Disruption mitigation by symmetric dual injection of shattered pellets in KSTAR

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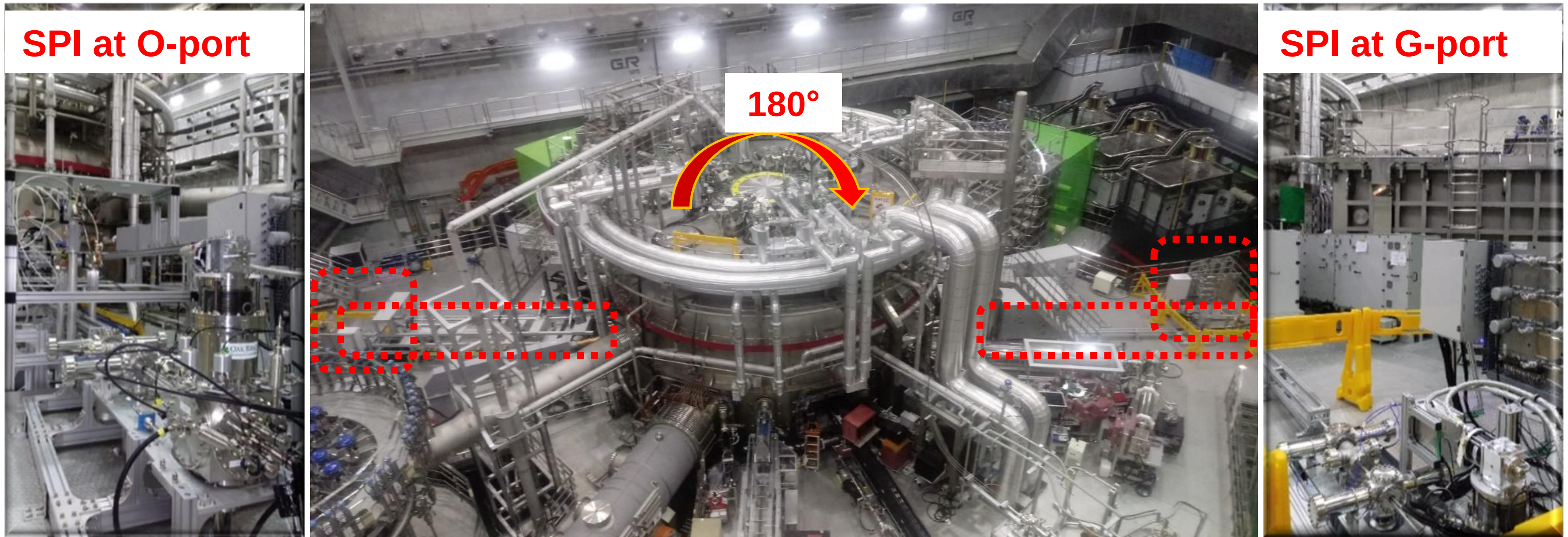
KSTAR disruption research aims to respond to the ITER research plan.

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 were installed in toroidally opposite locations of KSTAR for symmetric multi-injection (funded/supported by IO and USDOE/ORNL).

- Up-looking bent tube shatters the pellet and aims plasma center: ITER-like design
- Low Z (D_2), high Z (Ne, Ar), and their mixture can be injected selectively.
- Three barrels in each SPI control the pellet size: 4.5, 7.0, 8.5 mm → 4.5, 2 x 7.0 mm (from 2020)

  - KSTAR volume: $1.8 \times \pi \times (0.45)^2 \times 2 \times \pi \times 1.8 \sim 12.9\ m^3$
  - 4.5 mm: D# $=6.47\times10^{21}$, Ne# $=3.83\times10^{21}$ + (D# of shell 1.10×10^{21})
  - 7.0 mm: D# $=2.43\times10^{22}$, Ne# $=1.54\times10^{22}$ + (D# of shell 2.70×10^{21}) ← Replaced with 4.5 mm barrel
  - ~~8.5 mm: D# $=4.36\times10^{22}$, Ne# $=2.82\times10^{22}$ + (D# of shell 4.00×10^{21})~~ ← Replaced with 7.0 mm barrel



SPI topics in KSTAR during 2019~2020 campaigns

- Characteristics of single SPI: neon fraction effect with pellet size scaling

- Simultaneous injection of SPIs: synchronization issue (pure deuterium, mixture)
  - Dual injections from different toroidal locations (180° separation in KSTAR)
  - Multi-barrel injections from same toroidal and poloidal location (same injection tube)
  - Dual x multi-barrel injections = quadruple injections

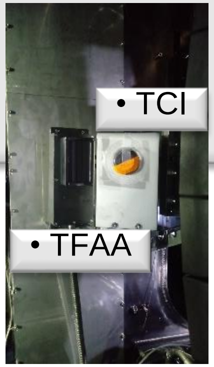
- Injection scheme using multi-barrels for achieving high density
  - Pure deuterium pellet followed by neon/deuterium mixture pellet

- Wall recovery from massive material injection (routine usage in SPI experiments)
  - Electron cyclotron wall cleaning (ECWC) in superconducting tokamak

KSTAR

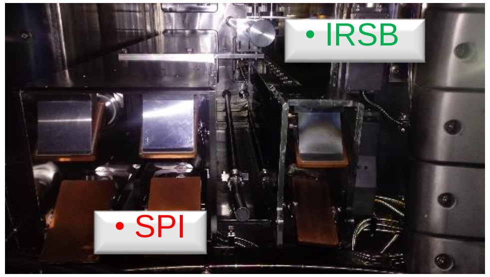
Installation/upgrade of diagnostics are concurrently progressing for investigating the disruption mitigation phenomena.

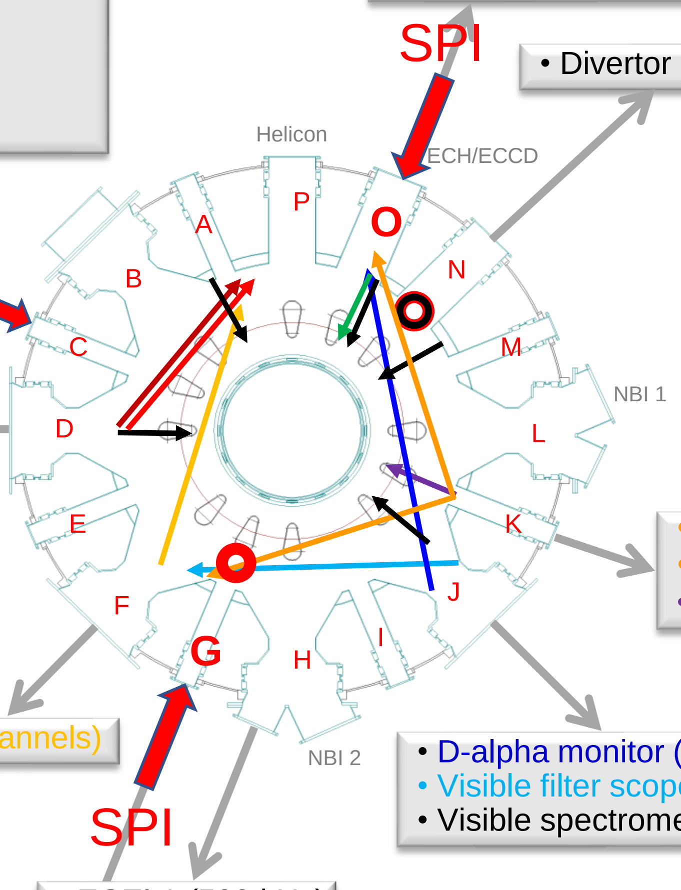
Toroidal AXUV arrays from O-port SPI
#1: +56.25 °
#2: -11.25°
#3: -33.75°
#4: -101.25°



- 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)

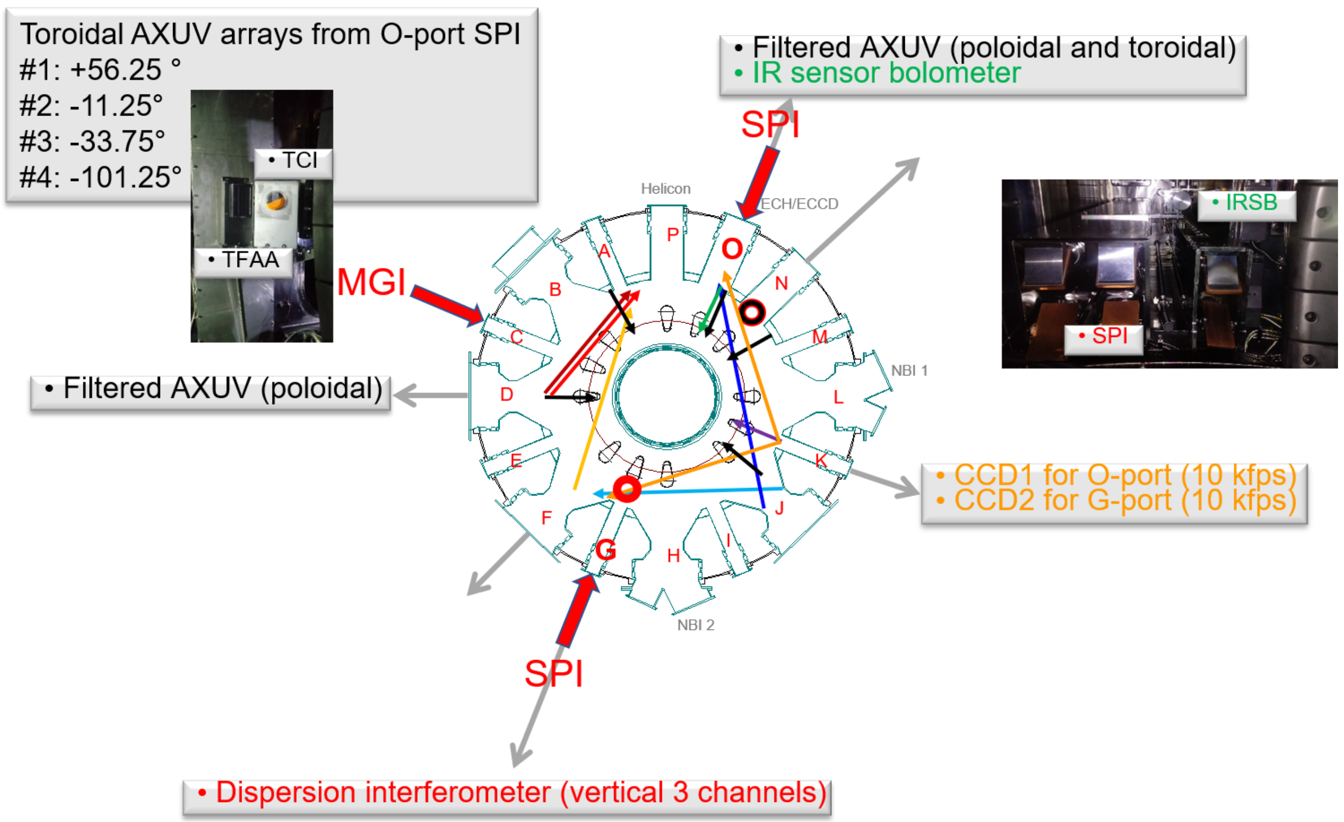
- Dispersion interferometer (vertical 3 channels)
- ECEI 2 (500 kHz)

- Hard X-ray monitor
- Neutron detector

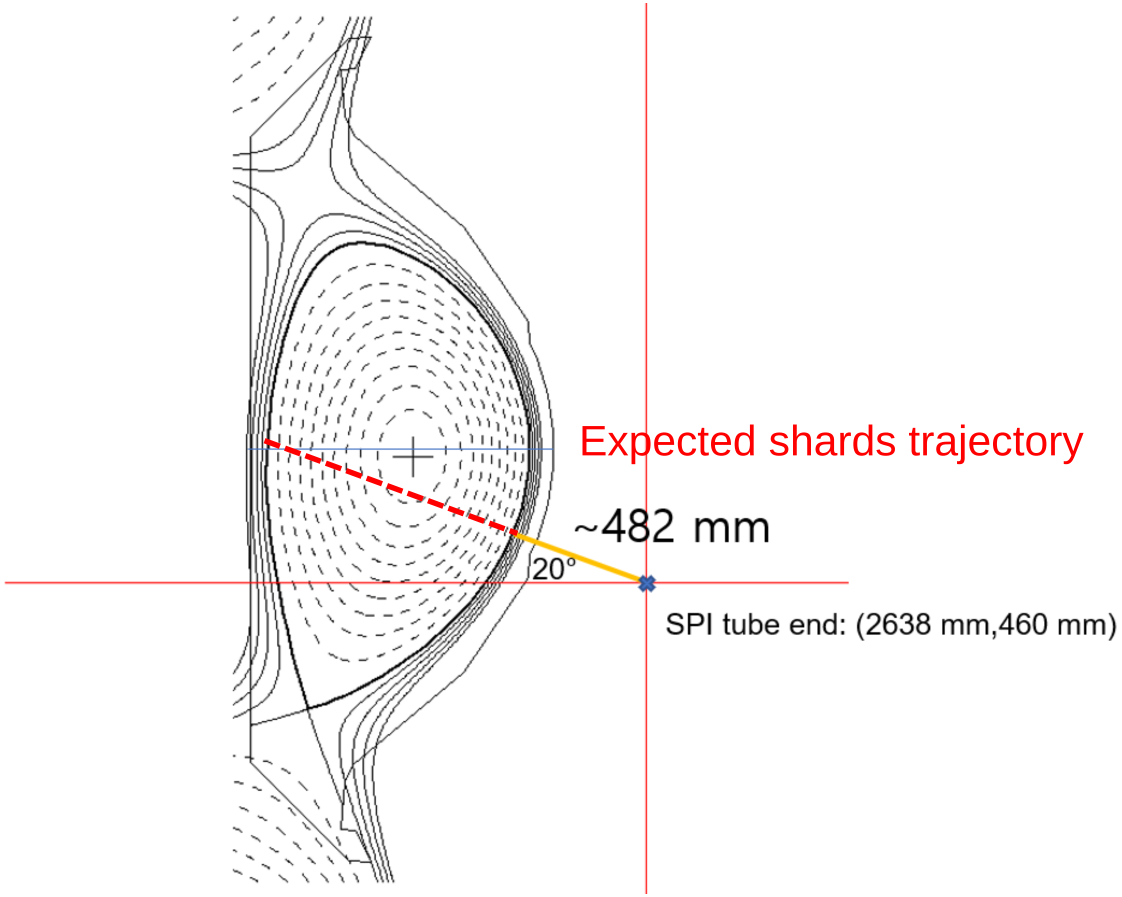
Although SPI physics is fairly *three-dimensional*, these diagnostics still cannot cover full toroidal range due to several limitations.

