Mitigation of disruption electromagnetic load with SPI

IAEA TM on Plasma Disruptions and their Mitigation, ITER Headquarters, France, 20–23 July 2020

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This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Motivation and Study

- In 2019 the JET-ILW was equipped with a Shattered Pellet Injectors (SPI) with a wide capability:
  - Pellet diameter d = [4.57, 8.1, 12.5] mm and effective length/d ratio = [1.4, 1.6, 1.54];
  - pellet compositions of D2, Ne with D2 shell, D2+Ne mixture and Ar;
  - propellant gas or mechanical punch to release the pellets.
- The first task was to provide SPI affected plasma characterisations using existing diagnostics;
- The current quench (CQ) time, $\tau_{80\text{-}20}$, is the key characteristic of mitigation effectiveness. The effect of pellet integrity prior to shattering, pellet size, Ne (Ar) fraction on $\tau_{80\text{-}20}$ for Ohmic plasmas was studied;
- The Asymmetrical Vertical Displacement Events (AVDEs) is a major threat to large size machines since it creates large sideways forces on the vessel and asymmetrical thermal loads on the first wall. SPI effectiveness on mitigation of AVDEs was investigated.

Outline

- Pellet characterisations
- Pellet C (small) and plasma characterisations
- Pellet B (medium) and plasma characterisations
- Effect of pellet integrity and size on TQ and CQ
- Effect of Ne (Ar) fraction on CQ duration
- Ip scan: effect of Ip on CQ duration
- Effect on Vessel reaction vertical force
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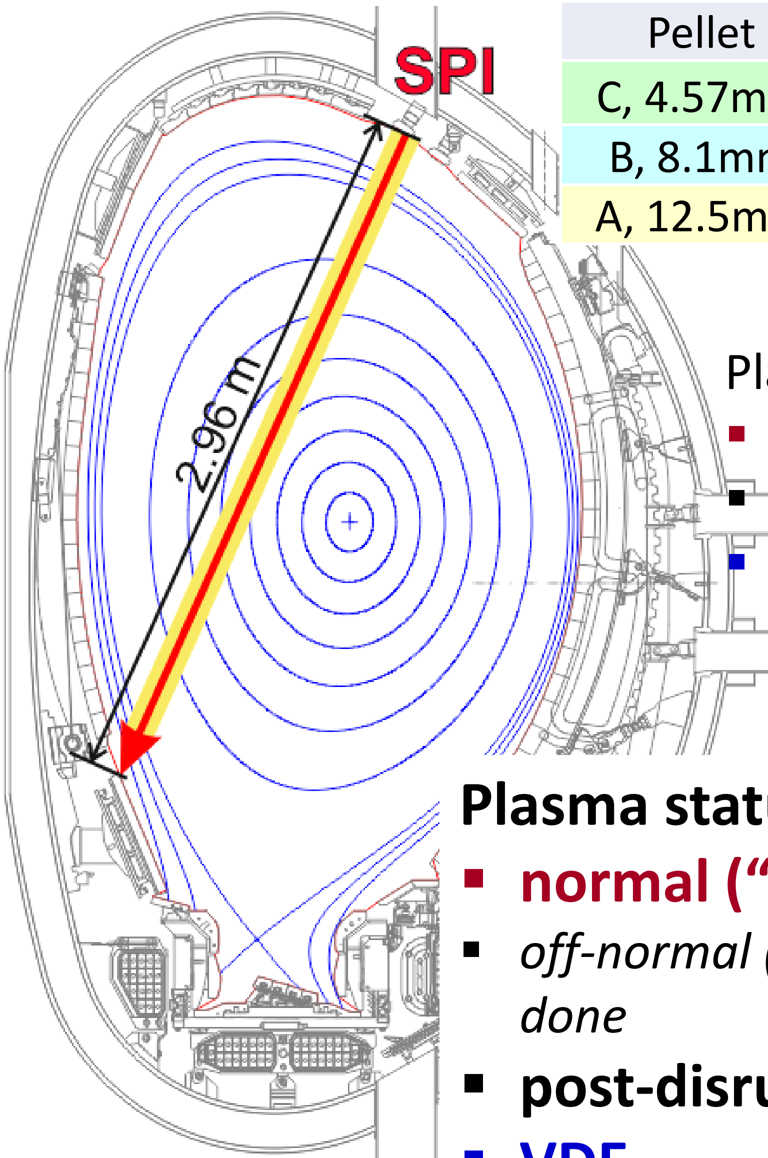
- Effectiveness of SPI in post-disruptive plasma
- Summary

Pellet and Plasma parameters



Pellet	Ne, atoms	D, atoms	Ne/(Ne+D2)	mass, g
C, 4.57mm	$(0.8\text{-}3.1)\cdot10^{21}$	$(2.0\text{-}5.3)\cdot10^{21}$	0.13-0.60	0.04-0.11
B, 8.1mm	$(0.4\text{-}2.7)\cdot10^{22}$	$(0.2\text{-}3.5)\cdot10^{22}$	0.10-0.93	0.24-0.92
A, 12.5mm	$(0.3\text{-}9.4)\cdot10^{22}$	$(0.1\text{-}1.4)\cdot10^{23}$	0.02-0.90	0.56-3.40

Plasma Current:
- **Main Ip = 2.0 MA**
- Scan, Ip =2.5, 3.0 MA
- **VDE, Ip =1.1 MA**

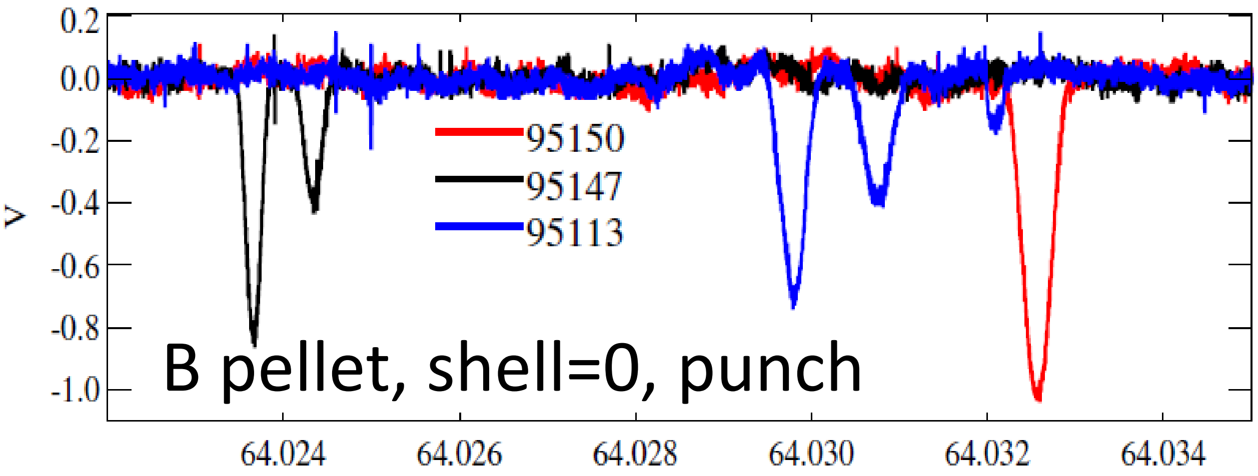
Toroidal Field:
- **Main Bt = 2.0 T**
- Scan, Bt =2.5, 3.0 MA
- **VDE, Bt =1.2, 1.8, 2.4 T**

Average liner density, $n_e l \approx 2\cdot10^{19}\ m^{-2}$

$N_{plasma} = n_e\cdot V = n_e l\cdot V/l \approx 6\cdot10^{20}\ m^{-3}$

Plasma status:
- **normal ("healthy") i.e., not prone to disruption**
- *off-normal (affected by LM) pre-disruptive plasma – was not done*
- **post-disruptive plasma**
- **VDE**

Microwave cavity diagnostic

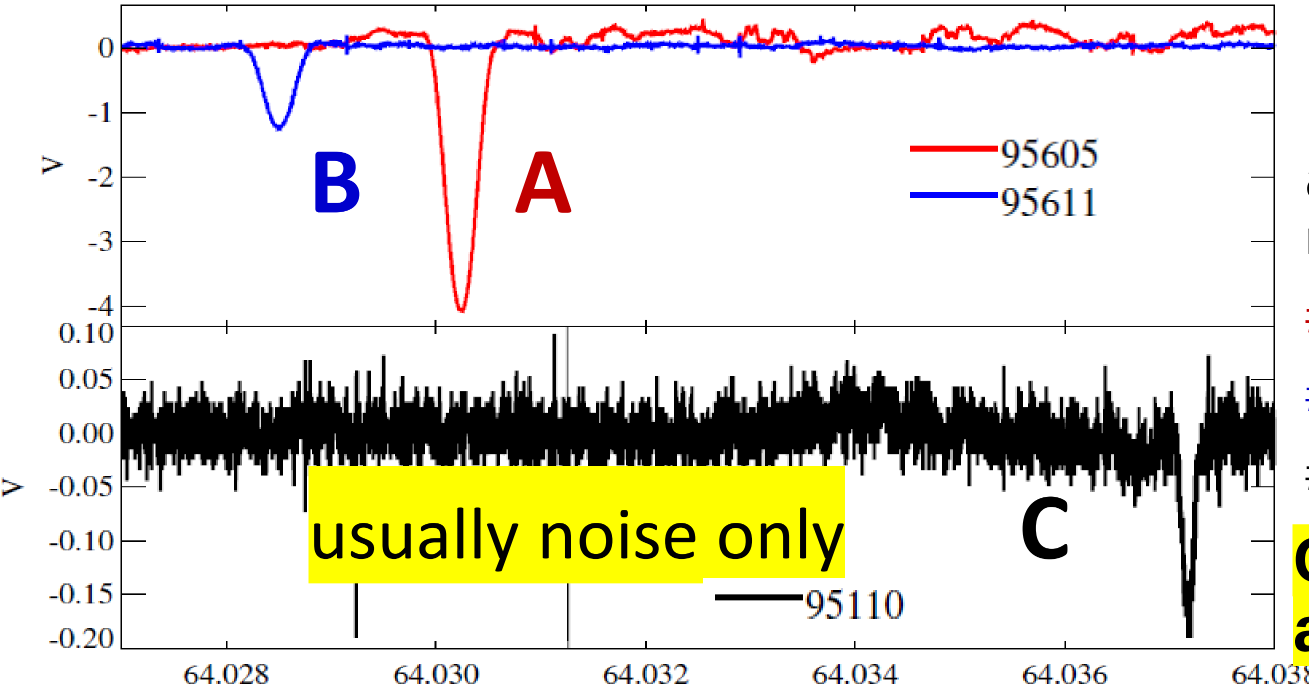


Pellet integrity, number of peaks

#95150 ~ 0.72 g, 0.4 mm

#95113 ~ 0.72 g, no shell

Shell must be ≥ 0.4 mm !



Pellet mass ~ amplitude (for given matter)

#95605 ~ 2.45 g

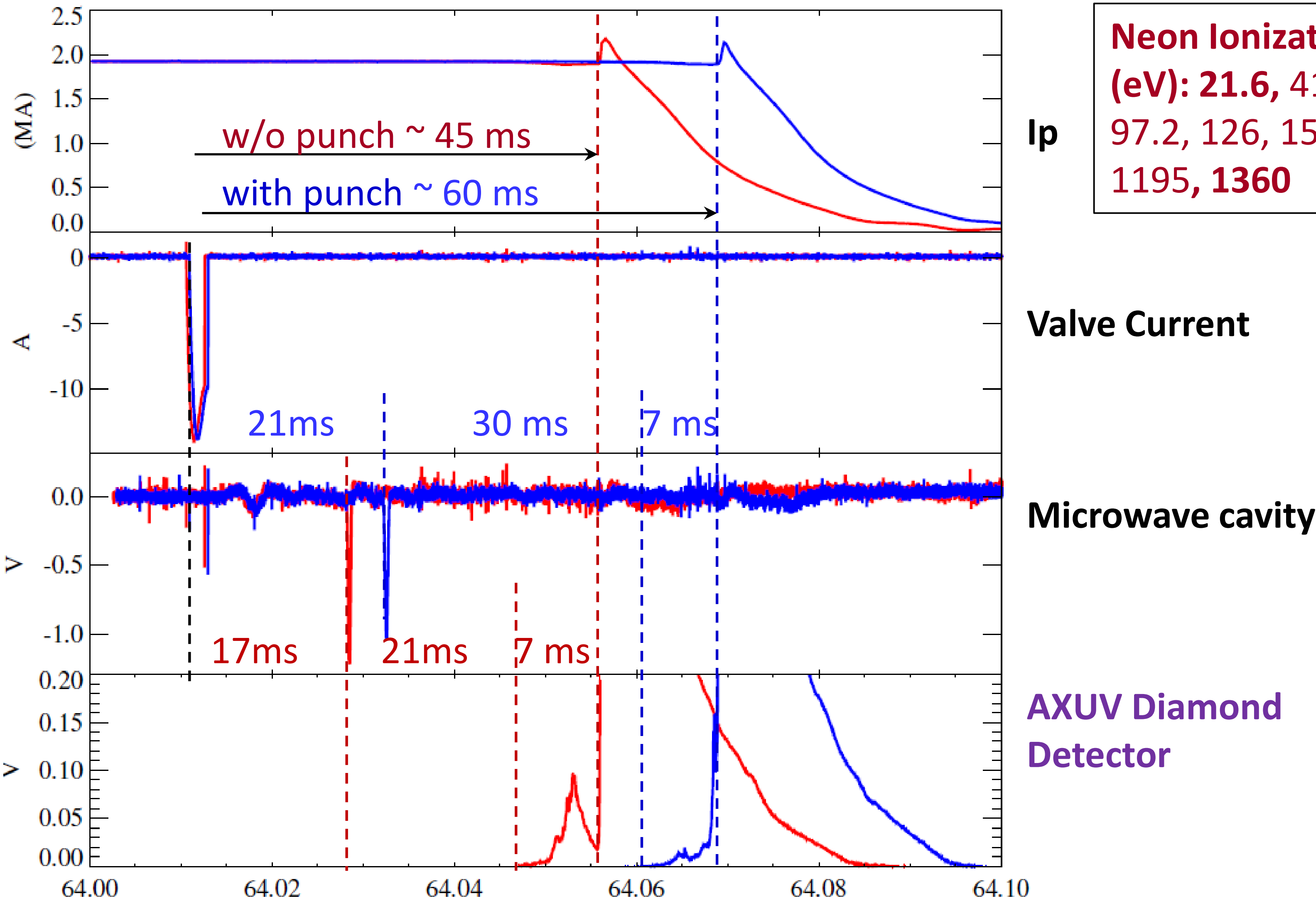
#95611 ~ 0.69 g

#95610 ~ 0.11 g

C pellets usually are not visible

B barrel w/o #95112 and with punch #95150

#95112, Ne/(Ne+D)=0.34, 0.48 g #95150, Ne/(Ne+D)=0.64, 0.72 g



Neon Ionization Energies (eV): 21.6, 41.1, 63.5, 97.2, 126, 158, 207, 239, 1195**, 1360**

