Simulation of Scrape-Off Layer Magnetic Field in W7-X

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Introduction

Coil misallignment has been confirmed as the main source of error fields in W7-X.

- The effect on limiter connection lengths is examined.
- Predictions of divertor asymmetries are made.
- Validation of fieldline diffusion is presented.

Methods

In order to understand scrape-off layer physics, we trace fieldlines with the FIELDLINES code.

- CAD, measured, and FEM coil models[1] are used.
- Limiter connection lengths are examined.
- Fieldline diffusion implemented to model divertor heat loads.

Fieldline Model

The equation of motion of a fieldline is $\frac{d\vec{R}}{ds} = \frac{\vec{B}}{|\vec{B}|}$. In cylindrical coordinates, applying $\frac{d\Phi}{ds} = \frac{B_\Phi}{R|\vec{B}|}$ yields the equations of motion $\frac{dR}{d\Phi} = \frac{RB_R}{B_\Phi}$, $\frac{dZ}{d\Phi} = \frac{RB_Z}{B_\Phi}$ for a toroidal field. These equations are integrated over Φ to trace fieldlines.

Diffusion is modelled by adding a perpendicular displacement $\vec{\delta} \cdot \vec{B} = 0$ to the equation of motion $\frac{d\vec{R}}{ds} = \frac{\vec{B}}{|\vec{B}|} + \vec{\delta}$, which results in the equations:

$$\frac{dR}{d\Phi} = \frac{RB_R + |\vec{B}|\delta_R}{B_\Phi + R|\vec{B}|\delta_\Phi}, \quad \frac{dZ}{d\Phi} = \frac{RB_Z + |\vec{B}|\delta_Z}{B_\Phi + R|\vec{B}|\delta_\Phi}$$

By assuming a small field pitch, $\delta_\Phi << 1$ and $B_\Phi \sim |\vec{B}|$, we can approximate:

$$\frac{dR}{d\Phi} = \frac{RB_R}{B_\Phi} + \frac{|\vec{B}|}{B_\Phi}\delta_R, \quad \frac{dZ}{d\Phi} = \frac{RB_Z}{B_\Phi} + \frac{|\vec{B}|}{B_\Phi}\delta_Z$$

This gives a displacement $\frac{|\vec{B}|}{B_\Phi}\vec{\delta}$ in the RZ-plane which we can apply in regular intervals of Φ. For 2D Brownian motion, the standard deviation of displacement over a single timestep with diffusion coefficient D is

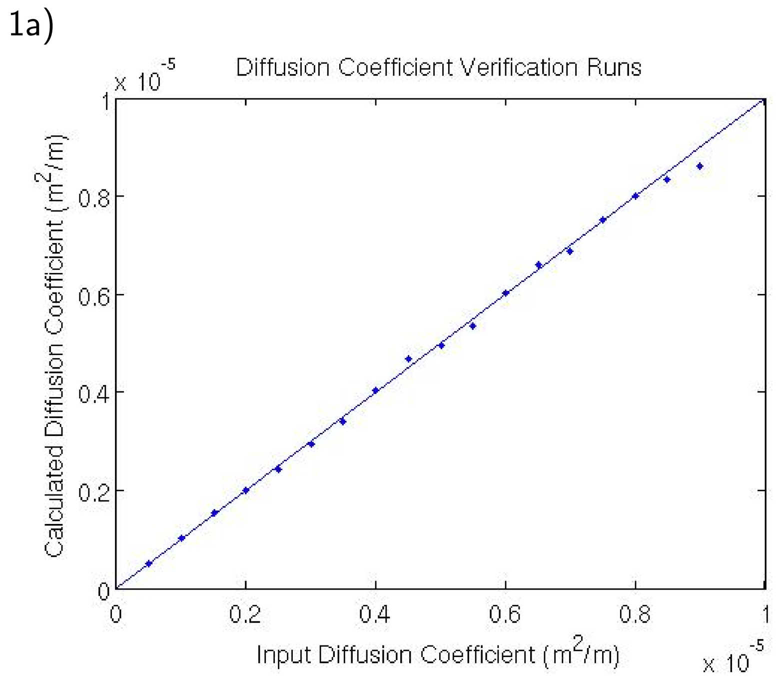
$$k = \sqrt{2Dds} = \sqrt{2DR|\vec{B}|d\Phi/B_\Phi}$$

