MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

First Principles Based Divertor Optimization
A Unified MCF Divertor Framework applied to W7-X

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EUROfusion

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Establish a traditional optimization method in our community

Introduce necessary divertor optimization metrics

Offer toolchain and benchmark

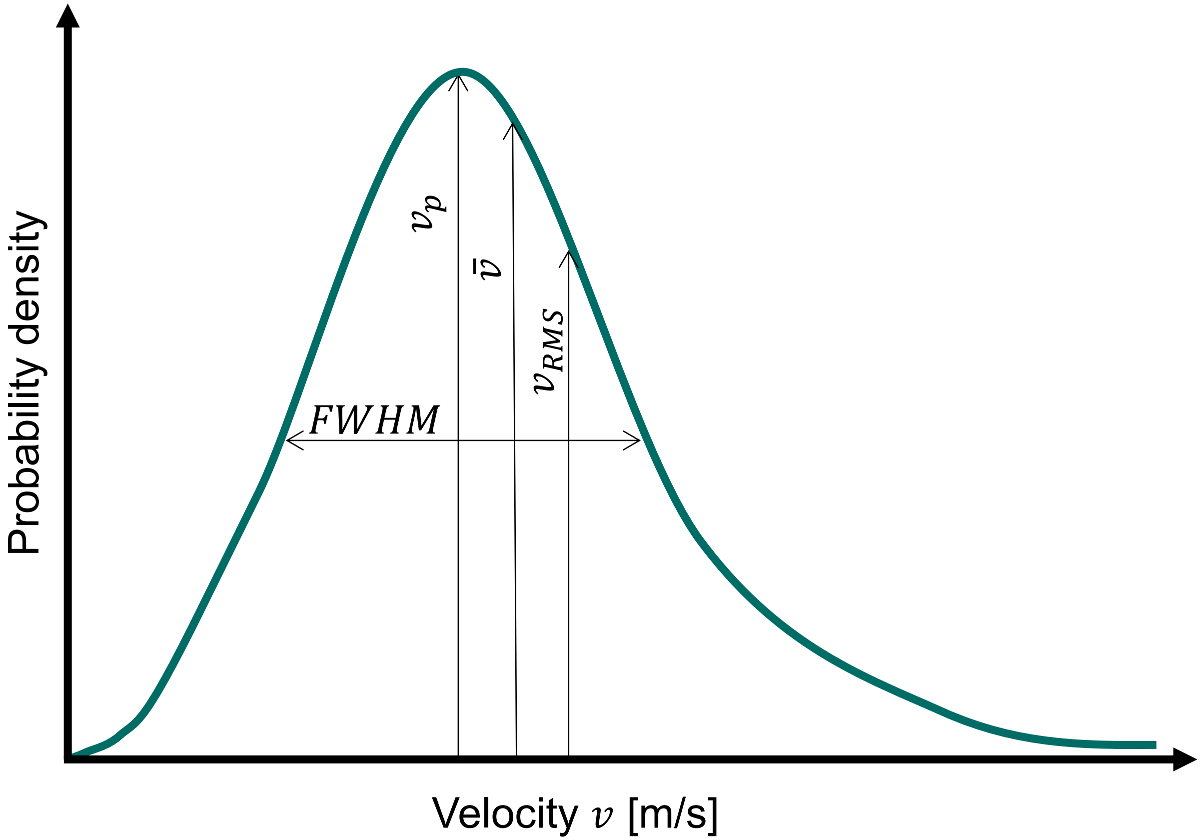
6σ – Traditional optimization method based on statistical analysis

Wendelstein 7-X

Plasma physics and nuclear fusion is full of stochastic processes!

How do we quantify them?

Maxwellian Probability Density Function (PDF)



Performance, reliability, & safety of nuclear power plants

eDF

Entergy ENTERGY NUCLEAR

SIEMENS

Stabilize human/nuclear rated unstable systems

16x B83 (5E+15 J) = 12.5E+9 x ITER (6.4E+6 J)

LOCKHEED MARTIN NORTHROP GRUMMAN BOEING

Design of landing rockets & safety of human rated spacecraft

SAFRAN AEROSPACE · DEFENCE · SECURITY

SPACEX

AIRBUS GROUP

Continuous quality & process optimization

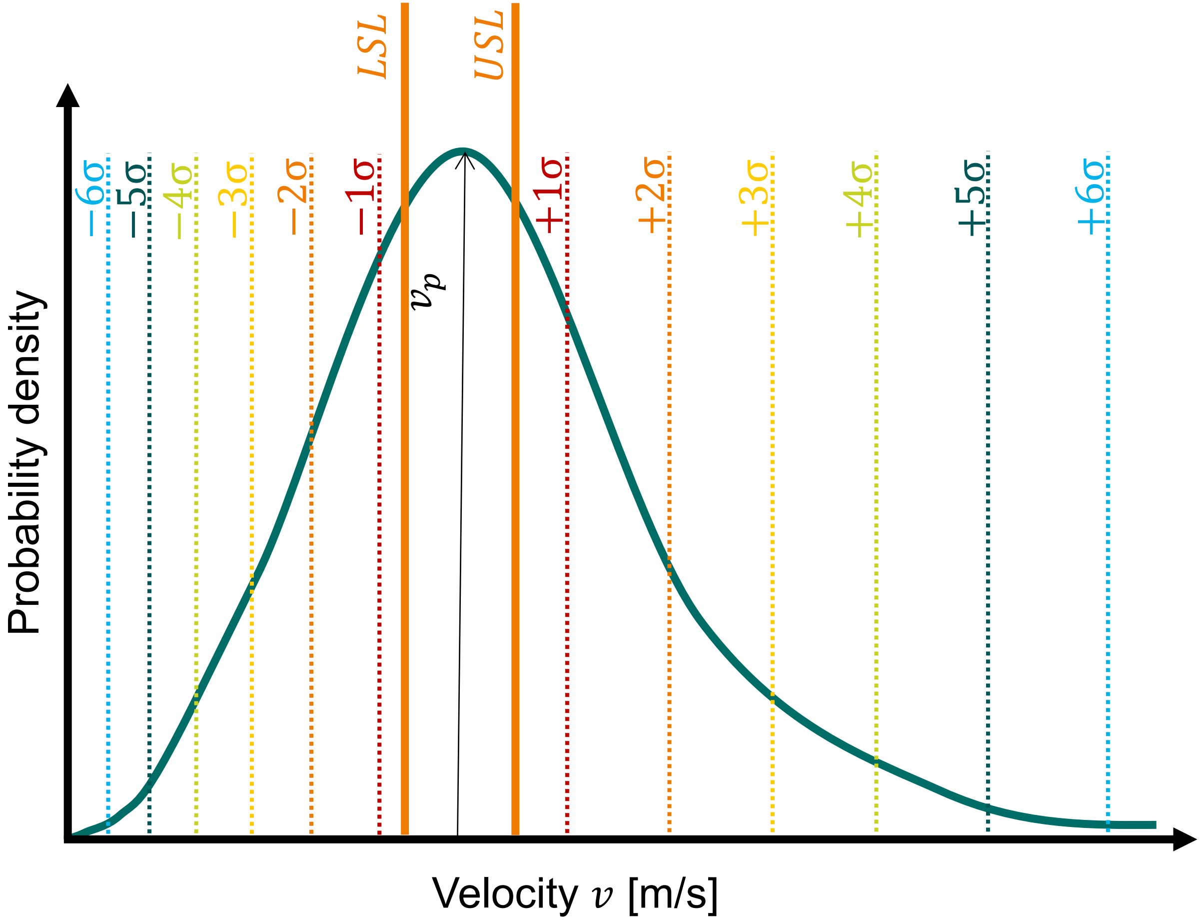
MOTOROLA

ARRI

General Electric

6σ – Traditional optimization method based on statistical analysis

Maxwellian Probability Density Function (PDF)



Accuracy

- Relation of most probable outcome on target

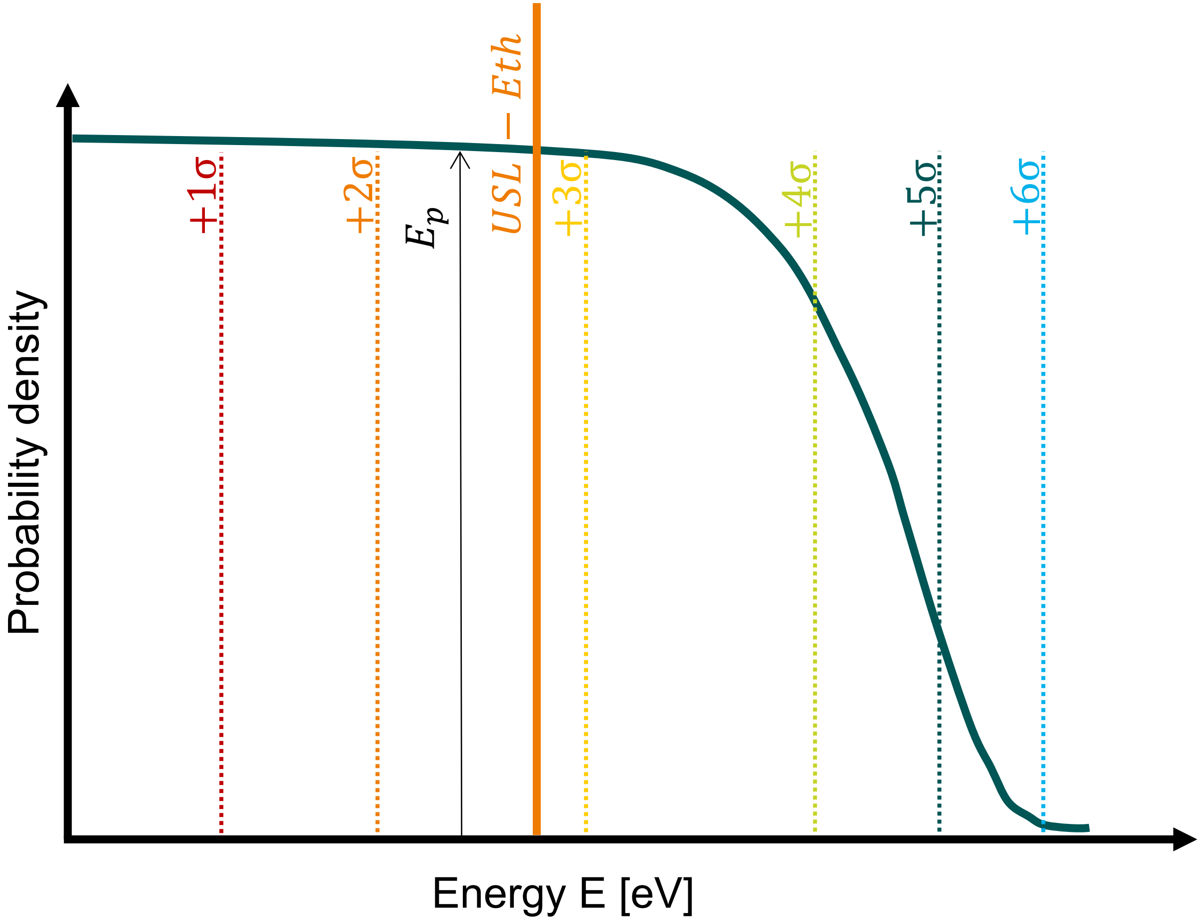
Precision

- Scatter within or around Lower Specification Limit (LSL) & Upper Specifiation Limit (USL)
- How close are outomes together

