The EU-DEMO Exhaust Modelling Roadmap – Numerical Implementation and Methods

S. Wiesen, L. Aho-Mantila, R. Osawa, F. Subba, L. Xiang, M. Siccinio, F. Maviglia, M. Coleman, F. Koechl, H. Zohm, M. Bernert, S. Brezinsek, S. Dasbach, A. Kit, D. Matveev, Y. Poels, A. Jaervinen, M. Wischmeier, M. van Berkel
and the EUROfusion DEMO central team (DCT)

FUSION TECHNOLOGY DEPARTMENT

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What is DEMO?

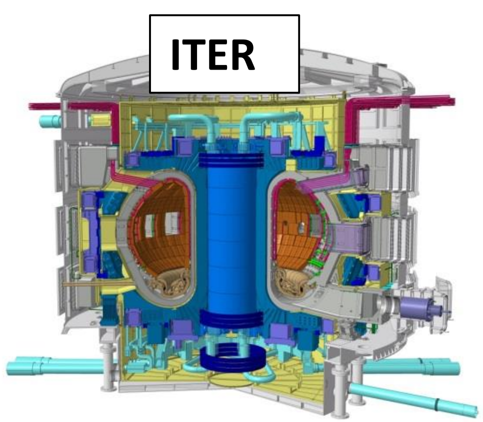
There is no unique definition of DEMO, and different parties have different opinions

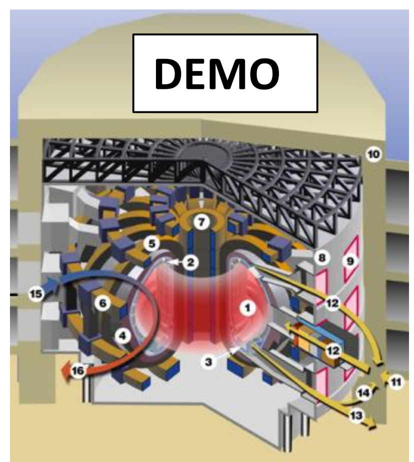
In the EU Roadmap, DEMO is the single step between ITER and a Fusion Power Plant (FPP)

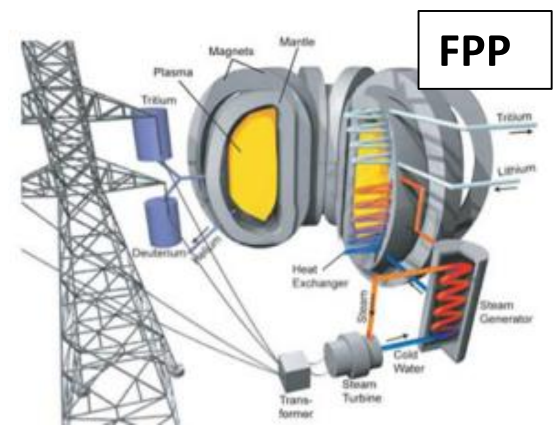
An EU high-level stakeholder group defined the following goals:

- large scale (100s of MW) predictable net electricity production $\Rightarrow$ *300 – 500* MW_e
- self-sufficient fuel cycle $\Rightarrow$ $TBR_{eff} > 1$
- high reliability and availability over a reasonable time span $\Rightarrow$ $\tau_{pulse} \geq 2$ *hrs*

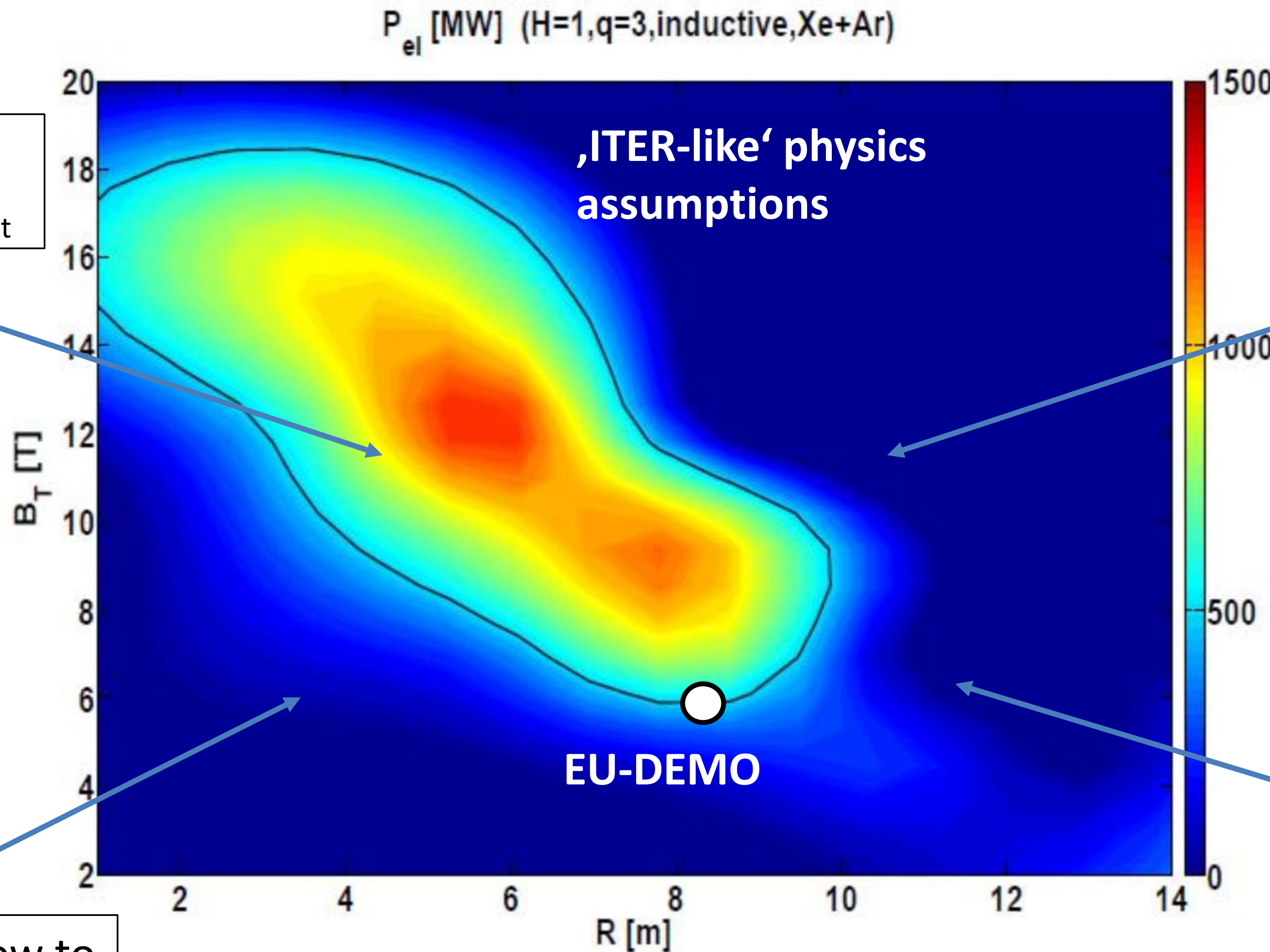
$\Rightarrow$ allow assessment of economic and environmental prospects of FPPs







DEMO design space heavily constrained by physics and technology



technology not (yet) mature to reach high B_t

synchrotron radiation losses too high

confinement too low to achieve necessary Q

divertor protection requires excessive impurity seeding

M. Siccinio et al., Nucl. Fusion 2017

The present EU-DEMO 'baseline'

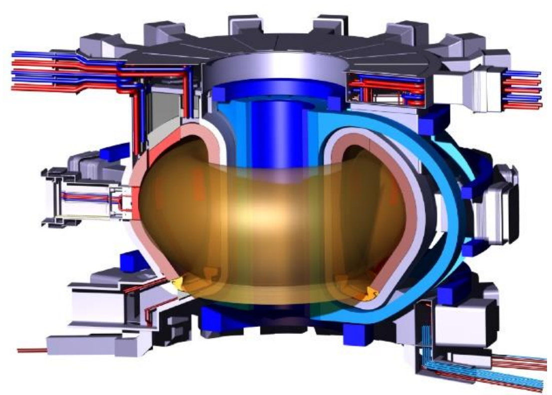
	EU-DEMO 2018 (PROCESS)
R [m]	9.00
A	3.1
B_0 [T]	5.86
q_{95}	3.89
δ_{95}	0.33
κ_{95}	1.65
I_p [MA]	17.75
P_{fus} [MW]	2000
P_{sep} [MW]	170.4
P_{LH} [MW]	120.8
H_{98}	0.98
β_N [% mT/MA]	2.5
Fusion Gain Q	>40
$P_{sep}B/q_{95}AR$ [MW T /m]	9.2
Pulse length [sec]	7200

Using ‚ITER-like' assumptions for physics and technology

- machine is ‚large' (1.5 x ITER in geometrical size)
- plasma parameters follow ITER physics basis, but normalised paramters differ (higher q_{95}, higher β_N)

Use of simple 0-D parameters like H_{98}, n/n_{GW} under DEMO conditions (high f_{rad}, high $n/n_{GW} > 1$…) questionable

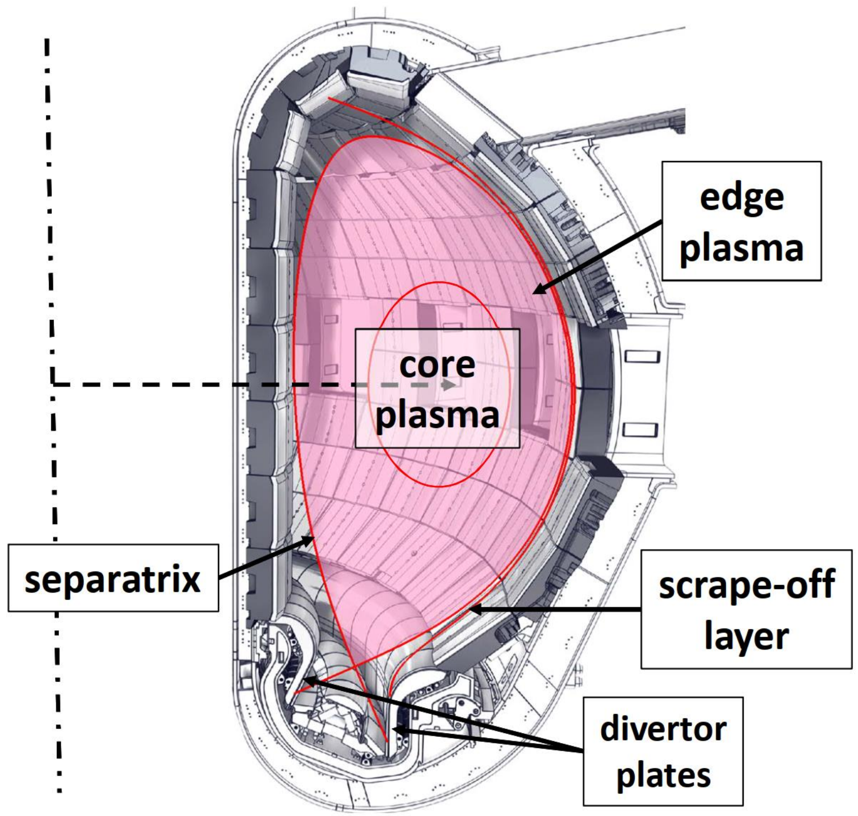
$\Rightarrow$ aim at predictive modelling of full plasma scenario (i.e. time dependent evolution of all profiles)

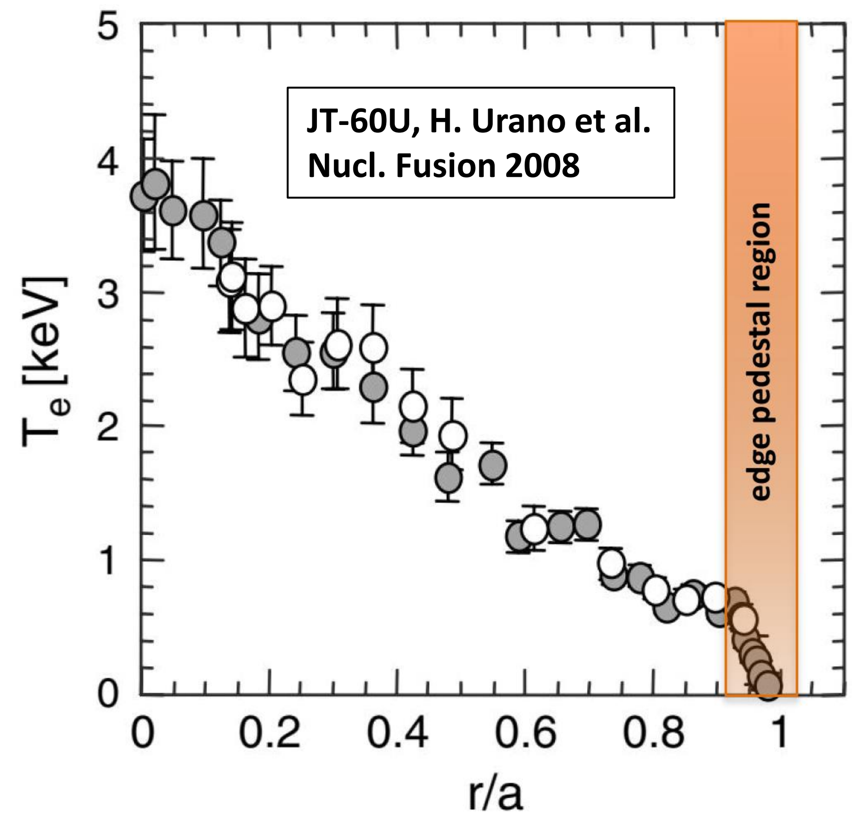


Open Choices:

- Plasma operating scenario
- Breeding blanket design concept
- Primary Blanket Coolant/ BoP
- Divertor configuration

Elements of the DEMO plasma scenario





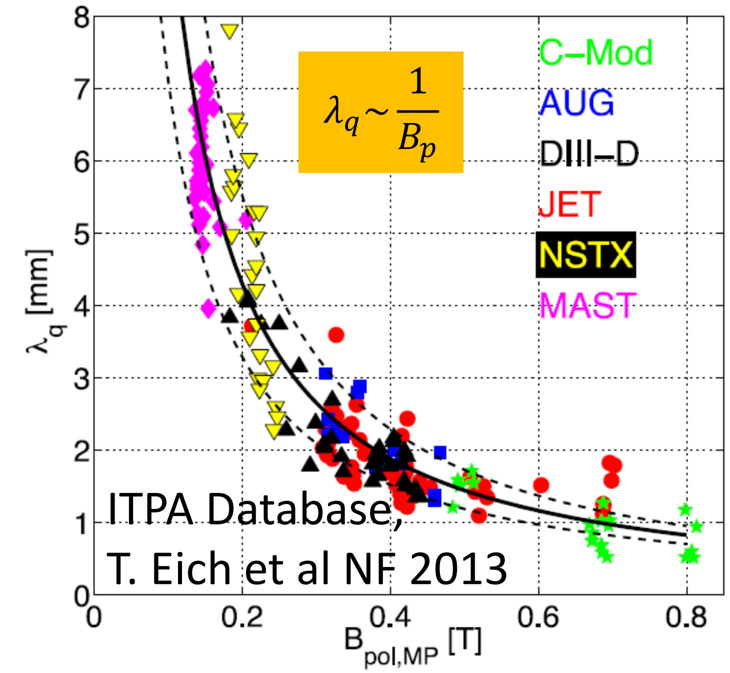
Assumption: plasma scenario broken down into 3 parts (non-linearly coupled)

- core: closed flux surfaces - burning plasma ($T_i \approx T_e \approx 30$ keV, $2 \times n_D \approx 2 \times n_T \approx n_e \approx 10^{20}$ m^{-3})
- scrape-off-layer / divertor: plasma flows along ‚open‘ field lines to divertor ($T_e = 5$ eV)
- edge: connects core and scrape-off-layer (closed flux surfaces, but different physics)

Power exhaust in a nutshell

$$q_{\|}^{up} = \frac{P_{SOL}}{A_{\|}} = \frac{P_{SOL} B}{2\pi R B_p \lambda_q} \propto \frac{P_{SOL} B_{tor}}{R}$$

Faitsch 2020



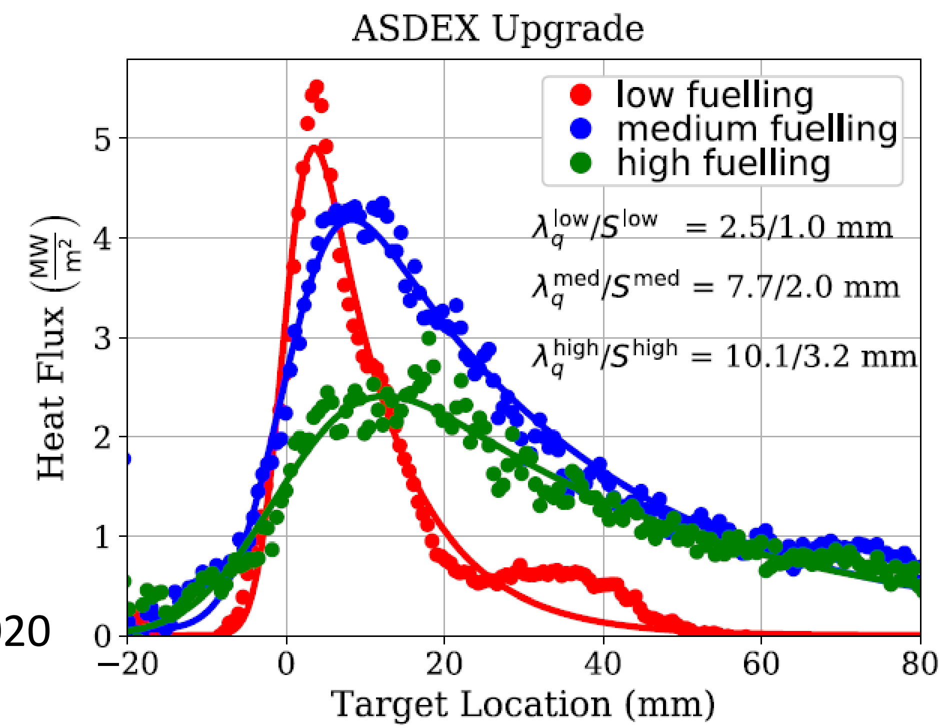
From the λ_q-scaling: upstream $q_{\|}$ ~ 30 GW/m^2 in DEMO (6 x higher than ITER)
→ Unmitigated $q_{\perp}^{target}$: 300 MW/m^2 for DEMO + radiation, neutrals, surface recombination
→ Clearly exceeds the tolerable material limit $q_{\perp}^{max}$ of 5-10 MW/m^2 (actively cooled W-PFC).

Achievable radiation in SOL:

$$f_{rad}^{achieve} = 1 - K \frac{p_u}{q_{\|}^u}(1 - f_{mom})$$

DEMO: high radiation in core → XPR

Power exhaust in a nutshell



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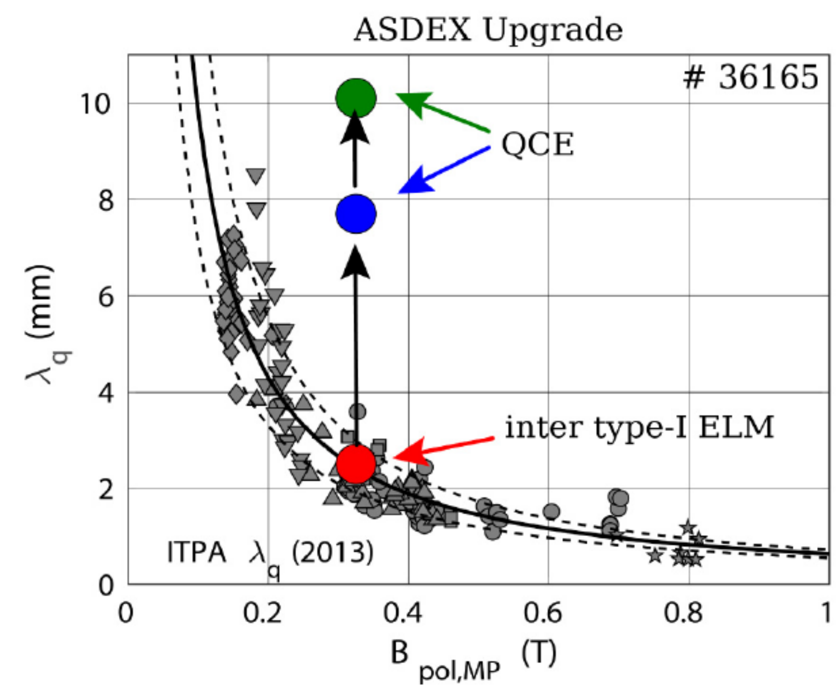

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Achievable radiation in SOL:

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DEMO: high radiation in core → XPR

... or other exhaust improved scenarios

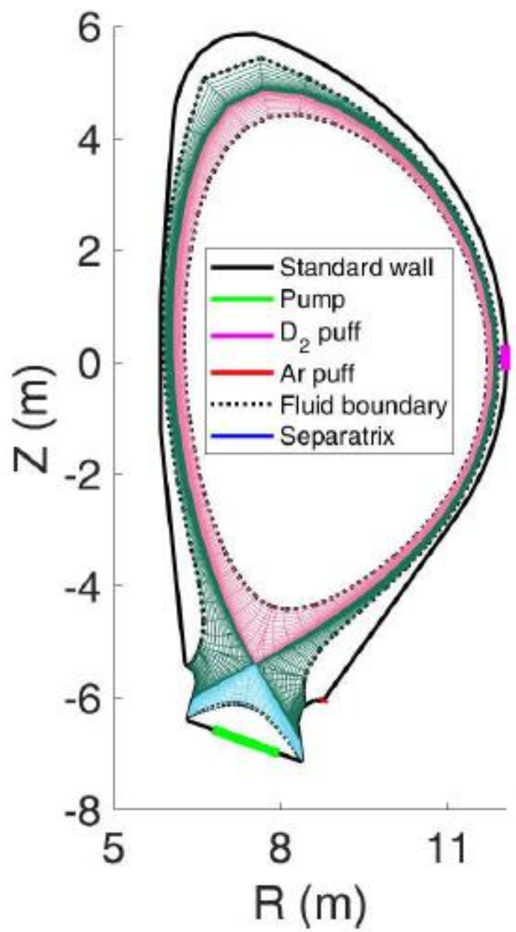
Baseline SOLPS-ITER fluid-kinetic model of EU DEMO divertor design

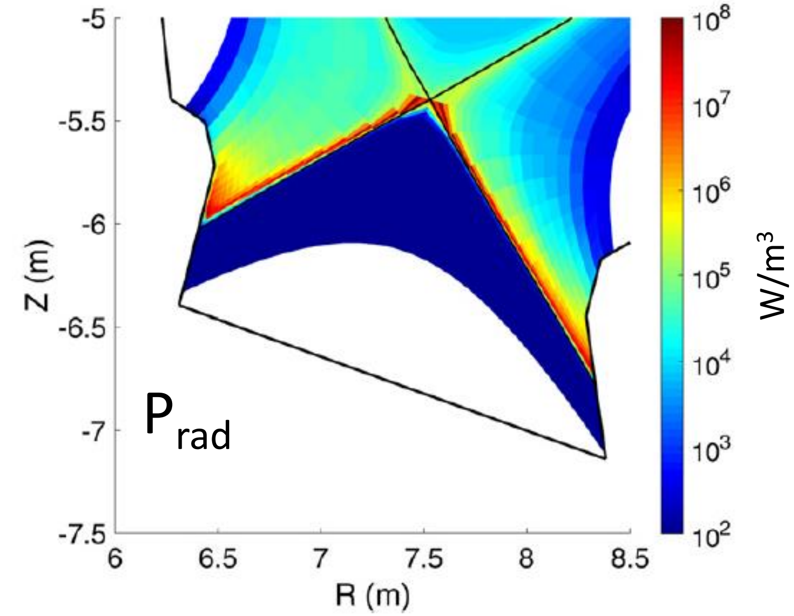
- **SOLPS-ITER D+He+Ar EU-DEMO reference, 21MA/4.9T scenario (2017), R=9m**
- assume: λ_q ~ 3mm
- 76% of P_{SOL} = 150MW dissipated by Ar radiation, f_{GW}= 0.42

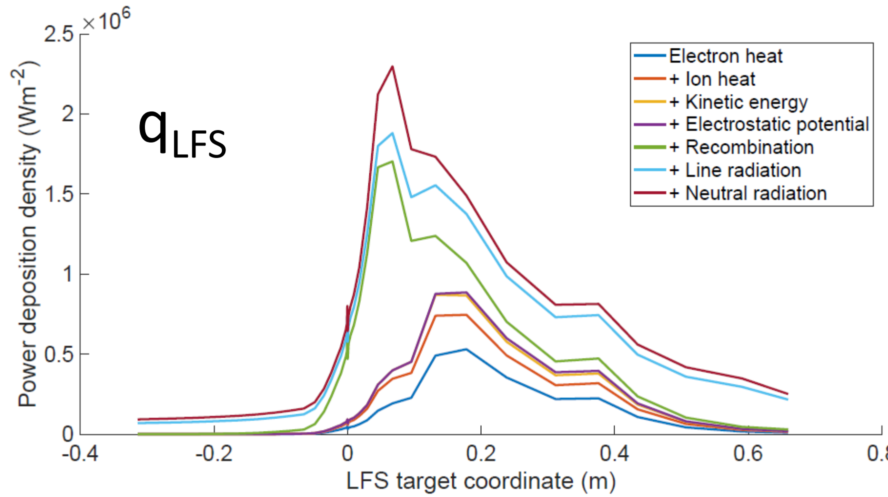
→ HFS fully detached
LFS partial detachment

