EUROfusion

High fusion performance at high T_i/T_e in JET-ILW baseline plasmas with high NBI heating power and low gas puffing

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JET

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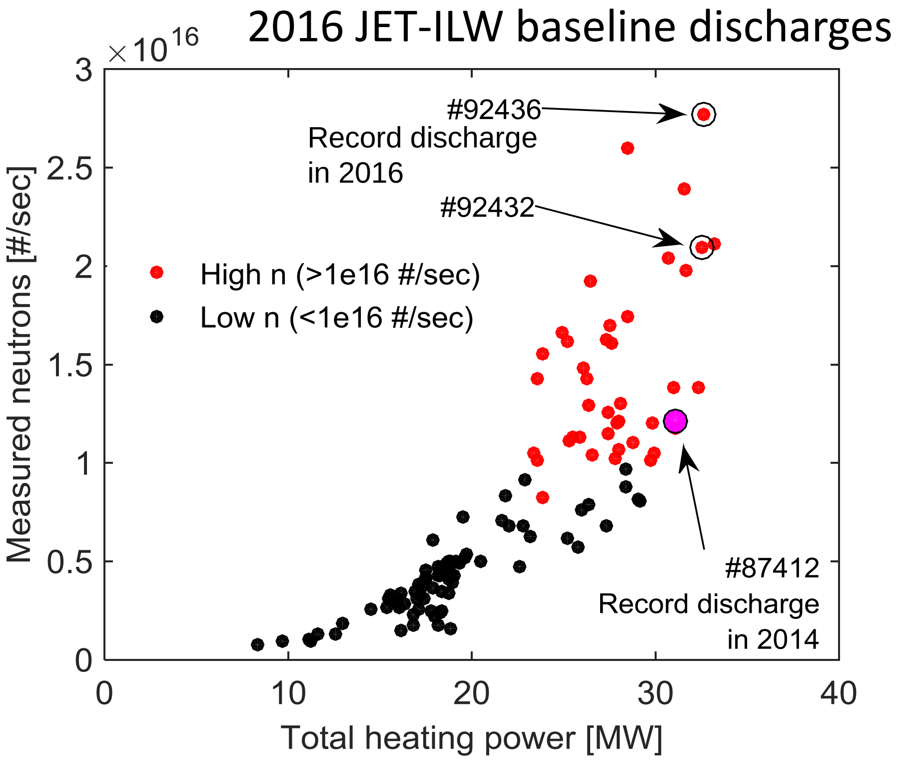
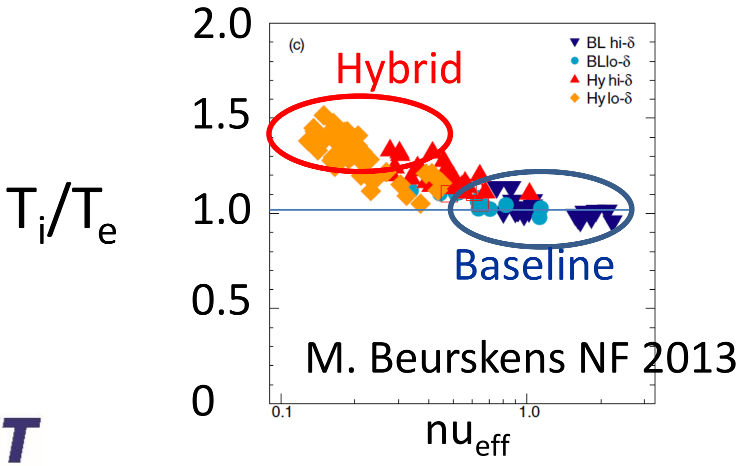
Key questions on 2016 JET-ILW baseline discharges





M. Beurskens NF 2013

1) The fusion performance achieved in 2016 (i.e. #92436) was much better than that expected based on previous experiments with the same high heating power in 2014 (i.e. #87412). Why?

2) Previously, high T_i/T_e was observed only in hybrid and advanced discharges where n_e is low. How could 2016 baseline discharges achieve $T_i>T_e$, despite the high n_e (i.e. n_e >7e19m^{-3})?

3) High T_i/T_e was not observed in the previous discharges with the same high heating power (i.e. #87412). How was it possible only in 2016?

Contents

Database

- ❖ 115 H-mode discharges from the 2016 baseline scenario development were selected.
- ❖ http://users.euro-fusion.org/tfwiki/images/1/1b/M15-01_GoodPulsesList_4wiki.xls
- Pulse number : 89062 - 92442
- I_p=2.16 – 3.47 [MA]
- B_t=2.35 – 3.03 [T]
- P_{NBI}=7.22 – 27.79 [MW]
- P_{ICRF} = 0.8 – 6.34 [MW]
- **n_{e0} > 7e19 [m^{-3}]**
- q_{95}= 2.72 – 3.75
- **Deuterium Gas puffing = 0 – 9e22 [sec^{-1}]**

Setting for statistical TRANSP analysis

- **Measured T_i is not available** in all discharges due to the difficulty of the CX data analysis in ITER-Like Wall i.e. No Carbon!

- Alternatively, statistical analysis of interpretive TRANSP runs were performed.
  - ✓ **T_i=T_e was assumed in TRANSP runs of all 115 discharges**
  - ✓ **For subset 11 discharges, where CX measurement is available, measured T_i was used for TRANSP runs**

- Except the above mentioned, an identical setting was used for all TRANSP analysis
  - ✓ Fitted HRTS T_e and n_e
  - ✓ Z_{eff} from Visible Bremsstrahlung assuming uniform profile
  - ✓ 100% Be or 100% Ni impurity assumption (used for error bars).
  - ✓ Total bulk Radiation from Bolometry assuming uniform radiation profile
  - ✓ NUBEAM (30000 Monte Carlo ptls)
  - ✓ TORIC (dipole phasing with Nphi=27, H minority, 3% concentration)
  - ✓ q profile from EFIT
  - ✓ Boundary equilibrium from EFIT
  - ✓ Internal equilibrium calculated by TEQ

