# The Island Divertor Concept of the Wendelstein 7 Stellarator Line:

## Concept, Experimental Experience and Up-Scaling to Reactor Relevant Size

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# Outline of the talk

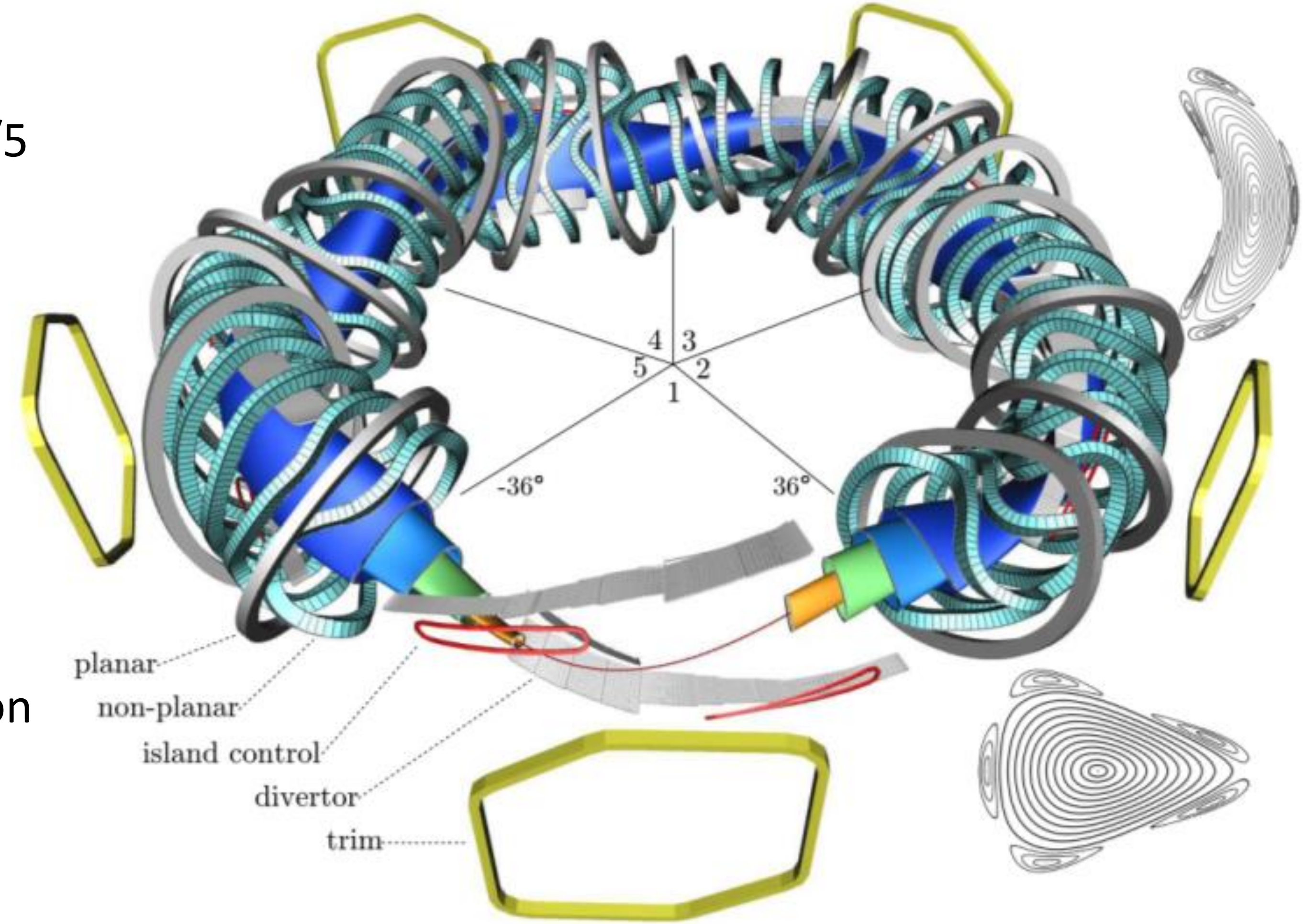
- The Island Divertor Concept
- Partial detachment in W7-AS
- Complete stable detachment in W7-X
  - First step towards stable quasi-stationary detached plasma operation in OP1.2b
  - $N_2$, Ne impurity seeding induced and assisted detachment
- EMC3/EIRENE: Up-scaling of the Island Divertor Concept to a Reactor Scale Device

# The Island Divertor Concept

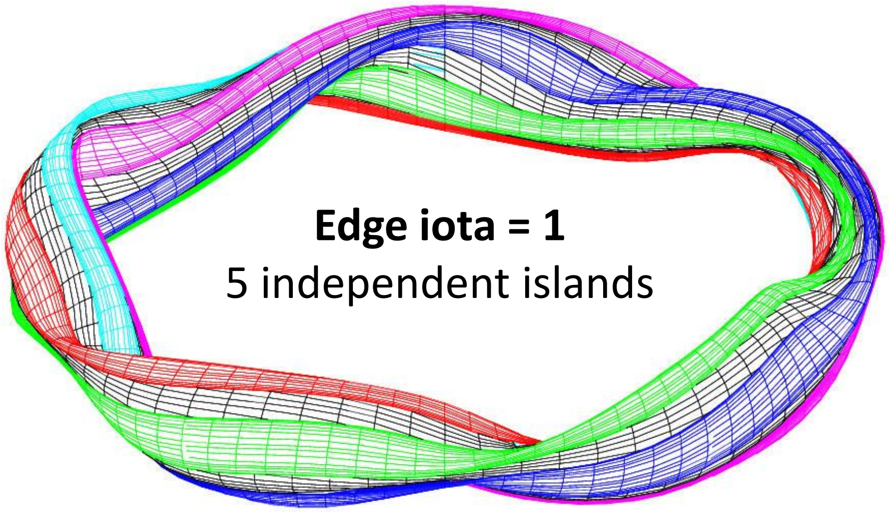
# W7-X magnet system

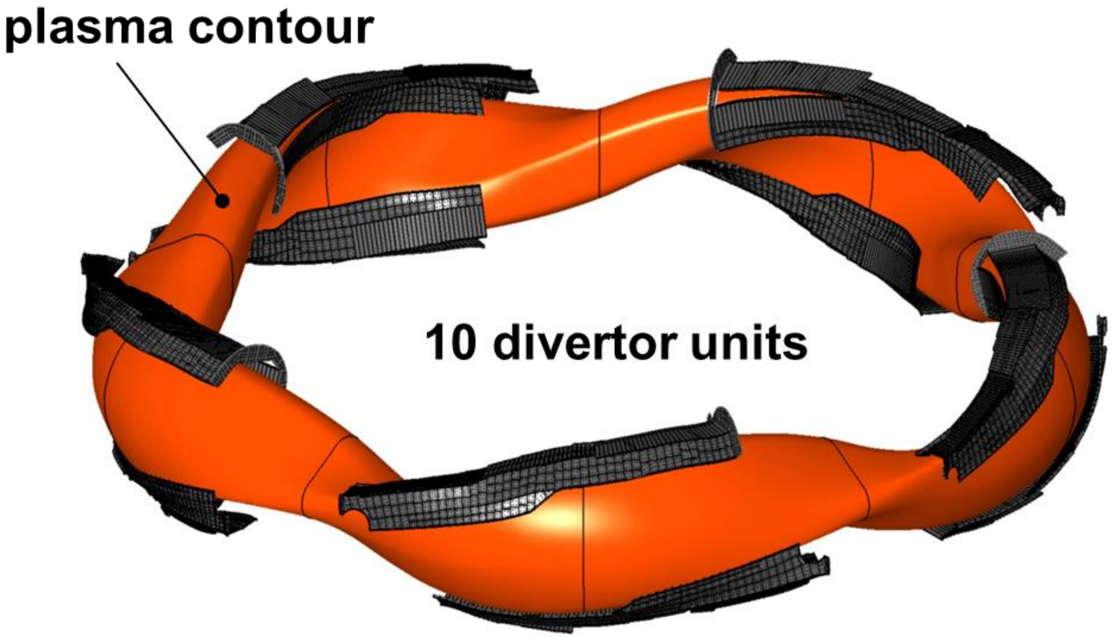
**Five periodic toroidal structure**

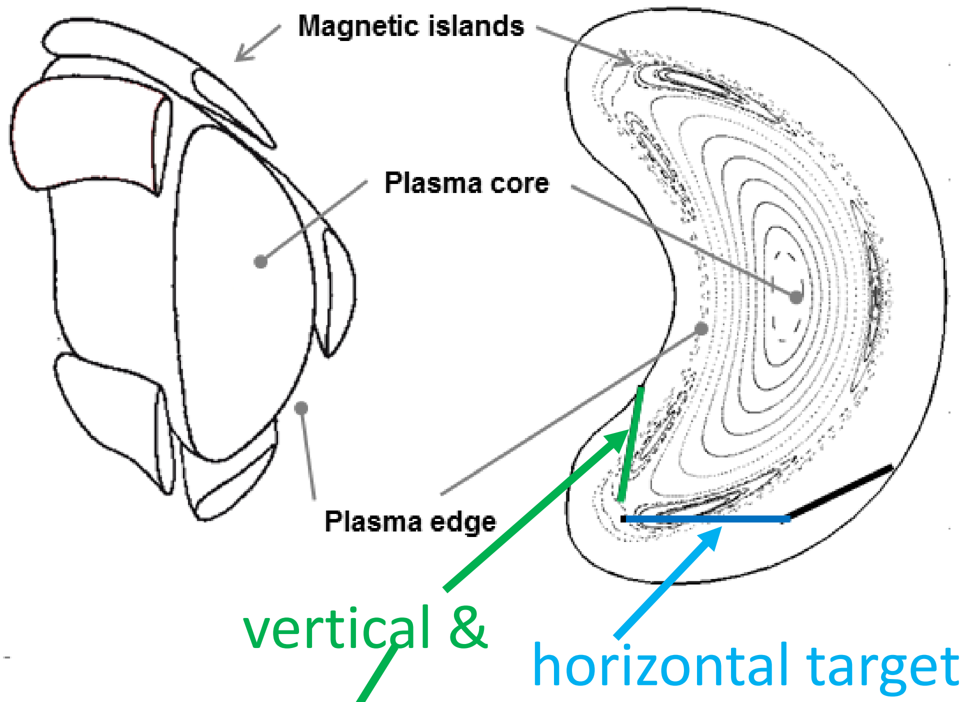
- **50 non-planar superconducting coils:**
  - Edge rotational transform $\iota_a = 1 = n/m = 5/5$ with intrinsic (“natural”) island chain
  - **Islands generated at resonant iota by intrinsic small $b_r \sim 10^{-3} \cdot B_0$**
- **20 planar superconducting coils:**
  - Adjustment of rotational transform $5/6 \leq \iota_a \leq 5/4$ and radial plasma position
- **10 island control coils:**
  - Variation of island size and poloidal position
  - Partial $b_{22}$ error field compensation
- **5 trim coils:**
  - Correction of dominating $b_{11}$ error field
  - Vertical position of plasma

