EPFL

Alternative divertors for improved tokamak operation

Christian Theiler
Swiss Plasma Center (SPC) - EPFL

FuseNet PhD event
EPFL, 23.8.2023

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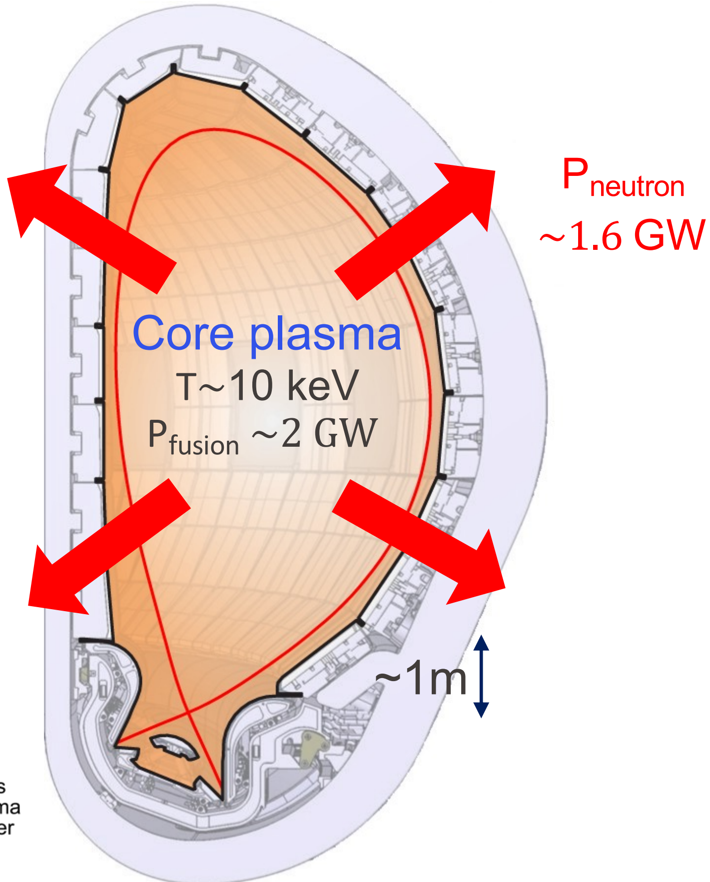
Center

Complexity and importance of the boundary plasma

Christian Theiler



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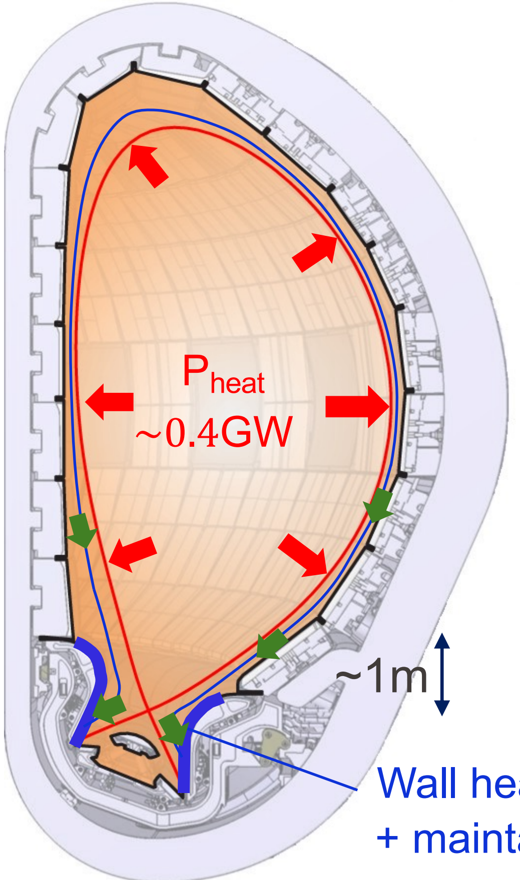

Wall heat flux ≤ 10MW/m^2; $T_e \lesssim$ 5 eV; Sufficient helium pumping
+ maintaining high energy confinement **→Exhaust challenge**

Swiss Plasma Center

Complexity and importance of the boundary plasma

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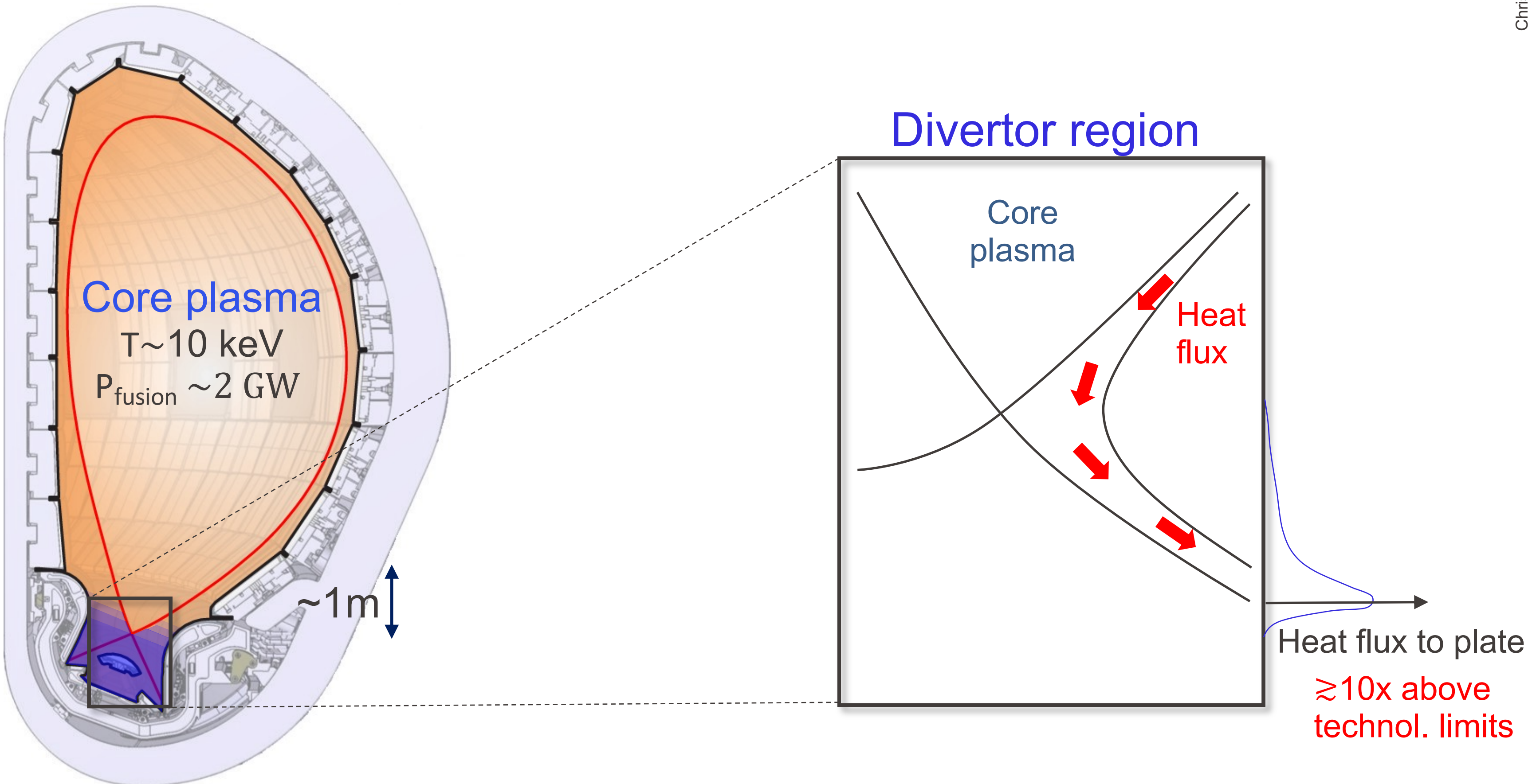
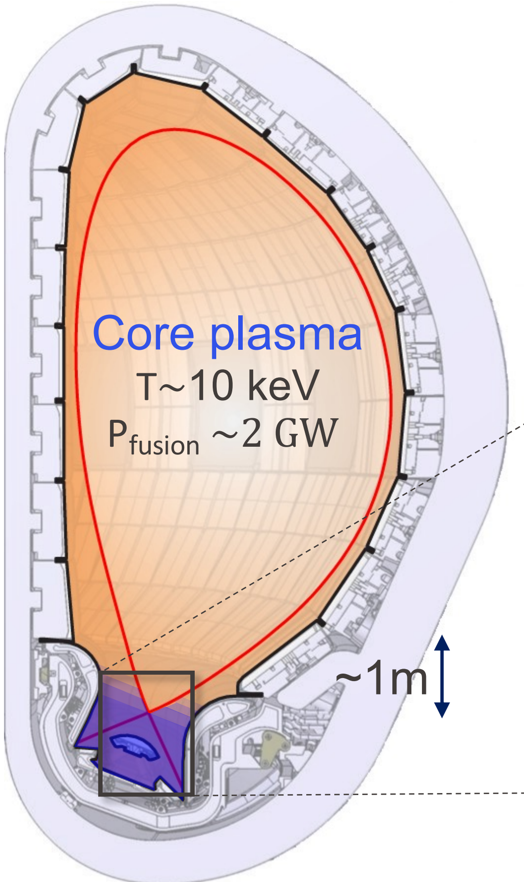
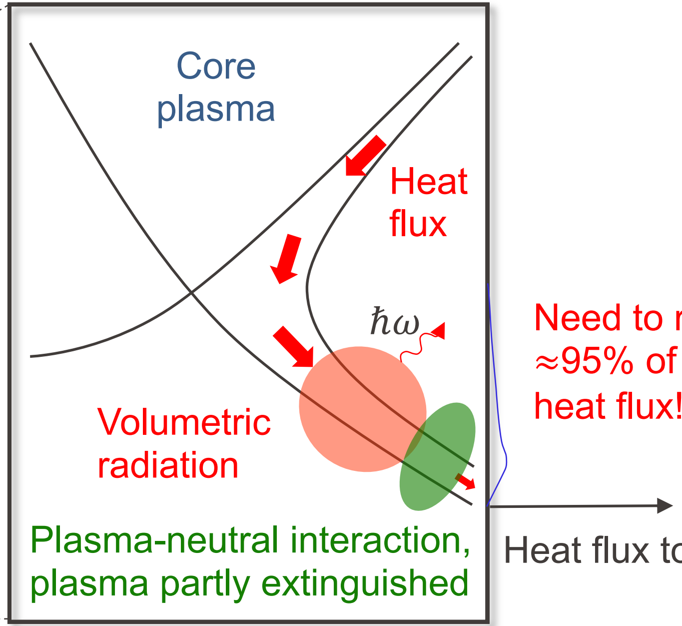


Complexity and importance of the boundary plasma

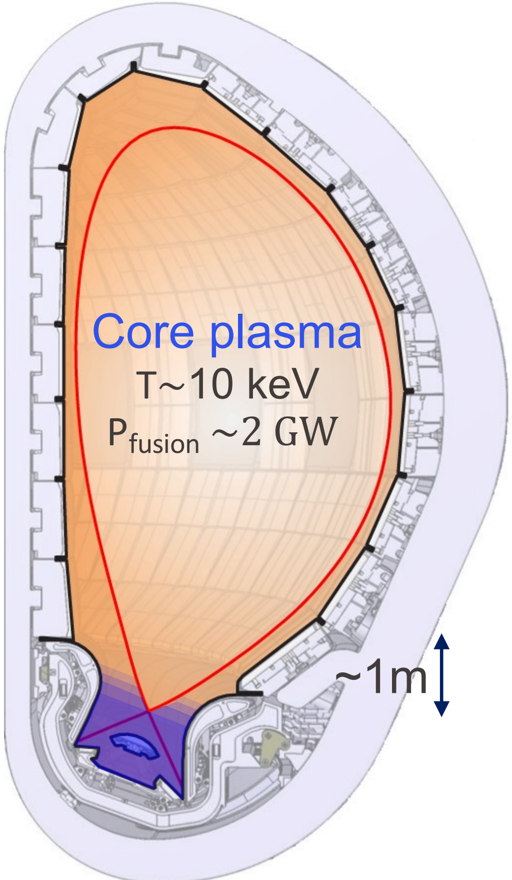


Divertor **detachment**



Need to radiate ≈95% of this heat flux!