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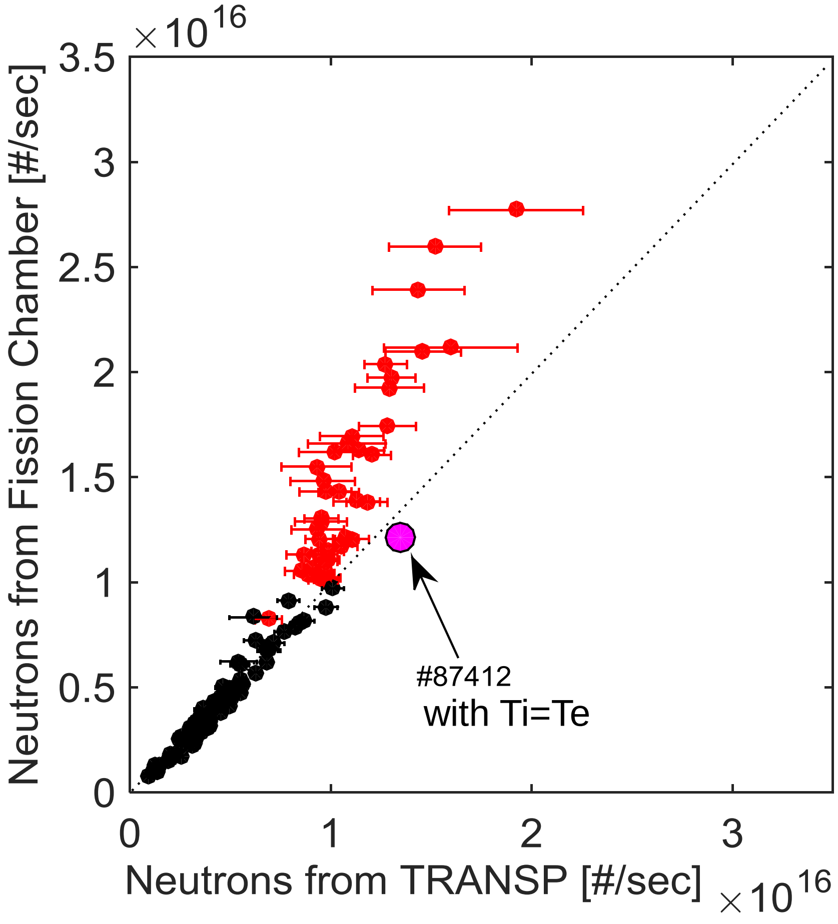
Statistical Investigation on $T_i > T_e$



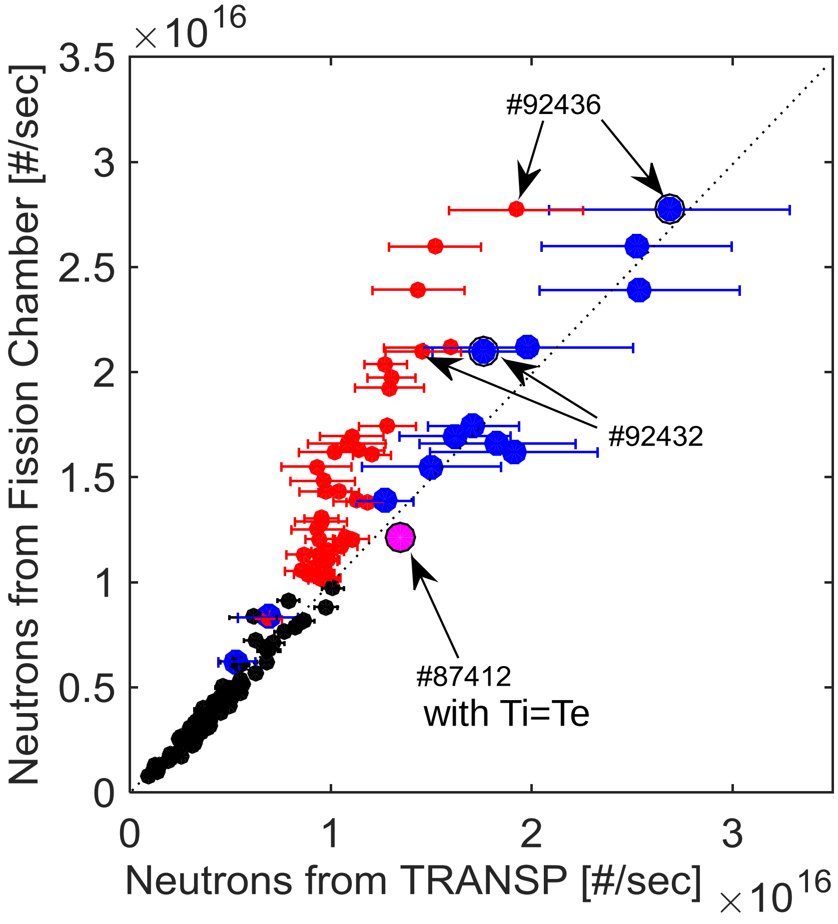
The error bars are the calculated neutrons with different impurity assumptions i.e. 100% Beryllium (left bar) or 100% Nickel (right bar)

High neutrons with T_i=T_e in TRANSP

Low neutrons with T_i=T_e in TRANSP

- TRANSP runs with T_i=T_e assumption underestimates the total neutrons at high heating power (>25MW).

