EUROfusion

# Overview of the TCV Tokamak Experimental Programme

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for the TCV team

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EPFL

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# Tokamak à Configuration Variable (TCV)



**Mid-size tokamak**

$R_0 = 0.9\text{m}$

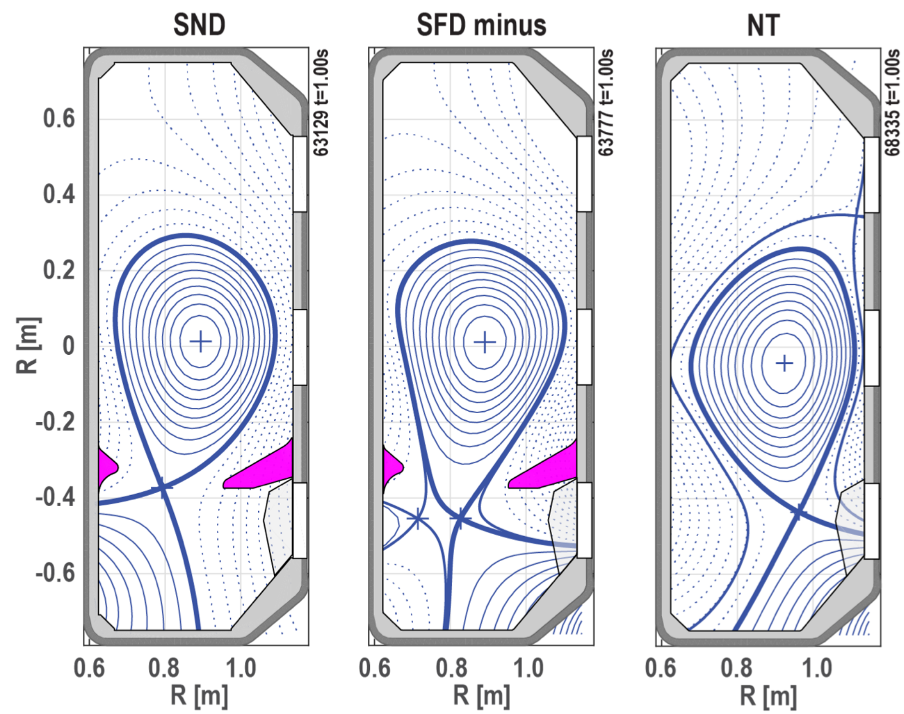
$B_0 \leq 1.5\text{T}$

$A = 4$

# New device capabilities

Fasoli, et al., NF (2020)

- New removable divertor baffles
- Numerous new or improved diagnostics
- NBI heating
  - Improved acceleration grid allows $P_{\mathrm{NBI}} \leq 1.3\mathrm{MW}$
- EC heating
  - X2 (83GHz): 2 x 700kW
  - X3 (118GHz): 2 x 450kW
  - New dual frequency gyrotrons (84/126GHz): 2 x 1MW




2019 2020

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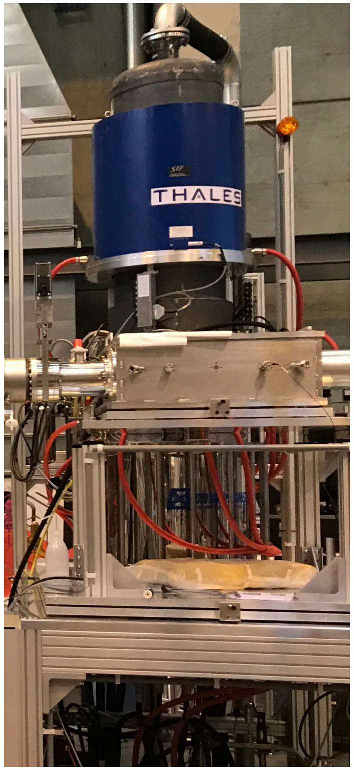
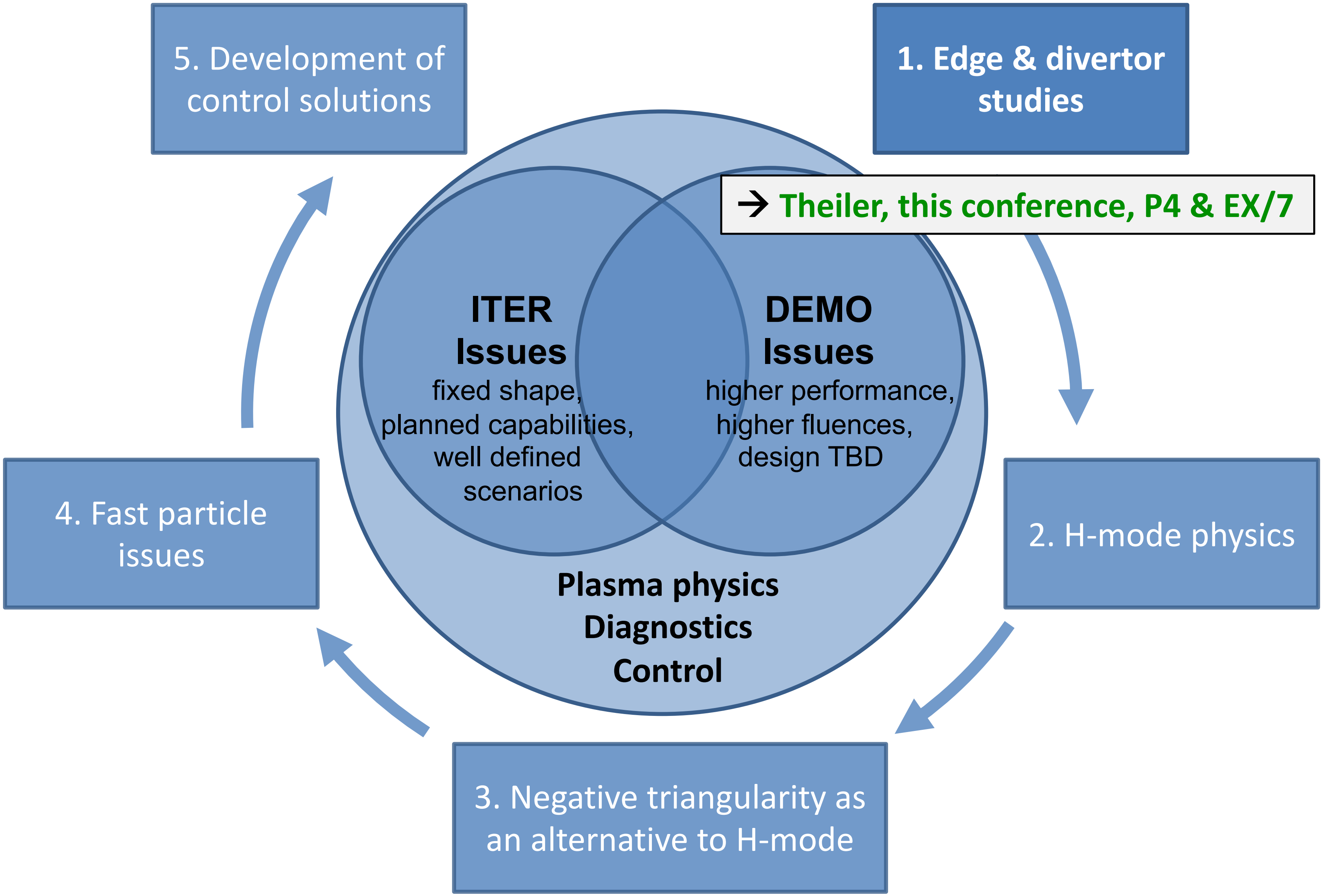
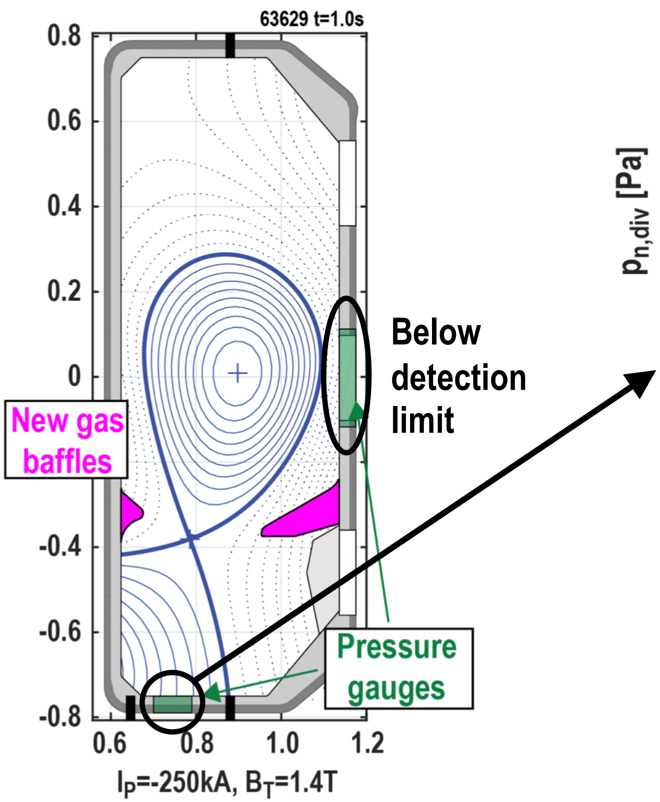


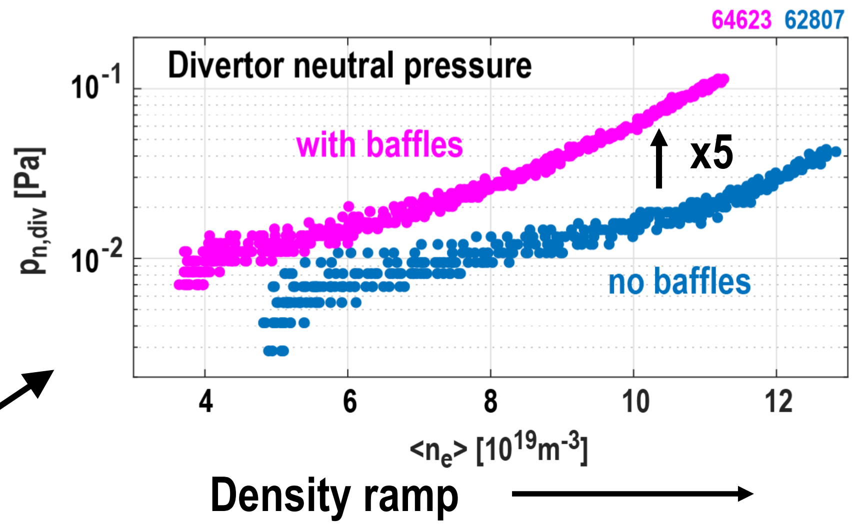
# TCV programme addresses ITER and DEMO needs



# Baffles increase divertor neutral pressure by up to a factor of 5

Reimerdes, et al., NF (2021)