Complexity and importance of the boundary plasma

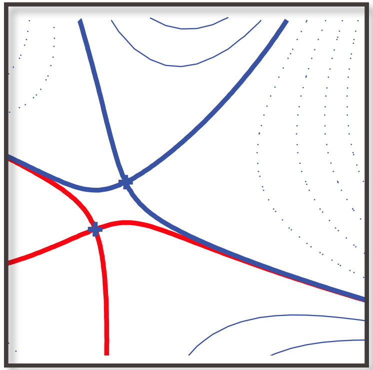


- Unclear if safe plasma exhaust achievable in conventional divertor while simultaneously assuring sufficient core performance, high plasma stability, protection against transient loss of detachment,…
- ITER is the key facility to test the conventional divertor
- As backup plan, alternatives need to be explored in parallel, in today's and in next step devices[1]

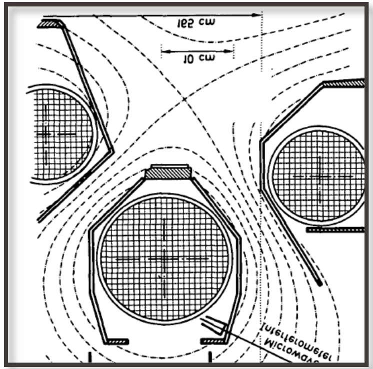
[1] European Research Roadmap to the Realization of Fusion Energy – 2018

Alternative divertor configurations and potential benefits

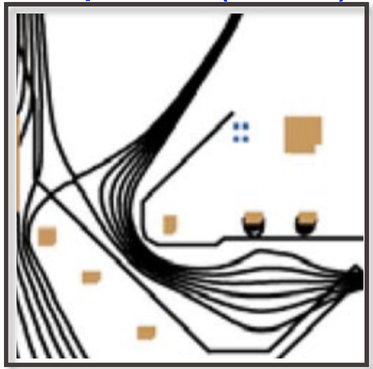
Snowflake (2007)



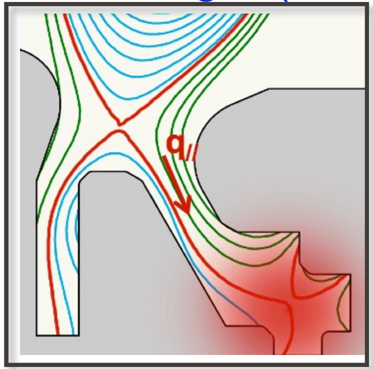
X-Divertor (1980s)



Super-X (2009)



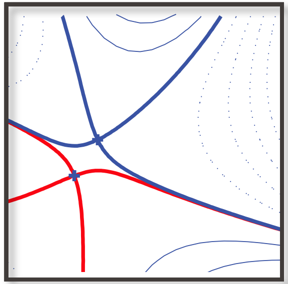
X-Point Target (2015)



See [Soukhanovskii *et al.*, PPCF 2017] for a historical overview of alternative divertors

Alternative divertor configurations and potential benefits

Snowflake



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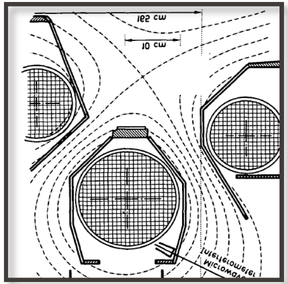
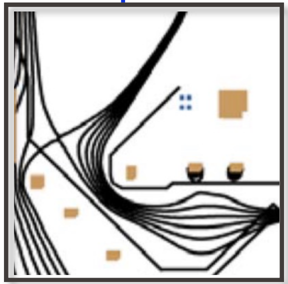
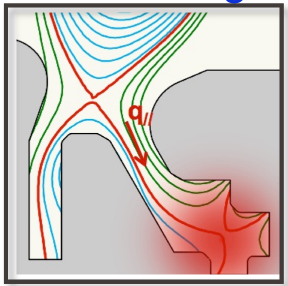


Super-X



X-Point Target



- These concepts potentially allow easier access to detachment and better control of the radiation region
  - ➢ Less impurity seeding needed?
  - ➢ Wider detachment window, more resilient to transients?
  - ➢ Improved compatibility of detachment with core performance?
- They provide a testbed to advance understanding of detachment physics and for model validation

Alternative divertor configurations and potential benefits

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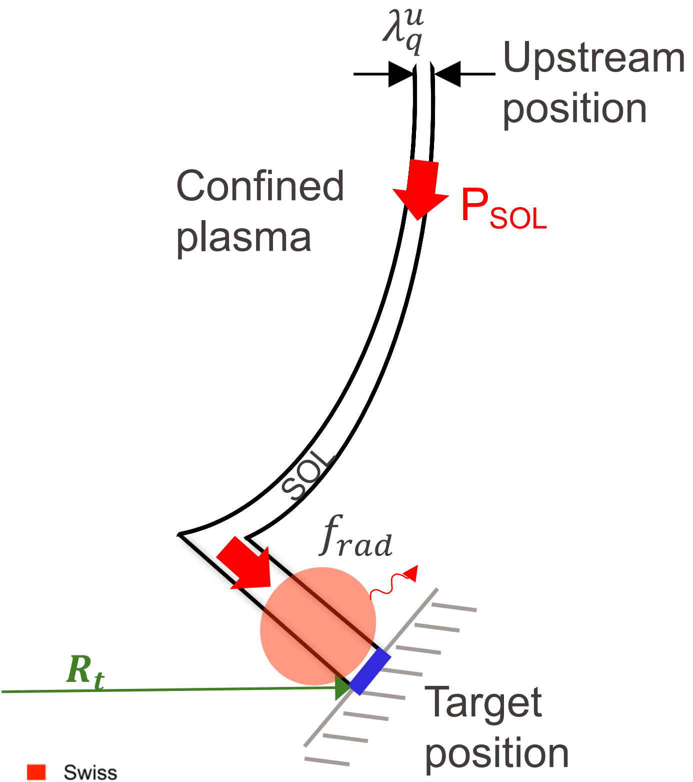

How to facilitated access to low target $T_{e,t}$ and thus detachment?

2-Point Model prediction (attached conditions, $\nu_{SOL}^* \gtrsim 15$, heat conduction) :

$$T_{e,t} \propto \left(\frac{P_{SOL}}{\lambda_q^u}\right)^{\frac{10}{7}} \cdot \frac{(1-f_{rad})^2}{L_\parallel^{4/7} n_u^2 R_t^2}$$

Increase field-line length

Increase radial pos. of target

Alternative divertor configurations and potential benefits

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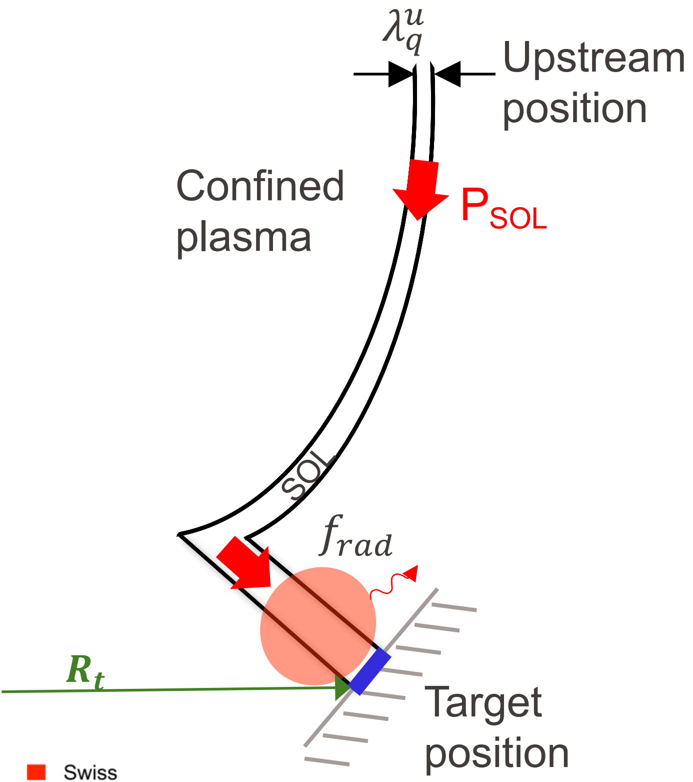

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Increase in radiation losses?

Wider SOL?

For more details, see
[Theiler et al., Nucl. Fusion 57, 072008 (2017)]

The Tokamak à Configuration Variable (TCV), a highly flexible and versatile device

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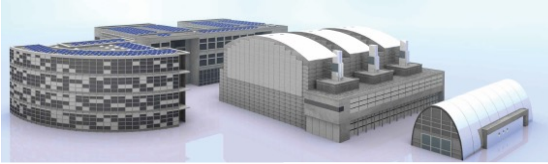
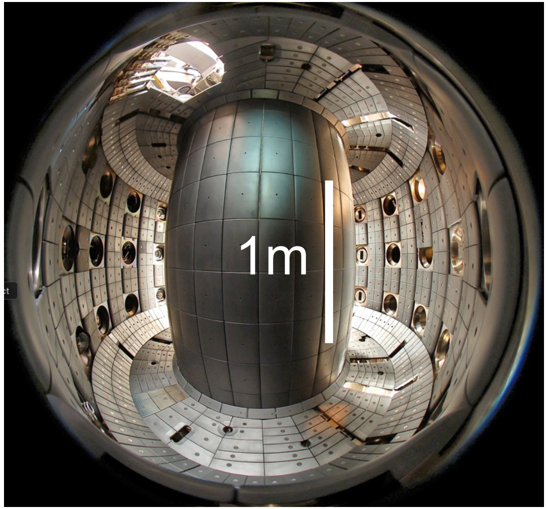


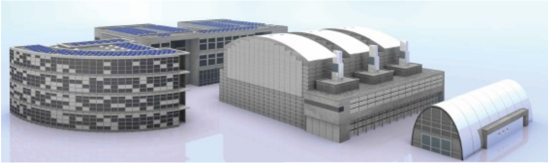
EPFL SWISS PLASMA CENTER



- "Medium-sized" carbon device
  - Major radius R=0.89m
  - Toroidal field $B_t \leq 1.5T$
  - Plasma current $I_p \leq 1MA$
- Flexible, real-time controllable electron cyclotron heating (~3.5 MW)
- 2MW neutral beam heating
- Unique shaping capabilities

➢ One of the key facilities of the EUROfusion research program

The Tokamak à Configuration Variable (TCV), a highly flexible and versatile device



