Neutron shielding of low aspect ratio torii modeled by Monte Carlo methods and Machine Learning

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RENAISSANCE FUSION

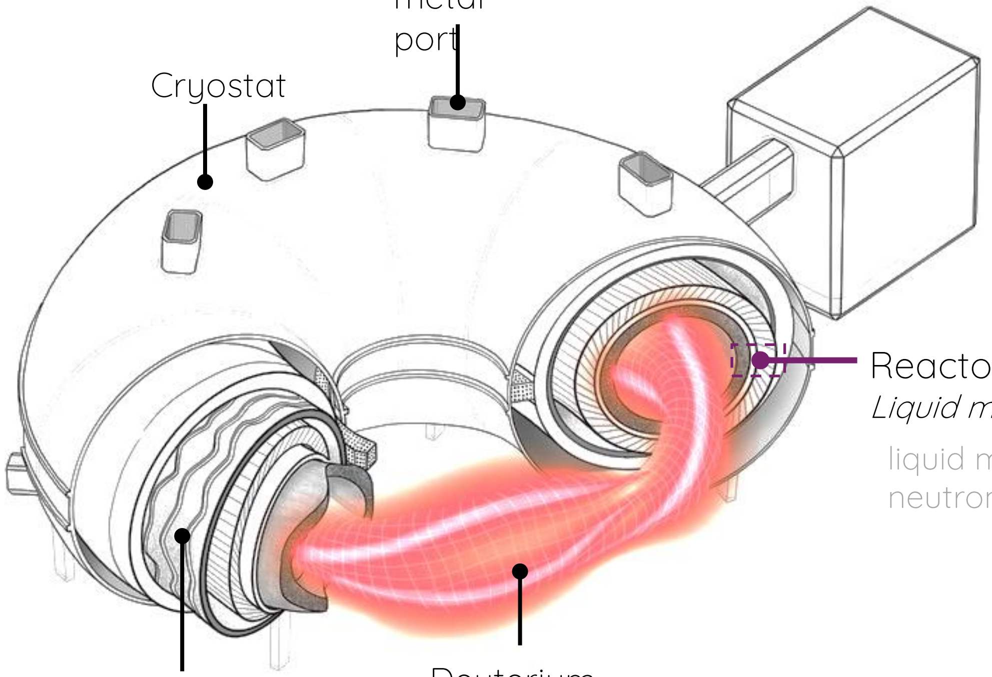
Overall Aim of Renaissance Fusion:
Build a compact stellarator with Liquid Metal first wall

Blanket functions :

