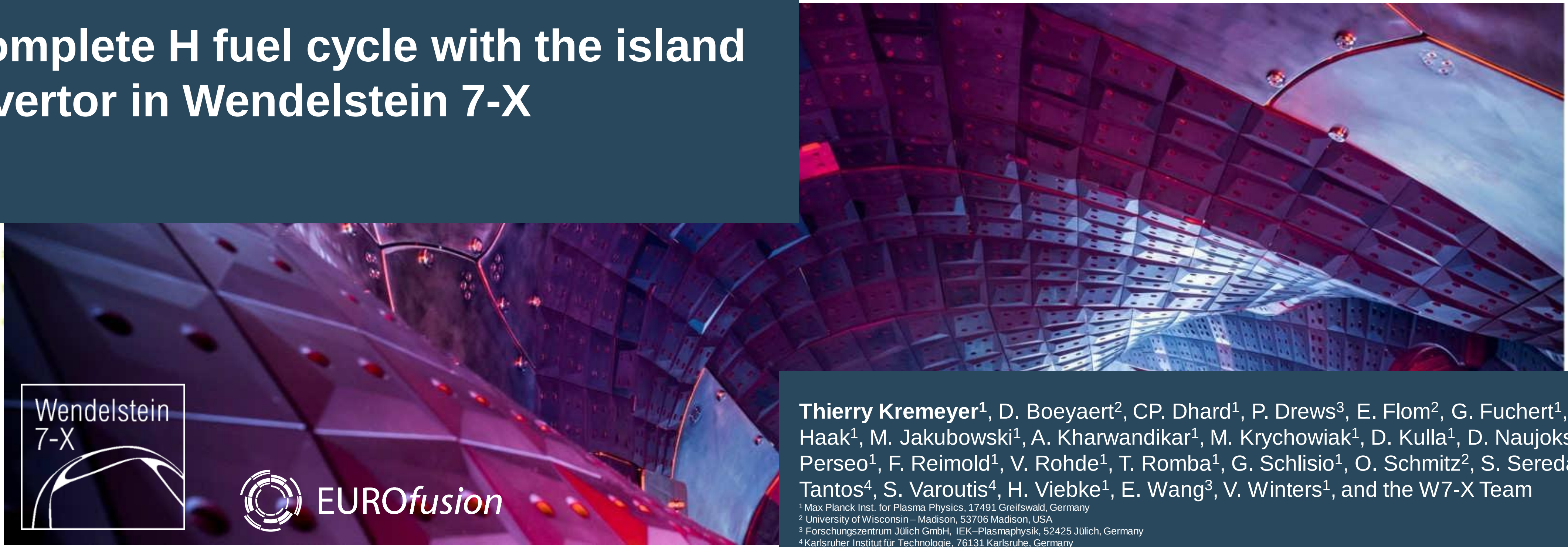
Complete H fuel cycle with the island divertor in Wendelstein 7-X



Thierry Kremeyer[1], D. Boeyaert[2], CP. Dhard[1], P. Drews[3], E. Flom[2], G. Fuchert[1], V. Haak[1], M. Jakubowski[1], A. Kharwandikar[1], M. Krychowiak[1], D. Kulla[1], D. Naujoks[1], V. Perseo[1], F. Reimold[1], V. Rohde[1], T. Romba[1], G. Schlisio[1], O. Schmitz[2], S. Sereda[2], C. Tantos[4], S. Varoutis[4], H. Viebke[1], E. Wang[3], V. Winters[1], and the W7-X Team

[1] Max Planck Inst. for Plasma Physics, 17491 Greifswald, Germany
[2] University of Wisconsin – Madison, 53706 Madison, USA
[3] Forschungszentrum Jülich GmbH, IEK–Plasmaphysik, 52425 Jülich, Germany
[4] Karlsruher Institut für Technologie, 76131 Karlsruhe, Germany

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

Outline

- **Why do we need a divertor?**
- **Wendelstein 7-X – Magnetic field and island divertor**
- **H fuel cycle**
- **Detachment**
- **Conclusion on particle exhaust at W7-X**
- **Extrapolate design criteria**

Disclaimer: All experiments shown with

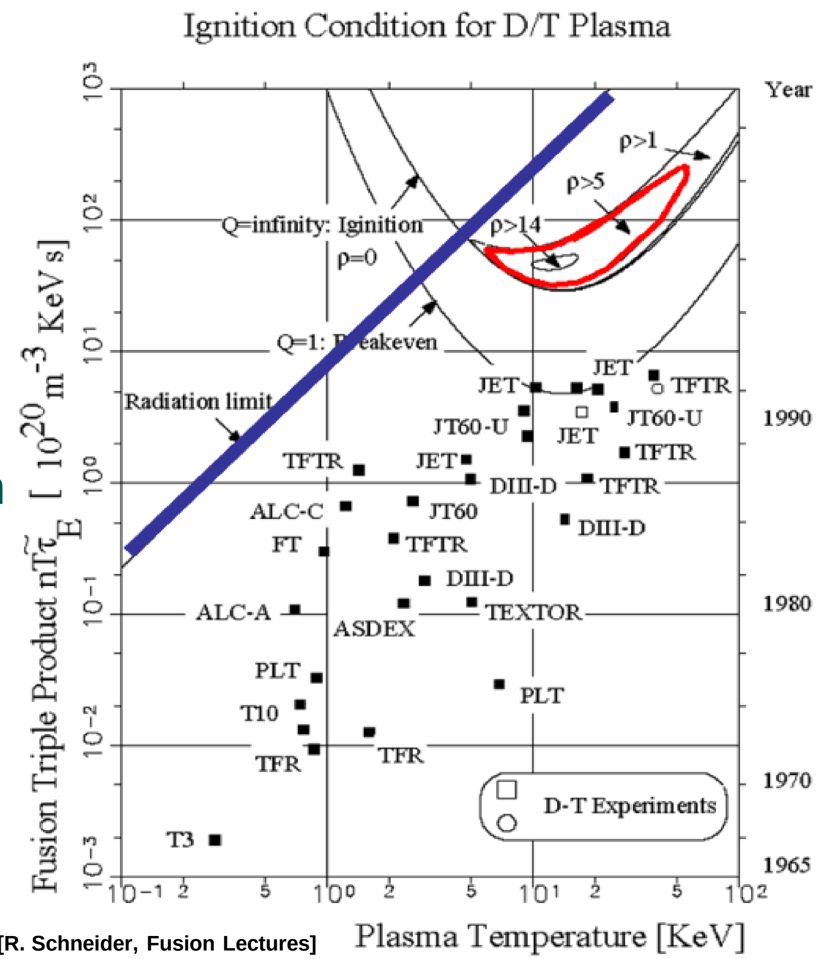
- Standard configuration
- Pure ECRH heating
- Pure gas fueling
- Boronized wall

