Neutronics source modeling for stellarator power reactors of the HELIAS-type

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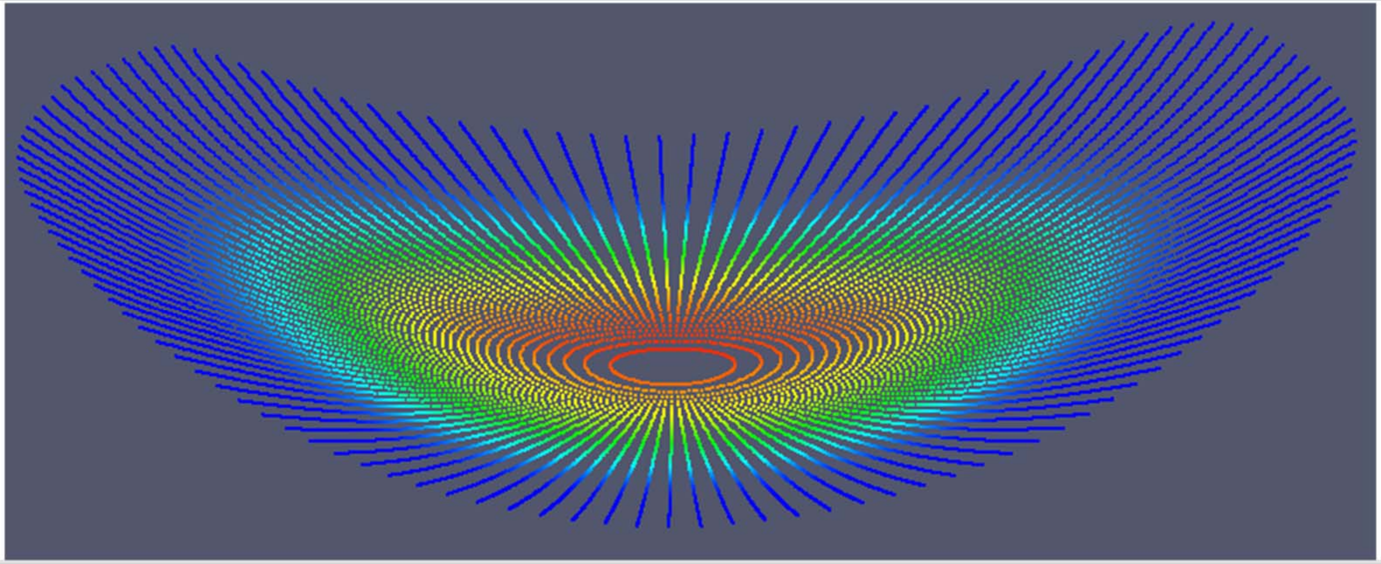


Outline

- Introduction
- Neutron source development
- Verification of the MCNP source subroutine
- Conclusion and outlook

INTRODUCTION

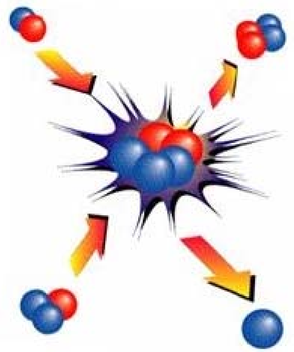
Motivation

- Objective: development of a suitable computational approach for neutronic analyses of a stellarator fusion reactor and to perform design analyses of the HELIAS power reactor

- Separated into three parts:
    1. Development of a neutron source model
    2. Approaches for stellarator modeling
    3. Design analyses for the HELIAS reactor

Fusion Basics

- Different magnetic confinement concepts are currently considered for a future fusion power reactor
- Magnetic fields generated with superconducting field coils confine the hot plasma inside a torus in which the fusion reaction take place
- Predominant fusion reaction in the fusion power reactor:



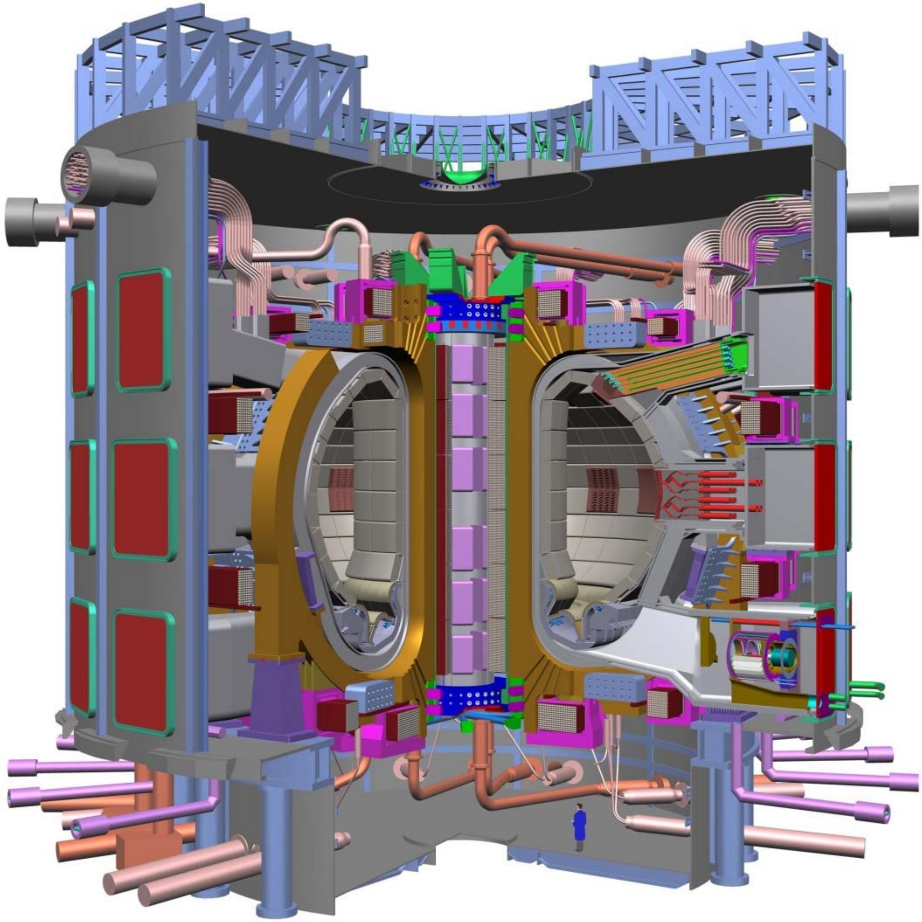
- Deuterium is naturally available, Tritium needs to be produced at the reactor → Neutron induced Tritium breeding reaction out of Lithium

Electricity Output of Fusion Power

Water + Lithium → Mean electrical consumption of a family house in Europe for 1 year

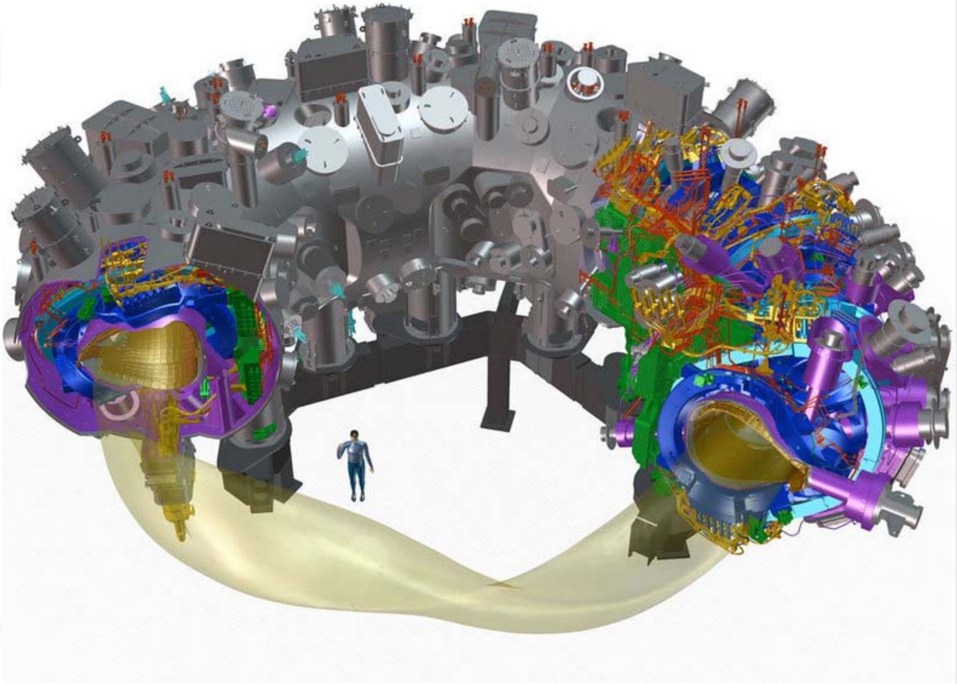
Credits: newsgag.net, apple.com, staticelectricsbrisbane.com.au