1. Heat removal
Extract heat from the plasma and transfer to the power conversion system

2. Tritium breeding
Produce tritium to fuel the fusion reaction – tritium breeding ratio (TBR)

3. Radiation shielding
Protect structures, coils, and environment from radiation damages

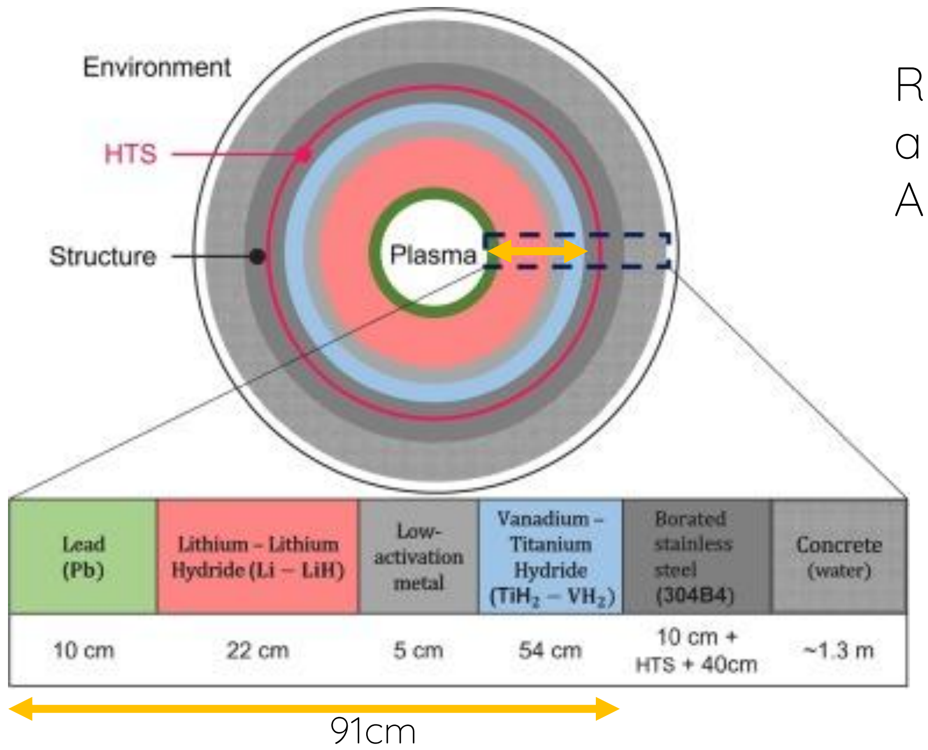


Major radius R	On axis field B	Aspect ratio A	Plasma volume V	Reactor Power P
3.8 m	10.2 T	4.1	65 m^3	1 GWe

Fama, F. et al. – 2022 - An optimized power conversion system for a stellarator-based nuclear fusion power plant
Prost, V., Volpe, F. A. - 2024 - Economically optimized design point of high-field stellarator power-plant
Prost, V., Ogier-Collin, S., Volpe, F. A. - 2024 - Compact fusion blanket using plasma facing liquid Li-LiH walls and Pb pebbles

1D neutronic model provided initial results but relied on simplistic cylindrical geometry

OpenMC - ENDF/B-VII.1



R = 3.8m
a = 0.9m
A = 4.1

	Functions and requirements	Targets	Designed
Heat extraction	Heat removal	-	> 92 % nuclear heat on LM layers
Heat extraction	Energy multiplication	≥ 1.0	1.1
	Tritium breeding ratio	≥ 1.15	1.6
		40 years with 80% availability	
Neutron shielding	Total fluence on HTS coils	$< 10^{19}$ n/cm^2	$0.9\ 10^{19}$ n/cm^2
Neutron shielding	LM vessel DPA	< 200 DPA	~100 DPA
Neutron shielding	Magnet structure DPA	< 200 DPA	< 1 DPA

↑ Primary confinement vessel

Limitations:
- Parametric manual search/optimization (long)
- 1D geometry is an initial guess but we need a more robust and generalizable tool

* *Prost, V., Ogier-Collin, S., Volpe, F. A. - 2024 - Compact fusion blanket using plasma facing liquid Li-LiH walls and Pb pebbles*

Developed a torus shape neutronic module to be included in stellarator systems code

Neutronic model

Input:
- Reactor major radius
- Reactor minor radius
- Fusion power
- Blanket material thicknesses

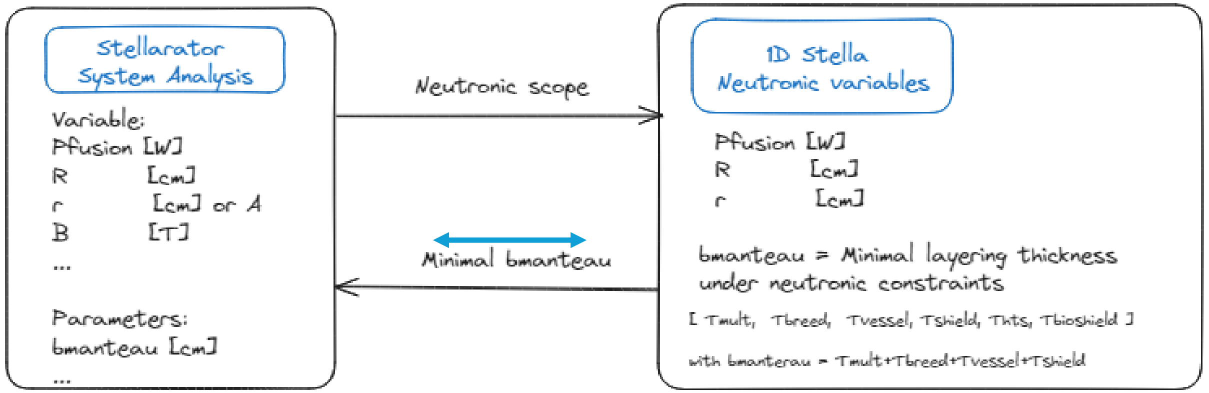
FIXED

THICKNESS TO MINIMIZE

Output:
- Tritium breeding ratio
- Energy multiplication
- Power deposited in LM layer
- Neutron flux
- Radiation damage

