Contributed poster

Strategy of disruption mitigation using multiple injection of shattered pellets in KSTAR

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Abstract

ITER adopts massive particle injection using shattered pellet injection (SPI) as a basic mitigation method to mitigate three major risk factors that can occur in the process of plasma disruption: heat load, electro-magnetic load, and runaway electrons. The injected particles composed of a combination of hydrogen and neon increase the density of plasma through the assimilation process to prevent runaway electrons and emit stored energy in the form of radiant energy. A safe and effective disruption mitigation strategy in the ITER disruption mitigation system (DMS) capable of injecting a total of 27 pellets depends on which combination of pellets are injected at what time. Among these strategies, the most basic issue is whether to sequentially or simultaneously inject hydrogen, which increases density, and neon, which emits energy. On the other hand, plasma dilution-cooled by hydrogen becomes plasma with completely different characteristics from typical tokamak plasma due to its high density and low temperature. The pellet assimilation in the dilution-cooled plasma and the radiation of stored energy may be different from those of typical tokamak plasma. However, experiments on dilution-cooled plasma have not been sufficiently conducted. KSTAR with two SPIs that form a symmetry in the toroidal direction can independently inject three different pellets for each SPI. KSTAR has conducted experiments to test the disruption mitigation strategy of ITER using multiple SPIs and diagnostics capable of diagnosing the plasma disruption process.

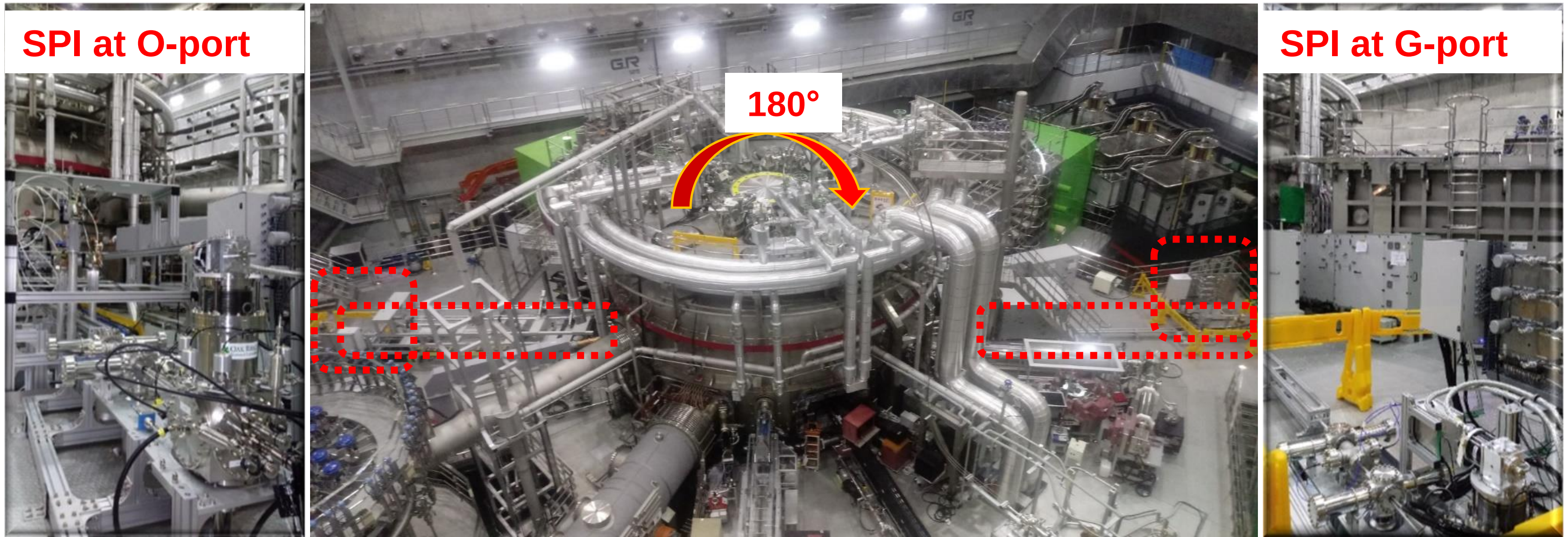
KSTAR disruption research aims to respond to the ITER research plan.

Ref.	System / Issue	Required R&D	Required experimental facilities
A.1	SPI-single injector. Pellet injection optimization for RE avoidance (incl. TQ and CQ mitigation)	Optimization of shard size, velocity, amount, gas vs. shard fraction, composition (D + impurity) to achieve RE avoidance with optimum TQ, CQ (incl. wall loads)	With different sizes and plasma parameters (including high I_p tokamak) With appropriate measurement capabilities
A.2	SPI-single injector demonstration for runaway mitigation	Determination of feasibility to dissipate the energy of formed runaway beams (amount, assimilation) and to improve scheme	With different sizes and plasma parameters With appropriate measurement capabilities
A.3	SPI-multiple injections	Determination of effectiveness of multiple injections to achieve RE avoidance with optimum TQ, CQ (incl. wall loads) compared to single injections (incl. timing requirements)	With at least two injectors from the same/similar locations (toroidal separation not required) With appropriate measurement capabilities
A.4	SPI-multiple injections	Determination of effectiveness of multiple injection from different spatial locations to achieve RE avoidance with optimum TQ, CQ (incl. wall loads)	With at least two injectors (toroidally well separated) With appropriate measurement capabilities
A.5	Alternative injections techniques	Demonstration of the feasibility of the technique to inject material in a tokamak and comparison of mitigation efficiency with SPI	Single tokamak demonstration with appropriate measurement capabilities
A.6	Alternative disruption mitigation strategies	Exploration of disruption mitigation by schemes other than massive injection of D_2 and high Z impurities	Single tokamak demonstration with appropriate measurement capabilities

Two identical SPIs are operated in toroidally opposite locations of KSTAR for symmetric multi-injection (funded/supported by IO and USDOE/ORNL).

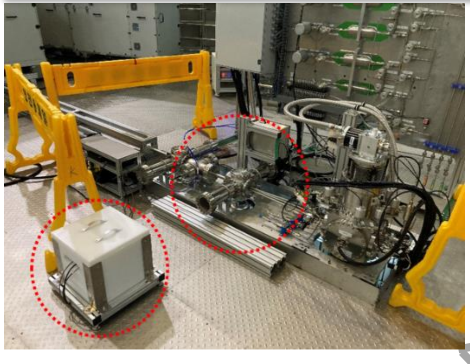
- Low Z (D_2), high Z (Ne, ~~Ar~~), and their mixture can be injected selectively.
- Barrel configuration in each year (shallow 12.5 degree shattering tube from 2022)
  - 4.5, 7.0, 8.5 mm (2019) → 4.5, 2 x 7.0 mm (2020) → 2 x 4.5, 7.0 mm (2021) → 4.5, 2 x 7.0 mm (2022)

  - Typical KSTAR target: plasma volume ~12.9 m^3, stored energy ~0.5 MJ thermal, plasma current ~0.8 MA
  - 4.5 mm: D# =6.47×10^{21}, Ne# =3.83×10^{21} + (D# of shell 1.10×10^{21})
  - 7.0 mm: D# =2.43×10^{22}, Ne# =1.54×10^{22} + (D# of shell 2.70×10^{21})
  - ~~8.5 mm: D# =4.36×10^{22}, Ne# =2.82×10^{22} + (D# of shell 4.00×10^{21})~~ ← Replaced with 7.0 mm

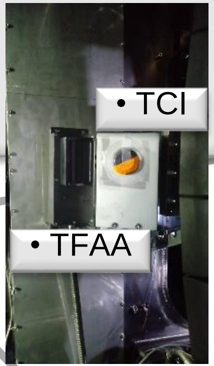


Almost all the planned diagnostics for studying disruption mitigation are operational.