Statistical Investigation on $T_i > T_e$



High neutrons with T_i=T_e in TRANSP

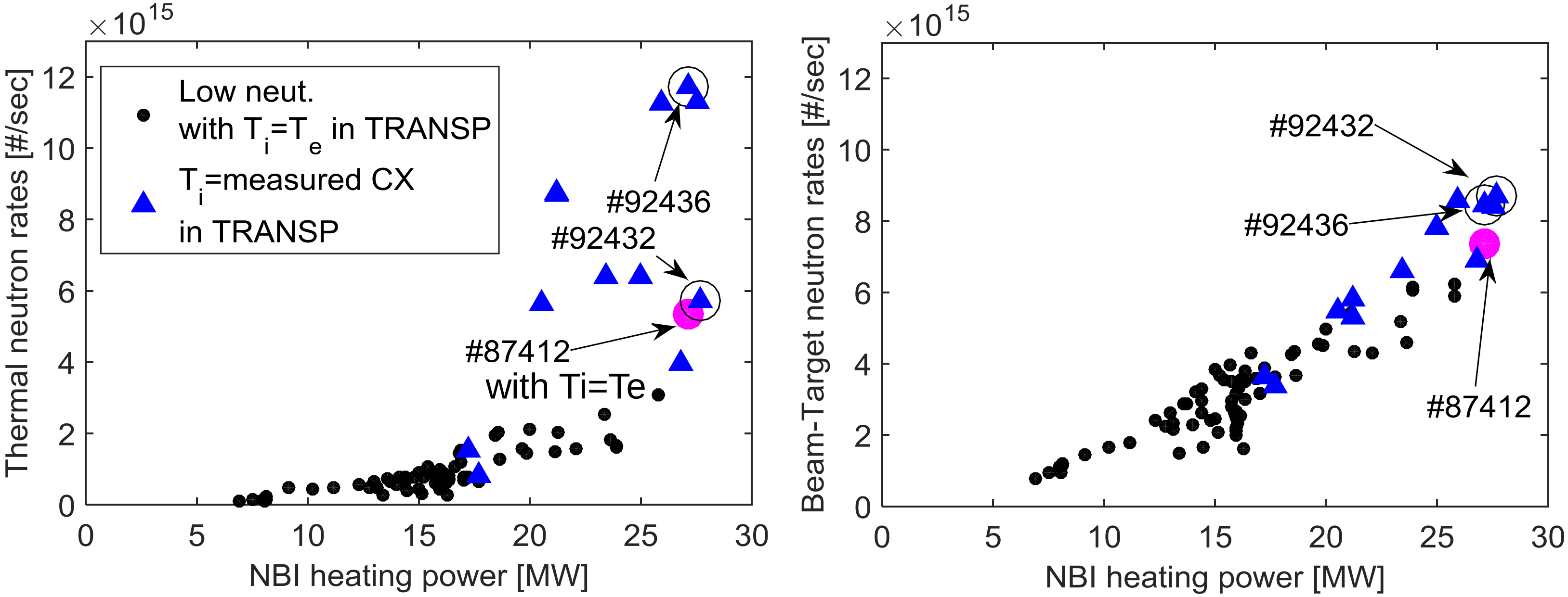
Low neutrons with T_i=T_e in TRANSP

T_i=CX measurement in TRANSP

- TRANSP runs with T_i=T_e assumption underestimates the total neutrons at high heating power (>25MW).
- TRANSP neutron predictions consistent with neutron measurements when measured T_i (>T_e) were used in the subset discharges .

The error bars are the calculated neutrons with different impurity assumptions i.e. 100% Beryllium (left bar) or 100% Nickel (right bar)

Neutron analysis



Increase in thermal neutron rate is the main contribution for the high fusion performance, rather than beam-target neutrons.

High T_i, exceeding T_e, is the key factor.

Key questions on 2016 baseline discharges

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→Higher thermal neutrons achieved due to higher T_i

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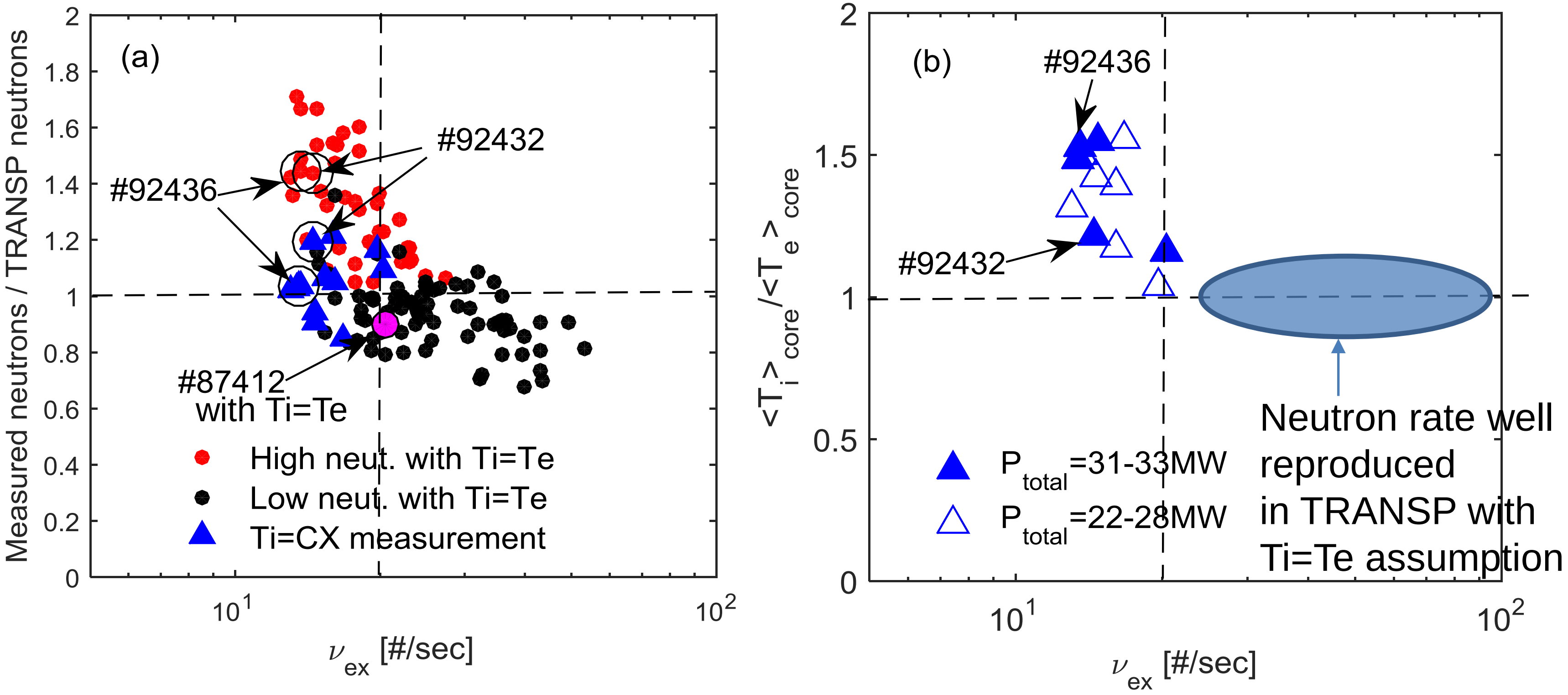
Collisionality



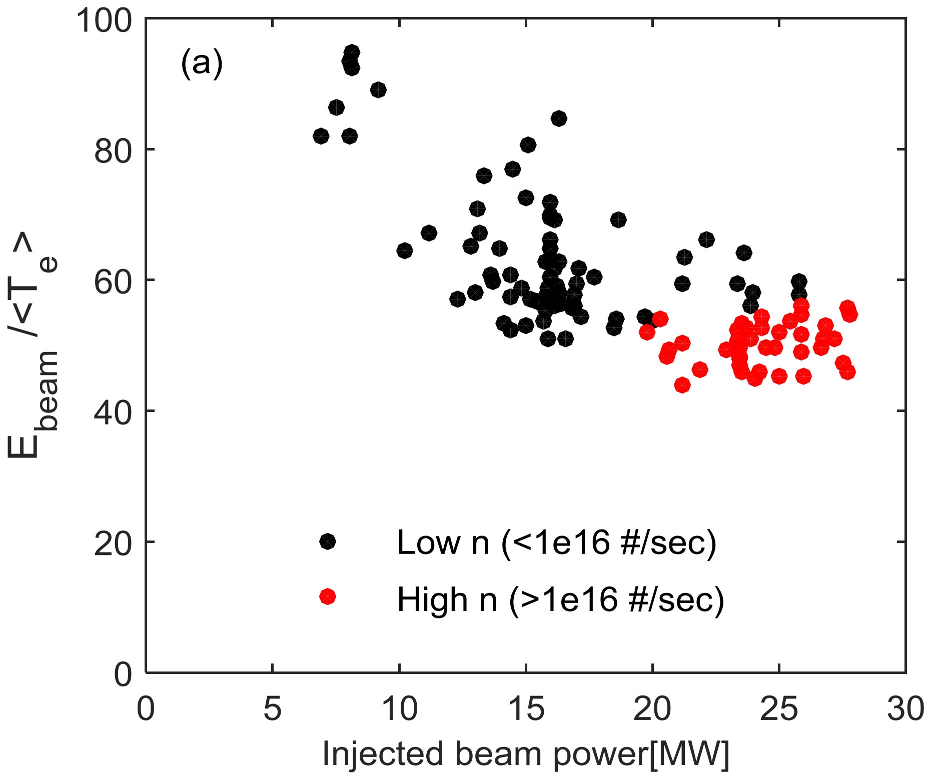
Neutron rate well reproduced in TRANSP with Ti=Te assumption