σ-level	DPMO (defects per million opportunities)	Yield %
0	> 691 462	< 31 %
1	691 462	31 %
2	308 537	69 %
3	66 807	93.3 %
4	6 210	99.38 %
5	233	99.977%
6	3.4	99.99966 %

6σ – Often only an upper or lower limit – Example: Sputtering

Integrated Maxwellian PDF



Upper Specification Limit – USL

Sputtering Thrershold E_{th} [eV]

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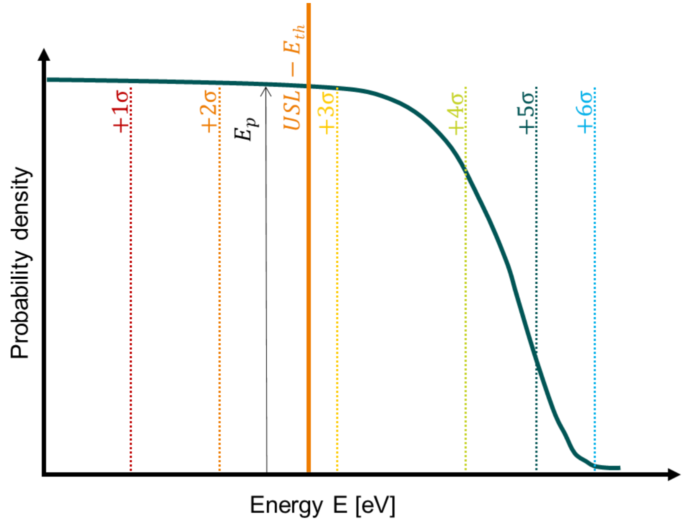
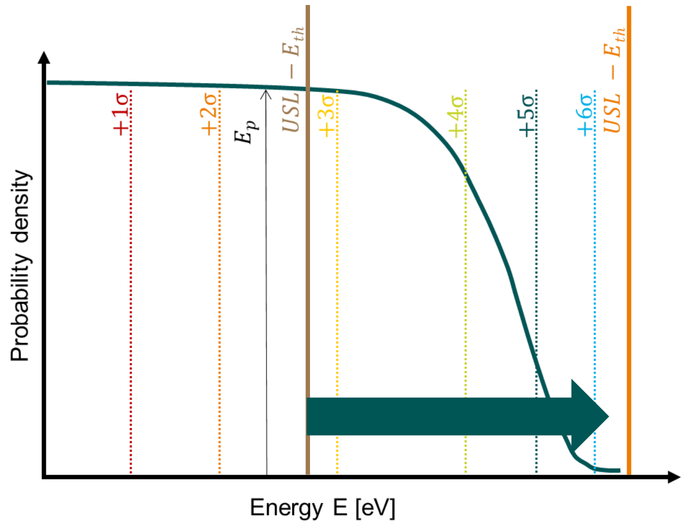
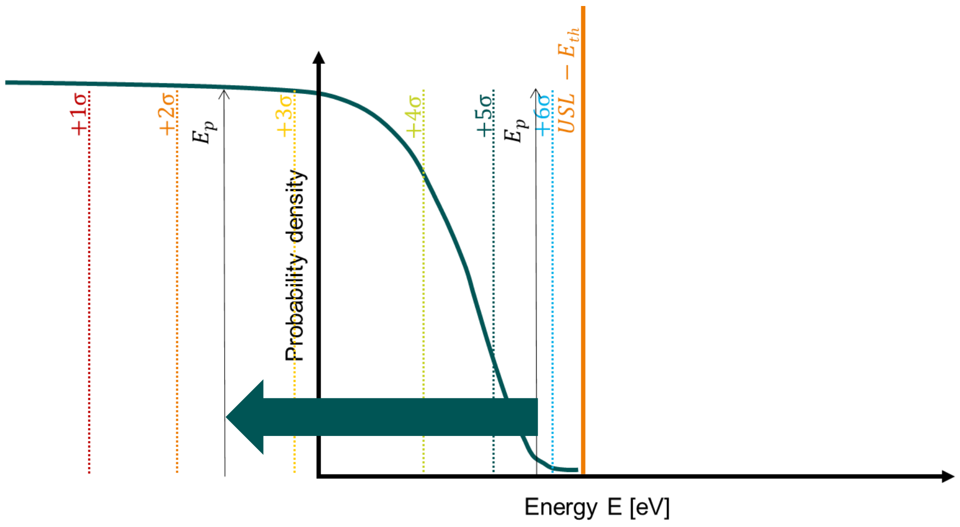
6σ – Three possible solution strategies



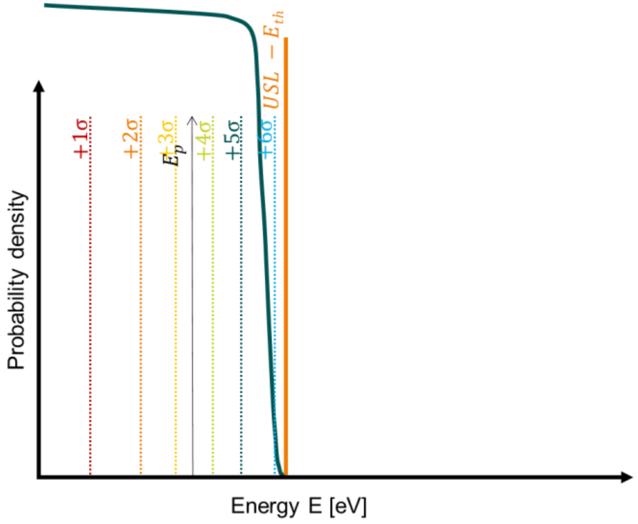
Move USL
Avoid – No solution



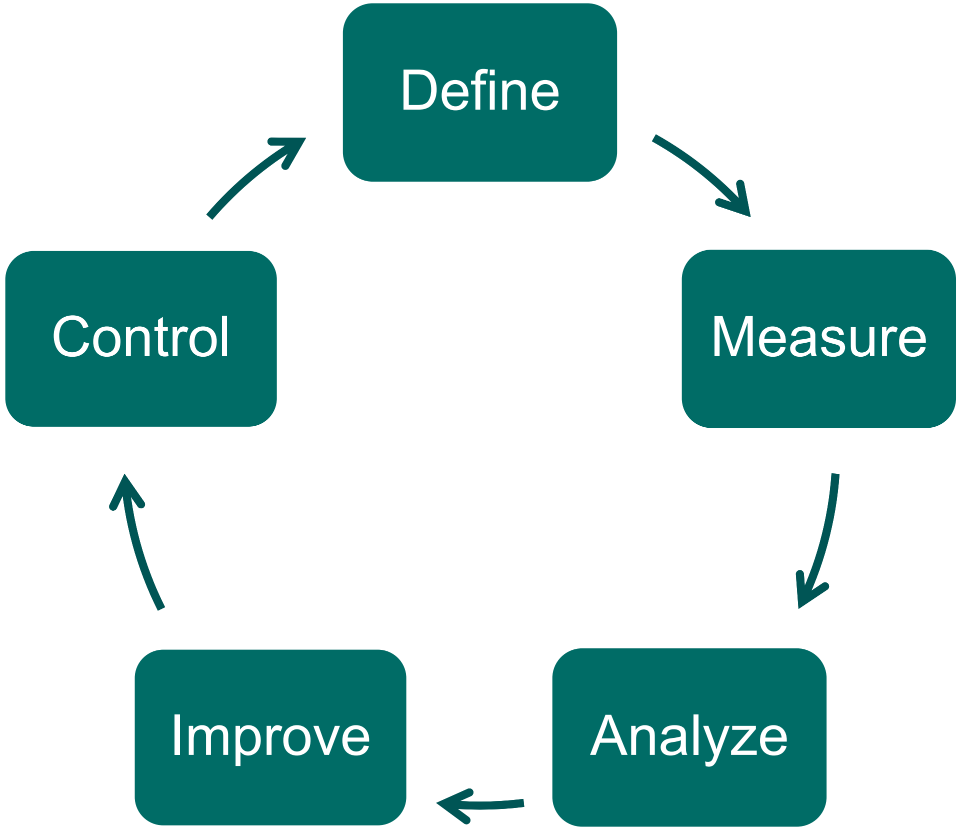
Aim low
Solve – Effective solution



Change PDF
Optimize - Efficient solution



6σ – DMAIC design cycle to optimize W7-X divertor



- Quality or performance steps one standard deviation apart
- Ensures efficient step size
  - Too small of step has fixed overhead without gain
  - Too large step might stretch system and bring overwhelming complexity to meet excessive requirements
  - Enables precise definition of boundaries in distributions

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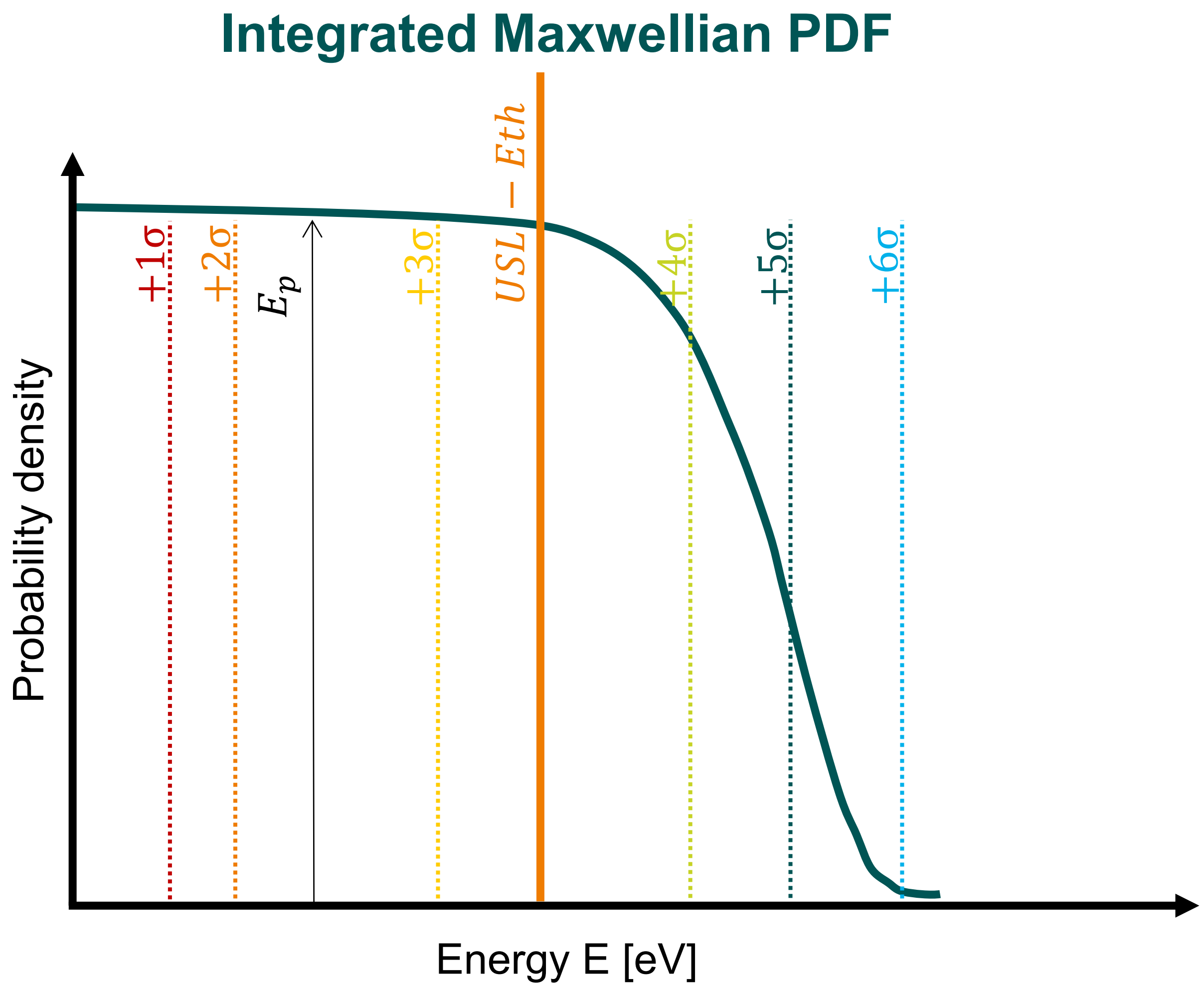
Efficient process → (σ-level 6)