- Optical pellet diagnostics (before shattering)

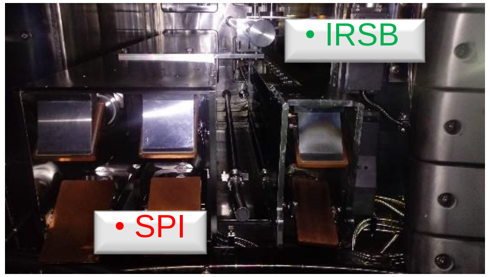


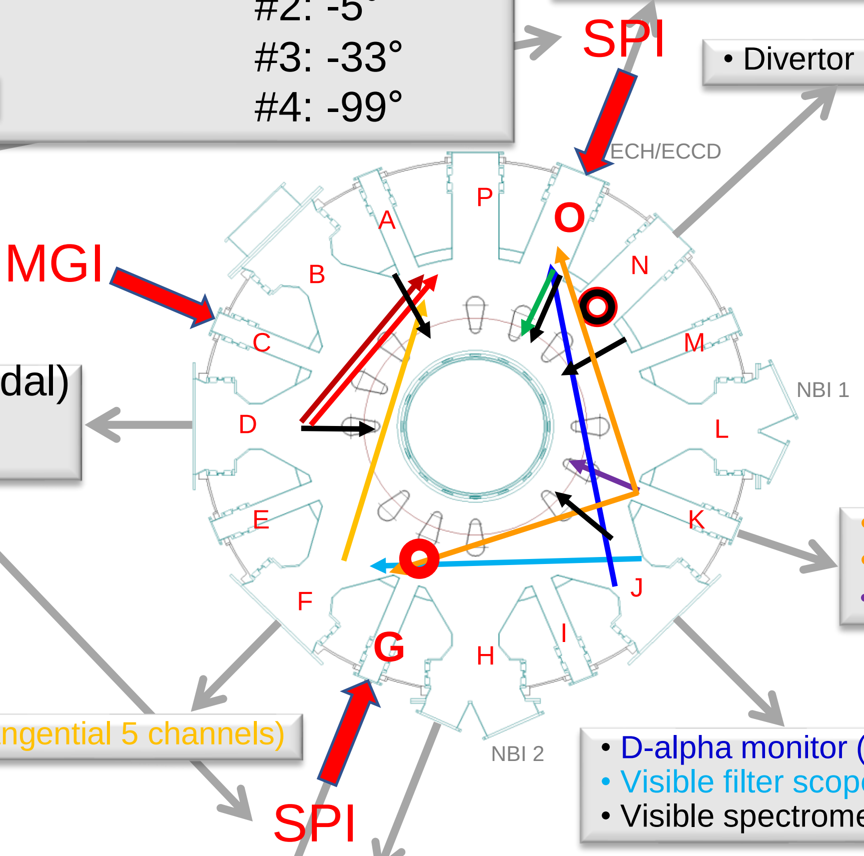
Toroidal AXUV arrays from O-port SPI
#1: -307 °
#2: -5°
#3: -33°
#4: -99°



- Filtered AXUV (poloidal and toroidal)
- IR sensor bolometer

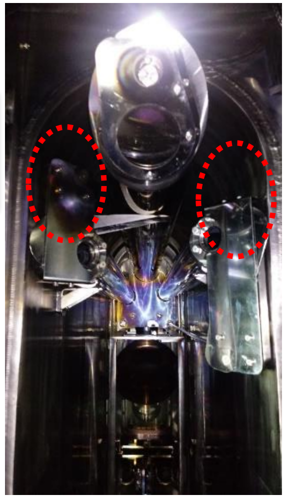
- Divertor IR TV (vertical, 0.25 Mpx@1 kfps)





- Filtered AXUV (poloidal)
- Tangential IR TV (100 Hz)
- Imaging bolometer (100 Hz)

- CCD1 for O-port (10 kfps)
- CCD2 for G-port (10 kfps)
- ECE radiometer



- Two-color interferometer (tangential 5 channels)

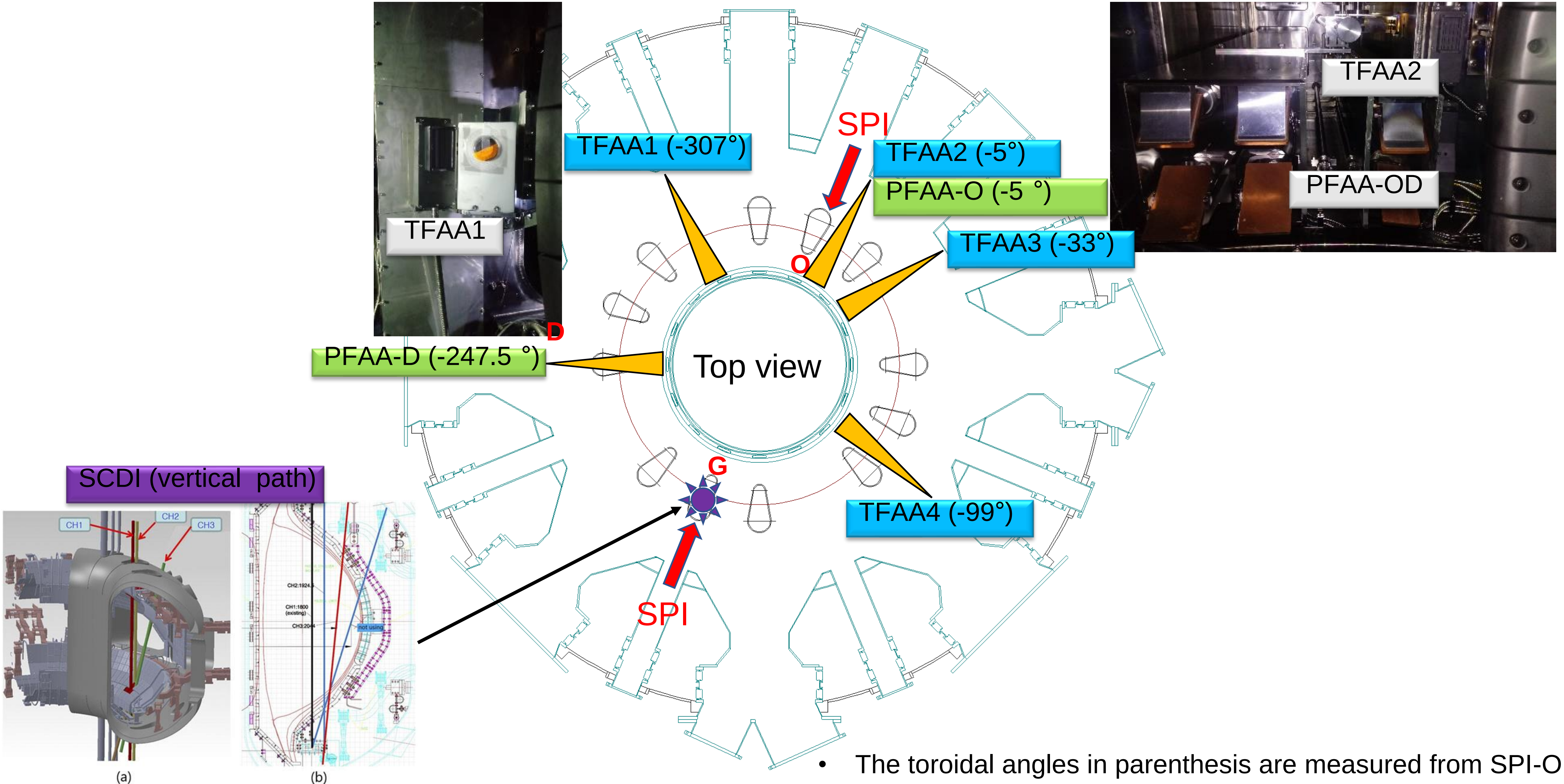
- D-alpha monitor (Ne, Ar, He filter)
- Visible filter scope (Ne, Ar, He filter)
- Visible spectrometer

- ECEI 1 (500 kHz)

- 1064 nm dispersion interferometer (vertical 3 channels)
- ECEI 2 (500 kHz)