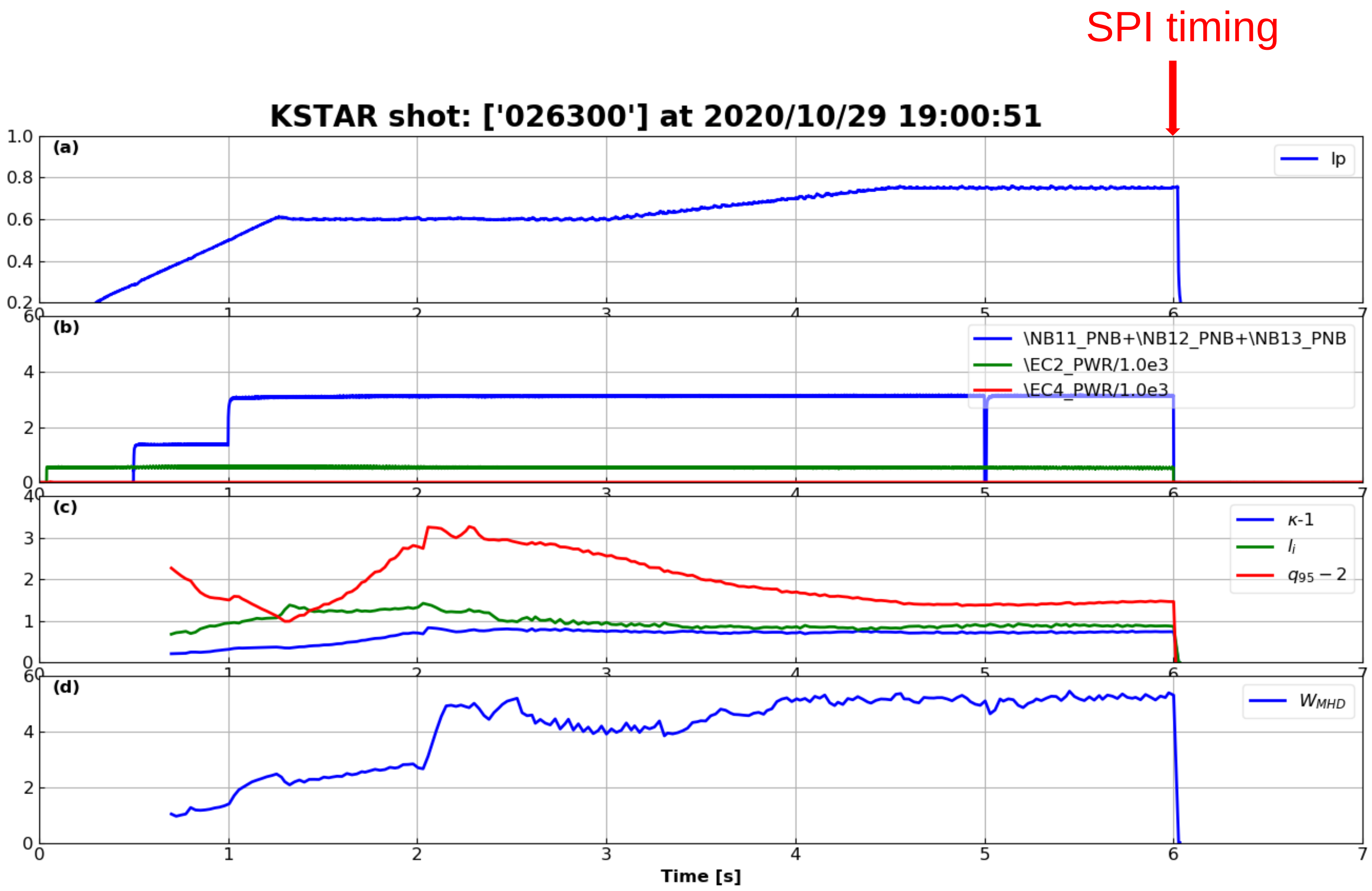
- Most of bolometry are located near/around O-port (and also in-between O- and G-ports).
- Short wavelength dispersion interferometer is located at G-port.

- To overcome the coverage issue, we typically conducted a pair of experiments using each SPI.



We fixed the reference discharge and *instead* experimented with varying the various SPI parameters.

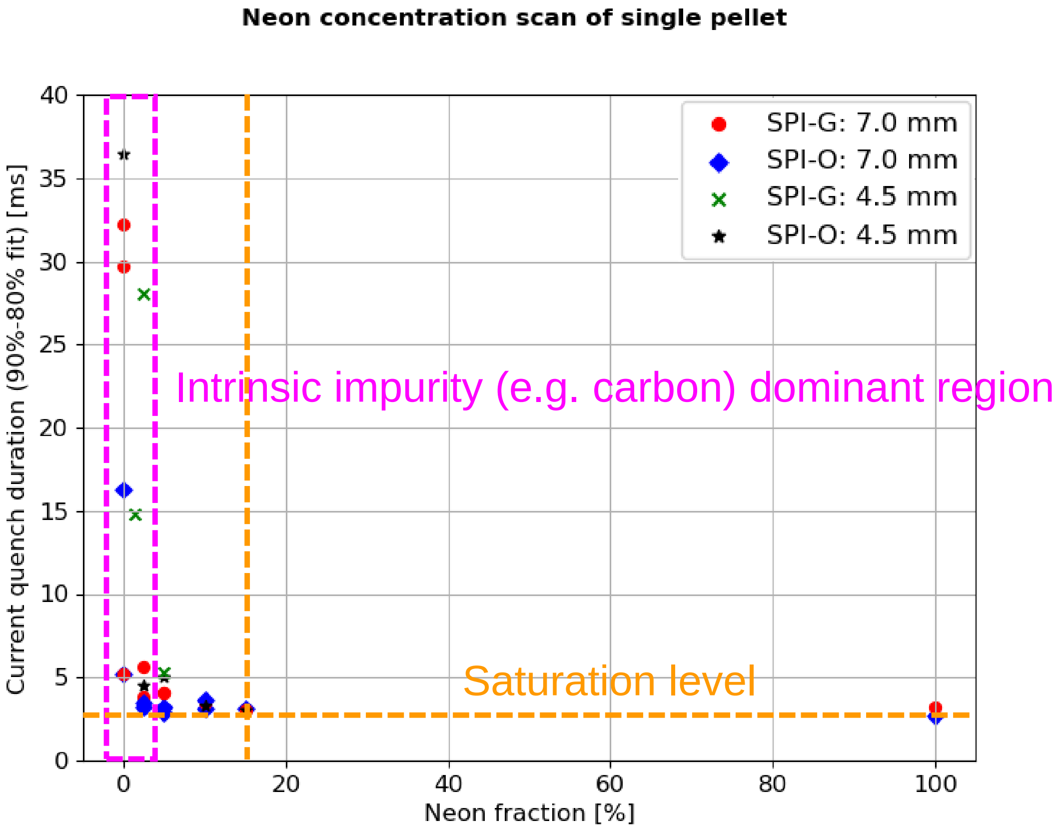




I_p~0.75 MA, W_{MHD}~0.5 MJ, q_{95}~3.5, NBI-heated H-mode discharge

Characteristics of single SPI: neon fraction effect

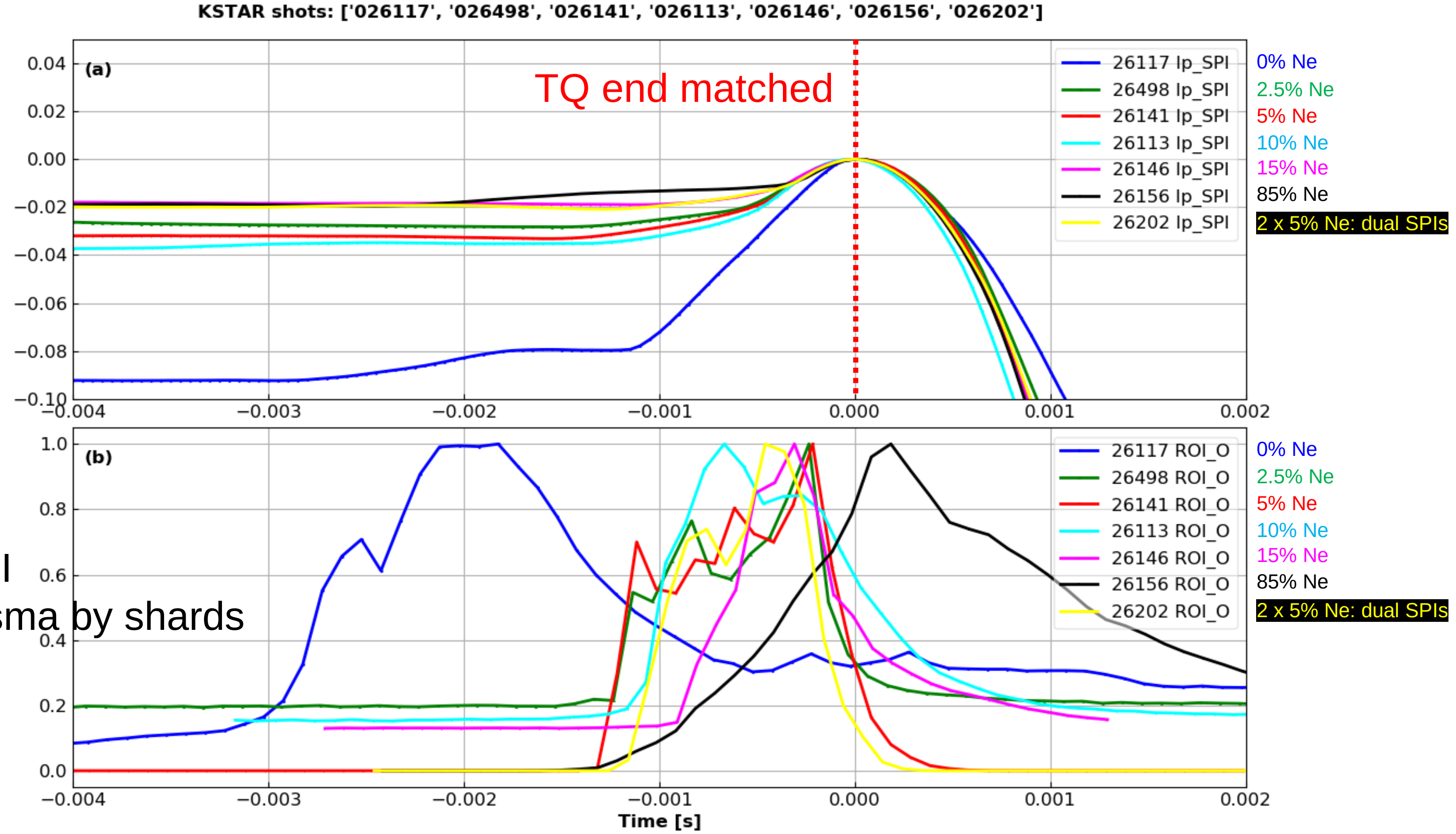
- When the neon fraction exceeds 15.0% in 7.0 mm pellet, saturation appears.
- Pellets with a small amount of neon show a large dispersion in the current quench duration.
  - When considering initial dilution cooling, the behavior of intrinsic impurities could play a role.