Comparison: Tokamak and Stellarator



Tokamak

Credit: iter.org

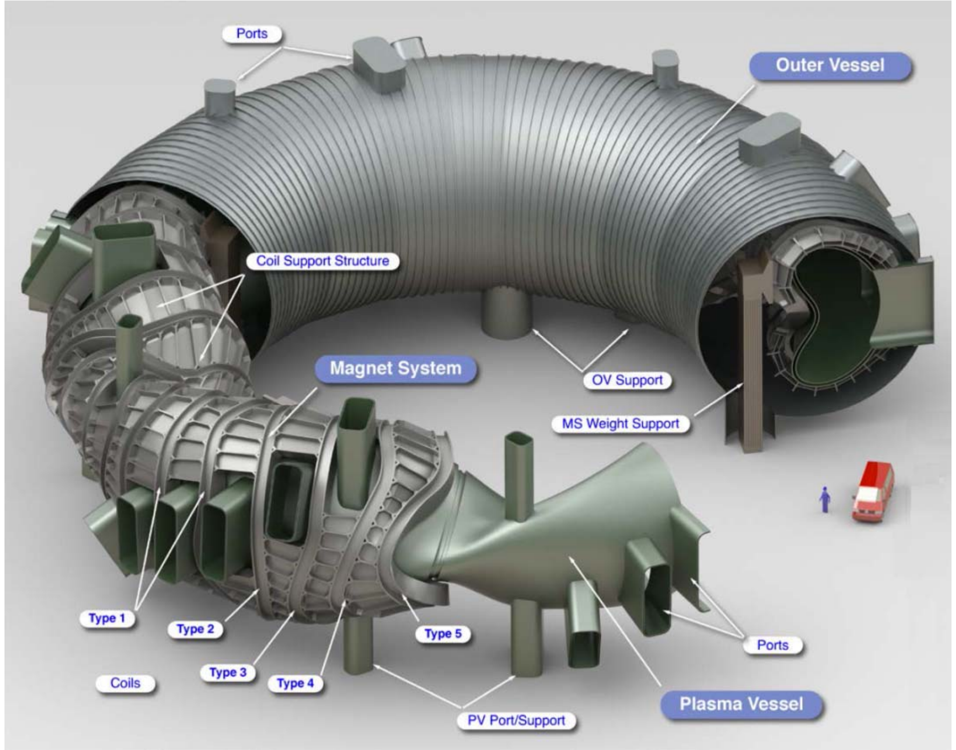


Stellarator

Credit: ipp.mpg.de

HELIAS in overview

- HELIAS = **HELI**cal-Axis **A**dvanced **S**tellarator
- Extrapolated and upgraded version of Wendelstein 7-X
- Demonstration power reactor study with D-T Fusion
- Plasma volume: ~1400 m^3
- Fusion power: ~3000 MW
- Technology for this reactor will be investigated

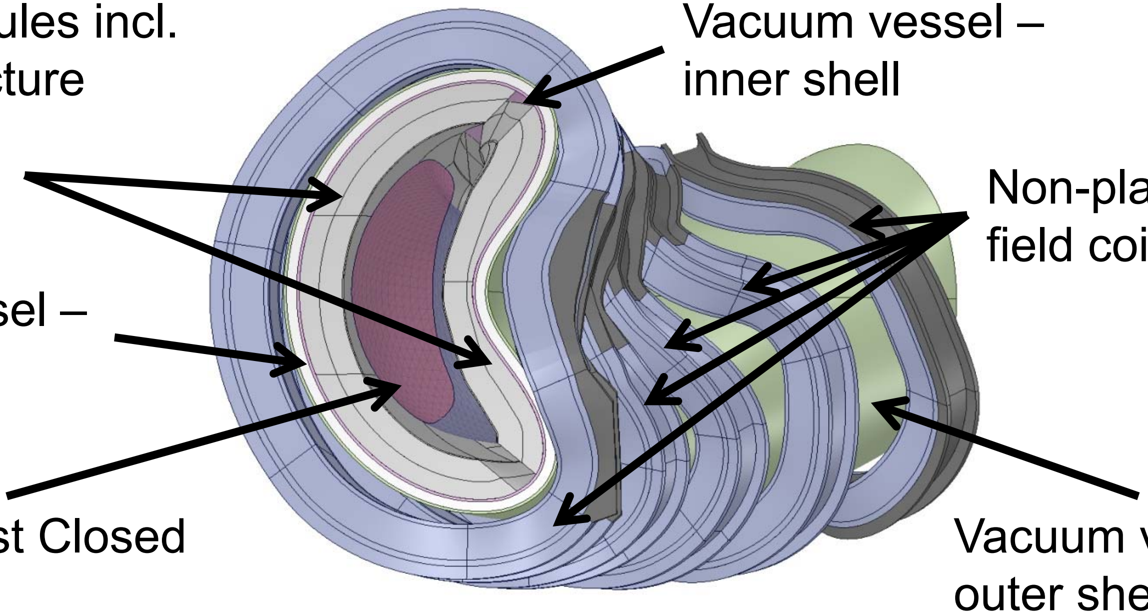


HELIAS 5-B

Credit: F. Schauer, et al., *HELIAS 5-B magnet system structure and maintenance concept*, Fus. Eng. Des. 88 (2013)

Objective of a neutronics simulation

Provide the distribution of the neutrons in space and energy. Based on this distribution, calculate the nuclear responses of interest in the reactor components. Therefore geometry and neutron source needs to be represented as accurately as possible.