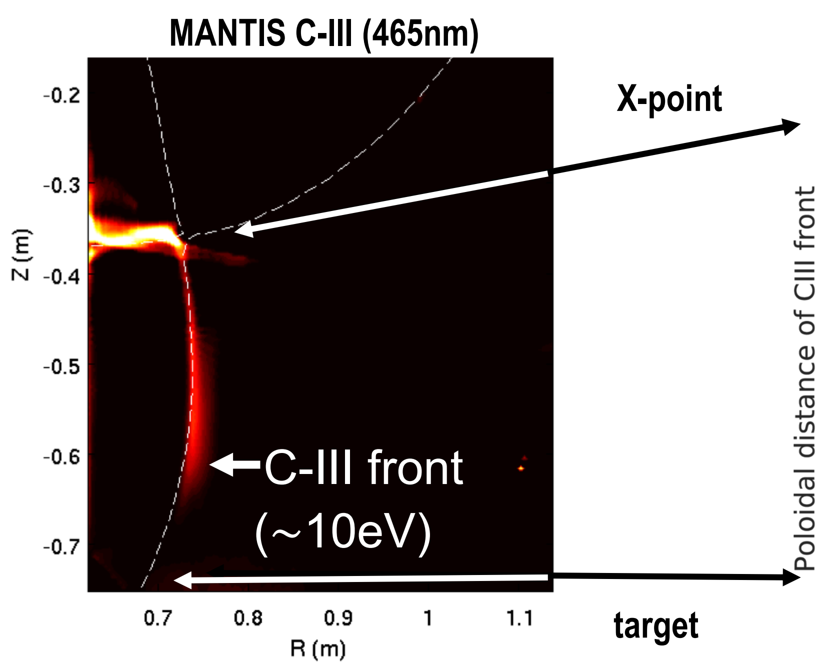

- De-couple divertor and main chamber neutral pressure

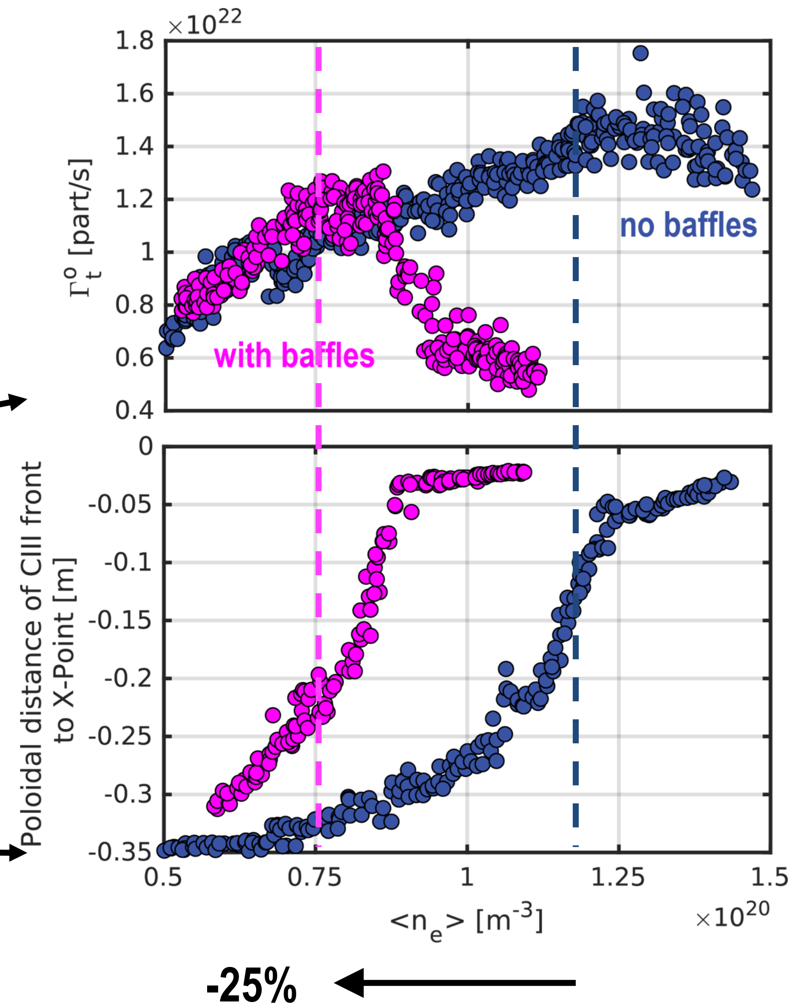
➢ Increase divertor dissipation – access to regimes of greater interest for next step devices

# Baffled divertor is colder and denser and detaches at a lower core density

Février, et al., NME (2021)

- Reciprocating divertor probe array (RDPA) measures $T_e$ and $n_e$ in the divertor [1]
- Detachment indicators
  - Target current roll over
  - C-III emission front location



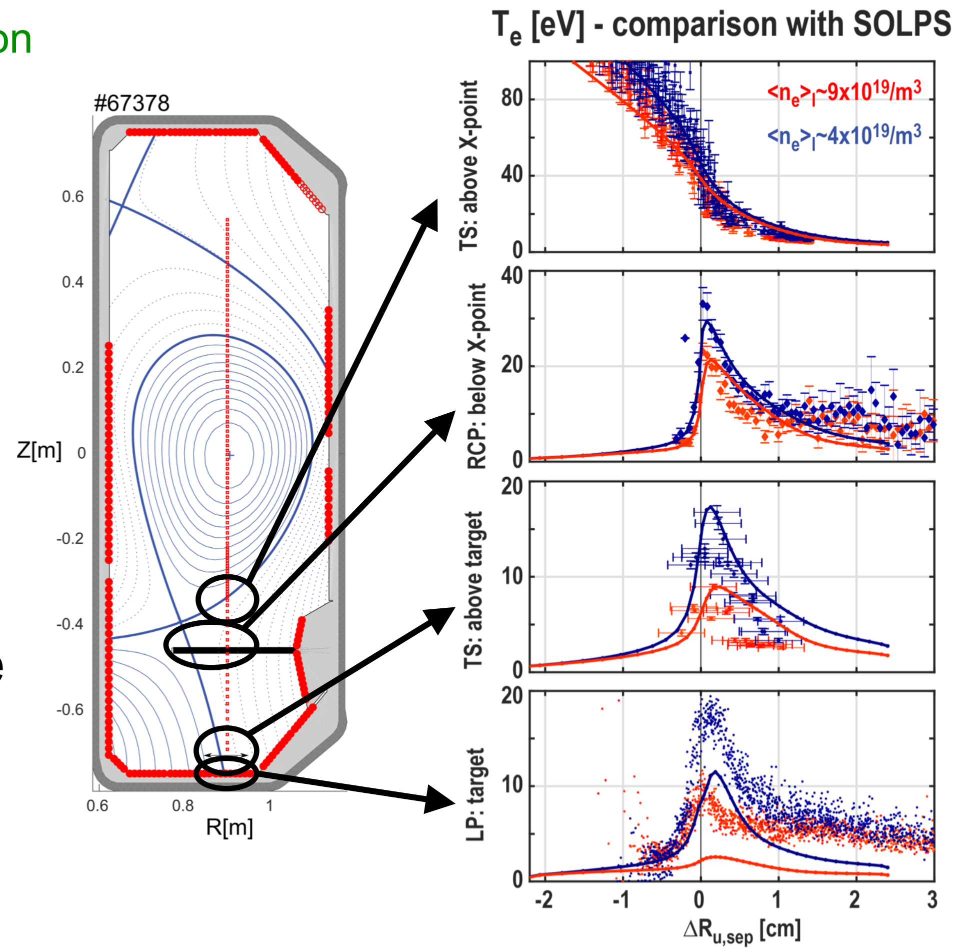




[1] De Oliveira, et al., in prep.

# Well diagnosed divertor challenges edge models, e.g. SOLPS-ITER



Wensing, et al., in preparation




- Target predicted to be too cold and too dense
- Neutral pressure predicted too high

➢ Identify description of molecular activated recombination as possible short-coming [1]

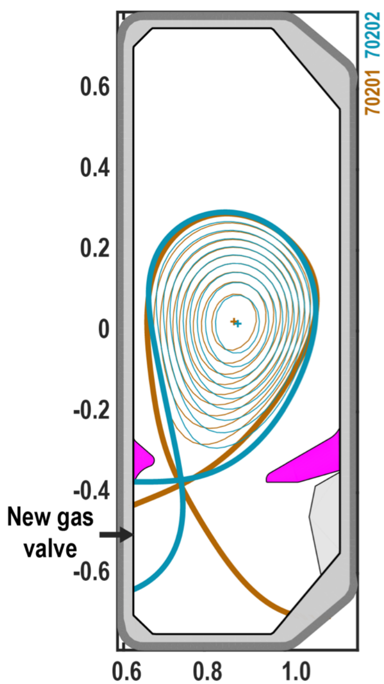
See K. Verhaegh, et al., P4 → We, 14h

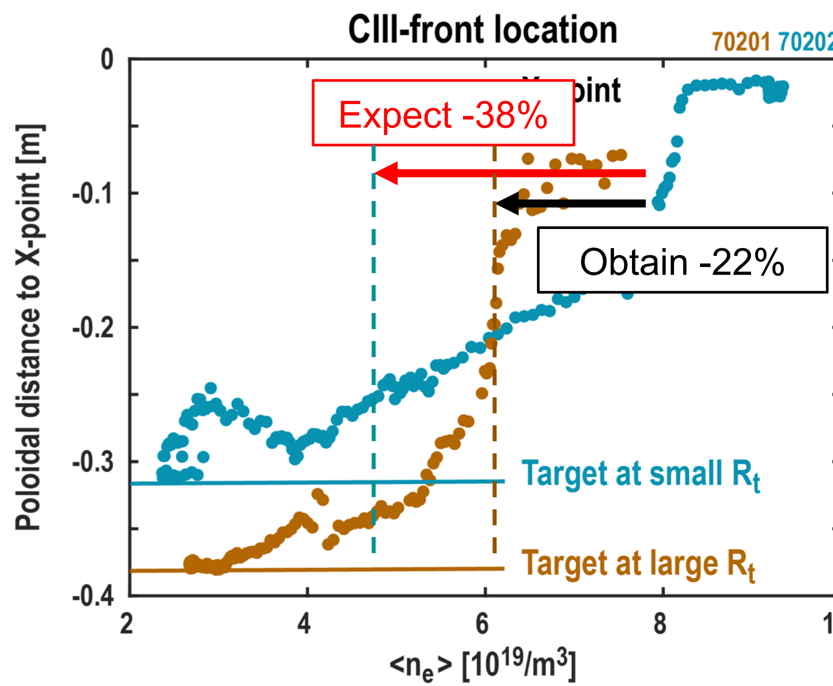
[1] Verhaegh, et al., NME (2021)

# "Super-X effect" partially recovered in baffled divertor

C. Theiler, et al., P4 → We, 14h & EX/7 → Fr, 18h

- SOLPS explains absence of target radius, $R_t$, dependence of detachment threshold in previous experiments [1]
  - Predicts that constant angle of leg wrt. to target and strong baffling restore dependence




[1] Fil, et al., PPCF (2020)

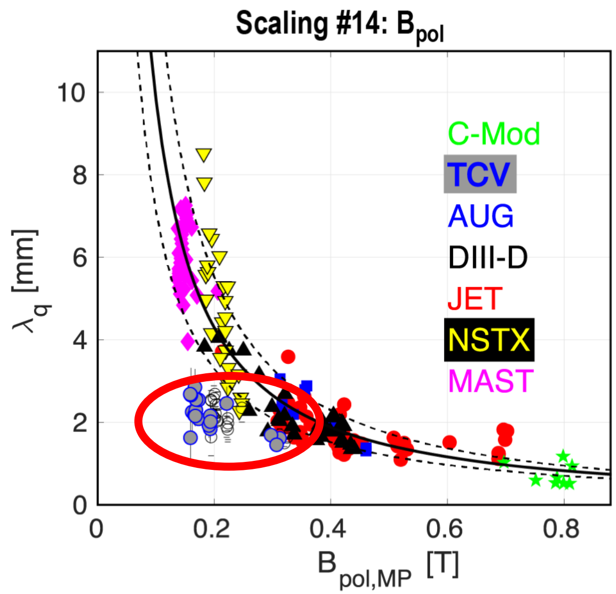
# TCV's H-mode SOL surprisingly narrow

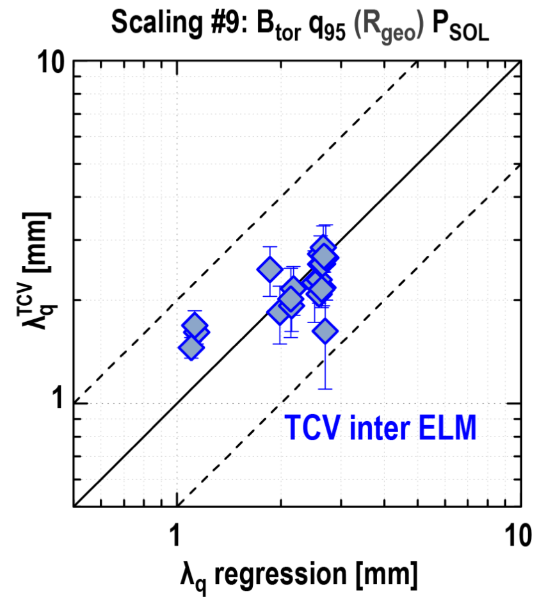


Maurizio, et al., NF (2021)