6σ – Often only an upper or lower limit – Example: Sputtering



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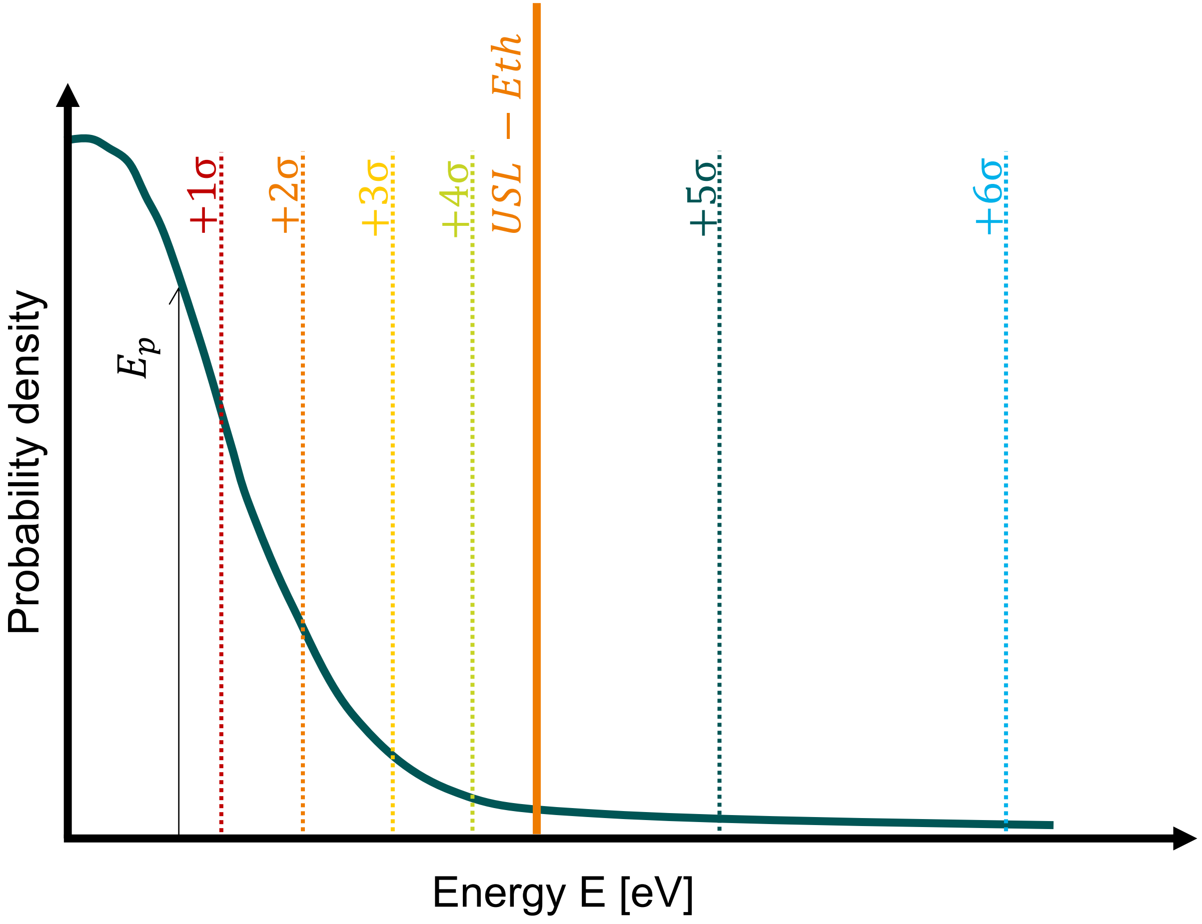

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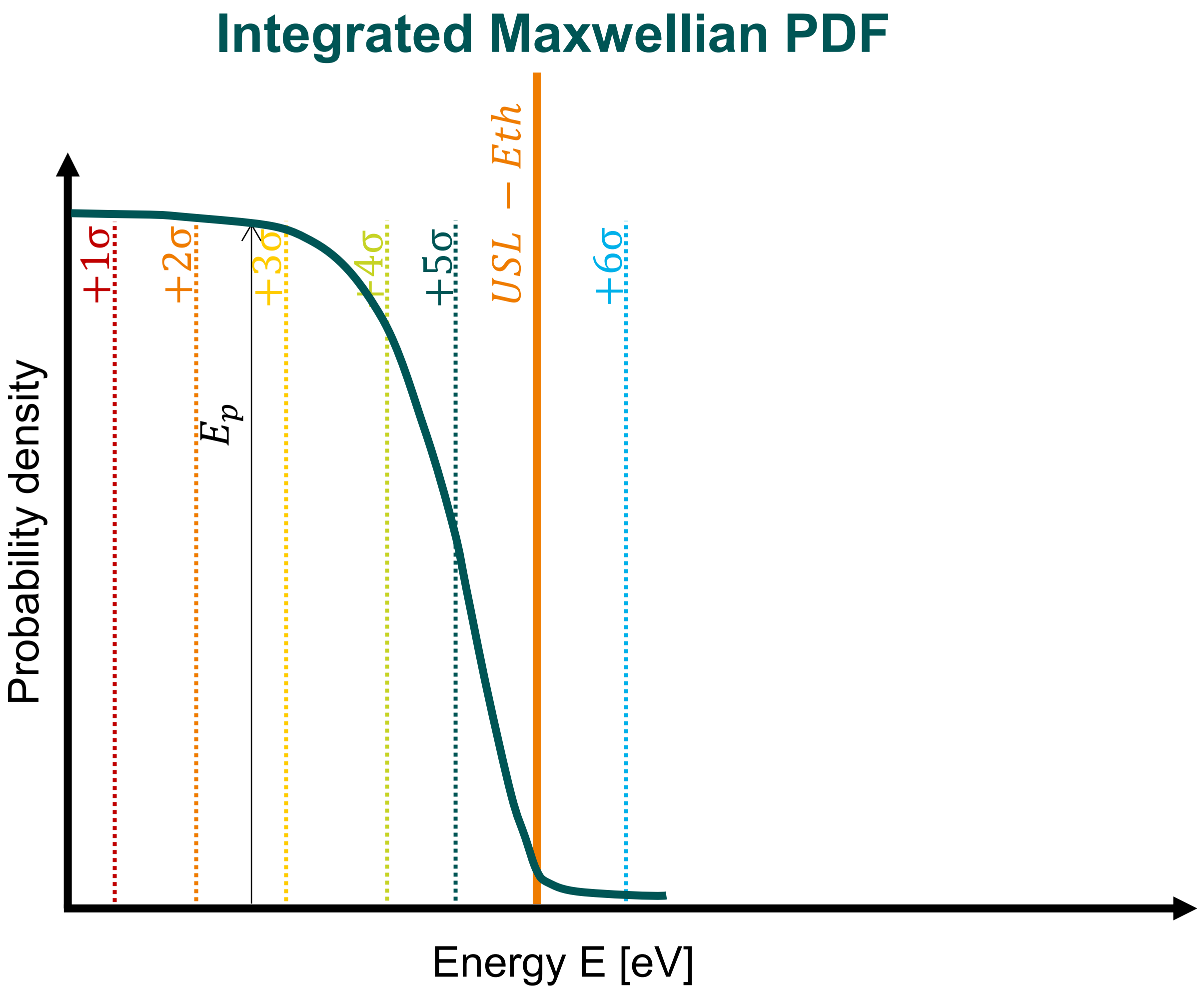

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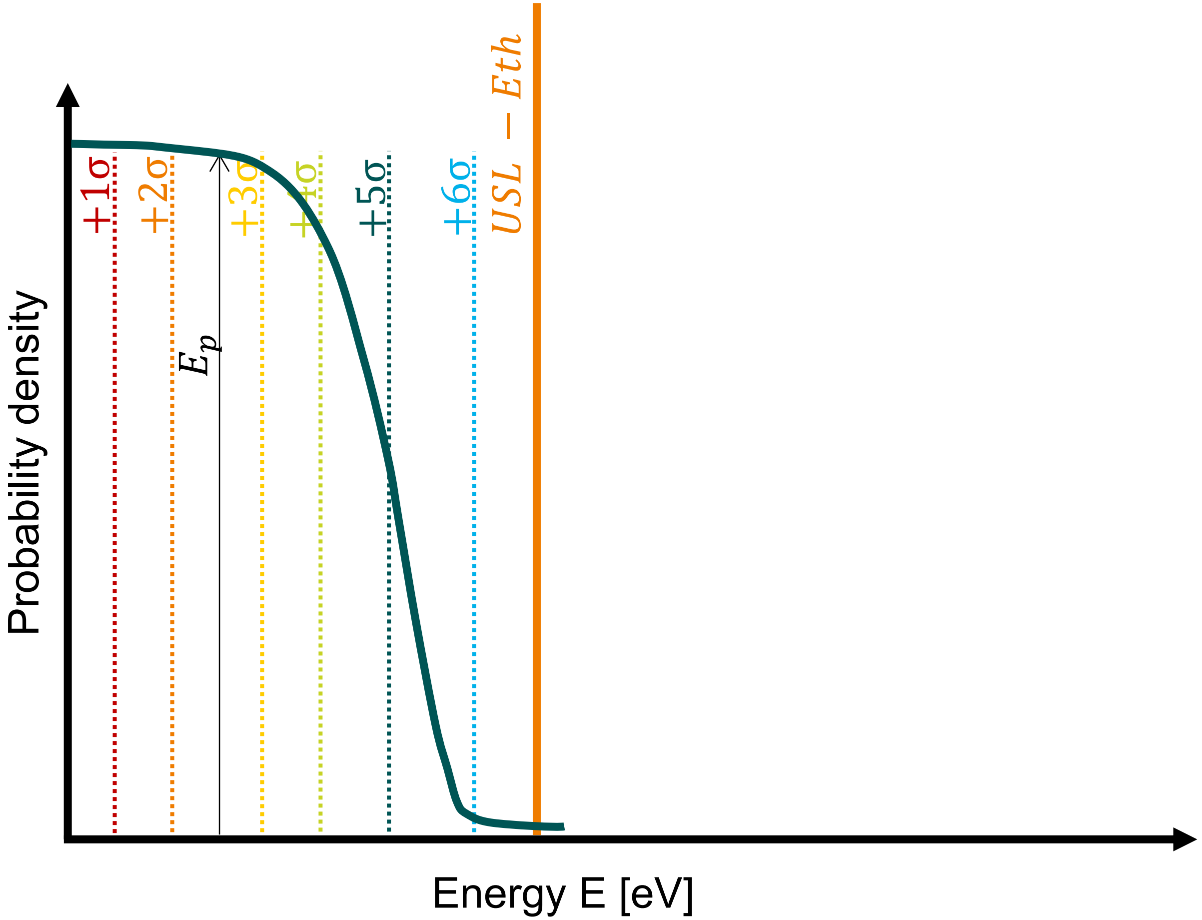

