Overview of the TCV Tokamak Experimental Programme

Holger Reimerdes

for the TCV team

28th IAEA Fusion Energy Conference, May 10-15, 2021

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Tokamak à Configuration Variable (TCV)

Mid-size tokamak

$R_0 = 0.9\text{m}$

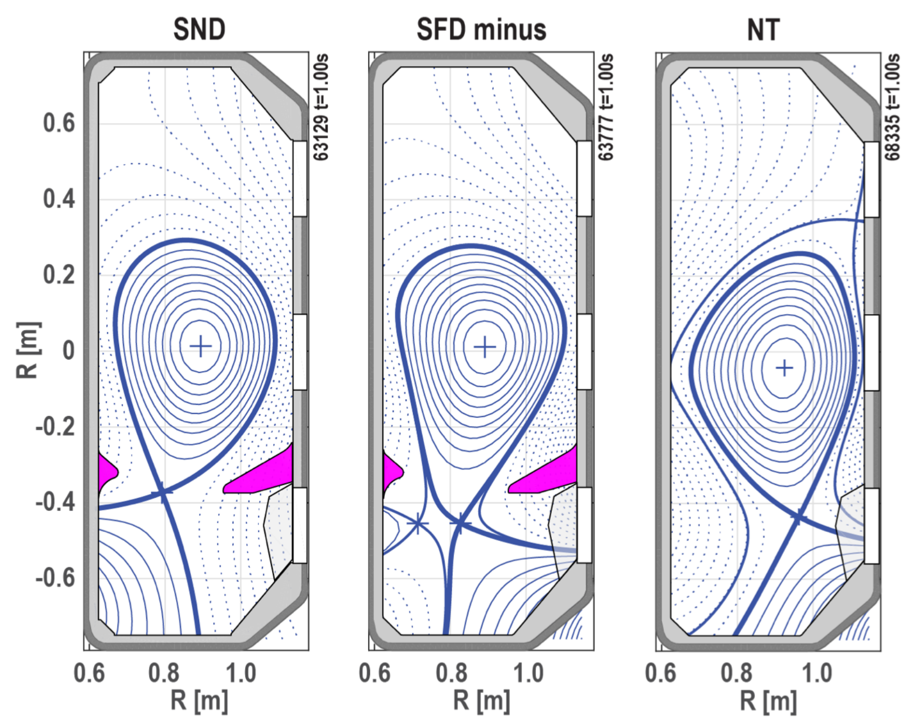
$B_0 \leq 1.5\text{T}$

$A = 4$

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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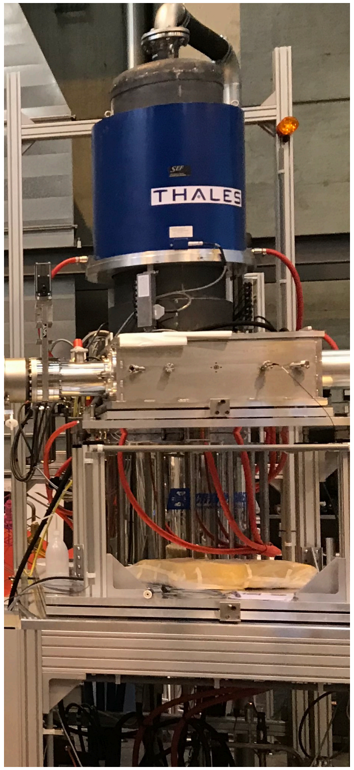
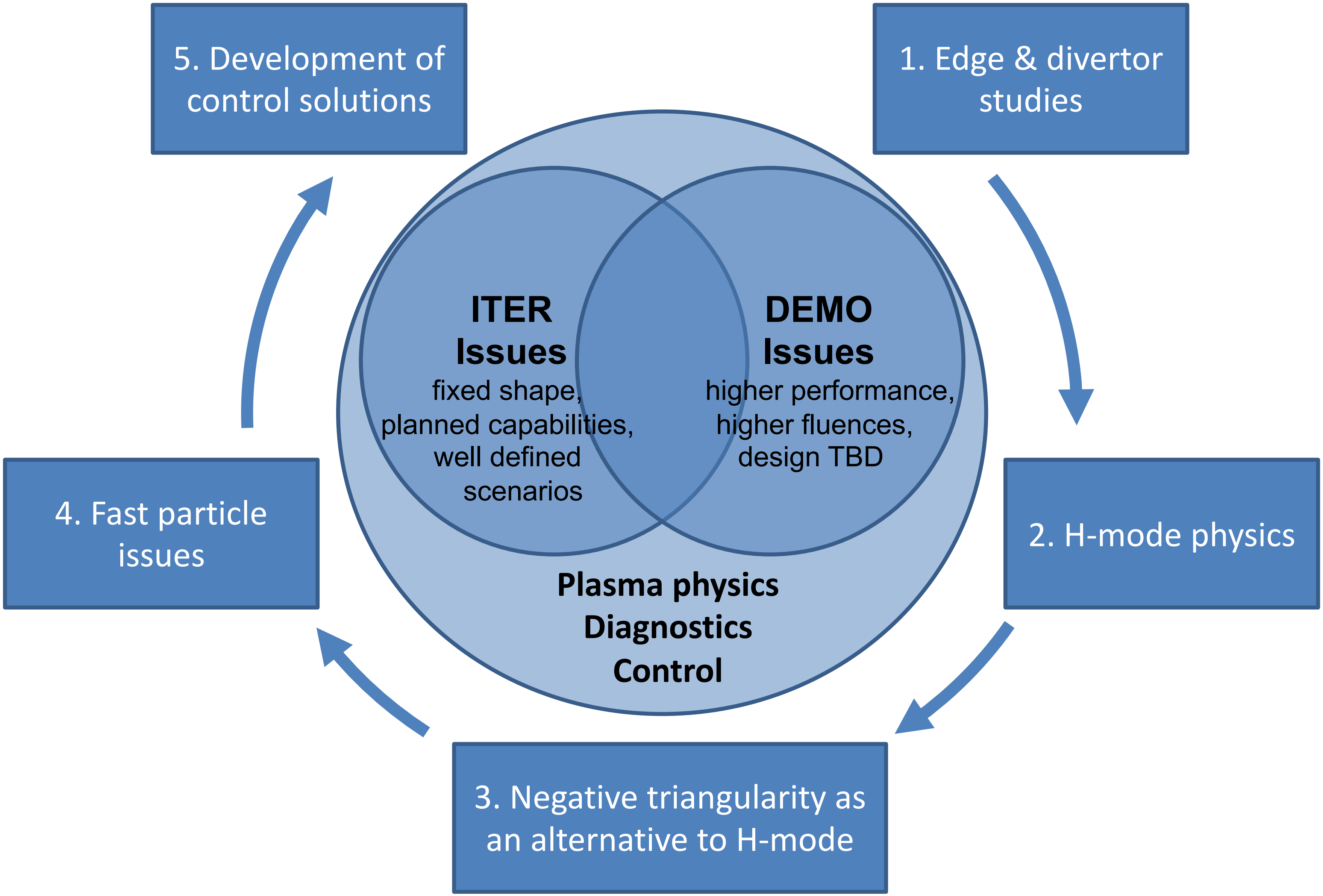


TCV programme addresses ITER and DEMO needs



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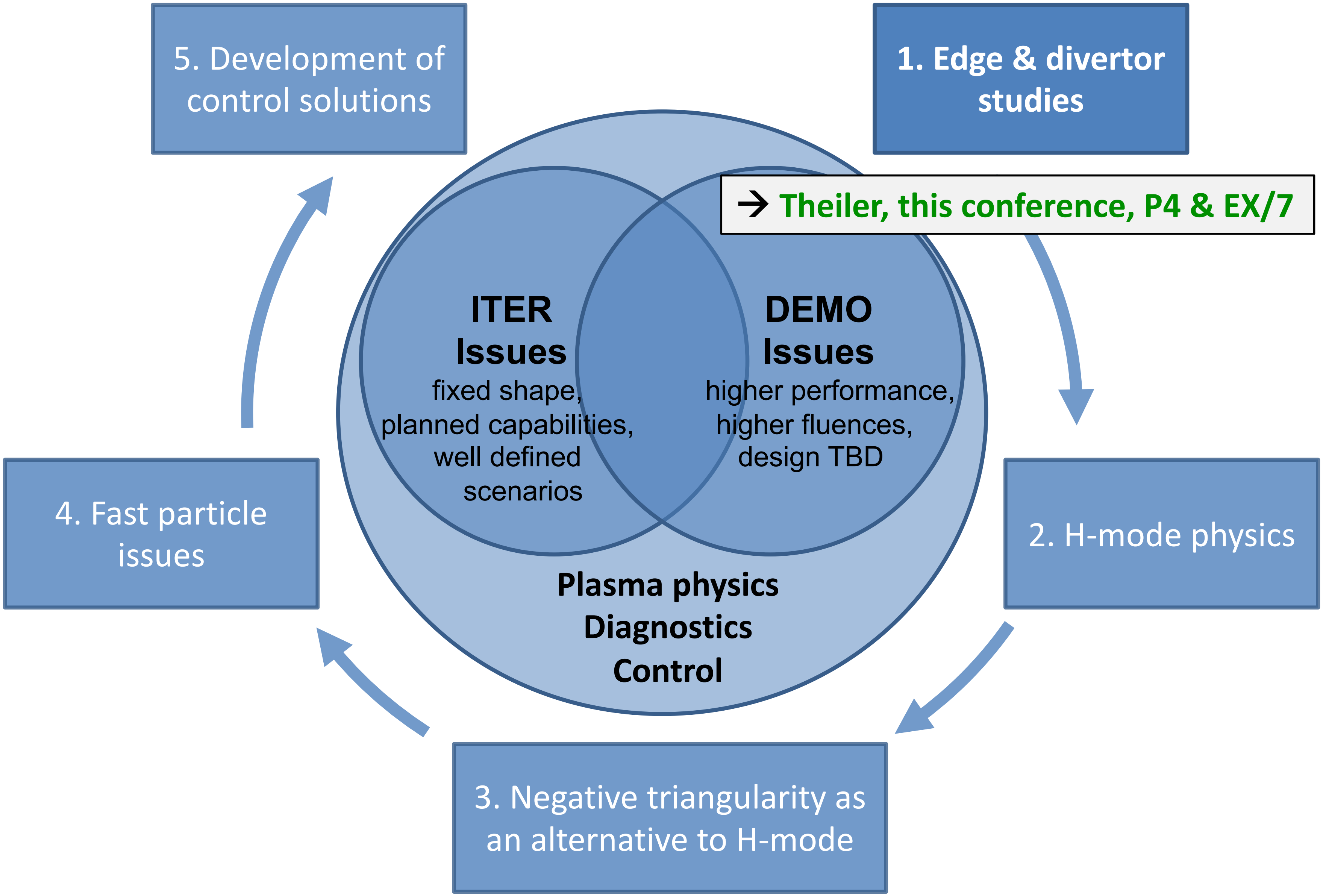
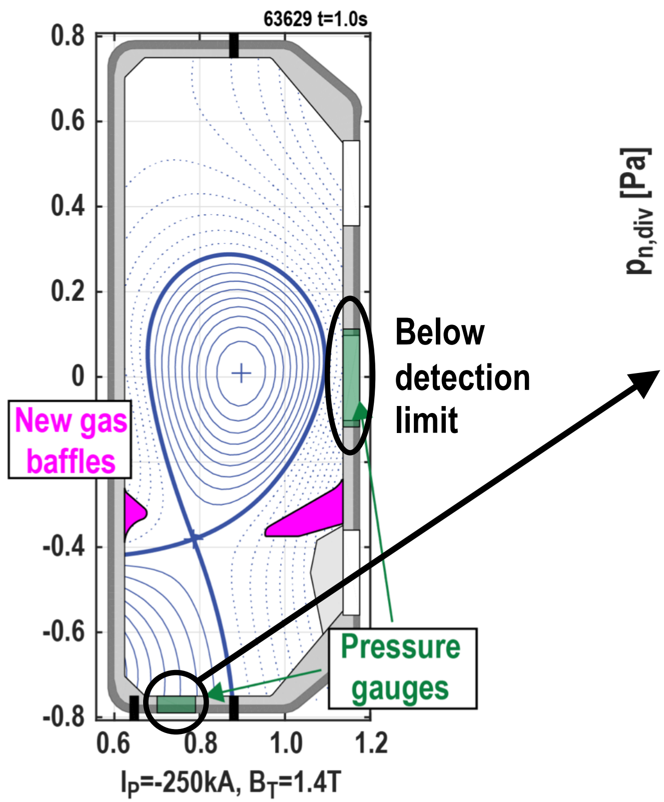
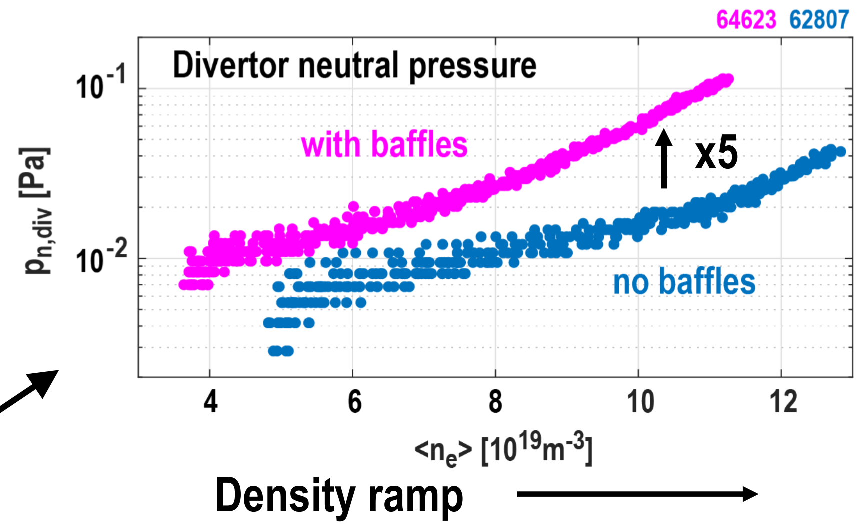