- So far, no XPR exposed in model

→ 2022: Scans of $p_{0,div}$ and c_{Ar} to assess operational window







F. Subba et al NF 2020

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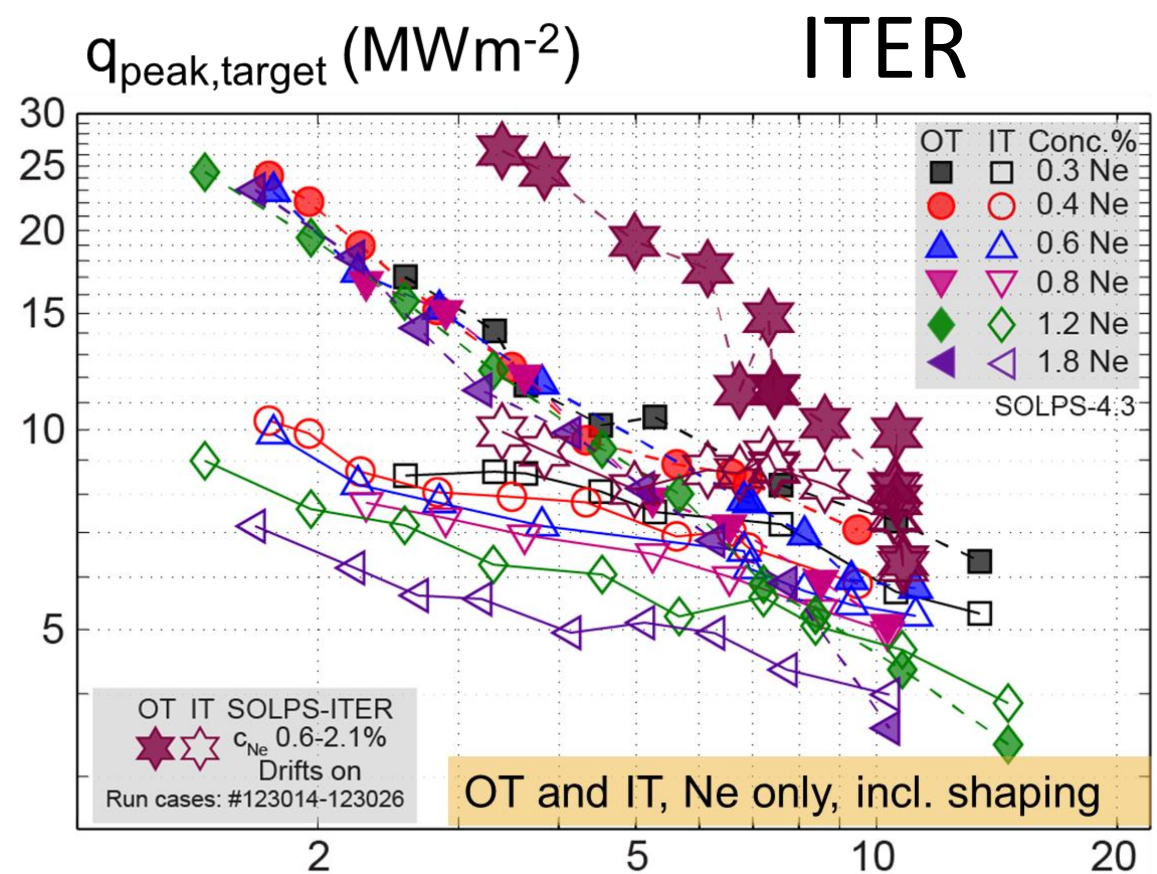
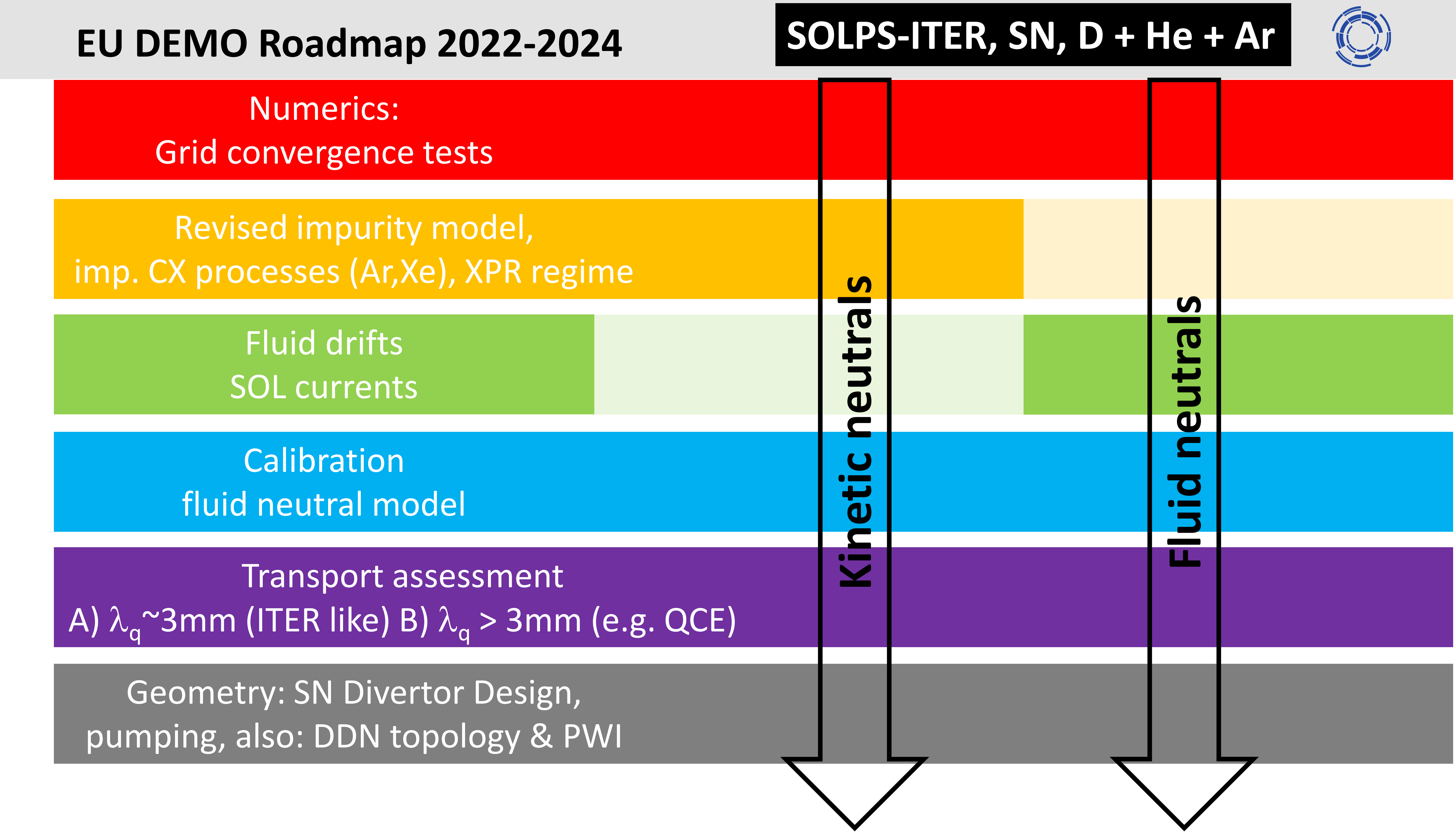
Role-model



Predict a possibiity to transform P_{sep} = 150 MW (=1.2 P_{LH}) to $q_{target,max}$ = 2 MW/m^2

- implicaties 67% of core radiaton (very different form ITER) – link to core plasma – tailoring radiation
- note that this does not include any transients – need time dependent modeling (e.g. how to accomodate QCE filaments, or pellets)

EU DEMO Roadmap 2022-2024

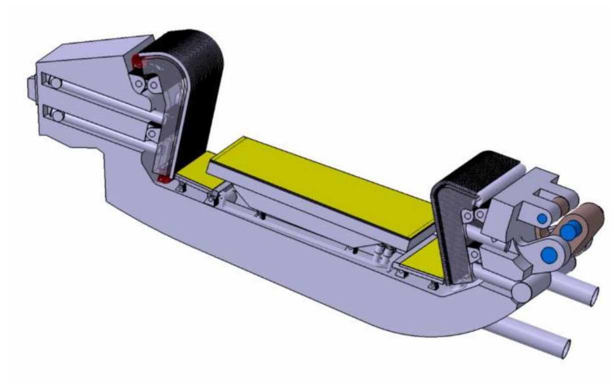


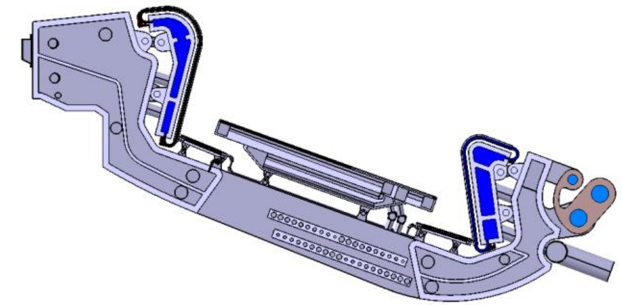
Review and design of EU DEMO divertor shape

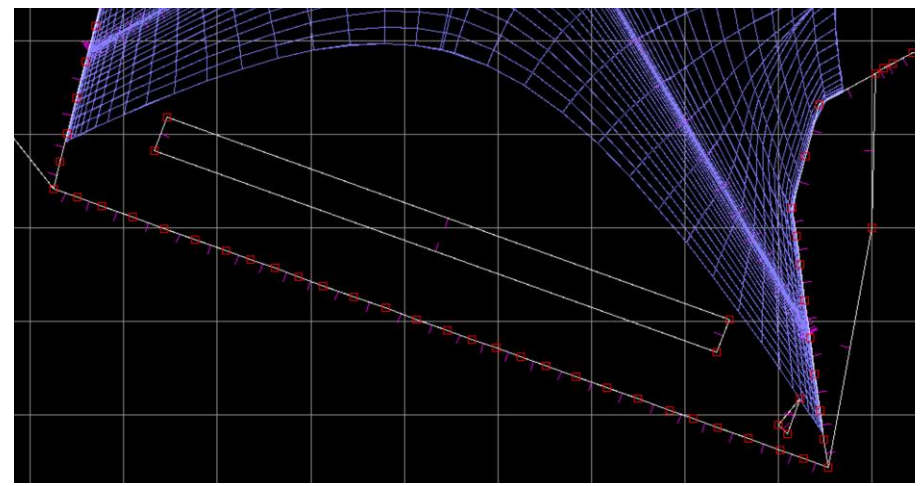
Divertor Optimization Shape & Engineering Systems

- Eg. inclusion of a liner, SOLPS-ITER being employed
- Assessment whetherin terms of baseline operational regime,
  the liner is advantageous w.r.t.
  He-exhaust and divertor performance
  (or otherwise too constraining in terms of the operational window for $p_{0,div}$)

→ **2022: further review of divertor structure and impact on plasma**
e.g. heat loads, neutral conductance, pumping, fuelling, erosion pattern of liner