- Measured with Thomson scattering, confirmed with IR
- 2-3 times smaller than other devices at same $B_{\mathrm{pol}}$

Empiric scalings [1]



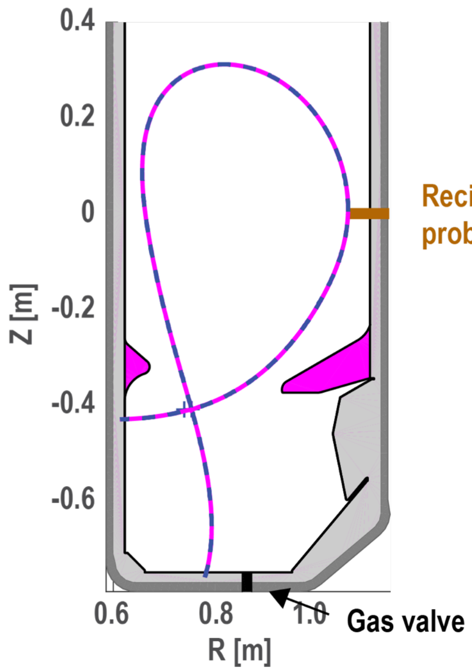



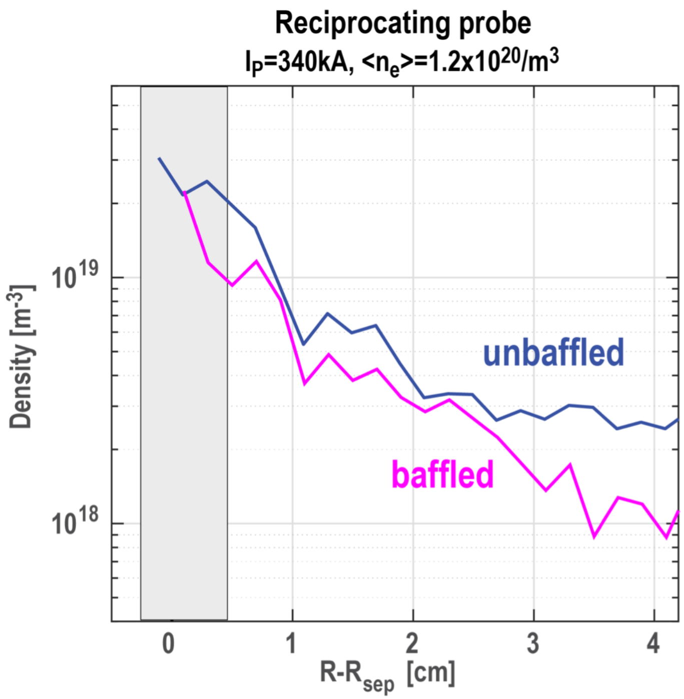

- TCV measurements agree with cross-machine scalings that include toroidal field, $q_{95}$ and heating power, e.g. #9[1]

[1] Eich, et al., NF (2013)

# SOL studies extend into far SOL

Tsui, et al., in preparation



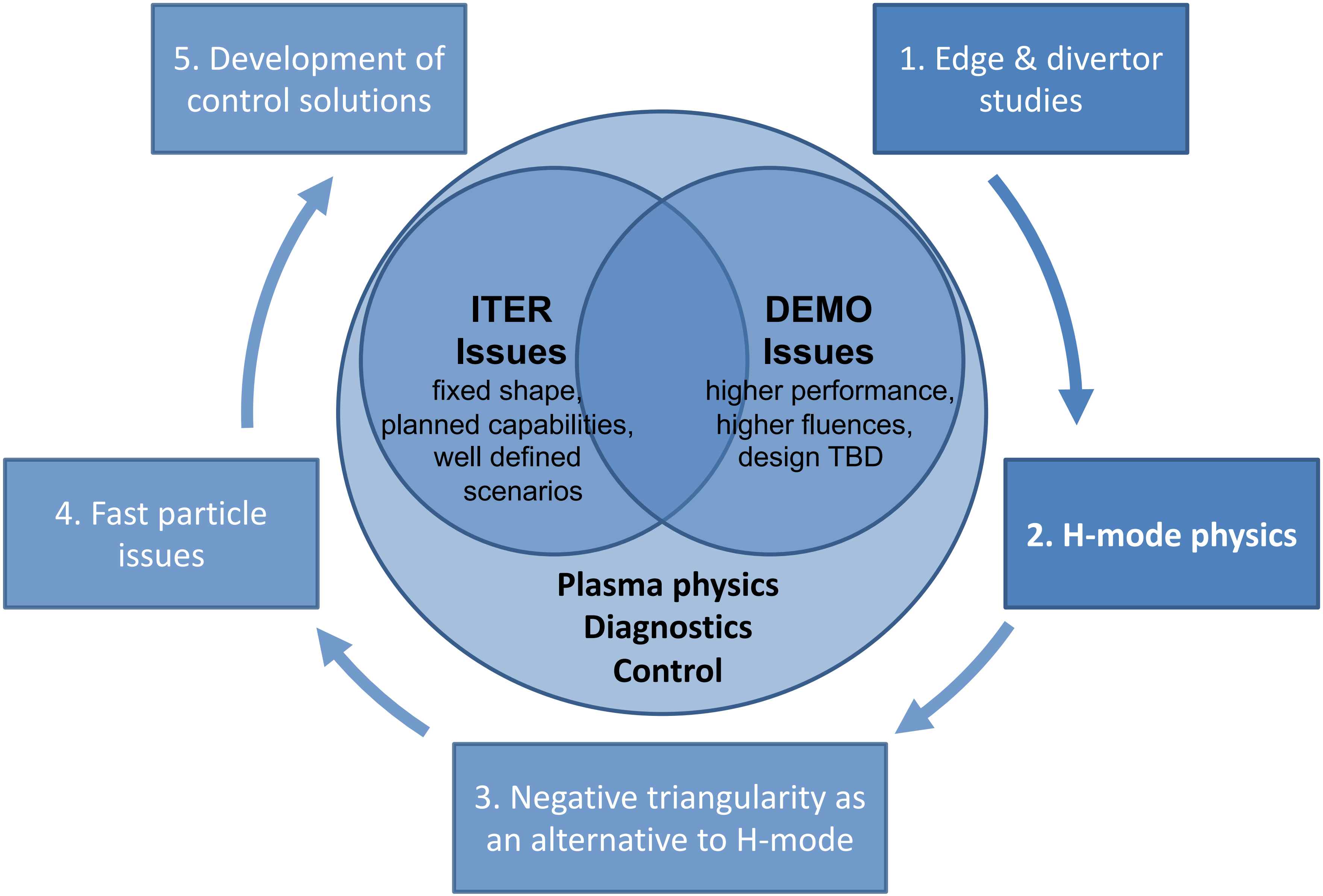

- Absence of density shoulder in baffled divertor links its formation to neutral pressure in the main chamber
- H-mode shoulder in baffled and un-baffled divertor alike

See N. Vianello, et al., P3 → We, 8h30

UC San Diego

# TCV programme addresses ITER and DEMO needs

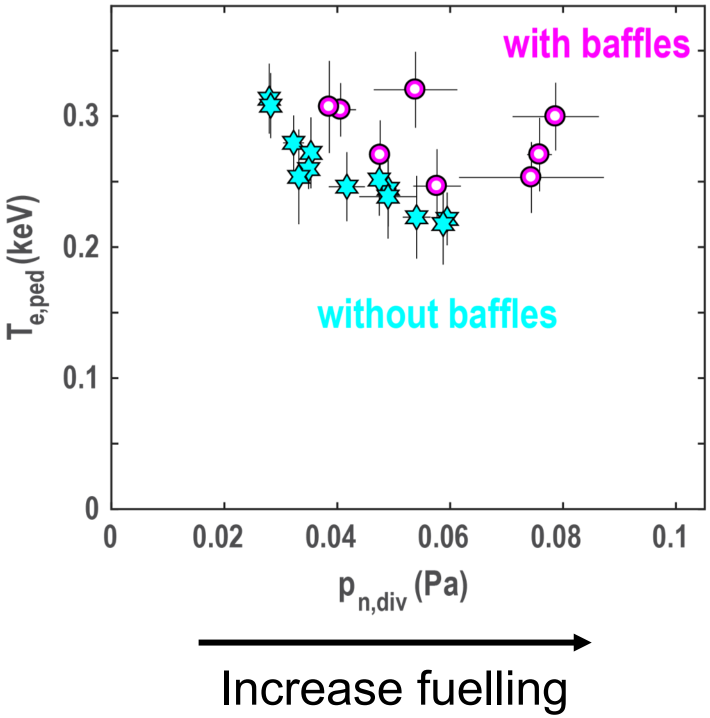




# Baffles decouple roles of $p_{\mathrm{n,main}}$ and $p_{\mathrm{n,div}}$ for pedestal performance

Sheikh, et al., NME (2021)

- 170kA H-mode ($q_{95}$~4.8), 1MW NBI
  - "Moderate" $\delta$ → type-I ELMs
- Higher pedestal temperature with baffle at high fuelling rates, i.e. high $p_{\mathrm{n,div}}$



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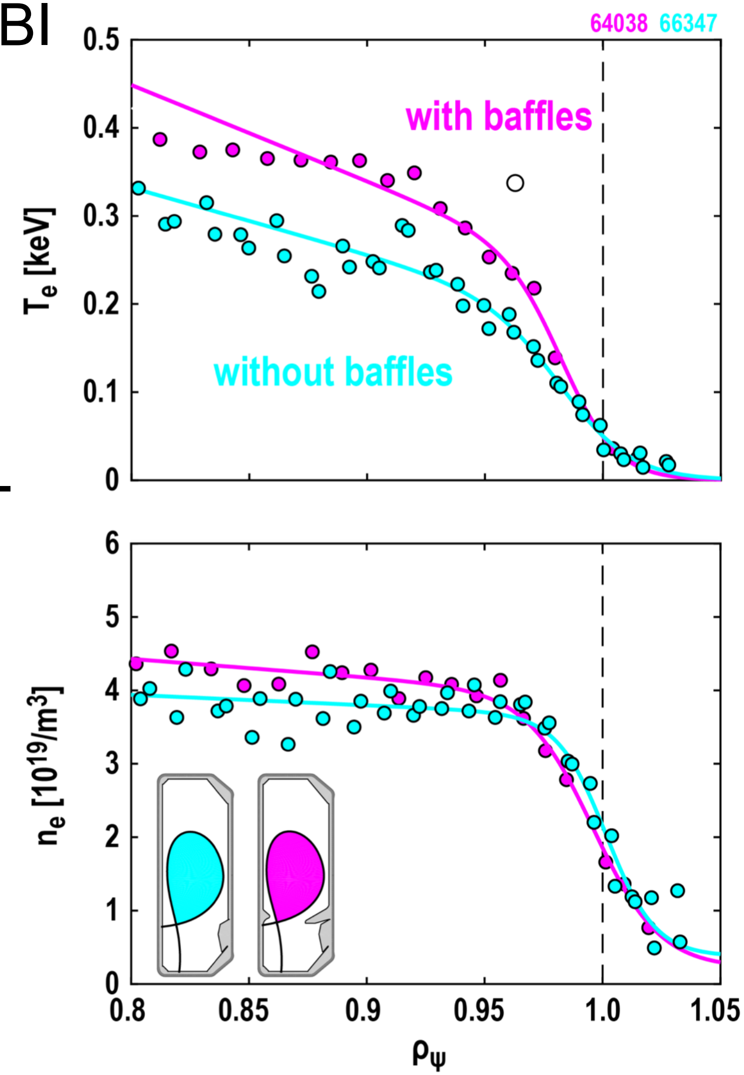
  - "Moderate" $\delta$ → type-I ELMs
- Higher pedestal temperature with baffle at high fuelling rates, i.e. high $p_{\mathrm{n,div}}$
- Baffles reduce outward shift of $n_e$-profile that causes degradation without baffles
  - Indicative of lower $p_{\mathrm{n,main}}$?