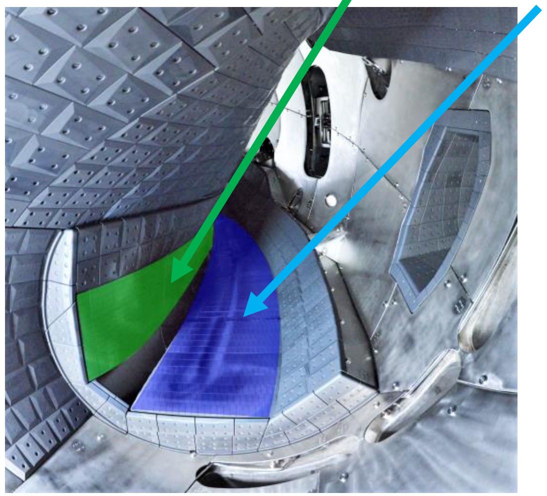


# Island Divertor Geometry in W7-X



**Standard configuration:**

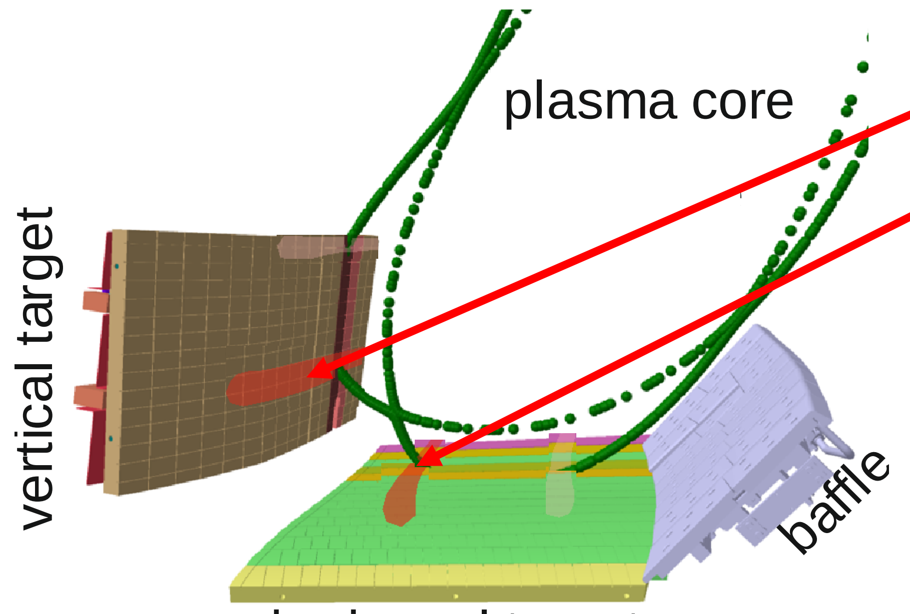
iota = 1

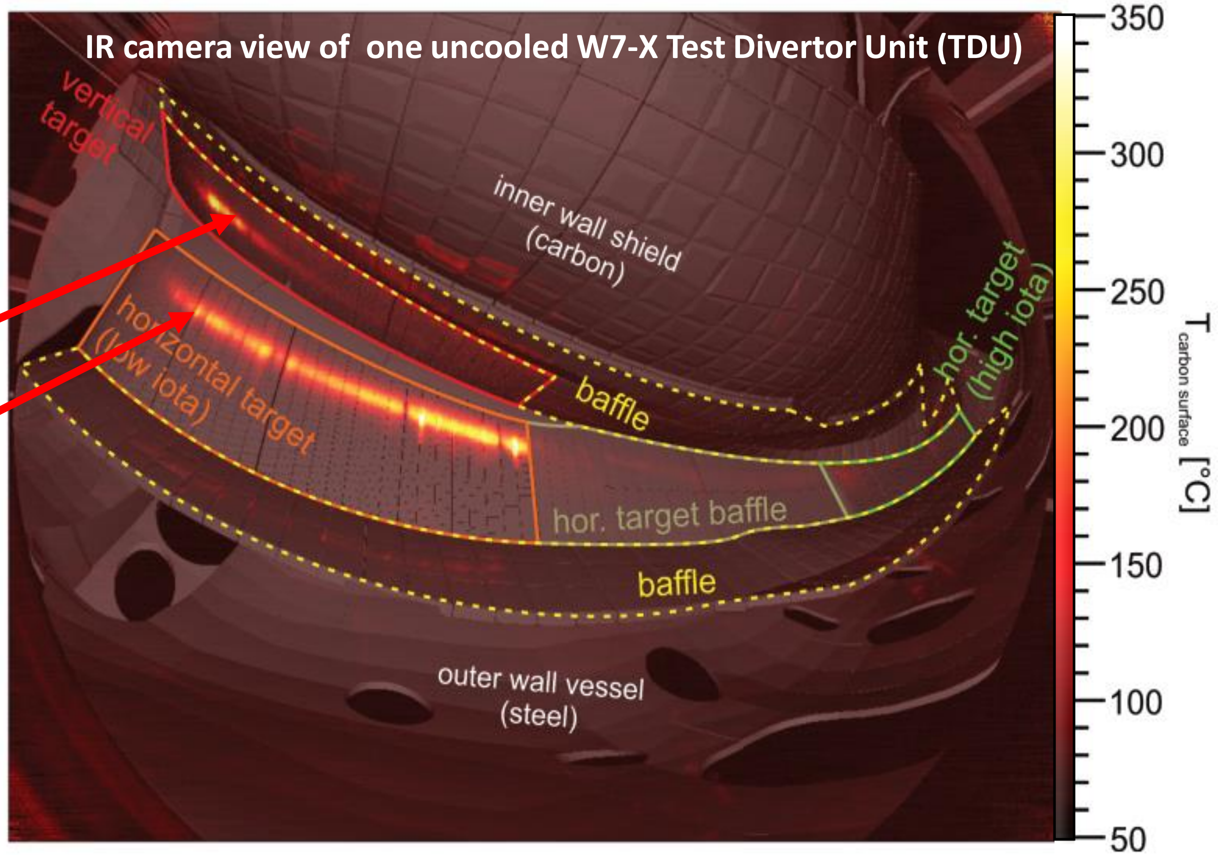
= n/m = 5/5

➔ 5 islands

# The island divertor at Wendelstein 7-X

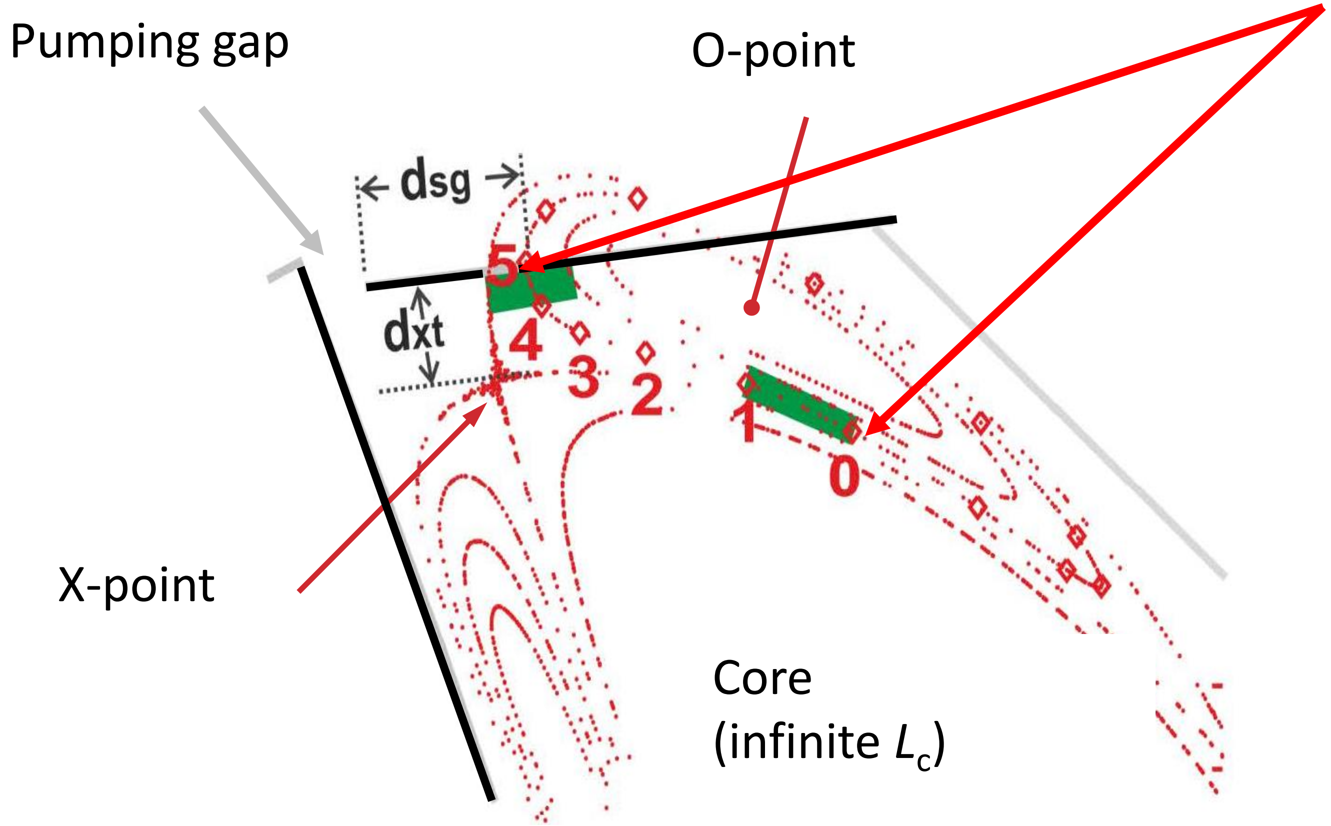
Island divertor at W7-X in **standard configuration** forms **two strike-lines** on horizontal and vertical target




