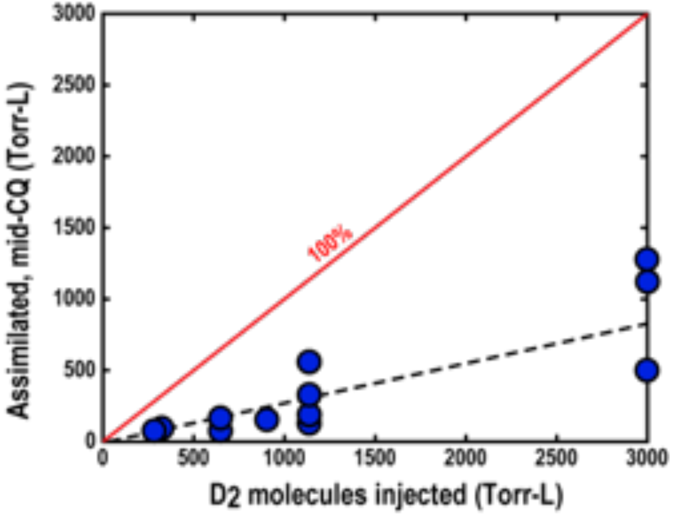
[Matsuyama ITER Task Report; Shiraki APS-DPP2021]

2.8ms after arrival

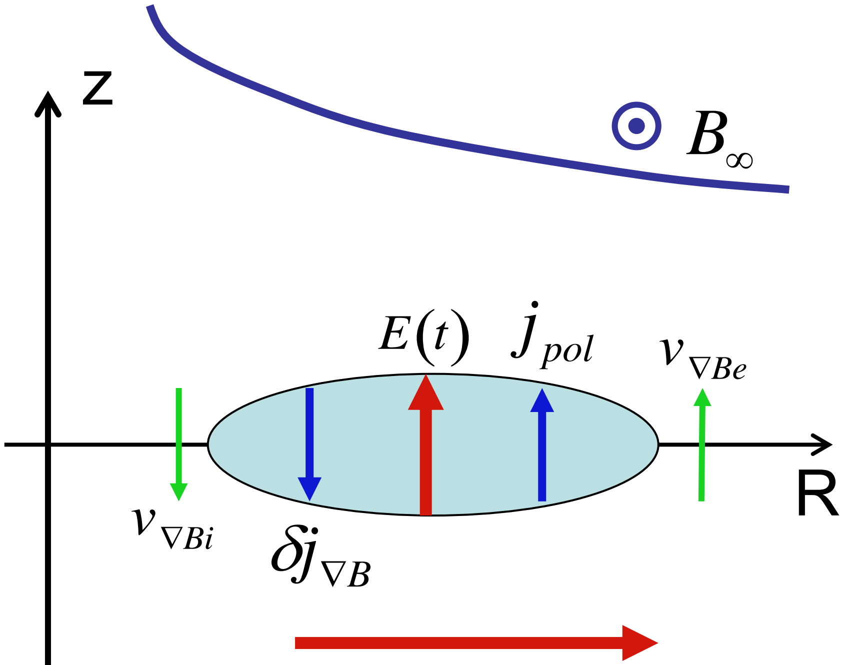


0.86ms after arrival





ExB drift of pellet-produced plasmoids



$$V_d \equiv \frac{E(t)\times B_\infty}{B_\infty^2}$$

$$v_{\nabla B} \approx \frac{T}{eRB_\infty}$$

$$j_{\nabla B} \equiv \sum_{i,e} nev_{\nabla B} \Rightarrow \delta j_{\nabla B} \approx \frac{2\left(n_0T_0 - n_\infty T_\infty\right)}{RB_\infty}$$

