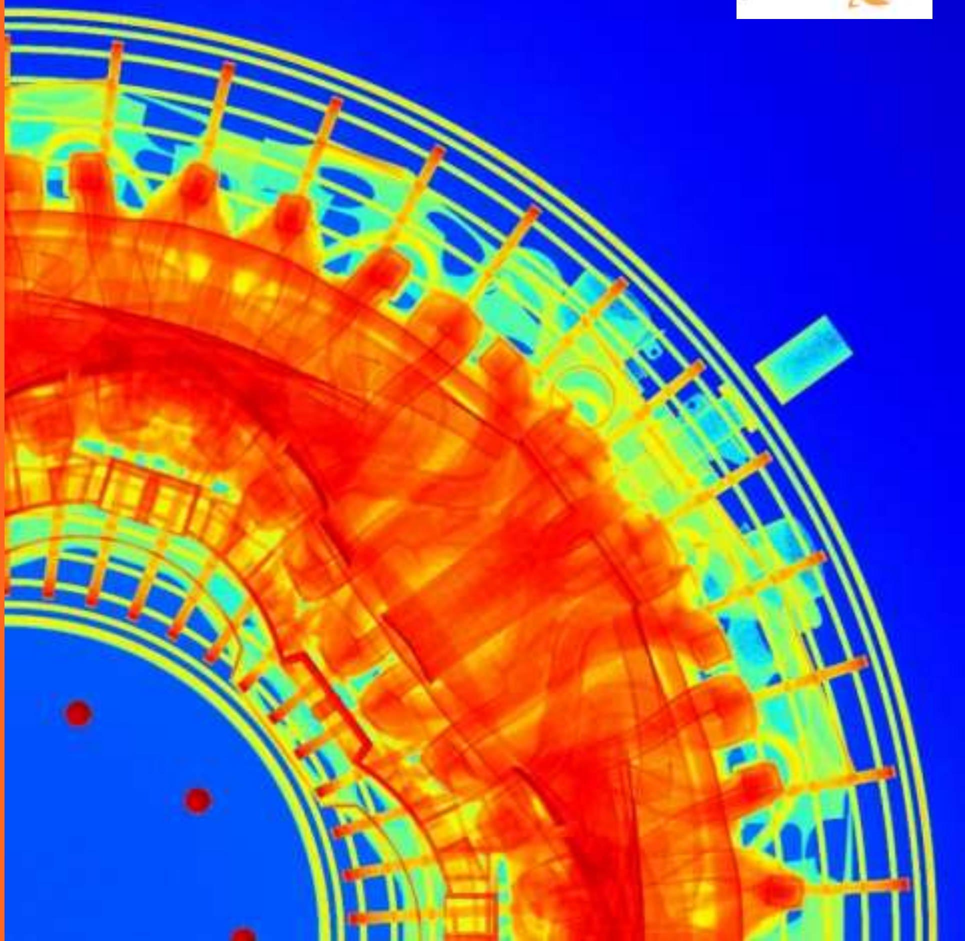
Serpent 2 neutronics model for W7-X

Serpent UGM

Simppa Äkäslompolo, J. Leppänen, J.P. Koschinsky, W7-X Team

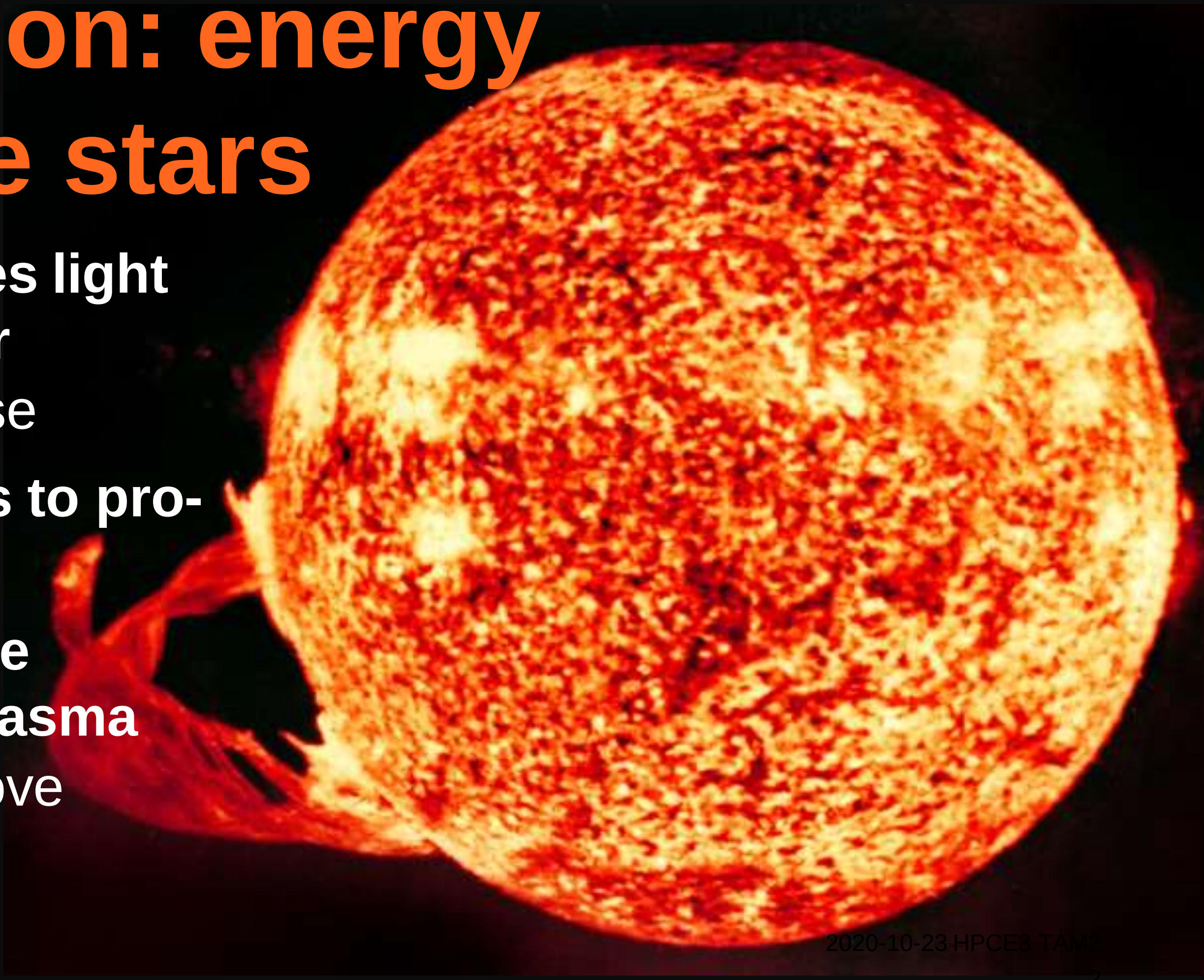
October 2020

Aalto University
School of Science



Nuclear Fusion: energy source of the stars

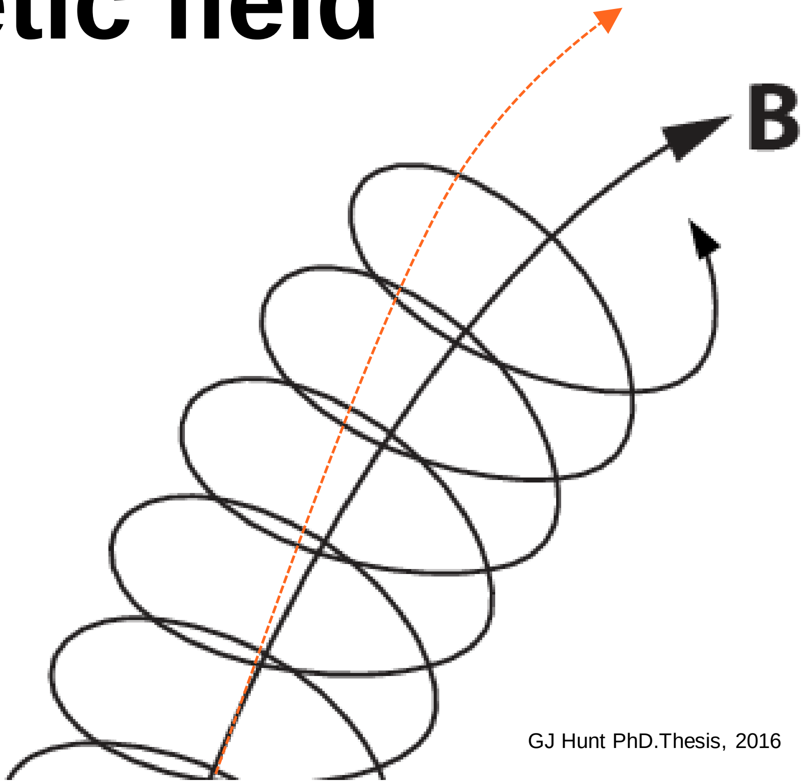
- **The Sun nuclear-fuses light elements into heavier**