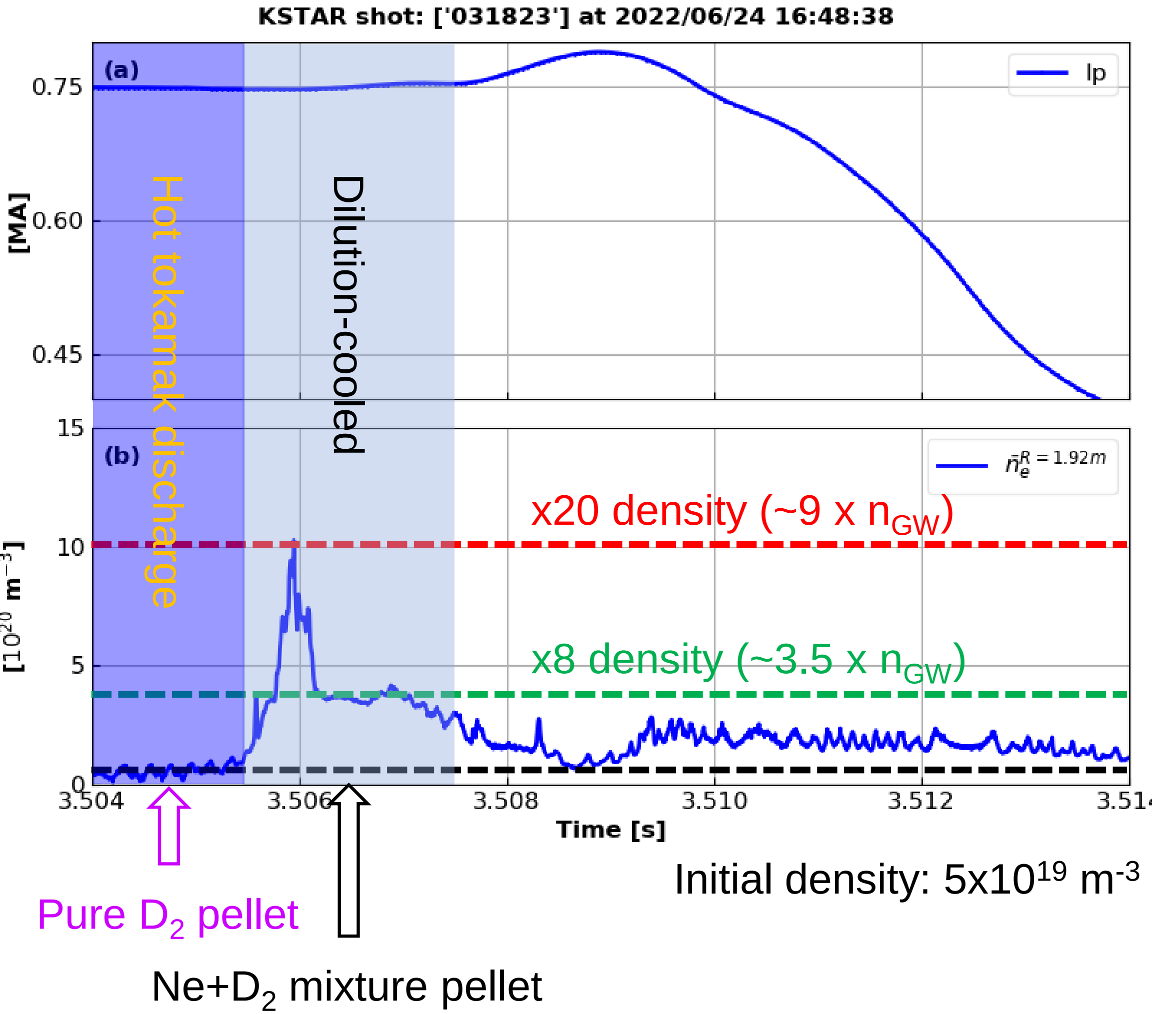
- Hard X-ray monitor
- Neutron detector

Especially, radiation asymmetry measurements are fully working.



- The toroidal angles in parenthesis are measured from SPI-O.

Low Z D_2 injection to avoid REs, and high Z neon injection to radiate stored energy
How to inject them? Simultaneously or sequentially?



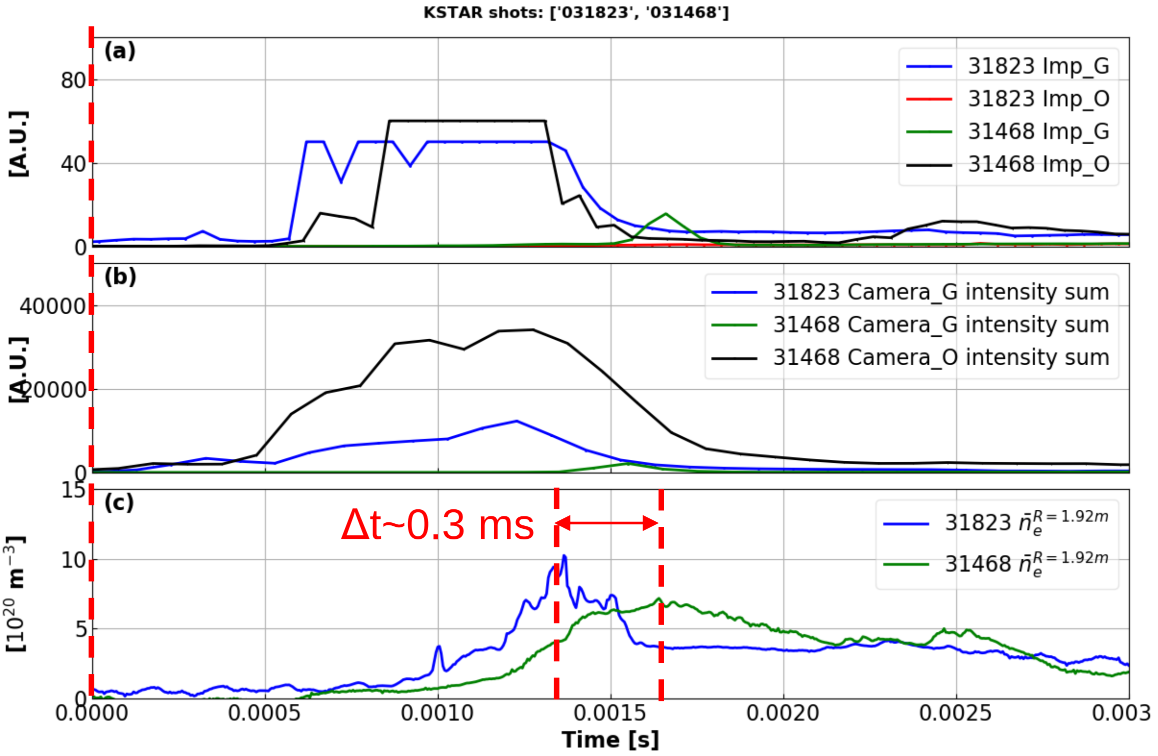
- Injection schemes using multiple barrels
  - Simultaneous injection:
    - Ne+D_2 mixture pellet (e.g., Ne:D = 10:90)
  - Staggered injection:
    - Pure D_2 pellet followed by Ne+D_2 mixture pellet
- However, pure D_2 pellet creates a totally different target.
  - So called, dilution-cooled discharge
  - ~One order higher n_e and ~one order lower T_e
    - Several times of Greenwald density limit
  - The effect of following Ne+D_2 mixture pellet can be different.
    - Amount of assimilation
    - Total radiated power and radiation asymmetry

For the staggered injection experiments, the toroidal asymmetry of the dilution-cooled discharge by pure D_2 was first investigated.

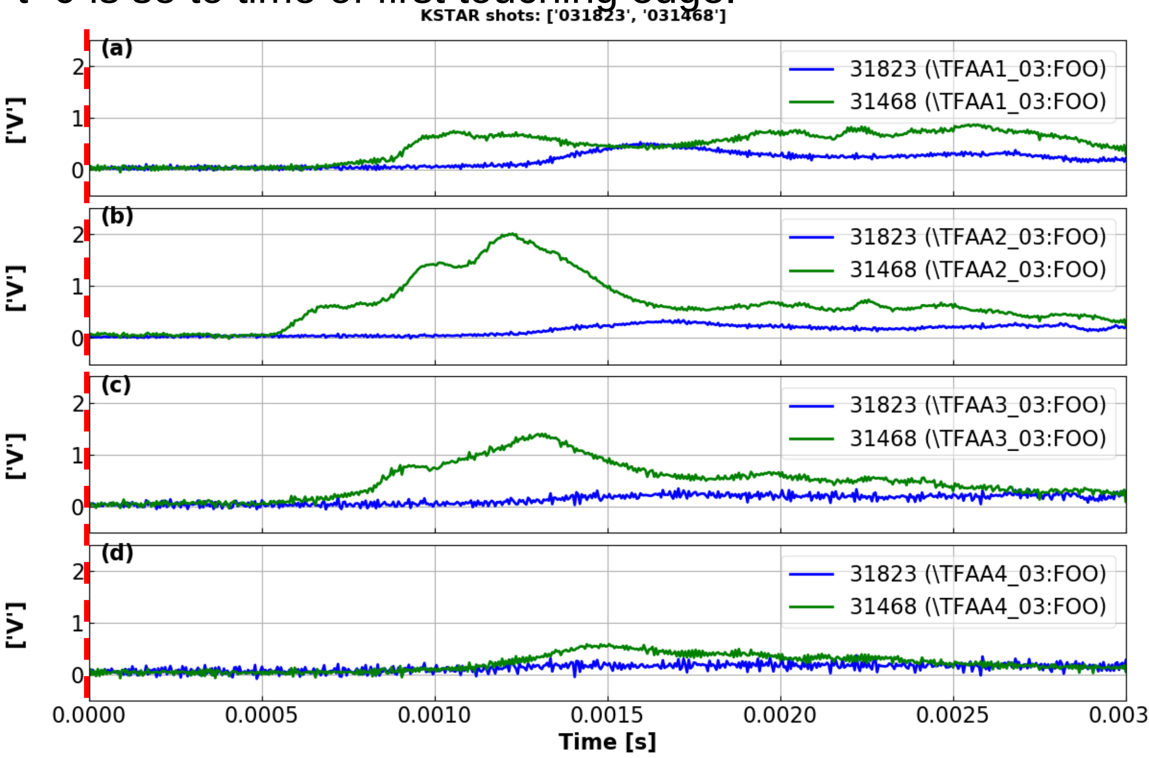
- The density increased by pure D_2 injection at a point 180 degrees away reached its peak in less than 0.5 ms delay.
  - The density behavior showed a stable shape that changed relatively slowly compared to the point of injection.
- Similarly, the radiation peak reached its peak at the opposite point in less than 0.5 ms delay.
- Since we need to compare the bolometer and interferometer 180 degrees apart at the same time, we need to know the time difference according to the location.