Why do we need a divertor? Particle control!

$$\rho = \frac{\tau_\alpha^*}{\tau_E}$$

Reactor perspective – He concentration shrinks operational space

- He produced in a reactor, has to be removed
- Depending on assumed concentration of additional impurities ρ must be less than 10-15, the lower the better



[R. Schneider, Fusion Lectures]

Operational perspective – Density control

- Particle exhaust > wall source ➡ wall independent density
- Particle exhaust = Particle source ➡ stable density in equilibrium
  - Flat profiles ➡ Particle exhaust = Wall source
  - Peaked profiles ➡ Particle exhaust = Core + Wall source

Only neutral particles can be removed

- Target to intercept,neutralize and exhaust particleflux ➡ Divertor

Divertor requirements and metrics

Reactor requirements: Exhaust enough particles to keep ρ < 10-15 $\Gamma_{He\text{-}Exhaust} = \Gamma_{He\text{-}Fusion}$

Particle exhaust - $\Gamma_{Exhaust} / \Gamma_{Ion\ Divertor} = \eta_{exhaust}$

Particle collection - $\Gamma_{Pumpgap} / \Gamma_{Ion\ Divertor} = \eta_{collection}$

Particle removal - $\Gamma_{Exhaust} / \Gamma_{Pumpgap} = \eta_{removal}$

Particle plugging - $\Gamma_{Divertor\ Recycling} / \Gamma_{Recycling} = \eta_{plugging}$

Covered in this Talk

Impurity control - Keep confined plasma clean

Minimize erosion - $T_e < 5$ eV

Erosion away from LCFS - Divertor > Limiter

Subsequent requirements:

Heat load control/exhaust

< 10 MW/m² - Detachment?

Shallow incidence angles; Avoid leading edges

Material science

Low activation

Tolerance to high displacements per atom

Wendelstein 7-X – Magnetic field and divertor

Magnetic islands form interface for the divertor

Magnetic islands twist around the central plasma and connect the different divertor modules

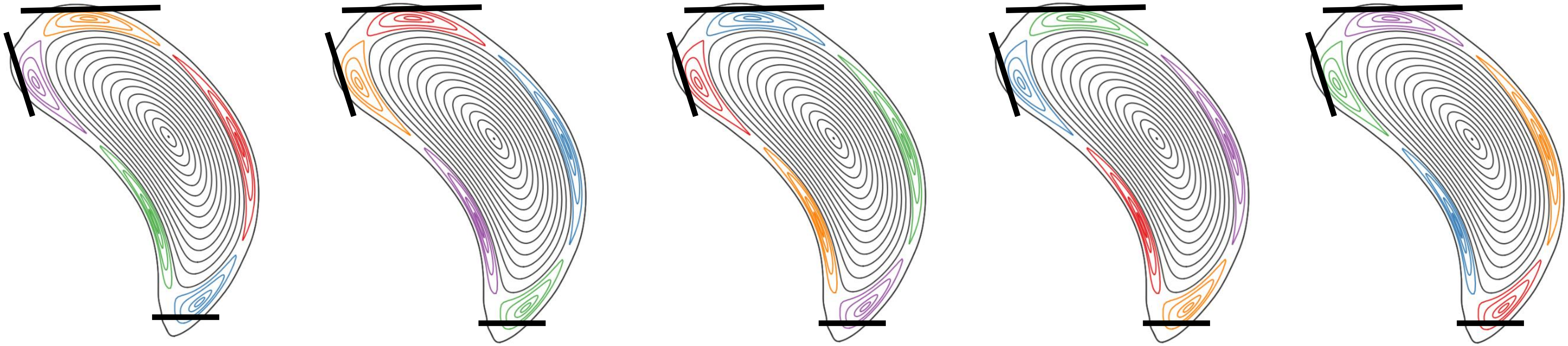
[V. Perseo]