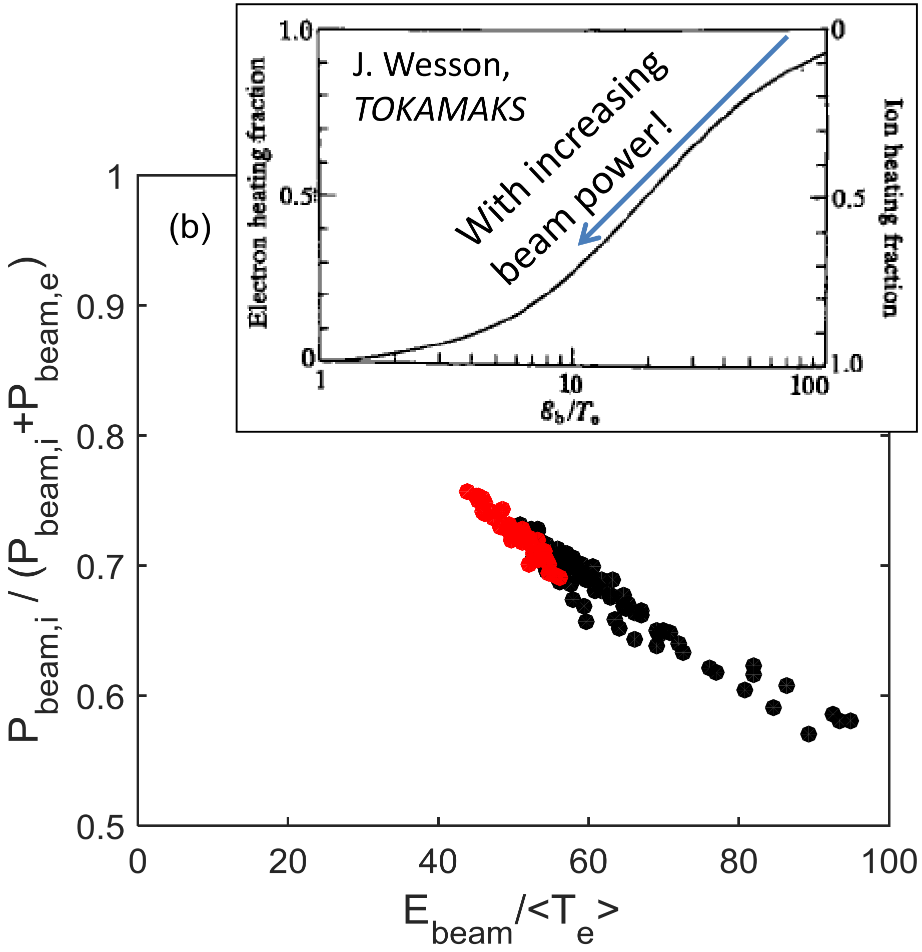
- The neutron under-estimation with T_i=T_e in TRANSP is more significant at low collisionality regime i.e. $T_i > T_e$ at low collisionality.

$$\nu_{ex} \equiv 0.32\times10^{-14}\frac{m_e}{m_i}\frac{<n_e[m^{-3}]>}{<T_e[keV]>^{3/2}}$$

- High heating → Increase in T_e → sufficient decrease in collisionality (despite high n_e) → Low equilibration power → decoupling T_i from T_e.