  - Large energy release
- **Fusion research aims to pro-duce electricity**
- **Very high temperature → gas ionized into plasma**
  - Electrons & ions move separately



NASA

The hot plasma is confined with a torus shaped magnetic field

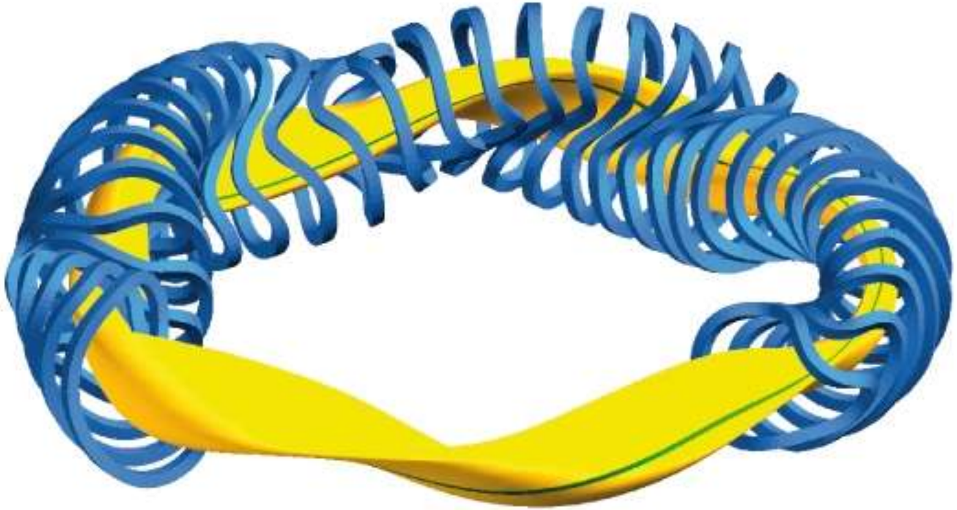
- **Charged particles follow the magnetic field,**
- **but only approximately:**
  - the confining field needs engineering.