CONSTRAINED TARGET PERFORMANCE

Neutronic module in the System Analysis



Performance:
- Accurate evaluation of the material configuration
- Fast evaluation of the reactor performance

Solution:
- Surrogate model for the high-fidelity neutronic model
- Optimization loop

Reduced ML model optimisation scheme

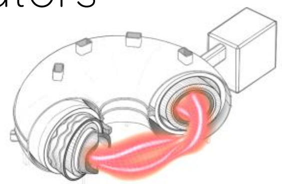
Neutronic simulations (~10-30mins)

Reduced ML model (~ms)

Genetic algorithm optimization

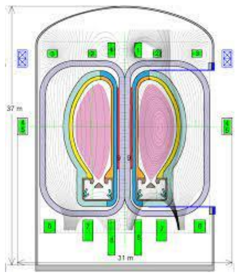
Verification with High fidelity code

Low aspect ratio stellarators

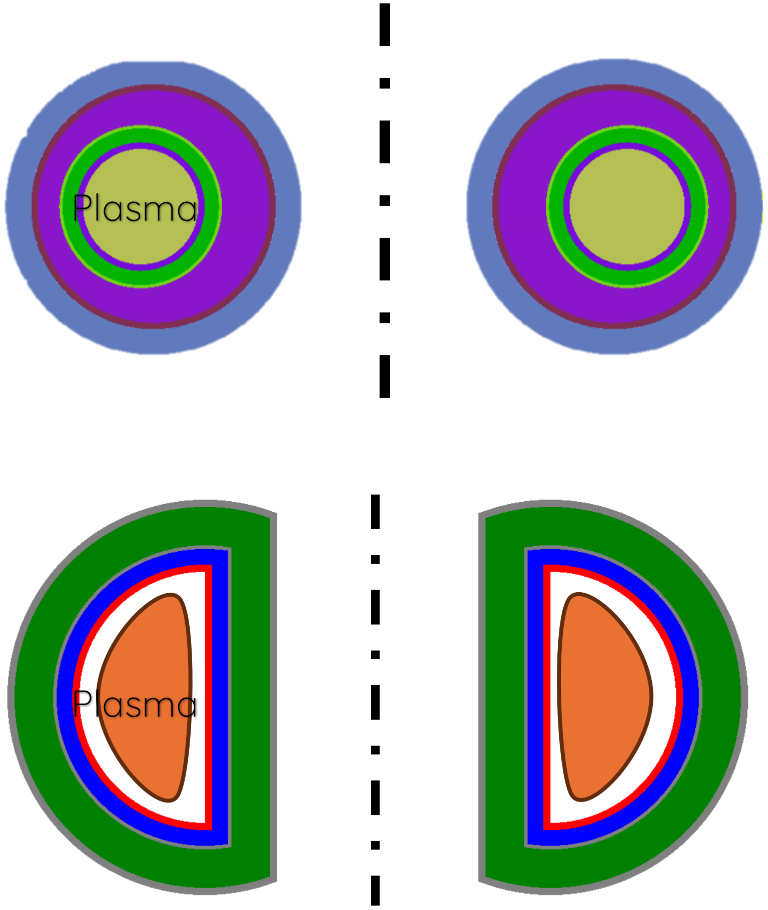


Parametric Torus

Spherical tokamaks



Parametric D-shaped torus



Input data for ML – generation of 20 000 configurations

Parameters variations:

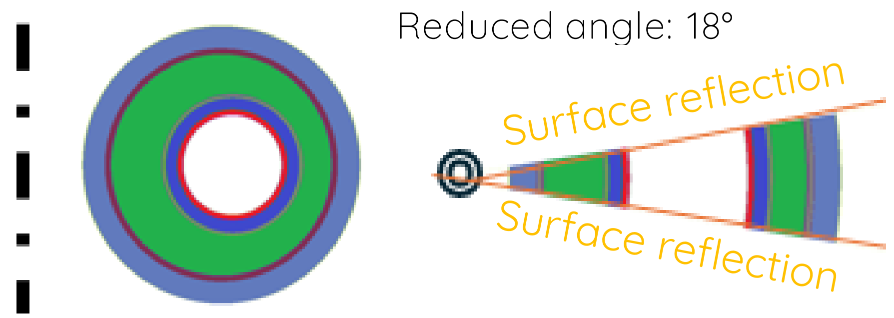
Parameters	Min	Max	Discretisation	
Reactor [cm]				
Minor Radius	50	200	10	
Major Radius	300	600	10	VARIED
Eccentricity	0	15	0.5	
Blanket [cm]				
Lead	1	20	0.5	VARIED
LiLih	5	45	0.5	
SiC	5	5	0.5	VARIED
VH2	10	60	0.5	
Steel (Boronated)	10	10	0.5	
REBCO baffers	0.0441	0.0441	0.0441	
Steel (Boronated)	40	40	0.5	

