First time realization of a detached, stable, efficient particle and heat exhaust regime in the island divertor of Wendelstein 7-X

Oliver Schmitz[1], Y. Feng[2], M. Jakubowski[2], R. Koenig[2], M. Krychowiak[2], M. Otte[2], F. Reimold[2], G. Anda[3], T. Barbui[1], C. Biedermann[2], S. Bozhenkov[2], S. Brezinsek[4], B. Buttenschoen[2], K.J. Brunner[2], P. Drewelow[2], F. Effenberg[1], D. A. Ennis[5], T. Estrada[4], E. Flom[1], H. Frerichs[1], O. Ford[2], G. Fuchert[2], Y. Gao[4], D. Gradic[2], O. Grulke[2], K. C. Hammond[2], U. Hergenhahn[2], U. Höfel[2], J. Knauer[2], P. Kornejew[2], G. Kocsis[3], T. Kremeyer[1], S. Kwak[2], H. Niemann[2], E. Pasch[2], A. Pavone[2], V. Perseo[2], L. Rudischhauser[2], G. Schlisio[2], T. Sunn Pedersen[2], J. Svensson[2], T. Szepesi[3], U. Wenzel[2], V. Winters[1], G.A. Wurden[6], D. Zhang[2], S. Zoletnik[3] and the W7-X experiment team

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Acknowledgement: This work was funded in part by the U.S. Department of Energy under grant DE-SC00014210 and DE-SC00013911 and has been carried out within the framework of the EUROfusion Consortium with funding from the Euratom research and training program 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Princeton Plasma Physics Laboratory
FES seminar
December 10, 2019

EUROfusion

Wendelstein 7-X IPP

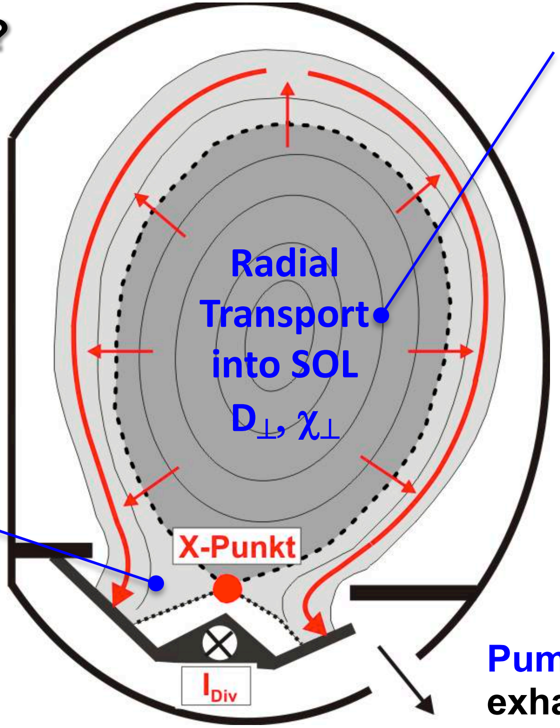
College of Engineering
UNIVERSITY OF WISCONSIN–MADISON

Heat flux detachment and a low level of eroding particle fluxes need to be combined with sufficient particle exhaust in a successful divertor concept

- **What's a divertor supposed to do?**

Divertor plasma defines plasma wall interface

- Heat and particle flux handling within technical limits
- Power dissipation
- Neutral compression
- Impurity retention



Plasma core performance is to be maximized

- Stable density control
- Low impurity influx (Z_{eff})
- Helium exhaust ($\tau_{p,He}^*/\tau_E$)

Pumping system: stable particle exhaust needs sufficient p_n

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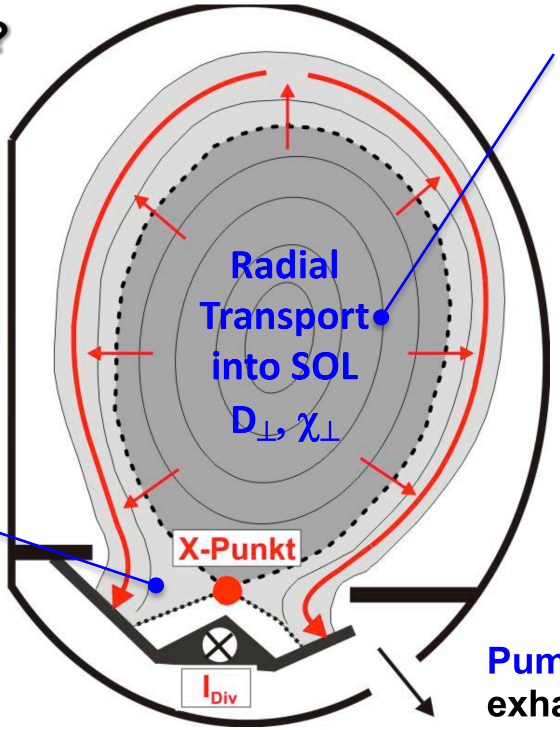

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- Helium exhaust ($\tau_{p,He}^*/\tau_E$)

Upstream
where particle and heat flux *come from* (separatrix region)

Pumping system: stable particle exhaust needs sufficient p_n

Downstream
where particle and heat flux *go to* (divertor targets)

Wendelstein 7-X IPP

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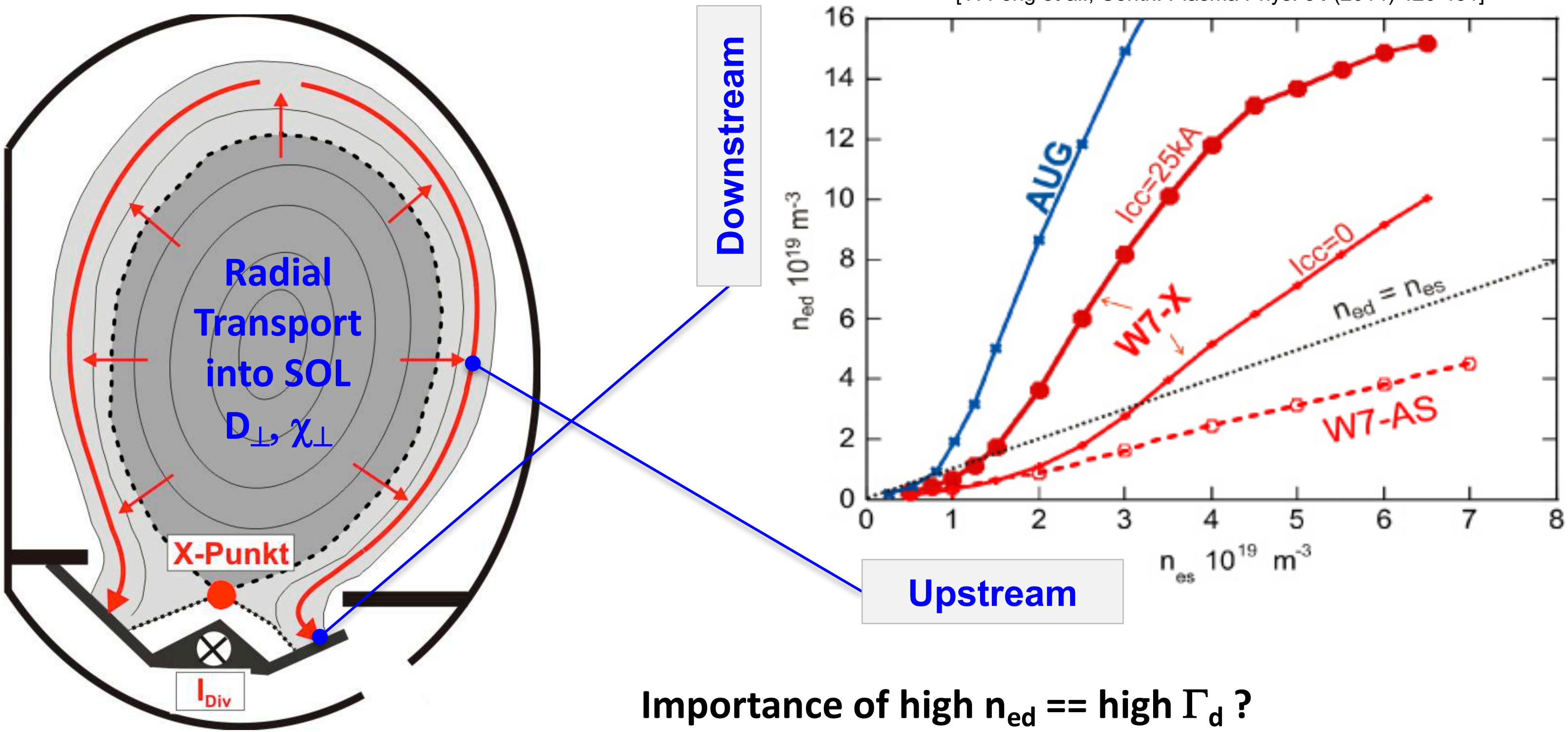
[Y. Feng et al., Contri. Plasma Phys. **54** (2014) 426-431]



Importance of high n_{ed} == high Γ_d ?

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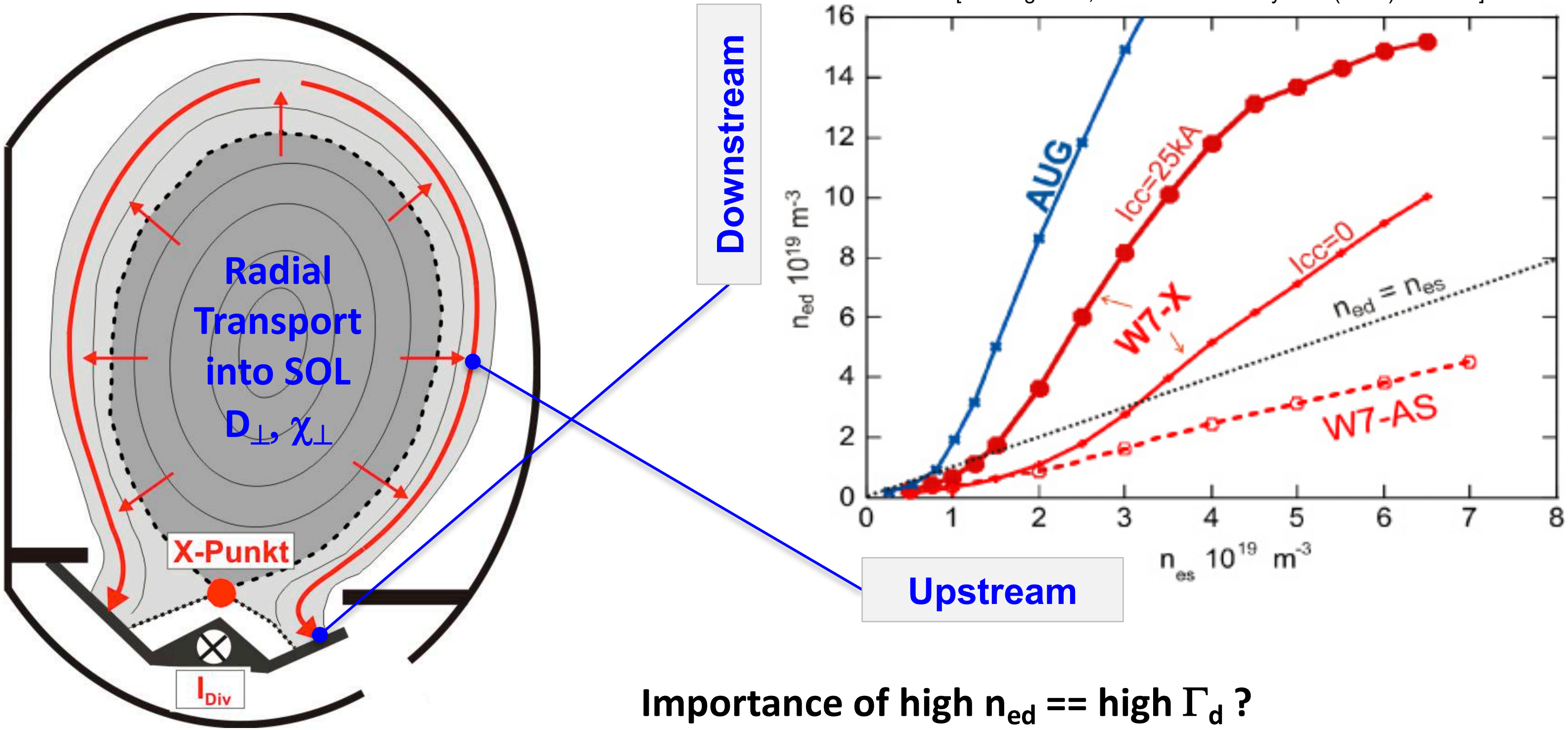


Importance of high n_{ed} == high Γ_d ?

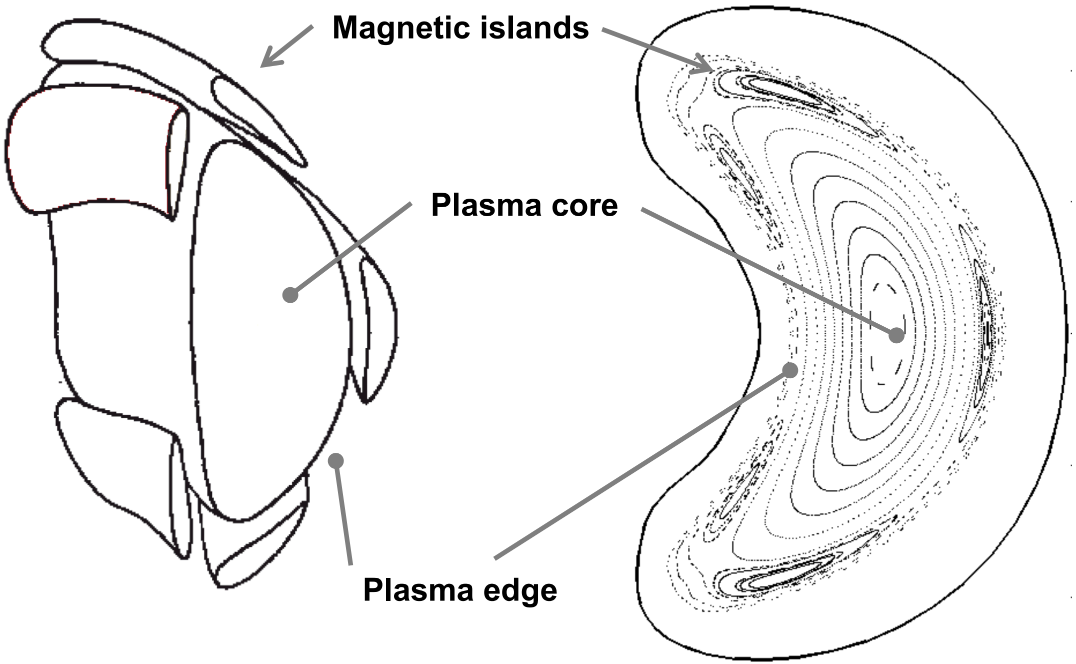
Ionization energy loss

Energy loss by impurity radiation

Rapid ionization

The island divertor at Wendelstein 7-X is a promising helical resonant divertor[1] concept for stellarators

- A low order resonance placed in the plasma edge defines the divertor structure



[X. Bonin et al., Nuclear Fusion **45** (2005) 22-29]

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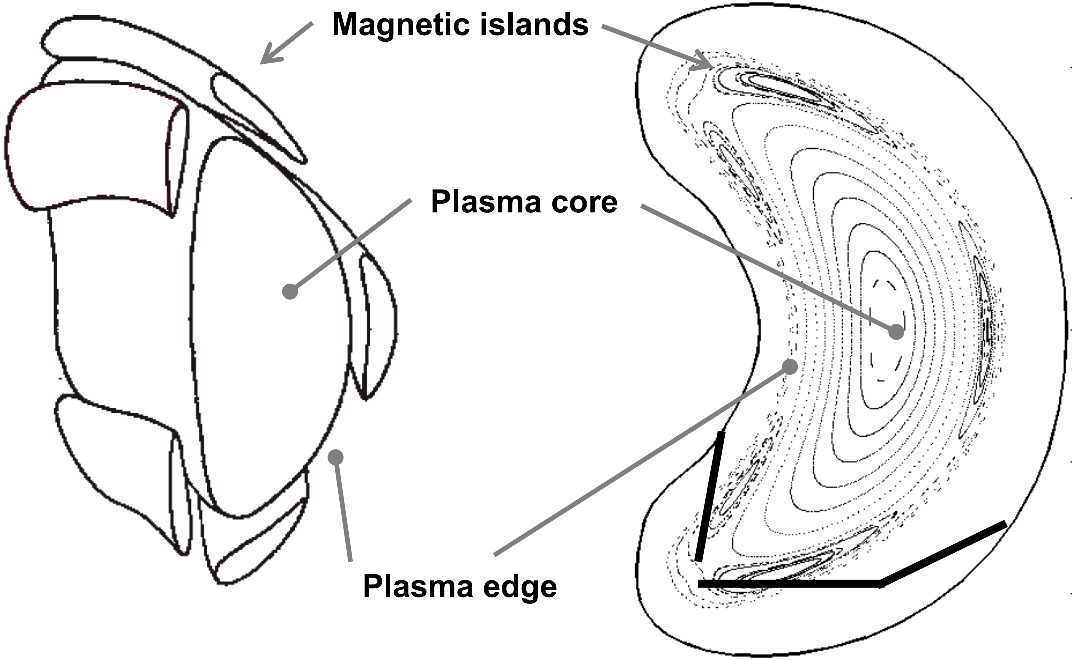

