MAX-PLANCK-INSTITUT
FÜR PLASMAPHYSIK

Divertor A Priori First Principles: Part I

Definition of Divertor Performance, Guarantee Requirements, and Design Maxims

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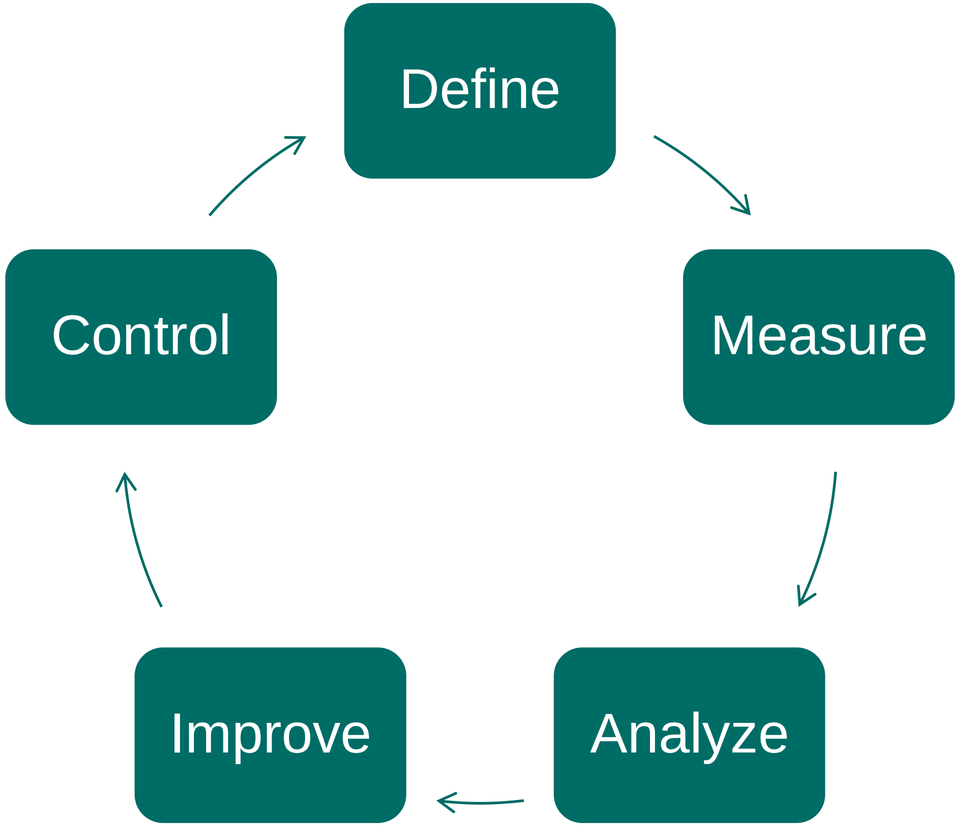
6 sigma – Management toolbox based on statistical analysis for process optimization and quality to handle complex systems



Define

Measure

Analyze

Improve

Control

- 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

σ-level	DPMO (defects per million opportunities)	Yield %
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 %

Efficient process ➡

For complex systems often combined with Lean management

➢ Lean-6σ, L6s, L6σ

A priori first principles
put focus on functionality, and enable innovation

A priori first principles are fundamental principles or truths that are know

without the need for empirical observation or experimentation

- **Humans are prone to think in analogies. New developments are ofte**
  approaches. Linear evolution rather than innovation
- **Limits innovation as focus is on trends, technology, form, design**
  - ➢ Maslow‘s Hammer, or Einstellungs bias

NASA SP-287

WHAT MADE APOLLO A SUCCESS?

CASE FILE COPY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Method

1. **Identify and challenge assumptions (5-Why Method)**
2. **De-couple problem into first principles**
3. **Create innovative solution**

particle removal ➡

3. **high neutral gas pressure** in the sub-divertor region (TMPs, cryopumps)

$$p_n * S_{eff} = \Gamma_{exh}$$

Assumption: S_{eff} is fixed

A priori first principle: $\mathbf{\Gamma_{exh}}$[1/s]

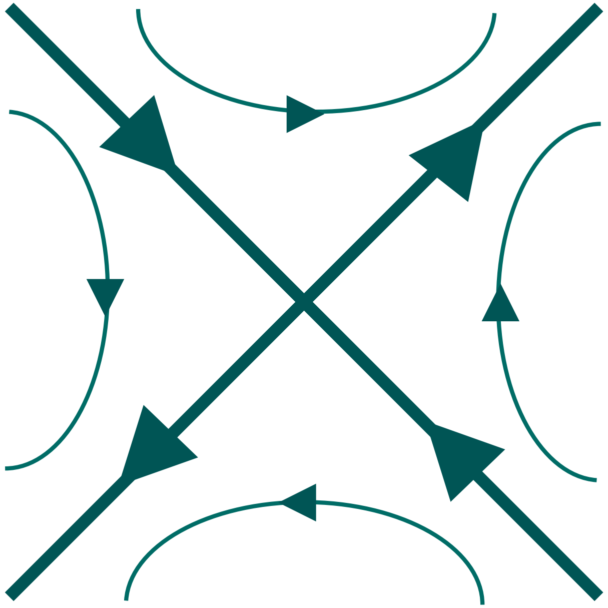
Magnetic confinement fusion

$$\nabla \cdot \vec{B} = 0 = \oint \vec{B} \cdot d\vec{A} \quad (1)$$

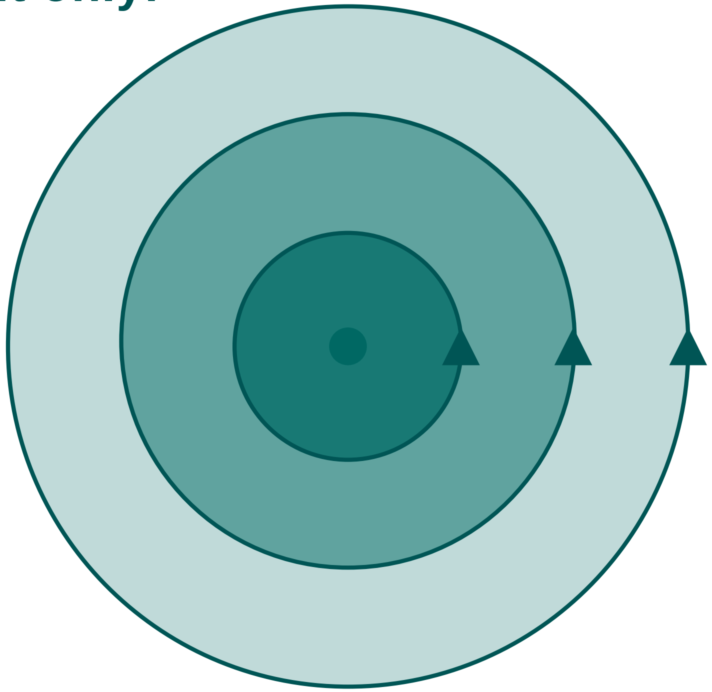
Hamiltonian system like an incompressible fluid, in 6D-Phase space

Only 3D cross sections visualizable in Poincaré

Fixed points exist, but only:



X-point (saddle point)



Collisionless plasma

„Frozen-in“

O-point (null/fix/center point)

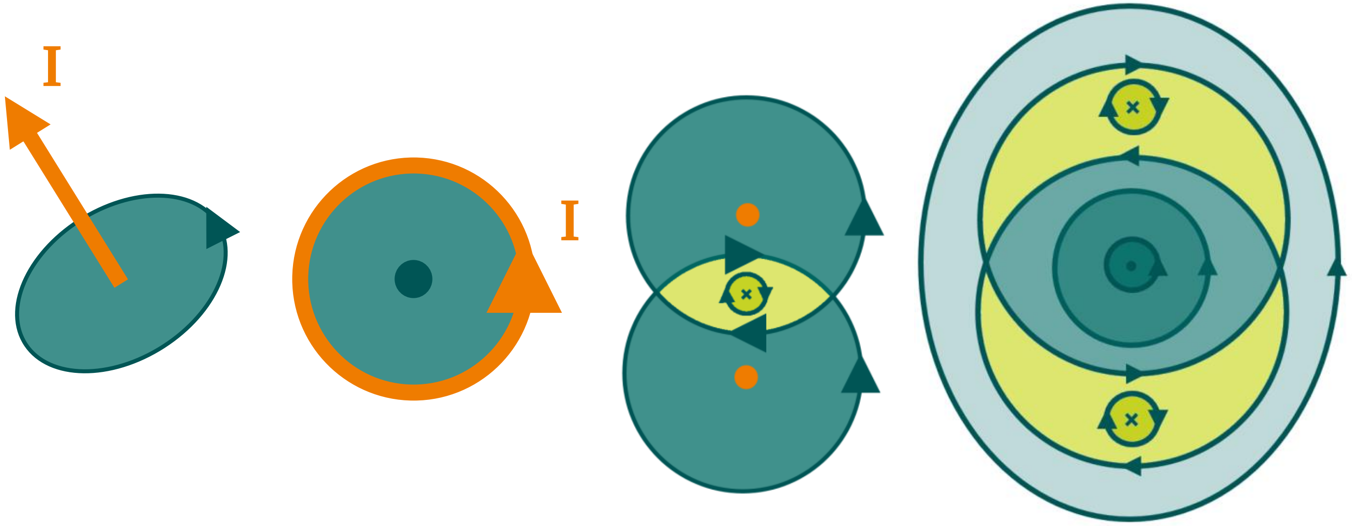
local maxima/minima

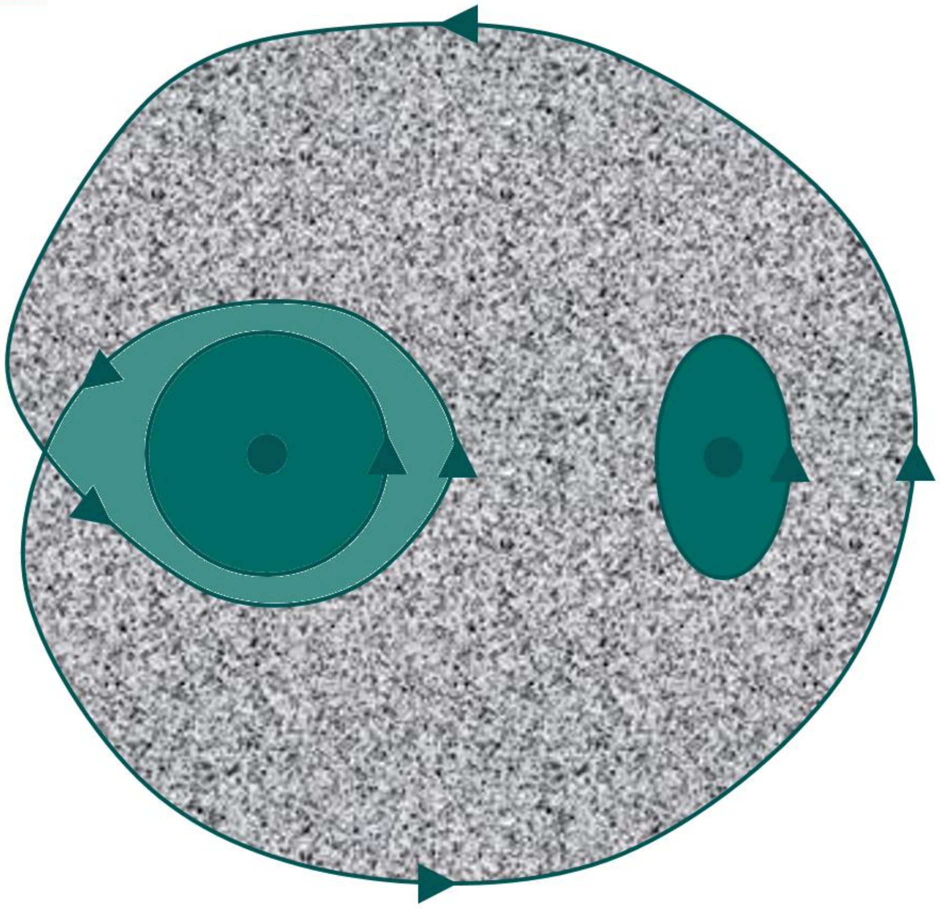
Magnetic field

$$\boldsymbol{\nabla} \cdot \vec{\boldsymbol{B}} = \mathbf{0} = \oint \vec{\boldsymbol{B}} \cdot \boldsymbol{d}\vec{\boldsymbol{A}} \quad (\mathbf{1})$$

How can O-Points be created?

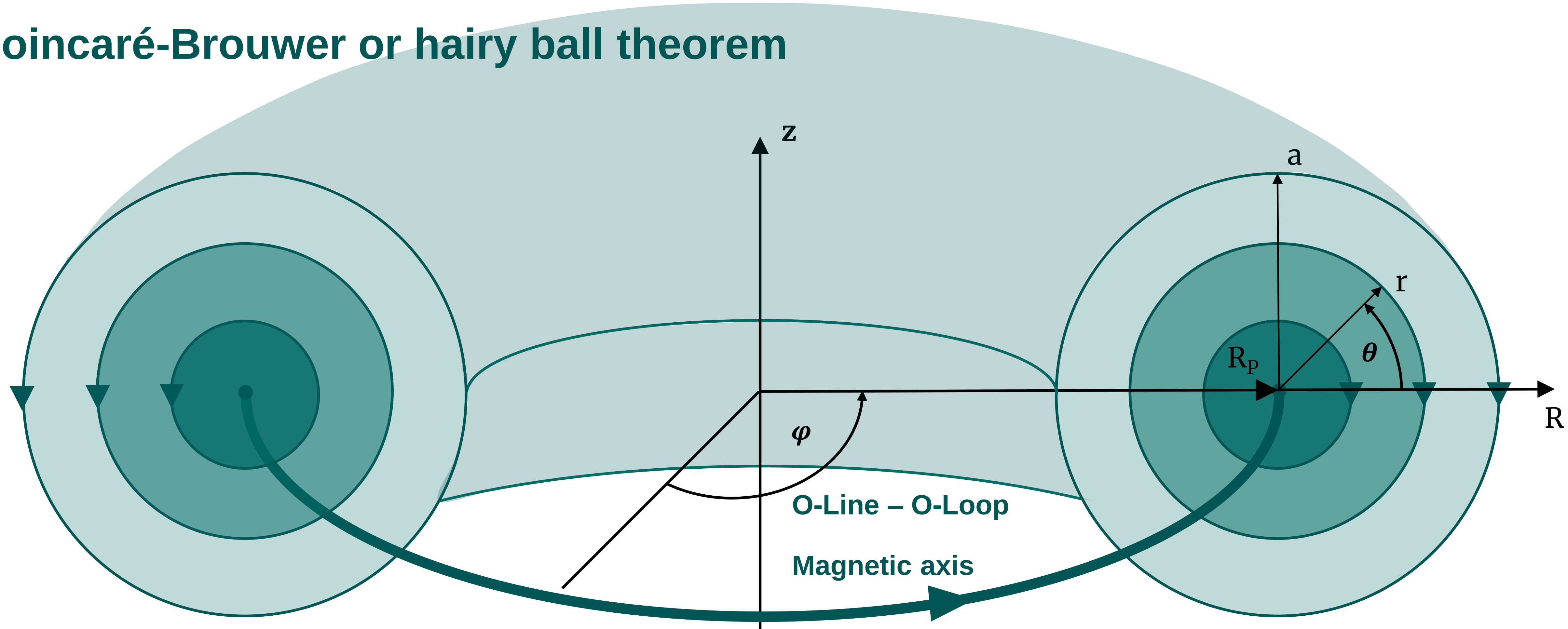
- Ampères law – Current in conductor, O-Point in conductor
- Ampères law – Current in coil, O-point in coil center
- Interference – Overlap of two or more other O-points
- Resonance – Rational surfaces of rotational transform
- Chaos – 2 or more O-points seperated by chaos





Magnetic confinement fusion – Toroid only closed flux surface for $\nabla\vec{B} = 0$

Poincaré-Brouwer or hairy ball theorem



O-Line – O-Loop

Magnetic axis

$$\vec{B}(\psi_t,\theta,\varphi) = \nabla\psi_t \times \nabla\theta + \nabla\varphi \times \nabla\psi_p(\psi_t,\theta,\varphi)$$

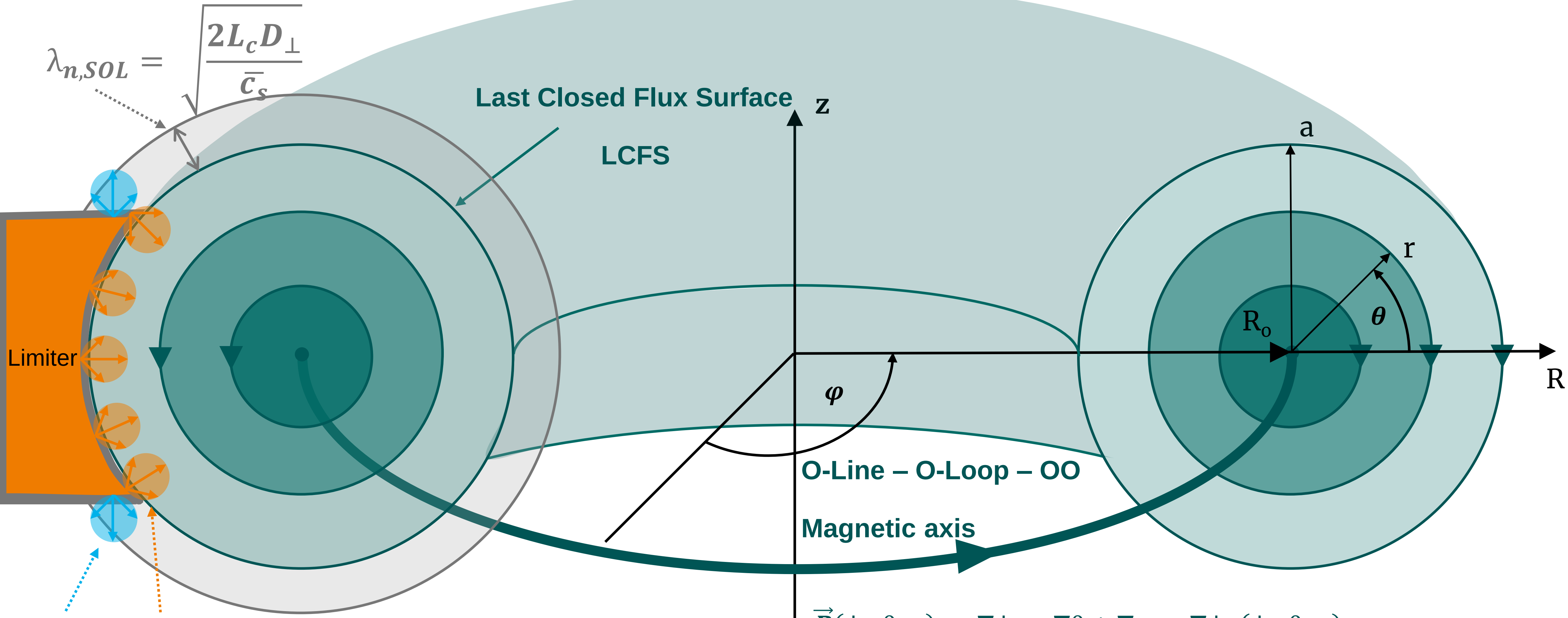
[Boozer, PhysFluids 1983]

Adapted [Stroht Springer 2018]

Magnetic confinement fusion – Toroid extends indefinite - Limiter

Scrape-Off Layer SOL

$$\lambda_{n,SOL} = \sqrt{\frac{2L_c D_\perp}{\bar{c}_s}}$$



Γ_0 and Γ_{imp} with assumed cosine $\vec{v}$ release distribution

$$\vec{B}(\psi_t, \theta, \varphi) = \nabla\psi_t \times \nabla\theta + \nabla\varphi \times \nabla\psi_p(\psi_t, \theta, \varphi)$$

[Boozer, PhysFluids 1983]

$$L_C = 2\pi R$$

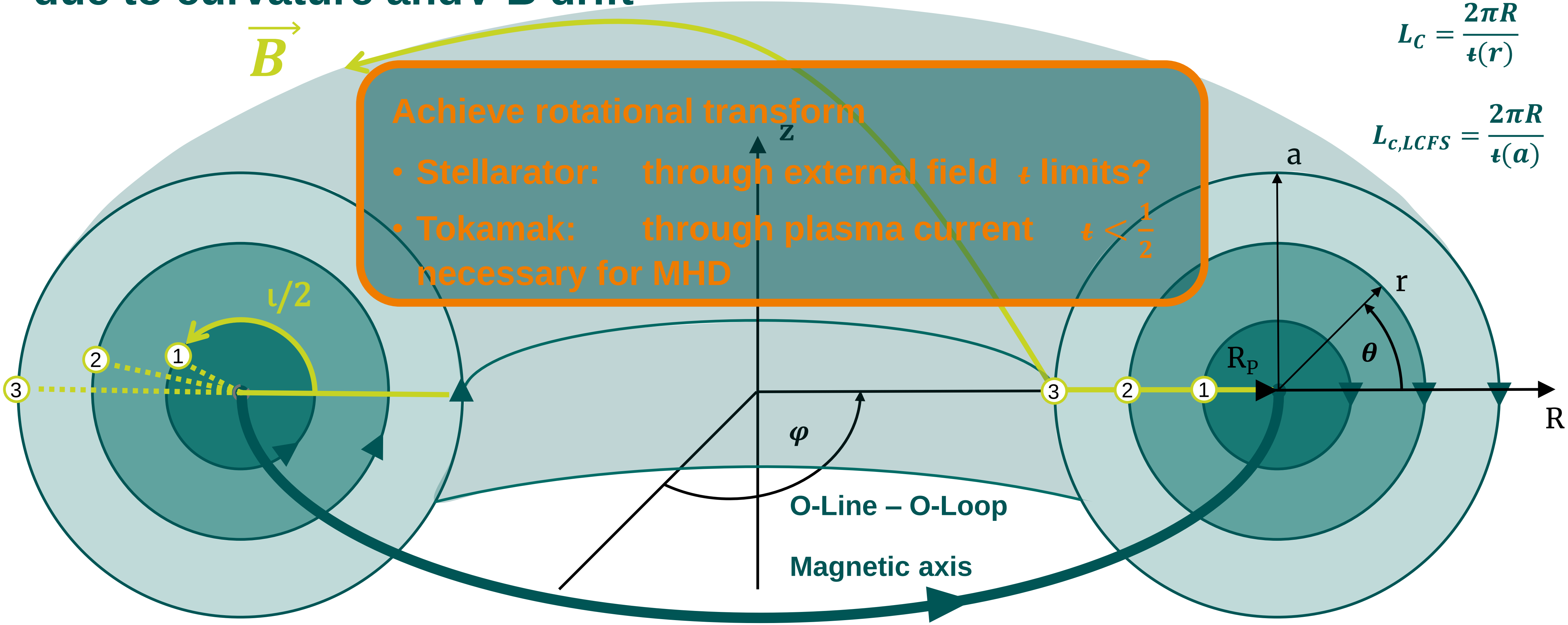
$$L_{c,oo} = 2\pi R_o$$

Limiter is Neutral and Impurity Source

Magnetic confinement fusion – Rotational transform necessary due to curvature and∇ B drift

$$L_C = \frac{2\pi R}{\bar{\iota}(r)}$$

$$L_{c,LCFS} = \frac{2\pi R}{\bar{\iota}(a)}$$



Achieve rotational transform

- **Stellarator: through external field $\bar{\iota}$ limits?**
- **Tokamak: through plasma current $\bar{\iota} < \frac{1}{2}$ necessary for MHD**

$$\bar{\iota} = \frac{\iota}{2\pi} = \frac{n}{m} = \frac{\mathit{poloidal\ transit}}{\mathit{toroidal\ transit}} = \frac{\mathit{toroidal\ mode\ number}}{\mathit{poloidal\ mode\ number}}$$

The divertor - Magnetic 3D Topology of two toroids

Neutralizing in plasma toroid:

Impurity source will directly ionize in plasma toroid

➡ decrease of ρ and operational space

Neutrals surround plasma toroid

➡ CX damage and $\Gamma_{\text{recy,edge}}$

Two toroids necessary!

