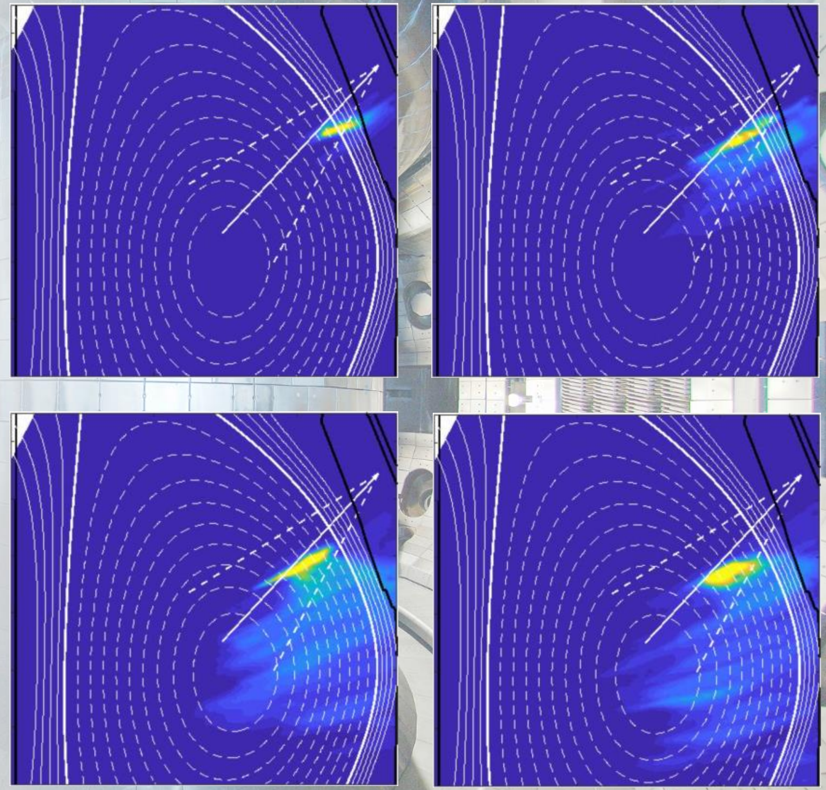
Density and Temperature Profiles after Low-Z and High-Z Shattered Pellet Injections on DIII-D

A. Lvovskiy[1]
with participation of
A. Matsuyama[2], D. Shiraki[3], T. O'Gorman[1],
N.W. Eidietis[1], E.M. Hollmann[4], J.L. Herfindal[2],
M. Lehnen[5], R. Boivin[1]

[1]General Atomics, San Diego, CA, USA
[2]National Institutes for Quantum Science and Technology, Rokkasho, Japan
[3]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[4]University of California San Diego, La Jolla, CA, USA
[5]ITER Organization, Saint-Paul-lez-Durance, France



Presented at
2023 Theory and Simulation of Disruptions Workshop
Princeton, July 19–21 2023

DIII-D NATIONAL FUSION FACILITY

GENERAL ATOMICS

Shattered pellet injection will be primary disruption mitigation approach on ITER

- **Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER**

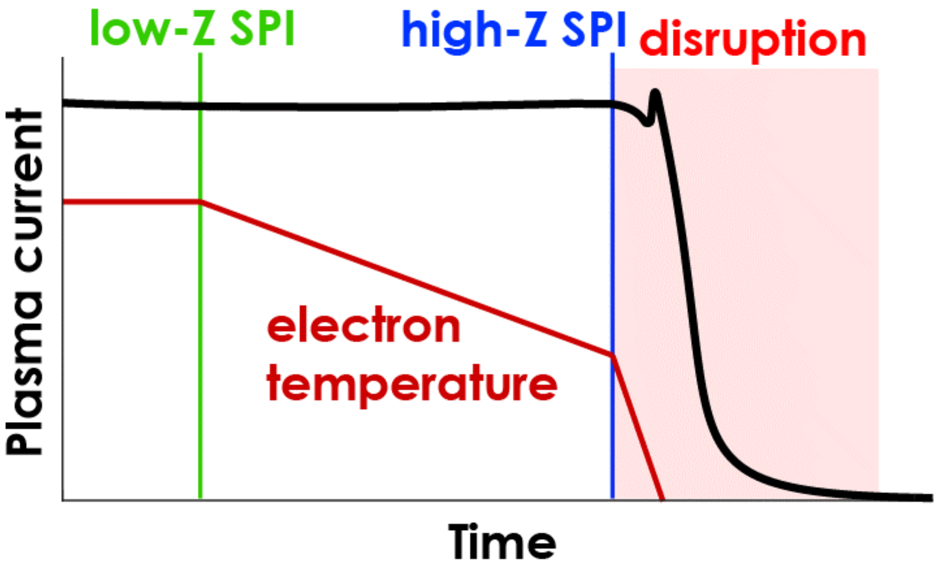
Shattered pellet injection will be primary disruption mitigation approach on ITER

- Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER
- Both low-Z and high-Z material needed

Shattered pellet injection will be primary disruption mitigation approach on ITER

- Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER
- Both low-Z and high-Z material needed
- But use of mixed or staggered SPI is yet to be decided

Staggered shattered pellet injection is considered for disruption mitigation on ITER



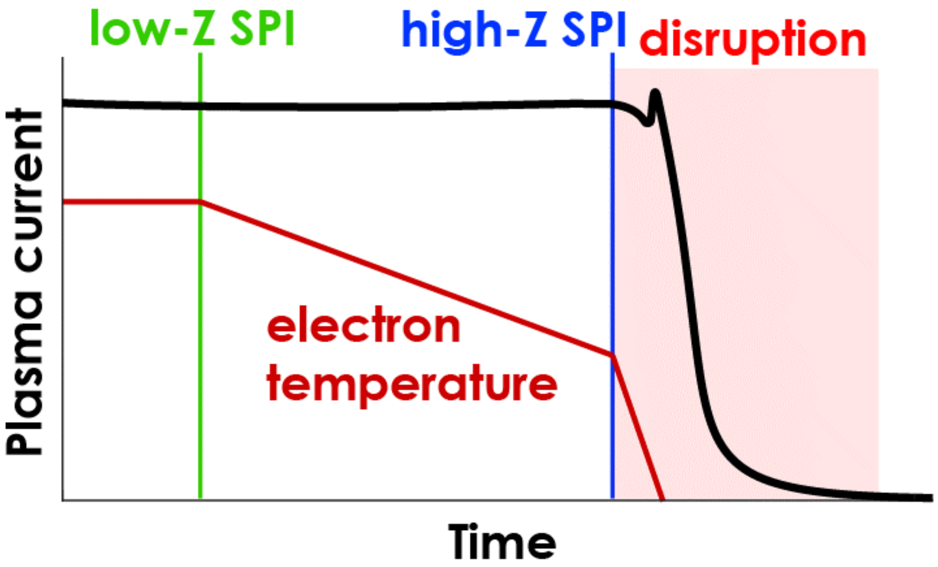
- Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER
- Both low-Z and high-Z material needed
- But use of mixed or staggered SPI is yet to be decided

Staggered SPI:

- Low-Z SPI slowly cools plasma, suppresses runaways via dilution and collisions
- High-Z SPI dissipates thermal energy via radiation, also sets current quench time

DIII-D NATIONAL FUSION FACILITY

Staggered shattered pellet injection is considered for disruption mitigation on ITER

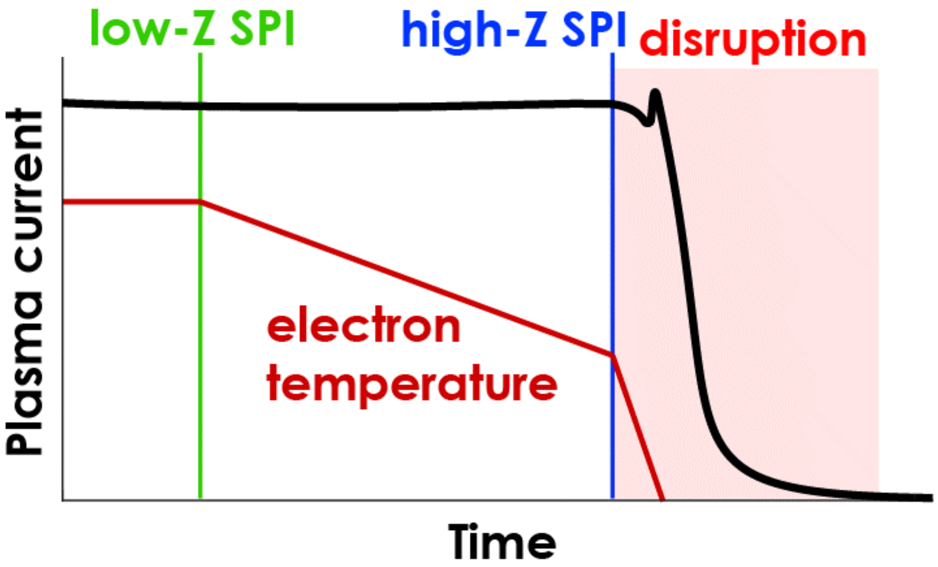


- Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER
- Both low-Z and high-Z material needed
- But use of mixed or staggered SPI is yet to be decided

Staggered SPI:

- Low-Z SPI slowly cools plasma, suppresses runaways via dilution and collisions
- High-Z SPI dissipates thermal energy via radiation, also sets current quench time
- Does staggered SPI work as planned?

Staggered shattered pellet injection is considered for disruption mitigation on ITER



- Shattered pellet injection (SPI) is chosen for disruption mitigation on ITER
- Both low-Z and high-Z material needed
- But use of mixed or staggered SPI is yet to be decided

Staggered SPI:

- Low-Z SPI slowly cools plasma, suppresses runaways via dilution and collisions
- High-Z SPI dissipates thermal energy via radiation, also sets current quench time
- Does staggered SPI work as planned?
- This talk: study of temperature and density profiles after low- and high-Z SPI on DIII-D

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

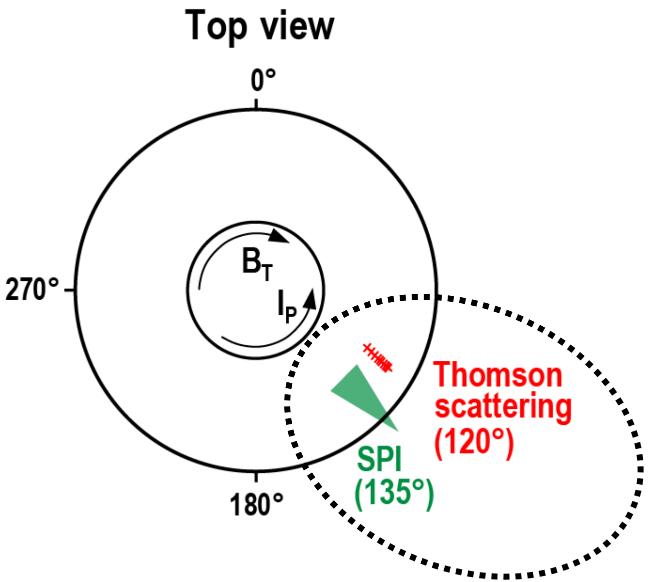
INDEX code

Comparison with experiment

How to improve penetration

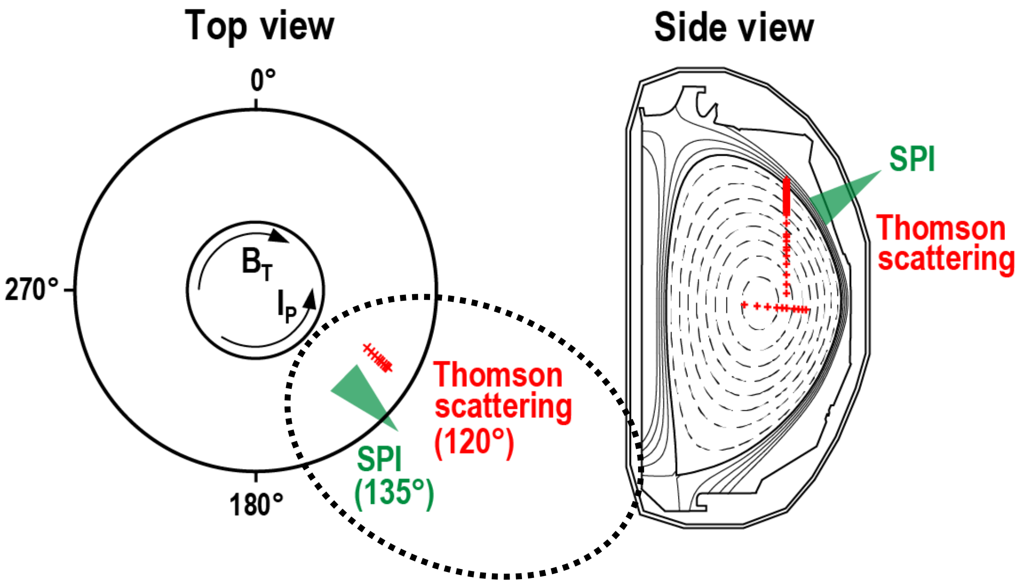
Final remarks

DIII-D is well suited to study shattered pellet injection



- The SPI system closest to Thomson scattering viewpoints is analyzed in this talk