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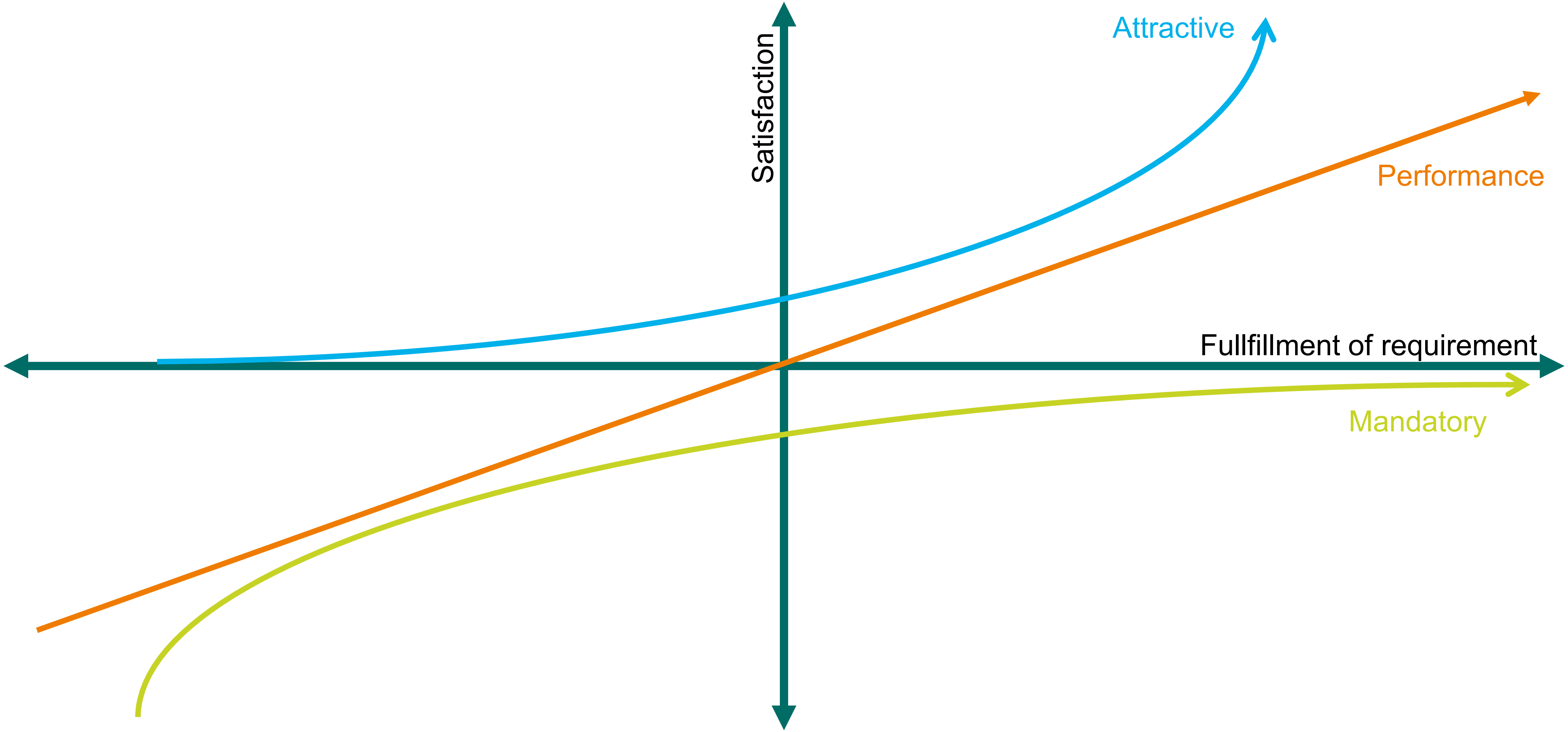
Kano model to categorize requirements



Understanding Divertor Requirements with the Kano Model

Mandatory (absolute)

- Survive heat
- Survive sputtering
- Survive forces
- Survive neutrons
- Survive …

Performance (relative)

- Particle exhaust
- Particle retention

Attractive

- High recycling regime
- Power radiation
- Volume recombination
- Tritium Core Recycling

Indifferent

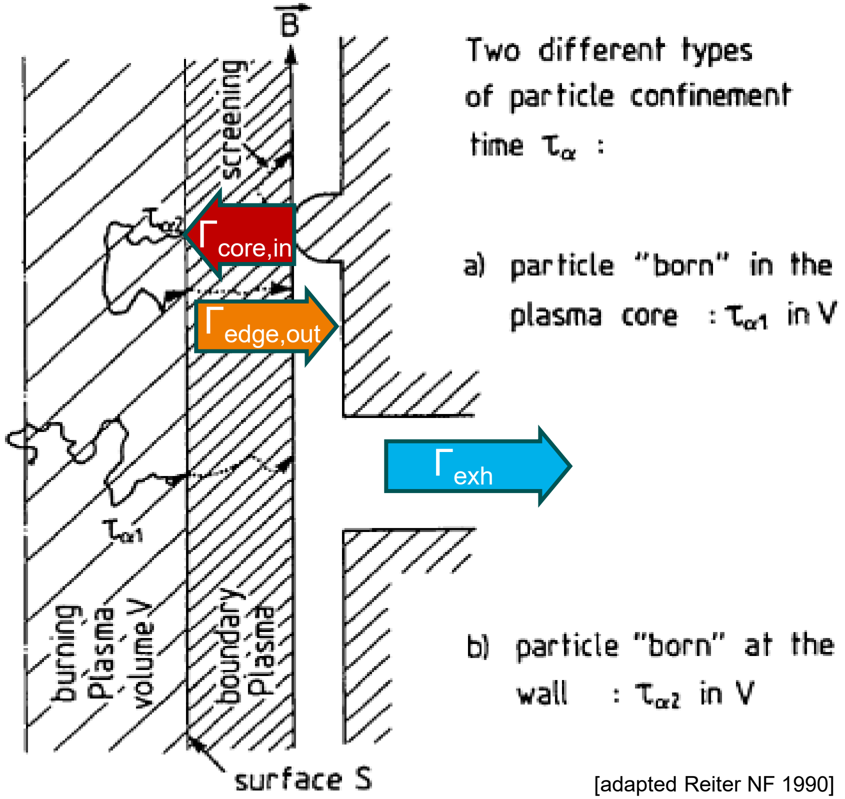
- ?

Reverse

- Impurity release

Divertor Reactor performance requirements – He/H exhaust & retention

- $\Gamma_{He,exh} = \Gamma_{\alpha,1}$ $\Gamma_{H,exh} = \Gamma_{p,1}$
- Function 1: Exhaust η_{exh} Function 2: Retention η_{ret}
- Exhausted particles do not have to be retained



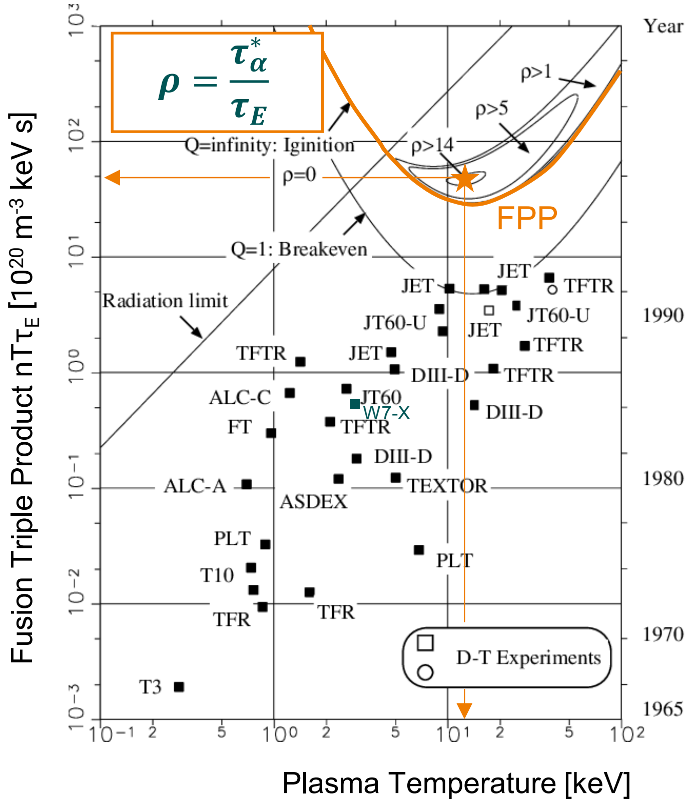
[adapted Reiter NF 1990]

Function 1:
$$\eta_{exh,\alpha} = \frac{\Gamma_{exh}}{\Gamma_{edge,out}}$$

Function 2:
$$\eta_{ret,\alpha} = 1 - \frac{\Gamma_{core,in}}{(\Gamma_{edge,out} - \Gamma_{exh})}$$

$$\tau_\alpha^* = \tau_{\alpha 1} + \frac{(1 - \eta_{exh,\alpha})\,\eta_{ret,\alpha}}{\eta_{exh,\alpha}}\tau_{\alpha 2}$$

[adapted Reiter NF 1990]



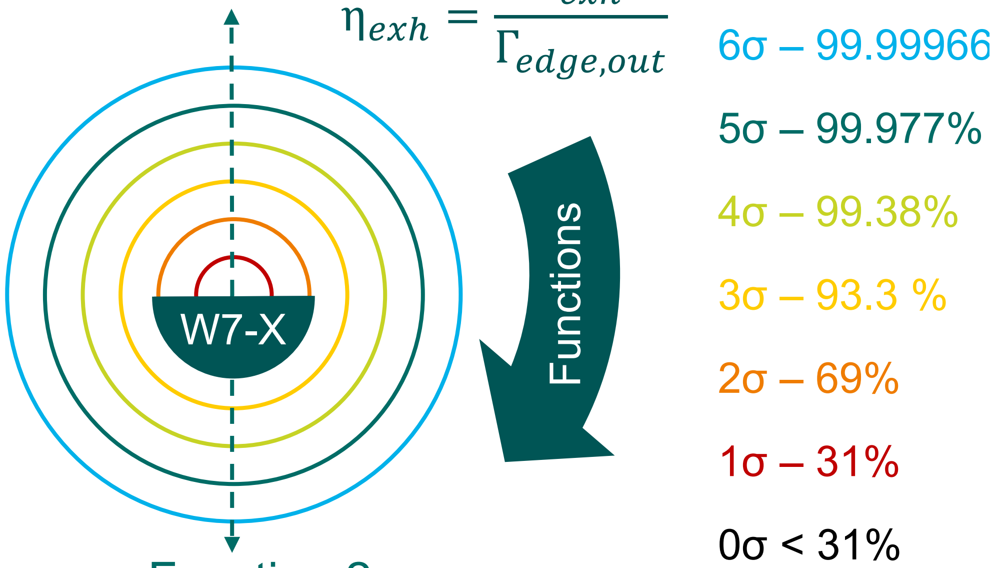
[adapted Reiter FSAT 2010]

