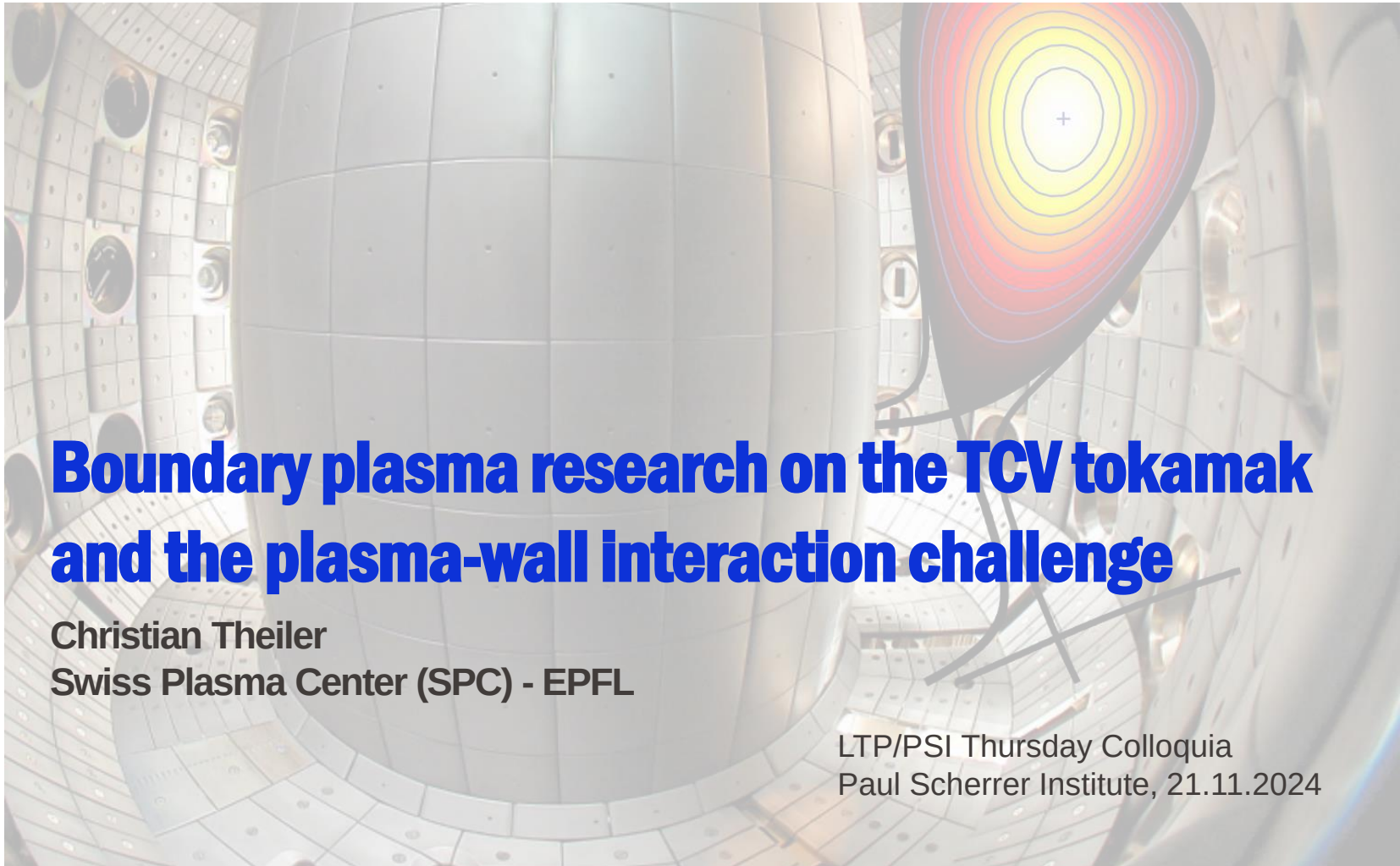
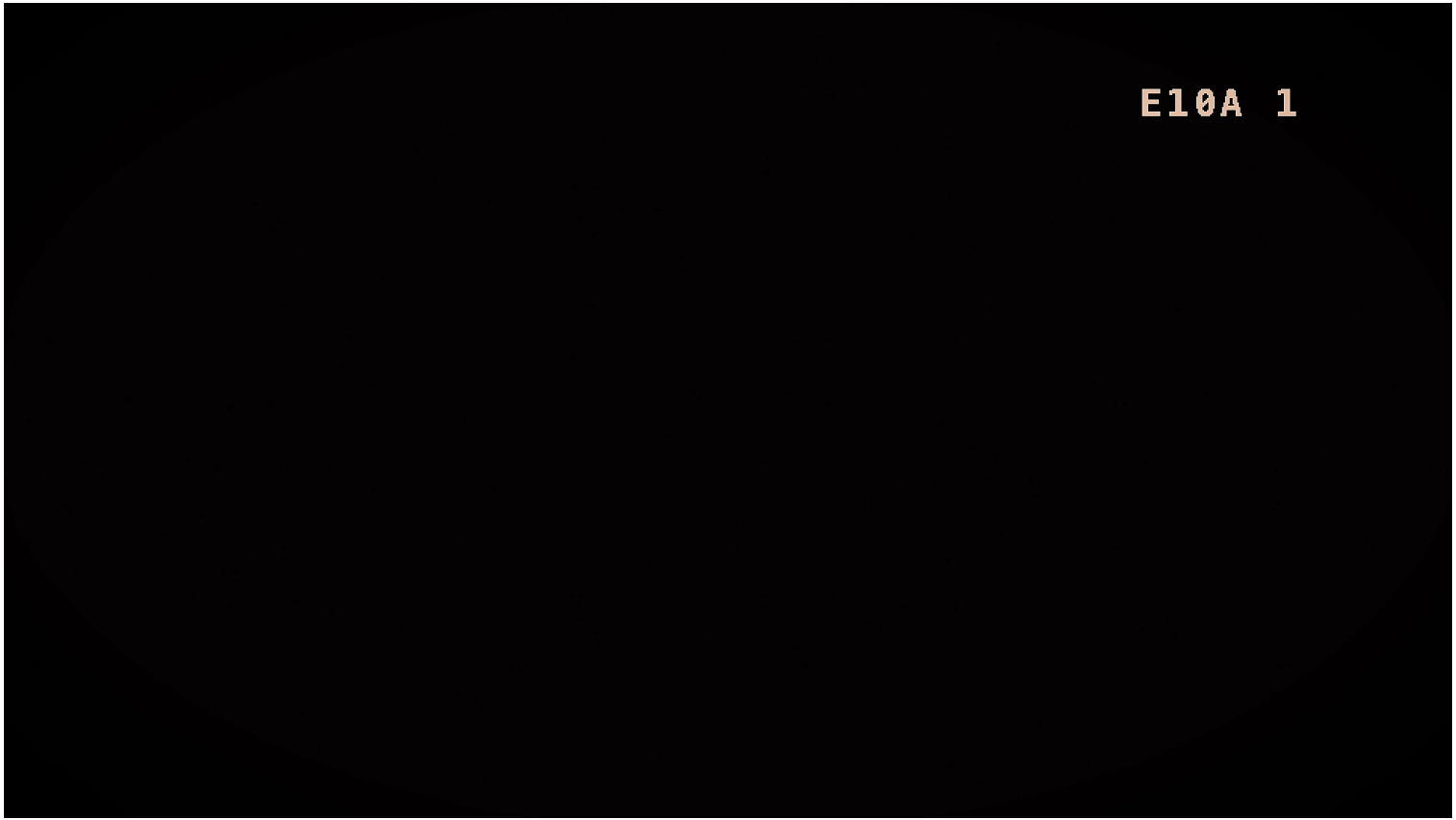


# Boundary plasma research on the TCV tokamak and the plasma-wall interaction challenge

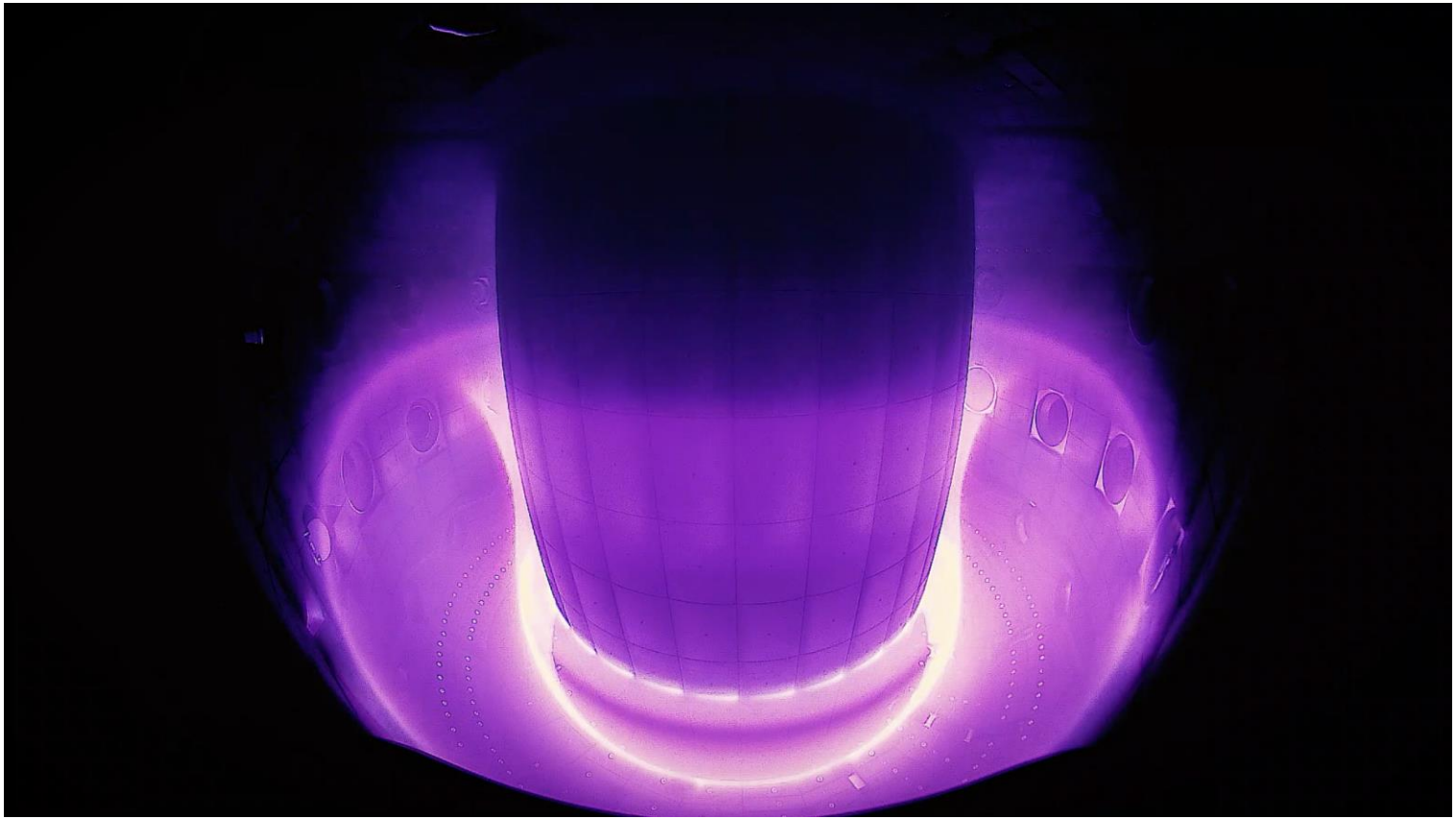
**Christian Theiler**
**Swiss Plasma Center (SPC) - EPFL**

LTP/PSI Thursday Colloquia
Paul Scherrer Institute, 21.11.2024

Swiss Plasma Center

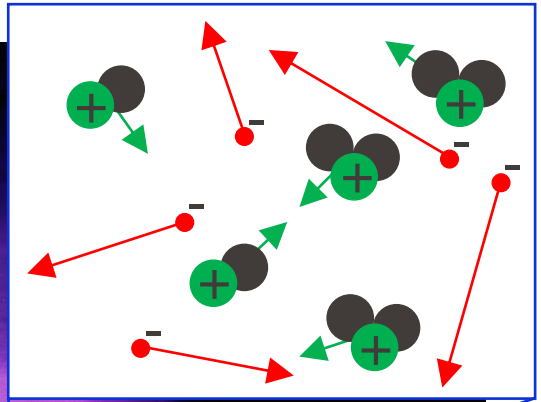



Video by C. Wüthrich



Video by C. Wüthrich

# Plasma

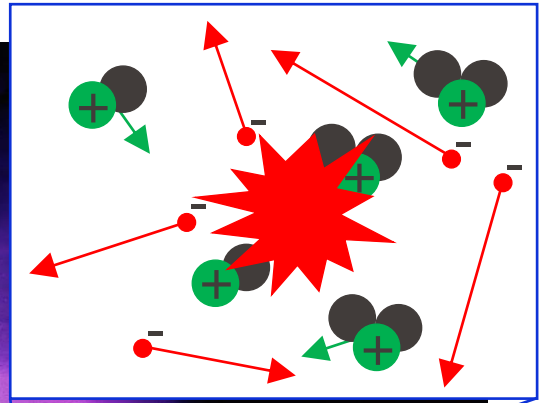




Video by C. Wüthrich

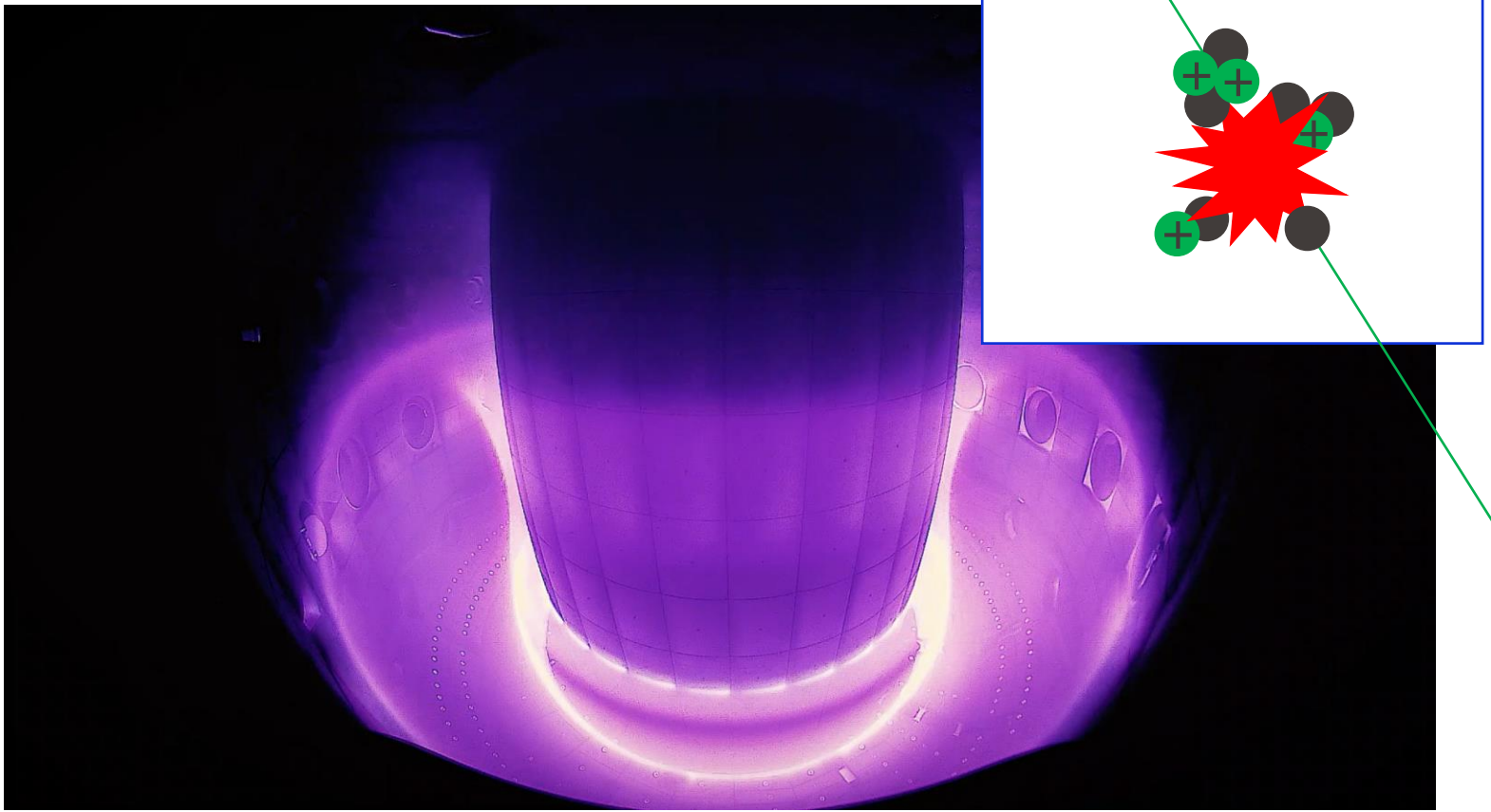
Christian Theiler

# Plasma



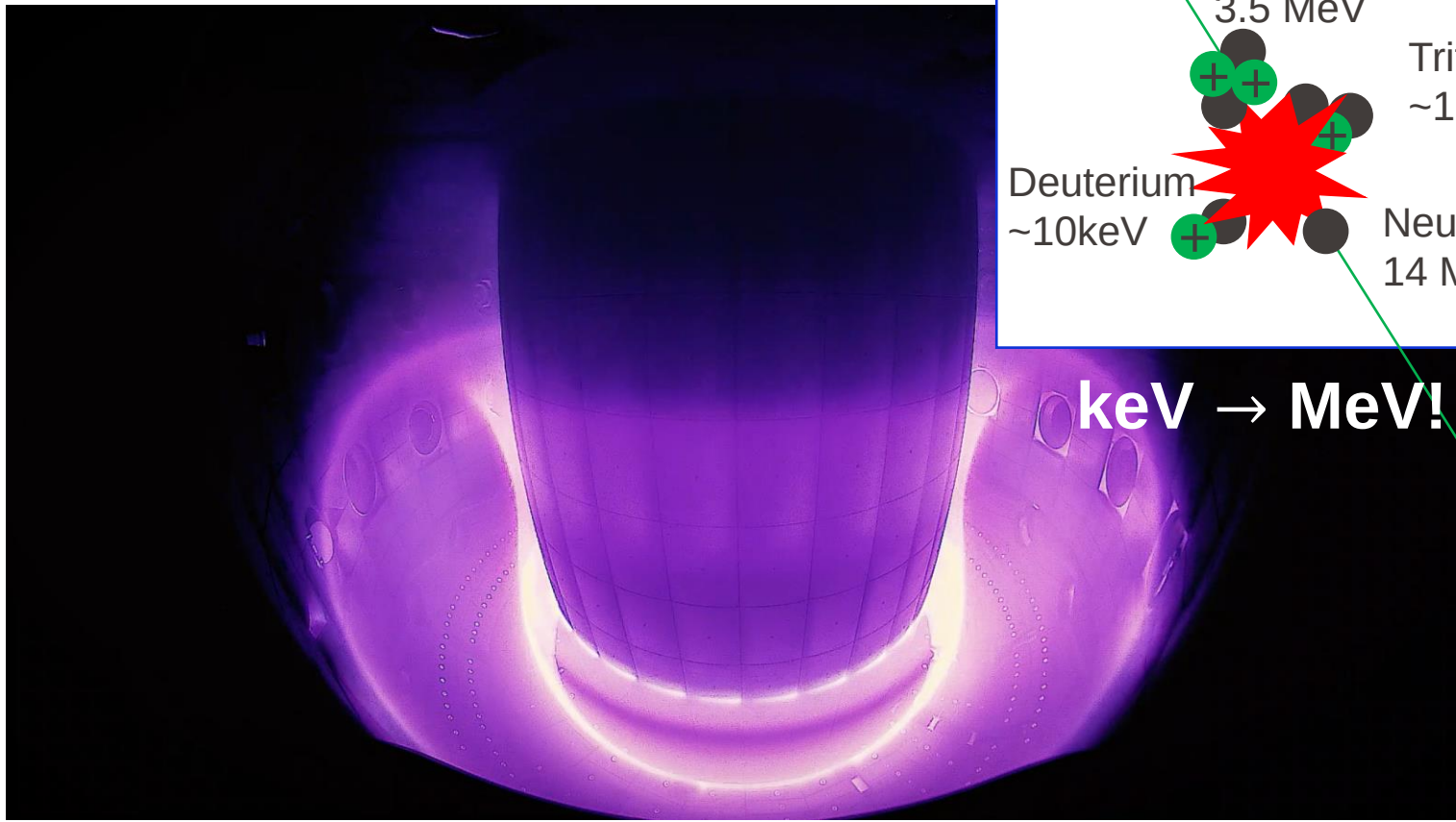
Video by C. Wüthrich

Christian Theiler

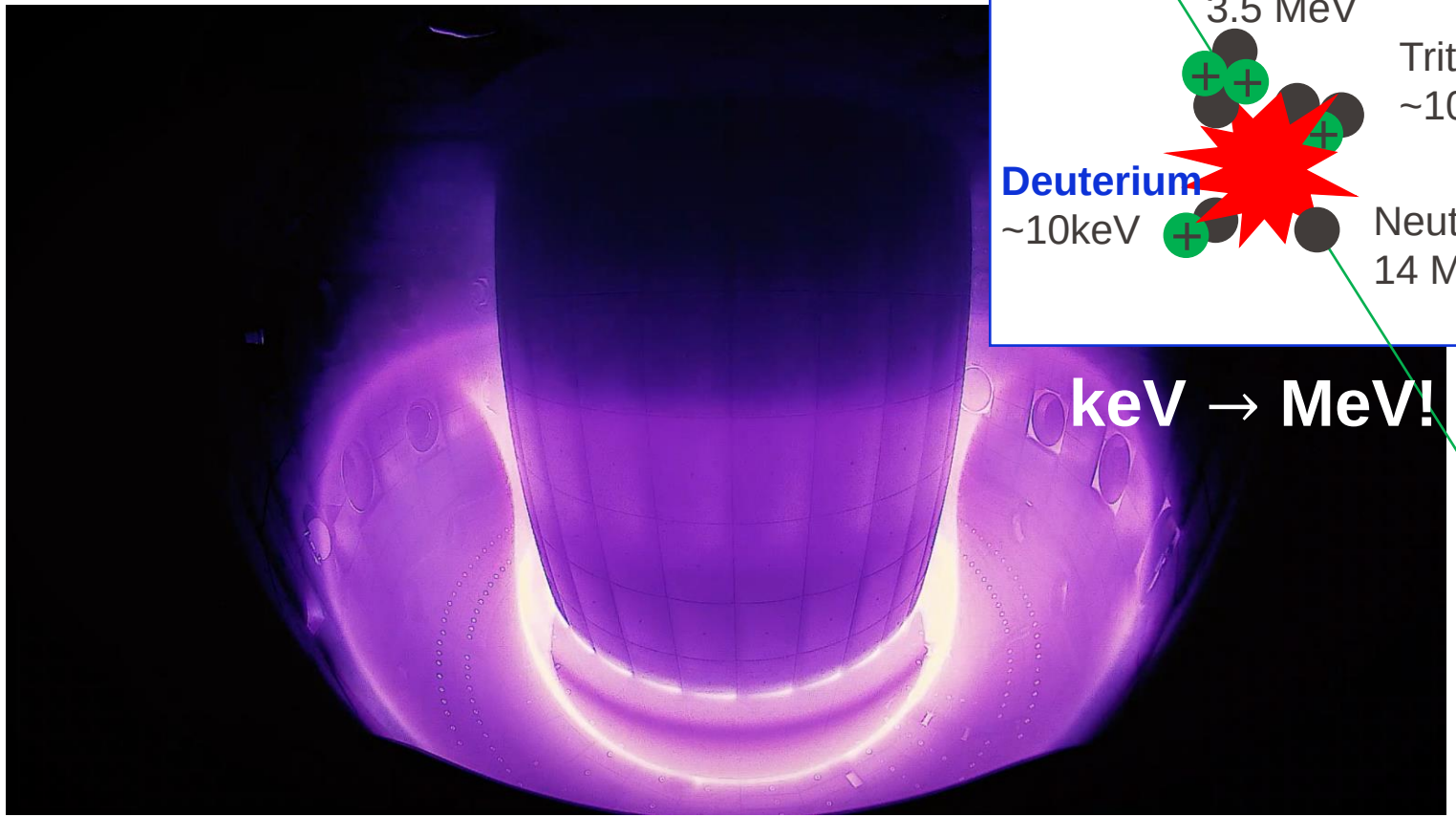




Video by C. Wüthrich




Video by C. Wüthrich



Helium
3.5 MeV

Tritium
~10keV

**Deuterium**
~10keV

Neutron
14 MeV

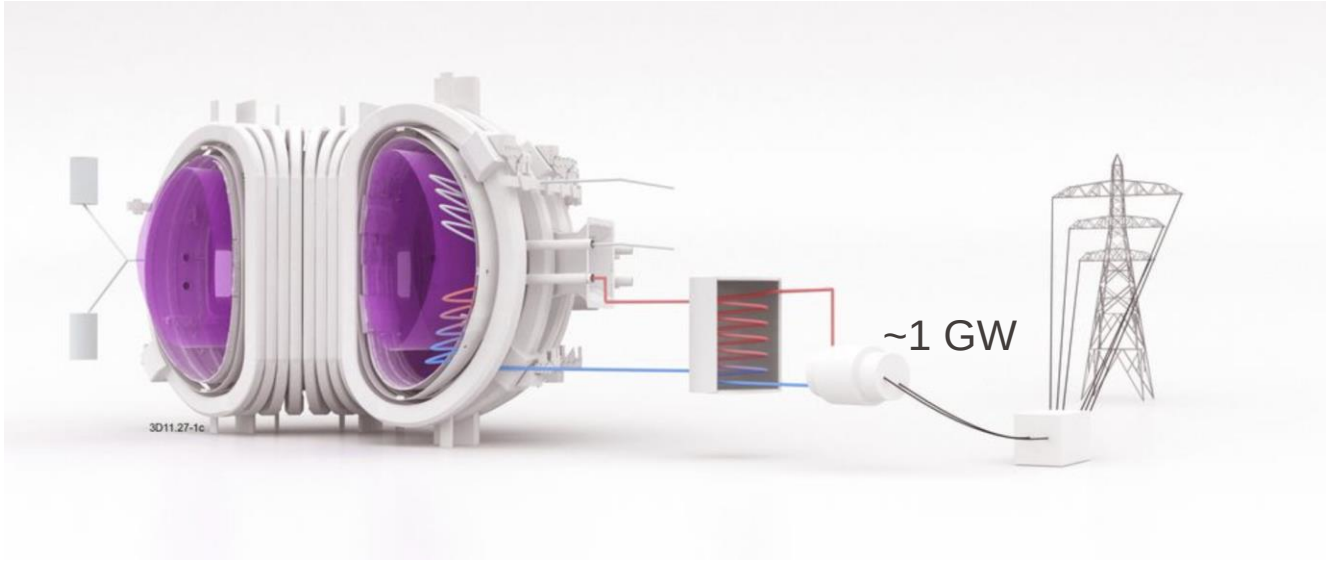
**keV → MeV!**

**$^{6}$Li**
↓
$^{4}$He + T

Video by C. Wüthrich

# The fusion energy quest

The goal of the worldwide fusion research effort is to master fusion on earth and to develop a safe, clean and essentially inexhaustible source for baseload electricity