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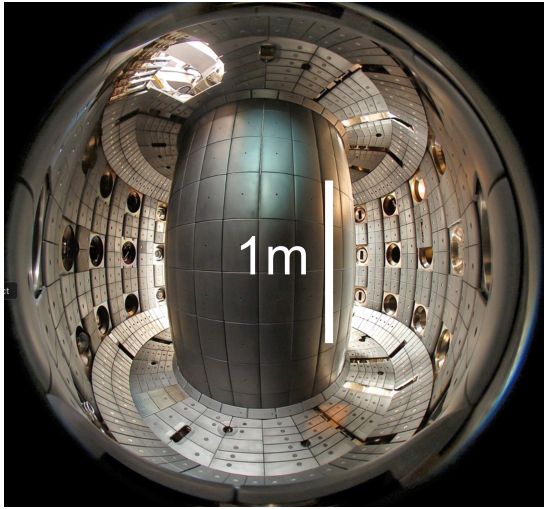
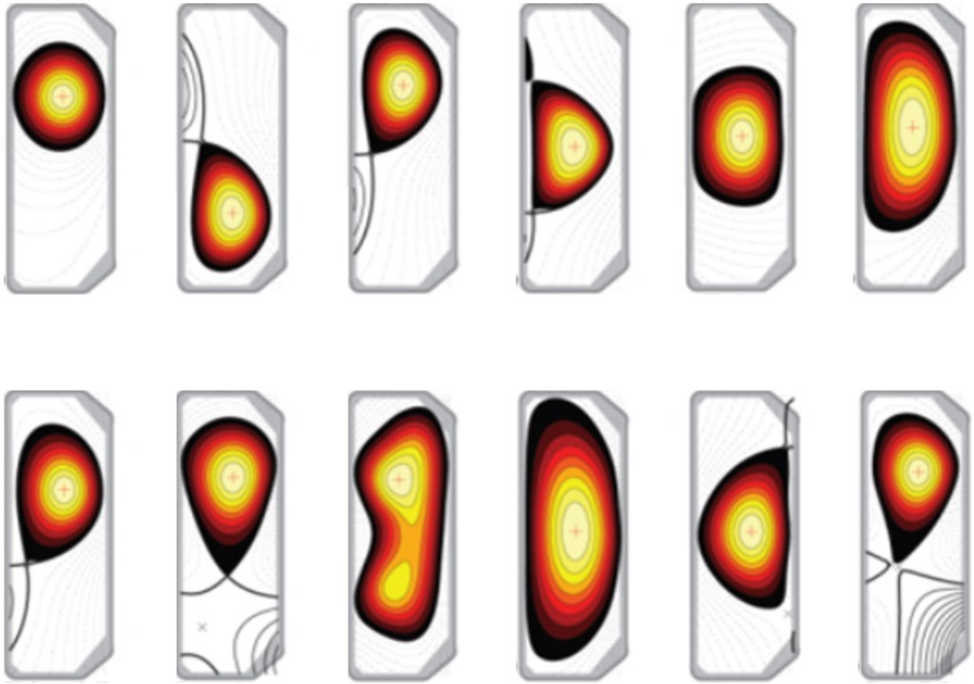
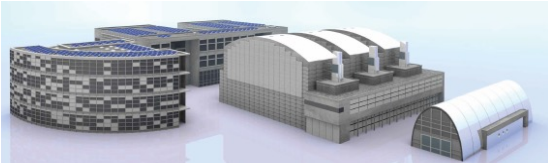
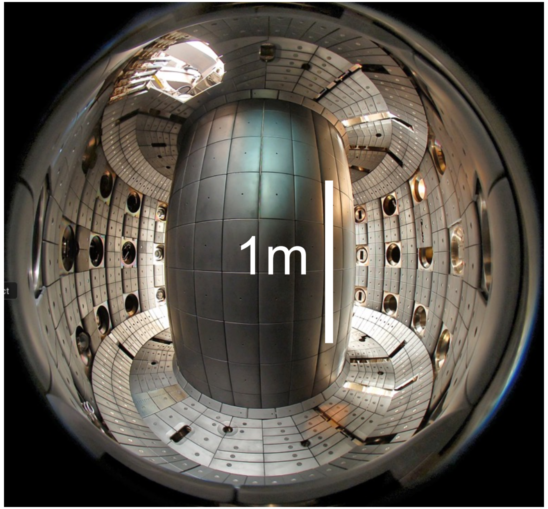




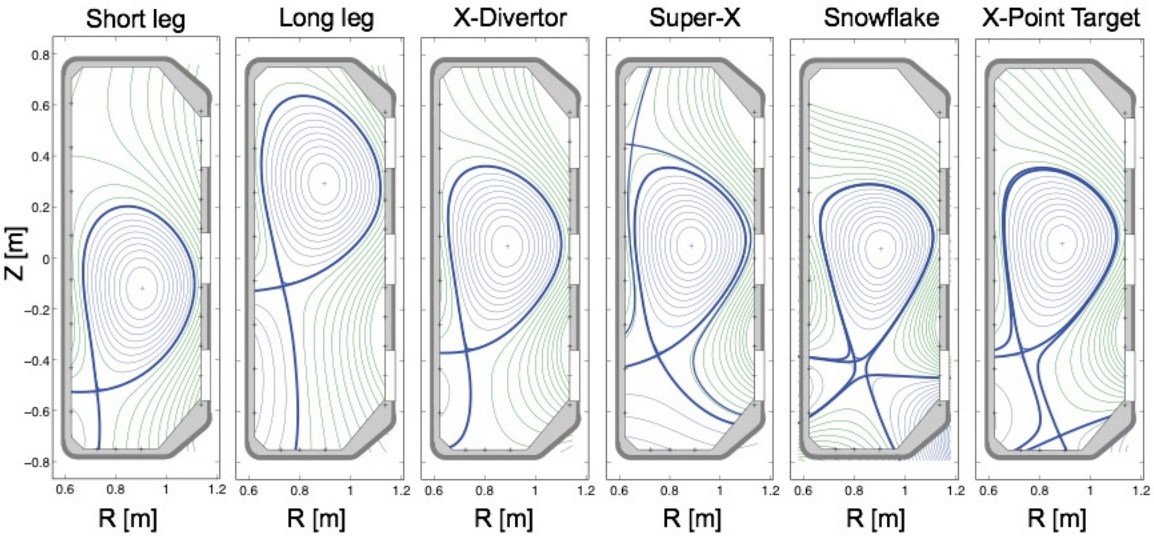
TCV - an ideal device to explore alternative divertors



SWISS PLASMA CENTER

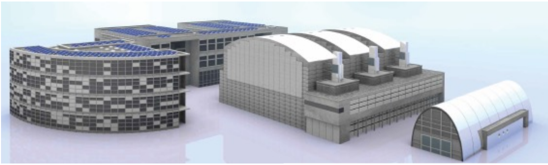


Extreme divertor magnetic shaping capabilities

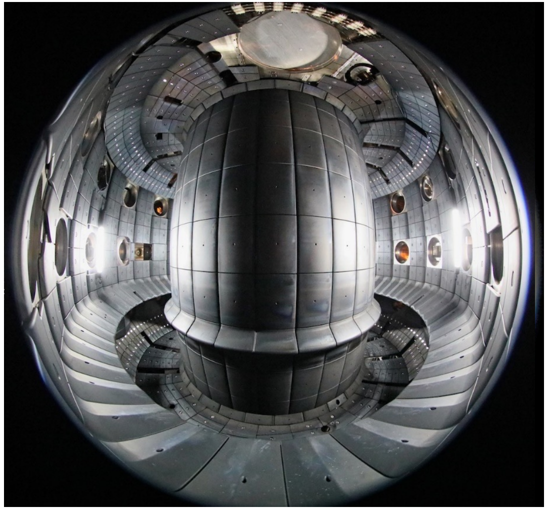


[Theiler et al., Nucl. Fusion 57, 072008 (2017)]

EPFL TCV - an ideal device to explore alternative divertors

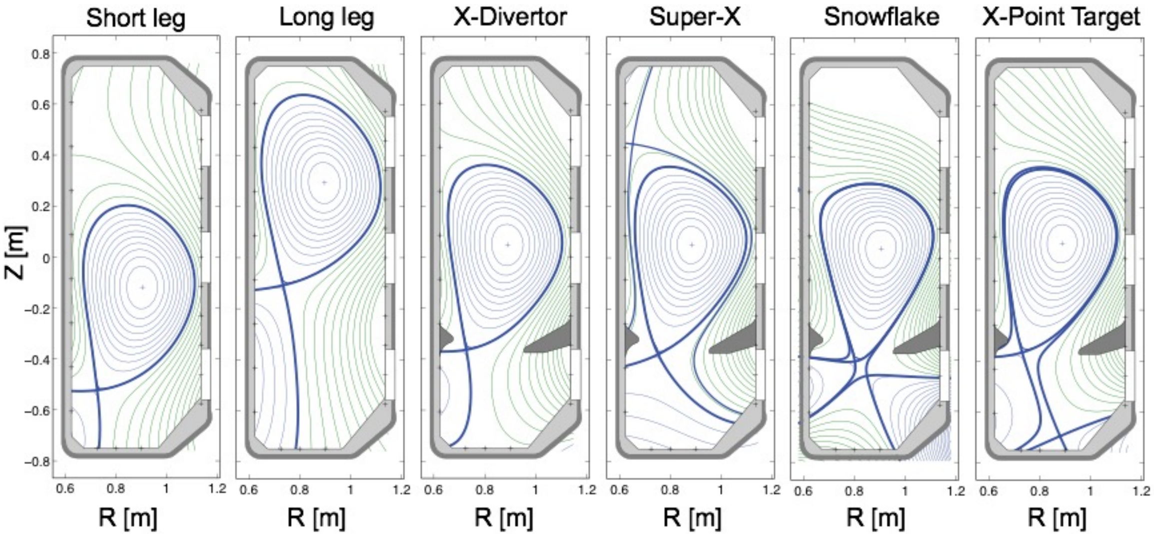


EPFL SWISS PLASMA CENTER



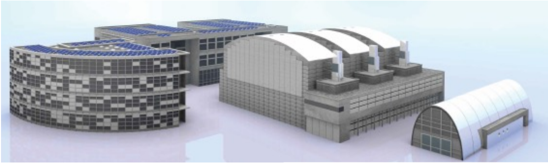
Extreme divertor magnetic shaping capabilities

Flexible wall structures



[Fasoli et al., Nucl. Fusion 60, 016019 (2020)]

TCV - an ideal device to explore alternative divertors



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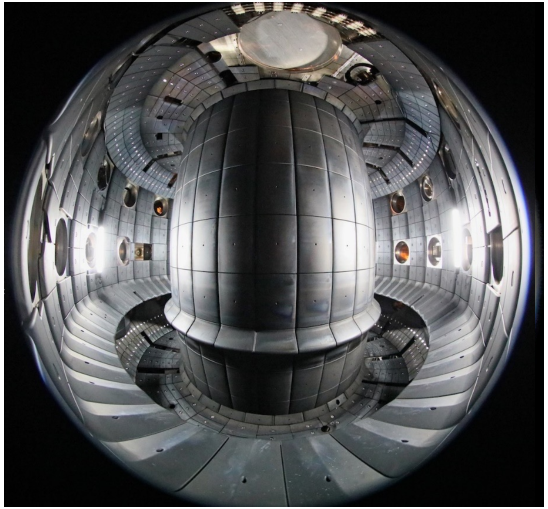