Plasma toroid:

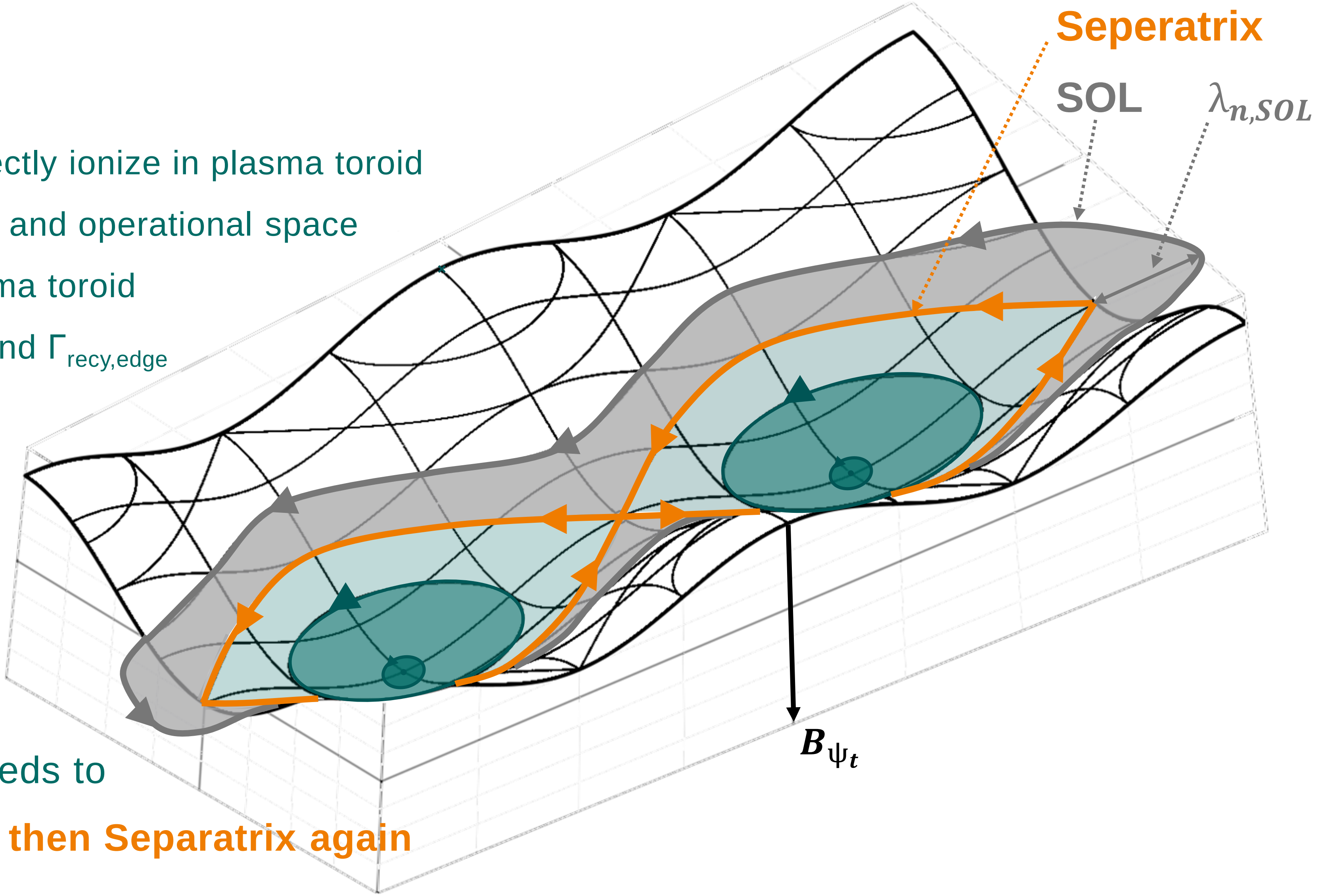
⬆ High p_p ⬇ Low p_0

Divertor toroid:

⬇ Low p_p ⬆ High p_0

To change toroids, plasma needs to

Cross **Separatrix, then SOL, then Separatrix again**



Adapted [Sam Derbyshire - CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=48150195]

Coordinates with 1 plasma and 1 divertor toroid

Plasma Toroid LCPFS $L_{c,LCPFS} = \frac{2\pi R_P}{\bar{\iota}_P(a_P)}$

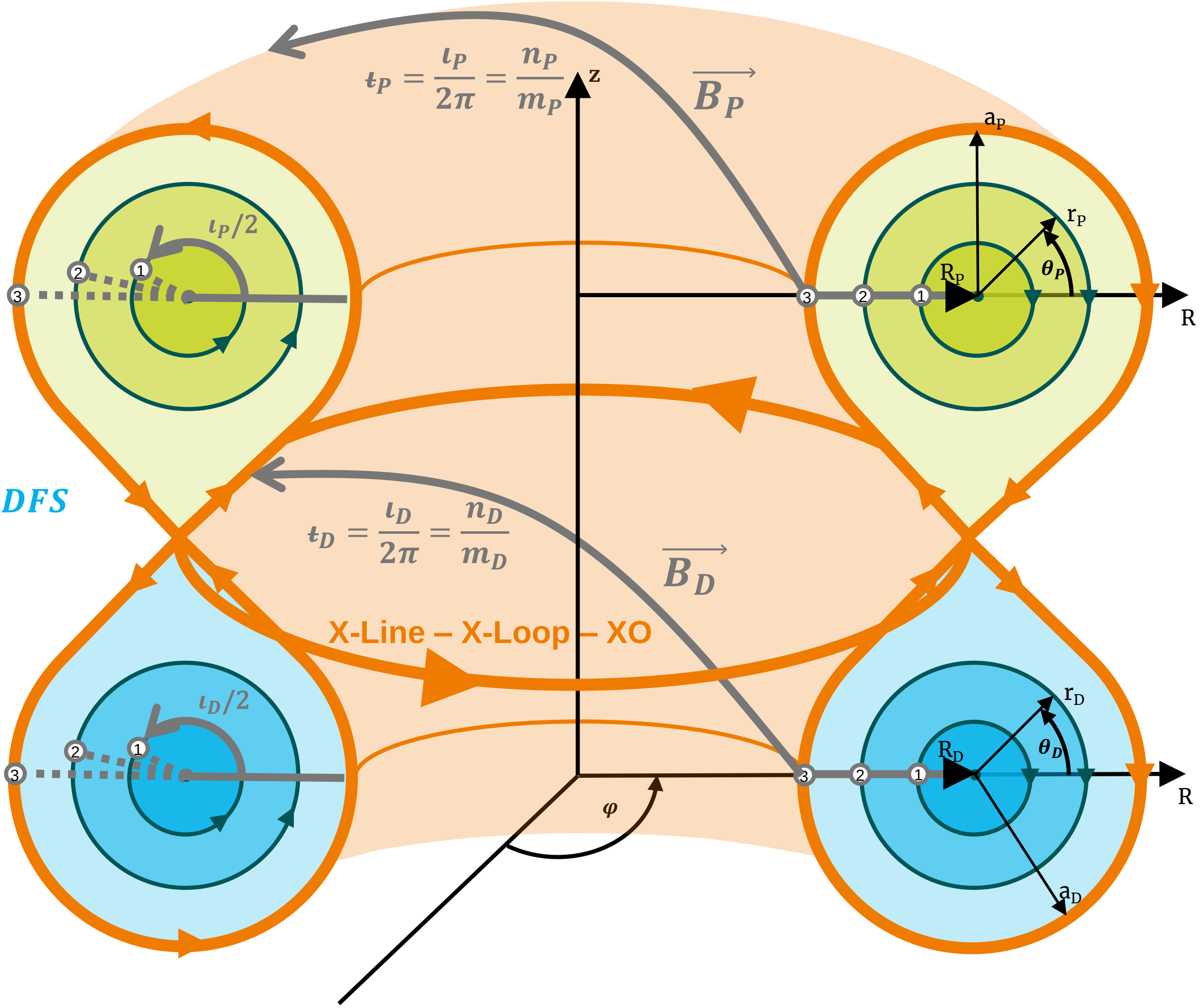
Divertor Toroid LCDFS $L_{c,LCDFS} = \frac{2\pi R_D}{\bar{\iota}_D(a_D)}$

Separatrix Surface XFS $L_{c,XFS} = L_{c,LCPFS} + L_{c,LCDFS}$

$$L_{c,XFS} = 2\pi\left(\frac{R_P}{\bar{\iota}_P(a_P)} + \frac{R_D}{\bar{\iota}_D(a_D)}\right)$$

X-Loop conncetion length

$$L_{c,XO} = \left(\frac{R_P + R_D}{2}\right)$$



SOL particle transport with 1 plasma and 1 divertor toroid

$\nabla \cdot \vec{v}$ particle transport through:

Diffusive transport:

Fick's law $\nabla \cdot \vec{v} \propto$ n, L_c

Neo-classical transport:

MHD $\nabla \cdot \vec{v} \propto$ n?, L_c

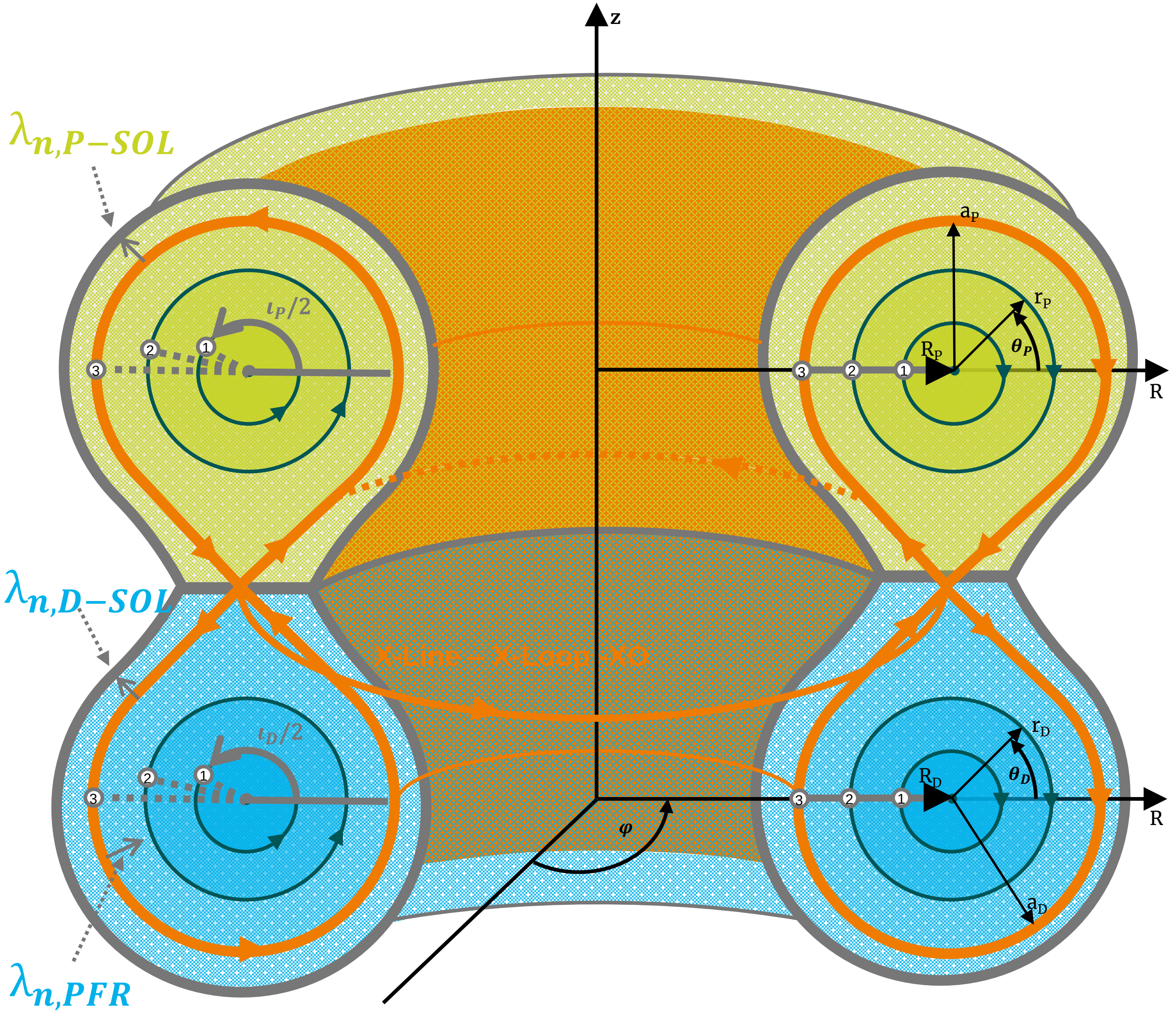
Turbulent transport:

Reynolds $\nabla \cdot \vec{v} \propto$ n, L_c

Assume $\nabla \cdot \vec{v}$ all combined as one $D_\perp$

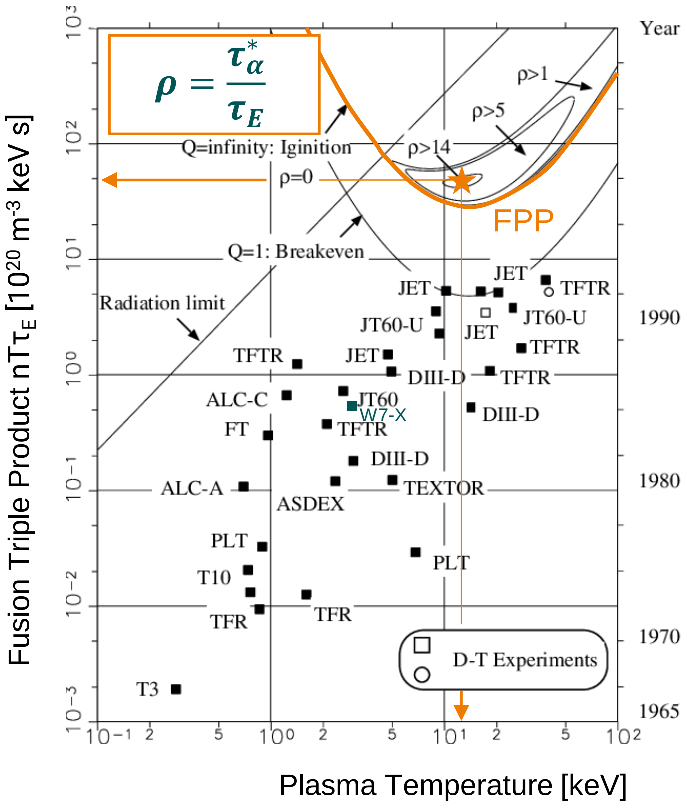
$$\lambda_{n,P-SOL} = \sqrt{\frac{L_{C,LCPFS} D_{\perp,P}}{0.5\ \overline{c_s}}}$$

[Stroht Springer 2018]



Reactor performance requirements

- $\Gamma_{He,exh} = \Gamma_{\alpha,1}$
- First maximize η_{exh},
- Then $\eta_{scr} = \eta_{scr,Edge} + \eta_{scr,SOL}$



Adapted [Reiter FSAT 2010]

FPP design point at $\boldsymbol{\rho} = 15$:

$$T_i \approx 11 \text{ keV}$$

$$n_i\tau_E \approx 10^{21} \text{ m}^{-3} \text{ s}$$

$$\boldsymbol{\tau_\alpha^*} = \tau_{\alpha 1} + \frac{\boldsymbol{R_{eff}}}{(\mathbf{1} - \boldsymbol{R_{eff}})} \tau_{\alpha 2}$$

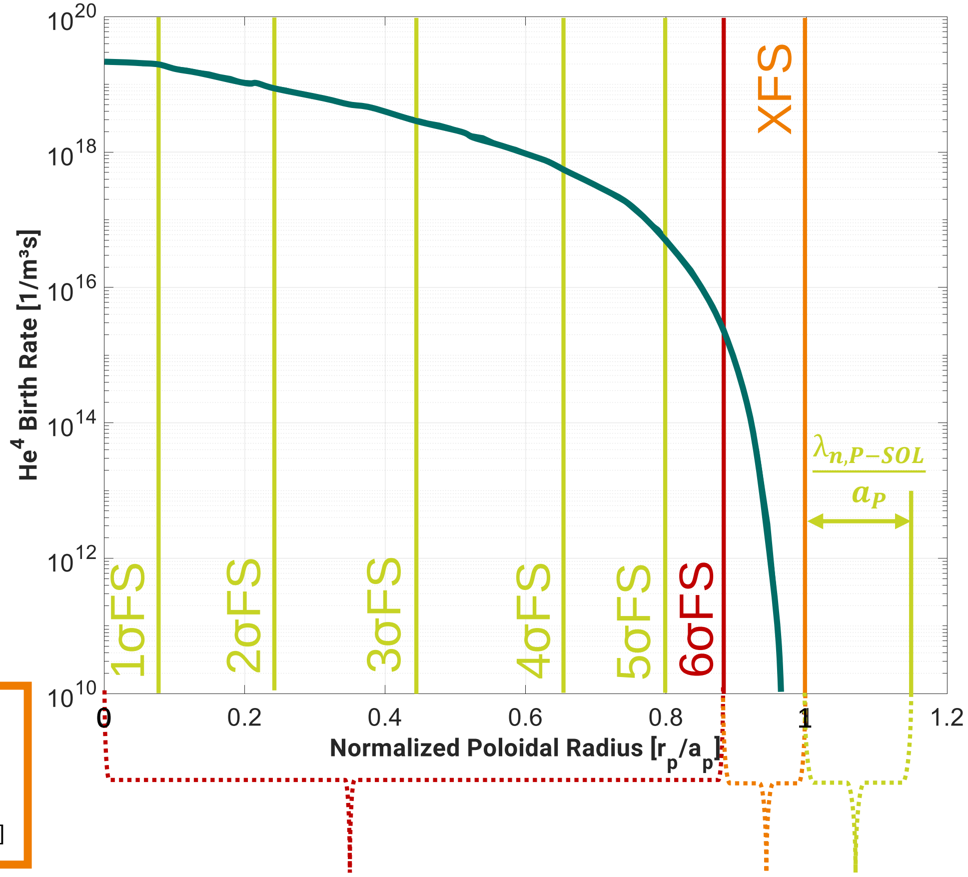
$$\boldsymbol{\tau_\alpha^*} = \tau_{\alpha 1} + \frac{(\mathbf{1} - \eta_{exh} + \eta_{wall})(1 - \eta_{scr})}{\eta_{exh} + \eta_{wall}} \tau_{\alpha 2}$$

[Reiter NF 1990]

6σ Goal:
3.4×10^{-6}

$$= \frac{(\mathbf{1} - \eta_{exh} + \eta_{wall})(1 - (\eta_{scr,Edge} + \eta_{scr,SOL}))}{\eta_{exh} + \eta_{wall}}$$