IR camera image of the divertor

# Magnetic island divertor




Number of toroidal turns

W7-X: $2\pi R \approx 35$ m

This example: $L_c/2 \approx 5 \times 35$ m $= 170$ m

$L_c$ = target to target field line connection length

**Position of X-point and strike line position relative to the pumping gap have significant impact on SOL parameters and divertor operation.**

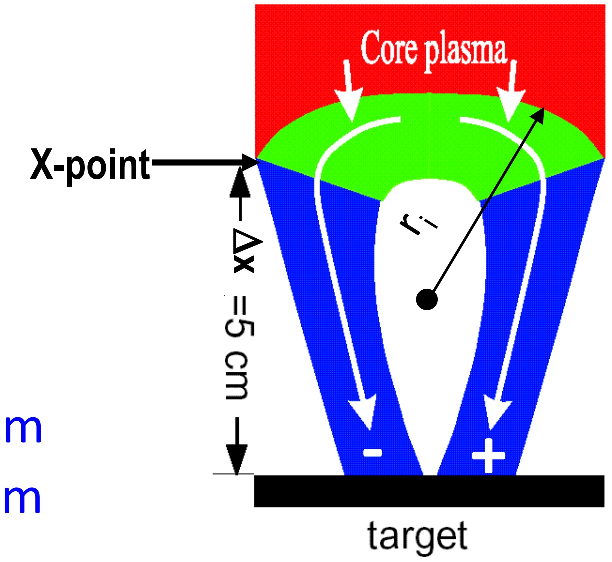
# Island Divertor Behaviour Dominated by Cross-Field Transport

**Energy:** ⊥ transport dominates if:

$$T < \left( \frac{\chi n}{\Theta^2 \kappa_e} \right)^{2/5} = \begin{matrix} 1\text{ eV} & \text{for tokamak} \\ 36\text{ eV} & \text{for W7-AS, W7-X} \end{matrix}$$

with $\chi$ = 2 $m^2/s$, n=5 $10^{19}$ $m^{-3}$, $\Theta$ = 0.1 (tokamak)
$\Theta$ = 0.001 (W7-AS, W7-X)

field line pitch inside island:
$\Theta = \Delta x / L_c$




**Particle and momentum:** ⊥ transport dominates if:

$$\frac{\tau_{\parallel}}{\tau_{\perp}} = \frac{2D}{\Theta V_{\parallel} \Delta x} > 1 \qquad \frac{\tau_{\parallel}}{\tau_{\perp}} = \begin{cases} 2\ 10^{-3} & \text{for tokamak (AUG) } \Delta x \approx 20\text{ cm} \\ 0.8 & \text{for W7-AS, W7-X } \Delta x \approx 5\text{cm} \end{cases}$$

Assumed particle and momentum transport governed by:

- class. || convection at $v_{||}=c_s=6\ 10^4$ m/s
- anomalous diffusion $D_\perp$ = 1 $m^2/s$

} estimate transport time scales as: $\tau_{||} = L_c/c_s$ $\tau_\perp = 2r_i^2/D = \Delta x^2/2D$

**Cross-field transport dominant in island divertor configurations**

Y. Feng, et al. NF 46, 807 (2006)

# W7-AS Results

# Reduced Frictional Momentum Losses in W7-X

**Schematic representation of geometry-related momentum loss:**

$$f_m = \frac{D}{2\Theta c_{sd}}\left(\int \frac{nV_{\parallel}/n_d c_{sd}}{\Delta^2}dl + \frac{1}{\lambda_\Gamma}\right)$$