Baffles increase divertor neutral pressure by up to a factor of 5

Reimerdes, et al., NF (2021)





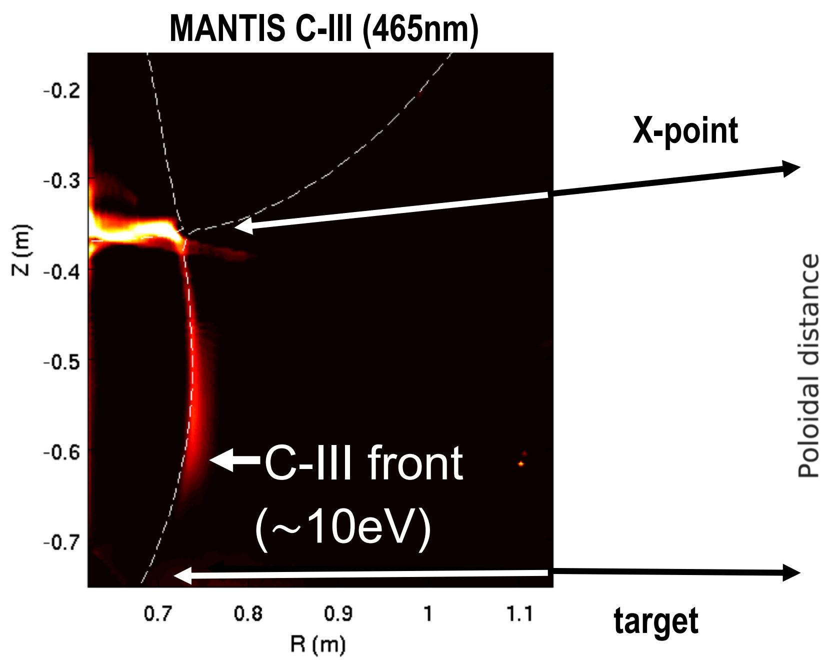
- De-couple divertor and main chamber neutral pressure

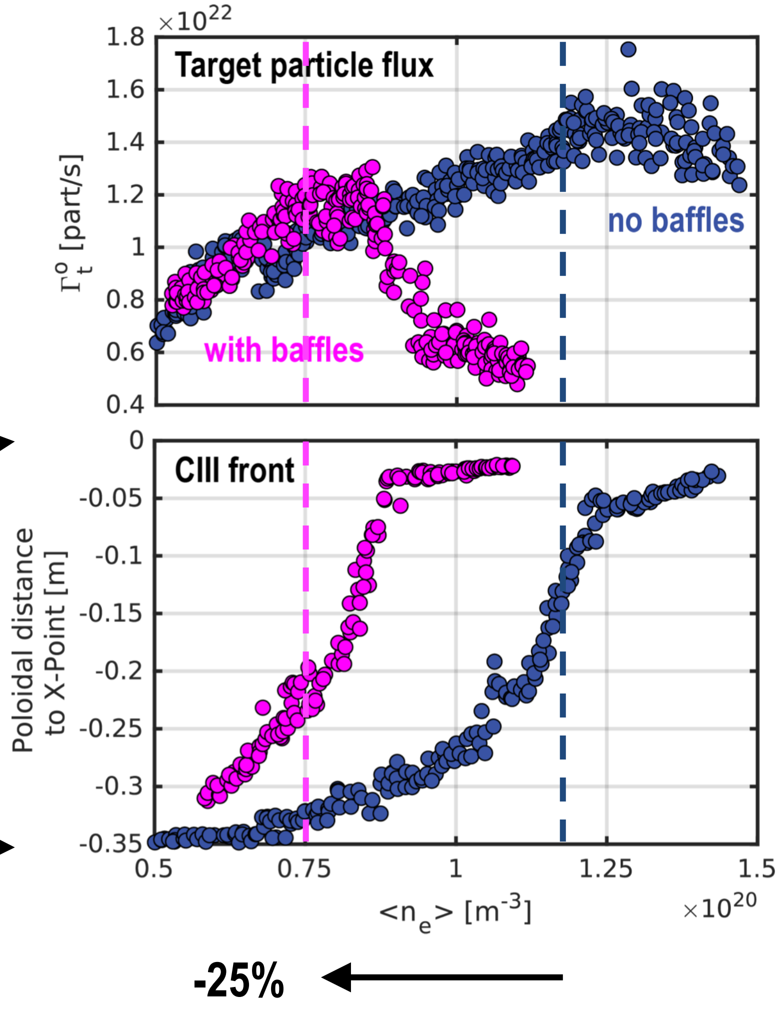
➢ Increase divertor dissipation – access to regimes of greater interest for next step devices

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

Février, et al., NME (2021)

- Detachment indicators
  - Target particle flux roll over
  - C-III emission front location



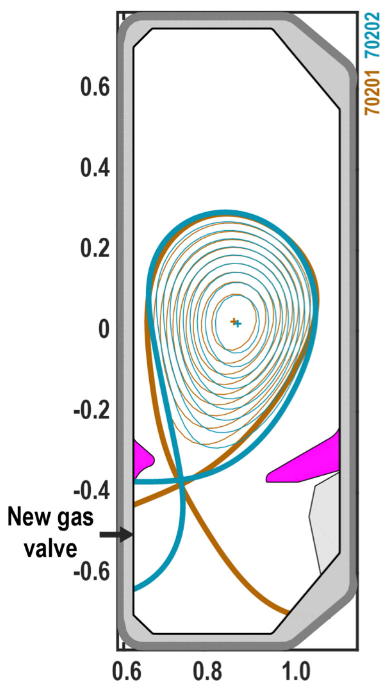


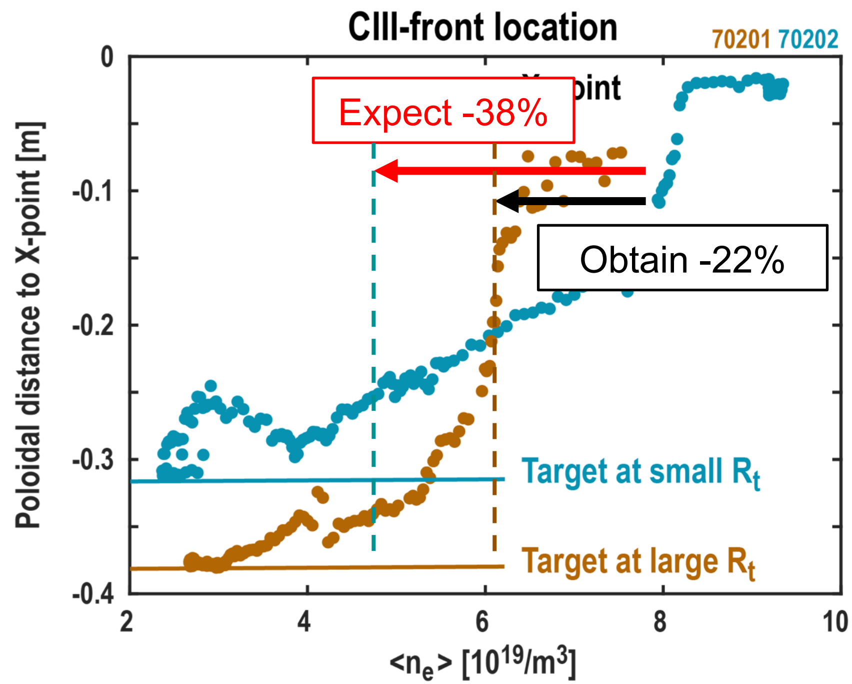
[1] De Oliveira, et al., in prep.

“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





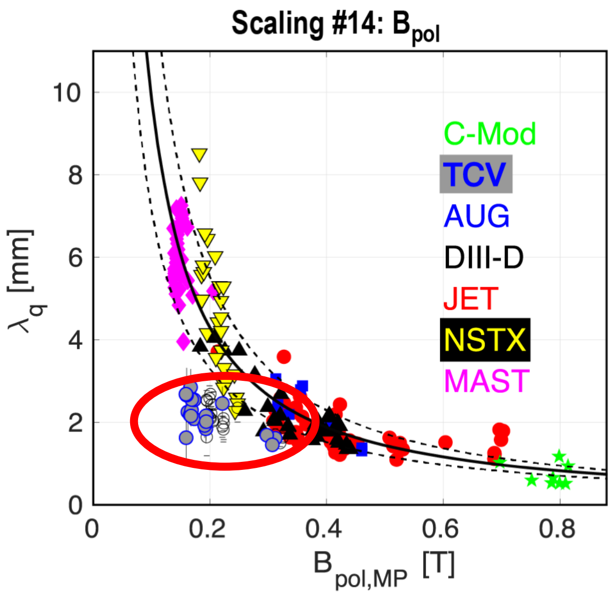
[1] Fil, et al., PPCF (2020)

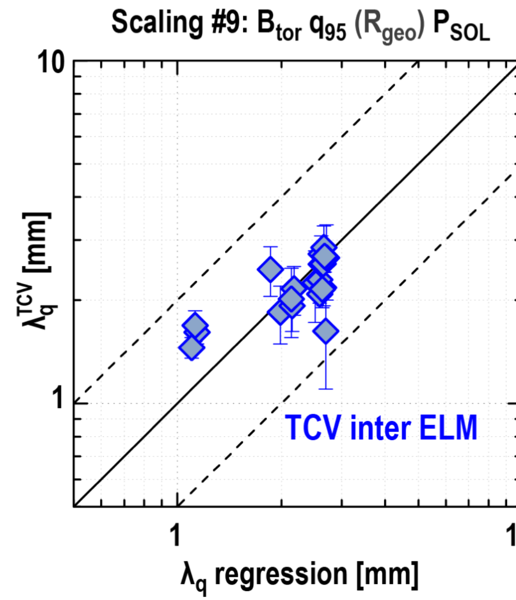
TCV's H-mode SOL surprisingly narrow

Maurizio, et al., NF (2021)