Heating power analysis





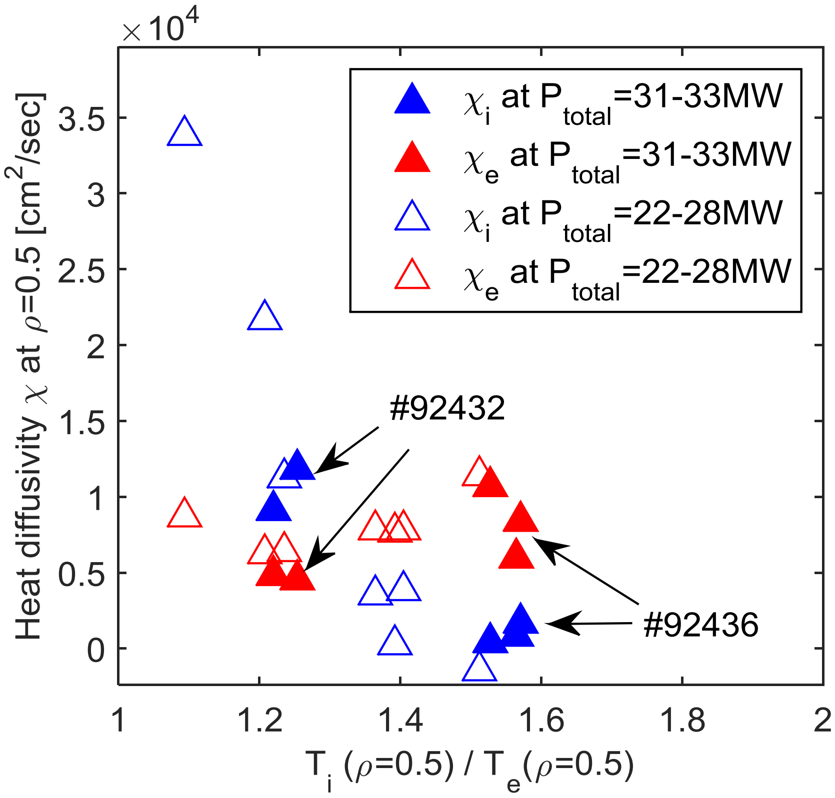
J. Wesson, *TOKAMAKS*

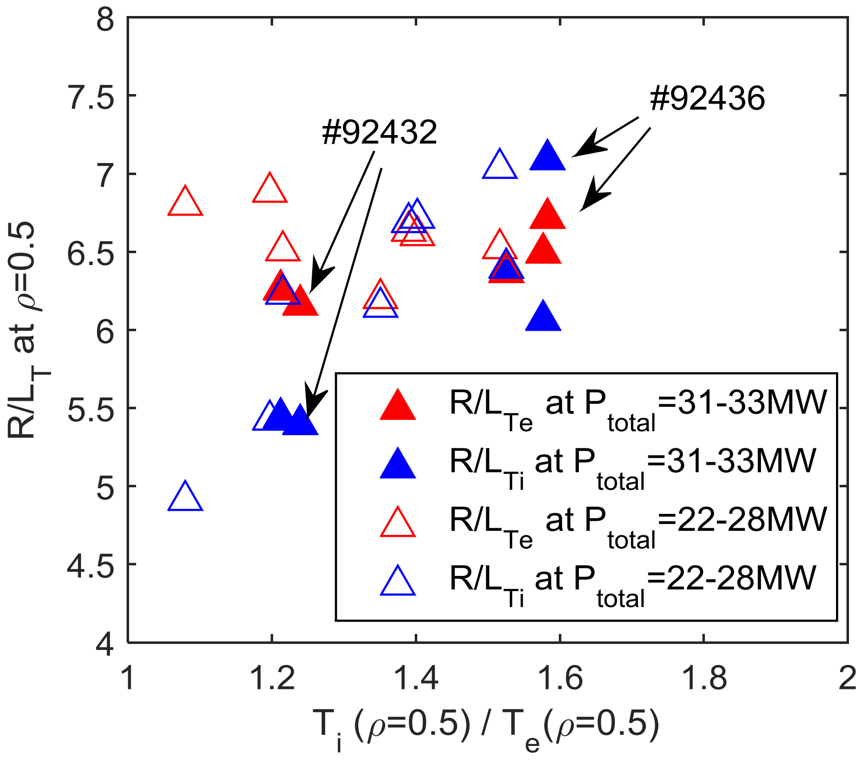
With increasing beam power!

High beam power increases T_e, thereby decreasing ε_{beam}/T_e.

→ ion heating fraction increases.

Transport analysis





Ion heat transport is reduced with high T_i/T_e, while electron heat transport isn't.

Key questions on 2016 baseline discharges

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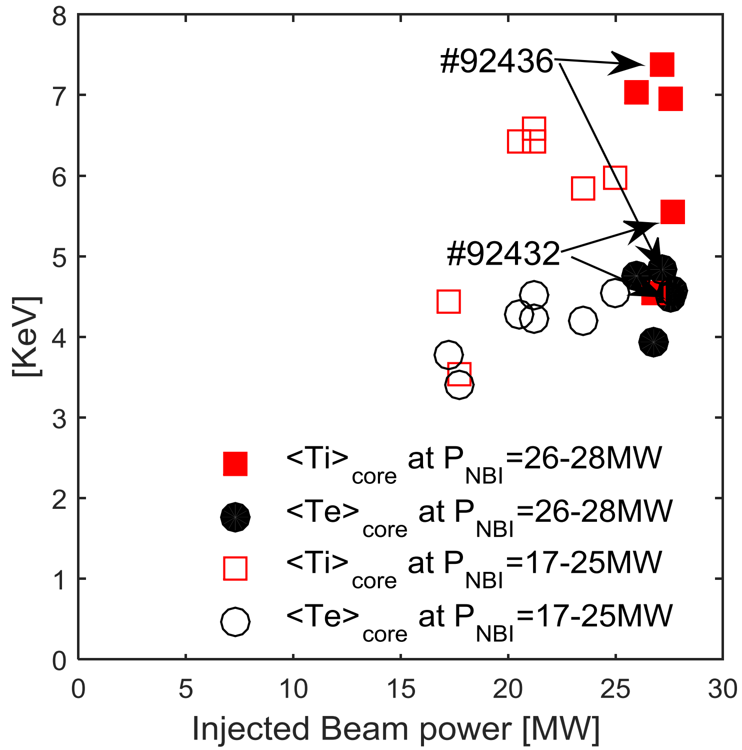
→P_{heat}(>25MW) was high enough to decrease the collisionality despite high n_e
→Ion heating fraction increases with heating power
→Ion heat transport was reduced with high Ti/Te

3) High T_i/T_e was not observed in the previous discharges with the same high heating power (i.e. #87412). How was it possible only in 2016?