- In the above graph, the amount of neon in 4.5 mm pellet is converted to that of 7.0 mm pellet for comparison.
  - For instance, 15.0% neon in 7.0 mm pellets ($3.4x10^{21}$ atoms) is equivalent to 68.0% in 4.5 mm pellets.

Cooling duration before TQ end: single SPIs and dual SPIs

- As the neon fraction increases, the cooling period shortens to the end of the TQ.
  - ~1 ms cooling duration except pure D and pure neon pellet
  - For effective superposition of multiple pellets, they should be synchronized within 1 ms.
- Dual SPIs (2 x 5%) does not show shorter cooling duration compared with 10% single SPI.

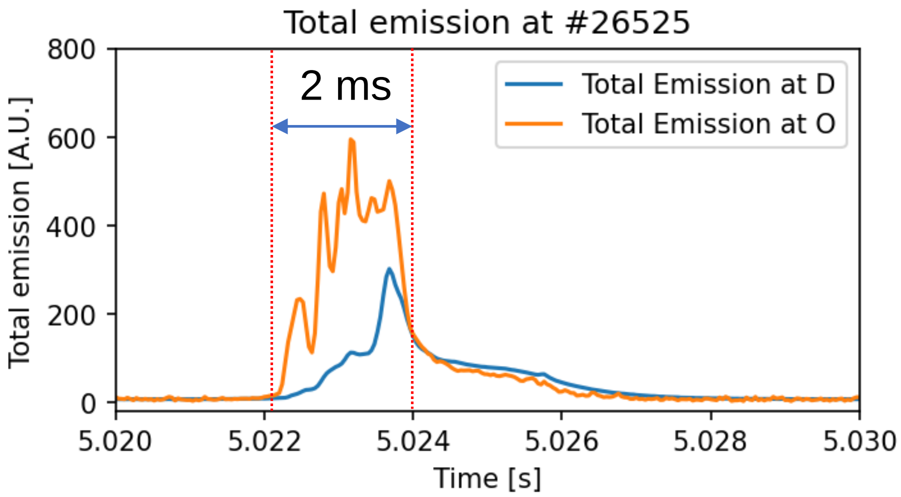


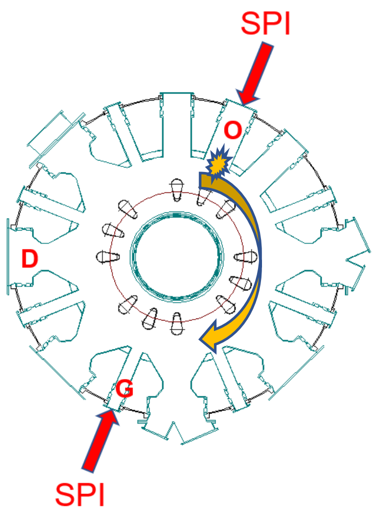
Sum of CCD intensity within ROI
For checking initial touch of plasma by shards

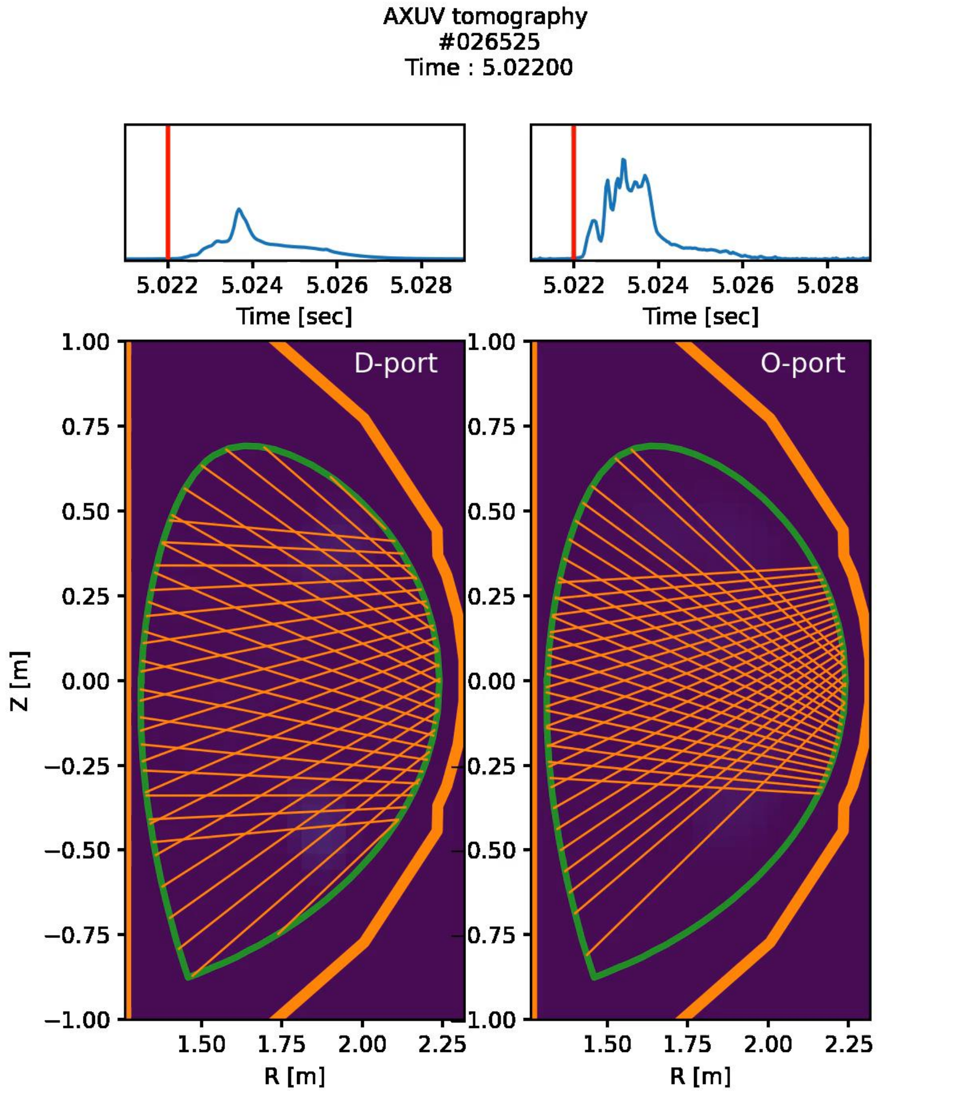
Radiation pattern of single SPI from O-port

- KSTAR shot no. 26525: single SPI from O-port
  - SPIO2 @ t=5.0000 sec: 7.0 mm Ne:D=10:90

- Strong radiation apperas near lower O-port (as expected).
- Relatively longer radiation duration compared with dual/quad
- Long delay between AXUV-O and AXUV-D
  - Rotation effect (?): clockwise direction of rotation

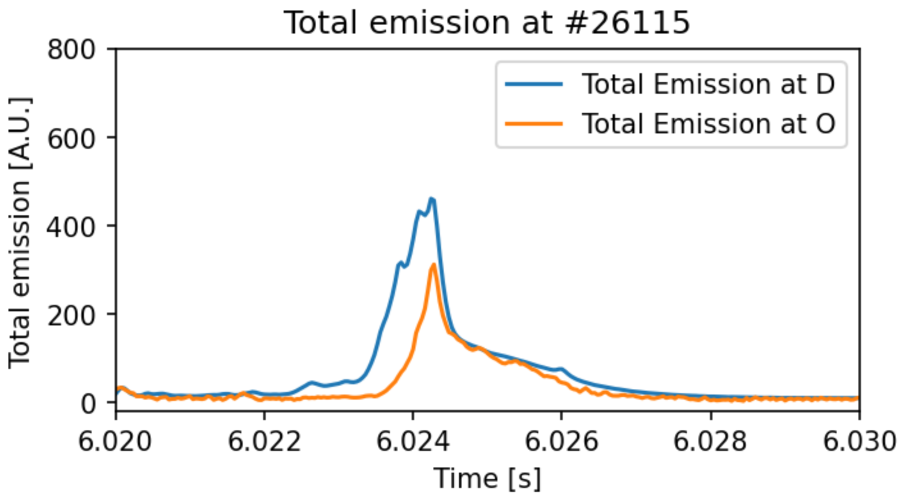


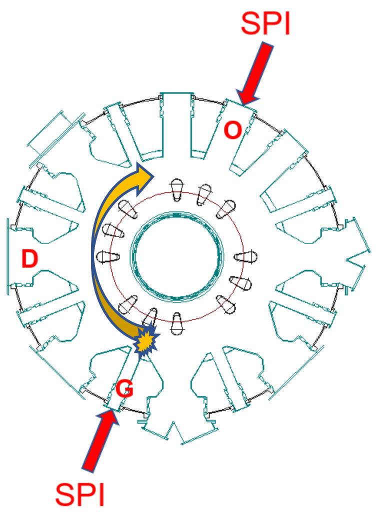


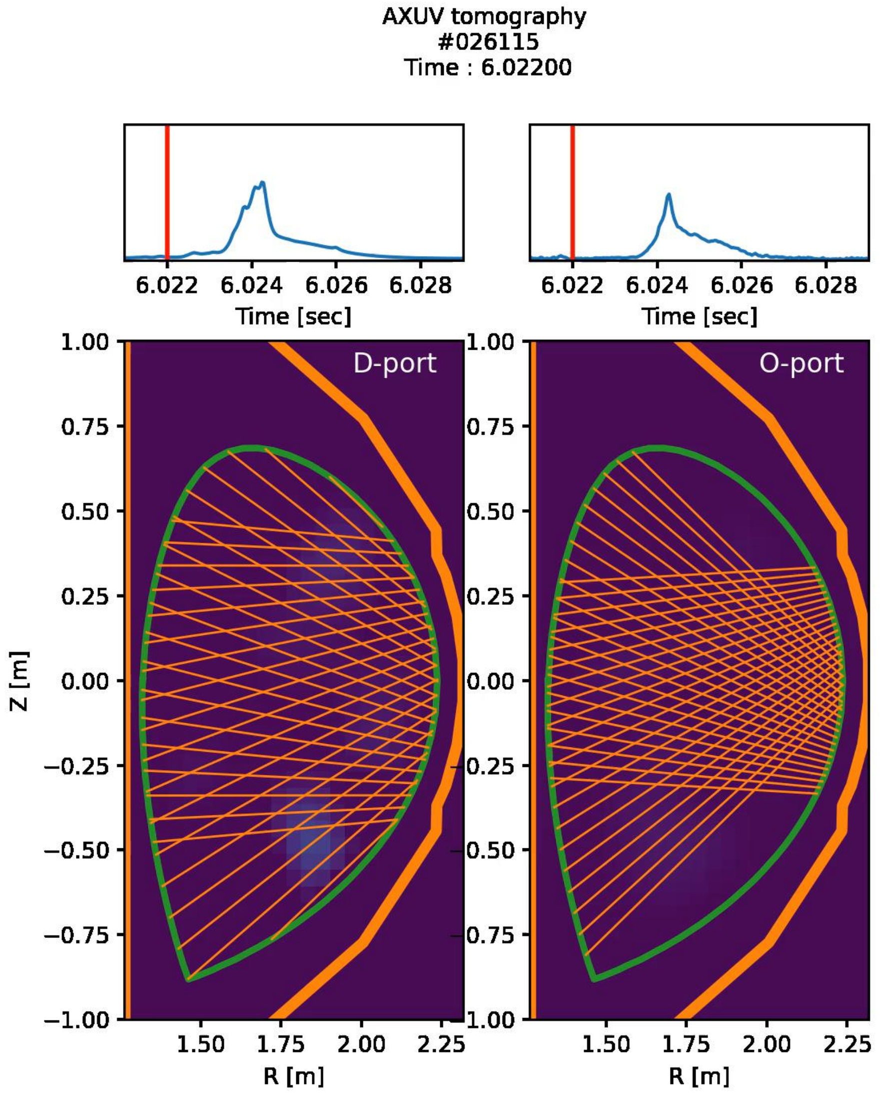


Radiation pattern of single SPI from G-port

- KSTAR shot no. 26115: single SPI from G-port
  - SPIG2 @ t=6.0 sec: 7.0 mm Ne:D=10:90
- Radiation appears from upper D-port initially (helical pattern).
- Short delay between AXUV-D and AXUV-O:
  - Rotation effect (?): clockwise direction of rotation







Dual/quadruple injection of SPIs

- 5.0% neon of 7.0 mm pellet was set as the *so called* standard pellet
  - taking into account the level of saturation (15.0% neon) in the single SPI experiments.

