Divertor & Exhaust Modelling of Stellarator Power Plants

In the Framework of a Systems Code

Felix Warmer, Jorrit Lion, Holger Niemann, and the W7-X Team

IR Team: F. Pisano, B. Cannas, M. Jakubowski, P. Drewelow, A.P. Sitjes and Y. Gao

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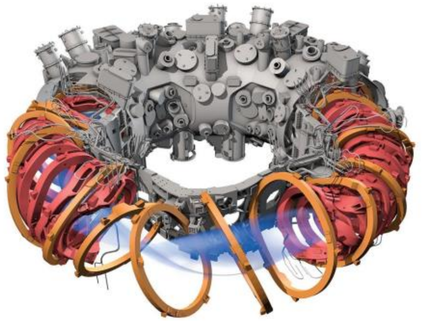
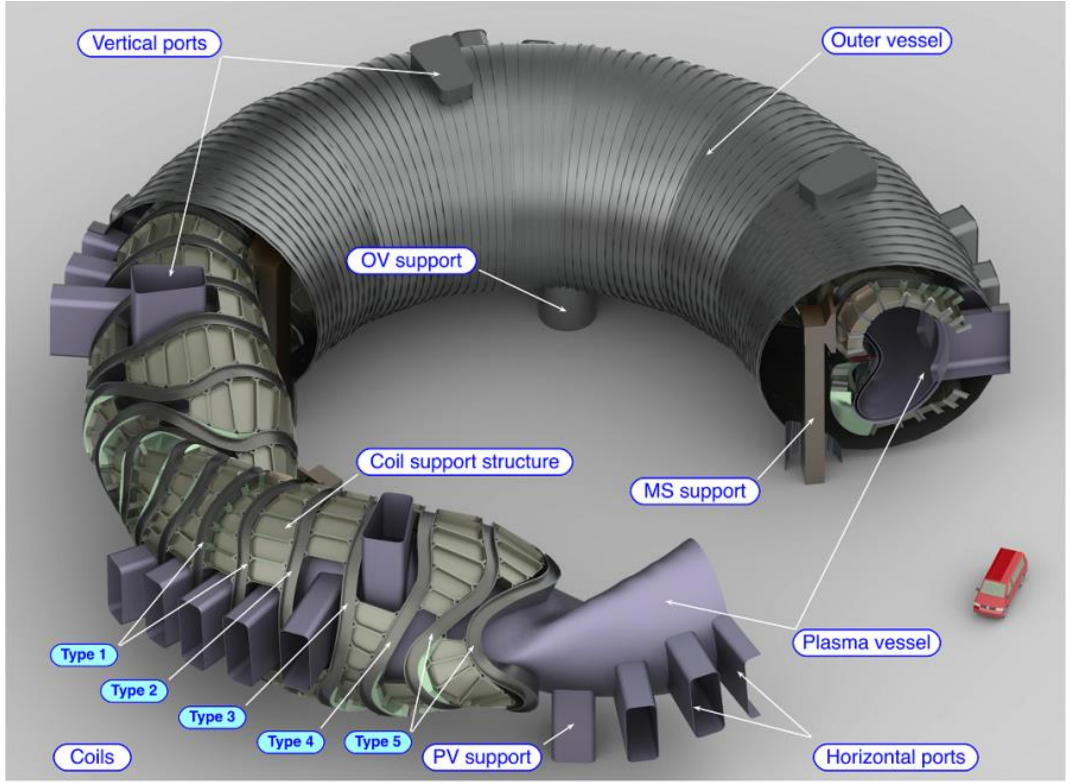
Motivation – Vision of a Stellarator Power Plant