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



Core – burning region

Edge SOL

Edge – pedestal/screening/radiation

SOL – screening/radiation

Opertational performance requirements
Density control

Stable density in equilibrium

- $\Gamma_{exh} = \Gamma_{source}$

Wall independent density control

- $\Gamma_{exh} > \Gamma_{wall}$

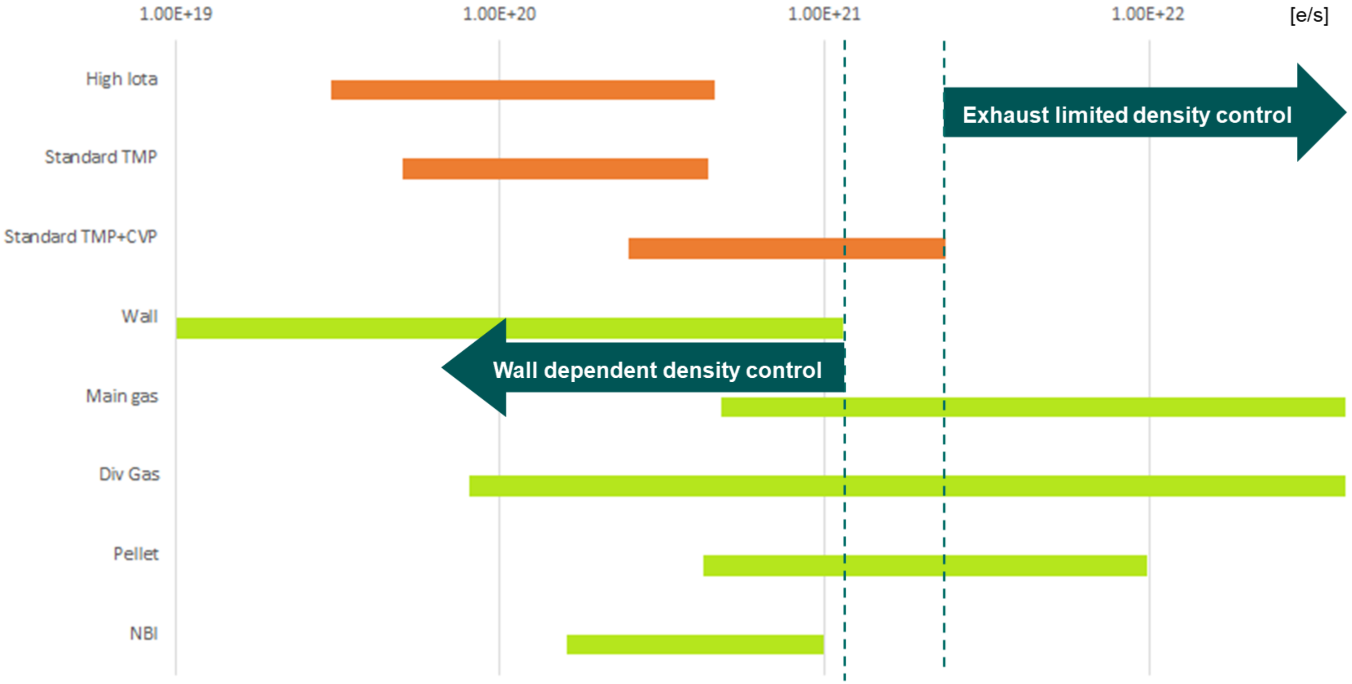
Exhaust limited density control

- $\Gamma_{exht} < \Gamma_{wall} + \Gamma_{NBI} + \Gamma_{pellet} (+\Gamma_{Gas})$

Fueling limited density control

- $\Gamma_{exh} > \Gamma_{wall} + \Gamma_{NBI} + \Gamma_{pellet} (+\Gamma_{Gas})$

Wendelstein 7-X achievable Γ_{exh} and Γ_{source}



➡ Combine divertor with throttle

Guarantee requirements

- Survive $P_{div} = P_{rec,surf}(\Gamma_{ion,div}) + P_{rec,vol}(\Gamma_{ion,div}) + P_{rad,div} + P_{n,div}$
- $q_{div} \leq 10$ MW/m² ($q_{max} \leq 20$ MW/m²)
- Survive neutron dpa (ITER 0.14 - 2.5dpa; DEMO 70 – 80 dpa)
- $T_{e,t} < 10$ eV (< 5 eV W sputtering; < 1.5 eV volume recomb.)

Divertor function: **Optimize performance metrics**

Maximize Γ_{exh} combined with throttle

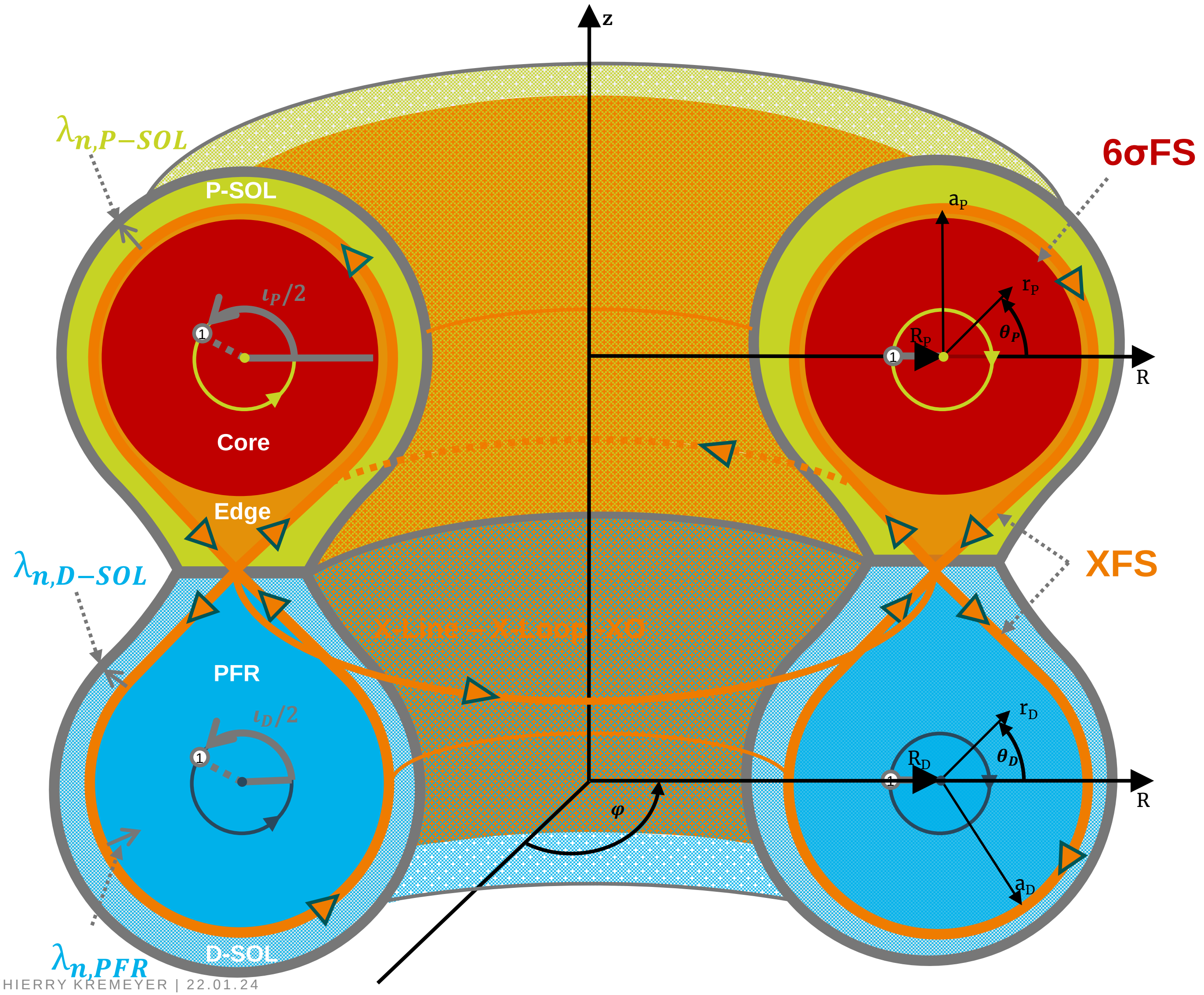
Maximize η_{exh}

$$\frac{(\mathbf{1} - \eta_{exh} + \eta_{wall})(1 - (\eta_{scr,Edge} + \eta_{scr,SOL}))}{\eta_{exh} + \eta_{wall}} = 3.4 \text{ x } 10{-}6$$

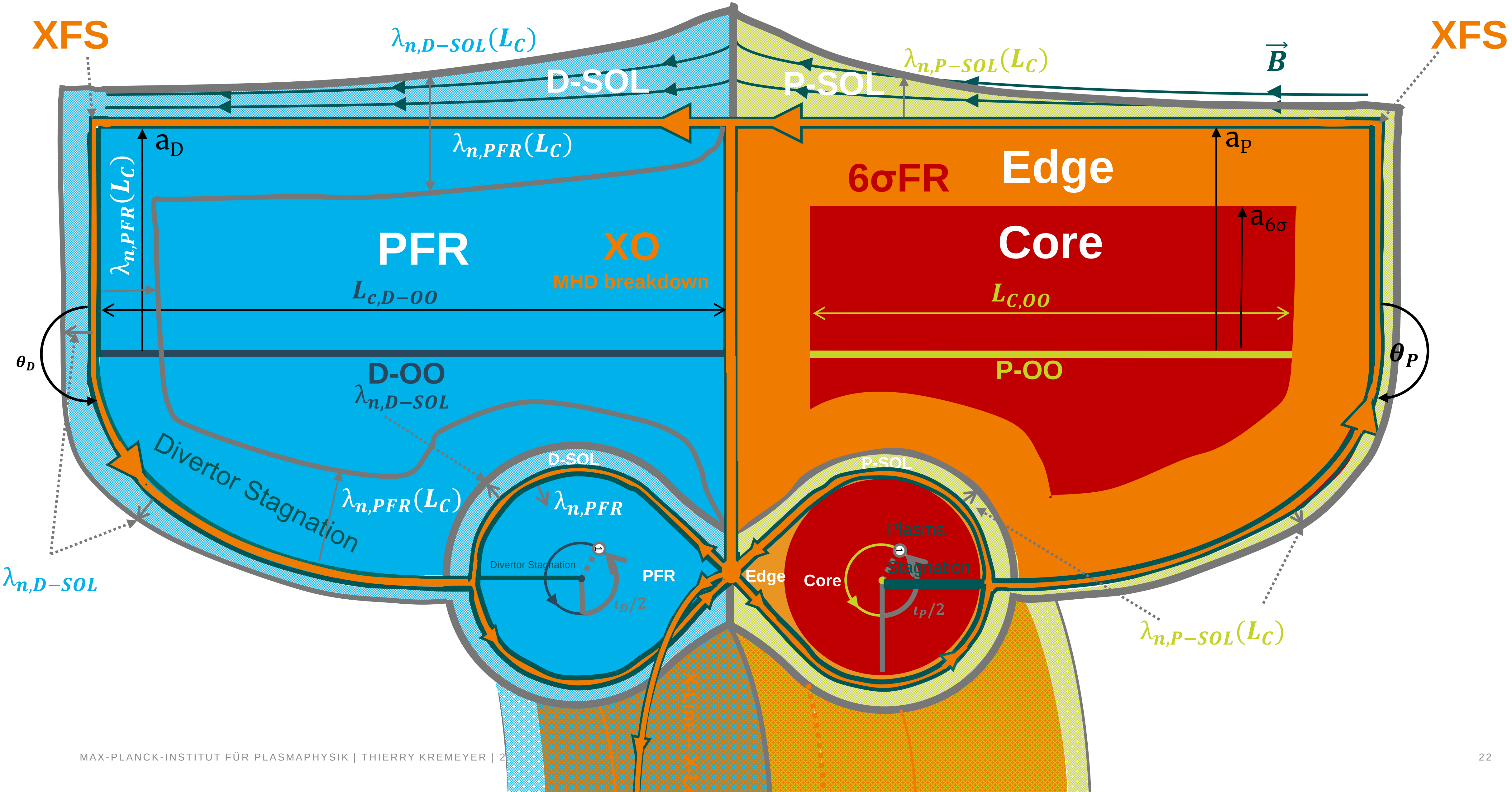
Maximize $\eta_{scr} = \eta_{scr,Edge} + \eta_{scr,SOL}$

Guarantee survival

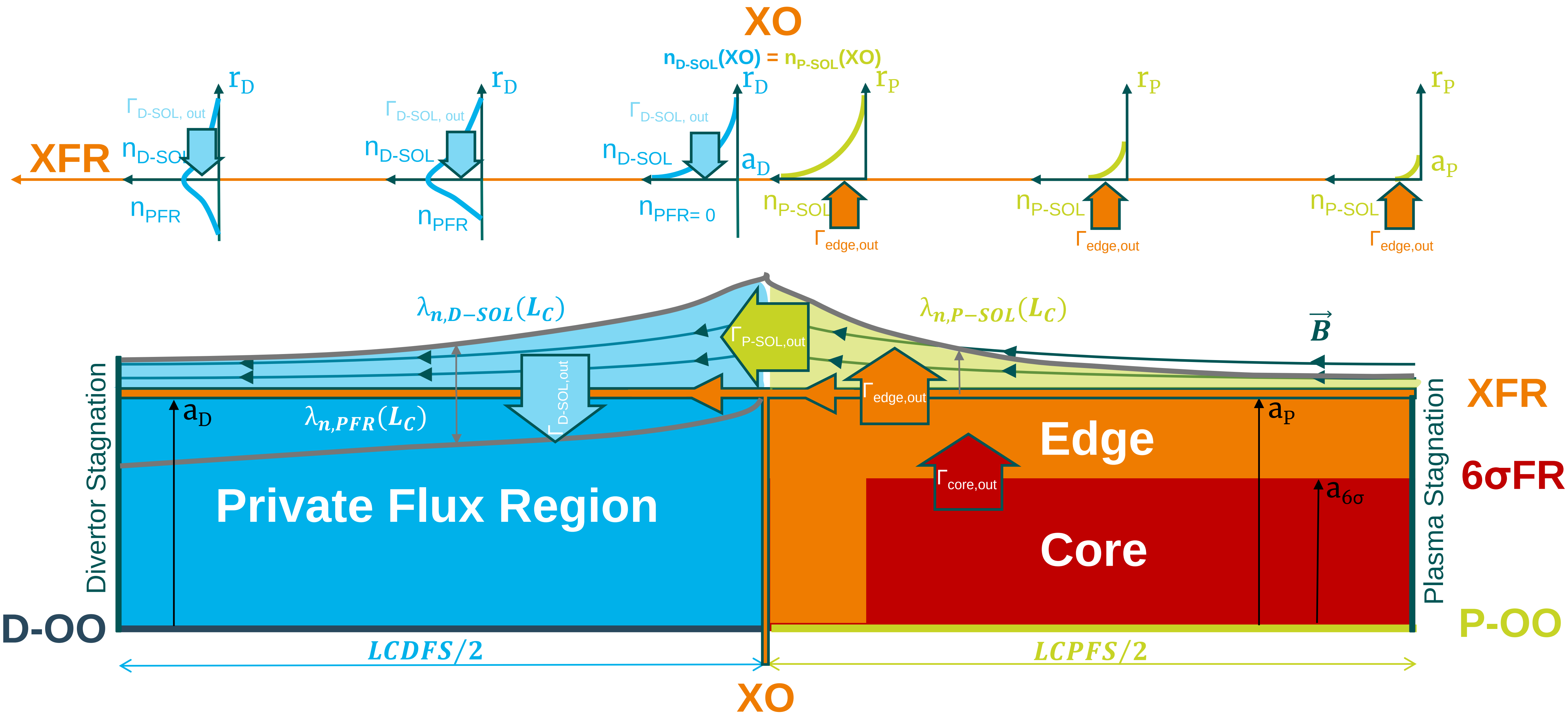
Critical toroidal Volumina and Flux Surfaces



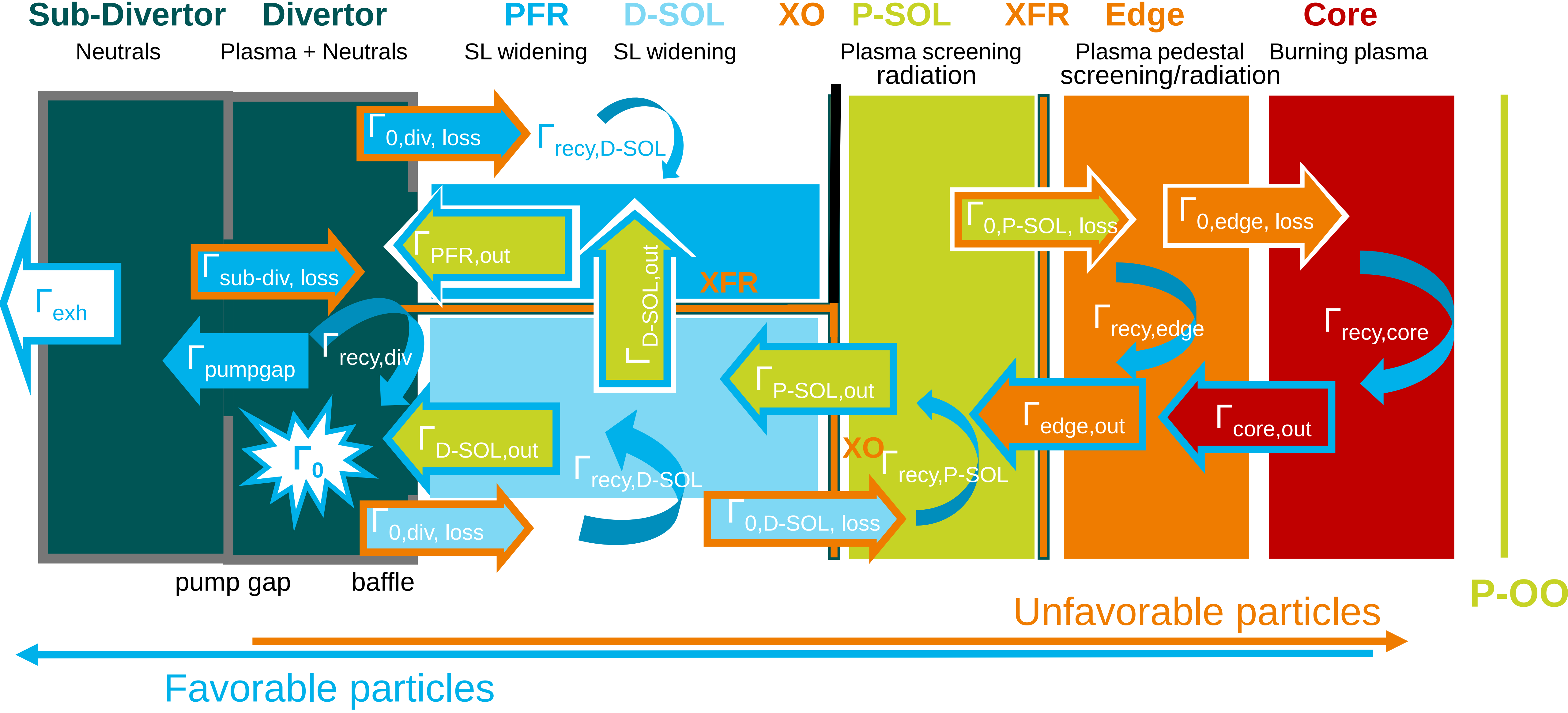
SOL from Plasma Stagnation point to Divertor Stagnation Point



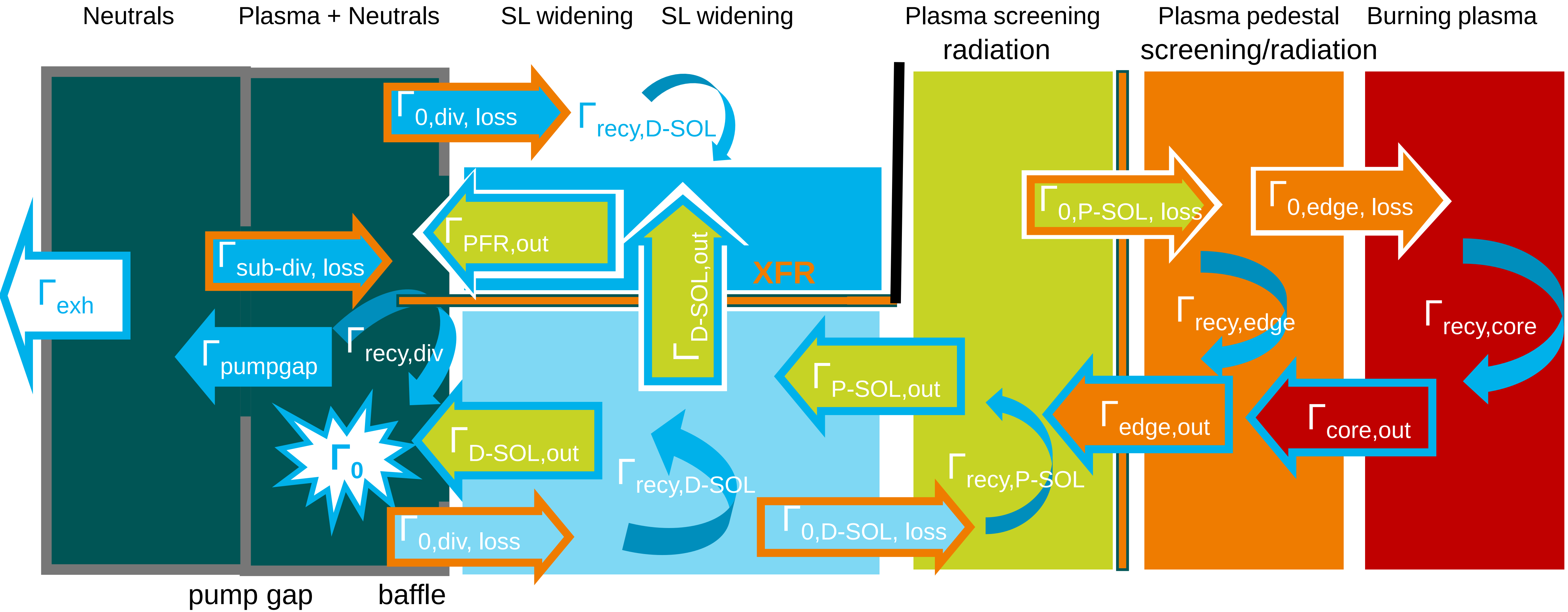
SOL transport Plasma Stagnation to Divertor Stagnation