Divertor Reactor performance requirements – He/H exhaust & retention

- $\Gamma_{He,exh} = \Gamma_{\alpha,1}$ $\Gamma_{H,exh} = \Gamma_{p,1}$
- Function 1: η_{exh} Function 2: η_{ret}
- Exhausted particles do not have to be retained

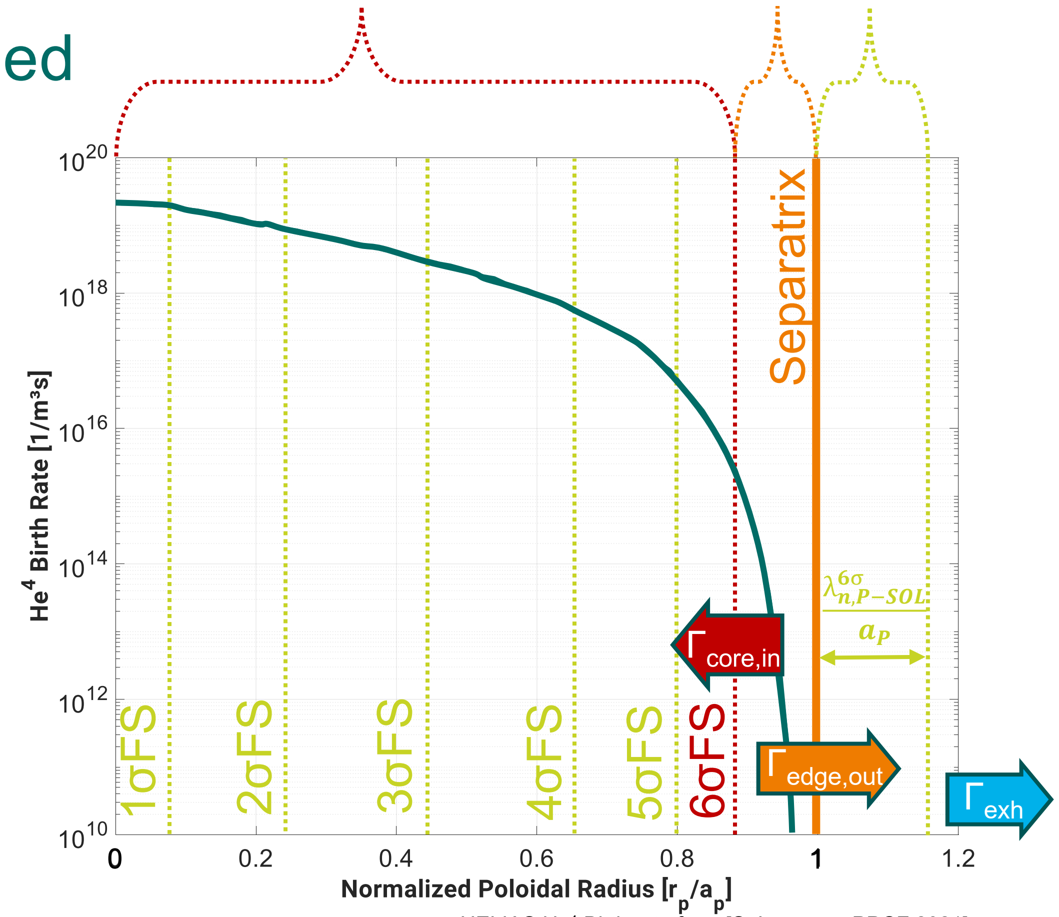
Function 1:

$$\eta_{exh} = \frac{\Gamma_{exh}}{\Gamma_{edge,out}}$$



Function 2:

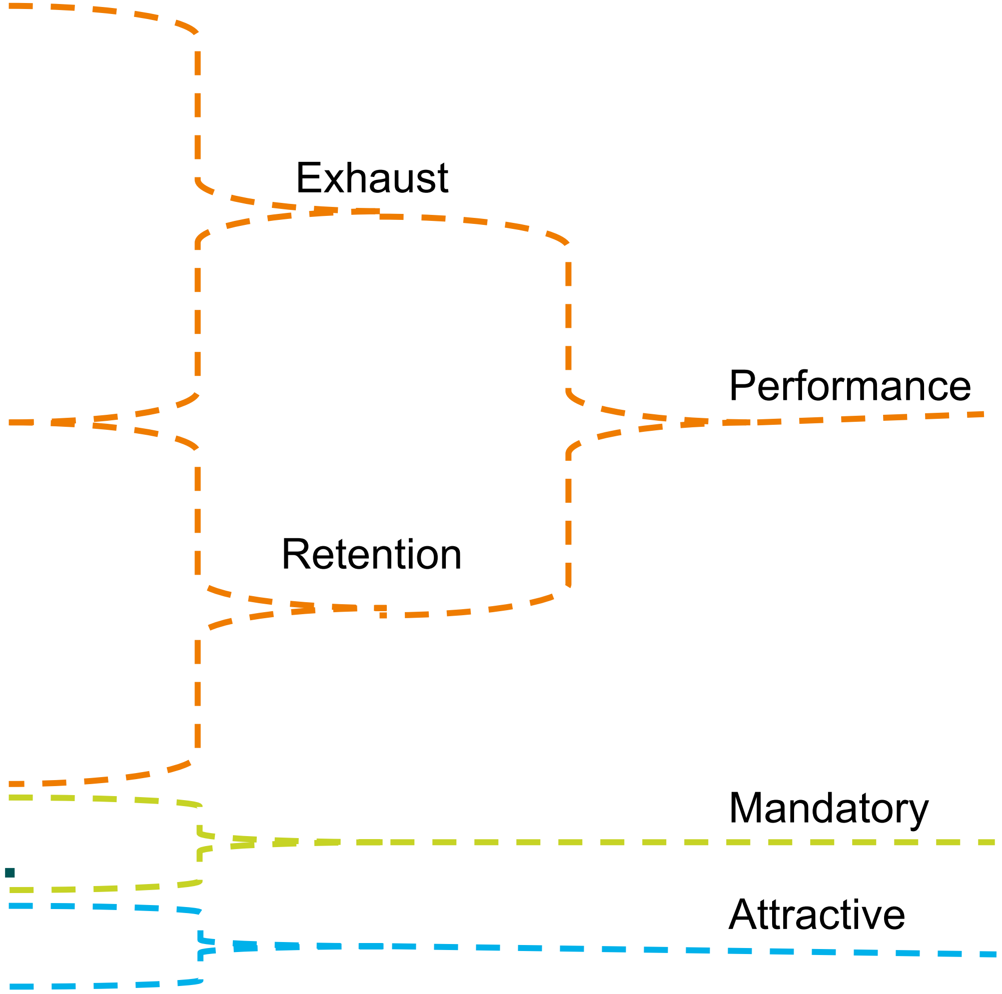
$$\eta_{ret} = 1 - \frac{\Gamma_{core,in}}{(\Gamma_{edge,out} - \Gamma_{exh})}$$



HELIAS He^4 Birth rate from [S. Lazerson PPCF 2021]

A priori first principle divertor functions

1. Divert plasma particles
2. Neutralize plasma particles
3. Collect neutral particles
4. Remove neutral particles
5. Contain particles in sub-divertor
6. Recycle neutrals in divertor
7. Plug particles in divertor
8. Screen impurity particles from core
9. Survive – Heat, Sputtering, Forces,…
10. Cost/Time function



A-priori first principle Design Metrics

Performance Function 1: Particle exhaust

$\eta_{exh} = \Gamma_{exh} / \Gamma_{edge,out}$

$= \eta_{diversion}\ \eta_0\ \eta_{coll}\ \eta_{removal}$

1.1 Particle diversion

$\eta_{diversion} = \Gamma_{div,in} / \Gamma_{edge,out}$

1.2 Particle neutralization

$\eta_0 = \Gamma_0 / \Gamma_{div,in} = \eta_{0,surf} + \eta_{0,vol}$

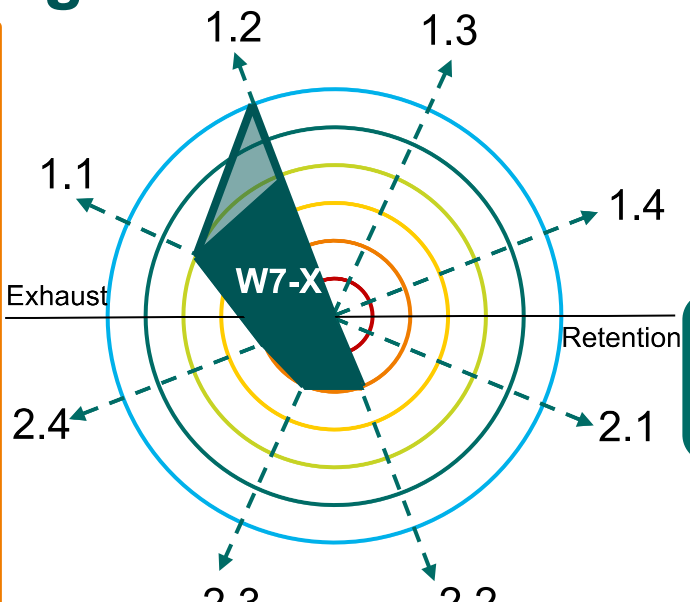
$\eta_{0,surf} = \Gamma_{0,surf} / \Gamma_{div,in}$