Therefore at each increment of Φ we apply a displacement:

$$\frac{|\vec{B}|}{B_\Phi}\delta_R = \frac{|\vec{B}|}{B_\Phi}n_R\sqrt{2DR|\vec{B}|d\Phi/B_\Phi}, \quad \frac{|\vec{B}|}{B_\Phi}\delta_Z = \frac{|\vec{B}|}{B_\Phi}n_Z\sqrt{2DR|\vec{B}|d\Phi/B_\Phi}$$

where n_R and n_Z are normally distributed random values with $\sigma = 1$

1a)



1b)

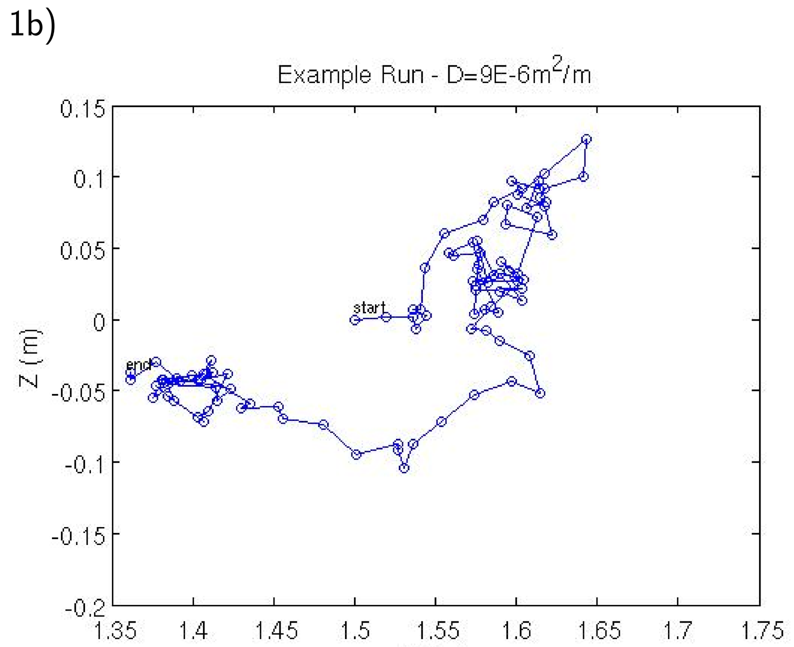


Figure 1 - Diffusion Model Benchmarking

The diffusion model was benchmarked in a purely toroidal field, tracing from a start point at $R = 1.5m$ with diffusion coefficient (D) varied. 4096 runs tracing 100 orbits at each value of D.

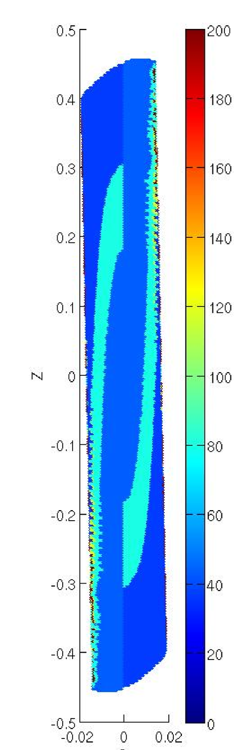
a) Diffusion coefficient verified by calculating $D_{eff} = MSD/(4 * L)$.
- MSD is mean squared displacement after 100 orbits, and $L = 100 * 2 * pi * 1.5m$ is estimated path length.
- $D_{eff} = D_{in}$ line added to plot for reference.

b) An example run illustrating random walk. Points taken at $\Phi = 0$ after each orbit.