Goals of the TCV Boundary Group:

- Assess benefits of most promising alternative divertors through proof-of-principle experiments, theoretical interpretation, and modelling
  - ➢ Provide basis for selection of the magnetic configurations to be tested in future devices
- Improve our fundamental understanding of boundary physics and detachment

Our approach

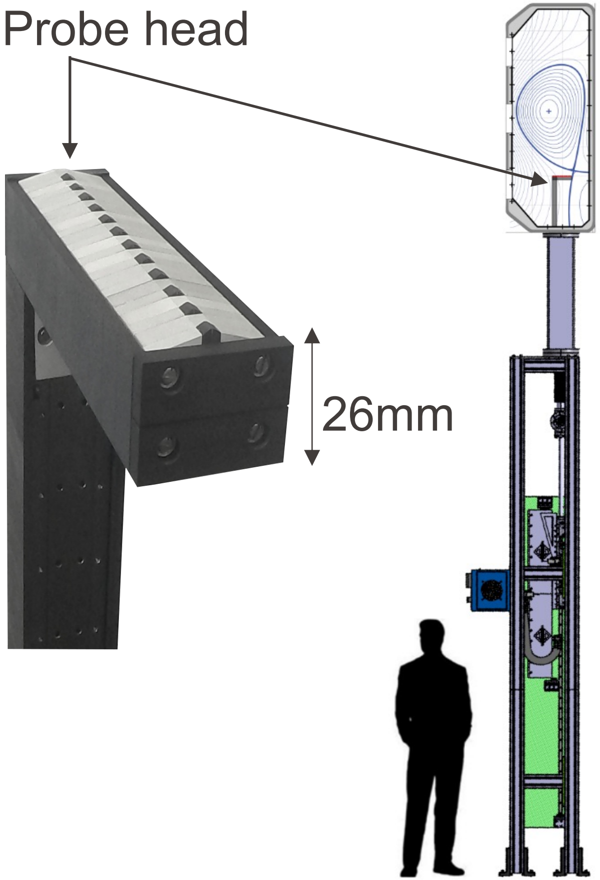
Development of new measurement devices (diagnostics)

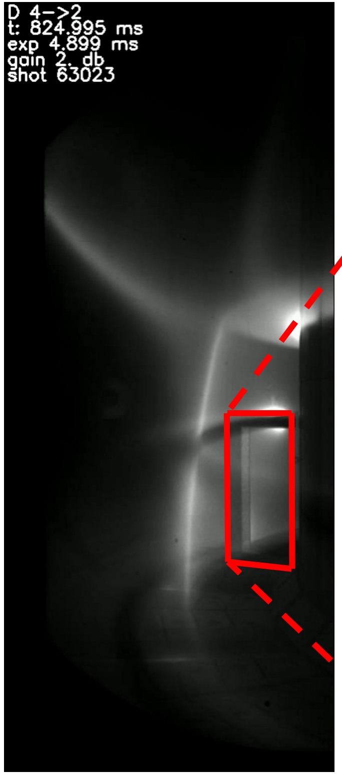
Heat exhaust experiments in alternative divertor configurations

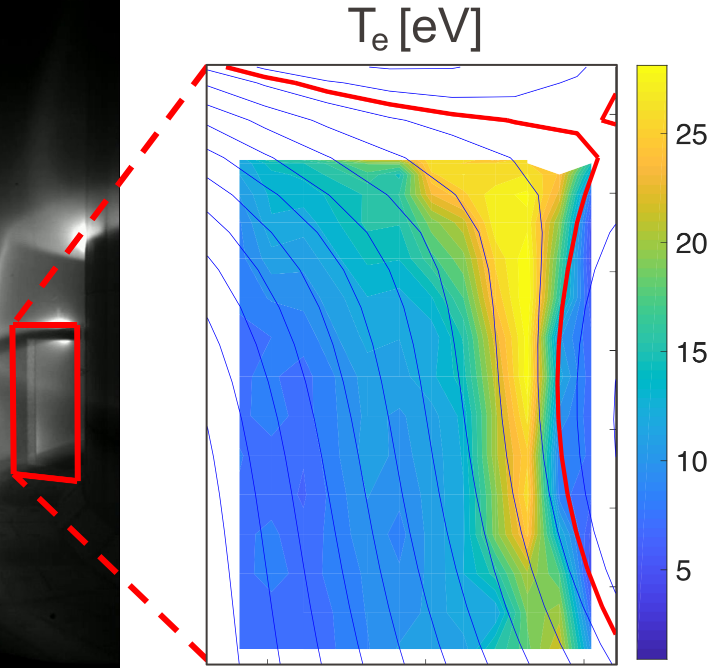
Experimental characterization of turbulence in the boundary plasma

Interpretation with and validation of state-of-the-art codes

Unprecedented 2D divertor probe measurements







[H. De Oliveira et al., Rev. Sci. Inst. 92, 043547 (2021)]
[H. De Oliveira et al., Nucl. Fusion 62, 096028 (2022)]

Unprecedented 2D divertor probe measurements

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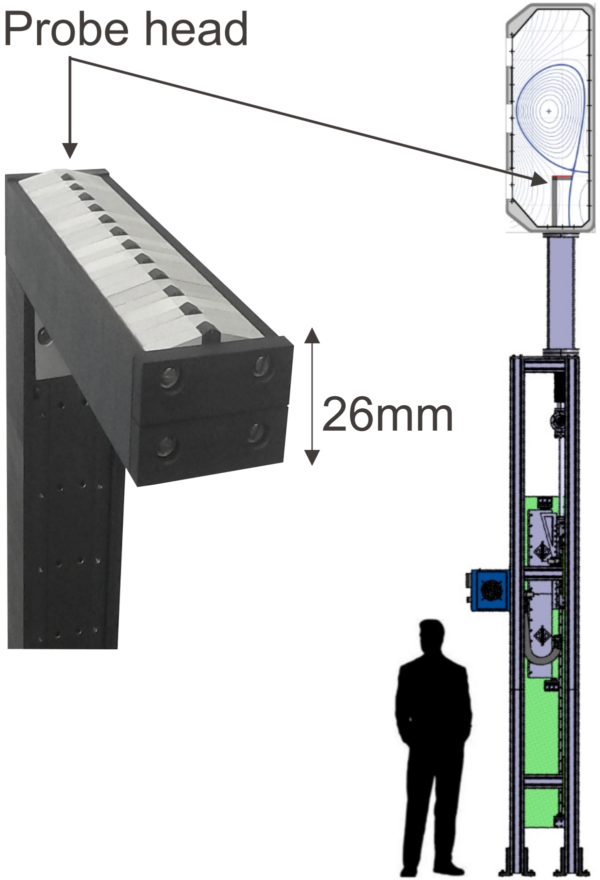

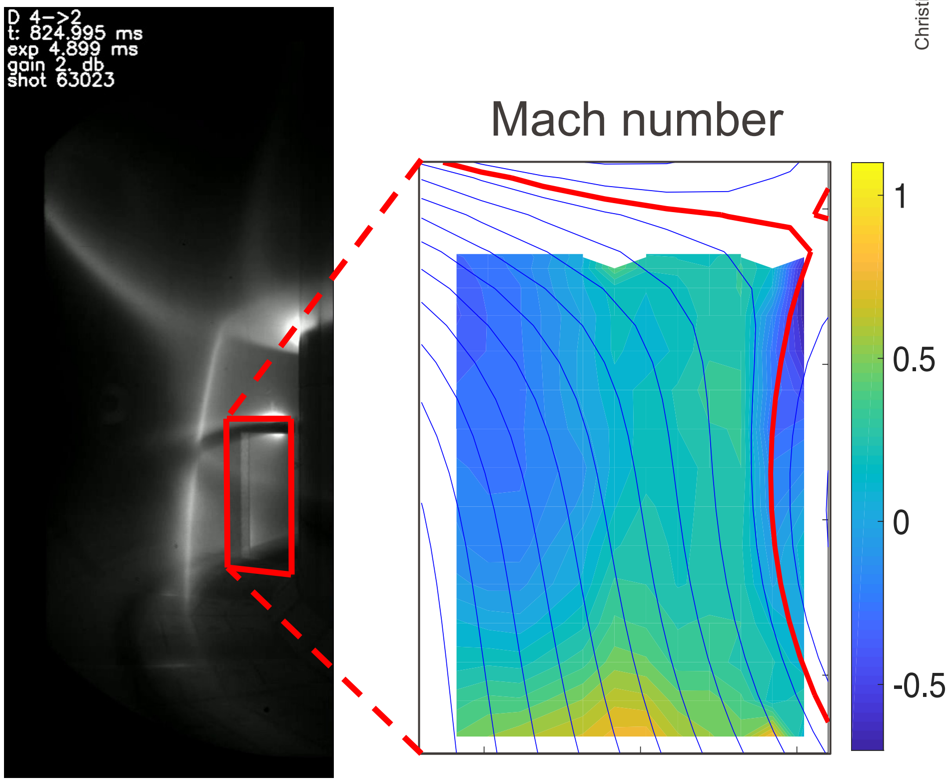

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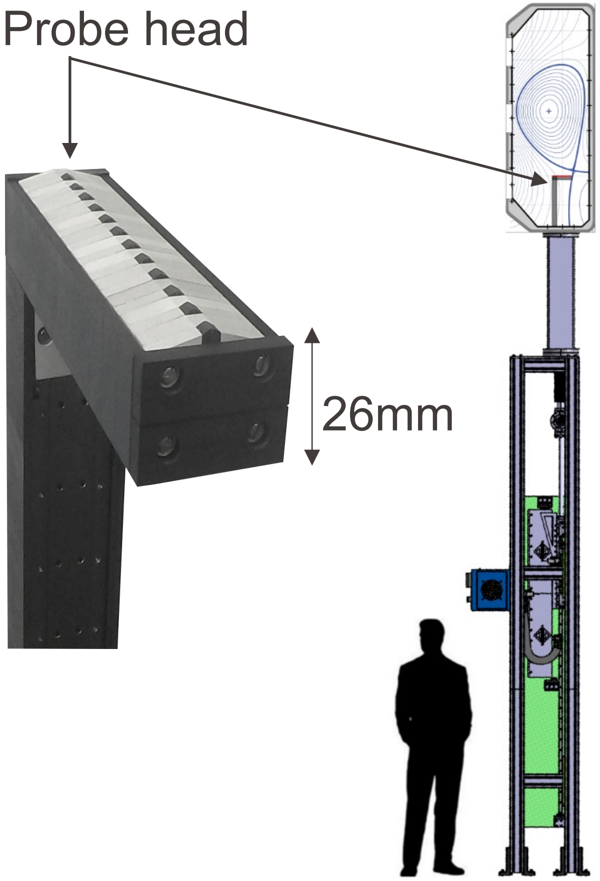