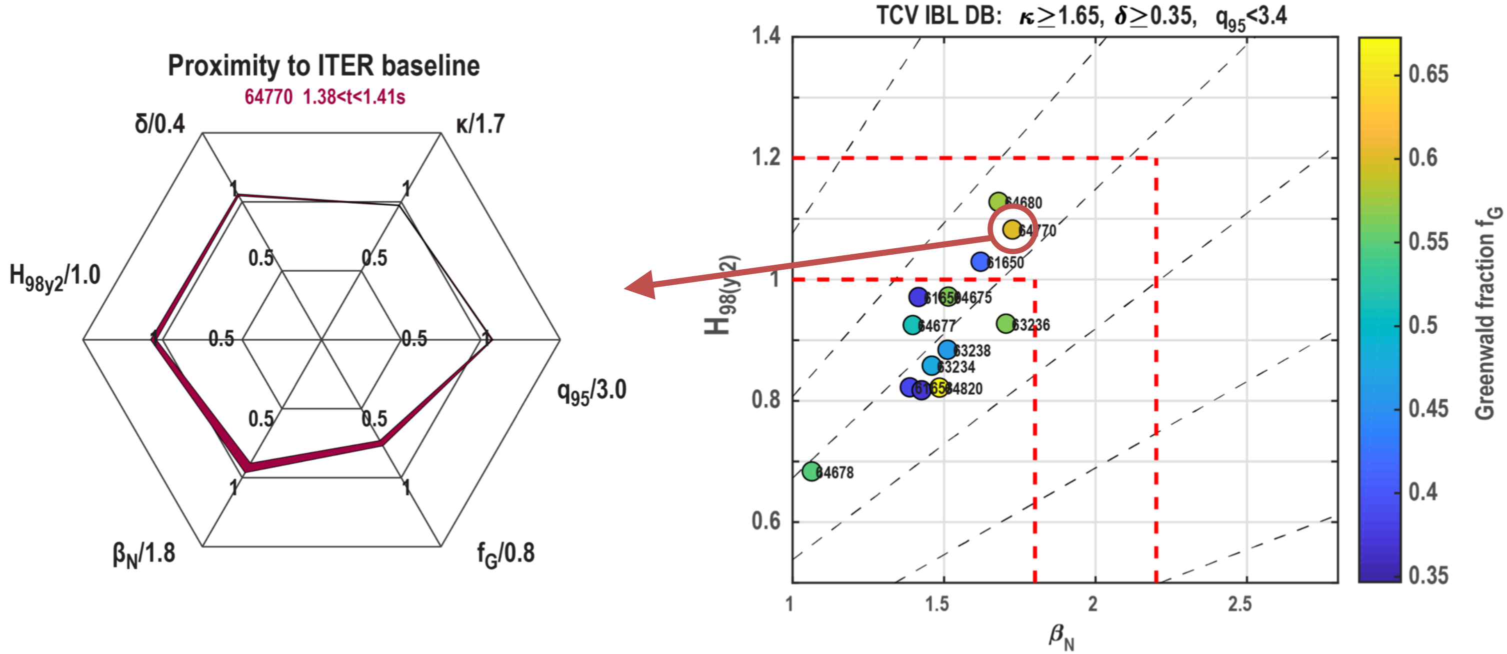
➢ Achieve 2-3x increase of radiated power without confinement degradation



# H-mode regime extended to ITER baseline parameters

O. Sauter, et al., P4 → We, 14h

- NBI heated ELMy H-mode with $q_{95}$ =3.0, $\beta_{\mathrm{N}}$=1.8, $H_{98(\mathrm{y},2)}$=1.0
  - Greenwald fraction, $f_{\mathrm{G}}$, lower




  - Density too high for X3 renders NTMs inevitable and prevents stationary scenario
  - Proximity to 'small ELM' regime at $q_{95} \geq 3.7$, higher $\delta$ and/or $f_{\mathrm{G,sep}}$

See M. Faitsch, et al., P4 → We, 14h

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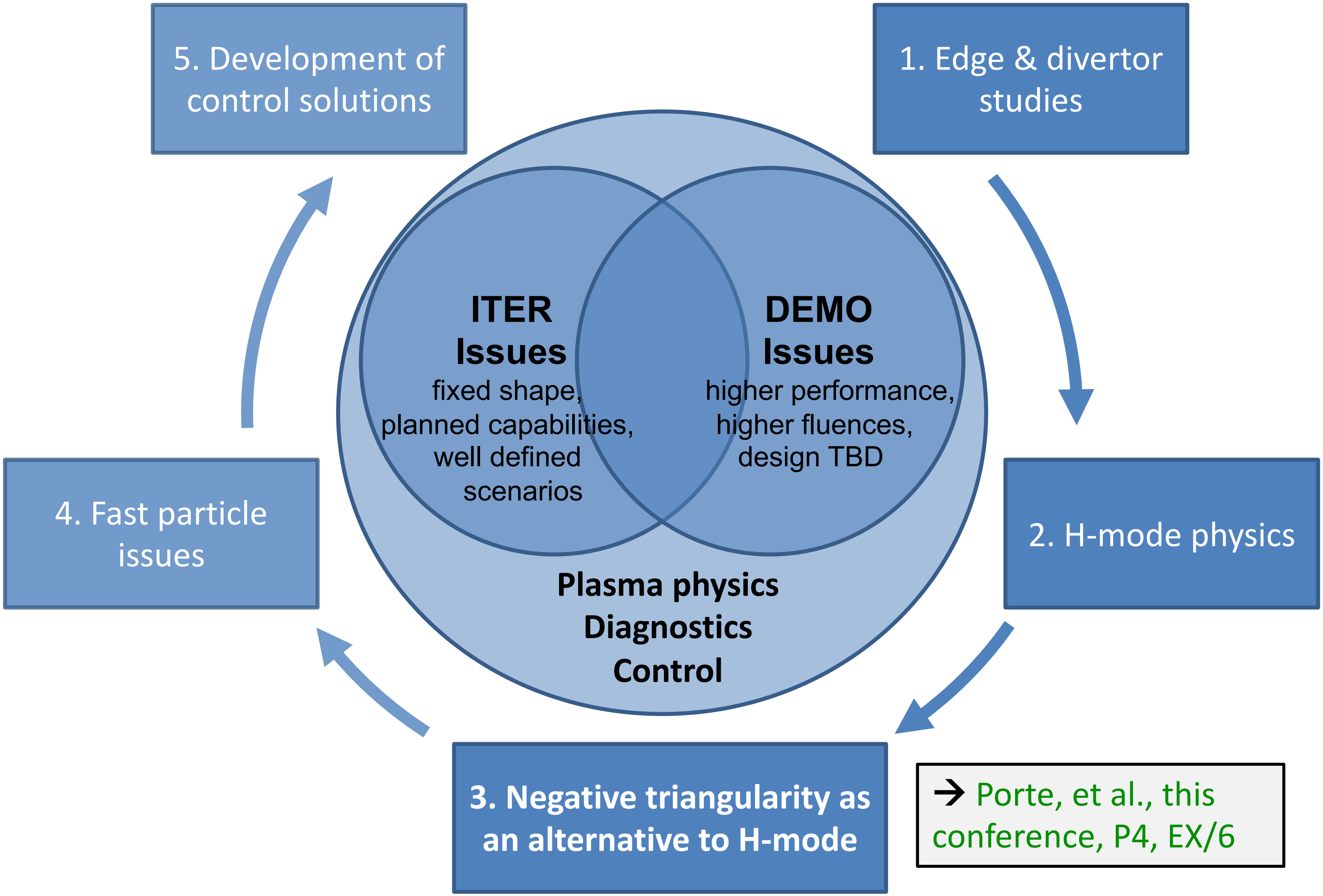



→ Porte, et al., this conference, P4, EX/6

# Investigate negative triangularity (NT) as an ELM-free alternative



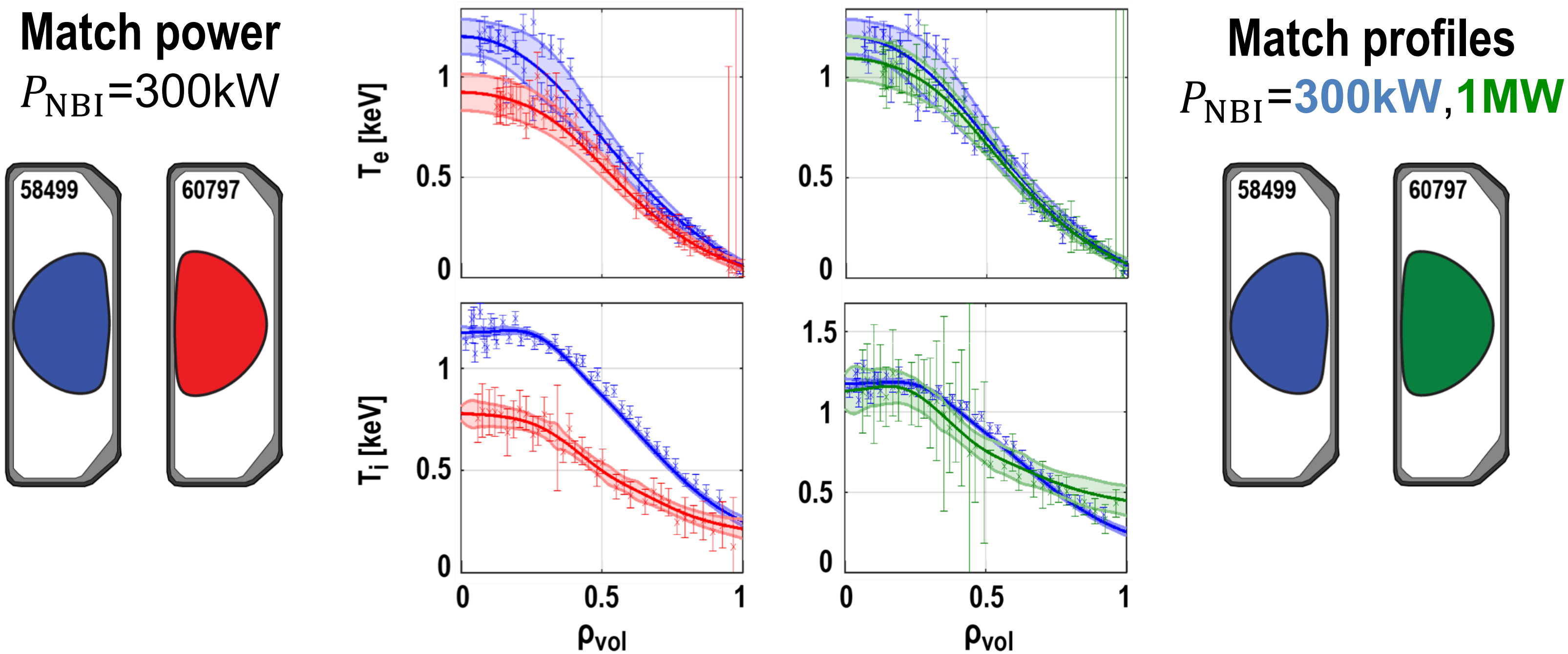
- NT promises H-mode confinement with L-mode edge
  - Pioneered in TCV in Ohmic and with strong ECH [1,2]
  - Reproduced and extended to high beta in DIII-D [3,4]
  - Recent studies also in ASDEX-Upgrade [5]
- Improved NT-confinement well documented in TCV with electron heating
- Turbulent transport dominated by TEM and explained by global, non-linear gyrokinetic calculations (GENE) [6]