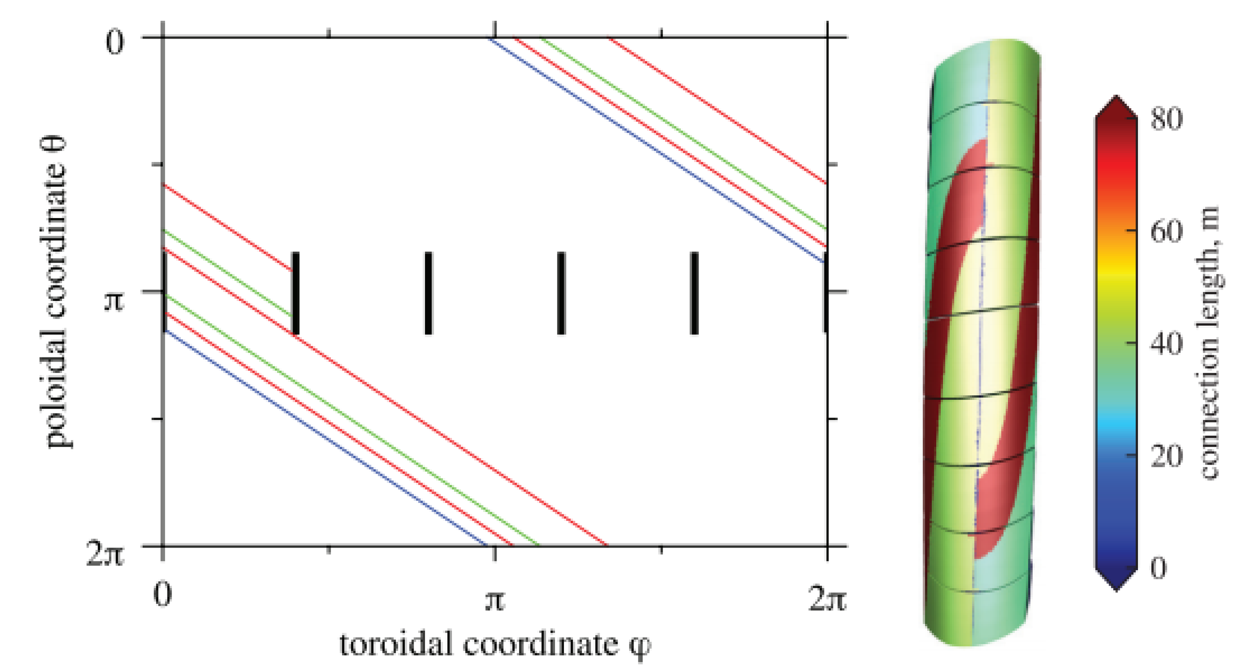
Limiter Connection Length Calculation

- Tracing confirms previous models of limiter connection length distribution[3].
- Error field induced asymmetry in limiter connection lengths resembles experimental results.
  - Features walk off limiter edge as observed in OP 1.1.

2a)

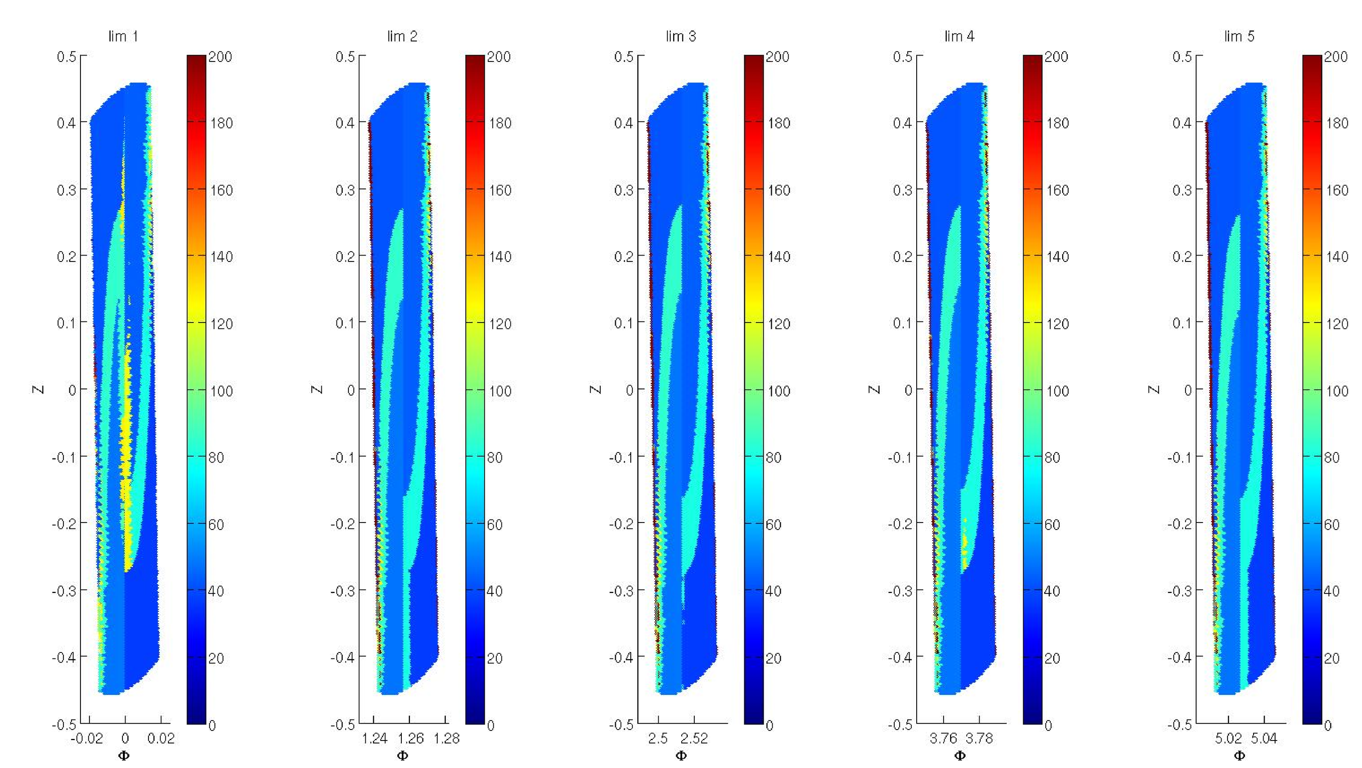


2b)