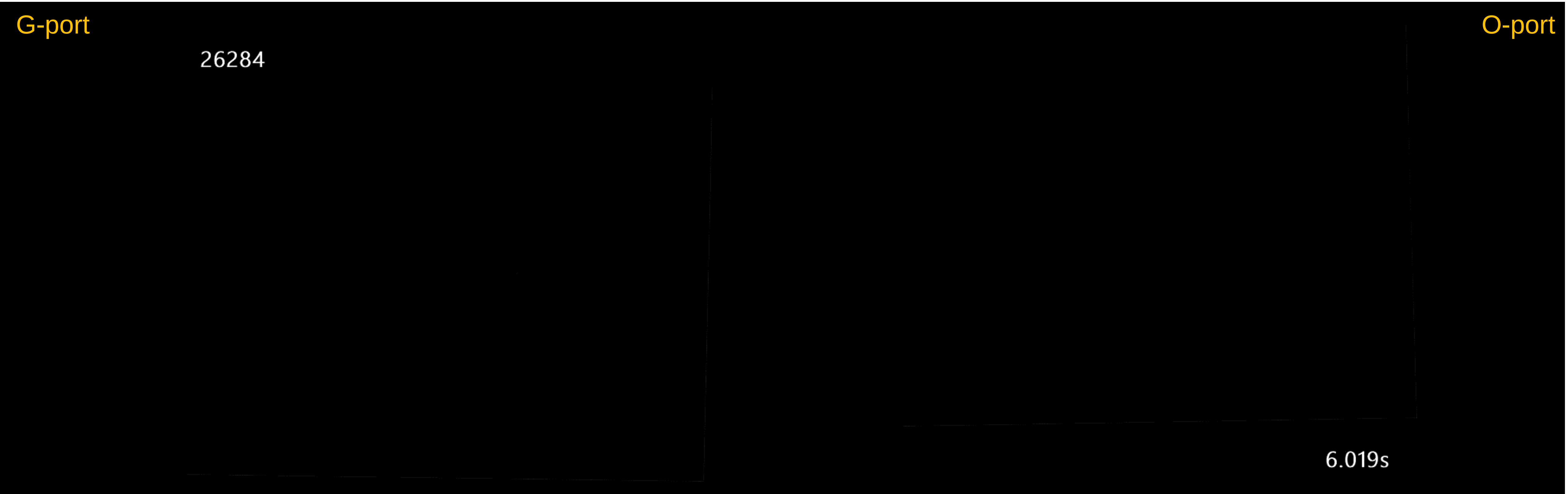
- Quadruple injection used 2.5% neon of 7.0 mm pellet from SPI-G2, -G3, -O2, and -O3.
- Dual injection used 5.0% neon of 7.0 mm pellet to keep the same amount of neon.

- The control parameter was the synchronization level among pellets.
  - Fast camera, filter scope, microwave cavity, and trigger time were used for checking the timing.
  - Sometimes, it is hard to determine exact timing of injection due to gas (?).
    - It is necessary to take into account the effects of gases generated during the shattering.
      - We plan to regulate the shattering process in 2021 through pellet speed control.

Dual view fast cameras seeing each SPI

- KSTAR shot no. 26284: 0.54 ms time difference between two pellets based on fast cameras
  - SPIO2 7.0 mm Ne:D=5:95 followed by SPIG2 7.0 mm Ne:D=5:95
  - $t_{touching}$=6.0205 sec
  - t_{TQend}=6.0218 sec

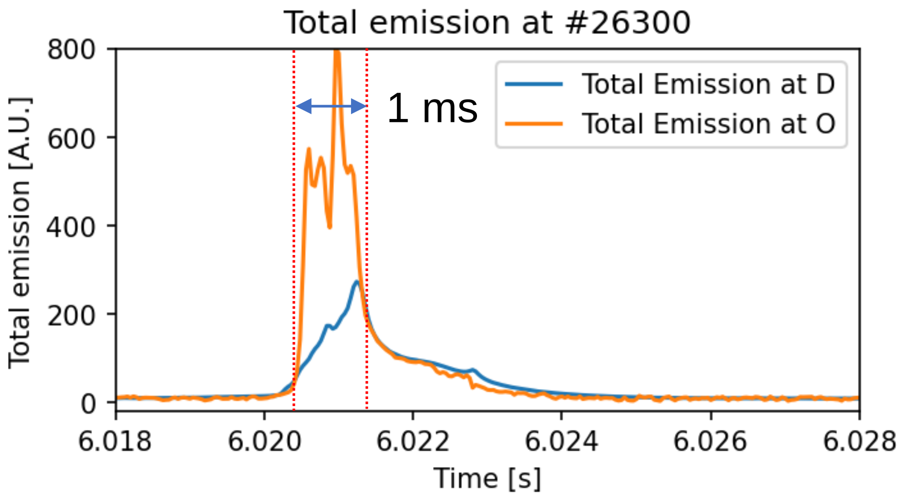
- Helical radiation pattern is clearly seen along field line.

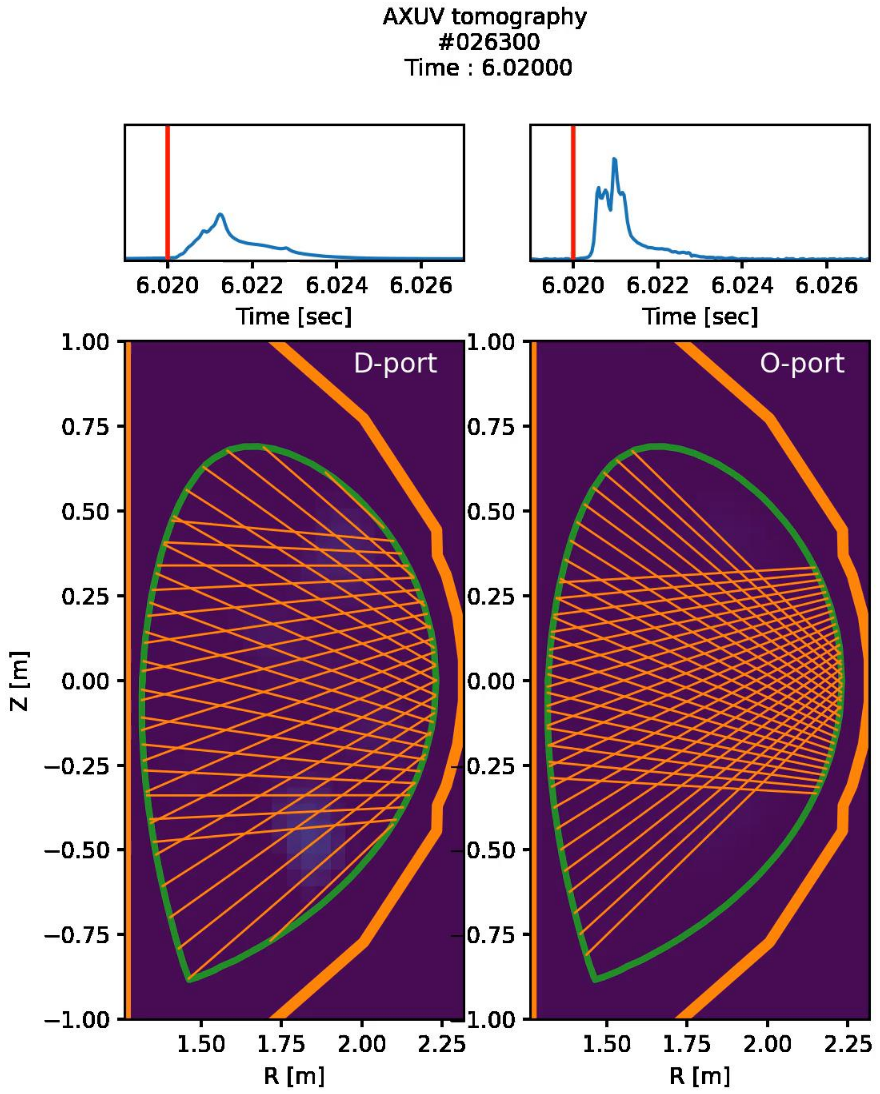


Radiation pattern of *synchronized (before TQ end)* dual SPIs

- KSTAR shot no. 26300: synchronized dual SPIs
  - SPIO2 @ t=6.0000 sec: 7.0 mm Ne:D=5:95
  - SPIG2 @ t=6.0005 sec: 7.0 mm Ne:D=5:95

- Short radiation duration compared with single injection
  - Rapid cooling even with same amount of neon atoms
    - Momentary local heat load (?)
    - Enough assimilation of particles (?)

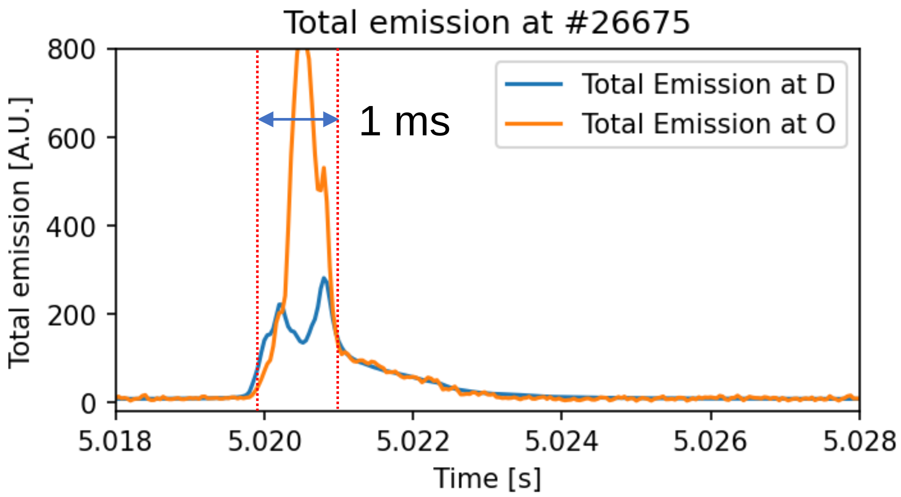


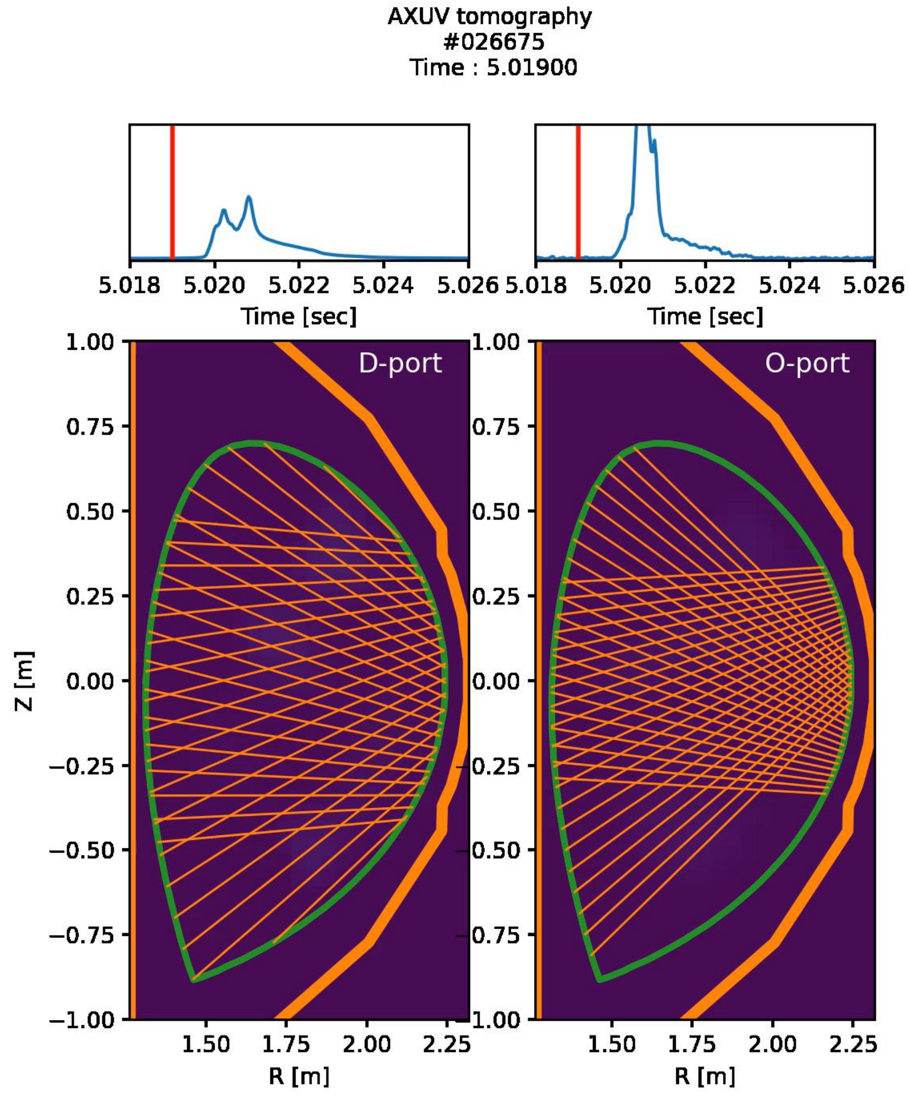


Radiation pattern of *synchronized* quadruple SPIs

- KSTAR shot no. 26675: synchronized dual SPIs
  - SPIO2 @ t=5.0000 sec: 7.0 mm Ne:D=2.5:97.5
  - SPIO3 @ t=5.0000 sec: 7.0 mm Ne:D=2.5:97.5
  - SPIG2 @ t=5.0000 sec: 7.0 mm Ne:D=2.5:97.5
  - SPIG3 @ t=5.0000 sec: 7.0 mm Ne:D=2.5:97.5