Blanket modules incl.
support structure
and shield

Vacuum vessel –
shield

Plasma : Last Closed
Flux Surface

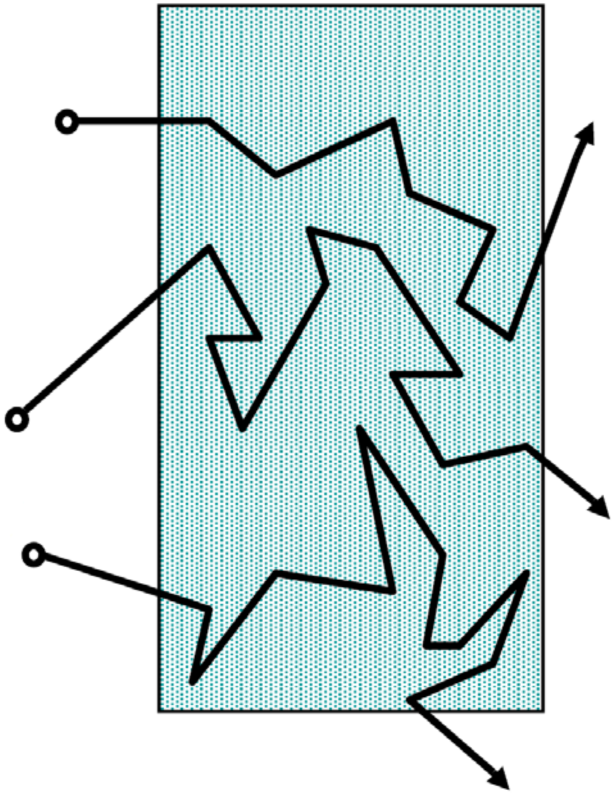
Vacuum vessel –
inner shell

Non-planar
field coils

Vacuum vessel –
outer shell

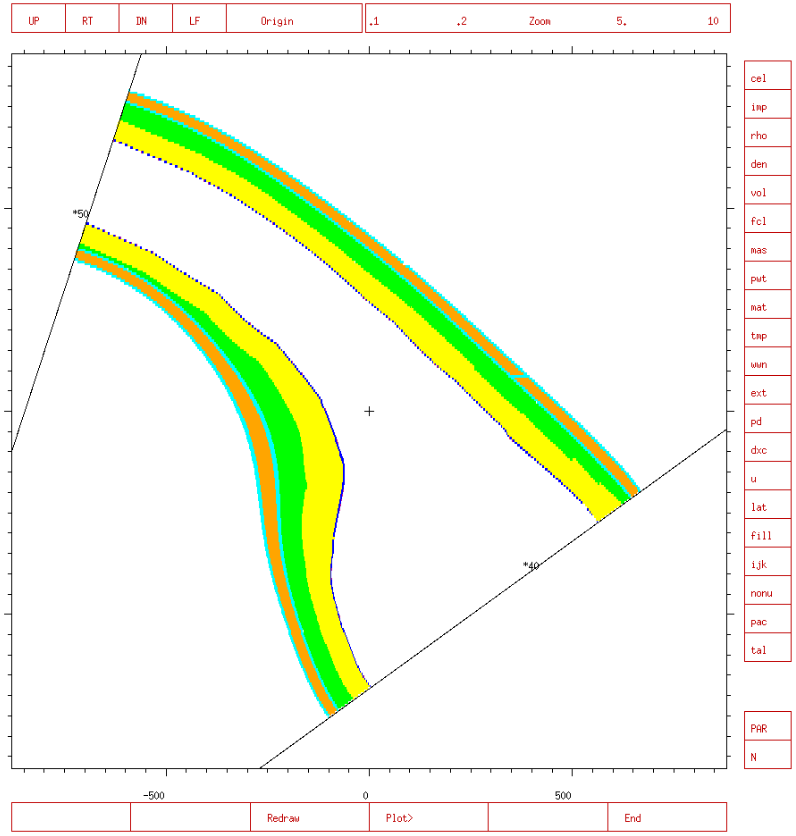
Monte Carlo Method and MCNP

- Simulation of the true physical process on a microscopic level
- Probabilistic method → statistical registration of stochastically processes
- Run many histories to get many events and count them → results are statistically reliable
- Every history contributes the same weight for the end result
- Monte-Carlo (MC) Method is the preferred method for fusion neutronics