Acceleration of the simulations

- Variance Reduction with Pre-build feature MAGIC*

```
wws.update_magic(ww_tally, value='rel_err', threshold=0.7)
```

- Reduced angle: profiting of the symmetries with



Generation:

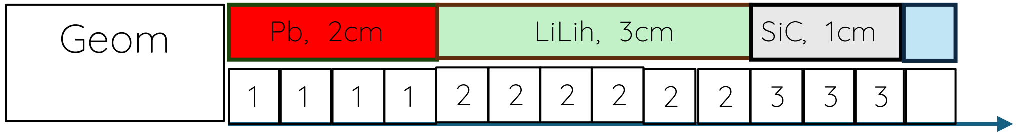
- Tallies output with tagged UUID result file
- Decrease 1 run time from days => tens of minutes => few minutes
- About 2 full weeks to generate the input data for ML

*https://inis.iaea.org/records/231pm-zzy35

ML model accurately predicts neutronic simulations

Configuration data :

R | r | ecc |layers (material, thickness)



Formalized in a 700 elements vector for layer configuration (discretization at 0.5 cm) with material coding

Results data :

TBR | Energy mult | Heat removal| Fluence on coils | DPA on coils structure| DPA LM vessel

Machine learning Model:

Optimization : Adam at learning rate 2E-3

layer	Activation	Constraints	Units	Batch Normalization	Dropout (Rate)
Input	-	-	703	-	-
Dense	ReLU	L1, L2	256	Yes	0.3
Dense	ReLU	L1, L2	128	Yes	0.3
Dense	ReLU	L1, L2	64	Yes	0.3
Dense	ReLU	L1, L2	32	Yes	0.3
Output	ReLU	L1, L2	6	-	-

- Train and Test sets: 80%, 20%
- Training time: 30 minutes with 16 cpus

Quantity	Diff {Pfus=1.8GW, R=3.8m, r=0.9m}
TBR	4.4%
Energy Mult	0.9%
Energy removal [%]	0.7%
Fluence on Coil [cm2/n]	26.8%
DPA on coil [dpa/n]	30.9%
DPA on Liquid metal [dpa/n]	46.0%

- Comparison with “Reference case”:
- The uncertainties are under control regarding the constraints’ precision and model accuracy

Genetic Algorithm for a minimal blanket – Get results in 15 min

Set the input reactor parameter for a minimal blanket

Reactor parameter			
Pfusion, Major radius, Minor radius, Eccentricity			
Blanket [cm]			
Parameters	**Min**	**Max**	**Discretisation**
Lead	1	20	0.5
LiLih	5	45	0.5
SiC	5	5	0.5
VH2	10	60	0.5
Steel (Boronated)	10	10	0.5
REBCO baffers	0.0441	0.0441	0.0441
Steel (Boronated)	40	40	0.5

Set the input Genetic Algorithm parameters

Category	**Parameters**
Genetic Algorithm	Population Size: 2000, Generations: 15, ...
Optimization Weights	TBR: 1.0, Energy Multiplication: 1.0, Heat Removal: 1.0, Fluence HTS: 1.0, DPA HTS: 1.0, Thickness: 1.0
Target Values	TBR: 1.15, Energy Multiplication: 1.0, Heat Removal: 95.0, Fluence HTS: 1.0e+19, DPA LMS: 200.0, DPA HTS: 200.0
Additional Parameters	Thickness Penalty Weight: 1.0, Adaptive Penalty: Min Weight: 0.1, Max Weight: 1000.0

Implementation : $\boldsymbol{\alpha}$-Fair allocation* principle

Suppose $x = x(n)$ chosen to

Maximise $\sum_r \omega_r \frac{x_r^{1-\alpha}}{1-\alpha}$

Subject to $\sum_r A_{jr} n_r x_r \leq C_j \,;\, j \in J$

$x_r \geq 0 \,;\, \mathrm{r} \in R$

Performance:

About 15 minutes per 16 CPUs.

