Disruption mitigation by multiple injection of shattered pellets in KSTAR

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IAEA technical meeting on plasma disruptions and their mitigation

Cadarache, France → On-line

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Contents

- Main goal of *symmetric* dual shattered pellet injectors (SPIs)
- Simultaneous injection of SPIs
  - Dual injections from different toroidal locations (180° separation in KSTAR)
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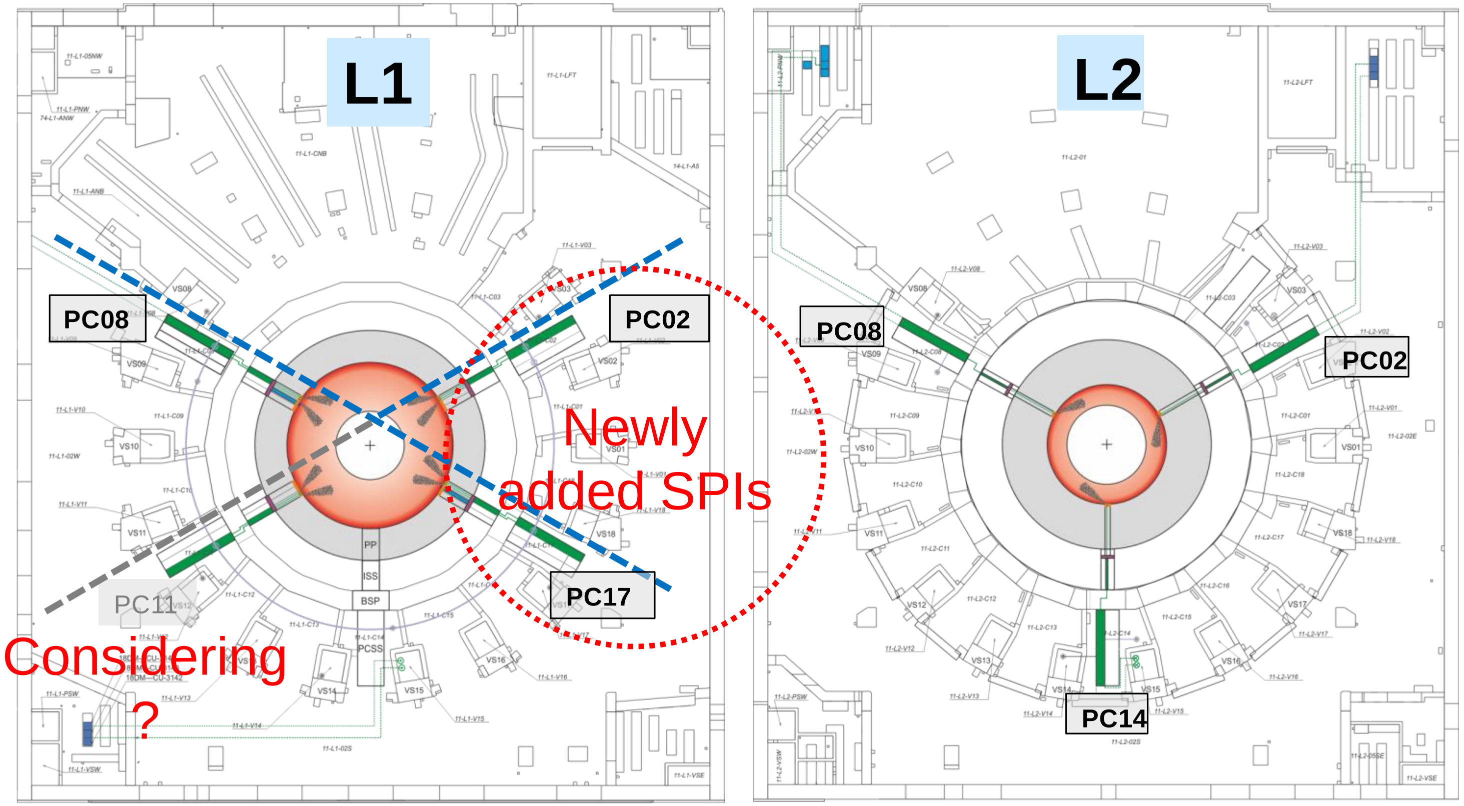
- Wall recovery from massive material injection in superconducting tokamak
- Summary and future plan

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

- When considering RE avalanche, initial avoidance of RE is important in ITER.
- Thus, ITER adopts massive low Z injection to increase density suddenly.
- For the purpose, two more SPIs will be added on equatorial plane.

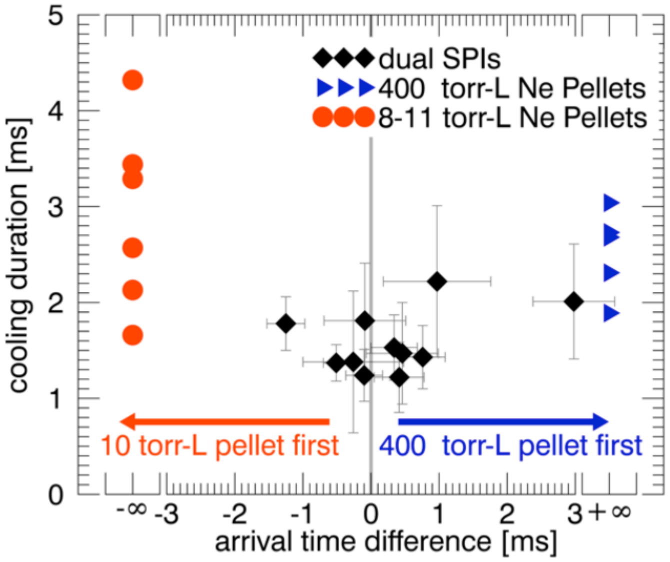


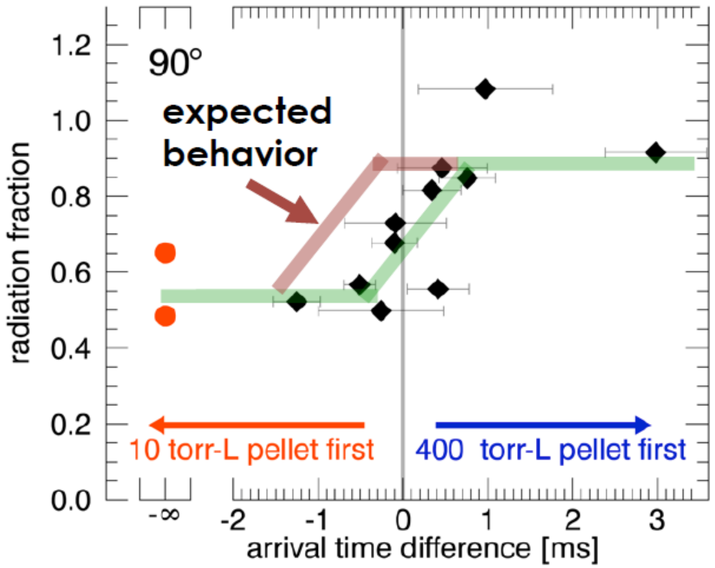
M. Lehnen, ITPA-CC meeting (2019).

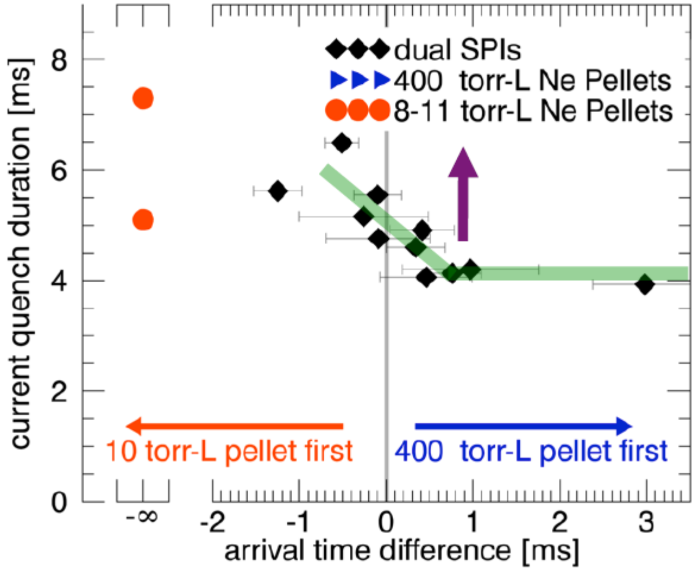
However, the feasibility of simultaneous multi-injection has not been fully demonstrated.

- Dual injections in DIII-D exhibited somewhat confusing results.
  - Simultaneous injection showed fast cooling time up to thermal quench.
  - On the other hand, total radiation in simultaneous injection seems to be decreased.
    - Slow current quench duration supports the reduction of total radiation as well.

Fast cooling due to dual SPIs → Less radiation → Slow current decay







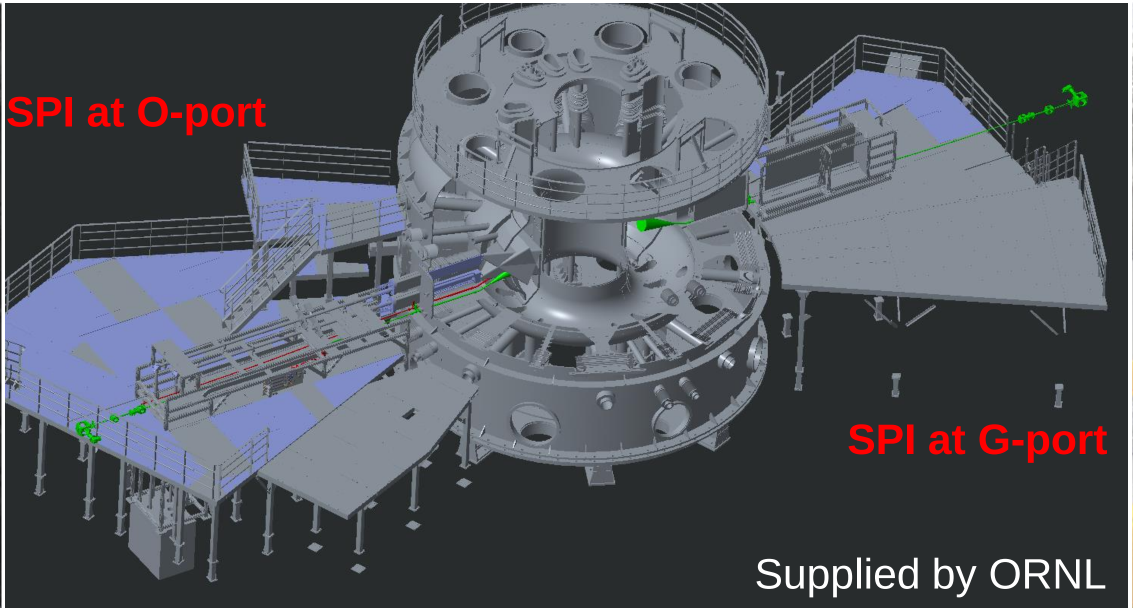
J.L. Herfindal et al., APS-DPP (2017).

The problem with simultaneous multiple SPIs is similar to obtaining enough water by melting snow ASAP.

- Snow can extinguish the bonfire itself: Bonfire vs. Snow ↔ Plasma vs. SPIs
- How to get enough density for suppressing runaway electrons?
- The problem could be complicated depending on the relation of players.

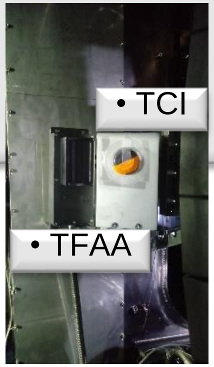
KSTAR installed dual SPIs for symmetric multi-injection.