GJ Hunt PhD.Thesis, 2016

The hot plasma is confined with a torus shaped magnetic field

- **Charged particles follow the magnetic field,**
- **but only approximately:**
  - the confining field needs engineering.
- **The stellarator is optimized with supercomputers.**
  - The confinement to be demonstrated.



Wendelstein 7-X stellarator (W7-X)

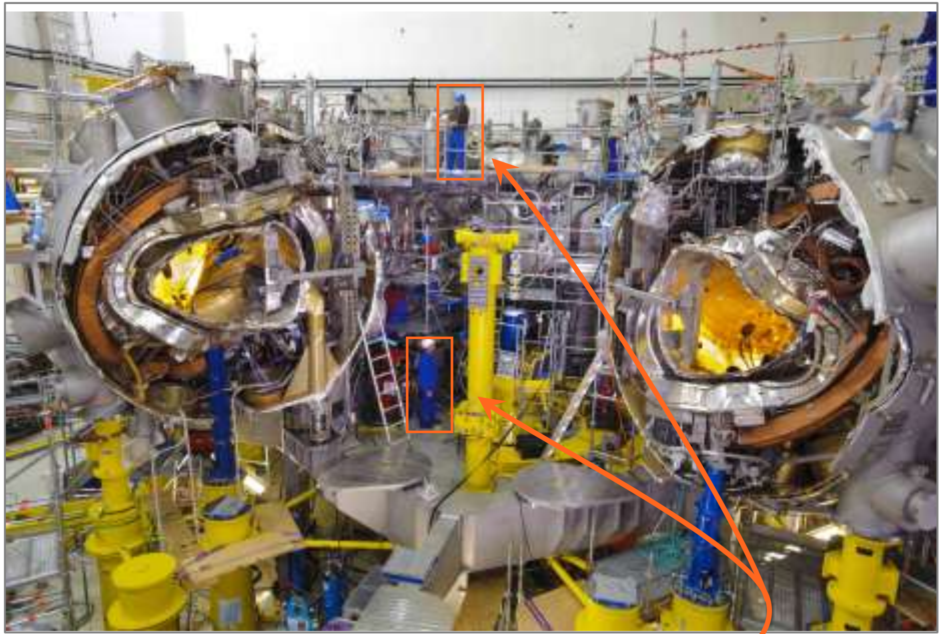
Magnetic coils & plasma shape

Aalto University
School of Science

W7-X is superconducting, steady state → complex

- **70.000 unique, 700.000 total parts**
  - Perhaps the largest integrated CAD model in existence
- **Inside the vacuum vessel:**
  - Fully water-cooled: 4 km water pipes [1]
- **Only key components included in the model**

[1] https://www.iter.org/doc/www/content/com/Lists/Stories/Attachments/680/ITER_W7X.pdf



W7-X Under construction.
Two humans for scale.

Aalto University
School of Science

Steps in expanding the model

1. Identify the most important component
2. Find the component in W7-X CAD model
3. Isolate and simplify in CATIA
4. Create a surface mesh
5. Test the mesh within SERPENT
6. Fix the mesh
7. Prepare the material definitions
8. Check the simulation

Freecad

`-checkstl` command line parameter

Neutrons are direct indicators of the fusion performance

- **Neutrons are produced in the fusion reactions**

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \longrightarrow ^{3}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}\ (2.45\ \mathrm{MeV})$$

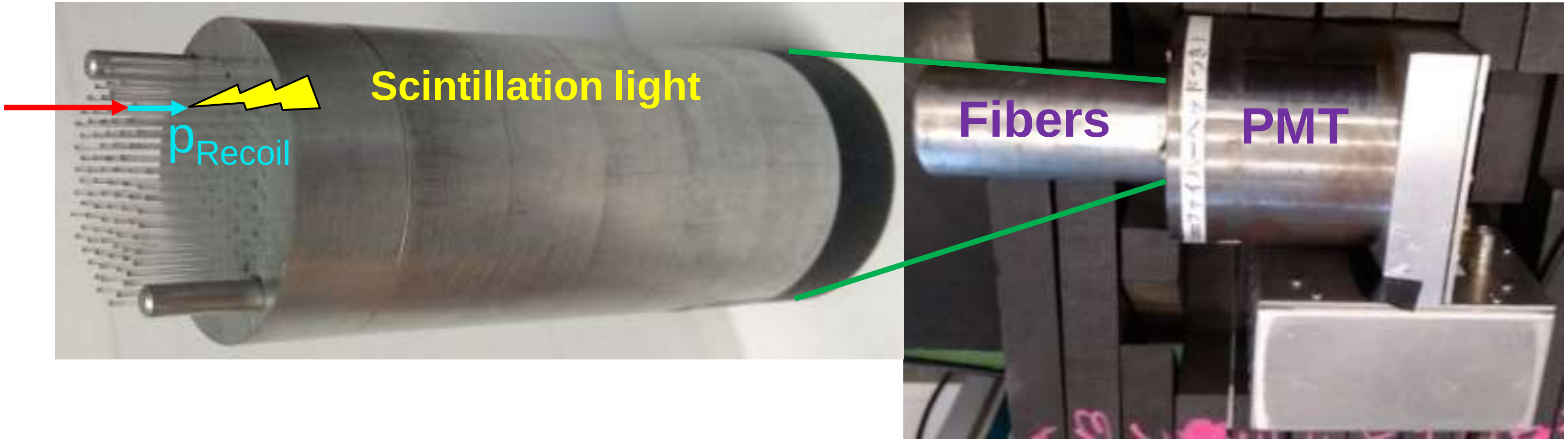
$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \longrightarrow ^{3}_{1}\mathrm{T} + ^{1}_{1}\mathrm{p}$$