Above figure by Pedersen et. al.[3]

2c)



2d)

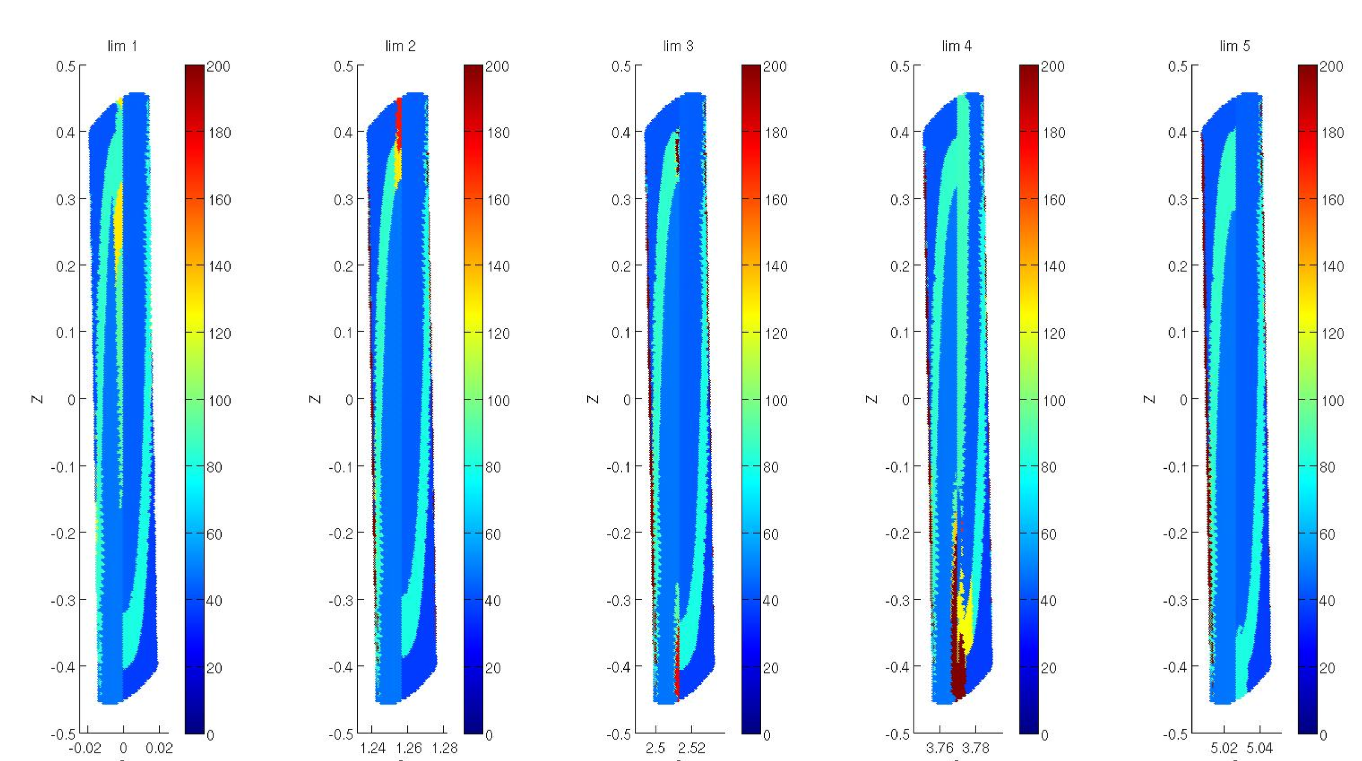


Figure 2 - Limiter Connection Lengths

All lengths in meters. All angles in radians.

a) Traced using ideal CAD coil positions, demonstrating stellarator symmetry.

b) Plots by Pedersen et. al.[3] confirming results for ideal case and illustrating connection paths.

c) Traced using coils adjusted for measured deviation in construction[1], showing broken symmetry.

d) Traced using coils adjusted for deviation in construction and deformation under load calculated by FEM[1].

Diffusion Modelling of Divertor Heat Flux

- Initial results do not indicate significant load asymmetry.
- Diffusing fieldlines traced from closed surface near edge with $D = 5x10^{-4}m^2/m$.
- Further modelling required to refine predictions.