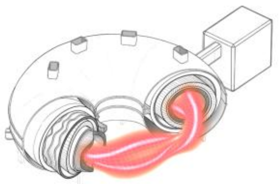
Verification

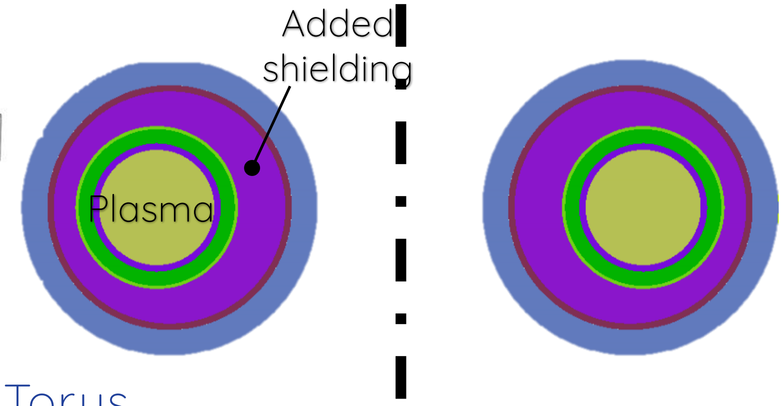
High Fidelity code

** A weighted α – fair allocation , Mo and Walrand 2000*

Surrogate models for 3D stellarator and tokamak predict neutronic simulations within tens of percent

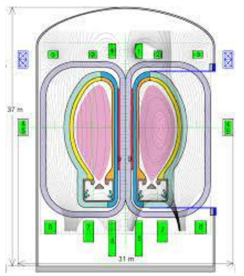
Low aspect ratio stellarators

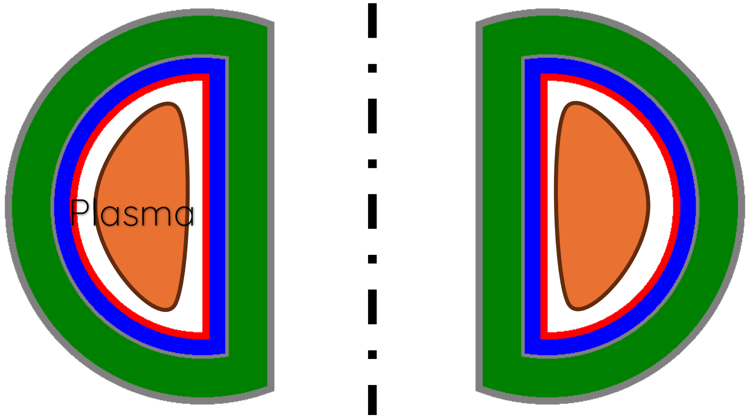




Parametric Torus with eccentricity

Spherical tokamaks





Parametric D-shaped torus*

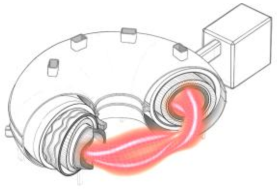
Quantity	3D High Fidelity	3D Surrogate	Differences
TBR	1.64	1.66	1.5%
Energy multiplication	1.20	1.20	0.2%
Heat removal	94.5	96.7	2.4%
Fluence HTS [cm2/n]	4.73E-11	5.31E-11	12.2%
DPA HTS [DPA/n]	1.65E-32	2.27E-32	37.6%
DPA LM [DPA/n]	5.09E-28	2.13E-28	-58.1%

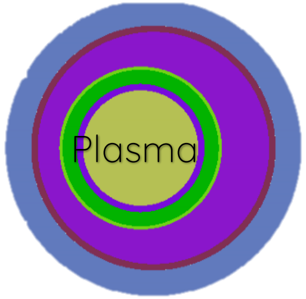
Quantity	3D High Fidelity	3D Surrogate	Differences
TBR	1.52	1.66	-8.4%
Energy Multiplication	1.21	1.19	1.4%
Heat Removal	93.7	95.2	-1.7%
Fluence HTS (cm^2/s/n)	7.20E-11	1.18E-10	-39.2%
DPA HTS (dpa/n)	1.55E-32	2.44E-32	-36.6%
DPA LM (dpa/n)	2.22E-28	2.52E-28	-12.2%