- In KSTAR, two identical SPIs were installed in toroidally opposite locations.
  - 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 (i.e., amount of particles): 4.5, 7.0, 8.5 mm → 4.5, 2 x 7.0 mm
    - KSTAR volume: $1.8 \times \pi \times (0.45)^2 \times 2 \times \pi \times 3.14 \times 1.8 \sim 12.9\ m^3$
    - 4.5 mm: D# $=2.18\times10^{21}$, Ne# $=3.83\times10^{21}$, Ar# $=5.37\times10^{21}$, (D# of shell 1.10×10^{21})
    - 7.0 mm: D# $=8.77\times10^{21}$, Ne# $=1.54\times10^{22}$, Ar# $=2.16\times10^{22}$, (D# of shell 2.70×10^{21})
    - 8.5 mm: D# $=1.60\times10^{22}$, Ne# $=2.82\times10^{22}$, Ar# $=3.96\times10^{22}$, (D# of shell 4.00×10^{21}) ← Punch will be installed.



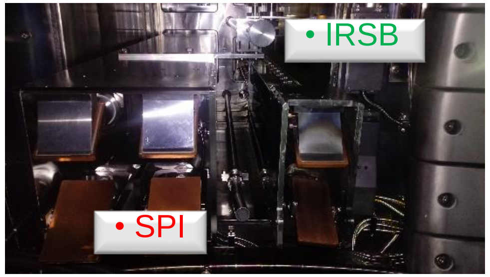
Installation/upgrade of diagnostics are concurrently progressing for investigating the disruption mitigation.

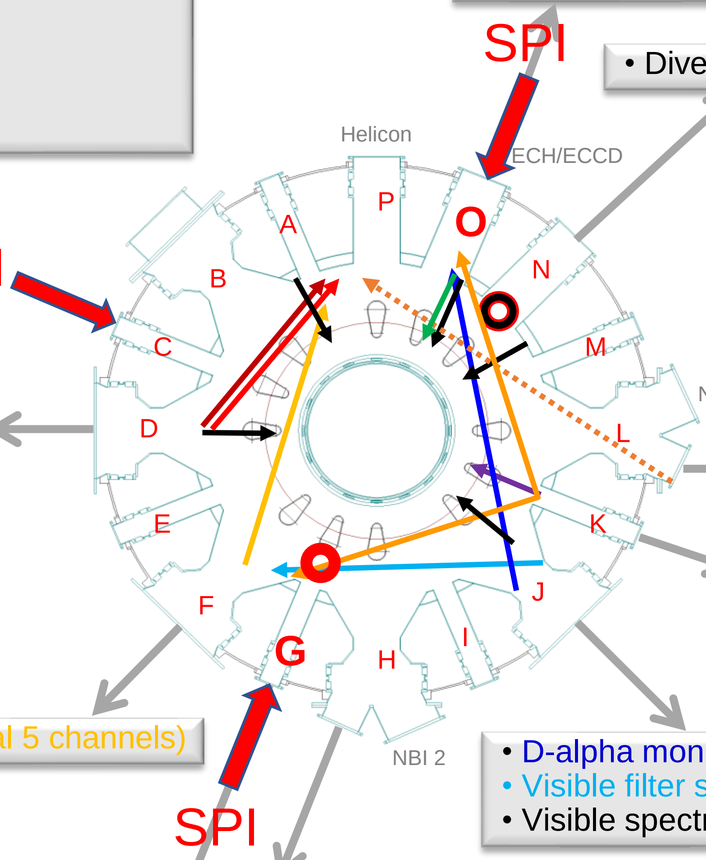
Toroidal AXUV arrays from O-port SPI
#1: +56.25 °
#2: -11.25°
#3: -33.75°
#4: -101.25°



- 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)

- *Fast imaging bolometer (>1 kHz)*

- 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

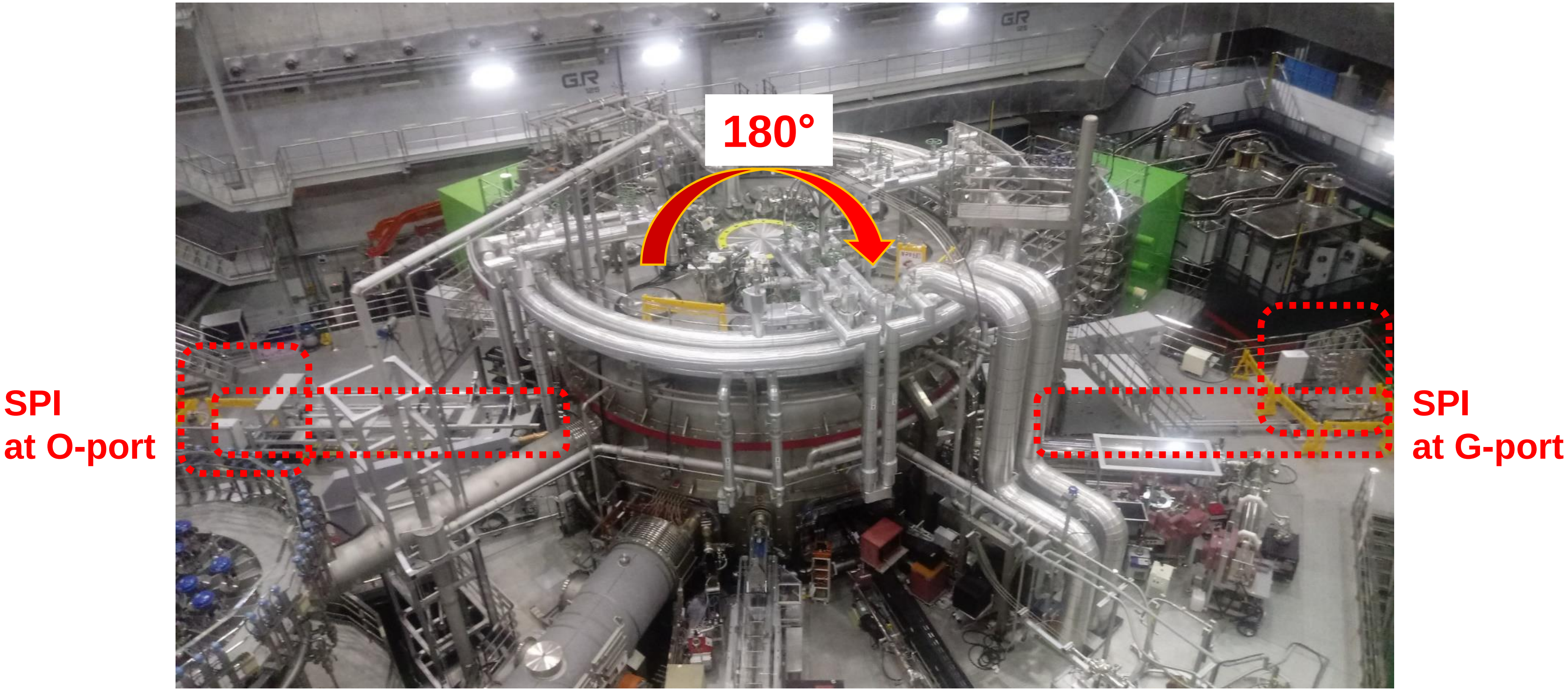
- ECEI 1 (500 kHz)

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

- Hard X-ray monitor
- Neutron detector

1st SPI injected in November, 2019 and 2nd SPI injected in January, 2020

- To achieve perfect symmetry, the flight tube length had to be ~ 12 m.
- This is longer than the ITER flight tube (~ 6 m).



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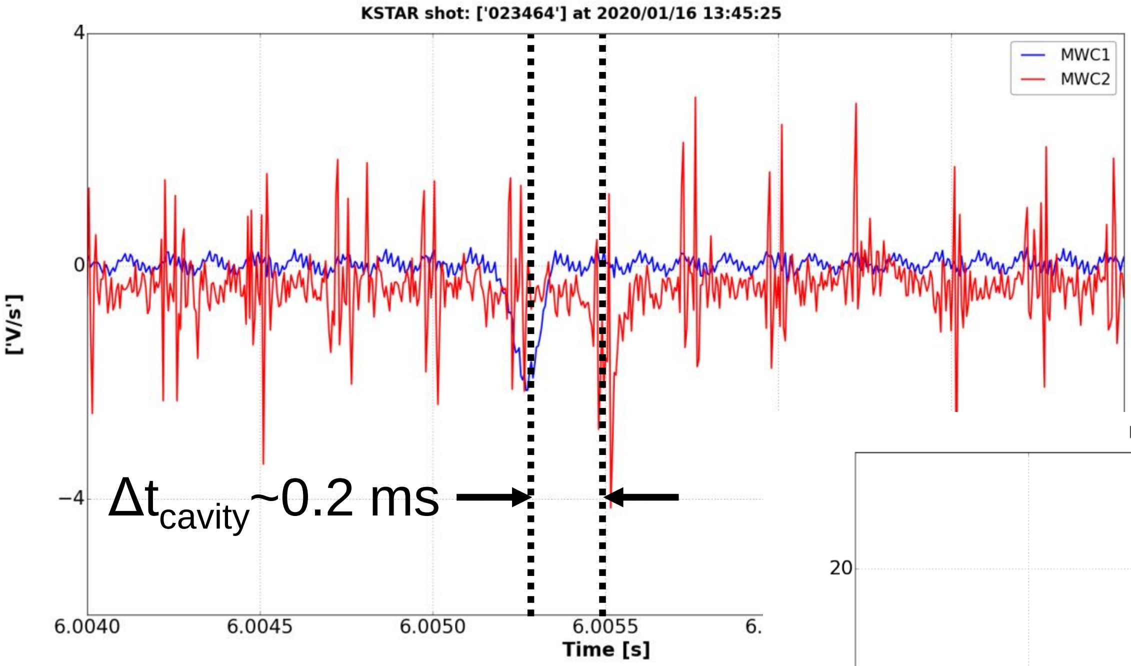
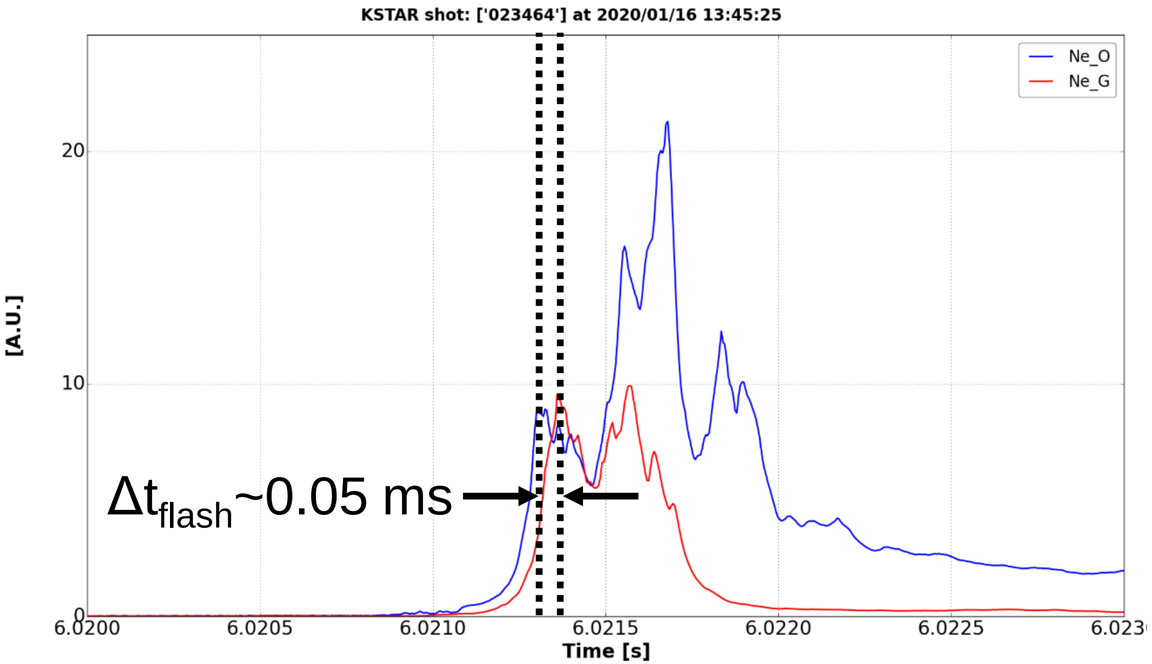
Simultaneous injection of dual SPIs showed good synchronization (Δt_{cavity}~0.2 ms) in microwave cavity signal and (Δt_{flash}~0.05 ms) in neon flash.

- This time difference is well within thermal quench duration (~1 ms).