$$j_{pol} \approx \frac{n_0 m_0}{B_\infty^2}\frac{dE}{dt}$$

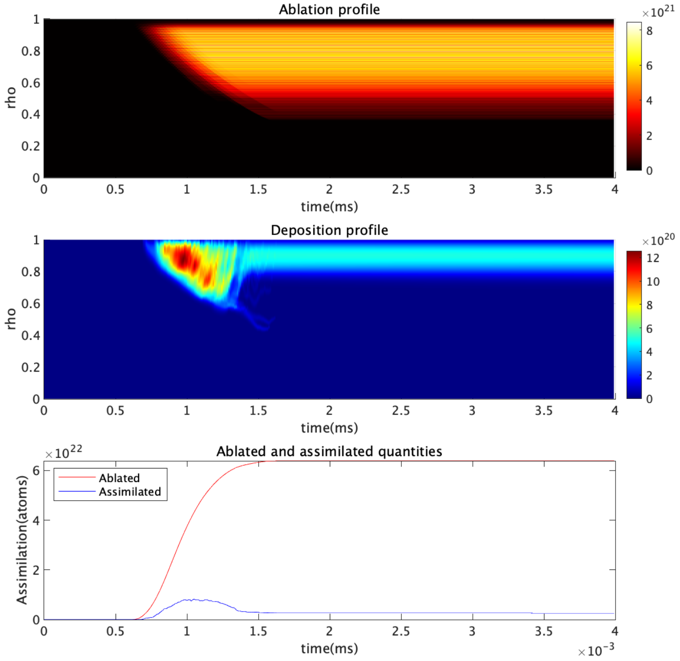
$$\frac{dE}{dt} \approx \frac{2\left(n_0T_0 - n_\infty T_\infty\right)}{Rn_0m_0}B_\infty$$

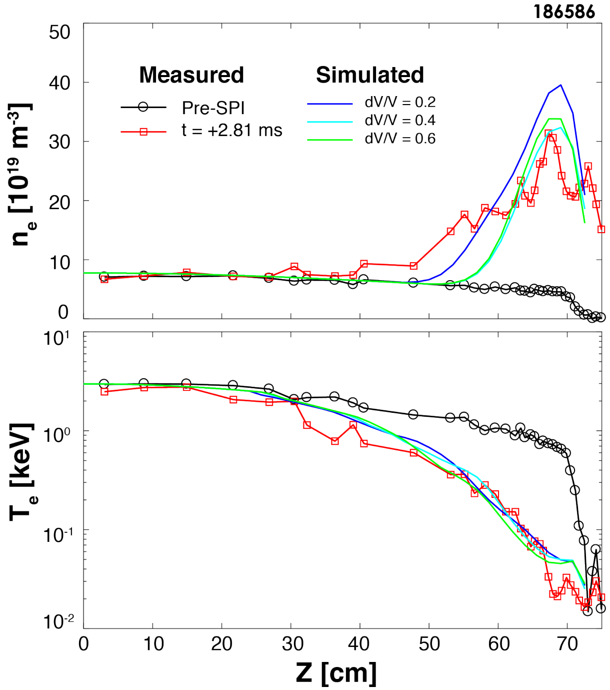
$$\boxed{\frac{dV_d}{dt} \equiv \frac{\frac{dE}{dt}\times B_\infty}{B_\infty^2} \approx \frac{2\left(n_0T_0 - n_\infty T_\infty\right)}{Rn_0m_0}}$$

First attempt to apply fueling pellet ExB model to DIII-D

[Matsuyama, ITER Task Report2021]

- ExB drift-damping model for non-shattered fuelling pellets [Koechl, PhD Thesis]
  → Support that ExB mechanism limits the core density rise by LFS injected pure hydrogenic SP