Example of
standard configuration

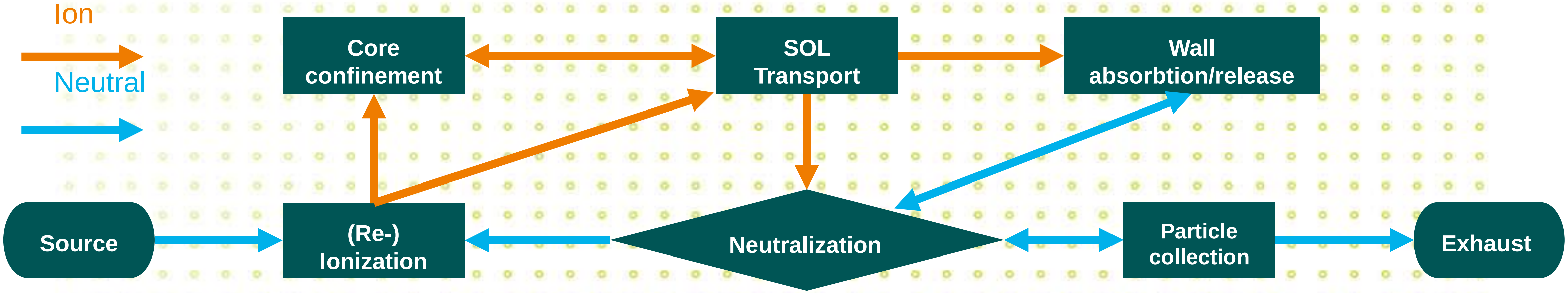
W7-X divertor:
island divertor

SOL with 5
independent islands

10 units
made of fine graphite

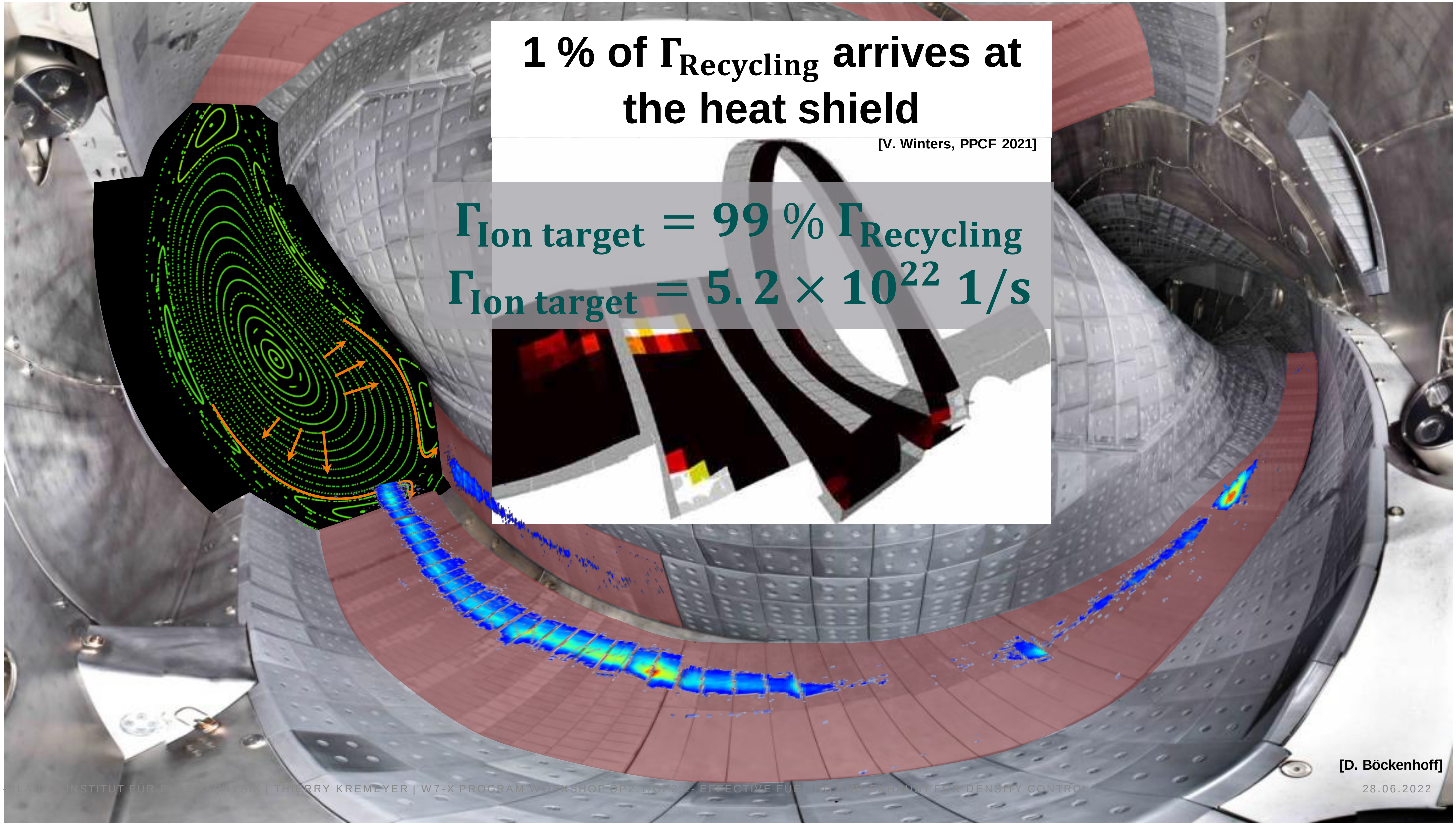


H fuel cycle

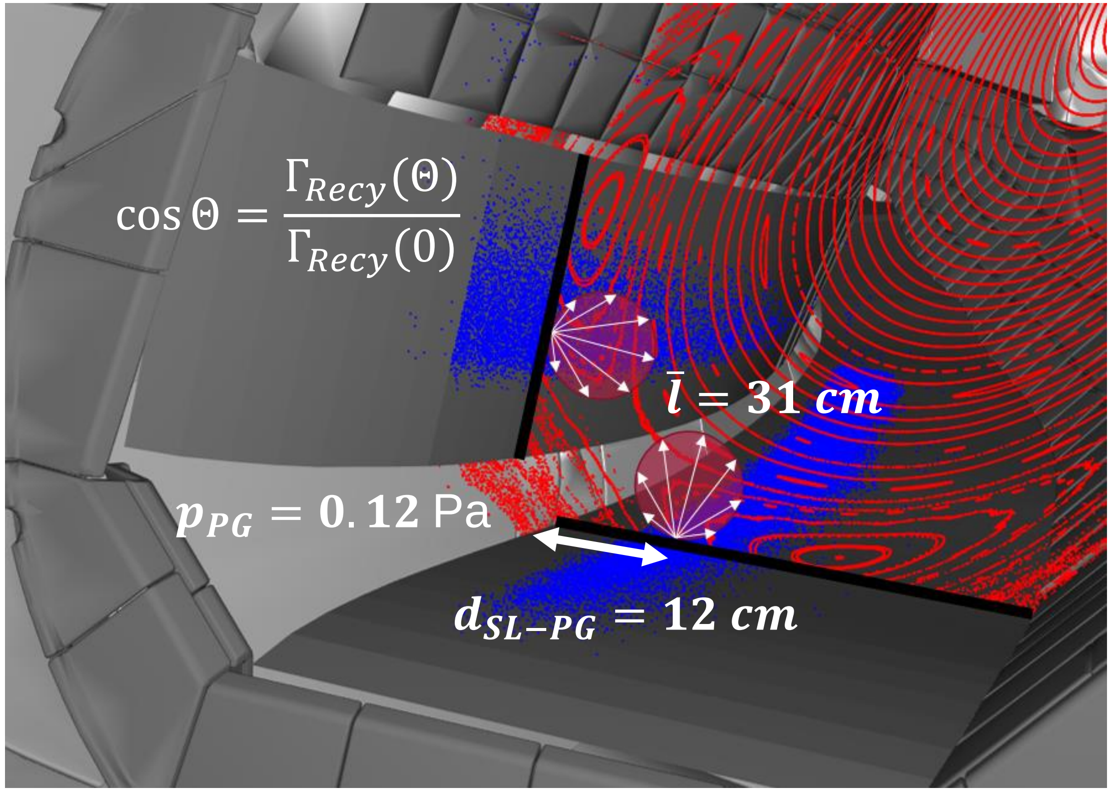


Ion
Neutral
Core confinement
SOL Transport
Wall absorbtion/release
Source
(Re-) Ionization
Neutralization
Particle collection
Exhaust

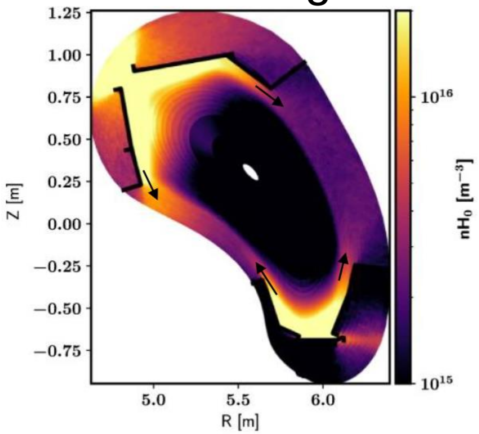
~99% of particles neutralize on divertor target