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

Empiric scalings [1]



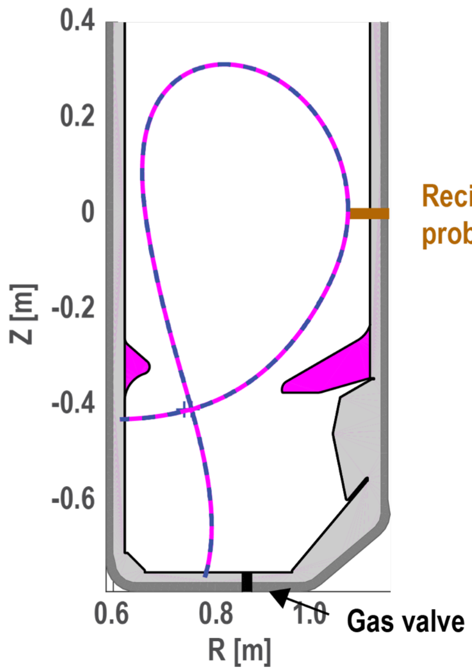


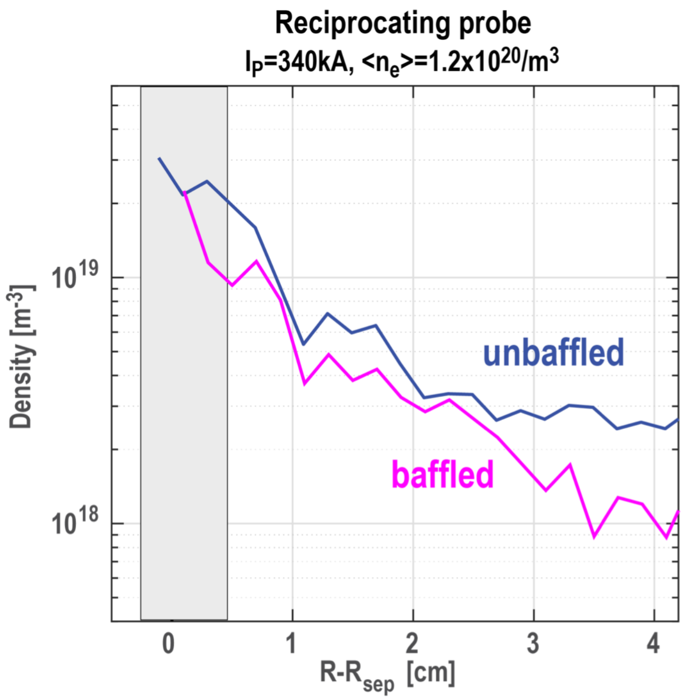
- TCV measurements agree with cross-machine scalings that include toroidal field, q_{95} and heating power, e.g. #9[1]

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

SOL studies extend into far SOL

Tsui, et al., in preparation





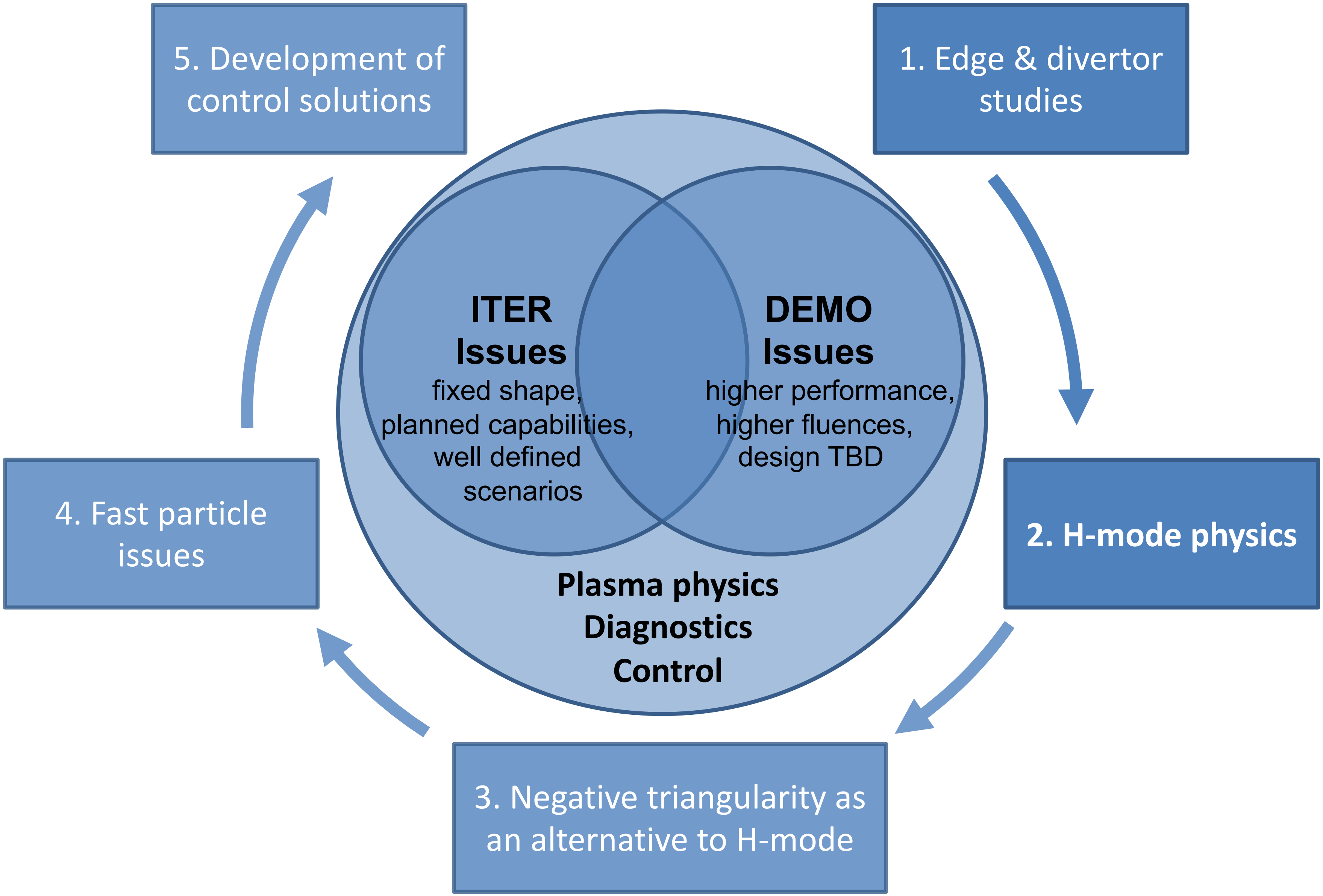
- Absence of density shoulder in baffled divertor links its formation to neutral pressure in the main chamber
- H-mode shoulder in baffled and un-baffled divertor alike

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

UC San Diego

EPFL

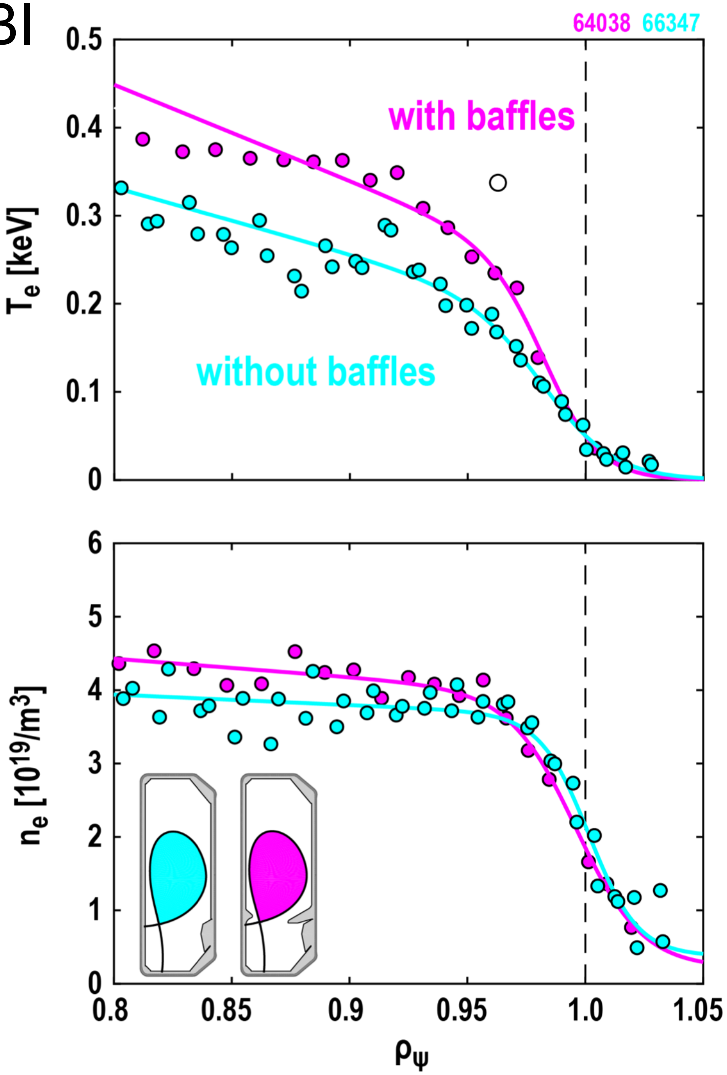
TCV programme addresses ITER and DEMO needs



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" δ → type-I ELMs
- Higher pedestal temperature with baffle at high fuelling rates, i.e. high $p_{\mathrm{n,div}}$



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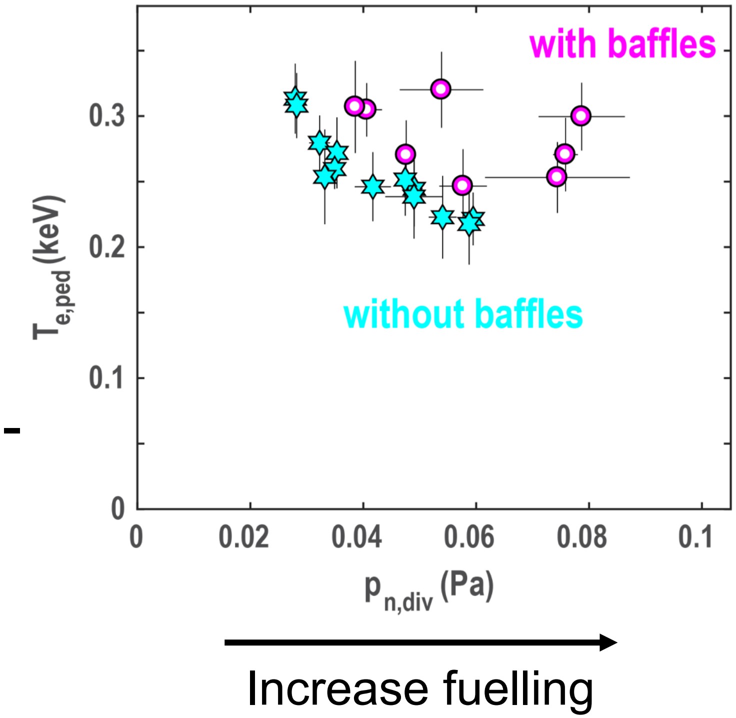
  - "Moderate" δ → type-I ELMs
- Higher pedestal temperature with baffle at high fuelling rates, i.e. high $p_{\mathrm{n,div}}$
- Baffles reduce outward shift of n_{e}-profile that causes degradation without baffles
  - Indicative of lower $p_{\mathrm{n,main}}$?