Particle exhaust metrics and efficiencies ampère divertor



Exhaust efficiencies



Exhaust efficiencies

Particle exhaust efficiency

$\eta_{exh} = \Gamma_{exh} / \Gamma_0 = \eta_{coll}\, \eta_{rem}$

D-SOL screening

$\eta_{scr,D\text{-}SOL} = \Gamma_{recy,\ D\text{-}SOL} / (\Gamma_{div,\ loss})$

Particle collection

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

P-SOL screening

$\eta_{scr,P\text{-}SOL} = \Gamma_{recy,\ P\text{-}SOL} / (\Gamma_{div,\ loss})$

Particle removal

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

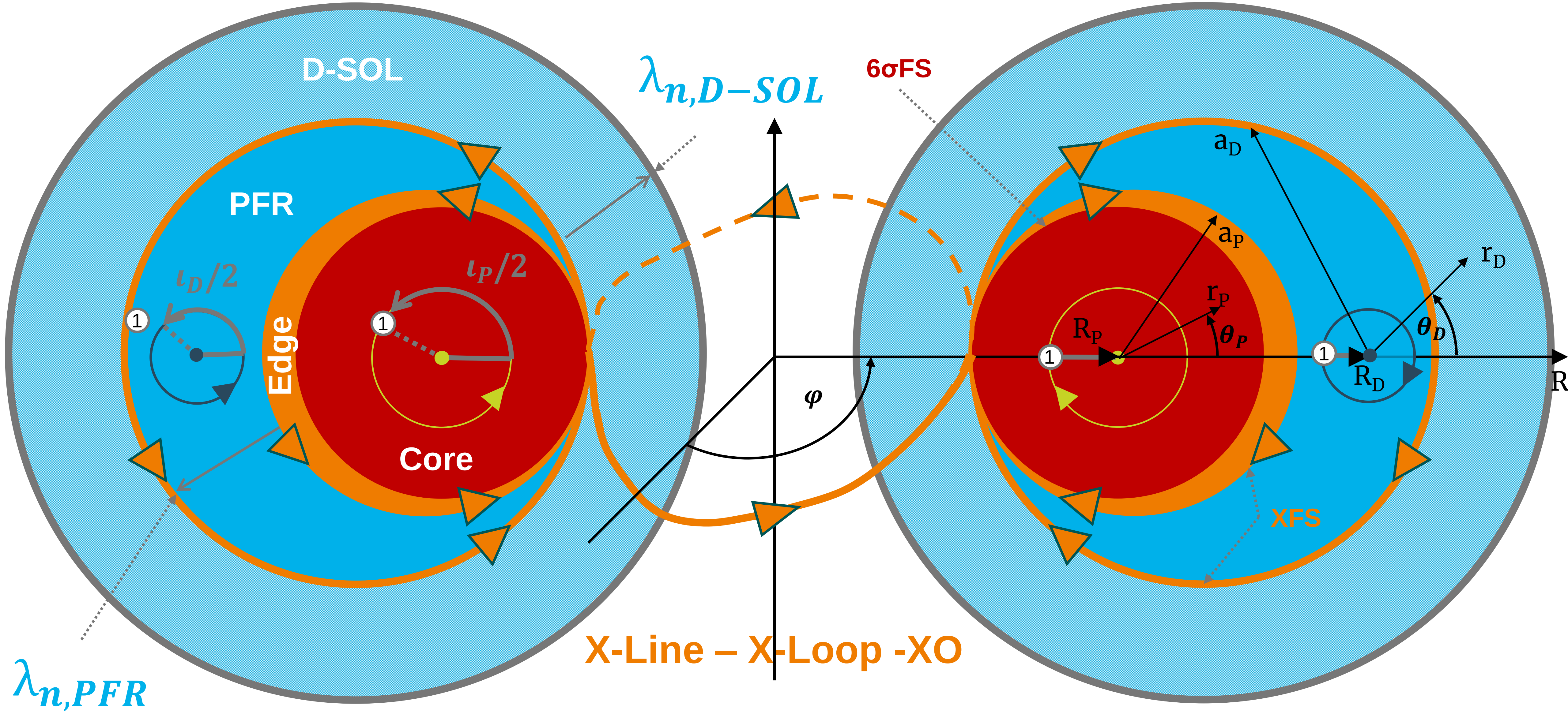
Edge screening

$\eta_{scr,edge} = \Gamma_{recy,\ edge} / (\Gamma_{P\text{-}SOL,\ loss})$

Particle plugging

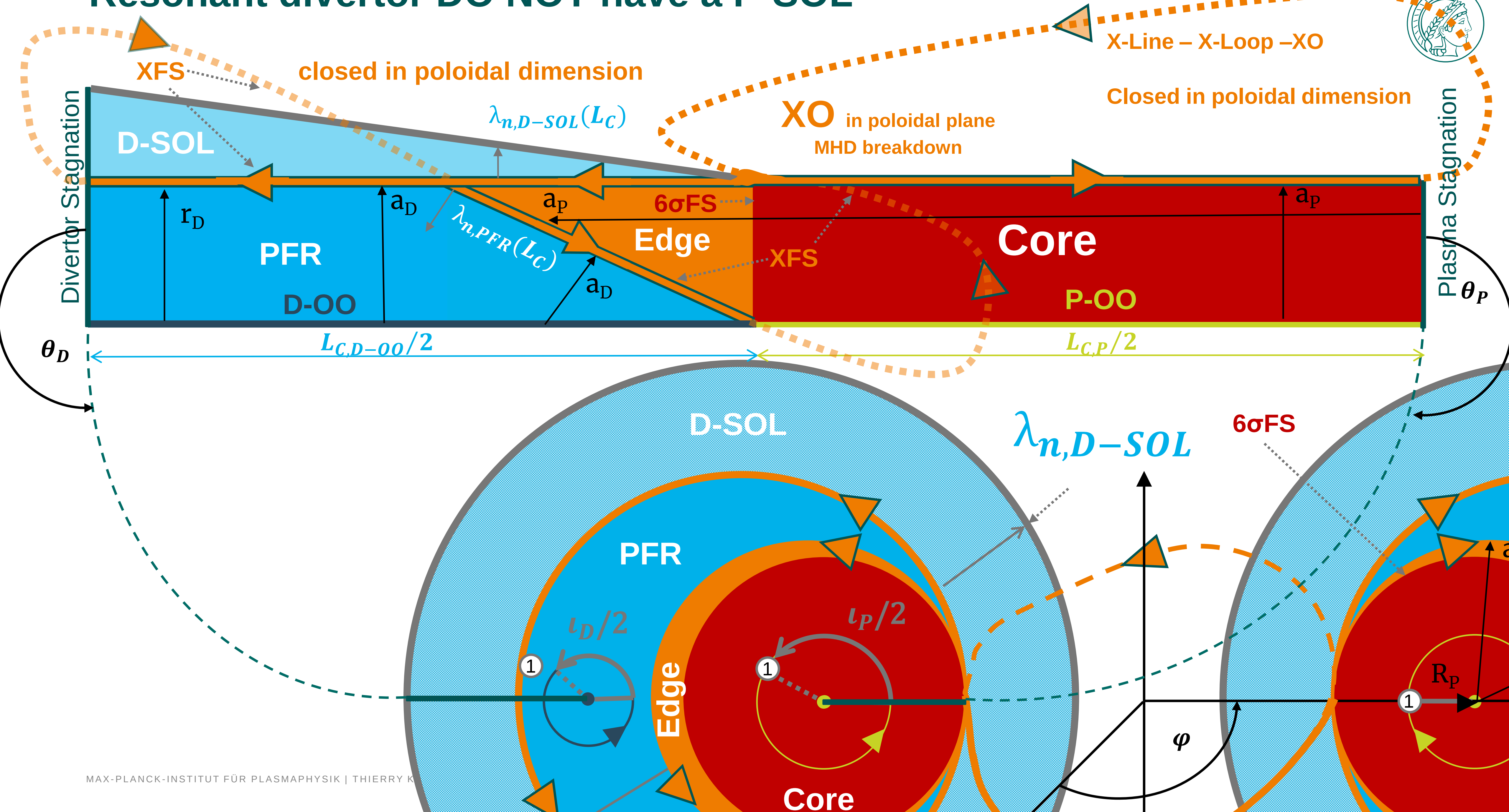
$\eta_{plug} = \Gamma_{recy,\ div} / (\Gamma_0 - \Gamma_{exh})$

Resonant divertor do not have a P-SOL

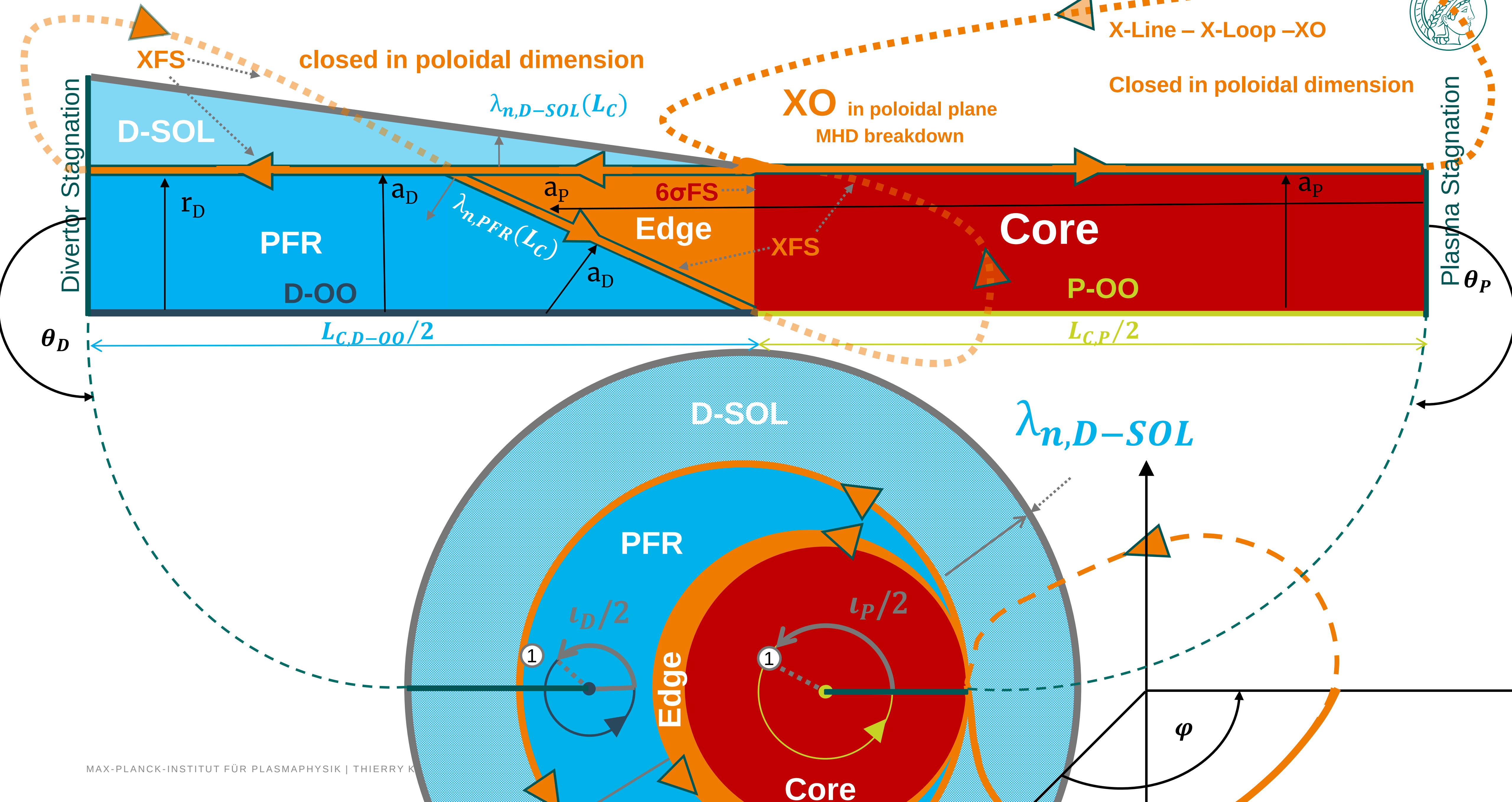


X-Line – X-Loop -XO

Resonant divertor DO NOT have a P-SOL

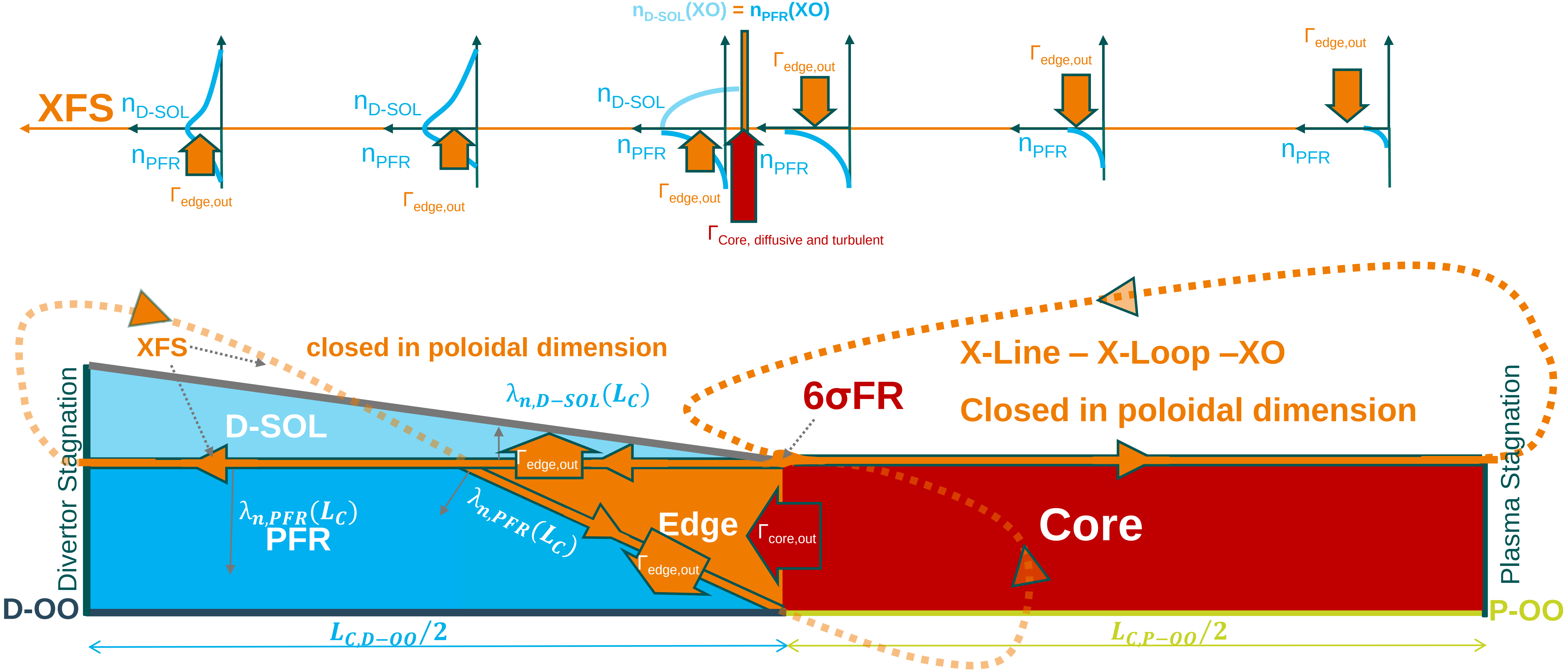


Resonant divertor DO NOT have a P-SOL



SOL transport Plasma Stagnation to Divertor Stagnation

Diffusion and Turbulent transport through XO-Core



Particle exhaust metrics and efficiencies resonant divertor

Sub-Divertor Neutrals

Divertor Plasma + Neutrals

PFR SL widening

XFR

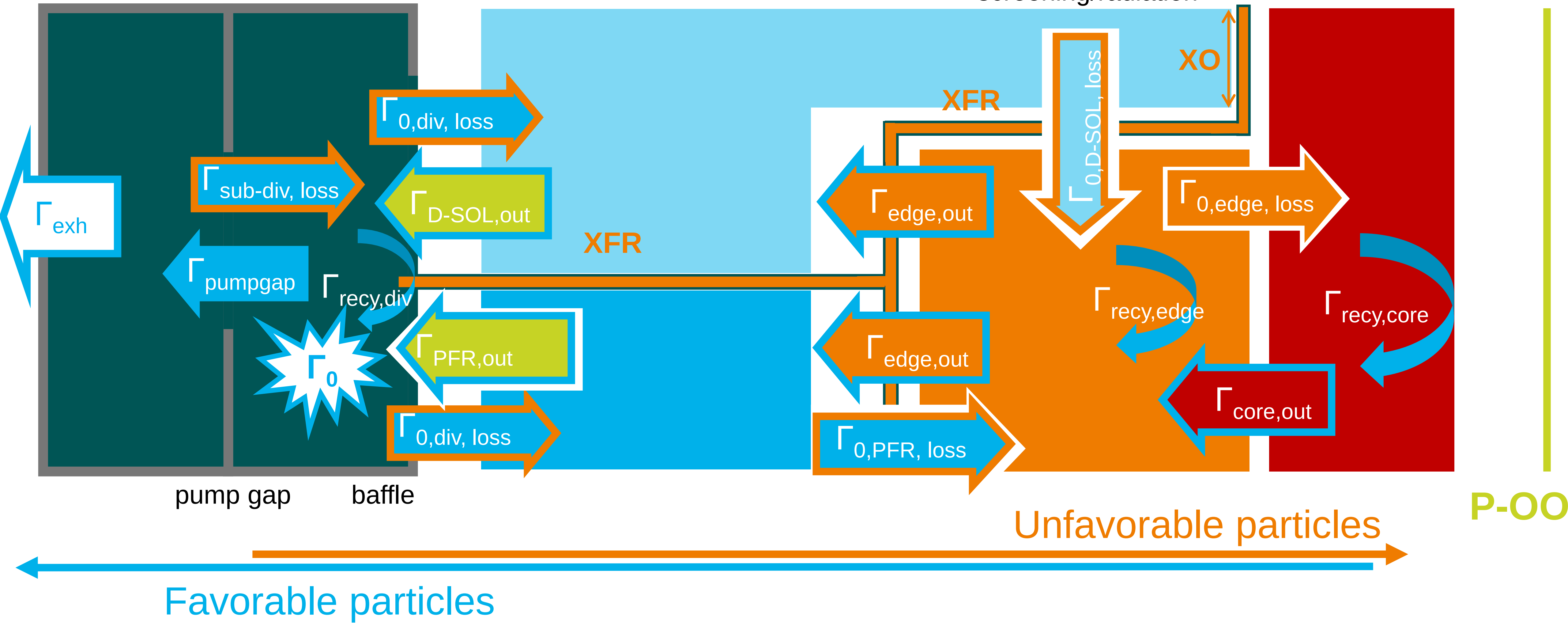
D-SOL SL widening

XFR

Edge Plasma pedestal screening/radiation

XO

Core Burning plasma



Γ_{exh}

$\Gamma_{sub\text{-}div,\ loss}$

$\Gamma_{pumpgap}$

$\Gamma_{recy,div}$

Γ_0

$\Gamma_{0,div,\ loss}$

$\Gamma_{D\text{-}SOL,out}$

$\Gamma_{PFR,out}$

$\Gamma_{0,div,\ loss}$

XFR

XFR

XO

$\Gamma_{0,D\text{-}SOL,\ loss}$

$\Gamma_{edge,out}$

$\Gamma_{edge,out}$

$\Gamma_{0,PFR,\ loss}$

$\Gamma_{recy,edge}$

$\Gamma_{0,edge,\ loss}$

$\Gamma_{core,out}$

$\Gamma_{recy,core}$

pump gap

baffle

P-OO

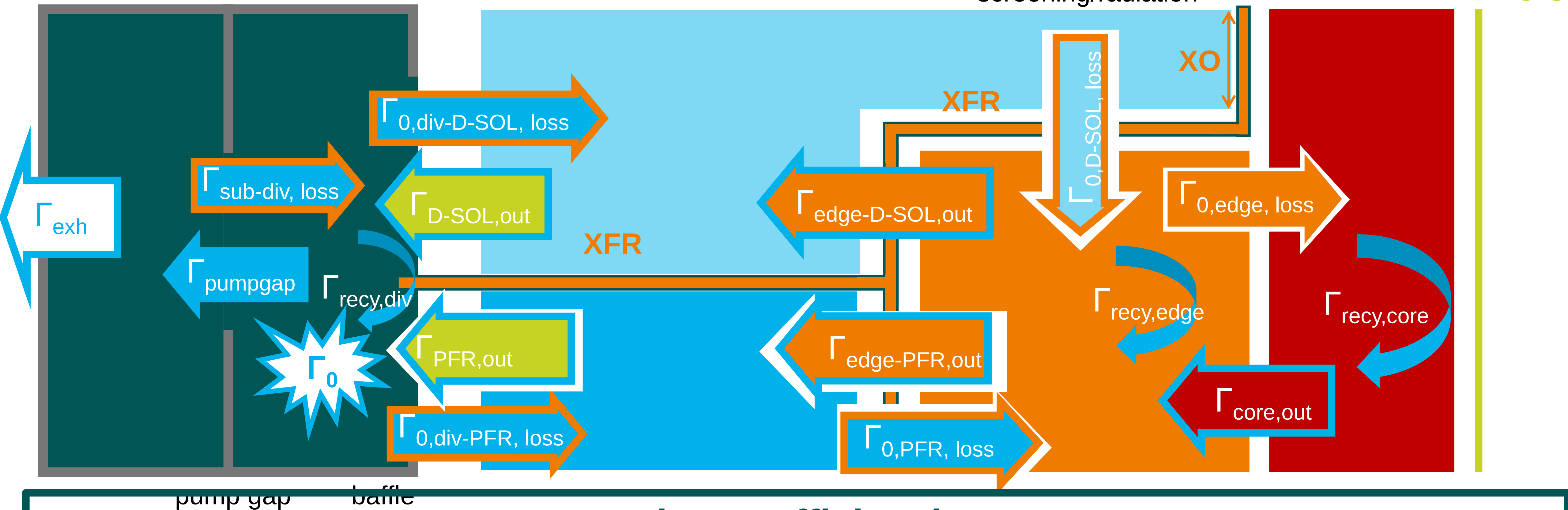
Unfavorable particles

Favorable particles

Particle exhaust metrics and efficiencies

Sub-Divertor **Divertor** **PFR** **XFR** **D-SOL** **XFR** **Edge** **XO** **Core**