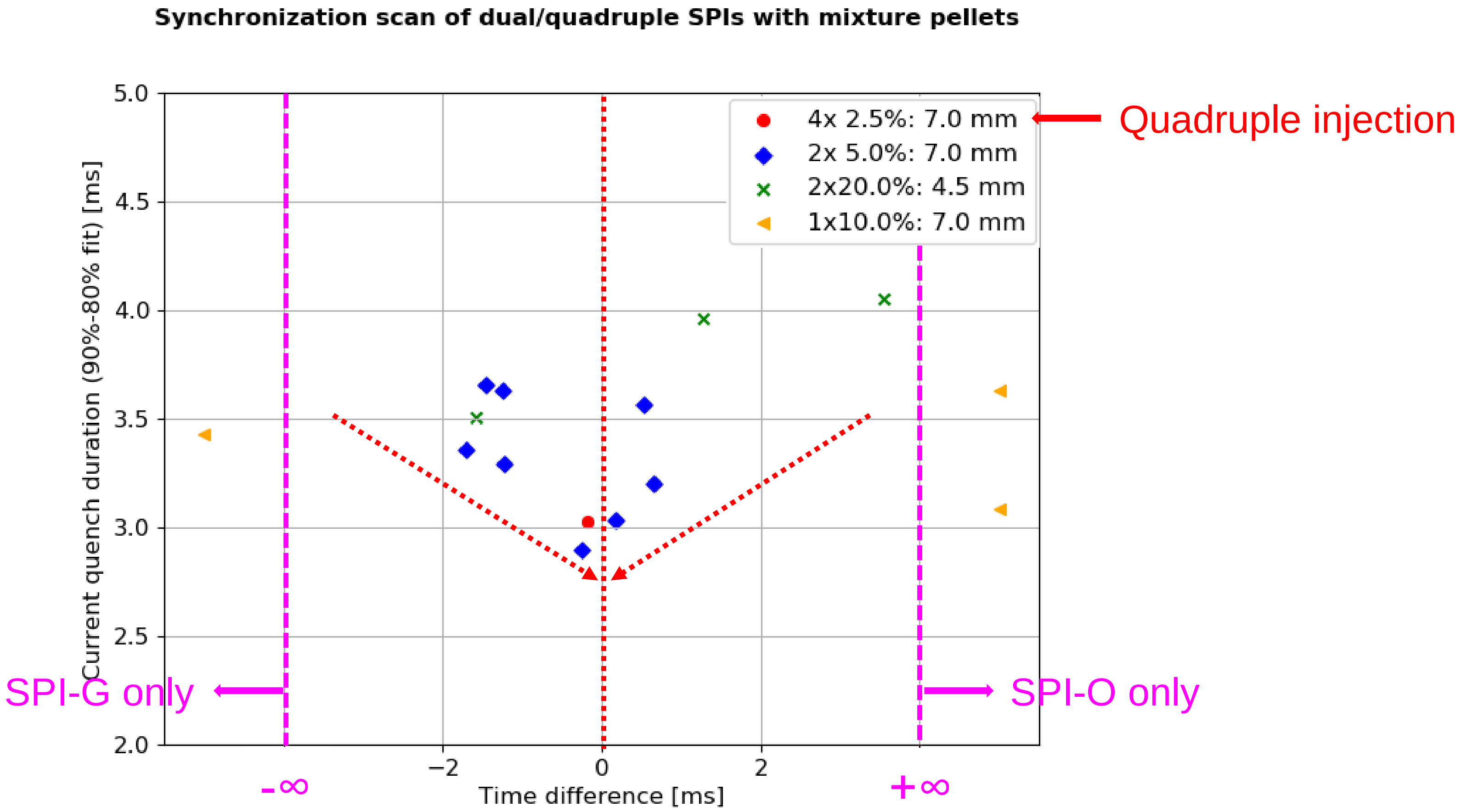
- Short radiation duration similar to sychronized dual SPIs
  - Momentary local heat load: it needs to be assessed further.





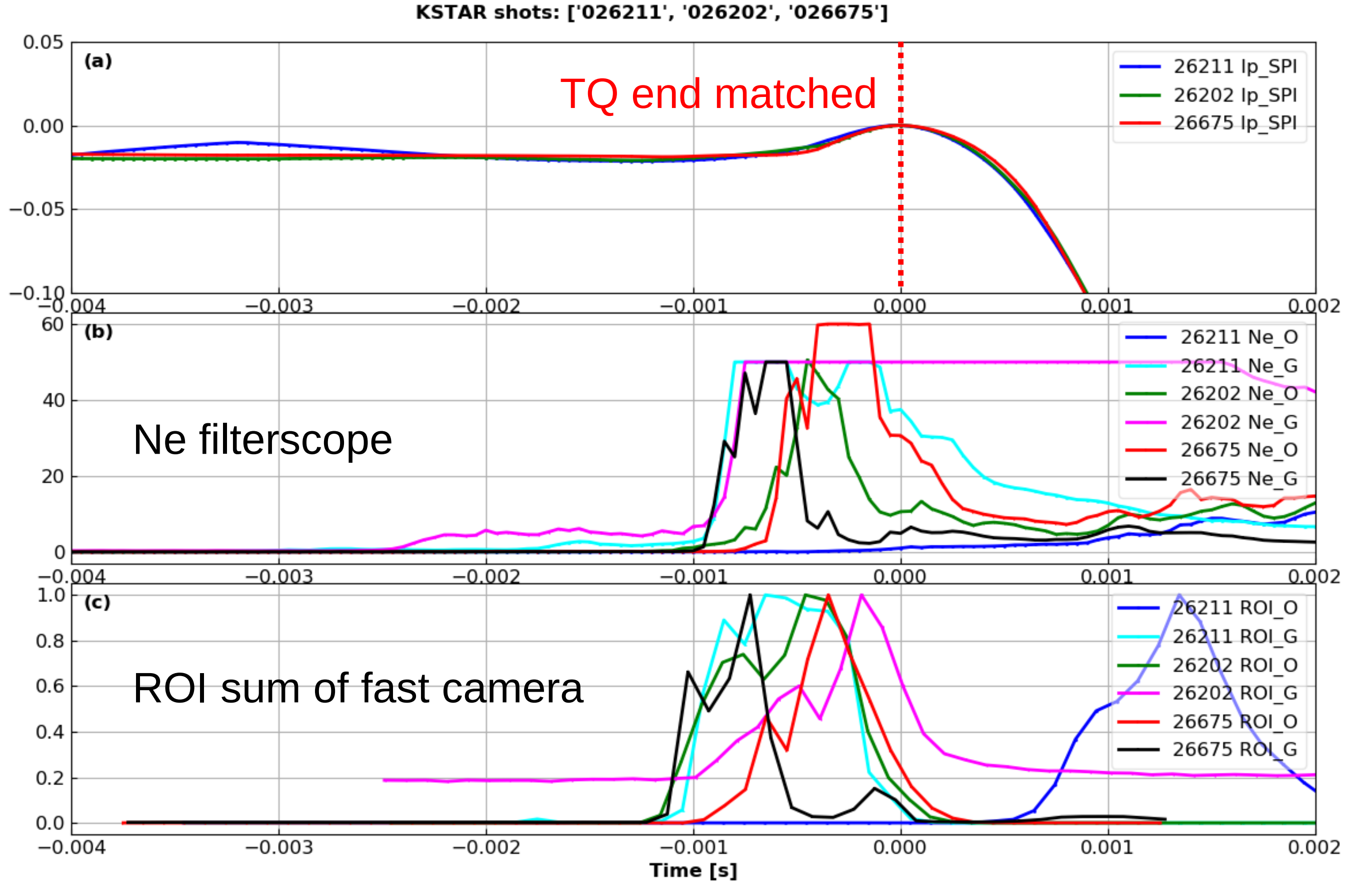
Dual/quadruple injection of SPIs

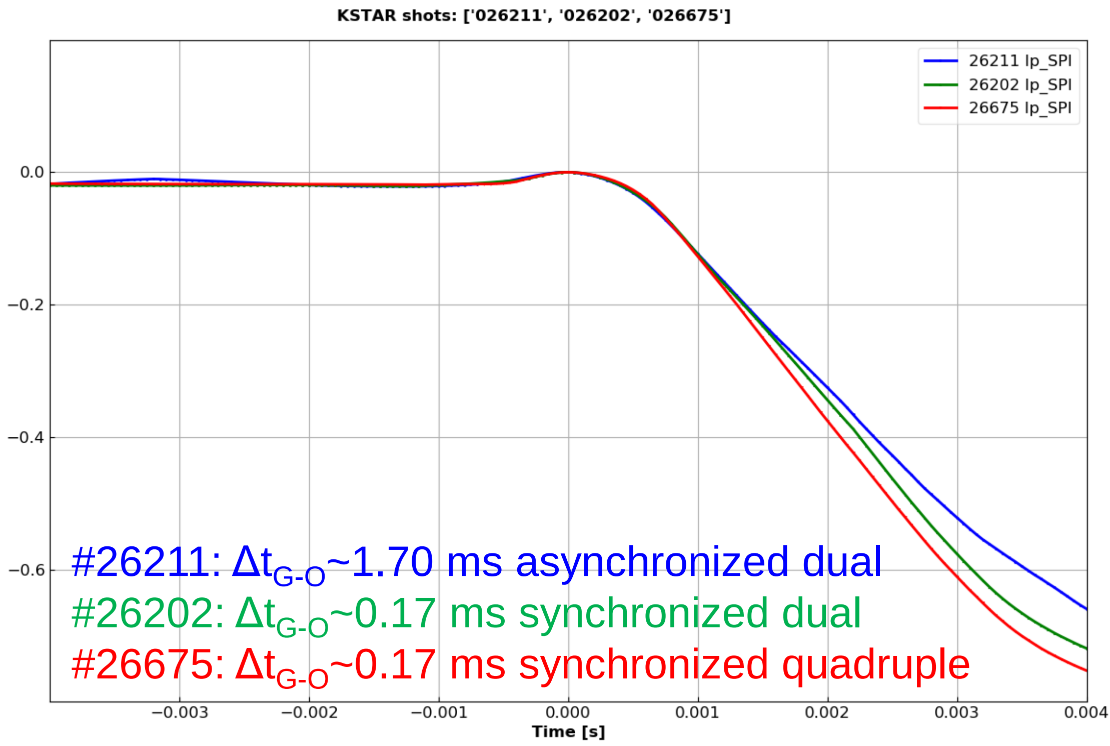
- Generally, synchronized cases show a short current quench duration (effective radiation cooling).
- Synchronized quadruple injection (red dot) shows the current quench rate comparable to synchronized dual injections.
  - This result supports ITER DMS strategy: multi-point x multi-barrel injections.