- SPI-G: pure D_2 7.0 mm (#31823) at the interferometer
- SPI-O: pure D_2 7.0 mm (#31468) at the bolometer

t=0 is se to time of first touching edge.

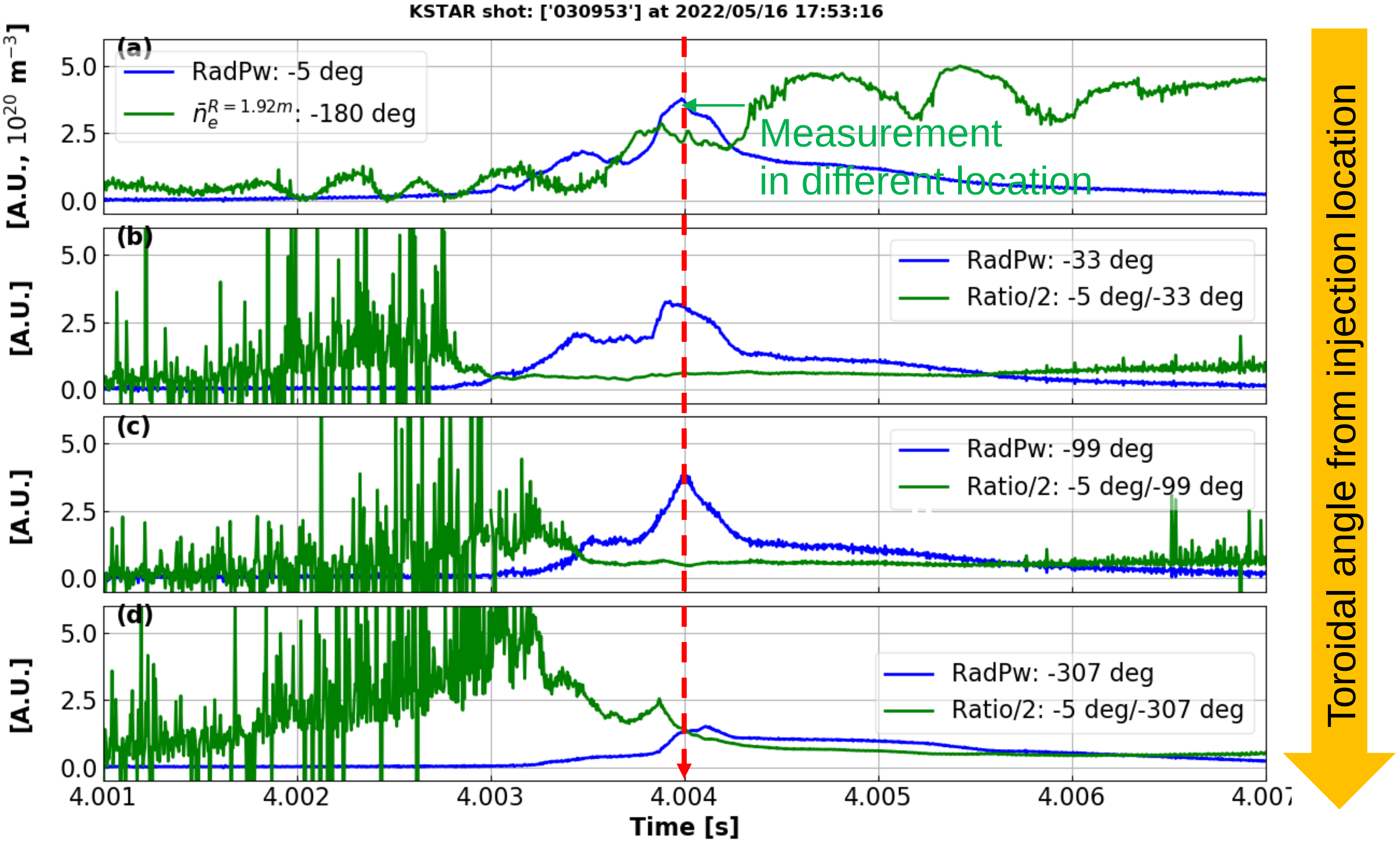


t=0 is se to time of first touching edge.



Single Ne-doped pellet (Ne#:D# = 10:90) increased density and radiated energy simultaneously.

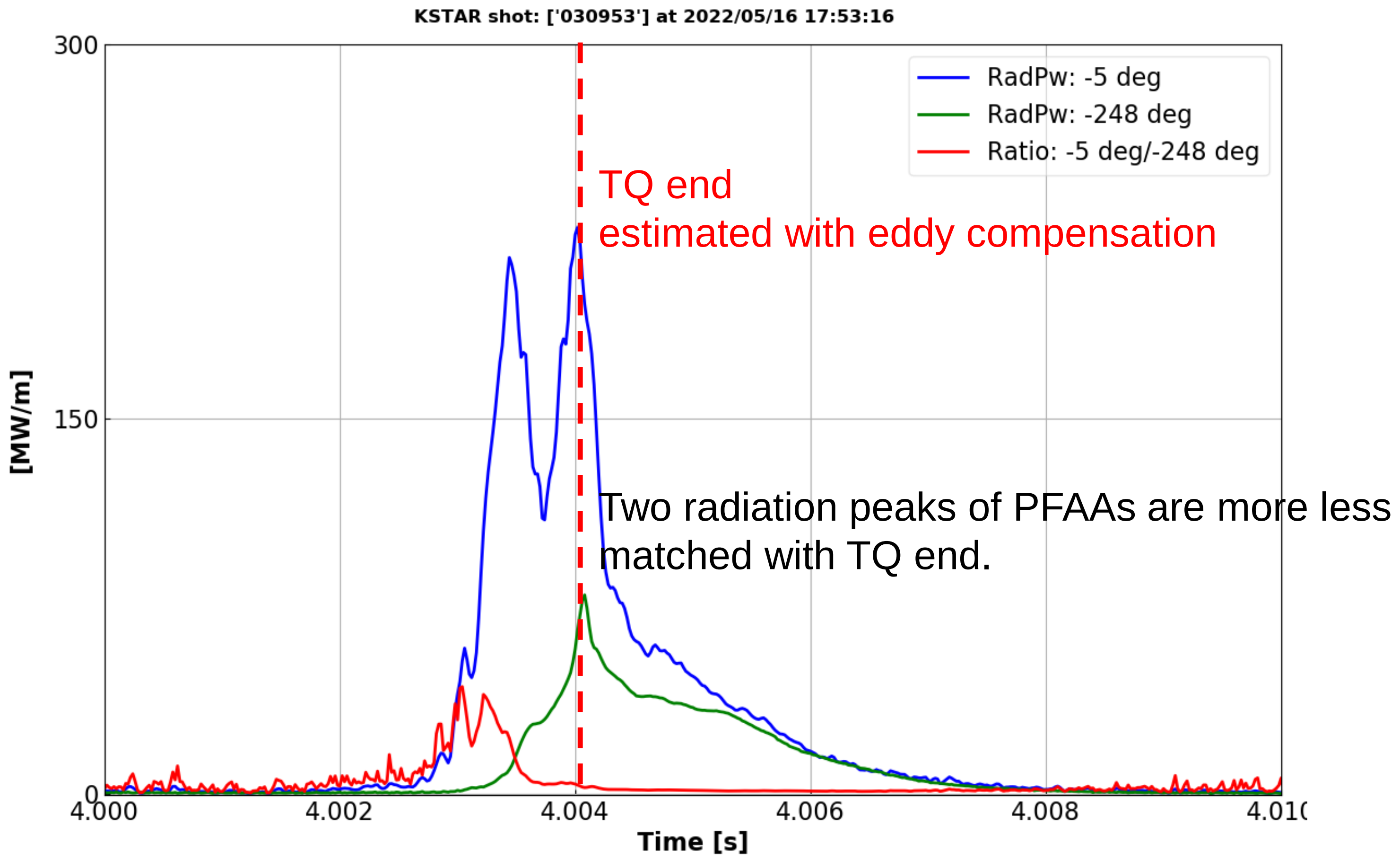
- Considering the time delay due to the difference in the position of dispersion interferometer and AXUV bolometer, the density and radiation seem to rise almost simultaneously at the point of injection.
- The radiation ratio between the injection point and the point 90 degrees away from the injection point is not as quite large as ~2 when the radiation at the injection point is peak.