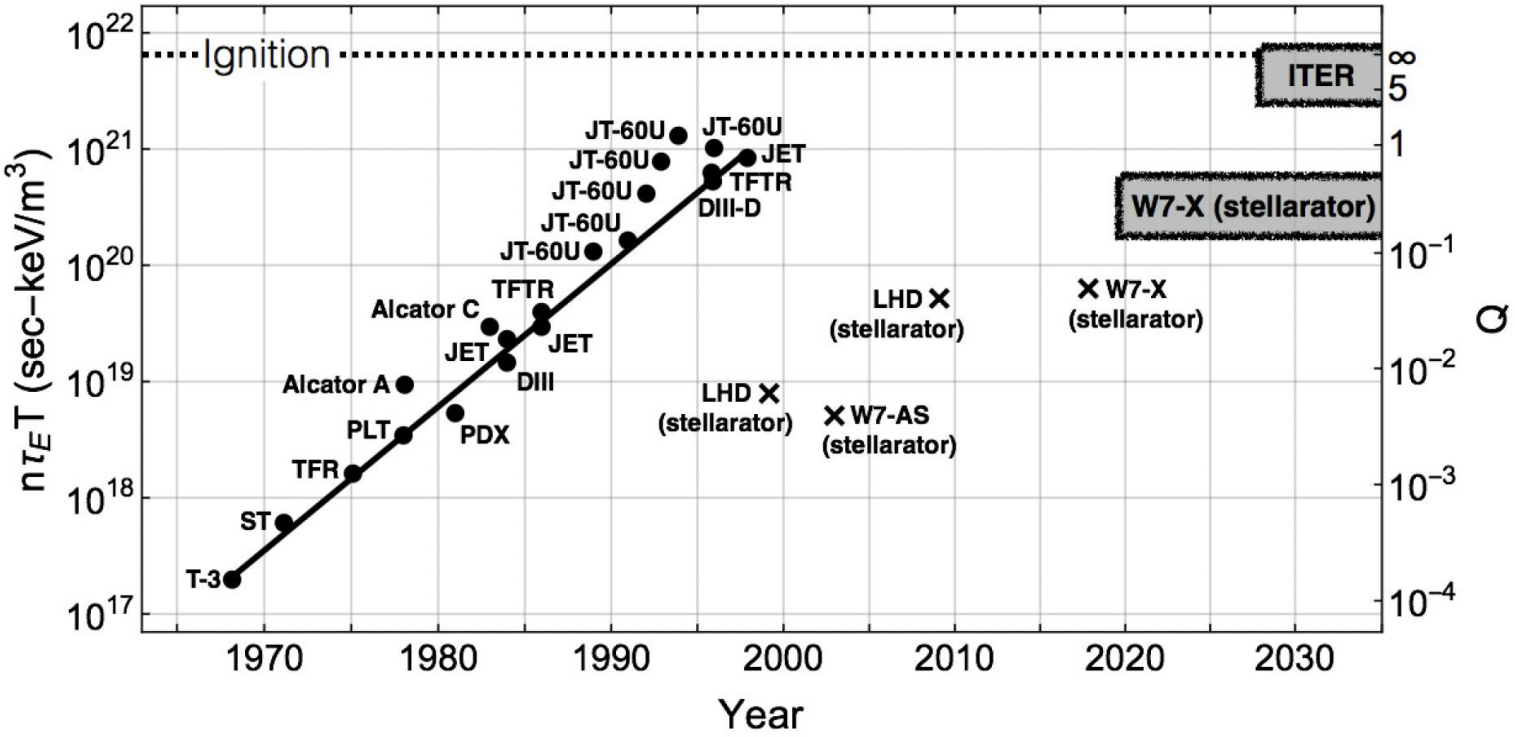
# The fusion energy quest

The goal of the worldwide fusion research effort is to master fusion on earth and to develop a safe, clean and essentially inexhaustible source for baseload electricity

- Reaction can be stopped at any time
- Reactor components activated for ~10-100 years only
- No $CO_2$ production
- Constant power, minimum land use
- Fuel reserves for thousands of years; essentially inexhaustible with Li from seawater or for DD-fusion
- …

Christian Theiler

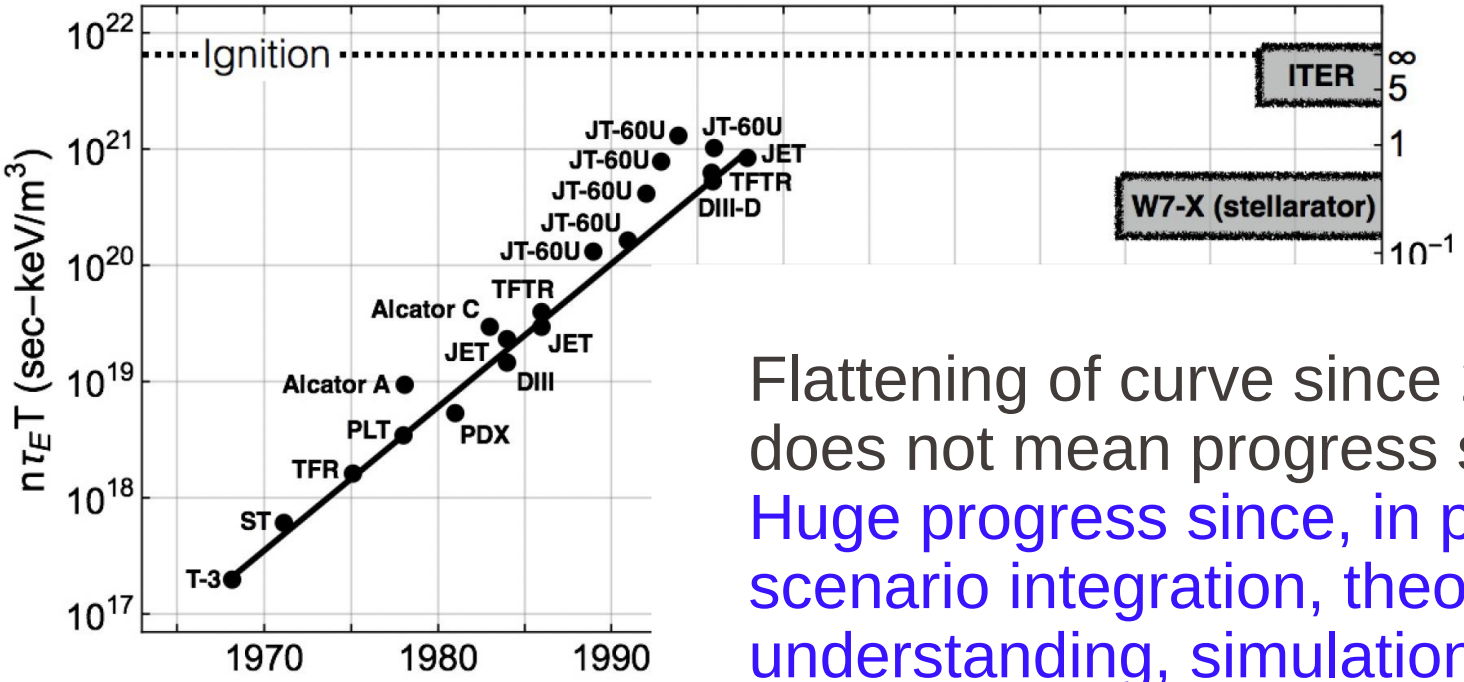
# Past progress in performance parameter $n\tau_E T$ (fusion "triple product")




Parisi and Ball, "*The Future of Fusion Energy*", World Scientific 2019

Christian Theiler

# Past progress in performance parameter $n\tau_E T$ (fusion "triple product")

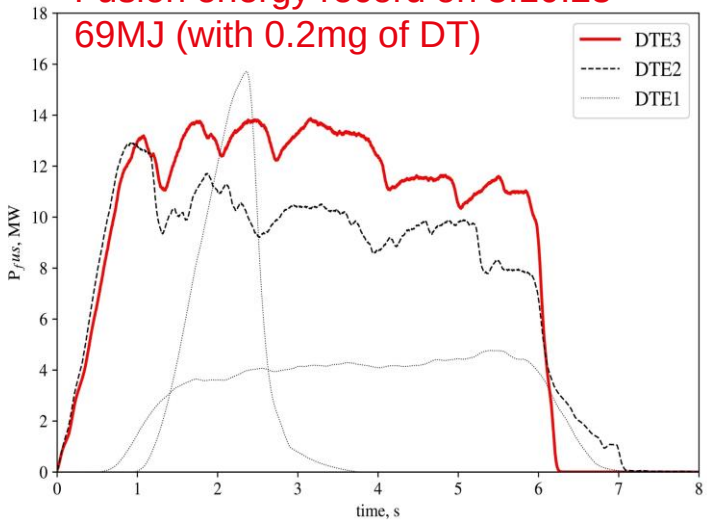



Flattening of curve since 2000 does not mean progress stalled!
Huge progress since, in plasma scenario integration, theoretical understanding, simulations, control, engineering,…

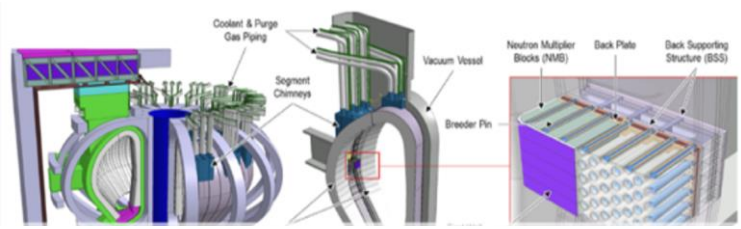
# Fusion is taking a more and more visible role world wide

Results: JET DT, NIF

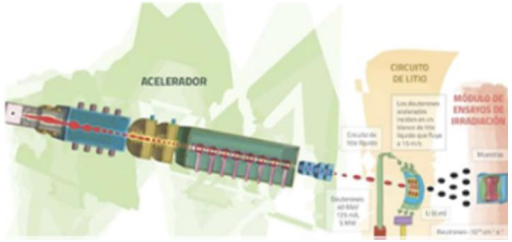
Fusion energy record on 3.10.23
69MJ (with 0.2mg of DT)



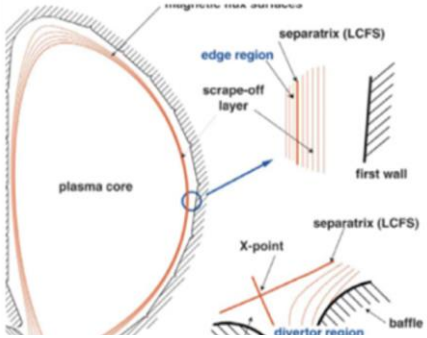

# Yet, challenges remain



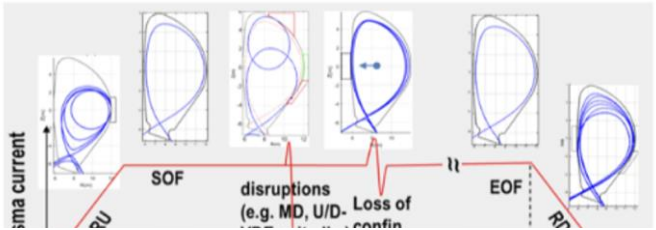

Tritium and blanket technologies



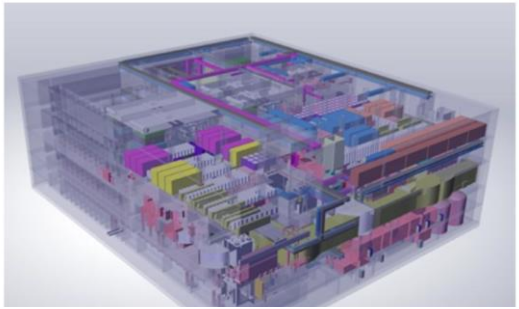

Materials



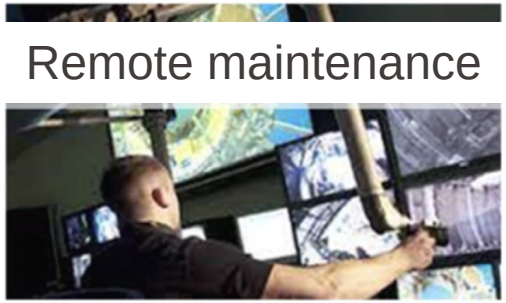

Divertor performance, power exhaust and extraction




Integrated plasma scenario



Safety and waste



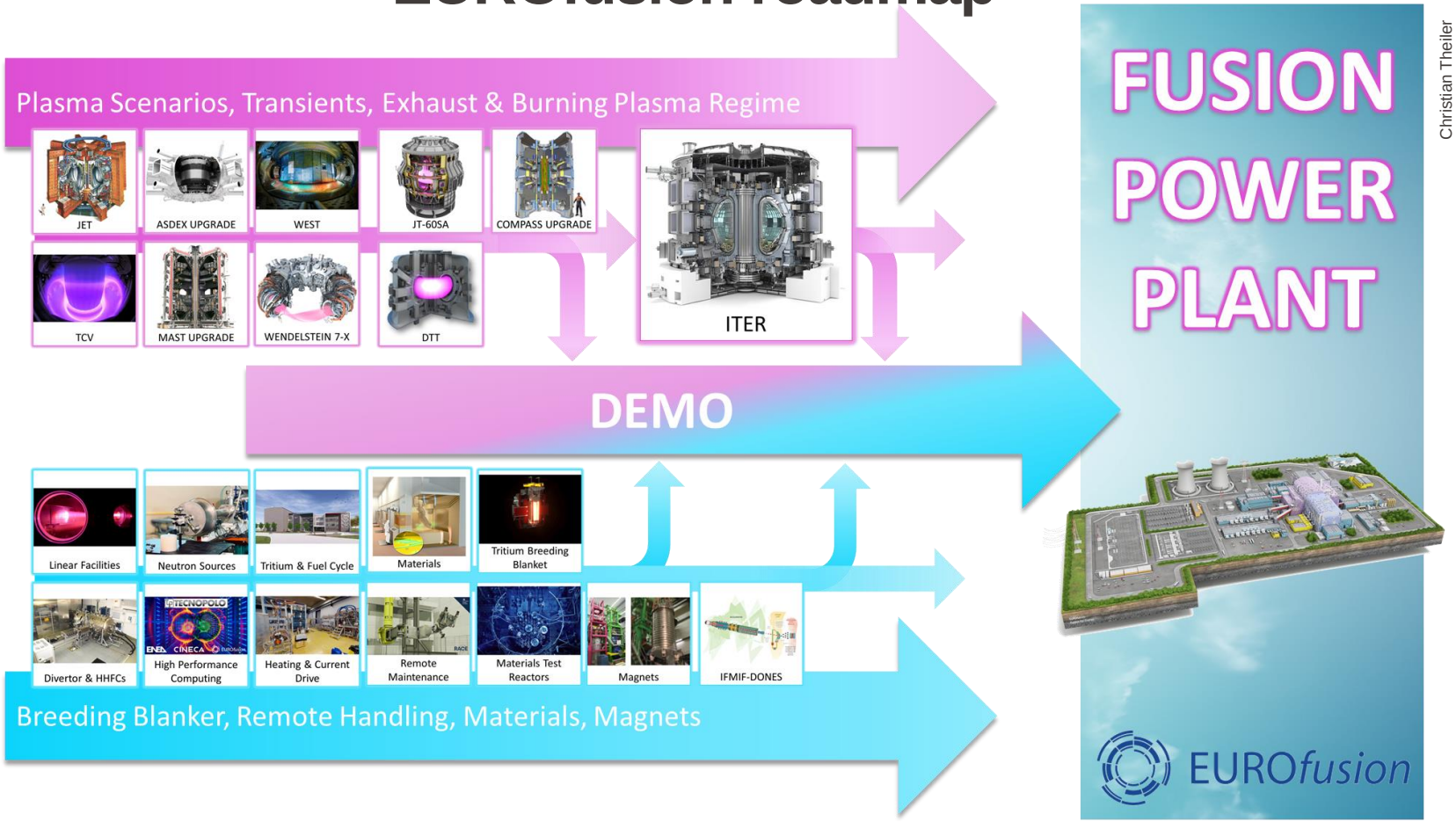
Remote maintenance



Fasoli, “Essay: Overcoming the obstacles to a magnetic fusion power plant“, PRL 2023

# EUROfusion roadmap

Christian Theiler

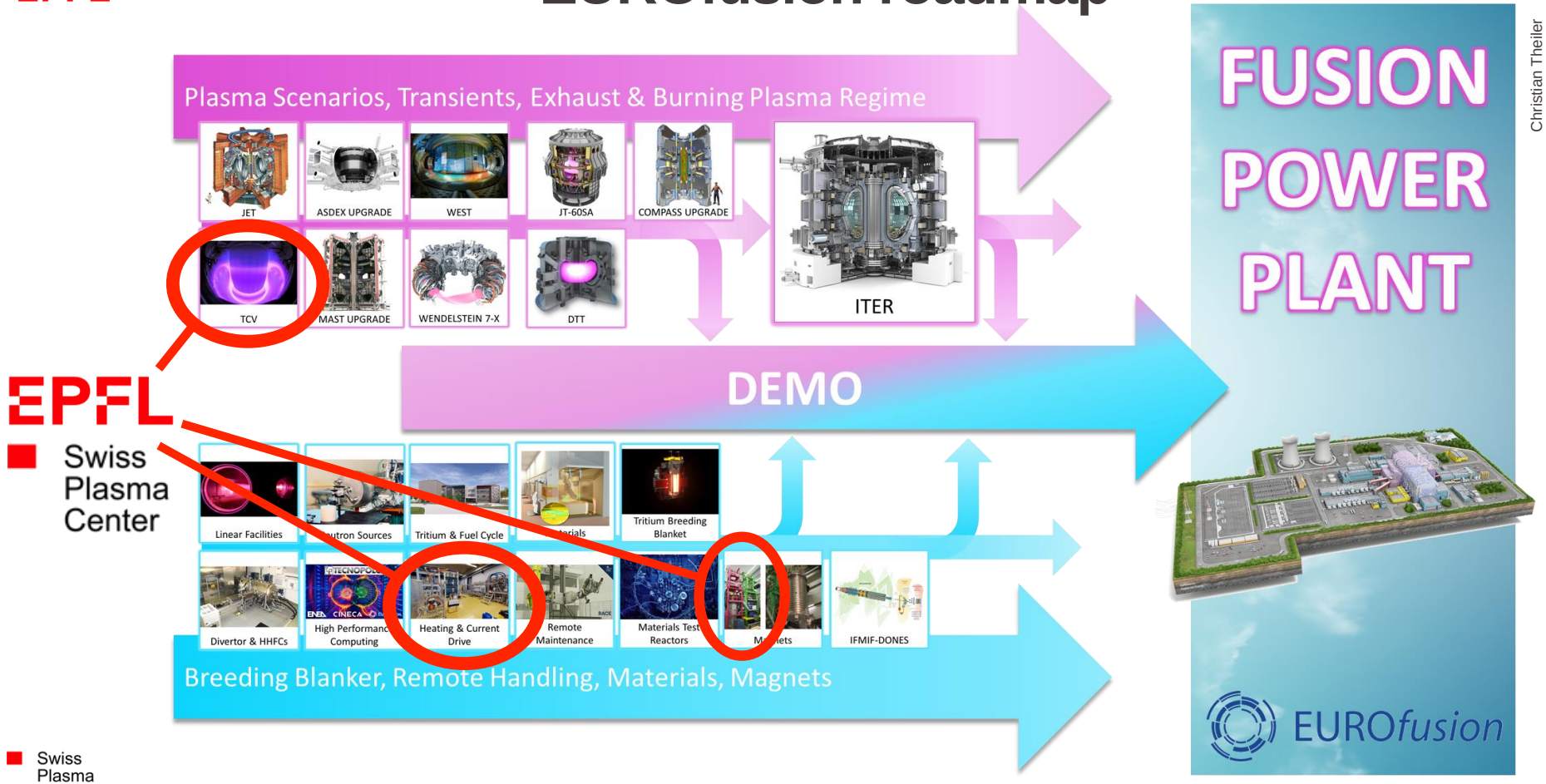





Fasoli et al., "*New approach to the European Roadmap to fusion energy*", to be published

# EUROfusion roadmap

Christian Theiler

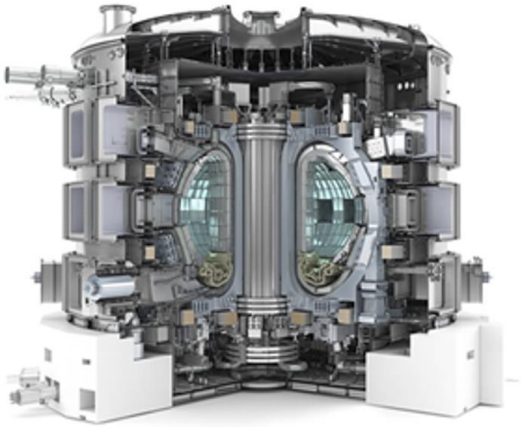



EPFL Swiss Plasma Center

Swiss Plasma Center

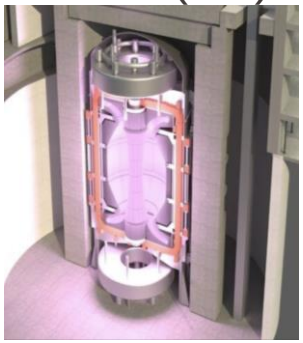
Fasoli et al., "*New approach to the European Roadmap to fusion energy*", to be published