[1] Pochelon, et al., NF (1999)
[2] Camenen, et al., NF (2007)
[3] Austin, et al., PRL (2019)
[4] Marinoni, et al., this conference, EX/6
[5] Happel, et al., APS 2020
[6] Merlo, et al., PPCF (2021)

# Good confinement quality extends to NBI heated NT …



Fontana, et al., NF (2020)



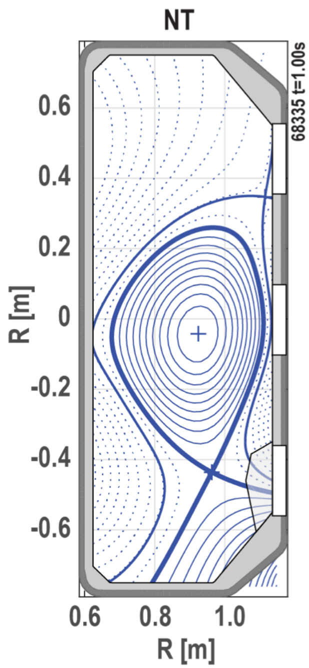

- Fluctuation amplitude decreases even with $T_e/T_i$~1
  - Linear gyrokinetic simulations (GENE) indicate mixture of TEM and ITG turbulence regime

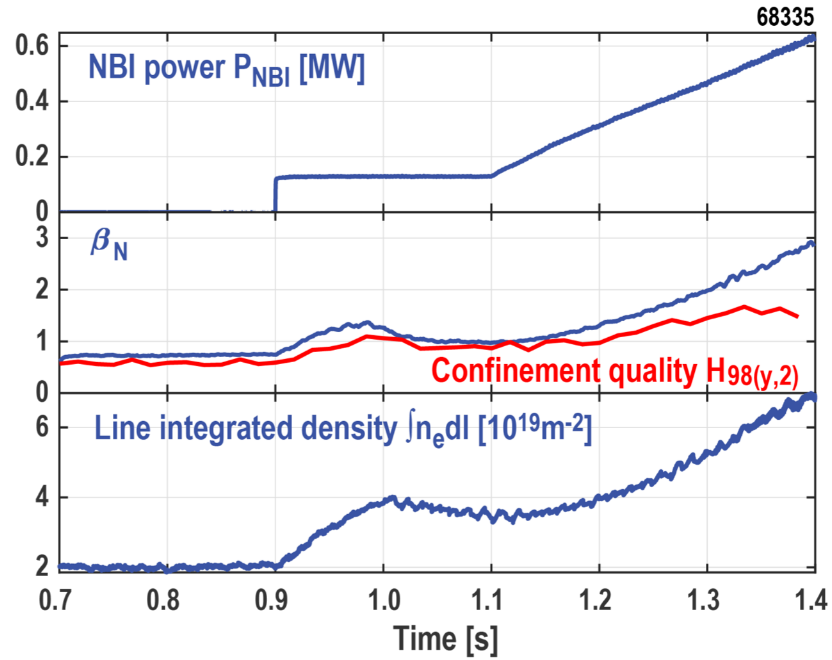
# … and high beta



L. Porte, et al., P4 → We, 14h & EX/6 → Fr, 15h40

- Combine new capabilities of NBI heating in diverted NT configurations




$\beta_N \sim 3$

$H_{98} \sim 1.5$

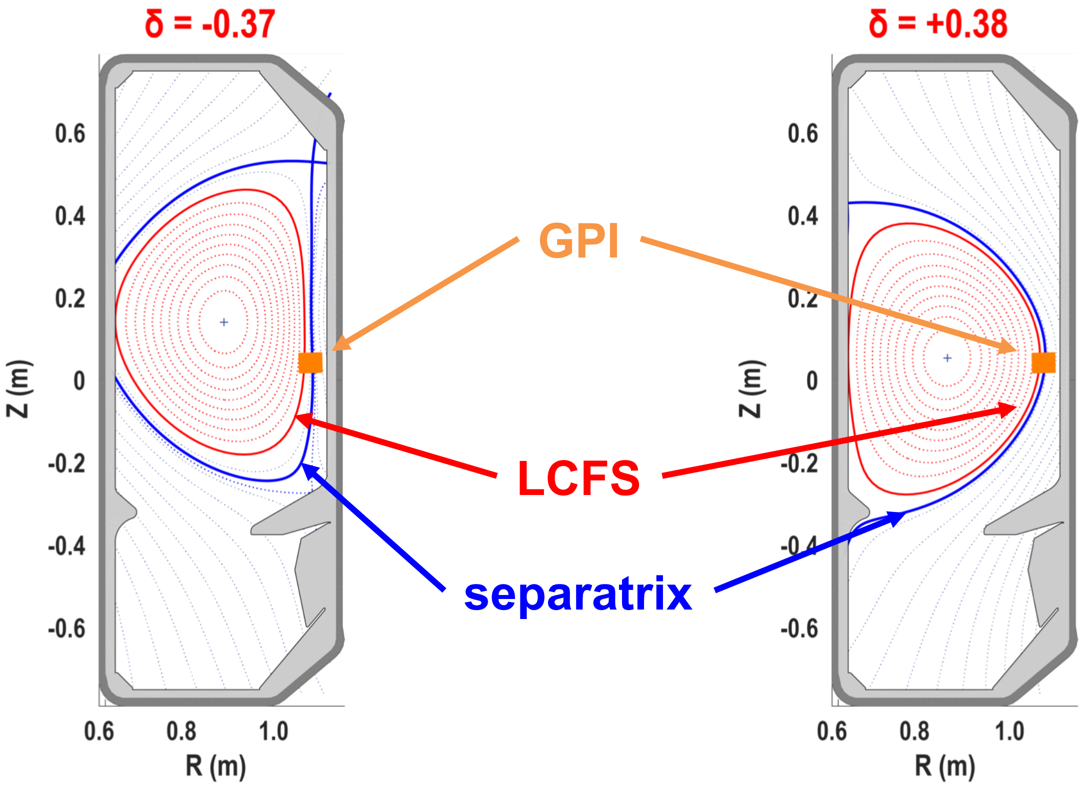
- H-factor increases with NBI heating power
  → more favourable $P_{\mathrm{heat}}$ and/or $n_e$ scaling than $H_{98(y,2)}$

# Turbulent transport decrease extends to edge …



Han, et al., NF (2021)

- Midplane GPI diagnostic images SOL turbulence



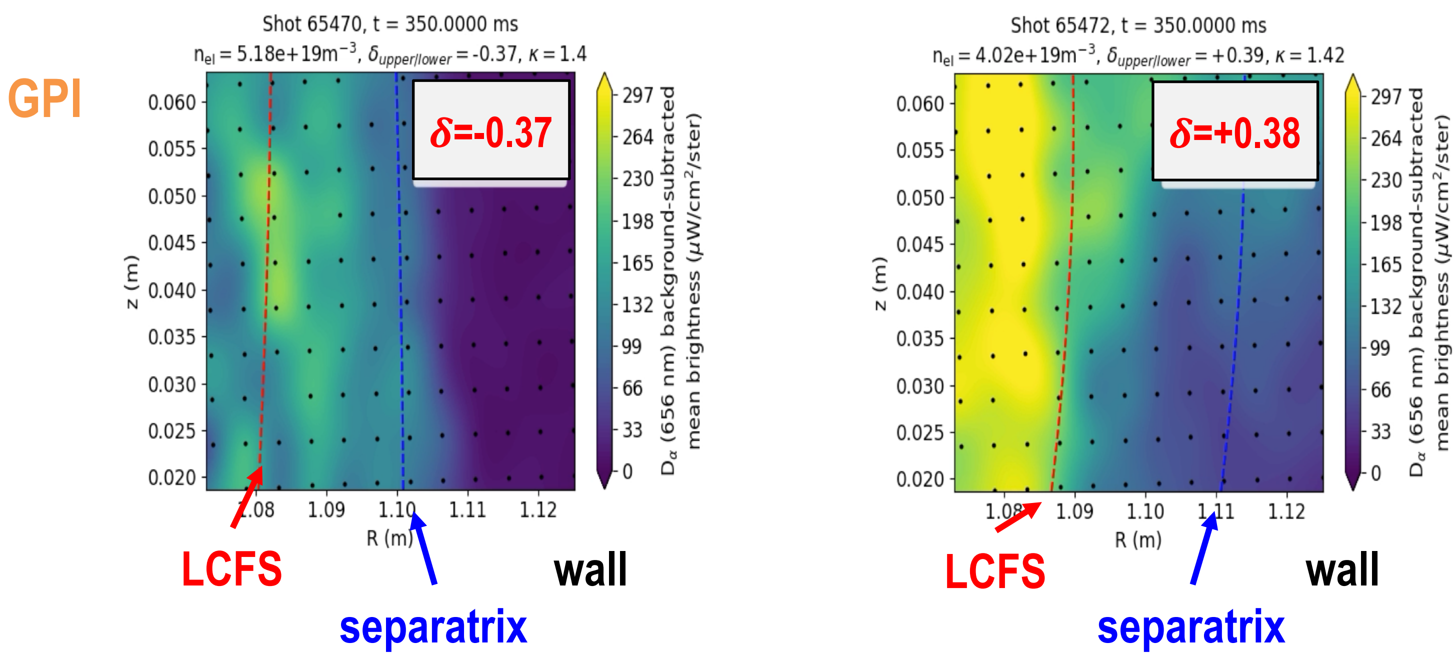



Massachusetts Institute of Technology

# Turbulent transport decrease extends to edge where it can be completely suppressed

Han, et al., NF (2021)

- Midplane GPI diagnostic images SOL turbulence




- In NT fluctuations disappear past **separatrix**
  - Leads to a suppression of main chamber PWI
  - Correlates with decrease of connection length