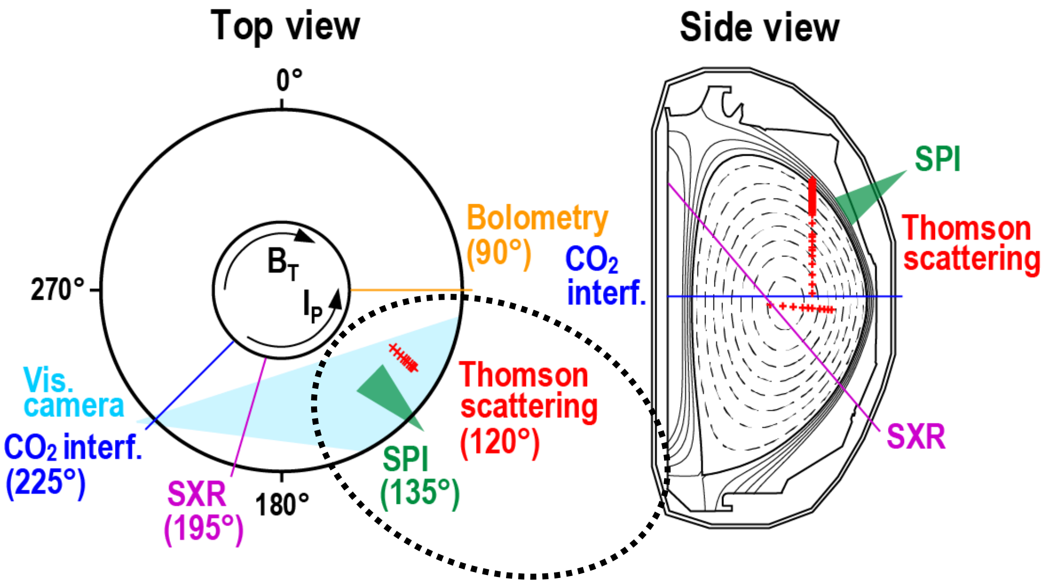
DIII-D is well suited to study shattered pellet injection



- **The SPI system closest to Thomson scattering viewpoints is analyzed in this talk**
- **Thomson scattering provides plasma temperature and density profiles**
  - Covers both plasma core and edge
  - Recent upgrade with narrow-bandwidth filters allows low-T_e measurements
  - Can be triggered asynchronously (e.g. using ablation light signal) to reliably catch plasma cooling dynamics

DIII-D NATIONAL FUSION FACILITY

DIII-D is well suited to study shattered pellet injection



- The SPI system closest to Thomson scattering viewpoints is analyzed in this talk
- Thomson scattering provides plasma temperature and density profiles
  - Covers both plasma core and edge
  - Recent upgrade with narrow-bandwidth filters allows low-T_e measurements
  - Can be triggered asynchronously (e.g. using ablation light signal) to reliably catch plasma cooling dynamics
- Other diagnostics provide pellet imaging, line-integrated density, soft X-ray, total radiated power

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

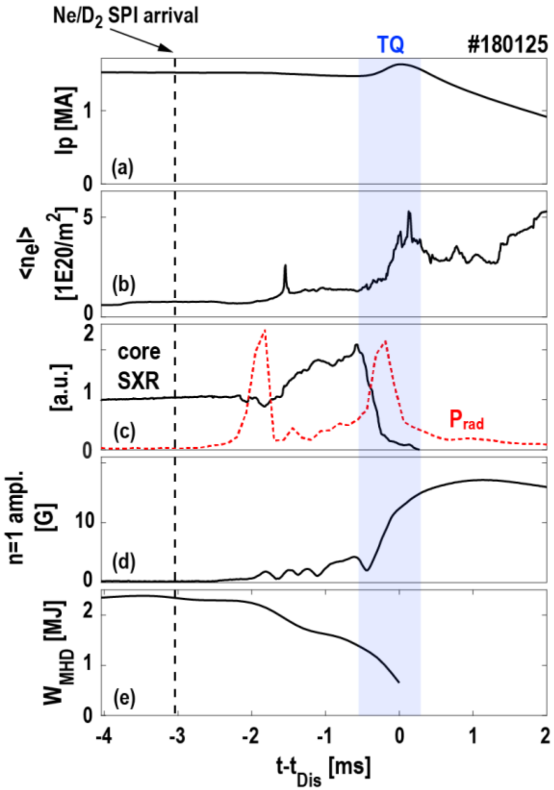
INDEX code

Comparison with experiment

How to improve penetration

Final remarks

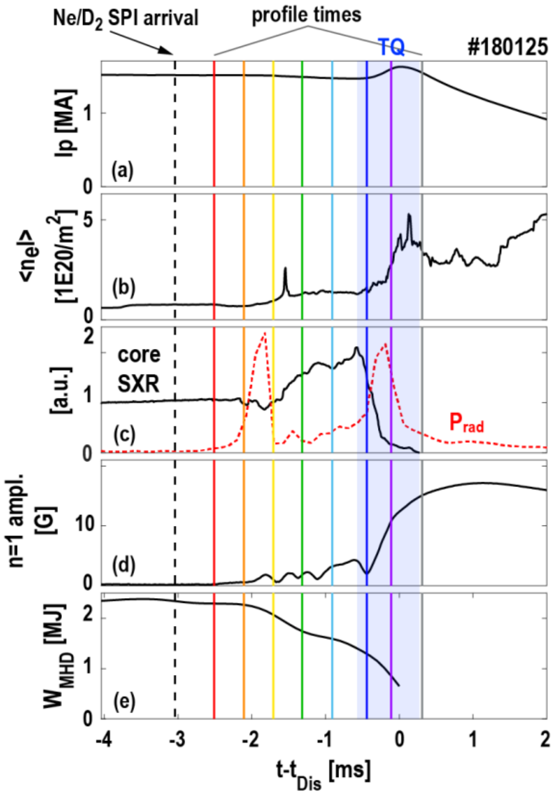
Mixed Ne/D_2 SPI quickly disrupts the plasma



- Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma
- It quickly (in 3 ms) disrupts plasma via radiative collapse

Non-thermal electrons: Hollmann et al, NF 2021

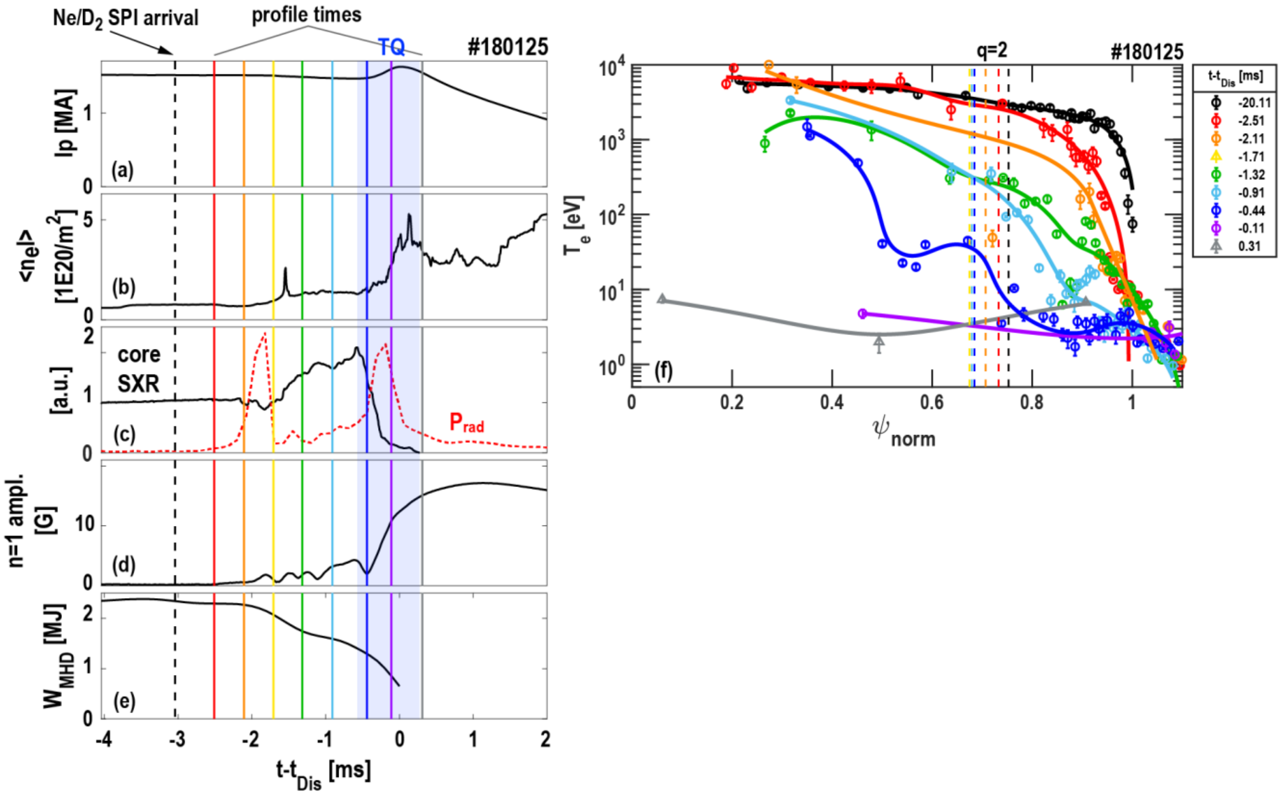
Mixed Ne/D_2 SPI quickly disrupts the plasma



- **Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma**
- **It quickly (in 3 ms) disrupts plasma via radiative collapse**