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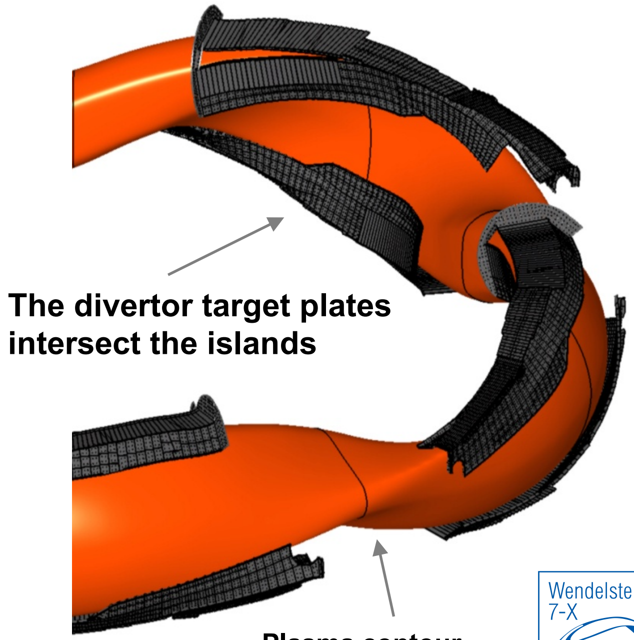
The Island Divertor is a modular divertor



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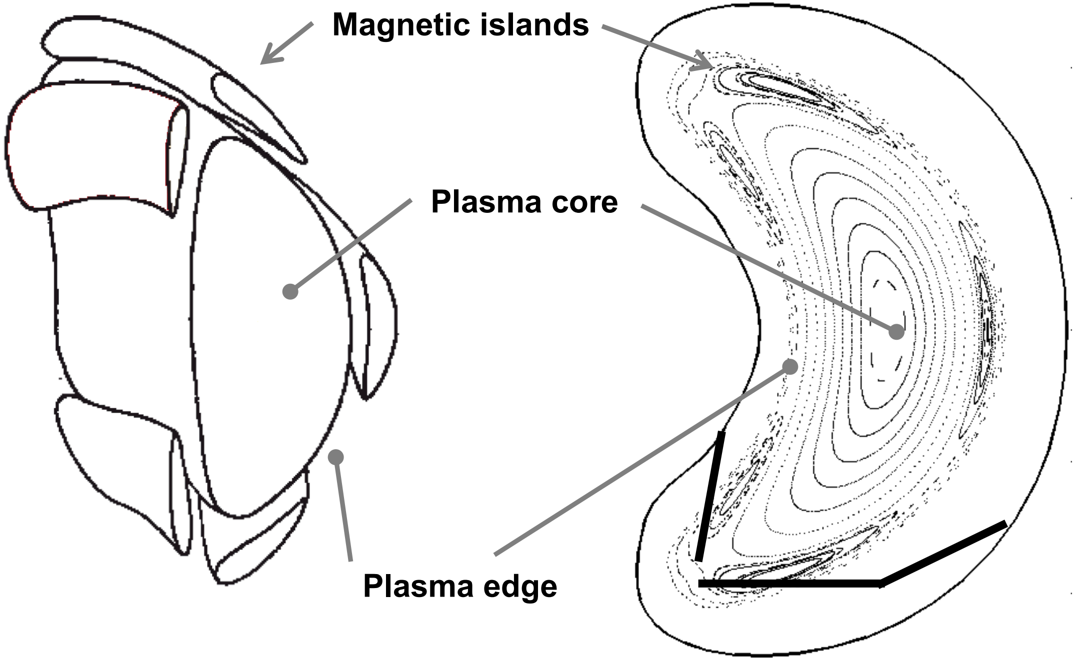

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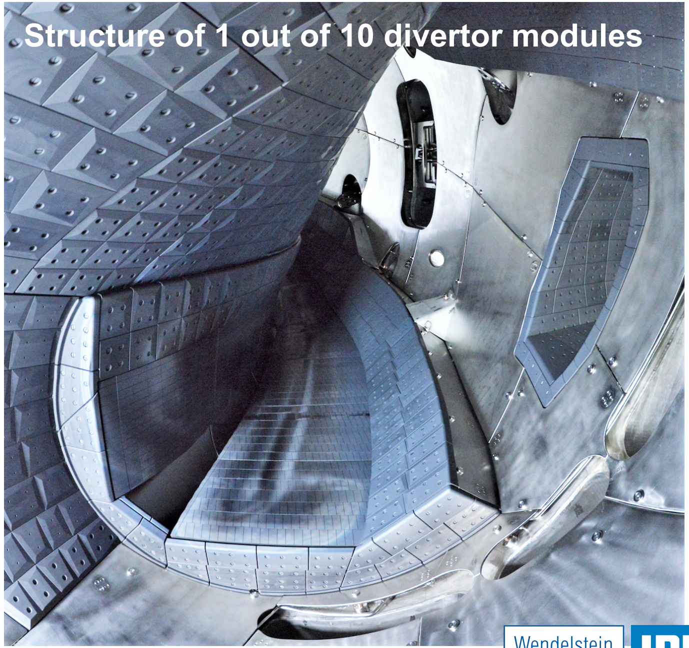

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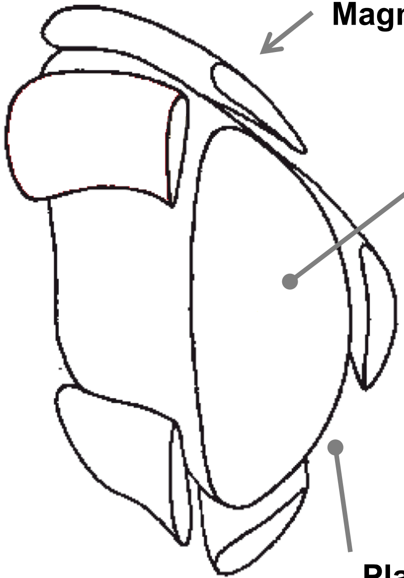

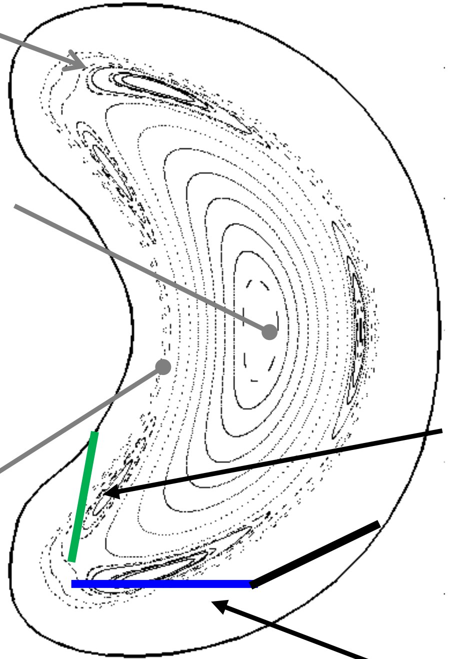

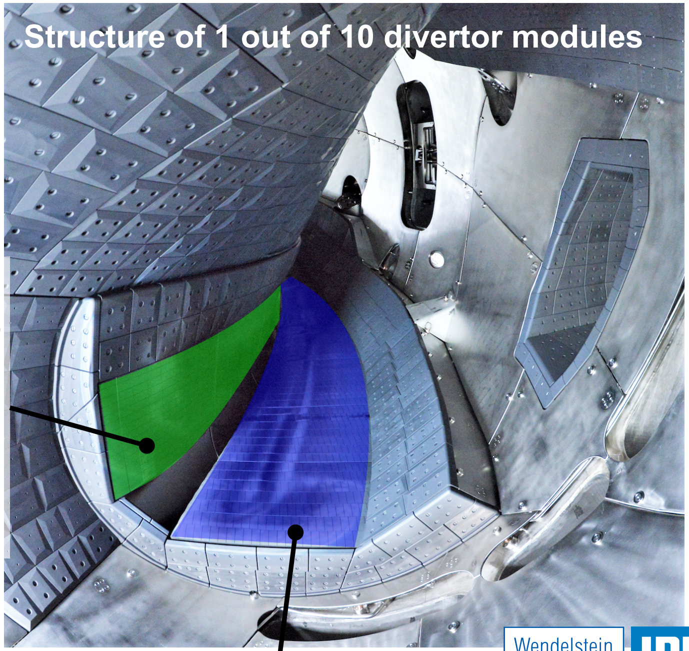

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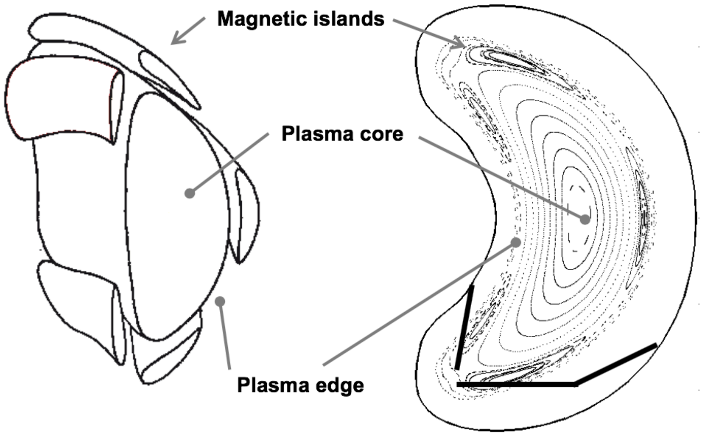

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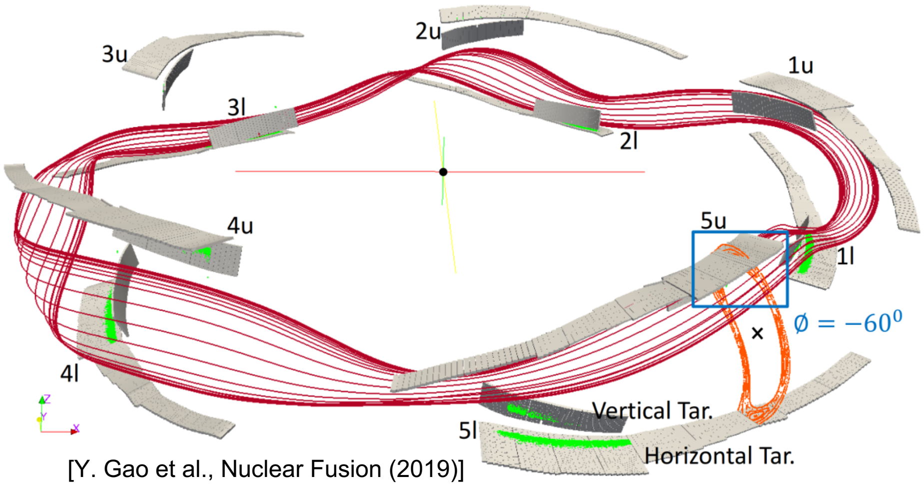

[Y. Gao et al., Nuclear Fusion (2019)]

Standard divertor configuration (SDC): pairs of modules 180 degree apart toroidally are connected by magnetic flux tubes

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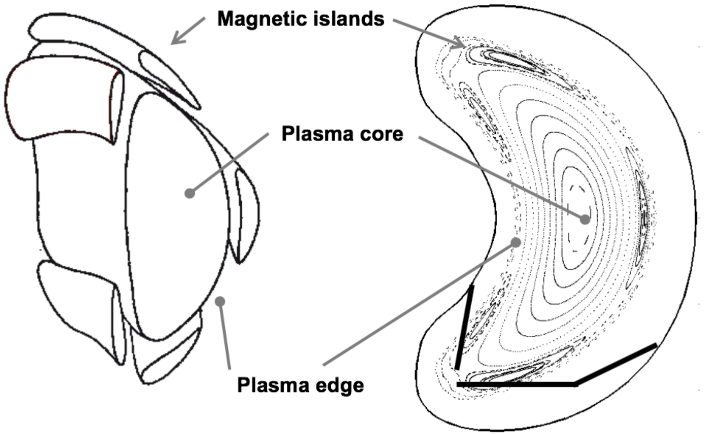

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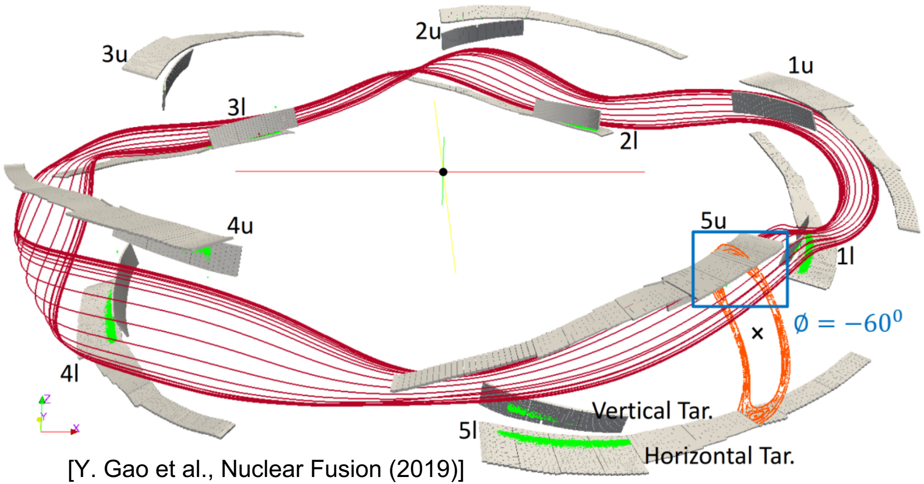

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This divertor concept was tested at W7-AS and now needs to be qualified as a viable stellarator system component for steady state plasma operation.

Wendelstein 7-X
IPP

Outline of this talk in form of an executive summary

- A **stable, thermally fully detached island divertor regime** with **small divertor particle fluxes** but still **sufficient divertor neutral pressures** was shown for the first time.

- This detached island divertor regime is **reached with minimal feedback control in a reliable fashion** and **the divertor operational point is defined through sufficient radiative losses at a given input power.**

  The **geometry of the magnetic islands** forming the divertor allow to **fine tune the divertor neutral distribution** for **maximized neutral pressure** in the detached state.

- This island divertor regime is **compatible with steady state particle exhaust** for the upcoming high-performance campaign of W7-X.

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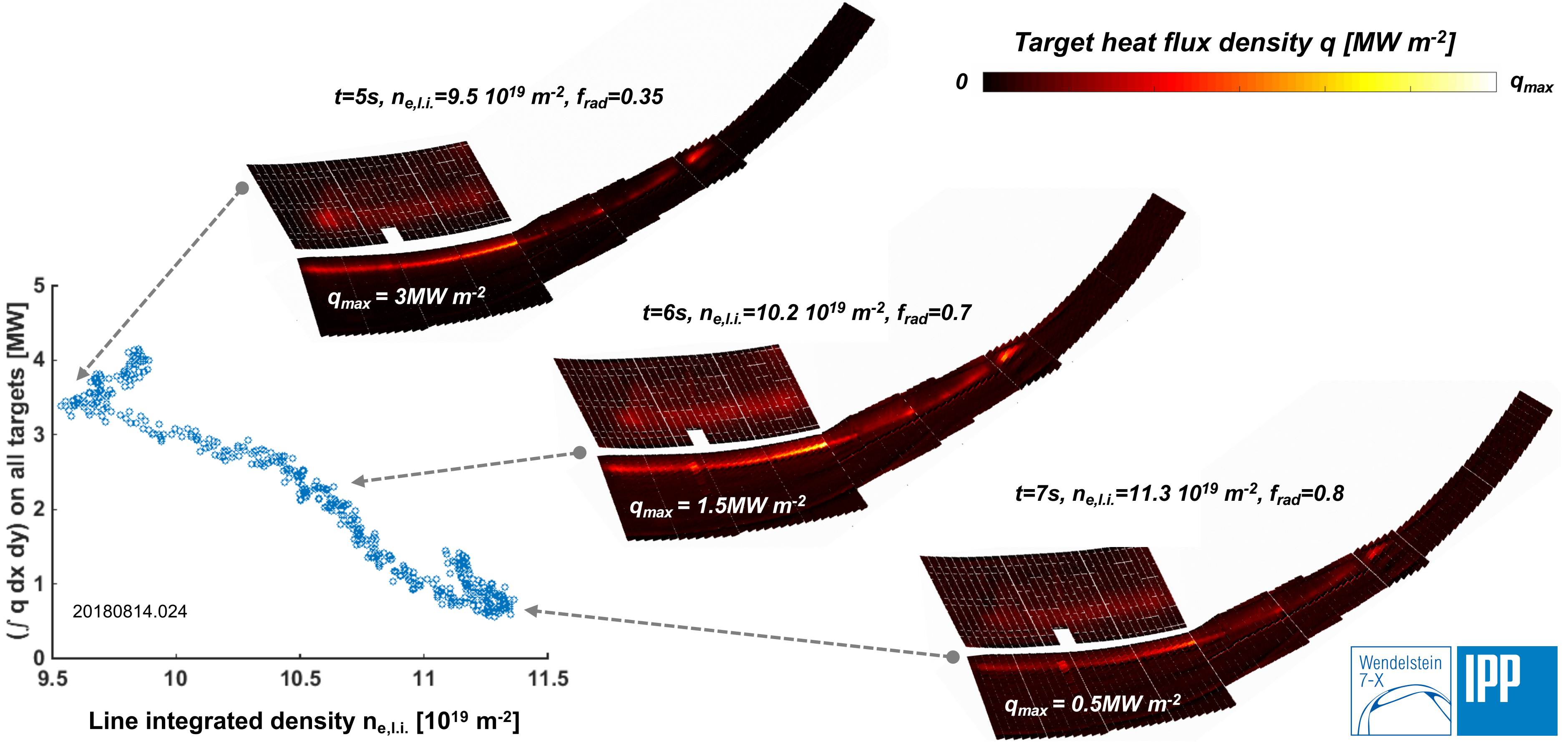
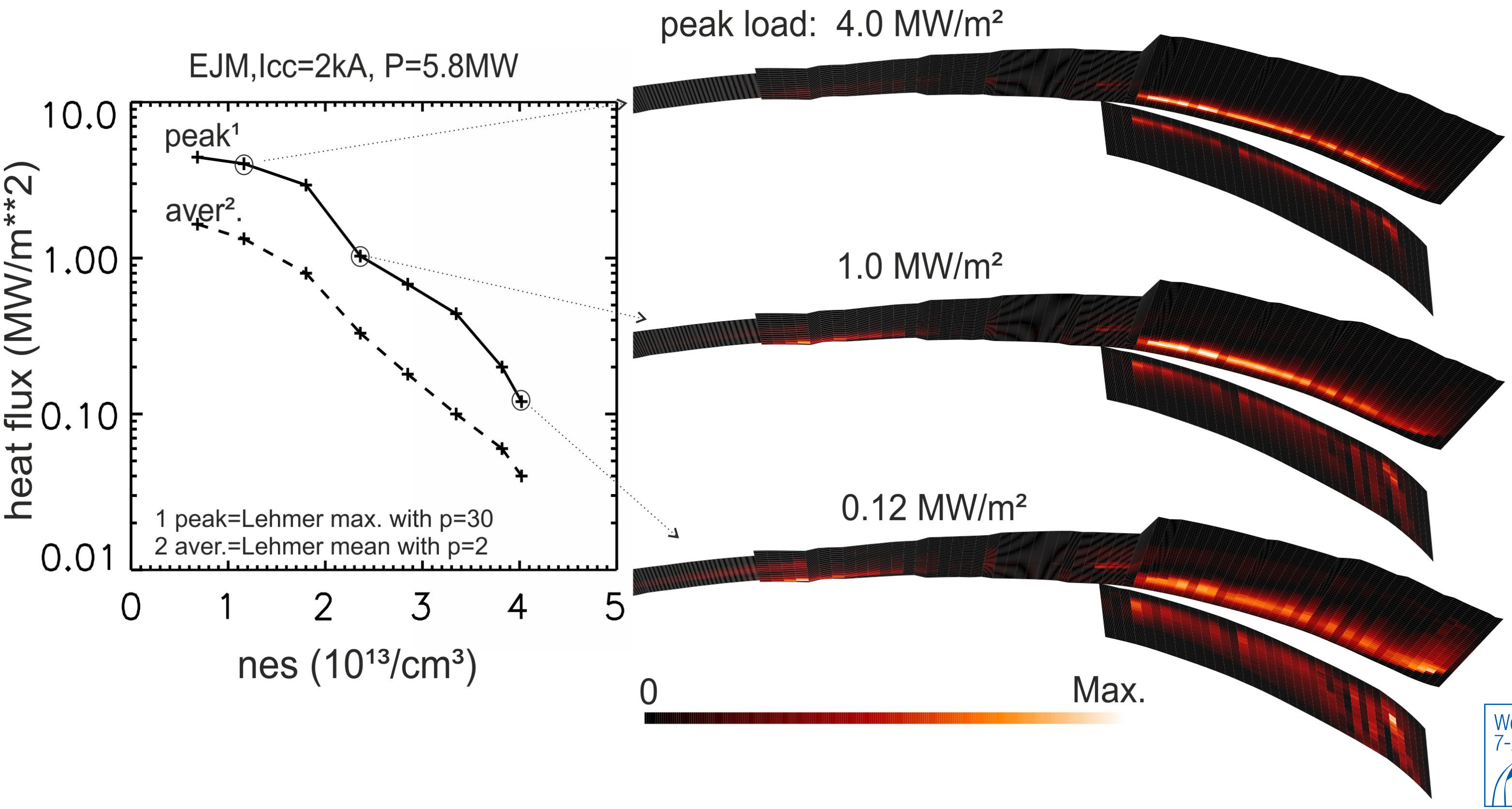
Full and homogeneous thermal detachment was obtained during a gradual density increase by just 20% - a reliable access scenario due to f_{rad} dependence