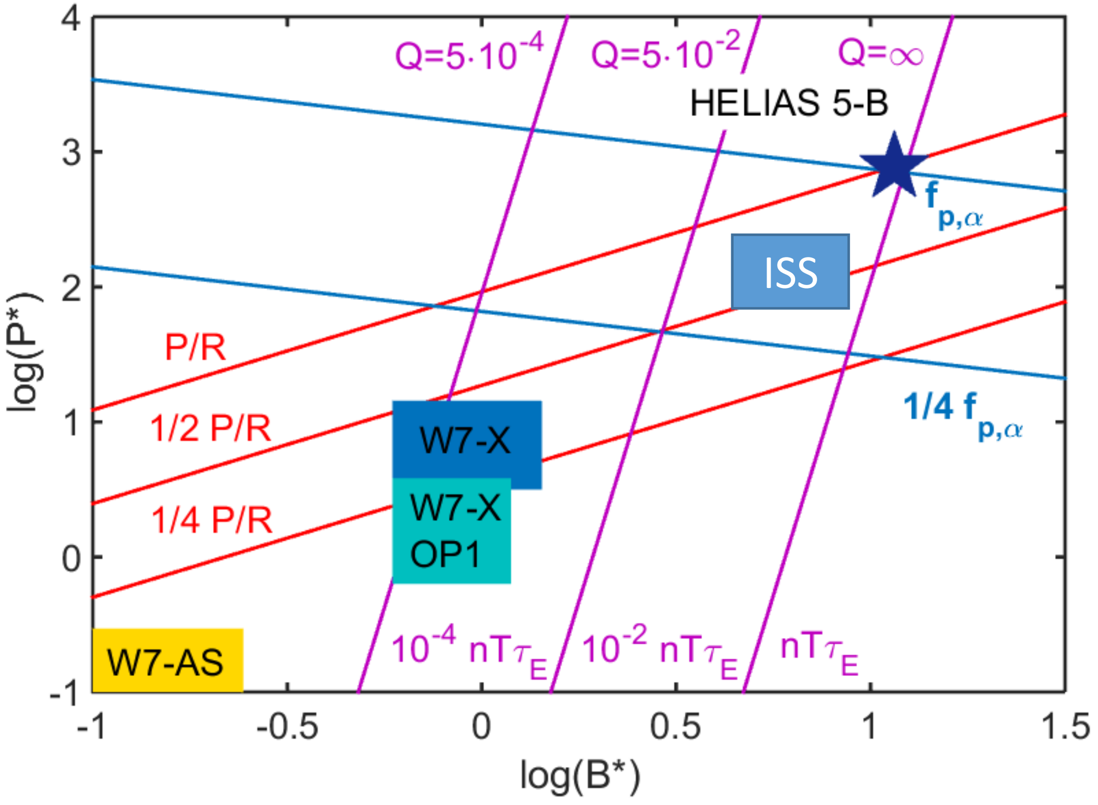
Wendelstein 7-X:
Prototype of a „Helical-Axis Advanced Stellarator“ (HELIAS)



	W7X	H5B
Major radius	5.5 m	22 m
$B_{avg.}$ on axis	< 3 T	< 5.9 T

Motivation – Exhaust as Integral Part of the Design

F. Warmer, et al., PPCF 58 (2016)



Device	Fusion Power	P_{SOL}/R [MW/m] (no radiation)
W7-X	-	~2
Intermediate Step Stellarator	500 MW (Q = 10)	~11
HELIAS 5-B	3000 MW	~27
ITER	400 MW	~20

Huge Parameter Space
→ Need to estimate Exhaust capability over a large design space !!

Content

1. **Modelling of the “Island Divertor” in Systems Codes**
    a) The Heuristic Model
    b) Model Validation

2. **Generic Stellarator with undefined Divertor Concept**
    a) 0-D Requirement Analysis
    b) Field Line Diffusion Modelling

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Modelling of the “Island Divertor” in Systems Codes

Heuristic Model:
Y. Feng, et al., PPCF 53 (2011)
F. Warmer, et al., FED 91 (2015)

Divertor Heat Load:

$$q_{div} = \frac{P_{div}}{A_{eff}} = \frac{P_{SOL}(1 - f_{rad})}{\lambda_{int} \cdot L_T}$$

Strikeline **width** and **length**

Heuristic Approach:

1) Diffusive cross-field transport
2) Helical geometry description
3) High radiation

$$\lambda_{int} = \sqrt{\chi_\perp \cdot \tau_\parallel} \qquad \Rightarrow \lambda_{int} = \sqrt{\chi_\perp \cdot \frac{\mathcal{L}_{X\to T}}{c_s}}$$