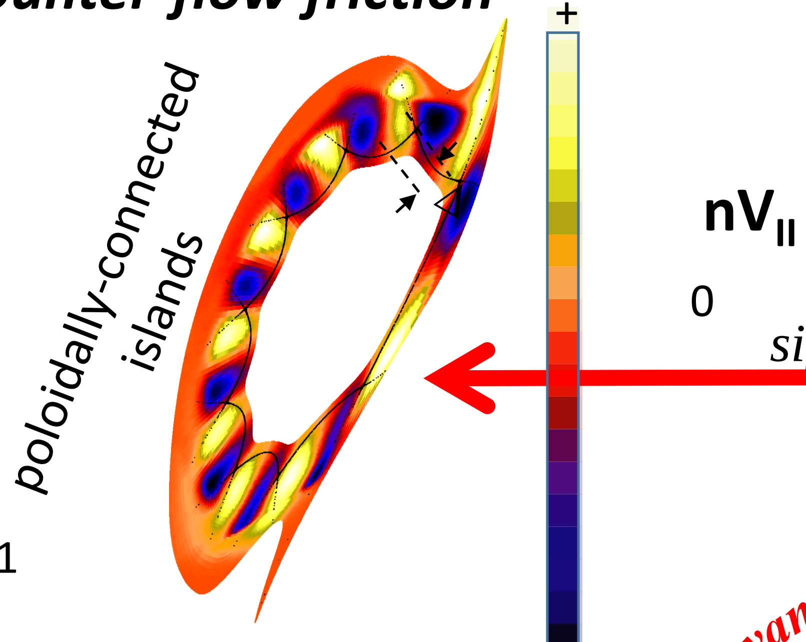
*significant in W7-AS*

*vanishes in W7-X*

*remains in W7-X*

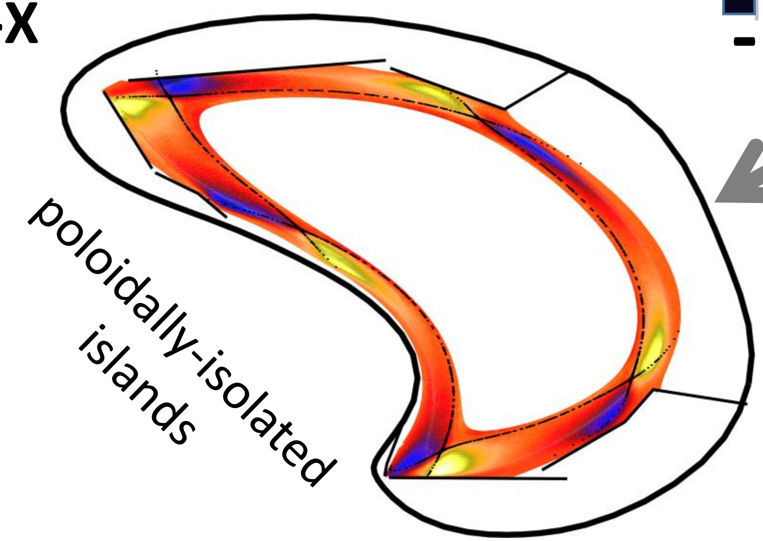
***Counter-flow friction***

**W7-AS**

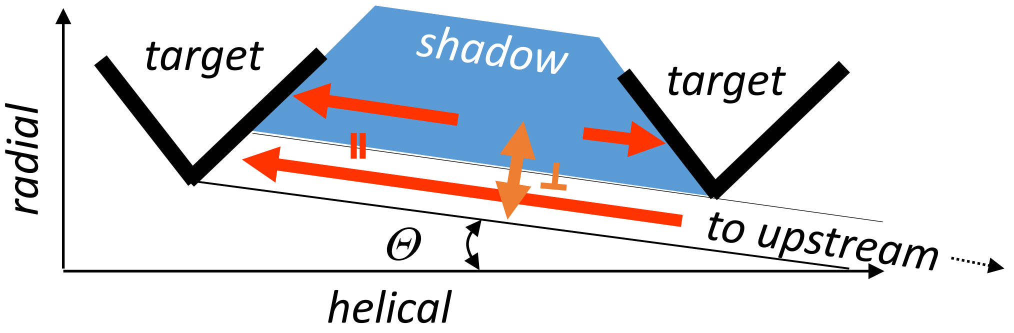



Y.Feng, PPCF 2011

**W7-X**




***Divertor shadow trapping***



# The Route to Stable Partial Detachment in W7-AS

## EMC3/Eirene modelling of an experiment (**impurities included**)

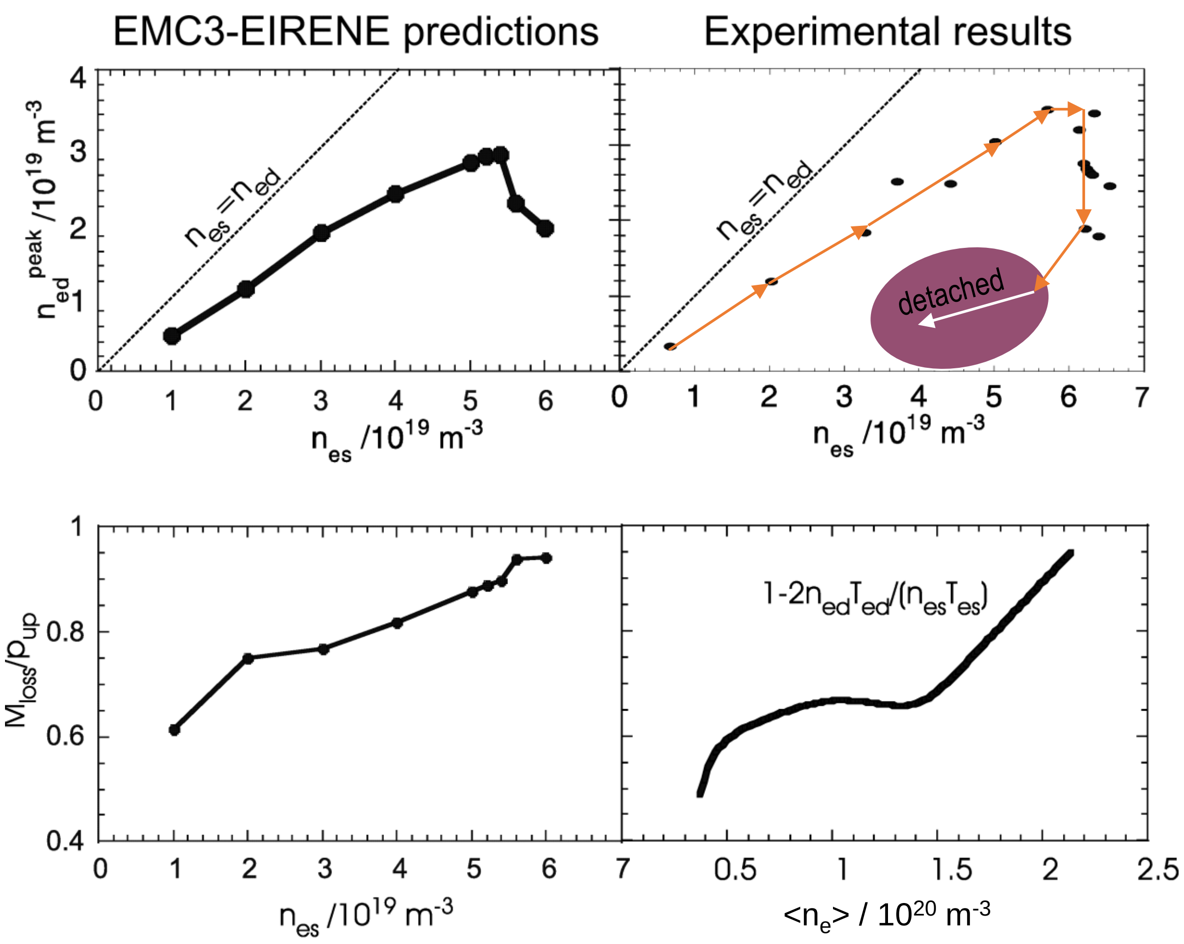
**Simulation input parameters:**

D=0.5 $m^2/s$,

$\chi_e = \chi_i = 3$ D,

sputtering coeff.: 3%,

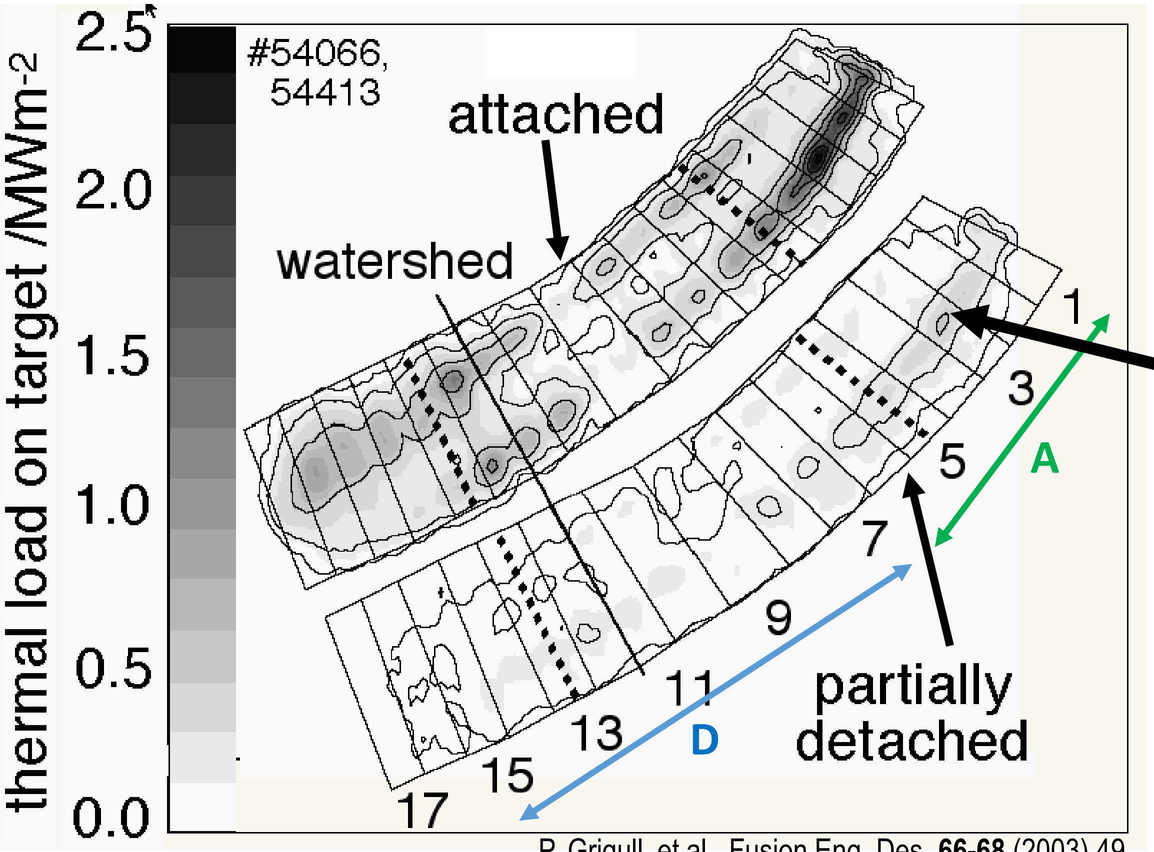
$P_{SOL}$ =1 MW => 0.85 MW (since core plasma radiation increases with $n_e$)



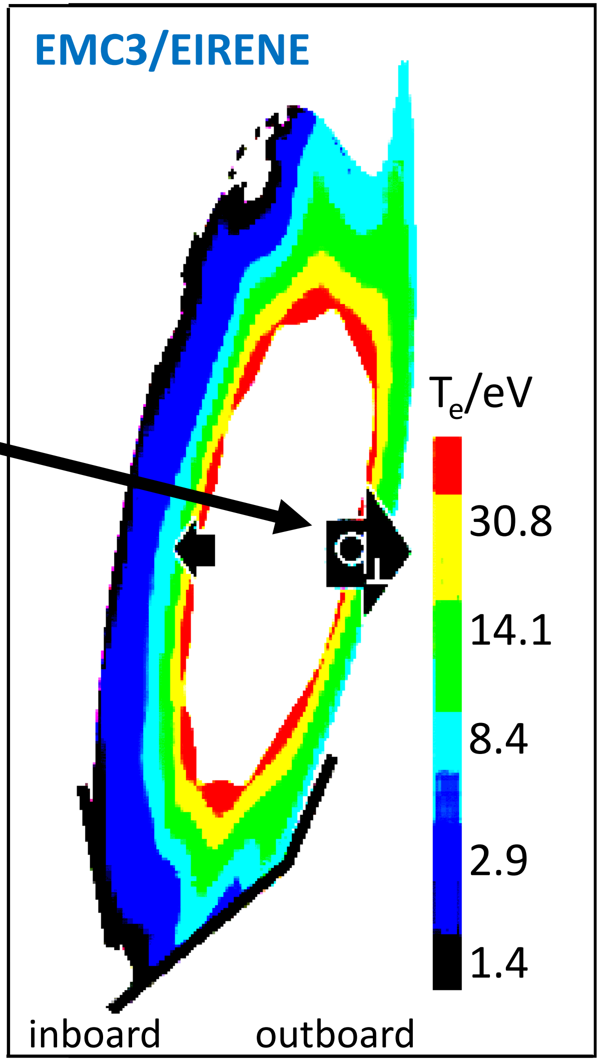

**As predicted:**

- high $n_{es}$, i.e. high <$n_e$>, required to reach detachment
- no high recycling
- high momentum losses at low densities