Monte Carlo Method and MCNP

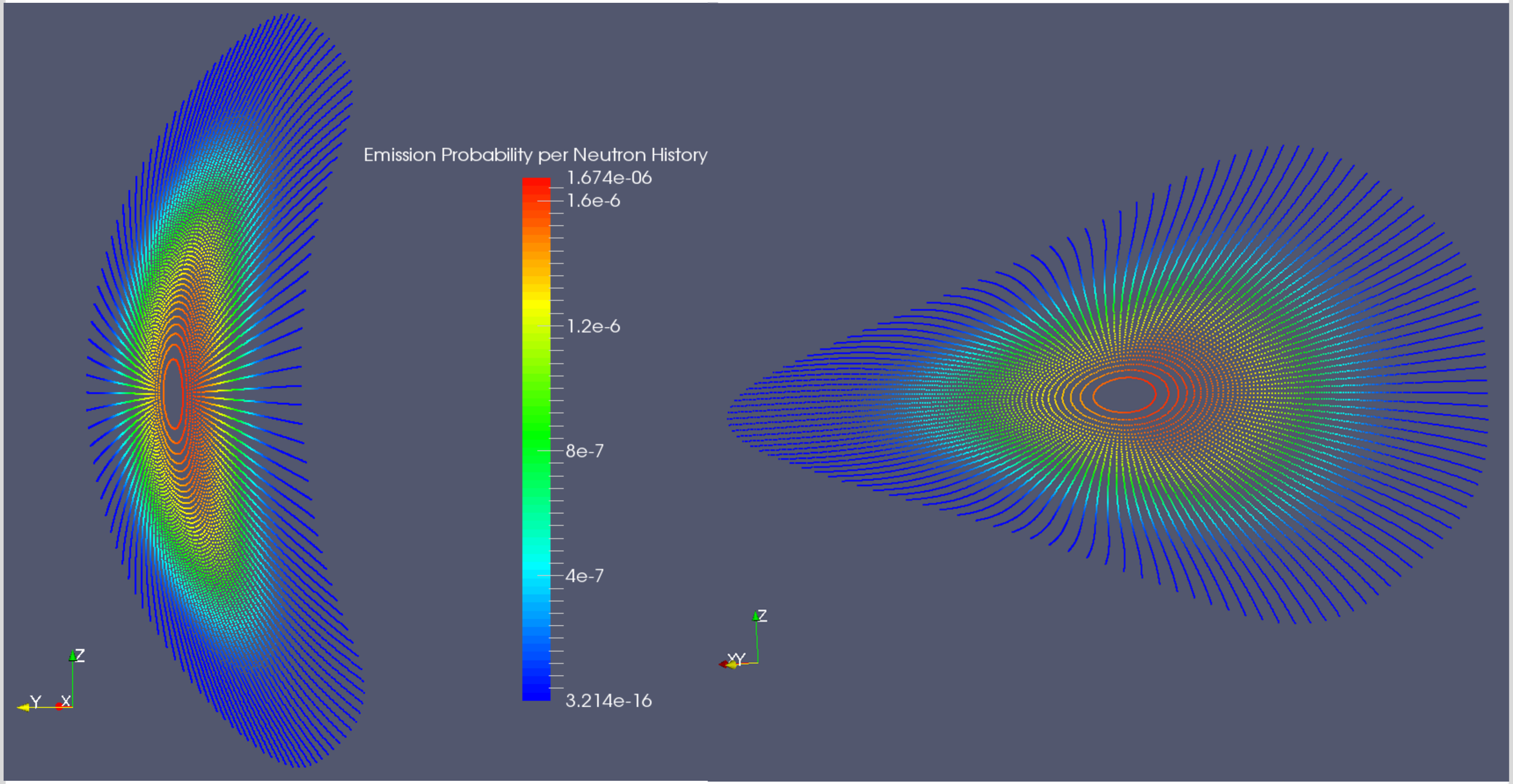
- MCNP (**M**onte **C**arlo **N**-**P**article) is a general-purpose particle transport code developed by *Los Alamos National Laboratory, USA*
- Code is well validated in fission, fusion and accelerator field
- Standard code for fusion neutronics calculations of ITER
- Treats an arbitrary three-dimensional configuration of materials in geometric cells → can handle complex geometry



Cross section at the XY center plane of the HELIAS 5-B in the MCNP geometry plotter