1.3 Particle collection

$\eta_{coll} = \Gamma_{coll} / \Gamma_0$

1.4 Particle removal

$\eta_{removal} = \Gamma_{exh} / \Gamma_{coll}$



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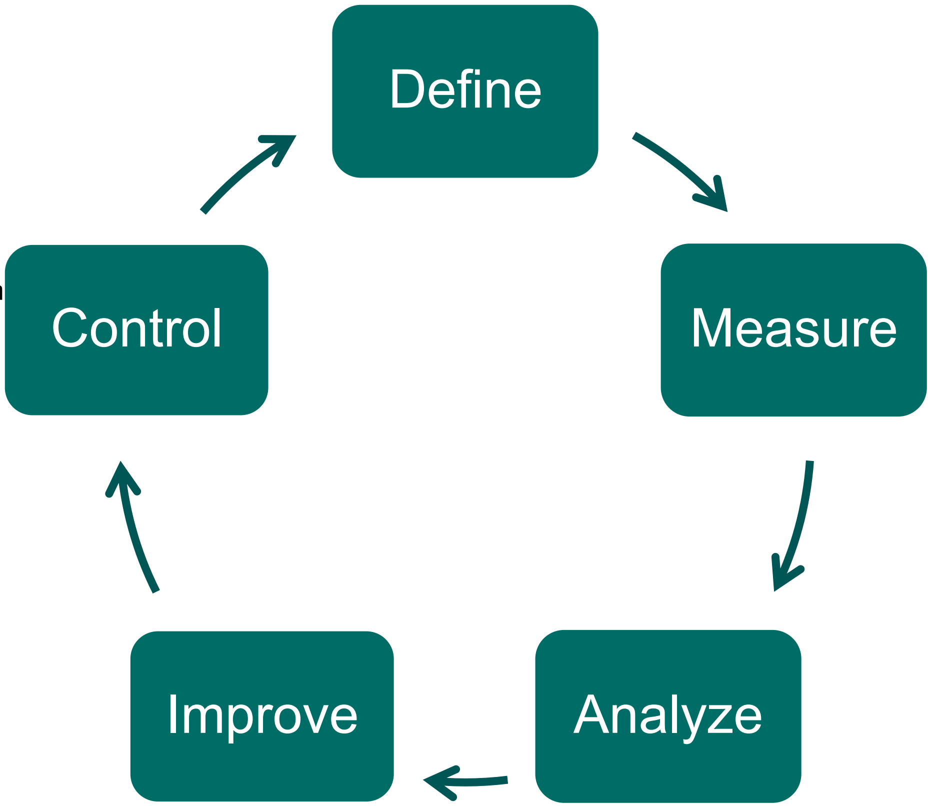


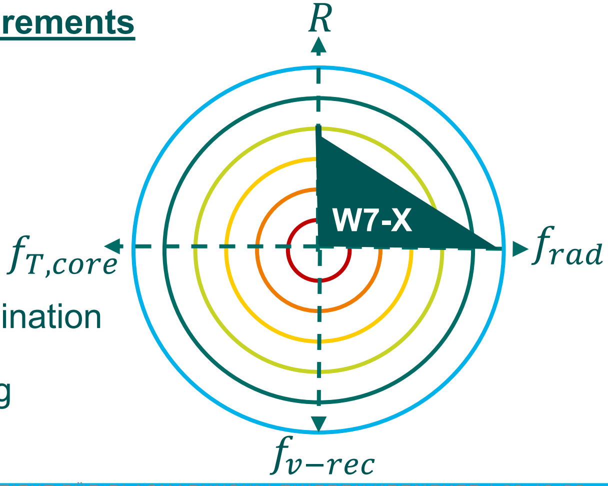
Attractive requirements

Recycling

Radiation

Volume Recombination

T-Core Recycling



Mandatory Requirement	Heatload	Sputtering	Mechanics	Neutrons
Metric	$FOS = \frac{\dot{q}_{max}}{\dot{q}_{div}}$	$\eta_{sptr,resist} = 1 - Y$	$FOS = \frac{yield\ stress}{working\ stress}$	DPA
W7-X	1.67	?	> 1	?

Control Models

Parametric Design

- Target maker
  - ~ Hours – by hand
  - 5-30 min – parametric on field line tracer
  - 300 ms – parametric on gordon
- Baffle maker – in development

EMC3Lite

- 30 s

COMSOL

- 2 h setup – newbie
- 20 min setup – experienced
- 15-30 min $\eta_{collection}$
- 4-5 h $\eta_{removal}$

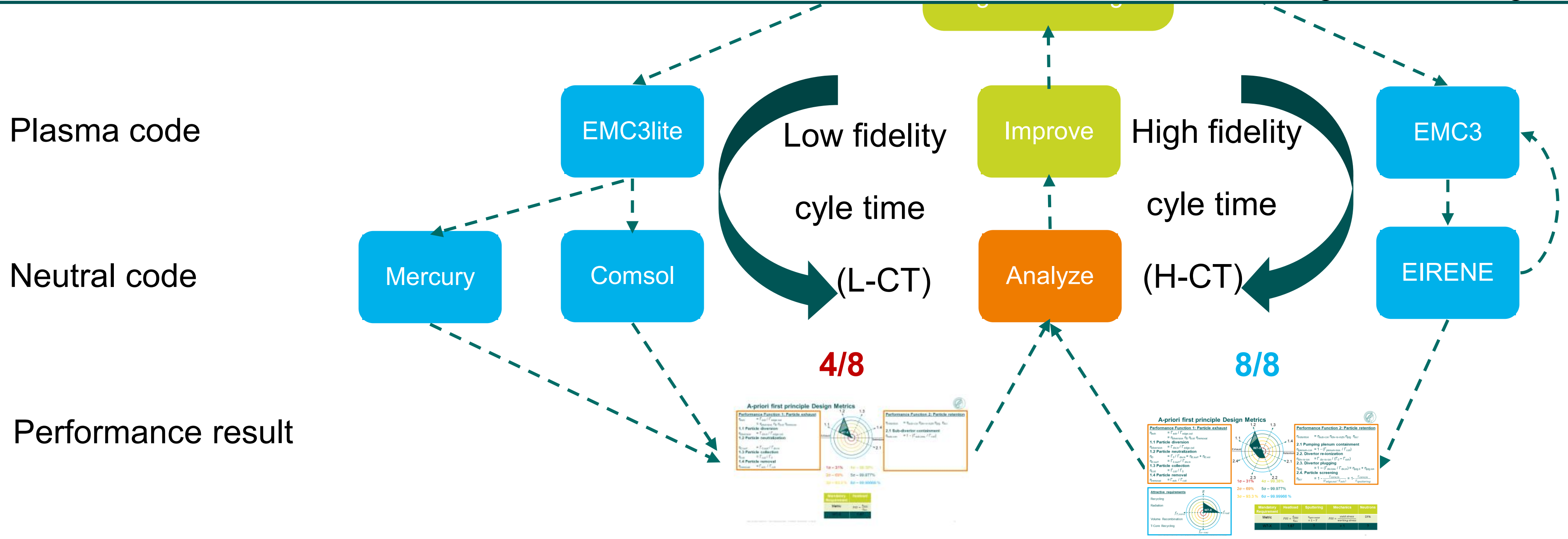
Mercury

- 2 min setup

Parallelisation:

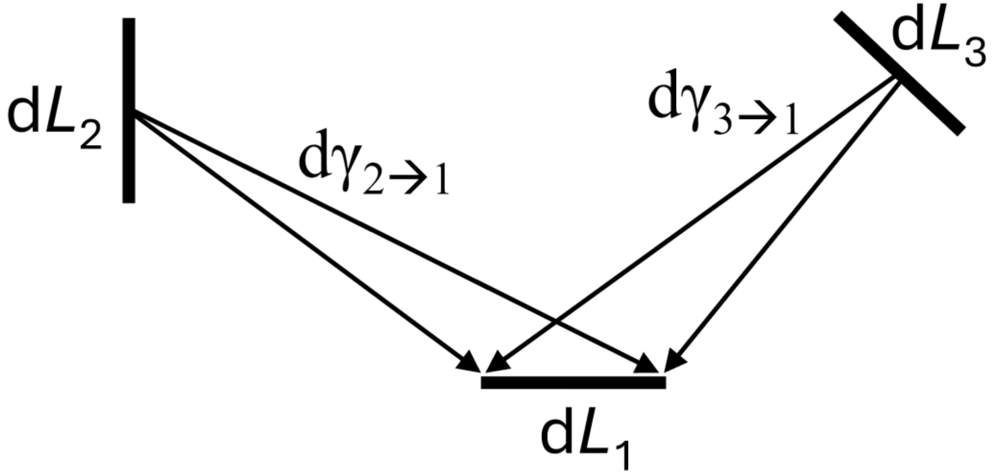
- Now 15-45 min $\eta_{collection}$
- from 90 min $\eta_{collection}$

Further reduction through coarsening of grids



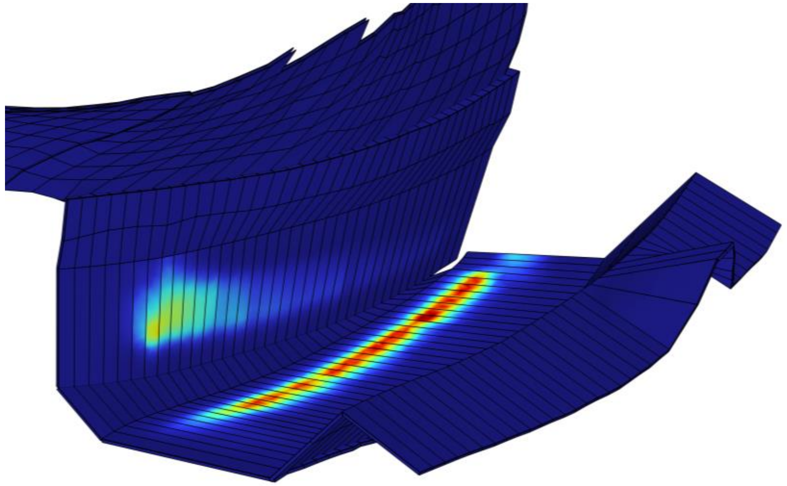
Understanding the AC method for the molecular flow regime

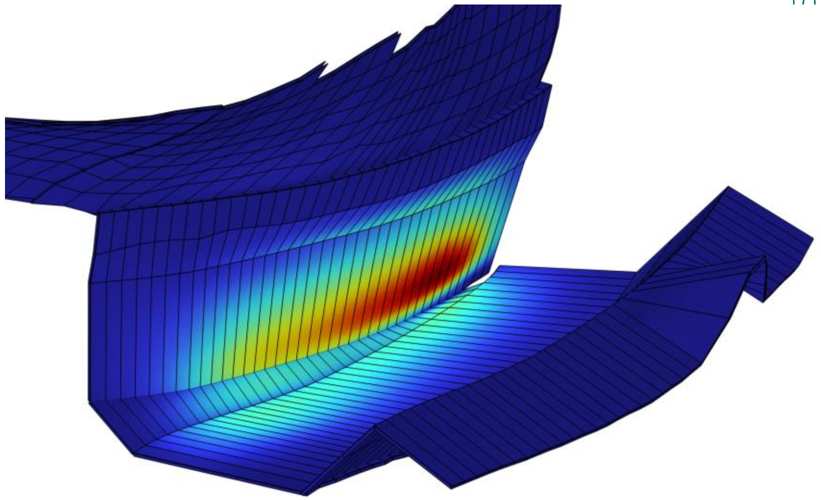
Raytracing (Computer Graphics) → AC method