Non-thermal electrons: Hollmann et al, NF 2021

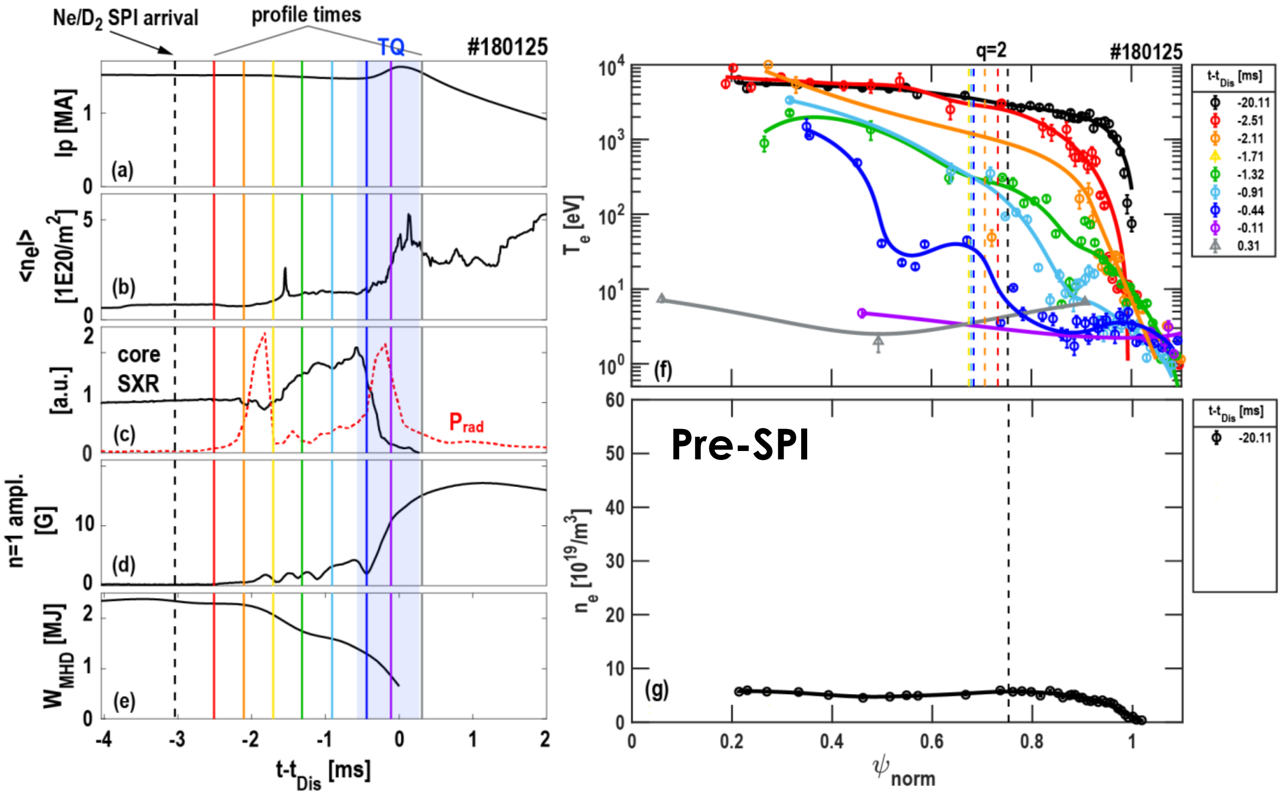
Mixed Ne/D_2 SPI quickly disrupts the plasma



- Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma
- It quickly (in 3 ms) disrupts plasma via radiative collapse

Non-thermal electrons: Hollmann et al, NF 2021

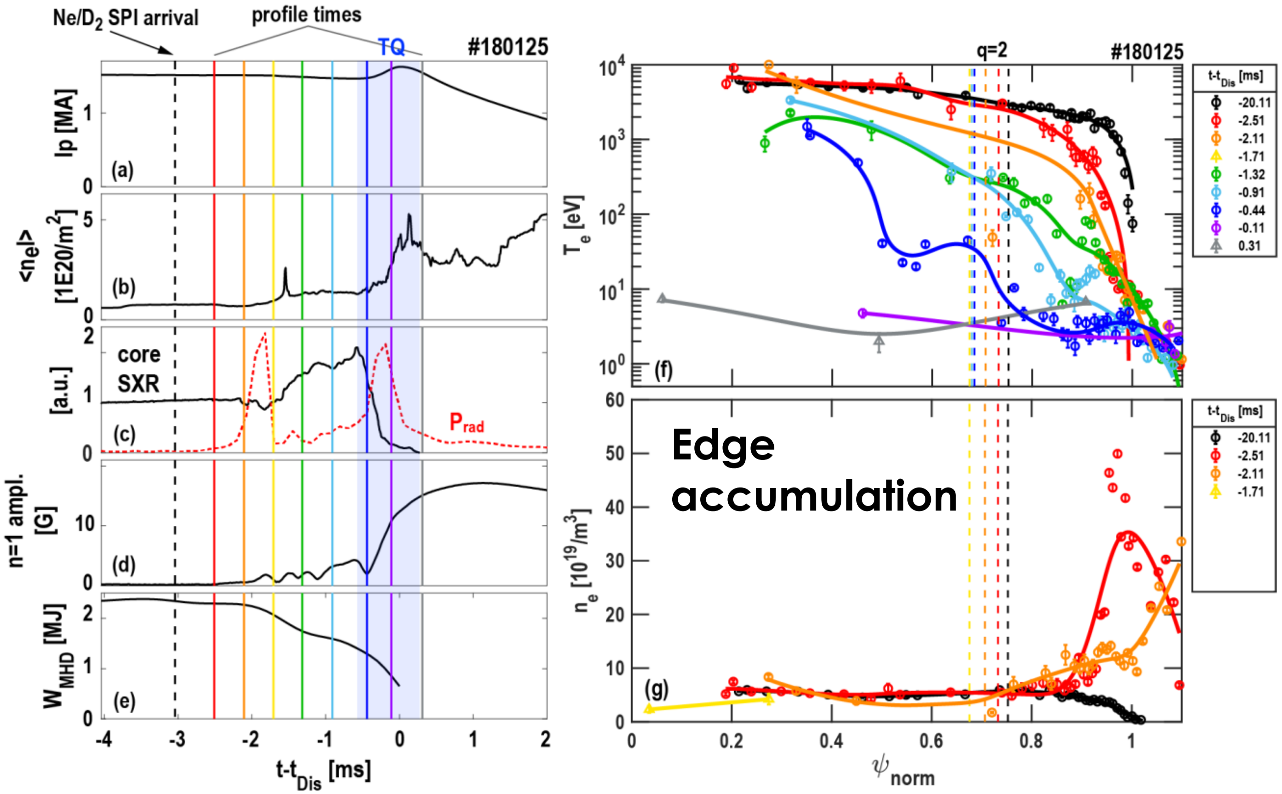
Mixed Ne/D_2 SPI quickly disrupts the plasma



- Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma
- It quickly (in 3 ms) disrupts plasma via radiative collapse

Non-thermal electrons: Hollmann et al, NF 2021

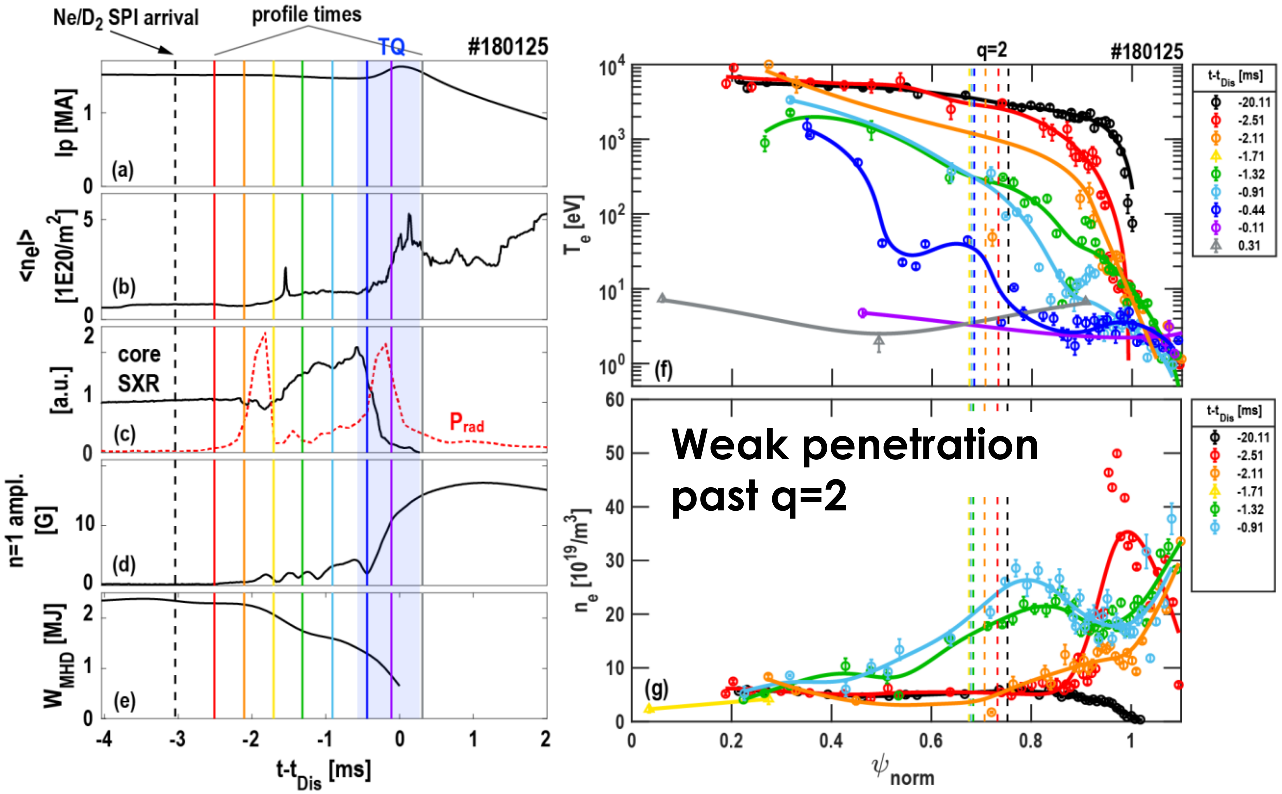
Mixed Ne/D_2 SPI quickly disrupts the plasma



- Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma
- It quickly (in 3 ms) disrupts plasma via radiative collapse

Non-thermal electrons: Hollmann et al, NF 2021

Mixed Ne/D_2 SPI quickly disrupts the plasma

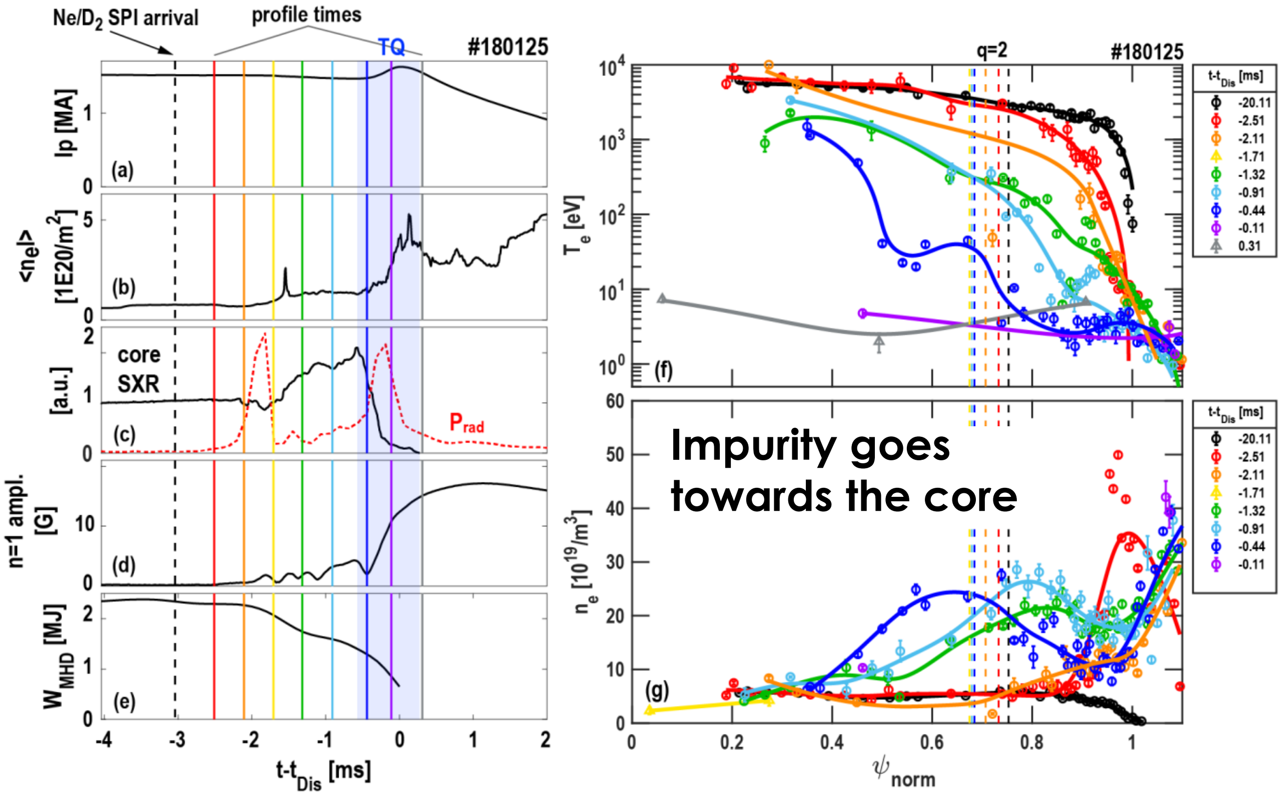


- Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma
- It quickly (in 3 ms) disrupts plasma via radiative collapse
- Injected material doesn't go past q=2 before TQ