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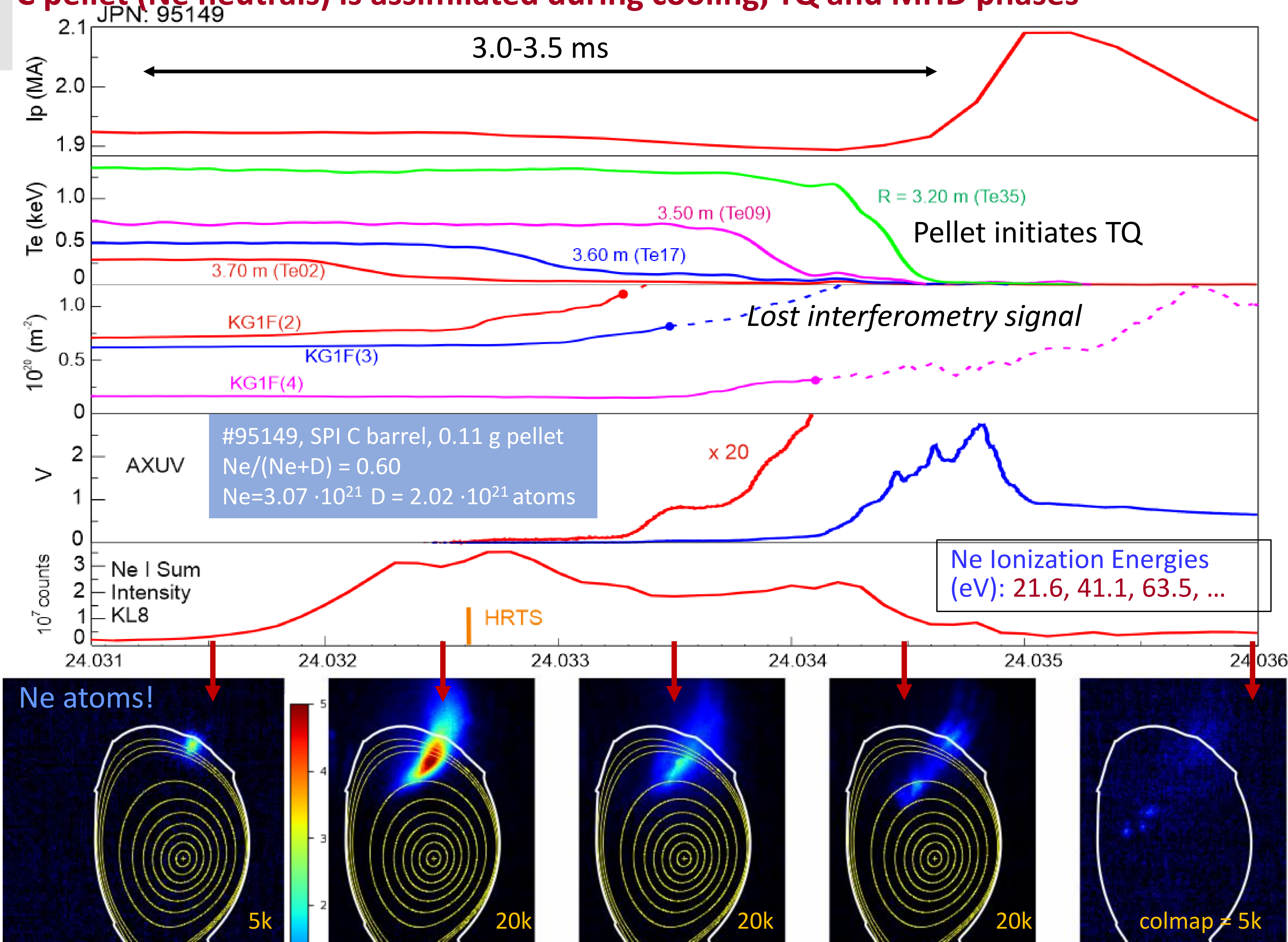
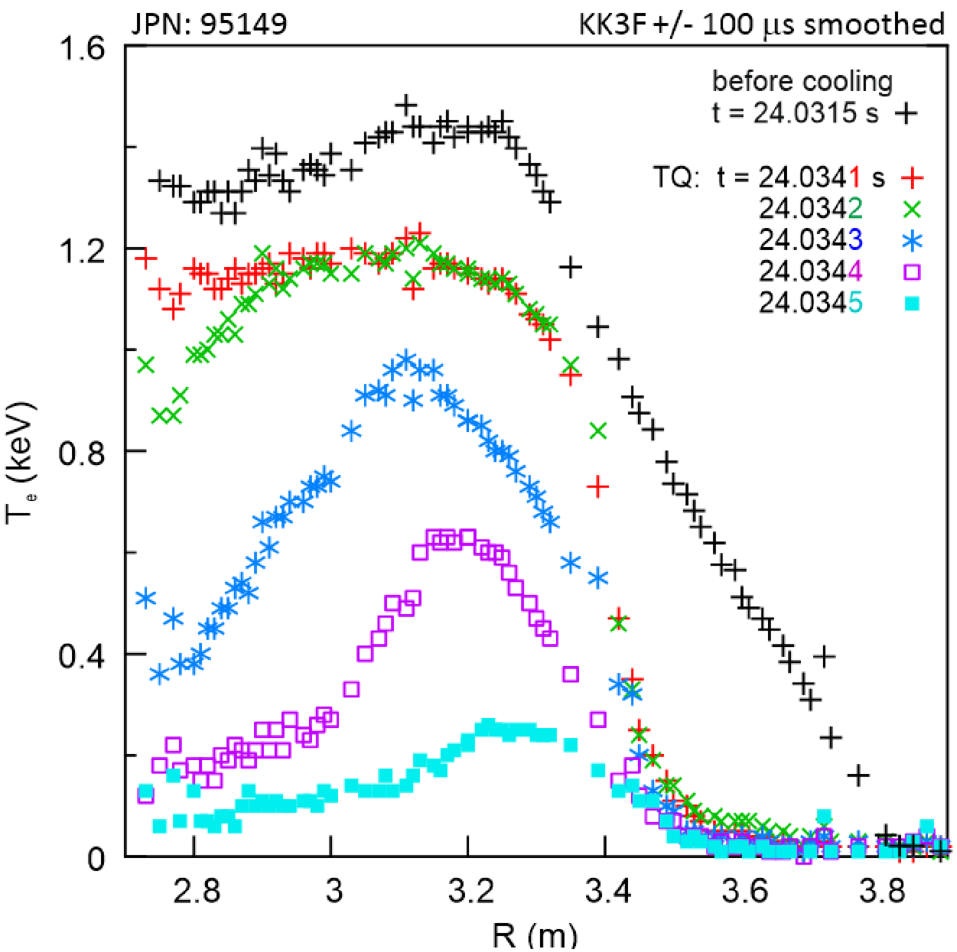
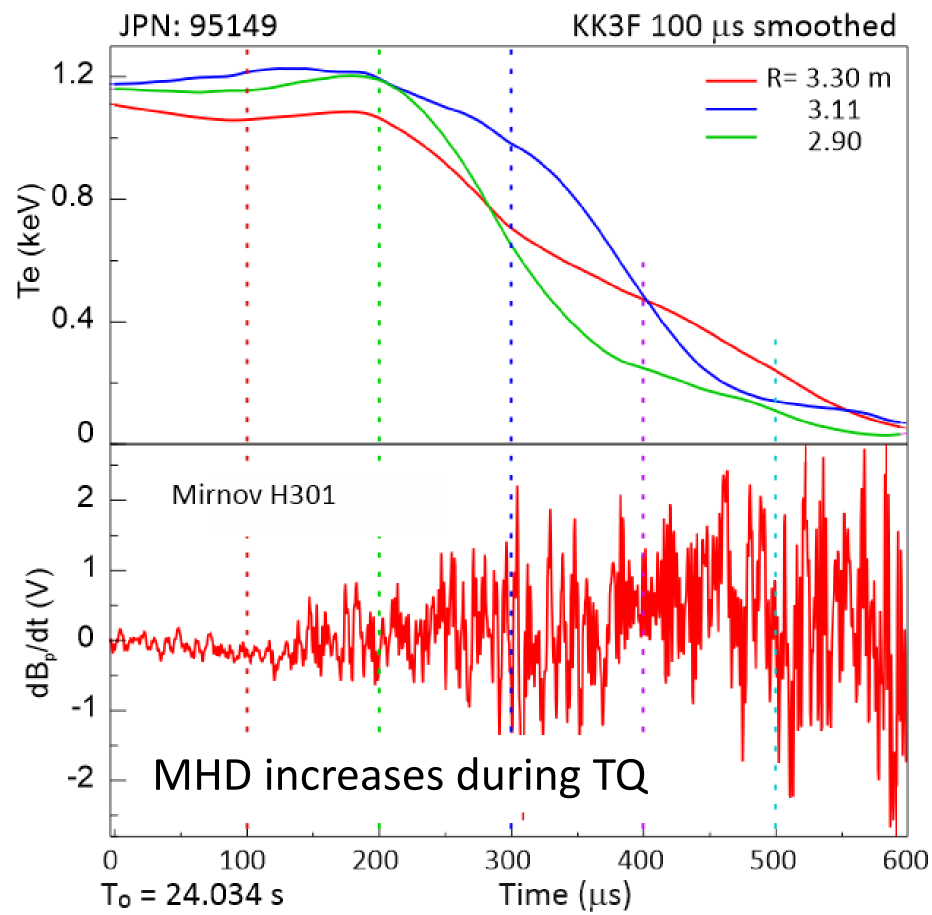
C pellet (Ne neutrals) is assimilated during cooling, TQ and MHD phases



Cooling and Thermal Quench Phases





Cooling phase = (2-2.5) ms

TQ duration = (400-500) μs

#95149, SPI C barrel, 0.11 g pellet Ne/(Ne+D) = 0.60
Ne = 3.07 $\cdot 10^{21}$, D = 2.02 $\cdot 10^{21}$ atoms

Ne Ionization Energies (eV): 21.6, 41.1, 63.5, 97.2, 126, 158, 207, 239, 1195, 1360

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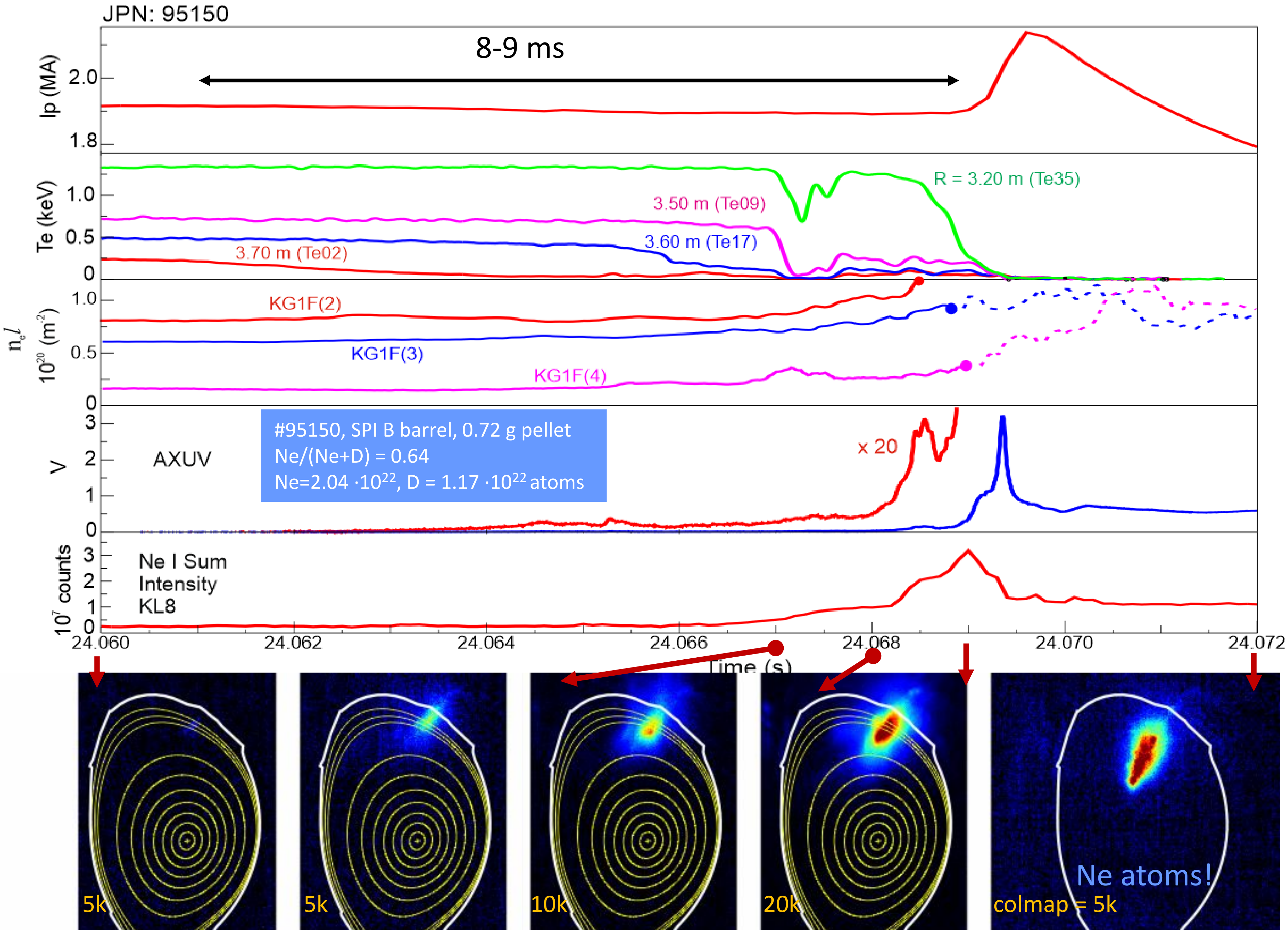
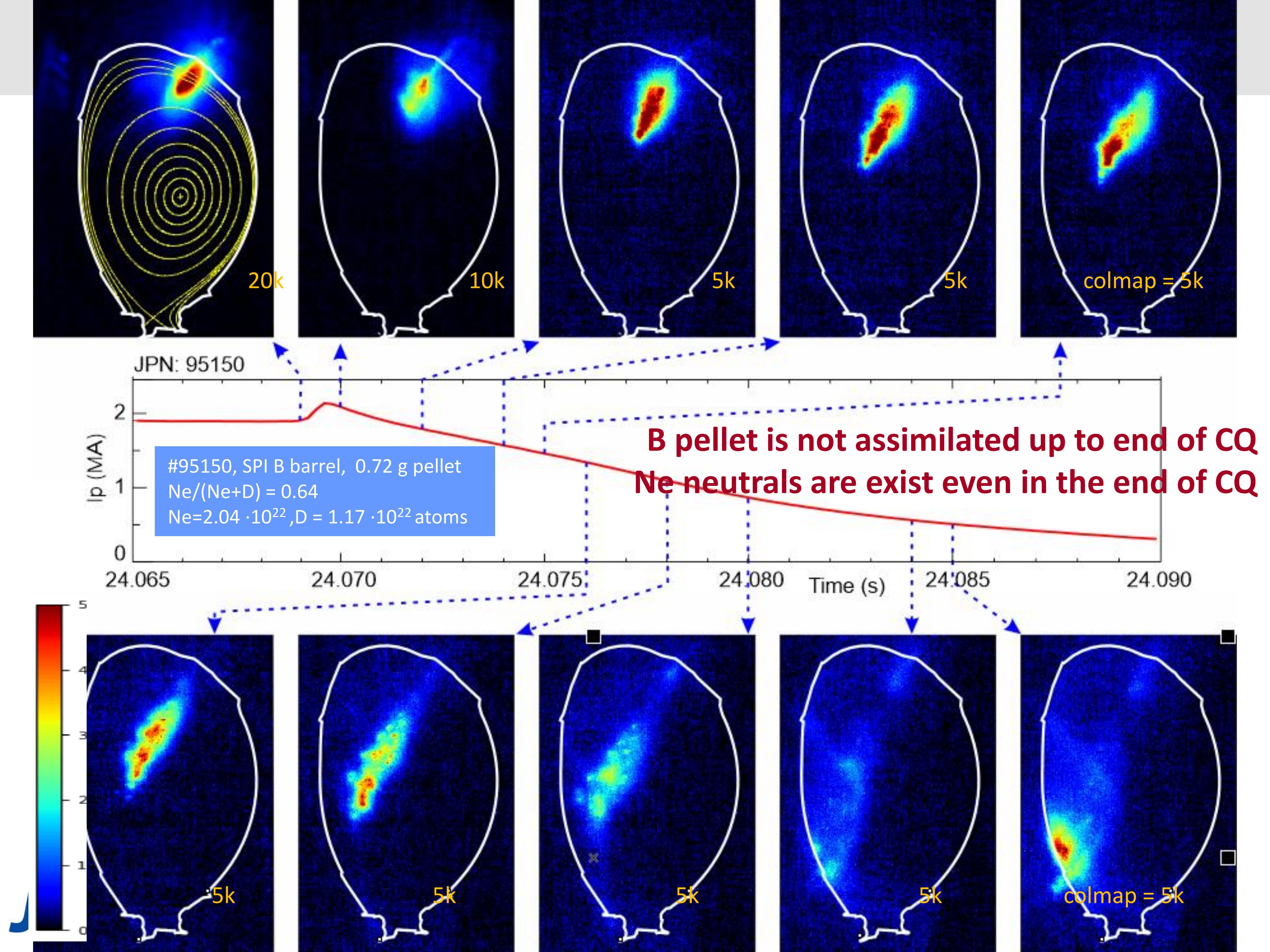
B pellet (Ne neutrals) is not assimilated during cooling, TQ and MHD phases