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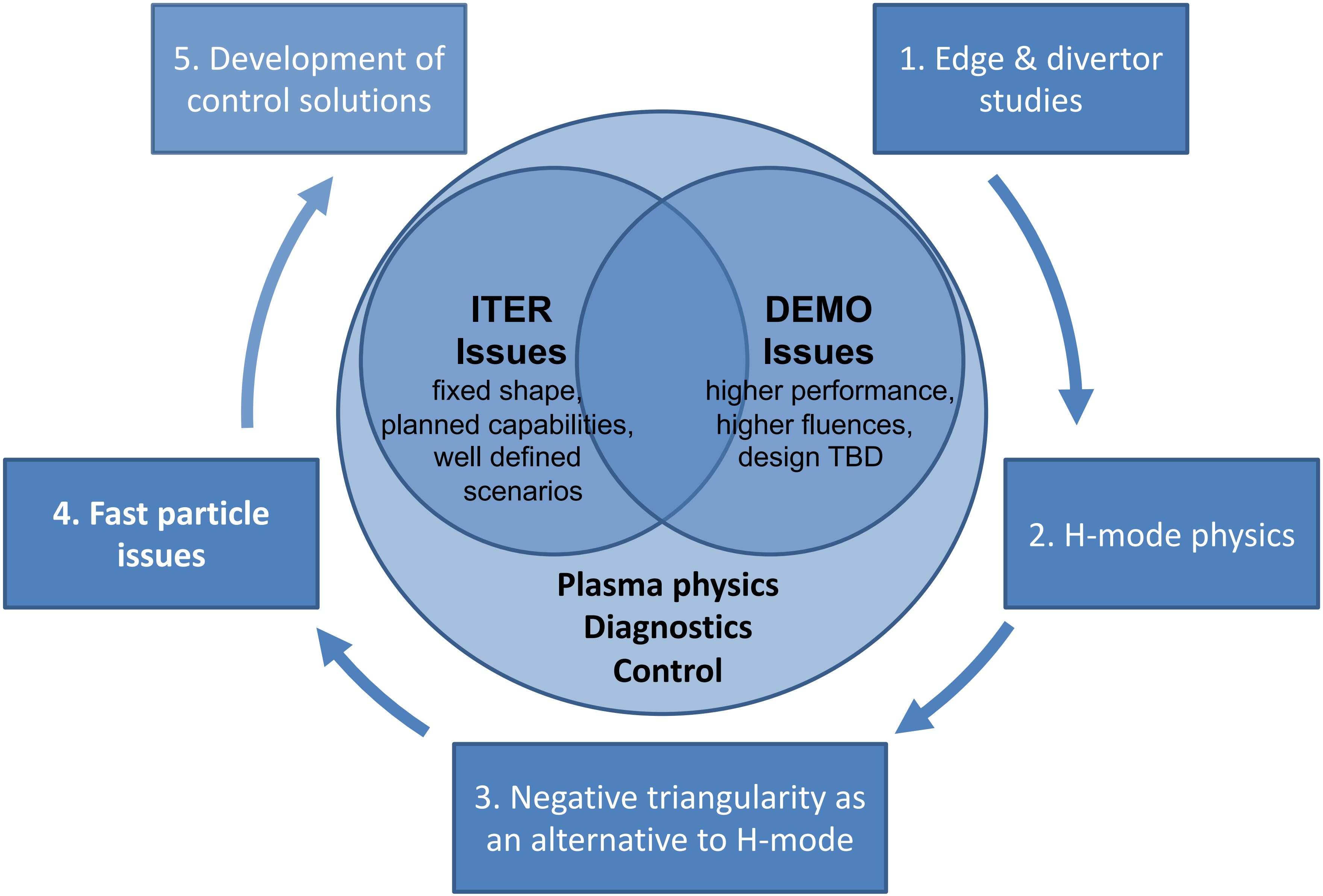
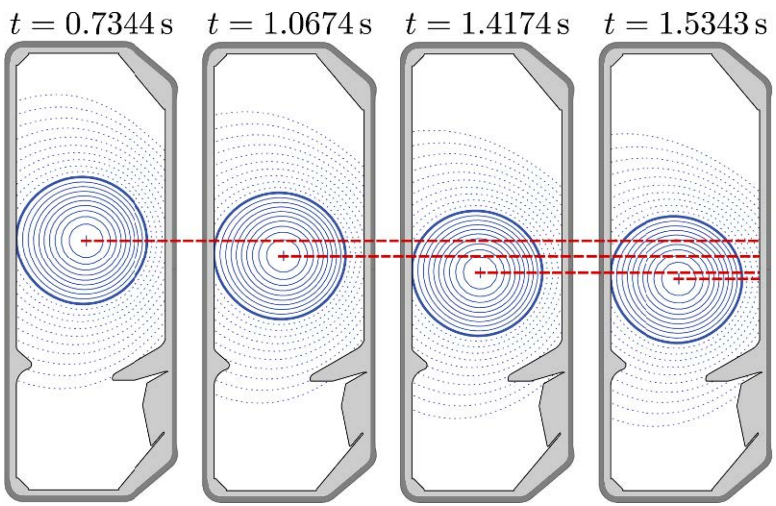


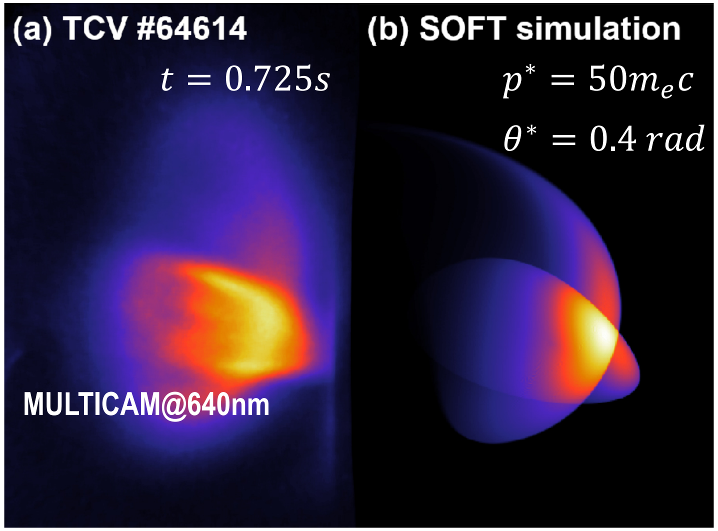
# Imaging RE synchrotron emission reveals momentum and pitch angle



Wijkamp, et al., NF (2021), Hoppe, et al., NF (2020)

- Image in the visible with filters to remove line radiation
- Shift plasma to test synthetic diagnostic (SOFT)



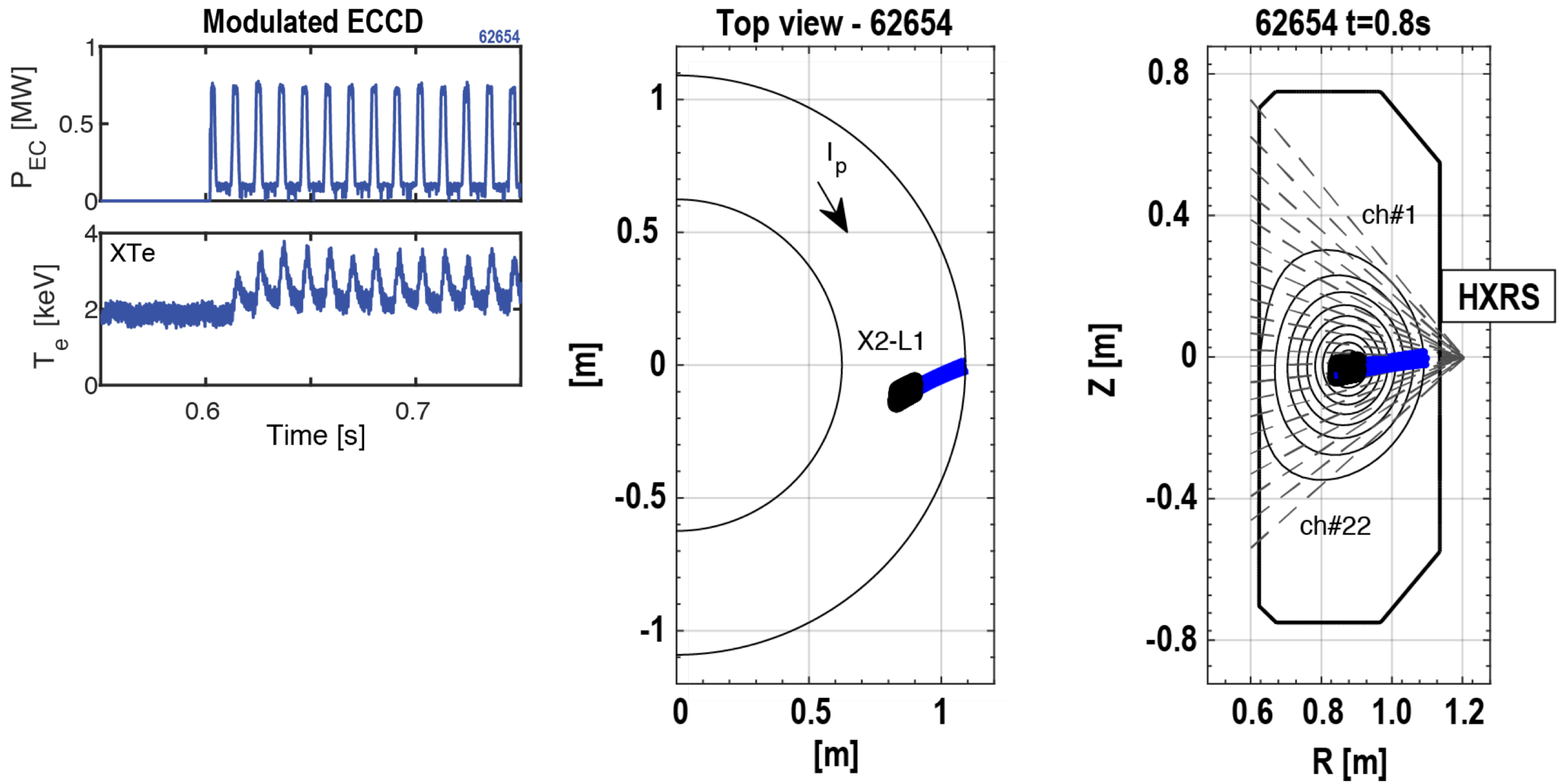

- Kinetic model predicts lower pitch for momentum
  - Significant non-collisional pitch angle scattering and radial RE transport – possibly caused by magnetic perturbation

# Dynamic response of electron to ECCD probes fast electron transport



Choi, et al., PPCF (2020)

- Modulation experiment minimises steady-state perturbation
- Measure with hard x-ray spectrometer system (HXRS)



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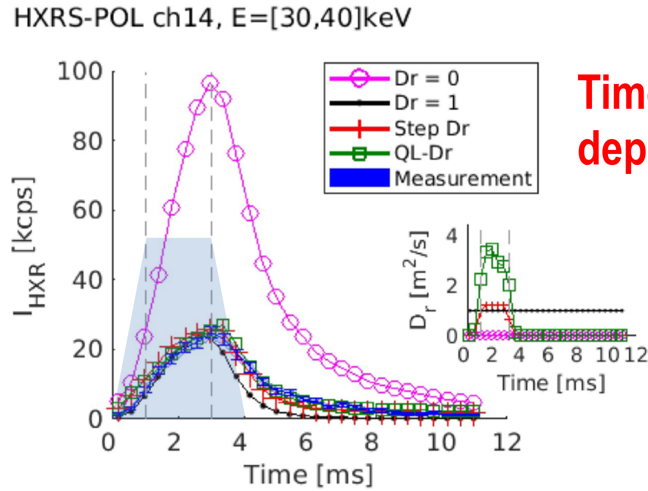
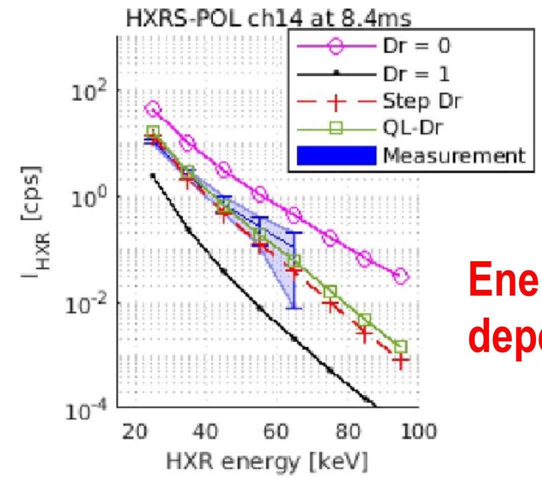
Choi, et al., PPCF (2020)

- Modulation experiment minimises steady-state perturbation
- Measure with hard x-ray spectrometer system (HXRS)
- Compare to time-varying Fokker-Planck model LUKE
  - Synthetic diagnostic module R5-X2




**Time dependence**




**Energy dependence**

➢ Good agreement only, if e-transport localised in real and momentum space (QL-Dr)