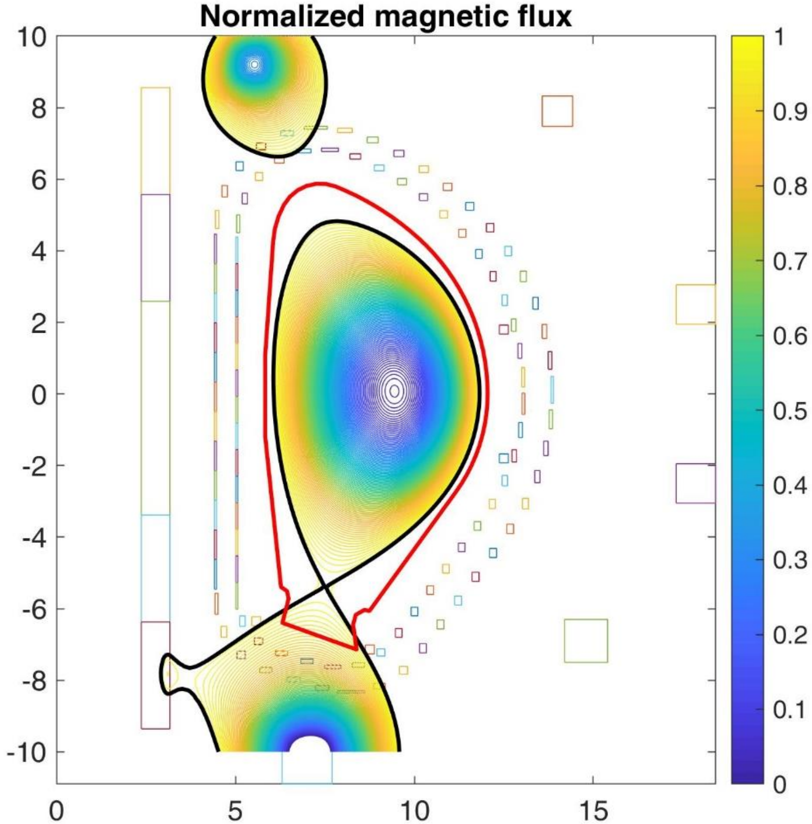




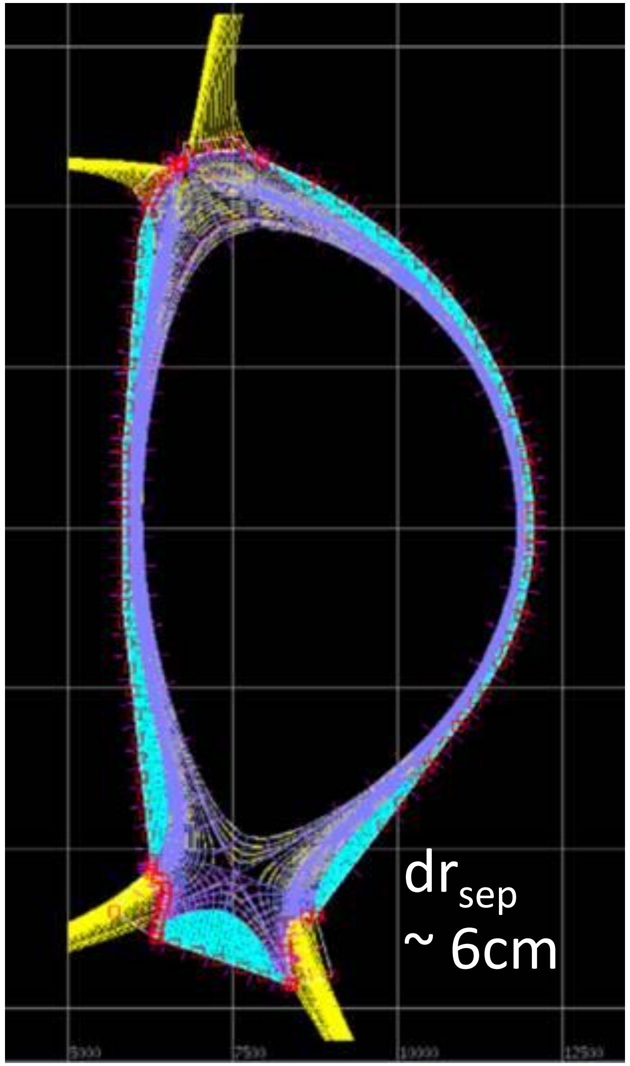
Courtesy F. Subba et al

Alternative approach: **automated design tool** for shape and magnetic field optimization accounting **for complex design & engineering constraints → W. Dekeyser et al this Wed**

EU DEMO Assessment of FW PWI employing ERO2.0



2021 equilibrium variant
Axis location: R=9.47 m, Z=0.06 m
Plasma current: 18.3 MA
$\mathbf{B_{tor}}$ **on axis:** 5.7 T



Courtesy
SOLPS-ITER grid, R. Osawa

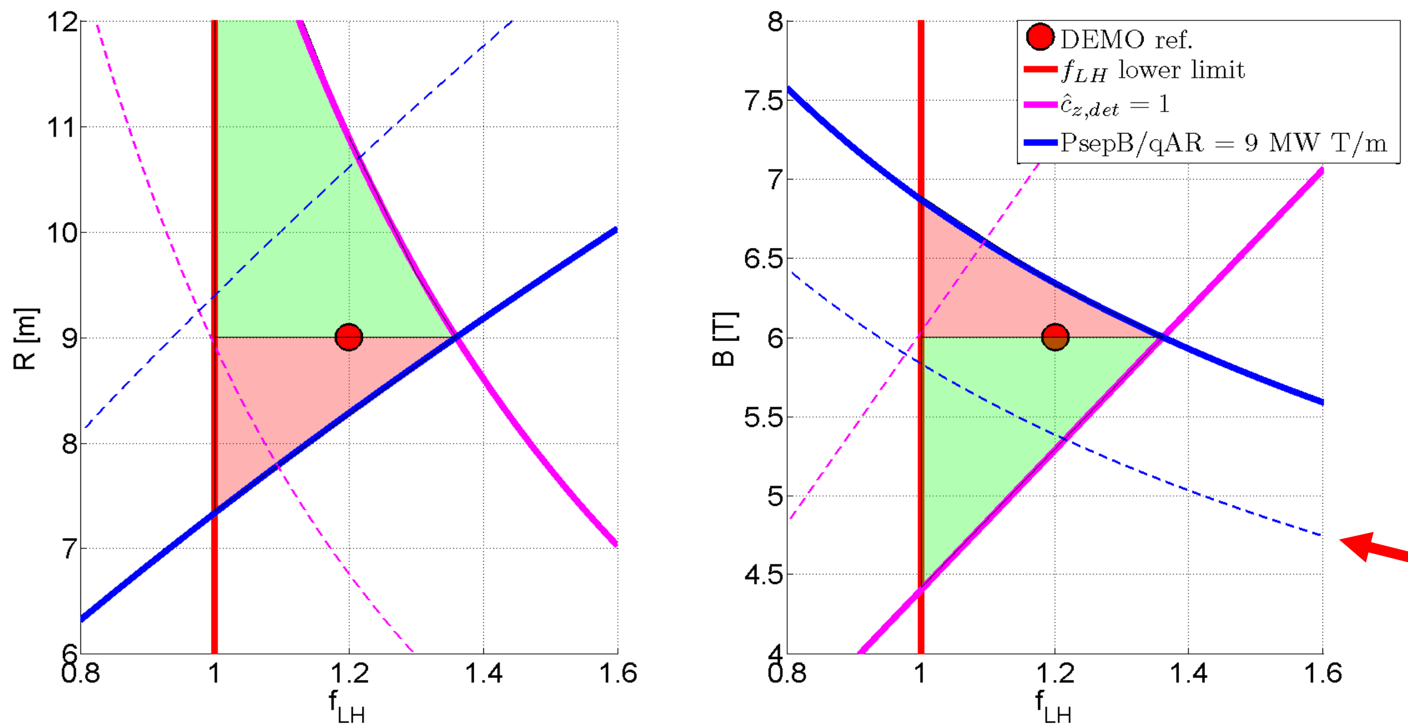
A quantitative assessment of the impact of 2nd XPoint on PWI & FW HF

- Requires extension of SOLPS-ITER simulation grid up to first wall
- **Provide detailed plasma/neutral distributions to ERO2.0** **volumetric & surface data, particle & heat fluxes, spectra, etc (EUROfusion TSVV7)**

Lifting the constraint of having the 2nd Xpoint not inside the vessel might provide **more flexibility to find an optimised (core) physics scenario**, e.g high-δ, QCE, (near) double-null, etc

Towards Reduced Models → Rapid Design, Systems Codes & Control

- Towards improved figure-of-merits for e.g. heat-flux (i.e. detachment) and c_Z
  → allows rapid design through systems code to find operational points for EU-DEMO
- Also assessment of: radial builds, plant analysis, plasma control systems (PCS), etc
- Current reduced models for exhaust based on incomplete scalings, no large $f_{rad,core}$ and no transients
  → Extensions of 0D/1D models calibrated or "trained" by high-fidelity models for the edge/SOL



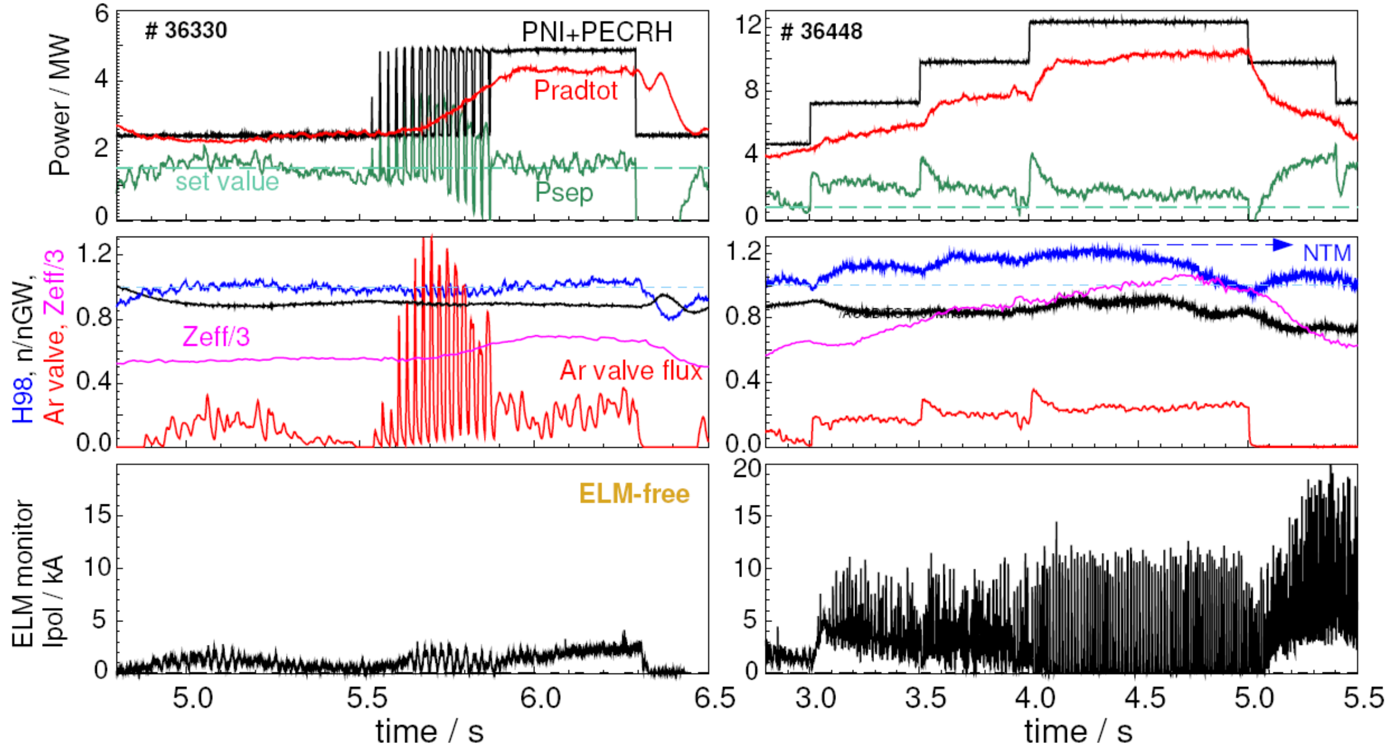
Based on
- Martin scaling for P_{LH}
- Goldston & Reinke Scalings for c_Z and λ_q

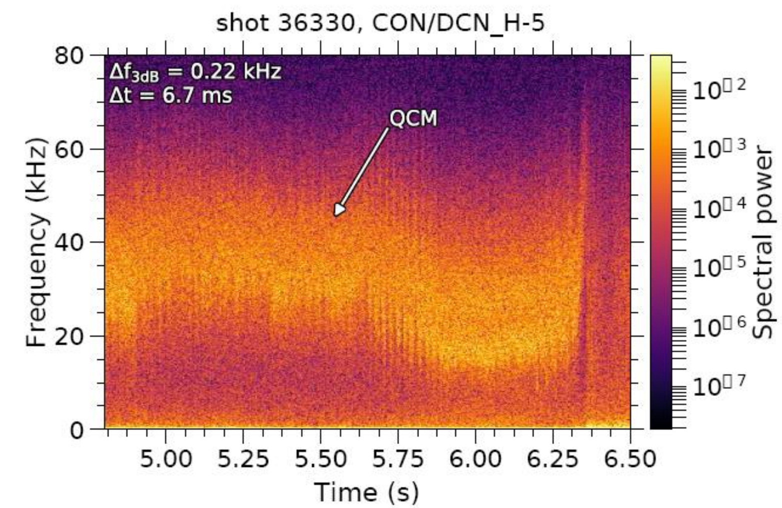
Conservative case:
$S = 0.5\lambda_q^{ref}$ $\hat{c}_{z,det} = 0.7$