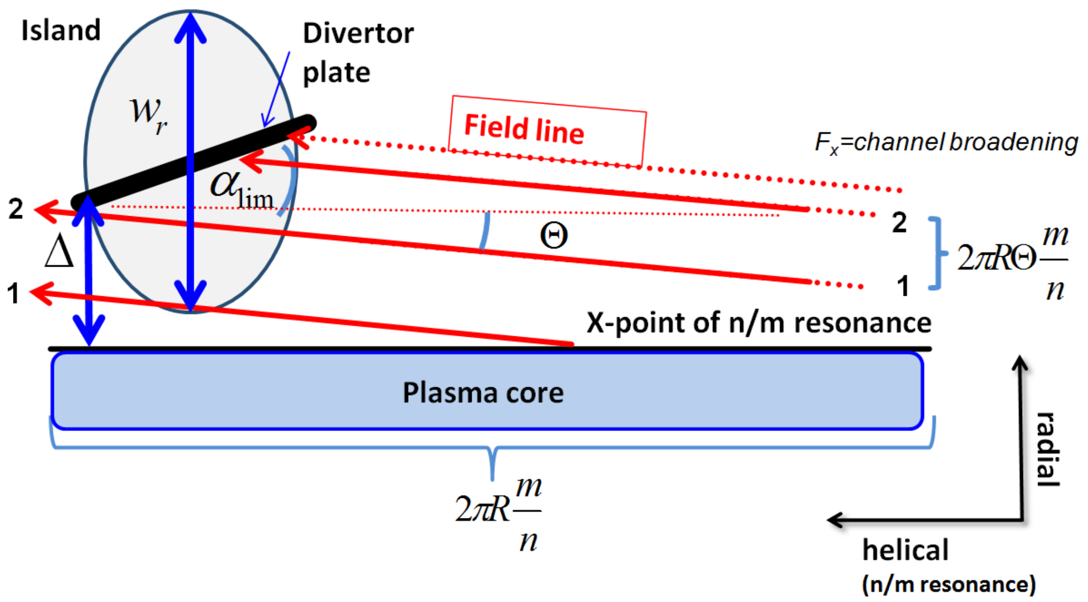
With the connection length: $\mathcal{L}_{X\to T} = \frac{\Delta}{\Theta}$

(Upgrade to 2-point model in future)

Modelling of the "Island Divertor" in Systems Codes

Heuristic Model: Y. Feng, et al., PPCF 53 (2011), F. Warmer, et al., FED 91 (2015)

Helical Geometry:



$$L_D = 2\pi R \cdot \frac{m}{n} \frac{\Theta}{\alpha_{\lim}} F_x$$

Field line pitch

Angle between field line and target

$$L_T = 2nL_D$$

2 plates per field period (up/down)

Combining decription for strikeline **width** and **length** gives heuristic model:

$$q_{div} = \frac{P_{SOL}(1-f_{rad})}{F_x \cdot 4\pi R \cdot m} \cdot \sqrt{\frac{c_s}{\chi_\perp \cdot \Delta}} \cdot \frac{\alpha_{\lim}}{\sqrt{\Theta}} \cdot f_{asym}$$

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From Infrared Measurement to Heat Load in W7-X

IR Team: Fabio Pisano, Barbara Cannas, Marcin Jakubowski, Peter Drewelow, Alepi Pugi Sitjes and Yu Gao

Very Large Database of Heat-Load Data:

- ✓ Two W7-X divertor campaigns 2017 & 18
- ✓ ~2500 discharges
- ✓ Across 4 magnetic configurations
- ✓ **>100 TB** Heat Load Data

Validation of the Heuristic Model with W7-X Data

Strikeline

Model Parameter		Experiment Equivalent for Validation
λ_{int}	Strikeline broadening	Heat Load from IR cameras, Langmuir
$A_{eff};\ L_T$	Wetted Area / Strikeline length	
f_a	Divertor asymmetry (Drifts)	
$c_s; T$	Sound velocity in SOL	Langmuir; Manipulator-Probes
Δ	X-point to Target distance	Poincaré Plot of Configuration
$\mathcal{L}_{X\rightarrow T}$	Connection Length	Field Line Tracing
$\Theta;\ b_r$	Field Line Pitch	
α_{lim}	Angle btw. field line and target	