Microwave cavity signals from SPI_O and SPI_G

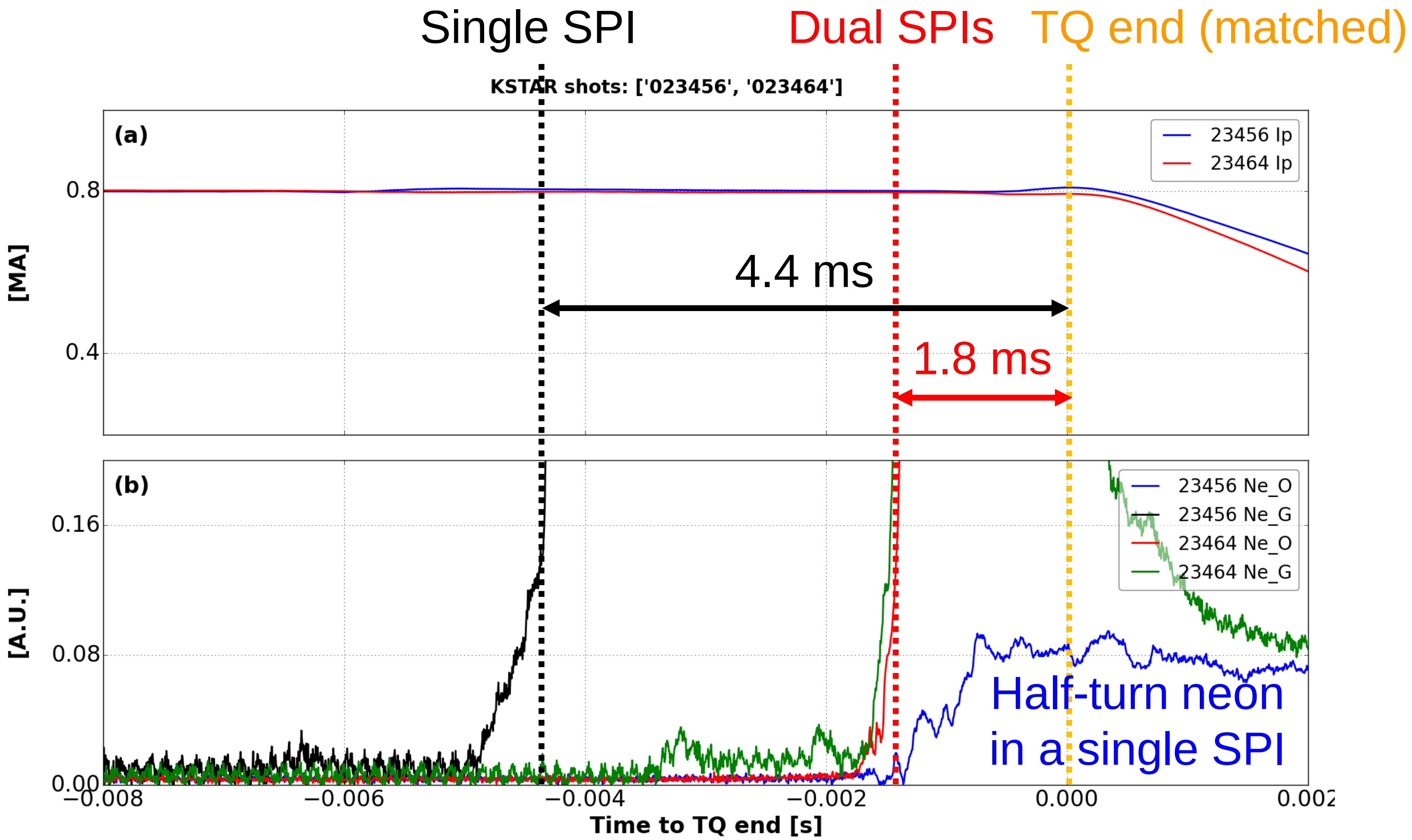


Neon flashes from O and G ports

Dual SPIs have a shorter cooling time to thermal quench when compared to a single SPI.

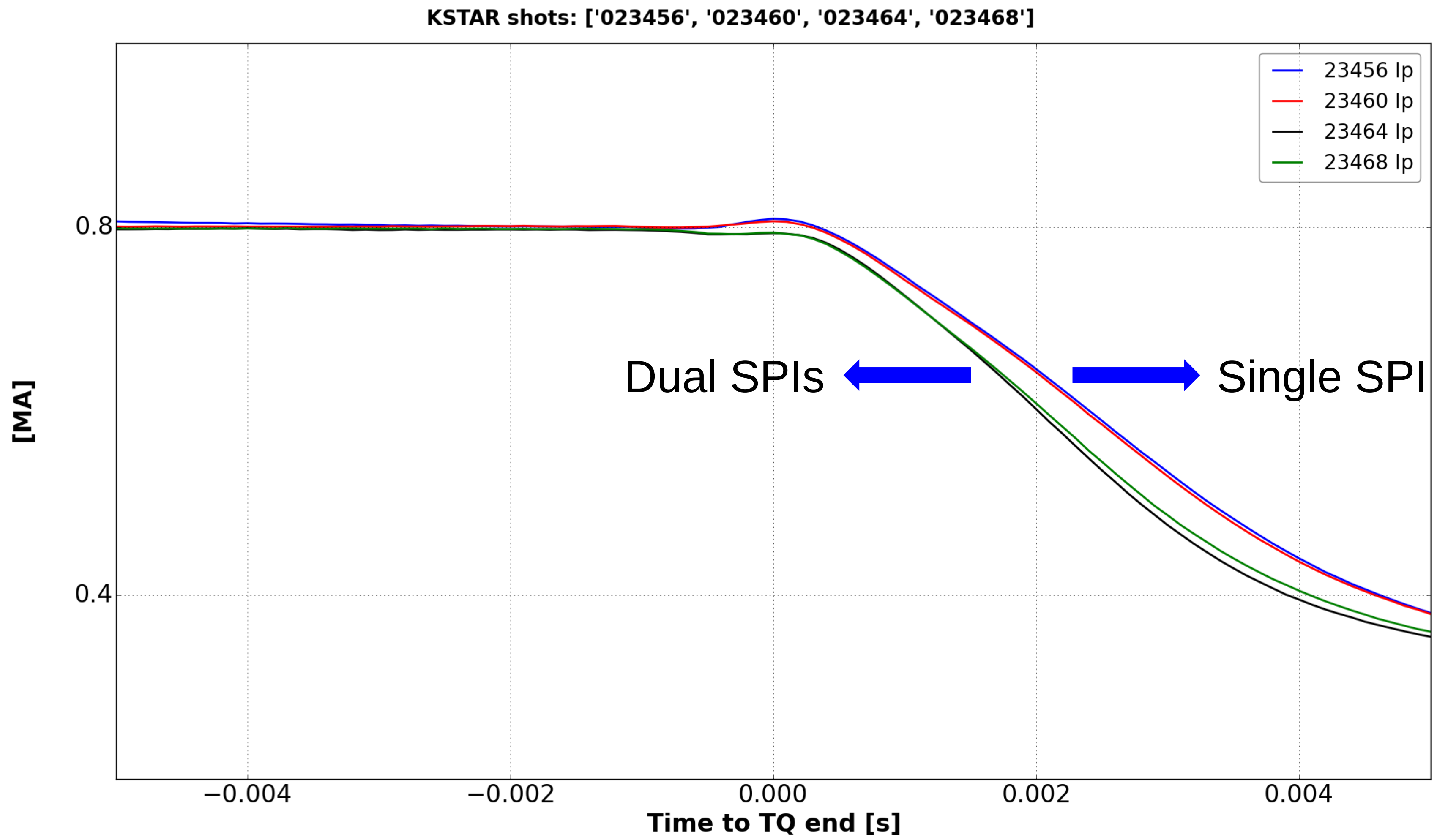
Ne:D atom ratio = 5:95 in 7.0 mm pellet

Target discharge: NB+EC heated 800 kA H-mode discharge (W_{MHD}~450 kJ, q_{95}~3.2, β_p~1)



Dual SPIs brought early thermal quench and also fast current quench rate in KSTAR.

- This result is different from previous DIII-D result with 120° separated SPIs.
- Why? Due to the exact symmetric injection of KSTAR SPI?

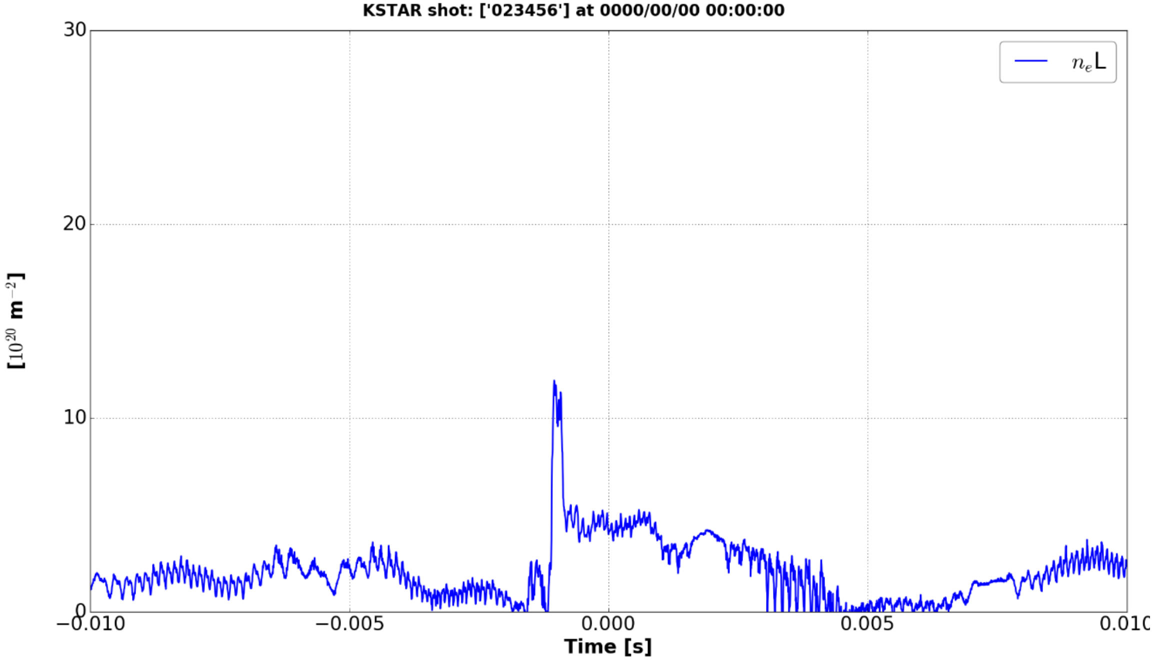


Dual SPIs made higher density during disruption mitigation
→ promising result in relation with ITER DMS strategy against RE suppression.

- New dispersion interferometer measured the abrupt density rise.
  - It uses short wavelength (1064 nm) for avoiding density cutoff and refraction.
  - Conventional two color interferometer suffered fringe jump during disruption mitigation.