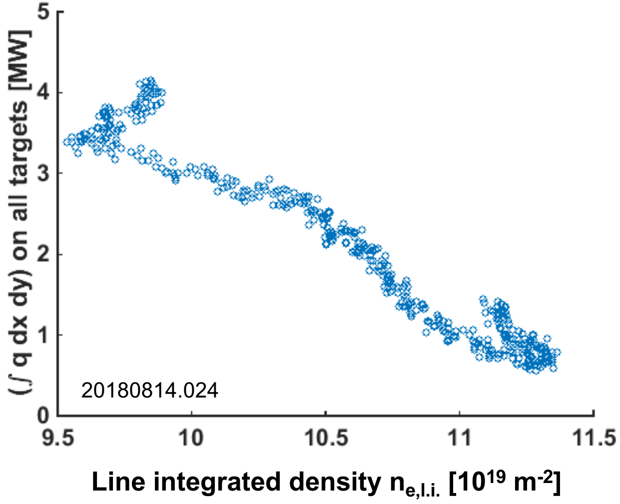


The homogeneous dissipation of the divertor power load during the density increase is reproduced in EMC3-EIRENE modeling



The heat flux reduction is driven by a density scaling of f_{rad} and a complete thermal detachment is combined with significant neutral pressures

Integral heat flux to targets vanishes with increasing density



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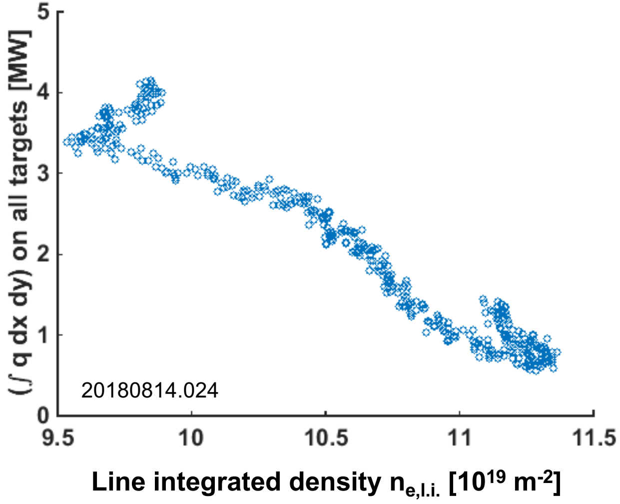
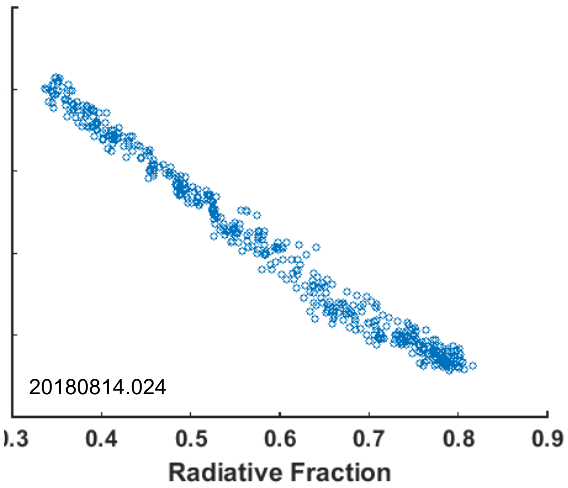


Radiative fraction drives heat flux dissipation into detached regime



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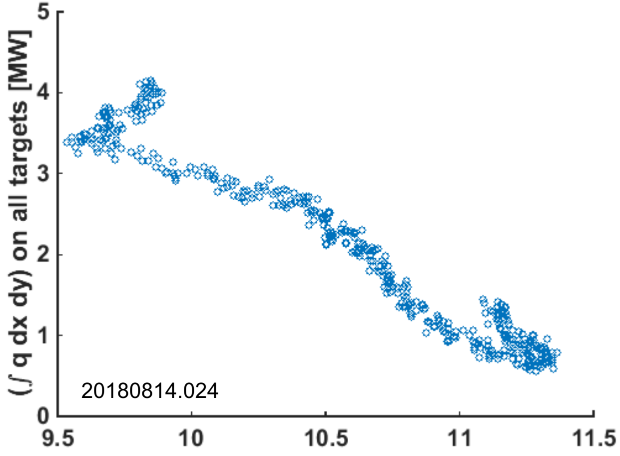

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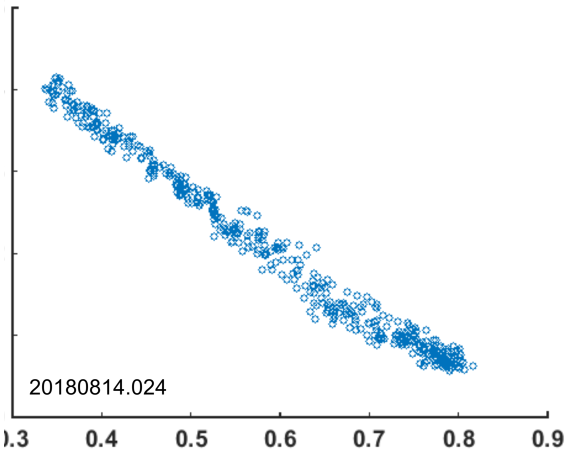
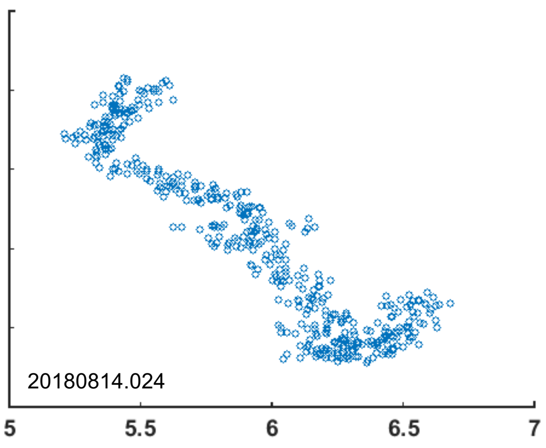
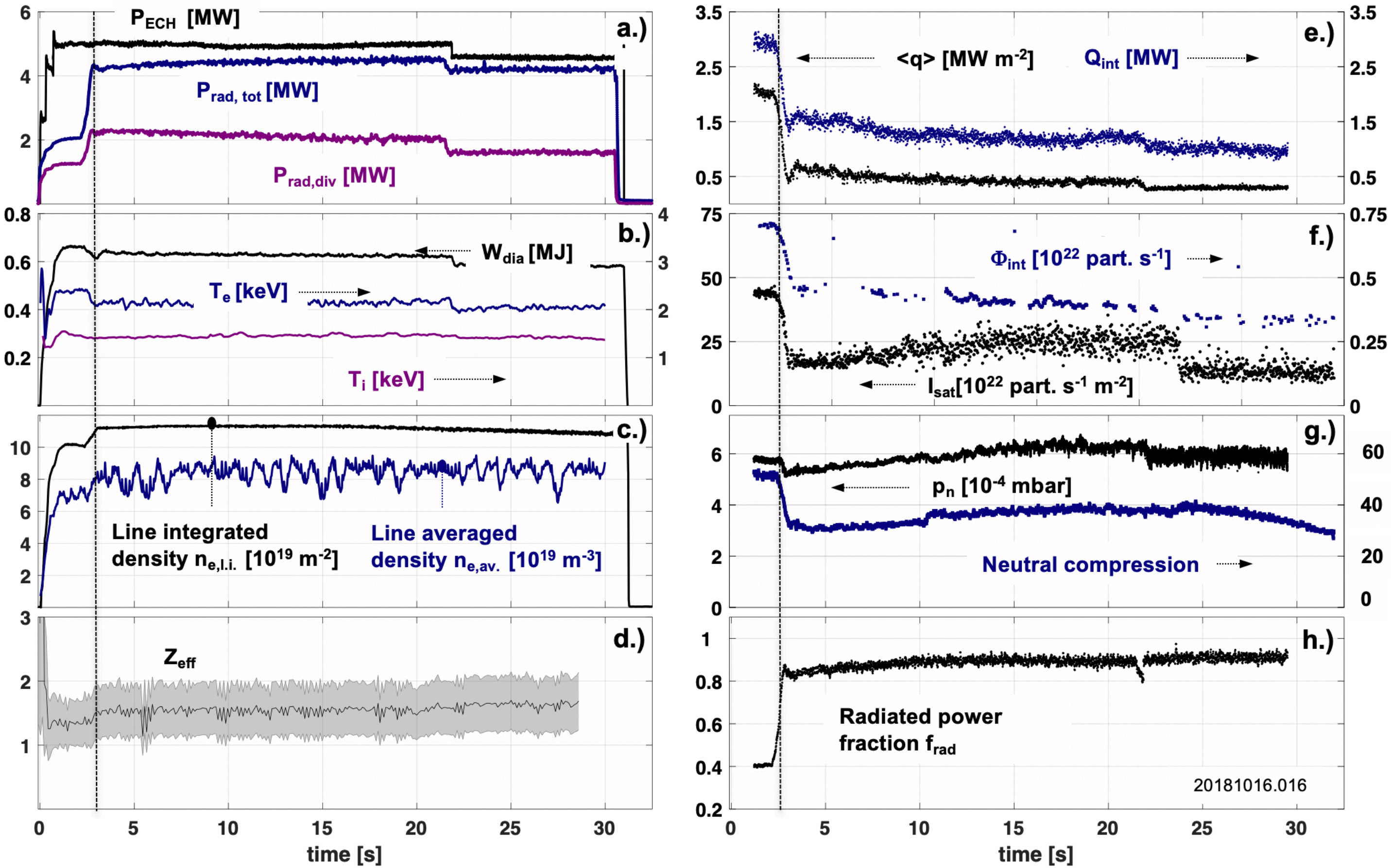


Small heat flux can be combined with significant neutral pressures



A regime of small integral heat flux (<0.5MW) and small peak (<0.2 MW m^{-2}) has been accomplished at up to 0.05-0.1 Pa (10^{-3} mbar) neutral pressure levels

This stable detachment was obtained with high divertor neutral pressures for up to 30s only limited by input energy limits in the uncooled divertor phase



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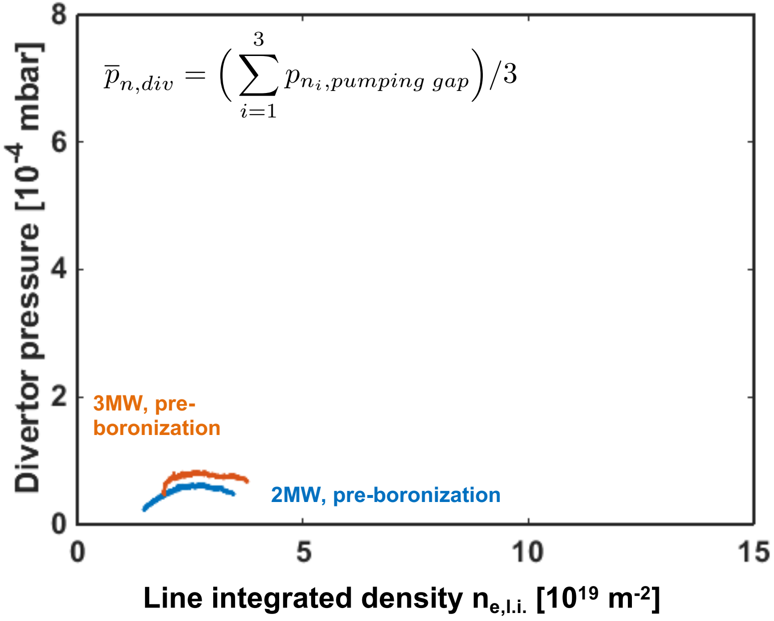
Wendelstein 7-X

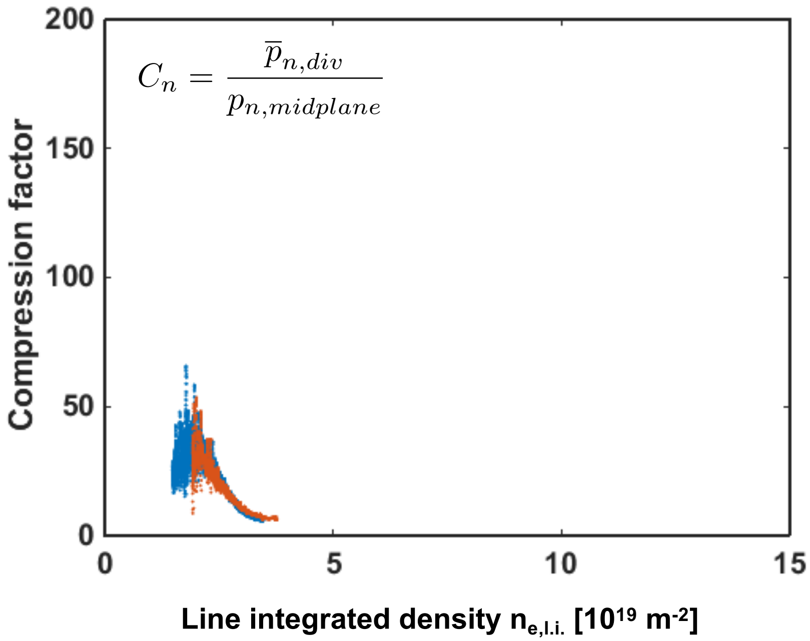
IPP

Moderate divertor neutral pressures within a quite limited density range was seen at W7-X without a boronization

Averaged neutral particle pressure at pumping gap



Neutral particle compression in divertor



Before boronization: oxygen and carbon were the dominant impurities

Boronization of W7-X yielded build up of substantial divertor neutral pressure at largely increased density limits

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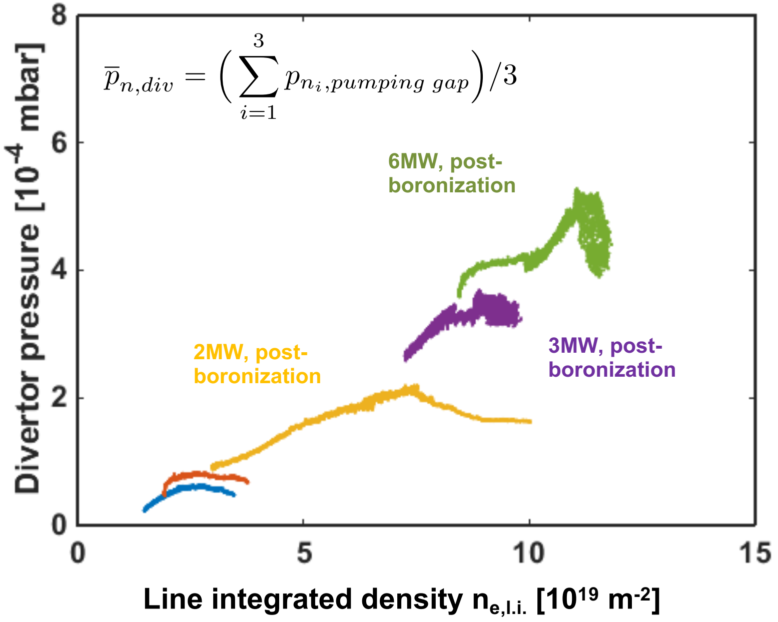