Configuration Parameters

EXAMPLE: Heat Load from Model and IR-Data

Yu Gao, Peter Drewelow, Holger Niemann, Marcin Jakubowski, Jorrit Lion

strikeline width λ_{int}

along stirkeline L_T

Just a rough EXAMPLE / ILLUSTRATION of what COULD be done in the FUTURE

Good data and potential for model validation and improvement

→ **Future Task**

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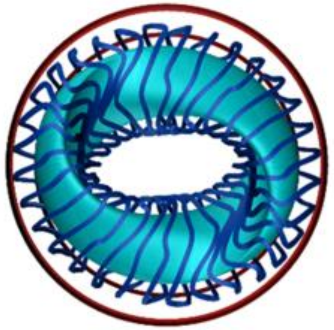
Generic Stellarator with undefined Divertor Concept

Quasi-
isodynamic

- ✓ Optimised for very small bootstrap current
- ✓ Robust magnetic field
- → **Resonant Island Divertor Concept**
- ✓ (tested in W7AS and now in W7X)

Quasi-helical
symmetric



Quasi-
axisymmetric

- ➢ "medium" <u>external</u> rotational transform to prevent disruptions
- ➢ High(!) bootstrap current to add rot. transf.
- → **Resonant Island Divertor not possible**
- ➢ Current-resilient divertor concept needed !

S.A. Henneberg, et al., NF 59 (2019)

0-D Requirements Analysis for Generic Stellarators

NO Divertor Concept → NO Model

→ **Reverse the Question:**

e.g. „Which wetted area do we need to achieve feasible divertor heat loads?“

<u>Allows to:</u>

→ Define requirements

→ Define limits
(e.g. BB space, which impacts TBR)

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Field Line Diffusion Model

Field Line Equation:

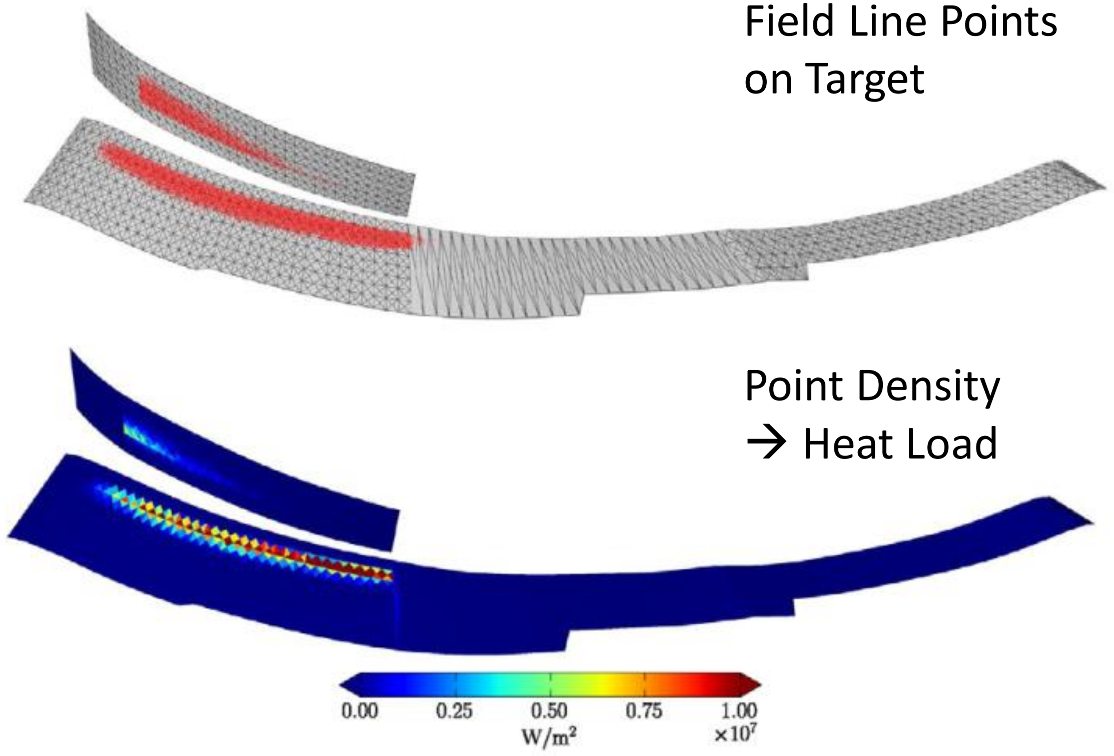
$$\frac{\mathrm{d}\vec{r}\,(l)}{\mathrm{d}l} = \frac{\vec{B}\,(\vec{r})}{\left|\vec{B}\,(\vec{r})\right|}$$