Neutrals | Plasma + Neutrals | SL widening | SL widening | Plasma pedestal screening/radiation | Burning plasma



Exhaust efficiencies

Particle exhaust efficiency

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

Particle collection

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

Particle removal

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

Particle plugging

$\eta_{plug} = \Gamma_{recy,\ div} / (\Gamma_0 - \Gamma_{exh})$

D-SOL screening

$\eta_{scr,D\text{-}SOL} = \Gamma_{recy,\ D\text{-}SOL} / (\Gamma_{div\text{-}D\text{-}SOL,\ loss})$

PFR screening

$\eta_{scr,PFR} = \Gamma_{recy,\ PFR} / (\Gamma_{div\text{-}PFR,\ loss})$

Edge screening

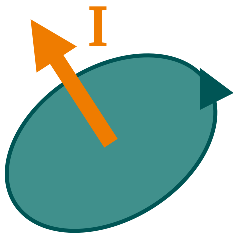
$\eta_{scr,edge} = \Gamma_{recy,\ edge} / (\Gamma_{0,PFR,\ loss} + \Gamma_{D\text{-}SOL,\ loss})$

A priori first principles

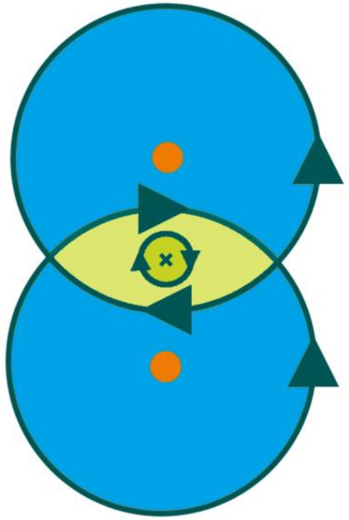
1. Divert plasma
2. Neutralize plasma
3. Collect neutral particles
4. Remove neutral particles
5. Plug neutral particles
6. Screen impurity particles
7. Survive

1. Divert Plasma Particles

Ampère



Interferent



Plasma Toroid

LCPFS $L_{c,LCPFS} = \frac{2\pi R_P}{\iota\!\!\!-_P(a_P)}$

Divertor Toroid

LCDFS $L_{c,LCDFS} = \frac{2\pi R_D}{\iota\!\!\!-_D(a_D)}$

Separatrix Surface XFS

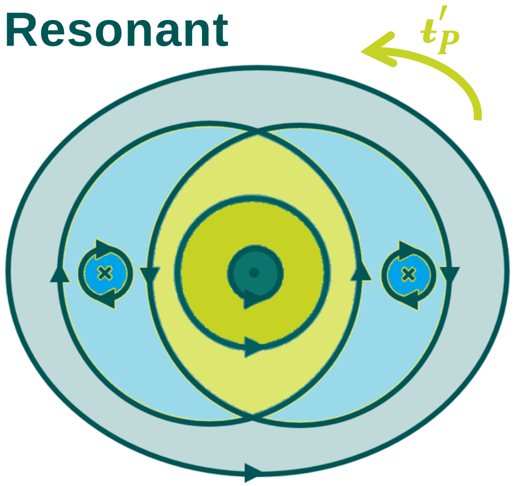
$$L_{c,XFS} = L_{c,LCPFS} + L_{c,LCDFS}$$

$$L_{c,XFS} = 2\pi\left(\frac{R_P}{\iota\!\!\!-_P(a_P)} + \frac{R_D}{\iota\!\!\!-_D(a_D)}\right)$$

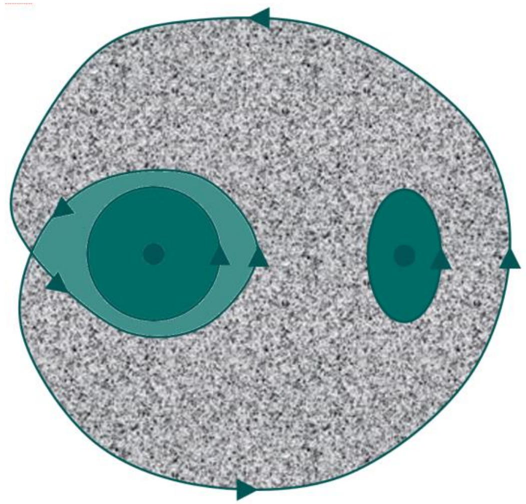
X-Loop conncetion length

$$L_{c,XO} = \left(\frac{R_P + R_D}{2}\right)$$

Resonant



Chaotic



Plasma Toroid

LCPFS $L_{c,LCPFS} = \frac{2\pi R_P}{\iota\!\!\!-_P(a_P)}$

Divertor Toroid

$$a_D = 2\sqrt{\frac{R_P b_{rm}}{\iota\!\!\!-'_P\; m}}$$

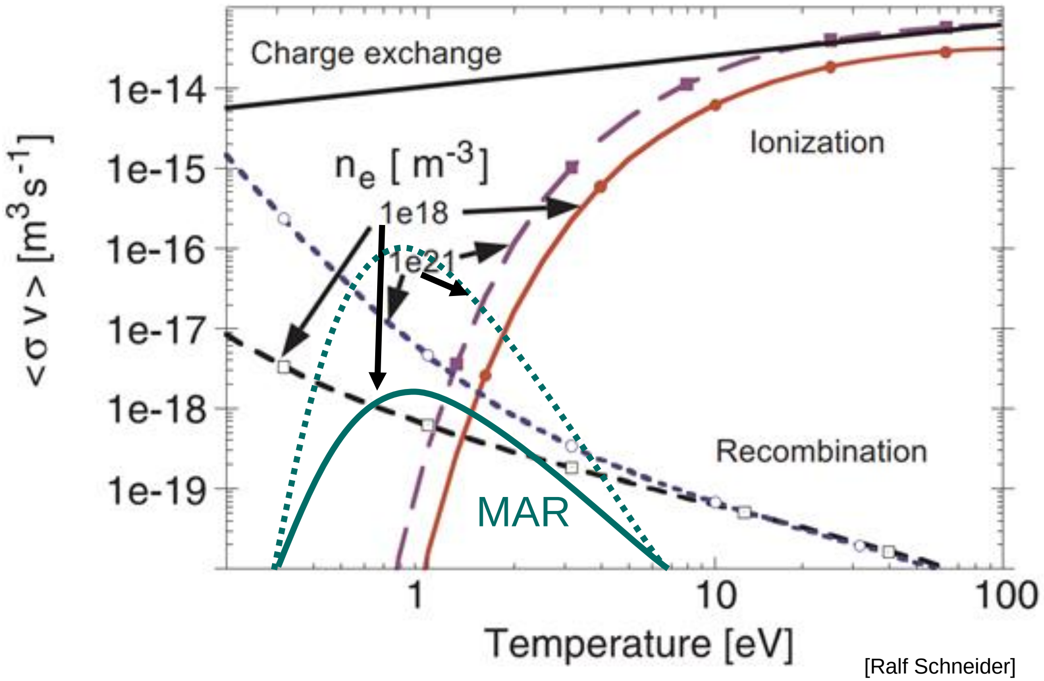
$$\iota\!\!\!-_D = 2a_P\sqrt{\frac{\iota\!\!\!-'_P b_{rm}}{R_P m}}$$

LCDFS $L_{c,LCDFS} \propto \frac{2a_D}{b_{rm}}$

2. Neutralize Plasma Particles

Only Neutral particles can be exhausted

- **Surface recombination** on target, $P_{rec,surf} = \Gamma_{ion,div}\ ((\gamma T_e)+(\frac{1}{2} m_{ion} v_{ion}^2)+\varepsilon_i)$
  - Particles released in cosine distribution and reflection
- **Volume recombination**, no/less heat and particle load on target, $T_{e,t} < 1.5$ eV, MAR $\sim n_e, n_0$, EIR $\sim n_e^3$
  - Particles released isotropic
- $q_{div} = \frac{P_{rec,surf}}{A_{wetted}} + P_{rad,div}$



[Ralf Schneider]

3. Collect Neutral Particles

• Direct collection	Only if $d_{SL\text{-}PG} < \bar{l}$
	Optimize $\boldsymbol{\cos \varphi_{pumpgap}}$
• Indirect collection	Build up neutral pressure
	Small divertor volume p = n/V
	Keep neutrals neutral
	No recycling if not necessary
	Optimize $\boldsymbol{1 - \cos \varphi_{LCFS}}$
• Continous flow	Driven by pressure gradient

4. Remove Neutral Particles

$\Gamma_{exh} = p_{0,sub\text{-}div}\ S_{eff}$

S_{eff} through Turbo Molecular Pumps or Cryo Pump

Decrease $\Gamma_{sub\text{-}div,\ loss}$

- Molecular flow Directed reflections with pump gap pannel, Funnel

Turn pumpgap into one-way

- Continuos flow at pumpgap Minimize $Kn = \frac{\bar{l}}{d}$

5. Plug Neutral Particles

Block escaping neutrals

– Relevance decreases as η_{exh} increases

• Hardware (Baffles):	Thermal loads
• Re-Ionization:	He is the hardest to ionize, minimize $\lambda_{iz,He}$, $T_e \geq 100$ eV, ~ n_e

6. Screen Impurity Particles

Maximize $\eta_{scr,Edge} + \eta_{scr,SOL}$ **minimize $\lambda_{iz,He}$, $T_e \geq 100$ eV, ~ n_e**

Minimize inward impurity ion transport

Survive

Exhaust heat necessary for particle exhaust – Possibly radiate rest

- Surface recombination on target
- Volume recombination in front of target
- Radiated power

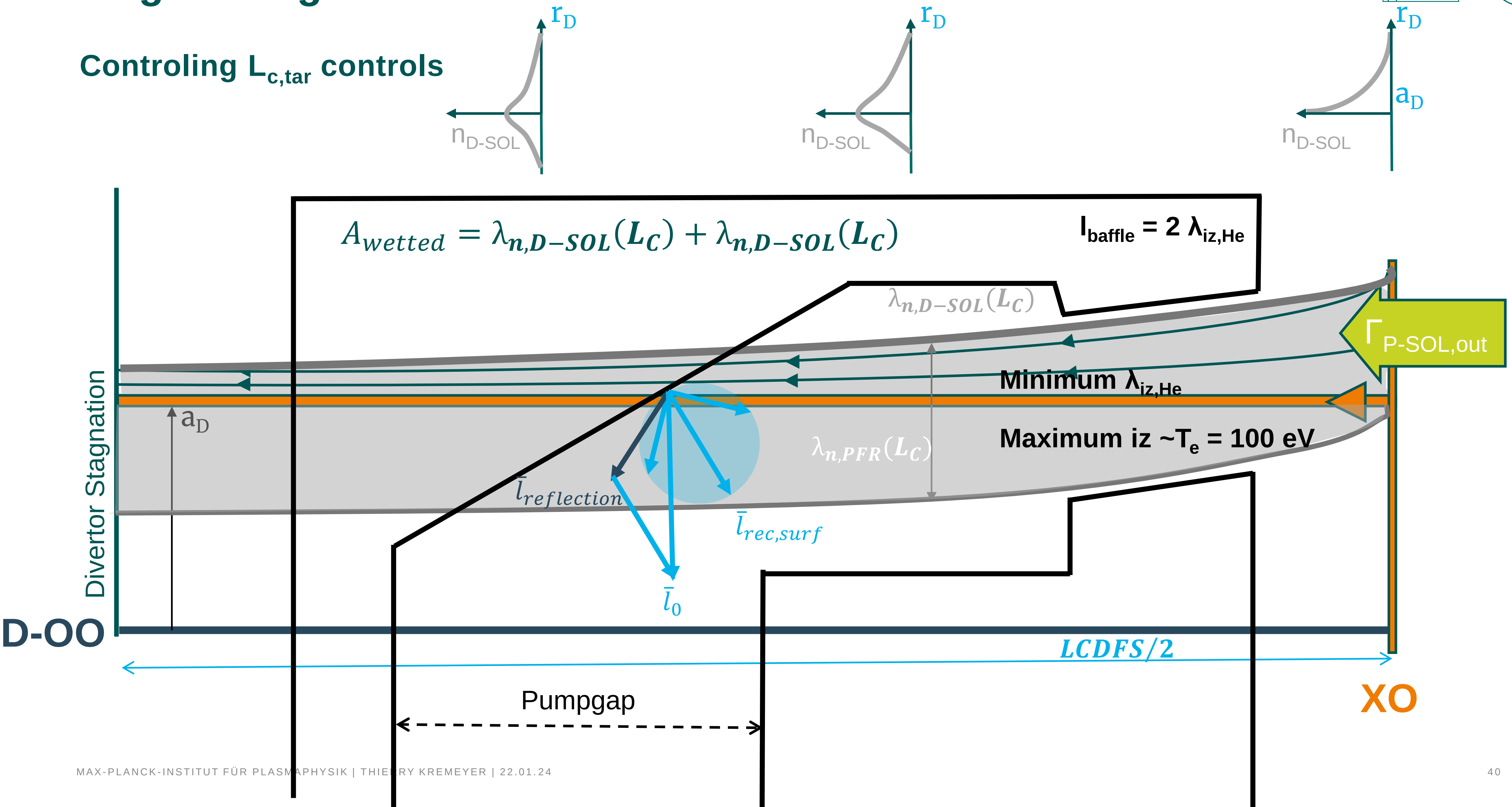
Radiation location and stability:

X-Point vs homogenous island radiation

- Neutron power

Target design

Controling $L_{c,tar}$ controls



$$A_{wetted} = \lambda_{n,D-SOL}(L_C) + \lambda_{n,D-SOL}(L_C)$$

$l_{baffle} = 2\ \lambda_{iz,He}$

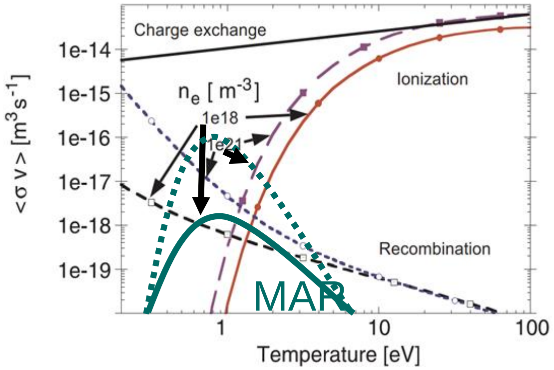
Minimum $\lambda_{iz,He}$

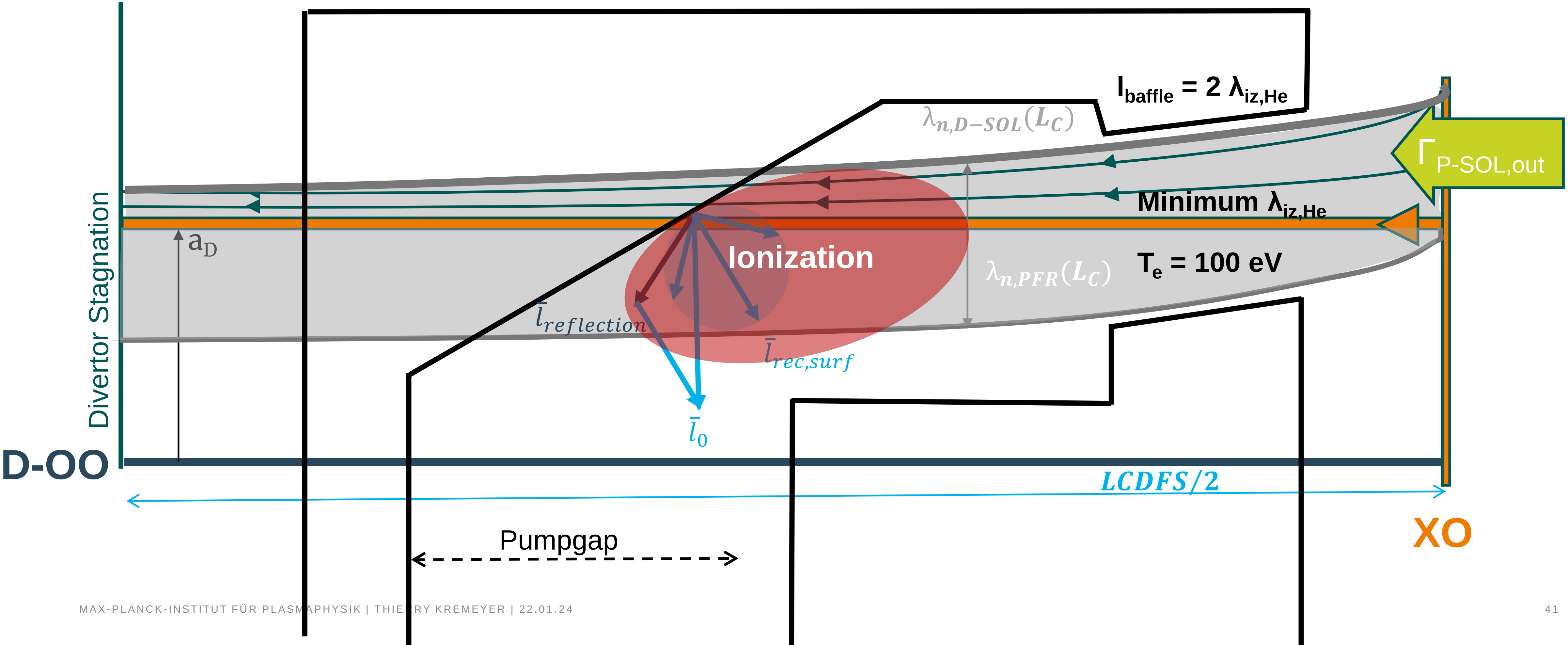
Maximum iz ~T_e = 100 eV

Target design

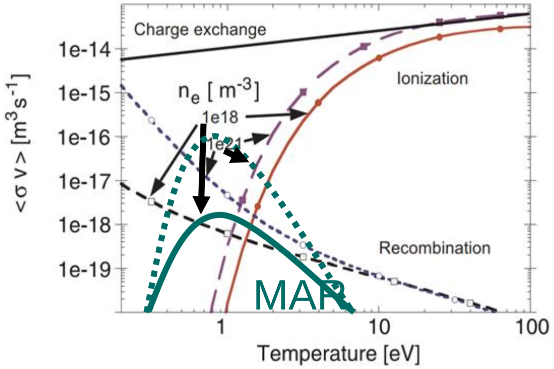
High recycling regime – yes! n_{up} vs n_{down}

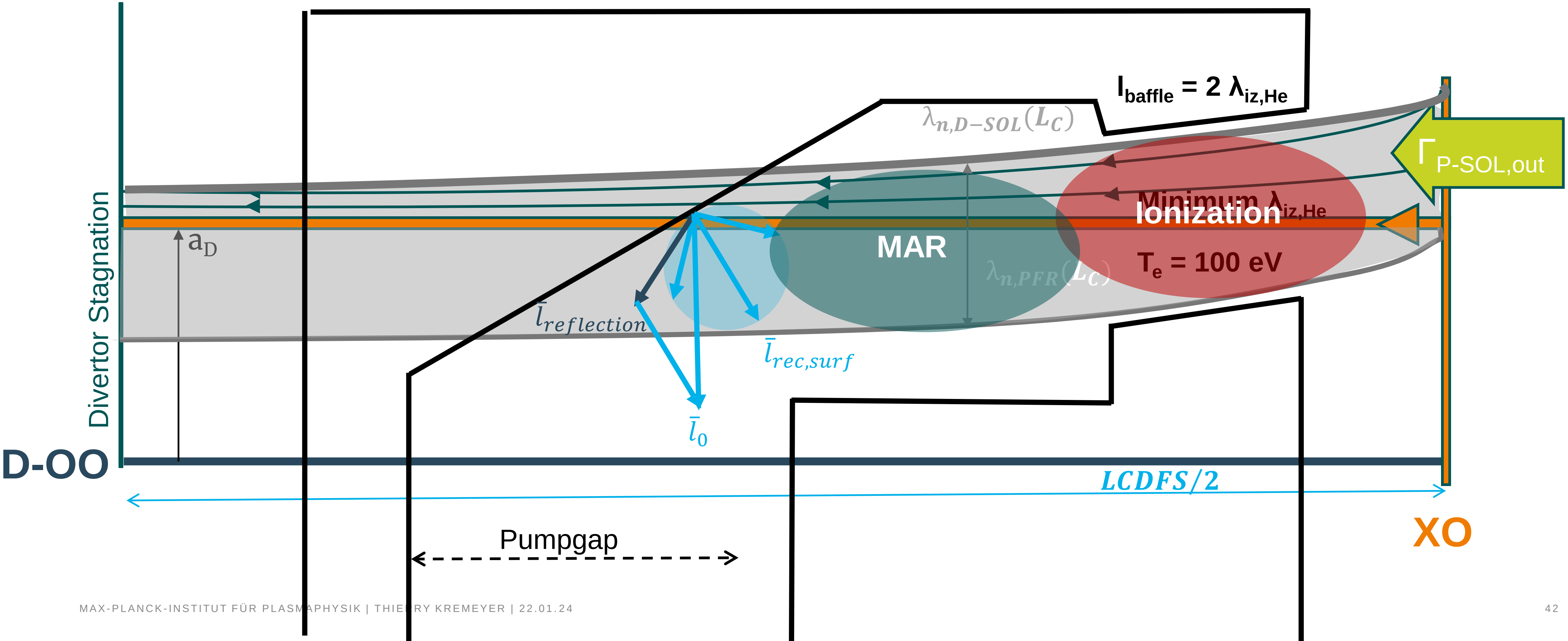
But do not maximize recycling, full recycling! It negates pumping!