Non-thermal electrons: Hollmann et al, NF 2021

DIII-D NATIONAL FUSION FACILITY

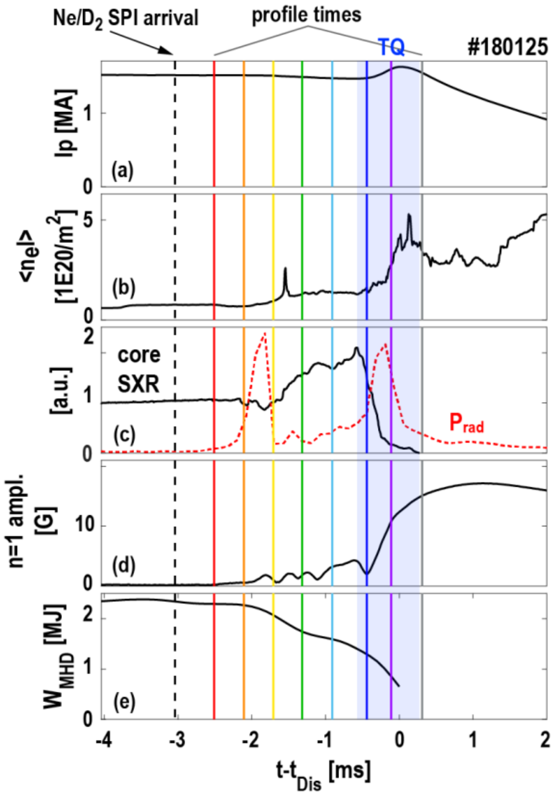
Mixed Ne/D_2 SPI quickly disrupts the plasma and penetrates into the core during and after thermal quench (TQ)

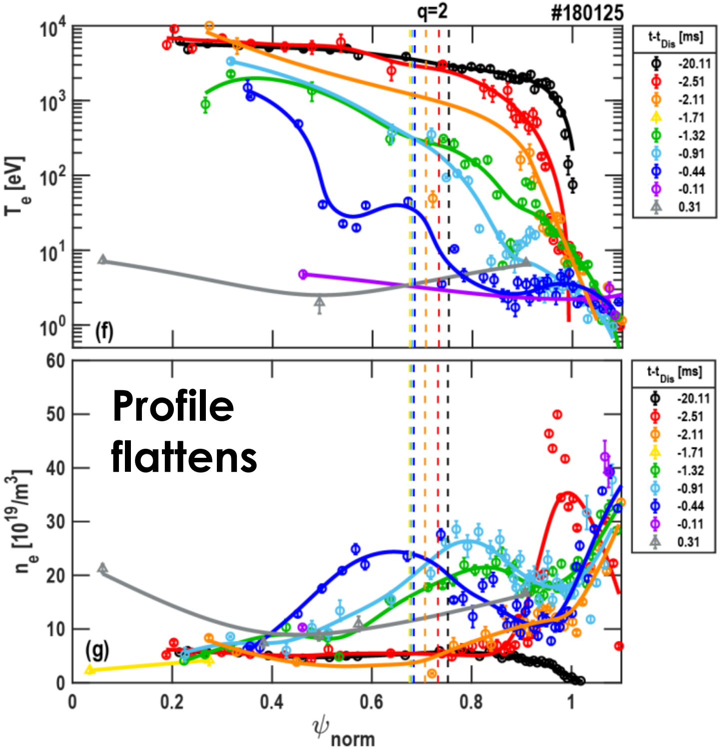


- **Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma**
- **It quickly (in 3 ms) disrupts plasma via radiative collapse**
- **Injected material doesn't go past q=2 before TQ, but mixes with the plasma during TQ**

Non-thermal electrons: Hollmann et al, NF 2021

Mixed Ne/D_2 SPI quickly disrupts the plasma and penetrates into the core during and after thermal quench (TQ)





- **Mixed Ne/D_2 shattered pellet (400/400 Torr·L) is injected into Super H-mode plasma**
- **It quickly (in 3 ms) disrupts plasma via radiative collapse**
- **Injected material doesn't go past q=2 before TQ, but mixes with the plasma during and after TQ**
  - Core density increases by 2x−4x after TQ

Non-thermal electrons: Hollmann et al, NF 2021

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

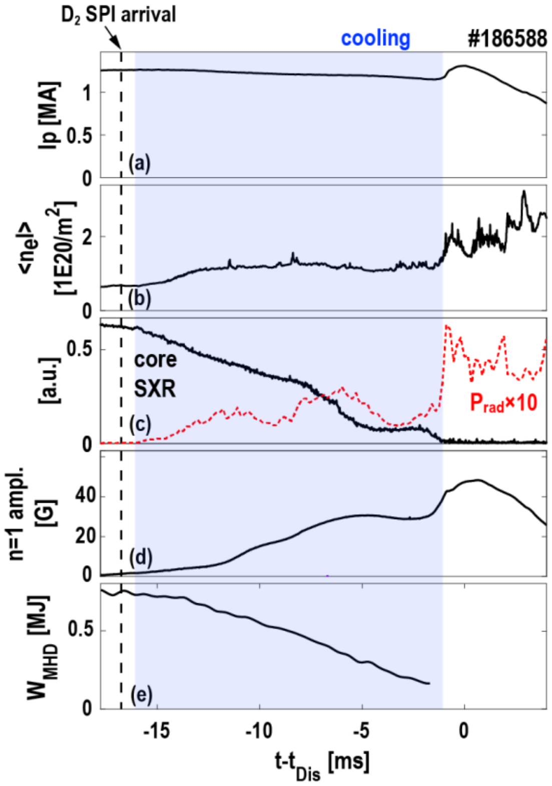
INDEX code

Comparison with experiment

How to improve penetration

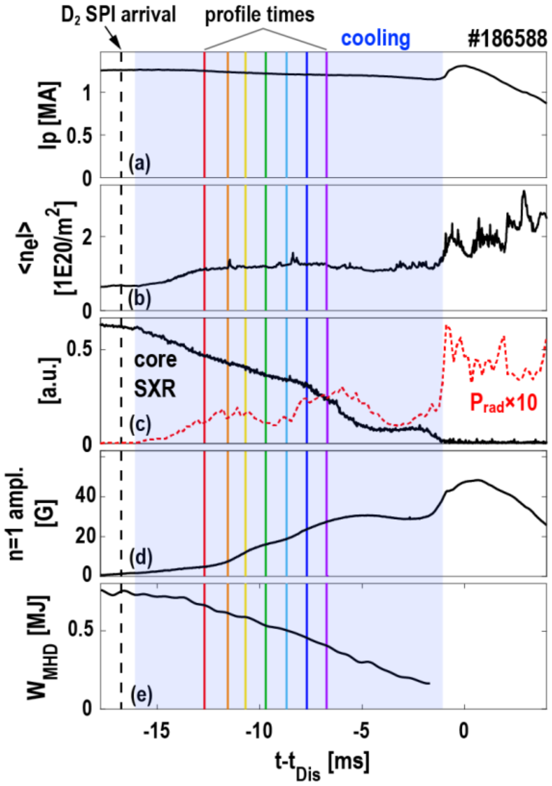
Final remarks

D_2 SPI slowly cools the plasma, it disrupts due to locked modes



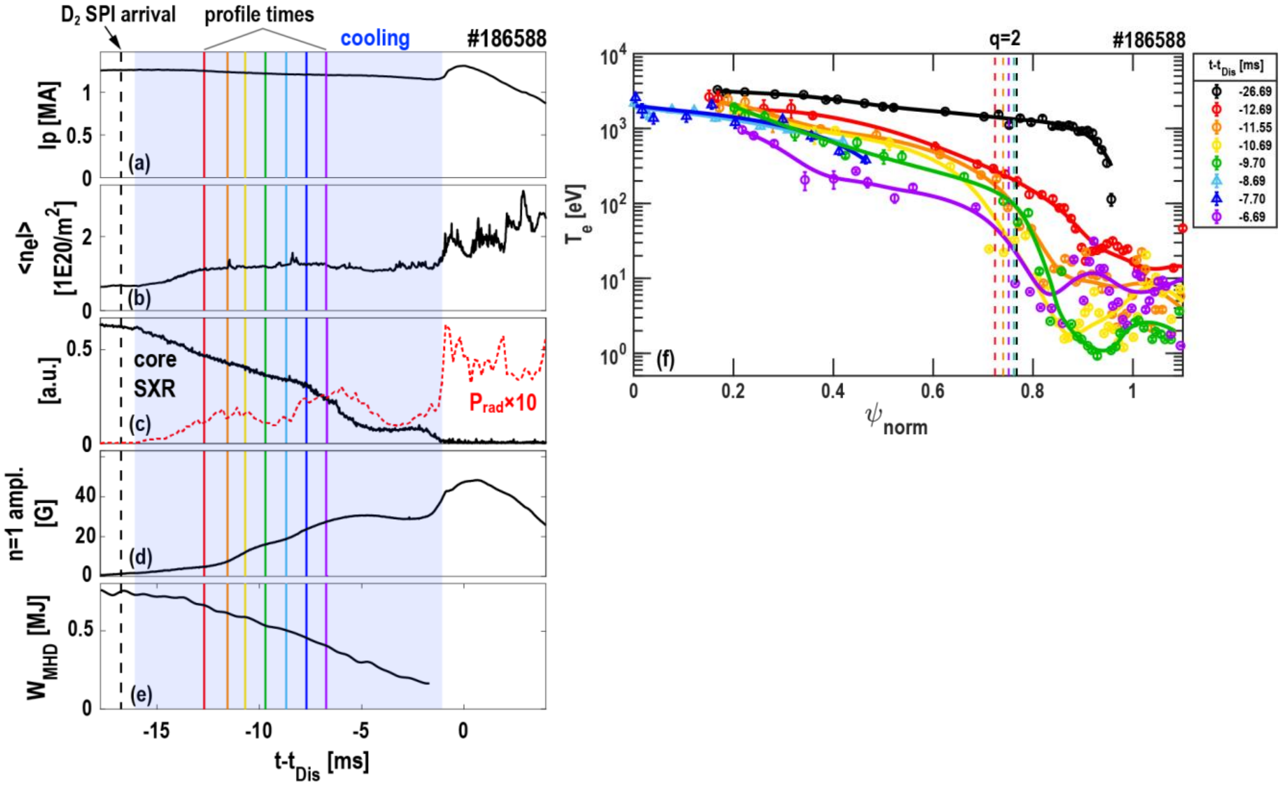
- Pure D_2 shattered pellet (700 Torr·L) is injected into H-mode plasma
- It slowly cools plasma via dilution and radiation over more than 15 ms
  - No classical TQ is observed
- Plasma energy decreases 4-fold by the Ip-spike time
- Plasma disrupts when n=1 amplitude reaches 45 G