$$\downarrow$$

$$^{2}_{1}\mathrm{D} + ^{3}_{1}\mathrm{T} \longrightarrow ^{4}_{2}\mathrm{He} + ^{1}_{0}\mathrm{n}\ (14.1\ \mathrm{MeV})$$

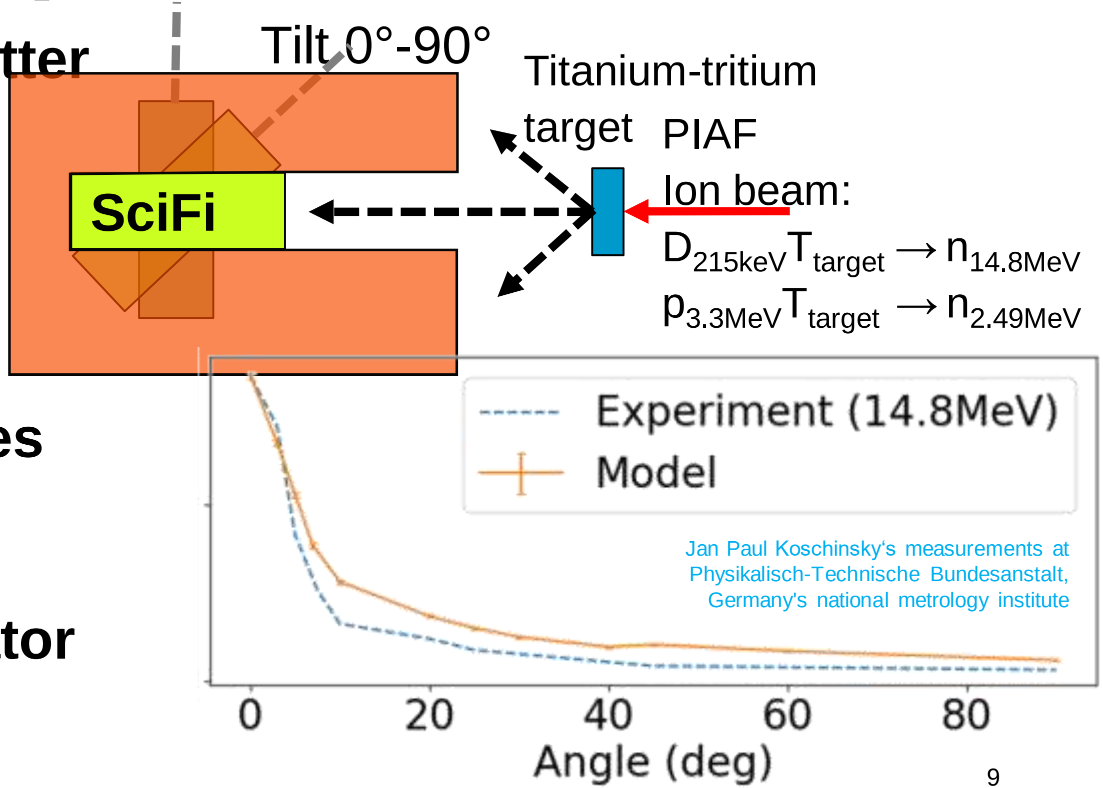
- **Currently W7-X operates only with hydrogen-1 ($^{1}_{1}\mathrm{H}$)**
  - Deuterium $^{2}_{1}\mathrm{D}$ under preparation
- **In W7-X, indication of confinement of fast ions**
  - Check the confinement of fast tritons
- **In this work measured with Scintillating Fibre 14 MeV neutron detector (SciFi)**

Scintillating Fibre 14.1 MeV neutron detector (SciFi)