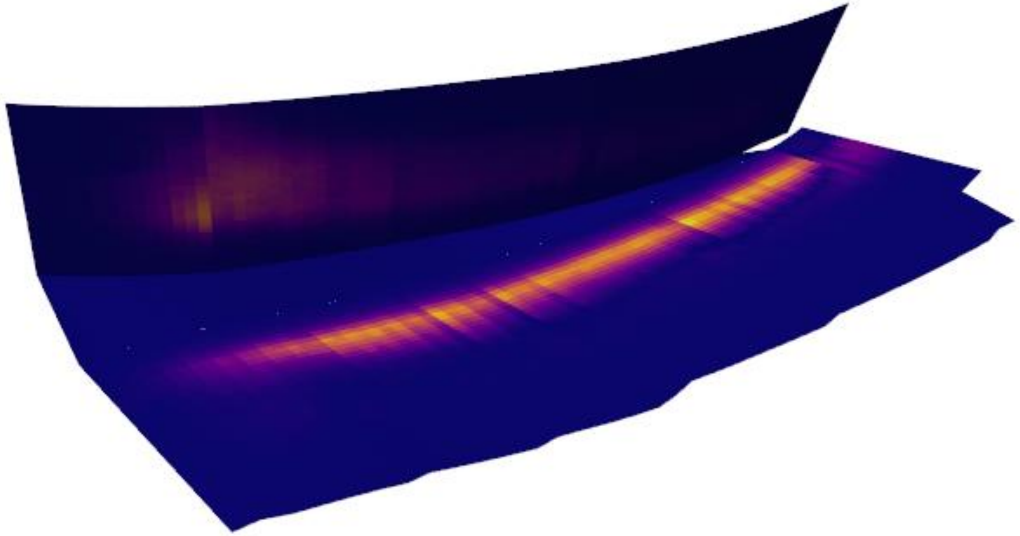
- Calculates probability densities instead of particle dynamics
- No discretisation of phase space

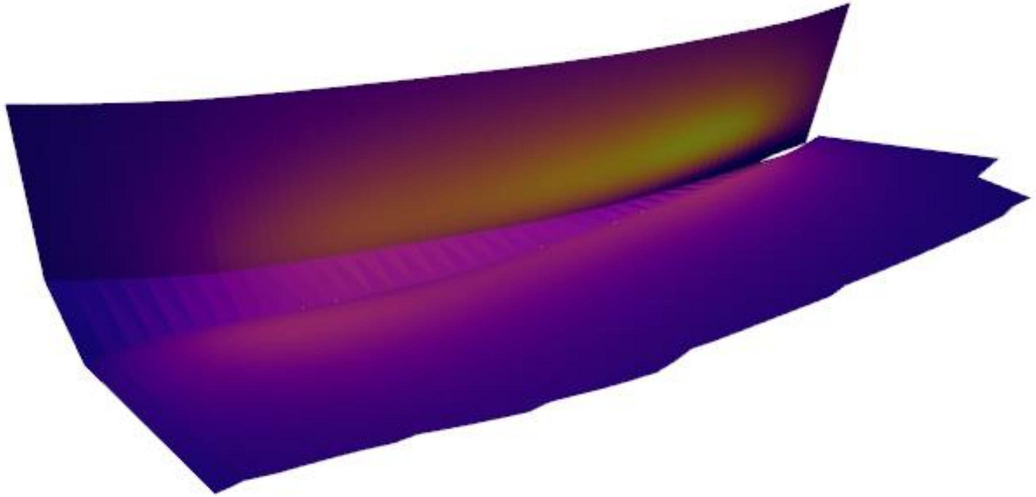
Solution with COMSOL Multiphysics





Solution with EMC3-Mercury



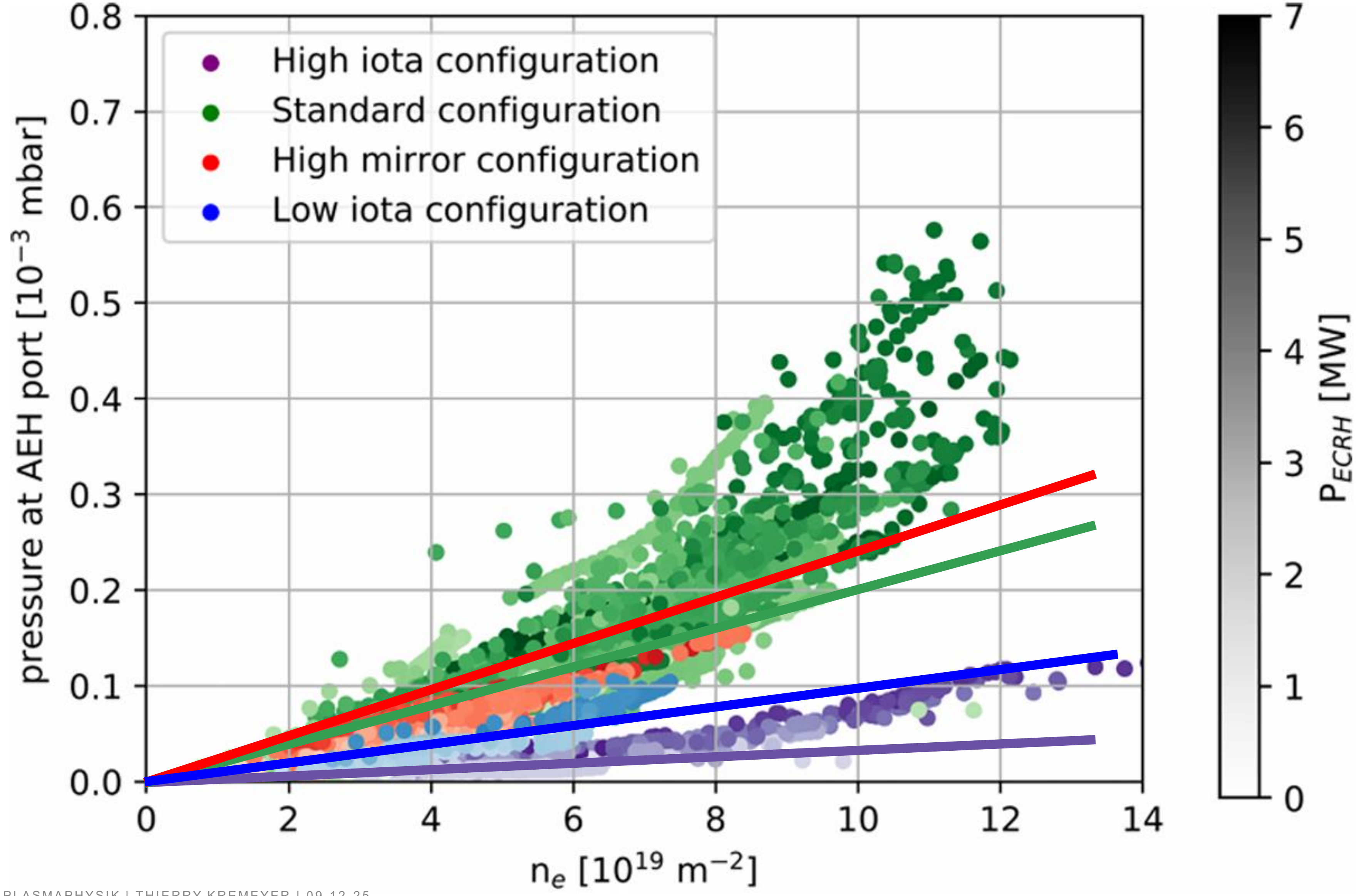


Location of neutralisation | **Neutral particle distribution**

Benchmark

Performance metric	Standard 5/5	High-Mirror 5/5	High-Iota 5/4	Low-Iota 5/6
Particle diversion	99.86 %	99.94 %	99.71 %	99.93%
× Particle collection	2.94 %	3.32 %	3.83 %	1.01 %
× Particle removal	2.99 %	3.45 %	2.84 %	3.14 %
= Particle exhaust	0.084 %	0.113 %	0.108 %	0.032 %

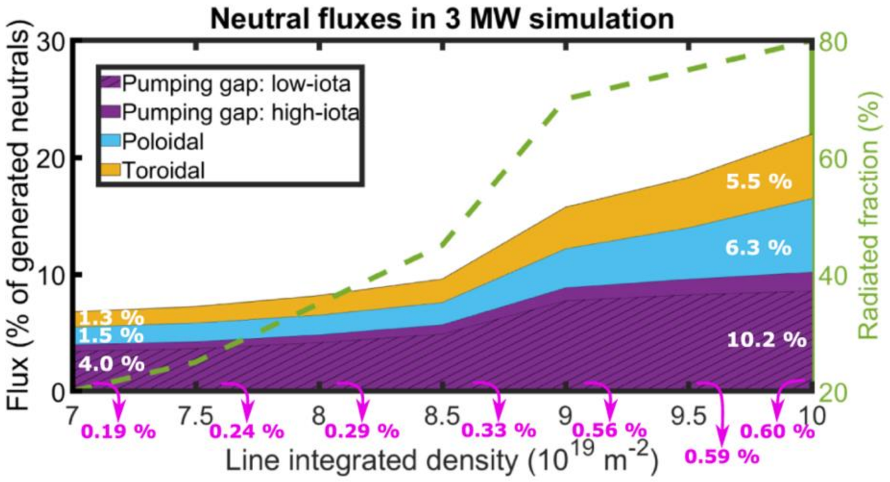
Experimental validation: Pressure at AEH port

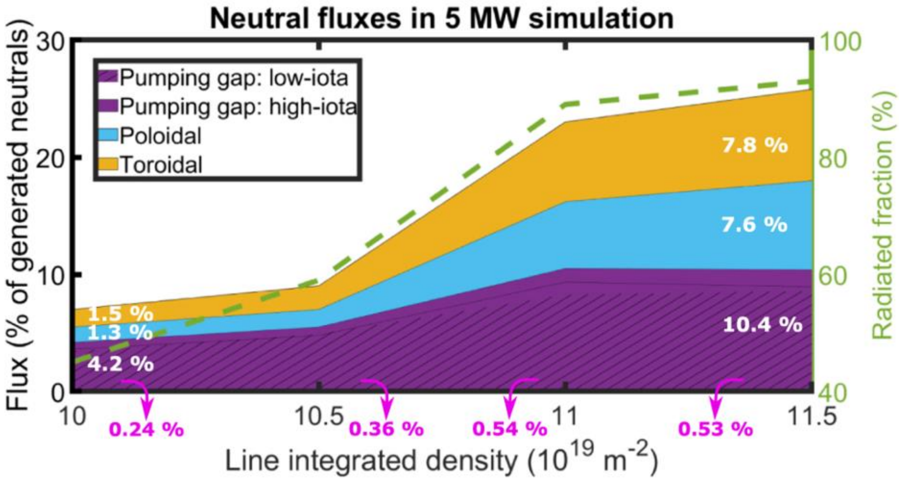


[V. Haak, PPCFET 2023]

Particle collection: Comparison to high-fidelity model

	AC method	EMC3-Eirene	(Wenzel et al., NF 2024)
Particle collection (Standard configuration)	2.83 %	4.0 % - 10.4 %	0.69 % ± 0.28 %