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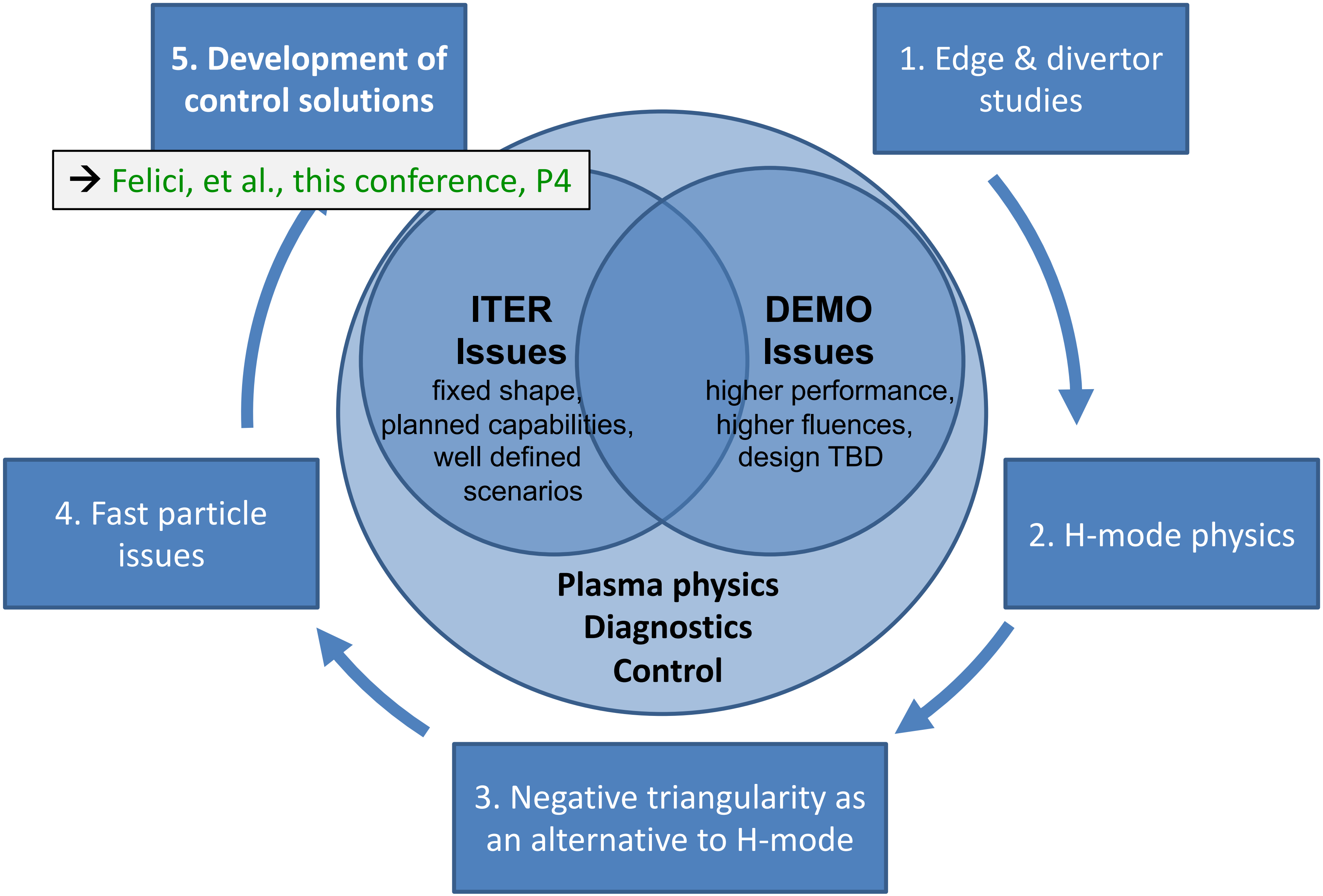
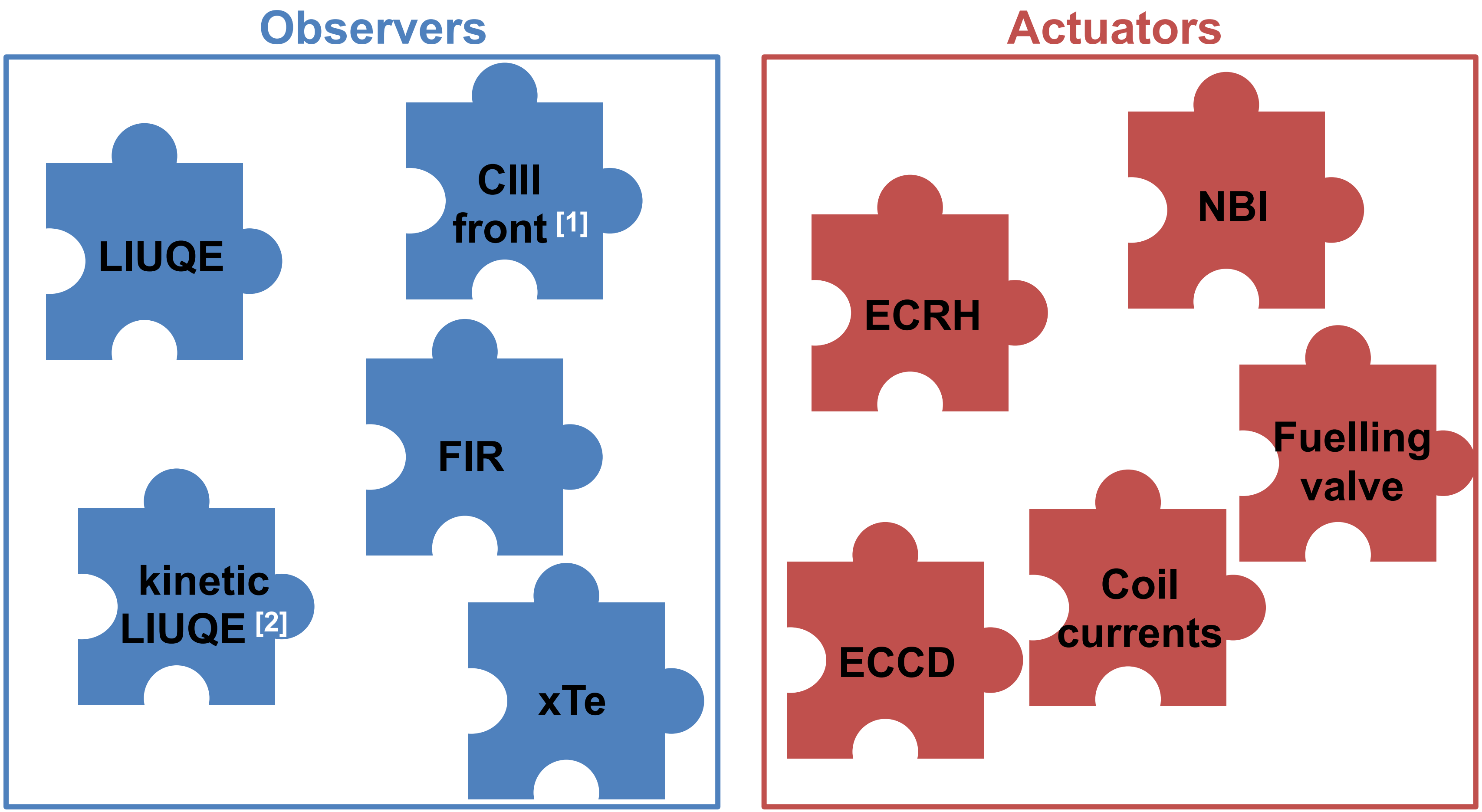


# TCV boasts numerous RT-observers, actuators and control solutions



F, Felici, et al., P4 → We, 14h

- Flexible digital control system




[1] Ravensbergen, et al., NF (2020)
[2] Carpanese, et al., NF (2020)

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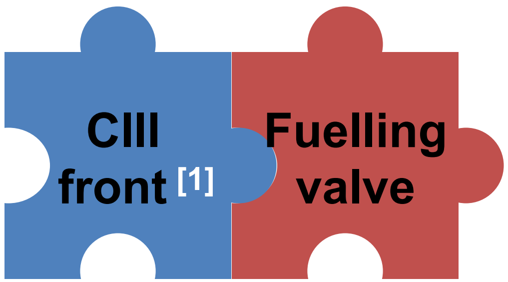
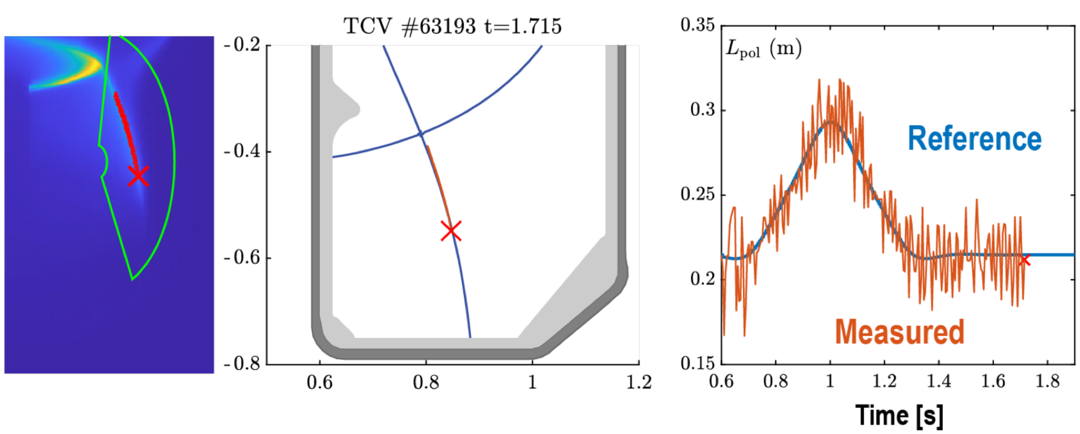
- Flexible digital control system

**Observers** **Actuators**




- Demonstrate feedback-control of the impurity emission front location




Ravensbergen, et al., Nat. Comm. (2021)

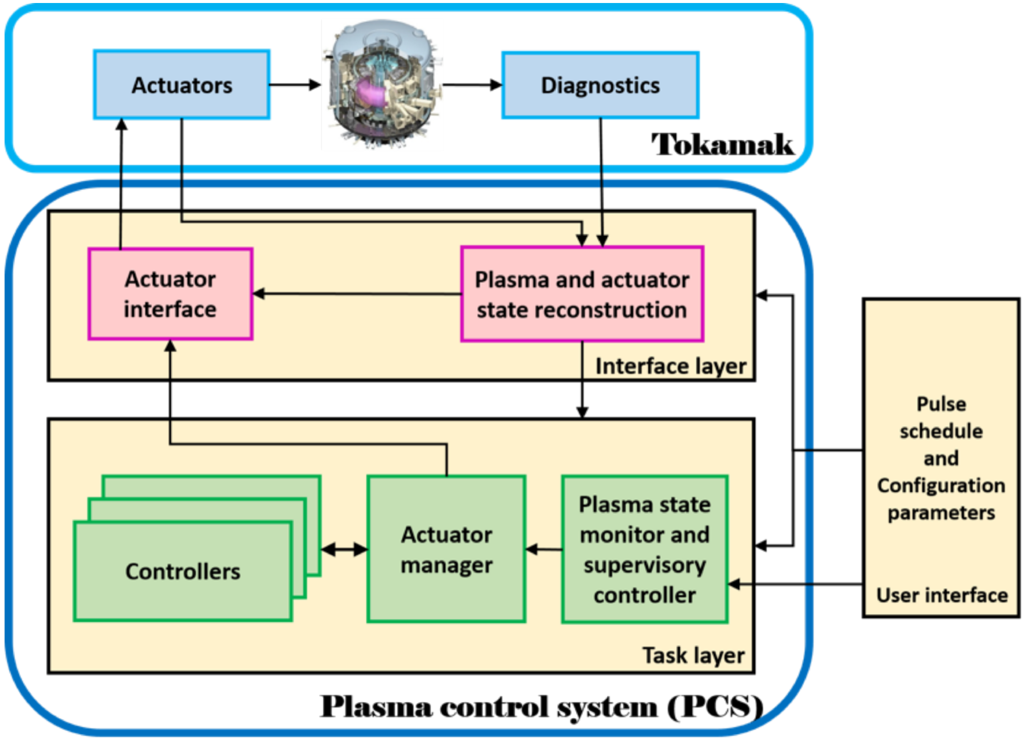

[1] Ravensbergen, et al., NF (2020)
[2] Carpanese, et al., NF (2020)

# Demonstrate new generic control framework



Vu, et al., submitted to Trans. on Nucl. Science

- Split into device-dependent *interface layer* and device-independent *task layer* [1]




- Used to control proximity to HDL using a scheme previously identified on ASDEX-Upgrade [2]

[1] Blanken, et al., NF (2019) [2] Maraschek, et al., PPCF (2018)