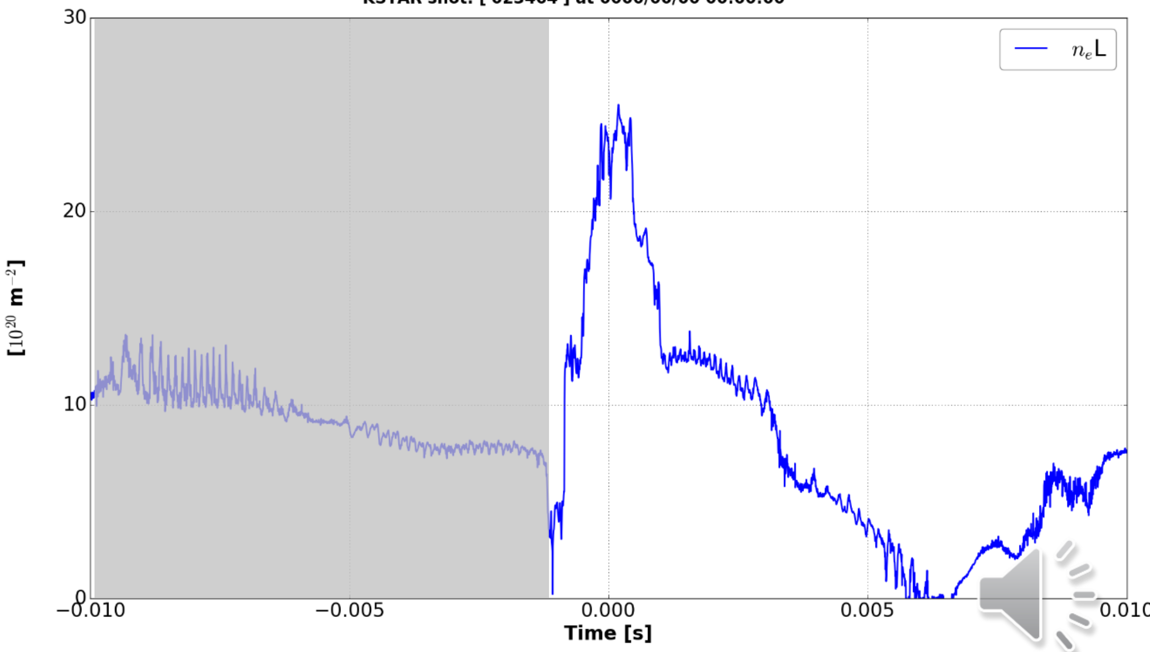
Nearly double density by dual SPIs

#23456: single SPI (7.0 mm)



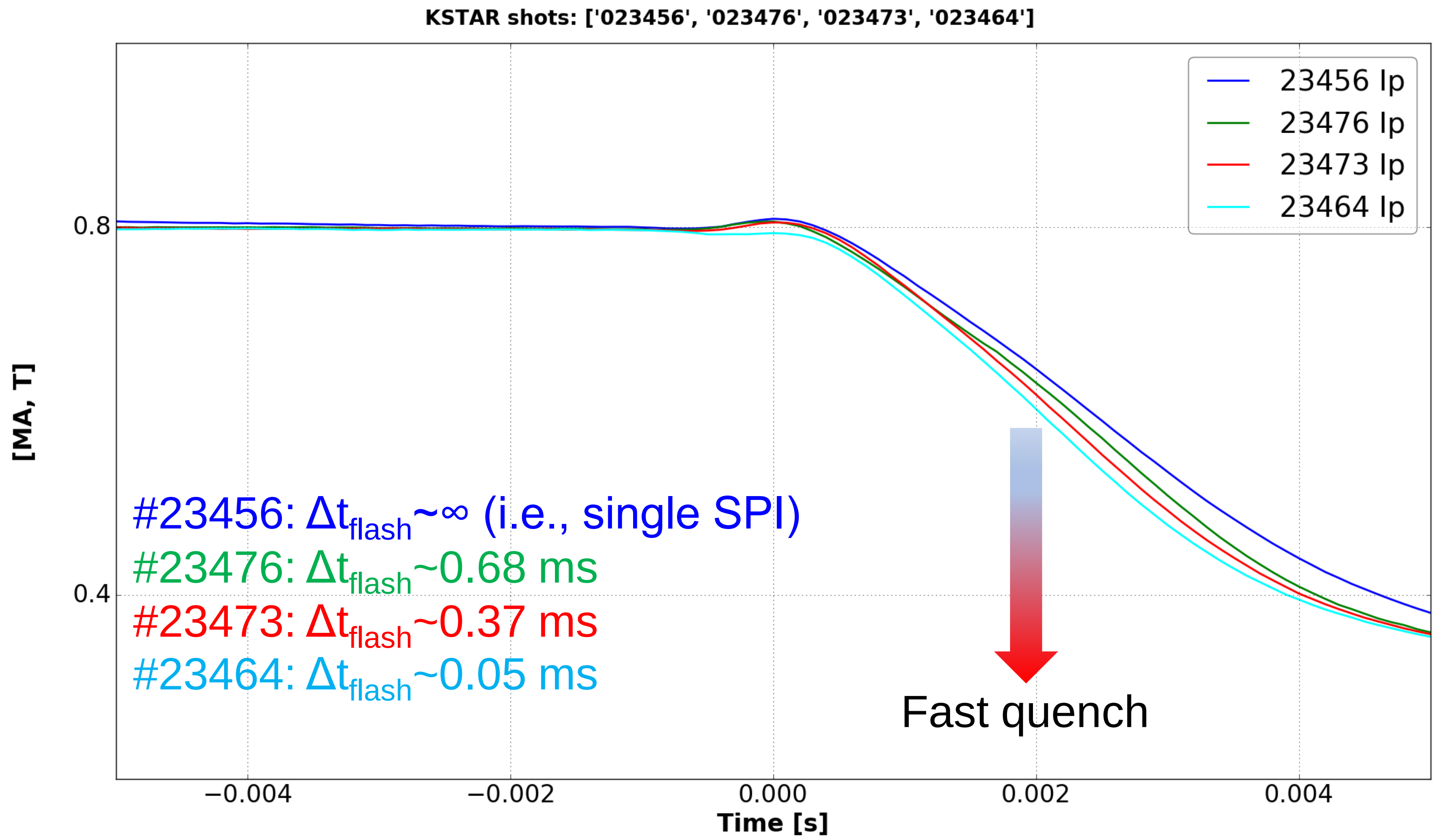
#23464: dual SPIs (7.0+7.0 mm)

← Δt_{flash}~0.05 ms



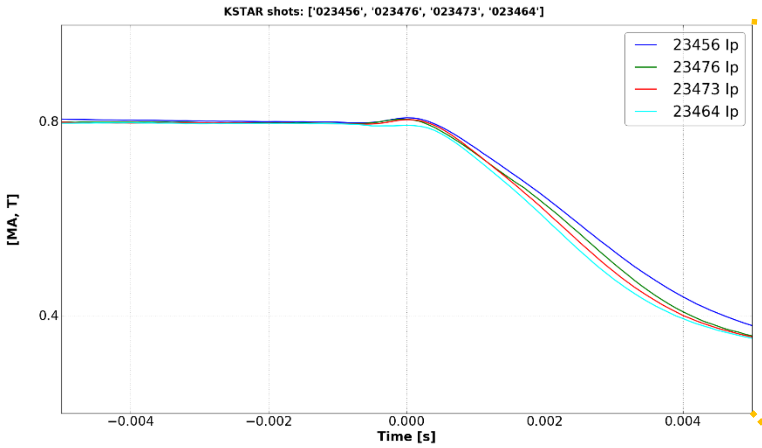
Intentional asynchronization of dual SPIs exhibited slower current quench in proportion to the time delay between two SPIs.

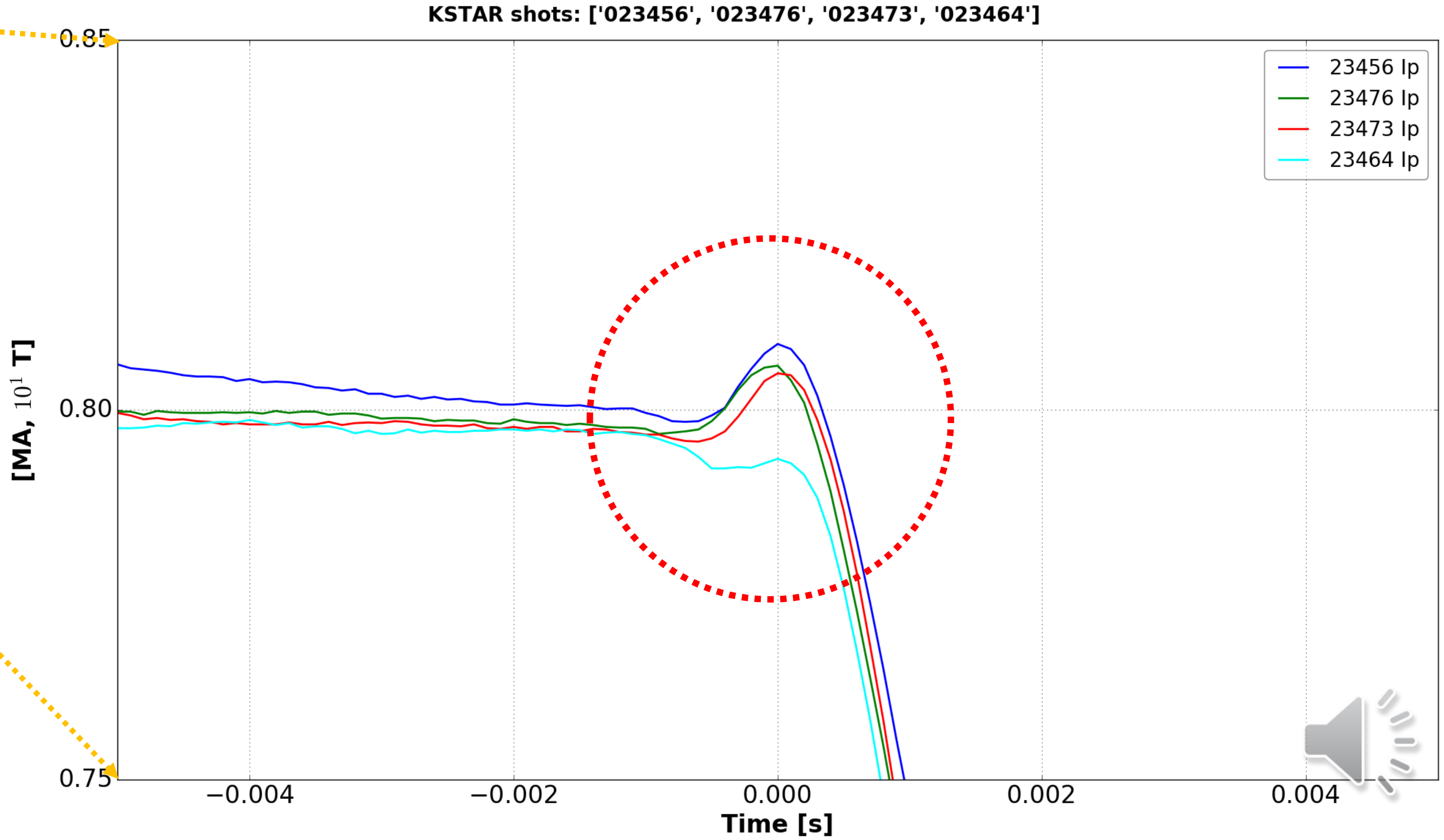
- Even within thermal quench duration, the delay level affected the quench rate.
- We measured the time delay by the abrupt increase of neon flash Δt_{flash}.



Different shape of I_p spike reflects different disruption processes during thermal quench depending on the level of synchronization.

- Is it originated from the geometry of SPIs (single vs. dual)?
- Or just from the amount/species of injected impurities?