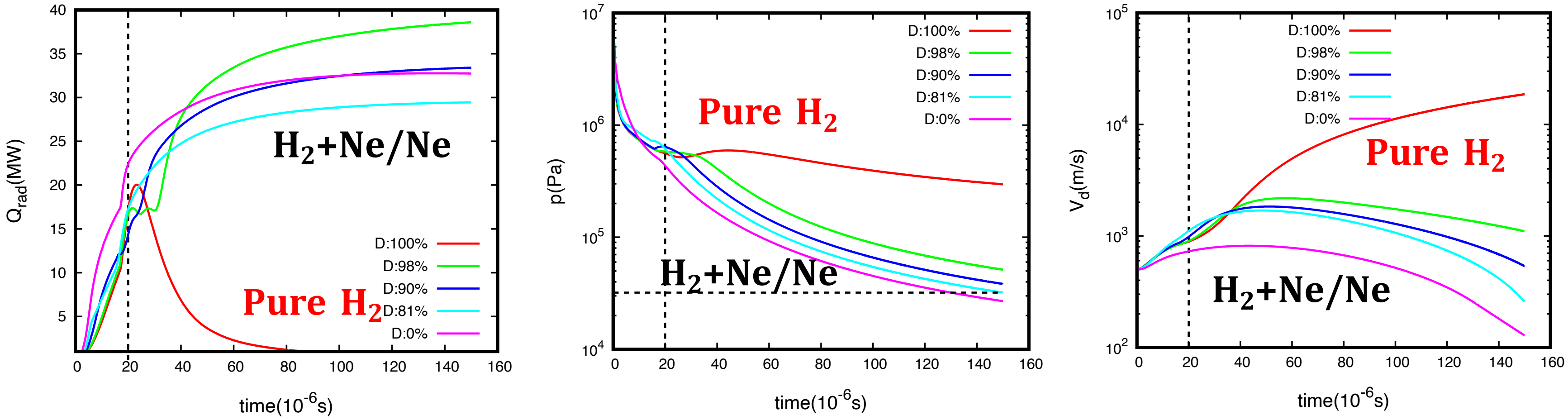


Why ExB drift losses become significant only for pure H_2 SPI?

[Matsuyama PoP2022]

- Plasmoid drift becomes significant only for hydrogenic pellets because the energy loss due to line radiation is small for hydrogen
  - Plasmoid tends to be over-pressured due to heating from the ambient plasma
- NGPS ablation cloud simulation

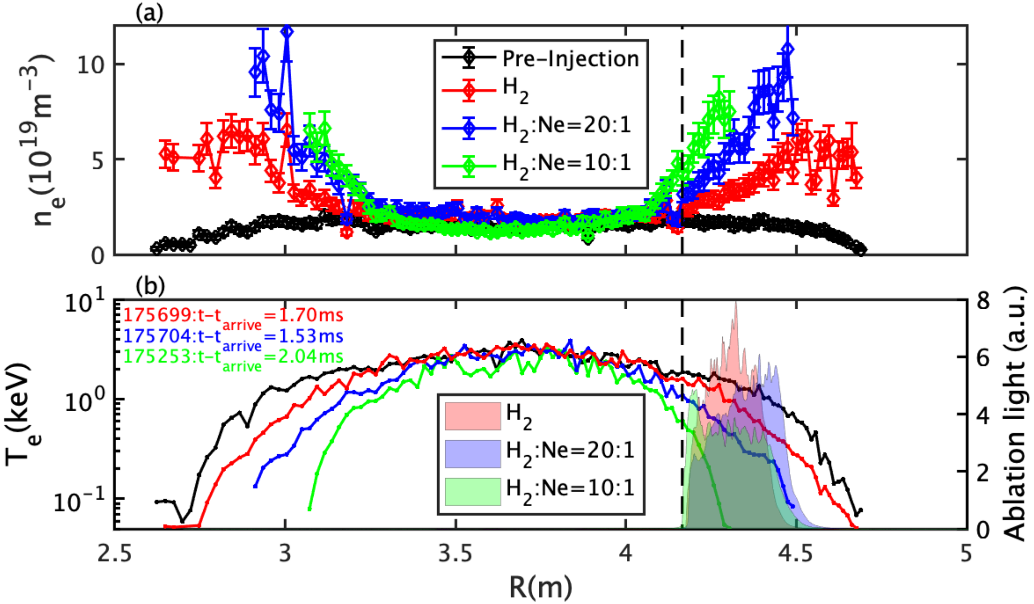
→ Even a few % neon mixture leads to a ‘bifurcation’ between with and without ExB drifts



Non-shattered pellet exp. in LHD has identified reduced ExB drift by neon

[Matsuayma, in preparation]

Post-injection profiles after the injection of 3 mm pure H_2 and Mixed H2+Ne (20:1/10:1) pellets



- Observation of the post-injection electron density profiles
- Clear correlation between assimilation depths and neon quantities

New factor necessary to be validated for effective disruption mitigation by present LFS injection configuration of ITER DMS