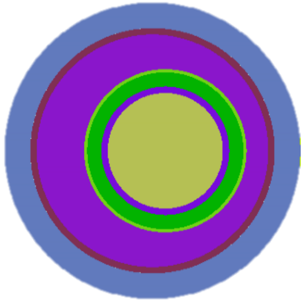
*Preliminary investigation of neutron shielding compounds for ARC-class tokamaks Fusion Engineering and Design 185 (2022) 113335

Optimization Module align with the Reference case

Low aspect ratio stellarators







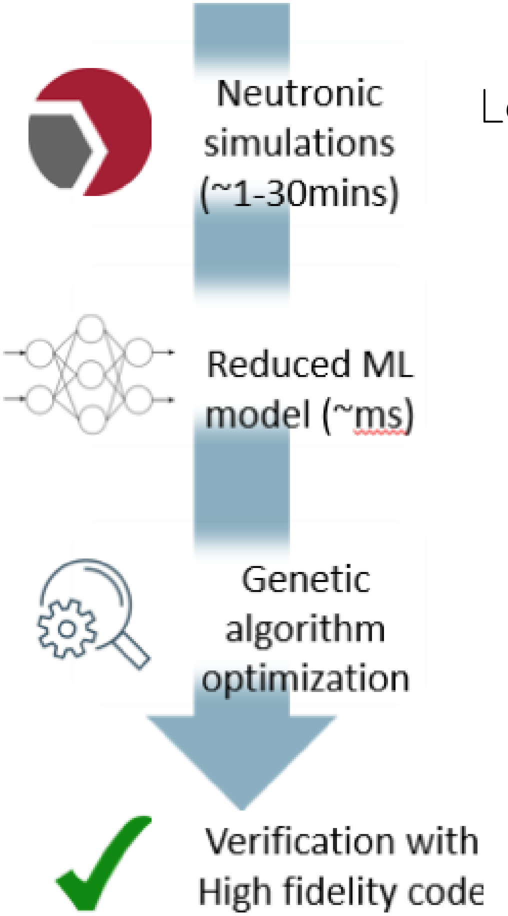
Parametric Torus with eccentricity

Thickness [cm]	Reference*	3D Surrogate	Status
Lead	10	11	Optimized
LiLih	22	22	Optimized
SiC	5	5	Fixed
VH2	54	53	Optimized
Steel	10	10	Fixed
HTS	0.04	0.04	Fixed
Total	101	101	

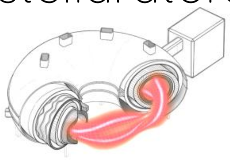
*Compact fusion blanket using plasma facing liquid Li-LiH walls and Pb pebbles Journal of Nuclear Materials 599(3):155239