NEUTRON SOURCE DEVELOPMENT

Neutron source distribution



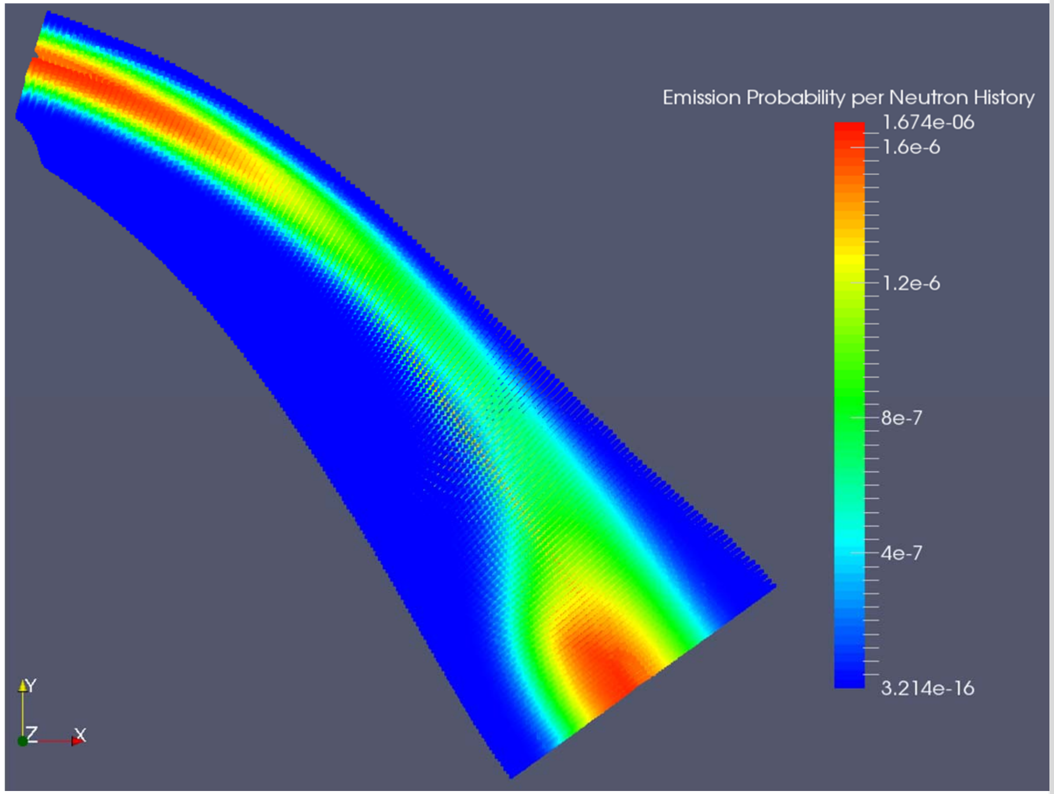
Bean-shape

Triangular-shape

Emission probability of the source perpendicular to the main axis

Neutron source distribution

- Plasma physics calculation performed with VMEC code
- Tabulated data contains data point and corresponding emission probability per neutron history which is distributed over ten orders of magnitude (10^{-6} to 10^{-16})
- Each data point represents the surrounded volume element



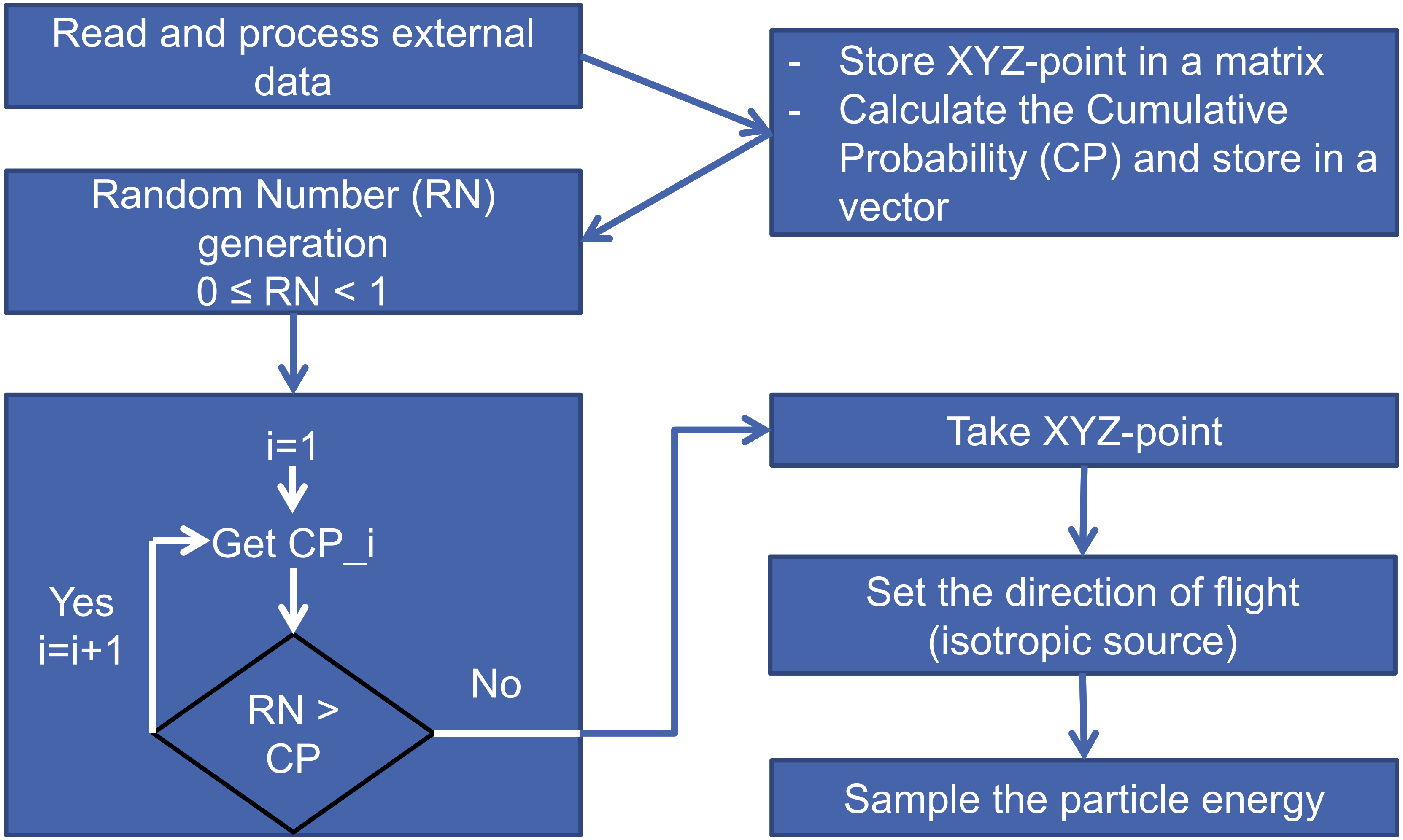
Emission probability of the source at the main axis of the half-field period, sliced at the XY center plane