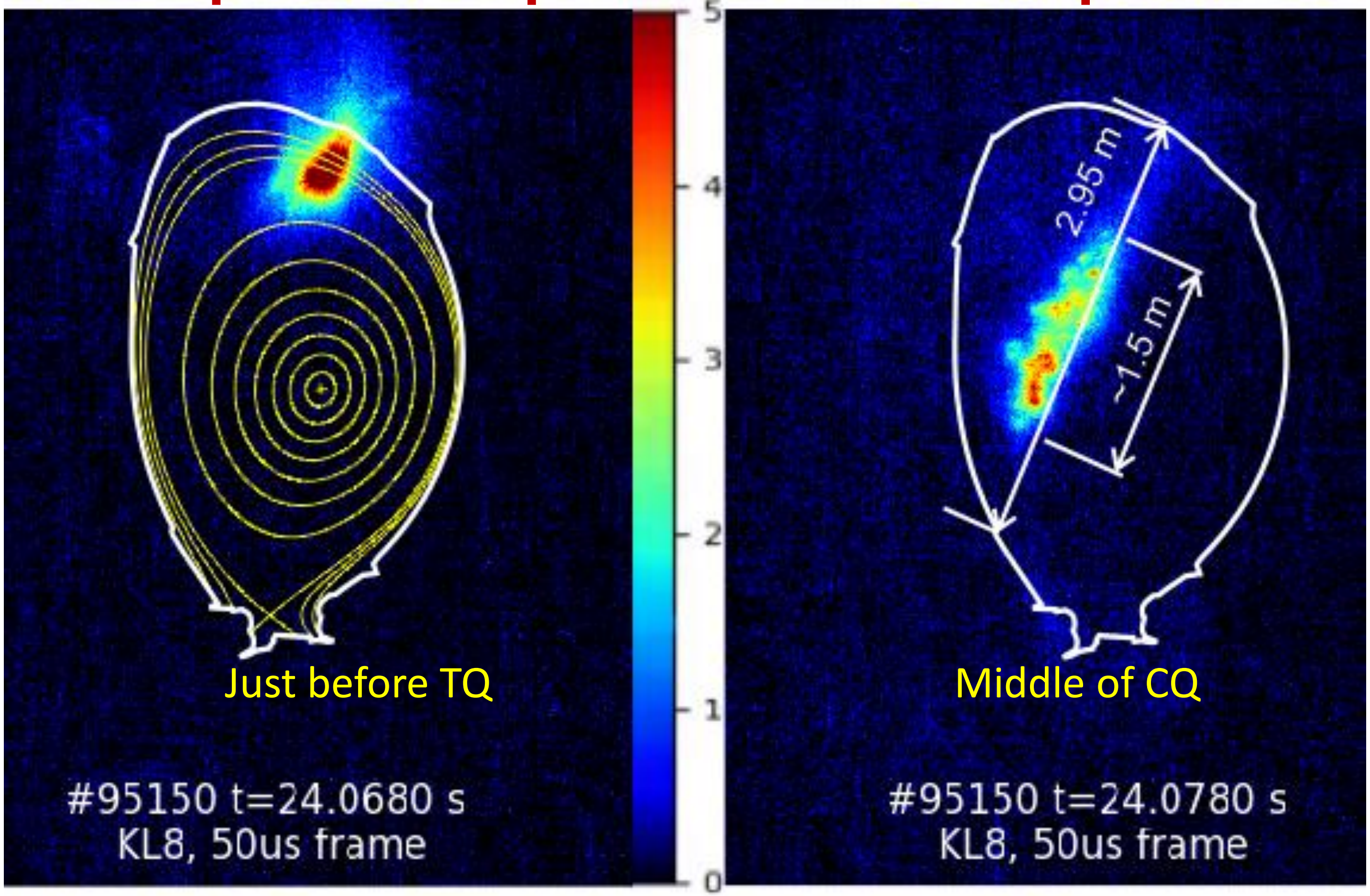



20k
10k
5k
5k
colmap = 5k
JPN: 95150
Ip (MA)
2
1
0
24.065
24.070
24.075
24.080
Time (s)
24.085
24.090
#95150, SPI B barrel, 0.72 g pellet
Ne/(Ne+D) = 0.64
Ne=2.04 ·10^22 ,D = 1.17 ·10^22 atoms
B pellet is not assimilated up to end of CQ
Ne neutrals are exist even in the end of CQ
5
4
3
2
1
0
5k
5k
5k
5k
colmap = 5k

Pellet cloud length ~ 1.5 m and speed ~ 200 m/s

Ne I (atom radiation)

B pellet with punch before disruption and during CQ



#95150, SPI
B barrel, 0.72 g pellet
Ne/(Ne+D) = 0.64
Ne=2.04 $\cdot 10^{22}$ atoms
D = 1.17 $\cdot 10^{22}$ atoms

Δt = 10 ms between two frames, each frame is “instantaneous” photo

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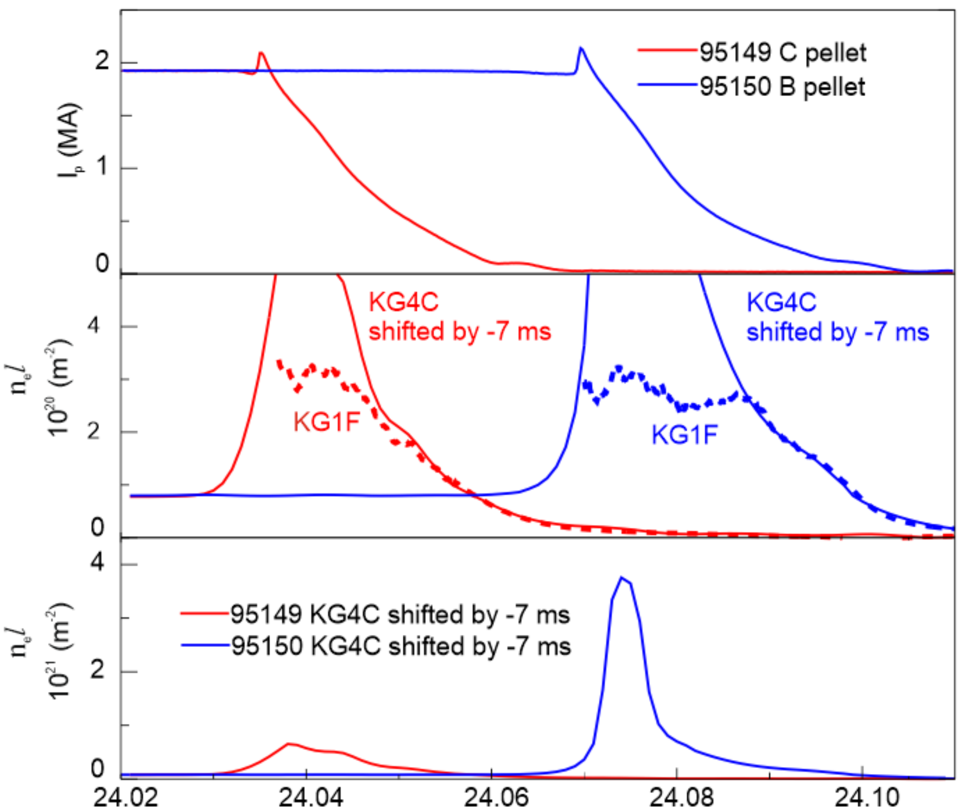
Fraction of ionised pellet atoms



KG4C - Polarimetry

#95149, SPI C barrel, 0.11 g pellet Ne/(Ne+D) = 0.60
Ne=3.07 $\cdot 10^{21}$ atoms, D = 2.02 $\cdot 10^{21}$ atoms

#95150, SPI B barrel, 0.72 g pellet Ne/(Ne+D) = 0.64
Ne=2.04 $\cdot 10^{22}$, D = 1.17 $\cdot 10^{22}$ atoms

ESTIMATIONS: Length 3 ≈ 2.7 m
Vol plasma ≈ 80 m^3

	C #95149	B #95150
Electrons in pellet, N_{SPI}	$3.3 \cdot 10^{22}$	$2.2 \cdot 10^{23}$
KG4C $n_e l$ (m^{-2})	$6.5 \cdot 10^{20}$	$3.8 \cdot 10^{21}$
Max Electrons in plasma $N_{plasma} \approx n_e l \cdot V/l$	$1.9 \cdot 10^{22}$	$1.1 \cdot 10^{23}$
N_{plasma}/N_{SPI} (%)	**59**	**52**

Speculations:

Ne atoms loose ~ 5-6 electrons on average

Neon Ionization Energies (eV): 21.6, 41.1, 63.5, 97.2, 126, 158, 207, 239, 1195, 1360

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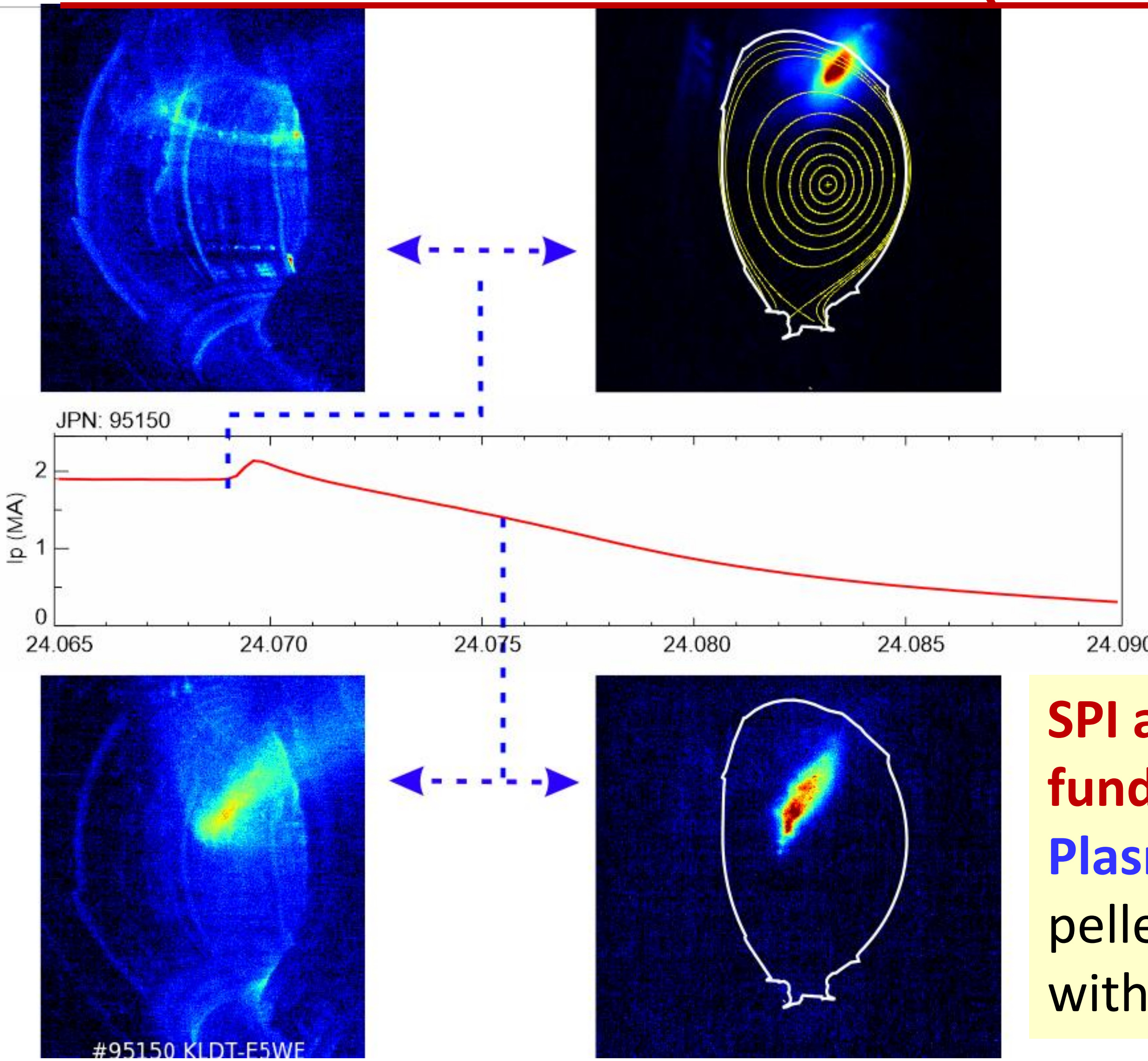
3D Plasma Streams

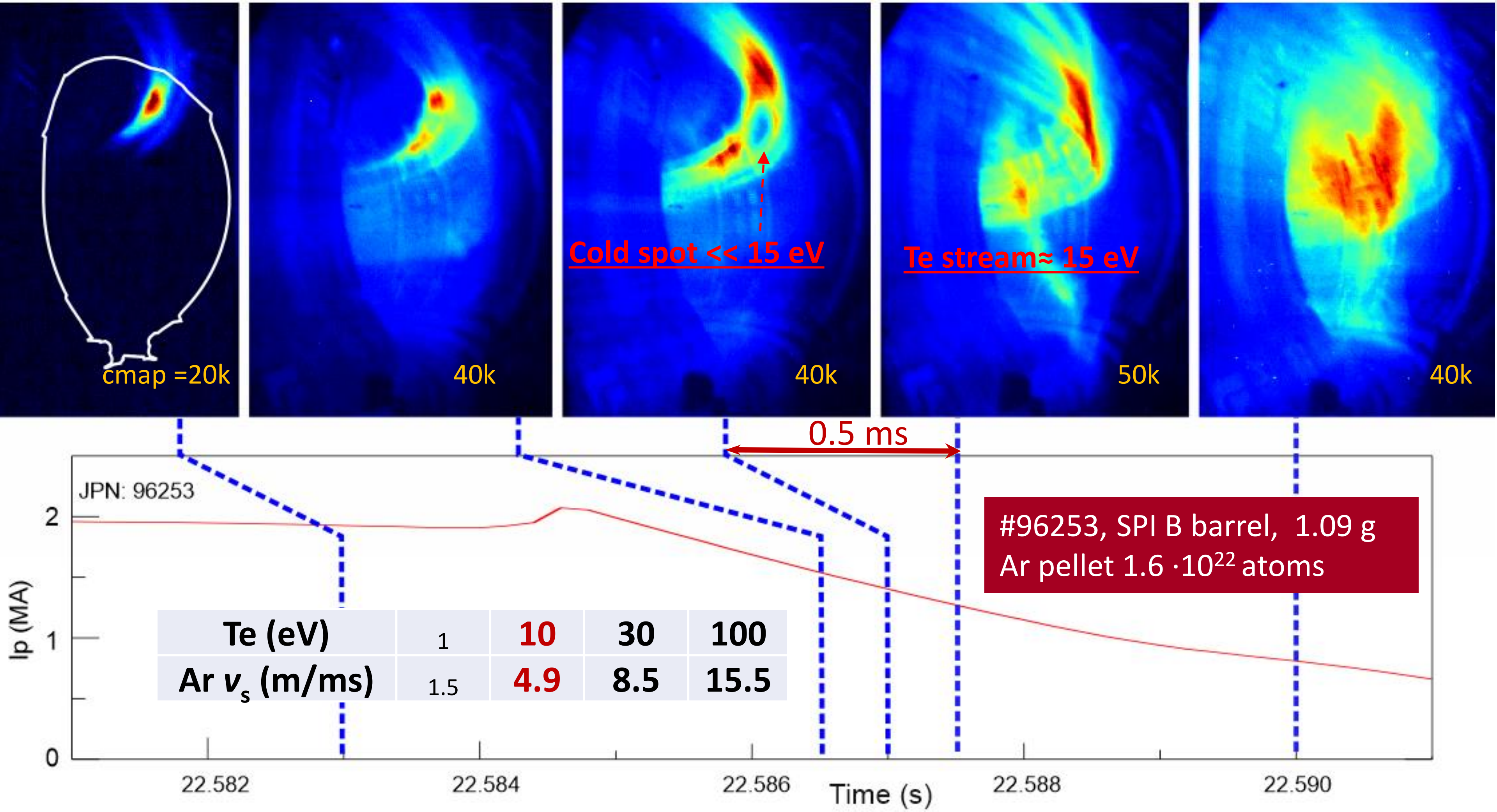
KLDT w/o filter KL8 Ne I (atom radiation) filter