Cooling duration before TQ end: dual SPIs and quadruple SPIs

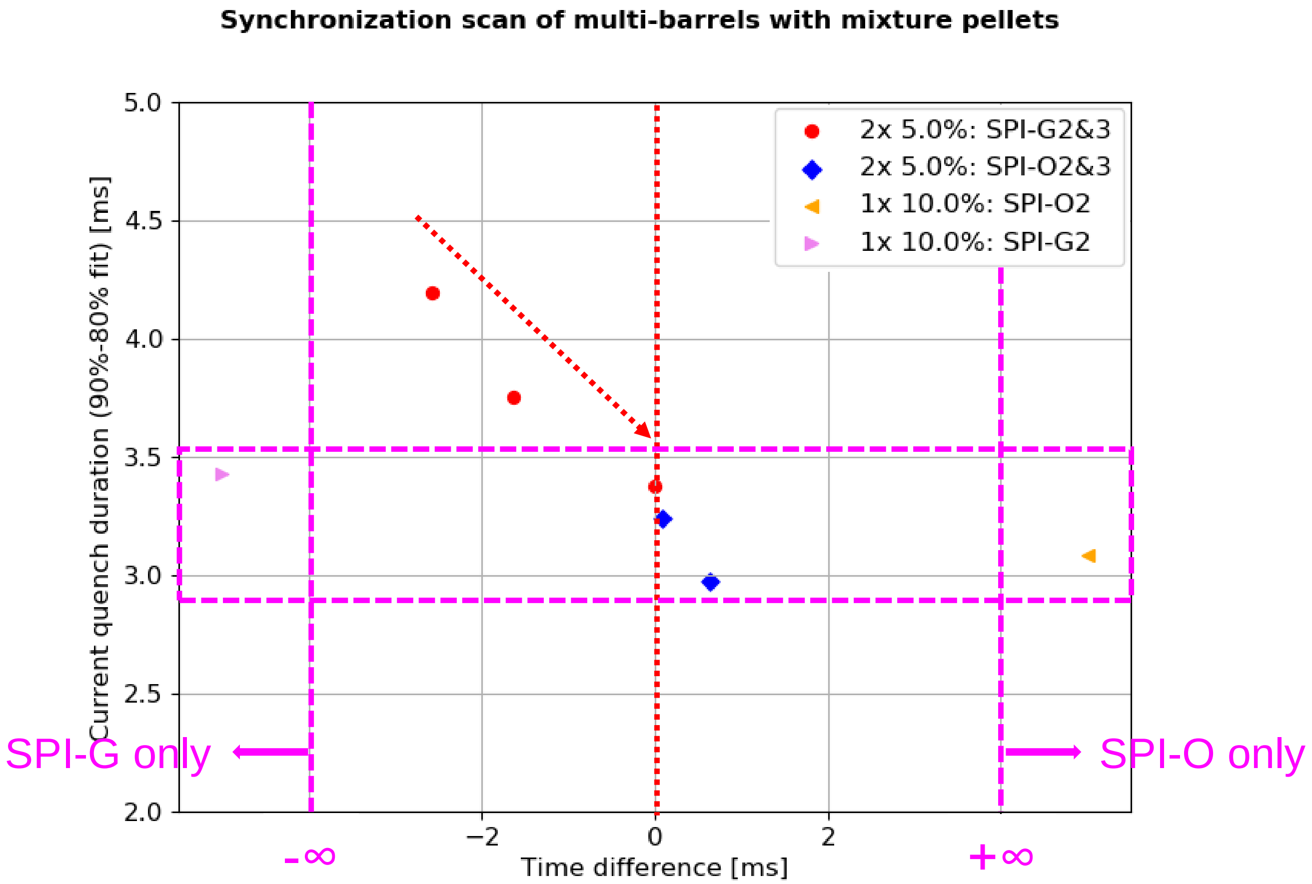
- Regardless of the synchronization level, the cooling duration does not make a significant difference.
- However, the current quenching duration is shortened depending on the level of synchronization.
- What causes this kind of result? More systematic study is needed.





Multi-barrel injection of SPIs

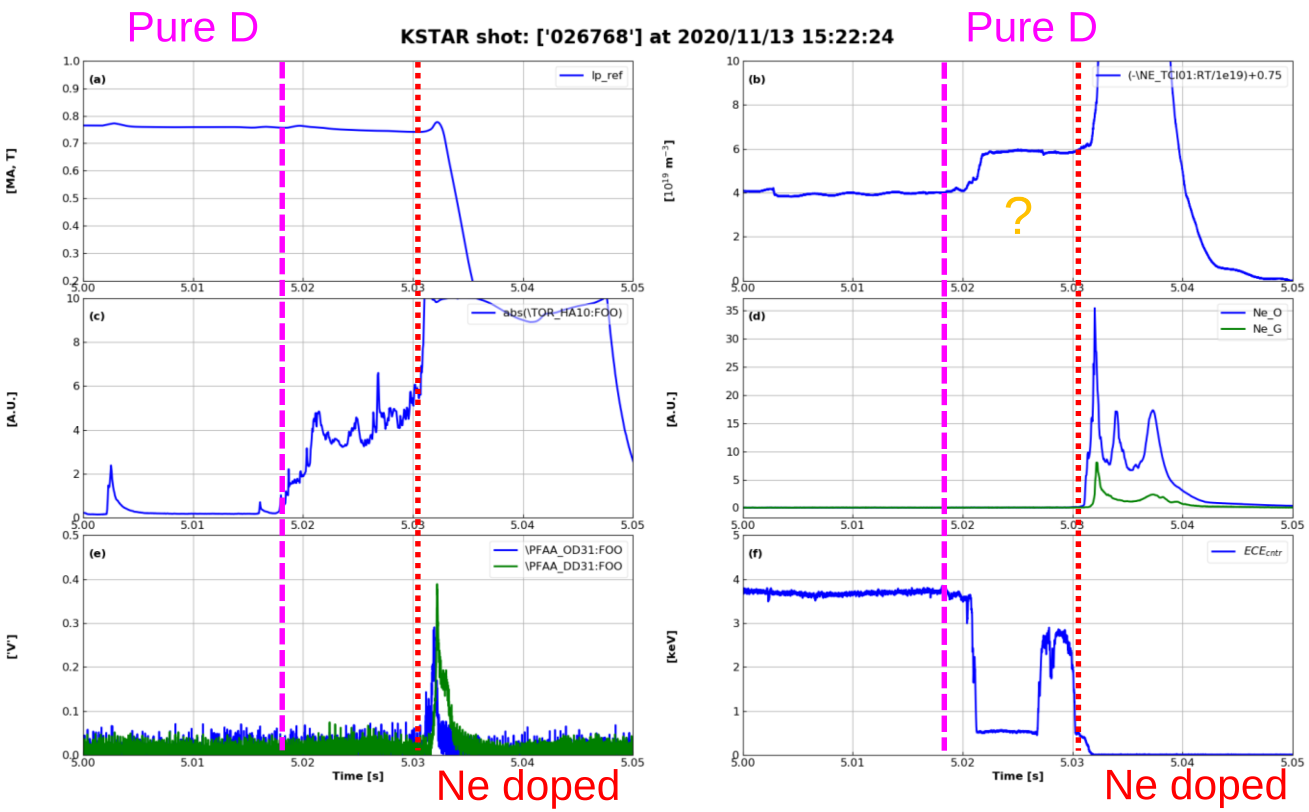
- Similarly, synchronized cases show a short current quench duration like dual injection.
- Well synchronized cases show the current quench rate comparable to single 10.0% neon pellet.



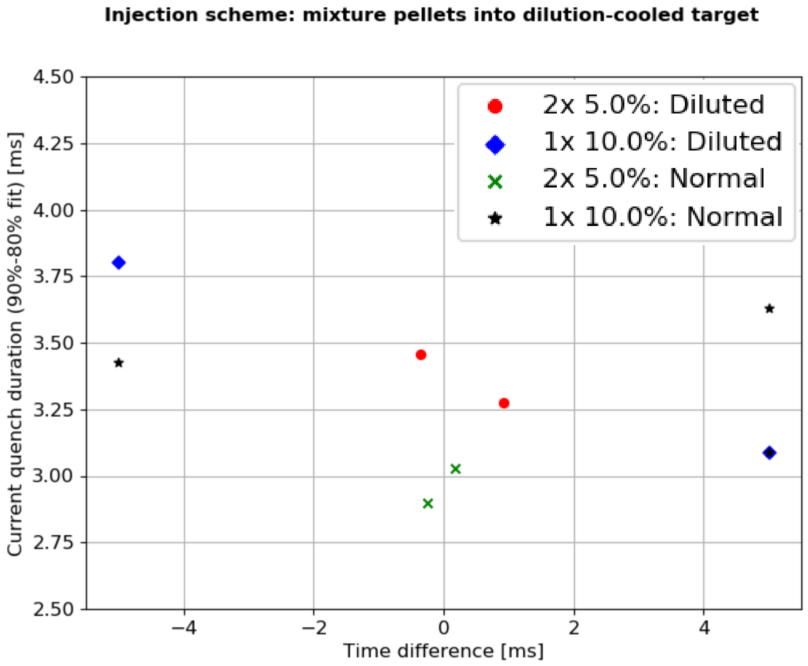
Impurity injection into dilution cooled target:

pure D pellet followed by Ne doped pellet

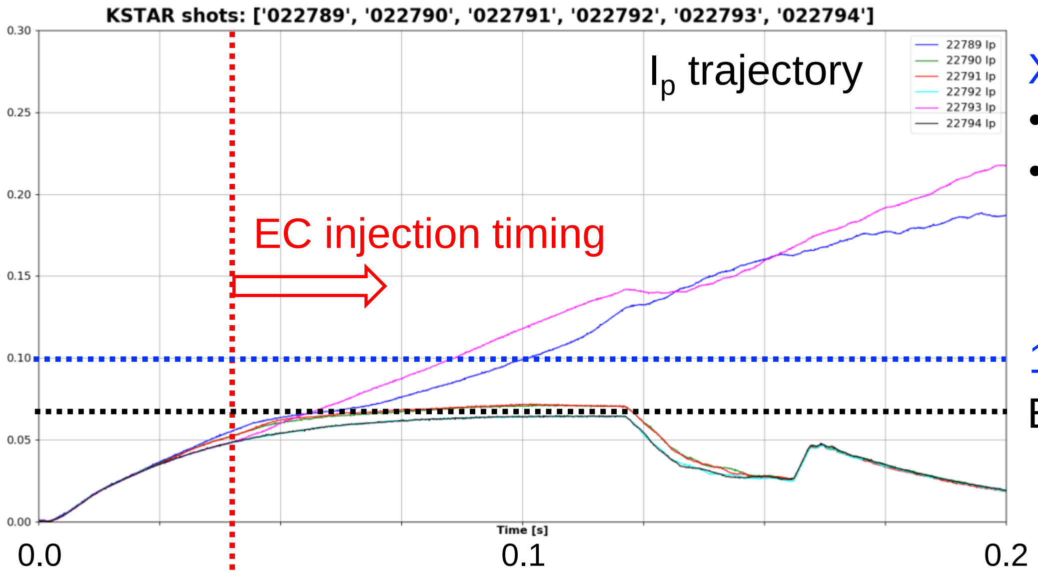
- Injection into dilution cooled target (pure D followed by Ne-doped pellet) was tested using multi-barrels
  - although the dilution level (density increase) was too low (just several % of assimilation).
  - It needs to be confirmed again with improved dispersion interferometer.
- In 2021, we will further test the feasibility of the scheme for RE avoidance during TQ.
  - We need larger size of pure D pellet (e.g., 7.0 mm) for more higher density.



Little or slight difference in CQ duration between diluted and normal targets



After using shattered pellet injection, the start-up condition goes out of the controllable range.