D_2 SPI slowly cools the plasma, it disrupts due to locked modes



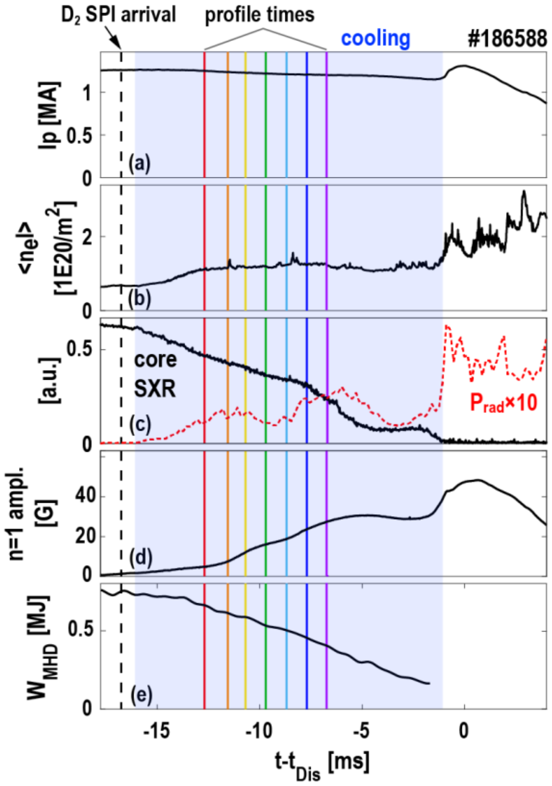
- **Pure D_2 shattered pellet (700 Torr·L) is injected into H-mode plasma**
- **It slowly cools plasma via dilution and radiation over more than 15 ms**
  - No classical TQ is observed
- **Plasma energy decreases 4-fold by the Ip-spike time**
- **Plasma disrupts when n=1 amplitude reaches 45 G**

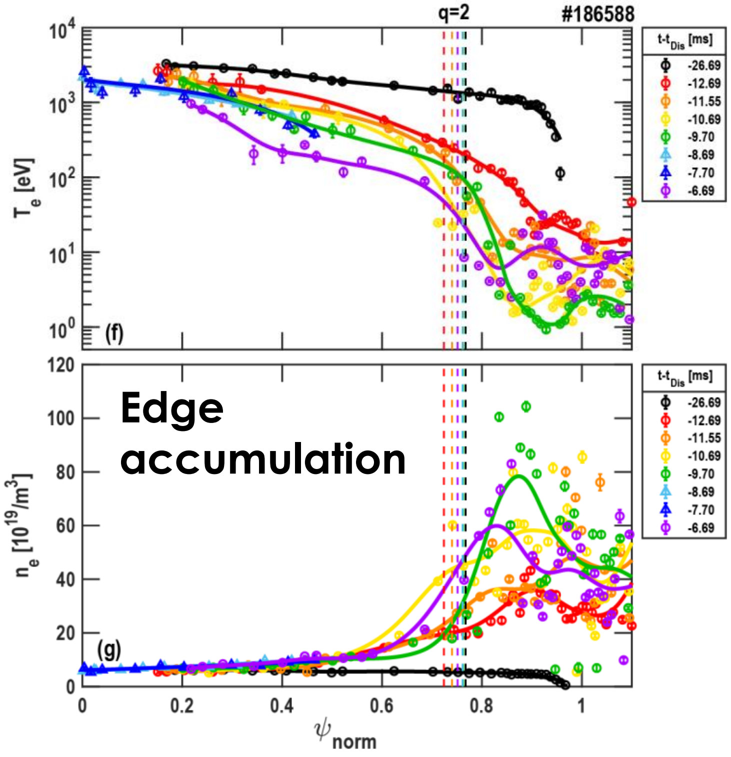
D_2 SPI slowly cools the plasma, it disrupts due to locked modes



- **Pure D_2 shattered pellet (700 Torr·L) is injected into H-mode plasma**
- **It slowly cools plasma via dilution and radiation over more than 15 ms**
  - No classical TQ is observed
- **Plasma energy decreases 4-fold by the Ip-spike time**
- **Plasma disrupts when n=1 amplitude reaches 45 G**

D_2 SPI slowly cools the plasma, it disrupts due to locked modes

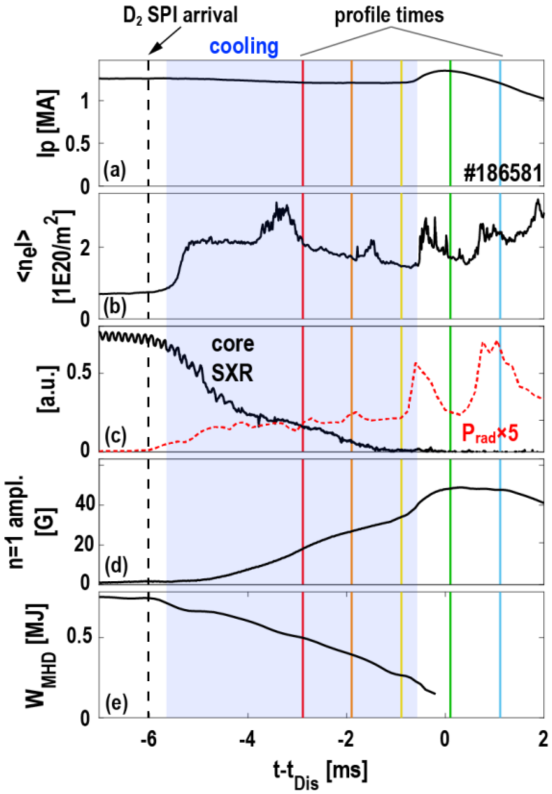


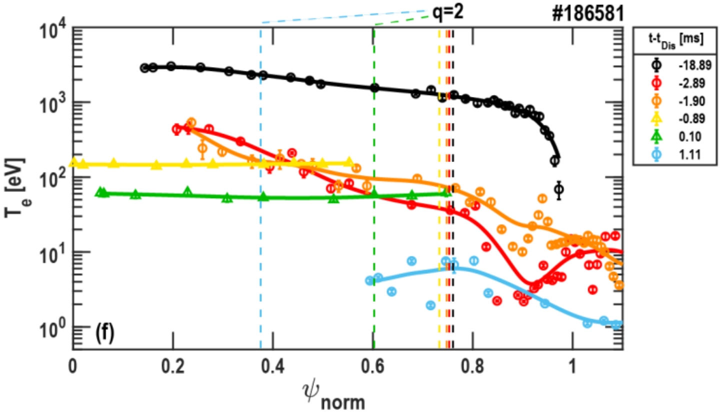


- Pure D_2 shattered pellet (700 Torr·L) is injected into H-mode plasma
- It slowly cools plasma via dilution and radiation over more than 15 ms
  - No classical TQ is observed
- Plasma energy decreases 4-fold by the Ip-spike time
- Plasma disrupts when n=1 amplitude reaches 45 G
- Very weak penetration past q=2 is observed before TQ

DIII-D NATIONAL FUSION FACILITY

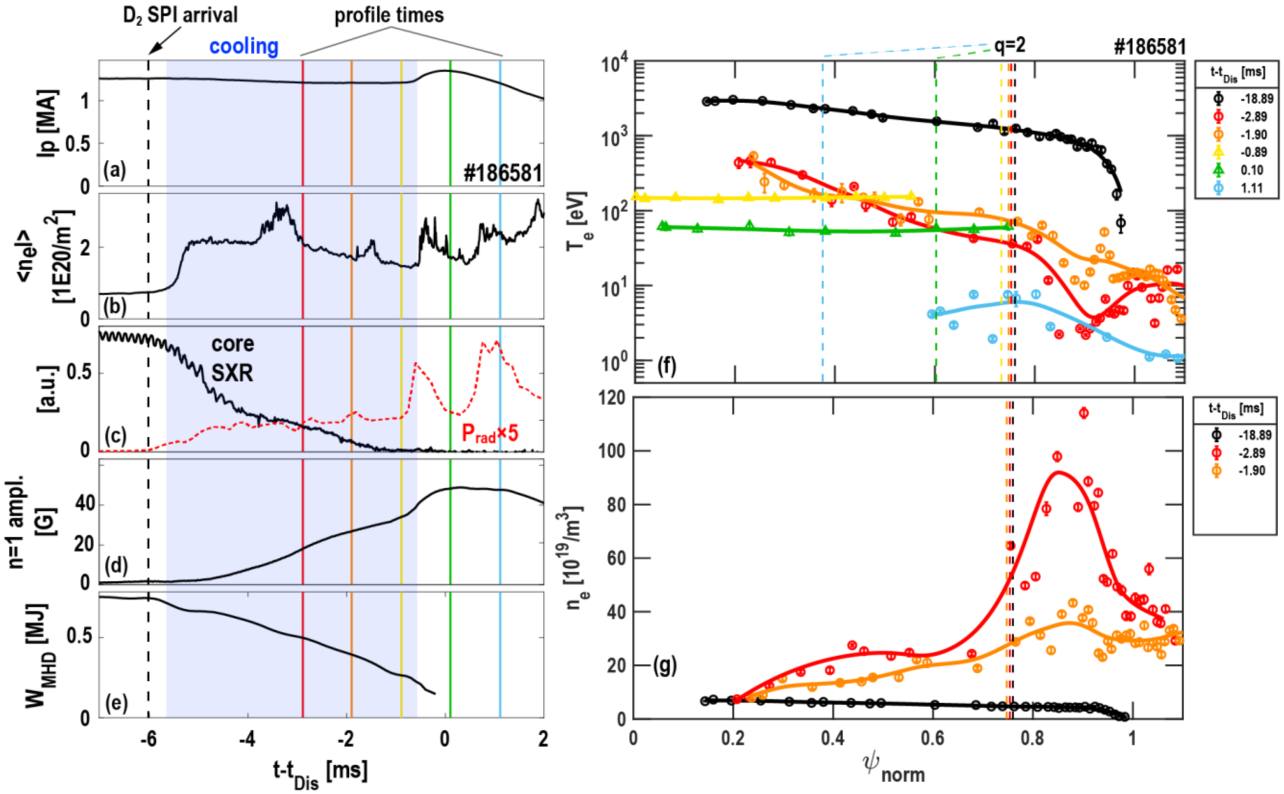
D_2 SPI slowly cools the plasma, it disrupts due to locked modes, poor core mixing is observed





- **Another pure D_2 SPI case with Thomson covering <u>late cooling phase</u>**
- **Similar delayed disruption**
- **Temperature profiles show relatively slow core cooling (>3 ms)**