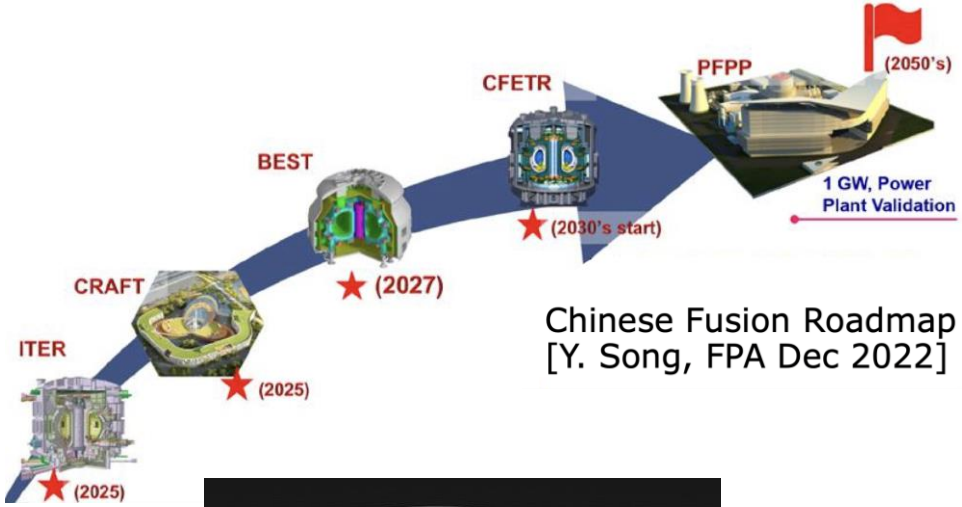
# Key initiatives worldwide (magnetic fusion only)



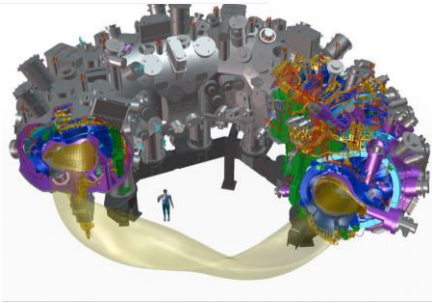
ITER

STEP (UK)

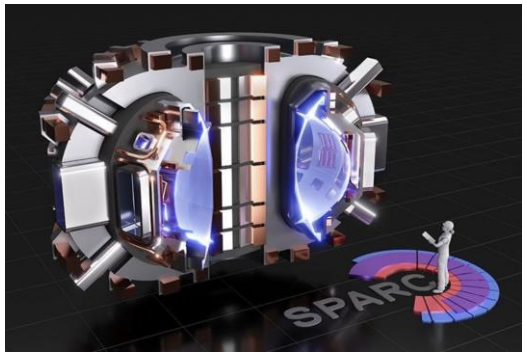





Chinese Fusion Roadmap
[Y. Song, FPA Dec 2022]



Stellarators (W7-X)



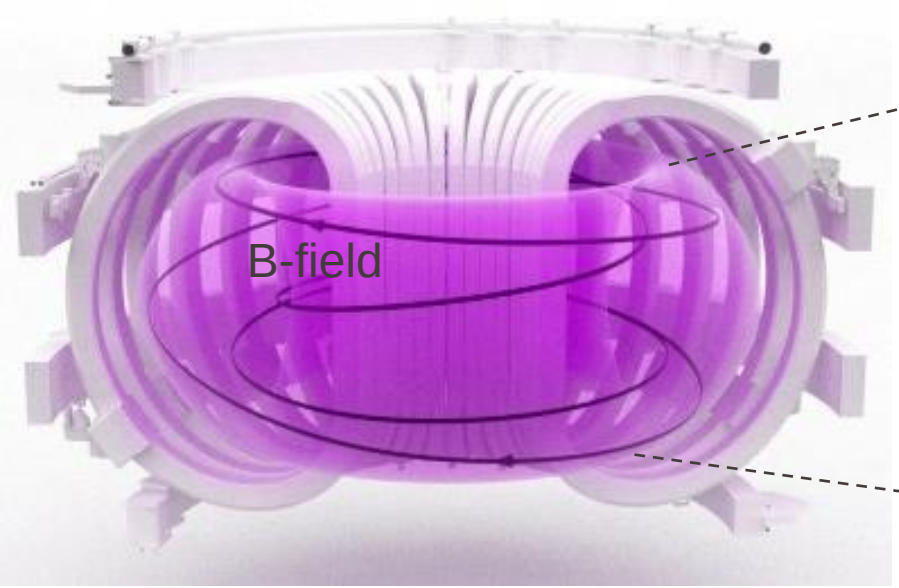

Private initiatives

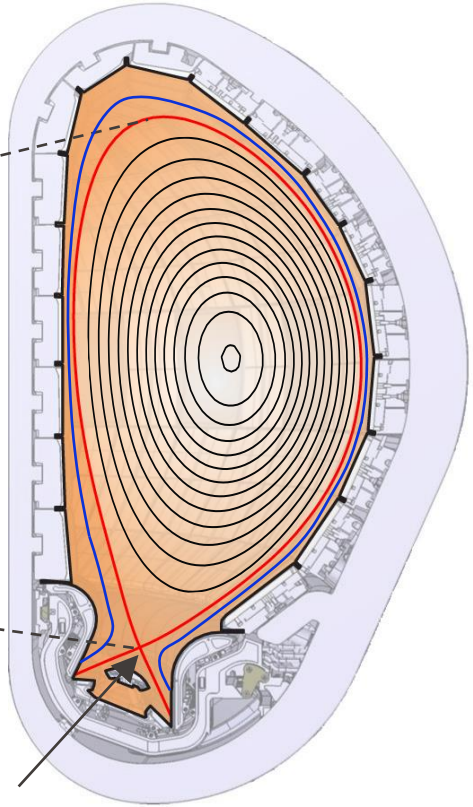


See e.g. Theiler et al., "*State of fusion technology and main actors*", Ch. 10 of SFOE report on Technology Monitoring of Nuclear Energy – 01.07.2024, available online: https://www.bfe.admin.ch/bfe/de/home/versorgung/kernenergie/aufgaben-des-bfe.html

# Complexity and importance of the boundary plasma





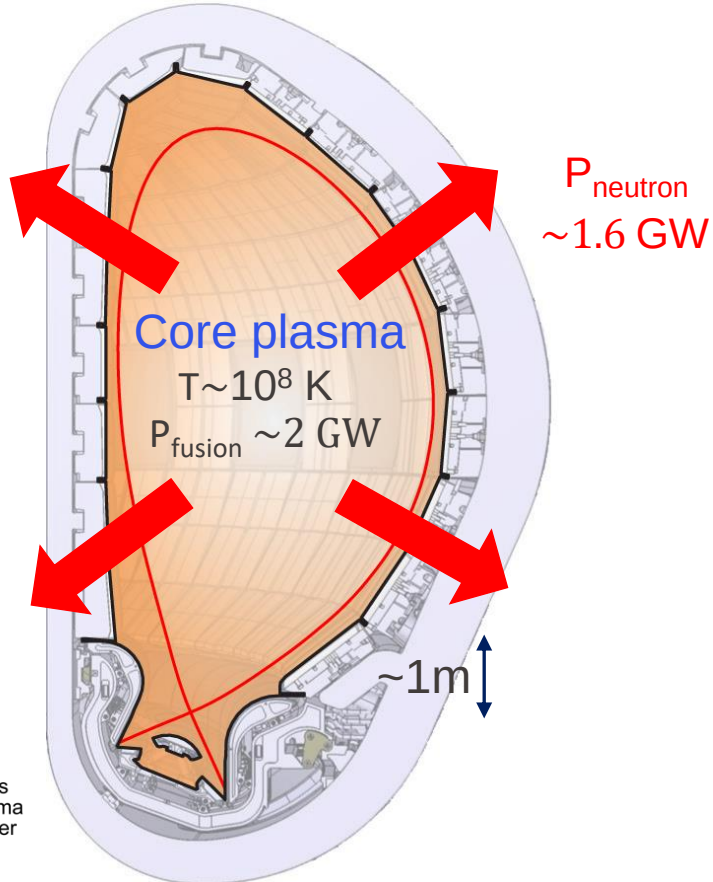



Magnetic X-point

# Complexity and importance of the boundary plasma



Christian Theiler

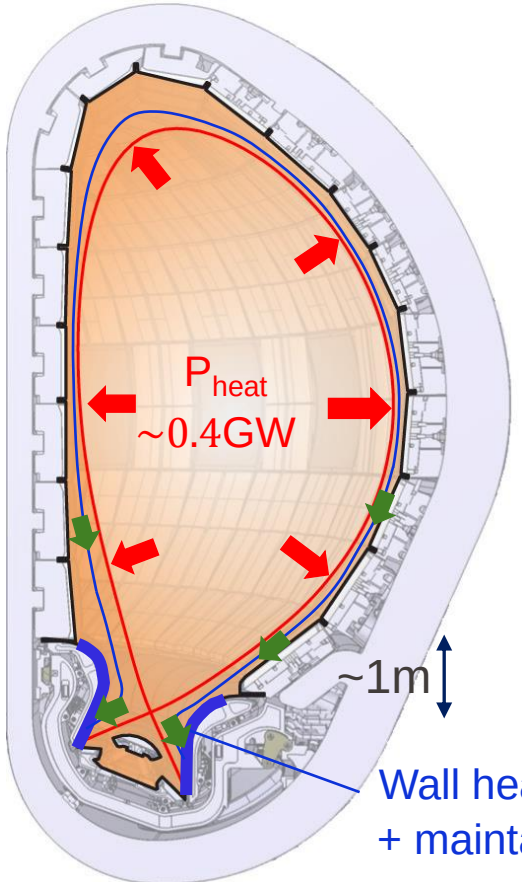



$P_{neutron}$
~1.6 GW

# Complexity and importance of the boundary plasma



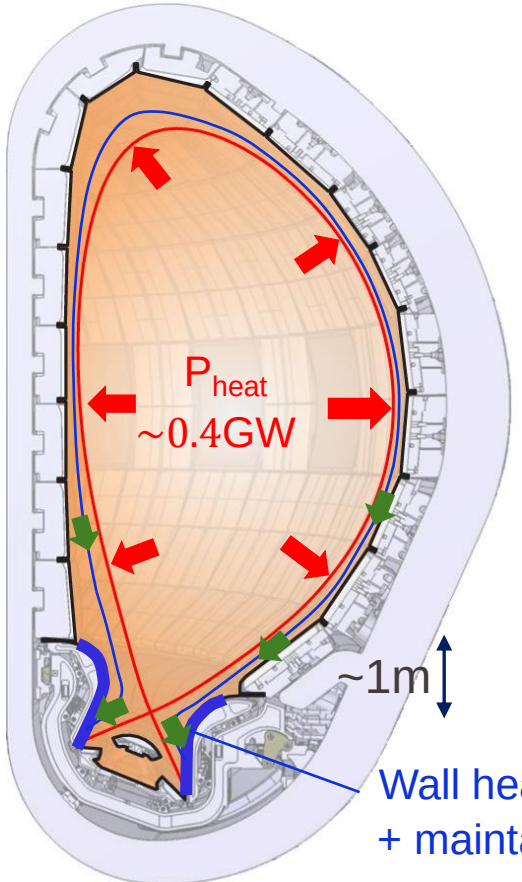
Christian Theiler




Wall heat flux $\leq 10 MW/m^2$; $T_{plasma} \lesssim 10^4$ K
+ maintaining high energy confinement

# Complexity and importance of the boundary plasma

Christian Theiler

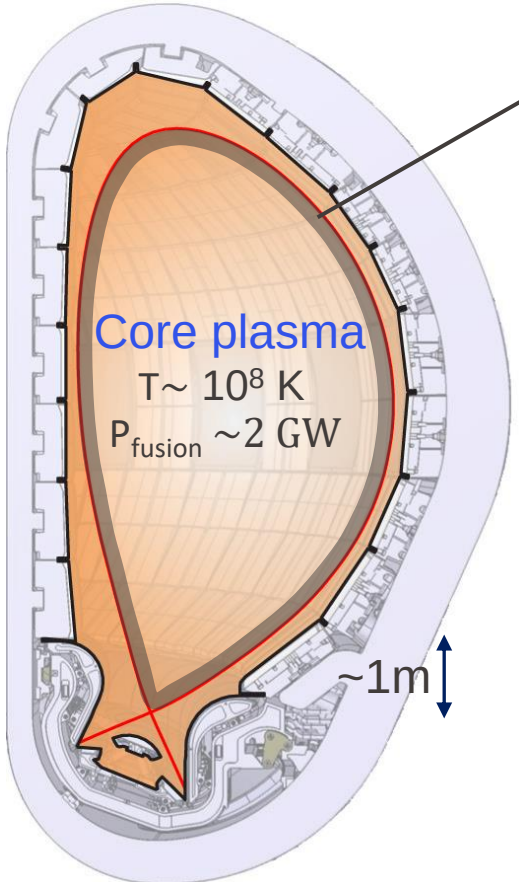



Wall heat flux $\leq$ 10MW/m$^2$; $T_{plasma} \lesssim 10^4$ K
+ maintaining high energy confinement

→ **Power exhaust challenge**

# Complexity and importance of the boundary plasma

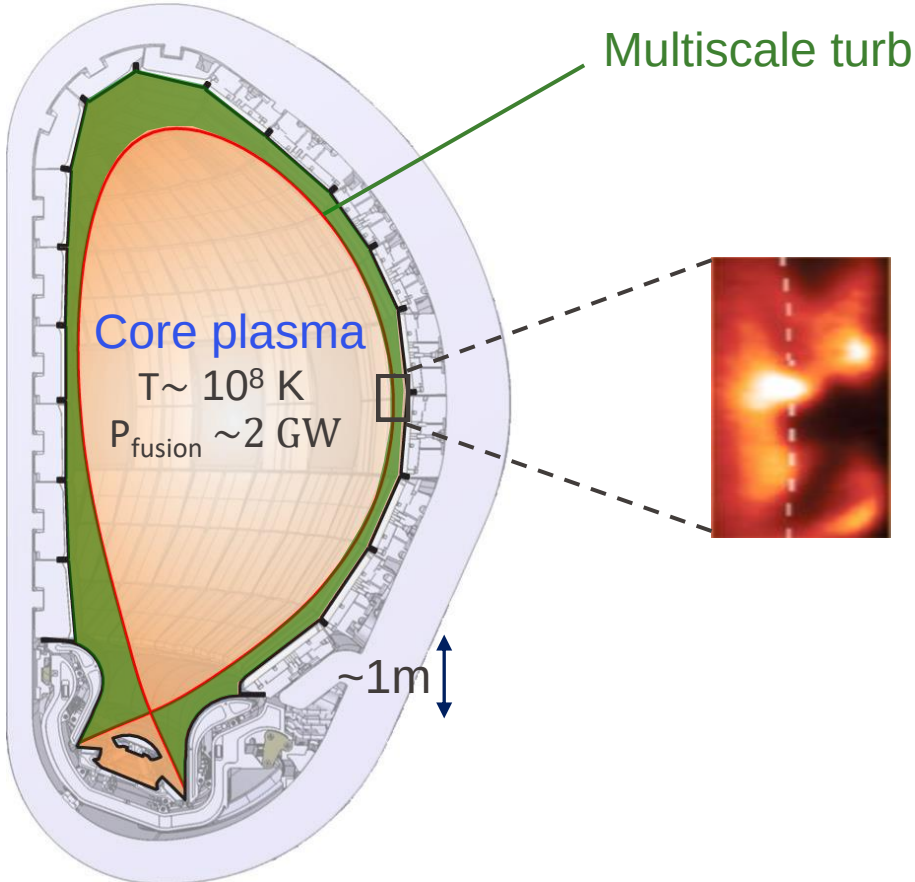
Christian Theiler




Transport barrier with reduced turbulence

# Complexity and importance of the boundary plasma

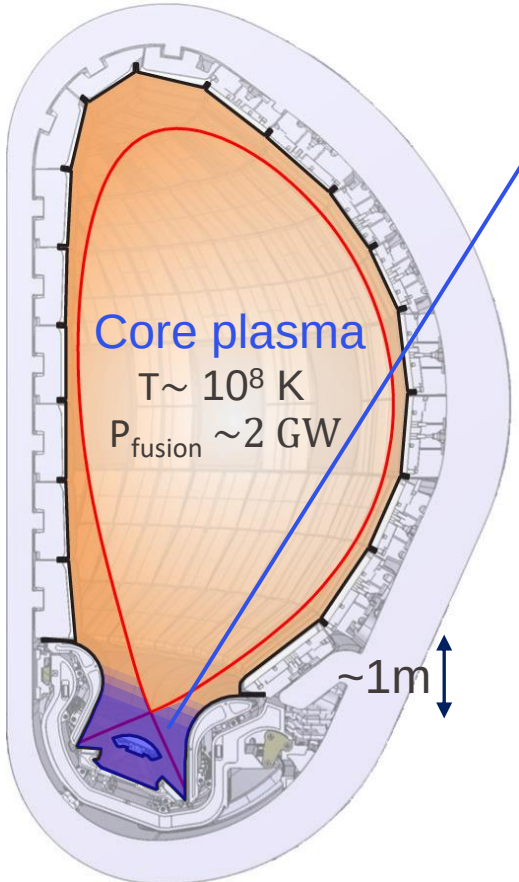
Christian Theiler



# Complexity and importance of the boundary plasma



Christian Theiler

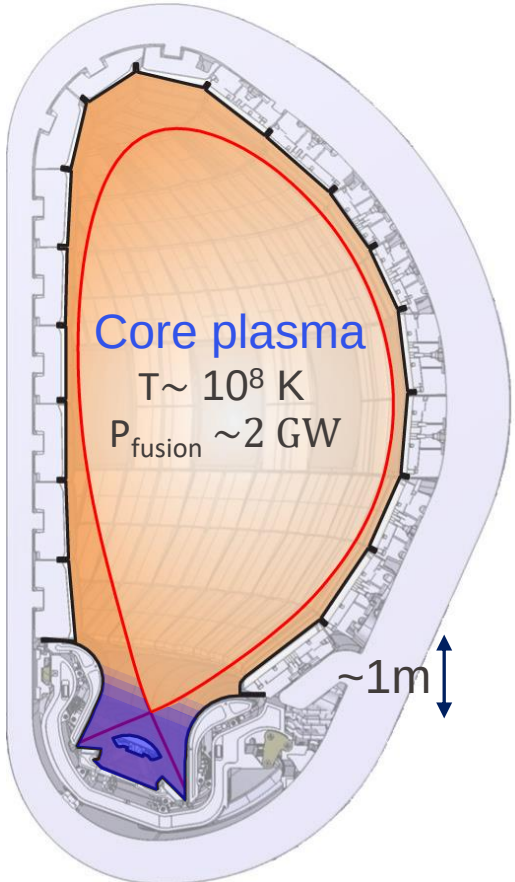



Plasma-neutral interaction

Complex atomic physics processes

# Complexity and importance of the boundary plasma

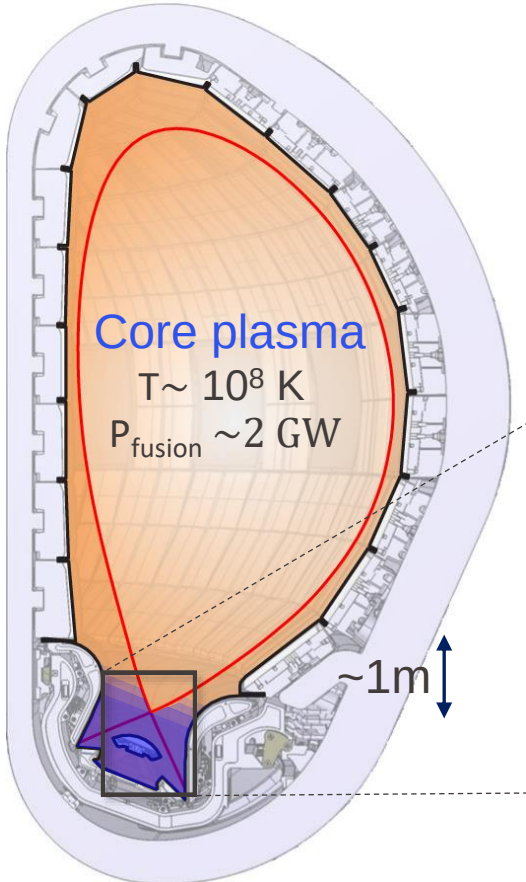
Christian Theiler

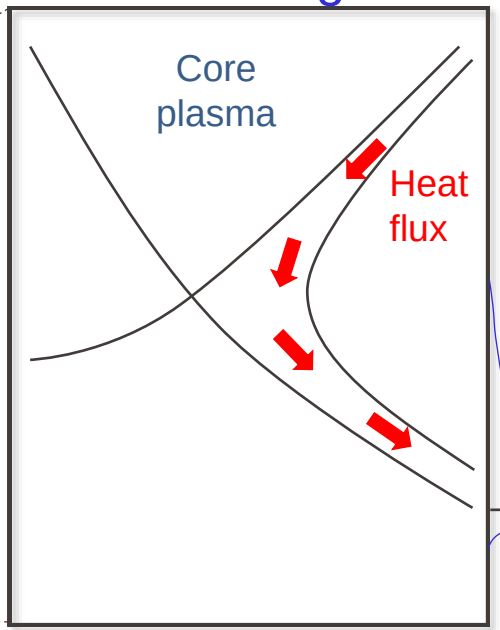



- Physics description requires complex mathematical models, including plasma fluid or kinetic models interacting self-consistently with the electric and magnetic fields and with multi-species neutral models

# Complexity and importance of the boundary plasma

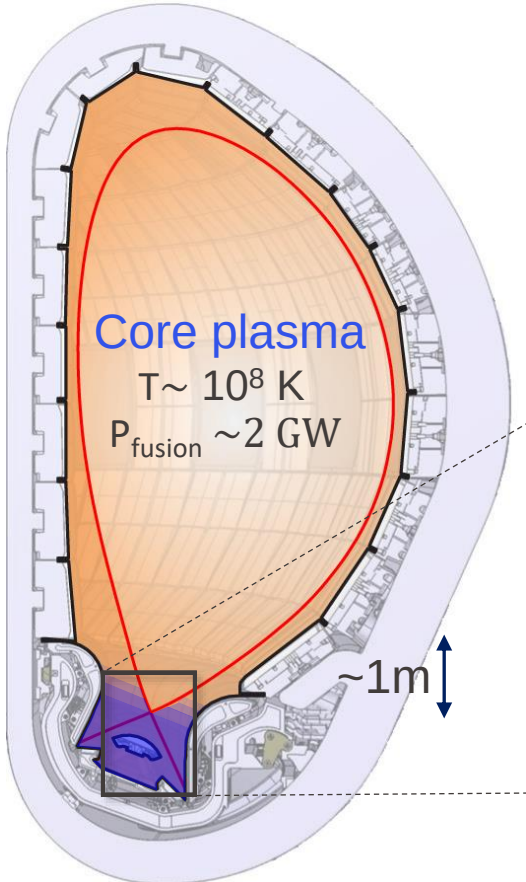
Christian Theiler



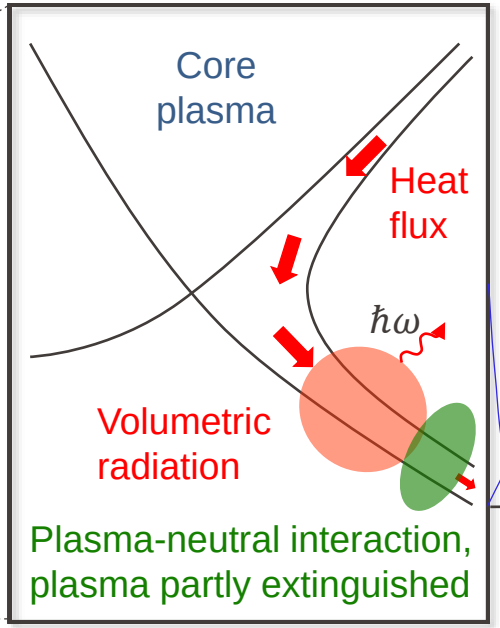



# Complexity and importance of the boundary plasma

Christian Theiler



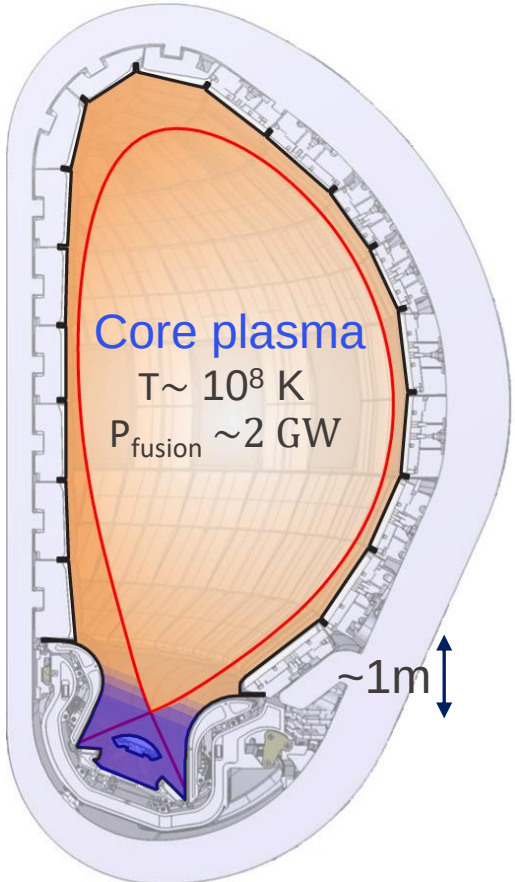

## Divertor **detachment**




Need to radiate ≈95% of this heat flux!