# Partial Detachment in W7-AS




P. Grigull, et al., Fusion Eng. Des. **66-68** (2003) 49

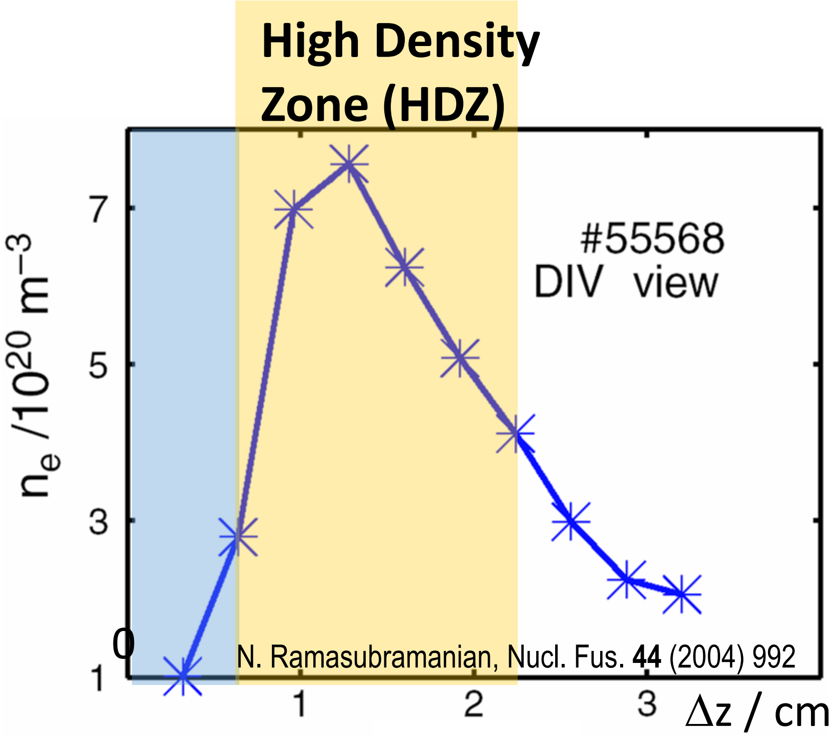



Y. Feng, et al. NF **46**, 807 (2006)

power flux reduced : about 20 x in region D
about 3 x in region A

**Partial** detachment essential ingredient of **stable** W7-AS divertor operation

# Drift Induced Volume Recombination Zone only at Upper Targets




height above the target

l.o.s. integrated $n_e$ profile

*from Stark broadening of n-n' = 8-2 Balmer line*

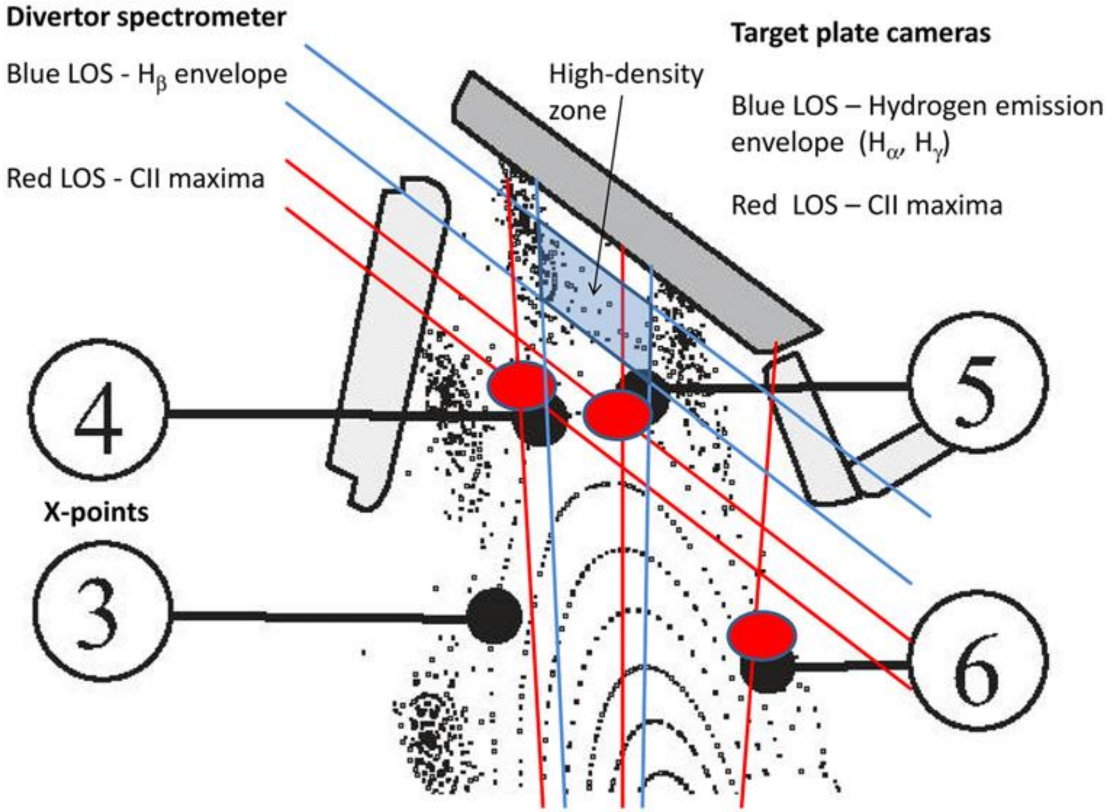
N. Ramasubramanian, Nucl. Fus. **44** (2004) 992

**Downstream density at the strike lines**

*(from target integrated Langmuir probes)*:

$n_e^{downstream} = 3.5\ 10^{19}\ m^{-3}$

## Heuristic tomographic inversion

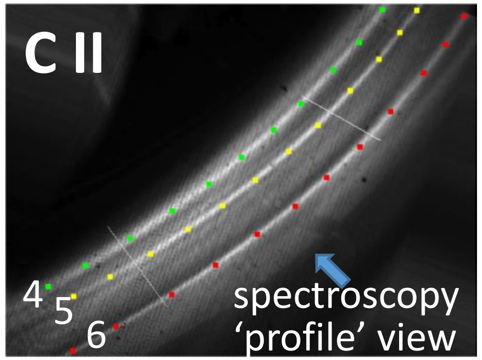



Main carbon radiation is located well away from HDZ

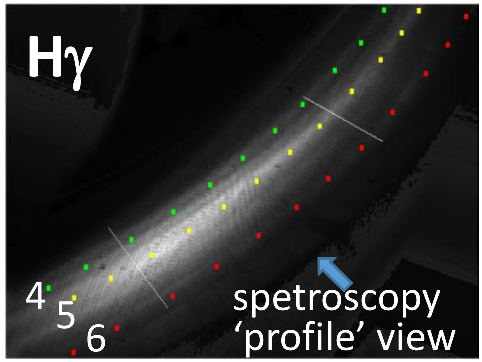
(U. Wenzel, et al., NF 55 (2015) 013017)

HDZ close to wall suggests wall recycling to be key ingredient to hydrogen condensation

(M.Z. Tokar, et al., J. Nucl. Mater. 1999)




**C II emission:** near X-lines

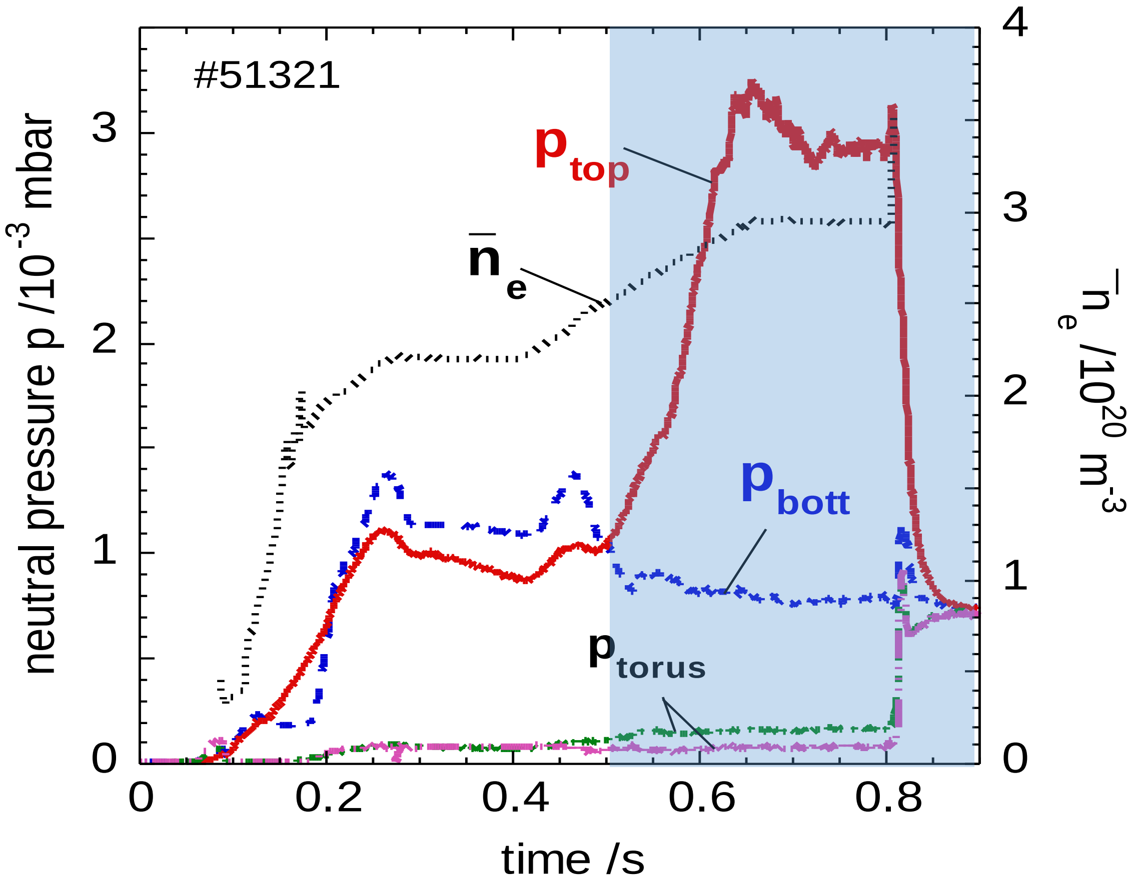



**$H_\gamma$ emission**: diffuse, shorter toroidal extension

# Increased Neutral Compression only at Upper Divertor (due to Drifts)

Strong neutral compression in upper divertor: ~ **factor 20**

coincides with onset of volume recombination




- steep increase of $p_o$ in
- sub-divertor volume during
- part. detachment
- sufficient $p_0$ for efficient pumping
- main chamber $p_o \approx 10^{-4}$ mbar
- **strong up/down asymmetry, inverts with B-field reversal**