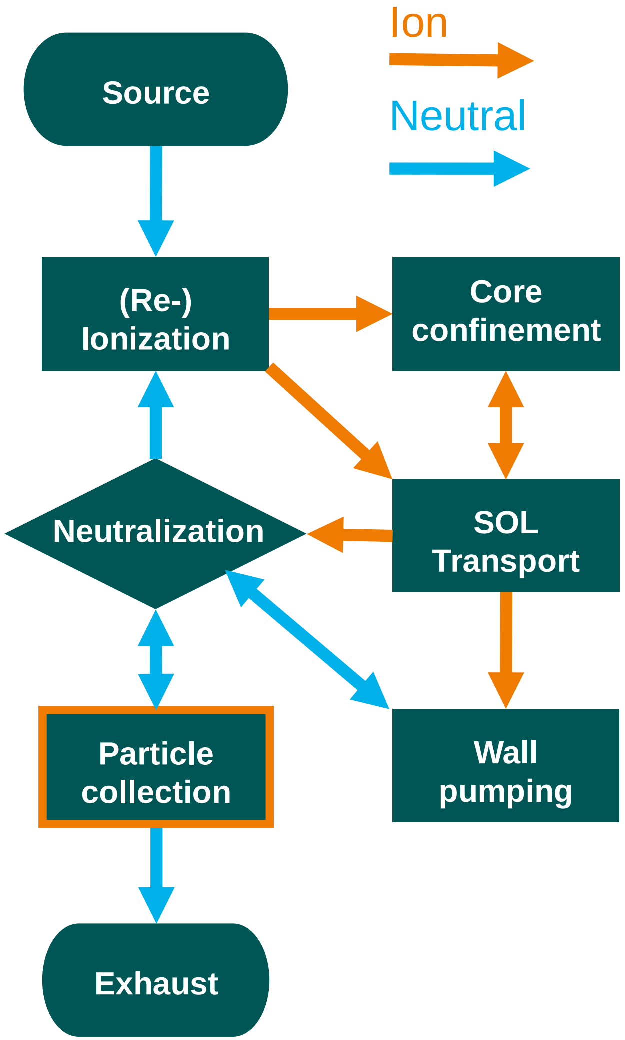
Particle collection with an open carbon divertor



EMC3-EIRENE modeling



[V. Winters, PPCF 2021]



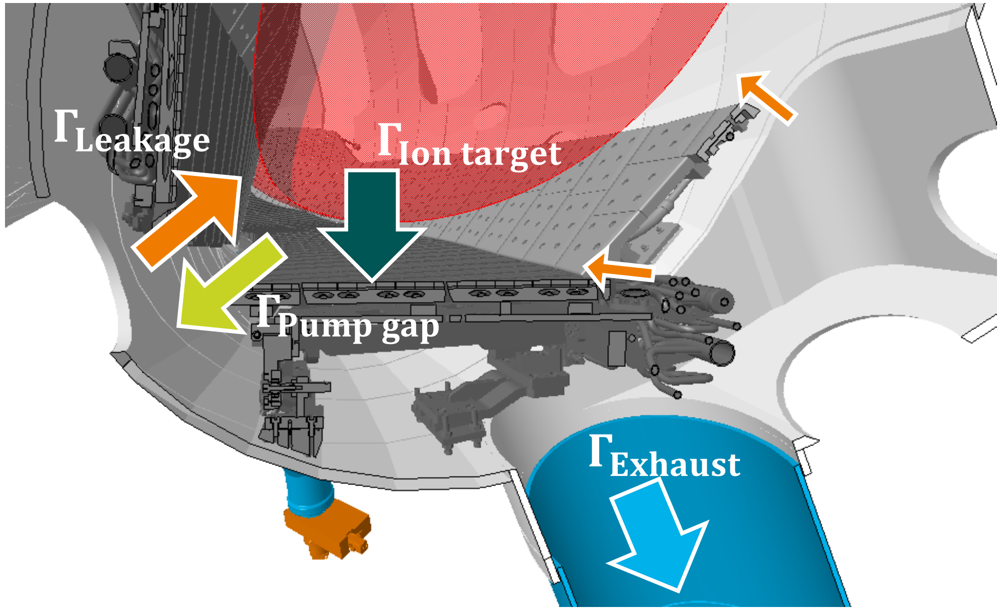
Particle collection:

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



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

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

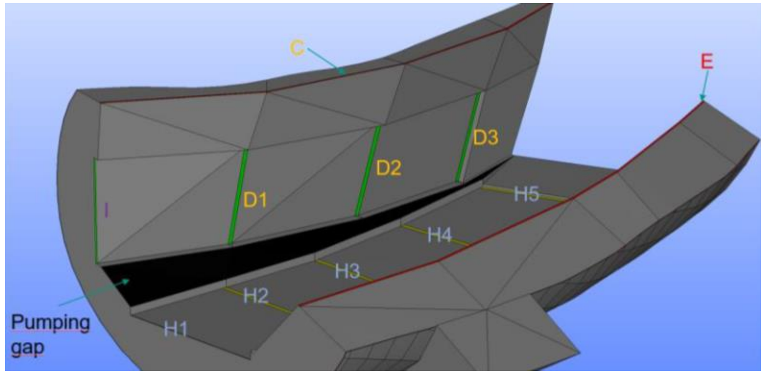
$$\Gamma_{\text{Exhaust}} = p_n \times S_{eff}$$

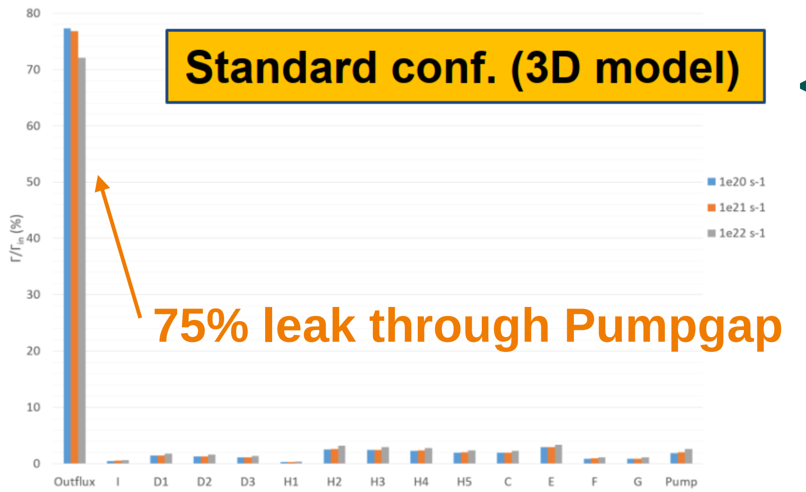
$$\Gamma_{\text{Exhaust}} = 6\%\Gamma_{\text{Pump gap}}$$