Add diffusive component to field lines:

$$p(x) = \frac{1}{\lambda} \exp\left(\frac{-x}{\lambda}\right)$$

$$r \in \left[0, \sqrt{\frac{12 D_{\perp} \lambda}{\upsilon}}\right]$$

Example for W7-X:



S.A. Bozhenkov, et al., FED 88 (2013)

Potential Workflow for a New Divertor Configurations

Inputs

New Magnetic Configuration
(VMEC+Extender, req. Coils)

Initial guess for First Wall AND/OR Divertor
(in CAD format)

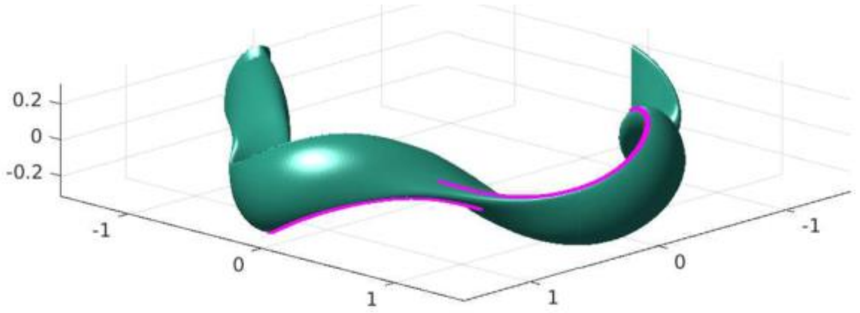
Field Line Diffusion Method

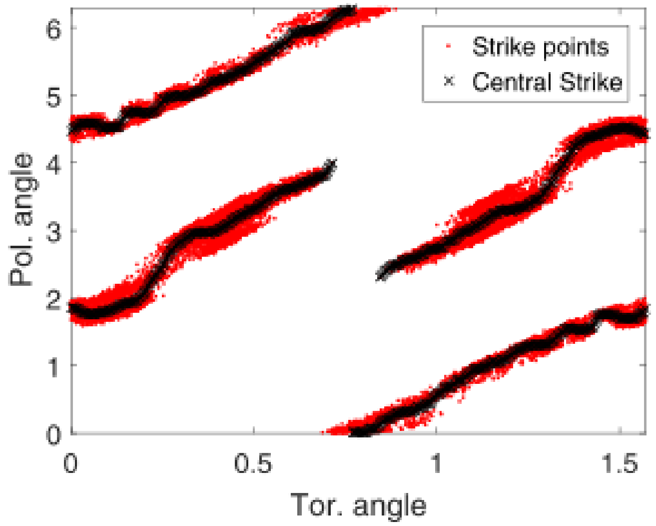
(Potential: Neural Network / Fit to condense results into power law model)

Strikeline Pattern
(iteration+optimisation)

→ **EMC3-Eirene Validation**

Example: resilient non-resonant divertor





A. Bader, et al.,
Phys. Plasmas 24 (2017)

Summary & Outlook

✓ **Heuristic island divertor model provides a good basis for systems codes**

✓ **100 TB of Heat Load Data from two W7-X Divertor campaigns available**
- Validation of each individual parameter possible (!)
- Not yet started, lack of resources

✓ **Systems Codes aspire to cover a wide range of stellarator configurations**
- Currently no divertor concept for Quasi-Axisymmetric configurations
- Provide 0-D requirements analysis by reversing the question
- Field line diffusion method to assess new configurations

Outlook:
- **A lot of work to do …. Master / PhD Projects ??**