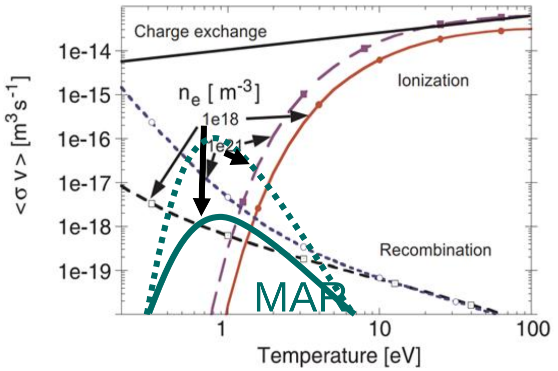


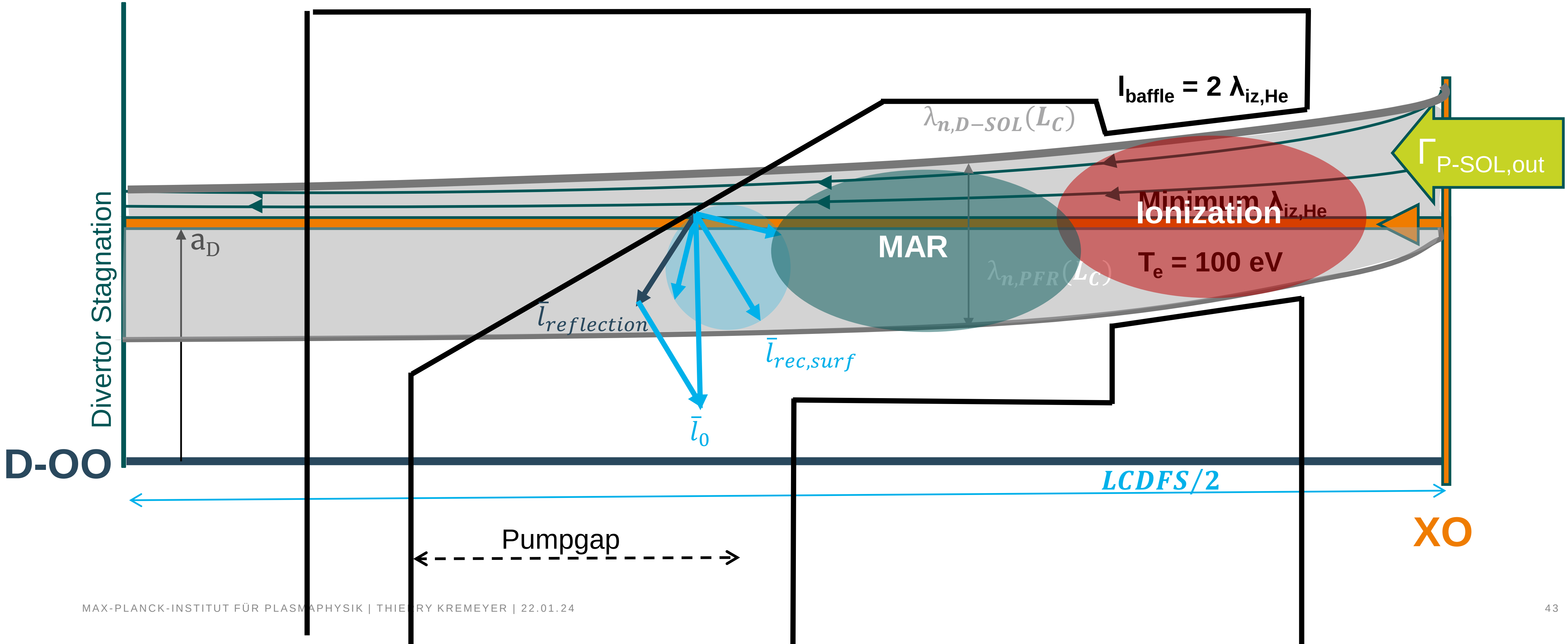
Target design



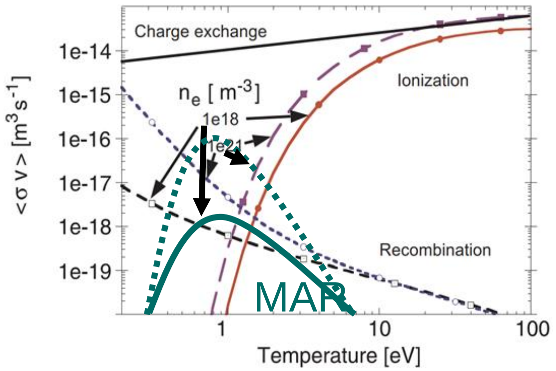


Ionizing target

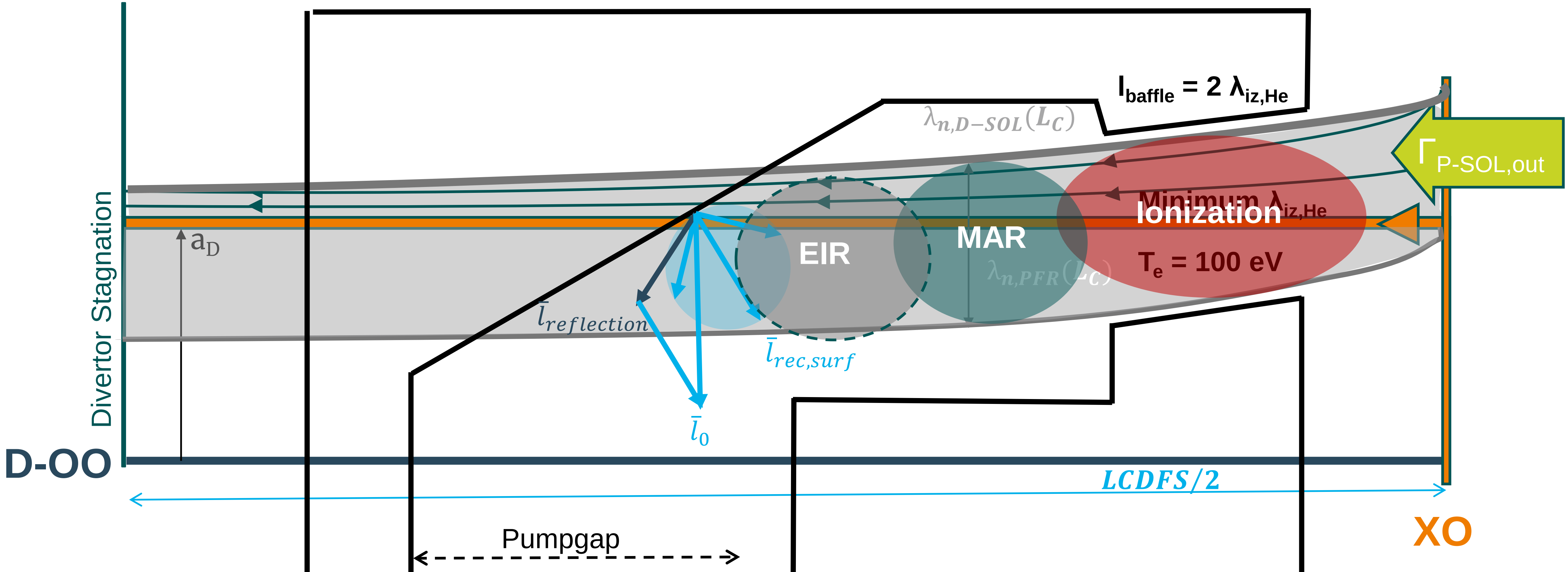




Target design



Put many neutrals in plasma path: high p_0 or $L_{c,tar}$



Fully volume recombining divertor

Design maxims

- Open communication is essential!   Divertor will be designed in many meetings
- Focus on mission, not on technology
  - Define clear requirements and ensure common understanding
  - Physicst - Engineer   need to understand each others requirements from the beginning
  - Avoid diluted structure of small independent groups
  - One supplier/tool, avoid 5 things that do the same
- Buildable in large quantities, not just once
- Keep it simple – simplify as much as possible!
  - Only do whats necessary
  - As accurate as necessary, as inaccurate as possible
  - Any avoided component can‘t fail
  - Best weld is no weld
- Where you can‘t avoid risks, communicate them cleary, do not compromise your standards, and double down on mitigation

Conclusion

FPP magnetic field will need at least 2 toroids – include in optimization!

Divertor performance has been resolved to:

- **Maximize Γ_{exh} combined with throttle**
- **Maximize η_{exh}**
- **Maximize $\eta_{scr} = \eta_{scr,Edge} + \eta_{scr,SOL}$**

Pedastal achievable by

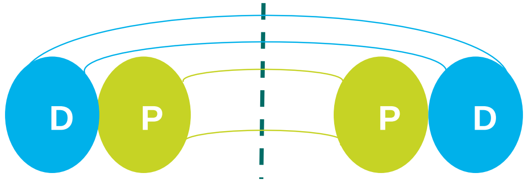
$$\nabla \cdot \vec{v}(LCPFS) > \nabla \cdot \vec{v}(6\sigma FS)$$

$$L_{c,LCPFS} >> L_{c,6\sigma FS}$$

Divertor metrics have been defined

- **L_c has direct impact on recombination, $A_{wetted,}$ any $\nabla \cdot \vec{v}$ mechanism, thus pedestal creation**
- **Short connection length ➡ Narrow Strike line** **Too long ➡ transport into Divertor O-loop**
- **Outer midplane is ideal divertor position** $\nabla \cdot \vec{v}(L_{c,XO}) > \nabla \cdot \vec{v}(a_D) > \nabla \cdot \vec{v}(t_D(a_D))$

$$L_{c,XO} = \left(\frac{R_P + R_D}{2}\right)$$



$R_D = R_P + a_p + a_D$

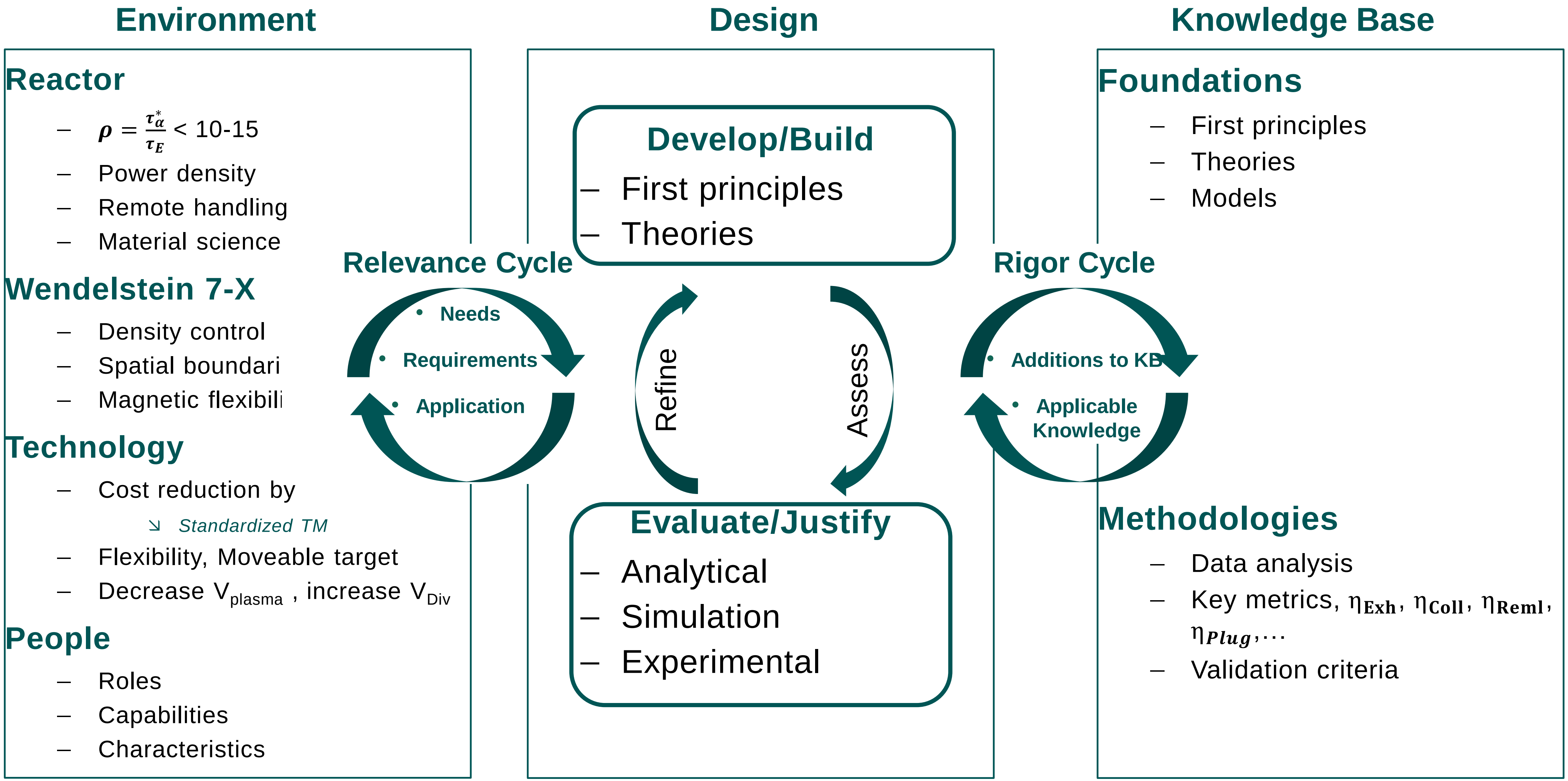
- **Chaotic divertors can offer extreme $L_{c,XO}$ as second toroid can be outside of coils**
- **Fully recycling neutral flux will negate pumping, but recyling between baffles plugs the divertor!**

A PRIORI FIRST PRINCIPLES
6-SIGMA APPROACH

1. Divert plasma particles
2. Neutralize plasma particles
3. Collect neutral particles
4. Remove neutral particles
5. Plug neutral particles
6. Screen impurity particles
7. Survive

Appendix

Design Science Research



Environment

Reactor

- $\rho = \frac{\tau_\alpha^*}{\tau_E} < 10\text{-}15$
- Power density
- Remote handling
- Material science

Wendelstein 7-X

- Density control
- Spatial boundari
- Magnetic flexibili

Technology

- Cost reduction by
  - ↘ *Standardized TM*
- Flexibility, Moveable target
- Decrease V_{plasma} , increase V_{Div}

People

- Roles
- Capabilities
- Characteristics

Design

Relevance Cycle

- Needs
- Requirements
- Application

Develop/Build

- First principles
- Theories

Refine

Assess

Evaluate/Justify

- Analytical
- Simulation
- Experimental

Rigor Cycle

- Additions to KB
- Applicable Knowledge

Knowledge Base

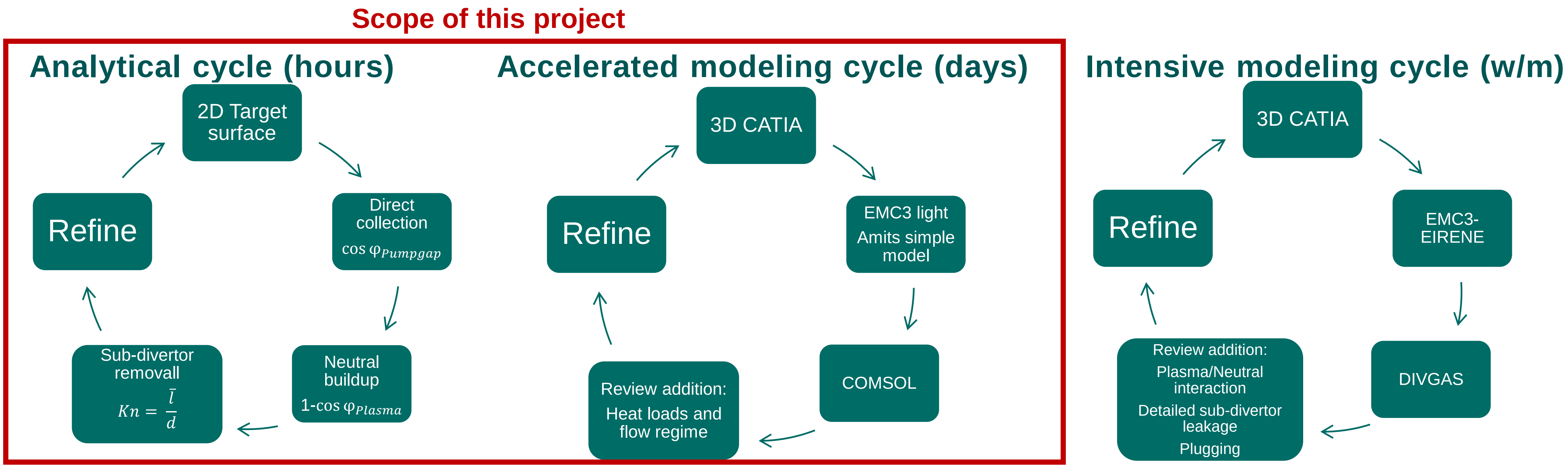
Foundations

- First principles
- Theories
- Models

Methodologies

- Data analysis
- Key metrics, $\eta_{\mathbf{Exh}}$, $\eta_{\mathbf{Coll}}$, $\eta_{\mathbf{Reml}}$, $\eta_{\boldsymbol{Plug}}$,…
- Validation criteria

Accelerated Design cycle - Reduced complexity by de-coupling problems



Scope of this project

Analytical cycle (hours)

2D Target surface

Direct collection $\cos\varphi_{Pumpgap}$

Neutral buildup $1\text{-}\cos\varphi_{Plasma}$

Sub-divertor removall $Kn = \frac{\bar{l}}{d}$

Refine

Accelerated modeling cycle (days)

3D CATIA

EMC3 light
Amits simple model

COMSOL

Review addition:
Heat loads and flow regime

Refine

Intensive modeling cycle (w/m)

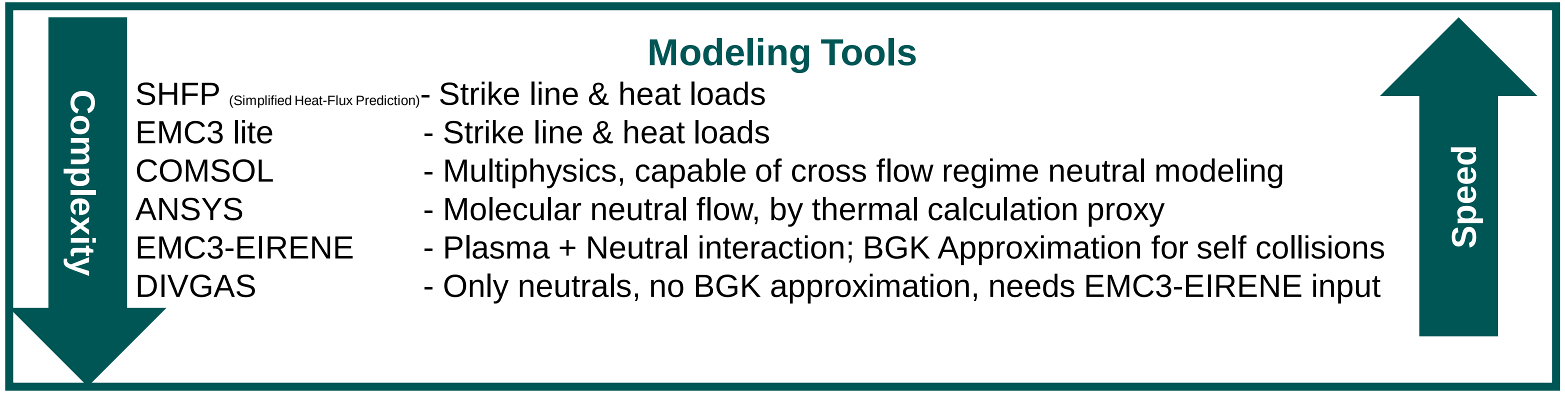
3D CATIA

EMC3-EIRENE

DIVGAS

Review addition:
Plasma/Neutral interaction
Detailed sub-divertor leakage
Plugging

Refine

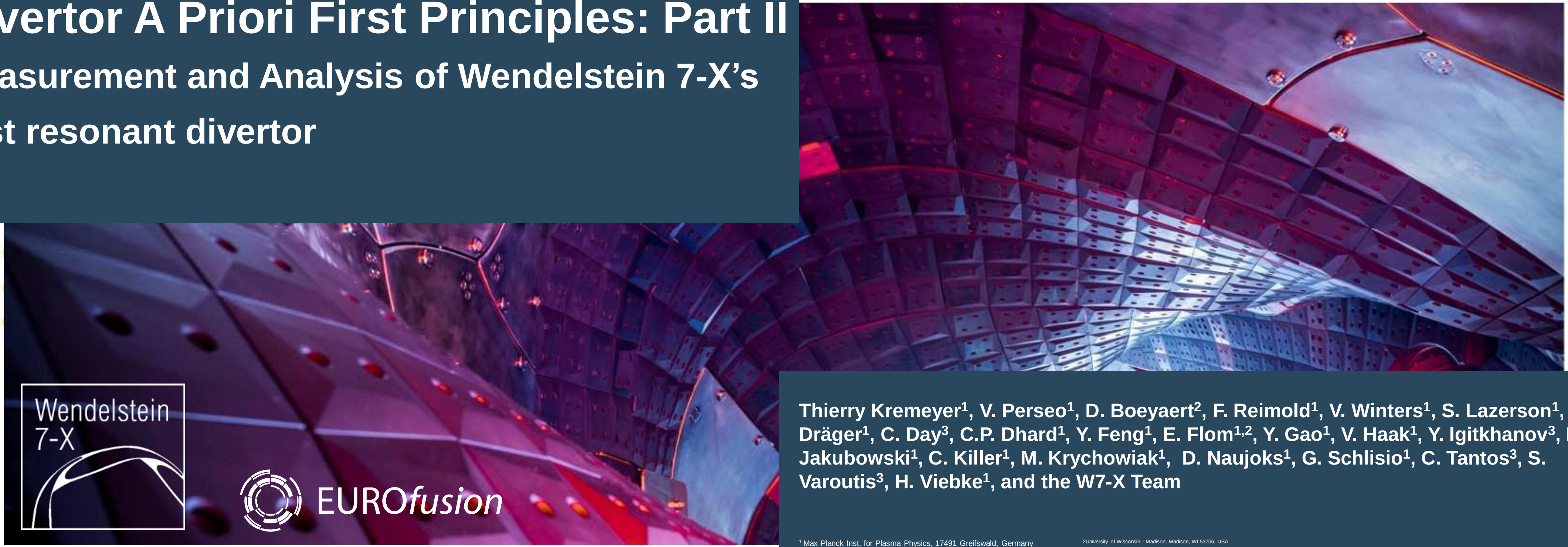


Modeling Tools

SHFP (Simplified Heat-Flux Prediction) - Strike line & heat loads
EMC3 lite - Strike line & heat loads
COMSOL - Multiphysics, capable of cross flow regime neutral modeling
ANSYS - Molecular neutral flow, by thermal calculation proxy
EMC3-EIRENE - Plasma + Neutral interaction; BGK Approximation for self collisions
DIVGAS - Only neutrals, no BGK approximation, needs EMC3-EIRENE input