Neutron source development

- Approach:

- ➢ Develop dedicated source subroutine for neutronics calculation → plasma distribution is too complex for the standard source
- ➢ Source position (X,Y,Z) and emission probability stored in an external file
- ➢ Calculate and store cumulative probability of the emission probability
- ➢ Sample source position through the cumulative probabilities → regions with higher emission probability have a higher sample frequency → same weight of all emitted neutrons
- ➢ Sample energy and direction of flight (angle)

Source point sampling



Read and process external data

- Store XYZ-point in a matrix
- Calculate the Cumulative Probability (CP) and store in a vector

Random Number (RN) generation
$0 \le RN < 1$

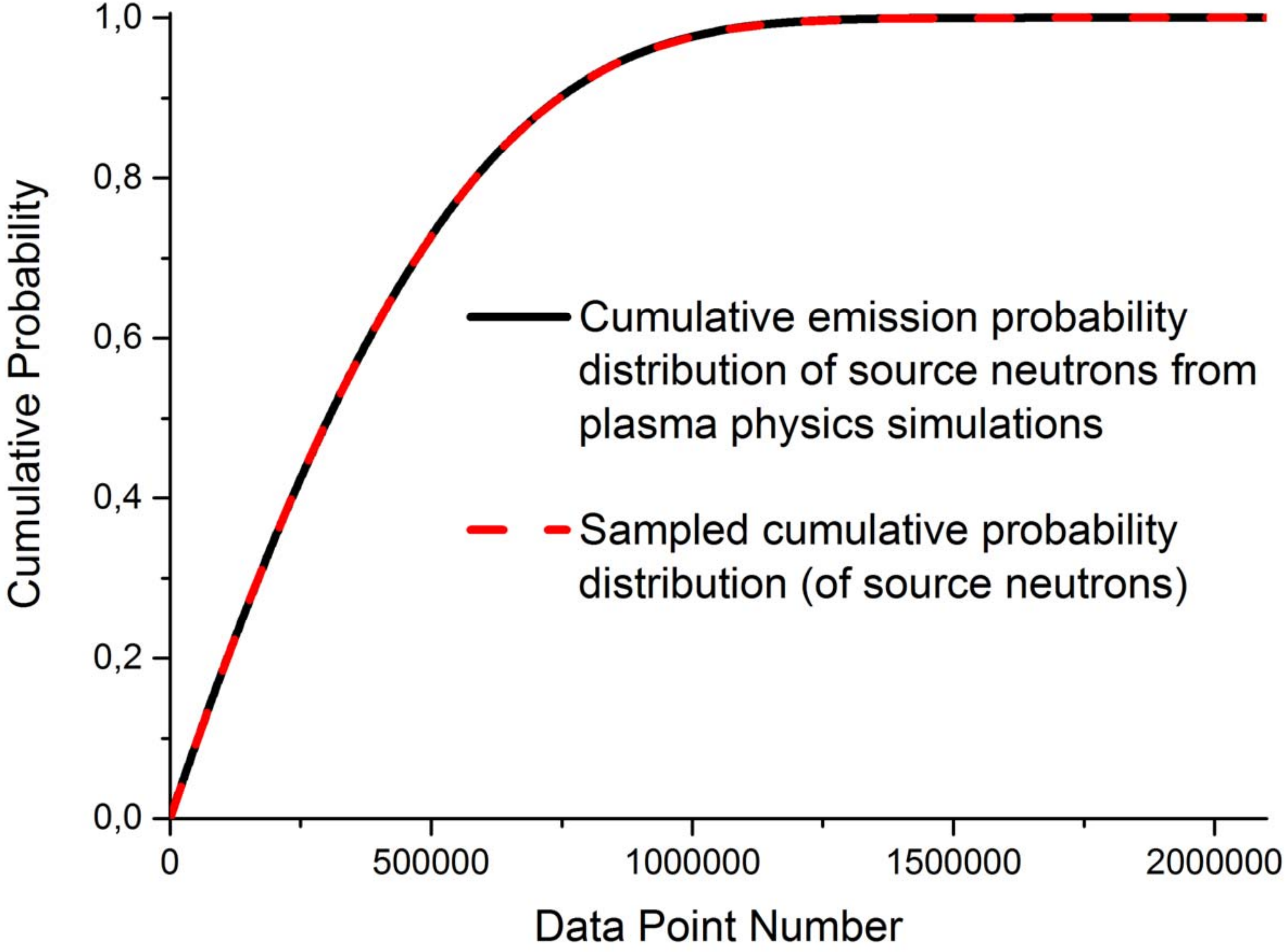
Take XYZ-point

Set the direction of flight (isotropic source)