Requirements for $T_i > T_e$

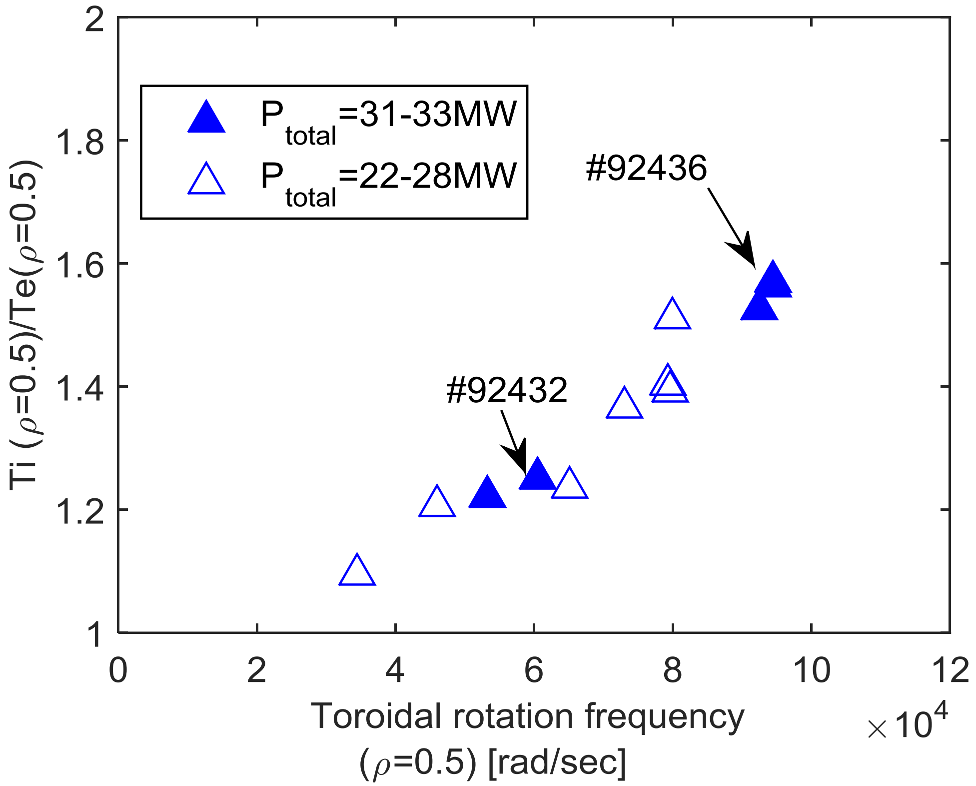


Requirements for high T_i/T_e

1. Low collisionality to decouple T_i and T_e
2. High ion heating fraction
3. Low ion heat transport

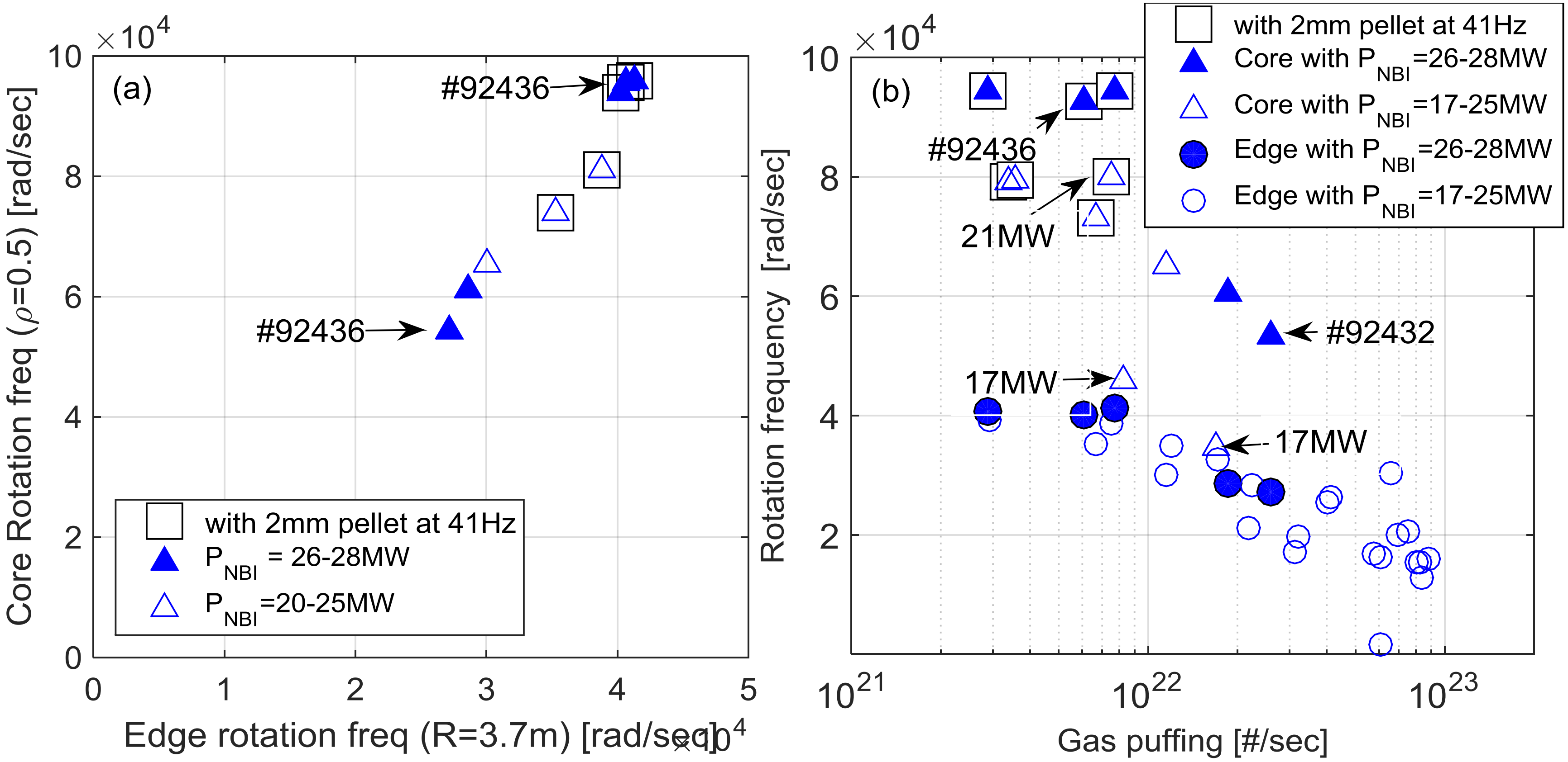
However, high beam power alone cannot explain the high T_i/T_e.

Impact of rotation



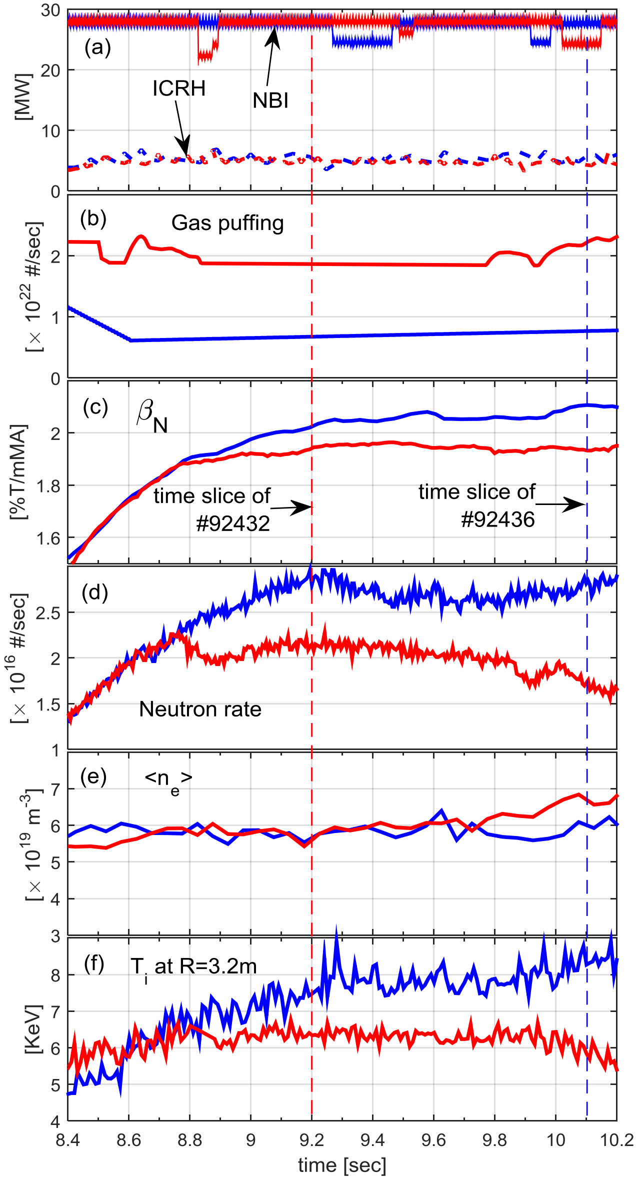
Core T_i/T_e is correlated with core rotation frequency.

Impact of gas puffing



- Core rot freq is correlated with edge rot freq, which is correlated with low gas puffing.
- Thanks to the use of ELM pacing pellets, low gas injection operation was possible, while keeping ELMs frequent enough.
- For high rot freq, high beam power is required for high momentum source, but low gas fuelling should be also important as neutrals at the edge may be a strong momentum sink.