# Complexity and importance of the boundary plasma

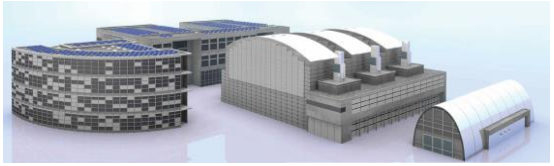
Christian Theiler



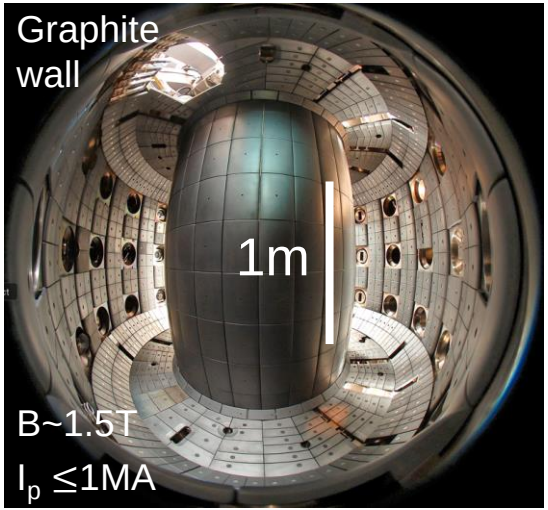

- Unclear if safe plasma exhaust achievable in conventional divertor while simultaneously assuring sufficient core performance, high plasma stability, protection against transient loss of detachment,…
- ITER is the key facility to test the conventional divertor
- As backup plan, alternatives need to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

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

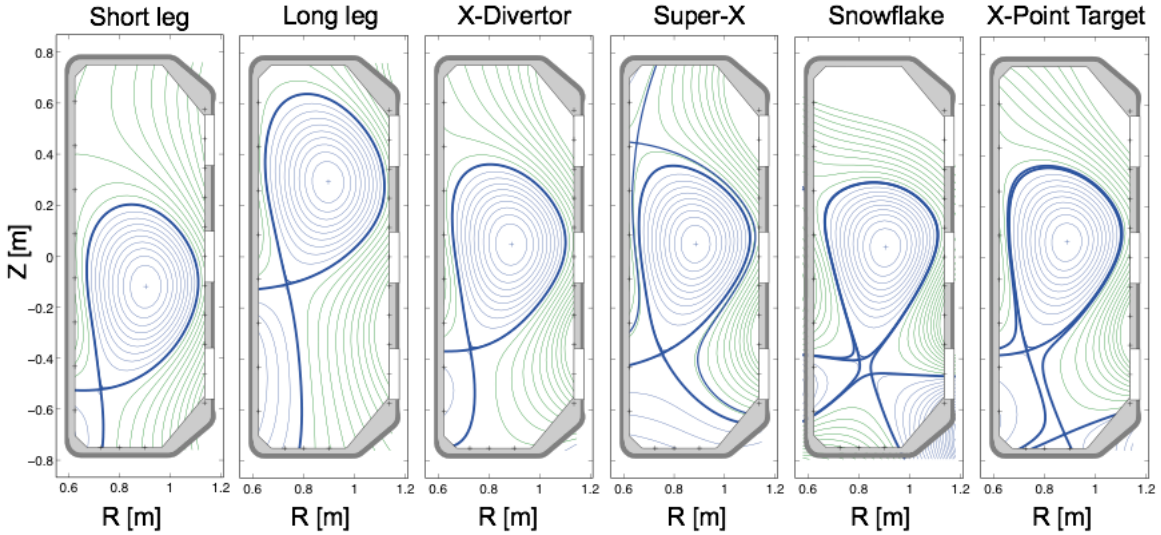
# The TCV tokamak – an ideal device to explore alternative divertors



EPFL SWISS PLASMA CENTER

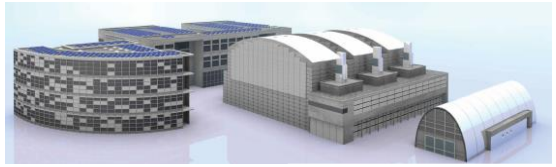



## Extreme magnetic shaping capabilities

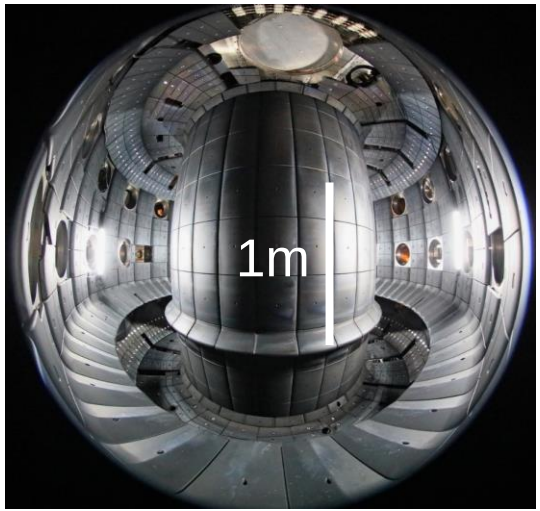



[C. Theiler et al., Nucl. Fusion 57, 072008 (2017)]

# The TCV tokamak – an ideal device to explore alternative divertors

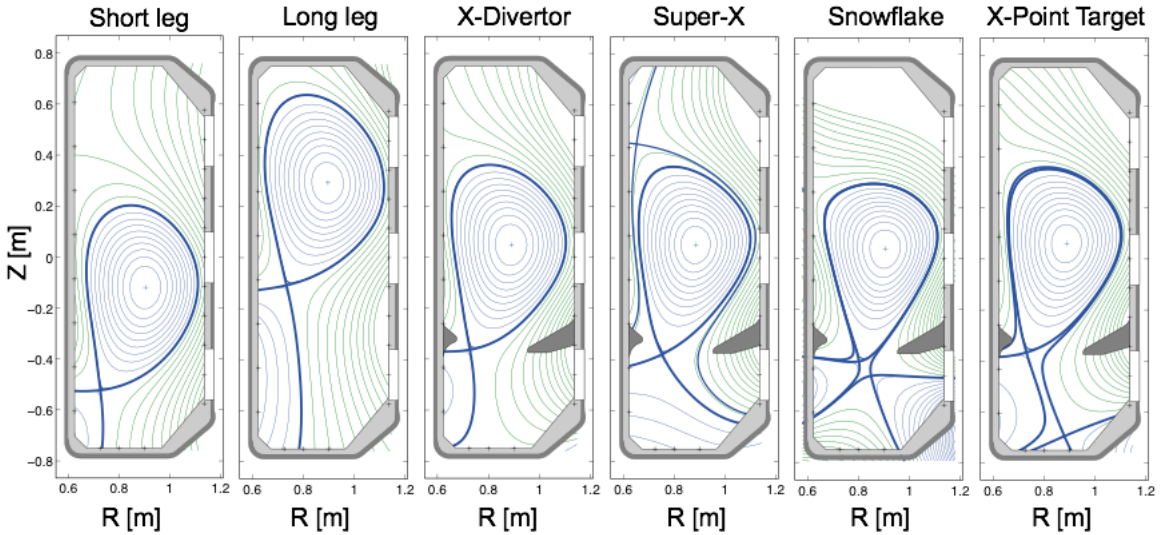


SWISS PLASMA CENTER



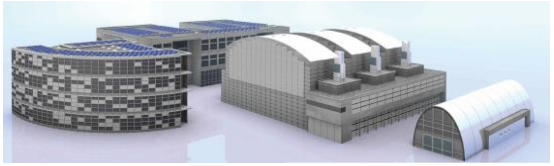

Extreme magnetic shaping capabilities

Flexible wall structures

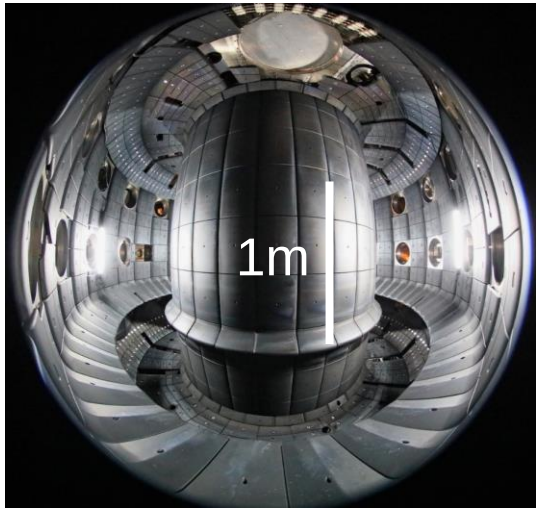



[A. Fasoli et al., Nucl. Fusion 60, 016019 (2020)]

# The TCV tokamak – an ideal device to explore alternative divertors



EPFL SWISS PLASMA CENTER




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 understanding of boundary physics and detachment in view of ITER

# Our approach

Development of new measurement devices (diagnostics)

Power exhaust experiments in alternative divertor configurations

Experimental characterization of turbulence in the boundary plasma

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

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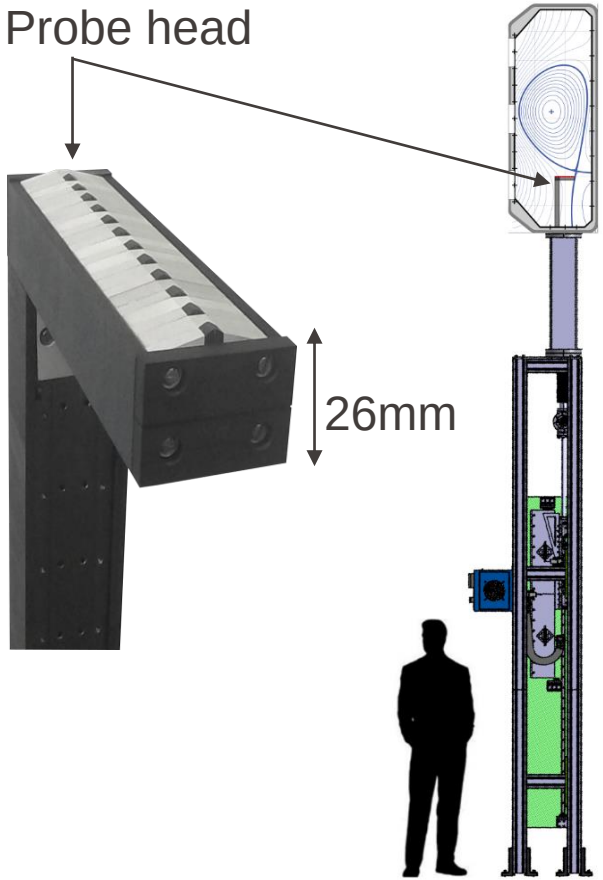
# Unprecedented 2D divertor probe measurements

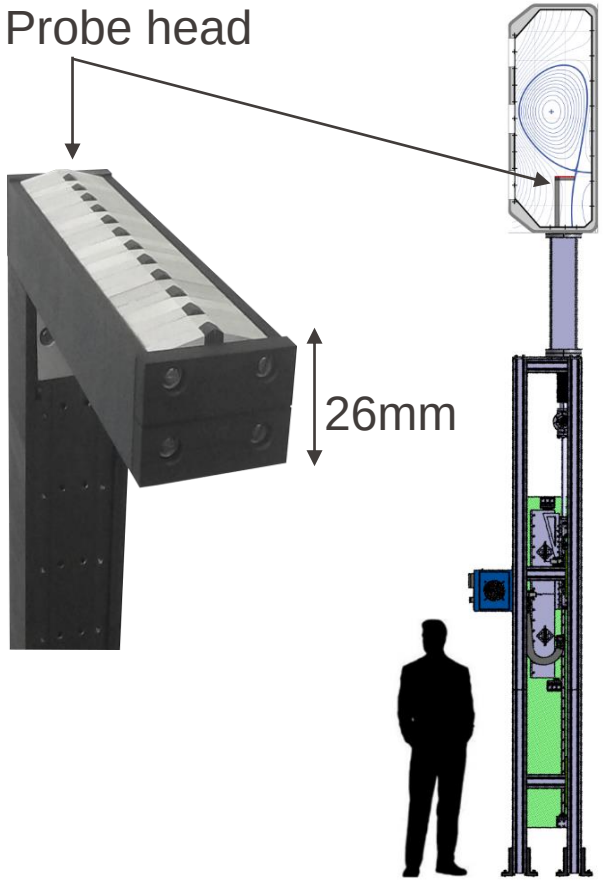
Christian Theiler




[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

Christian Theiler

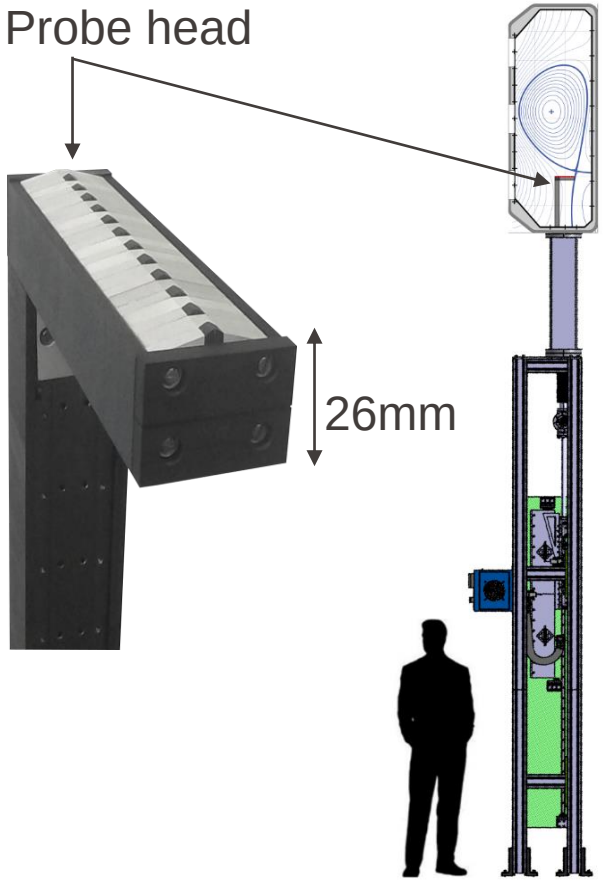


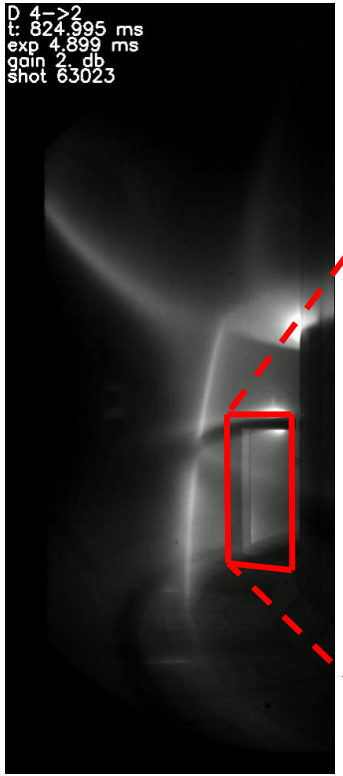


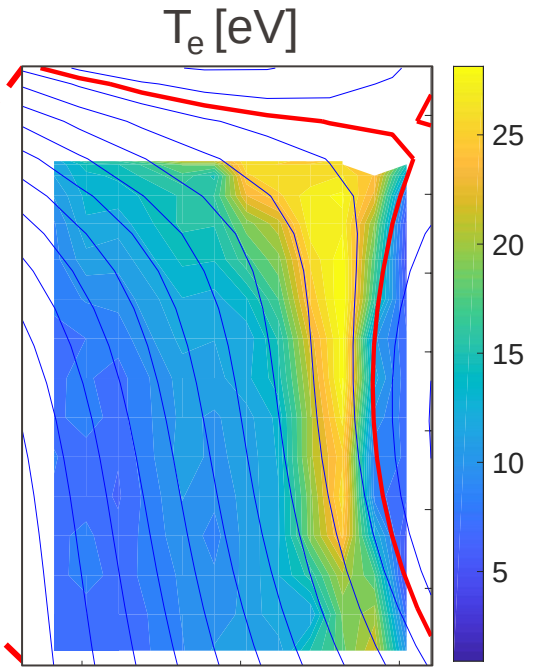
[H. De Oliveira et al., Rev. Sci. Inst. 92, 043547 (2021)]
[H. De Oliveira et al., Nucl. Fusion 62, 096028 (2022)]

# Unprecedented 2D divertor probe measurements

Christian Theiler




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

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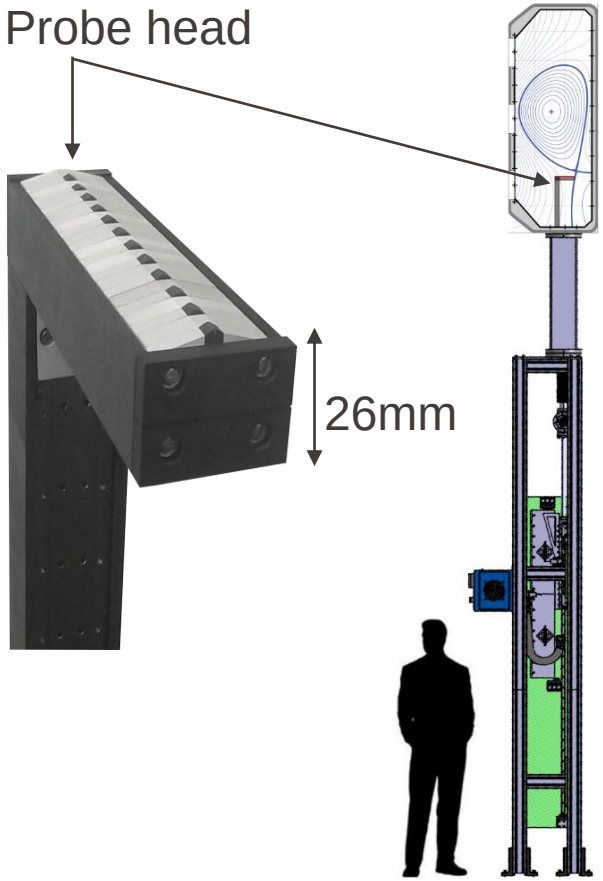


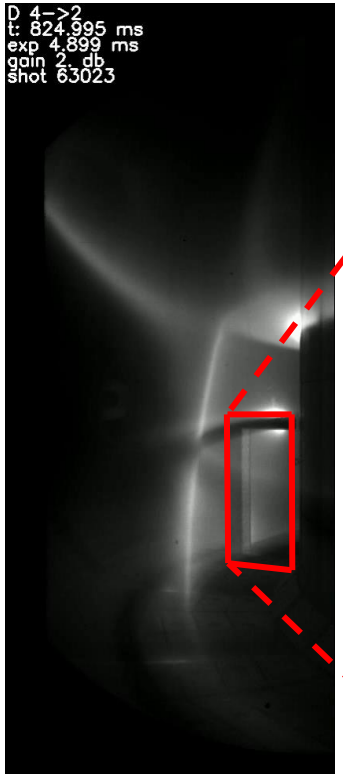


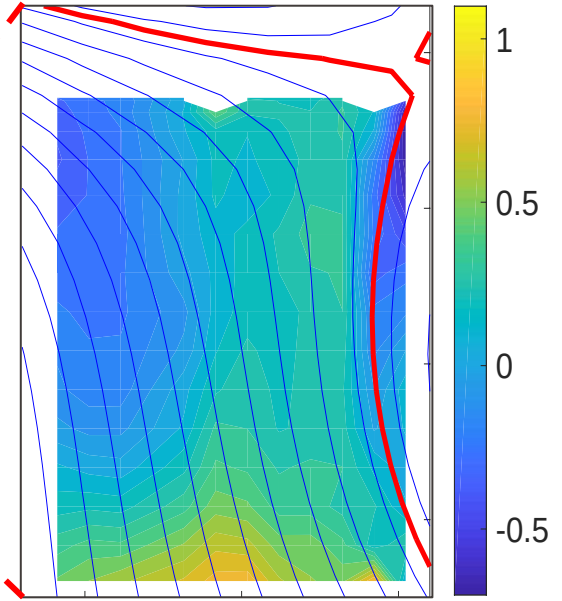




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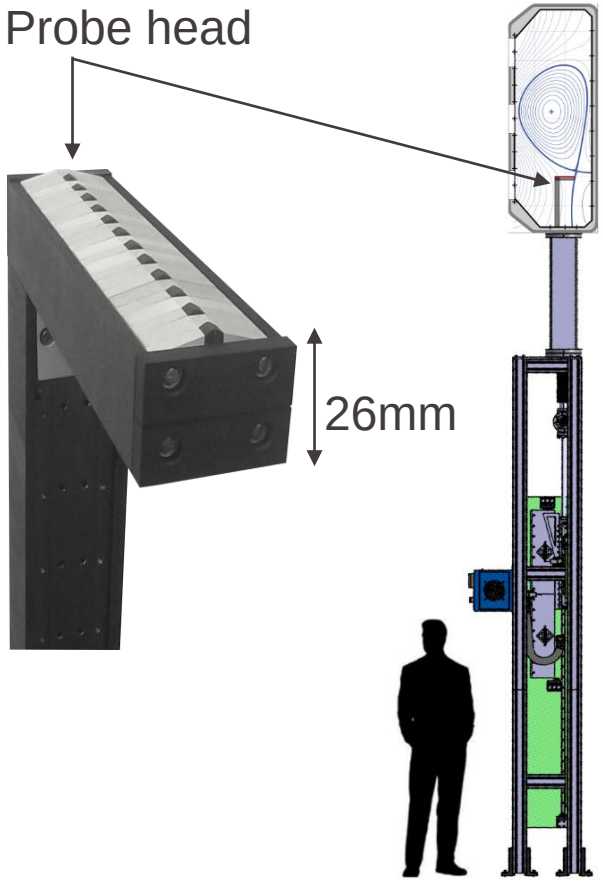