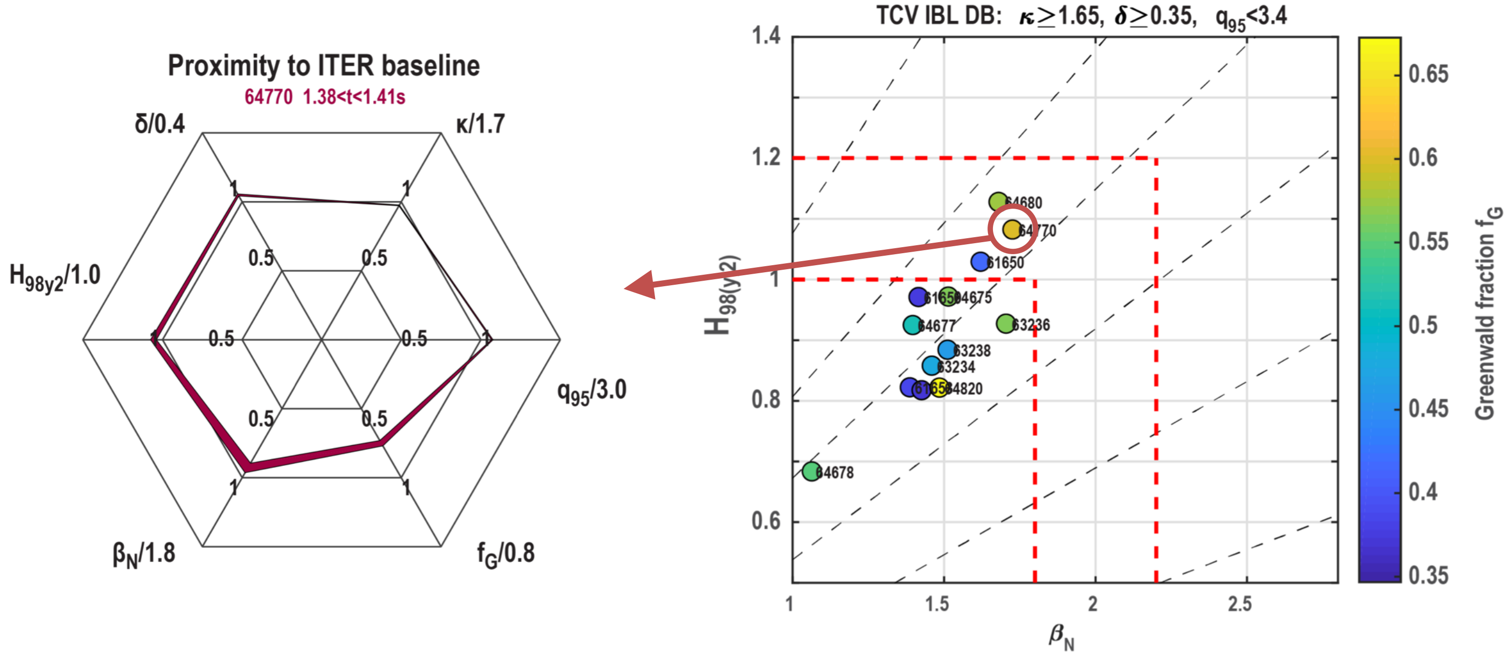


➢ Achieve 2-3x increase of radiated power without confinement degradation

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, β_N=1.8, $H_{98(y,2)}$=1.0
  - Greenwald fraction, f_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 δ and/or $f_{G,sep}$

See M. Faitsch, et al., P4 → We, 14h

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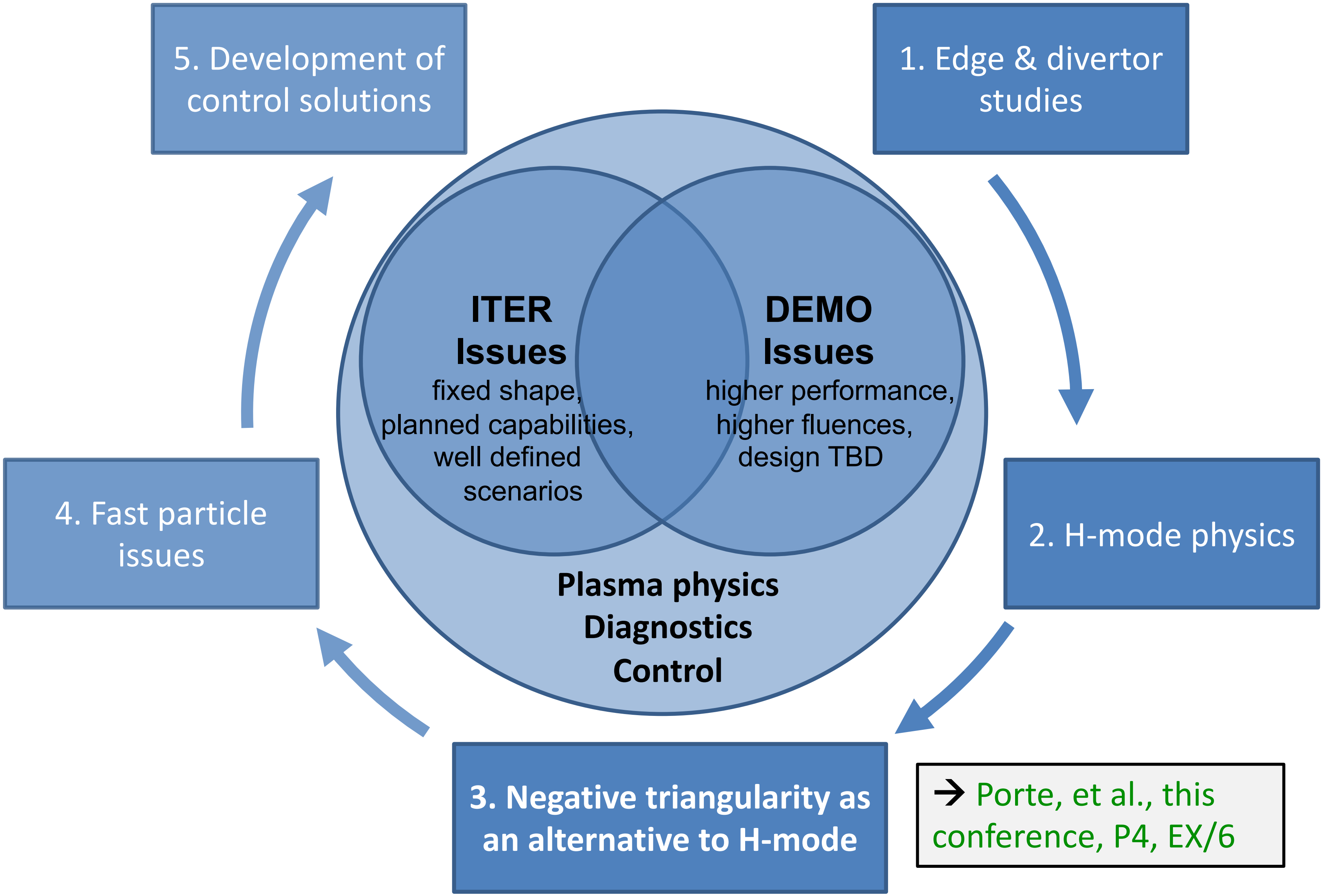


EPFL

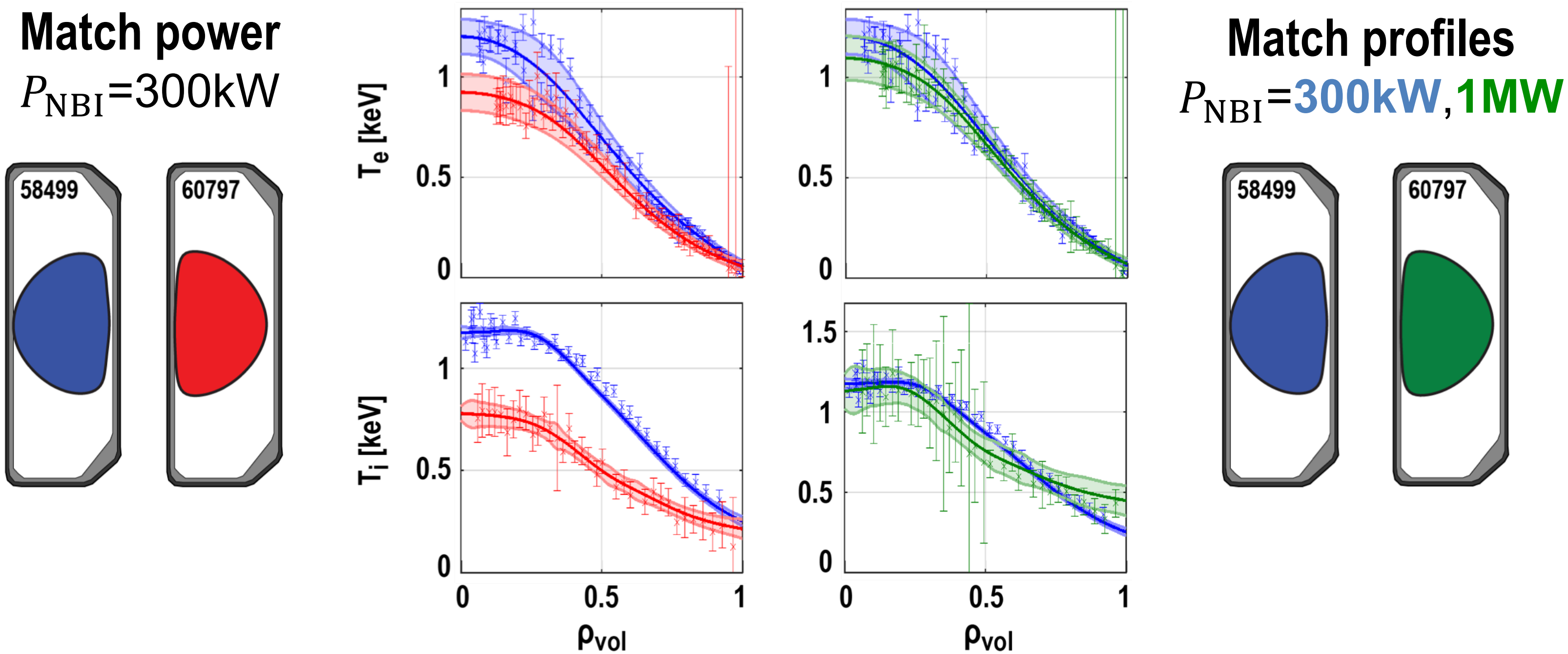
Investigate negative triangularity (NT) as an ELM-free alternative

- 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)