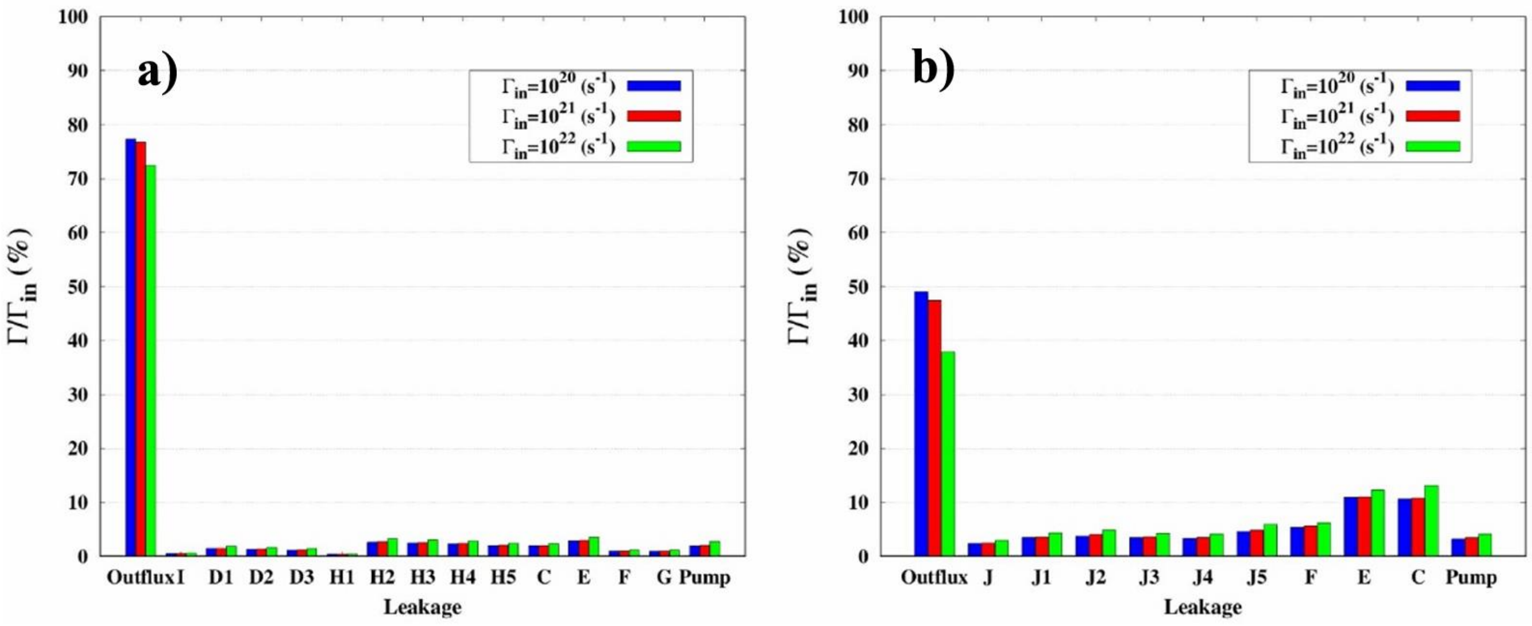




[D. Boeyaert, PPCFET 2024]

Particle removal: Comparison to high-fidelity model

	AC method		DIVGAS		EMC3-Eirene
Divertor section	Low-Iota	High-Iota	Low-Iota	High-Iota	Low-Iota
Particle removal	2.99 %	2.84 %	1.9 % - 2.7 %	3.0 % - 4.0 %	4.75 % - 5.88 %

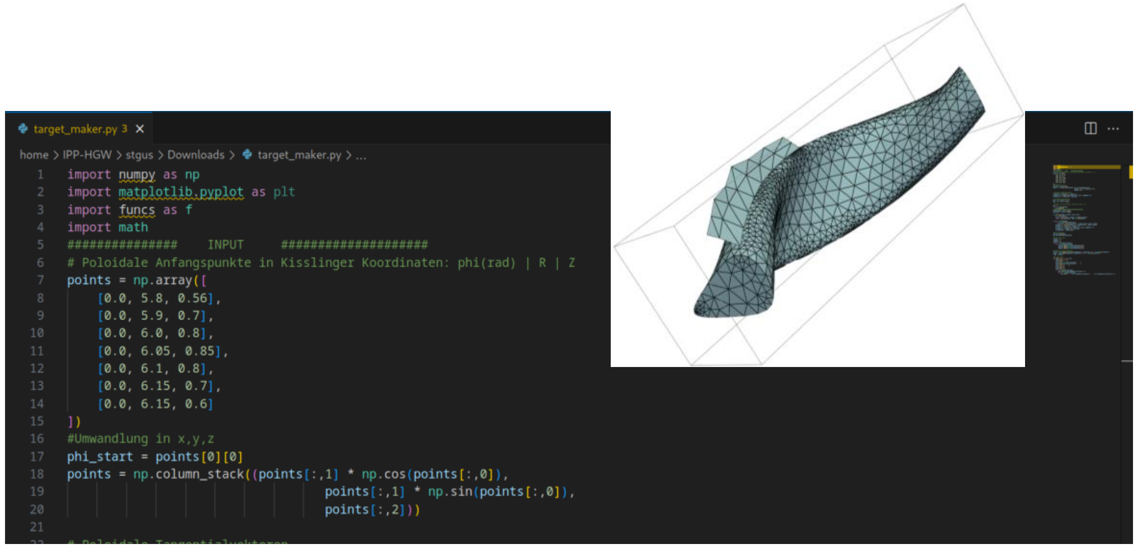


[S. Varoutis, NF 2024]

Parametric Divertor Chamber Maker

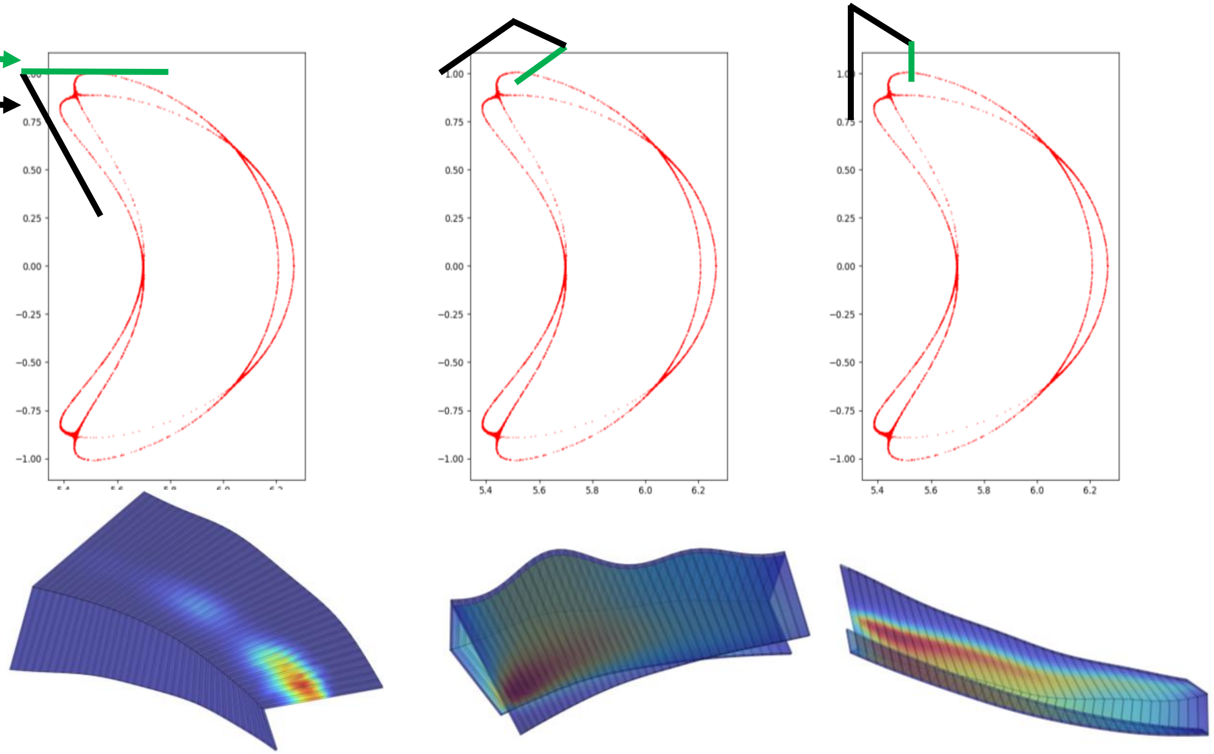
Field aligned, parametric design in Kisslinger format for

- **Target maker**
- **Pump opening maker**
- **Baffle maker – under development**



Target – Separatrix angle

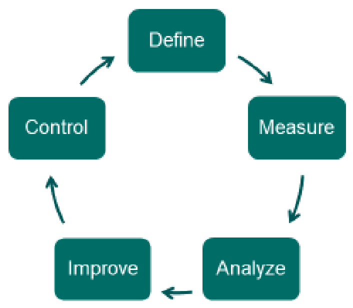
0° 45° 90°



Low fidelity particle collection efficiency

1.7% 76.8% 64.1%

6σ – DMAIC design cycle to optimize W7-X divertor



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Efficient process ➡

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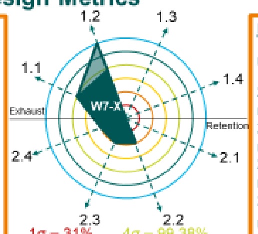
$\eta_{removal} = \Gamma_{exh} / \Gamma_{coll}$



1σ – 31% 4σ – 99.38%

2σ – 69% 5σ – 99.977%

3σ – 93.3 % 6σ – 99.99966 %

Performance Function 2: Particle retention

$\eta_{retention} = \eta_{sub\text{-}con}\ \eta_{div\text{-}re\text{-}inztn}\ \eta_{plg}\ \eta_{scr}$

2.1 Pumping plenum containment

$\eta_{plenum\text{-}con} = 1 - (\Gamma_{plenum\text{-}loss} / \Gamma_{coll})$

2.2. Divertor re-ionization

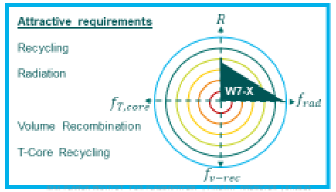
$\eta_{div\text{-}re\text{-}ion} = \Gamma_{div\text{-}re\text{-}ion} / (\Gamma_0 - \Gamma_{exh})$

2.3. Divertor plugging

$\eta_{plg} = 1 - (\Gamma_{div,loss} / \Gamma_{div,in}) = \eta_{plg,0} + \eta_{plg,ion}$

2.4. Particle screening

$\eta_{scr} = 1 - \frac{\Gamma_{core,in}}{(\Gamma_{edge,out} - \Gamma_{exh})} = 1 - \frac{\Gamma_{core,in}}{\Gamma_{sputtering}}$



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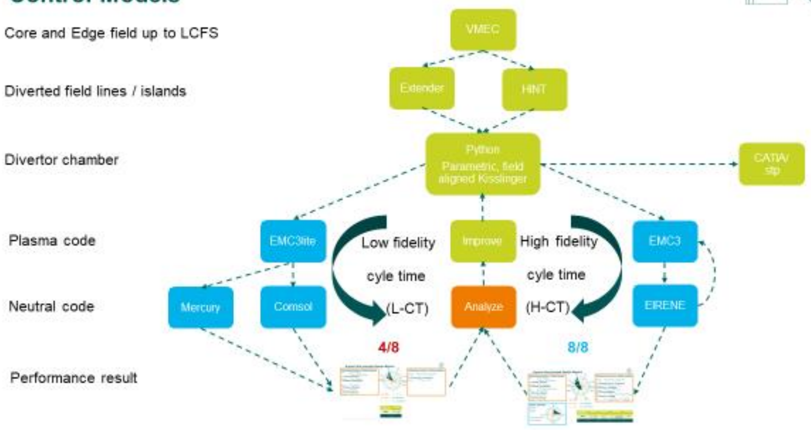
W7-X	1.67	?	> 1	?

Control Models



Solution with COMSOL Multiphysics

Solution with EMC3-Mercury

Location of neutralisation Neutral particle distribution