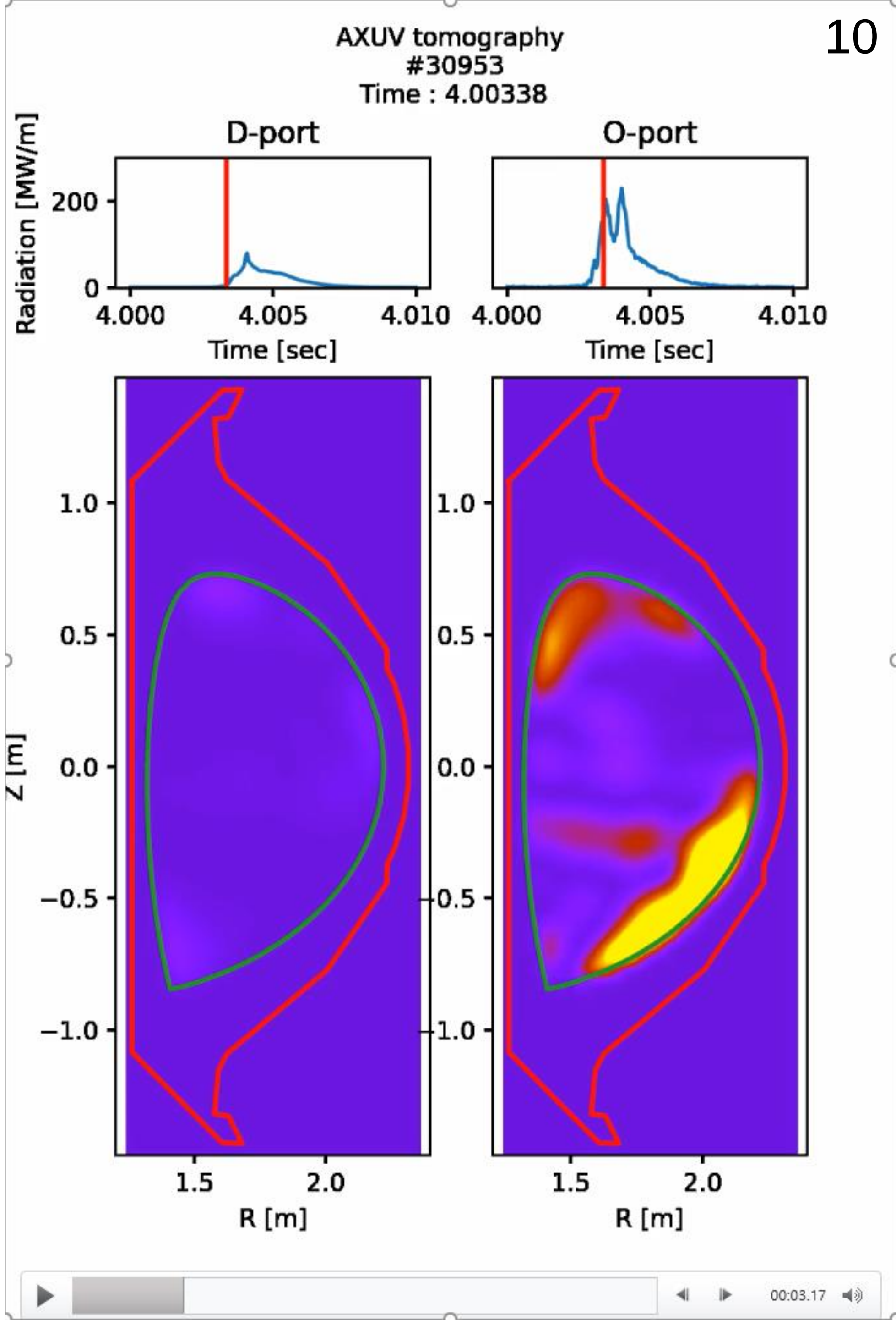


- SPI-O: 10% Ne-doped 7.0 mm pellet
  - Ne-doped pellet meets $\bar{n}_e = 5 * 10^{19}\ m^{-3}$
  - and several keV of T_e
- Small time delays (~0.1 ms) of radiation peak among different toroidal locations (red dashed line)
- Red dashed line is more less matched with estimated thermal quench (TQ) end using eddy-compensated I_p spike.
  - The peak is delayed by eddy current.
  - Actual Ip spike is typically 0.7~0.8 ms ahead from eddy-contained I_p spike.

Radiation on poloidal cross-section in single Ne-doped pellet from SPI-O

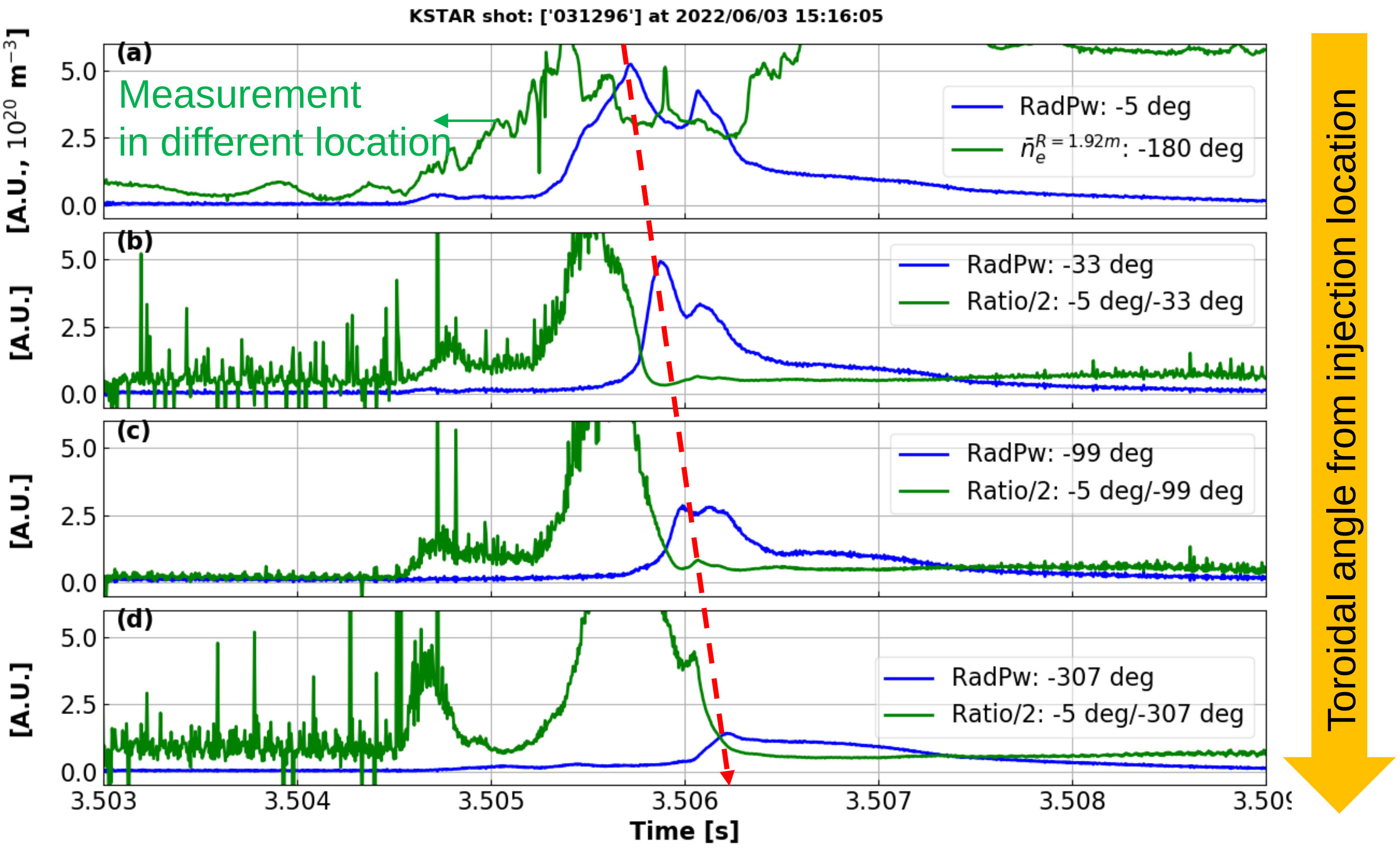
- As expected, single Ne-doped pellet shows initial strong radiation from outer lower region of O-port near SPI-O.
  - Note that KSTAR SPI has an up-looking bent tube at outer lower region with aiming plasma core.





In staggered injection, Ne-doped pellet meets very dense and cold plasmas already created by preceding pure D_2 pellet.