Siccinio, NF 2019

Ar injection support transition into (close-to) ELM-free scenarios

Kallenbach 2020





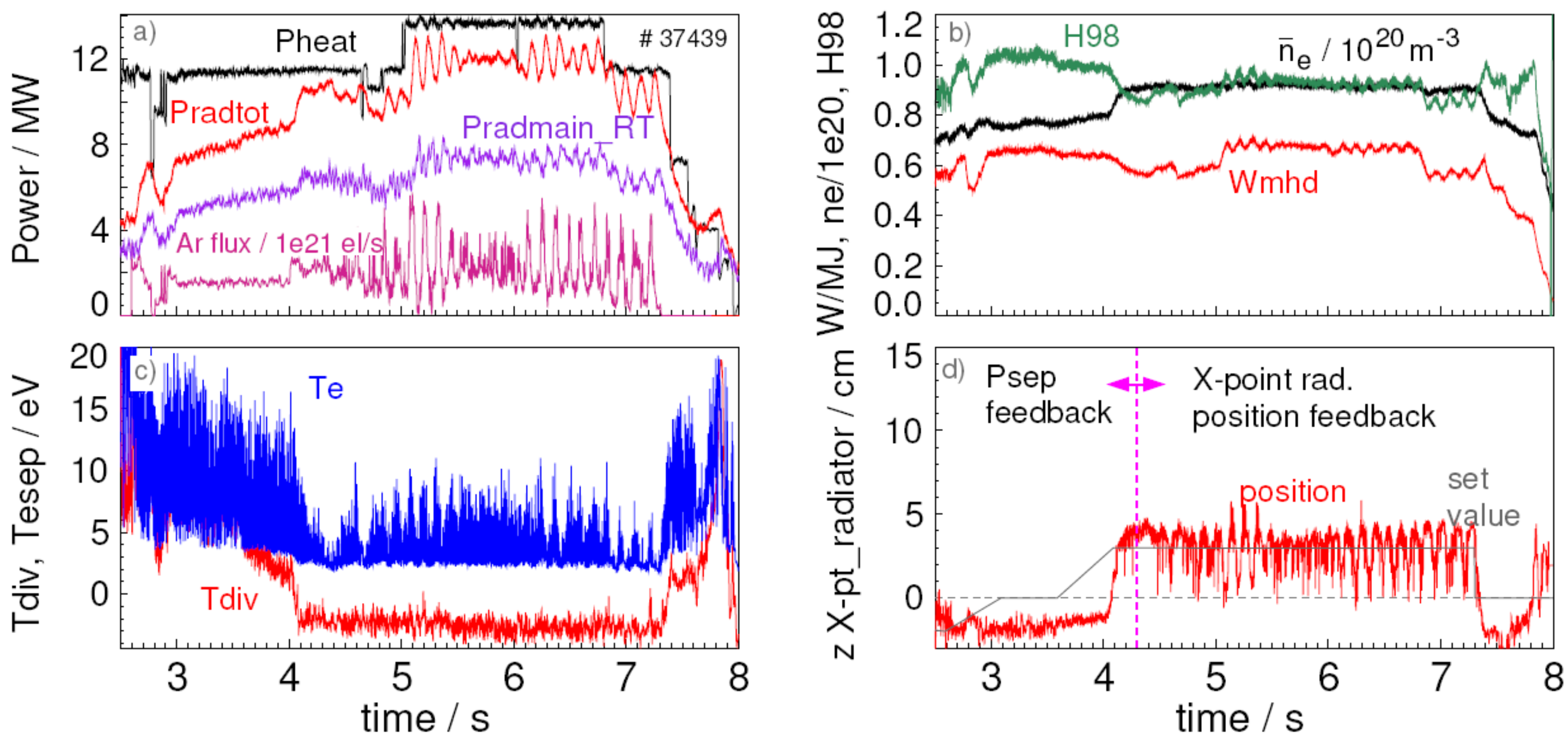
- Ar radiation provides additional power loss to extend the no-ELM regime to higher heating powers

- At higher power (12MW) closer to DEMO conditions: QCM disappears, H98=1.2 close to beta-limit, keeping scenario with smaller ELMs w/ partially detached conditions

- $P_{sep}=P_{heat}-P_{rad,main}$ control scheme hampered by radiation loss in confined region
→ full ELM suppression not achievable at higher power

Demonstration of Ar-seeded, high-power XP radiator regime

Kallenbach 2020

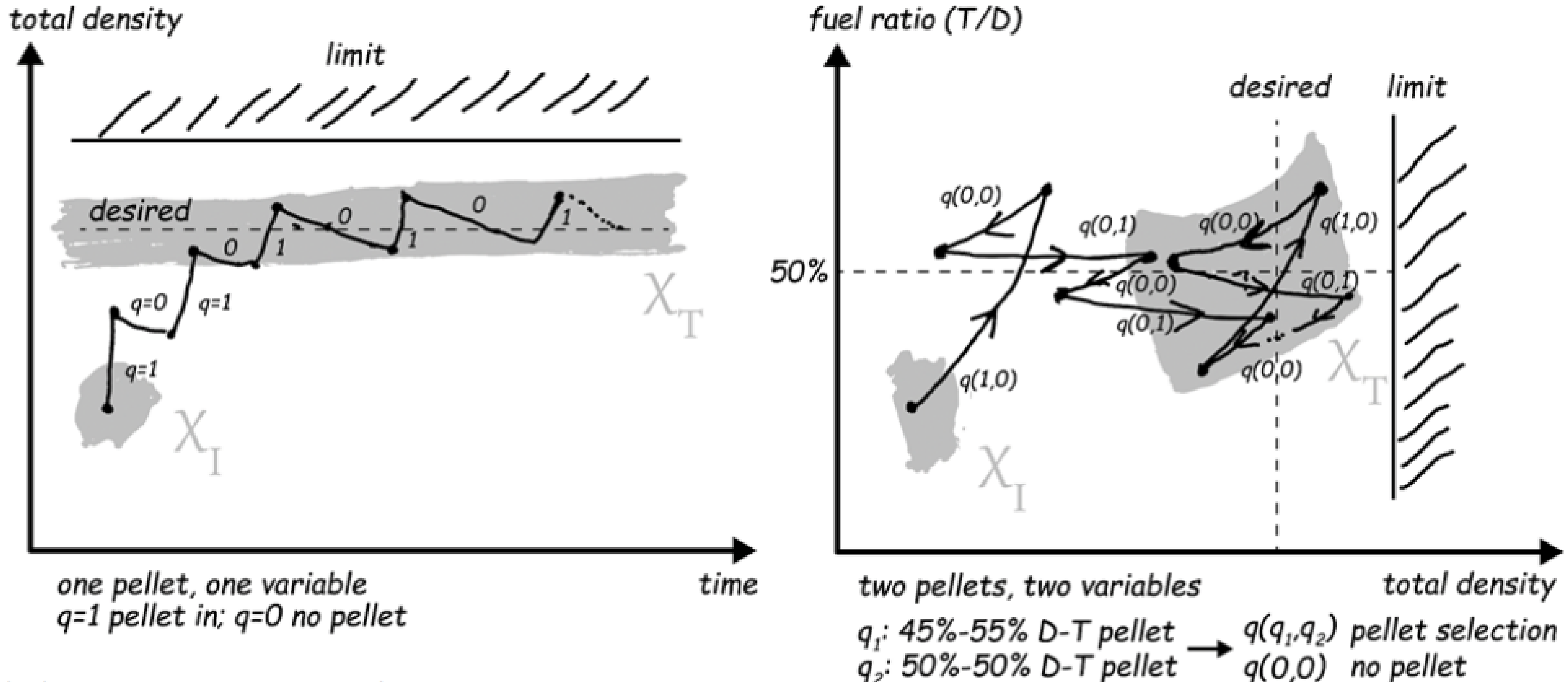


- Replacing P_{sep} control with XPR location control → stable! Also at highest power
- At higher power, transition into detached regime observed concomitantly with strong XPR, but lower H98 ~ 0.9

See also M. Bernert et al this Thu

Core performance control determines exhaust challenge

Power undulations that the exhaust controller need to suppress, originate from the core and are (partly) generated by core controllers (gas and pellets)

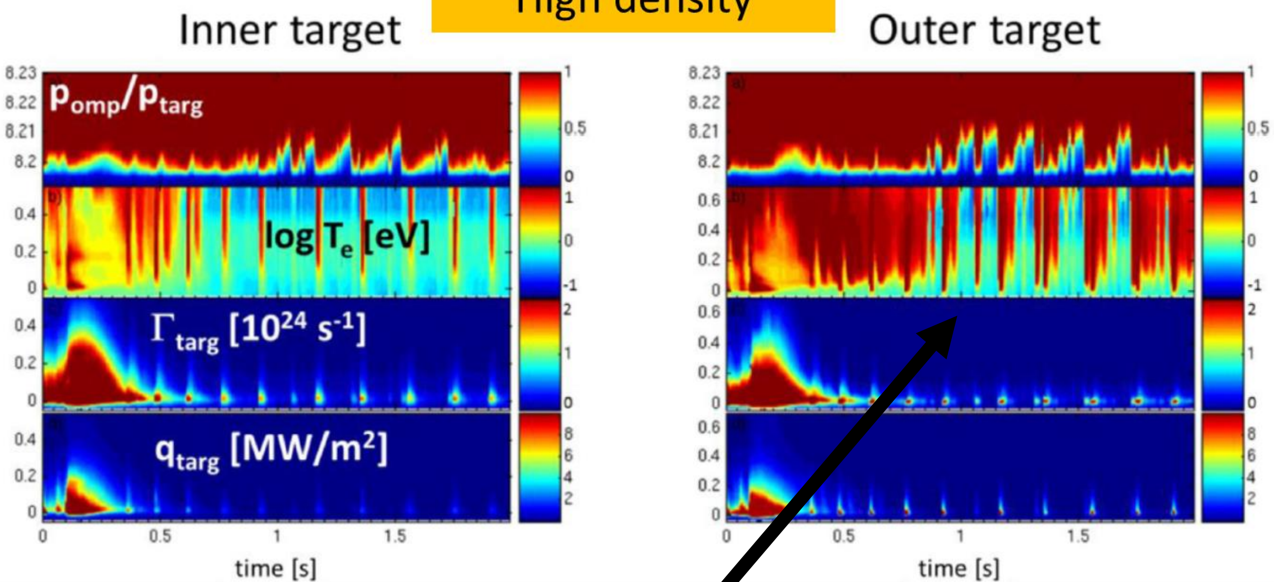


Van Berkel, 2021, *VIDI-proposal*

Bosman *et al* 2021 *J. Phys. Commun.* **5** 115015: shows that rudimentaire density core profile control with pellets is possible

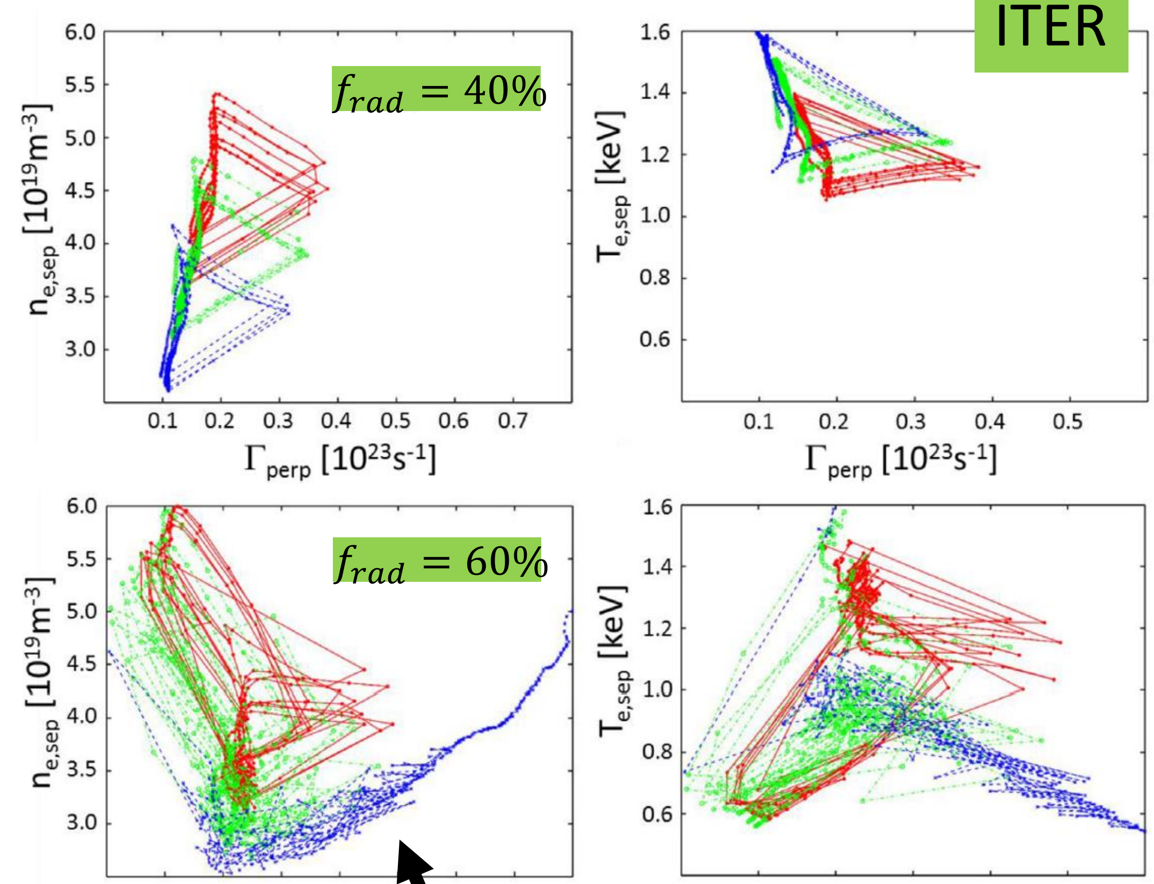
JINTRAC Flight-Simulator model of pellet ablation: ITER example

High density



Bursts of transient P_{SOL} increase during pellet ablation
→ causes re-attachment at LFS/HFS divertor