Sample the particle energy

VERIFICATION OF THE MCNP SOURCE SUBROUTINE

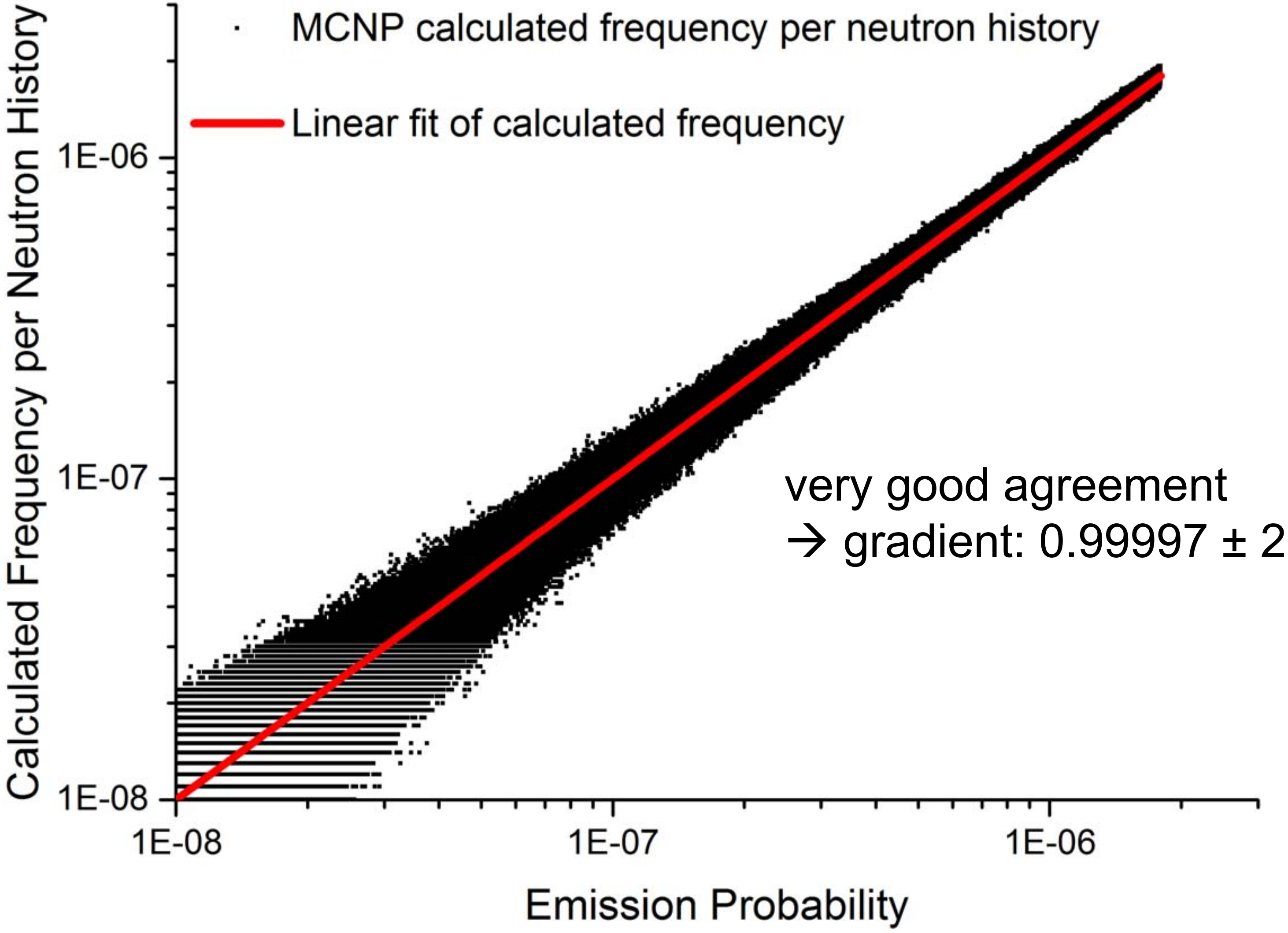
Cumulative probability of the emission probability



Checking of the source points

- Comparison of the XYZ-points from the plasma physics and the neutron physics calculation
- Feature in MCNP: store all sampled source points in an external file
- Used 10^9 particle, size of external file ~115 GB
- Post processing: generate frequency of the sampled source points → list with XYZ-points and frequency
- Compare the generated frequency with the emission probability from original data file
- Test performed with MCNP5 and MCNP6

Checking of the source points



very good agreement
→ gradient: 0.99997 ± 2.4x10^{-5}

Calculated frequency of the source positions compared with the original emission probability

SUMMARY AND OUTLOOK

Summary

- Source development and testing have been successfully finished for MCNP5 and MCNP6
- Cumulative probability of sampled and original data fit to each other
- Random sampling of XYZ-points in MCNP works and reproduce the original data
- → Source has been verified for reliability and is ready for usage

Outlook

- CAD based geometry modeling of the stellarator
- Generating a CAD based MCNP geometry with three different geometry translation approaches
- Nuclear design analyses and optimization:
  - Neutron wall loading
  - Tritium breeding performance
  - Shielding performance
  - Nuclear heating

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