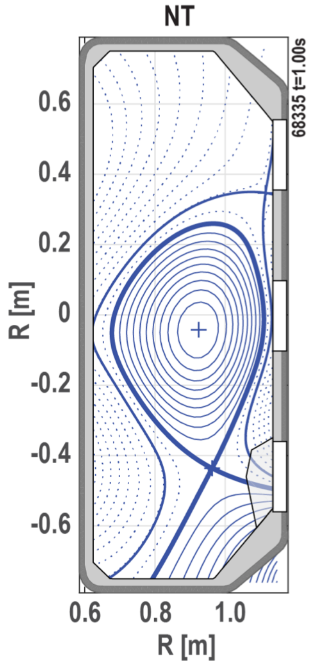


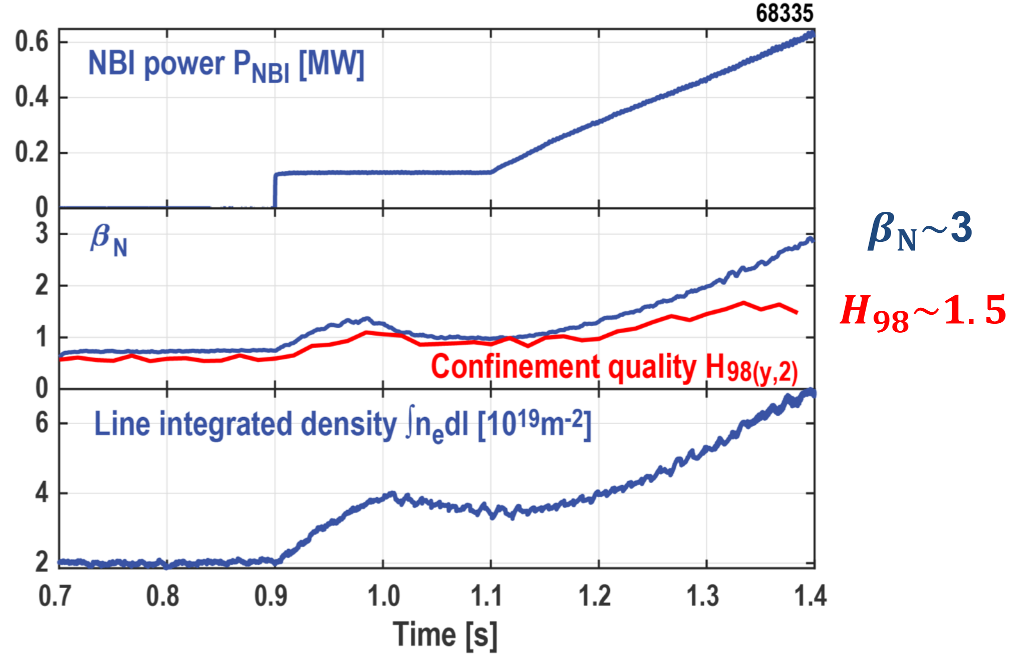
- Fluctuation amplitude decreases even with $T_{\mathrm{e}}/T_{\mathrm{i}}\sim 1$
  - Linear gyrokinetic simulations (GENE) indicate mixture of TEM and ITG turbulence regime

… and high beta

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

- Combine new capabilities of NBI heating in diverted NT configurations



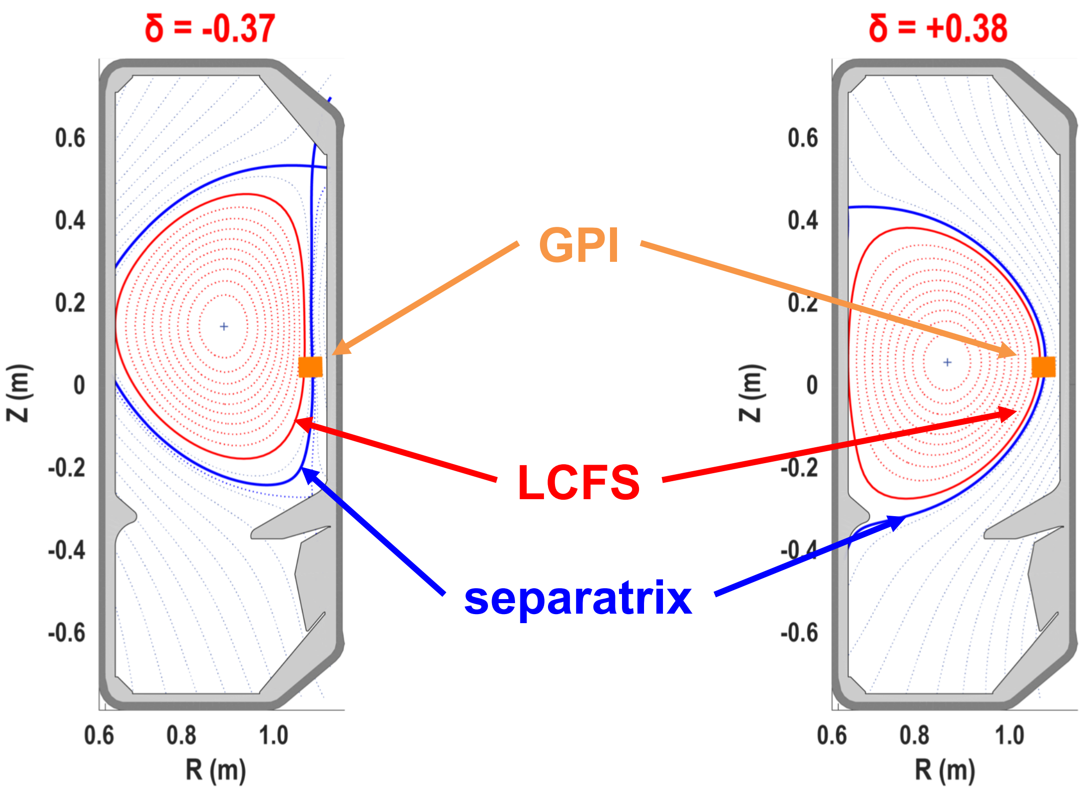


- H-factor increases with NBI heating power
→ more favourable P_{heat} and/or n_e scaling than $H_{98(\mathrm{y},2)}$

Turbulent transport decrease extends to edge …

Han, et al., NF (2021)

- Midplane GPI diagnostic images SOL turbulence



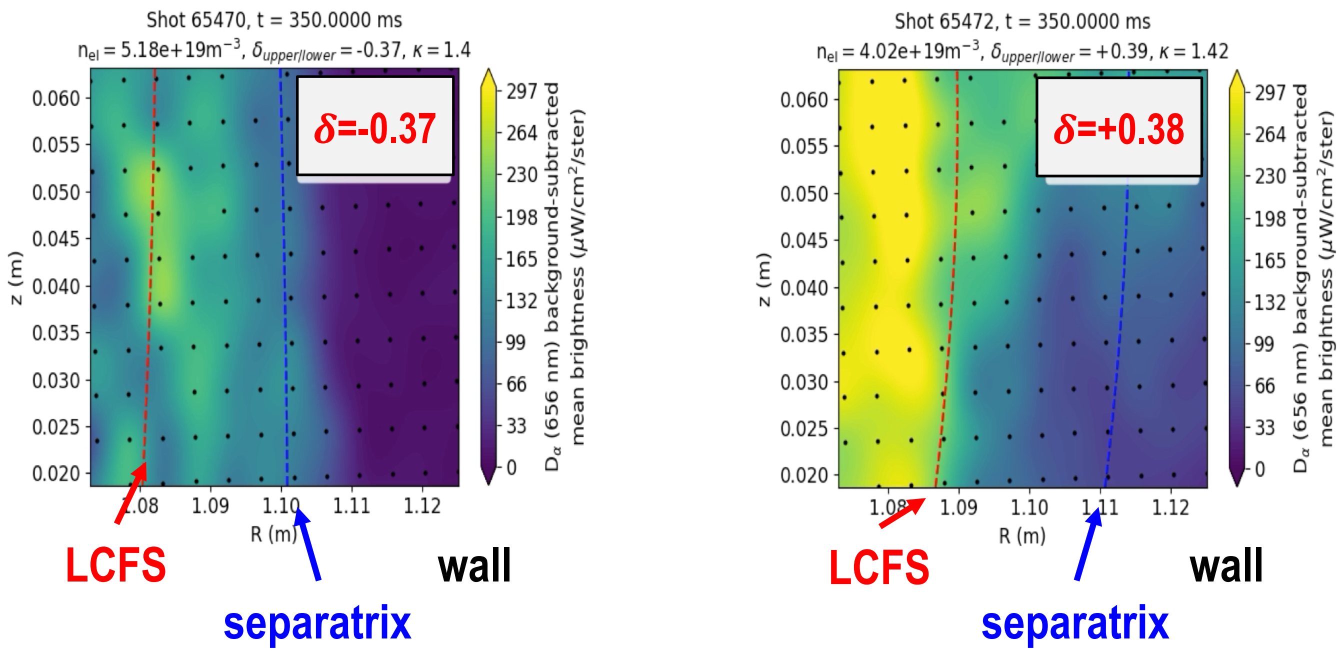
Massachusetts Institute of Technology

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

Han, et al., NF (2021)

- Midplane GPI diagnostic images SOL turbulence

GPI



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

Massachusetts Institute of Technology

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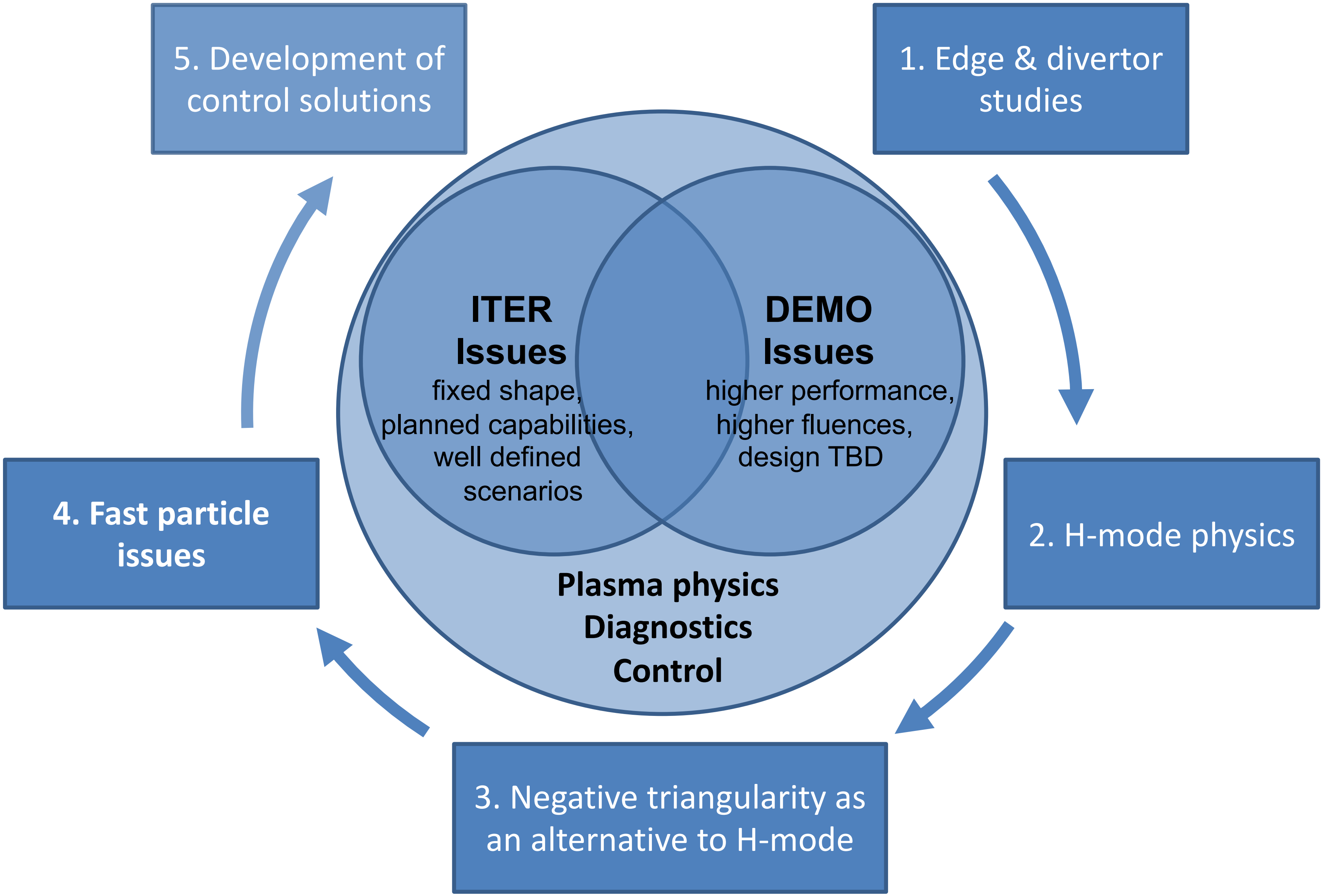
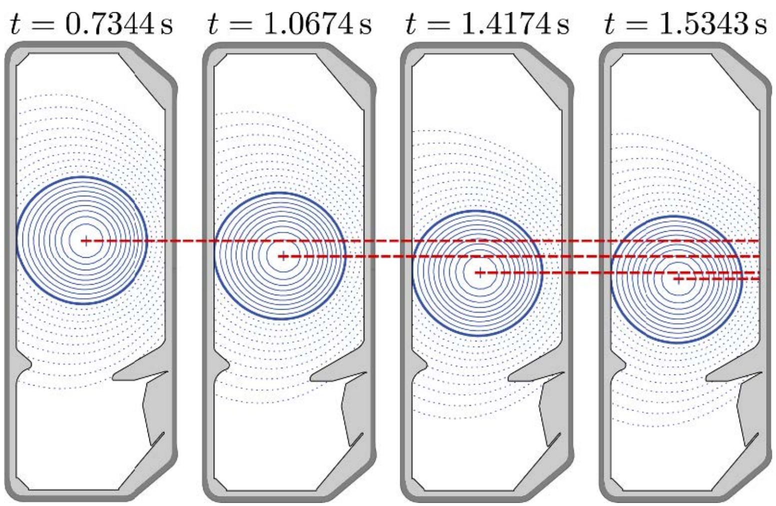
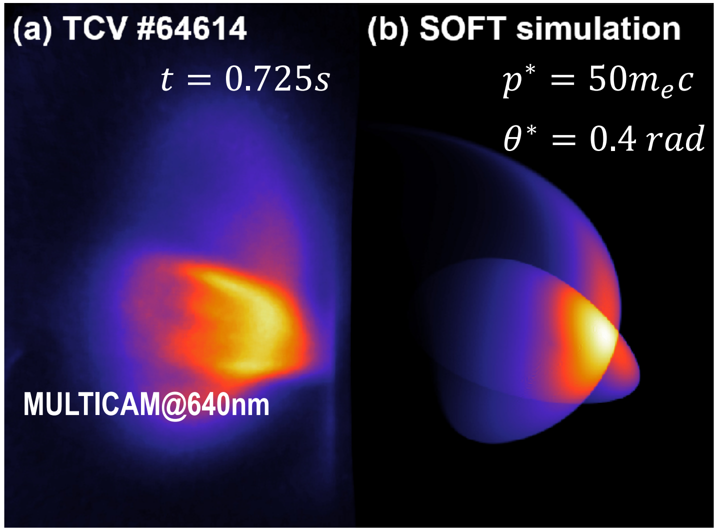