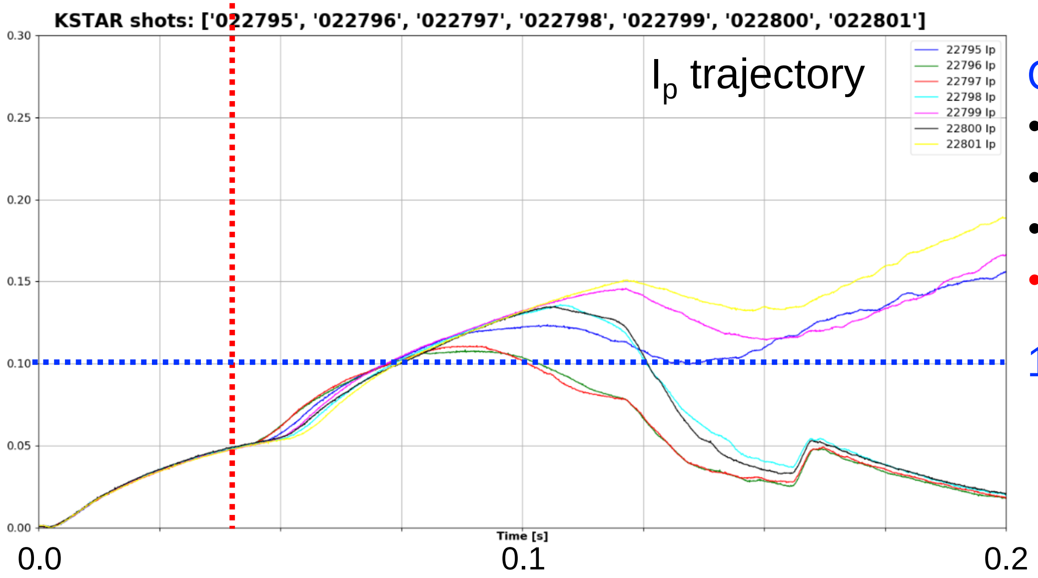


X2 harmonic EC-assisted at BT=1.8 T

- 4 shots among 6 shots failed.
- Sometimes, almost no breakdown

100 kA

Eddy current pick-up level

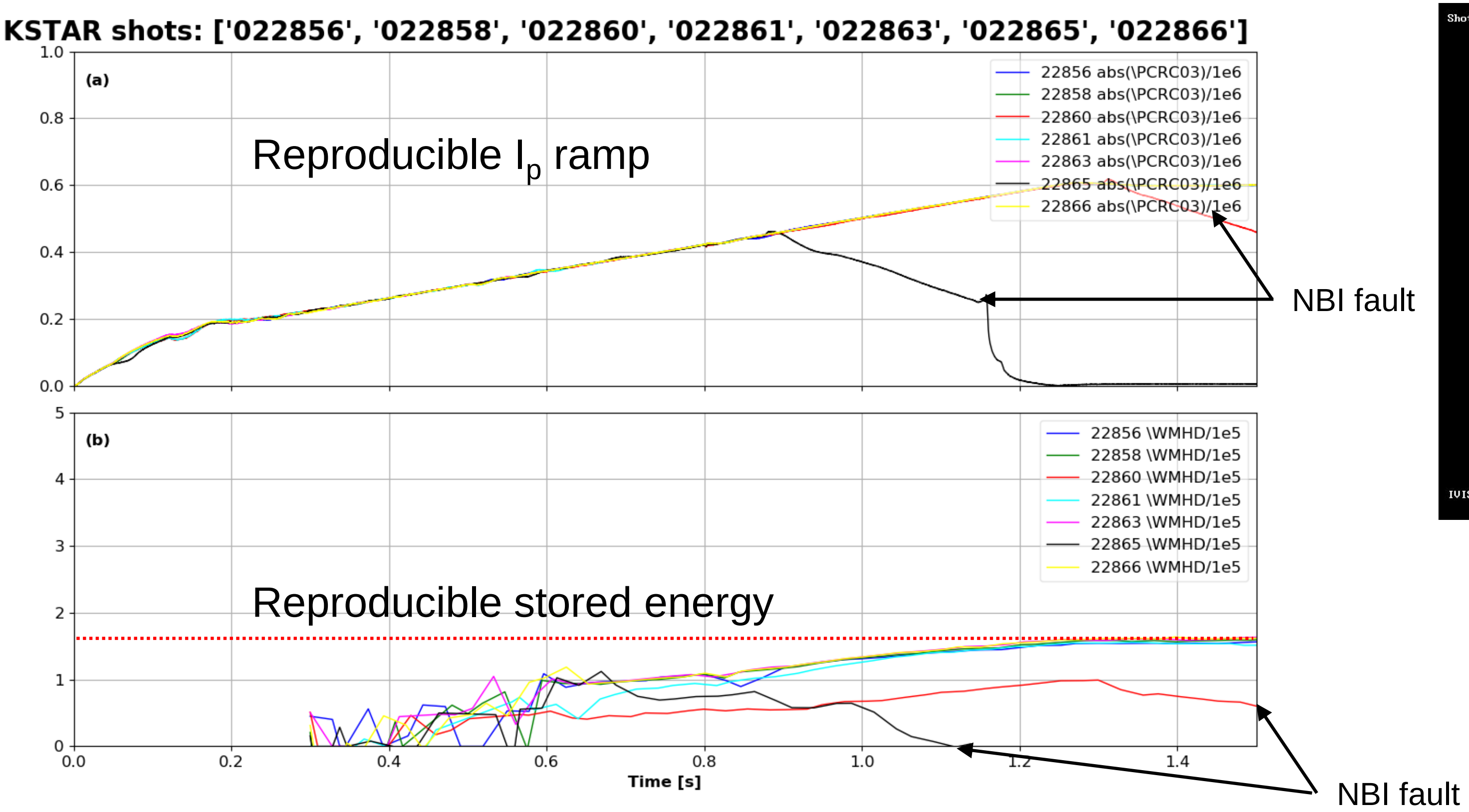


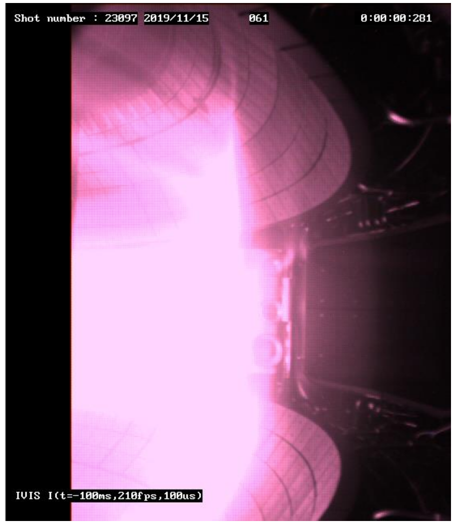
O1 harmonic EC-assisted at BT=3.5 T

- 4 shots among 7 shots failed.
- Better absorption of O1 harmonic ECH
- Better initial rise of plasma current
- But burn-through failed.

100 kA

Electron cyclotron wall cleaning can be a good solution for wall recovery from massive material injection.





ECWC

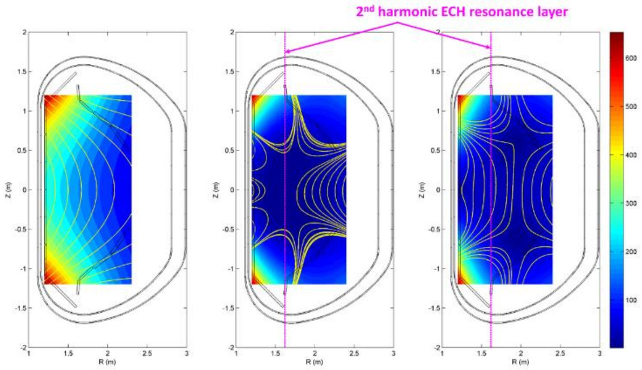
Ne:D=0.05:0.95 (all 7 mm SPI pellets except 4.5 mm pellet of #22856)

X2 harmonic EC-assisted start-up at B_T=1.8 T + X2 harmonic ECWC

- #22856 (SPI) → #22857 (ECWC) → #22858 (SPI) → #22869 (ECWC) → #22860 (NBI fault) → #22861 (SPI) → #22862 (ECWC) → #22863 (SPI) → #22864 (ECWC) → #22865 (NBI fault) → #22866 (SPI)

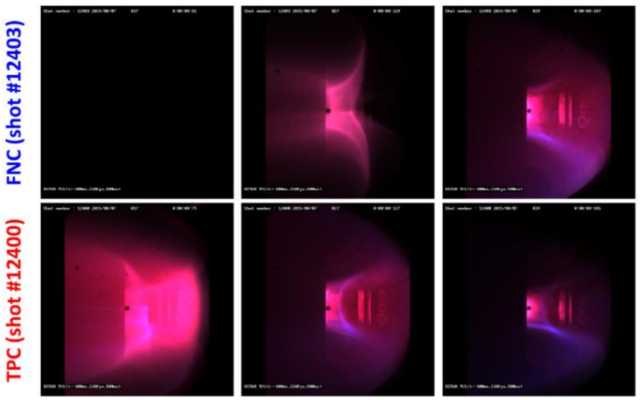
How can we implement the stable ECWC in ITER?

- Trapped particle configuration (TPC) uses mirror-like field structure for reducing convective loss.
  - Magnetic mirror ratio in KSTAR, Rm= 1.6, $v_{\parallel}/v_{\perp} > \sqrt{(R_m - 1)} = 0.77$
- Particle trapping ratio of ~30 % is found from single particle calculation.
- TPC can guarantee robust generation and better wetted area.
- TPC can be generated in ITER like KSTAR with using diverted coils.

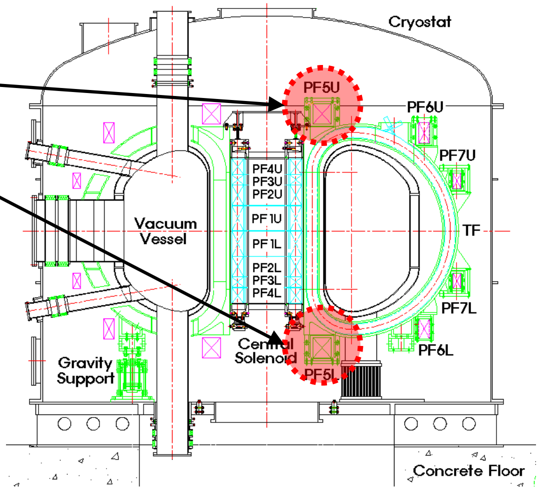


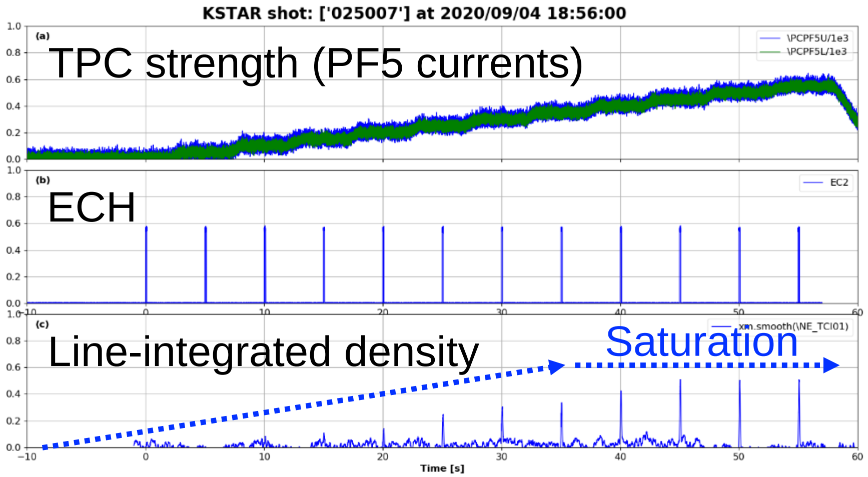
TPC made by PF#5 | Reference field null | Reference TPC

Field structure
with
camera image



-20 ms | 30 ms | 85 ms





Summary and discussion

- When the neon fraction exceeds 15% in 7 mm pellet, saturation appears in current quench duration.
  - However, as the neon fraction increases, the cooling duration (toward TQ) shortens without clear saturation.
- Generally, synchronized cases show shorter current quench duration both in dual and multi-injection.
  - However, the cooling duration does not make a significant difference depending on synchronization level in dual SPIs.
  - More systematic study is further needed.
- ITER-like quadruple injection also showed shorter current quench duration.
  - It supports the ITER SPI strategy with simultaneous multi-injection from multi-points.
- However, dual/quadruple injection shows short radiation duration.
  - Thus momentary local heating and enough particle assimilation need to be assessed further.
- Injection scheme for avoiding RE was tested: pure D pellet followed by Ne doped pellet
  - Further optimization with larger D pellet is needed for achieving higher density.
- Wall recovery method suitable for superconducting tokamak was established and routinely used.
  - ECWC with 2^{nd} harmonic EC power in TPC configuration

Acknowledgements

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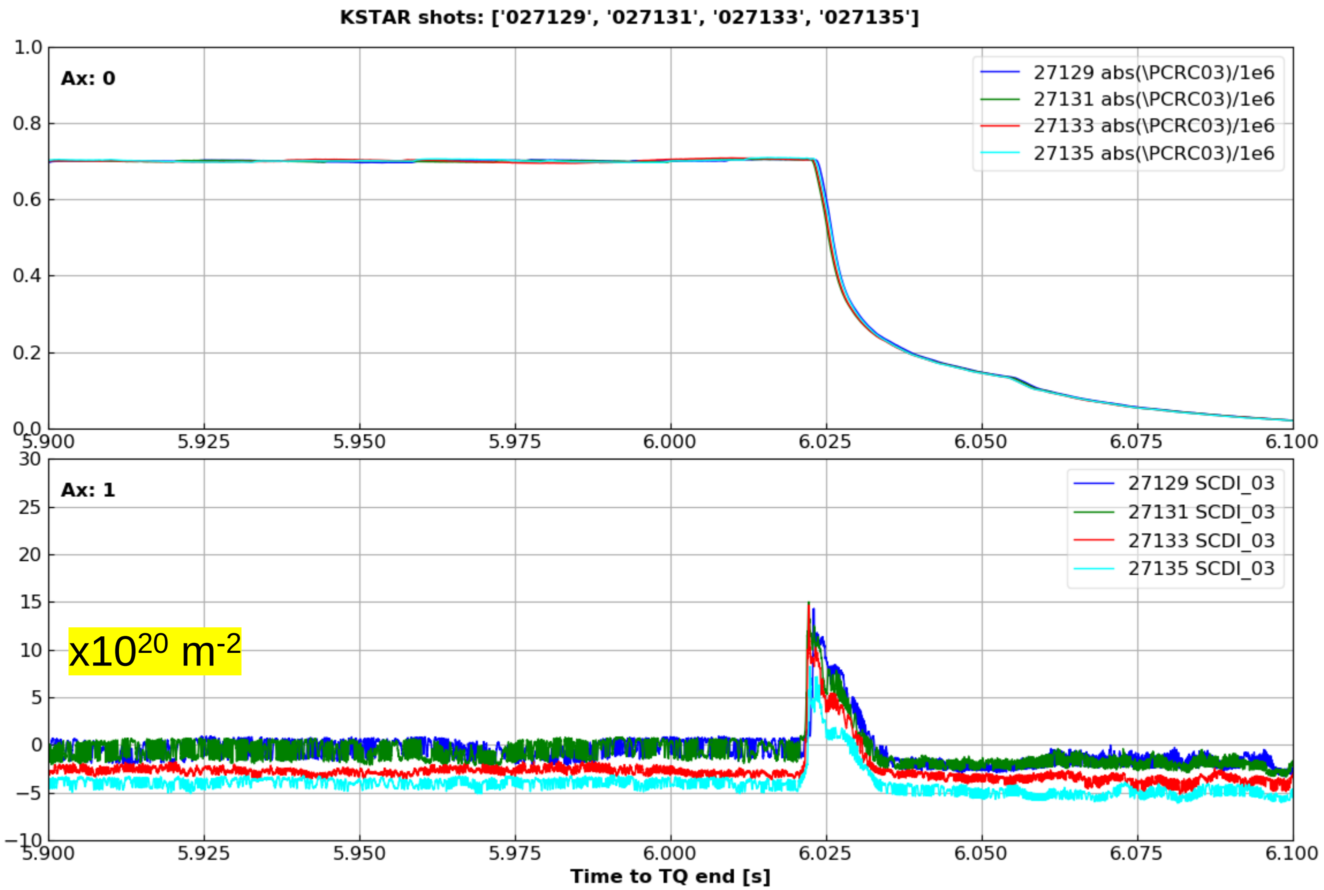
- Especially, this work was done in collaboration with the ITER DMS Task Force and also funded by the ITER Organization under contracts IO/CT/43-1830, IO/CT/43-1909, IO/CT/43-1918, and IO/CT/43-2034.