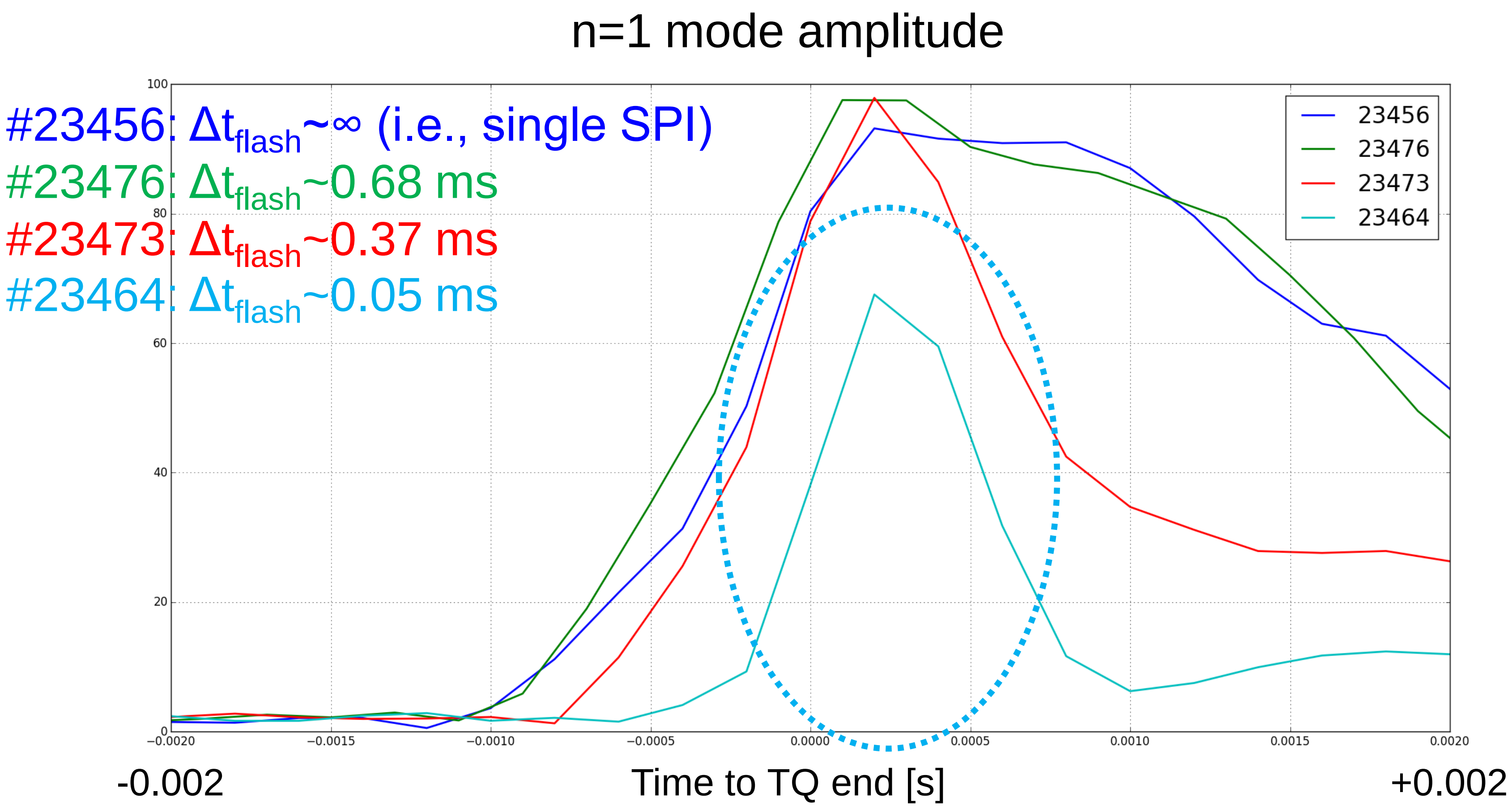




#23456: Δt_{flash}~∞ (i.e., single SPI)
#23476: Δt_{flash}~0.68 ms
#23473: Δt_{flash}~0.37 ms
#23464: Δt_{flash}~0.05 ms

n=1 mode amplitude of exact synchronization was meaningfully low during thermal quench.

- How much does it affect the mixing of impurity?
- #23473 showed similar peak amplitude but rapid drop when compared to #23456 and #23476.



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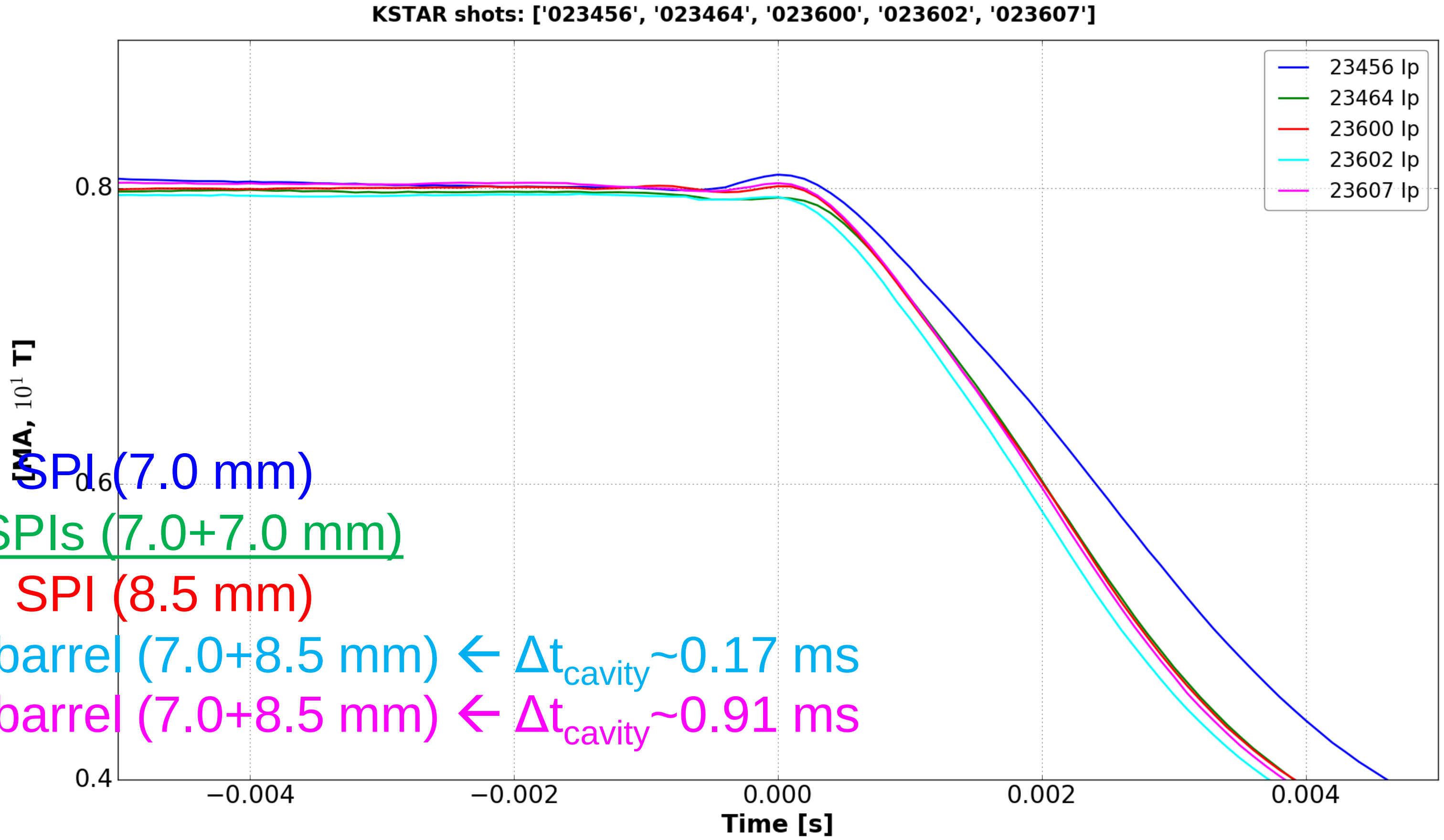
Multi-barrel injection from same toroidal and poloidal location showed similar current quench rate with dual SPIs.

- Same amount of neon was used in both 7.0 mm and 8.5 mm pellets.
  - 7.0 mm: Ne (1.2×10^{21}) / D (2.3×10^{22}) vs. 8.5 mm: Ne (1.2×10^{21}) / D (4.2×10^{22})
- Is the dilution cooling also important? #23456 (7.0 mm) vs. #23600 (8.5 mm)



#23456: single SPI (7.0 mm)

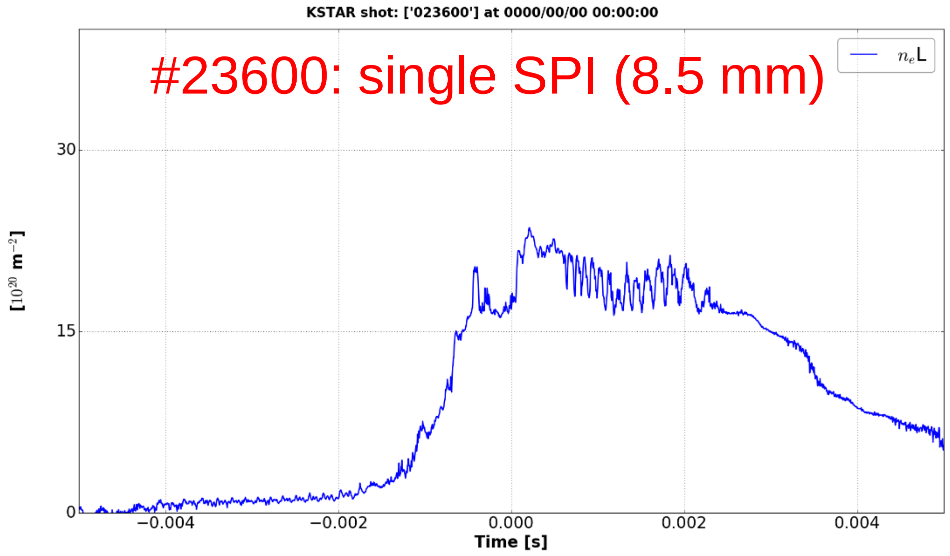
#23464: dual SPIs (7.0+7.0 mm)

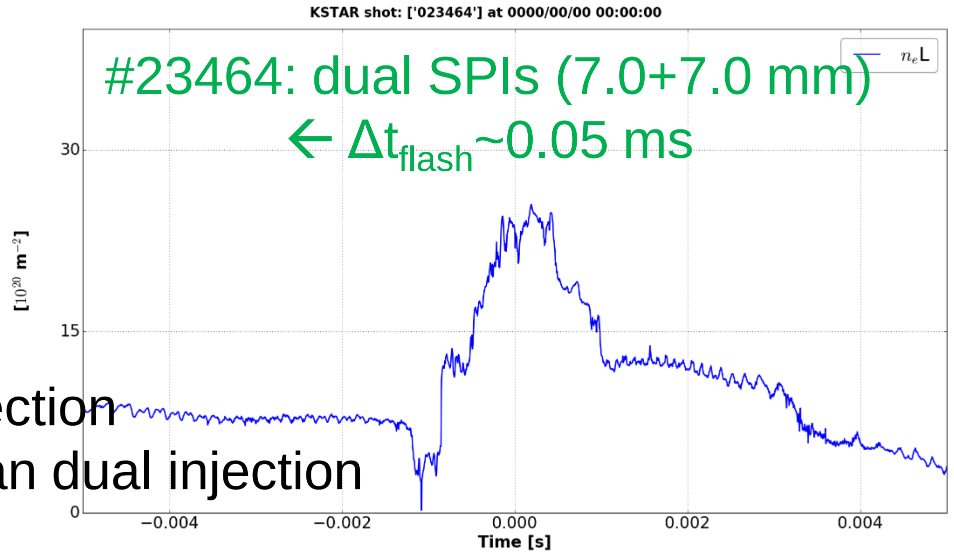
#23600: single SPI (8.5 mm)

#23602: multi-barrel (7.0+8.5 mm) ← Δt_{cavity}~0.17 ms

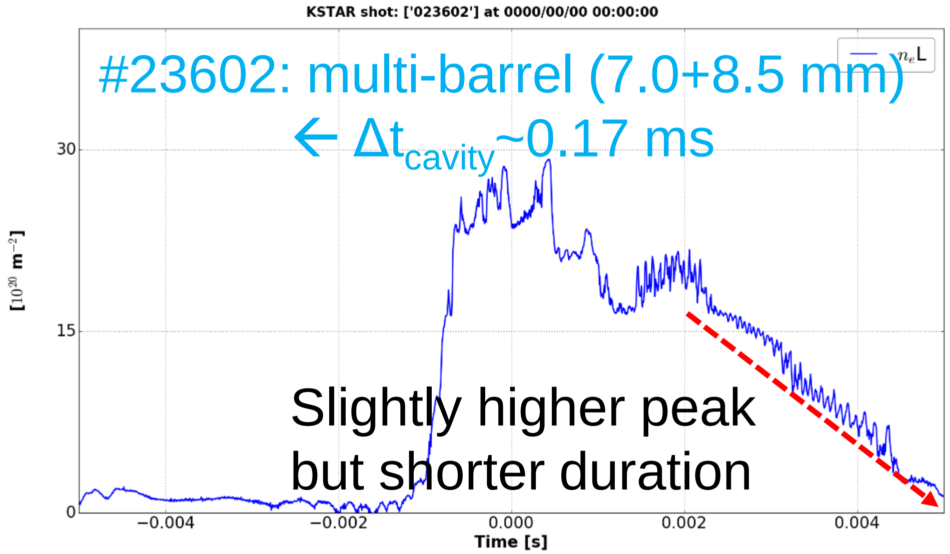
#23607: multi-barrel (7.0+8.5 mm) ← Δt_{cavity}~0.91 ms