**➡ drift effects**

P. Grigull, et al., Fusion Eng. Des. **66-68** (2003) 49

# W7-X Results

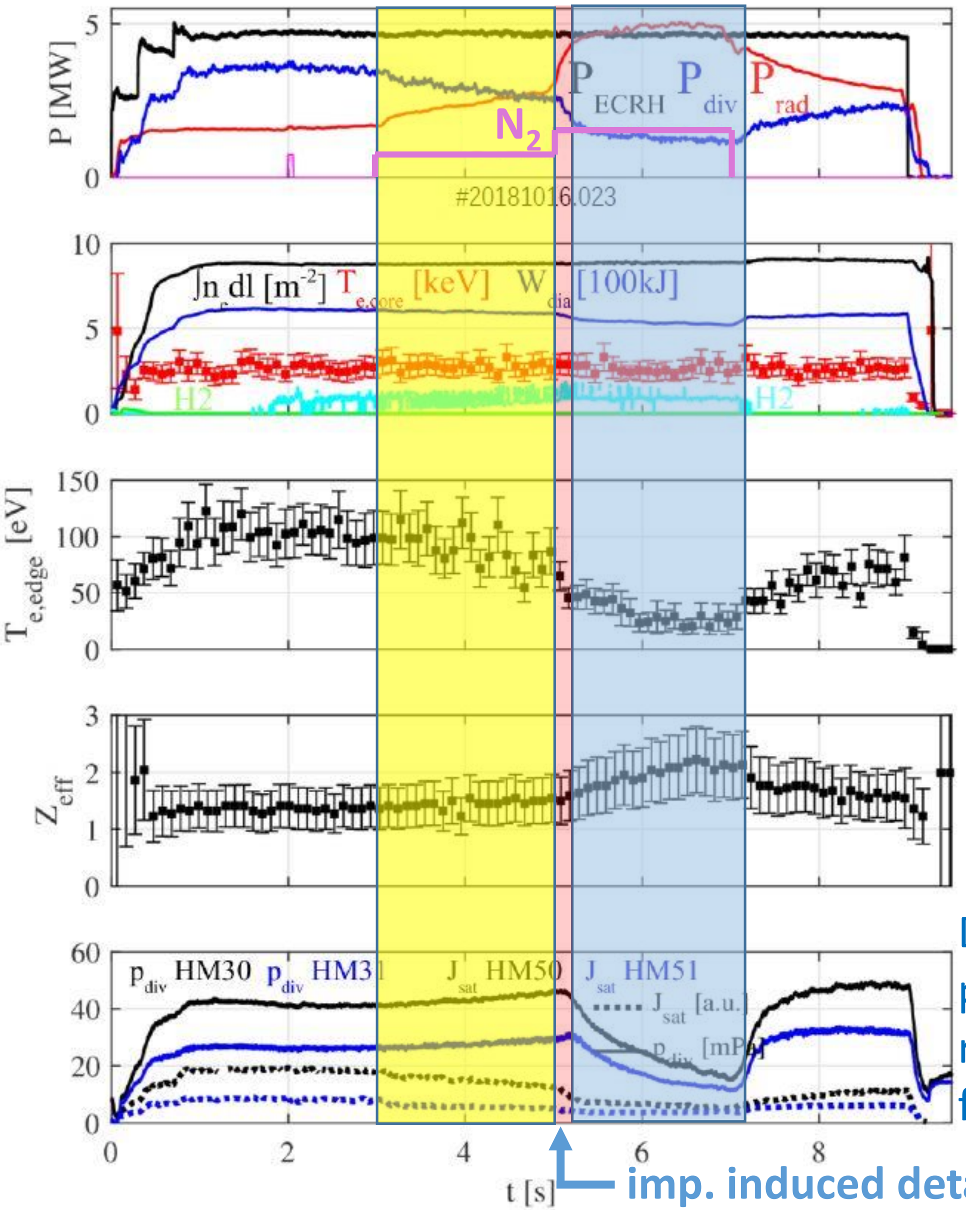
I am sorry that the still unpublished material on W7-X had to be removed from the slides collection

# Impurity seeding assisted radiative mantle induced detachment

WENDELSTEIN 7-X

# Continuous $N_2$ enhances effective recycling and homogenous power exhaust
# Short Neon injections allow for long sustained radiative power exhaust

IPP




Continuous $N_2$ seeding at two levels

Short Ne puffs at two levels, stationary steps in power balance (O~10s)

**"Radiating belt"**

$\Delta W_{dia}$ = -12% at max $P_{rad}$

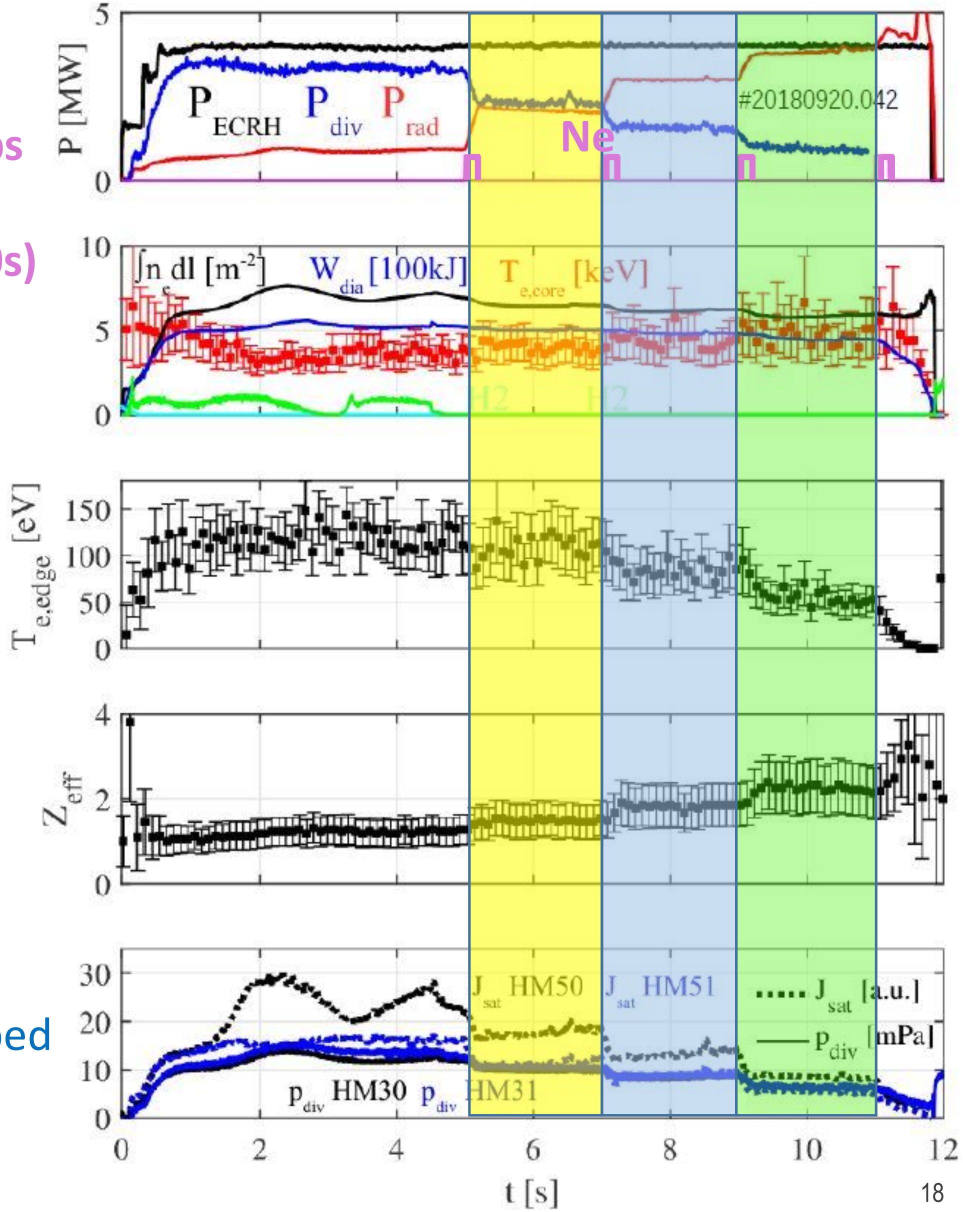
$\Delta W_{dia}$ = -15% at $f_{rad}$ ~ 0.9

$Z_{eff}$=1.2-2.1

$Z_{eff}$=1.2-2.2

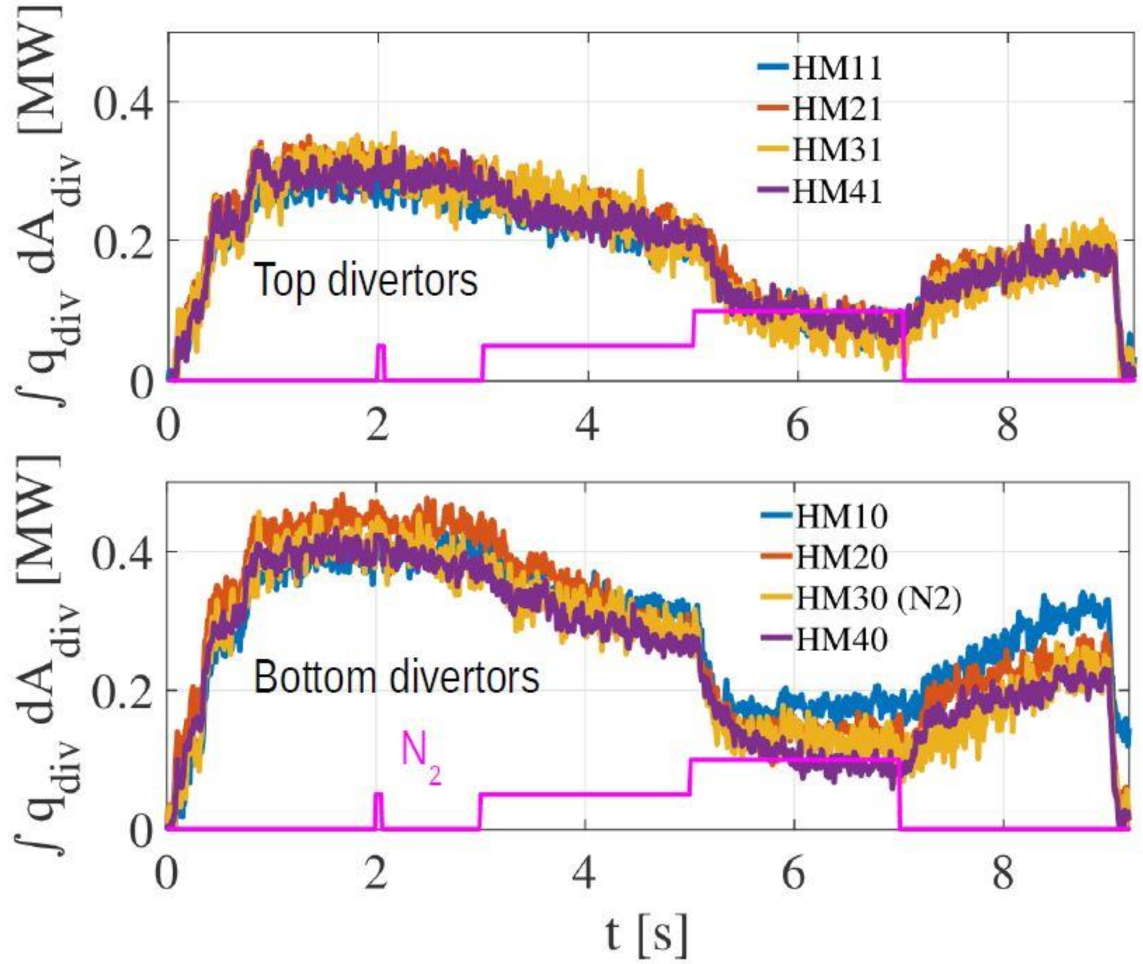
Divertor pressure first rises then drops for $f_{rad}$<90%