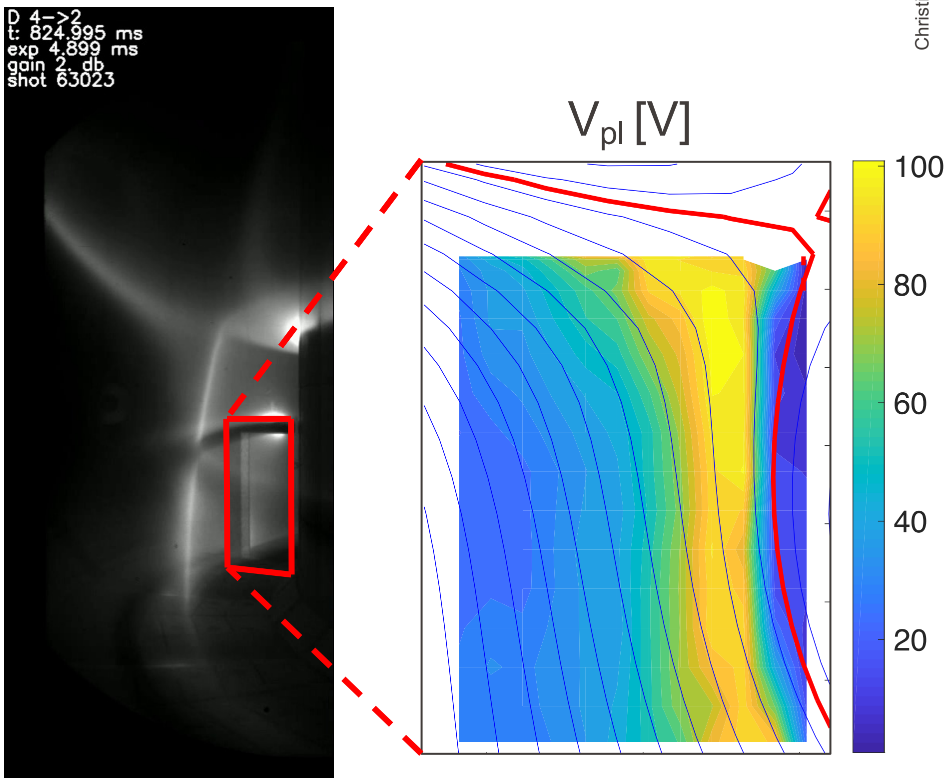

[H. De Oliveira et al., Rev. Sci. Inst. 92, 043547 (2021)]
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Heat exhaust experiments in alternative divertor configurations

Experimental characterization of turbulence in the boundary plasma

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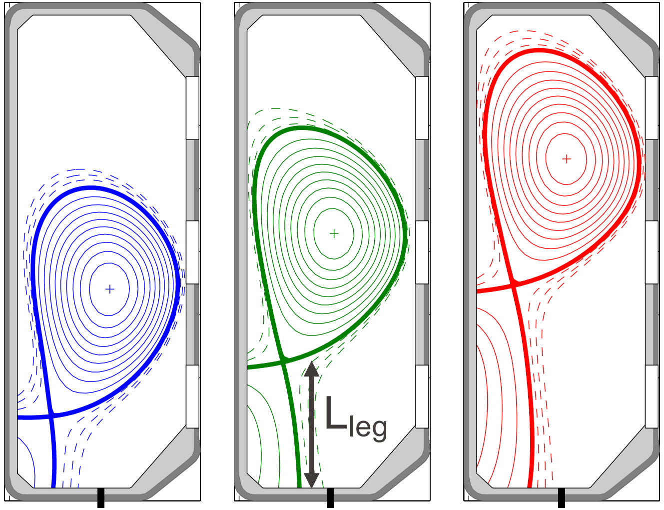
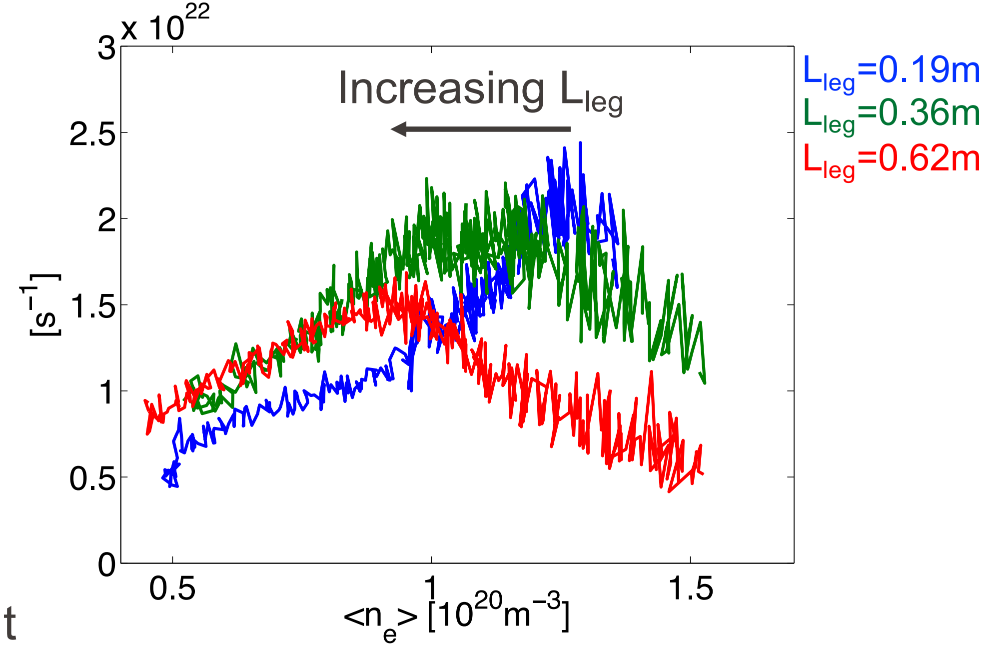
Increased leg length found to substantially reduce detachment threshold and increase window

- L-mode density ramps



Total ion flux to floor

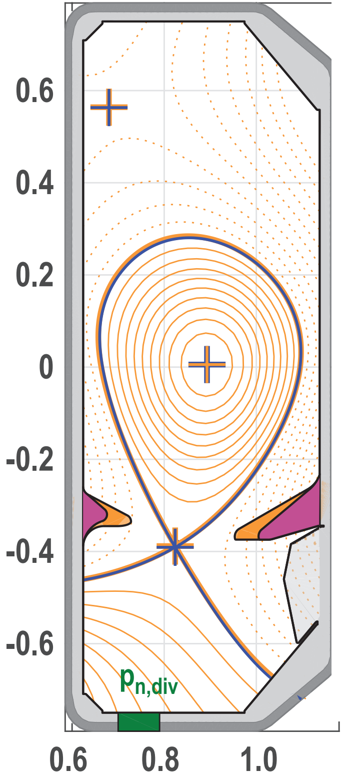


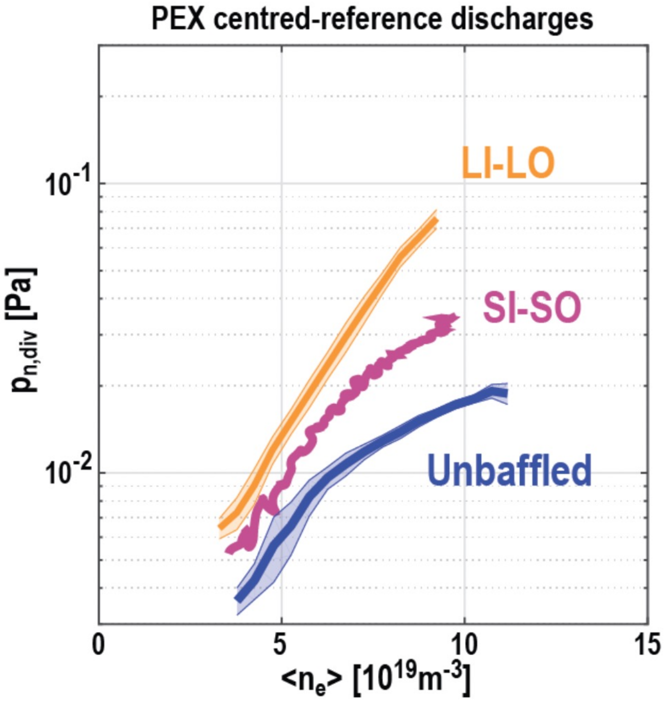
- ~30% reduction of detachment threshold density with increasing L_{leg}

[H. Reimerdes et al., Nucl. Fusion 57, 126007 (2017)]

Baffling increases divertor neutral pressure, reducing detachment threshold

L-mode density ramps

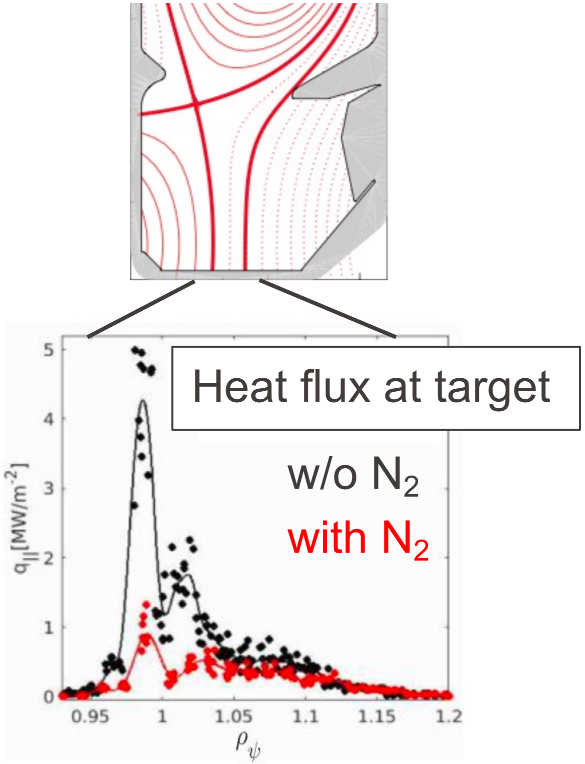




- Up to 5x increase in divertor p_n with baffles
- Up to a ~30% reduction in detachment threshold[1,2]

[1] O. Février et al., Nucl. Mater. Energy 27, 100977 (2021)
[2] H. Reimerdes et al., Nucl. Fusion 61, 0245002 (2021)]

Lower target heat fluxes in H-mode *X-* and *X-Point Target*



[H. Raj et al., Nucl. Fusion 62, 126035 (2022)]