3a) 3b)

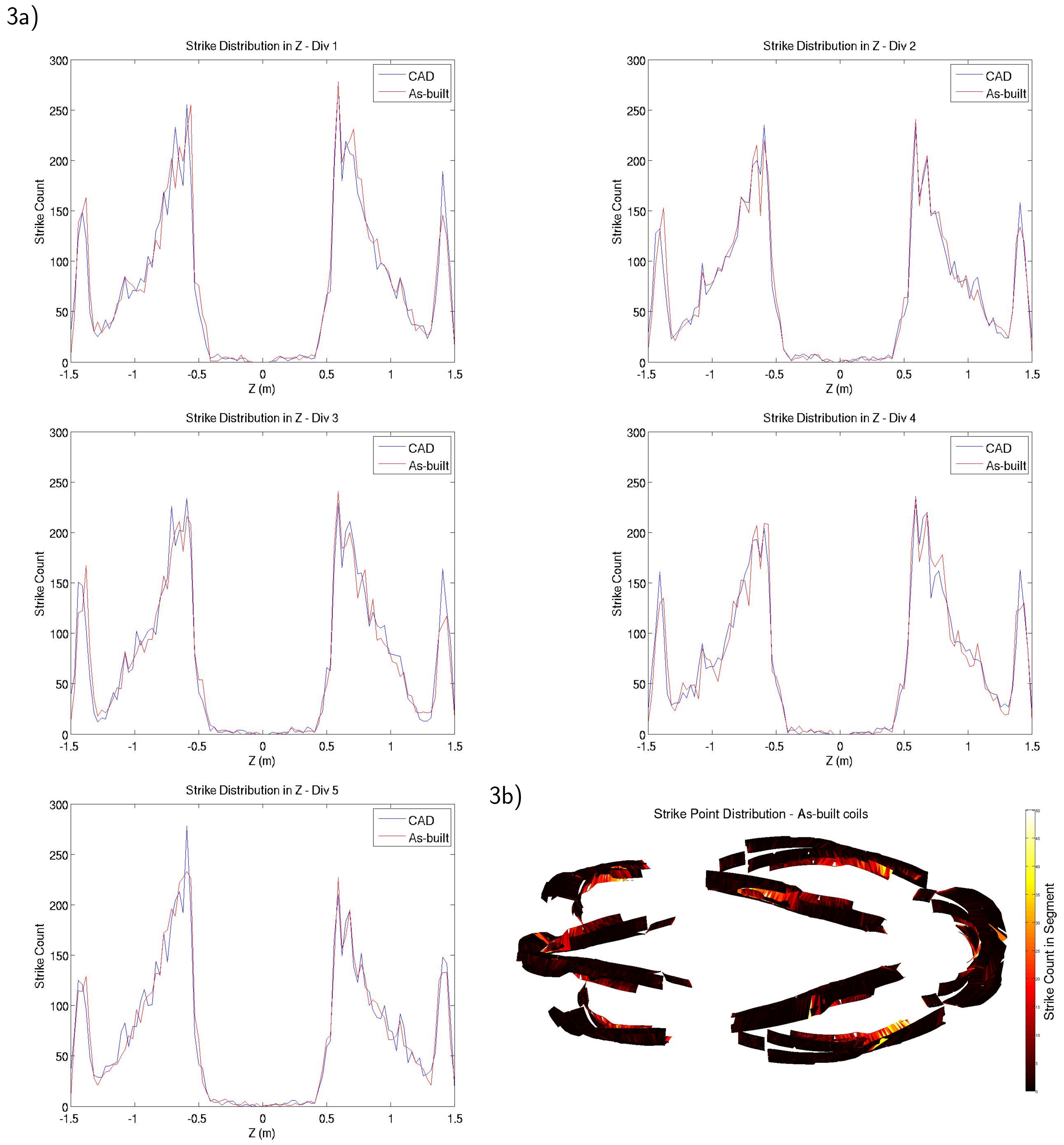


Figure 3 - Divertor Strike Point Dsitribution

a) Histograms of strike point distribution in Z (100 bins) for each divertor section. Little difference can be seen between the ideal CAD coils and coils adjusted for deviation in construction. The plots demonstrate the expected symmetry in Φ and Z.

b) A 3D model of the divertor system showing strike point distribution for the as-built coils.

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Ackowledgments

This work was made possible by funding from the Department of Energy for the Summer Undergraduate Laboratory Internship (SULI) program. This work is supported by the US DOE Contract No. DE-AC02-09CH11466.

EUROfusion

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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.