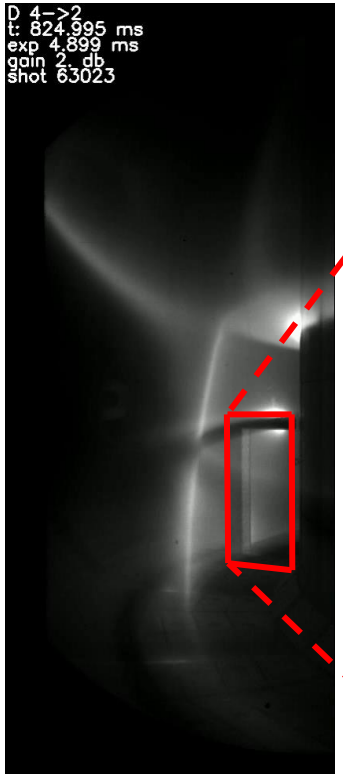


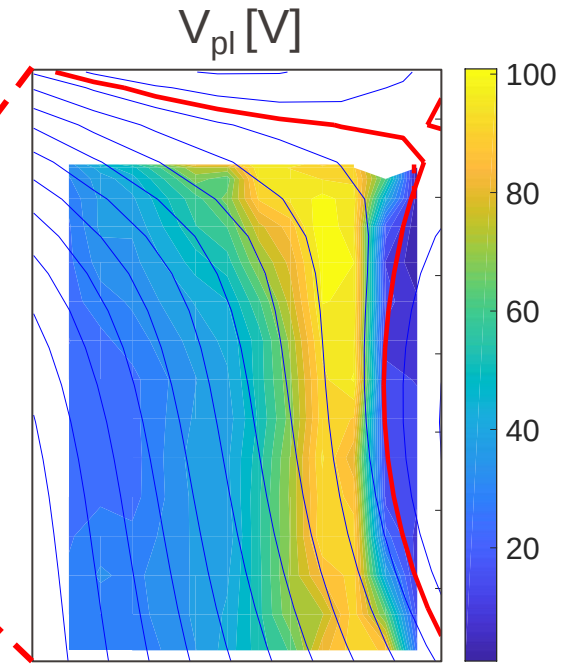




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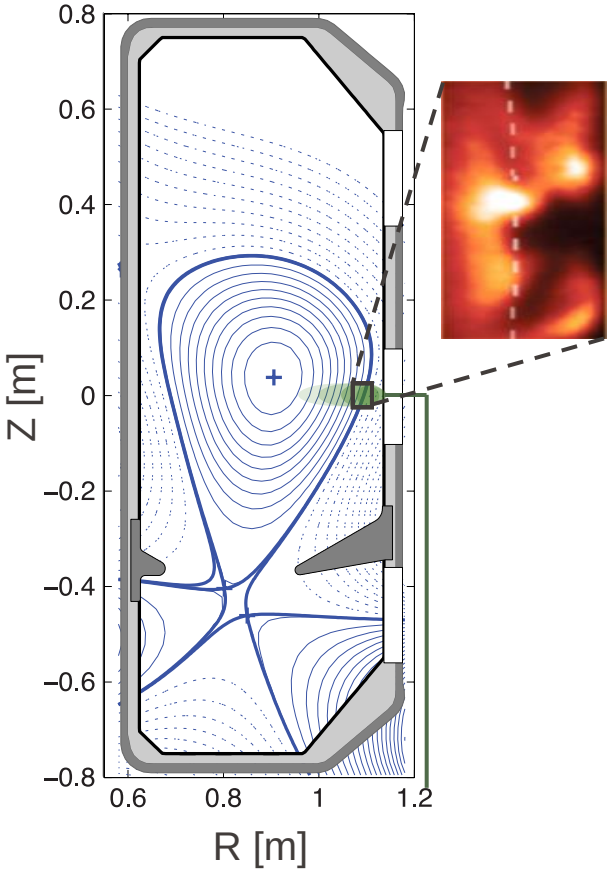
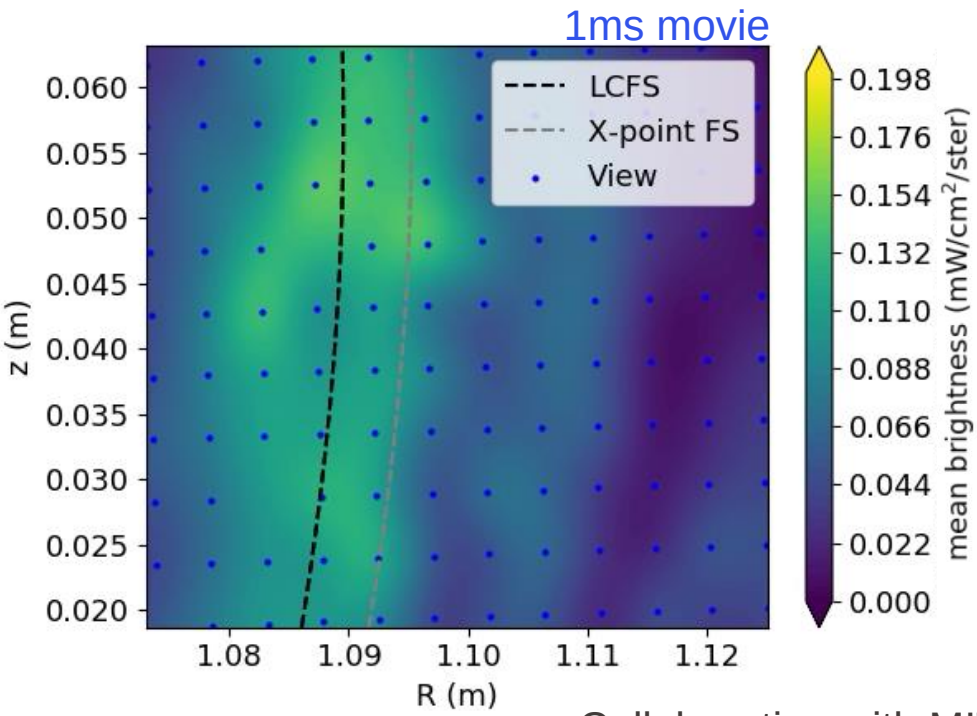
# 2D turbulence imaging in different regions



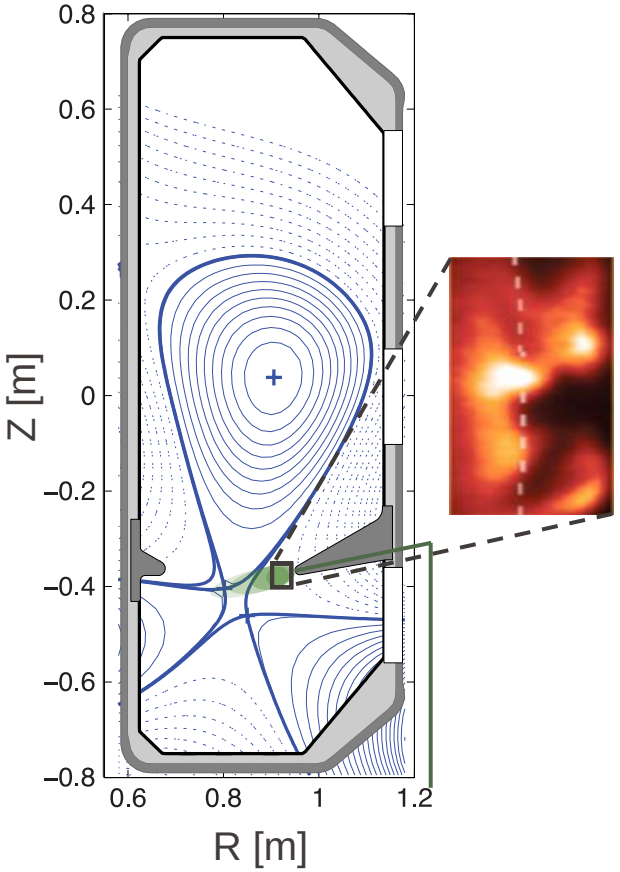

Collaboration with MIT

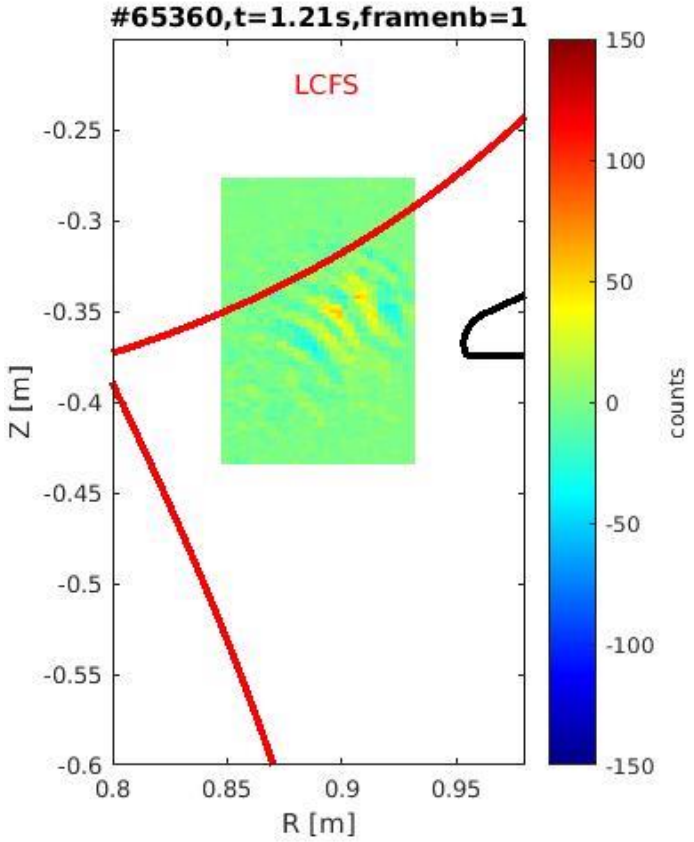
[N. Offeddu et al., Rev. Sci. Inst. 93, 123504 (2022)]

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

# 2D turbulence imaging in different regions

Christian Theiler




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

# Our approach

Development of new measurement devices (diagnostics)

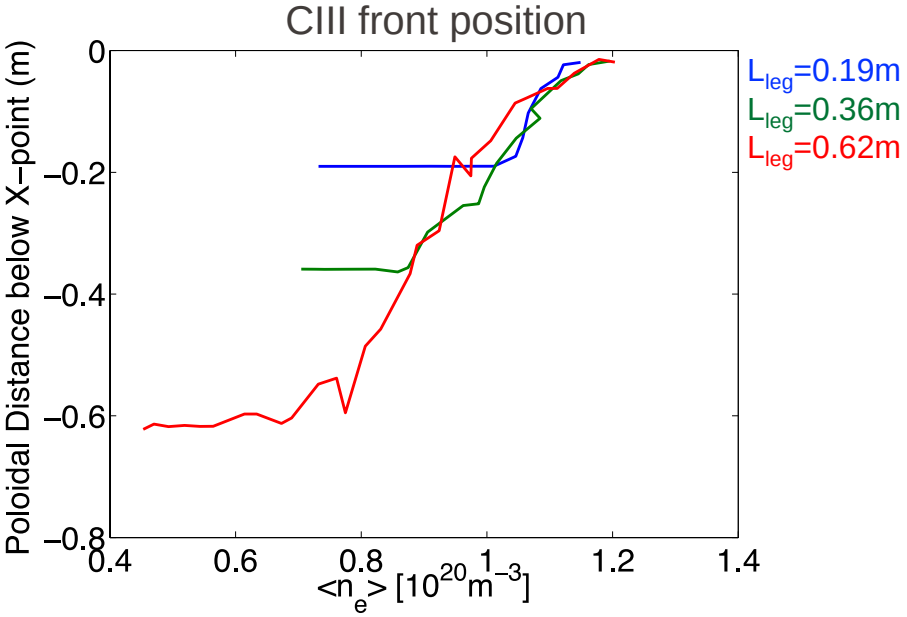
Power exhaust experiments in alternative divertor configurations

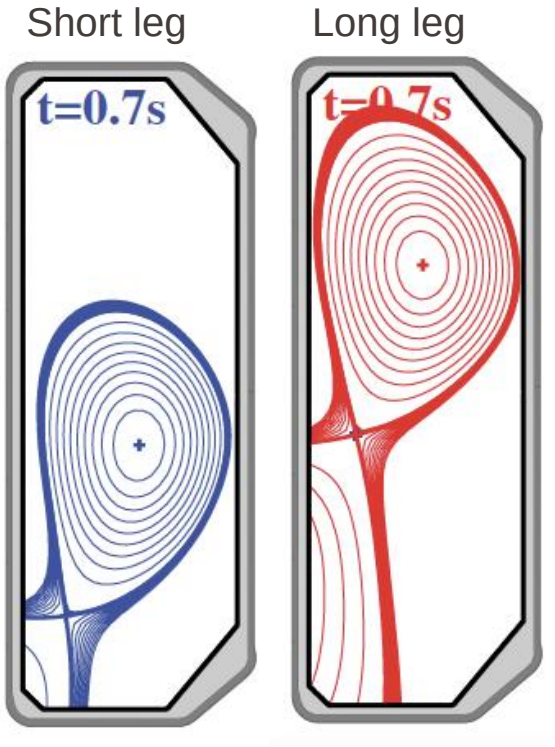
Experimental characterization of turbulence in the boundary plasma

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

Christian Theiler

# Facilitated detachment access and wider detachment window with increasing leg length




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

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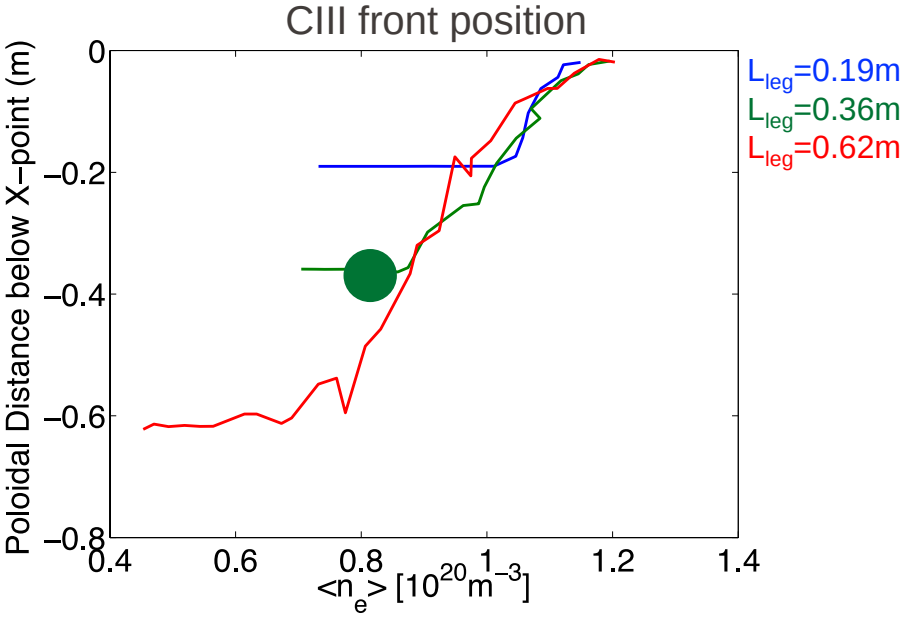


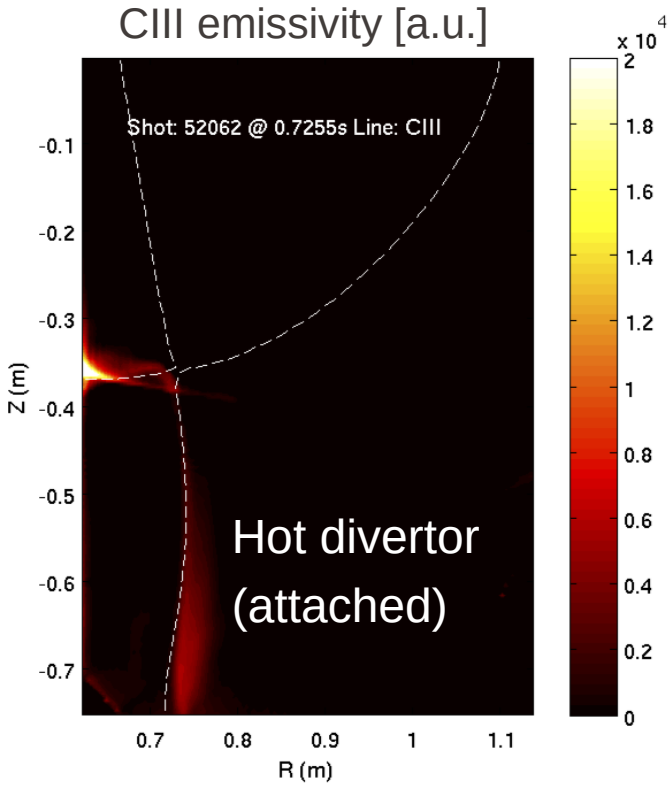


[H. Reimerdes et al., Nucl. Fusion 57, 126007 (2017)]

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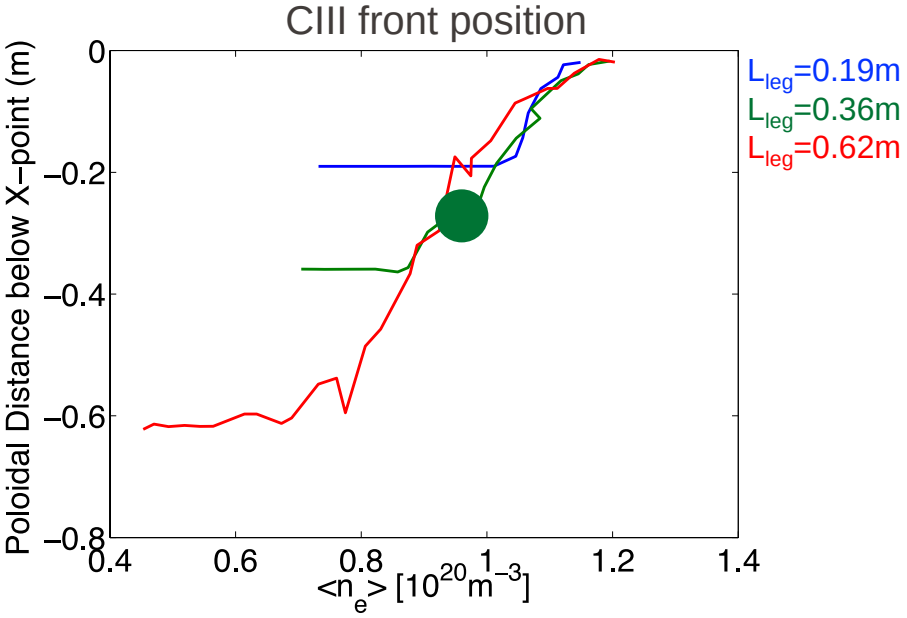


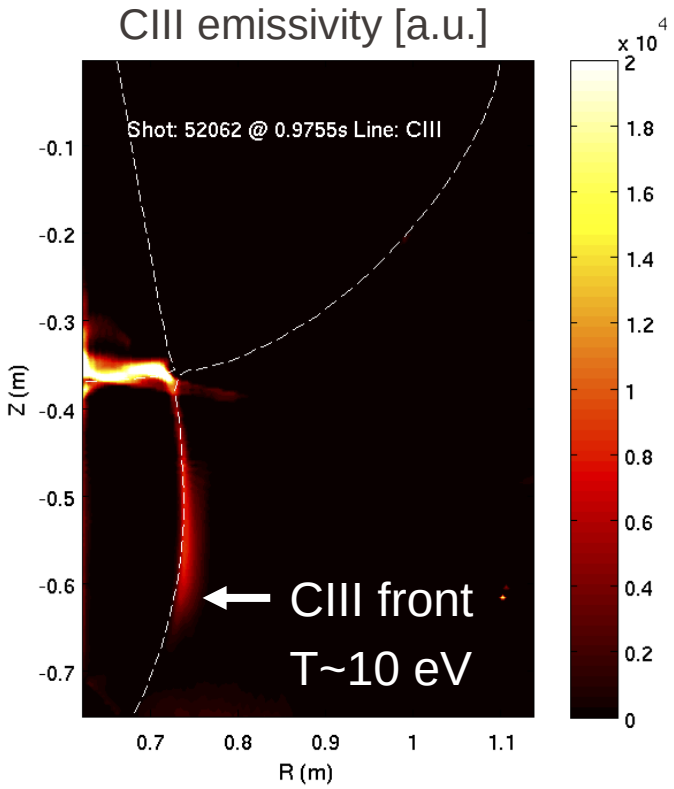


[H. Reimerdes et al., Nucl. Fusion 57, 126007 (2017)]

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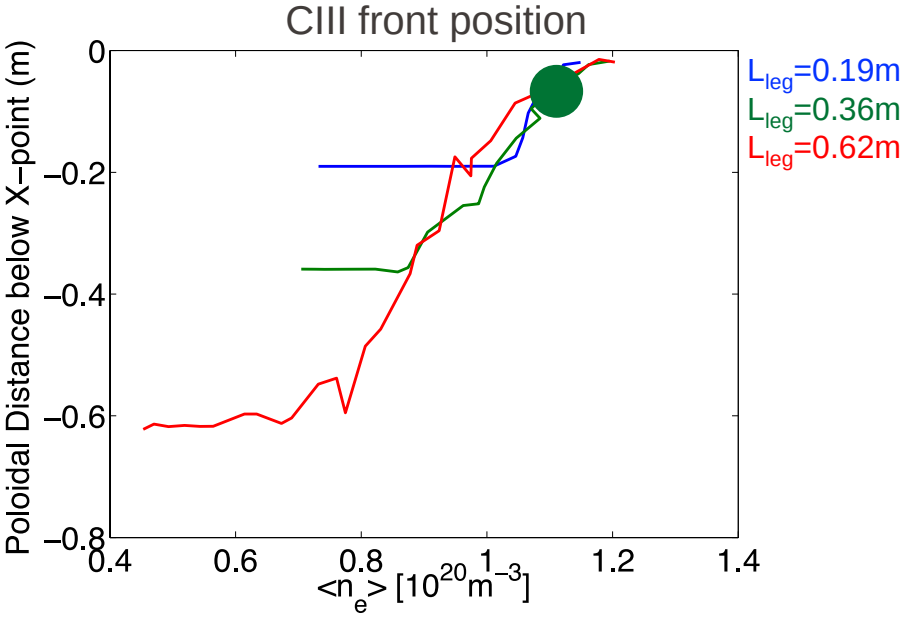


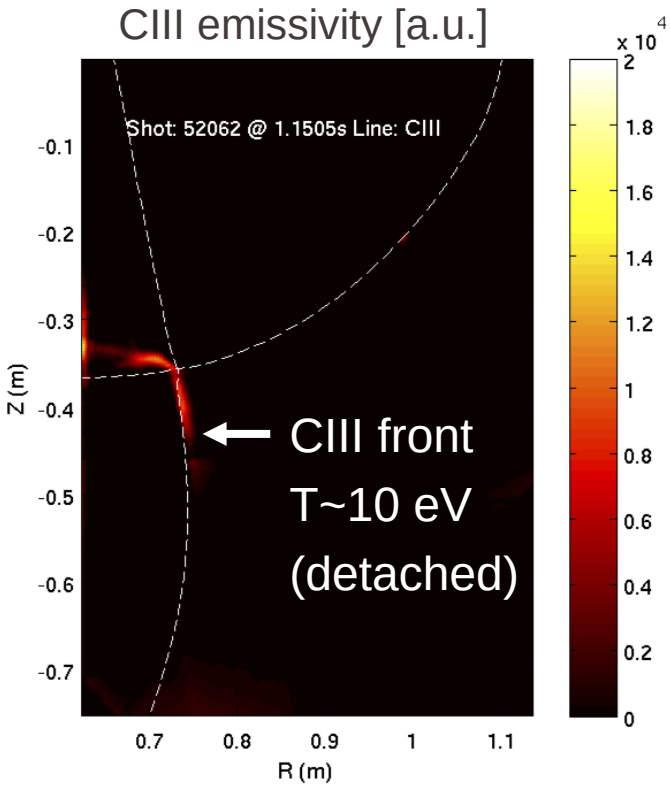


[H. Reimerdes et al., Nucl. Fusion 57, 126007 (2017)]

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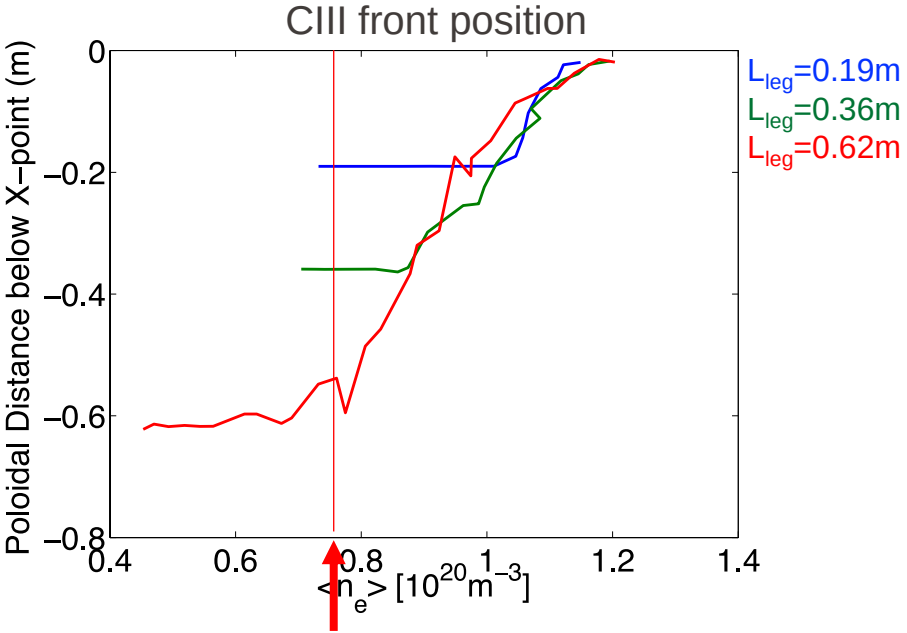
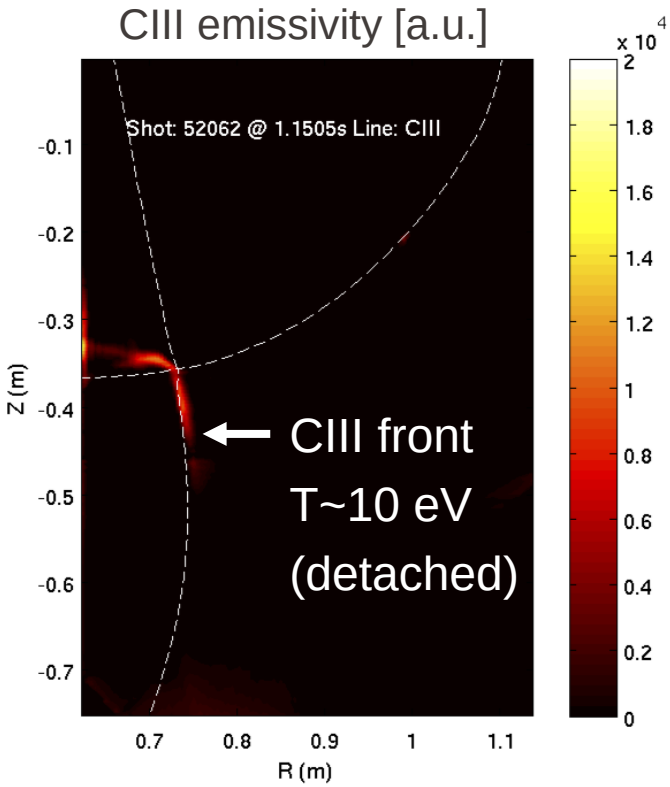