#95150, SPI
B barrel, 0.72 g pellet
Ne/(Ne+D) = 0.64
Ne=2.04 $\cdot 10^{22}$ atoms
D = 1.17 $\cdot 10^{22}$ atoms

SPI affected plasma is always fundamentally 3D;
Plasma stream initiated by Ar pellet should be visible by KL8 with Ar II filter, next slide…

3D Plasma Streams - KL8 camera Ar II images



Te (eV)	1	10	30	100
Ar v_s (m/ms)	1.5	4.9	8.5	15.5

Plasma travels along magnetic field with ion sound speed $v_s = \sqrt{\frac{T_e}{m_i}}$

Ar Ionization Energies (eV): 15.8, 27.6, 40.9, 59.8, 75, 91.3, 123.3, 143.9, 422.6, 479 .....

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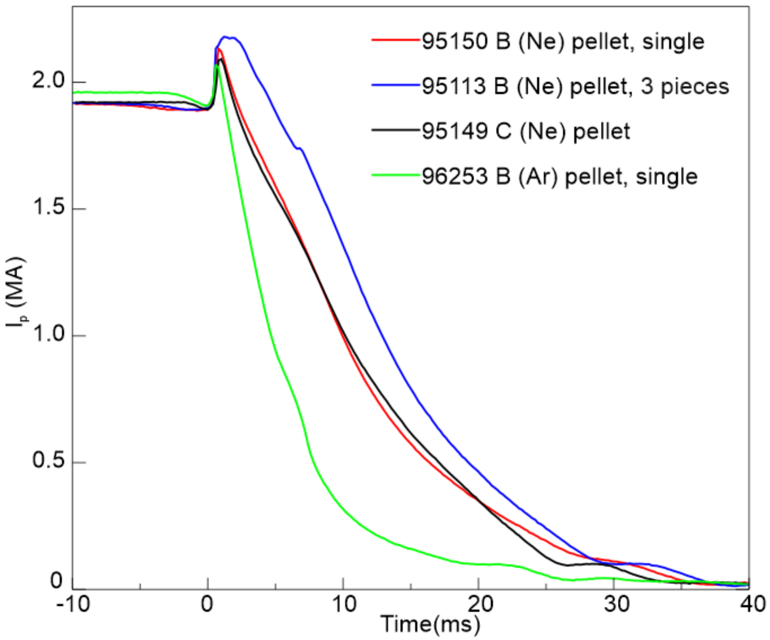
Effect of pellet *integrity* and *size* on TQ and CQ

Pulse	Bt	Barrel	Z	Z, atoms	D, atoms	Z/(Z+D)	Mass, g	Pellet integrity	tau	com
95150	2.0	B	Ne	2.0E+22	1.2E+22	0.64	0.72	Single	**23**	Ohmic
95113	2.0	B	Ne	2.0E+22	1.2E+22	0.64	0.72	3 pieces	**22**	Ohmic
95149	2.0	C	Ne	3.1E+21	2.0E+21	0.60	0.11	-	**24**	Ohmic
96253	2.9	B	Ar	1.6E+22	0.0E+00	1.00	1.09	Single	**11**	NBI+ICRH

There is marginal effect of pellet integrity and size on CQ duration



Ar (hot plasma, Te ≈ 5.5 keV) more efficient than Ne (warm plasma, Te ≈ 1.3 keV)

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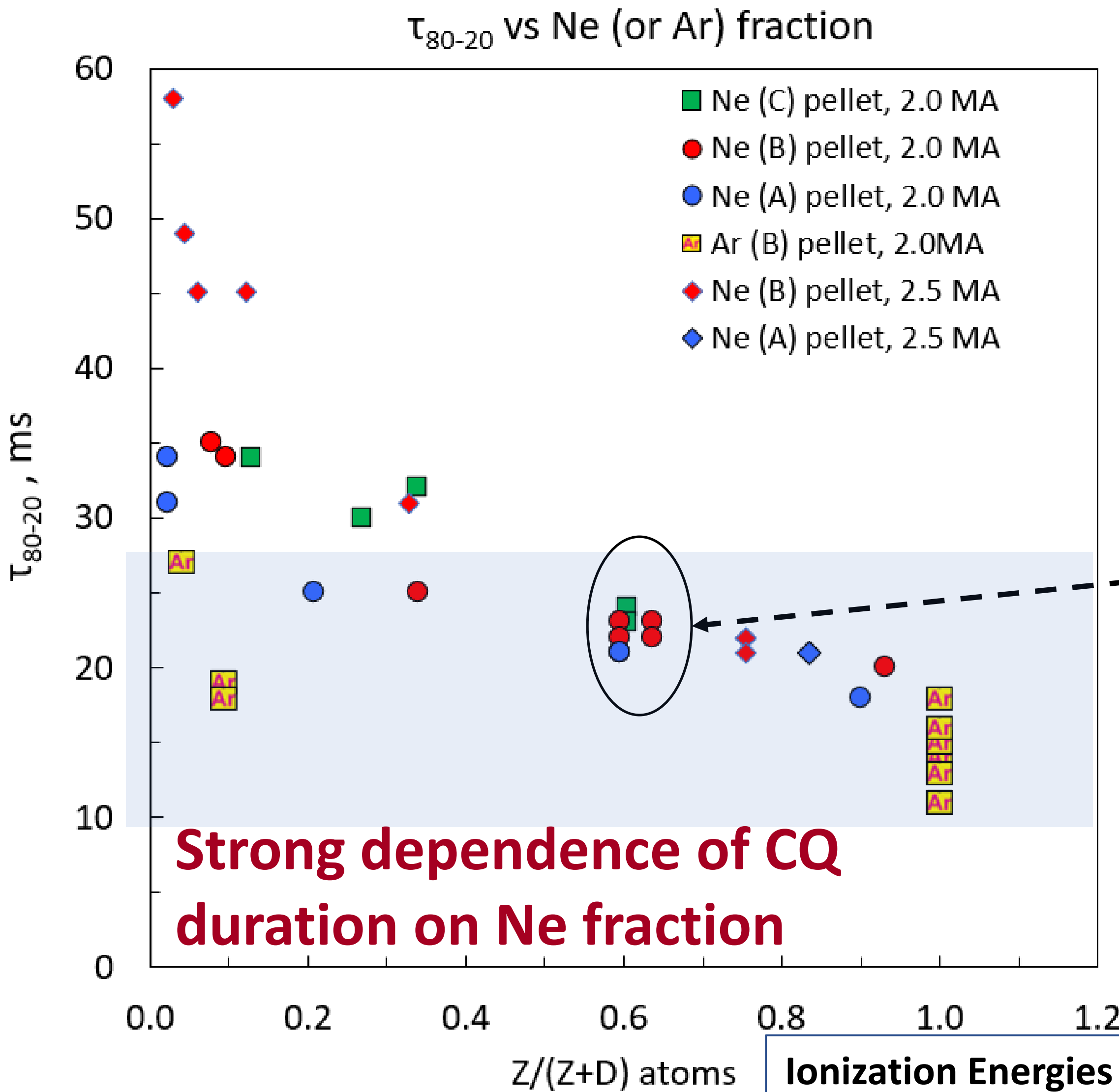
Effect of Ne(Ar)/(Ne(Ar)+D) atom fraction on CQ duration



Strong dependence of CQ duration on Ne fraction

τ_{80-20} for JET should be in the region of **(10 – 27.5) ms**, with the lower threshold given by force loads and the upper threshold is justified by minimisation of thermal loads.

There is a marginal effect of pellet size [(0.1-0.7-2.5)g or (3-20-69)·10^{21} Ne atoms] **on CQ duration**

Ar is more efficient than **Ne**

Ionization Energies (eV):

Neon 21.6, 41.1, 63.5, 97.2, 126, 158, 207, 239, 1195, 1360

Ar 15.8, 27.6, 40.9, 59.8, 75, 91.3, 123, 144, 422.6, 479 …

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Ip scan: effect of Ip on CQ duration

SHOT	Barrel	Ne, atoms	D, atoms	Ne/(Ne+D2)	mass, g	I_p^{dis}	$\tau_{80\text{-}20}$ ms
95612	B	1.94E+22	1.31E+22	0.60	0.69	**2.9**	**23**
95611	B	1.94E+22	1.31E+22	0.60	0.69	**2.4**	**22**
95609	B	1.94E+22	1.31E+22	0.60	0.69	**1.9**	**22**
95150	B	2.04E+22	1.17E+22	0.64	0.72	**1.9**	**23**
95113	B	2.04E+22	1.17E+22	0.64	0.72	**1.9**	**22**
95149	C	3.07E+21	2.02E+21	0.60	0.11	1.9	24
95148	C	3.07E+21	2.02E+21	0.60	0.11	1.9	24
95103	C	3.07E+21	2.02E+21	0.60	0.11	**1.9**	**23**
95107	C	3.07E+21	2.02E+21	0.60	0.11	**1.1**	**19**

CQ duration does not depend on pre-disruptive Ip for B pellet

May be some dependence for C pellet (?)

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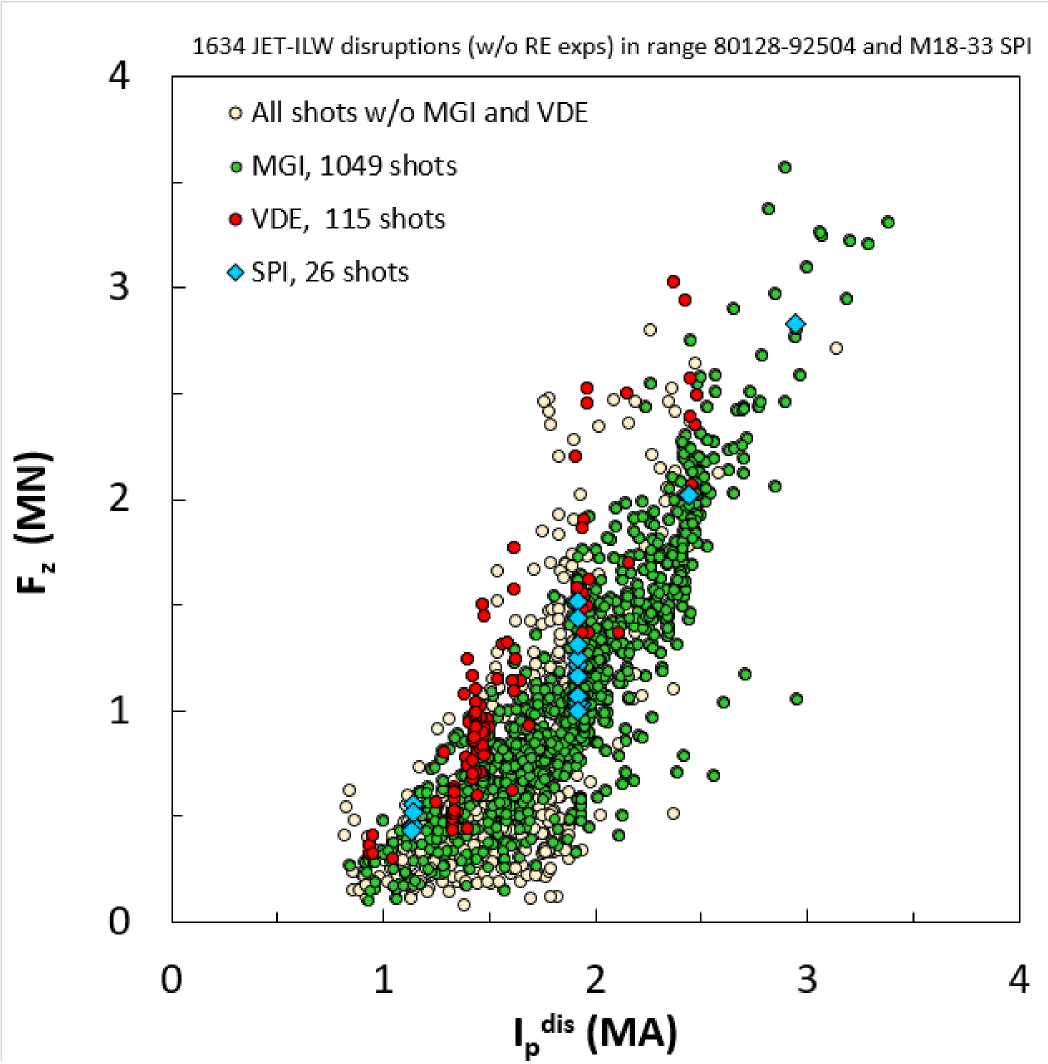
Effect SPI on JET-ILW Vessel reaction vertical force



F_Z for **SPI** (and **MGI)** mitigated disruptions are below non-mitigated **VDEs** and below the upper bound of non-mitigated disruptions