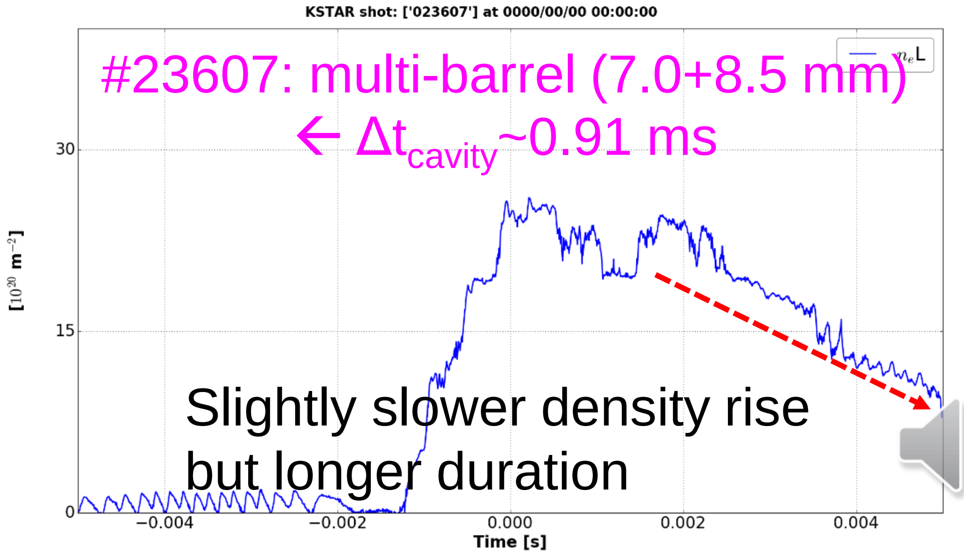
Multi-barrel injection from same location also made higher density during disruption mitigation
→ promising result in relation with ITER DMS strategy against RE suppression.





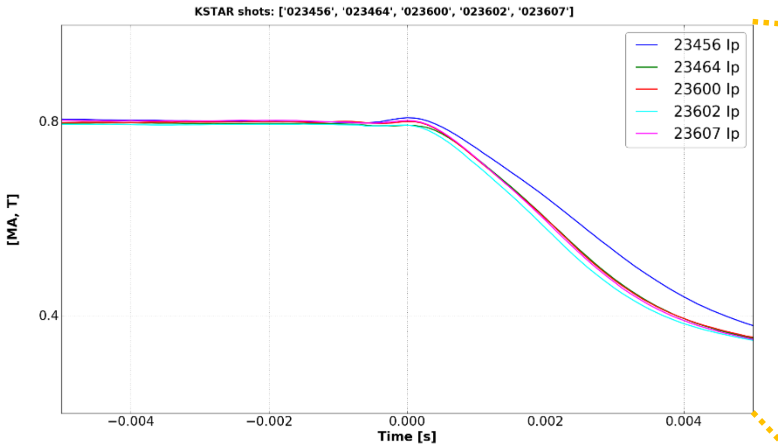
Multi-barrel injection even higher than dual injection





Synchronized dual (#23464) and also synchronized multi-barrel (#23602) showed smaller I_p spike than others.

- I_p spike of #23607 is more close to that of #23600.
- Should we consider both the geometry effect and the amount of particles?
  - Is the disruption process between #23464 and #23602 similar?



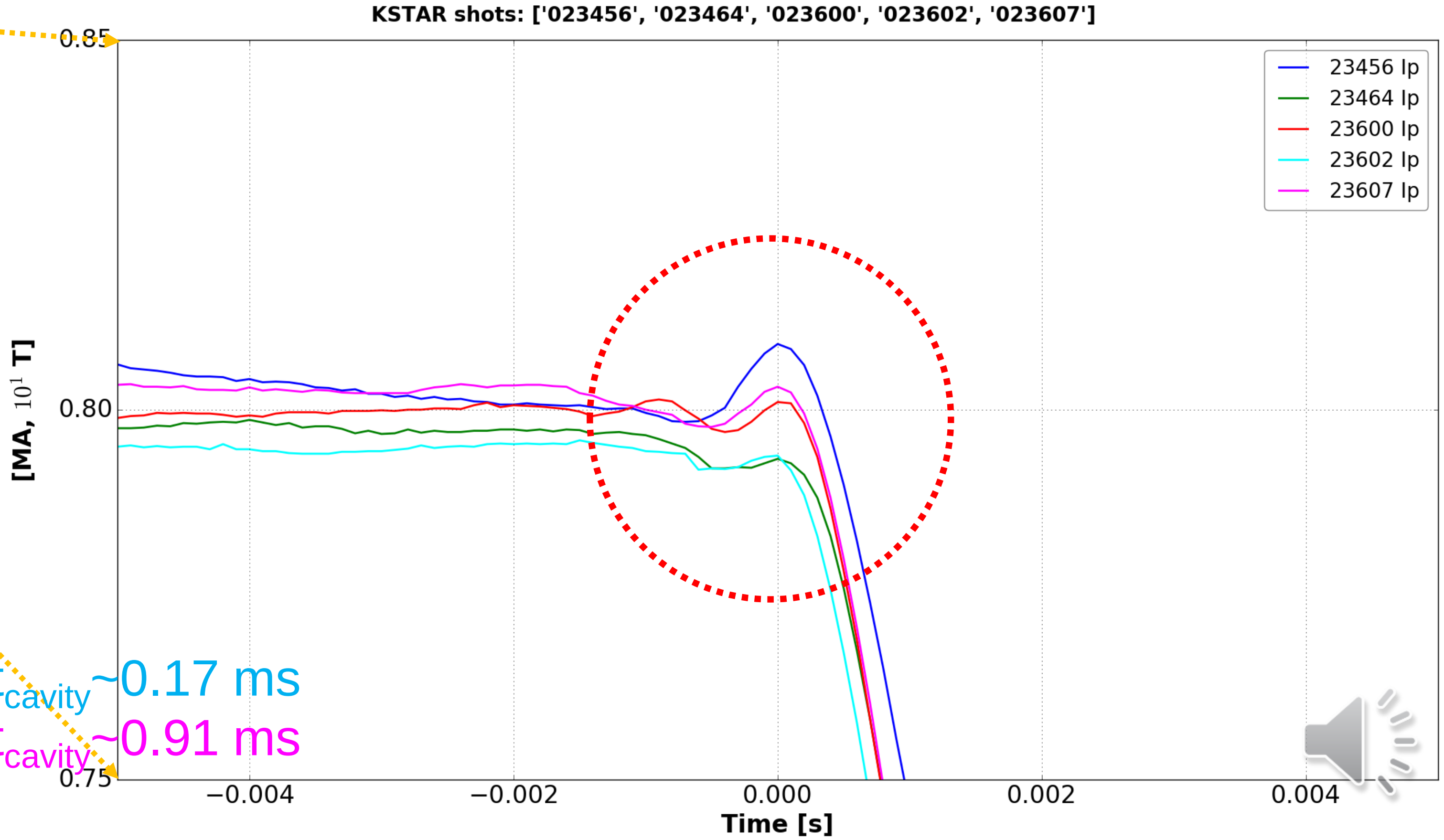
#23456: single SPI (7.0 mm)

#23464: dual SPIs (7.0+7.0 mm)

#23600: single SPI (8.5 mm)

#23602: multi-barrel (7.0+8.5 mm) ← Δt_{cavity}~0.17 ms

#23607: multi-barrel (7.0+8.5 mm) ← Δt_{cavity}~0.91 ms



Larger perturbation (SPI) on single side caused more strong n=1 MHD activity.

- Probably, the disruption process between #23464 and #23602 could be different.

n=1 mode amplitude

#23456: single SPI (7.0 mm)
#23464: dual SPIs (7.0+7.0 mm)
#23600: single SPI (8.5 mm)
#23602: multi-barrel (7.0+8.5 mm) ← Δt_{cavity}~0.17 ms
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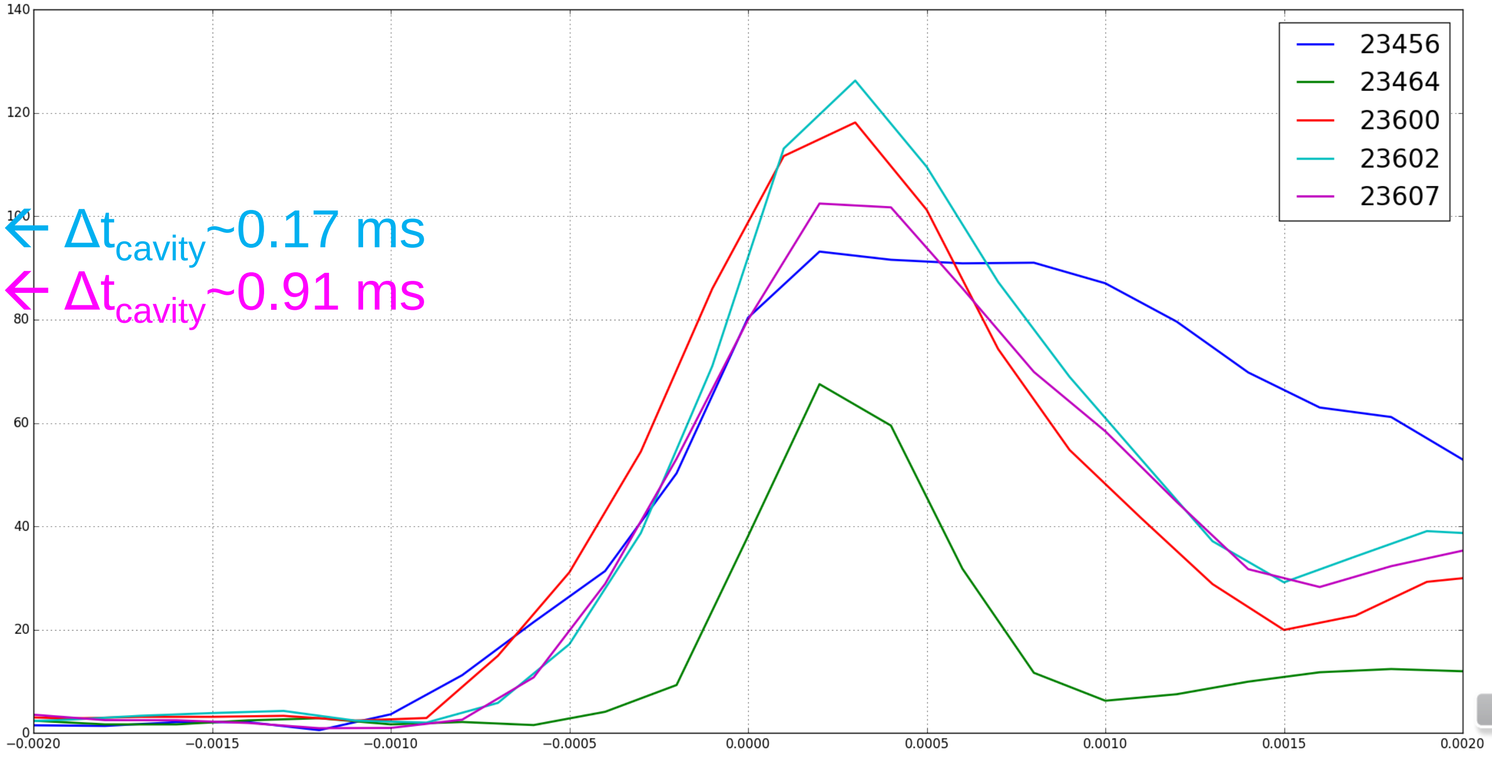