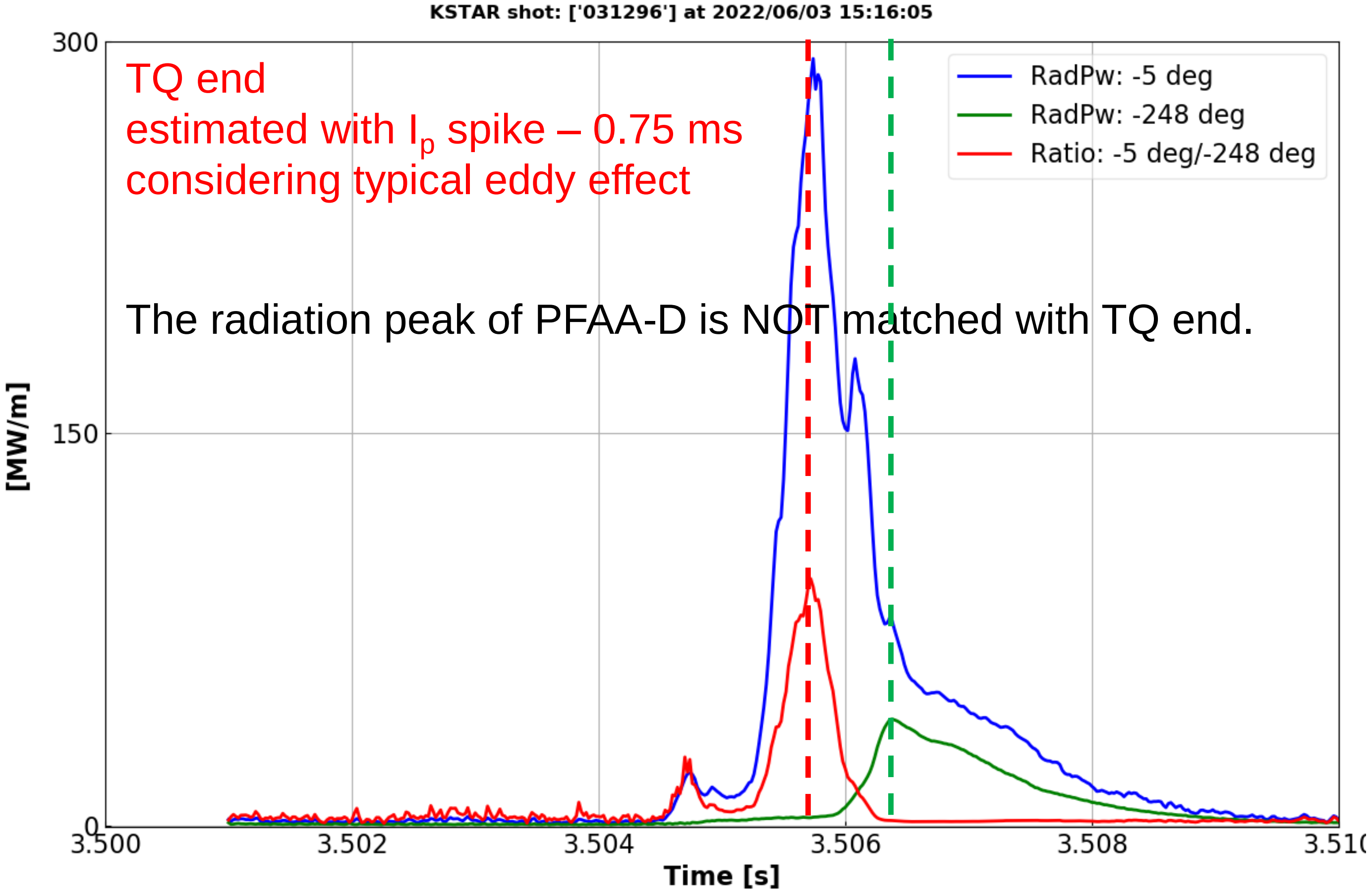
- Considering the time delay due to the difference in the position of dispersion interferometer and bolometer, the density seems to be fully build up and maintained at the injection timing of Ne-doped pellet.
- The radiation ratio between the injection point and the point 90 degrees away from the injection point is as quite huge as ~7 when the radiation at the injection point is peak.

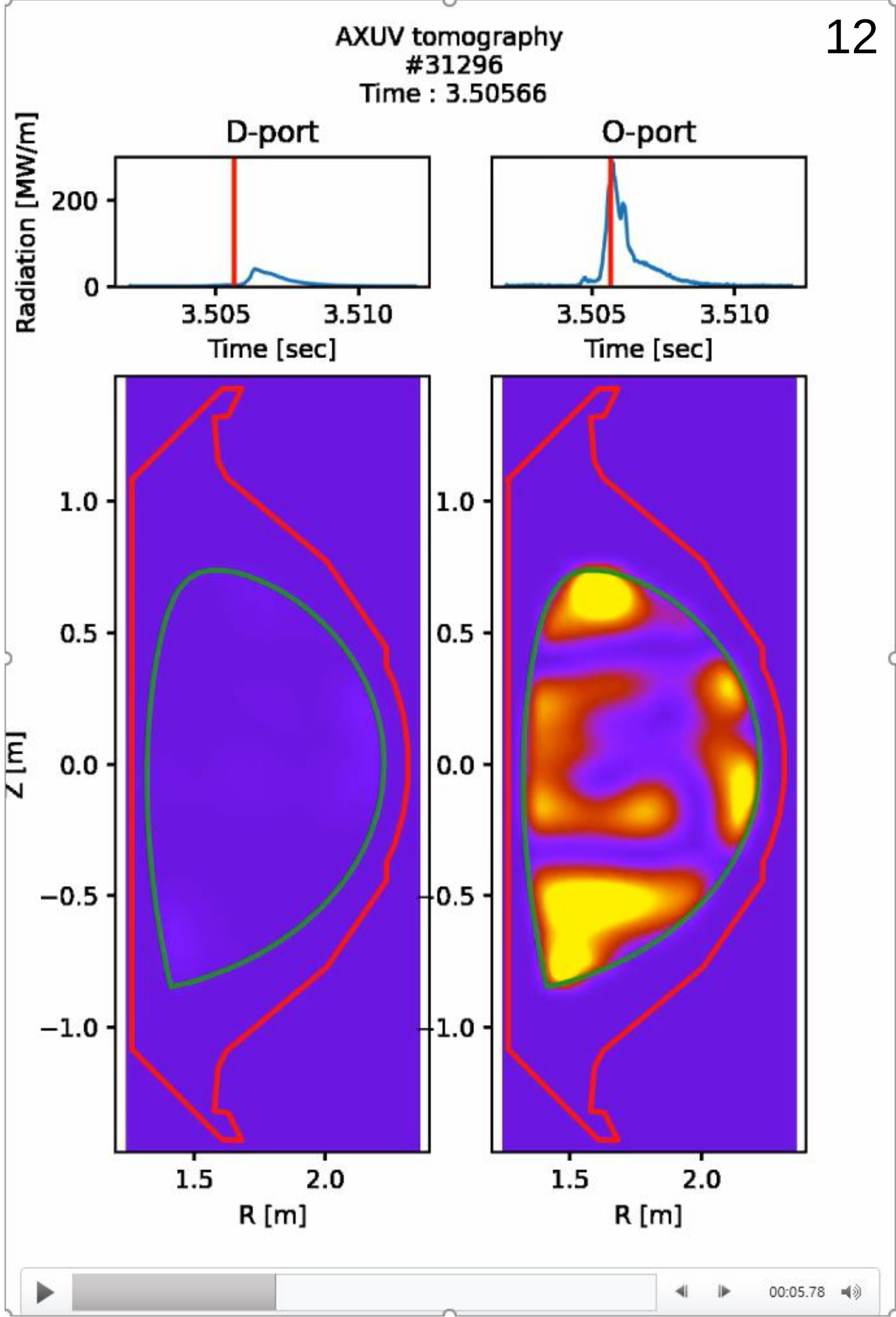


- SPI-G: pure D_2 7.0 mm pellet
  ~1 ms delay
- SPI-O: 10% Ne-doped 7.0 mm pellet
  - Ne-doped pellet meets $\bar{n}_e = 3 * 10^{20}\ m^{-3}$
  - and several hundreds eV of T_e
- Time delays (~0.5 ms) of radiation peak among different toroidal locations
- Estimated TQ end is more less matched with the peak of radiation at the injection point of Ne-doped pellet.

Radiation on poloidal cross-section in staggered injection: D_2 from SPI-G, Ne from SPI-O