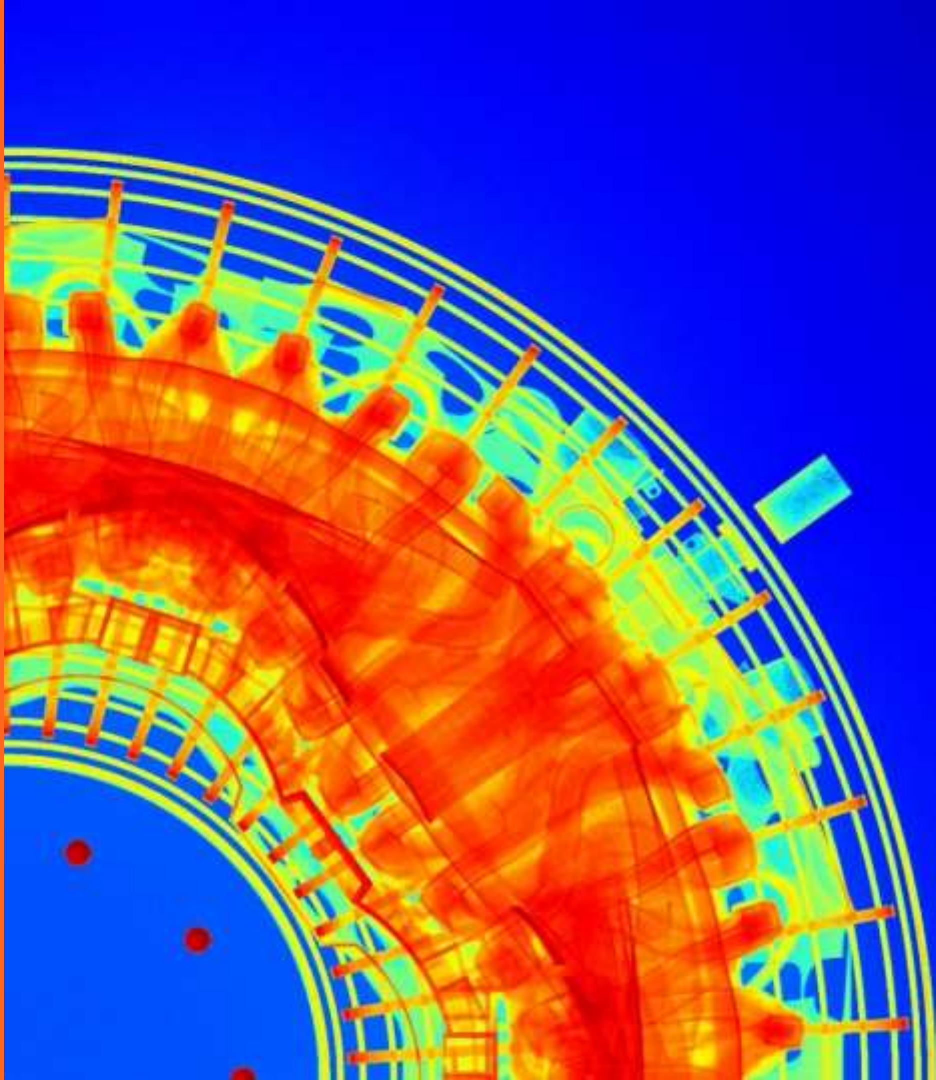
SciFi has anisotropic detection efficiency → implemented in DTL

- **SciFi detects neutrons better along fibres. Measured.**
- **SciFi optionally in a bPE collimator box.**
- **Model qualitatively reproduces the count-rates with bPE when using the directionality measured w/o the collimator**



Aalto University
School of Science

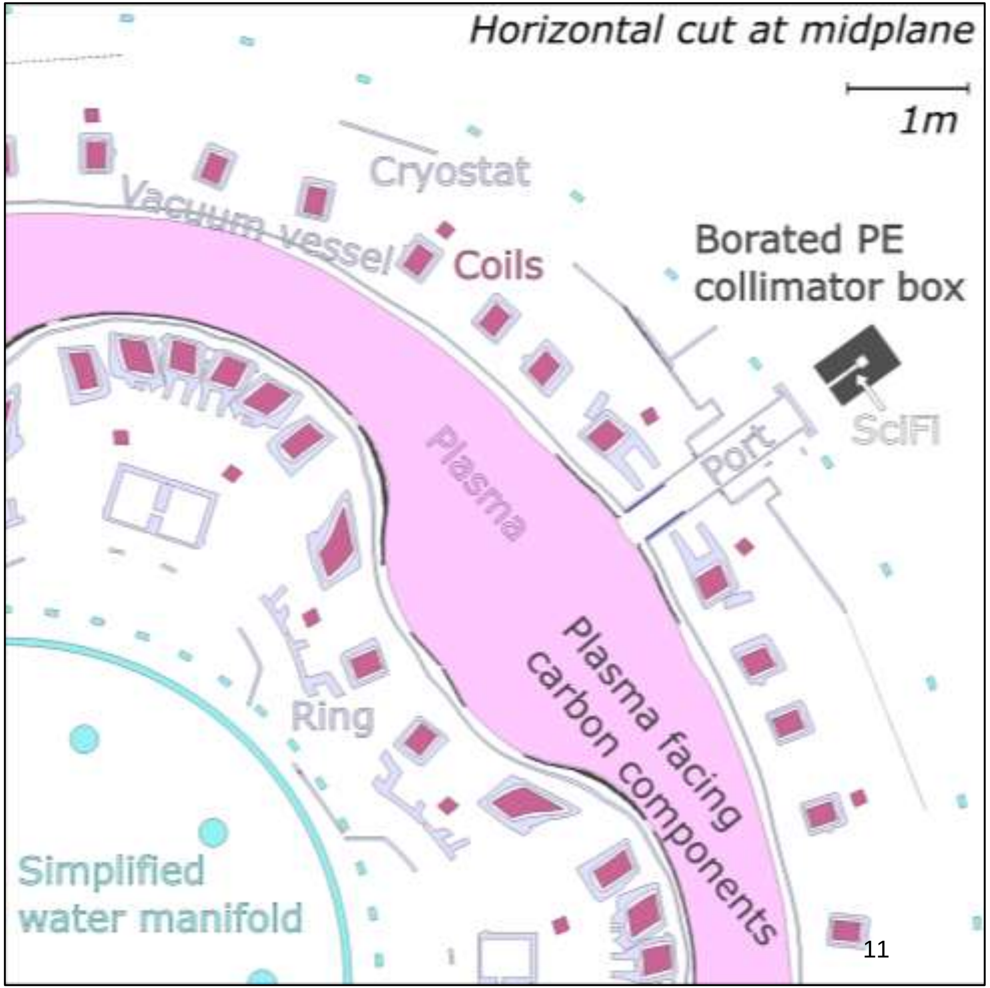
The Serpent 2 model of W7-X



Aalto University
School of Science

Many key components included

- **Triangular surface mesh (STL) based geometry definition**
  - (3×10^6 triangles, 15GB total memory)
- **Certain components with CSG, such as:**
  - simplified water manifold, torus hall, PE collimator