-0.002 Time to TQ end [s] +0.002

KSTAR

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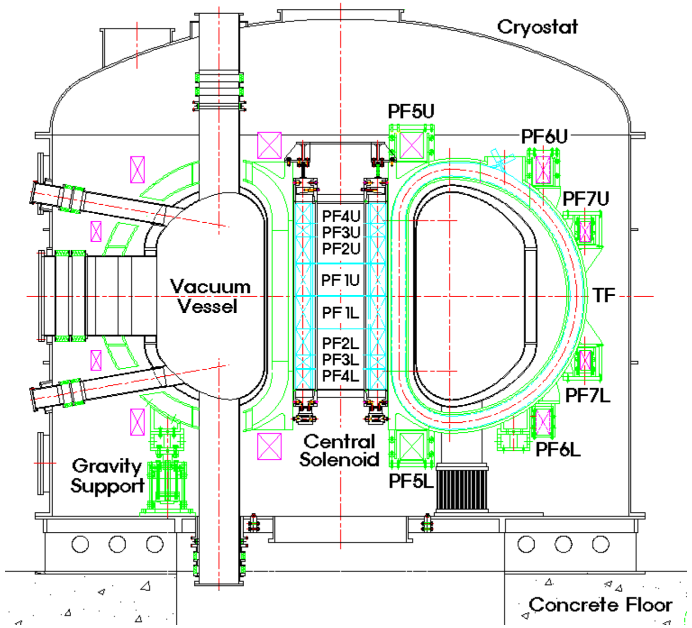
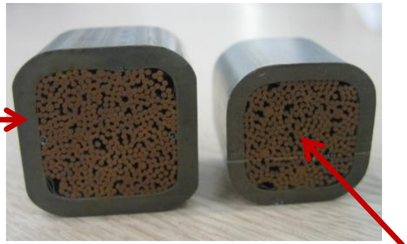
Issues (difficulties) of plasma start-up in superconducting tokamak

- Low loop voltage (~4 V, ~0.4 V/m) due to the restriction of superconducting coils
- Long field penetration time (40~50 ms) due to connected vessels and passive stabilizer
- Restriction in glow discharge cleaning due to toroidal field even after massive material injection

- Field structure deformation due to ferromagnetic incoloy 908 effect ← KSTAR specific issue
  - Incoloy 908 used in superconducting coil jacket has similar thermal expansion rate with Nb_3Sn.
  - However, ferromagnetic incoloy 908 (μ~10) nonlinearly deforms magnetic field structure.



Incoloy 908 →

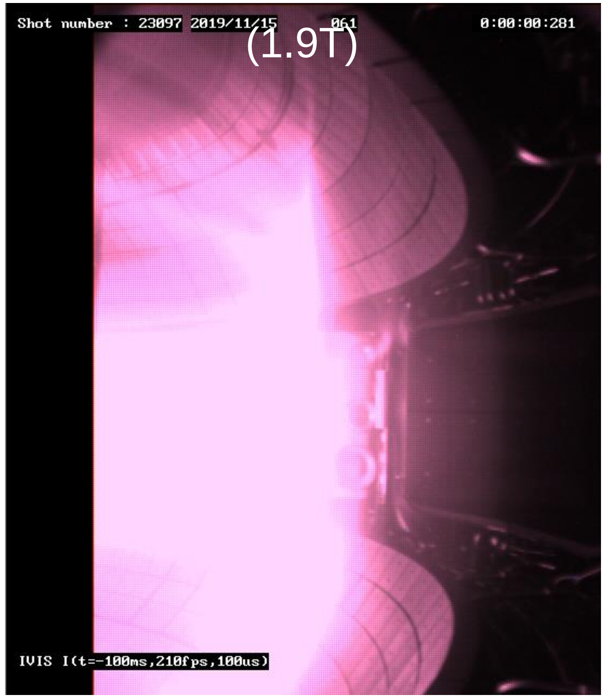


Nb_3Sn

KSTAR superconducting coils	
Coil name	Amount
TF coil	16
PF1 Coil	2
PF2 Coil	2
PF3 Coil	2
PF4 Coil	2
PF5 Coil	2
PF6 Coil	2
PF7 Coil	2
Total	30

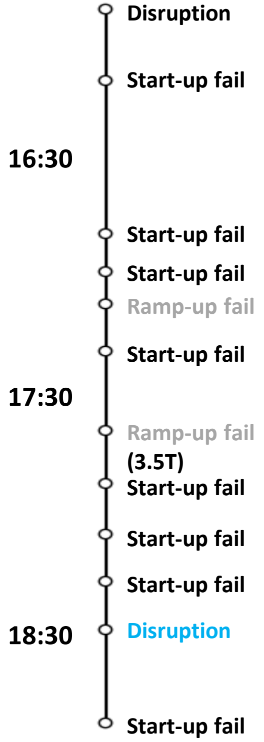
Recovery of wall condition after SPI by electron cyclotron wall cleaning (ECWC) in superconducting tokamak

- Establishment of wall recovery procedure with ECWC at B_t 1.8~1.9 T
  - Routine usage in SPI session: 16 minutes shot interval < pellet formation time
  - Little start-up failure with ECWC regardless of SPI species (D_2, Ne)
  - Reproducible discharge and stored energy



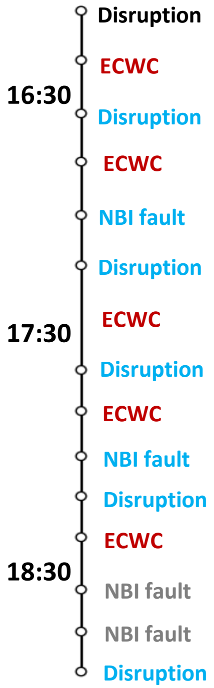
ECWC

Hard time without ECWC during 1st SPI session



Nov. 4th

Success with ECWC during 3rd SPI session



Nov. 6th

Summary and future plan

- KSTAR investigated the feasibility of multiple SPI injections to support the ITER DMS strategy.
  - Promising additive results were observed with simultaneous dual injection in two symmetric SPIs.
  - Simultaneous multi-barrel injection at the same location also showed promising additive results.
  - Synchronization is still important, even within the TQ duration (<1 ms).

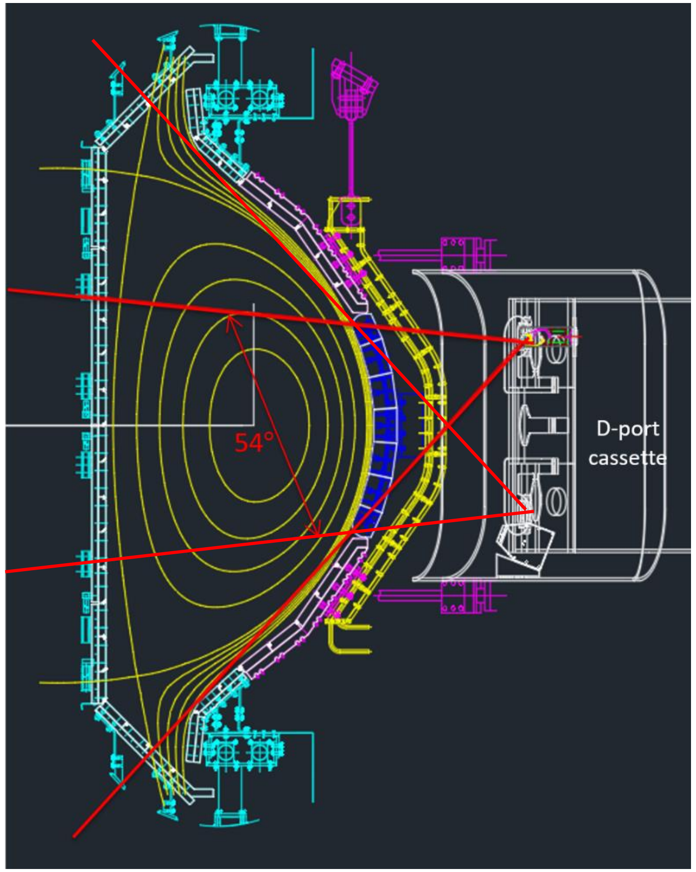
- Depending on the injection methods, the evolution of the disruption process seems to be different.
  - The n=1 mode amplitude is low as expected in synchronized dual injection.
  - The different behavior of I_P spike also reflects the different evolution of internal current profile.
  - Understanding of disruption process is important for optimizing the disruption mitigation method.

- KSTAR established a recovery process after disruption mitigation in the superconducting tokamak.
  - ECWC was effective for superconducting tokamak where glow discharge cannot be used.

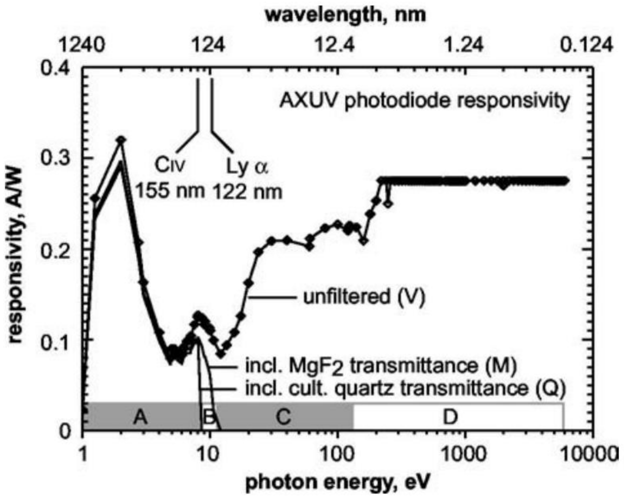
- In 2020 campaign, we will further investigate the feasibility of injecting multiple SPIs simultaneously.
  - Multi-barrel injections from two SPIs are possible using the same size barrels.
  - Upgraded diagnostics (bolometers, interferometers and fast cameras) will support the study.

Supplement

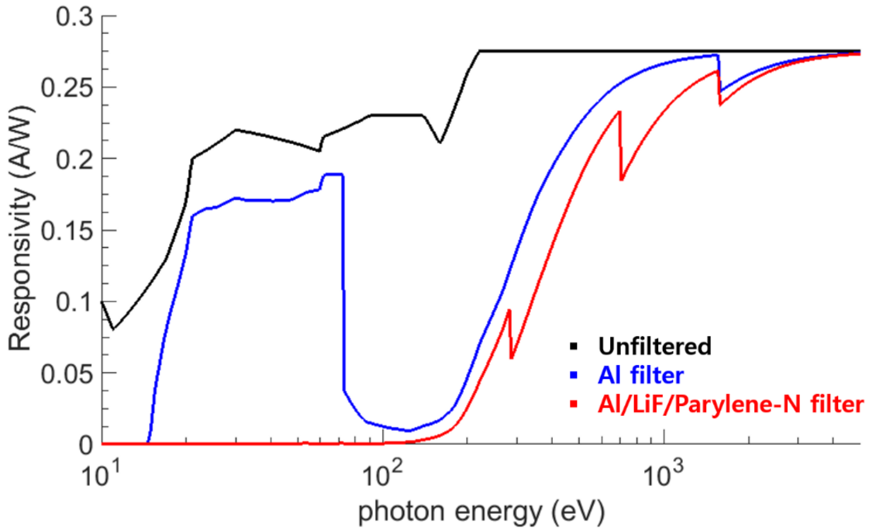
Absolute measurement of radiation power during SPI mitigation is crucial for checking the feasibility of simultaneous injection (funded by ITER DTF).