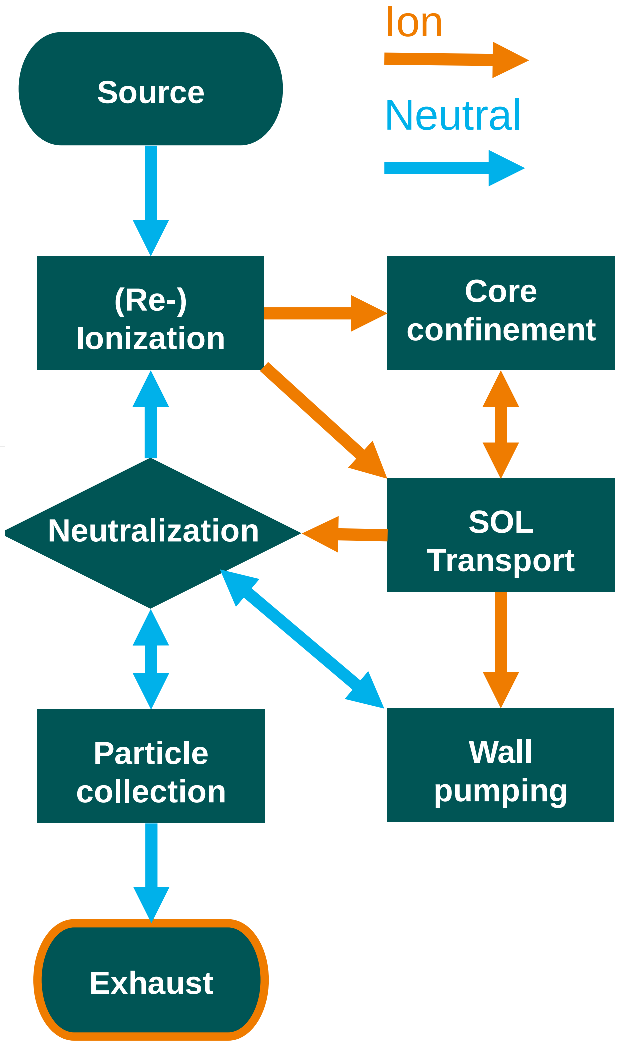
$$\Gamma_{\text{Leakage}} = \Gamma_{\text{Pump gap}} - \Gamma_{\text{Exhaust}}$$

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

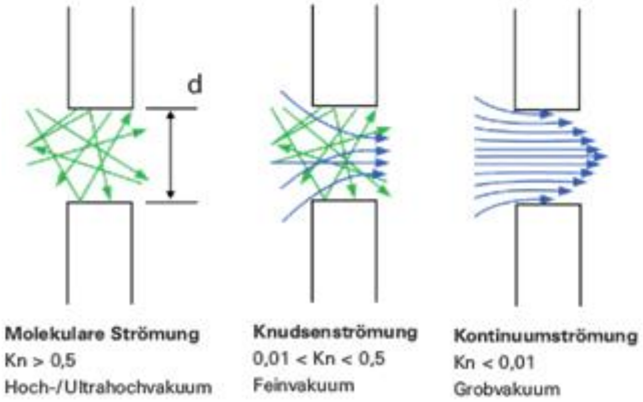
DIVGAS modeling







Continous flow minimizes leakage



[www.pfeiffer-vacuum.com]

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

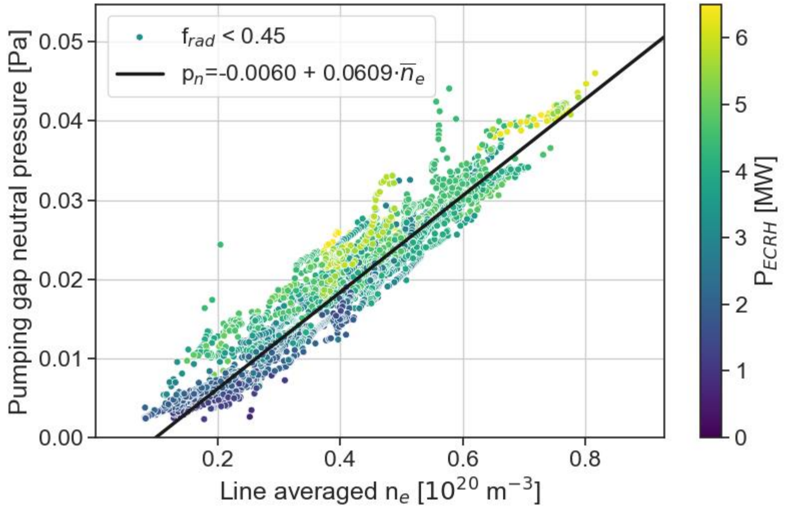
How to access continous flow regime?

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

I_{cc} = 0kA $\quad d_{SL-PG} = 12.1\ cm$
I_{cc} = 2kA $\quad d_{SL-PG} = 6.2\ cm$
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
p_{pg} [Pa]	0.12	0.82	40