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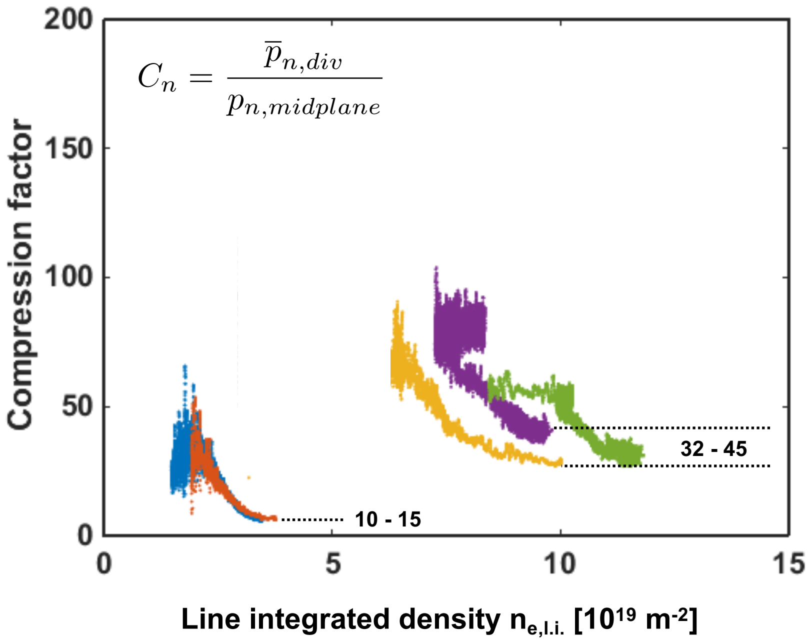
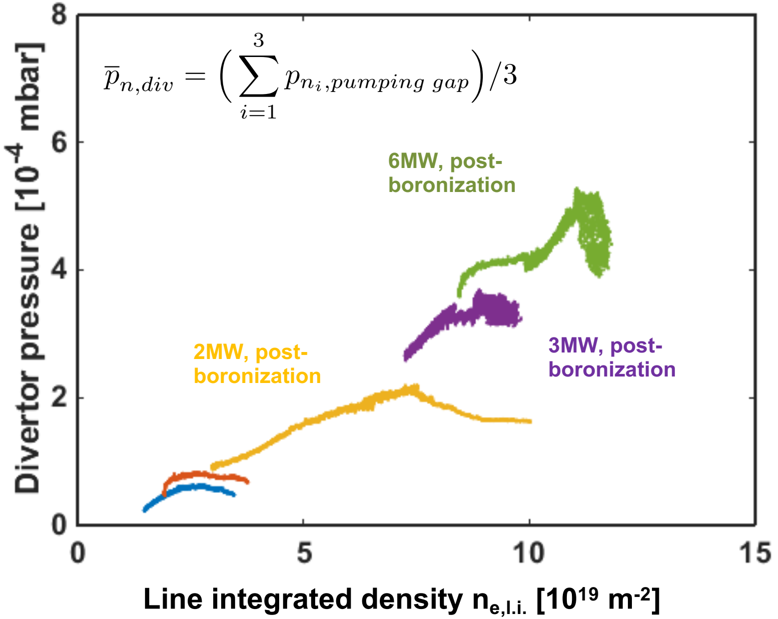


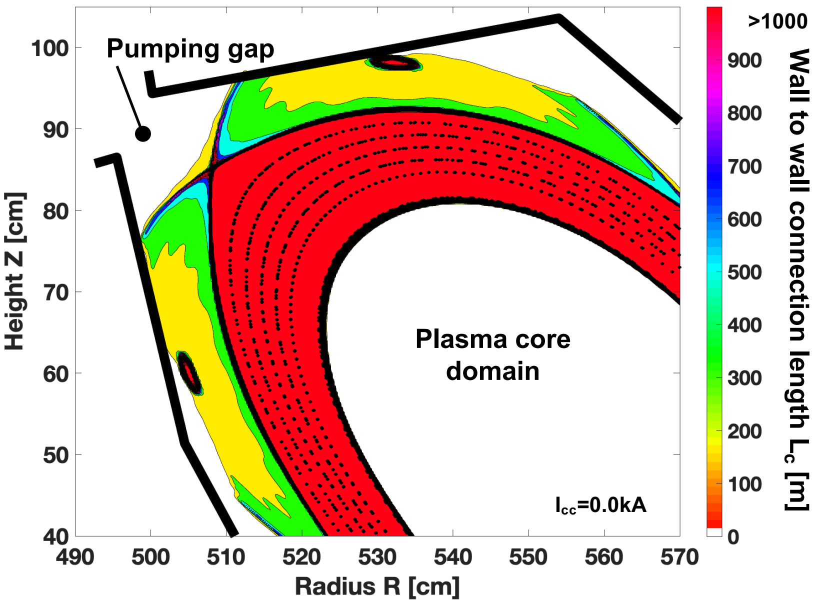
After boronization: oxygen content was reduced by up to a factor of 20

This attractive scenario could be fine tuned by adjustment of the structure of the magnetic island that form the divertor

Averaged neutral particle pressure at pumping gap

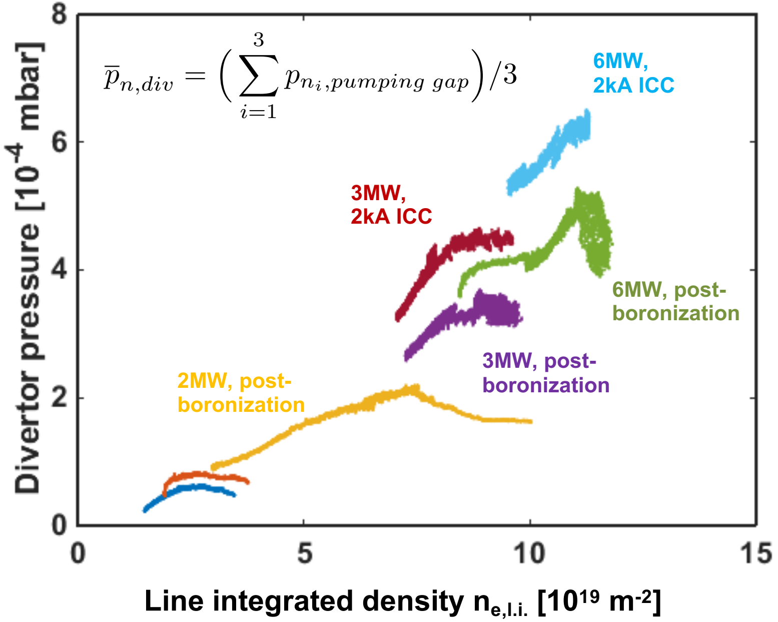


Structure of the magnetic island

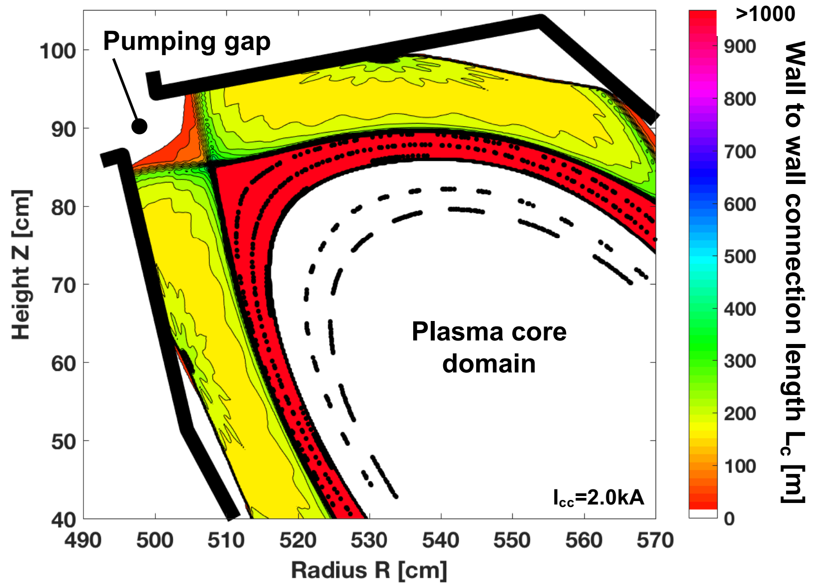


Applying a stationary divertor control current allows to increase the divertor neutral pressure by up to 50%

Averaged neutral particle pressure at pumping gap



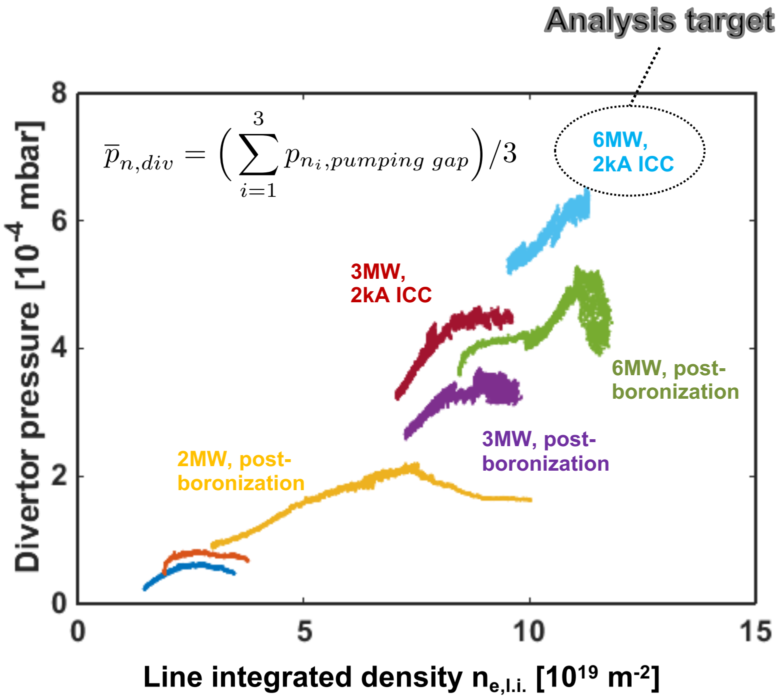
Change of island structure with divertor control coil current I_{cc}



- Island widening, closure of outer gap
- Strike point moves towards gap
- Connection length L_c reduced

Wendelstein 7-X
IPP

Increasing the divertor island size allows to increase the divertor neutral pressure by up to 50% compared to small island configuration



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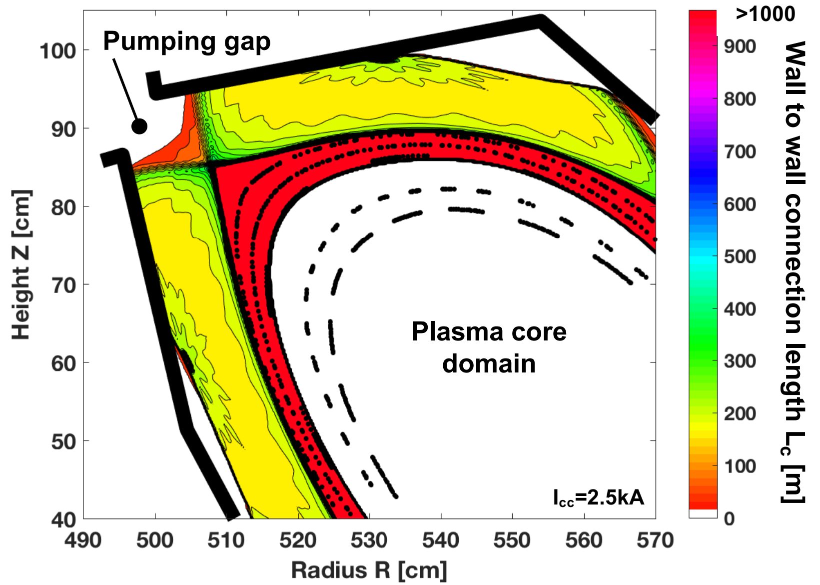

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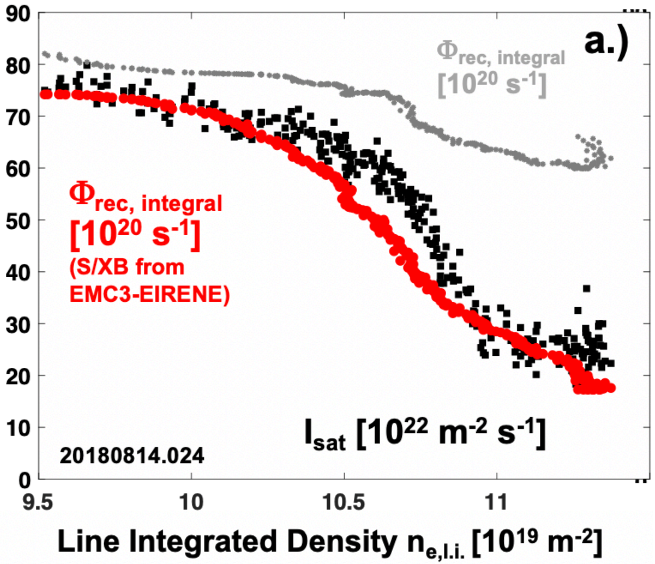
Particle flux detachment develops together with power detachment and pressure build up due to increasing radiation



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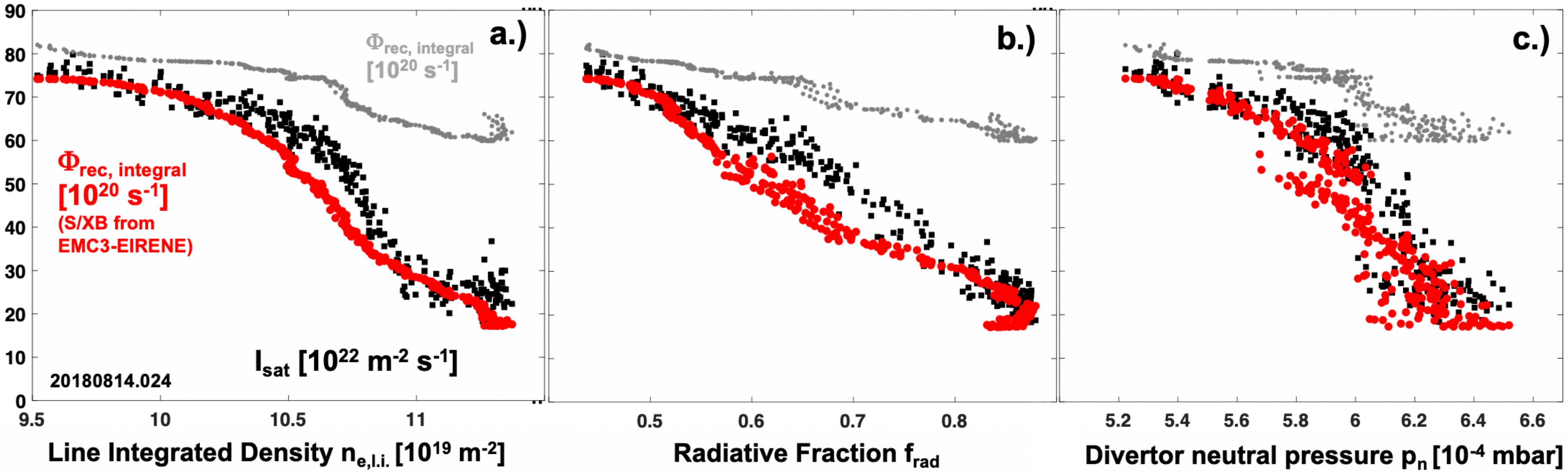
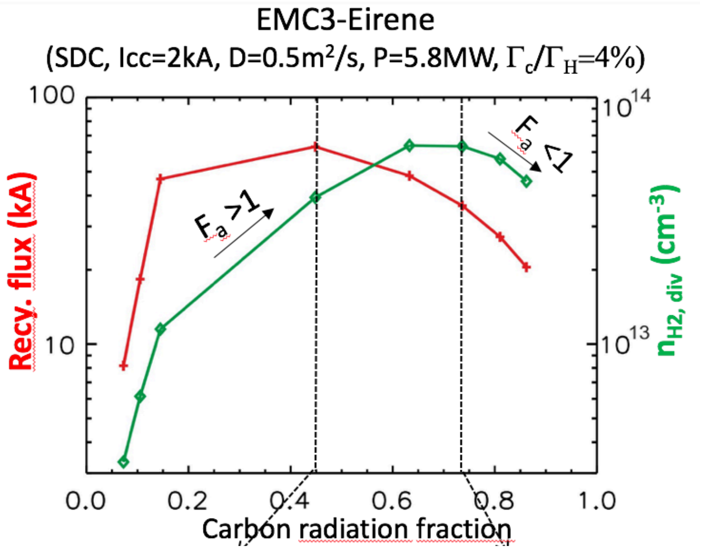


Both, heat and also particle fluxes are detached but still a high neutral pressure of up to 6.5 10^{-4} mbar are reached! What is behind this interesting feature?

Wendelstein 7-X IPP

Particle flux detachment can be combined with sustainment of neutral particle exhaust under power detachment in the island divertor



Distribution of neutrals in island divertor module defines neutral influx $\Gamma_{in,\,H0}$ into pumping domain.