Imaging RE synchrotron emission reveals momentum and pitch angle

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)





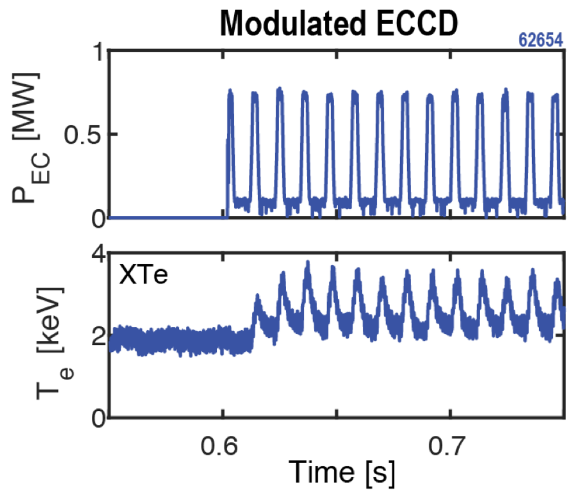
- Kinetic model predicts lower pitch for momentum
  - Significant non-collisional pitch angle scattering and radial RE transport – possibly caused by magnetic perturbation

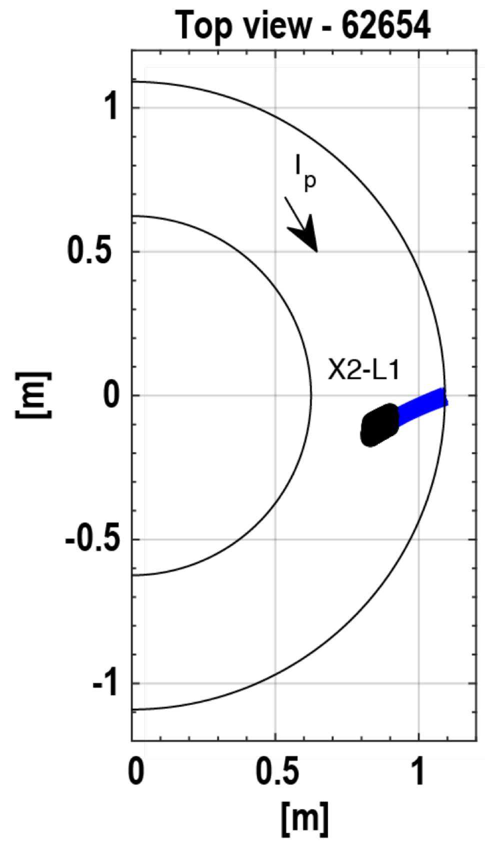
EPFL

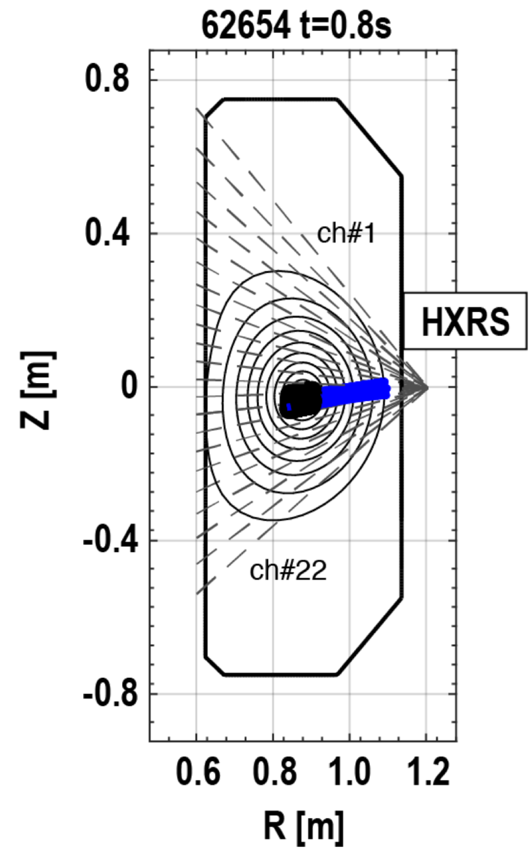
Dynamic response of electron to ECCD probes fast electron transport

Choi, et al., PPCF (2020)

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



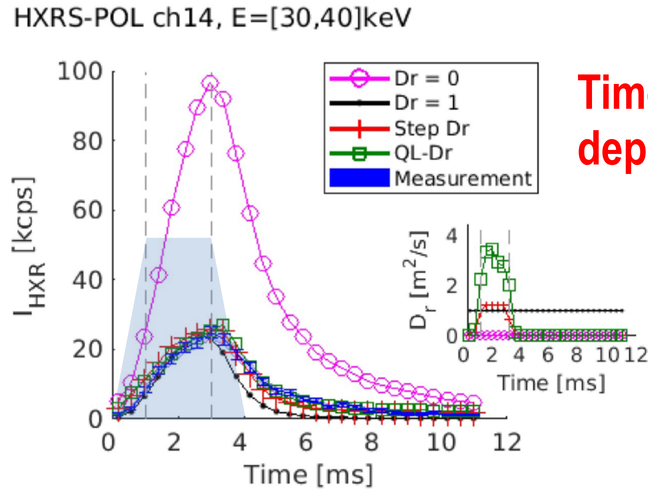




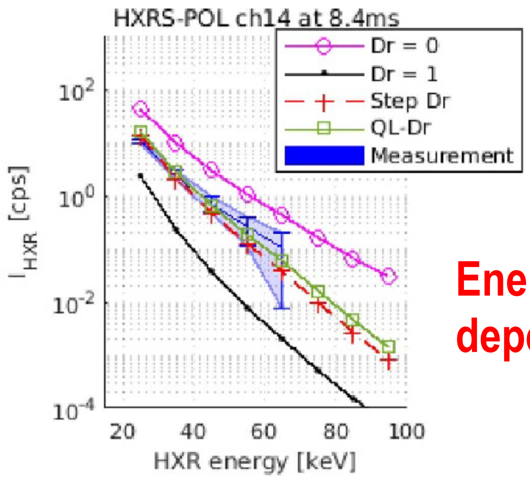
Dynamic response of electron to ECCD probes fast electron transport

Choi, et al., PPCF (2020)