Vessel reaction vertical force vs. pre-disruptive Ip

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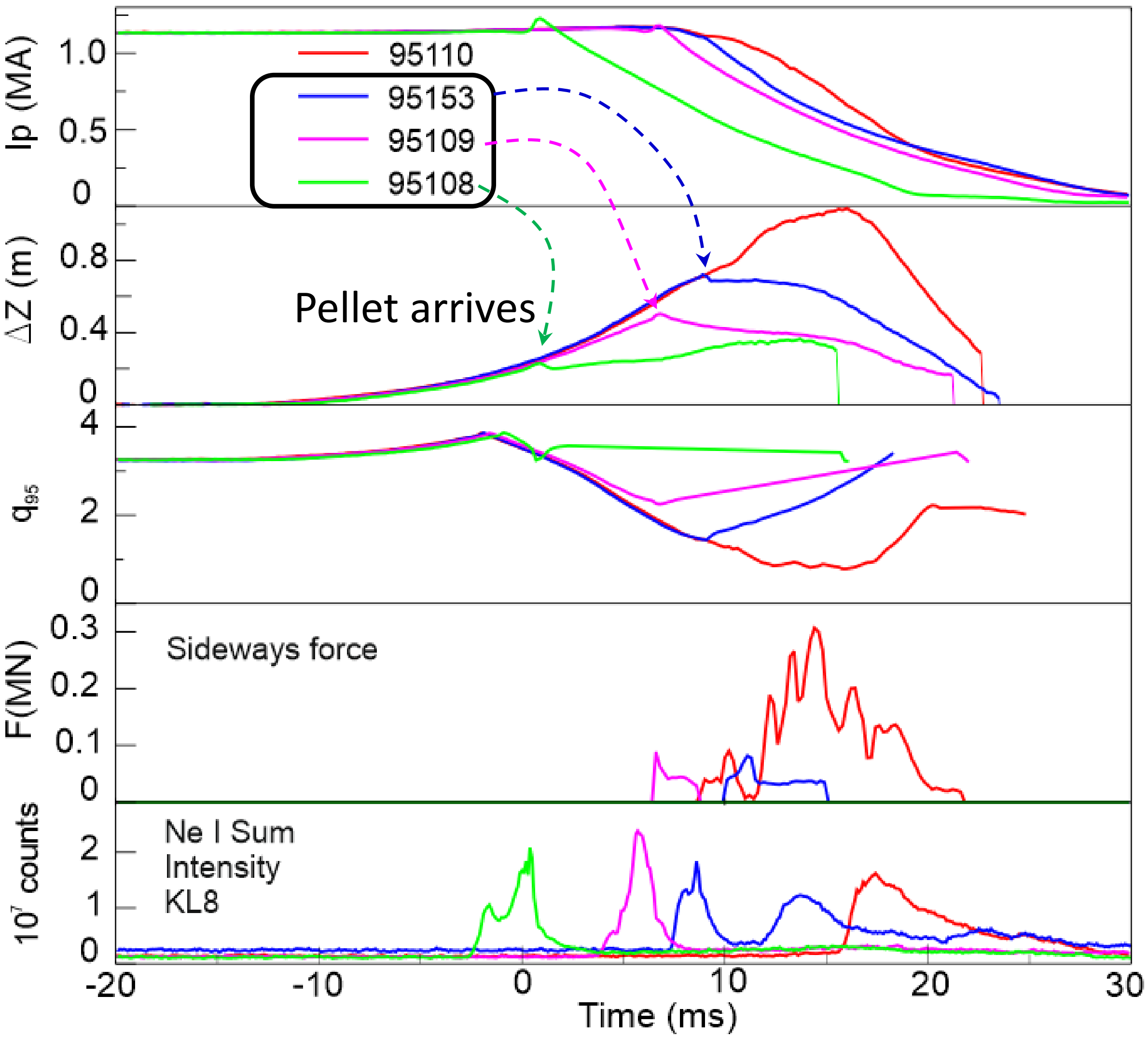
effectiveness of SPI on AVDEs



- ✓ **C barrel**
- ✓ **Ne/(Ne+D) = 0.6**
- ✓ **m = 0.1 g**

AVDE, SPI was late

SPI prevents AVDE,
similar to MGI effect *(see Gerasimov S.N. et al Nucl. Fusion 55 (2015) 113006)*

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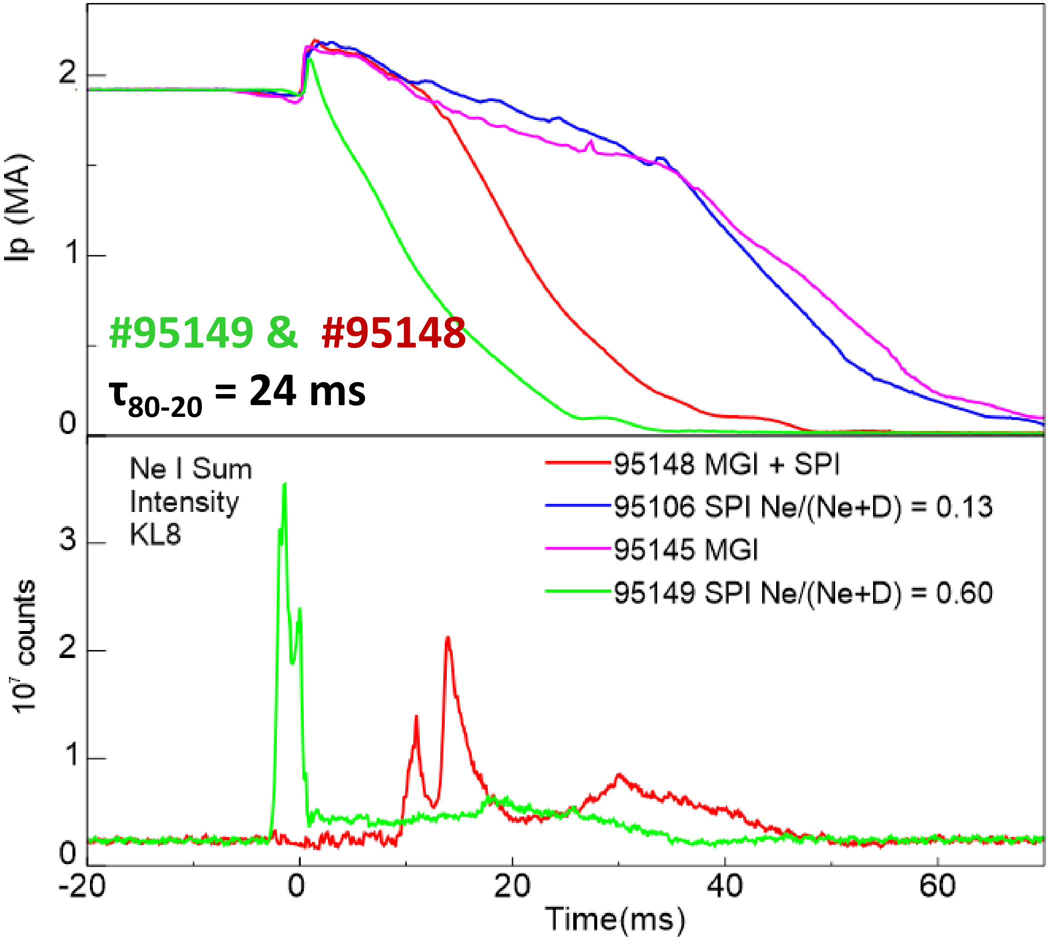
Effectiveness of SPI on post-disruptive plasma



Induced disruptions:

- ✓ **DMV3,** D2 0.084barl

  4.1E21 D atoms
- ✓ **SPI C,** Ne/(Ne+D) = 0.13

  5.3E21 D + 7.7E20 Ne atoms

Induced (#95149) and mitigated #95148

#95148, SPI C barrel, 0.11 g pellet
Ne/(Ne+D) = 0.60
Ne=3.07 $\cdot 10^{21}$ atoms, D = 2.02 $\cdot 10^{21}$ atoms

CQ duration does not depend on plasma status:

- ✓ normal ("healthy") i.e., not prone to disruption
- ✓ post-disruptive plasma

Summary

- **There is a marginal effect of pellet integrity on CQ duration**
- **Strong dependence of CQ duration on Ne fraction**
- **There is a marginal effect of pellet size on CQ duration**
- **SPI effectiveness ($\tau_{80\text{-}20}$) does not depend on pre-disruptive Ip for B pellet**
  - ✓ *may be some dependence for C pellet*
- **SPI prevents AVDE, similar to MGI effect**
- **SPI effectiveness ($\tau_{80\text{-}20}$) does not depend on plasma status:**
  - ✓ **normal ("healthy") i.e., not prone to disruption**
  - ✓ **post-disruptive plasma** *(only one pulse was done!)*
  - ✓ *off-normal (affected by LM) pre-disruptive plasma has not been tested yet*

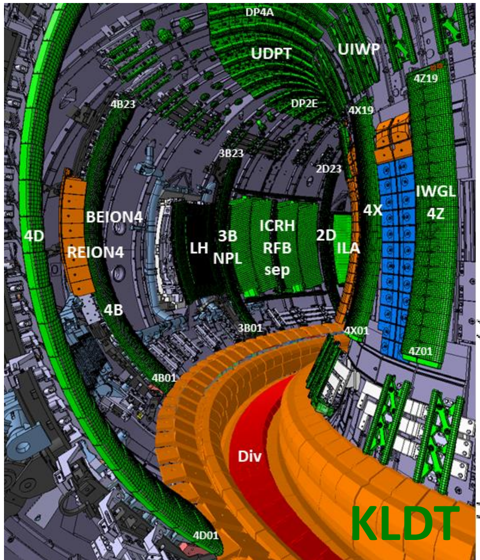
Summary - implications for ITER

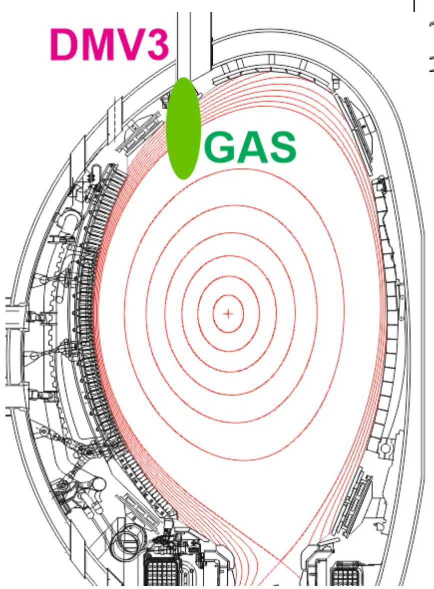
- **The JET-ILW study on SPI provided vast experimental data including plasma characterisation for various SPI:**
  - **Pellet cloud dimension and speed;**
  - **Pellet assimilated and ionisation during cooling, TQ, MHD and CQ phases;**
  - **Plasma density temporal evaluation including CQ;**
  - **ECE cut-off observed during TQ even for smallest pellet, it suggests excising of high density blooms;**
  - **Clear unique observation of cold 3D Ar plasma helical streams**
- **The study provided massive experimental data on effect of SPI on mitigation of disruption electromagnetic loads:**
  - **Strong dependence of CQ duration on Ne fraction;**
  - **There is a marginal effect of pellet size on CQ duration;**
  - **SPI effectiveness on pre-disruptive Ip;**
  - **It was demonstrated that SPI is effective tool to prevent AVDE;**
  - **Fist experiments suggest that SPI effectiveness does not depend on plasma status**
- **This presentation includes careful description of the used diagnostics and possible issues with data interpretation with aim to implement synthetic diagnostics in numerical models**
- **JET-ILW unique experimental data that can help to improve the understanding of disruptions and to develop and to calibrate numerical models, which could be used to predict the loads with future machines, such as ITER**