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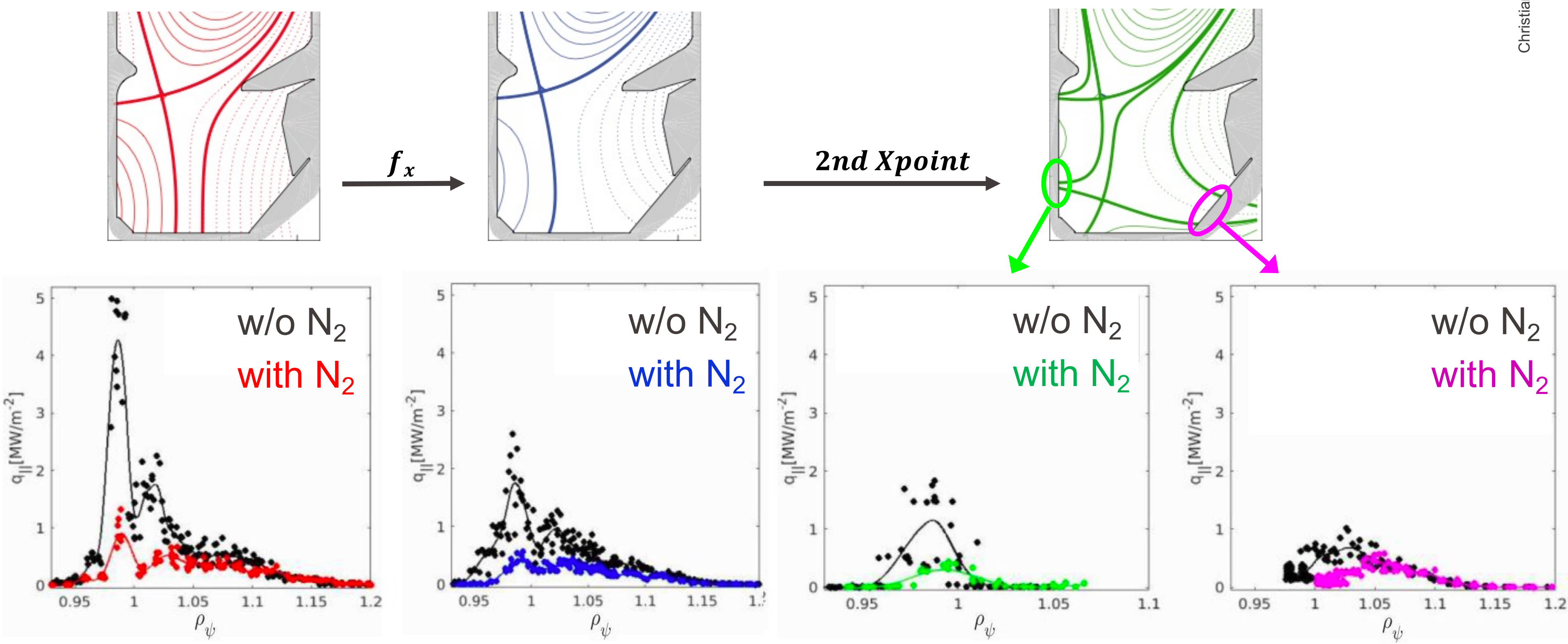
Lower target heat fluxes in H-mode *X-* and *X-Point Target*



➢ Benefits achieved without any compromise on the core plasma

[H. Raj et al., Nucl. Fusion 62, 126035 (2022)]

Our approach

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Development of new measurement devices (diagnostics)

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Suite of Gas Puff Imaging diagnostics for 2D SOL turbulence characterisation

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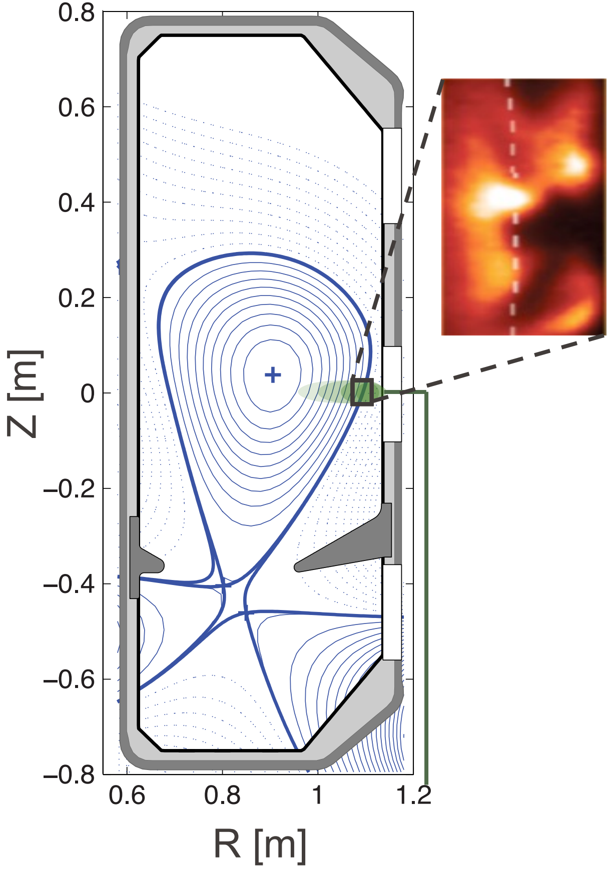
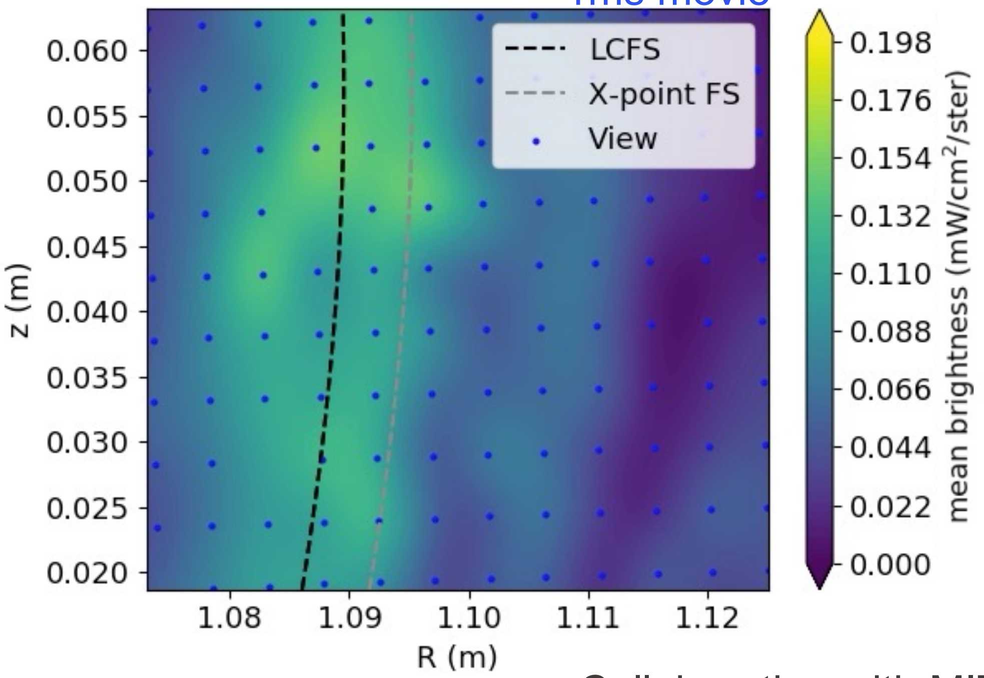


1ms movie



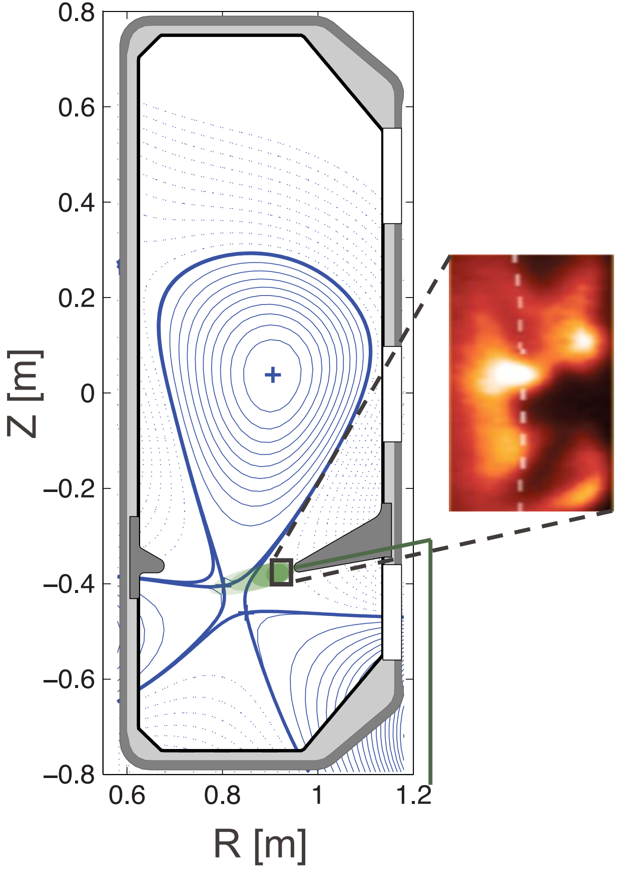
Collaboration with MIT

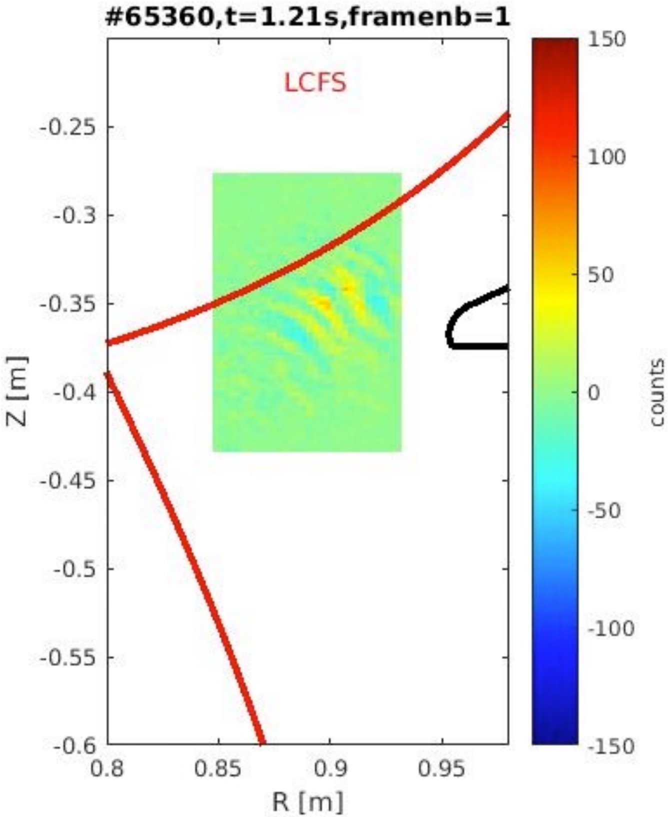
[N. Offeddu et al., Rev. Sci. Inst. 93, 123504 (2022)]

[N. Offeddu et al., Nucl. Fusion 62, 096014 (2022)]

Swiss Plasma Center

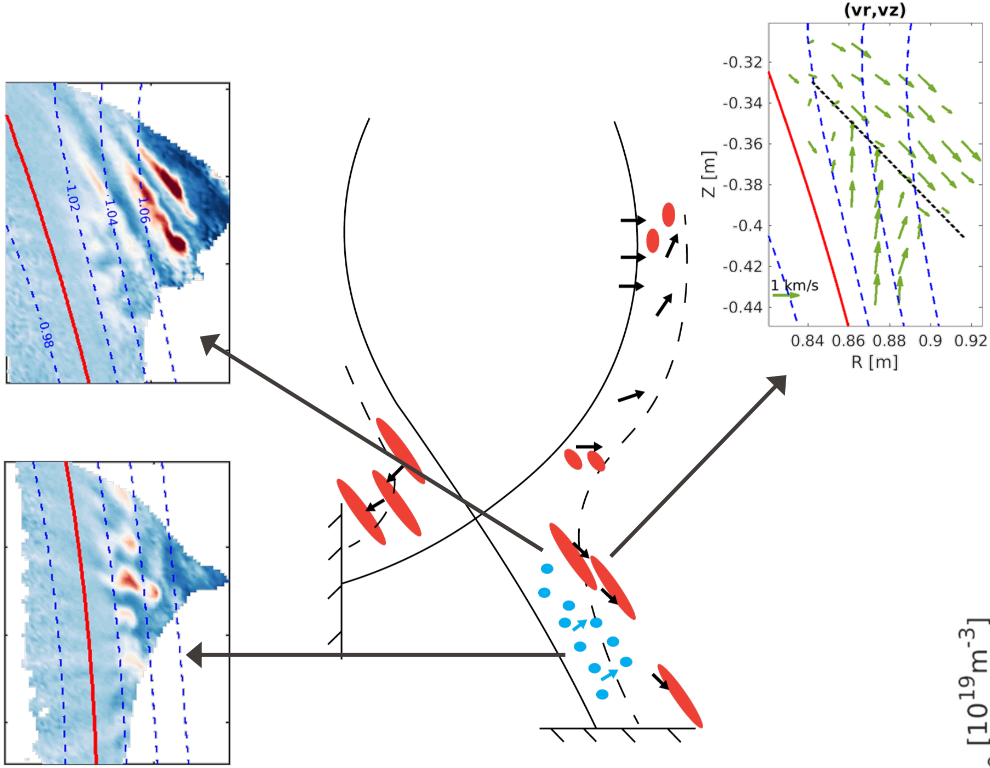
Suite of Gas Puff Imaging diagnostics for 2D SOL turbulence characterisation