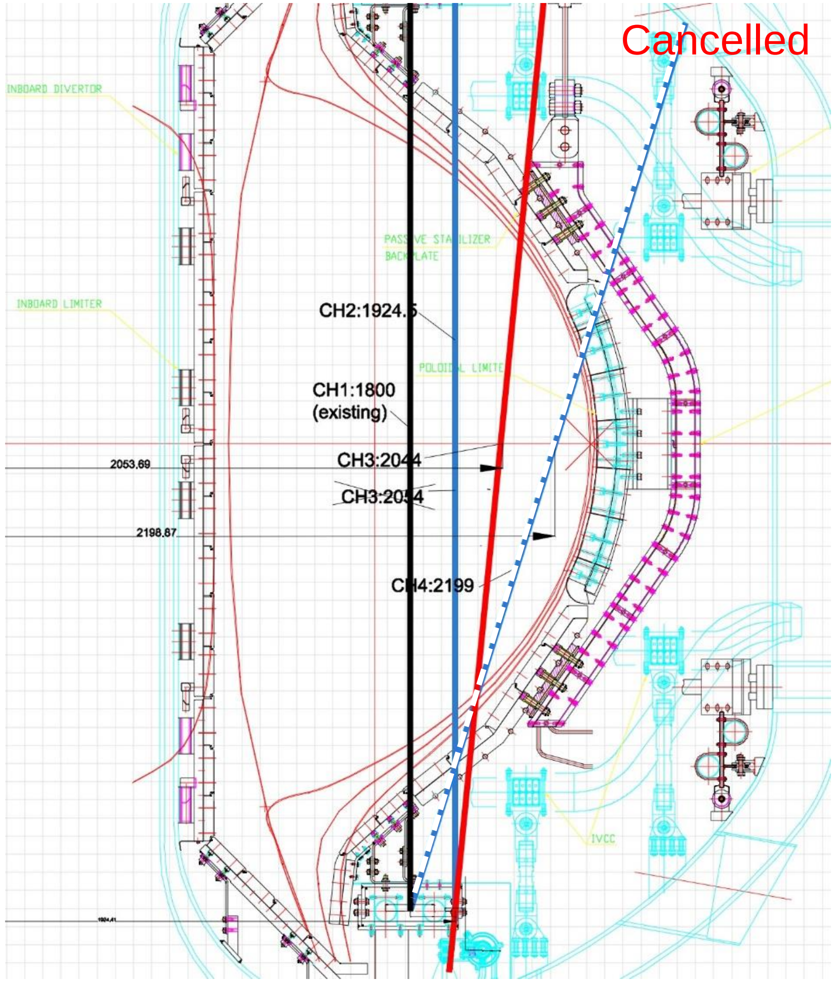
- US DOE also supported this work under DE-SC0020299 and DE-AC05-00OR22725.

- The authors are grateful for the valuable support from ECWC researchers (T. Nakano, S.H. Hong, H.H. Lee).

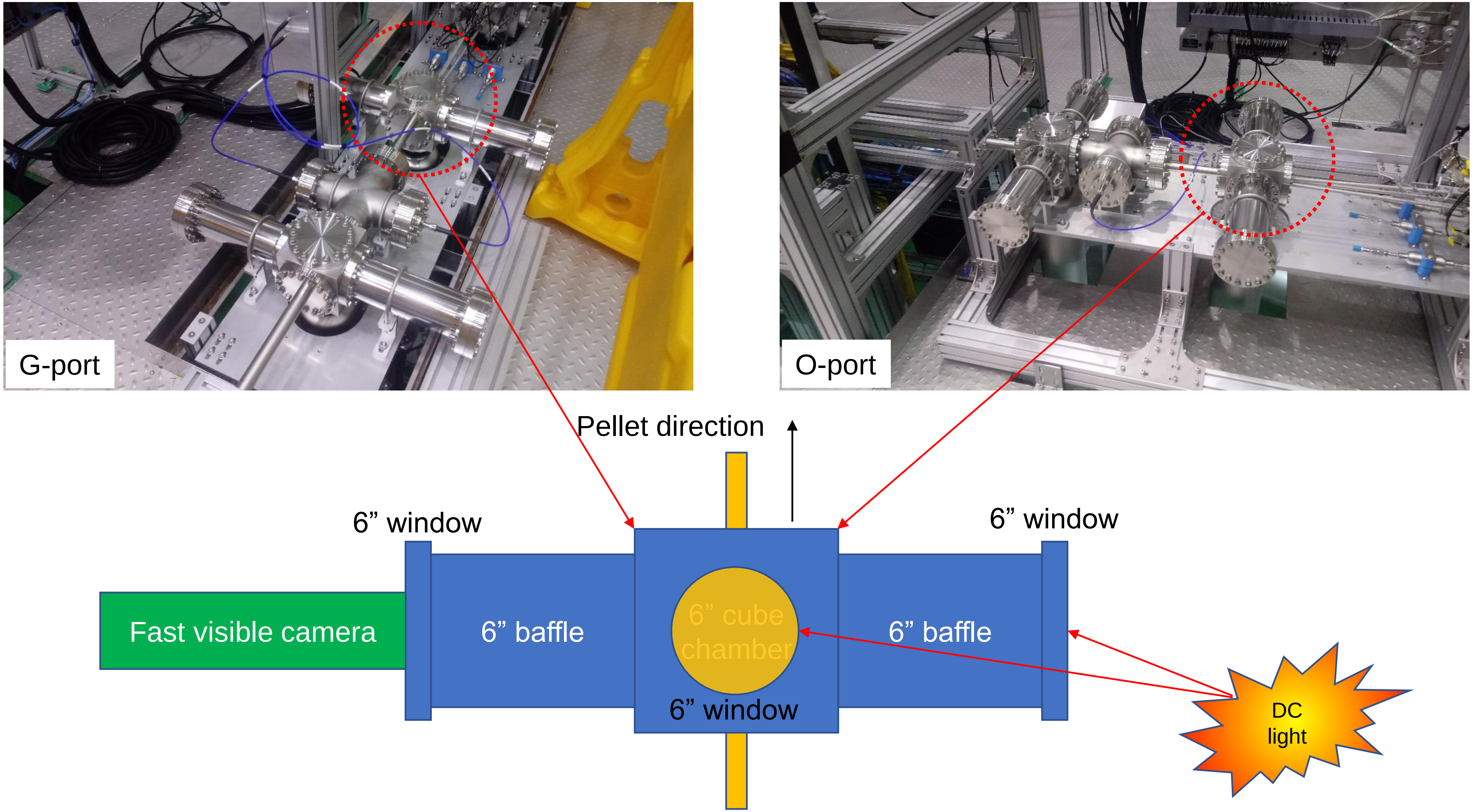
On-going work: *new vibration-free* single crystal dispersion interferometer (1064 nm) for measuring very high density during massive material injection (funded by IO)

- Continuous test for improving density measurement was conducted during ECWC session (November 25th, 2020).
- Finally, we got very nice signal with new vibration-free configuration.
  - This configuration was applied only in 3rd channel of SCDI.
  - All three channels will have new configuration from 2021 campaign.

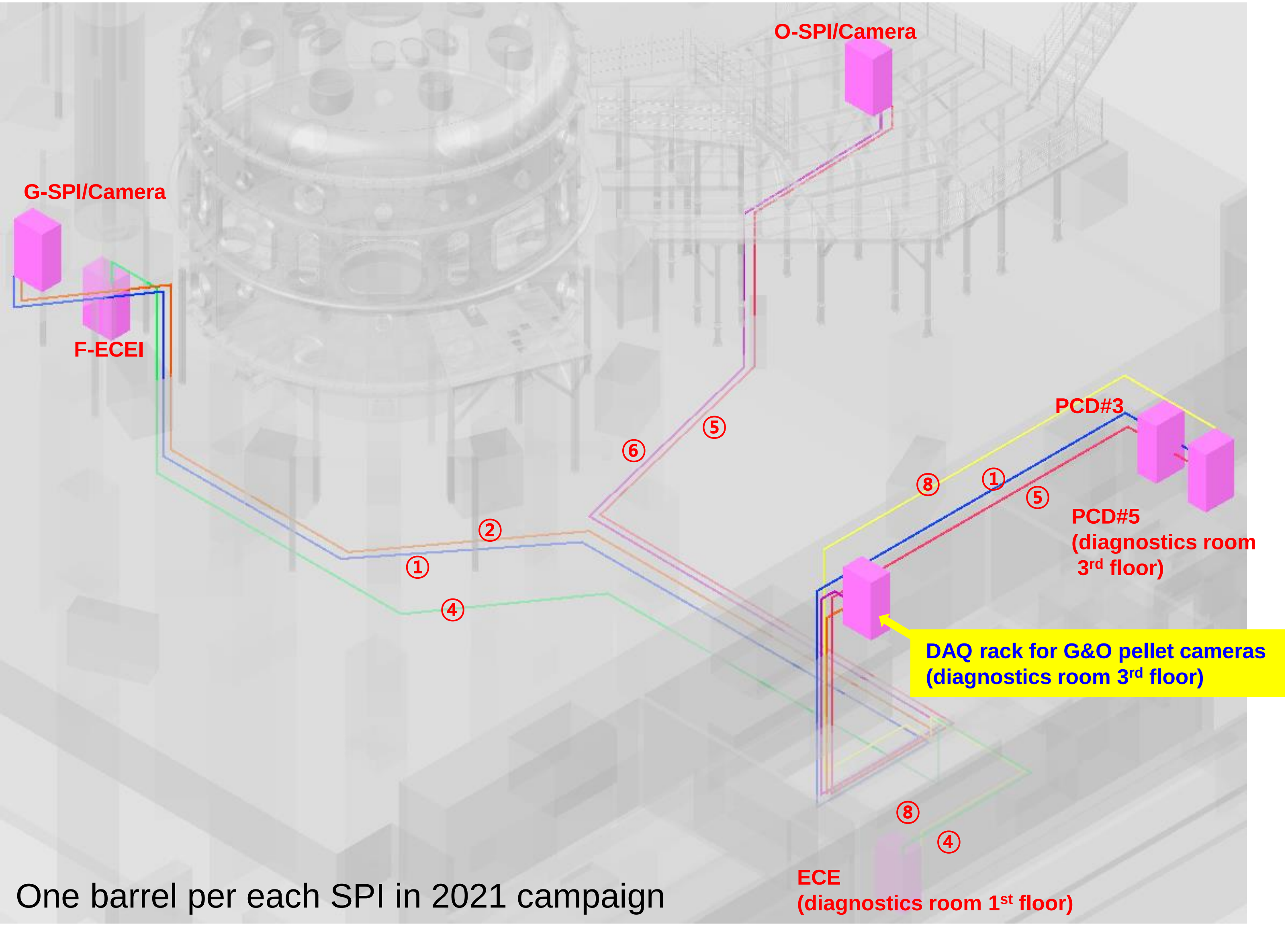




On-going work: imaging diagnostics for checking pellet integrity especially for small pellet: funded/supported by IO and ORNL



On-going work: integration of real-time diagnostics with PCS and SPI



①: 80m (x 4ea)
- G-SPI → PCS #3
- ST-ST Muti mode 62.5μm (AFL-500)

②: 70m (x 2ea)
- G-Camera → DAQ rack for G&O pellet camera
- LC-LC Multi mode 2C 1G (Ethernet fiber optic converter)

④: 60m (x 4ea)
- F-ECEI → ECE
- miniSAS 100 m

⑤: 70m (x 4ea)
- O-SPI → PCS#3
- ST-ST Muti mode 62.5μm (AFL-500)

⑥: 60m (x 2ea)
- O-Camera → DAQ rack for G&O pellet camera
- LC-LC Multi mode 2C 1G (Ethernet fiber optic converter)

⑧: 40m (x 4ea)
- PCS #5 → ECE