Indicative for detachment access

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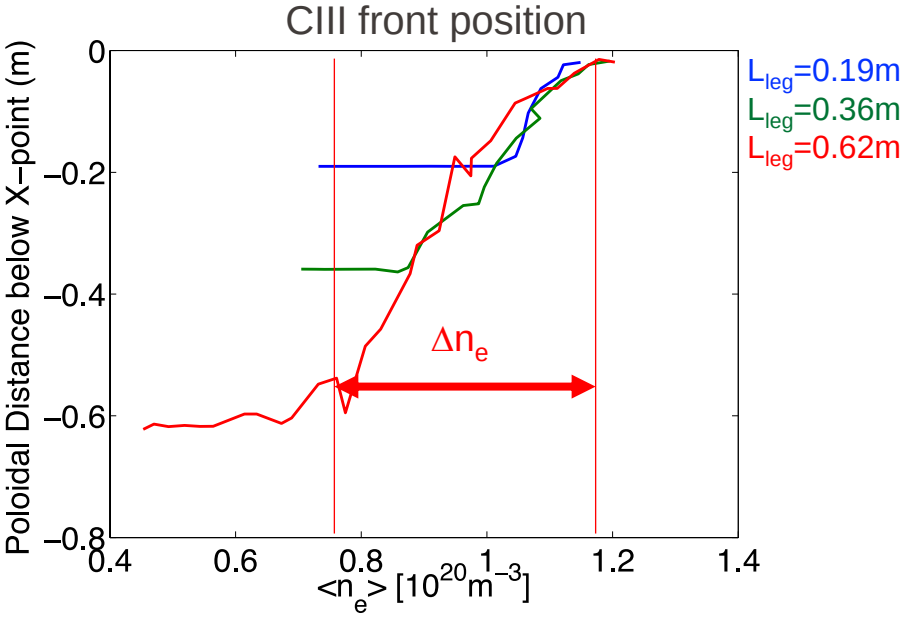
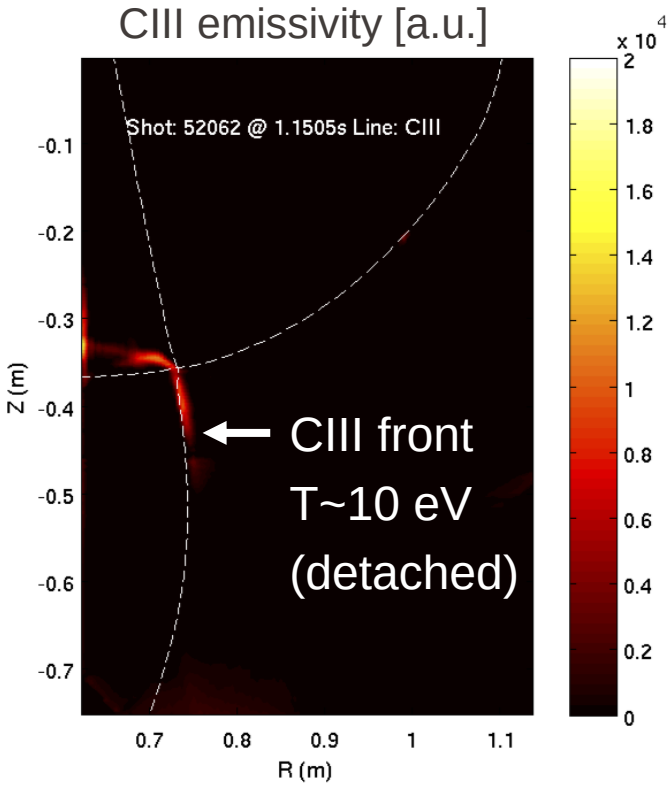


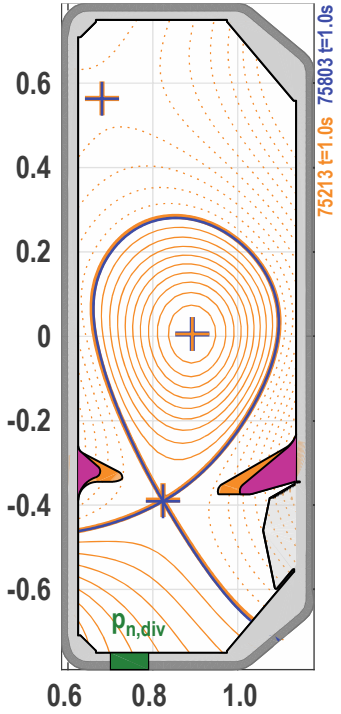

$\Delta n_e$ a measure for the controllability of the radiation location

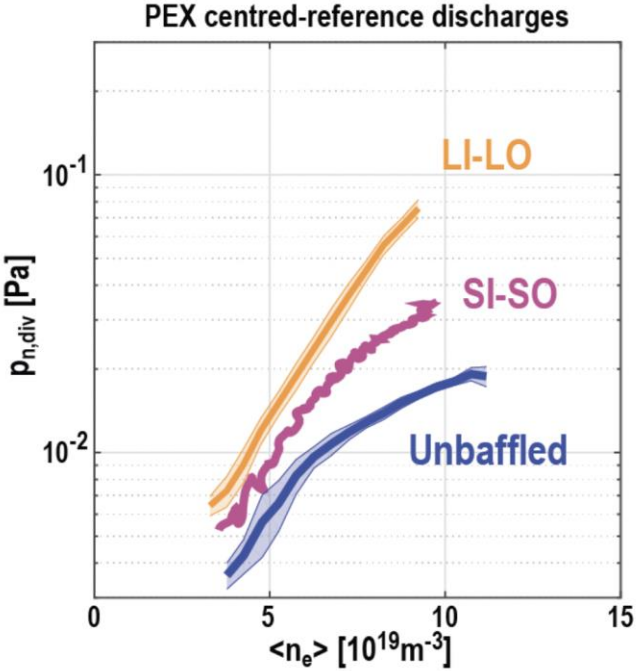
[H. Reimerdes et al., Nucl. Fusion 57, 126007 (2017)]

# Increased divertor neutral pressure and reduced detachment threshold with baffles

Christian Theiler

L-mode density ramps



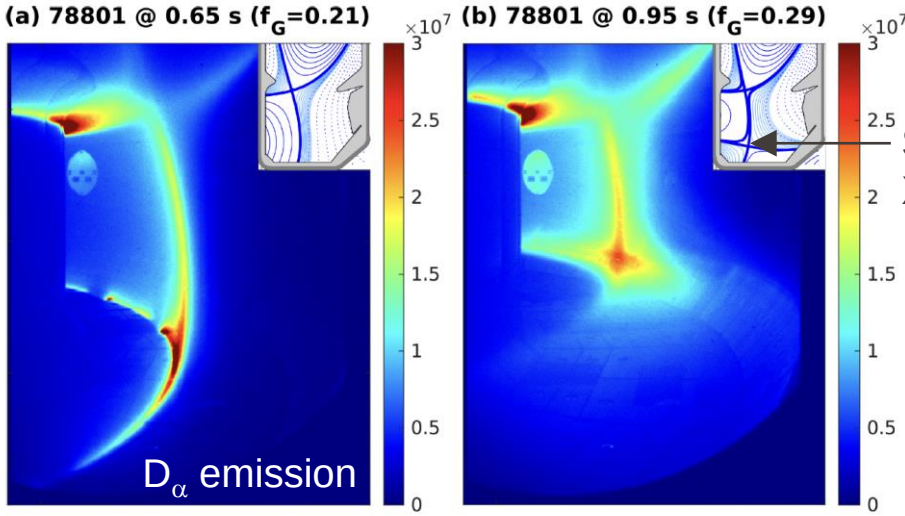



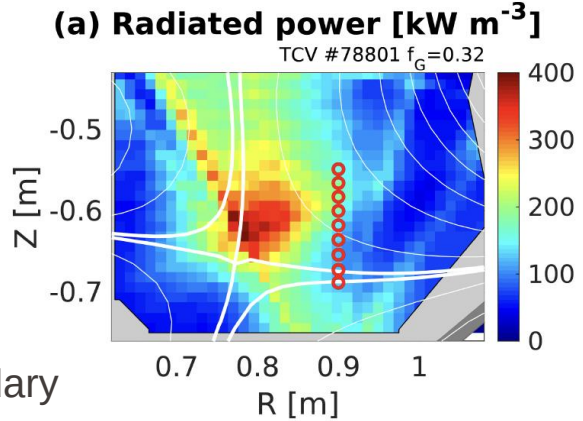

- Up to 5x increase in divertor neutral pressure with baffles
- Up to a ~30% reduction in detachment threshold

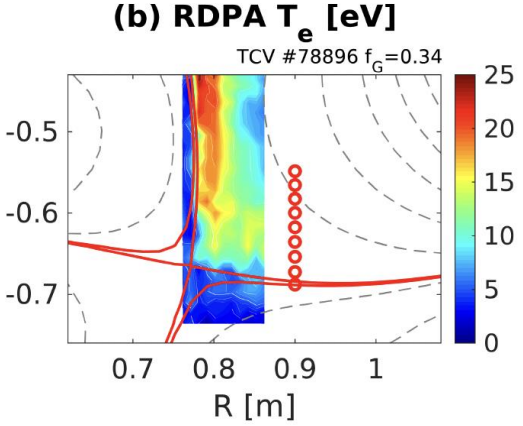
[H. Reimerdes et al., Nucl. Fusion 61, 024002 (2021)]
[O. Février et al., NME 27, 100977 (2021)]

# Discovery of the *X-point target radiator* regime

Radiation localization around secondary X-point



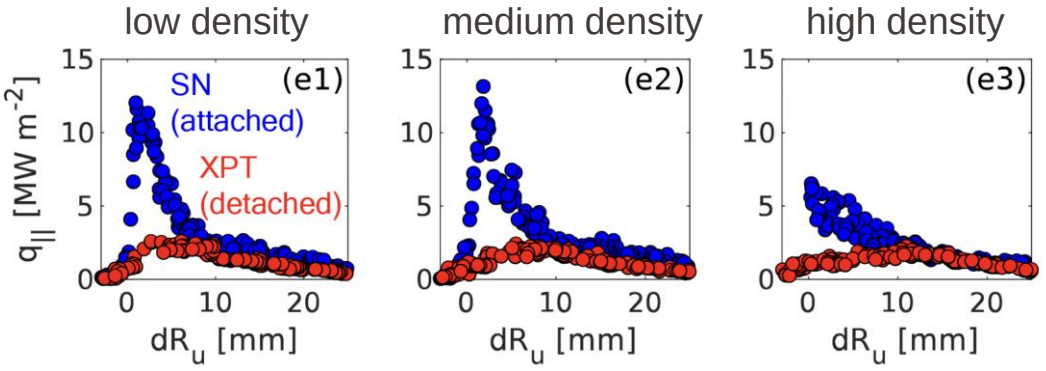



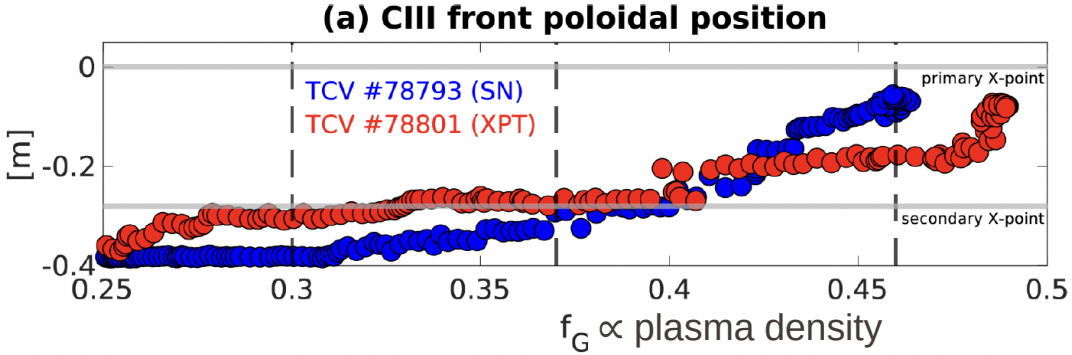

[K. Lee et al., subm. to Phys. Rev. Lett.]

# X-point target radiator shows tremendous power exhaust benefits

Christian Theiler

Greatly reduced parallel target heat fluxes and CIII front sensitivity on upstream density

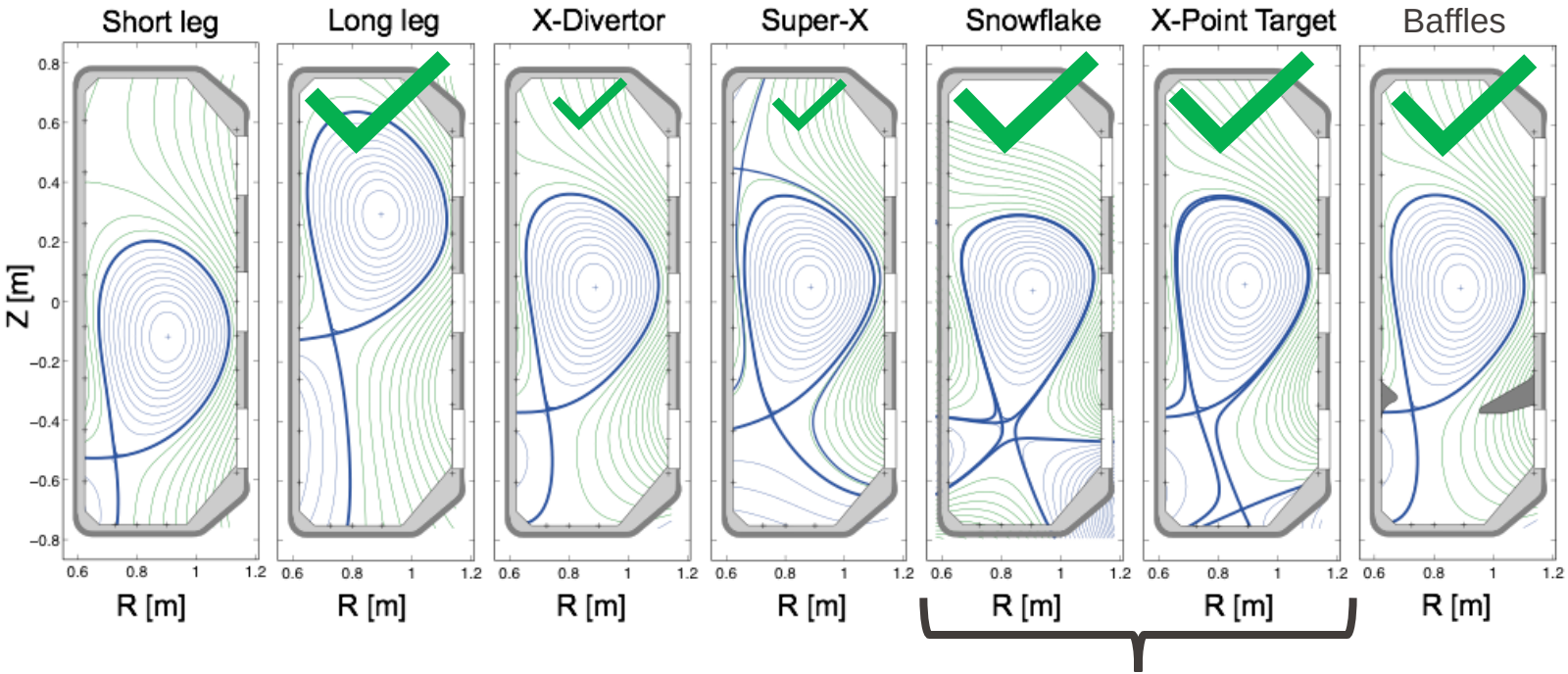



[K. Lee et al., subm. to Phys. Rev. Lett.]

# Key benefits of geometrical properties assessed





# Our approach

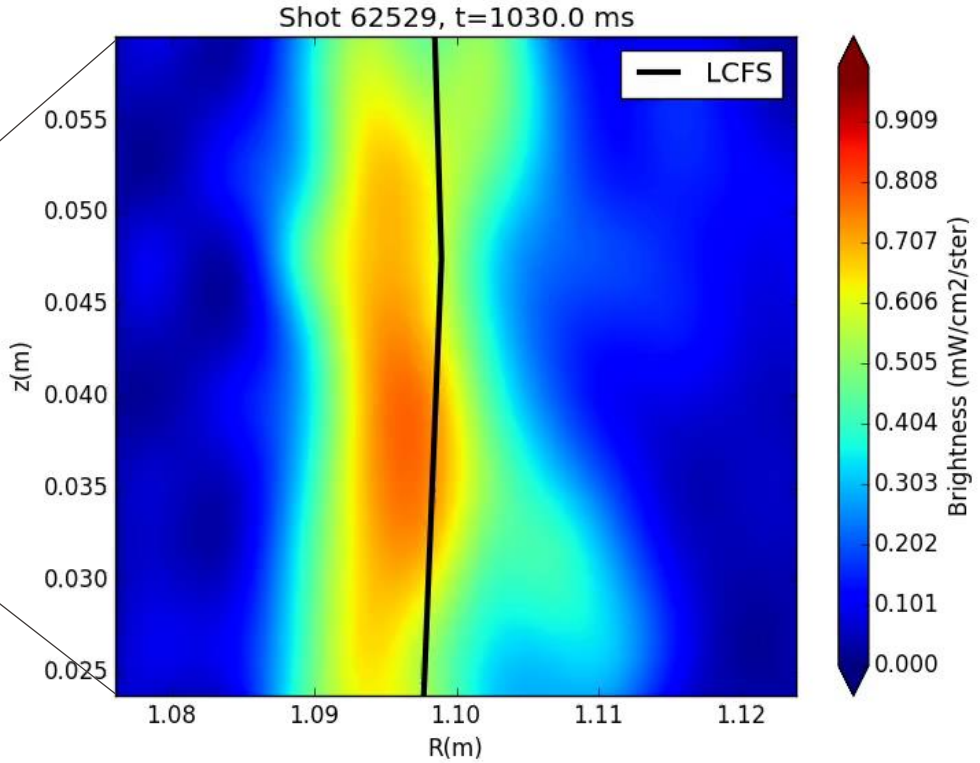
Development of new measurement devices (diagnostics)

Power exhaust experiments in alternative divertor configurations

Experimental characterization of turbulence in the boundary plasma

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

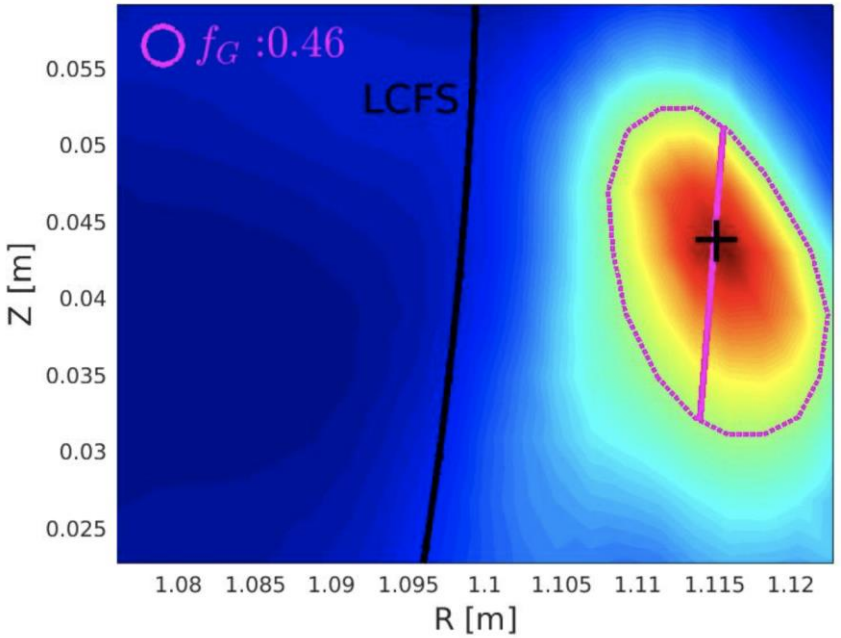
# Plasma dynamics in the “open” field line region of tokamaks are dominated by filamentary structures




Christian Theiler

# With Gas Puff Imaging, we can visualize and analyze filaments in the plane perp. to B

Christian Theiler




→ Filament size, velocity and statistical properties

# Key filament property: their cross-field velocity





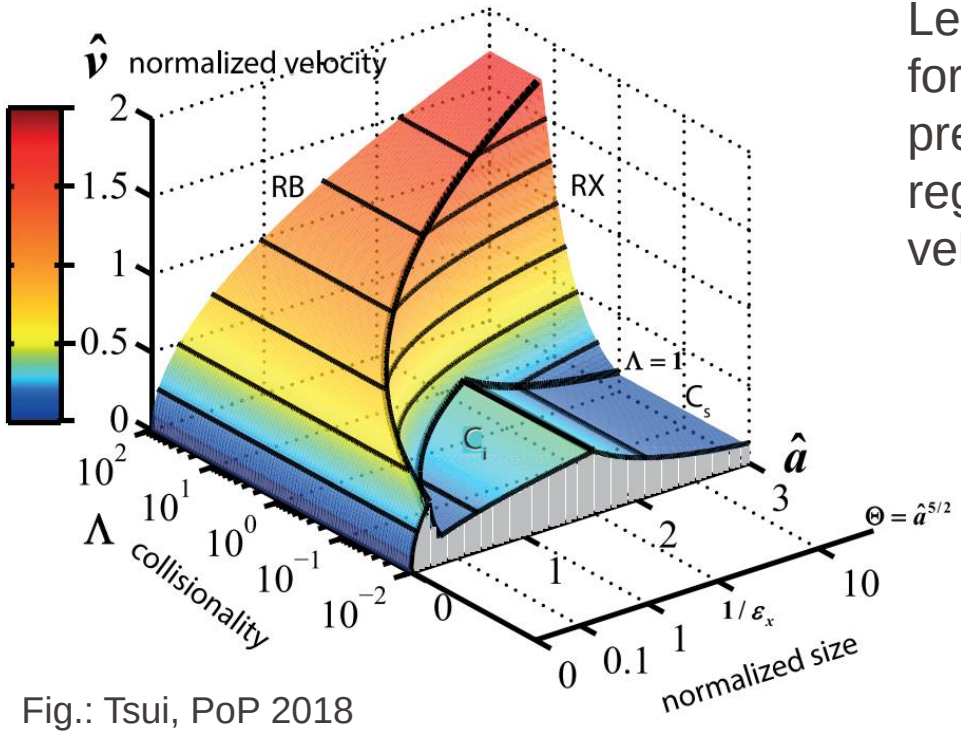
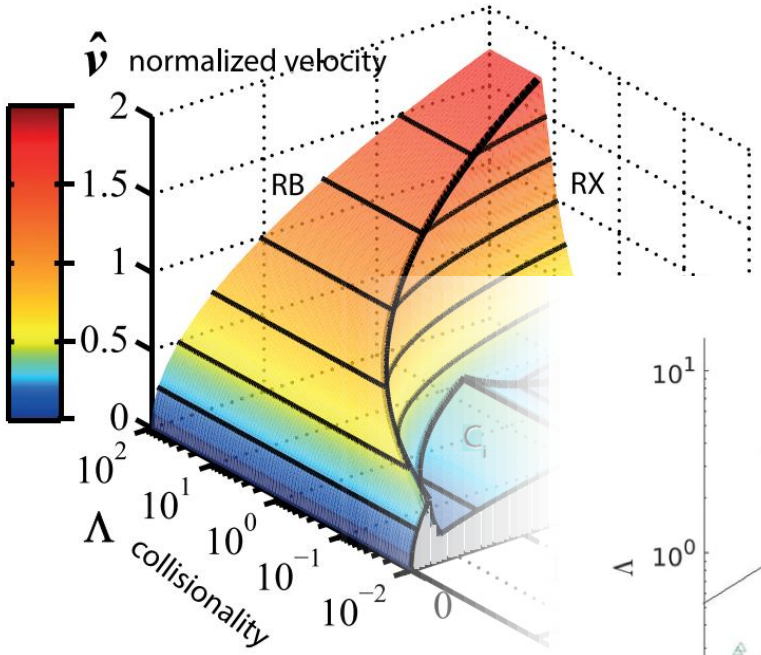