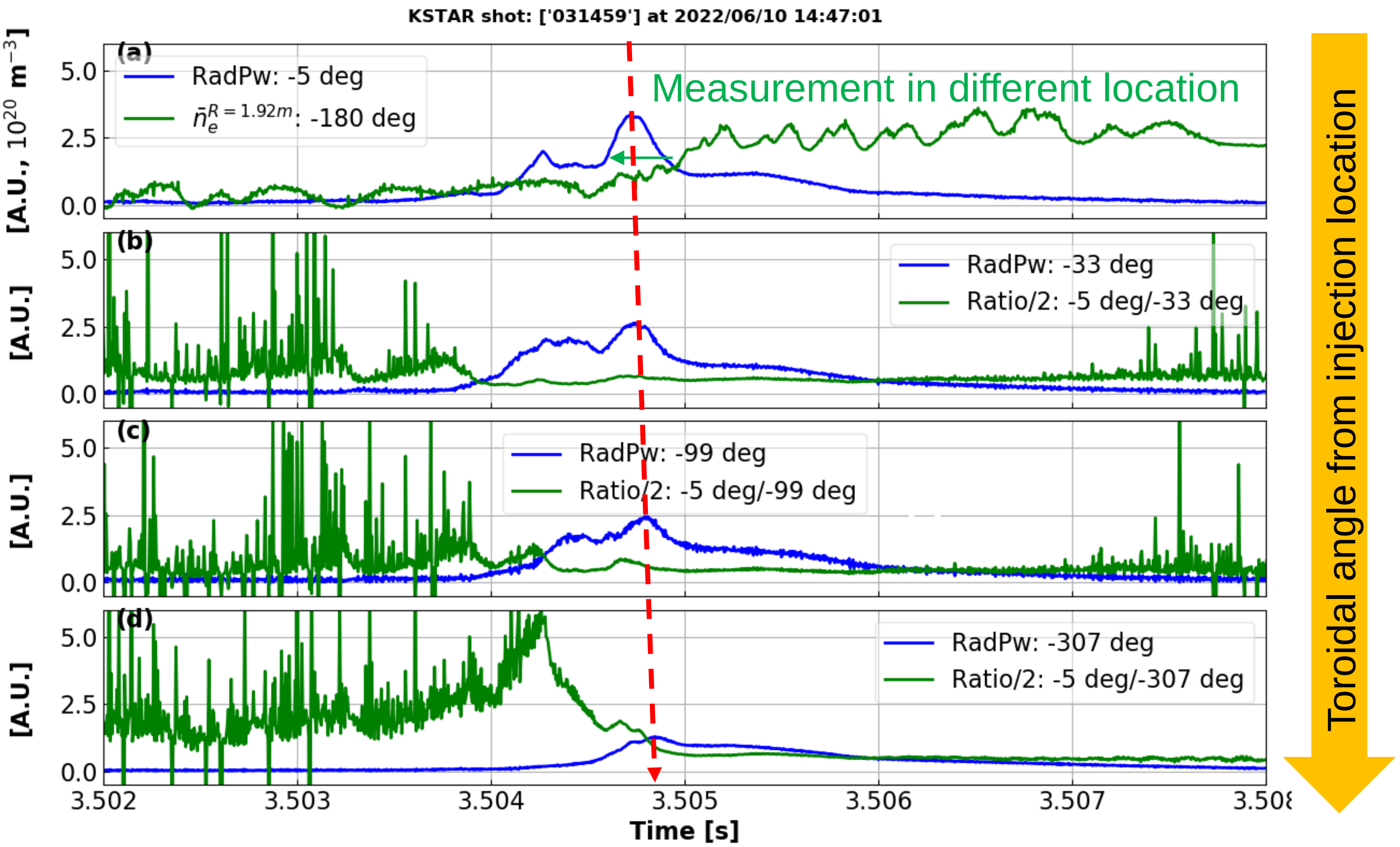
- In staggered injection, initial radiation pattern on poloidal cross-section of O-port is NOT quite localized near injection location.





Single Ne-doped pellet with high Ne fraction (Ne#:D# = 85:15) shows similar radiation asymmetry with single 10% Ne-doped pellet.

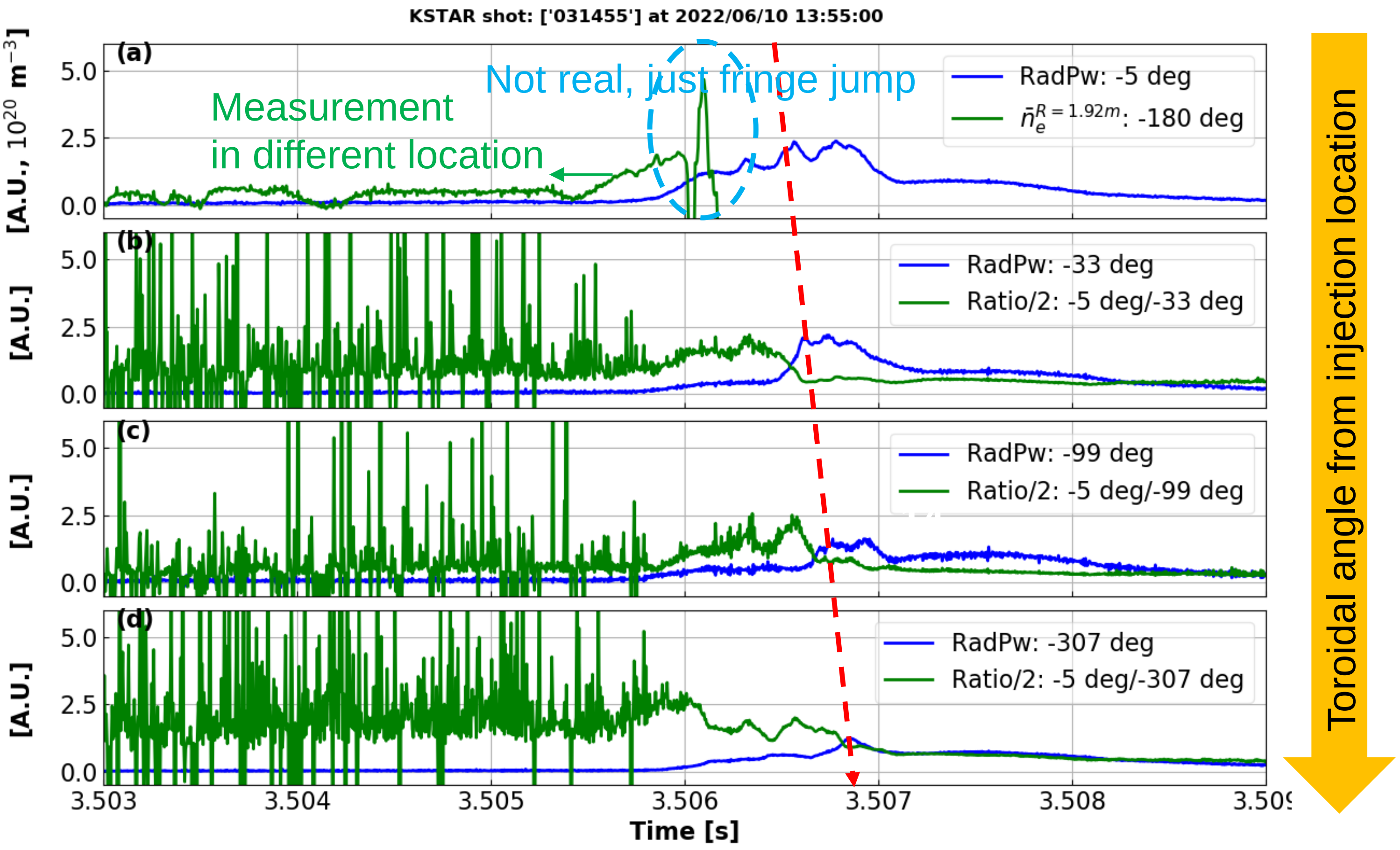
- The radiation ratio between the injection point and the point 90 degrees away from the injection point is not as quite large as ~1.7 when the radiation at the injection point is peak.
- So far, any meaningful radiation asymmetry due to Ne fraction was not observed but it needs to be re-tested with intact pellet.



- SPI-O: 85% Ne-doped 7.0 mm pellet
  - Ne-doped pellet meets $\bar{n}_e = 5 * 10^{19}\ m^{-3}$
  - and several keV of T_e
- The pellet was broken into 2 pieces during firing, although the separation is only Δt=0.23 ms.
- Small time delays (~0.2 ms) of radiation peak among different toroidal locations
- Again, estimated TQ end is more less matched with the peak of radiation at the injection point of Ne-doped pellet.

Staggered injection of high Ne fraction pellet (Ne#:D# = 85:15) shows also high radiation asymmetry.

- The radiation ratio between the injection point and the point 90 degrees away from the injection point is as quite huge as ~5 when the radiation at the injection point is peak.
- Although the density is slightly uncertain due to the fringe jump of dispersion interferometer, it is certain that the following Ne-doped pellet will encounter very dense and cold plasmas.



- SPI-G: pure D_2 7.0 mm pellet
  ~1 ms delay
- SPI-O: 85% Ne-doped 7.0 mm pellet
  - Ne-doped pellet meets $\bar{n}_e \sim 10^{20}\ m^{-3}$
  - and several hundreds eV of T_e

- Time delays (~0.4 ms) of radiation peak among different toroidal locations

KSTAR

Summary

- In order to verify the effectiveness of staggered injection of multiple pellets, a series of experiments using dual multi-barrel SPIs of KSTAR have been being performed.
- By staggered injection, it was possible to form a high density several times Greenwald density at the injection time of Ne-doped pellet, which mainly causes radiative dissipation of stored energy.
- However, high-density dilution-cooled plasma formed by the preceding D_2 pellet showed a tendency to toroidally localize the radiation by the following Ne-doped pellet.
    - It seems that the parallel transport is very limited in the dilution-cooled plasmas.
- On the other hand, in the poloidal cross-section of injection location, radiation is observed in a non-localized pattern compared to the single Ne-doped pellet.
    - The nested flux surfaces might already become stochastic by the preceding D_2 pellet.
- Even if it is not the intended staggered injection, staggered injection can occur due to several factors in multi-pellet injection. It may be necessary to examine the effect of this case further.