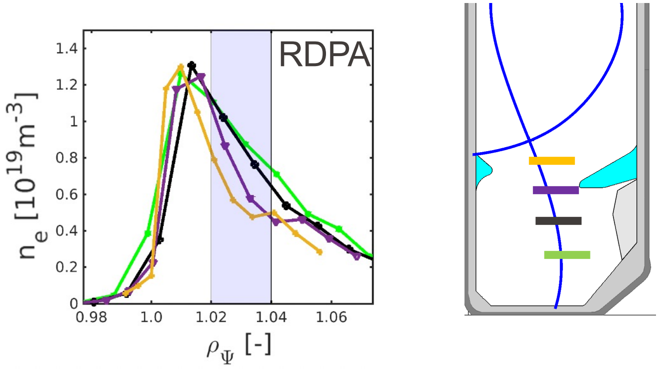


[C. Wüthrich et al., Nucl. Fusion 62, 106022 (2022)]

Characterisation of divertor fluctuations



- Different filament types have different flow pattern, yet similar v_r (~400m/s)
- Divertor blobs estimated to contribute significantly to profile broadening[1]
- Consistent with profile broadening measured along leg[1]



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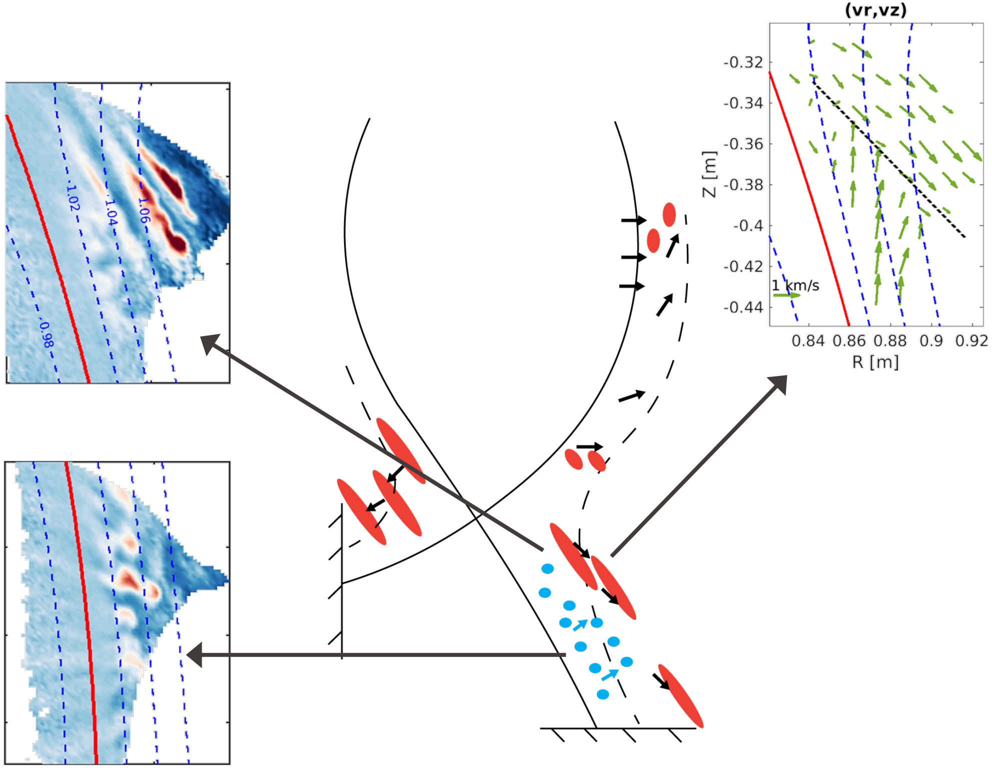

- Different filament types have different flow pattern, yet similar v_r (~400m/s)
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- Consistent with profile broadening measured along leg[1]

Key questions: How do fluctuations and associated transport vary with divertor geometry?

[C. Wüthrich et al., Nucl. Fusion 62, 106022 (2022)]

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Development of new measurement devices (diagnostics)

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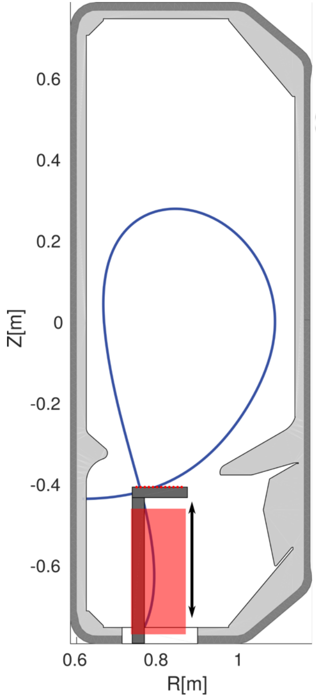
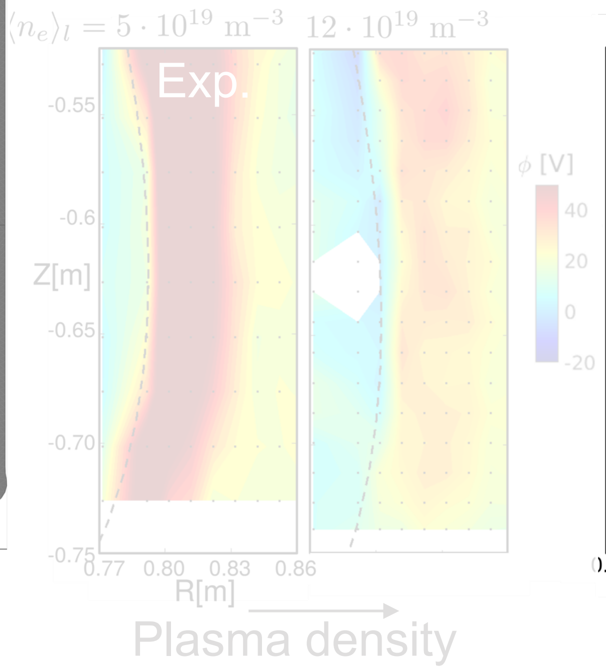
Experimental characterization of turbulence in the boundary plasma

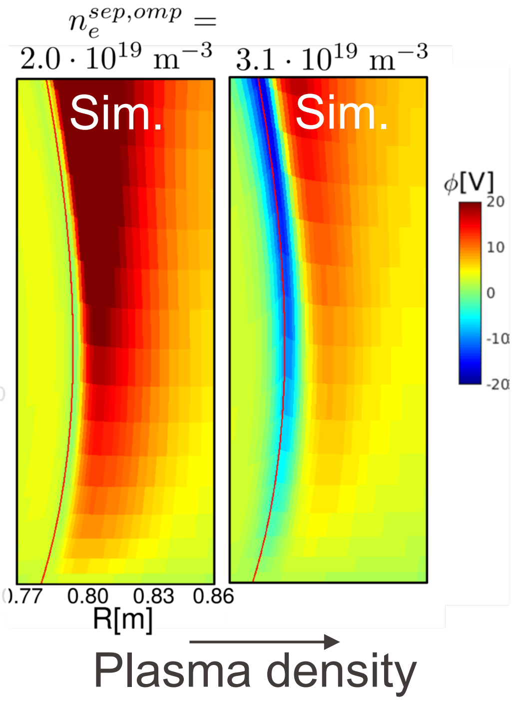
Interpretation with and validation of state-of-the-art codes

Interpretation with and validation of edge transport codes

Experimental confirmation of complex electric potential structure in divertor predicted by the SOLPS-ITER code







[M. Wensing, H. De Oliveira et al., Nucl. Mater. Energy 25, 100839 (2020)]

Interpretation with and validation of edge transport codes

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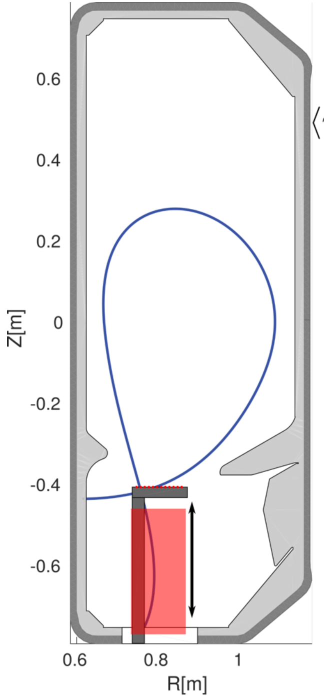
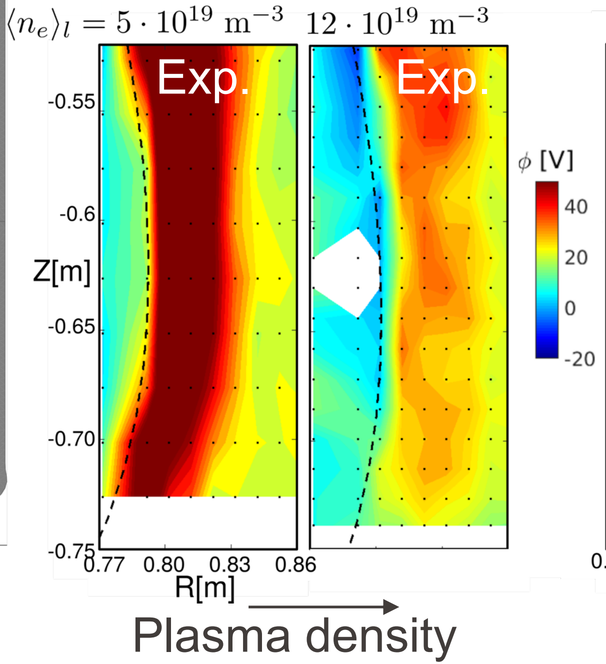
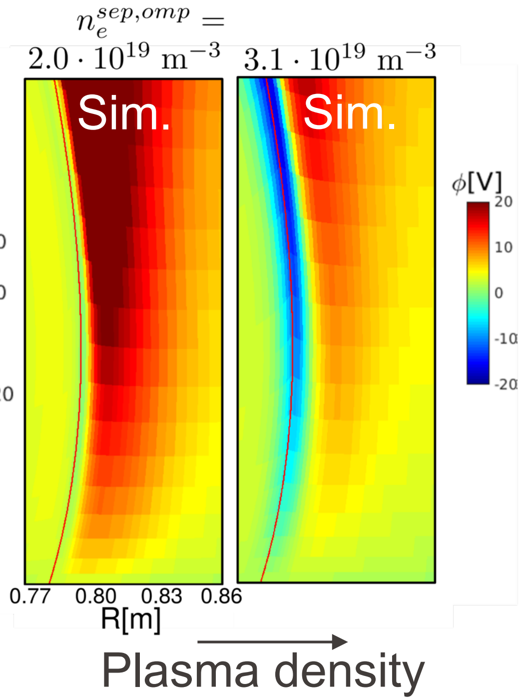
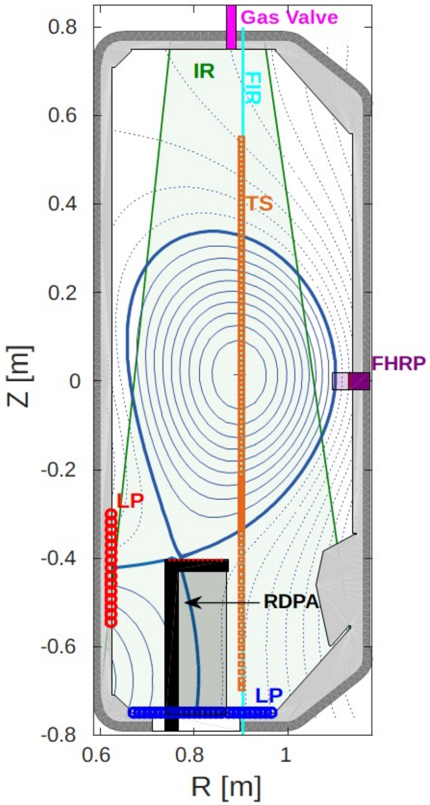