#92436 and #92432

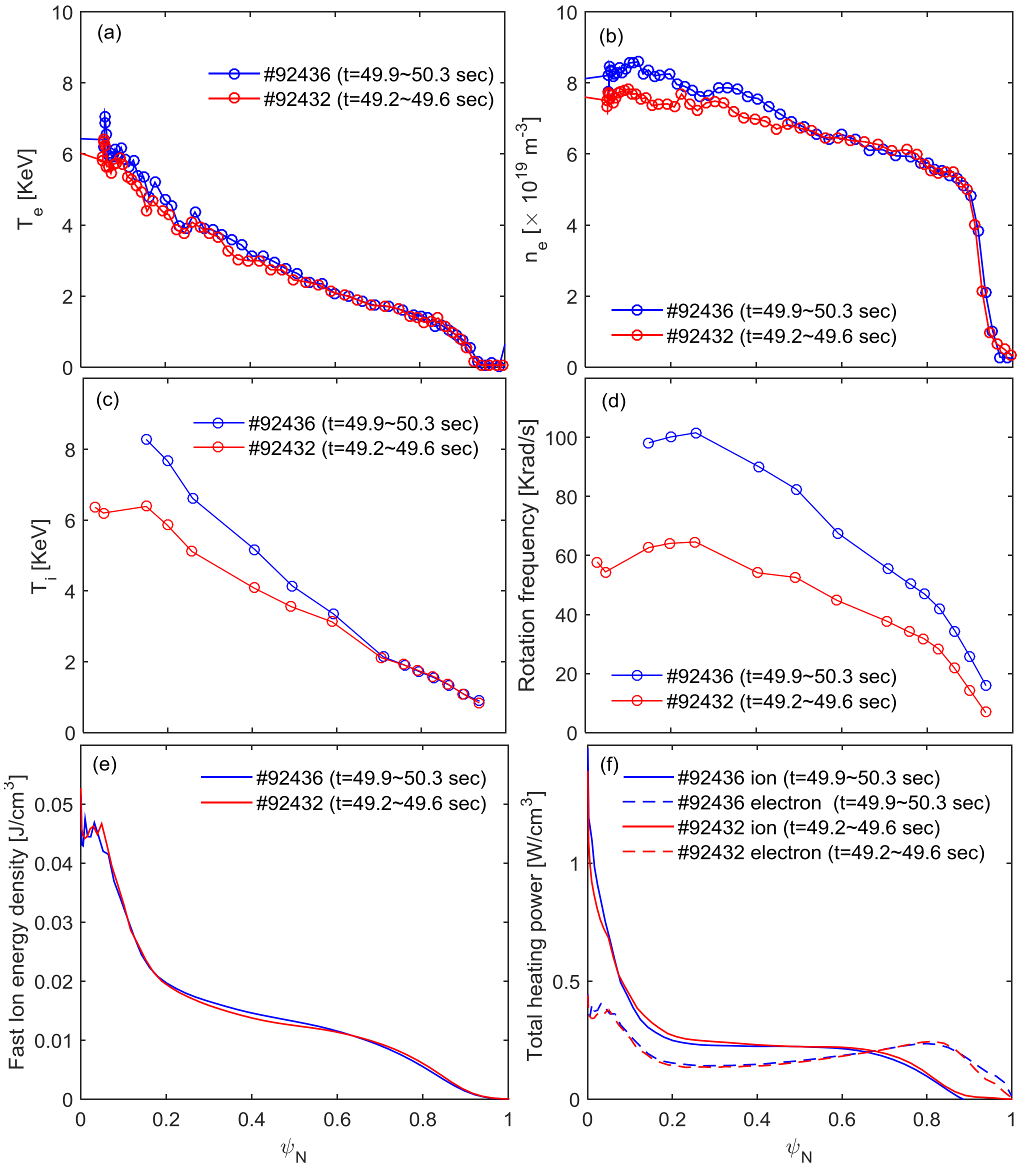


▬ #92436 ▬ #92432

Identical control room parameters in the two discharges, <u>except gas fuelling</u>

	92436	92432
Ip	3MA	3MA
Bt	2.8T	2.8T
P_{NBI}	27.5MW	27.5MW
P_{ICRH}	5MW	5MW
Gas	7e21 #/sec	2e22 #/sec
H98	1.1	1.0
Neutron Yield	2.8e16 #/sec	2.1e16 #/sec

#92436 and #92432



Similar T_e and n_e profiles

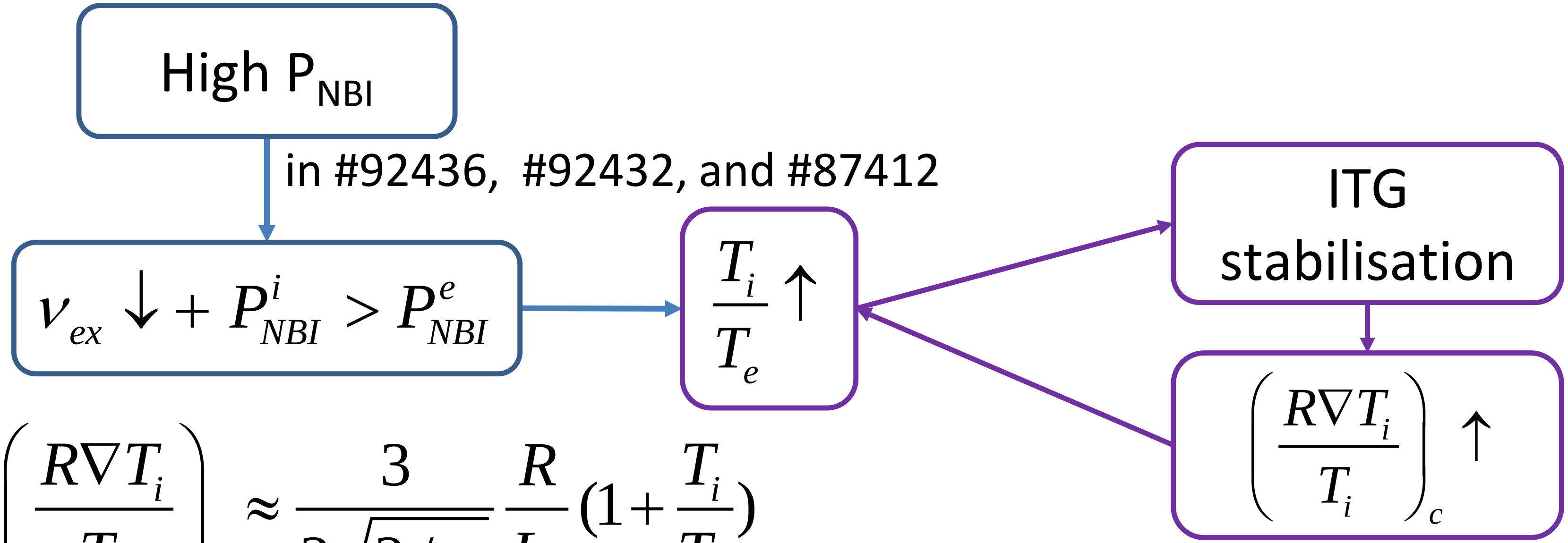
Similar fast ion distribution

Similar heating profiles

Rotation is clearly higher in #92436 (low gas) than in #92432 (high gas)