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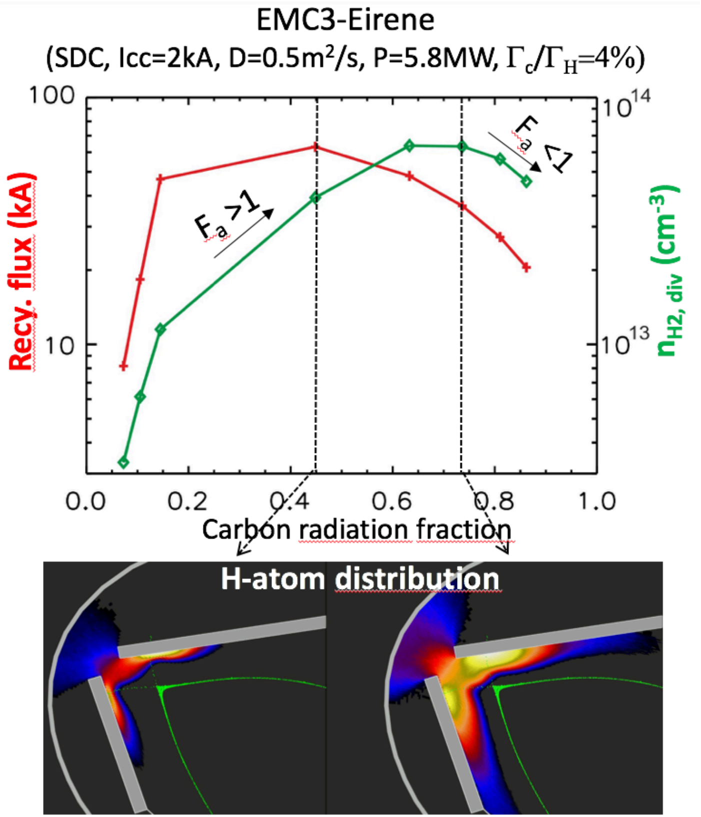

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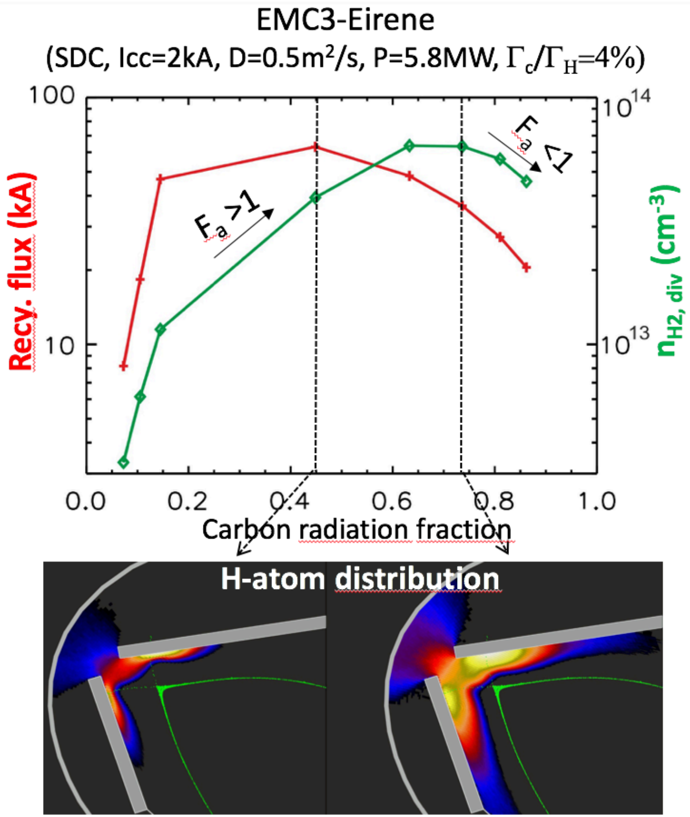
Intuitive model: [Y. Feng et al., W7-X workshop, 2017]
[Y. Feng et al., Nuclear Fusion **56** (2016) 126011]

- **Neutral distribution is defined by local plasma parameters in island**
- **Mean free ionization λ_{io} lengths vs. mean distance to pump entrance l_p defines p_n**
- **Increasing f_{rad} reduces T_e and hence increases ionization length scale λ_{io}, also $n_{e,target}$ is reduced**
- **More neutrals can enter the pumping domain**

3D modeling predicts that f_{rad} moderates the neutral ionization distribution such that an increase of λ_{io} yields increasing p_n with reduced Φ_{target}



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$$\Gamma_{in}^{H0} \propto \Gamma_{ef}^{H+} \cdot \exp(-F_a)$$

$F_a = \bar{l}_{gap} / \bar{\lambda}_{ion}$ **attenuation factor**

Γ_{ef}^{H+} **recycling flux**

$\bar{l}_{gap}$ **mean distance to pumping gap**

$\bar{\lambda}_{ion}$ **mean ionization length scale**

Key plasma parameter

$$\lambda_{io} = \frac{v_n}{n_e < \sigma v > (T_e)}$$

Regulated through f_{rad}

[Y. Feng et al., Nuclear Fusion **56** (2016) 126011]

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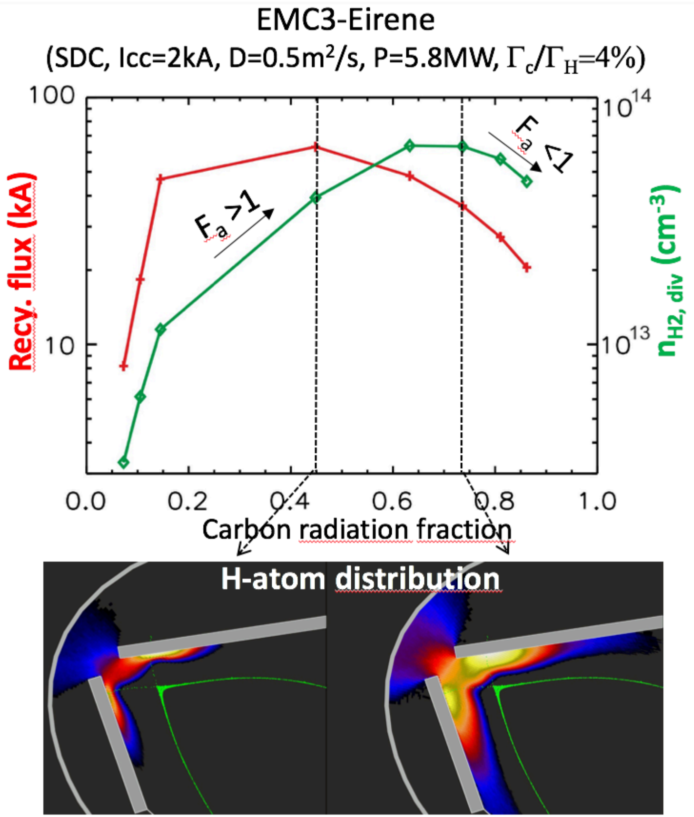
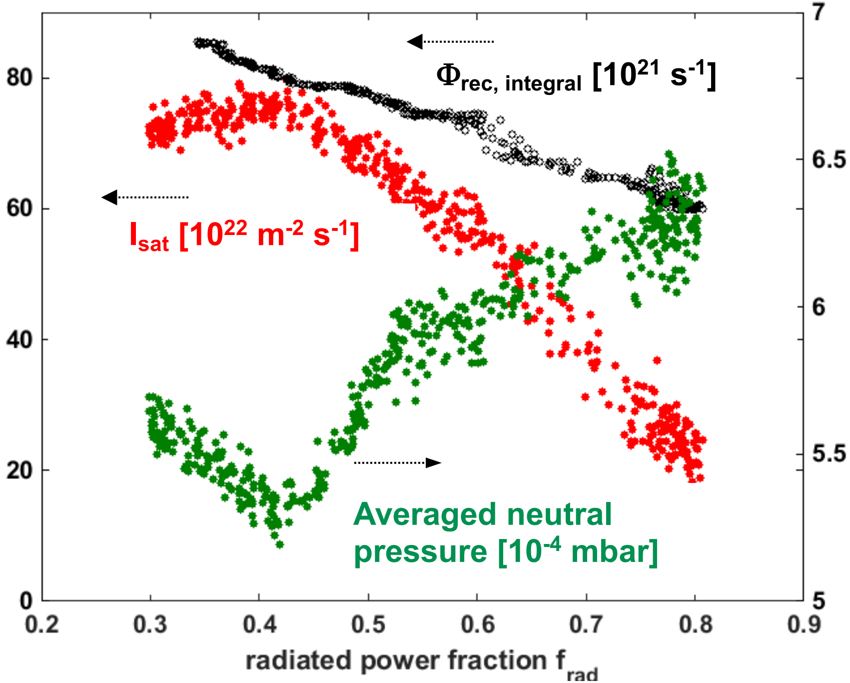


Experimental data support this intuitive model



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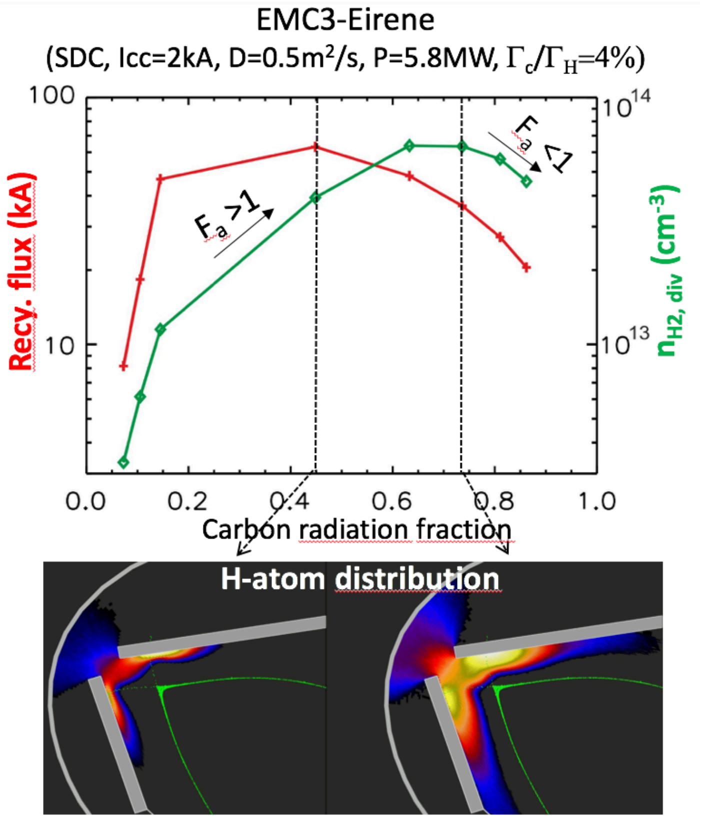
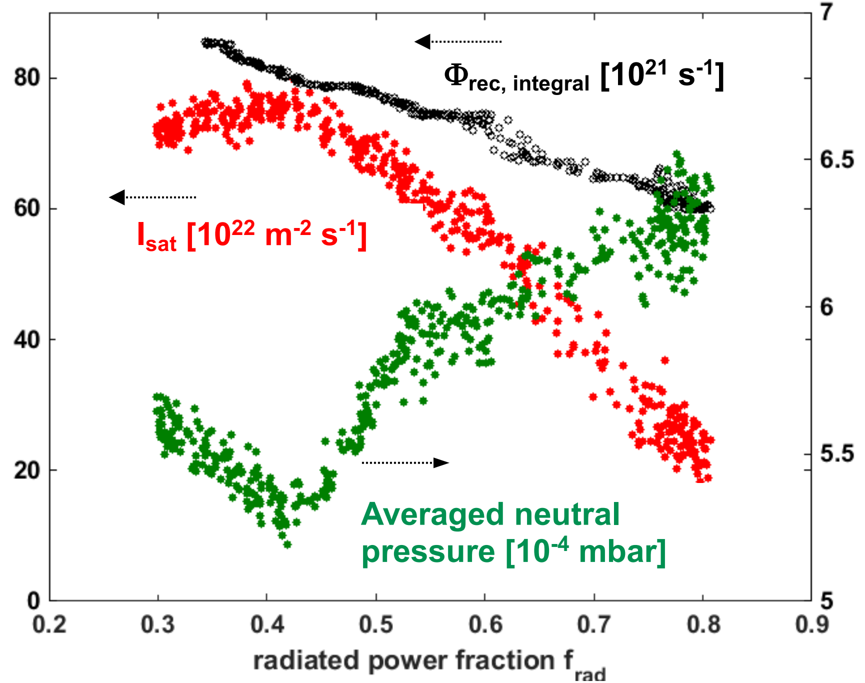
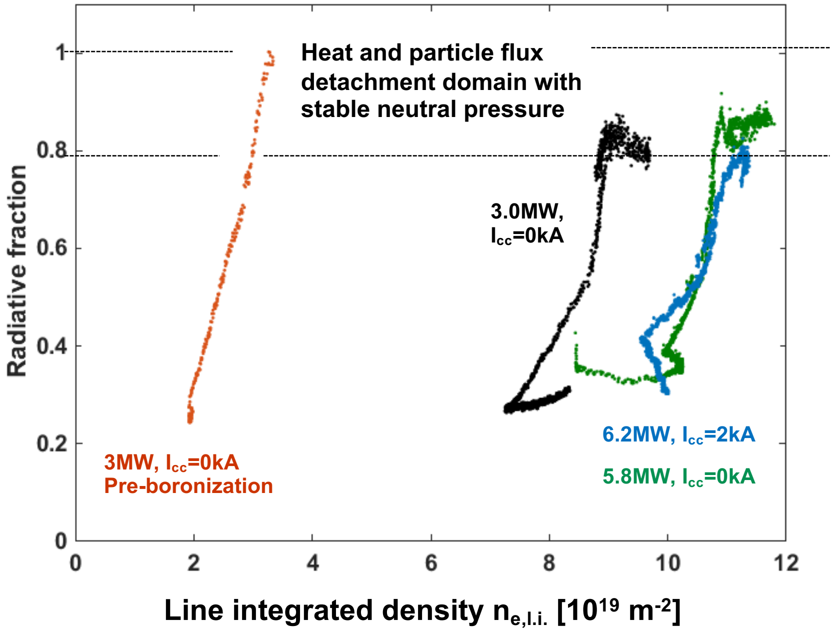


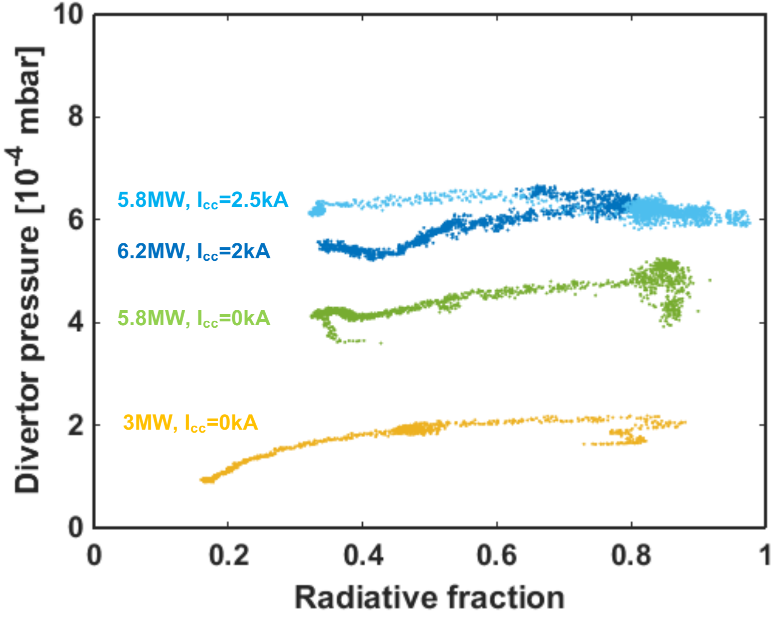
Experimental data support this intuitive model



No p_n roll-over is observed in the experiment due to f_{rad} limit from ECH heating scenario

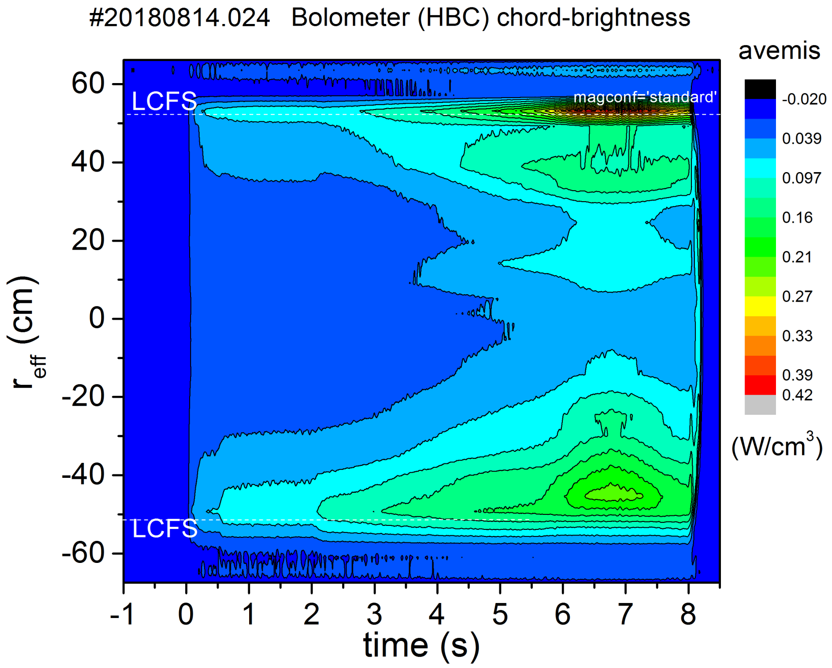
The radiation fraction is dependent of the heating power for a given density range – this is the basis for the regulation of divertor temperature in the island





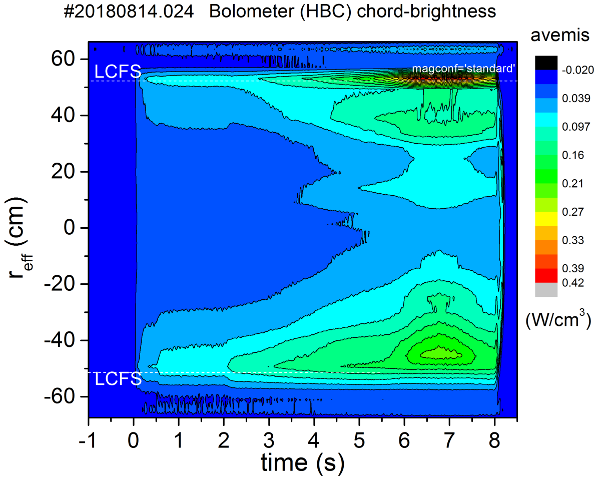
The radiated fraction depends on density which in turn is defined by the available heating power through ECRH – this sets the stage for the detached regime.