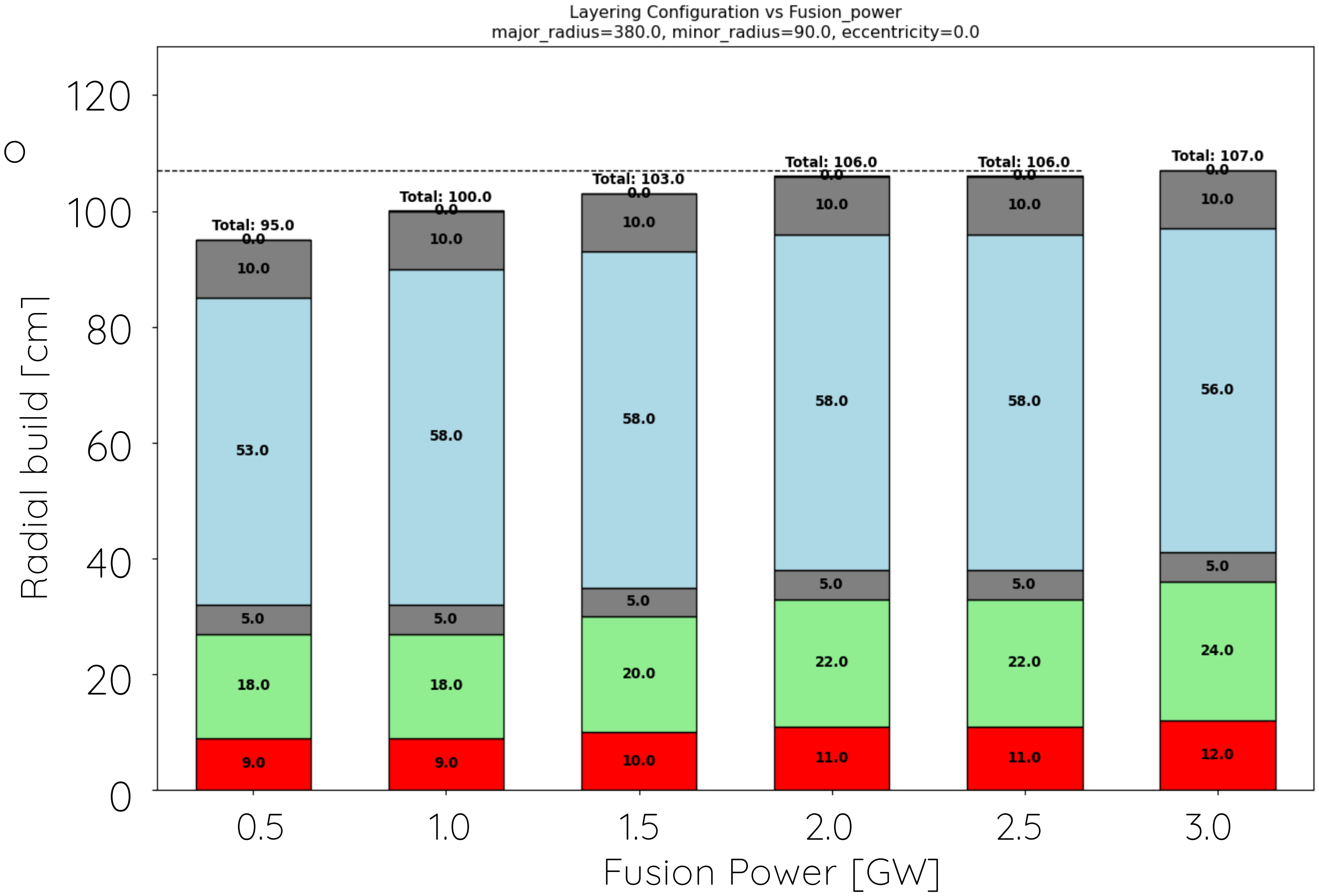
Reduced ML model optimization scheme highlights benefits for high power reactors (1 GWe vs 100 MWe)