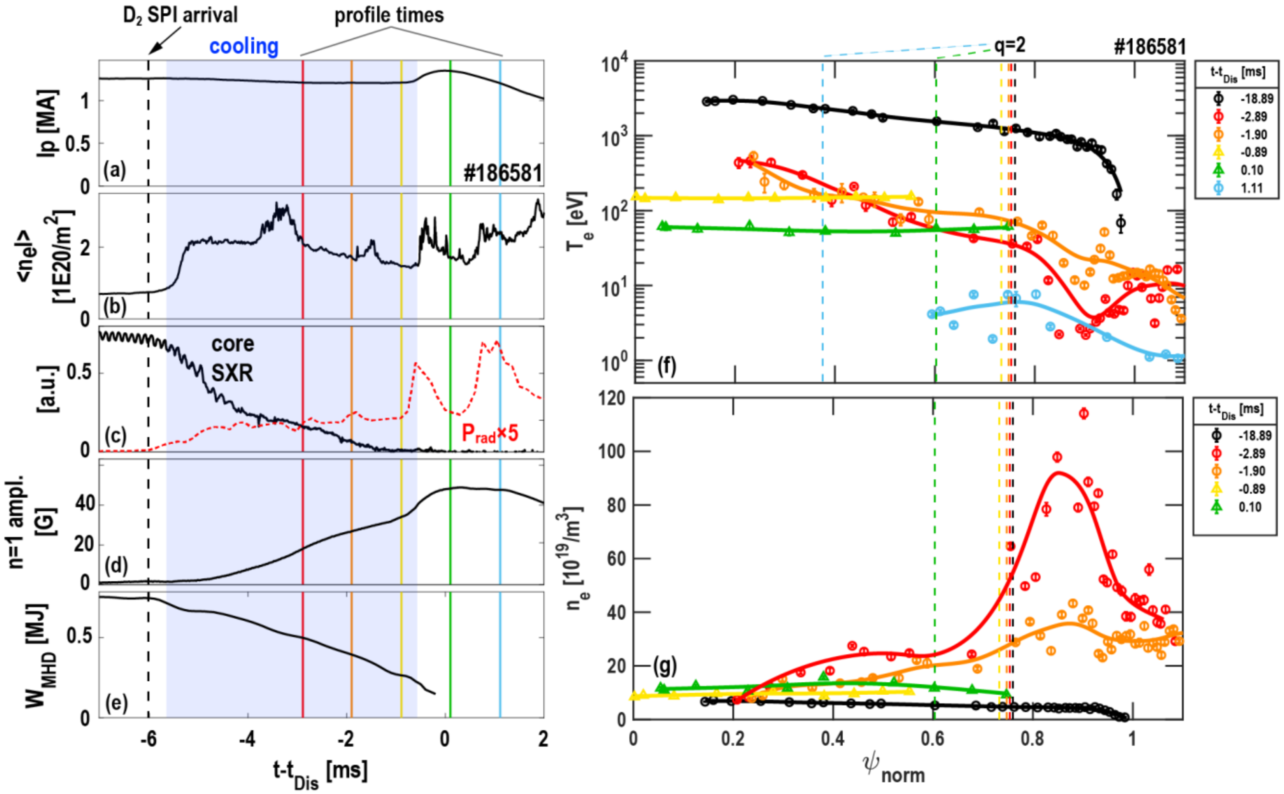
D_2 SPI slowly cools the plasma, it disrupts due to locked modes, poor core mixing is observed



- **Another pure D_2 SPI case with Thomson covering late cooling phase**
- **Similar delayed disruption**
- **Temperature profiles show relatively slow core cooling (>3 ms)**
- **Post-SPI elevated density profile decreases over time**

DIII-D NATIONAL FUSION FACILITY

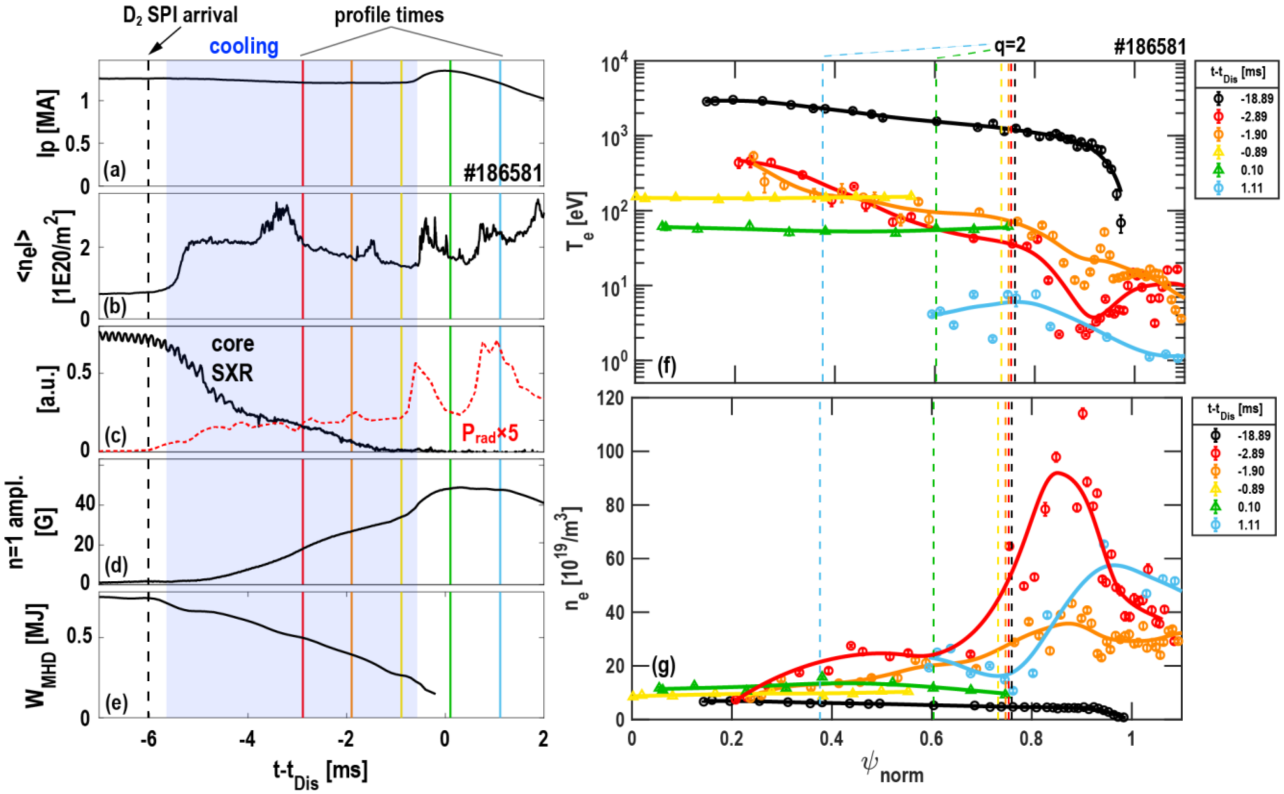
D_2 SPI slowly cools the plasma, it disrupts due to locked modes, poor core mixing is observed



- Another pure D_2 SPI case with Thomson covering late cooling phase
- Similar delayed disruption
- Temperature profiles show relatively slow core cooling (>3 ms)
- Post-SPI elevated density profile decreases over time

DIII-D NATIONAL FUSION FACILITY

D_2 SPI slowly cools the plasma, it disrupts due to locked modes, poor core mixing is observed



- **Another pure D_2 SPI case with Thomson covering <u>late cooling phase</u>**
- **Similar delayed disruption**
- **Temperature profiles show relatively slow core cooling (>3 ms)**
- **Post-SPI elevated density profile decreases over time**
- **Density does not flatten even after the Ip-spike**

DIII-D NATIONAL FUSION FACILITY

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

INDEX code

Comparison with experiment

How to improve penetration

Final remarks

INDEX simulations are employed to interpret observed post-SPI density profiles

- **INDEX is a 1.5D code self-consistently solving transport equations in magnetic flux coordinates coupled to Grad-Shafranov equilibrium calculations[1,2]**
- **It evaluates the SPI ablation rate based on the Neutral Gas Shielding model[3]**
- **The ablated particles are included as the surface-averaged neutral source in the particle balance, and the subsequent ionization processes are solved using the rate equations**
- **The SPI model was extended to include the effect of outward mass relocation due to the grad-B-induced (ExB) drift[4–6]**
- **Presently grad-B-induced drift is not based on first principles but employs simplified considerations following the back-averaged model[7]**

[1] Matsuyama et al, IAEA FEC 2021
[2] Matsuyama et al, PPCF 2022
[3] Parks and Turnbull, Phys. Fluids 198
[4] Rozhansky et al, PPCF 1995
[5] Parks et al, PoP 2000
[6] Pegourie et al, NF 2006
[7] Jardin et al, NF 2000

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

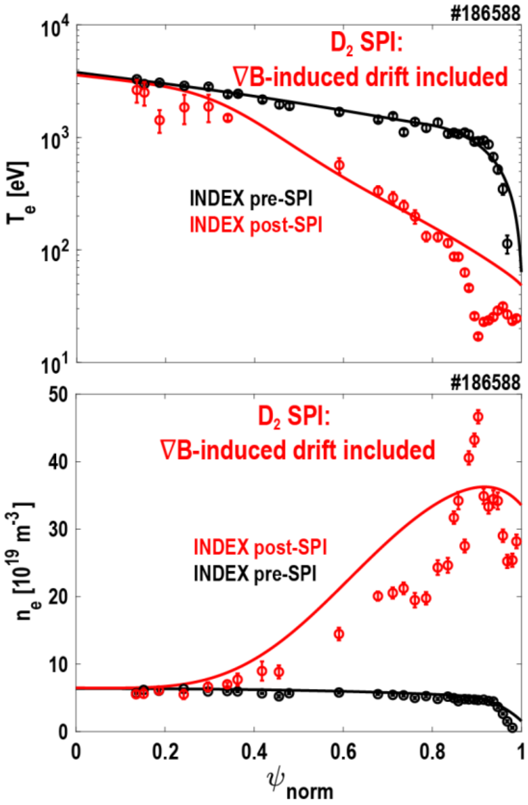
INDEX code

Comparison with experiment

How to improve penetration

Final remarks

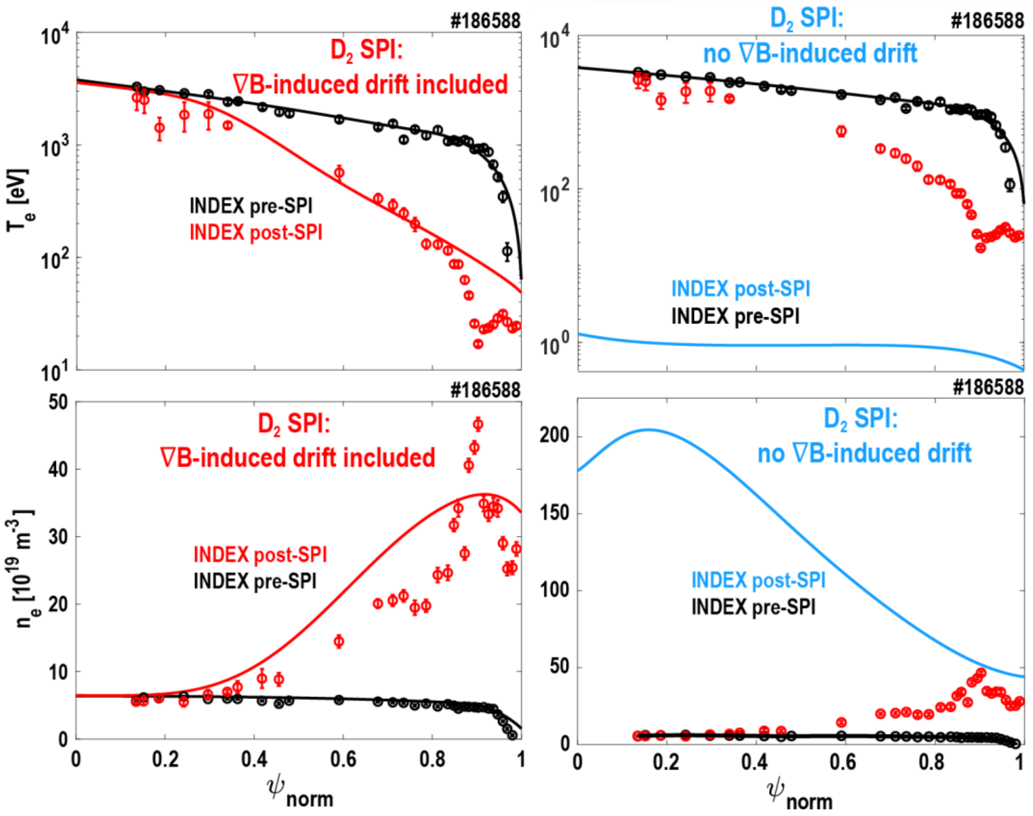
Grad-B-induced drift of ablation cloud to the edge can explain limited core fueling after D_2 SPI