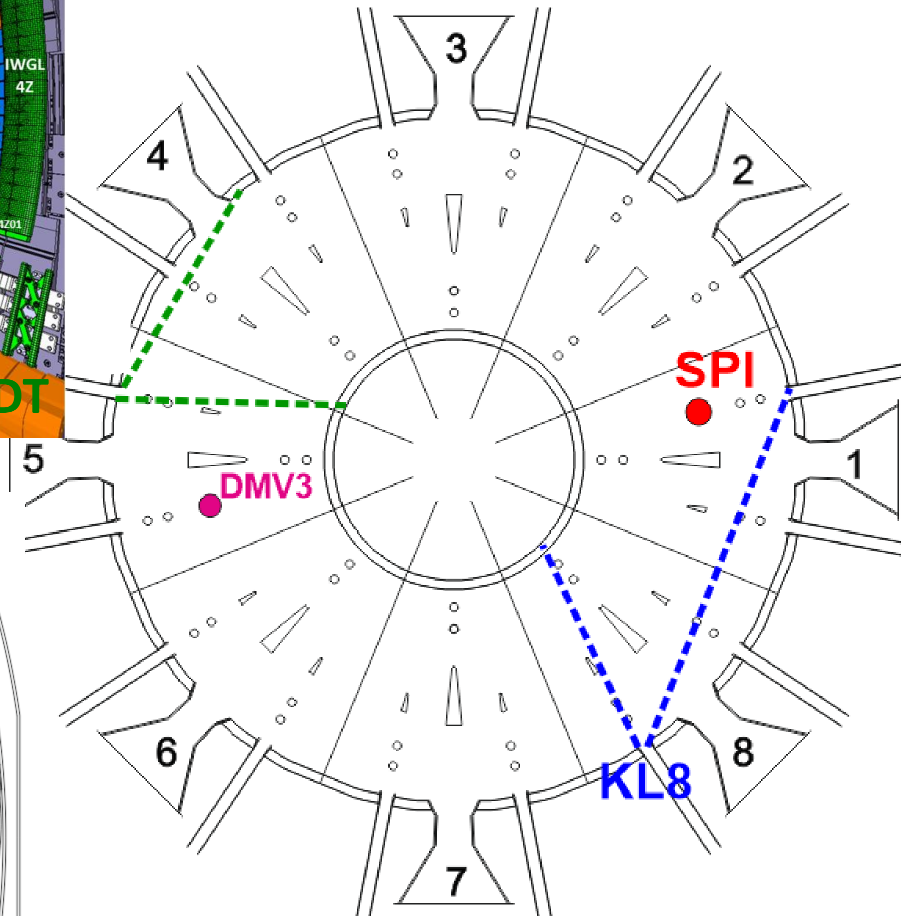
Appendix

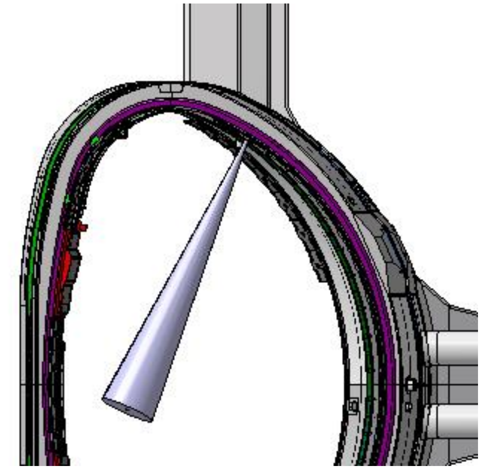
SPI related JET-ILW diagnostics

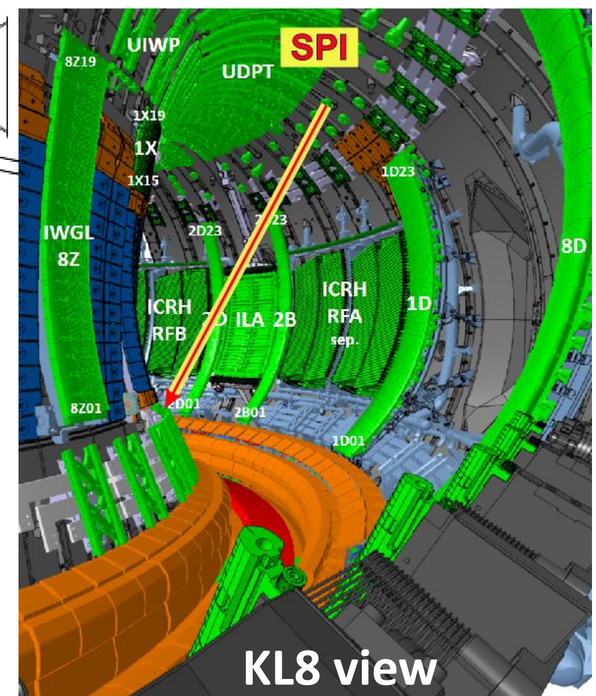
SPI, DMV3, and Fast Visible Cameras











KL8 Rate = (20-10) kHz, Frame = (33.3-50) µs

Filter: Ne I (692.8nm) to see atoms

[ArI], Ar II (611.6nm) to see ions

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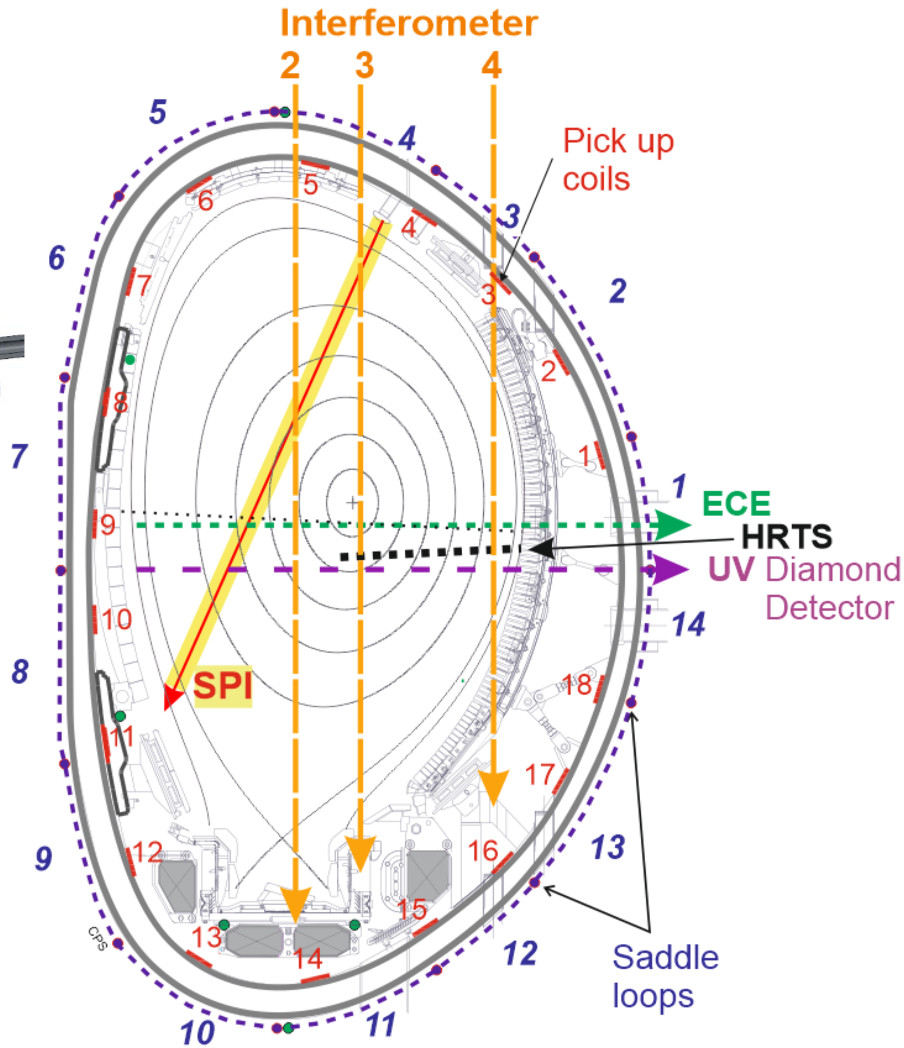
SPI related diagnostics

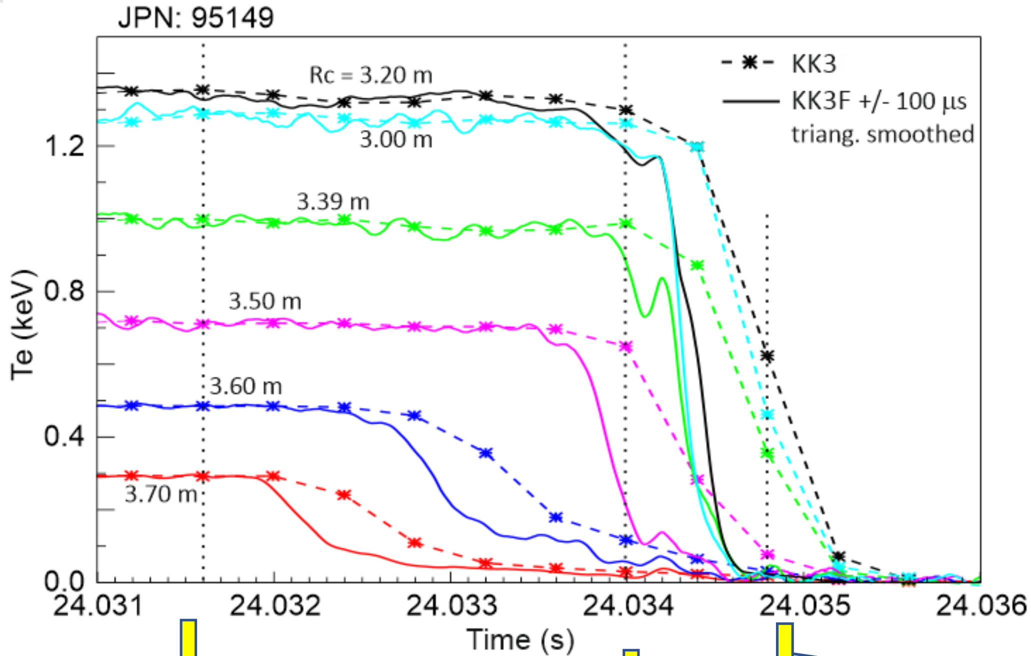
- ✓ **Barrel Valve Currents**
  - *DE/SPI-IFVX<I*, where X = A, B or C barrel
- ✓ **Microwave cavity diagnostic:**
  - Pellet mass ∝ amplitude *DE/SPI-MCRW<SIG*
  - Pellet integrity, number of peaks
  - Velocity peak width

- ✓ **ECE 2X-mode (Oct. 7)**
- ✓ **HRTS (Oct. 5)** R ≈ (2.95 - 4.0) m
- ✓ **AXUV** Diamond Detector **(Oct. 6)**

  sees radiation E > 5.5 eV (λ < 226 nm)
  - *DH/S6U-XTAL<SLW:001* (20V range)
  - *DH/S6U-XTAL<SLW:003* (2V range)
- ✓ **Interferometer (Oct. 7)**
  - KG1F/LID2;3;4 (beam: 195 μm) Uid=aboboc
  - KG1F/LDC2;3;4 (beam: 119 μm) Uid=aboboc
- ✓ **Magnetics**



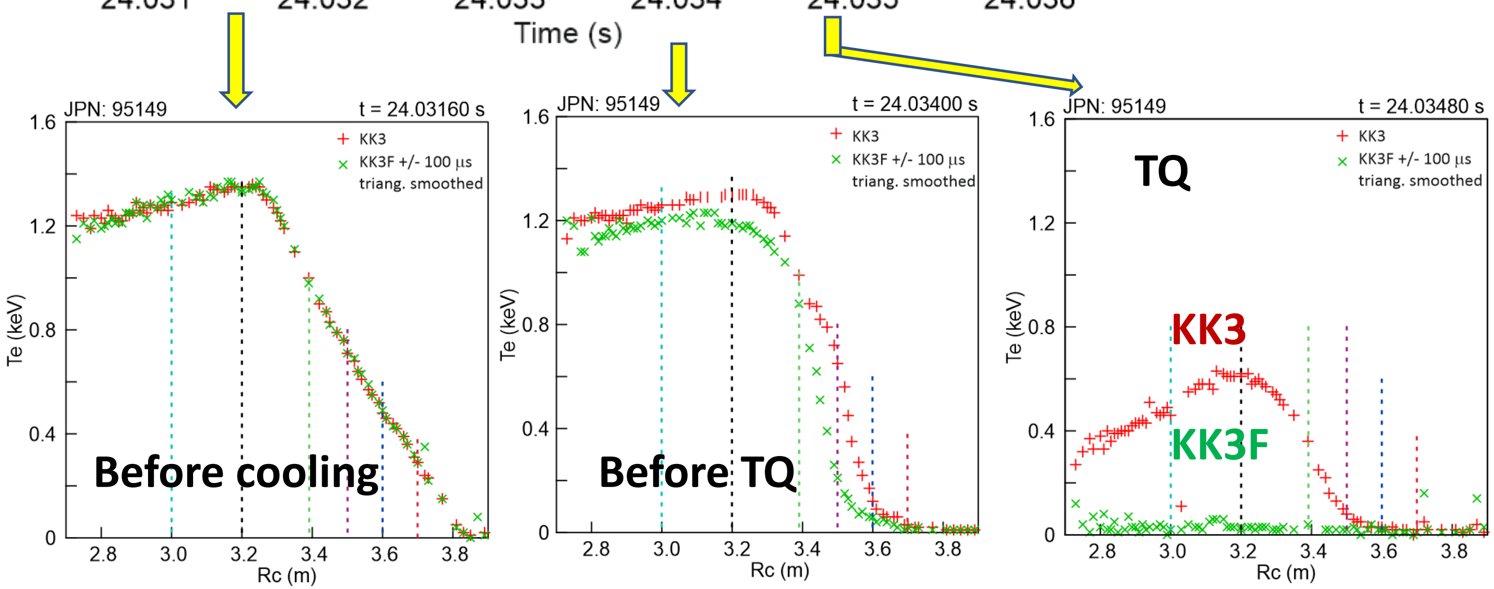
ECE: KK3 vs KK3F



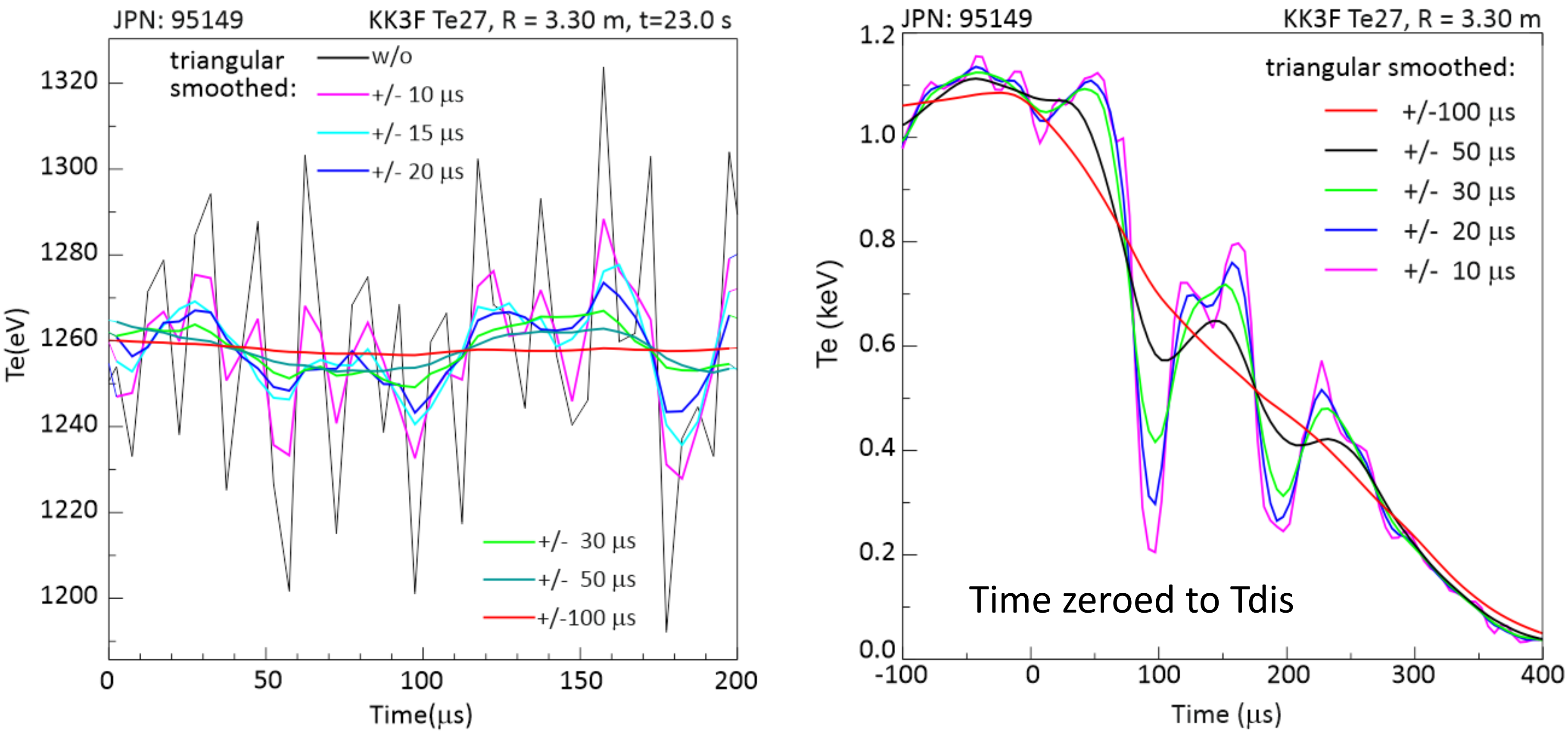
- KK3: amplifiers with in-built low pass filters + UXD1@2.5kHz
- KK3F: UXD7 @200kHz

KK3F must be used for fast events!

#95149, SPI
C barrel, 0.11 g pellet
Ne/(Ne+D) = 0.60
Ne=3.07 $\cdot 10^{21}$ atoms
D = 2.02 $\cdot 10^{21}$ atoms

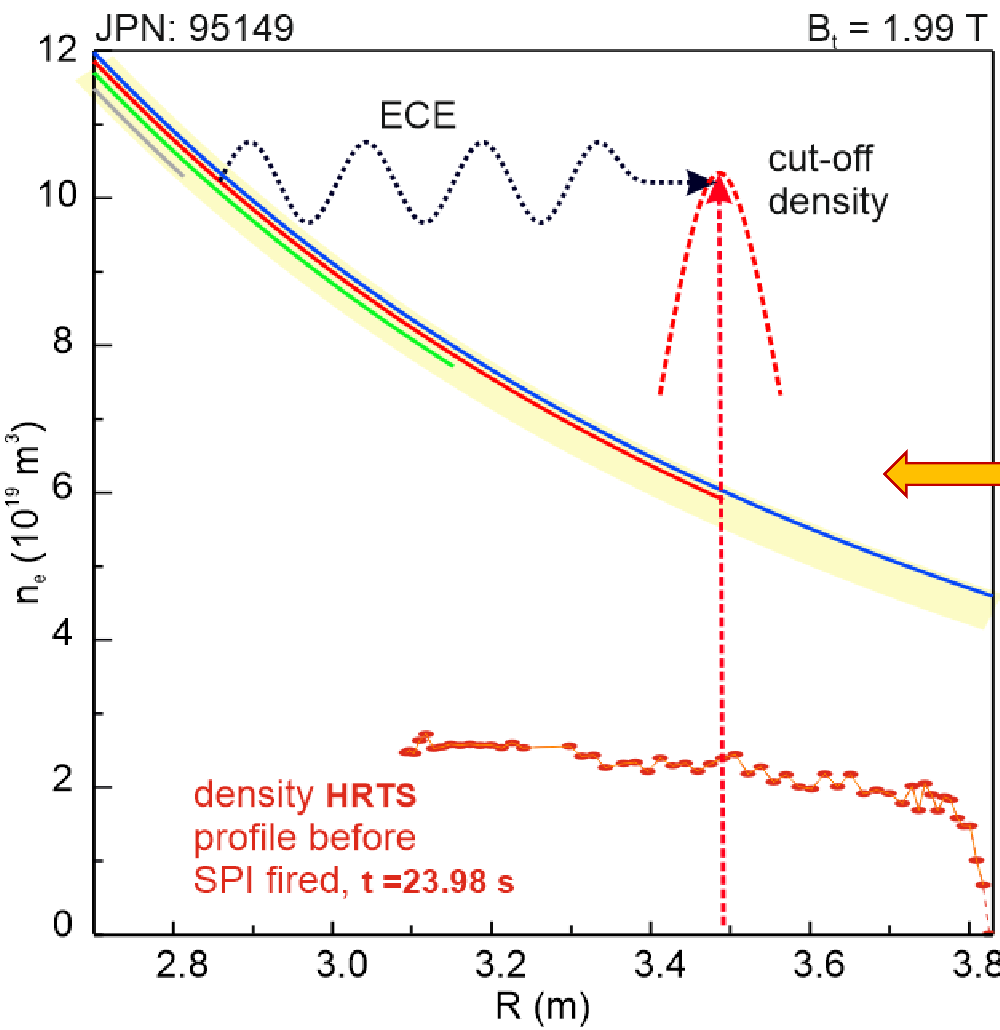


KK3F needs smoothing



- The ECE signal is recorded at 200 kHz i.e. 5 µs time step
- Smoothing eliminates the noise (+/- 60 eV for #95149)
- TQ duration ≈ 500 µs, +/-100 µs smoothing removes the noise, but does not affect the overall time behaviour
- Fast event ≈ 50 µs , +/-20 µs smoothing looks reasonable

ECE cut-off issue



The ECE signals can be affected*:

1. increase in the electron density to the cut-off level;
2. ECE emission scattering by density fluctuations;
3. formation of a non-Maxwellian electron distribution function.