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



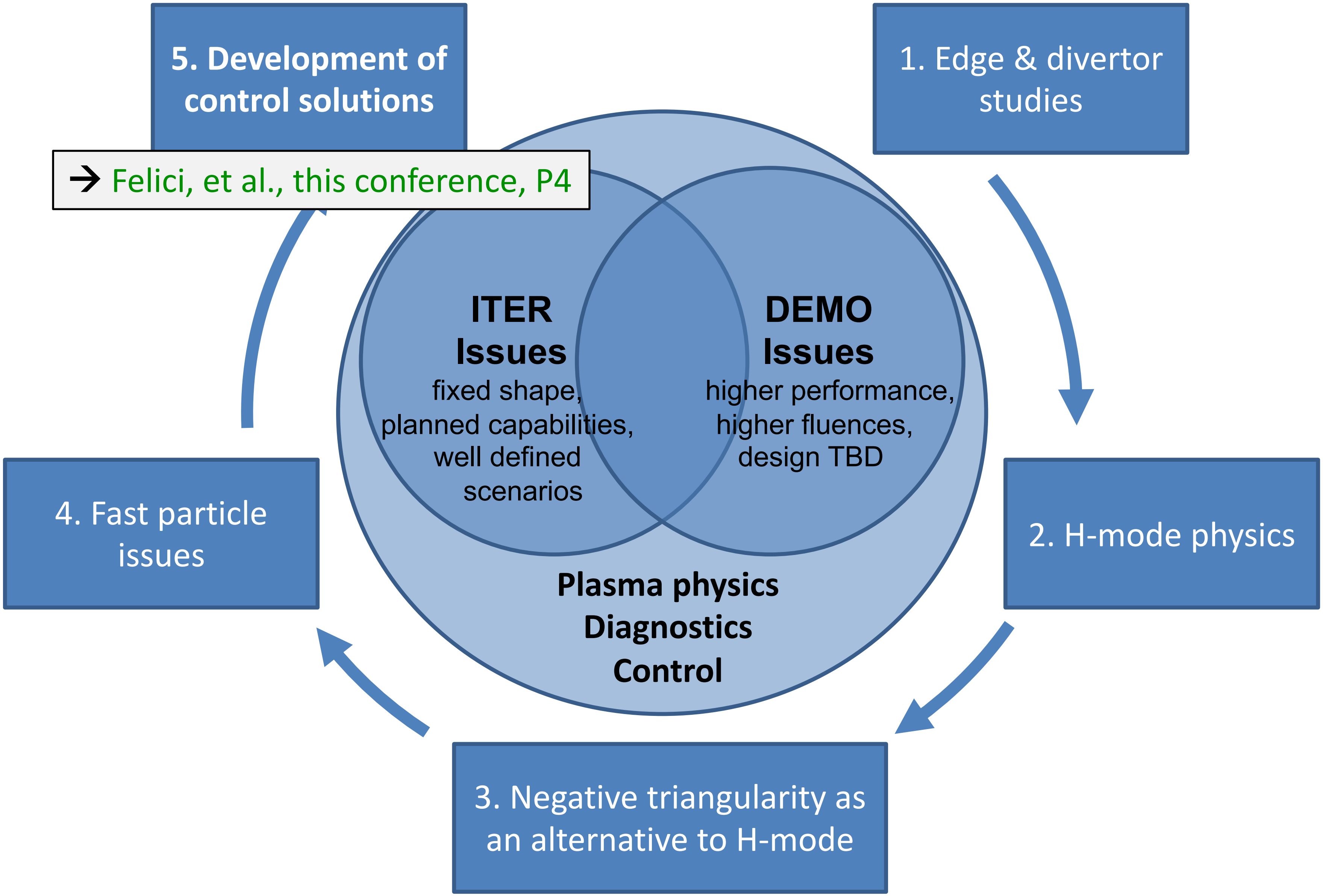
Time dependence



Energy dependence

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

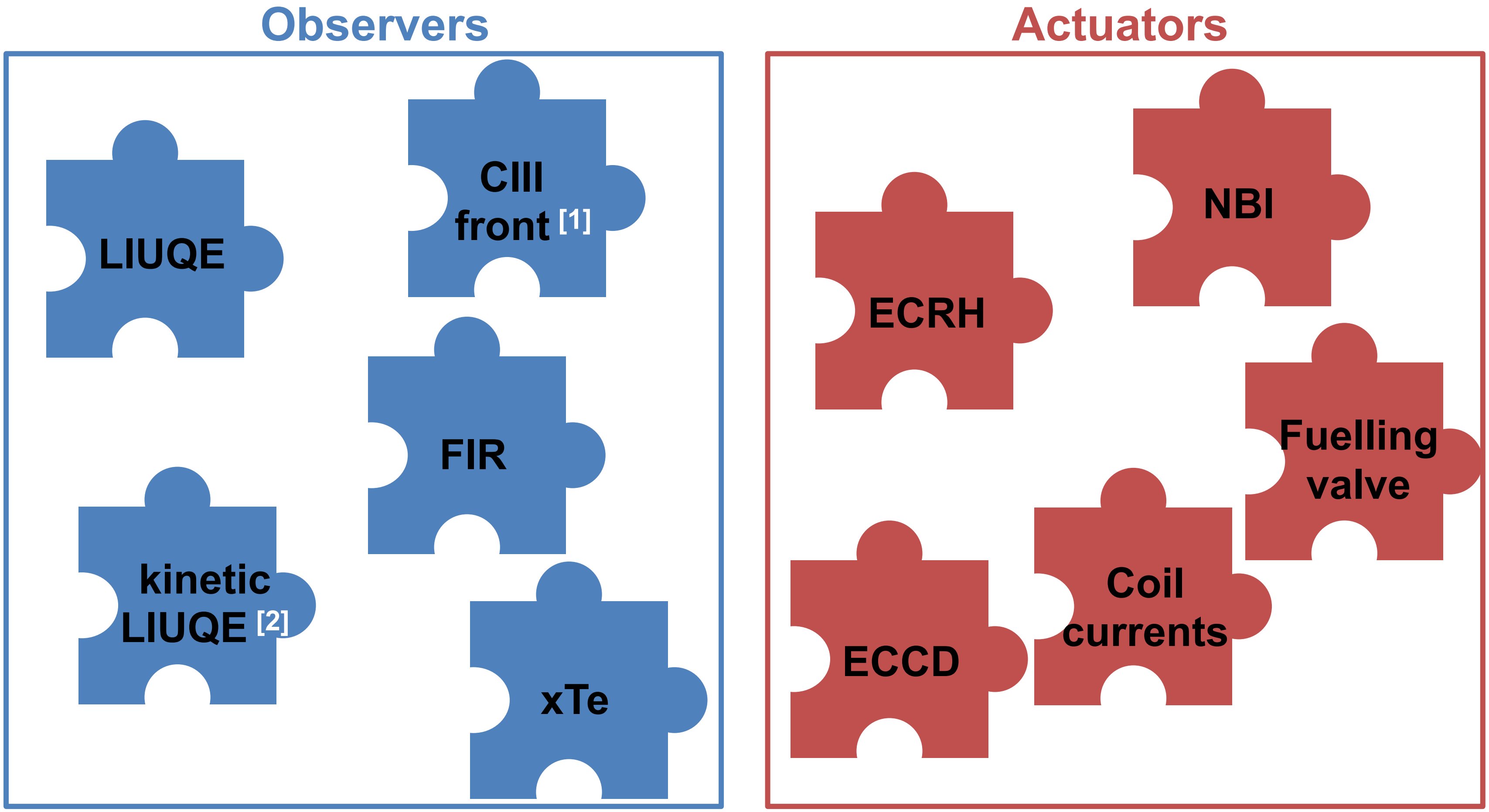
TCV programme addresses ITER and DEMO needs



TCV boasts numerous RT-observers, actuators and control solutions

F, Felici, et al., P4 → We, 14h

- Flexible digital control system



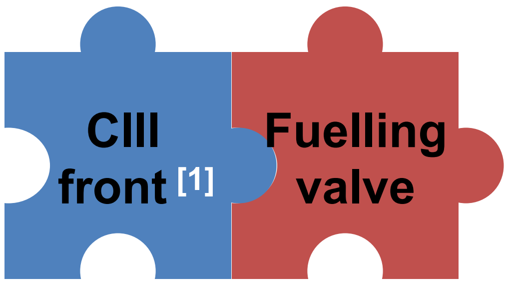
[1] Ravensbergen, et al., NF (2020)
[2] Carpanese, et al., NF (2020)

TCV boasts numerous RT-observers, actuators and control solutions

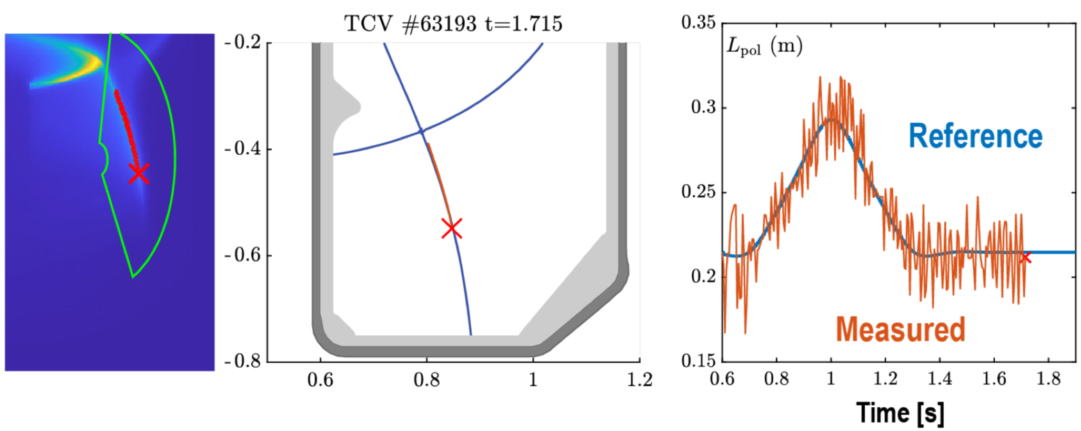
F, Felici, et al., P4 → We, 14h

- Flexible digital control system

Observers | **Actuators**



- Demonstrate feedback-control of the impurity emission front location



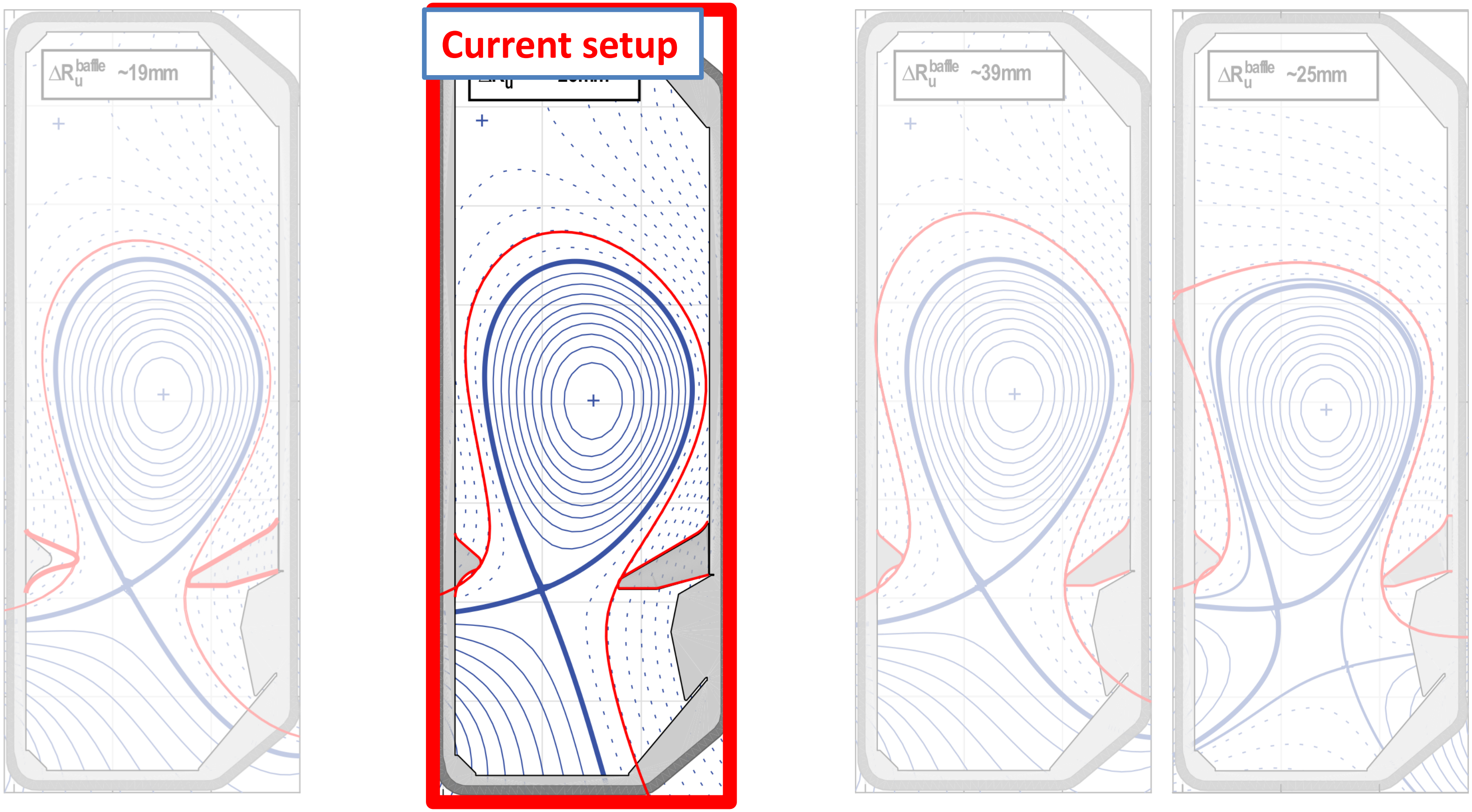
Ravensbergen, et al., Nat. Comm. (2021)