Fig.: Tsui, PoP 2018

Leading filament propagation model for tokamaks [Myra et al., PoP 2006] predicts four different propagation regimes, with different cross-field velocity scalings

# Key filament property: their cross-field velocity

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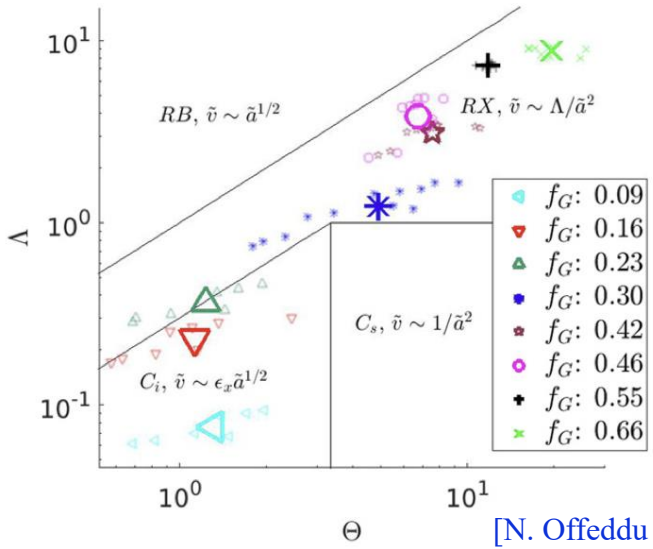


- Filament regime identified in TCV

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

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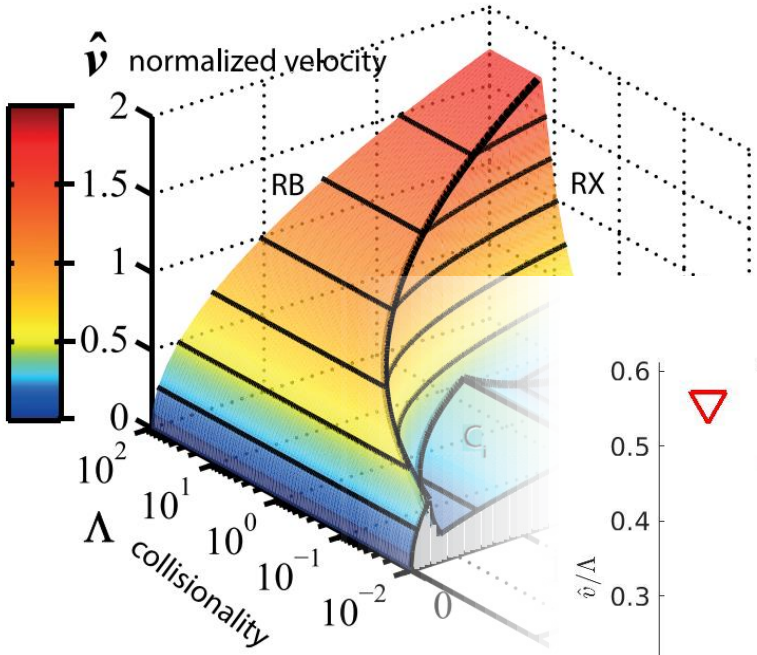


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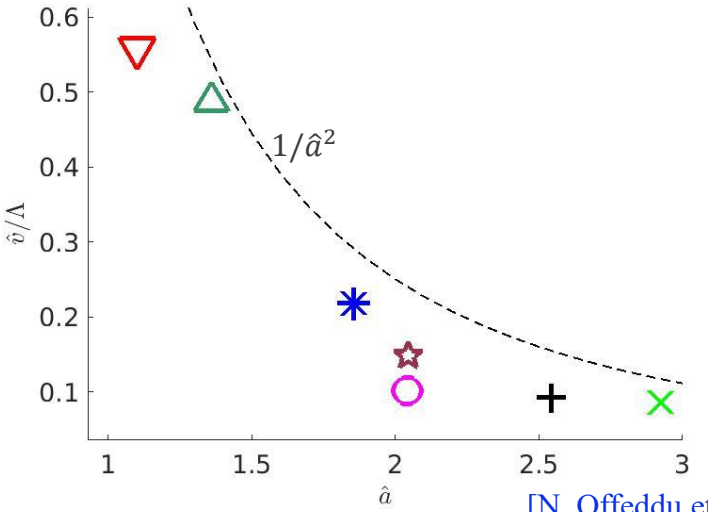
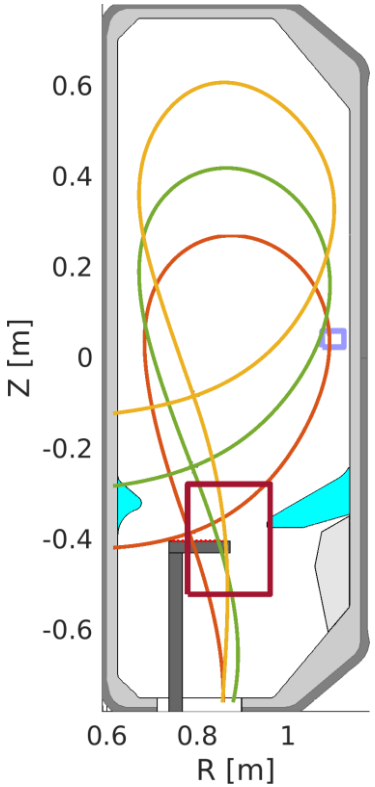


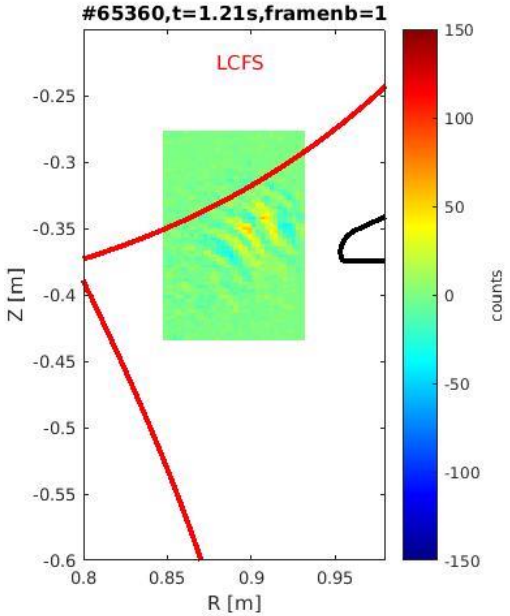

- Filament regime identified in TCV
- Velocity behaves as expected

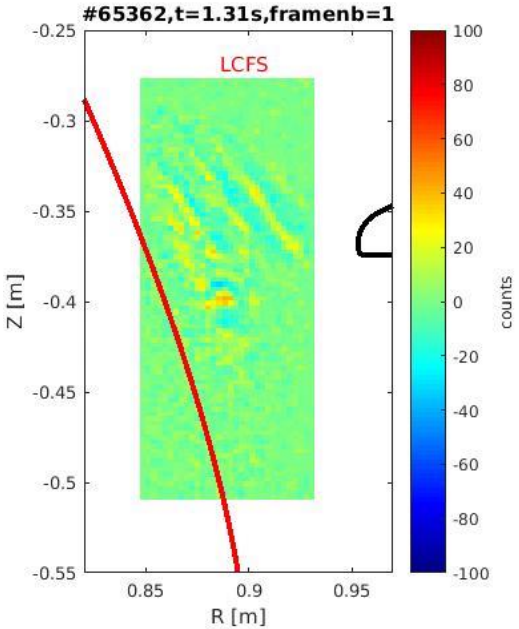
[N. Offeddu et al., Nucl. Fusion 62, 096014 (2022)]

# What exactly happens around the X-point?

Christian Theiler






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

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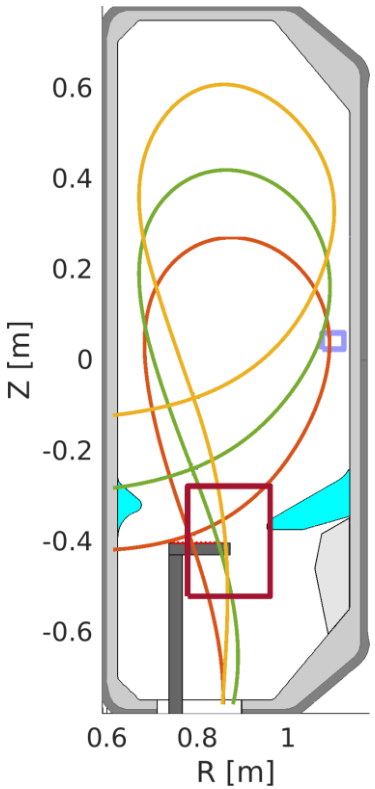
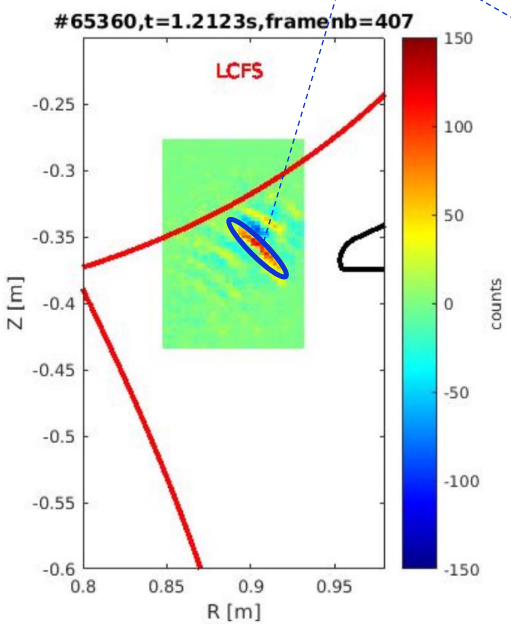
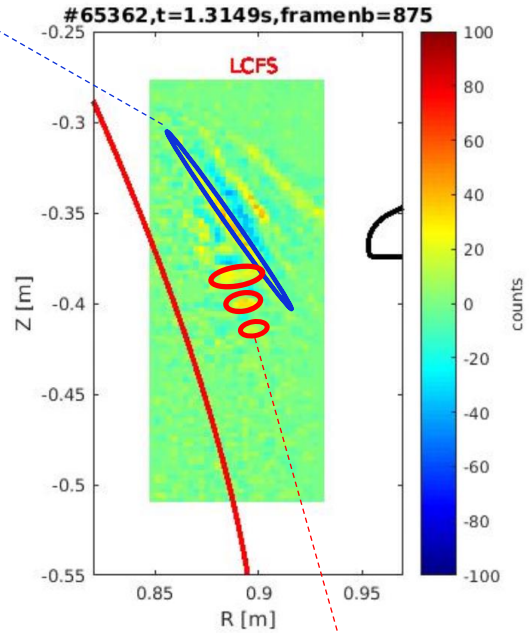



Shape and motion as expected if traced along B-field from “upstream”




These structures live only in the divertor

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

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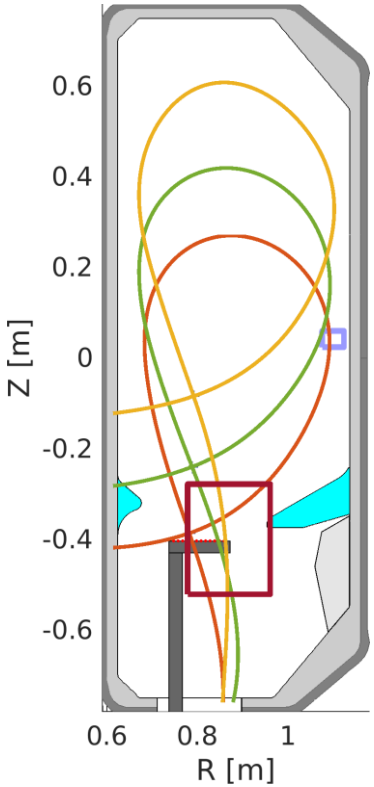
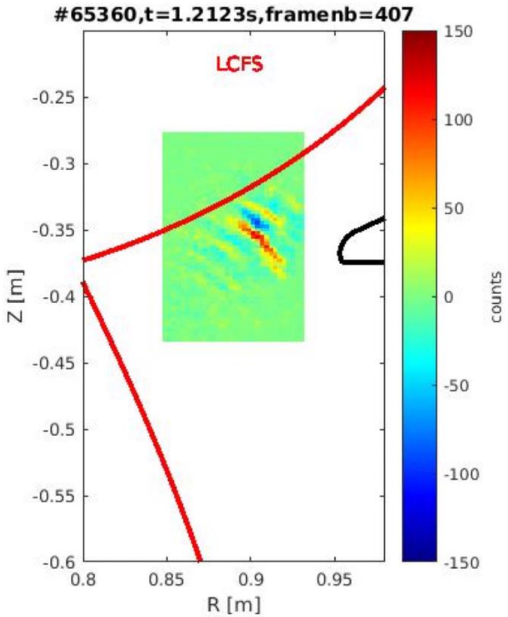



- Divertor filaments estimated to contribute significantly to cross-field transport
- Consistent with density profile broadening measured along the divertor leg with probes



[C. Wüthrich et al., Nucl. Fusion 62, 106022 (2022)]
[C. Wüthrich et al., Nucl. Fusion 2024, in press]

# Our approach



Development of new measurement devices (diagnostics)

Power exhaust experiments in alternative divertor configurations

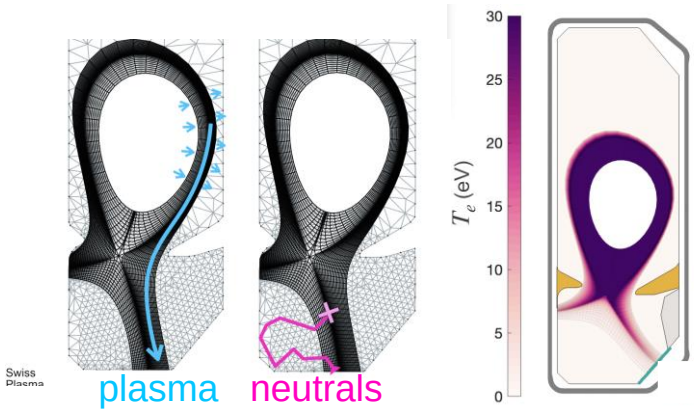
Experimental characterization of turbulence in the boundary plasma

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

# Main tools of the TCV boundary group

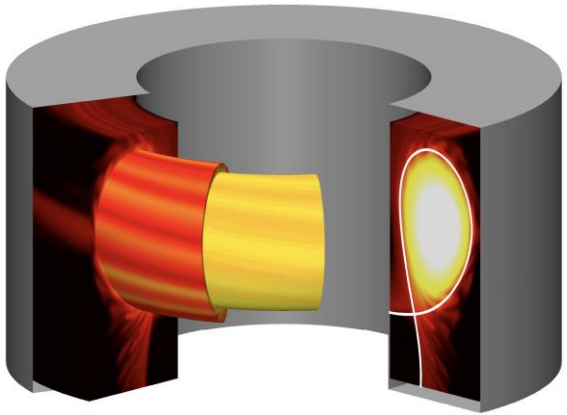
## Edge transport codes, primarily SOLPS-ITER[1]

- Fluid plasma, kinetic neutrals
- 2D, turbulence represented by ad-hoc diffusion coefficients
- Relatively fast, used to design the ITER divertor




## GBS[2]

- Fluid plasma, kinetic neutrals
- Global, 3D
- First principles turbulence
- Computationally more challenging



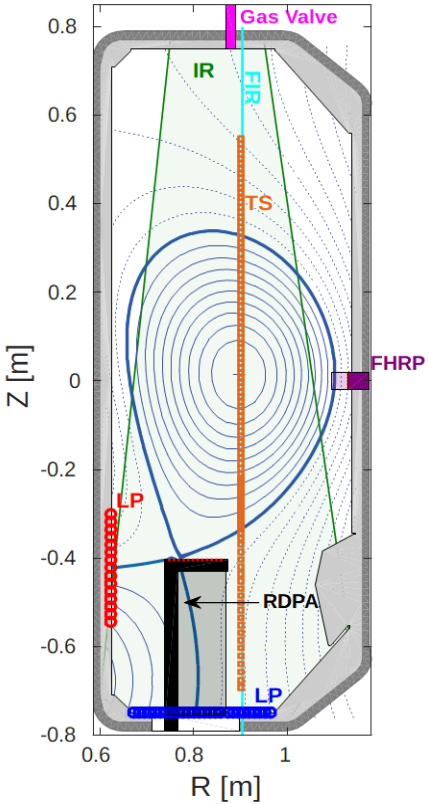


[1] S. Wiesen et al., JNM 2015

[2] P. Ricci et al., PPCF 2012

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

Christian Theiler



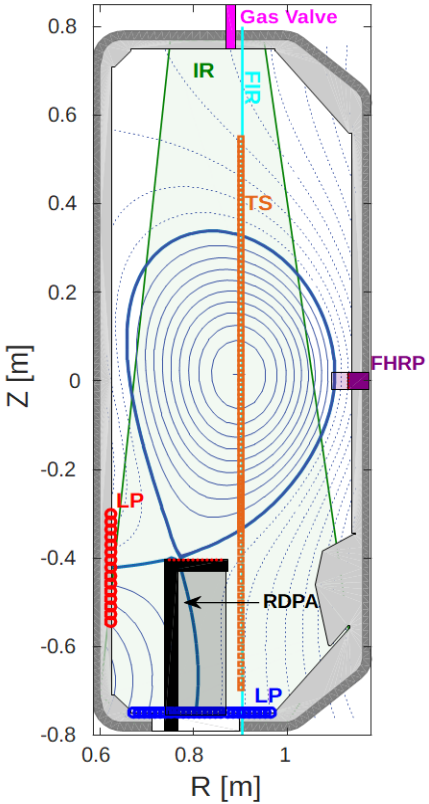

- Plasma ran at reduced magnetic field to reduce computational costs
- Diagnosed with a wide range of diagnostics ⟶ 45 different observables; **all data** is **publicly available** for future code validation studies
- Simulations quantitatively validated against experiment, using rigorous metric and validation quality factor

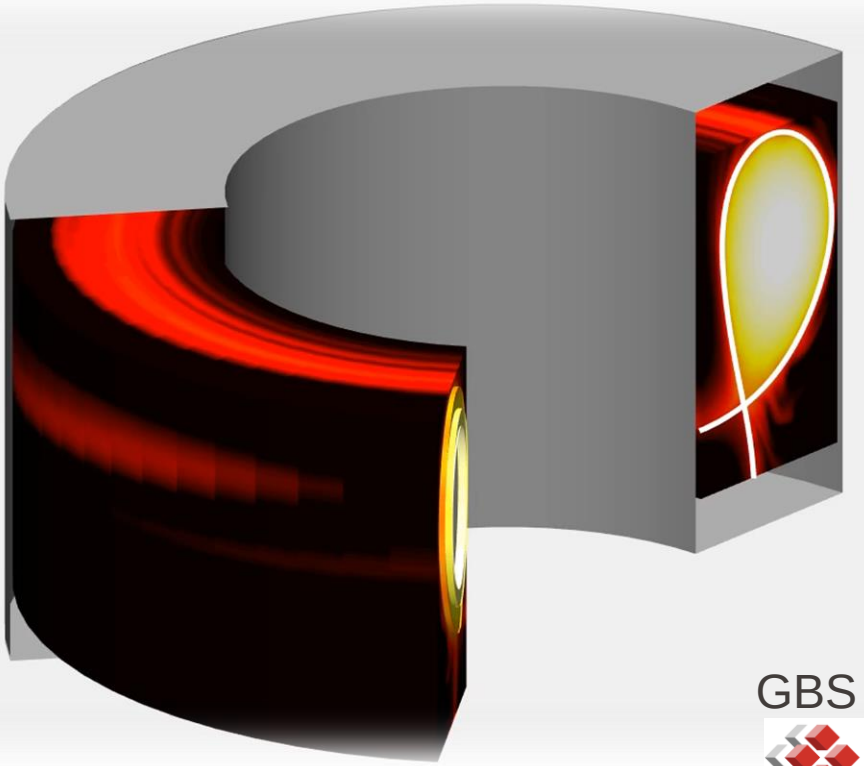


[D. S. Oliveira, T. Body et al., Nucl. Fusion 62, 096001 (2022)]

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

Christian Theiler



GBS simulation

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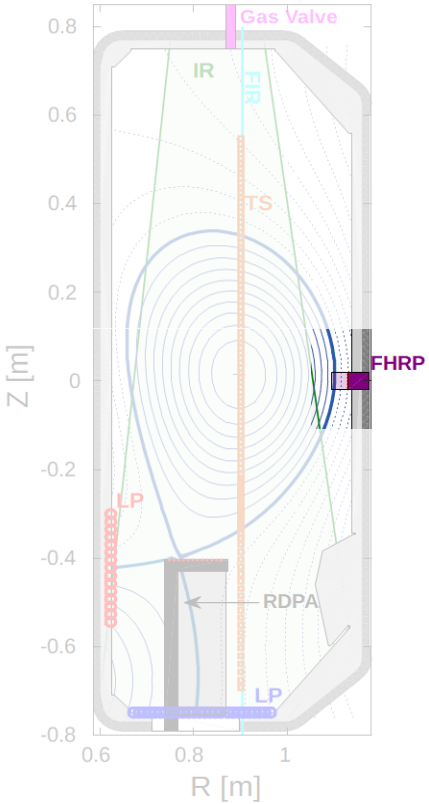
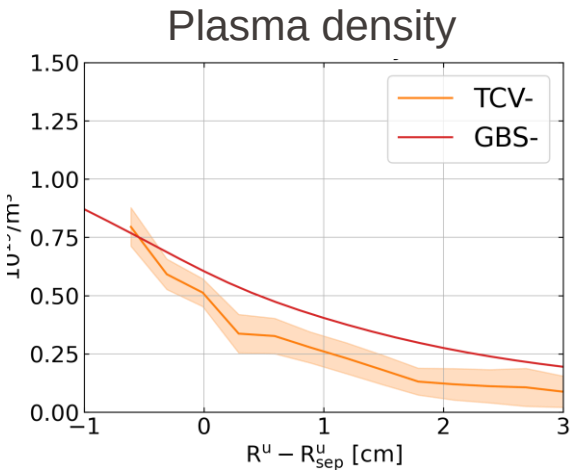
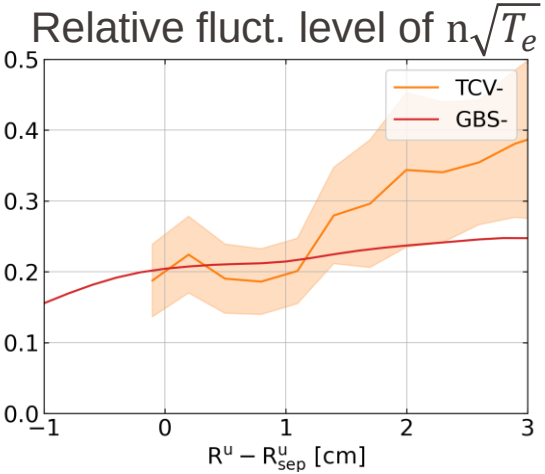
Visualisation by M. Giacomin