- **INDEX with grad-B-induced drift (ExB drift) well reproduces the experiment with pure D_2 SPI**
- **Estimated that only 10% of injected material is assimilated**

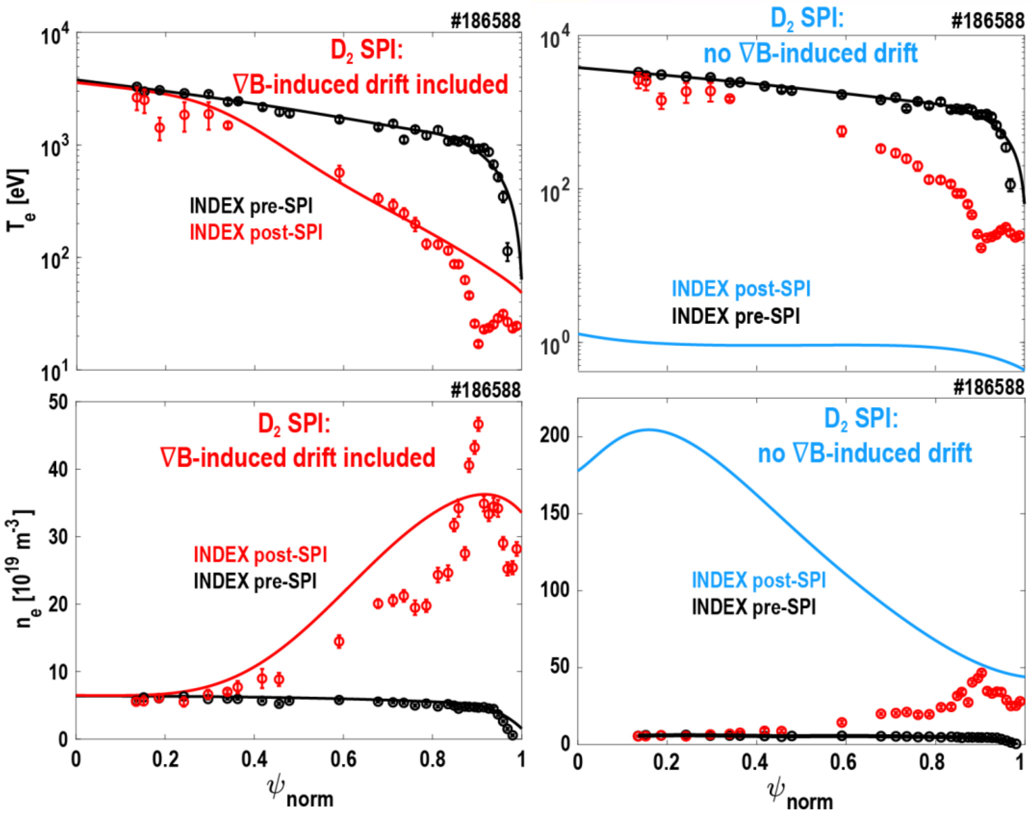
DIII-D NATIONAL FUSION FACILITY

Grad-B-induced drift of ablation cloud to the edge can explain limited core fueling after D_2 SPI



- **INDEX with grad-B-induced drift (ExB drift) well reproduces the experiment with pure D_2 SPI**
- **Estimated that only 10% of injected material is assimilated**
- **Density profile w/o drift is clearly overestimated**

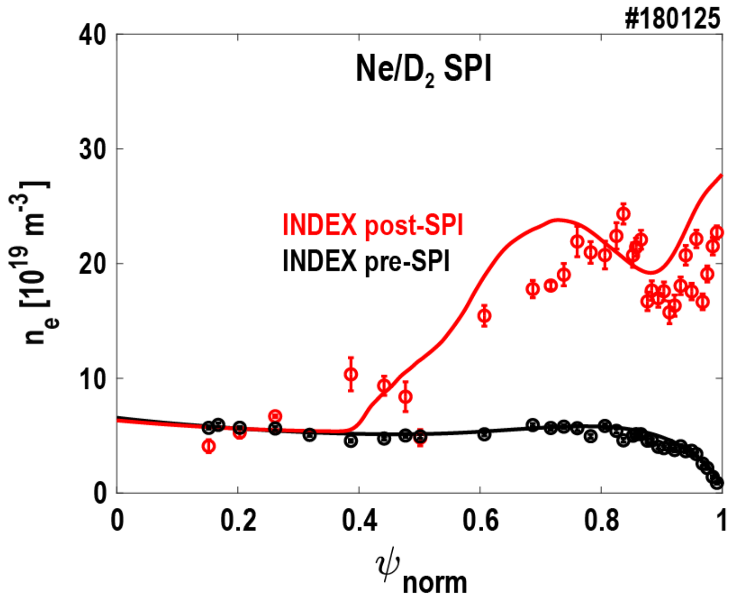
Grad-B-induced drift of ablation cloud to the edge can explain limited core fueling after D_2 SPI



- **INDEX with grad-B-induced drift (ExB drift) well reproduces the experiment with pure D_2 SPI**
- **Estimated that only 10% of injected material is assimilated**
- **Density profile w/o drift is clearly overestimated**
- **Presumably, low line radiation of D plasmoid, heating by surrounding plasma and overpressure make the drift so significant ($dV_{drift}/dt \propto \mathrm{nT}$)**

DIII-D NATIONAL FUSION FACILITY

Density profile after mixed Ne/D_2 SPI is well reproduced without grad-B-induced drift enabled



- **For comparison, no drift implication needed to reproduce the experiment with mixed Ne/D_2 SPI**
- **Though it does not simplify these simulations**
- **Increased radiative cooling may make surface-averaged ablation rate less accurate**
  - Accounted via reduced ablation[1]
- **Non-thermal electrons and pre-TQ MHD may enhance pellet ablation**
  - Accounted via increased thermal conductivity[2]

[1] Parks, TSDW 2017
[2] Hollmann et al, NF 2021

Drift of ablated material is known for fueling pellets, but experimental profiles after SPI were obtained for the first time

- **Small solid fueling pellets are known to produce plasmoids drifting in inhomogeneous magnetic field[1–7]**
- **There is a bunch of theoretical models describing such experiments[8–15]**
- **However, to our knowledge, there is no experimentally measured deposition of large perturbative SPI nor models[16*–17*] interpreting experimental profiles**
- **In this work such observations are presented for the first time and a simplified model is developed to explain and predict density profiles after pure D_2 and mixed Ne/D_2 SPI**

[1] Lang et al, PRL 1997
[2] Mueller et al, PRL 1999
[3] Baylor et al, PoP 2000
[4] Baylor et al, NF 2007
[5] Terranova et al, NF 2007
[6] Garzotti et al, NF 2010
[7] Baldzuhn et al, PPCF 2019

[8] Strauss et al, PoP 1998
[9] Strauss et al, PoP 2000
[10] Parks et al, PoP 2000
[11] Rozhansky et al, PPCF 2003
[12] Aiba et al, JPS 2004
[13] Pegourie et al, NF 2007
[14] Ishizaki et al, PPCF 2011
[15] Vallhagen et al, JPP 2023

[16*] Samulyak et al, NF 2021 (no comparison with experiment)
[17*] Kong et al, EPS 2022 (comparison with interferometer)

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

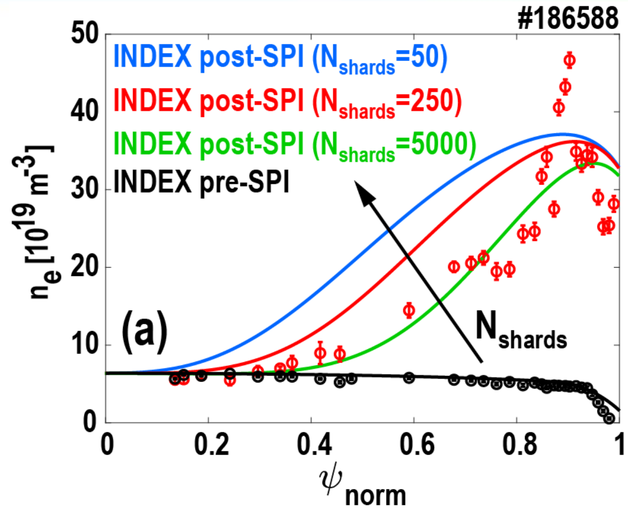
INDEX code

Comparison with experiment

How to improve penetration

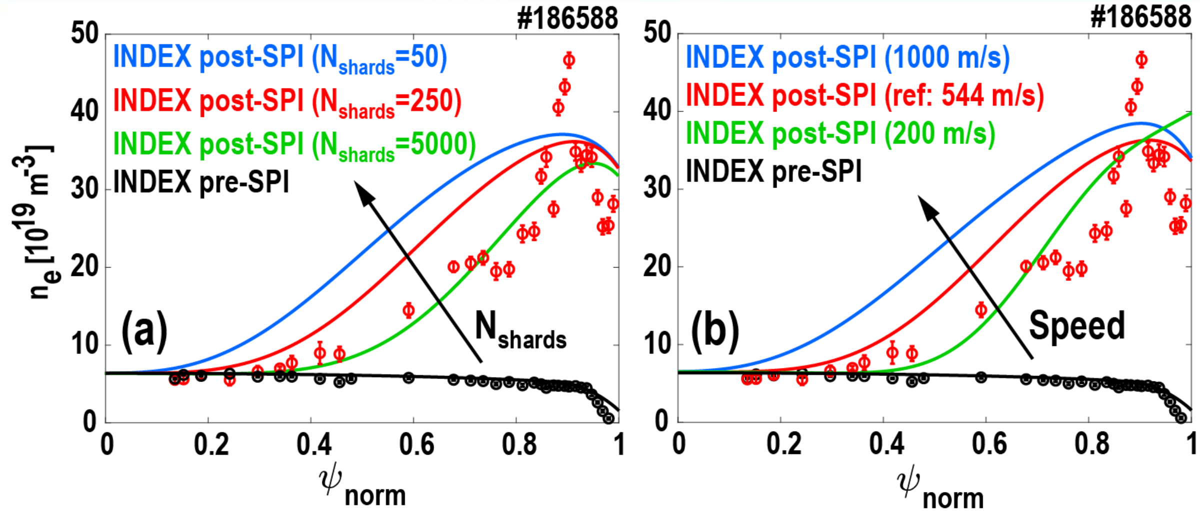
Final remarks

Modeling suggests that larger shards can improve core penetration



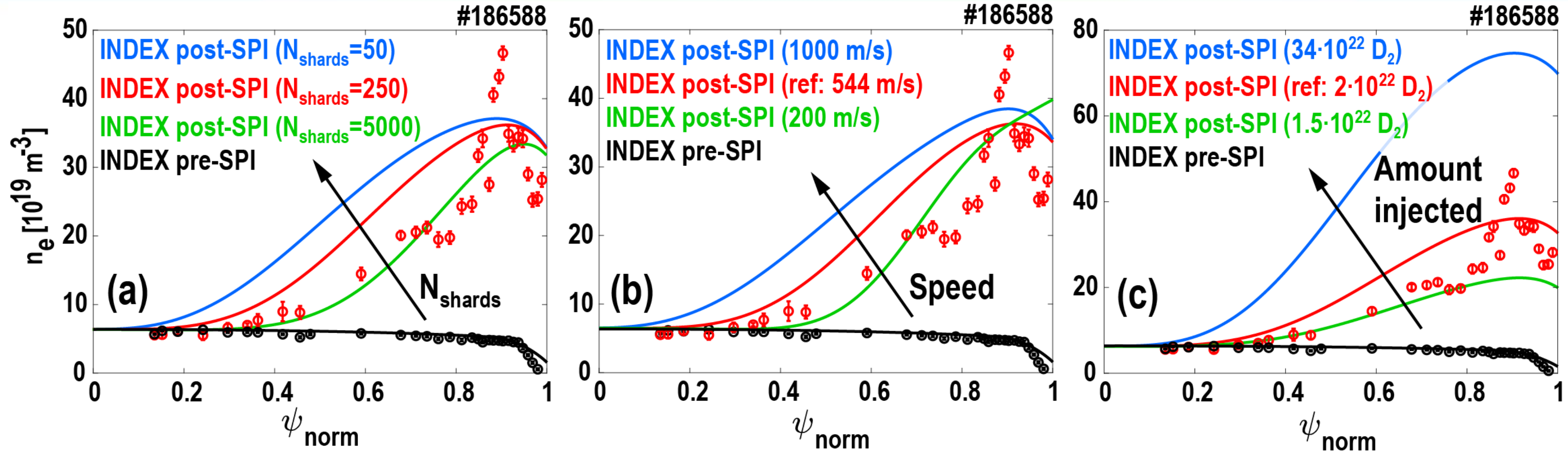
- **Increasing shard size improves D penetration into the plasma**
  - Larger shards have more time to ablate