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

Conclusion – TCV overview

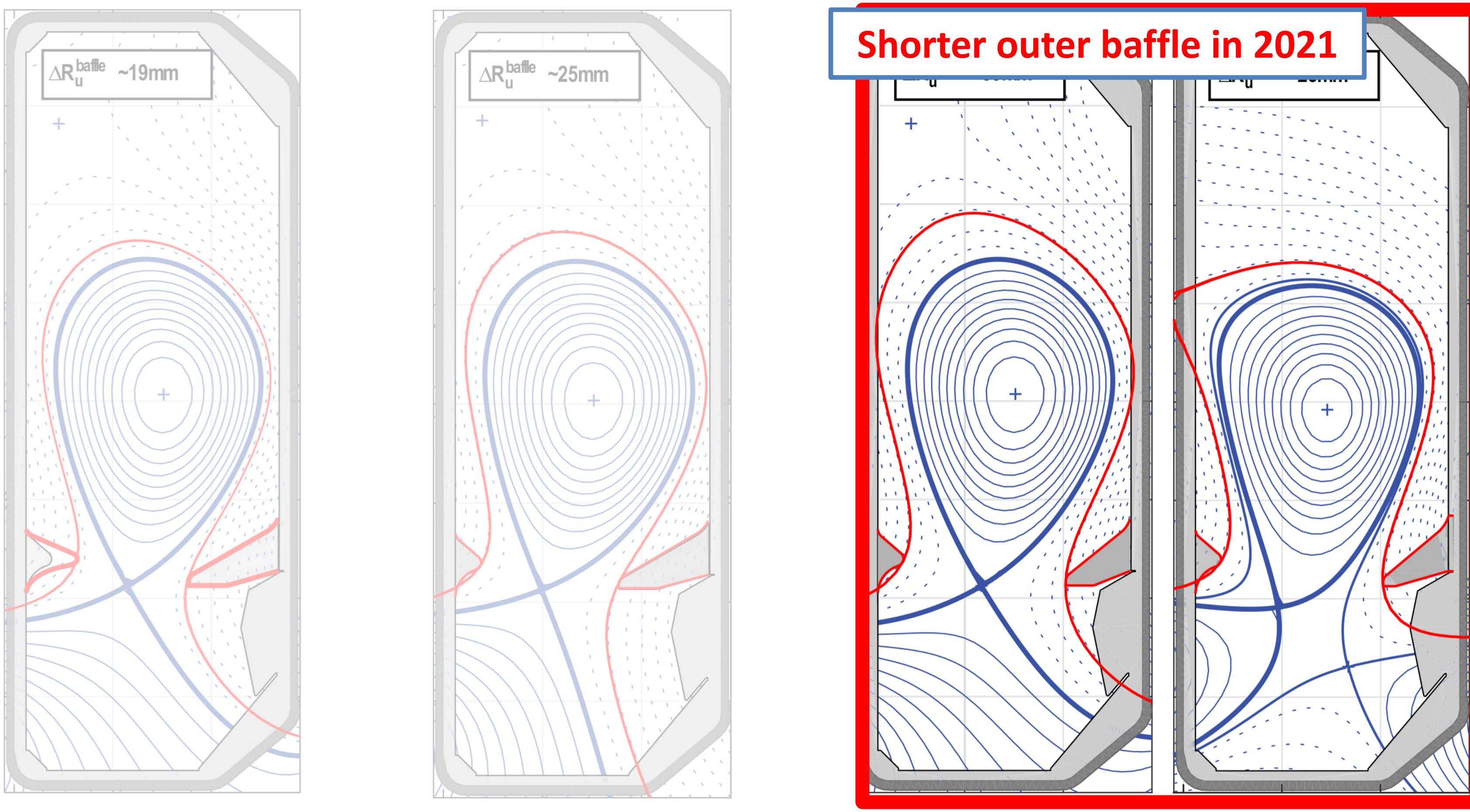
- Rich programme balances ITER and DEMO needs with scientific discoveries (doublets not even mentioned)
  - Strong integration in **European programme**
  - Complemented with **domestic programme** and **international collaborations**
- Extend signature flexibility with flexible baffles for dedicated campaigns

Outlook: New sets of baffles



➢ Allow of more or less closed divertor

Outlook: New sets of baffles



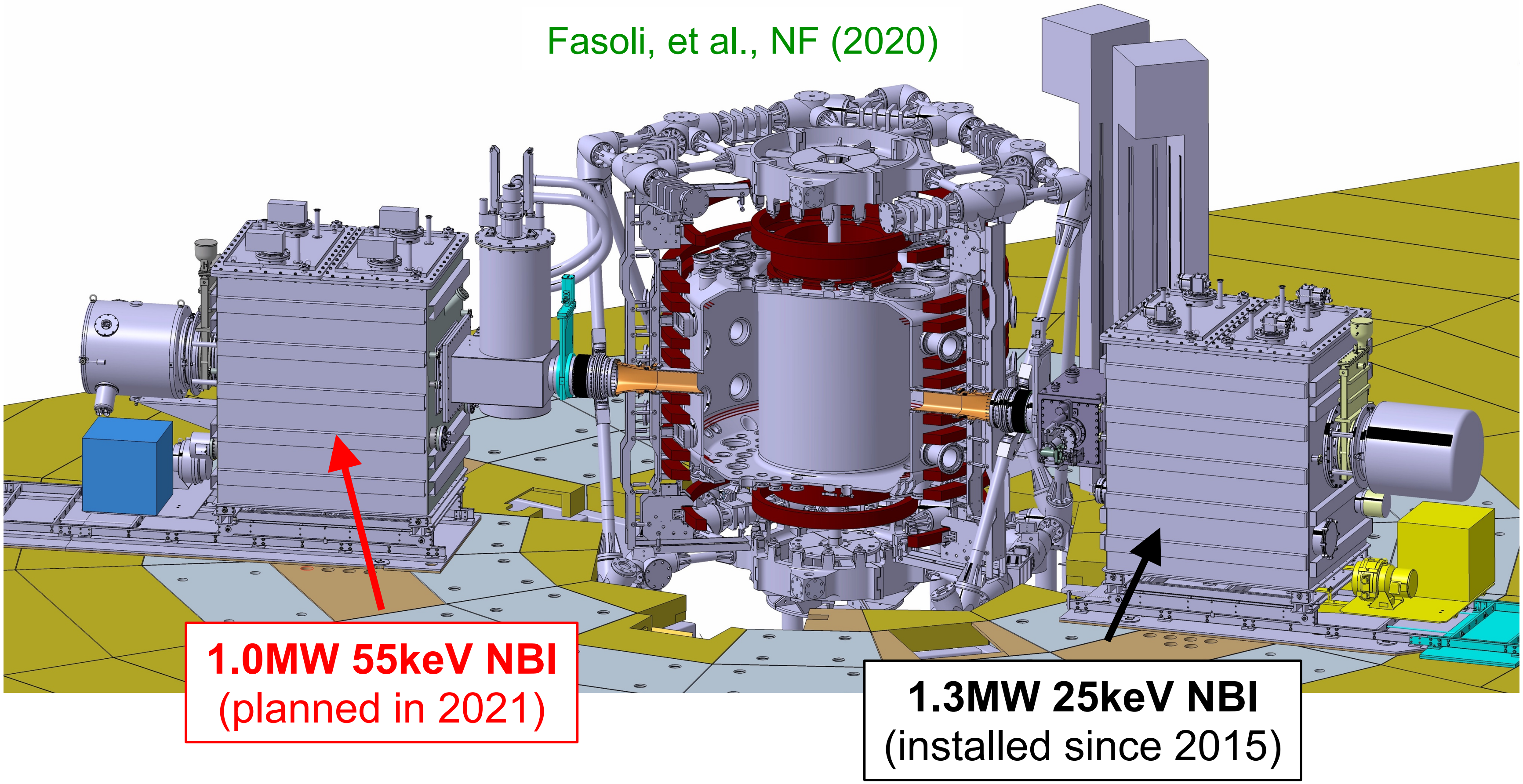
- ➢ Allow of more or less closed divertor

Outlook: New sets of baffles

- ➢ Allow of more or less closed divertor

Outlook: 2nd NBI in 2021

Fasoli, et al., NF (2020)



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

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

M. Agostini, E. Alessi, S. Alberti, Y. Andrebe, H. Arnichand, J. Balbin, F. Bagnato, M. Baquero-Ruiz, M. Bernert, W. Bin, P. Blanchard, T.C. Blanken, D. Brida, S. Brunner, J.A. Boedo, C. Bogar, O. Bogar, T. Bolzonella, F. Bombarda, F. Bouquey, C. Bowman, D. Brunetti, J. Buermans, H. Bufferand, L. Calacci, Y. Camenen, S. Carli, D. Carnevale, F. Carpanese, F. Causa, J. Cavalier, M. Cavedon, J.A. Cazabonne, J. Cerovsky, R. Chandra, A. Chandrarajan Jayalekshmi, O. Chellaï, P. Chmielewski, D. Choi, G. Ciraolo, I.G.J. Classen, S. Coda, C. Colandrea, A. Dal Molin, P. David, M.R. de Baar, J. Decker, W. Dekeyser, H. de Oliveira, D. Douai, M. Dreval, M.G. Dunne, B.P. Duval, S. Elmore, O. Embreus, F. Eriksson, M. Faitsch, G. Falchetto, M. Farnik, A. Fasoli, N. Fedorczak, F. Felici, O. Février, O. Ficker, A. Fil, M. Fontana, E. Fransson, L. Frassinetti, I. Furno, D.S. Gahle, D. Galassi, K. Galazka, C. Galperti, S. Garavaglia, M. Garcia-Munoz, B. Geiger, M. Giacomin, G. Giruzzi, M. Gobbin, T. Golfinopoulos, T. Goodman, S. Gorno, G. Granucci, J.P. Graves, M. Griener, M. Gruca, T. Gyergyek, R. Haelterman, A. Hakola, W. Han, T. Happel, G. Harrer, J.R. Harrison, S. Henderson, G.M.D. Hogeweij, J.-P. Hogge, M. Hoppe, J. Horacek, Z. Huang, A. Iantchenko, P. Innocente, K. Insulander Björk, C. Ionita-Schrittweiser, H. Isliker, A. Jardin, R.J.E. Jaspers, R. Karimov, A.N. Karpushov, Y. Kazakov, M. Komm, M. Kong, J. Kovacic, O. Krutkin, O. Kudlacek, U. Kumar, R. Kwiatkowski, B. Labit, L. Laguardia, J.T. Lammers, E. Laribi, E. Laszynska, A. Lazaros, O. Linder, B. Linehan, B. Lipschultz, X. Llobet, J. Loizu, T. Lunt, E. Macusova, Y. Marandet, M. Maraschek, G. Marceca, C. Marchetto, S. Marchioni, E.S. Marmar, Y. Martin, L. Martinelli, F. Matos, R. Maurizio, M.-L. Mayoral, D. Mazon, V. Menkovski, A. Merle, G. Merlo, H. Meyer, K. Mikszuta-Michalik P. A. Molina Cabrera, J. Morales, J.-M. Moret, A. Moro, D. Moulton, H. Muhammed, O. Myatra, D. Mykytchuk, F. Napoli, R.D. Nem, A.H. Nielsen, M. Nocente, S. Nowak, N. Offeddu, J. Olsen, F.P. Orsitto, O. Pan, G. Papp, A. Pau, A. Perek, F. Pesamosca, Y. Peysson, L. Pigatto, C. Piron, M. Poradzinski, L. Porte, T. Pütterich, M. Rabinski, H. Raj, J.J. Rasmussen, G.A. Rattá, T. Ravensbergen, H. Reimerdes, D. Ricci, P. Ricci, N. Rispoli, F. Riva, J.F. Rivero-Rodriguez, M. Salewski, O. Sauter, B.S. Schmidt, R. Schrittweiser, S. Sharapov, U.A. Sheikh, B. Sieglin, M. Silva, A. Smolders, A. Snicker, C. Sozzi, M. Spolaore, A. Stagni, L. Stipani, G. Sun, T. Tala, P. Tamain, K. Tanaka, A. Tema Biwole, D. Terranova, J.L. Terry, D. Testa, C. Theiler, A. Thornton, A. Thrysøe, H. Torreblanca, C. K. Tsui, D. Vaccaro, M. Vallar, M. van Berkel, D. Van Eester, R.J.R. van Kampen, S. Van Mulders, K. Verhaegh, T. Verhaeghe, N. Vianello, F. Villone, E. Viezzer, B. Vincent, I. Voitsekhovitch, N.M.T. Vu, N. Walkden, T. Wauters, H. Weisen, N. Wendler, M. Wensing, F. Widmer, S. Wiesen, M. Wischmeier, T.A. Wijkamp, D. Wünderlich, C. Wüthrich, V. Yanovskiy, J. Zebrowski