Higher core T_i in #92436

Possible explanation on high T_i/T_e



High P_{NBI}

in #92436, #92432, and #87412

$\nu_{ex} \downarrow + P^i_{NBI} > P^e_{NBI}$

$\frac{T_i}{T_e} \uparrow$

ITG stabilisation

$\left(\frac{R\nabla T_i}{T_i}\right)_c \uparrow$

$$\left(\frac{R\nabla T_i}{T_i}\right)_c \approx \frac{3}{2\sqrt{2/\pi}} \frac{R}{L_s}\left(1+\frac{T_i}{T_e}\right)$$

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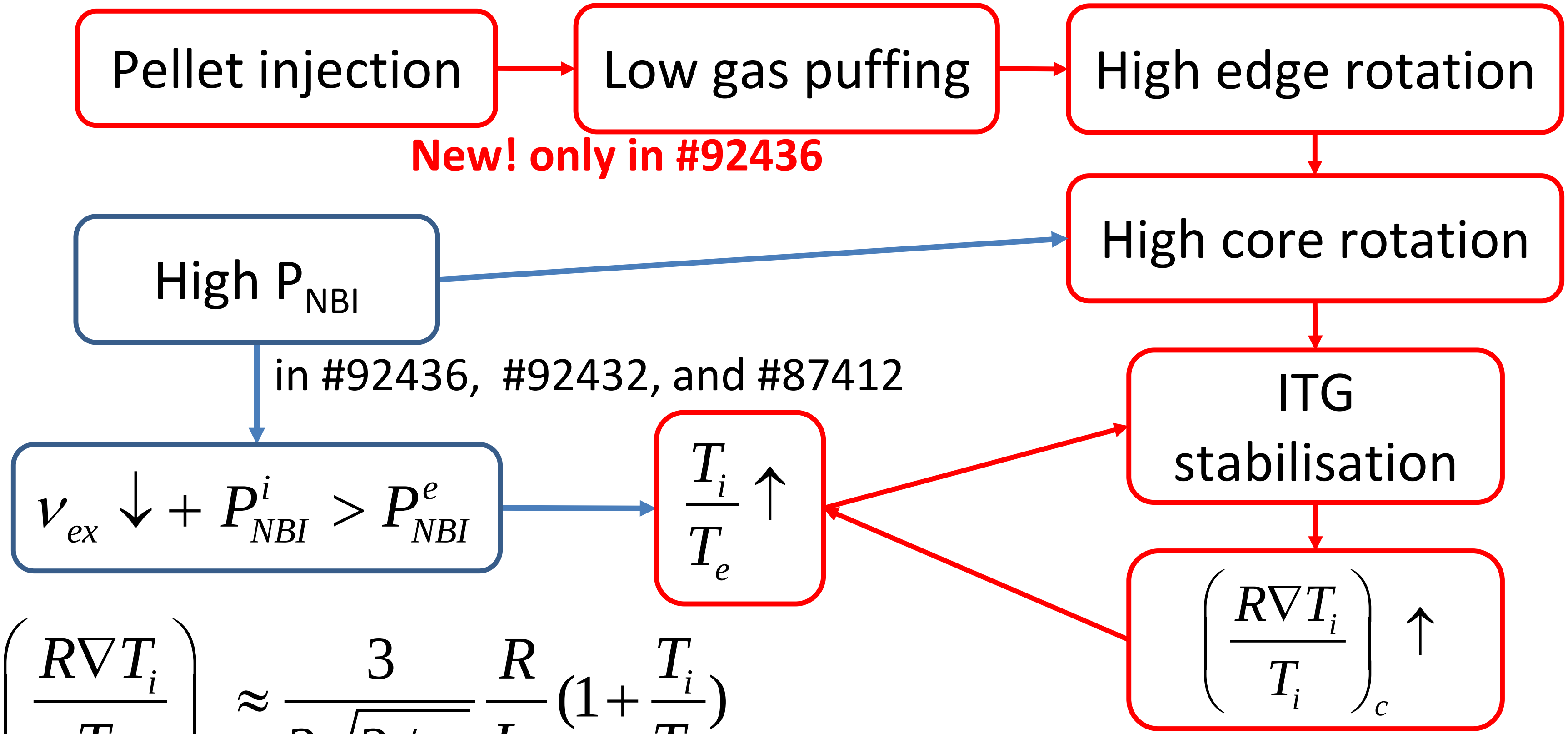
- High P_{NBI} , reducing collisionality and increasing ion heating ratio, enabled $T_i > T_e$.
- High T_i/T_e is also correlated with low ion heat transport i.e. positive feedback between high T_i/T_e and ITG stabilisation

Possible explanation on high T_i/T_e



Pellet injection

Low gas puffing

High edge rotation

New! only in #92436

High P_{NBI}

High core rotation

in #92436, #92432, and #87412

ITG stabilisation

$\nu_{ex} \downarrow + P^{i}_{NBI} > P^{e}_{NBI}$

$\frac{T_i}{T_e} \uparrow$

$\left(\frac{R\nabla T_i}{T_i}\right)_c \uparrow$

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T.S Hahm Phys. Fluids B. Vol. 1. No6 1989

- Low gas puffing increases rotation freq, helping further ITG stabilisation.
- Use of low gas puffing was possible by pellet injections, which were the only main difference in #92436, compared to #92432 and #87412

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→P_{heat}(>25MW) was high enough to decrease the collisionality despite high n_e
→Ion heating fraction increases with heating power
→Ion heat transport was reduced with high T_i/T_e

3) High T_i/T_e was not observed in the previous discharges with the same high heating power (i.e. #87412). How was it possible only in 2016?
→High T_i/T_e is correlated with high rotation frequency.
→Rotation frequency increases with low gas puffing.
→Low gas puffing was only possible in 2016 baseline discharges, thank to the pellet injections.

Summary

- 2016 baseline discharges with high beam power (max. 28MW) achieved a very good fusion performance. This comes from core confinement improvement (not only from the pedestal).
- High T_i, exceeding T_e, was observed in baseline discharges despite the high n_e. This enabled the high neutron yield.
- High T_i/T_e was possible because of
  1. Low collisionality
  2. High fraction of beam heating to ions
  3. Reduced ion transport, which should be due to the positive feedback between high T_i/T_e and ITG stabilisation.
- **High T_i/T_e is correlated with high rotation freq**, implying ExB flow shear may improve the positive feedback.
- **High rotation is not only correlated with high beam power, but also with low gas puffing, which was possible by pellet injections in 2016.** Neutrals at the edge could be a momentum sink.
- Further details available in *Hyun-Tae Kim et al, NF 58 (2018) 036020*