Modeling suggests that larger shards can improve core penetration



- **Increasing shard size improves D penetration into the plasma**
  - Larger shards have more time to ablate
- **Increasing mean speed of shards also improves penetration**
  - Though in a real experiment greater pellet speed would lead to smaller shards

Modeling suggests that larger shards and greater amount injected can improve core penetration



- **Increasing shard size improves D penetration into the plasma**
  - Larger shards have more time to ablate
- **Increasing mean speed of shards also improves penetration**
  - Though in a real experiment greater pellet speed would lead to smaller shards
- **Increasing amount injected can also help with core fueling**
  - Forefront shards cool the plasma reducing ablation of following shards

Introduction

Experimental setup

Mixed Ne/D_2 SPI

Pure D_2 SPI

INDEX code

Comparison with experiment

How to improve penetration

Final remarks

Summary and conclusions

- **Staggered scheme of low-Z and high-Z SPI is expected to reduce thermal loads and provide improved RE suppression**
- **Experiments on DIII-D show favorable slow plasma cooling after D_2 SPI but poor assimilation of D_2 by core plasma even during and after TQ**
- **1D modeling suggests grad-B-induced drift of deuterium ablation cloud towards the edge caused by low line radiation and heating**
- **Larger pellet shards and greater amount injected are predicted to improve core fueling**
- **Optimization of H_2 SPI in ITER is necessary**

Paper is to be submitted to Nuclear Fusion

Future work

- **Experimentally verify predictions of 1D model (very recent study on DIII-D, yet to be analyzed)**
- **Develop mature model based on first principles**
- **Improve model to:**
  - **include simulations of Ne-doped D_2 SPI**
  - **separate effects of grad-B-induced drift, non-thermal electrons, pre-TQ MHD for mixed Ne/D_2 SPI**
  - **study whole post-SPI dynamics and estimate total material assimilation**

Acknowledgments and Disclaimer

- This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences, using the DIII-D National Fusion Facility, a DOE Office of Science user facility, under Award DE-FC02-04ER54698 and Service Contract IO/19/CT/4300001939.

Backup

Assumptions used in the modeling

Back-averaged density increase caused by single shards:

$$\Delta n_{dep} = \Delta N / [(1+\beta) V_p(1) - V_p(\rho')]$$

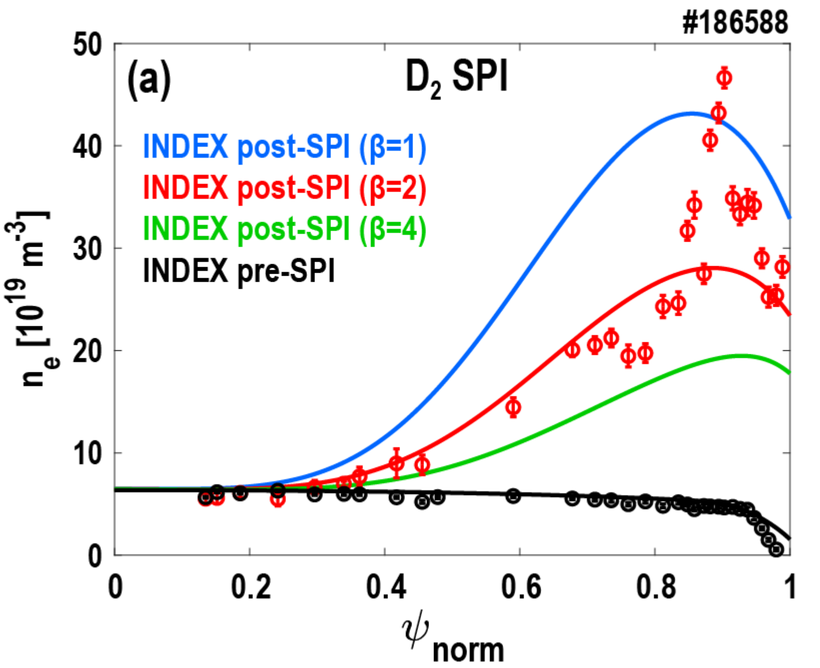
number of atoms ablated from the shard (ΔN)

extent of the radial drift (β)

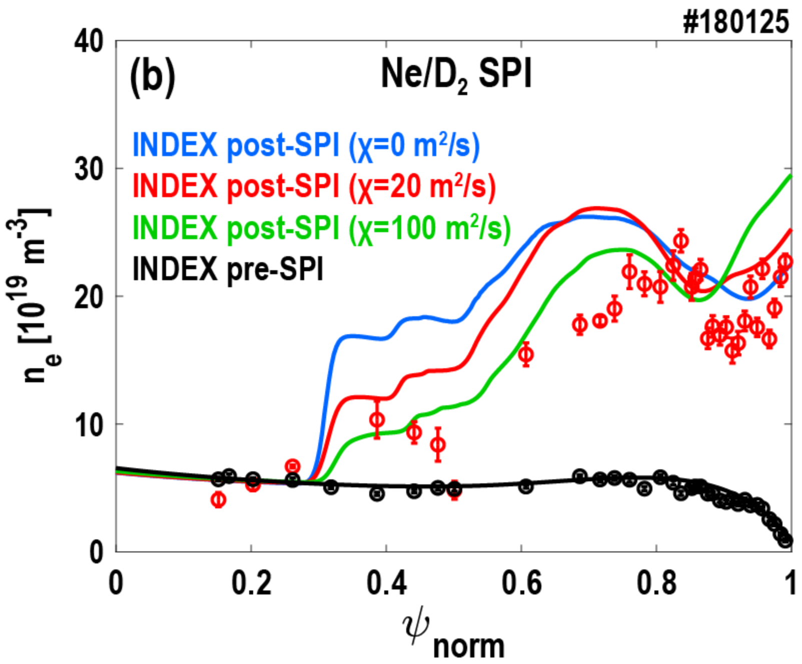
interior plasma volume with $\rho < \rho'$ ($V_p(\rho')$)

- Shard size distribution is based on the fragmentation model [Parks GA Rep. 2016, Hu NF 2018] with the number of shards chosen based on sensitivity studies
- The average speed is assumed to be 90−100% of the pre-shattered speed, including a small loss of the forward momentum
- The speed dispersion is estimated from the laboratory tests [Gebhart FST 2021] and taken as 50% with the mass dependence of the shard speed included so that only small shards are distributed in the front and rear of the plume
- The fraction of the pellet turned into gas during the shattering process is 30% with only 1/3 of this reaching the plasma, while the remaining 2/3 are subtracted from the injected mass as loss

Appendix

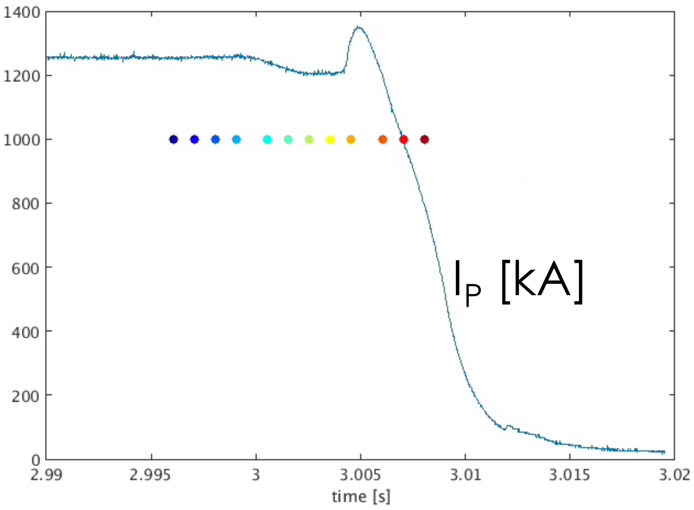


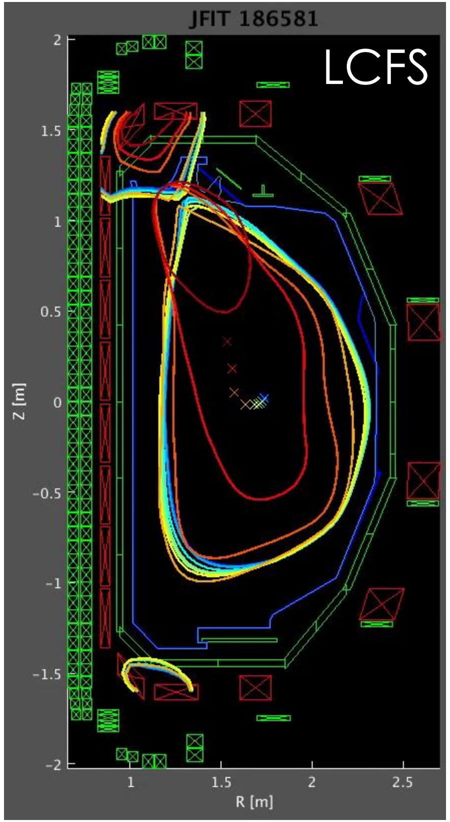
Scan of factor β, assuming that 50% of injected mass does not interact with plasma

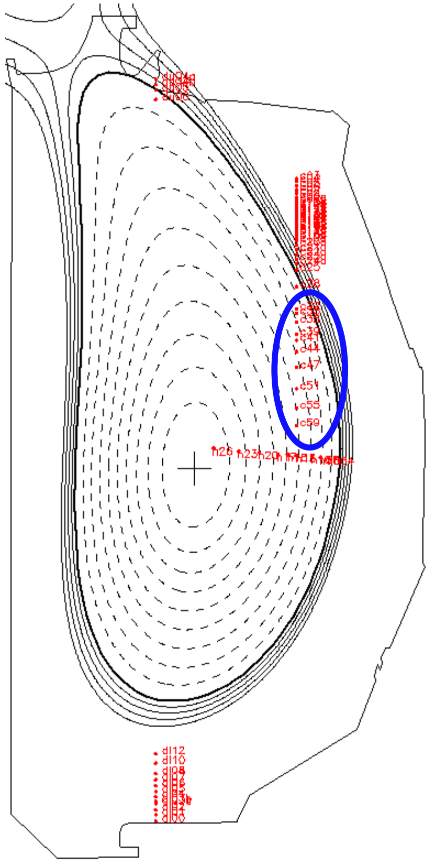


Scan of thermal transport coefficient χ

Plasma shrinks during CQ which limits Thomson measurements in the core







DIII-D NATIONAL FUSION FACILITY