# Generally good sim-exp agreement near the main plasma




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

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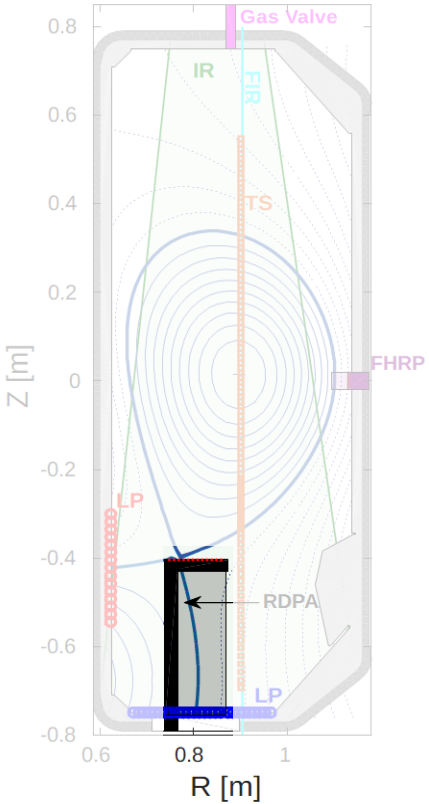
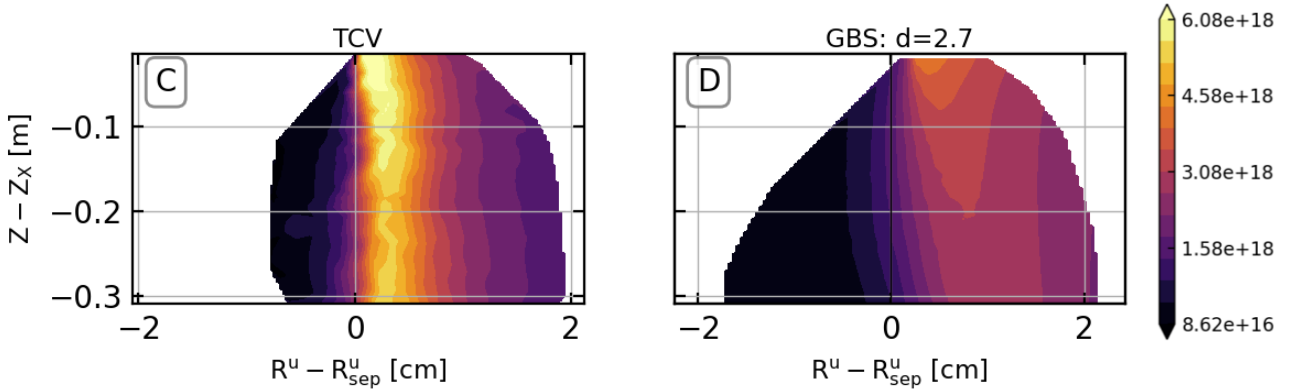
# Experiment and simulations start to deviate in divertor




Plasma density [$m^{-3}$]




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

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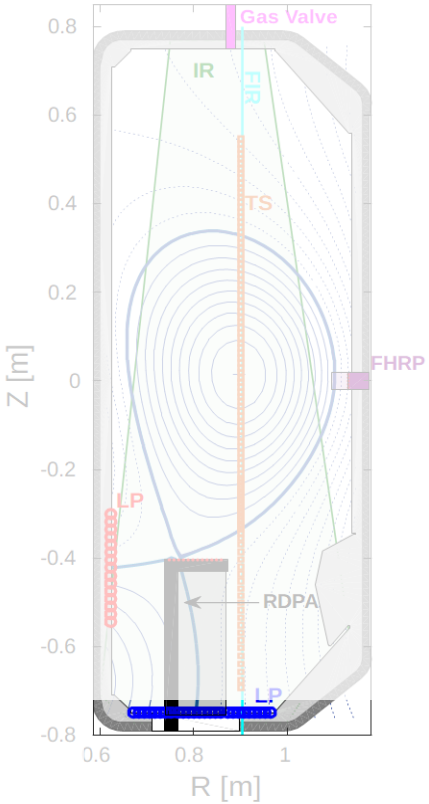
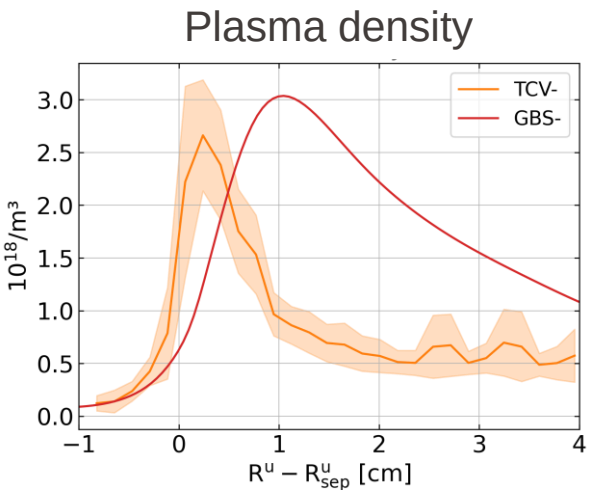
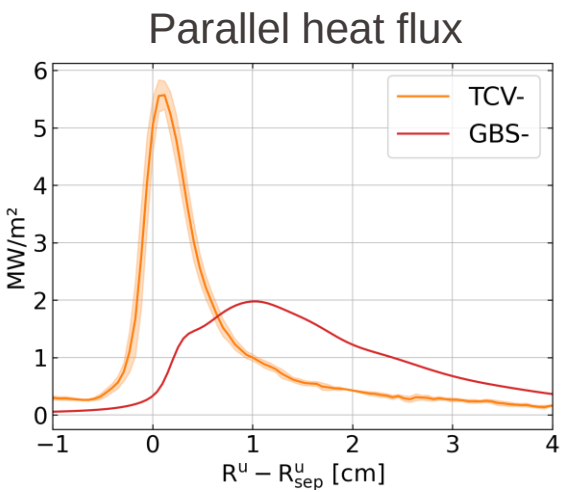
# Floor profiles wider and shifted outwards in simulations

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# Validation metric reflects better upstream agreement

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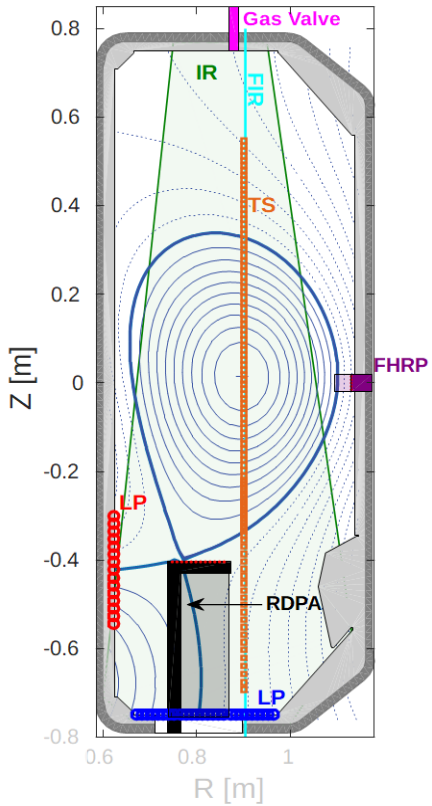
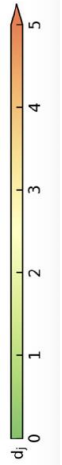



| Diagnostic | observable | GBS(+) $d_j$ | GBS(+) $S$ | GBS(−) $d_j$ | GBS(−) $S$ |
|---|---|---|---|---|---|
| Fast horizontally-reciprocating probe (FHRP) for outboard midplane | $n$ | 1.35 | 0.841 | 0.712 | 0.899 |
| | $T_e$ | 0.66 | 0.765 | 0.426 | 0.825 |
| | $V_{pl}$ | 0.482 | 0.774 | 2.21 | 0.78 |
| | $J_{sat}$ | 1.27 | 0.89 | 0.663 | 0.893 |
| | $\sigma\,(J_{sat})$ | 4.73 | 0.889 | 1.64 | 0.939 |
| | skew $(J_{sat})$ | 2.44 | 0.81 | 1.81 | 0.912 |
| | kurt $(J_{sat})$ | 2.8 | 0.829 | 2.37 | 0.934 |
| | $V_{fl}$ | 4.52 | 0.833 | 6.38 | 0.901 |
| | $\sigma\,(V_{fl})$ | 5.11 | 0.949 | 8.78 | 0.963 |
| | $M_{\parallel}$ | 2.18 | 0.925 | 7.9 | 0.92 |
| | $(\chi;Q)_{\mathrm{FHRP}}$ | **(0.62;** | **4.02)** | **(0.61;** | **4.25)** |
| Thomson scattering (TS) for divertor entrance | $n$ | 1.09 | 0.877 | 0.59 | 0.908 |
| | $T_e$ | 3.28 | 0.89 | 3.93 | 0.907 |
| | $(\chi;Q)_{\mathrm{TS}}$ | **(0.52;** | **0.883)** | **(0.5;** | **0.908)** |
| Reciprocating divertor probe array (RDPA) for divertor volume | $n$ | 3.2 | 0.853 | 1.87 | 0.882 |
| | $T_e$ | 7.18 | 0.925 | 4.54 | 0.919 |
| | $V_{pl}$ | 5.6 | 0.926 | 4.86 | 0.903 |
| | $J_{sat}$ | 3.09 | 0.856 | 2.3 | 0.869 |
| | $\sigma\,(J_{sat})$ | 4.29 | 0.832 | 3.28 | 0.823 |
| | skew $(J_{sat})$ | 3.43 | 0.779 | 1.5 | 0.715 |
| | kurt $(J_{sat})$ | 2.13 | 0.883 | 1.67 | 0.901 |
| | $V_{fl}$ | 31.3 | 0.915 | 113 | 0.882 |
| | $\sigma\,(V_{fl})$ | 59.6 | 0.911 | 6.42 | 0.897 |
| | $M_{\parallel}$ | 11.3 | 0.912 | 14.7 | 0.91 |
| | $(\chi;Q)_{\mathrm{RDPA}}$ | **(0.99;** | **4.17)** | **(0.87;** | **4.12)** |

| Diagnostic | observable | GBS(+) $d_j$ | GBS(+) $S$ | GBS(−) $d_j$ | GBS(−) $S$ |
|---|---|---|---|---|---|
| Infrared camera (IR) for low-field-side target | $q_{\parallel}$ | 4.19 | 0.878 | 10.2 | 0.939 |
| | $(\chi;Q)_{\mathrm{LFS\text{-}IR}}$ | **(1.0;** | **0.293)** | **(1.0;** | **0.313)** |
| Wall Langmuir probes for low-field-side target | $n$ | 1.81 | 0.861 | 4.2 | 0.89 |
| | $T_e$ | 6.01 | 0.937 | 3.63 | 0.911 |
| | $V_{pl}$ | 9.63 | 0.951 | 3.79 | 0.925 |
| | $J_{sat}$ | 2.9 | 0.891 | 16.1 | 0.942 |
| | $\sigma\,(J_{sat})$ | 4.93 | 0.859 | 3.34 | 0.894 |
| | skew $(J_{sat})$ | 3.02 | 0.849 | 9.03 | 0.922 |
| | kurt $(J_{sat})$ | 1.96 | 0.904 | 15.5 | 0.971 |
| | $J_{\parallel}$ | 2.93 | 0.765 | 7.53 | 0.863 |
| | $\sigma\,(J_{\parallel})$ | 3.26 | 0.884 | 10.4 | 0.92 |
| | $V_{fl}$ | 6.54 | 0.854 | 5.66 | 0.794 |
| | $\sigma\,(V_{fl})$ | 5.83 | 0.907 | 6.88 | 0.916 |
| | $(\chi;Q)_{\mathrm{LFS\text{-}LP}}$ | **(0.96;** | **4.83)** | **(1.0;** | **4.97)** |
| Wall Langmuir probes for high-field-side target | $n$ | 4.49 | 0.879 | 3.75 | 0.909 |
| | $T_e$ | 13.7 | 0.958 | 6.21 | 0.926 |
| | $V_{pl}$ | 9.85 | 0.959 | 6.66 | 0.93 |
| | $J_{sat}$ | 2.59 | 0.861 | 8.76 | 0.93 |
| | $\sigma\,(J_{sat})$ | 4.51 | 0.797 | 4.16 | 0.874 |
| | skew $(J_{sat})$ | 3.2 | 0.796 | 4.14 | 0.767 |
| | kurt $(J_{sat})$ | 1.54 | 0.92 | 3.39 | 0.961 |
| | $J_{\parallel}$ | 5.35 | 0.821 | 10.1 | 0.864 |
| | $\sigma\,(J_{\parallel})$ | 4.15 | 0.84 | 3.31 | 0.876 |
| | $V_{fl}$ | 3.72 | 0.809 | 4.27 | 0.768 |
| | $\sigma\,(V_{fl})$ | 5.77 | 0.852 | 5.6 | 0.877 |
| | $(\chi;Q)_{\mathrm{HFS\text{-}LP}}$ | **(0.94;** | **4.75)** | **(1.0;** | **4.84)** |
| Overall | $\chi;Q$ | **(0.87;** | **18.9)** | **(0.86;** | **19.4)** |



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

# Key outcome of the detailed exp-sim comparison

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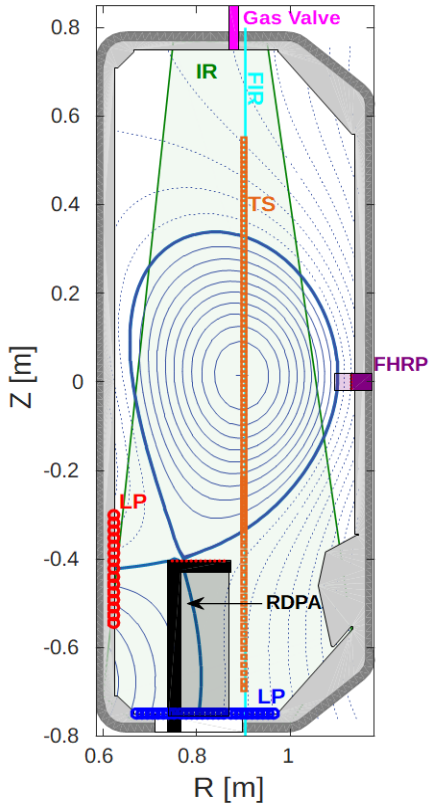



- Generally good sim-exp agreement near the main plasma (profile shapes, fluctuation levels,…)
- Poorer agreement in the divertor volume and near the wall, with significant deviations also among different codes
- More refined GBS simulations, including plasma-neutral interaction and relaxing some other approximations, currently ongoing

# Conclusions and next steps

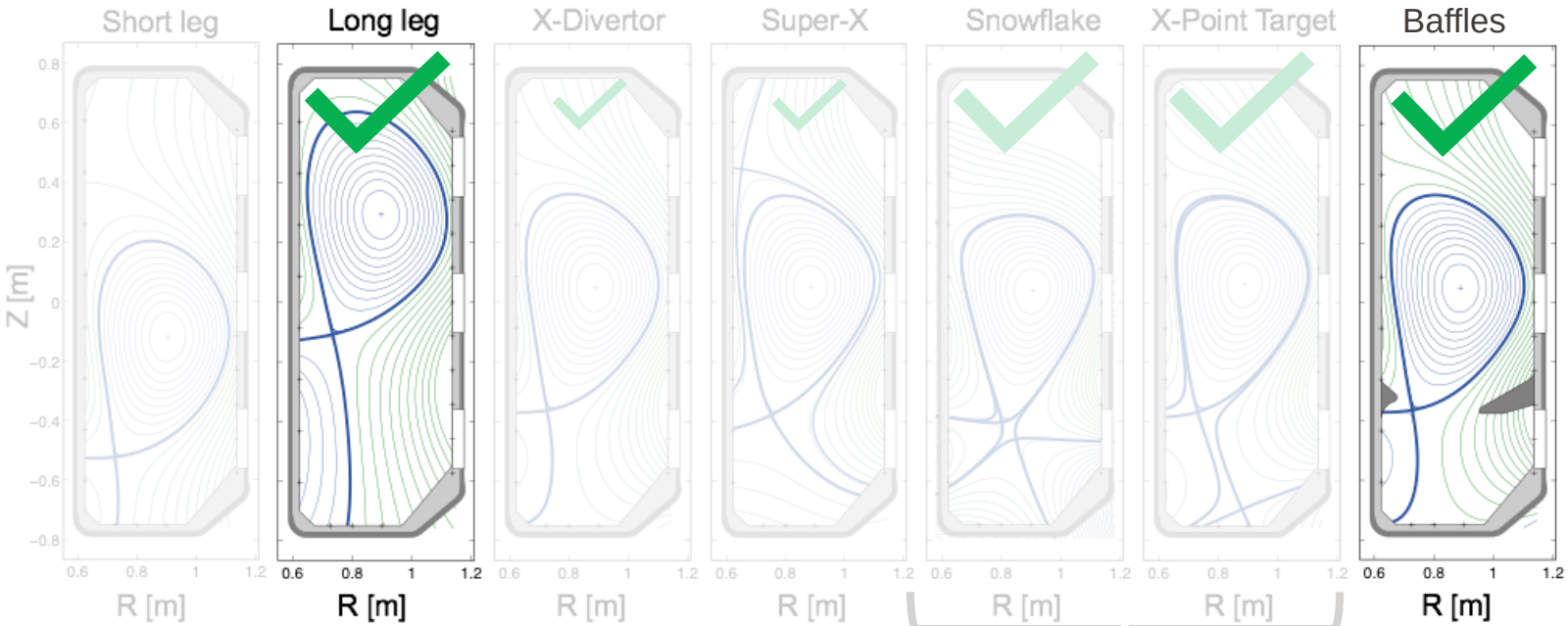


- Magnetic confinement fusion is a very attractive future energy source; Significant challenges on the path to a reactor remain, notably related to the boundary plasma and the challenge of safe *power exhaust*
- TCV's unique shaping capabilities and excellent diagnostic coverage are used to assess the prospects of alternative divertor magnetic geometries, some of which show high potential to substantially benefit power exhaust
- 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

- What's next?

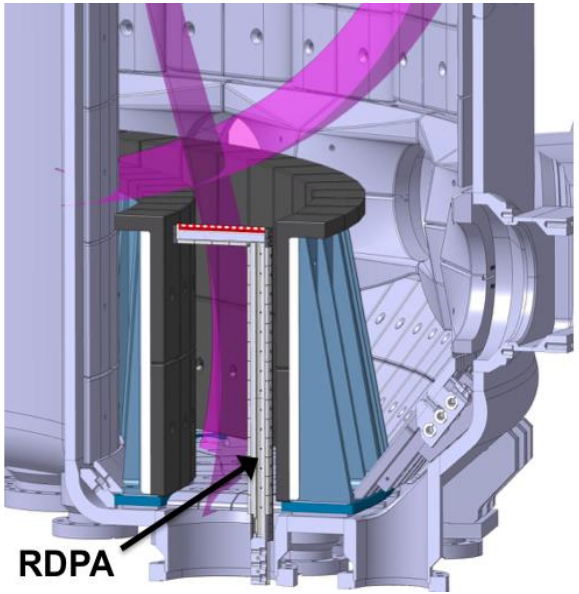
# Key benefits of geometrical properties assessed

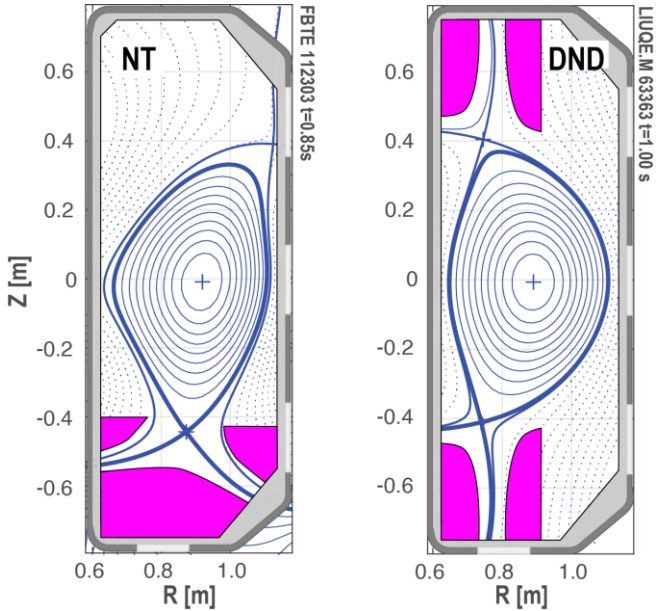




# Extension of TCV's experimental capabilities to combine these elements in optimized manner

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



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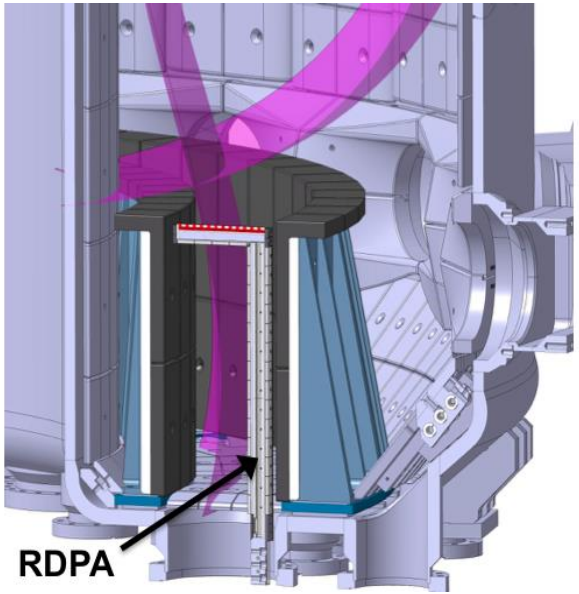
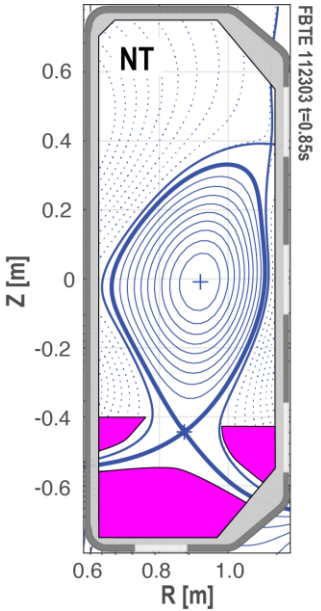
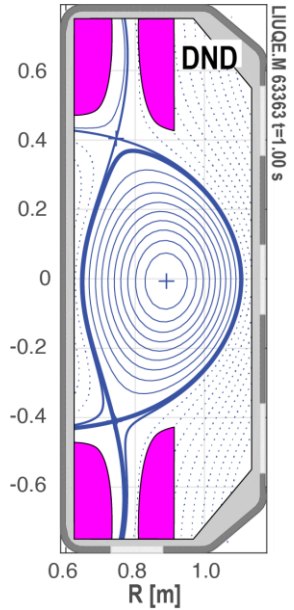
# Extension of TCV's experimental capabilities to combine these elements in optimized manner

2026: Develop validated physics basis of the concept




2028: Full integration with optimized core solution

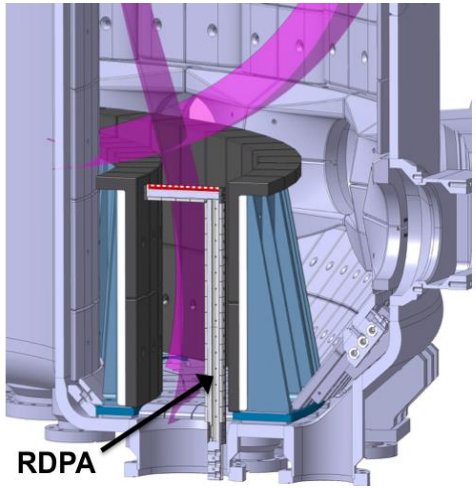


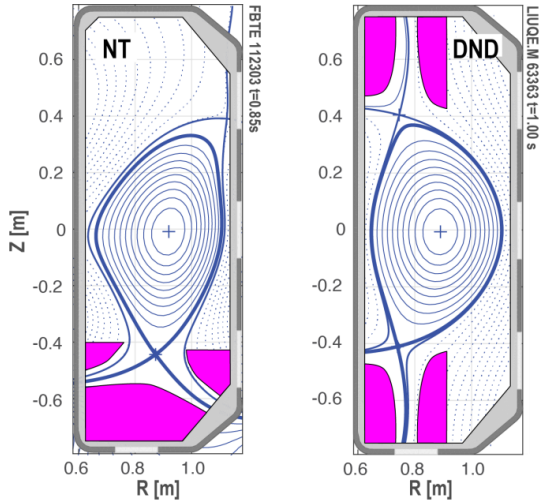



# Extension of TCV's experimental capabilities to combine these elements in optimized manner

2026: Develop validated physics basis of the concept

2028: Full integration with optimized core solution




- Part of a broader upgrade of SPC facilities, selected for the Swiss Roadmap for Research Infrastructures 2023, expected to be granted 2025-2028