Aalto University
School of Science

Model optimization resulted in 100x faster model & higher quality

- **Geometry search mesh parameters**
- **Geometry structure**
  - Split geometry into disjoint domains
  - Organize mesh model into hierarchy of universe levels
- **VR WW via 3 iterations.**
  - Global VR
  - Detector optimization
    - bPE collimator not included

Weight windows & NBUF full

- **`SET NBUF 1000000`**
  (for 40 threads)
- **14.1 MeV → 1 MeV**
  Little absorption, weak scattering
- **VR weight windows change 11 orders of magnitude**
  - (in the figure, more in total!)
- **Need a routine to analyse the buffer?**
  - dump the buffer to a file for analysis?

Neutron following is embarrassingly parallel

- **Every neutron history is independent**
  - Collect histograms
  - Buffer neutrons
- **Serpent 2 is MPI+OpenMP parallel**

- **Run on 32 nodes with 40 threads each for 3 hours**
  - Larger simulations possible to reduce noise or increase resolution
- **4.5×10^9 initial neutrons (868 histories/(CPU s)**

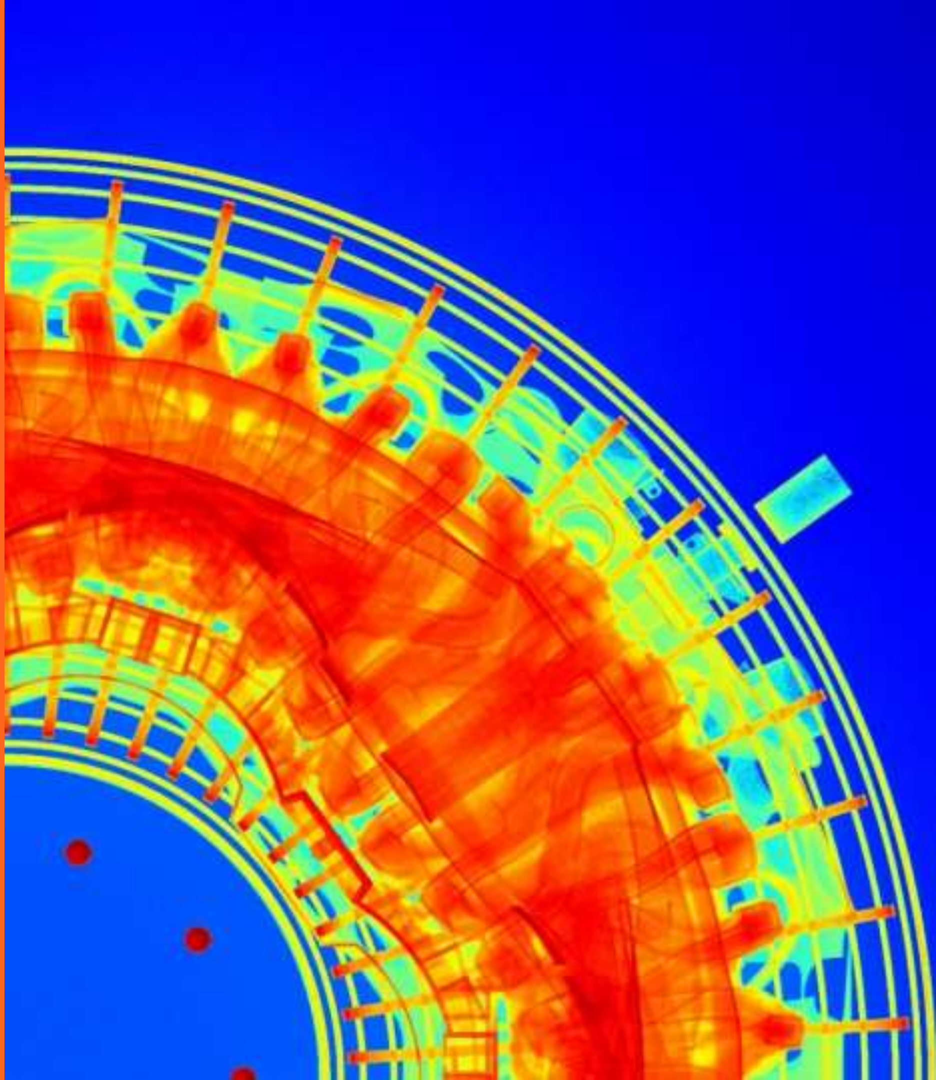
Instrument function:
DTL dx,dy,dz by birth location

$$\Phi_{\mathrm{det}} = \frac{1}{V_{\mathrm{det}}} \int_{\mathrm{tracks}} \theta w \,\mathrm{d}l$$

$$\frac{\mathrm{counts}}{\mathrm{s}} = \sum_{\mathrm{bins}} \int_{\mathrm{bin}} \underbrace{A_{\epsilon} \Phi_{\mathrm{det}} \frac{V_{\mathrm{plasma}}}{N V_{\mathrm{bin}}}}_{\text{instrument function}} S \,\mathrm{d}V,$$