ITER



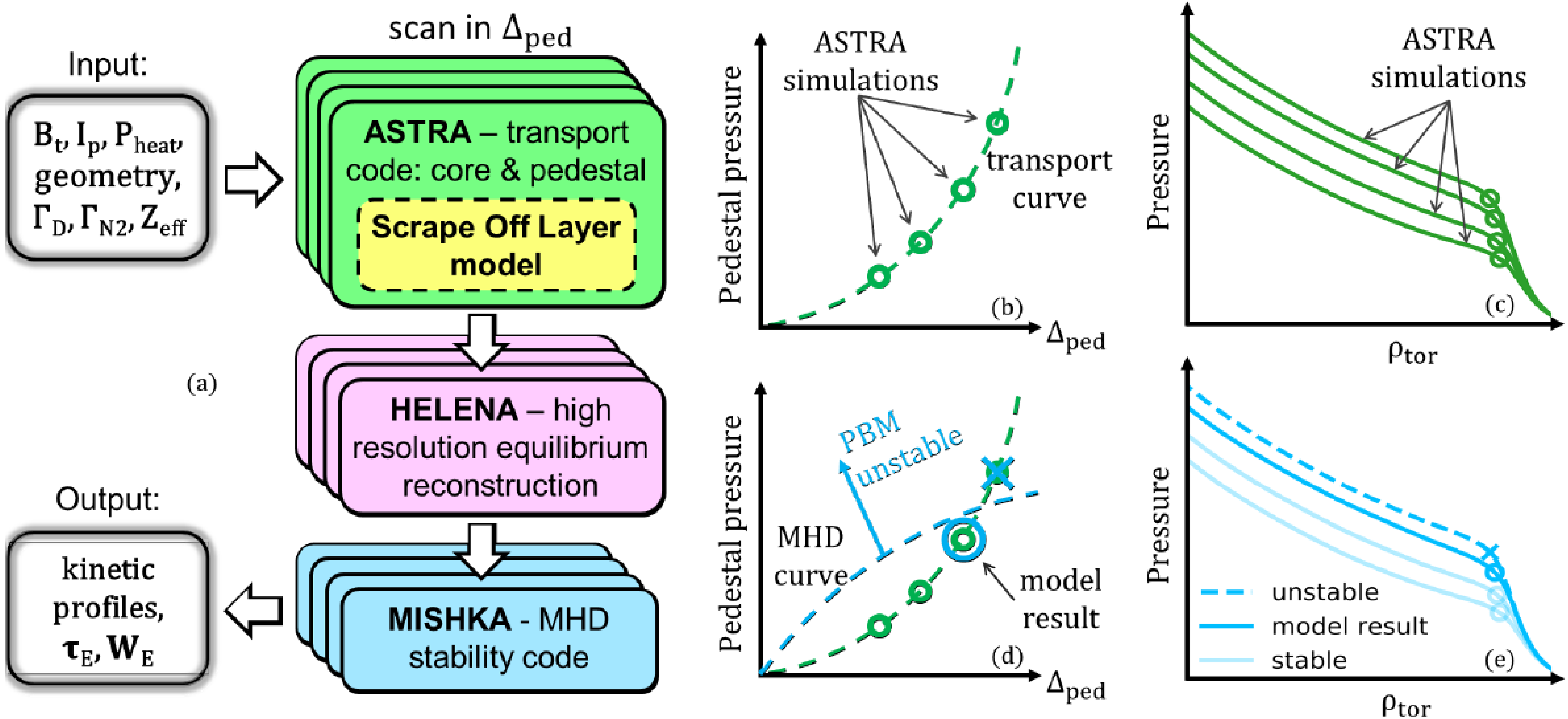
Impurity radiation control required

JINTRAC

[Wiesen, Köchl, NF 2017]

Towards fast Integrated modelling, flight-simulator type

Integrated Model based on Engineering Parameters



Courstesy
T. Luda et al, NF2020, EPS 2022

Towards fast Integrated modelling, flight-simulator type

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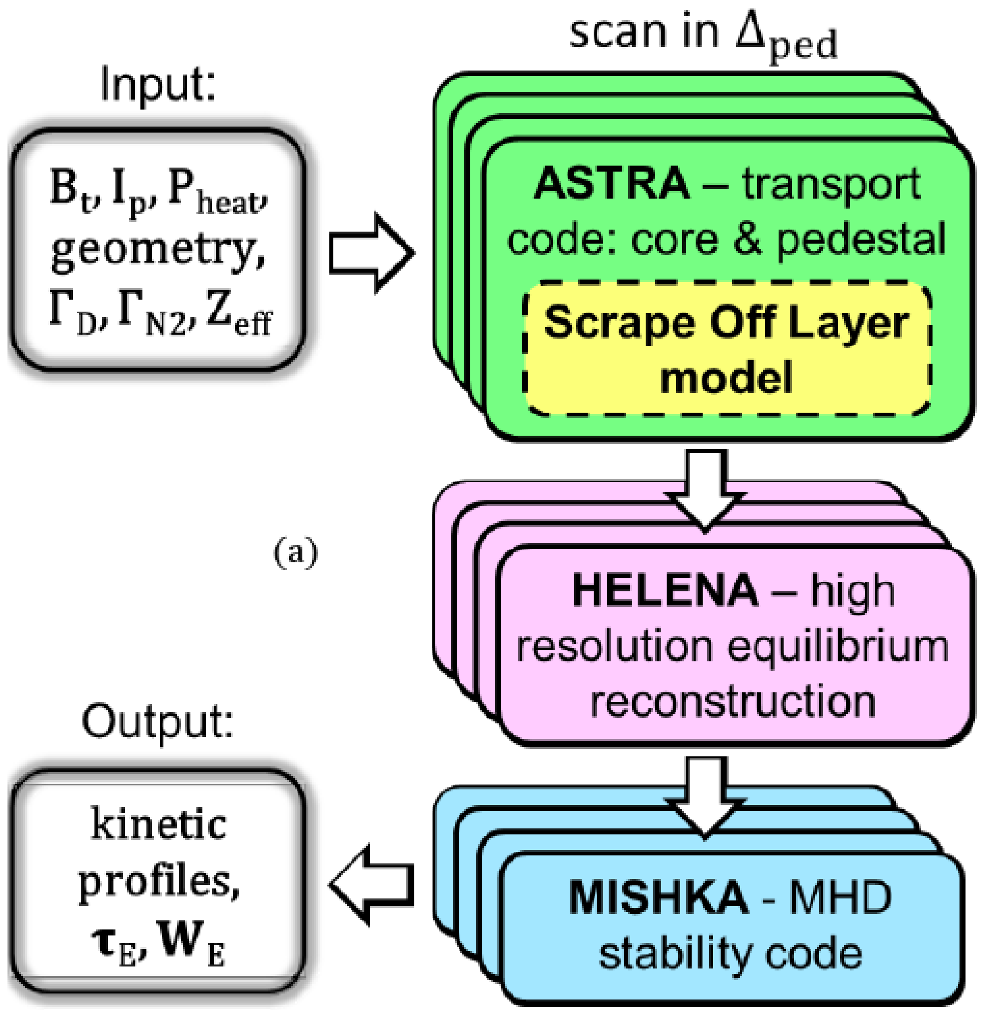


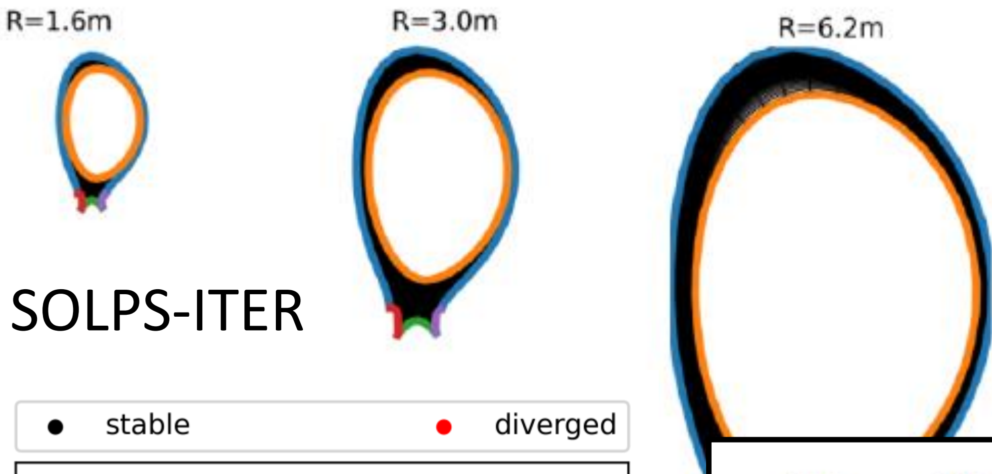
- Existing (reduced) SOL models are only valid for low-density or are not sufficiently reproducing details, e.g. Lengyel model
  → requires calibration or extensions
  D. Moulton NF2021, *A. Jaervinen session on Wed*

- Existing pedestal models are quite "core-centric" e.g. include beta-dependence of pedestal width (e.g. EPED) → better pedestal models reqd, potentially heuristic or data-driven models?

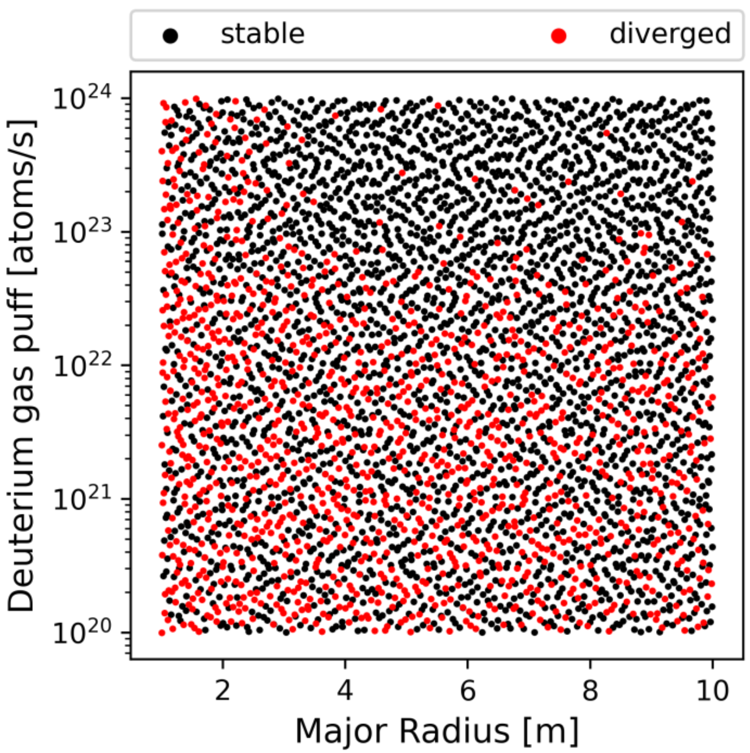
  Q: how to deal with line radiation in pedestal required in DEMO, $f_{rad,ped}$ ~ 30% or high n_{sep} ?

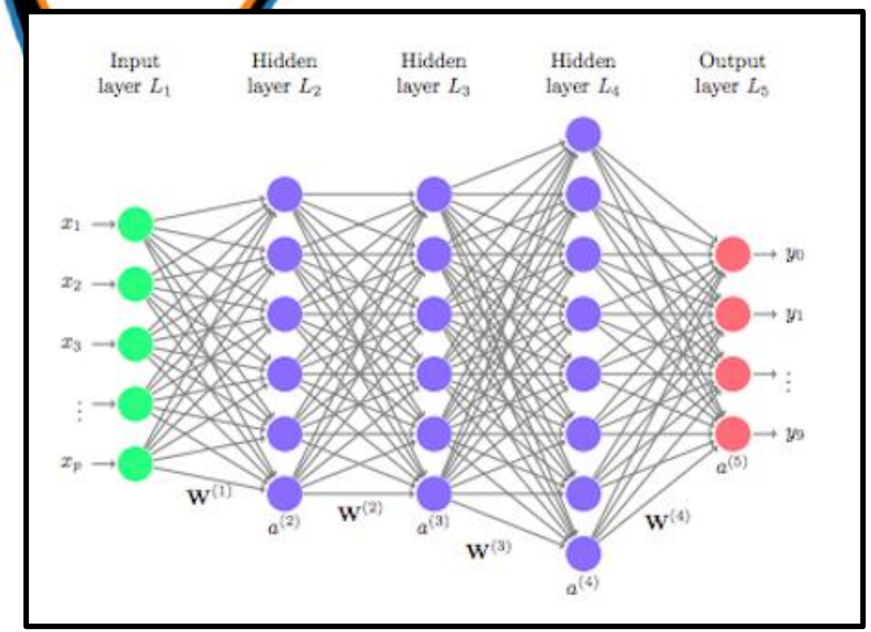
Courstesy
T. Luda et al, NF2020, EPS 2022

Speeding up the SOL: fast model based deep learning models



SOLPS-ITER



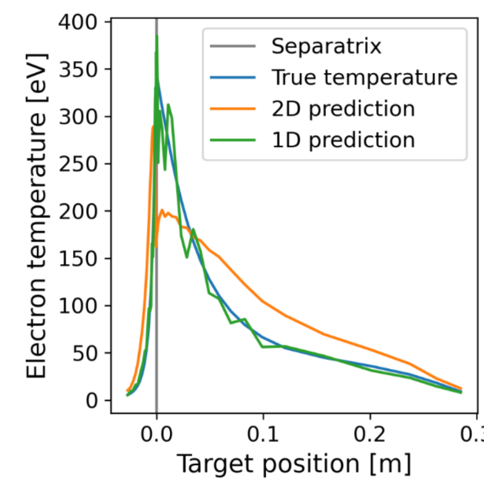


NN trained by using data from SOLPS-ITER baseline simulations with fluid neutrals