Divertor A Priori First Principles: Part II

Measurement and Analysis of Wendelstein 7-X's first resonant divertor



Thierry Kremeyer[1], V. Perseo[1], D. Boeyaert[2], F. Reimold[1], V. Winters[1], S. Lazerson[1], S. Dräger[1], C. Day[3], C.P. Dhard[1], Y. Feng[1], E. Flom[1,2], Y. Gao[1], V. Haak[1], Y. Igitkhanov[3], M. Jakubowski[1], C. Killer[1], M. Krychowiak[1], D. Naujoks[1], G. Schlisio[1], C. Tantos[3], S. Varoutis[3], H. Viebke[1], and the W7-X Team

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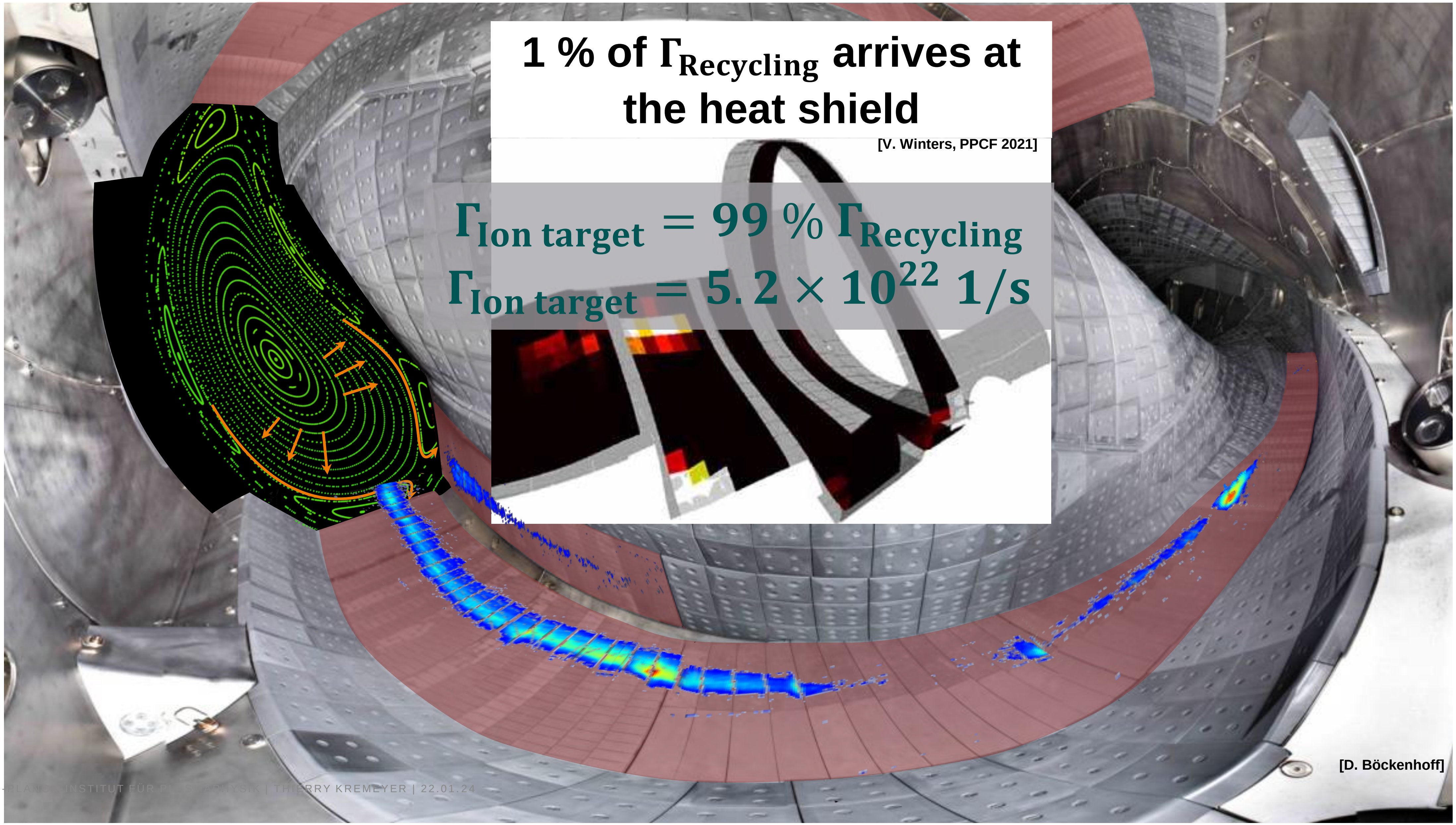
~99% of particles neutralize on divertor target



1 % of $\Gamma_{\text{Recycling}}$ arrives at the heat shield

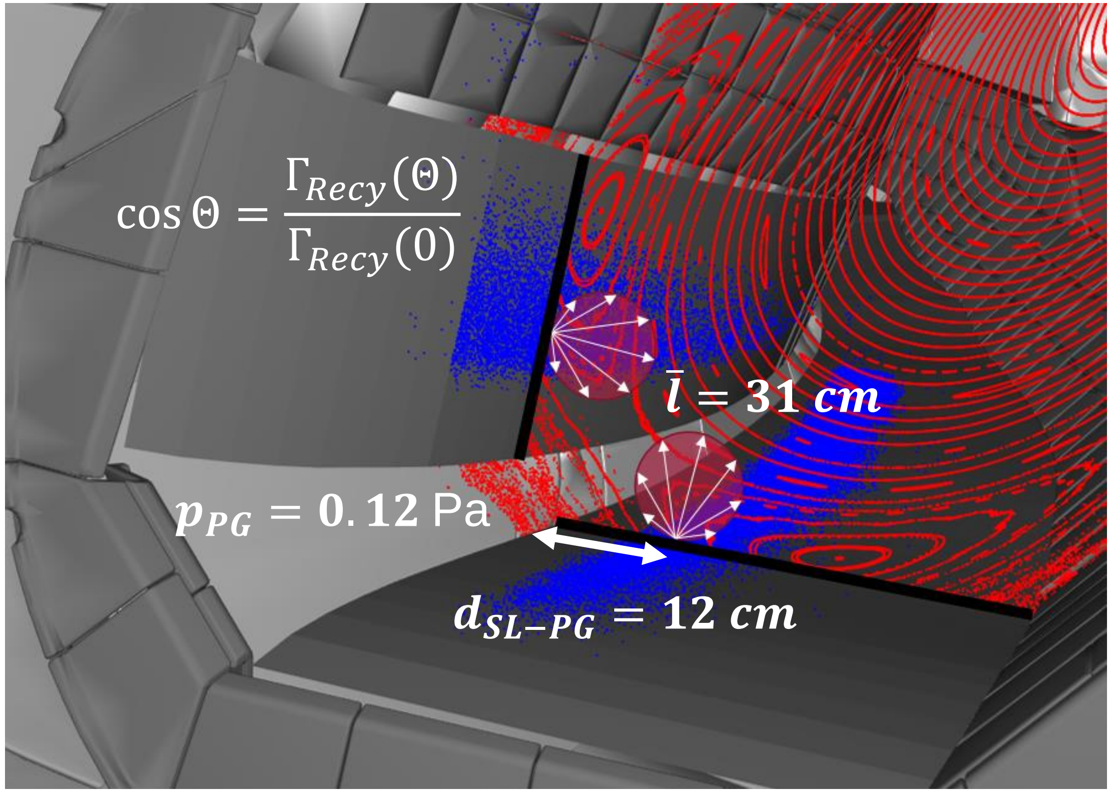
[V. Winters, PPCF 2021]

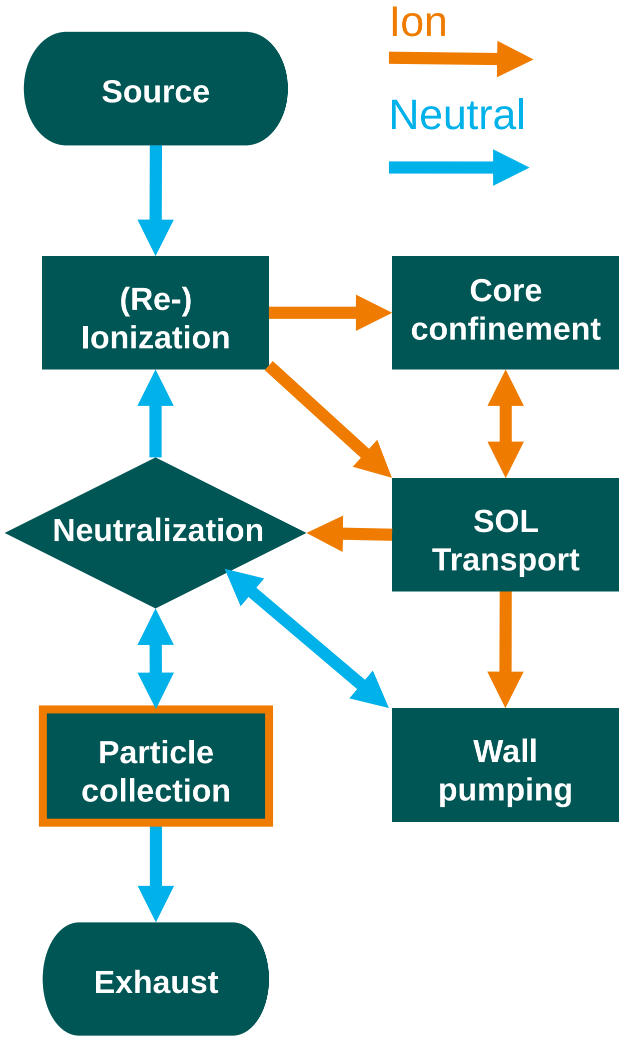
$$\Gamma_{\text{Ion target}} = 99\ \%\ \Gamma_{\text{Recycling}}$$

$$\Gamma_{\text{Ion target}} = 5.2 \times 10^{22}\ 1/\text{s}$$

[D. Böckenhoff]

Particle collection with an open carbon divertor





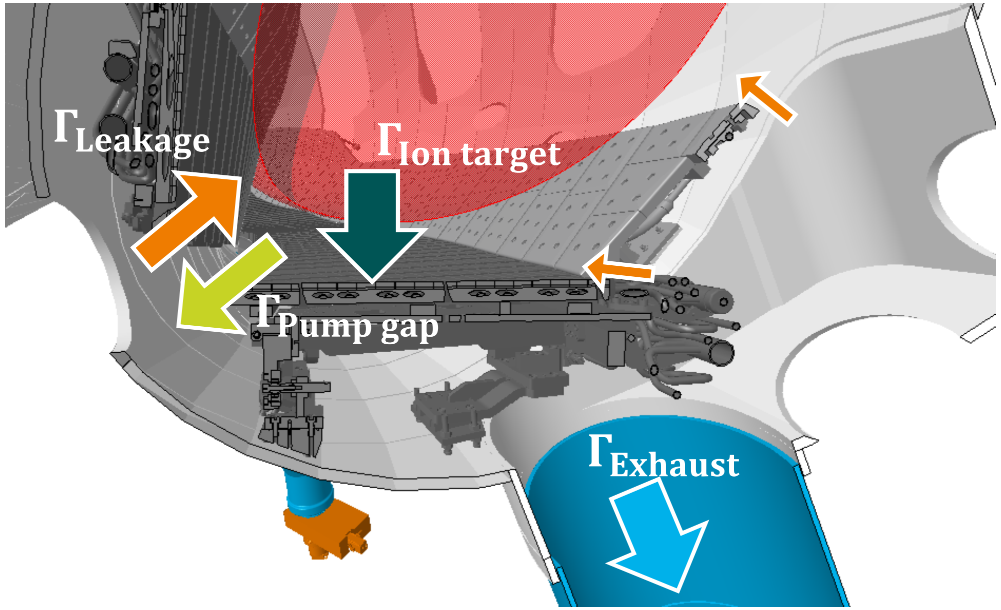
Particle collection:

Pumpgap opening ~ 68°- 90°	~7.3 % of Γ_{Target}
EMC3-EIRENE	4.0 % of Γ_{Target}

Only particles that dont

ionize on the way, make it to pump gap

Particle removal and sub-divertor leakage



$$\Gamma_{\mathrm{Ion\ target}} = 5.2 \times 10^{22}\ 1/s$$

$$\Gamma_{\mathrm{Pump\ gap}} = 4\ \%\ \Gamma_{\mathrm{Ion\ target}}$$

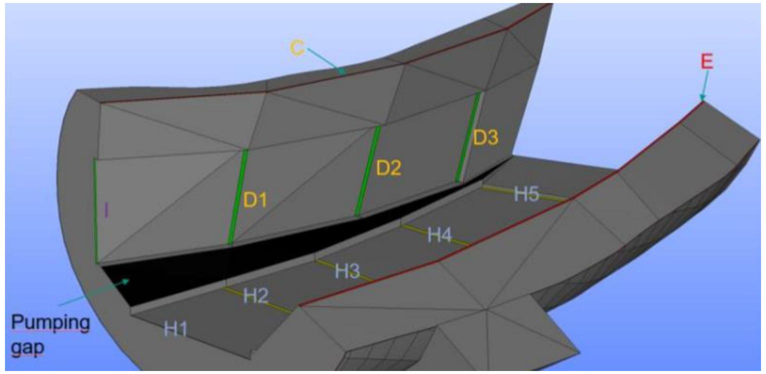
$$\Gamma_{\mathrm{Exhaust}} = p_n \times S_{eff}$$

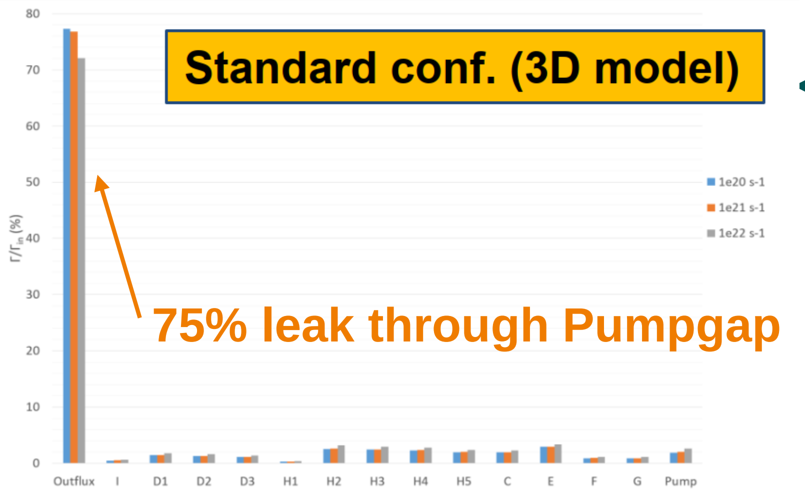
$$\Gamma_{\mathrm{Exhaust}} = 6\%\Gamma_{\mathrm{Pump\ gap}}$$

$$\Gamma_{\mathrm{Leakage}} = \Gamma_{\mathrm{Pump\ gap}} - \Gamma_{\mathrm{Exhaust}}$$

$$\Gamma_{\mathrm{Leakage}} = 94\%\ \Gamma_{\mathrm{Pump\ gap}}$$

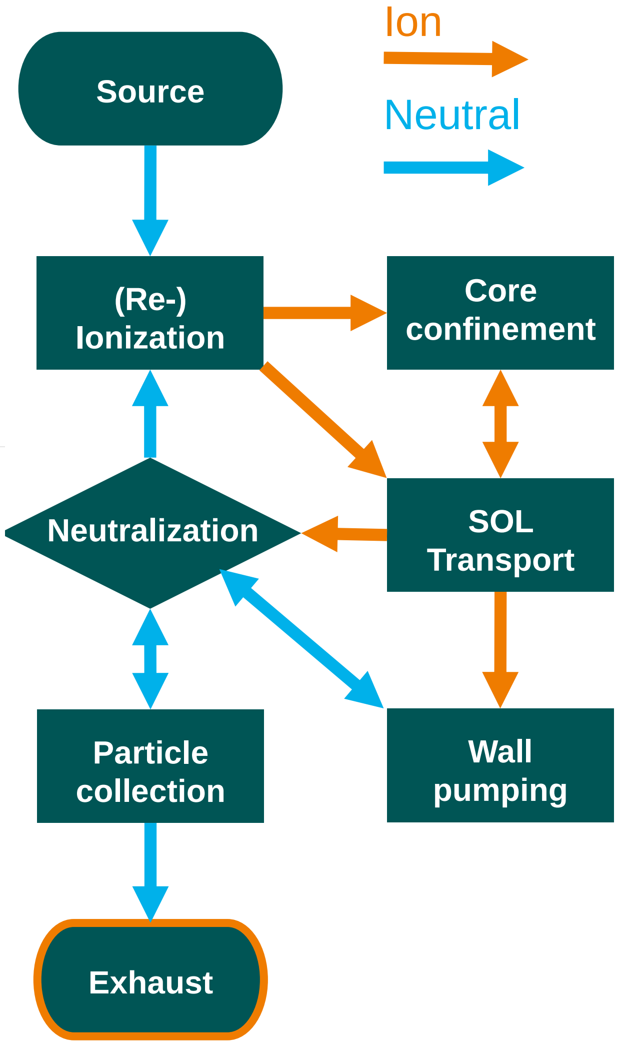
DIVGAS modeling





Standard conf. (3D model)

75% leak through Pumpgap



Ion

Neutral

Source

(Re-) Ionization

Core confinement

Neutralization

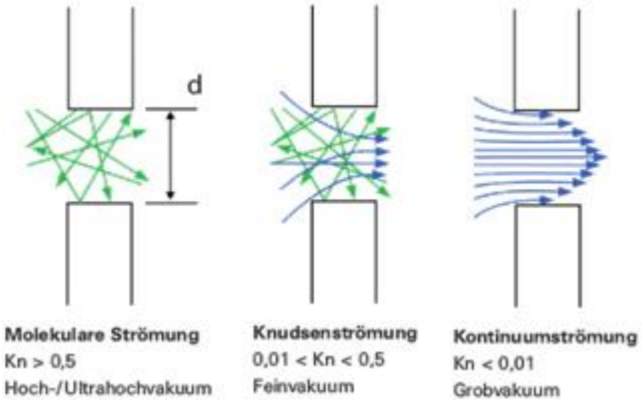
SOL Transport

Particle collection

Wall pumping

Exhaust

Continous flow minimizes leakage



[www.pfeiffer-vacuum.com]

$Kn = \frac{\bar{l}}{d}$ $d_{PG} = 90\,mm$

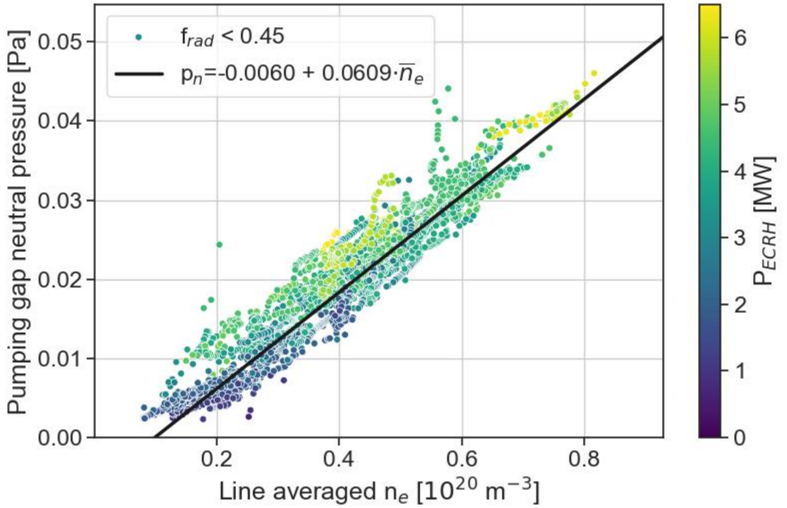
How to access continous flow regime?