Acknowledgements

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- Especially, this work was done in collaboration with the ITER DMS Task Force and also funded by the ITER Organization under contracts IO/CT/43-1830, IO/CT/43-1909, IO/CT/43-1918, and IO/CT/43-2034.

- US DOE also supported this work under DE-SC0020299 and DE-AC05-00OR22725.

Just back-up slides from here.

ITER needs simultaneous and/or sequential multi-injection of SPIs for fulfilling the requirements (especially for runaway electron avoidance).

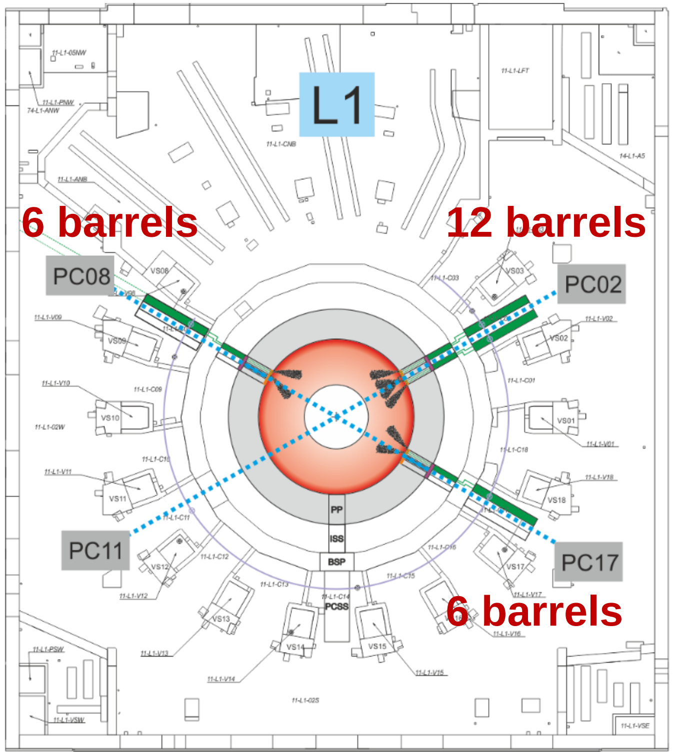
- Raising the density is presently the strategy for runaway electron avoidance in ITER.
  - The predicted injection quantities require multiple pellet injection.
- The stored energy should be dissipated while avoiding melting of plasma facing components.
  - Heat loads from the radiation flash have to be minimized through multiple injection locations.
- The ITER Disruption Mitigation System has significant injection capabilities.
  - 24 pellets in equatorial ports and 3 pellets in upper ports

Equatorial ports

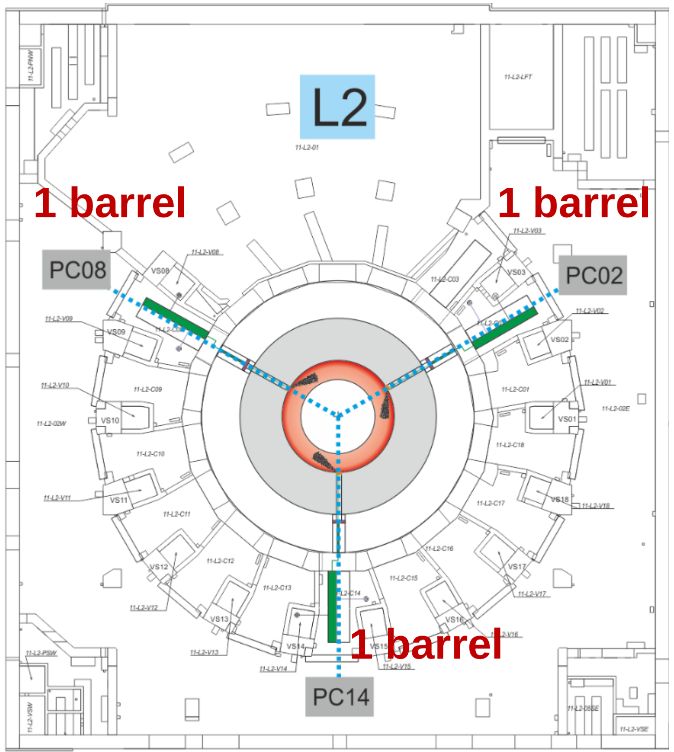
28.5 mm pellets for

- TQ heat load mitigation
- CQ heat load mitigation
- CQ EM load mitigation
- RE avoidance
- RE energy dissipation

Equatorial level



Upper level



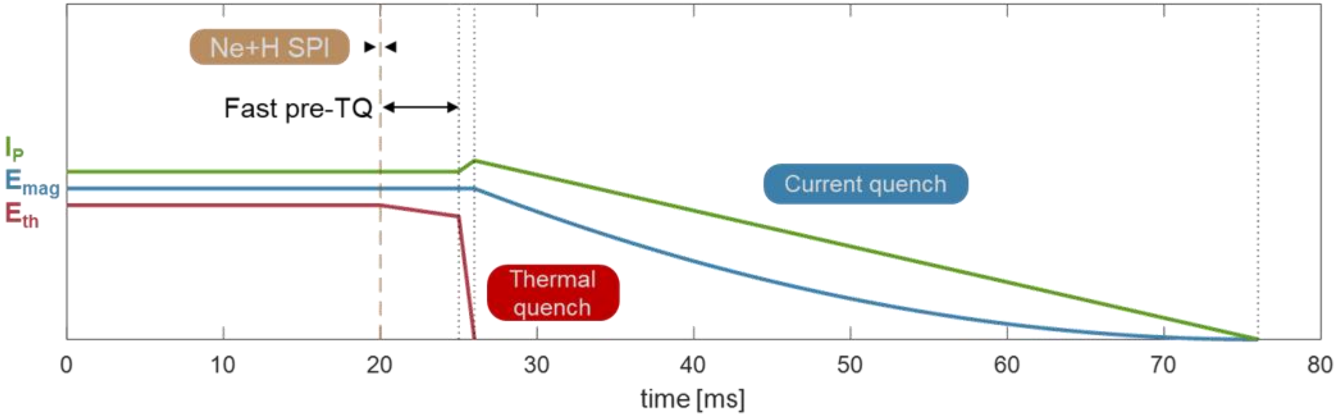
Upper ports

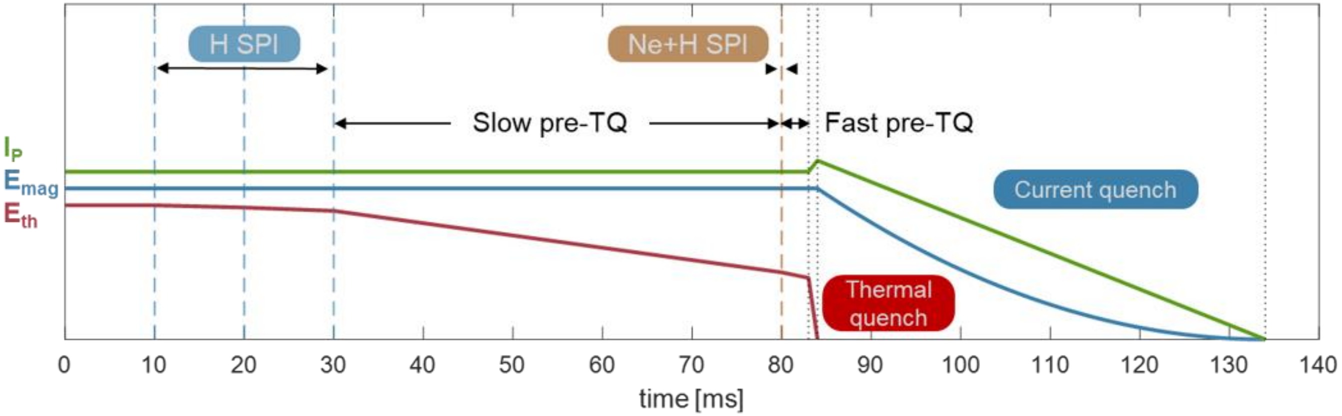
For post-TQ injection

- CQ heat load mitigation
- CQ EM load mitigation

Courtesy of M. Lehnen

Two injection schemes of ITER DMS





Top: typical injection scheme
Bottom: staggered injection scheme

Courtesy of M. Lehnen

- Main role of each impurity:
  - Ne: radiation cooling for dissipating stored energy
  - H: dilution cooling (densification) for avoiding runaway electron formation
- Separation of dilution cooling and radiation cooling
  - H SPI followed by Ne/H mixture SPI
  - Enough densification during slow pre-TQ
  - Reduction of hot tail due to dilution cooling
- Issues of separation (= totally different target discharge)
  - Characteristics of dilution cooled target
    - Formation of dilution cooled target
    - Pre-TQ time depending on dilution, etc.
  - Performance of Ne/H mixture SPI
    - Assimilation of Ne/H mixture SPI in dilution-cooled target
    - Radiation characteristics of Ne/H mixture SPI