Radiation in detached state is localized predominantly around separatrix – exact resolution so far very challenging due to limited resolution of bolometer

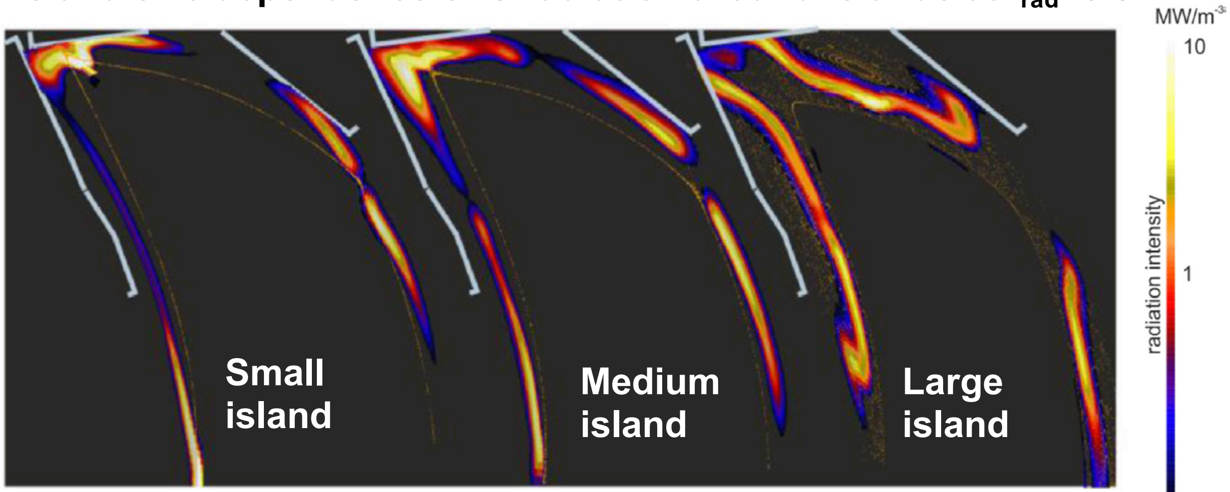


Exact power balance in the plasma edge layer is a high priority topic to disentangle radiation contributions

Radiation in detached state is localized predominantly around separatrix – exact resolution so far very challenging due to limited resolution of bolometer



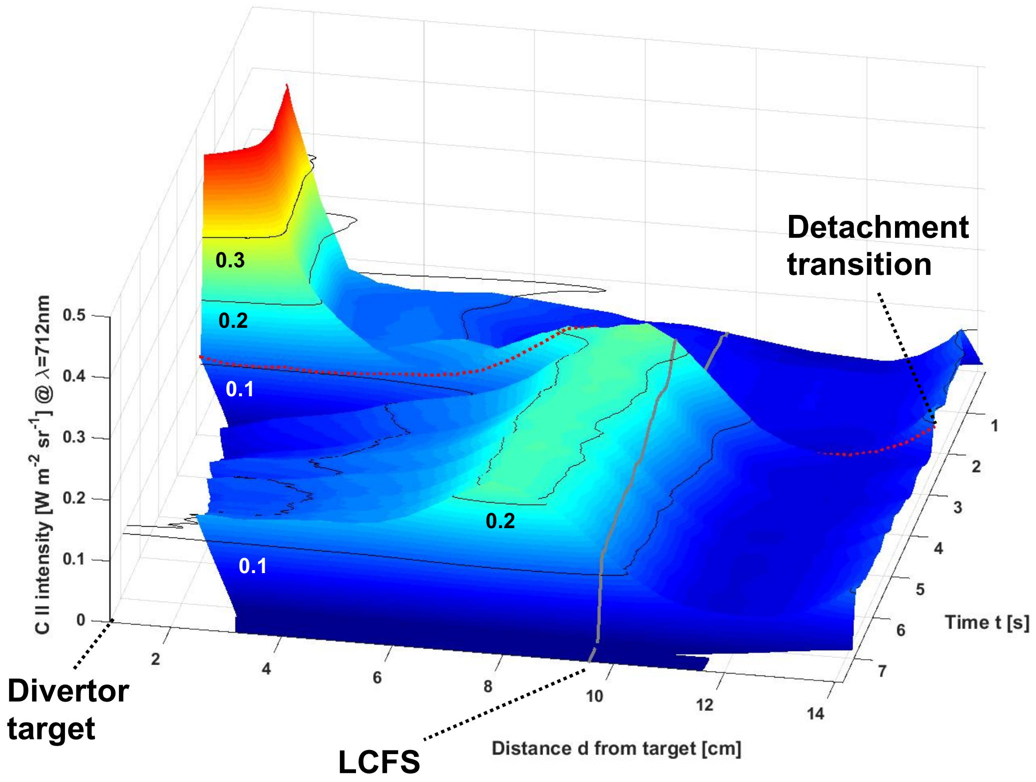
Island size dependence of C radiation around islands at f_{rad}=0.8



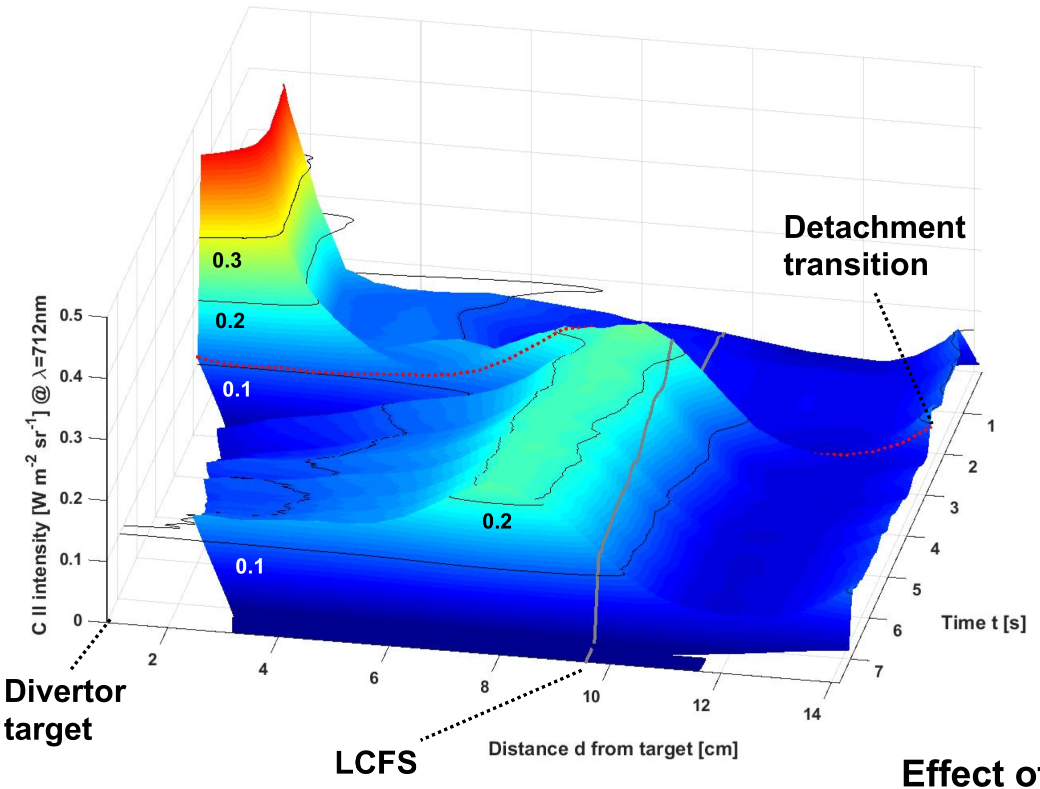
Radiation localized at strike point → **Radiation fills island domain** → **Radiation reaches separatrix**

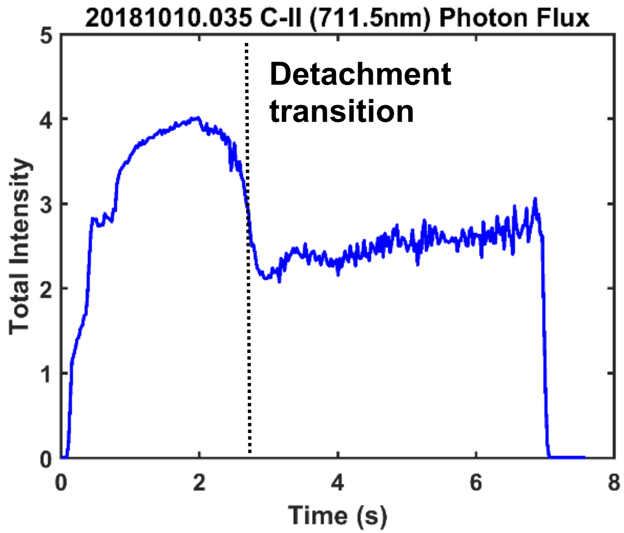
Exact power balance in the plasma edge layer is a high priority topic to disentangle radiation contributions – modeling suggests radiation inside SOL up to f_{rad} ~0.8

Carbon impurity source and C-II line emission define the local radiation equilibrium which detaches from surface



Carbon impurity source and C-II line emission define the local radiation equilibrium which detaches from surface



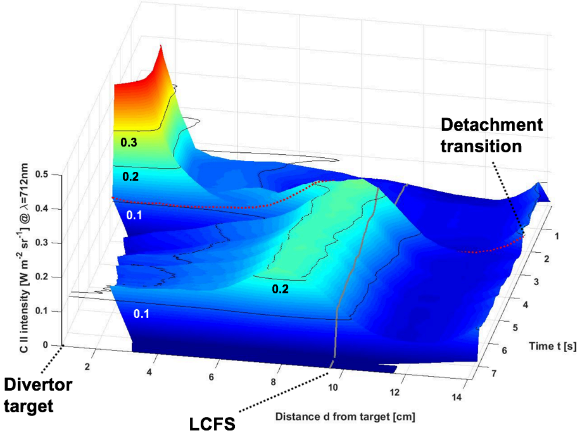


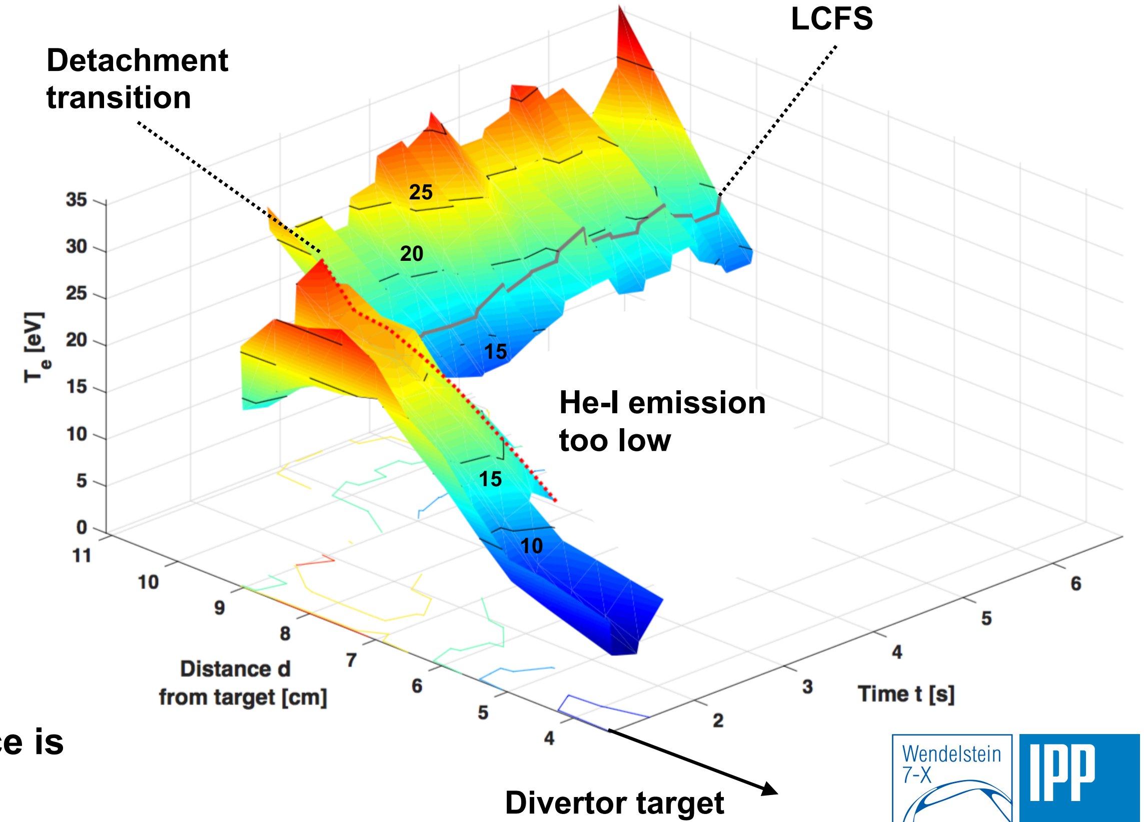
The integrated C-II emission is reduced but the **C-source estimated (10^{22} part. s^{-1}) shows almost no significant reduction.**

Effect of local plasma parameters!

Carbon radiation distribution is followed by position of 15 eV isothermal surface in island divertor domain

Iso-thermal surface (T_e ~15 eV) moves inward with radiation front.





Density at the position of this surface is almost constant (n_e ~ 5.0 10^{19} m^{-3})

Outline of this talk in form of an executive summary

- A **stable, thermally fully detached island divertor regime** with **small divertor particle fluxes** but still **sufficient divertor neutral pressures** was shown for the first time.

- This detached island divertor regime is **reached with minimal feedback control in a reliable fashion** and **the divertor operational point is defined through sufficient radiative losses at a given input power.**

  The **geometry of the magnetic islands** forming the divertor allow to **fine tune the divertor neutral distribution** for **maximized neutral pressure** in the detached state.

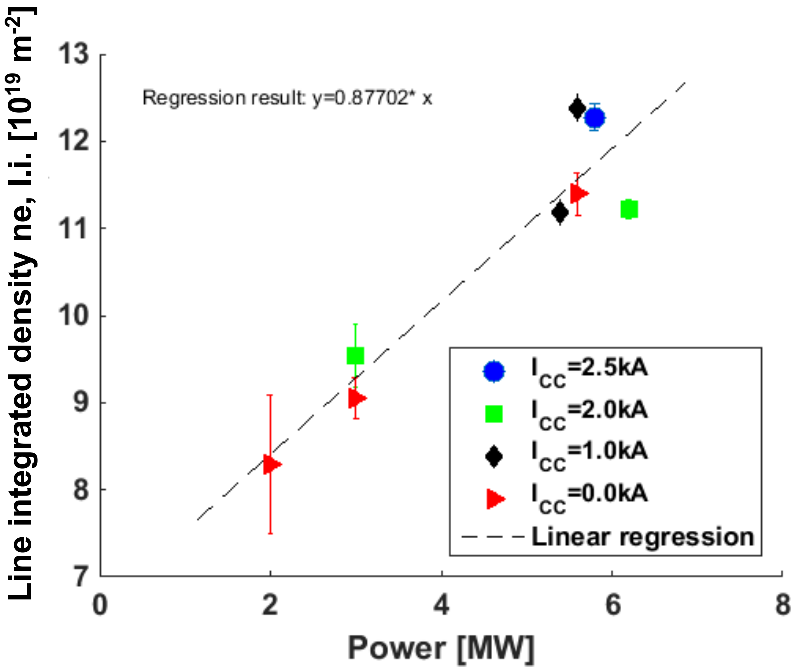
- This island divertor regime is **compatible with steady state particle exhaust** for the upcoming high-performance campaign of W7-X.