Poloidal arrays of filtered AXUVs



Spectral responsivity of AXUV*



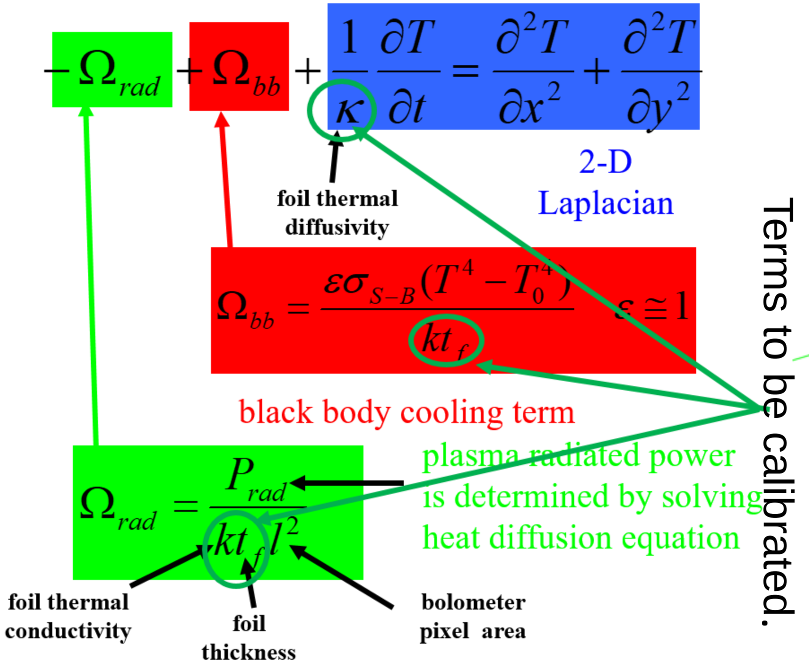
Effective responsivity with filter

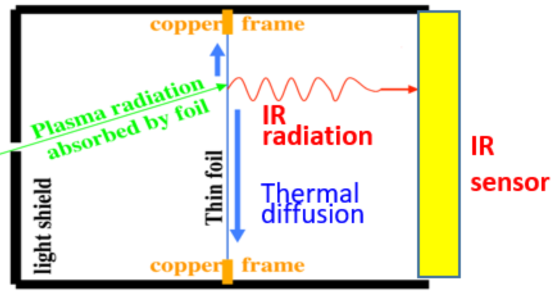
- Filtered AXUV arrays
  - A, B band : measurable by MgF_2 filter
  - C band (11 eV ~ 130 eV)
    - Filter cutoff energy ~ 130 eV
    - Flat transmission over 130 eV

*D.S. Gray *et al*, Rev. Sci. Instrum. **75** 376 (2004).

Alternative measurement of radiation power is also being prepared along with AXUV sensor based diagnostics (funded by ITER DTF).

- When considering the non-linear spectral responsivity and degradation§, other type of bolometer is needed for absolute power calibration.
- IR sensor based bolometer is being developed by POSTECH and NIFS.





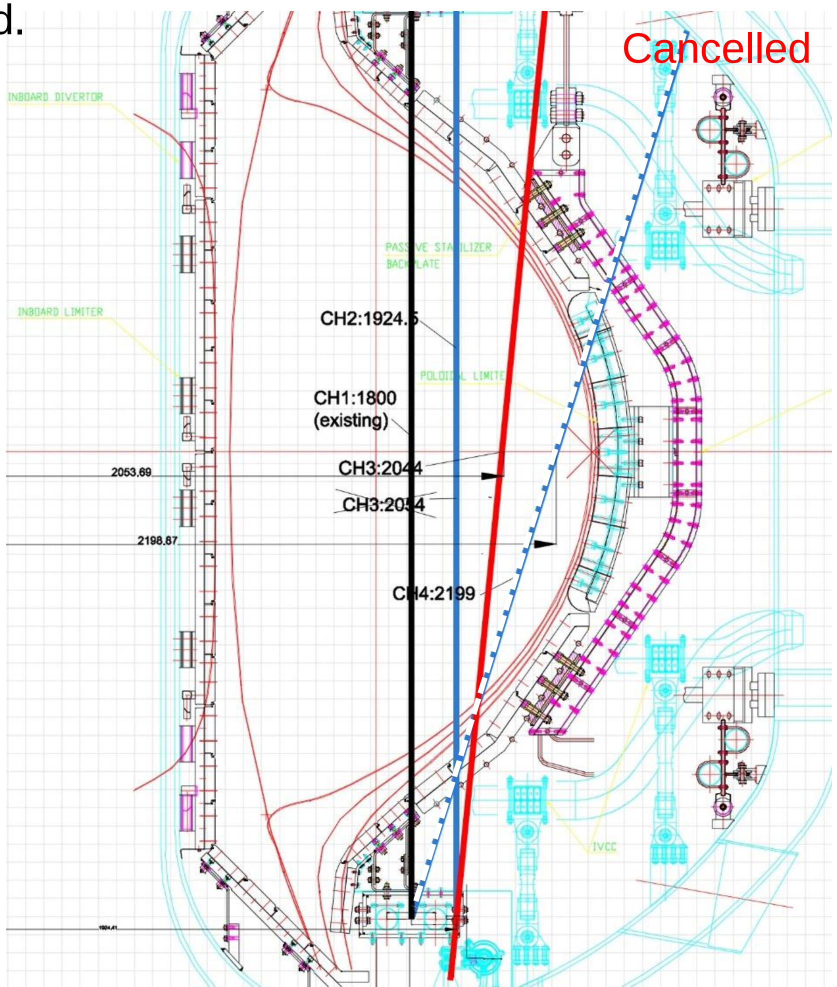
Concept of thin foil-IR sensor based bolometer

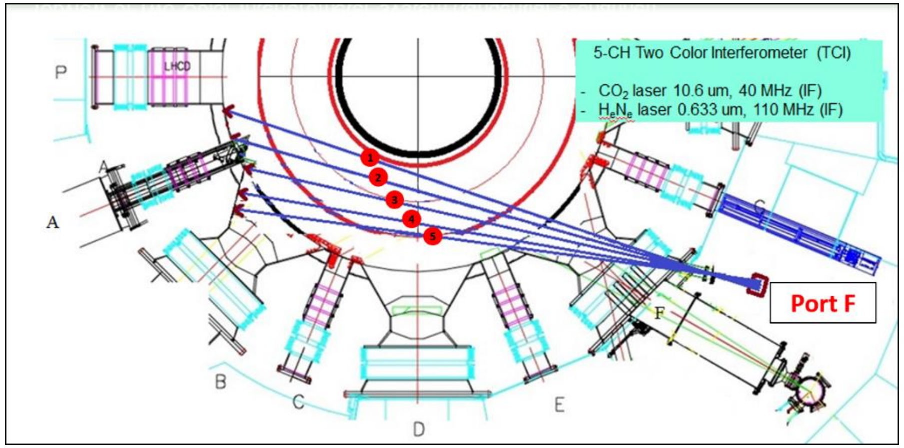
§M. Bernett et al., *Rev. Sci. Instrum.* **85**, 033503 (2014).
*B.J. Peterson *et al., Rev. Sci. Instrum.* **74** 2040 (2003).

Resulting density rise is the final goal of simultaneous multi-SPIs for avoiding runaway electrons (funded by ITER DTF).

- Present two-color-interferometers in KSTAR have tangential line of sights.
  - It is not adequate for measuring SPI effect when toroidal symmetry is broken.
- Dispersion interferometer is being installed vertically at G-port (SPI location).
  - Dispersion interferometer is intrinsically robust to mechanical vibration.
  - Short wavelength (1064 nm) is being considered.
    - Refraction issue due to density gradient
  - Multi-channel expansion is under discussion.

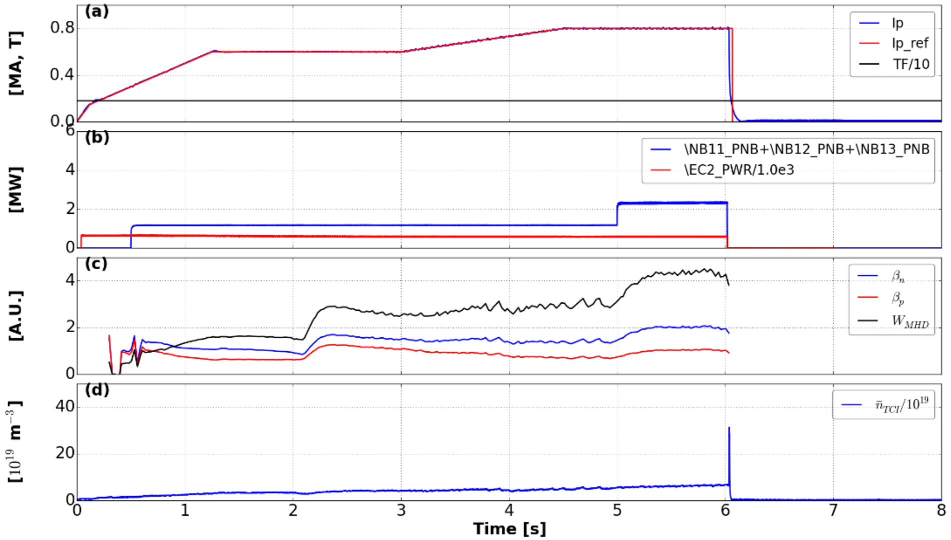
Cross-sectional-view
of the dispersion interferometer layout

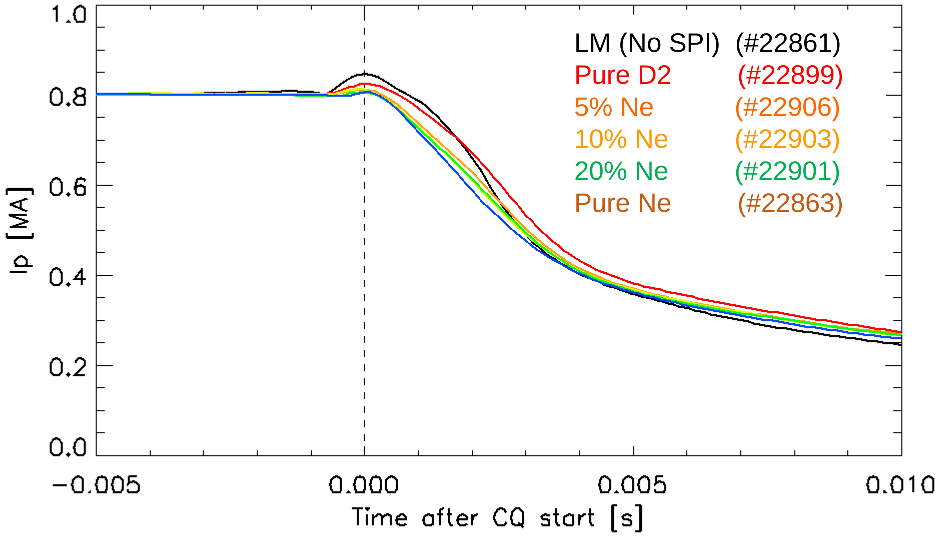




Top-view of the TCI layout

Current quench rate exhibited the tendency of saturation with increasing neon fraction.

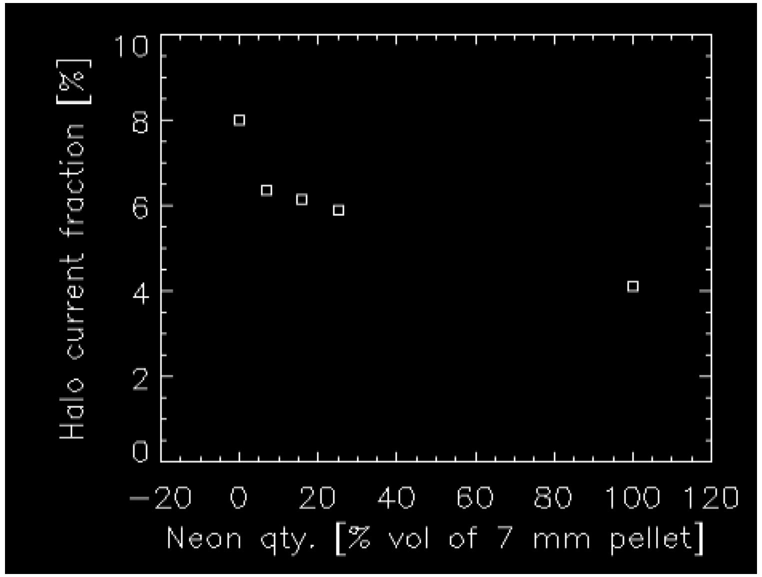




Current quench rate depending on neon fraction

- 800 kA H-mode target
- 7 mm SPI at t=6.0 sec

- $W_{th} + W_{mag}$ ~ 1 MJ dissipation
- $3\text{x}10^{21}$ m^{-3} CQ density achieved



Halo current fraction depending on neon fraction