X2 in fusion power → ~5/6 cm increase thickness

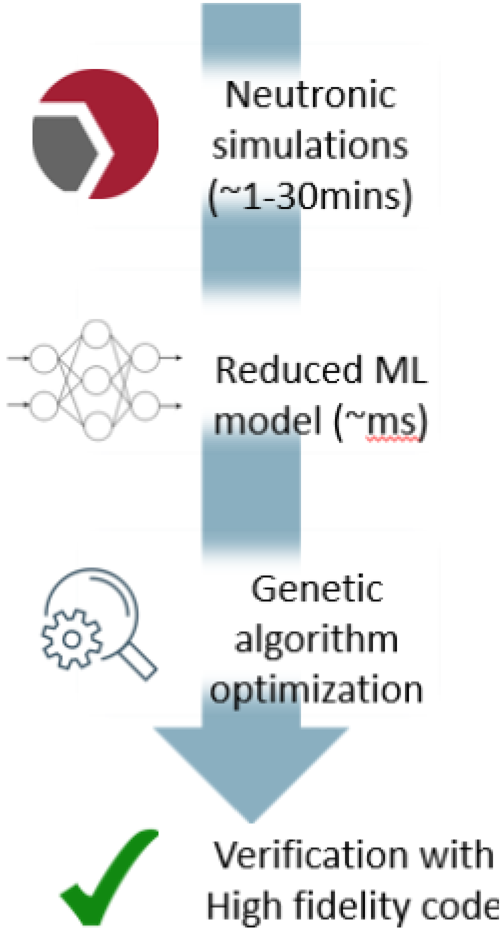


Low aspect ratio stellarators

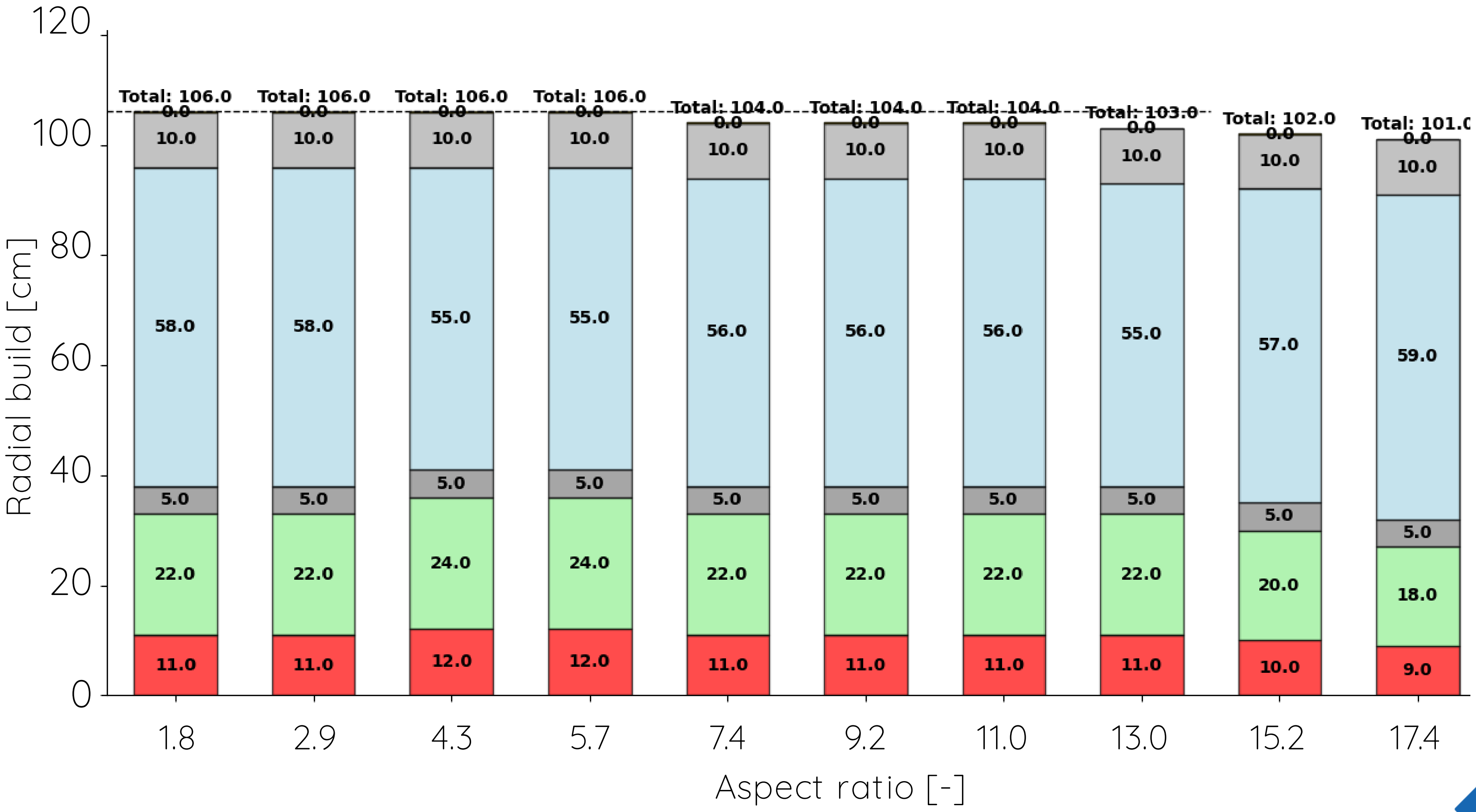




Model optimization scheme shows limited impact of reactor's aspect ratio



Neutron flux scales with ~ $A^{-1/3}$
With constant volume (100 m^3) and power (2 GW)



Take aways

- Machine learning model developed for rapid neutronics performance prediction
- Genetic algorithm used to optimize blanket configuration
- Key findings:
  - Efficient optimization of blanket thickness and composition
  - Slight increase in blanket thickness needed for higher fusion power
  - Limited impact of reactor aspect ratio on neutronics performance
- Methodology enables rapid, optimized design for compact fusion reactors
- Studies (scan over aspect ratio and run power) within hours range instead of multiple days with manual search
- Potential for extension to other reactor design aspects