Summary
+
Initial simulations for ITER DMS performance

Summary: Modeling efforts to validate physics basis for ITER DMS

- **Pellet ablation rate for H_2/H_2+Ne/Ne pellets**
  - Validated up to keV range plasmas by LHD

- **Cold front dynamics in pre-TQ phase**
  - Intercode benchmarking (1D INDEX vs 2D JOREK)
  - Modeling/Experiment comparison of TQ timescale

- **Impact of plasmoid drift**
  - Significant particle losses for pure hydrogenic SPI
  - Smaller drifts for mixed Ne + H_2 pellets

→ These factors have been taken into account by initial SPI injection parameter survey as input for Preliminary Design Review of ITER DMS (Feb 2022)

Global trends of SPI injection parameter dependence have been shown

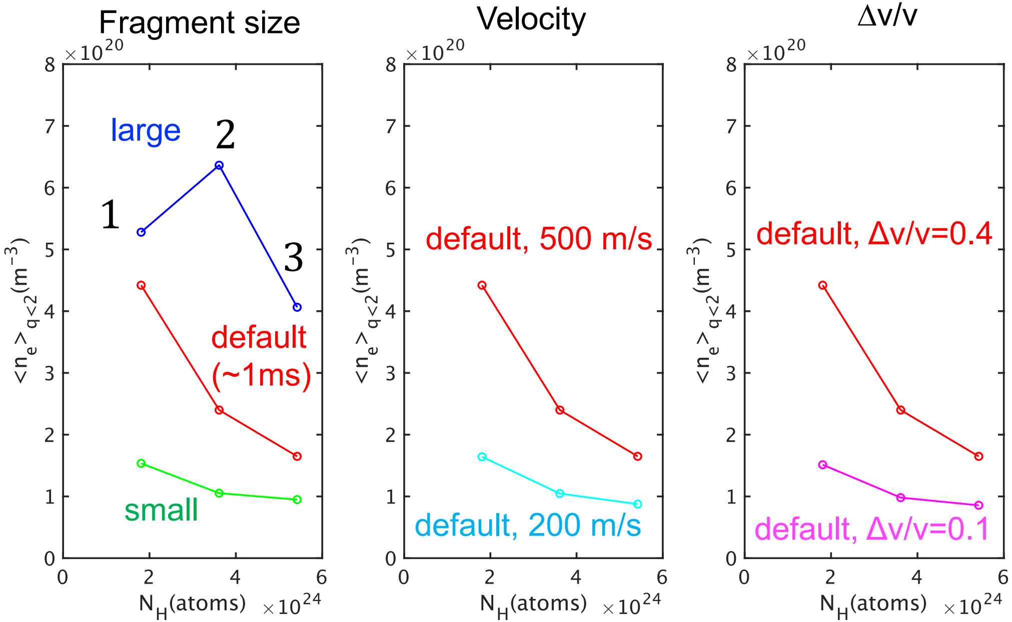
A. Matsuyama ITER_D_6WA4YA

- 1D INDEX ITER simulations
  - 15 MA Hyd. L-mode scenario
  - 5×10^{22} Ne atoms

- Simulation suggest efficient core fueling before TQ for given injection quantity with
  - Large fragment size
  - Higher injection velocity
  - Higher velocity dispersion

- Caveat:
  - Simulation does not take into account gas fraction and microparticles associated with SPI fragments

→ MGI-like edge particle deposition?