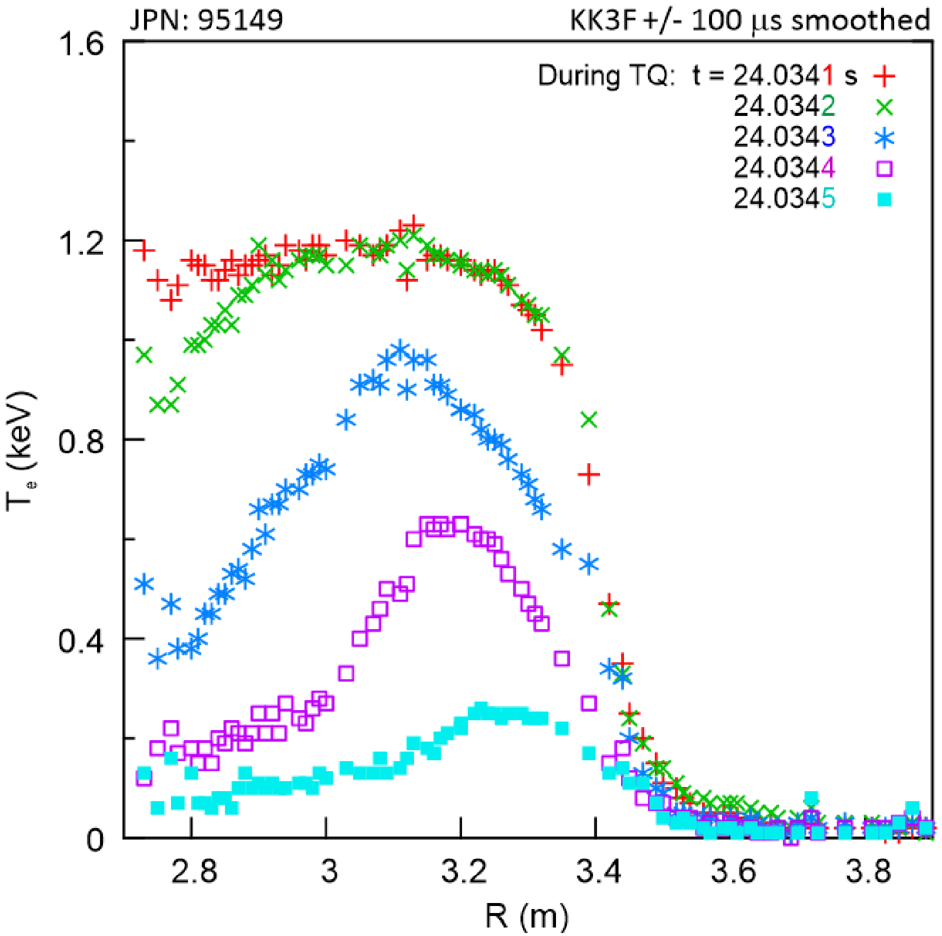
- ECE 2X-mode emission comes from the point R_{ECE}
- cut-off density at the radius $R > R_{ECE}$ is

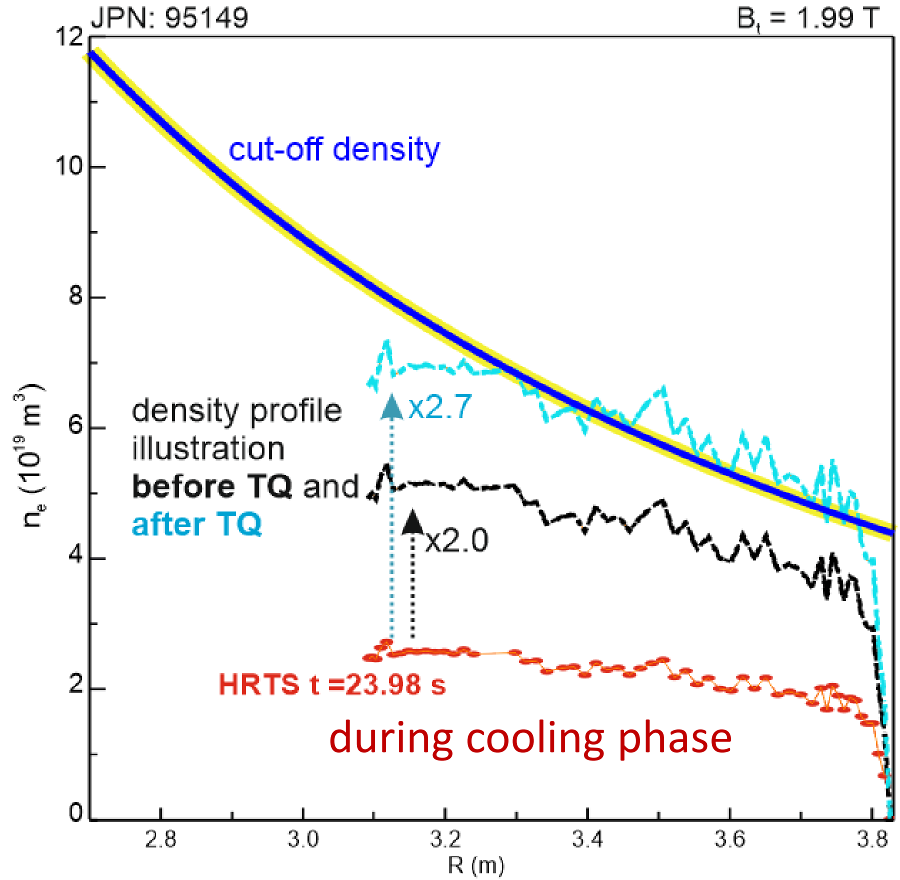
$$n_{cut\text{-}of} \approx 3.9 \cdot 10^{19} (B_{to} R_o / R_{ECE})^2 (1 - 0.5 R_{ECE} / R)$$

- cut-off density can be approximated by single curve

**Yu.F. Baranov et al 2012 Nucl. Fusion 52 023018) (the contribution of the poloidal field to the total magnetic field was neglected)*

ECE (100 μs smoothing) cut-off during TQ?

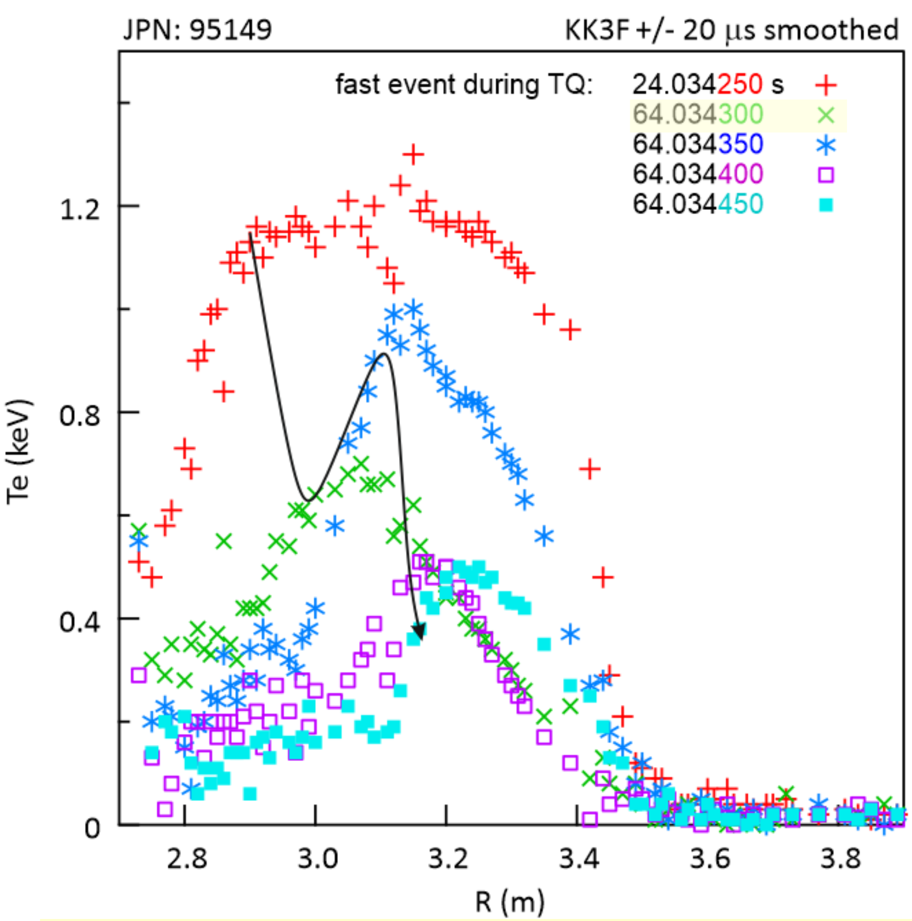


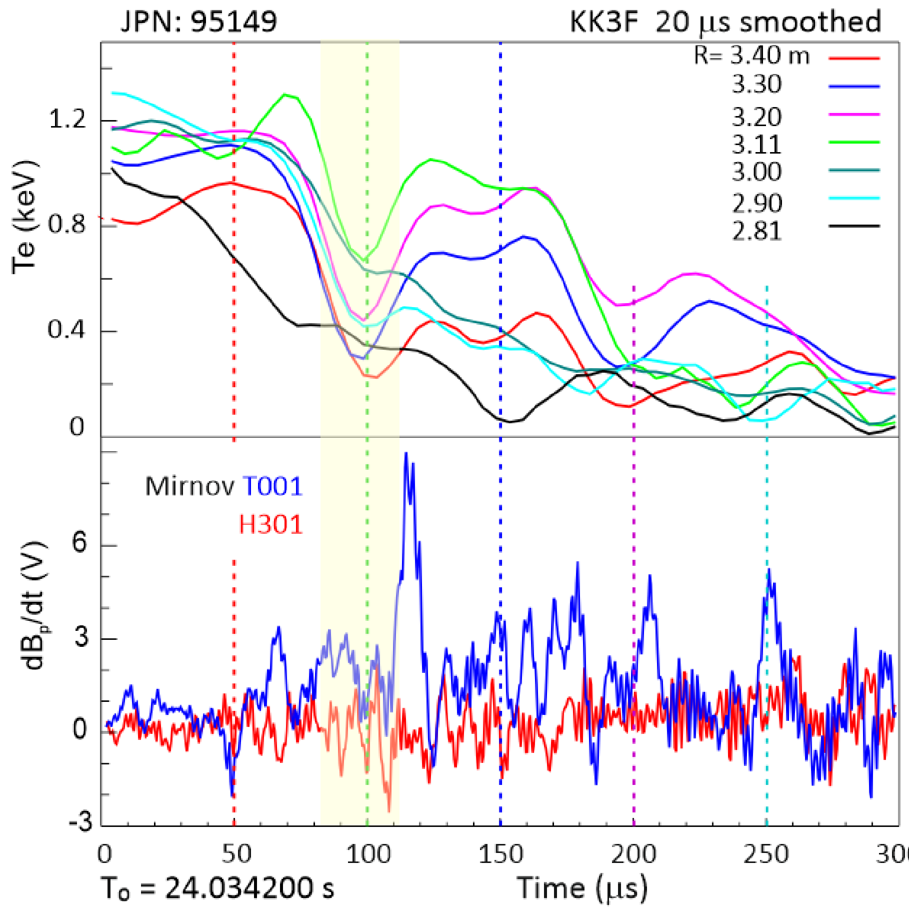


ECE cut-off is unlikely, but for small pellet

#95149, SPI C barrel, 0.11 g pellet Ne/(Ne+D) = 0.60
Ne = 3.07 $\cdot 10^{21}$, D = 2.02 $\cdot 10^{21}$ atoms

ECE pit during TQ: fast event or cut-off?



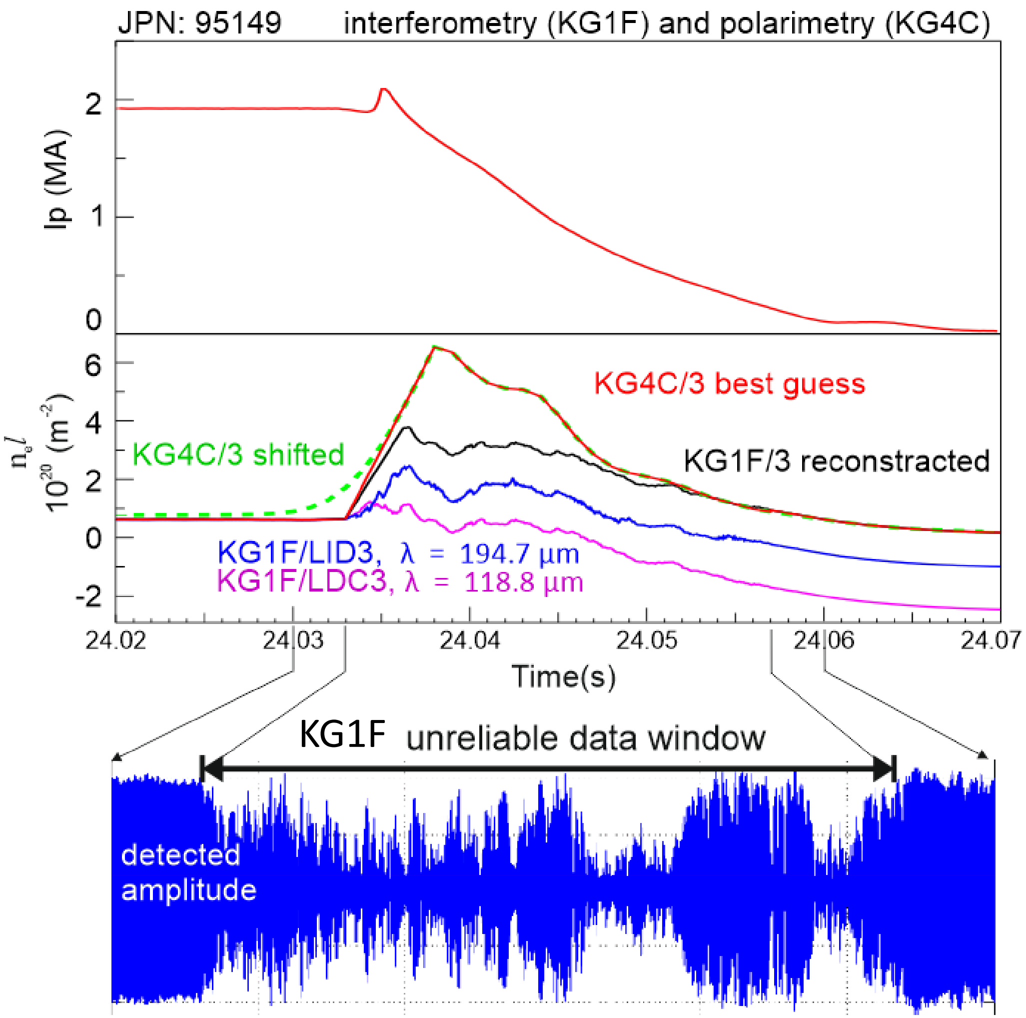


Highly likely it is ECE cut-off rather than MHD event

#95149, SPI C barrel, 0.11 g pellet Ne/(Ne+D) = 0.60
Ne = 3.07 $\cdot 10^{21}$, D = 2.02 $\cdot 10^{21}$ atoms

JET

Interferometry (KG1F) and Polarimetry (KG4C)



#95149, SPI C barrel, 0.11 g pellet Ne/(Ne+D) = 0.60
Ne=3.07 $\cdot 10^{21}$ atoms, D = 2.02 $\cdot 10^{21}$ atoms

Interferometry (KG1F)

Both beams suffer from fringe jumps

λ (μm) = 194.7 → 1 fringe = $1.14 \cdot 10^{19}$ m^{-2}

λ (μm) = 118.8 → 1 fringe = $1.87 \cdot 10^{19}$ m^{-2}

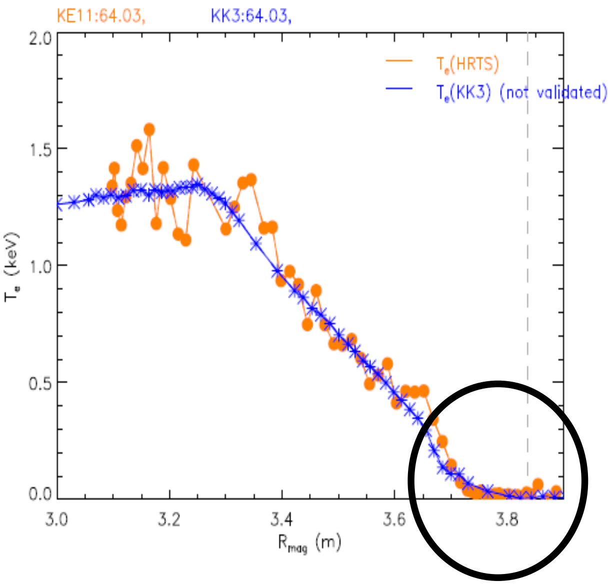
Polarimetry (KG4C)

No fringes, so no jumps!