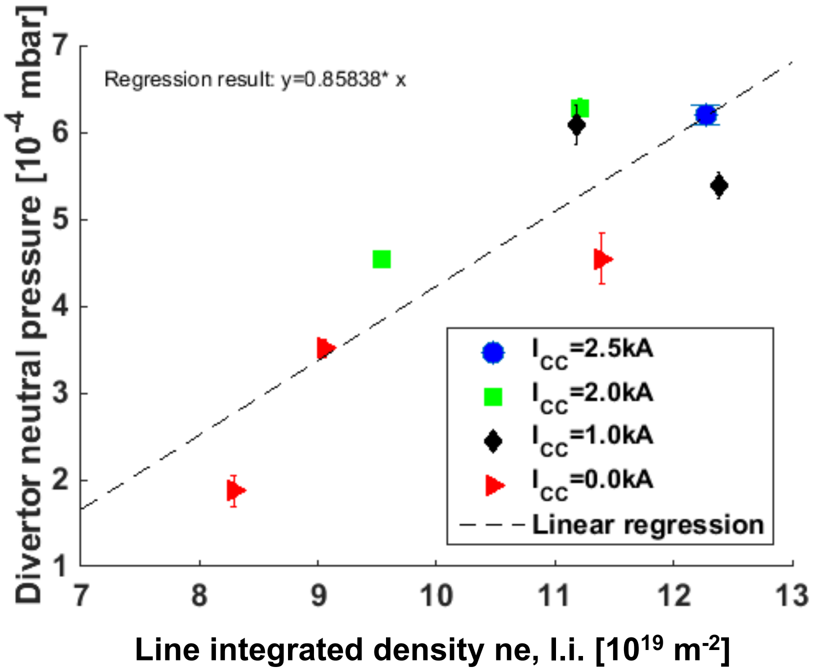
Wendelstein 7-X

IPP

Linear scaling of plasma density with input power enables build up of sufficient divertor neutral pressures and maximize by island size increase

Data were averaged over stable detached windows for various experimental programs with [$0.75<f_{rad}<0.9$]





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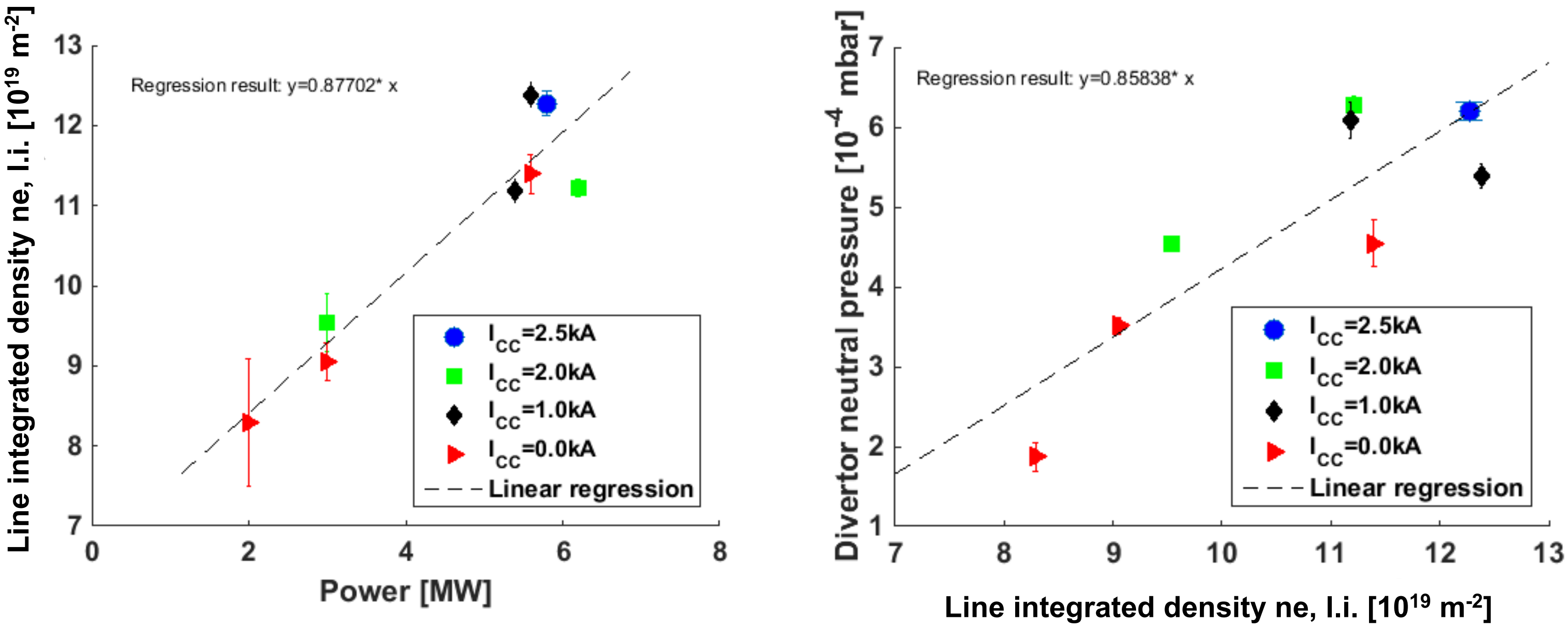


The divertor neutral pressures obtained scale favorably towards steady state

Pumping particle flux level reached under reliably detached conditions is compatible with exhaust requirements for steady state

- **Basic observation:** increase of neutral back pressures of <8.0 10^{-4} mbar averaged across all available pump ducts for after Boronization from <5.0 10^{-5} mbar before Boronization
- **Existing pumping capacity from Turbo-Pumps:** 10 x 3 x 1250 l/s=37500 ltr. Hydrogen /s
- **Expected pumping capacity with Cryo-pump:** 70.000 ltr. Hydrogen /s

	Value	TMP scenario	Cryo scenario
OP1.2.b	**Pumped flux Γ_{pump}**	**5.2 10^{20} H2/s**	**9.25 10^{20} H2/s**
OP1.2.b	**Fueled flux Γ_{in}**	**5.0 10^{20}** - 1.0 10^{21} **H2/s**	5.0 10^{20} - 1.0 10^{21} H2/s
OP1.2.b	Based on example 20180814.024 with **8.0 10^{-4} mbar** averaged divertor pressure		
OP1.2.a	**Pumped flux Γ_{pump}**	9.0 10^{19} H2/s	1.6 10^{20} H2/s
OP1.2.a	**Fueled flux Γ_{in}**	2.2 10^{20} - 2.0 10^{21} H2/s	Does not scale, low n_e
OP1.2.a	Executed based on example 20180801.039 and 20171207.024 with **5.0 10^{-5} mbar** averaged divertor pressure		

Summary and conclusions

- The attractive detached island divertor regime was reached through intrinsic radiation scaling with density, which is defined by the input power.
- Magnetic island size, magnetic connection length and strike line position as actuators
- This regime was only limited by input energy limits, which will be overcome with the actively cooled High-Heat Flux (HHF) divertor.
- The results so far have laid ground for a promising outlook on the overall steady state compatibility of the island divertor concept.

A possible hierarchy of the process

Input power level defines density, Φ_{rec} and f_{rad} level

↓

Φ_{rec} builds p_n with λ_n tuned by local T_e

f_{rad} >0.75 yields detachment

↓

Heat and particle flux detachment with large enough neutral source access to pump domain for steady state exhaust

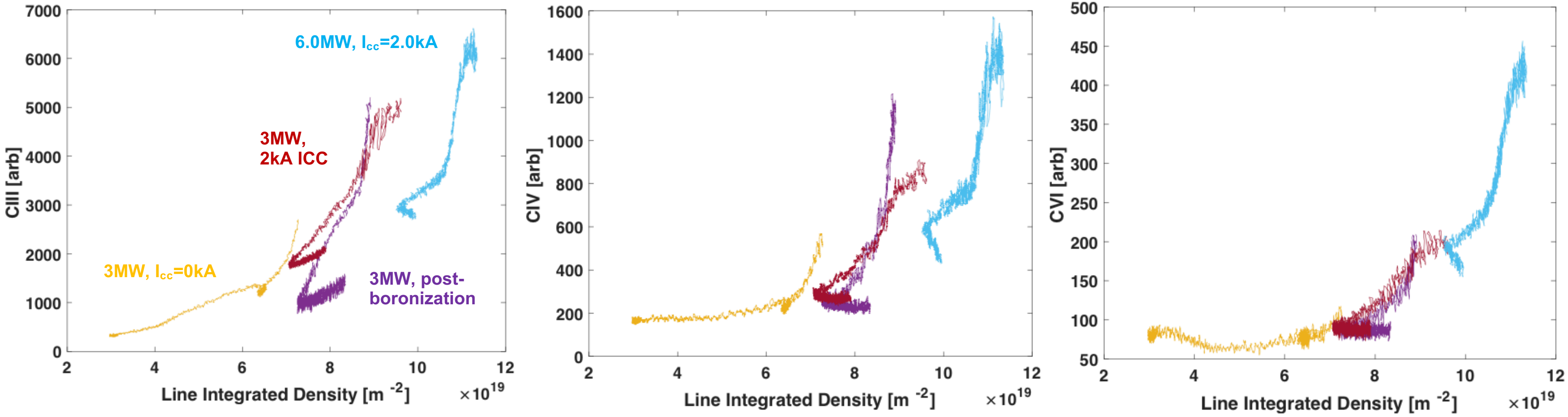
Wendelstein 7-X

IPP

Appendix

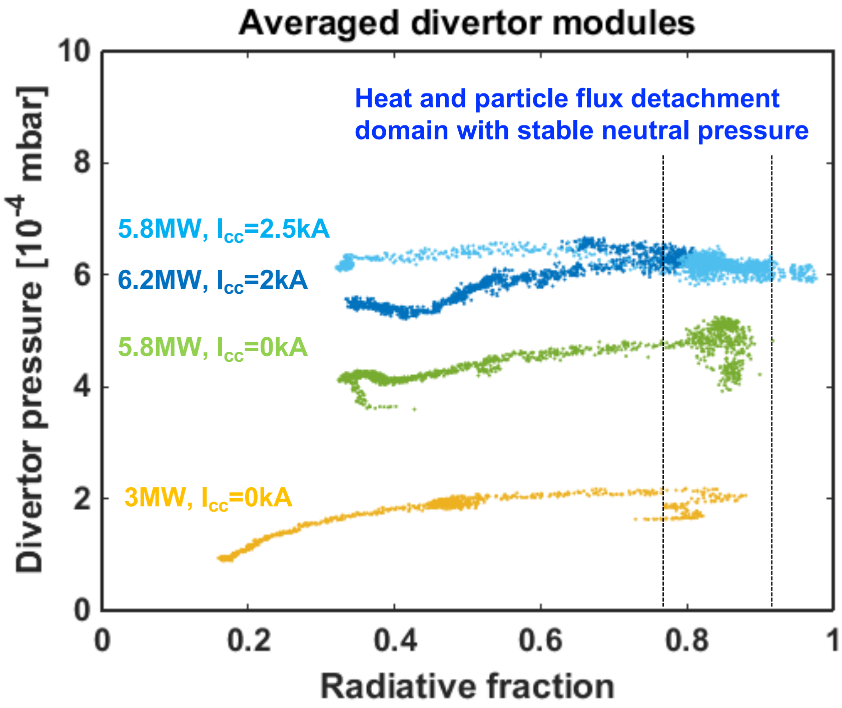
Carbon charge states emit across the island divertor volume featuring a quadratic dependence on density which defines divertor T_e

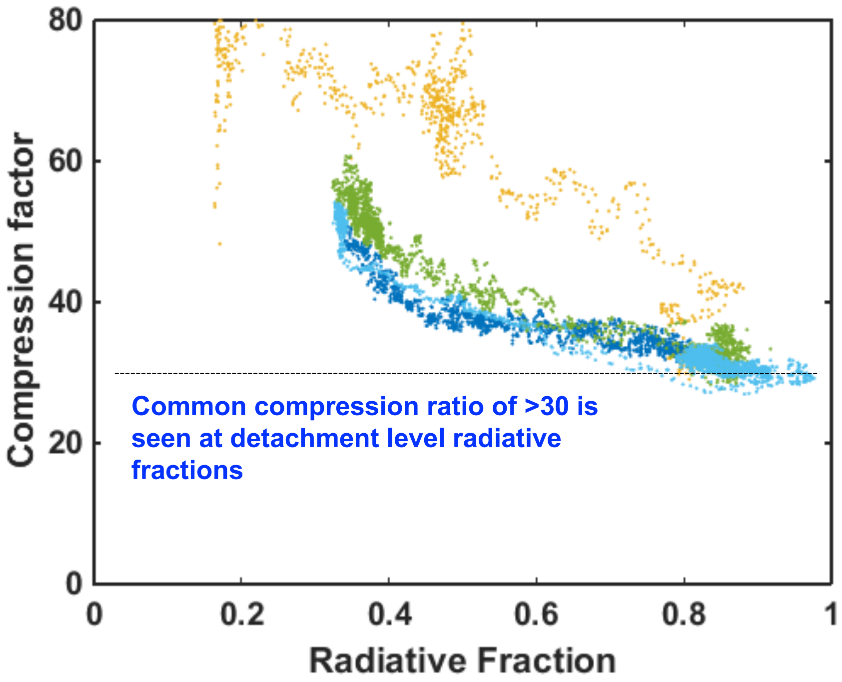
Quadratic rise of carbon line radiation close to the target (C-III), in the island domain (C-IV) and around separatrix (C-VI) supports facilitation of detachment by intrinsic impurity radiation



Carbon as intrinsic impurity supports the necessary radiative losses localized inside and in the close vicinity of the island domain.

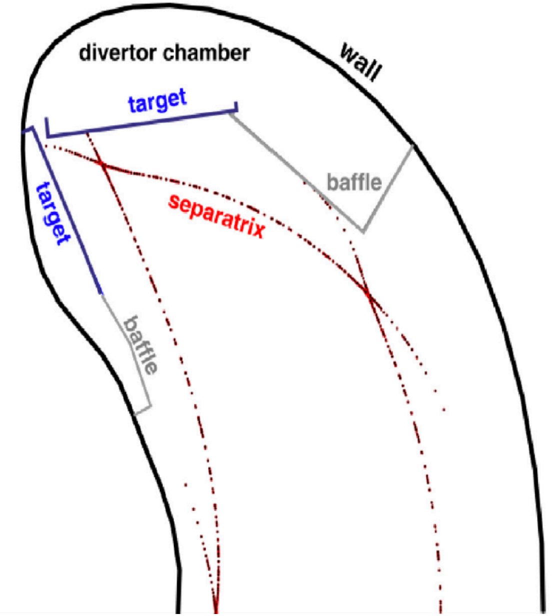
The divertor neutral pressure level depends on density scaling with increasing heating power – access to detachment for $f_{rad}>0.75$





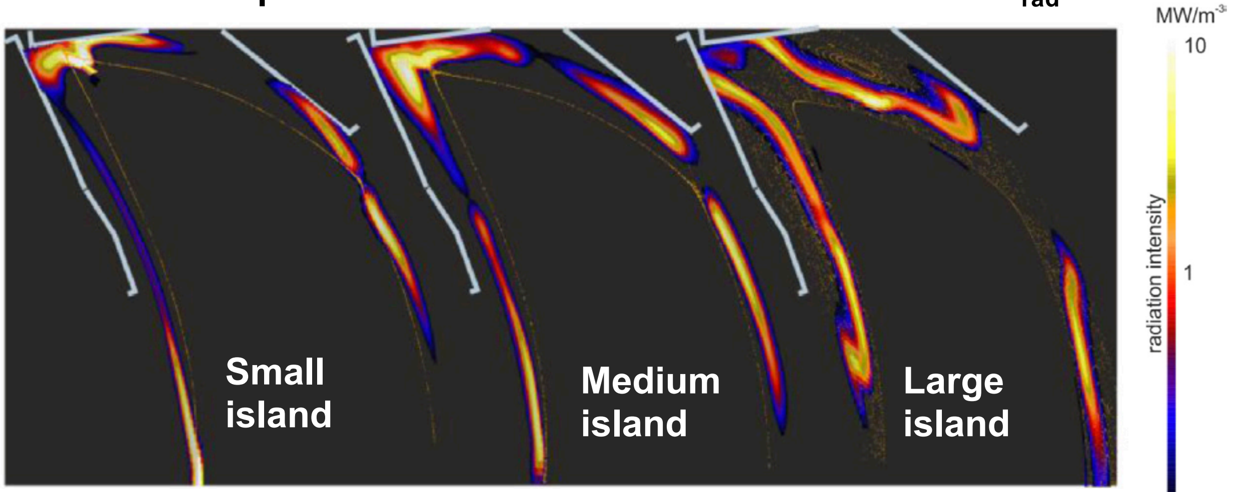
At a radiated fraction of $0.75 < f_{rad} < 0.9$ a saturated neutral pressure p_n regime is seen with p_n being set by the plasma density

The volume of the magnetic island is predicted to serve as a reliable interface layer with a beneficial radiation and ionization equilibrium



[Y. Feng et al., Nuclear Fusion **56** (2016) 126011]

Island size dependence of C radiation around islands at f_{rad}=0.8



Radiation localized at strike point → Radiation fills island domain → Radiation reaches separatrix

Interplay of radiation distribution with power dissipation and divertor neutral capture is key to understand the island divertor!

The EMC3-EIRENE model in a nutshell

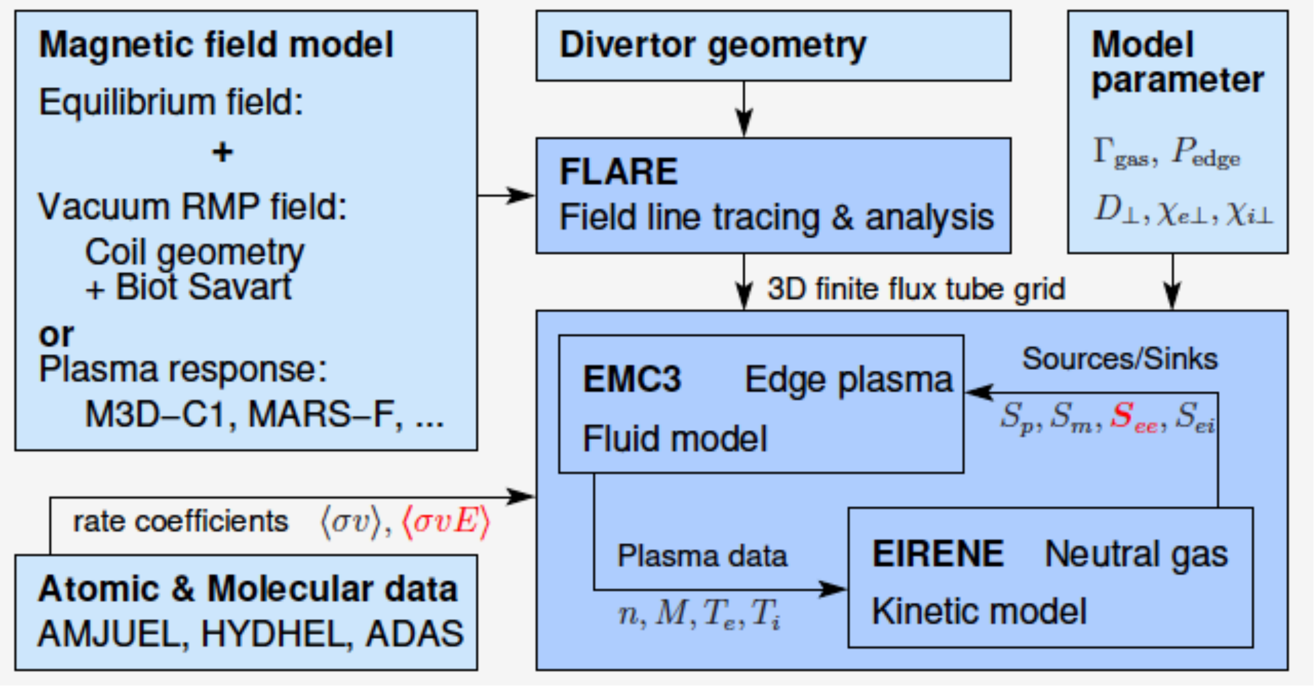
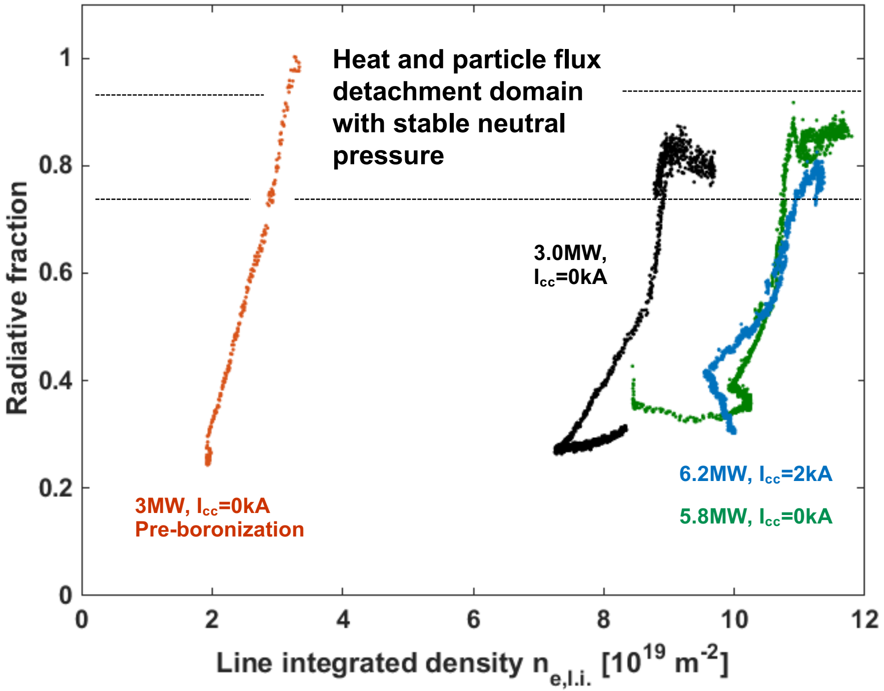