- **Probability of detecting a neutron born in a given location.**
- **Bin the flux as a function of neutron birth location**
  - Anisotropic efficiency (calib.)
- **Integrate over neutron source**
  - Effective active area (calib.)
  - `srcrate` (isotropic src)

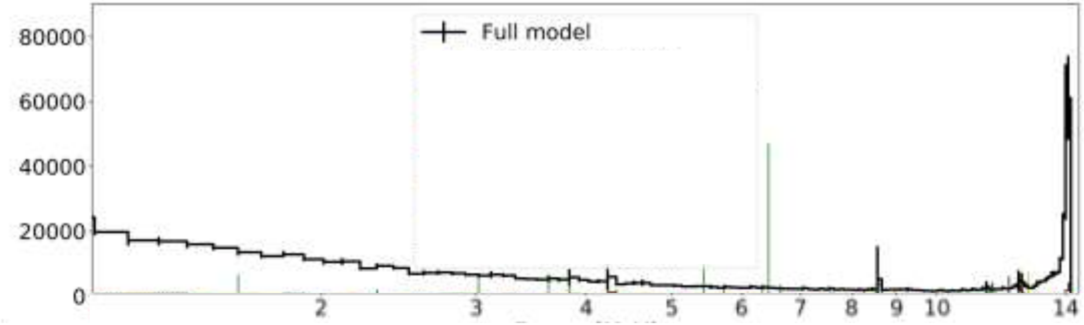
Results



Aalto University
School of Science

Components shadow neutrons, little back-scattering

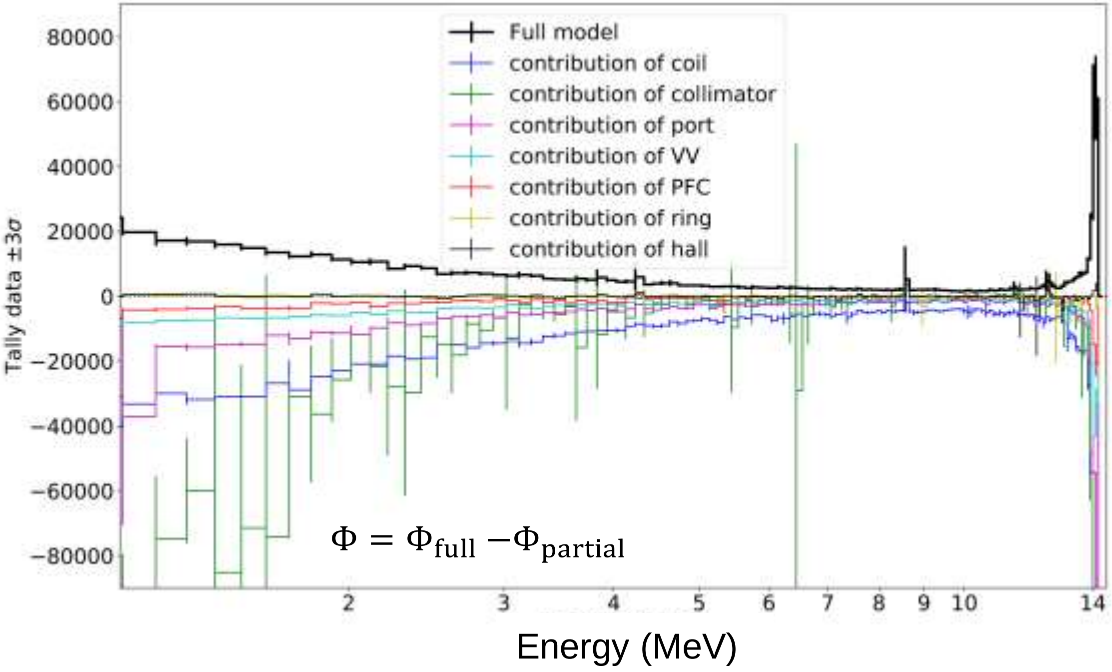
- **The detector sees scattered neutrons**



Energy (MeV)

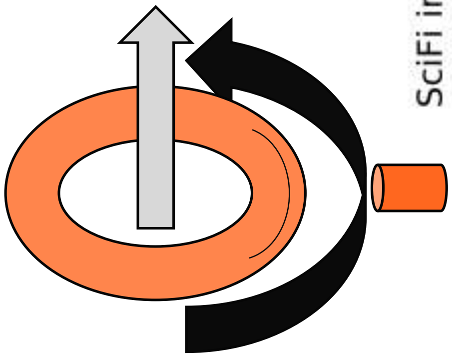
Components shadow neutrons, little back-scattering