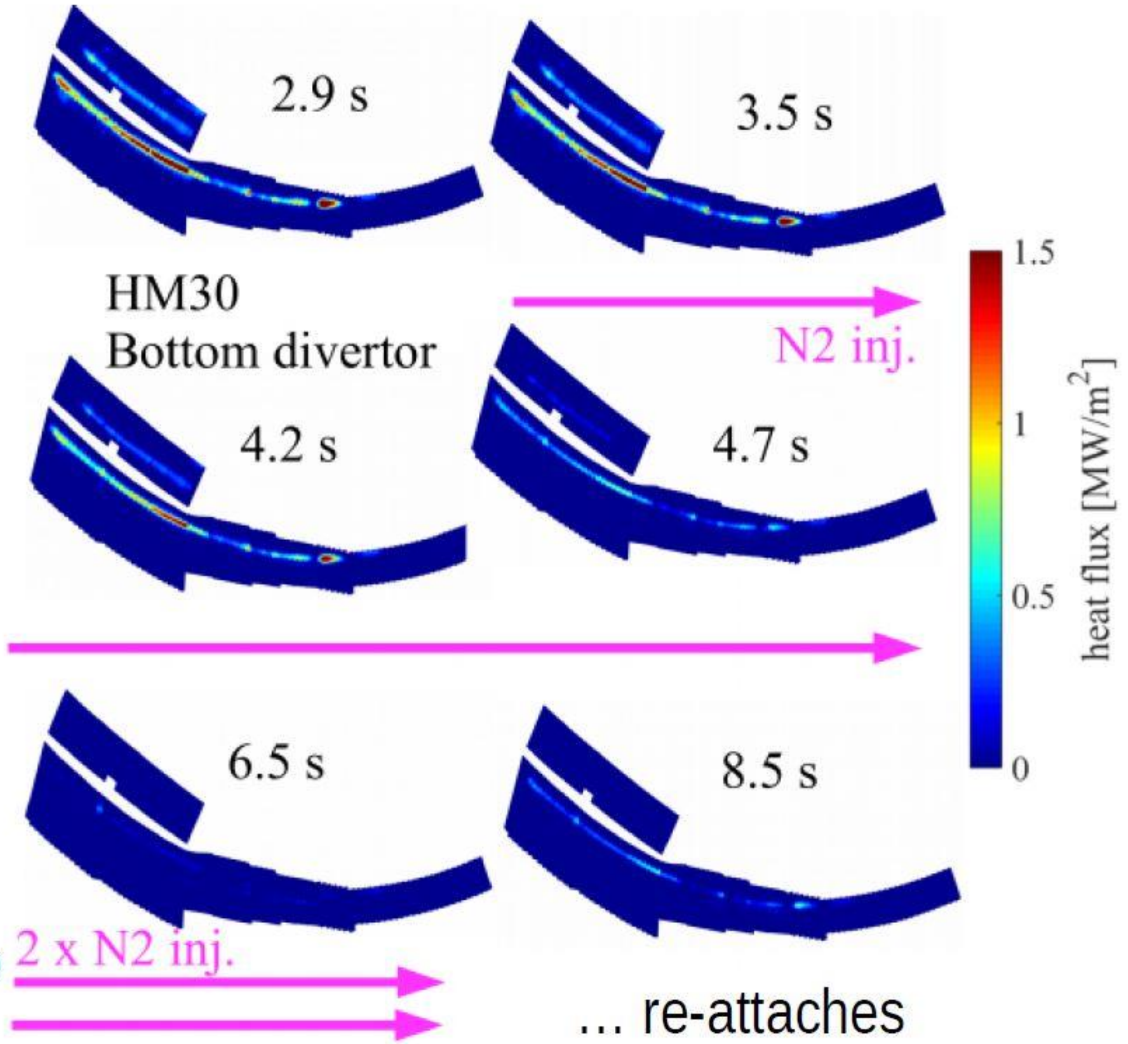
Divertor pressure dropped step by step




imp. induced detachment transition

# Good control over detachment with N seeding: Detachment onset and re-attachment




→ symmetric cooling, absolute offsets due to drift and heating

… re-attaches in post-seeding phase

# Is the Island Divertor Reactor Compatible?

# W7-R

**W7-R ≙ W7-X linearly up-scaled by factor 4**

*see: C.D. Beidler et al., Nucl. Fusion 41 (2001) 1759* **HSR5/22**

R = 4 x 5.4 m = 22 m

a = 4 x 0.5 m = 2 m

radial island size: $r_r \sim \sqrt{R}$ increases by factor 2

polidal island size $r_p \sim a$ increases by factor 4

Poloidal island size even more largely exceeds characteristic perpendicular transport scales

➔ no cross field momentum interaction between adjacent island fans

➔ high recycling

Edge iota = 5/5 = 1, high mirror magnetic config. (optimised for minimal bootstrap current)

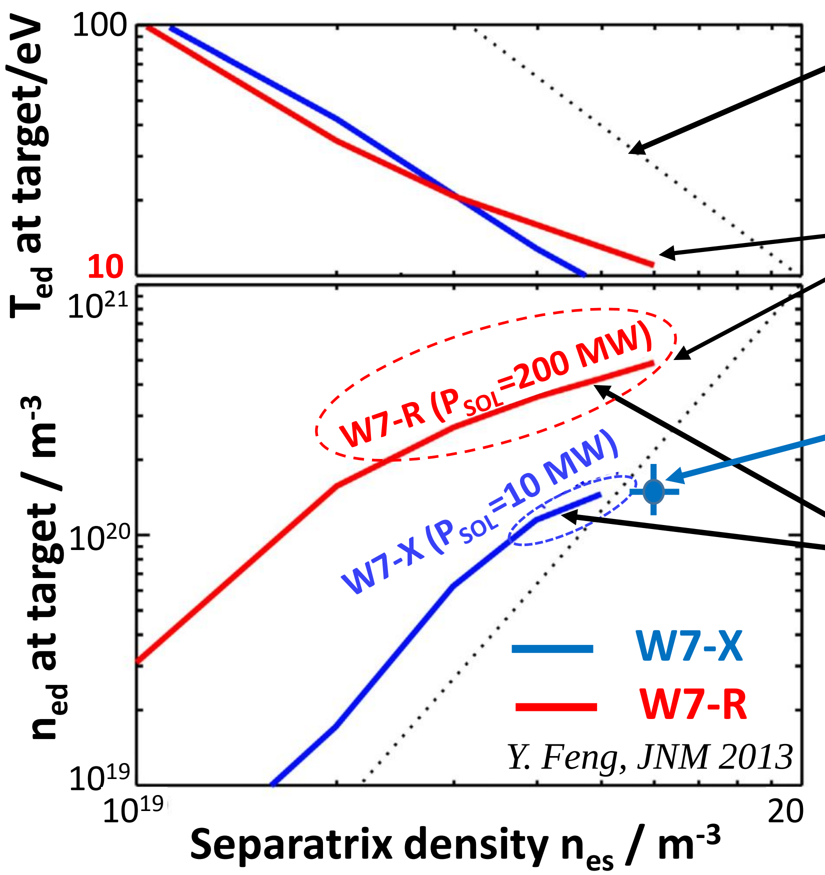
W7-X exp.: high density detached plasmas ➔ very small bootstrap currents ~ -1 kA obs.

# W7-X ➔ W7-R (4x W7-X): Up-/Downstream Plasma Parameter Scaling with Machine Size

Wendelstein 7-X | IPP

**EMC3/EIRENE**

High mirror config.,
$\iota_a$ = n/m = 5/5 = 1
$P_{SOL}$ = 200 MW
D = 0.5 $m^2/s$
$\chi_{e,i}$ = 3D
No impurity radiation
$L_c$ = 4 x $L_c$(W7-X)
$P_{SOL} \sim A_{LCFS}$




tokamak high recycling conditions

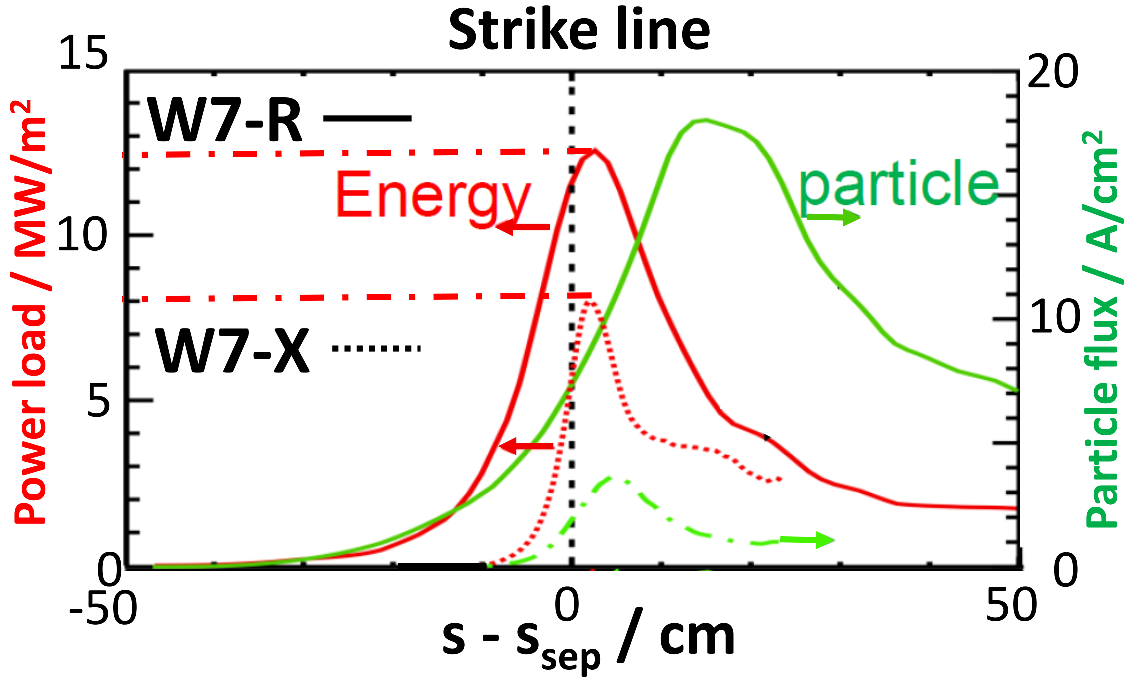
Higher $n_{ed}$ required in W7-R to reach $T_d$ = 10 eV