Figure courtesy of H. Frerichs

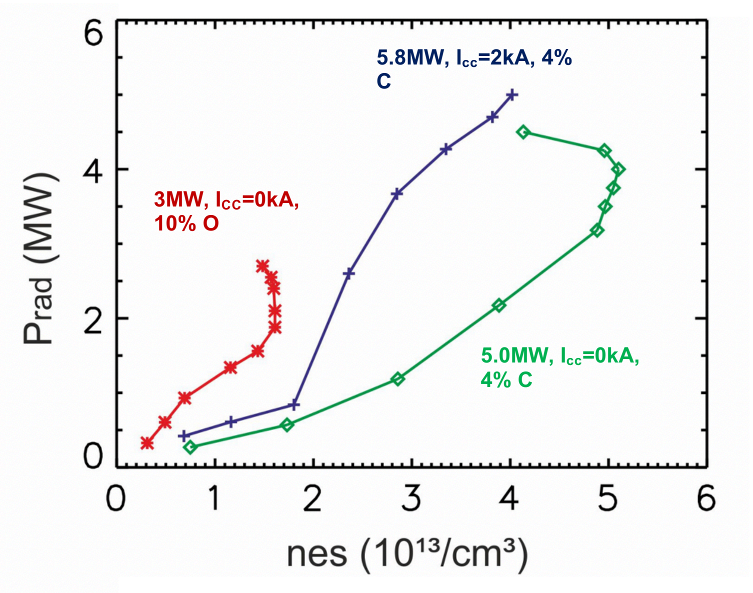
[Y. Feng et al., JNM **266-269** (1999) 812] [Y. Feng et al., PPCF **59** (2017) 034006]

[Y. Feng et al., Contri. Plasma Phys. **54** (2014) 426-431]

The radiation fraction is dependent of the heating power for a given density range – this is the basis for the regulation of divertor temperature in the island



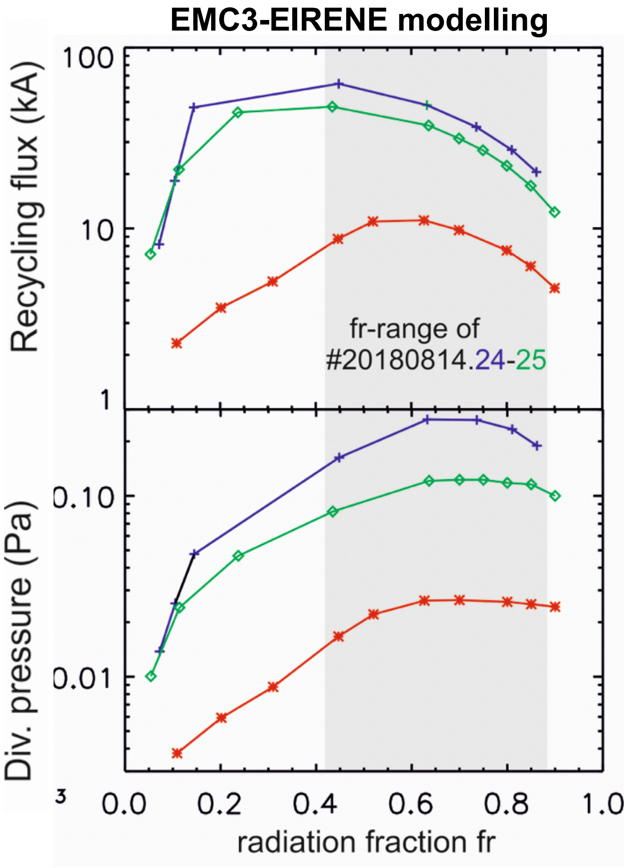
EMC3-EIRENE predicts comparable scaling of radiation in island with density

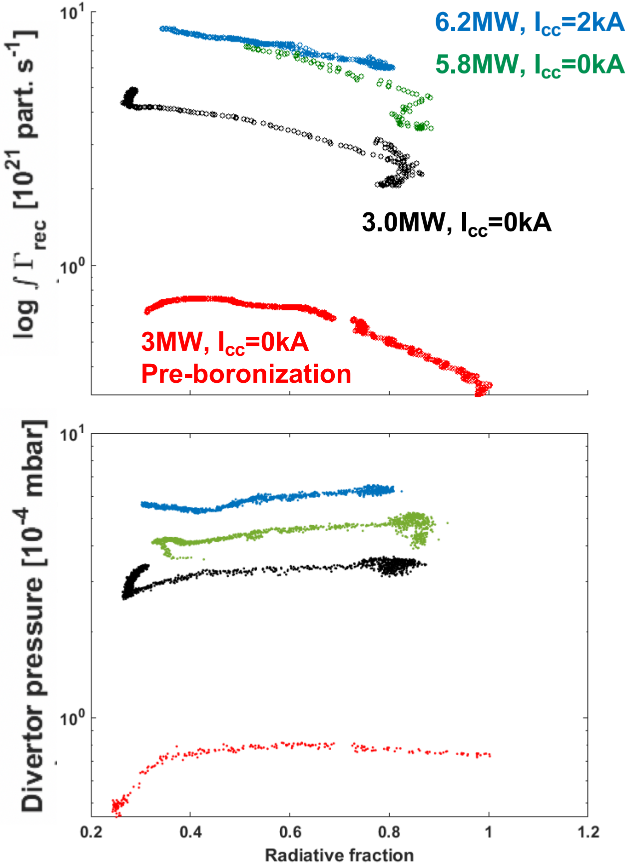


The radiated fraction depends on density which in turn is defined by the available heating power through ECRH – this sets the stage for the detached regime.

Wendelstein 7-X IPP

Dependence of target parameters on f_{rad} is consistent between experiment and EMC3 model, but a significantly weaker dependence is found in measurement





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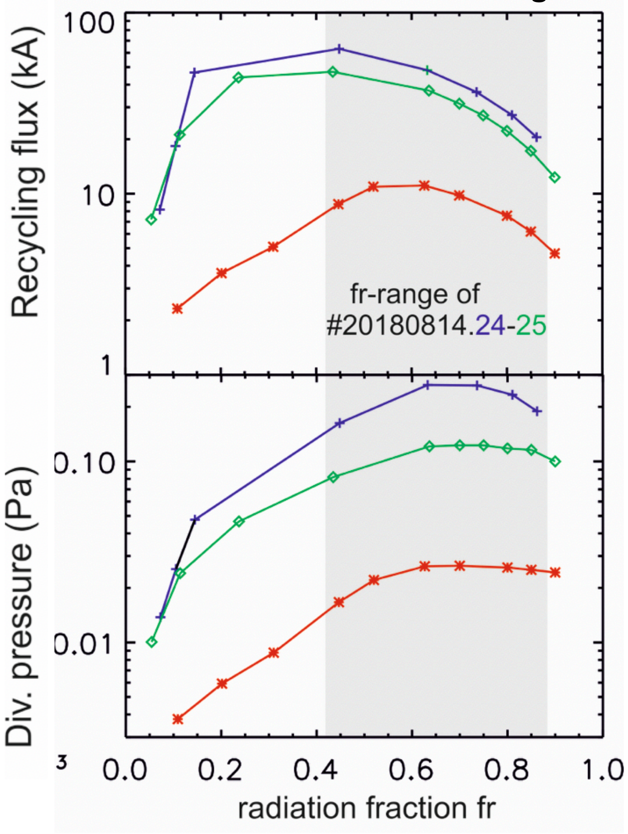
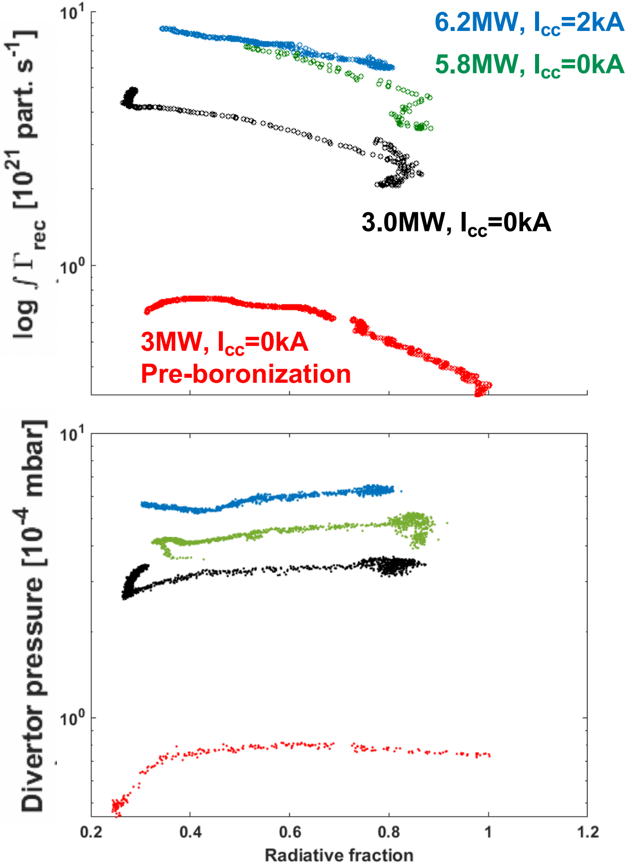
EMC3-EIRENE modelling





A possible hierarchy of the process

Power level defines density and hence Φ_{rec}

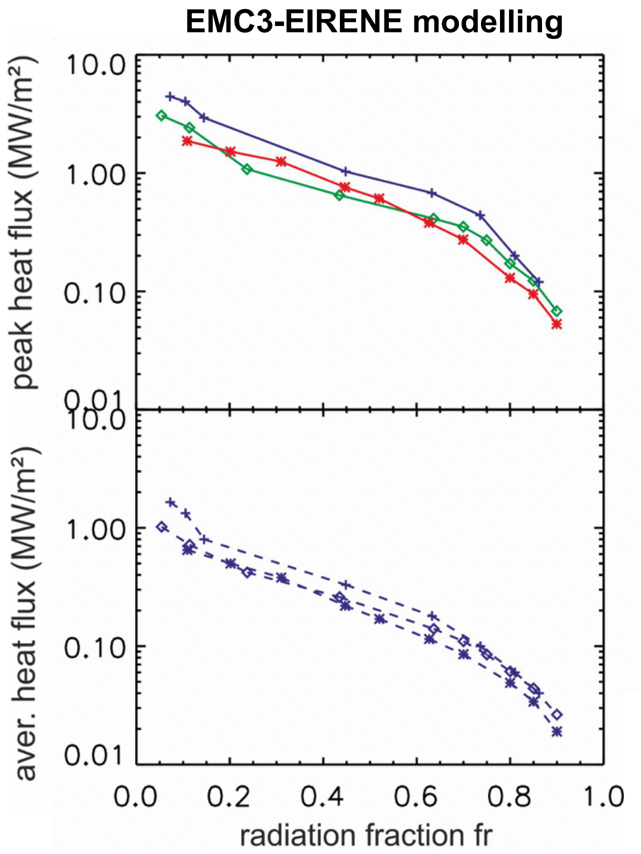
↓

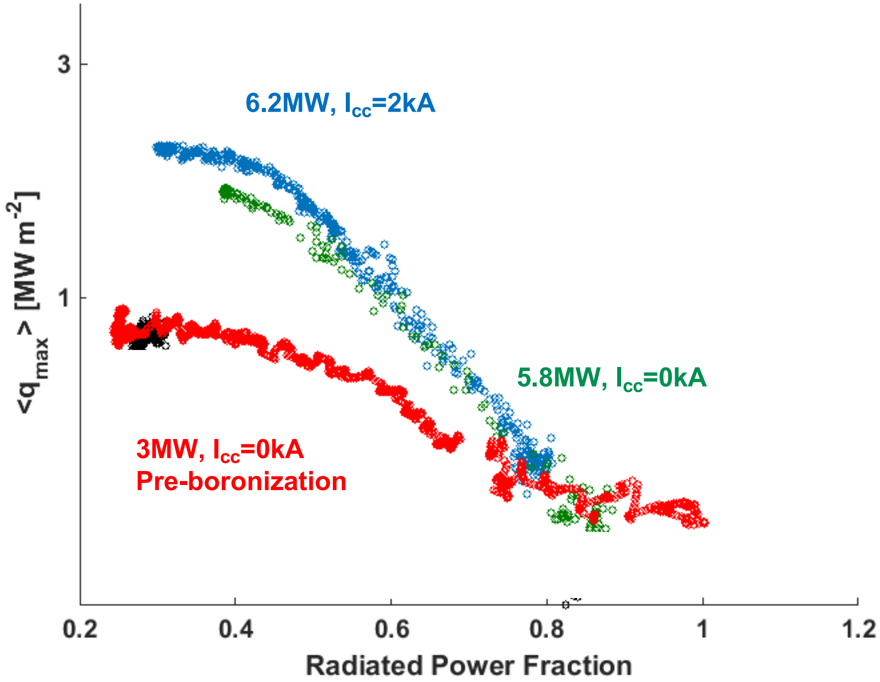
Φ_{rec} provides source for p_n

↓

Optimal neutral particle distribution for good pump access is defined by f_{rad}

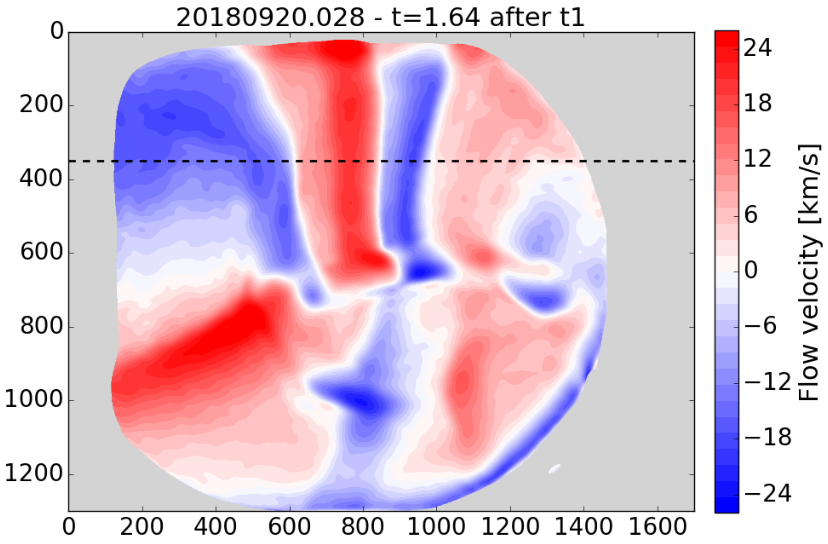
Dependence of target parameters on f_{rad} is consistent between experiment and EMC3 model, but a significantly weaker dependence is found in measurement

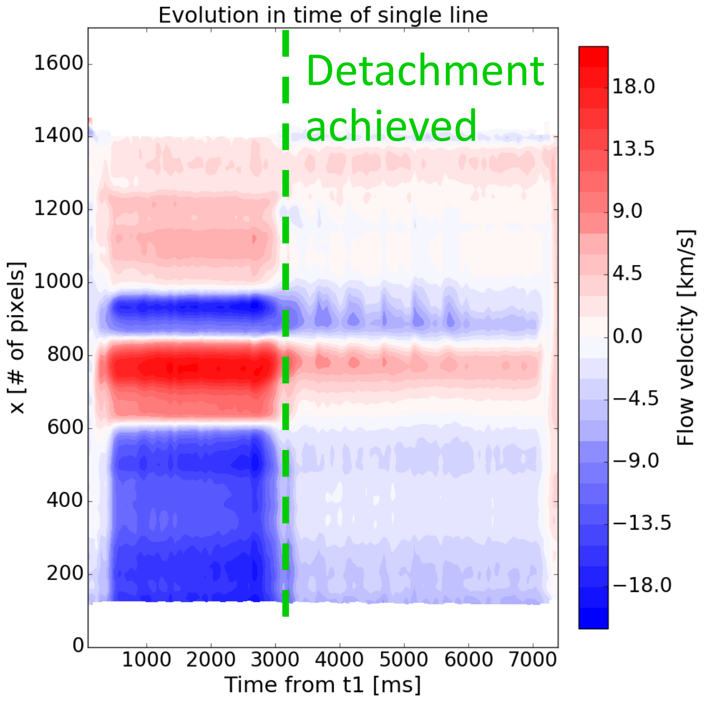




Power dissipation due to radiation from intrinsic impurity yields thermal detachment

Particle flows are reduced at transition into detachment





Acknowledgement: V. Perseo