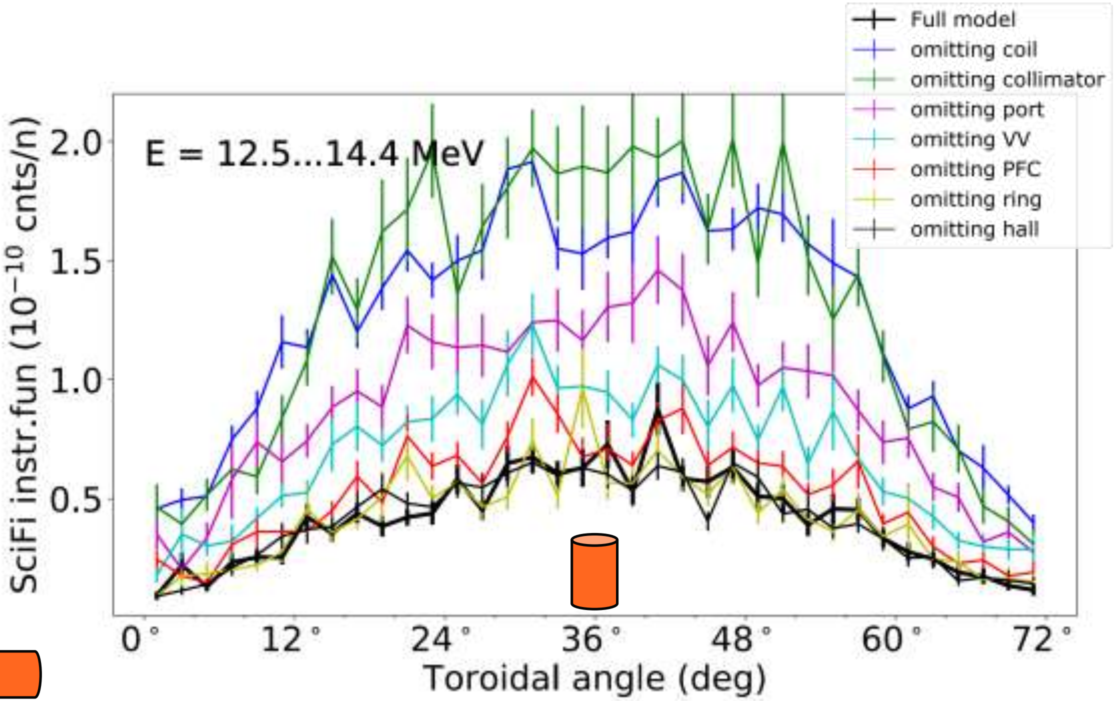
- **The detector sees scattered neutrons**
- **Sensitivity study: remove various components**
  - components shadow neutrons



SciFi is wide-angle

- Detection efficiency near the plasma centre at various locations around the torus
- Non-local measurement



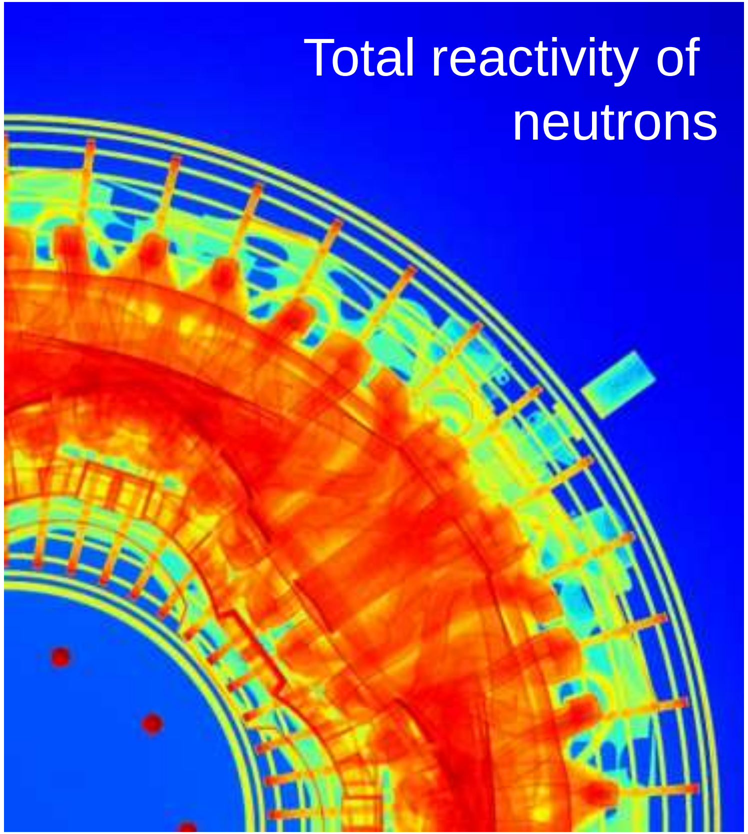


Aalto University
School of Science

Estimate: 50 ms integration time needed for SciFI

1. **Calculate fusion rate using ASCOT suite of codes**
2. **Calculate neutron flux at the SciFi detector using Serpent**
3. **Convert flux to counts using measured calibration factors**

→ 160 cnts/s from neutrons (14.1MeV) → estimate SciFi needs 50 ms integration time



Summary

arXiv:2010.10043 [physics.comp-ph]
Proceedings of the 2020 SOFT-conference
(Symposium on fusion technology)

- **A proof-of-principle Serpent 2 neutronics model of the W7-X stellarator was constructed:**
  - key components included
  - model optimization crucial
- **The SciFi detector is expected to require 50 ms integration time**
  - The detector measures neutrons from a large plasma volume

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 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. This work was partially funded by the Academy of Finland project No. 328874 and No. 324759. The authors wish to acknowledge CSC – IT Center for Science, Finland, for computational resources as well as the Max-Planck computing & data facility for the same. The HPCE^3 programme and Walter Ahlström foundation contributed to the funding of the work. The authors want to thank the operators and team at PTB for support during the measurements performed at the PTB ion accelerator facility, especially E. Pirovano, A. Lücke, M. Zboril and A. Zimbal.

Aalto University
School of Science