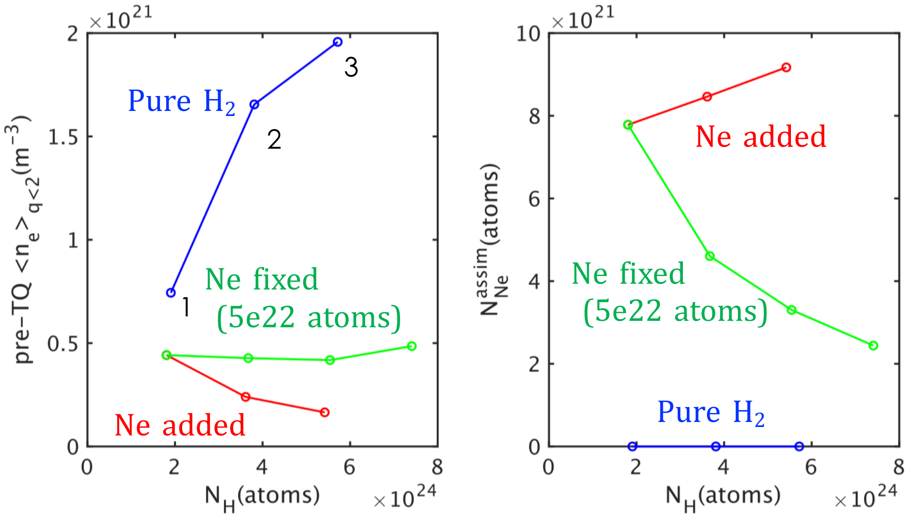
	large	default	small
N	68	487	5185
$\langle r_s \rangle$	~ 2 mm	~ 1 mm	~ 0.5 mm
r_s^{max}	< 2.5 cm	< 2 cm	< 1 cm

Pellet compositions need to be flexible depending on target plasmas

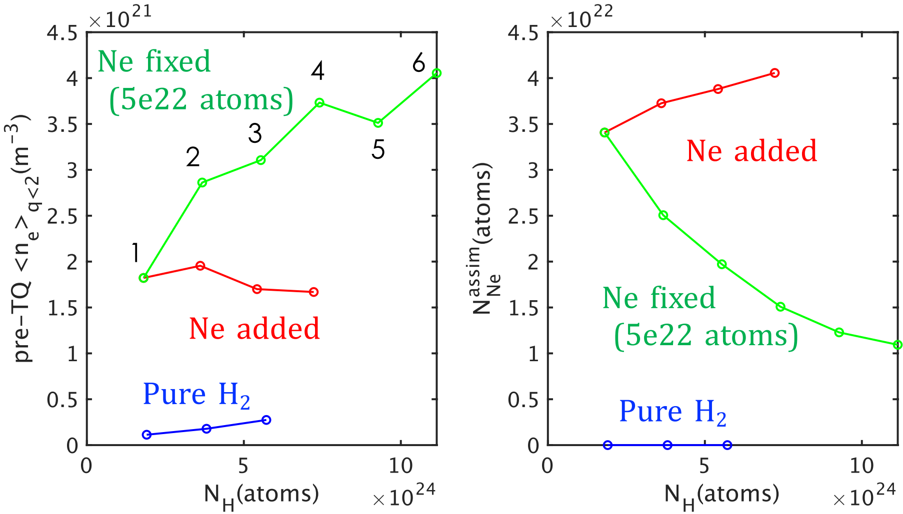
Multiple 28.5 mm pellet injection (1D INDEX)

A. Matsuyama ITER_D_6WA4YA

15 MA Hydrogen L-mode ($T_e(0)$~5keV)



15 MA DT H-mode ($T_e(0)$~25keV)



- Key observation:
  - Multiple H_2/Ne pellets into L-mode is ineffective and pure H_2 injection is a vital option for RE avoidance even suffering from ExB drift loss
  - For DT H-mode, the mitigation of ExB drift loss by neon is required for enhance assimilation

Discussion and future issues

- **To improve the present SPI simulation database of the ITER DMS performance, more effort to address relevant physics is essential towards Final Design Review (2023):**

Contributed work in this TM

- Further validation against experimental data [Stein-Lubrano, Heinrich, Herfindal, Yoo, J. Kim, Gerasimov]
- Plasmoid drift and energy balance models for H_2/H_2+Ne/Ne pellets [Aleynikov]
- 3D MHD TQ trigger models for different pellet composition: cooling of local flux tube, interpretation of locked mode signals, influence of intrinsic impurities [Lyon, Di, Hu, Hoelzl, Shilin Hu]
- B-field dependence of the pellet ablation rate in different ITER operation scenarios from third field to full fields
- Effect of gas (propellant, sublimated ones) and microparticles on the TQ trigger → requirements for pellet shattering and SPI systems [SPI technology session, tomorrow]
- Requirement and best injection scheme for TQ mitigation in ITER [Strauss, Tang]
- Injection scheme consistent with disruption predictions (DMS trigger) and RE mitigation scenario by secondary injection [Paz-Soldan, and other related talks]

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