[M. Wensing, H. De Oliveira et al., Nucl. Mater. Energy 25, 100839 (2020)]

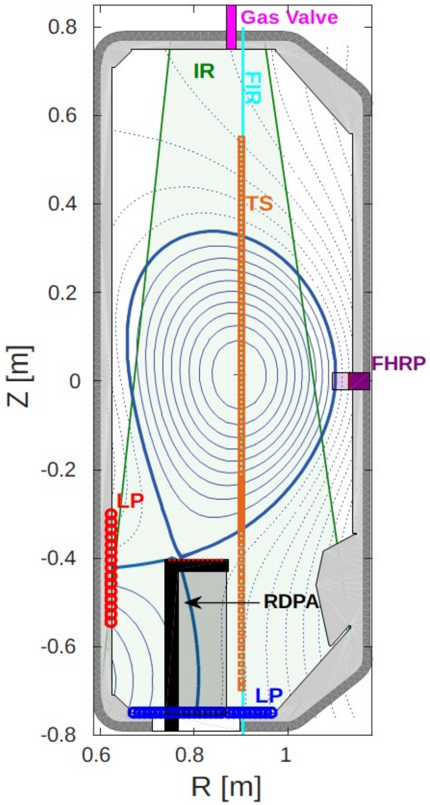
First full size turbulence simulations of TCV diverted plasma and comparison with the experiment

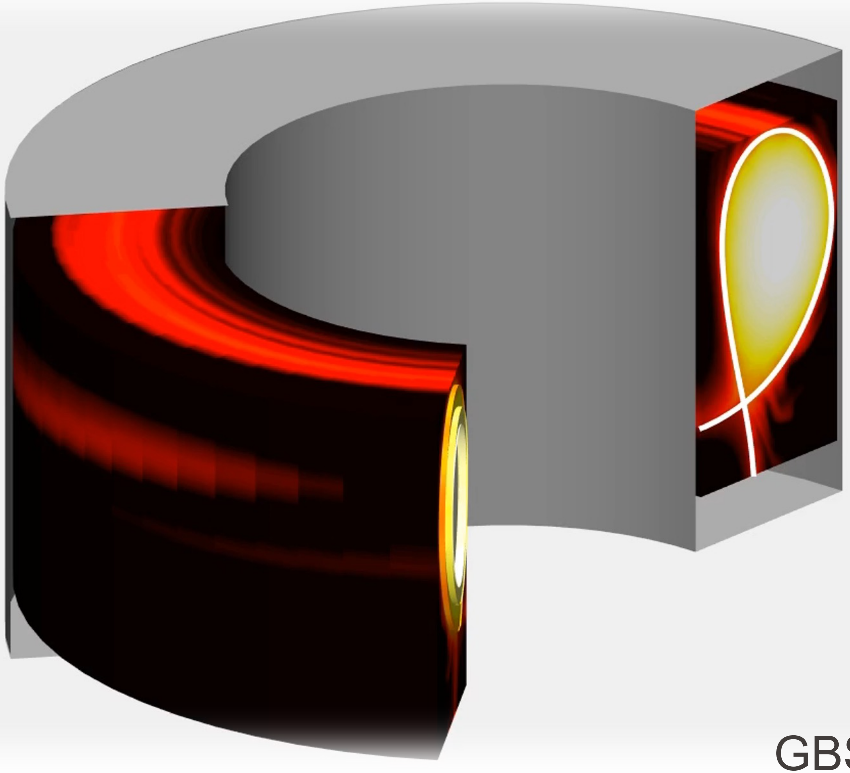


- Plasma ran at reduced magnetic field to reduce computational costs
- Diagnosed with a wide range of diagnostics $\longrightarrow$ 45 different observables; **all data** is **publicly available** for future code validation studies
- Simulations performed with three state-of-the-art turbulence codes: GBS (EPFL), GRILLIX (MPG), Tokam3X (CEA)

[D. S. Oliveira, T. Body et al., Nucl. Fusion 62, 096001 (2022)]

First full size turbulence simulations of TCV diverted plasma and comparison with the experiment





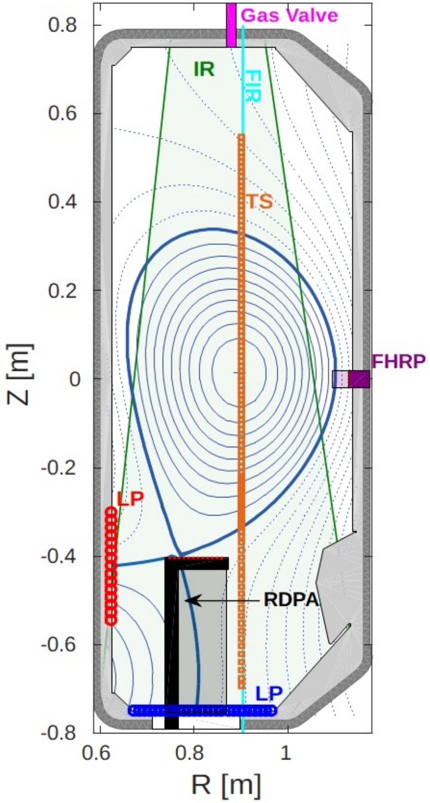
GBS simulation

Visualisation by M. Giacomin

Swiss Plasma Center

Christian Theiler

First full size turbulence simulations of TCV diverted plasma and comparison with the experiment



Key results of the detailed exp-sim comparison

- Generally good sim-exp agreement near the main plasma (profile shapes, fluctuation levels,…)
- Poorer agreement in the divertor volume and near the wall, with significant deviations also among the different codes
- Number of follow-up studies ongoing to improve agreement, by us and by other groups, on the way towards fully predictive boundary modellling

EPFL

Concluding remarks

- Alternative divertor magnetic geometries have the potential to substantially alleviate the heat exhaust challenge
- Experiments and extrapolation through validated modelling constitutes a viable path to take the step from proof-of-principle demonstration to developing an optimal divertor solution
- TCV is an ideal device for this research
    - High flexibility and accessibility
    - Broad local expertise at SPC (TCV team, theory, modelling, small-scale devices,…)
    - Fully embedded in the EUROfusion program

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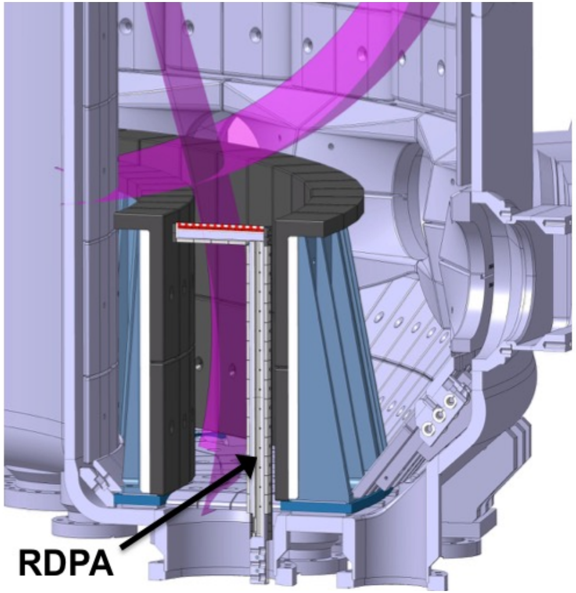
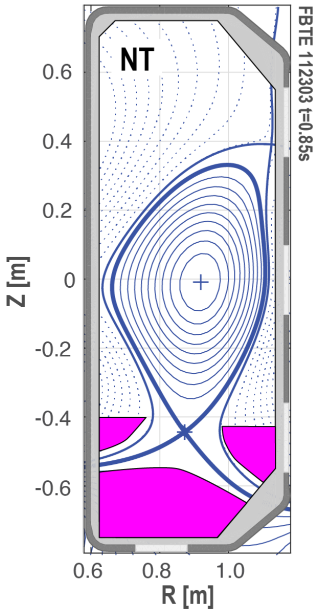
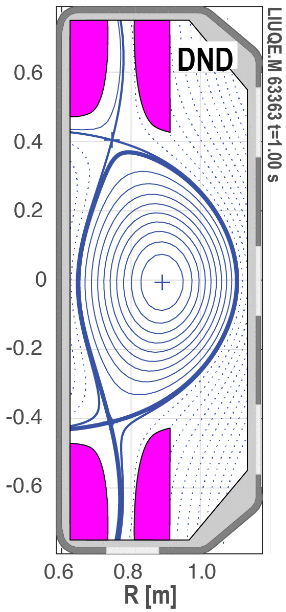
Outlook: Extension of TCV's experimental capabilities

- Test new concept of a tightly-baffled, long-legged divertor in next TCV upgrade

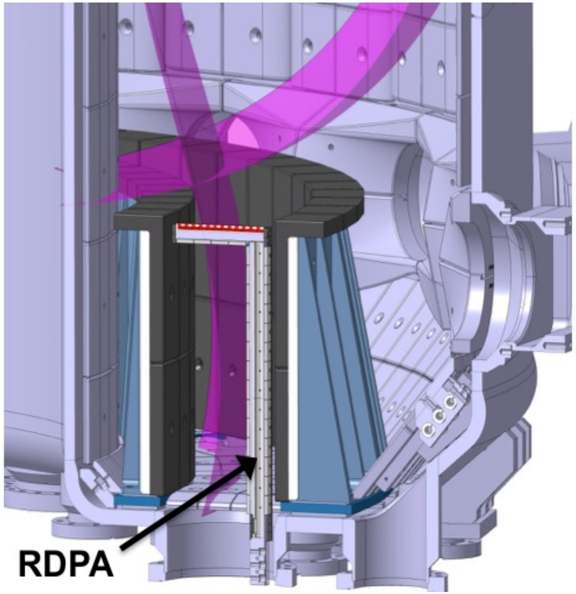






Outlook: Extension of TCV's experimental capabilities

2026: Develop validated physics basis of the concept



2028: Full integration with optimized core solution