Input parameters R, B, ...
Dimensions: 8

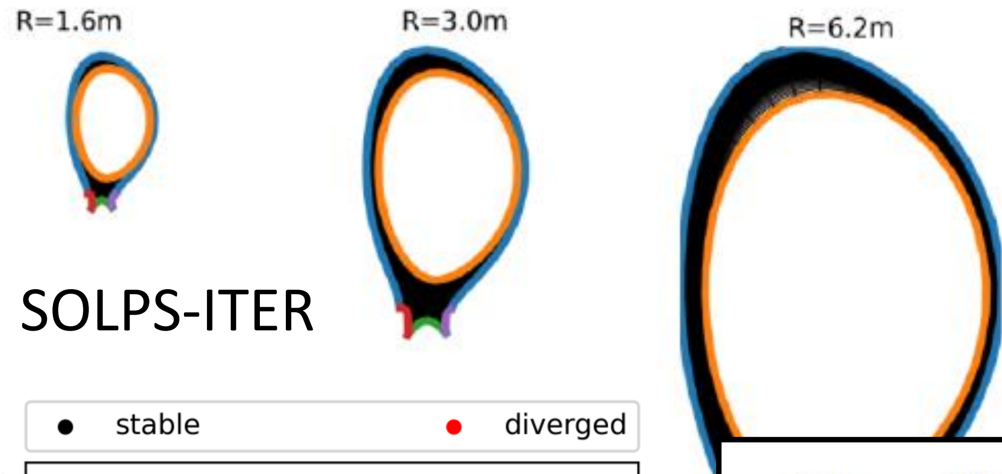
Fuily Connected Neural Network
3 hidden layers
200 Neurons per layer

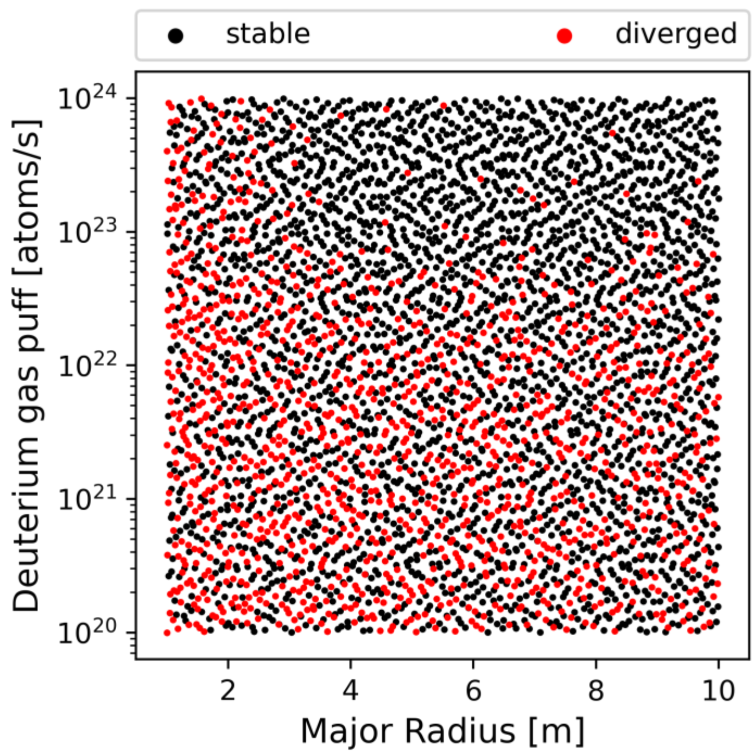
Plasma temperatures
at outer target - Dimensions: 48

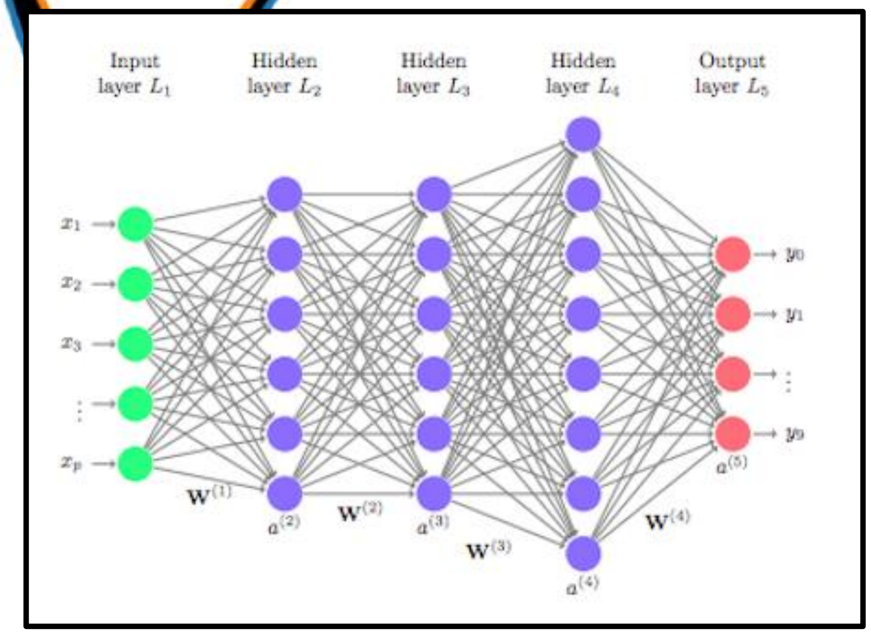


S. Dasbach et al, PSI2022

Speeding up the SOL: fast model based deep learning models







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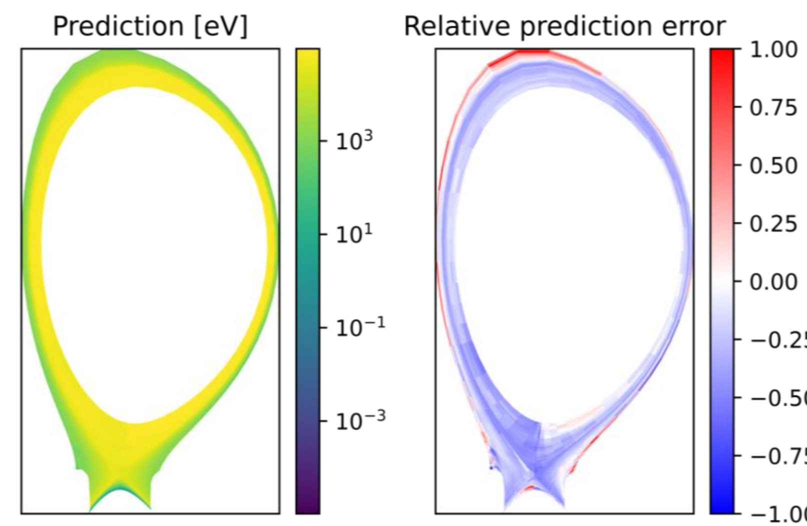
Input parameters R, B, …
Dimensions: 8

Convolutional Neural Network
3 hidden layers
200 Neurons per layer

Plasma temperatures
full 2D profiles



S. Dasbach et al, PSI2022

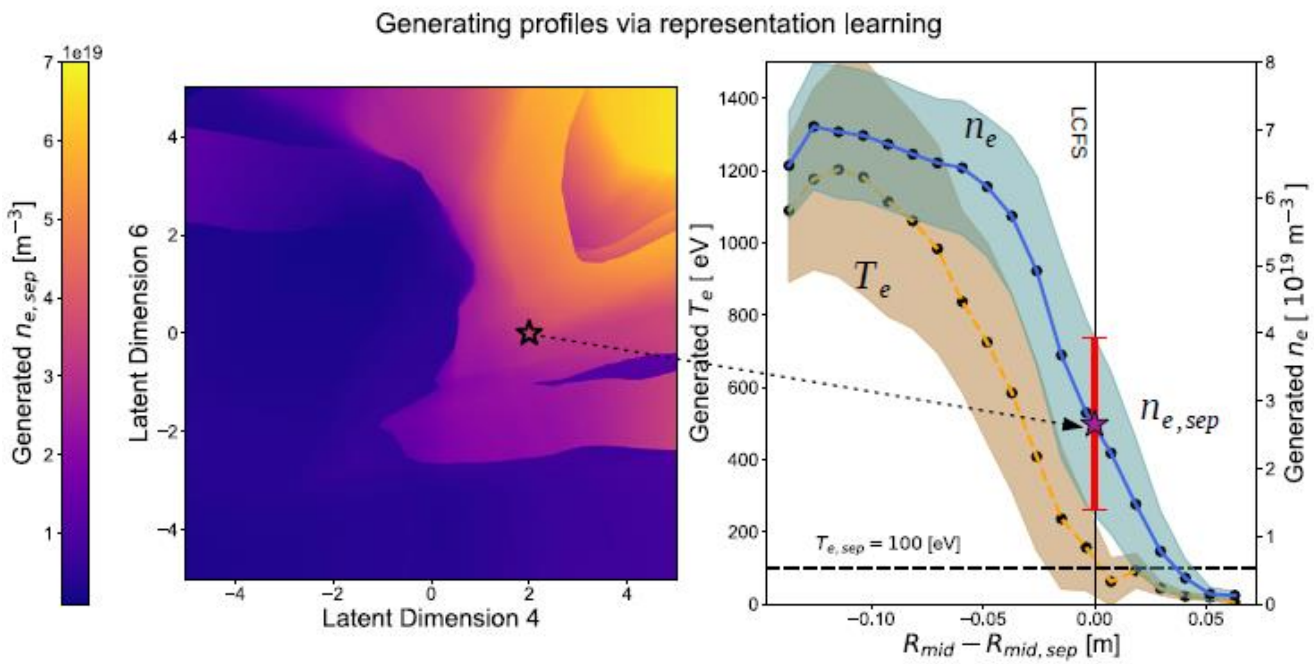
Representation learning:

Learn a latent variable z with prior $p(z) = N(\mu_x = 0, \sigma_x = 1)$ that represents profiles

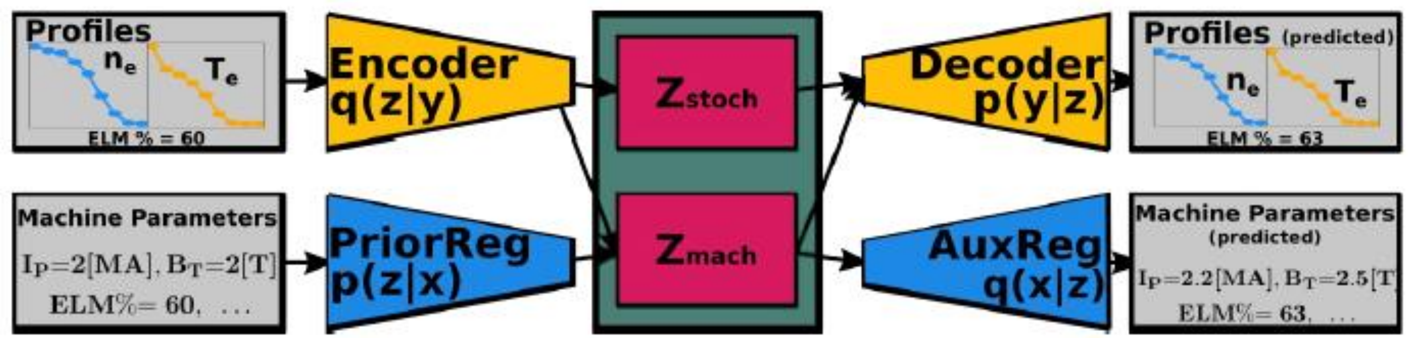
$$y: p(y,z) = p(y|z)p(z)$$

with variational autoencoder (VAE) framework.