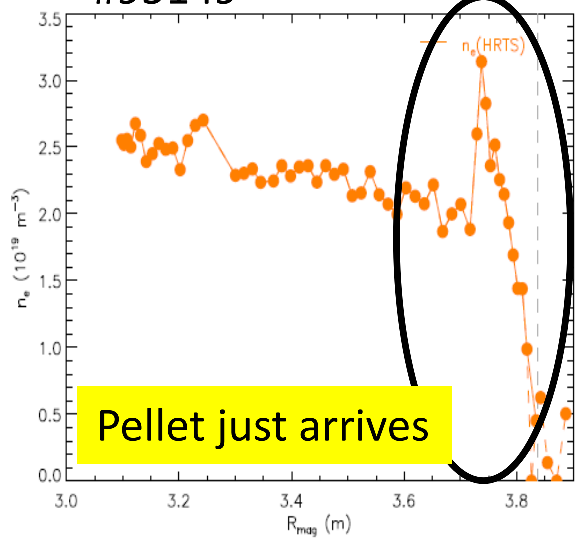
Time delay, shift - unknown

Provides estimation of the line density

HRTS PPF data issues*

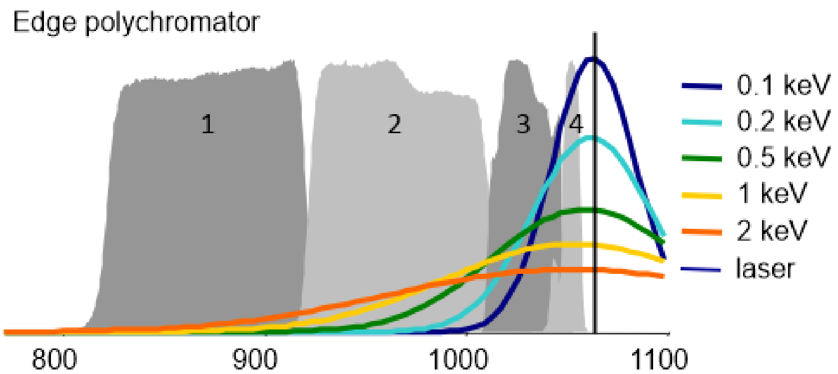


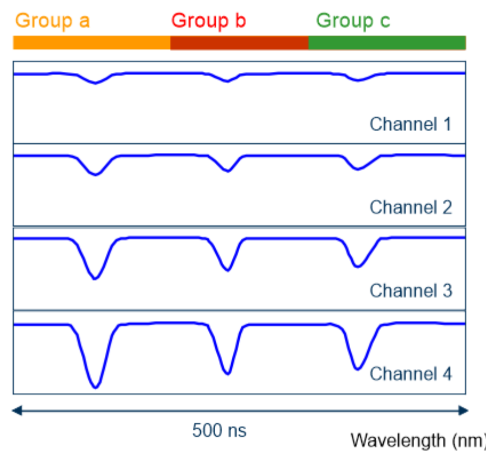
#95149

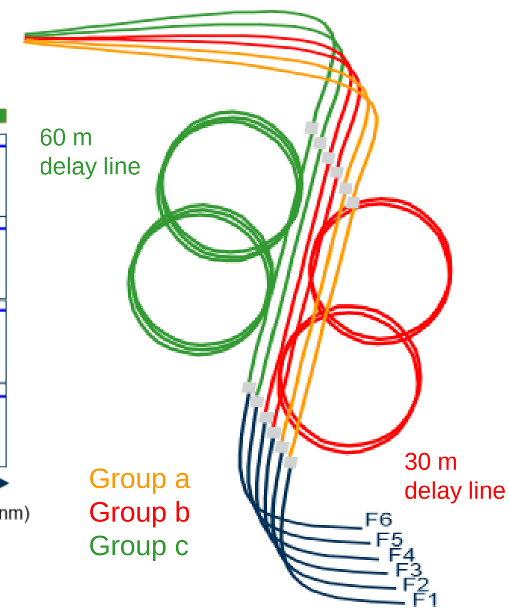


Can we trust the n_e & T_e values (PPF) at low Te?

No, if the temperature is too low, < 100 eV !

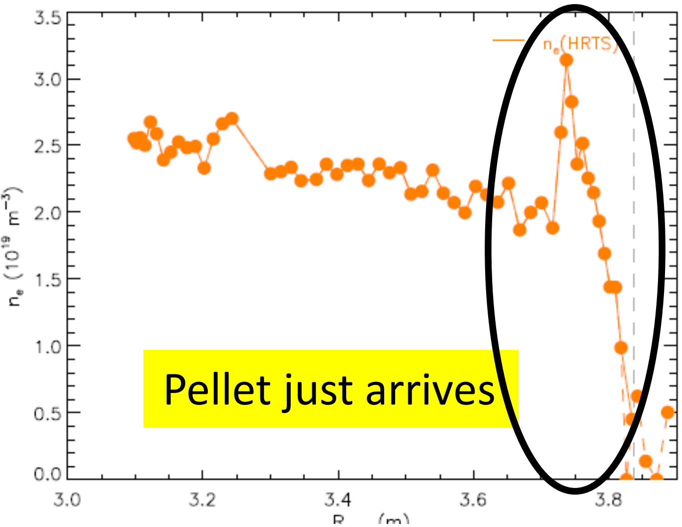


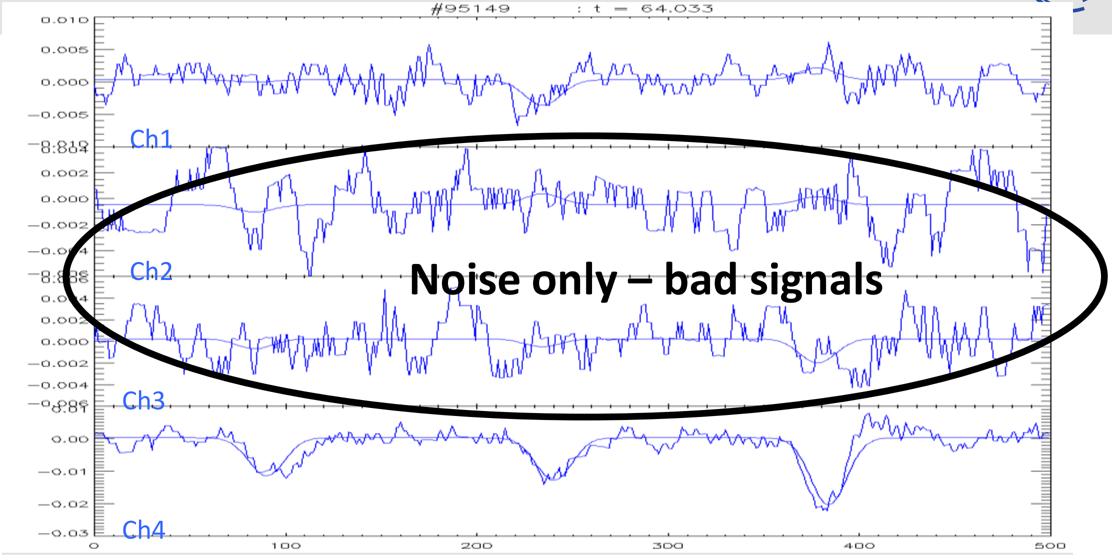




**thanks to Jo Flanagan*

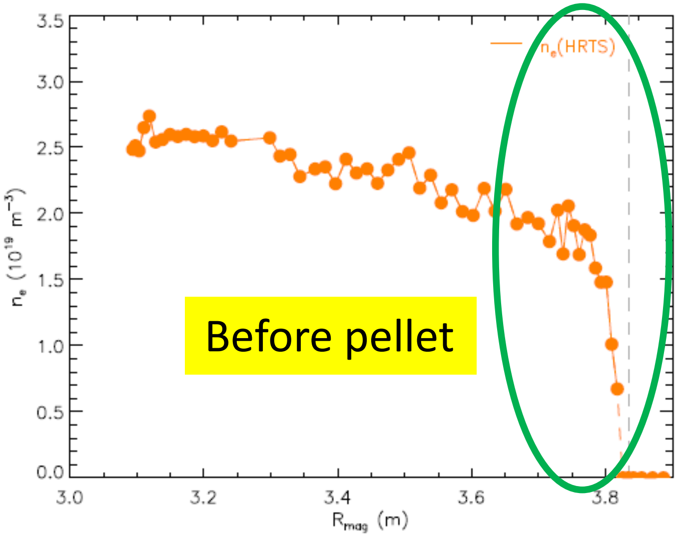
HRTS Data for 2 laser pulse at t = 63.9826 s and t = 64.0326 s

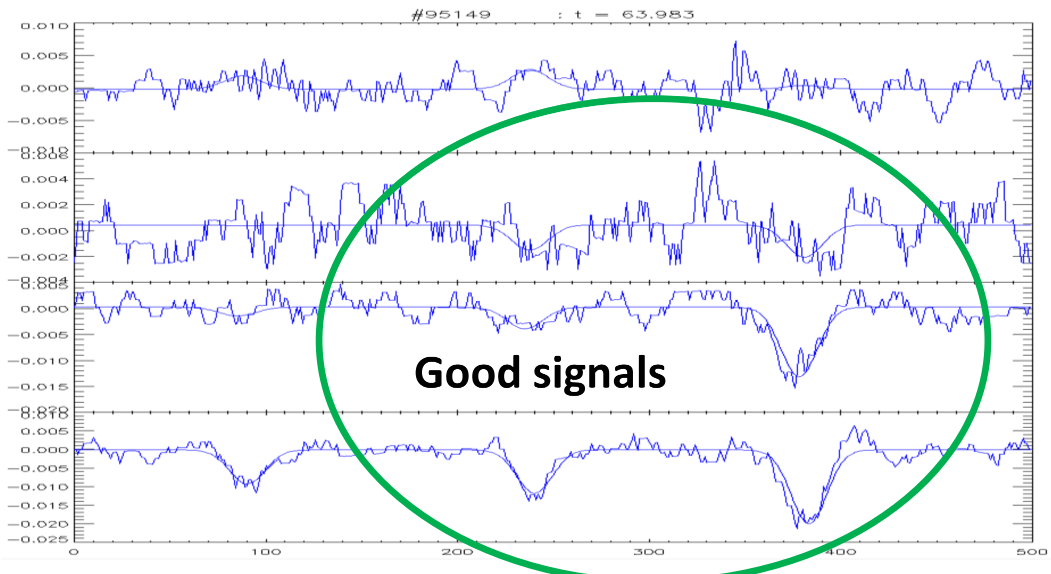




Noisy lines = raw data smooth lines = fit

4 spectral channels with scattered TS light blips for three adjacent spatial points per laser pulse





Summary - JET diagnostic interpretations

- ECE
  - Fast ECE (KK3F) must be used for fast (> 1 kHz) events;
  - KK3F signals are noisy, so they need (triangular) smoothing: 100 μs for fast events (as TQ) and 20 μs for very fast events;
  - The ECE signals highly likely affected by ECE emission cut-off during SPI experiments, definitely for B and A size pellets;
- Interferometry and Polarimetry
  - Both beams (λ = 194.7 μm and 118.8 μm) suffer from fringe jumps;
  - Polarimetry provides estimation of the line density, however it suffers from slow response and unknown time delay;
  - There is no reliable density measurements so far (beam λ ≈ 10 μm is needed);
- HRTS
  - HRTS data (T_e and n_e) are unreliable if the temperature is too low (< 100 eV);
  - When T_e< 100 eV, PPF (may) contain misleading data;
- Fast Cameras
  - Two images with neutral (Ar I) and ion (Ar II) filters from the same point are desperately needed;
  - The possibility to use Ne I filter must be investigated, if "YES" Ne I filter must be purchased;
- SPI affected plasma is always fundamentally 3D, which must be taken in to account during experiment and modelling!

Back up slides

Ip scan: effect of Ip on CQ duration

SHOT	Barrel	Ne, atoms	D, atoms	Ne/(Ne+D2)	mass, g	I_p^{dis}	τ_{80-20} ms
95612	B	1.94E+22	1.31E+22	0.60	0.69	**2.9**	**23**
95611	B	1.94E+22	1.31E+22	0.60	0.69	**2.4**	**22**
95609	B	1.94E+22	1.31E+22	0.60	0.69	**1.9**	**22**
95150	B	2.04E+22	1.17E+22	0.64	0.72	**1.9**	**23**
95113	B	2.04E+22	1.17E+22	0.64	0.72	**1.9**	**22**
95149	C	3.07E+21	2.02E+21	0.60	0.11	1.9	24
95148	C	3.07E+21	2.02E+21	0.60	0.11	1.9	24
95103	C	3.07E+21	2.02E+21	0.60	0.11	**1.9**	**23**
95107	C	3.07E+21	2.02E+21	0.60	0.11	**1.1**	**19**

CQ duration does not depend on pre-disruptive Ip for B pellet

May be some dependence for C pellet (?)

JET SPI capabilities

Pellet		Pellet Volume, mm3	Estimated Speed (m/s)		Time to plasma, ms
Pellet A Diameter (D, mm) for RA Studies	12.5	2362	150 - 200	punch	30 - 40
Length/D Cold Zone Ratio for Barrel A	1.44		200 - 300	w/o punch	20 - 30
Effective Length/D Ratio for Pellet A	1.54				
Pellet B Diameter (D, mm)	**8.1**	**668**	**150 - 200**	**punch**	**30 - 40**
Length/D Cold Zone Ratio for Barrel B	**1.5**		**250 - 350**	**w/o punch**	**15 - 25**
Effective Length/D Ratio for Pellet B	**1.6**				
Pellet C Diameter (D, mm)	4.57	105	250 - 500	w/o punch	12 - 25
Length/D Cold Zone Ratio for Barrel C	1.3				
Effective Length/D Ratio for Pellet C	1.4				
track, m	6				

From Larry Baylor's data file