- Increase pump gap opening
- Increase pump gap pressure
  - Shifting strike line closer to pump gap
  - Increasing density
  - Change the target geometry

I_{cc} = 0kA $d_{SL-PG} = 12.1\ cm$
I_{cc} = 2kA $d_{SL-PG} = 6.2\ cm$
Increase of p_{PG} by 25%

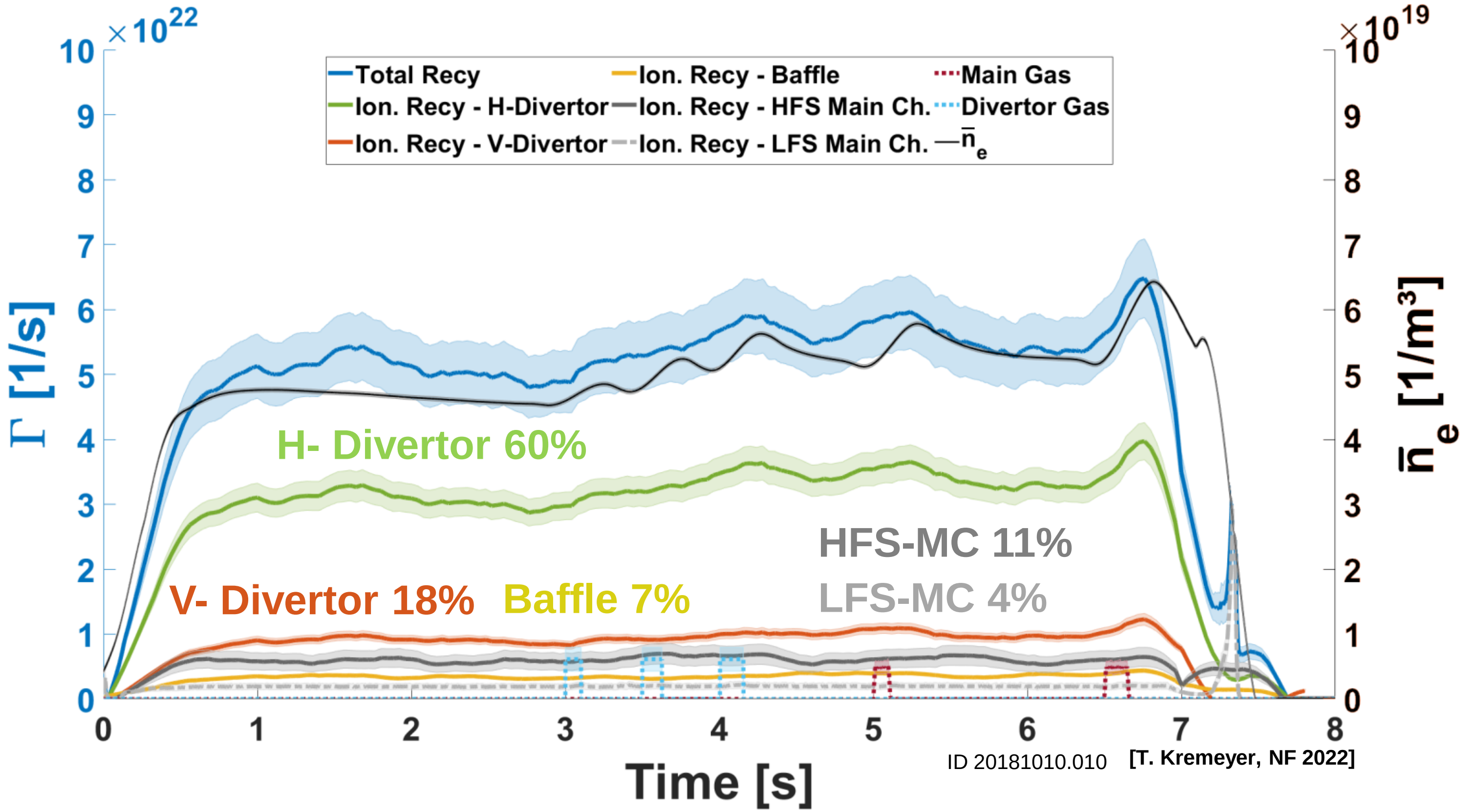
Shifting SL as close as possible to PG
Increase of p_{PG} ~50%?

	Best OP1.2	Knudsen	Continuos
Kn	3.4	< 0.5	< 0.01
$\bar{l}$ [m]	0.31	0.045	0.0009



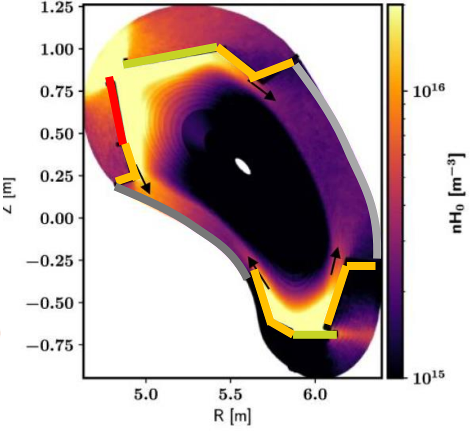
[V. Perseo]

Re-ionisation shows good plugging



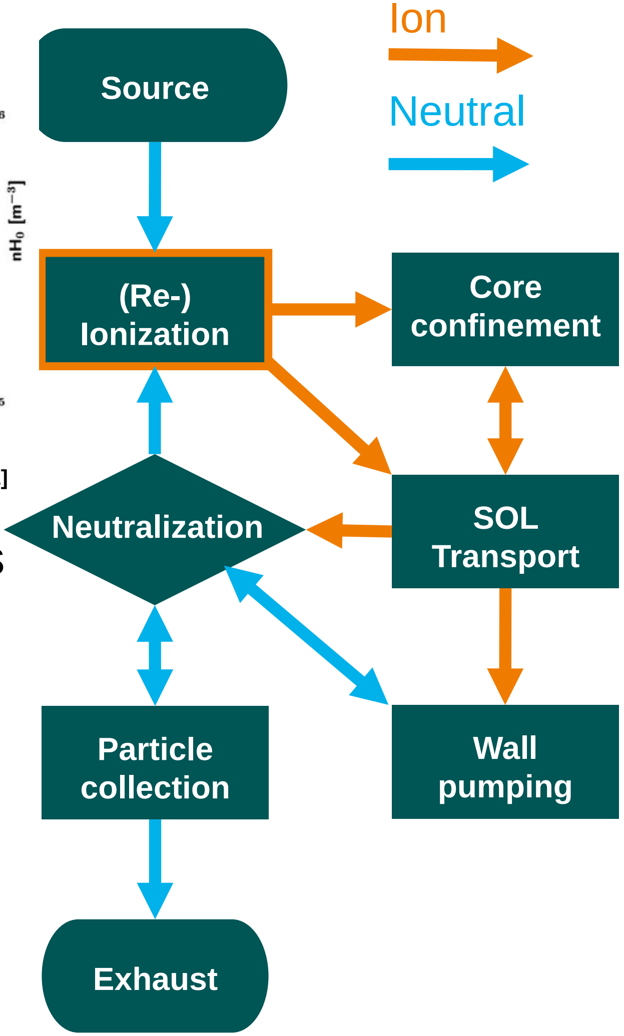
ID 20181010.010 [T. Kremeyer, NF 2022]

EMC3-EIRENE modeling



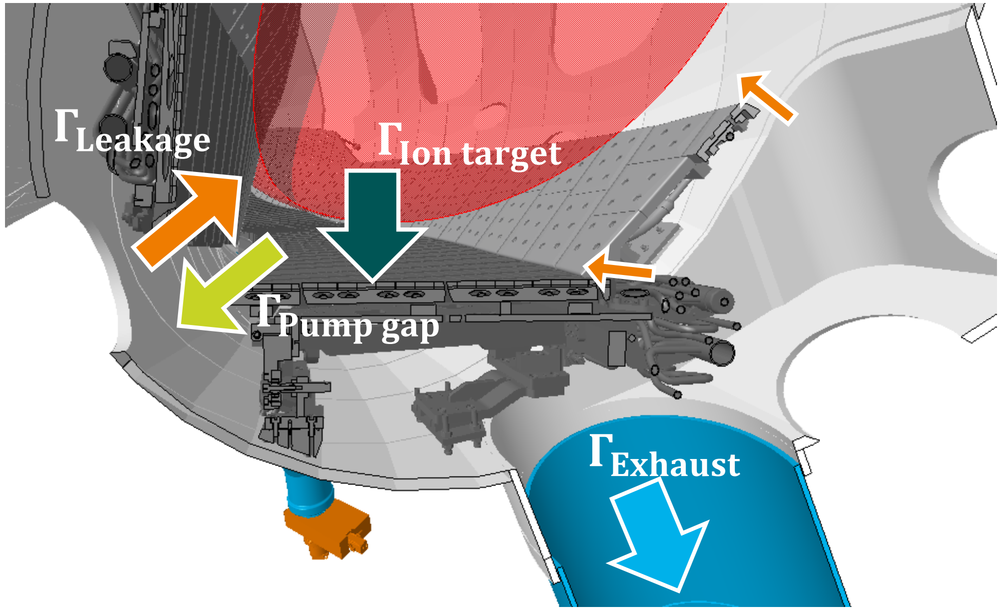
[V. Winters, PPCF 2021]

- Neutral particles escape poloidally and toroidally from divertor



Experimental	EMC3-EIRENE
$\eta_{Plugging}$ = 85 %	$\eta_{Plugging}$ = 96 %
HFS-ionization = 11 %	Poloidal losses = 2.5 %
LFS-ionization = 4 %	Toroidal losses = 1.5 %

Full magnetic flexibility at effective, but in-efficient exhaust



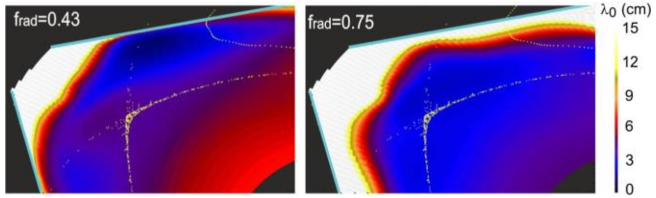
- Particle collection dominated by pump gap opening angle to strike line
- Sub-divertor leakage dominated by pump gap
- Exhaust and Wall source at same order
- Good plugging, despite toroidally open divertor
- Stable detachment opens up neutral channels
- W7-X detachment decreases particle flux towards divertor

Attached → Detached

$$\Gamma_{\text{Ion divertor}} = 99\ \%\ \Gamma_{\text{ion}}$$
$$\eta_{\text{Collection}} = 4\ \%\ \Gamma_{\text{Ion target}}$$
$$\eta_{\text{Removal}} = 6\%\ \Gamma_{\text{Pump gap}}$$
$$\eta_{\text{Exhaust}} =< 1\%\ \Gamma_{\text{Ion divertor}}$$
$$\eta_{\text{Plugging}} = 85\ \%\ \Gamma_{\text{Ion divertor}}$$

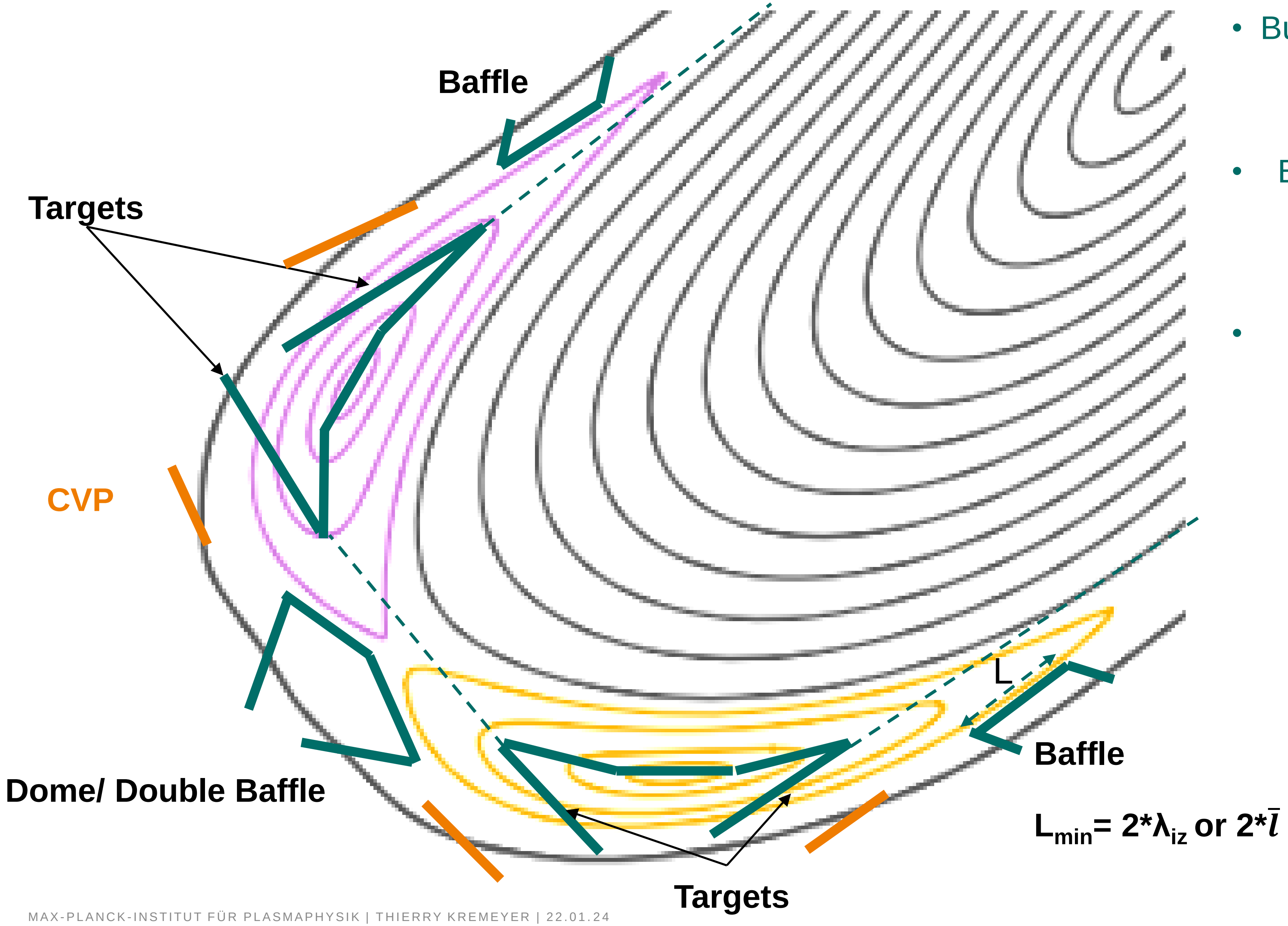
$\Gamma_{\text{Ion divertor}}$ decreases 60 %

$$\eta_{\mathit{Collection}} = 12\ \%\ \Gamma_{\text{Ion target}}$$



η_{Plugged}

2D Target cross section of „standardized“ sections



L_{min}= 2*λ_{iz} or 2*$\bar{l}$

- Build up neutral pressure

  Optimize $1 - \cos\varphi_{LCFS}$

- Block escaping neutrals

  Hardware (Baffles) !Thermal loads!

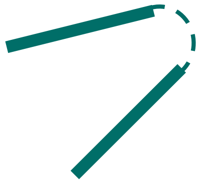
  Re-Ionization

- Direct collection

  Optimize $\cos\varphi_{pumpgap}$

  CVP ideally normal to target

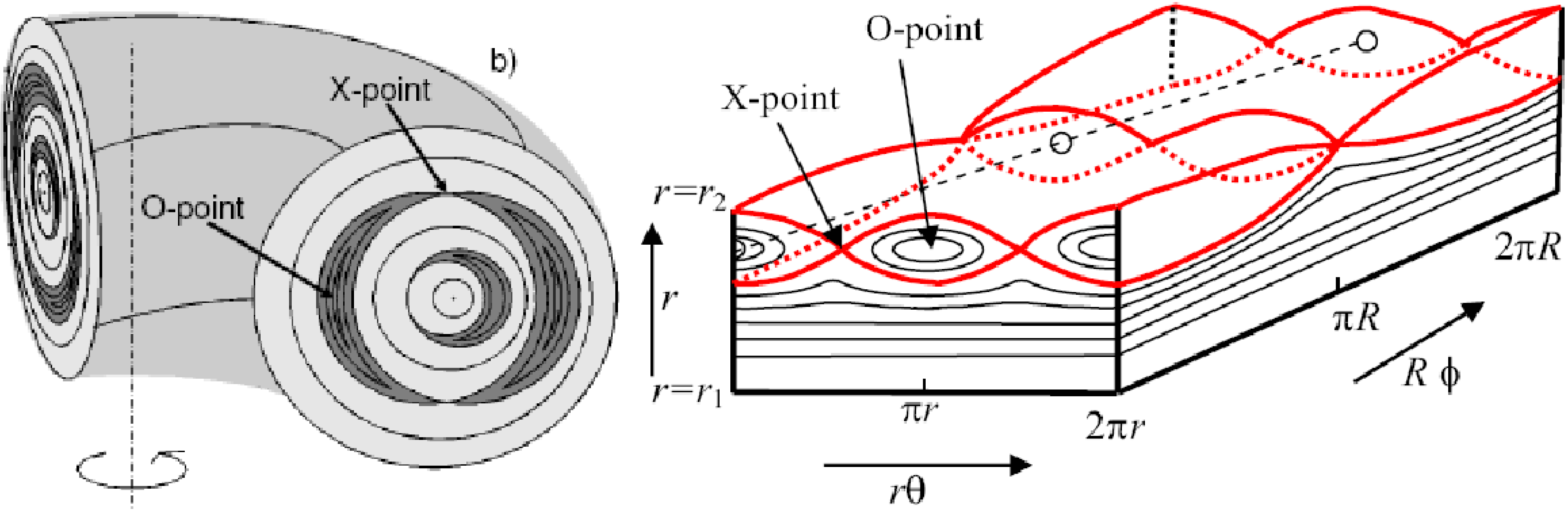
Smallest possible angle?



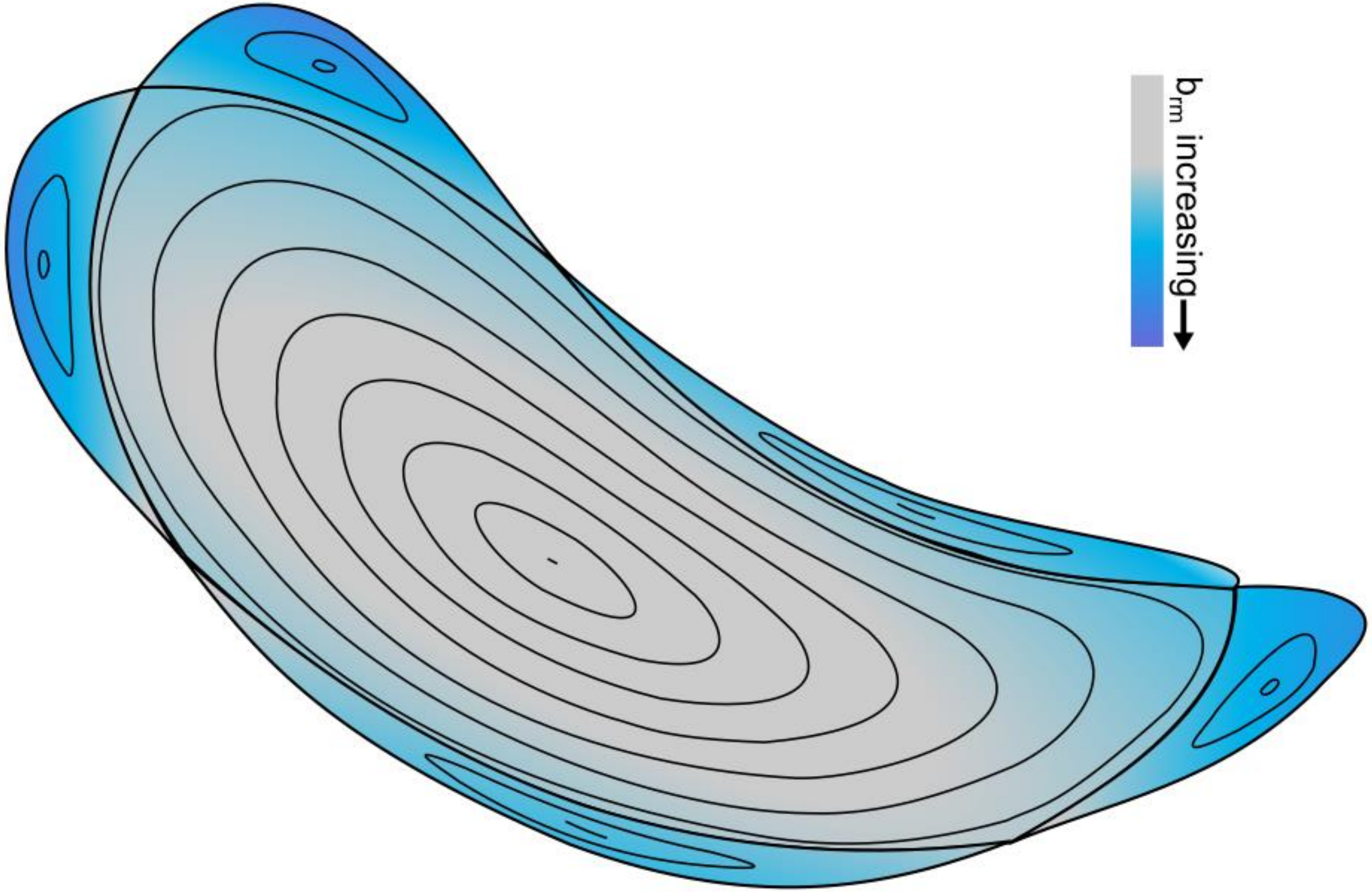
Smallest possible radius?

Exhaust optimized, reactor relevant divertor target geometry for W7-X based on a first principles, design science research approach

- **Maximize particle exhaust**
  - Throttle makes exhaust an active control parameter
- **Reactor relevance**
  - Evaluate design at higher power densities (30MW?)
  - Feasibility of remote handling in future
- **Decrease design cycle time**
- **Decrease cost**
  - Utilize standardized target module, developed in parallel
  - Smaller?
  - Uncooled? (Allow for 30s, 1 min, 5 minute,? minutes operation)
- **Retain magnetic flexibility**
  - Moveable targets?



Hommen, G. "Development of a dynamic model of magnetic islands in fusion plasmas."


b_{rm} increasing