Futhermore, also a condition prior on machine parameters, x, i.e., learn $p(z|x)$
→ domain invariant VAE (DIVA)



NN Trained by using Data from JET Pedestal database Frassinetti NF2021



A. Kit et al, PSI2022

Exploiting deep learning algorithms for controling $n_{e,ped}/n_{e,sep}$

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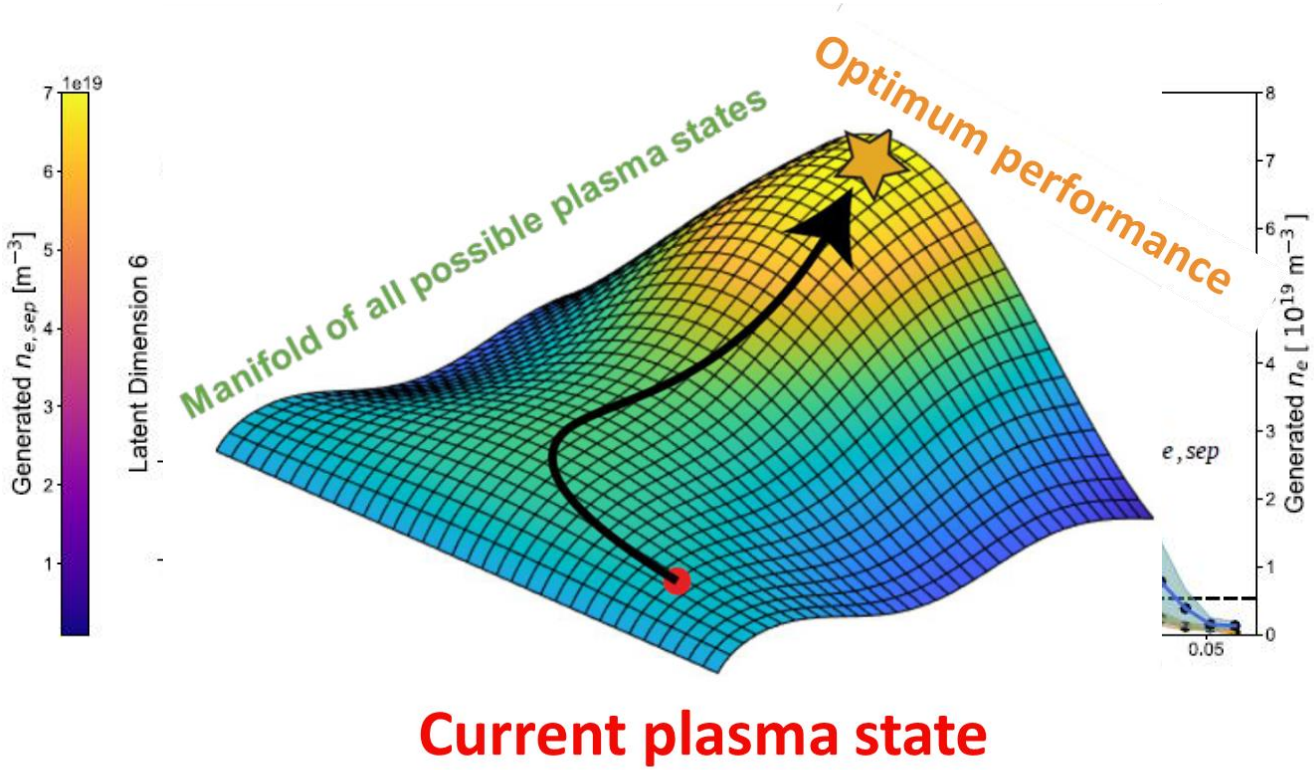

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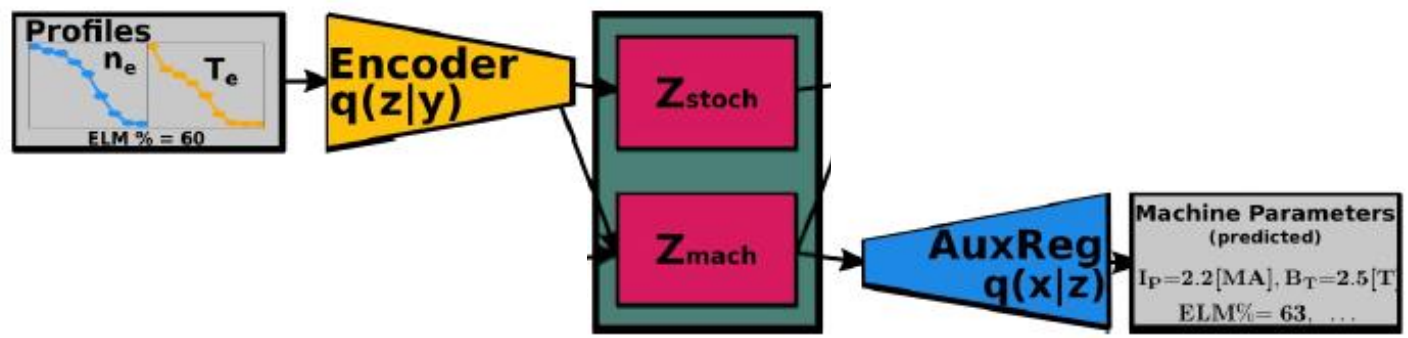
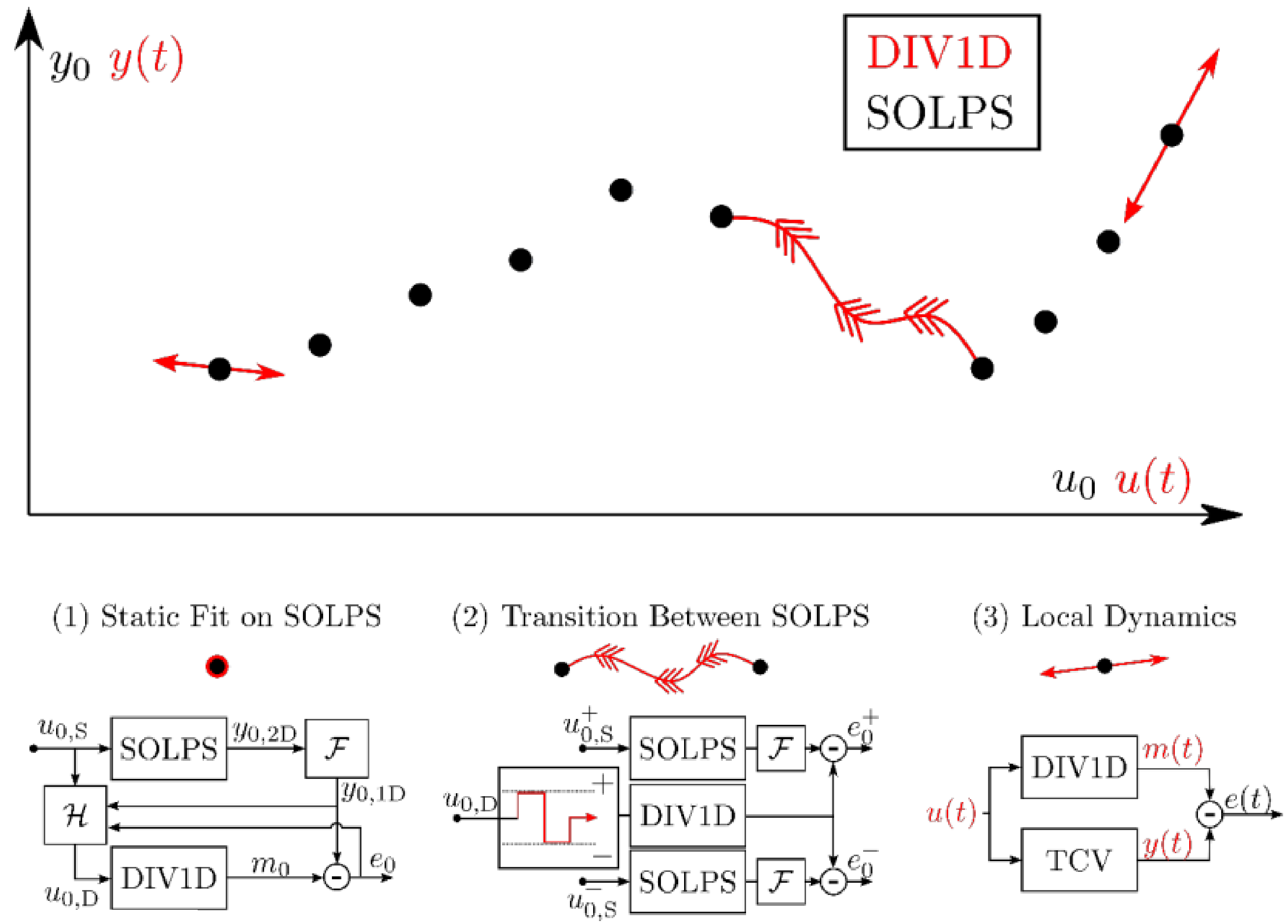


A. Kit et al, PSI2022

Detachment dynamic modelling for control

- Complementing SOLPS with DIV1D:
  - (1) Fit on SOLPS
  - (2) Transition between points
  - (3) Describe Measured Dynamics
- Requires Methods
  - F: mapping 2D to 1D
  - H: DIV1D input policy
- State of Validation DIV1D
  - (1) Reasonable agreement
  - (2) Sensitive in density ramp (WIP)
  - (3) Dynamics are fast for control



courtesy M. van Berkel et al

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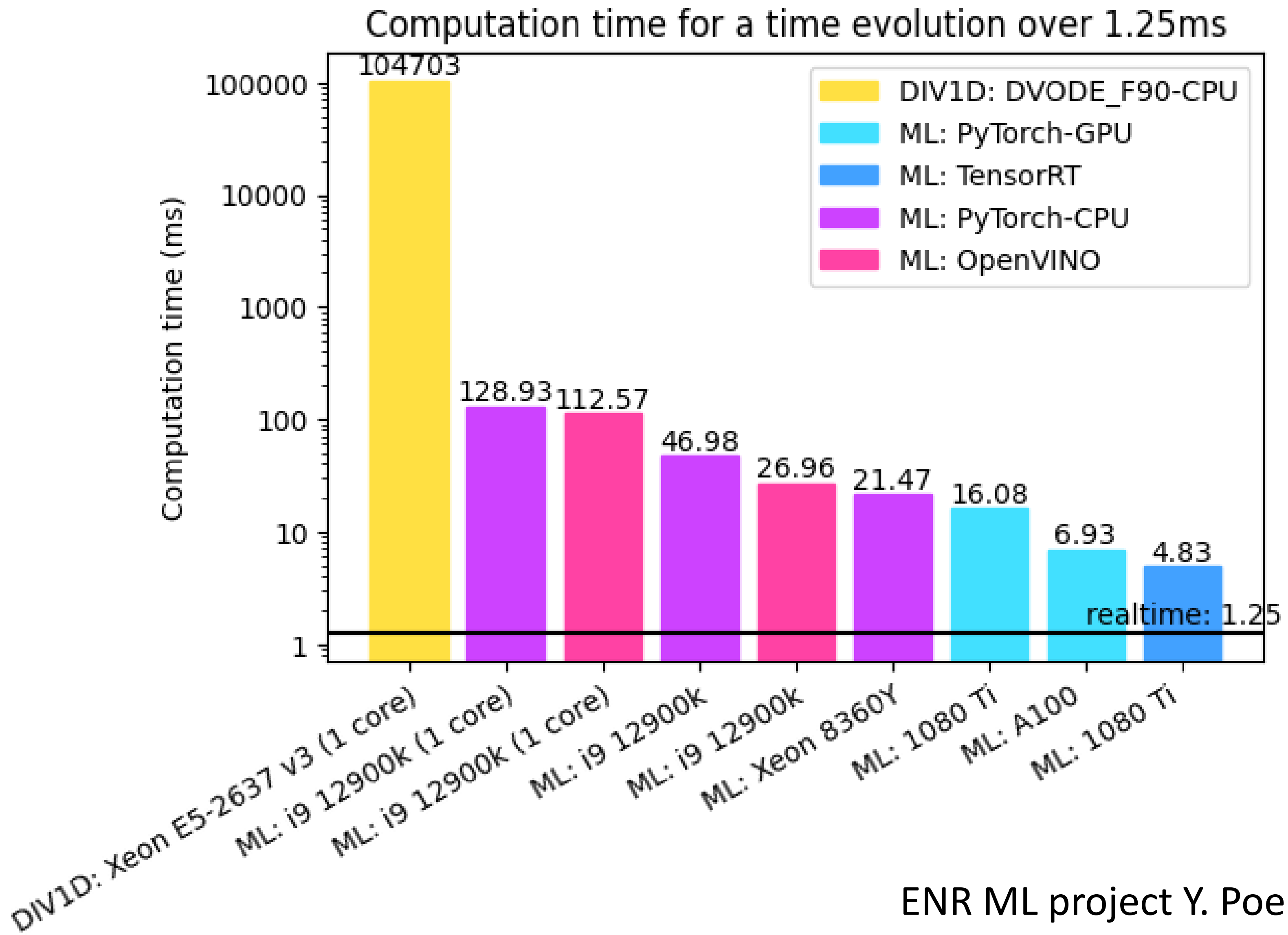
  (2) Sensitive in densit
  (3) Dynamics are fast



ENR ML project Y. Poels et al

courtesy M. van Berkel et al

Summary

The conceptional design phase for EU-DEMO implies a revision of the exhaust modelling roadmap until 2024 and beyond.

- For identifying a (controllable) exhaust scenario to be employed in EU-DEMO, the required physics foundation of candidate regimes is to be re-assessed w/ validated numerical tools
  → Towards revised physics model: fluid drifts, neutral kinetics, non-coronal effects on impurity transport and radiation levels in the edge.
  → Establishment of a SOLPS-ITER EU-DEMO simulation database a la ITER

Multi-fidelity approach advantageous to explore EU-DEMO exhaust operational window.

- An integrated & optimised core-edge scenario is needed compatible to maintain energy dissipation fraction of up to 95% in the edge, of which 30% in core
  → extension of flight-simulators by integrating fast & calibrated exhaust models
- Recent activities on development of fast NN-based surrogate exhaust models
  → promising and might become relevant for fast flight-sims, PCS & systems codes