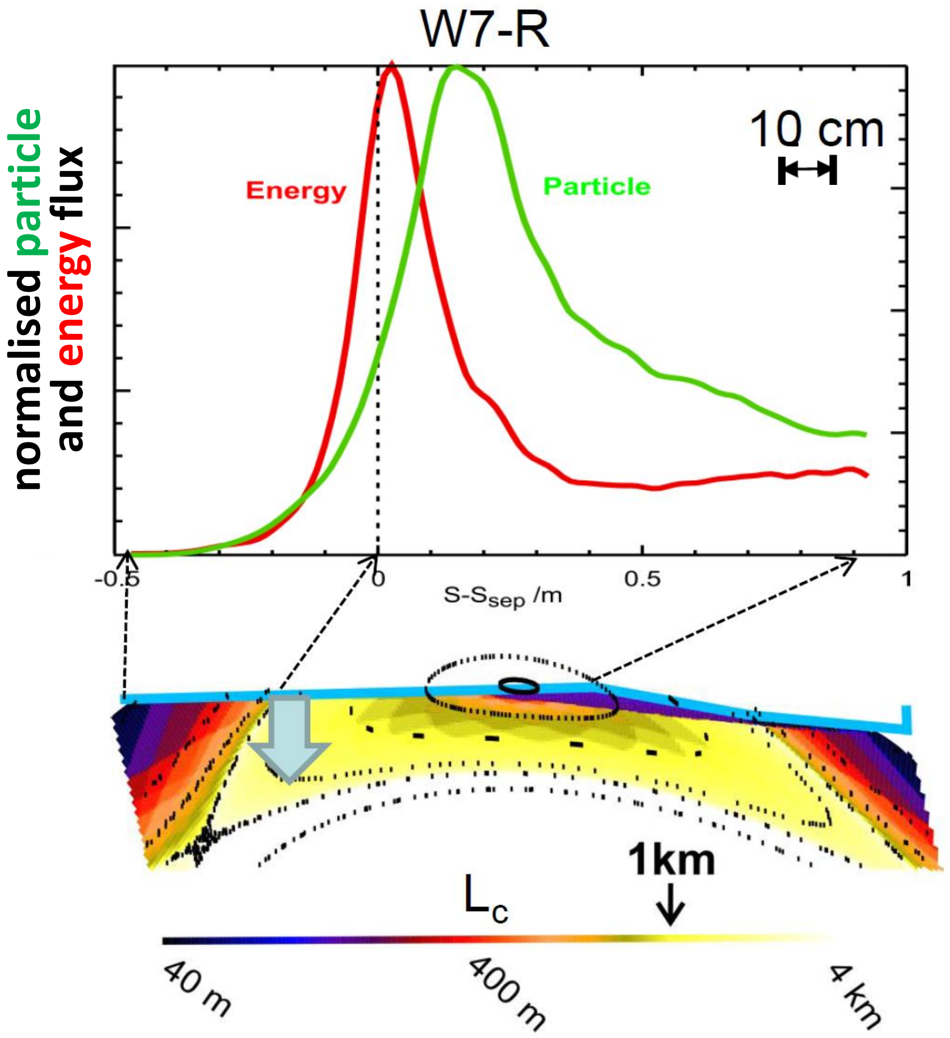
#20181016.009 (6 MW ECRH in O2-mode)

flattening with $n_{es}$ ↑ due to increasing ⊥ transport

- Higher downstream density $n_{ed}$ in reactor required to reach $T_d$ = 10 eV because
  a) $L_c$ increases with machine size
  b) $P_{SOL}$ increases with surface area

# Spreading of the power and particle deposition profiles




Total toroidal strike line length due to discontinuous target only ≈0.1 x ($2\pi R^2 N_x$) - very similar to tokamak

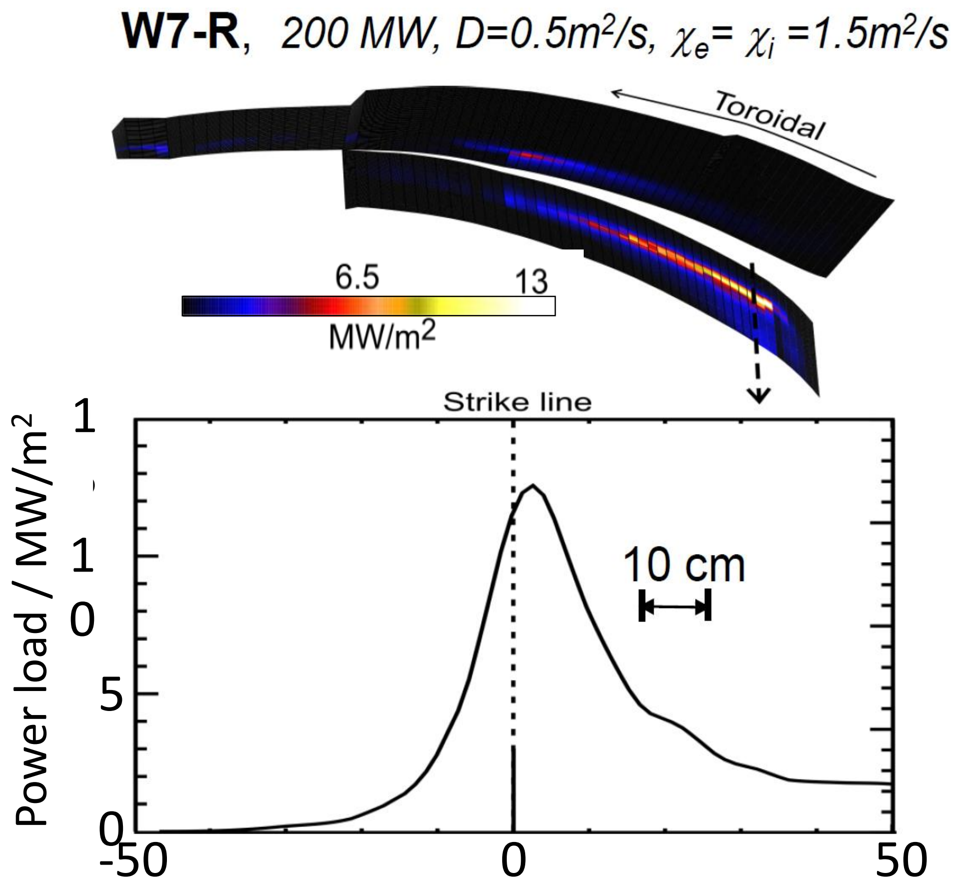
**but**

$L_c$ ~ 10x longer (≳ 1 km) ➔ broadening of power & particle deposition profile

*Profiles broader than $L_c^{1/2}$-scaled W7-X widths due to the higher $n_{ed}$ in W7-R*

Y. Feng, EFPW, 2012, JNM 2013

# Radiation Fractions Required for Stellarator Reactors: W7-R ➔ HSR5/22




**Divertor power load up-scaling from W7-X to W7-R[+] to HSR5/22***

EMC3 is used for up-scaling geometry and transport

**W7-X** EMC3-model: $P_{SOL}$ = 10 MW ➔ peak load 8 MW/m²

$P_{SOL}$ = 5 MW ➔ peak load 4 MW/m²

**W7-X experiment:** attached: 3.5 MW/m²

detached: 0.4 MW/m²

**factor 9 peak power load reduction!**

**W7-R** EMC3-model: $P_{SOL}$ = 200 MW ➔ peak load 12 MW/m²

**HSR5/22:** $P_{SOL}$ = 600 MW ➔ peak load 36 MW/m²

**3 GW fusion power** (up-scaled from W7-R)

Assume $f_{rad}$=0.86: ➔ peak load 5 MW/ m²

$f_{rad}$=0.93: ➔ factor 2 safety margin (2.5 MW/m²)

**W7-X modelling & experimental experience:**
86% radiation still gives maximum sub-divertor pressure while 93% radiation may result in a 30-40% drop in neutral pressure and thus pumping efficiency

**C.D. Beidler, NF 2001 [+]Y. Feng, JNM 2013*

# Outlook from present modelling & experimental experience

86% radiation still gives maximum sub-divertor pressure while
93% radiation may result in a 30-40% drop in neutral pressure and thus pumping efficiency

N-seeding experiments showed easy detachment and feedback control – similar, well controllable behaviour to carbon, seems adequate replacement for C an all W device, $Z_{eff}$ ~ 2

Ne-seeding experiments showed significant radiation fractions from confined plasma region with long residence times as expected. $Z_{eff}$ still low ~2.2

Experiments before boronisation (high oxygen conc.) gave no access to high recycling but still complete stable (4 s) detachment via high edge radiation was achieved ($Z_{eff}$= 3.5-4.5)

➔ Present indications hint in the direction, that W7-stellarator reactor plasmas may allow stable detached plasma operation just with radiation from the SOL, but would also allow stable detached plasma operation with some radiation fraction from the edge of the confined plasma edge, if needed.

# Summary

- **Island divertor operation dominated by perpendicular transport**
- **W7-AS**
  - stable partial detachment
  - Small operation window
  - Friction between counter-streaming flows prevent access to high recycling regime at bottom divertor
  - Strong drift effects induce high density (8 E20 m-3), high recycling, recombining divertor plasma at top divertor with high sub-divertor neutral pressure of 0.3 Pa
- **W7-X**
  - Complete stable detachment (5 MW, 26 s) with access to higher recycling regime and pumping as much as is being fuelled
  - Drift effects play no role during detached plasma operation
  - Homogeneous peak power load reduction across all 10 divertors during detachment
  - Optimisation potential with respect to island size and Lc as well as radiation fraction to find best compromise between peak power load reduction and exhaust
  - Stable detachment with controlled $N_2$ and Ne seeding
- **W7-R / HSR5/22**
  - Crude up-scaling to a reactor scale device suggests manageable peak target heat loads with likely access to good particle exhaust with complete stable detached plasmas

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The views and opinions expressed herein do not necessarily reflect those of the European Commission.