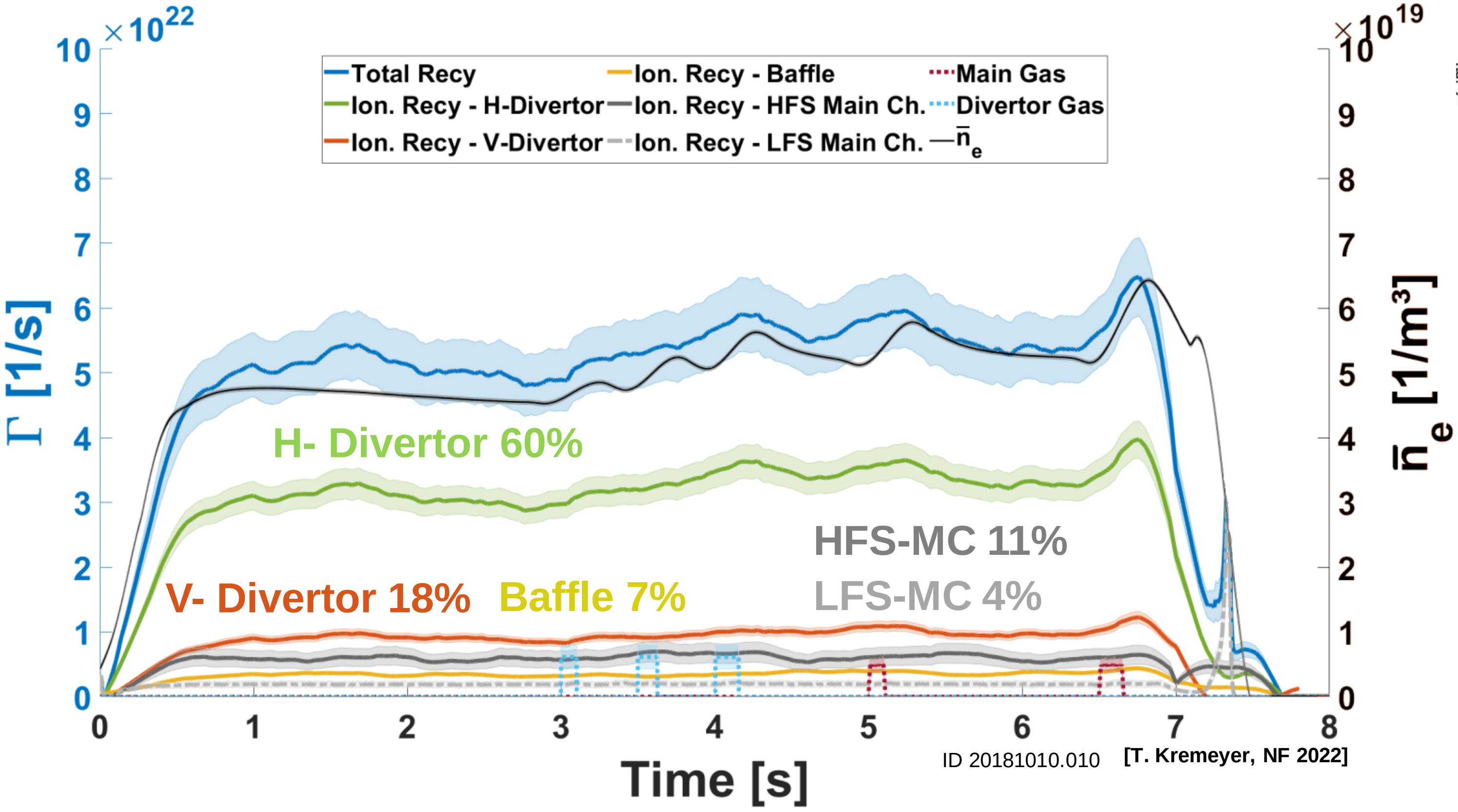


[V. Perseo]

Re-ionisation shows good plugging

$$\Gamma_{H}^{tot} = \Phi_{H\alpha} * S/XB_{eff}$$

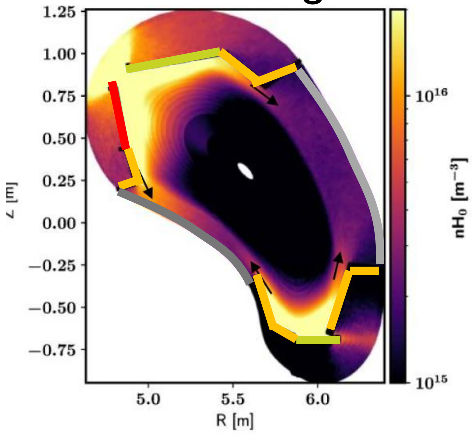
$S/XB_{eff,Div} = 34 \pm 2.3$ $\quad$ $S/XB_{eff,MC} = 19 \pm 4.8$



[T. Kremeyer, NF 2022]

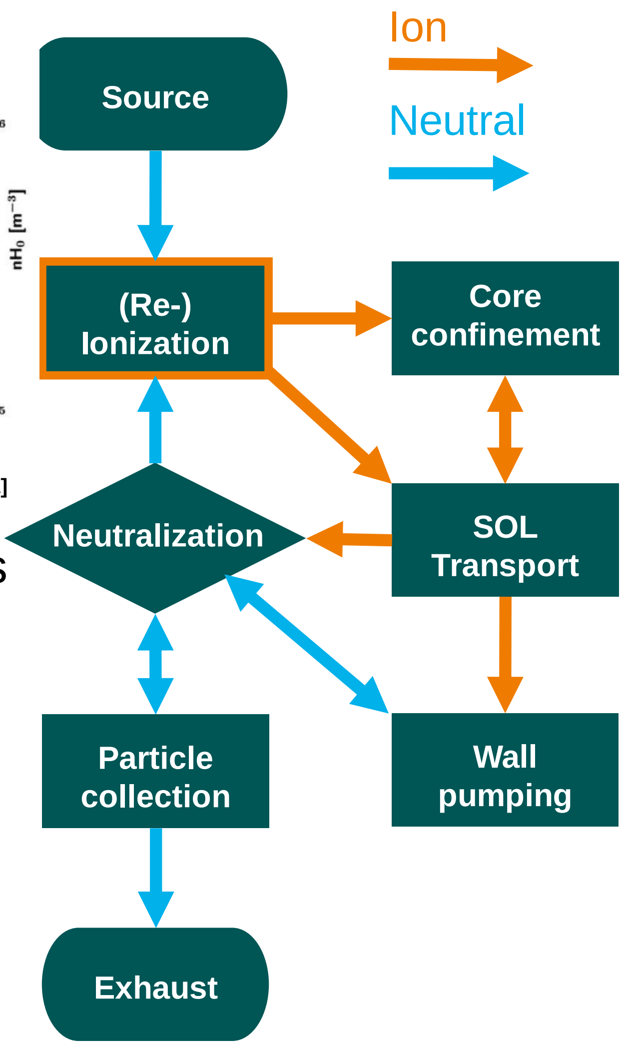
$$\Gamma_{Plugged} = 85\ \%\ \Gamma_{Ion\ target}$$

EMC3-EIRENE modeling



[V. Winters, PPCF 2021]

- Neutral particles escape poloidally and toroidally from divertor



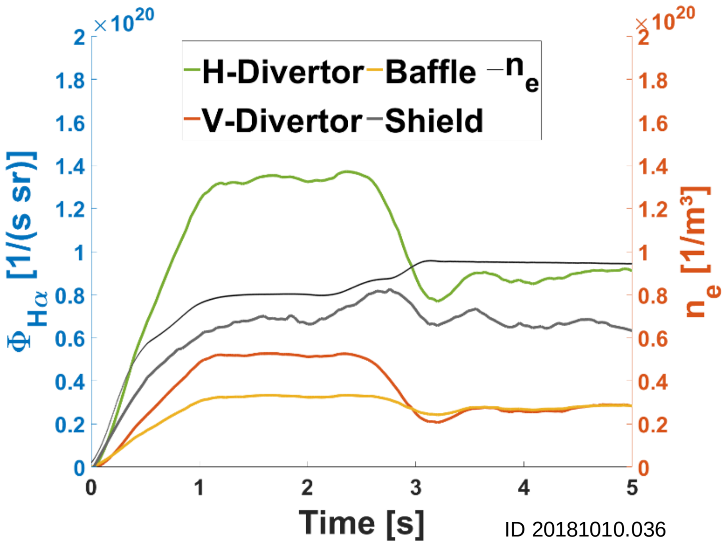
Detachment at W7-X

Detachment definition and power balance

Observations of detachment in Tokamak are:

- 'roll-over' and decrease of the ion saturation current, j+sat, of Langmuir probes built into the divertor targets
- H_α radiation from the target regions does not roll over/decrease, but continues to increase with n_e
- A further feature of detachment is that it occurs when the target Langmuir probes indicate low temperatures, $T_e \approx$ a few eV or less "

- Stangeby, Plasma Boundary Book IoP 2001



ID 20181010.036

Detachment easily accesible with stable radiation front

But H_α decreases

Particle and Power detachment achieved by radiating power in the SOL through seeded and/or intrinsic impurities

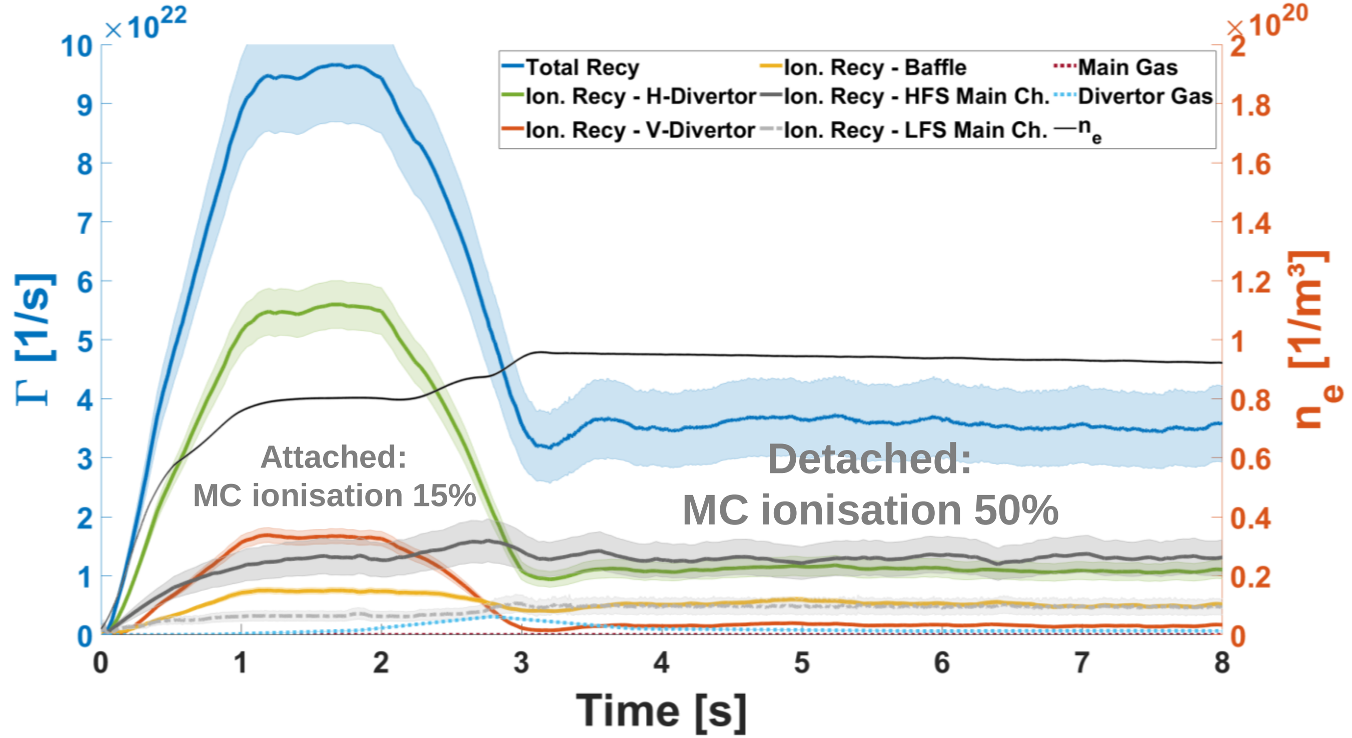
Power balance

$$P_{in} = \Gamma_{rec}(\gamma T_t + \epsilon_i) + f_{rad} P_{in}$$

Recyling flux reduced at high f_{rad}

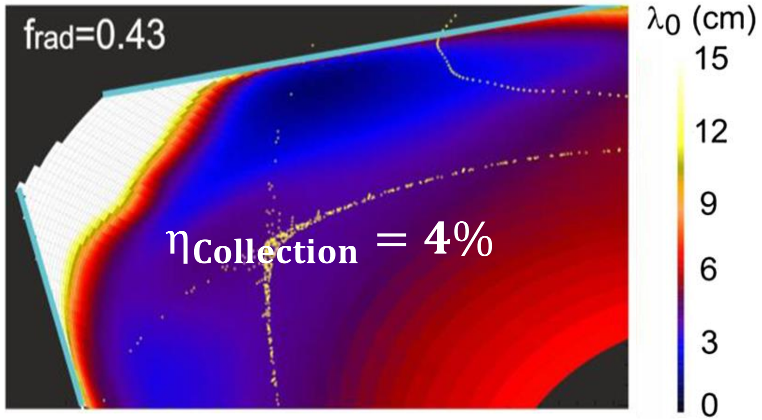
[M. Jakubowski, NF2021] [Y. Feng, NF2021]