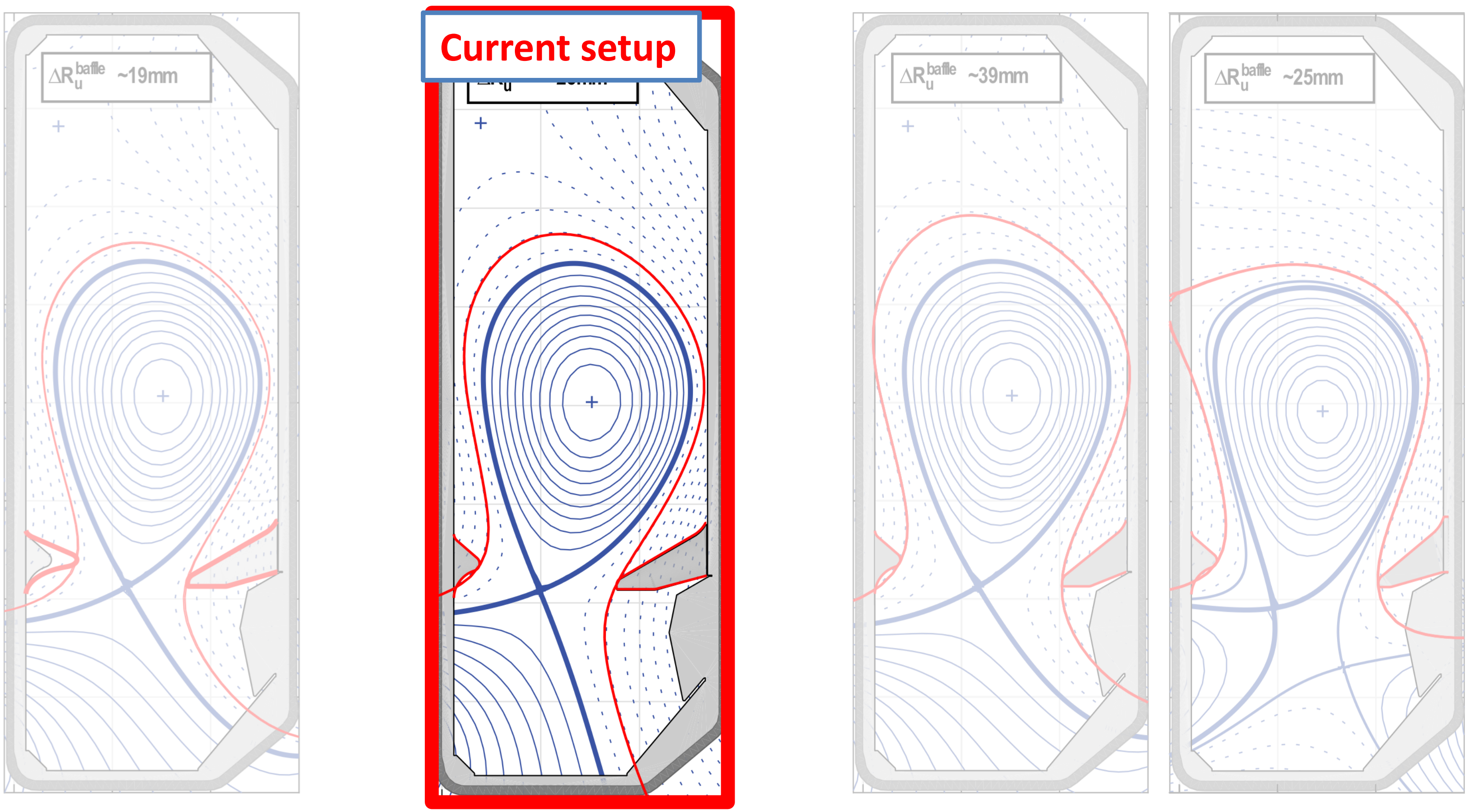
# Conclusion – TCV overview



- Rich programme balances ITER and DEMO needs with scientific discoveries (doublets not even mentioned)
  - Strong integration in **European programme**
  - Complemented with **domestic programme** and **international collaborations**

- Extend signature flexibility with flexible baffles for dedicated campaigns

# Outlook: New sets of baffles




- Allow of more or less closed divertor

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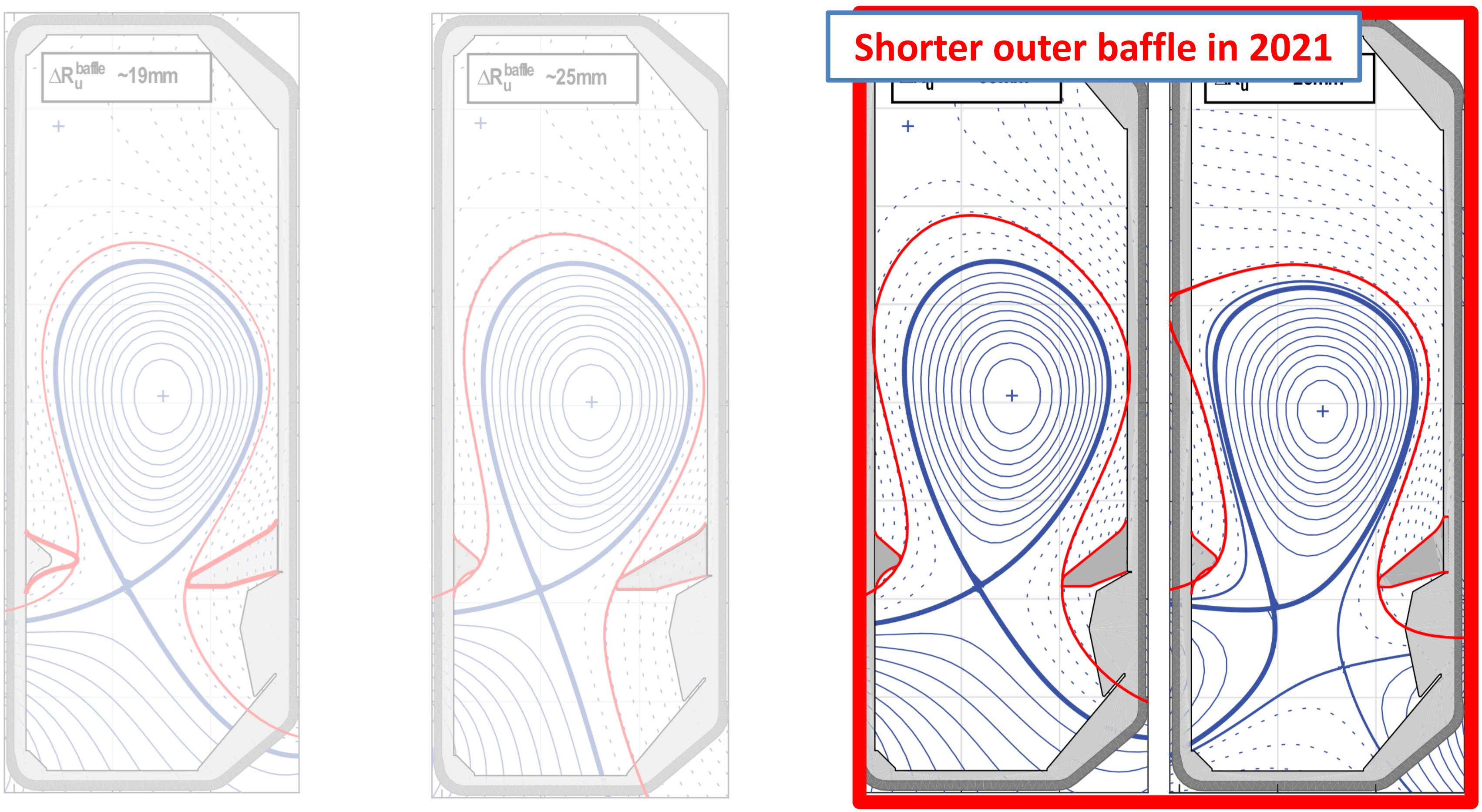


➢ Allow of more or less closed divertor

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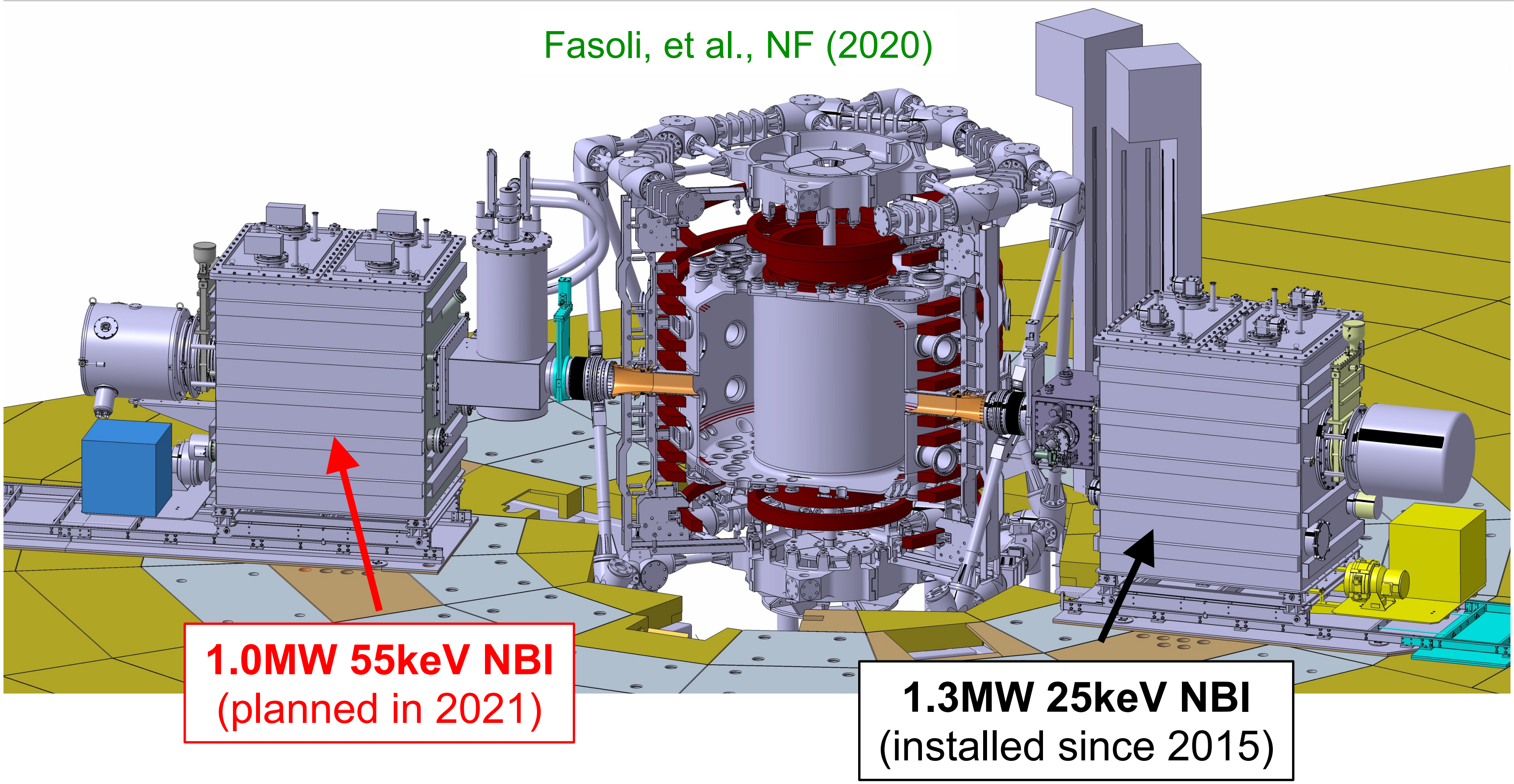
# Outlook: New sets of baffles




- ➢ Allow of more or less closed divertor

# Outlook: 2nd NBI in 2021




- Control torque
- Advance fast ion studies
  - Range of fast-ion driven mode scenarios already developed
  - New fast-ion loss diagnostic (FILD) commissioned

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# Medium-term vision



- Increase flexible heating power with third dual-frequency gyrotron
- Use flexibility to test specific divertor solutions
  → ”tightly baffled, long-legged divertor”

# The TCV team



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