Detachment reduces particle flux, brings higher collection, but weaker plugging

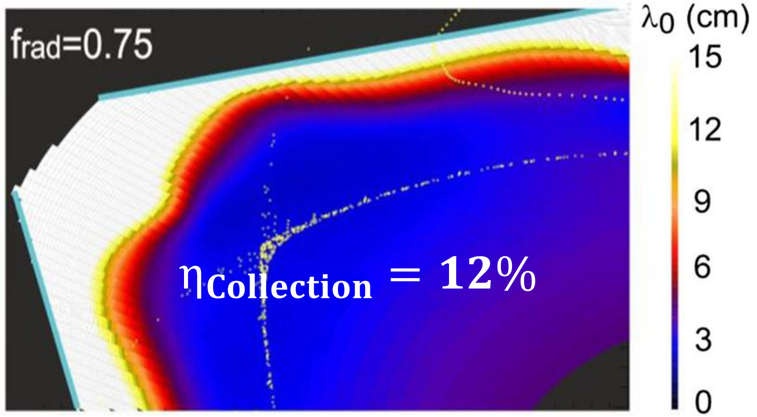


$\Gamma_{\text{Ion divertor}}$ ↘ 60 %

↘ $\eta_{\text{Plugged}} \approx 50$ %



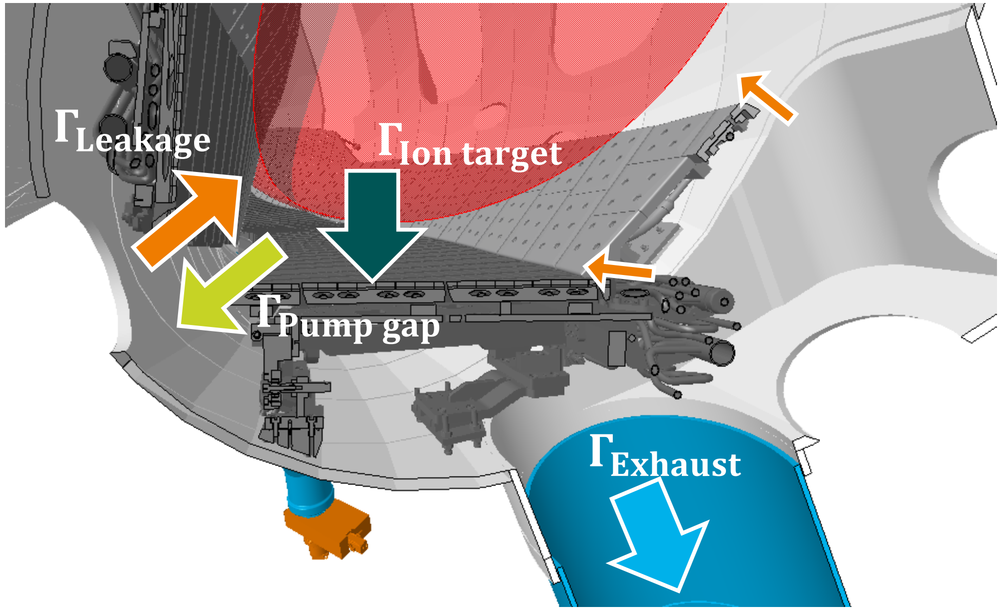
ID 20181010.036 [Y. Feng NF2021]



	Pump gap [mbar]	Midplane [mbar]
Attached	6.2 E-4 ± 6.0 E-5	3.0 E-6 ± 6.7 E-7
Detached	7.0 E-4 ± 5.2 E-5	**1.2 E-5** ± 1.6 E-6

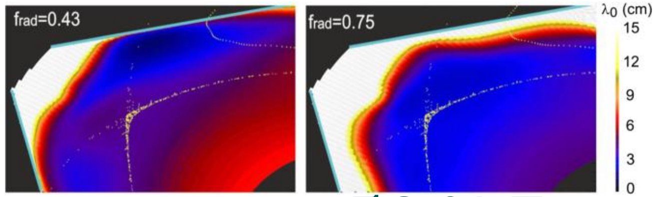
Full magnetic flexibility at effective, but in-efficient exhaust

- 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
- Reasonable plugging, despite toroidally open divertor
- Stable detachment opens up neutral channels
- W7-X detachment decreases particle flux towards divertor



Attached → Detached

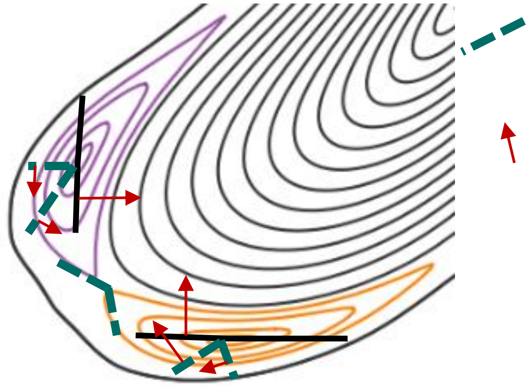
Attached	Detached
$\Gamma_{Ion\ target} = 99\ \%\ \Gamma_{Recycling}$	$\Gamma_{Ion\ divertor}$ decreases 60 %
$\eta_{Collection} = 4\ \%\ \Gamma_{Ion\ target}$	$\eta_{Collection} = 12\ \%\ \Gamma_{Ion\ target}$
$\eta_{Removal} = 6\%\ \Gamma_{Pump\ gap}$	
$\eta_{Exhaust} =< 1\%\ \Gamma_{Ion\ target}$	
$\eta_{Plugged} = 85\ \%\ \Gamma_{Ion\ target}$	$\eta_{Plugged} = 50\ \%\ \Gamma_{Ion\ target}$



Design criteria for a reactor divertor

Particle collection

- **Maximize pump gap opening angle – Cosine law initial flight path**

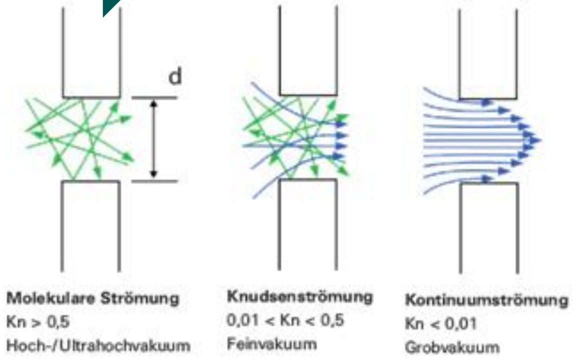


- **How does initial flight path of neutrals change with W?**

Particle removal

- **Minimize Knudsen number**
- **Increase pressure**

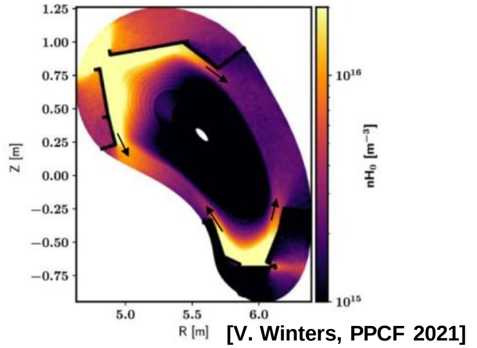
➡ **Particle collection**



$$Kn = \frac{\bar{l}}{d}$$

Particle plugging

- **Close poloidal and toroidal neutral channels**
- **Block neutrals by baffles where thermal loads allow**
- **Ionize neutrals**



[V. Winters, PPCF 2021]

- **Weakend by detachment**
- **BUT less relevant as $\eta_{exhaust}$ increases**

How much exhaust do we need?

$\rho < 10$ ➡ SOL ➡ ? ➡ $\eta_{exhaust}$

Target geometry should provide more, throttle pumps