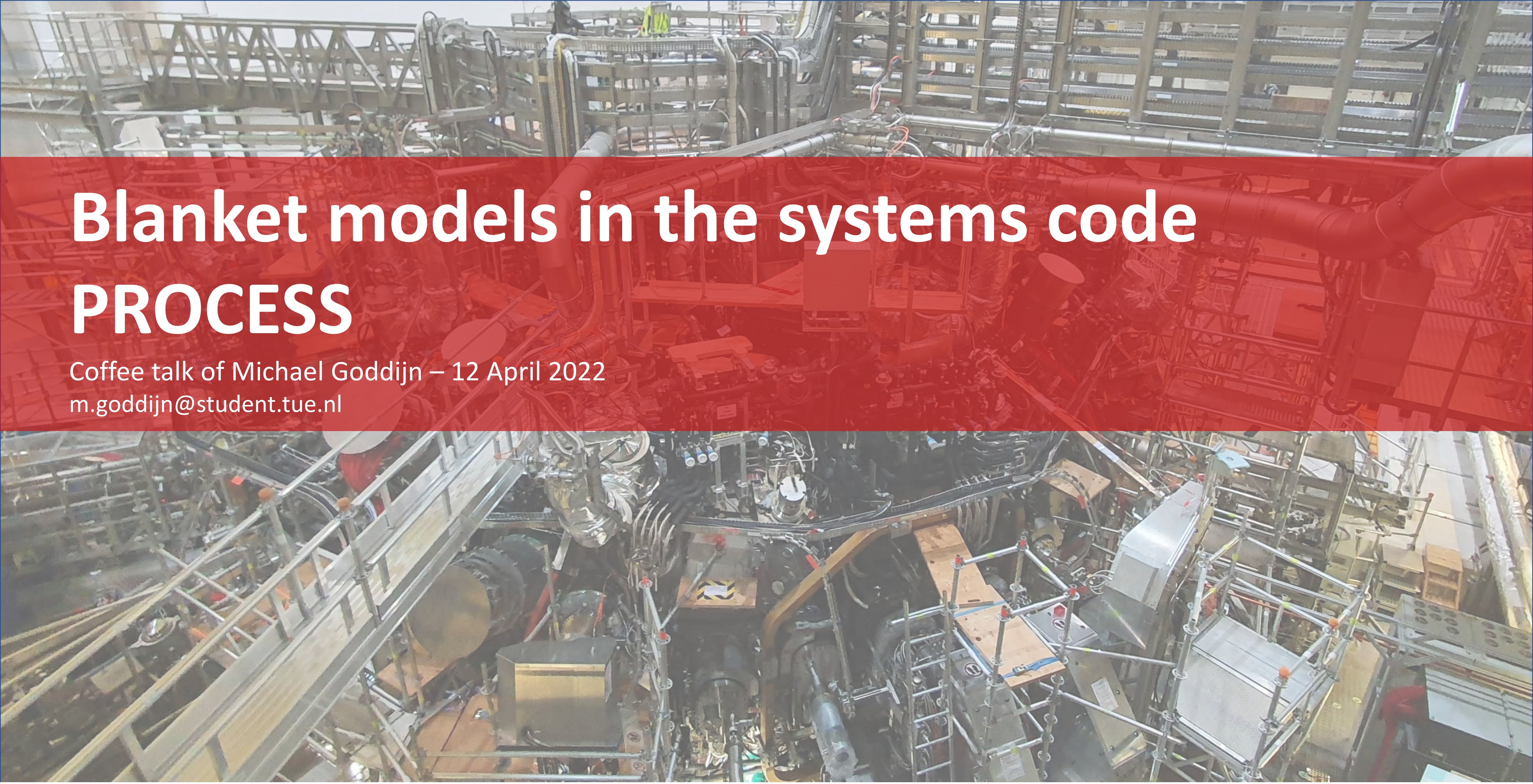


Blanket models in the systems code PROCESS

Coffee talk of Michael Goddijn – 12 April 2022

m.goddijn@student.tue.nl

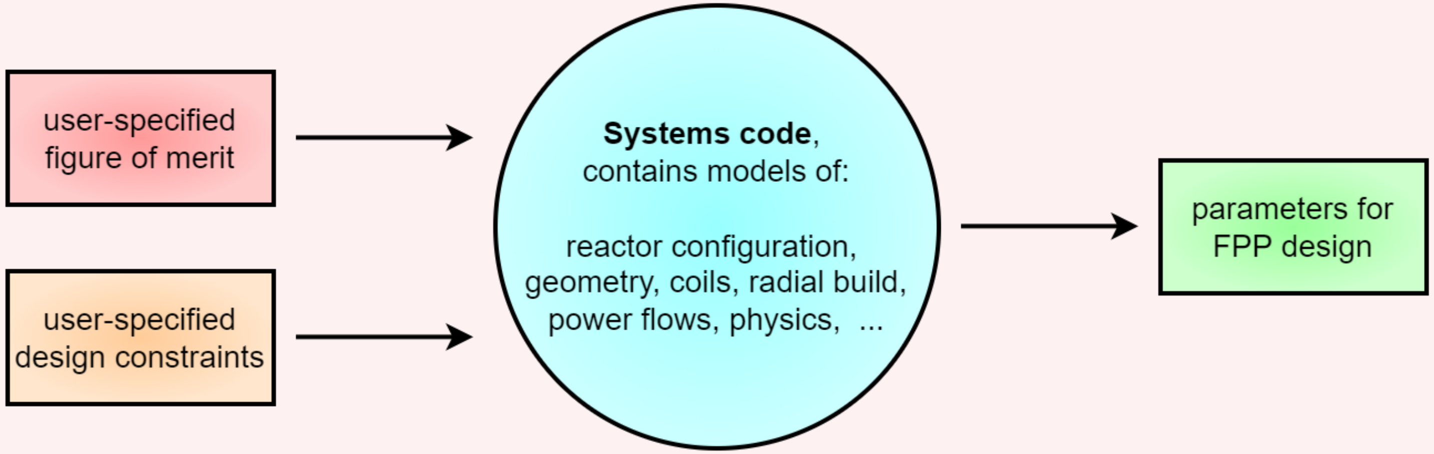
Systems code PROCESS

Tool for designing a
fusion power plant (FPP)

Goals of a systems code:
- consistent FPP design
- effect of varying inputs
- optimise the design

0D and 1D models

For stellarators:
"sPROCESS"

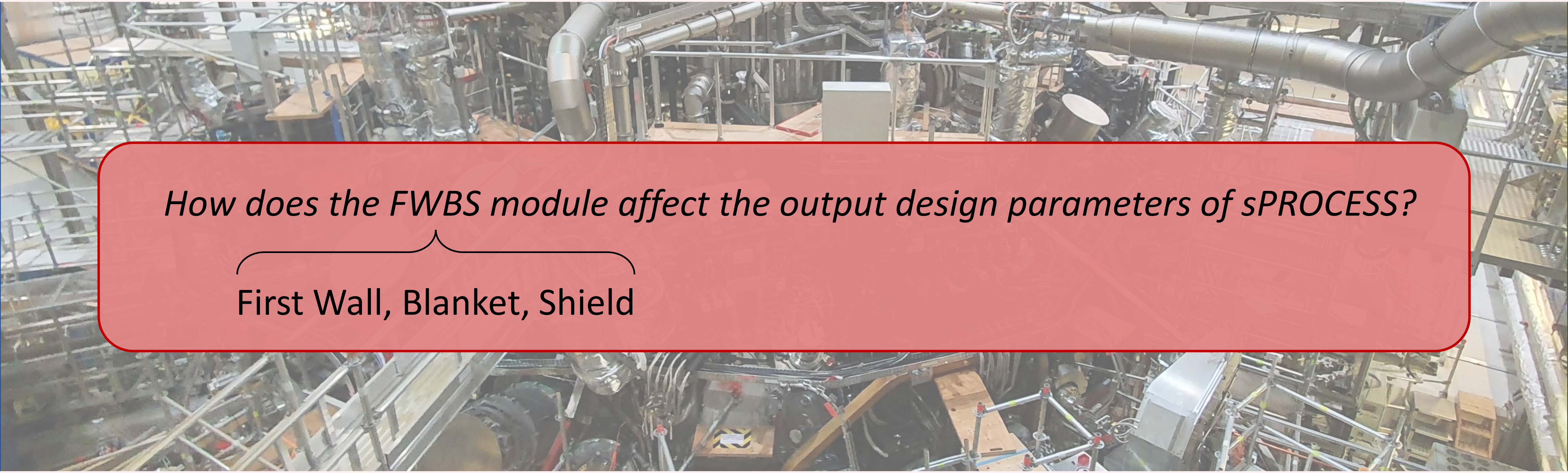


figures of merit:
- major radius
- neutron wall load
- fusion gain
- cost of electricity
- capital cost
- total injected power
- pulse length
- availability
- ...

design constraints:
- max. bèta
- power balance
- max. density
- max. neutron wall load
- radial build
- min. net electric power output
- max. divertor heat load
- min. availability
- ...

output parameters:
- machine geometry
- physics
- power flows
- forces on coils
- radial build
- electrical requirements
- weights
- costs
- ...

Research question

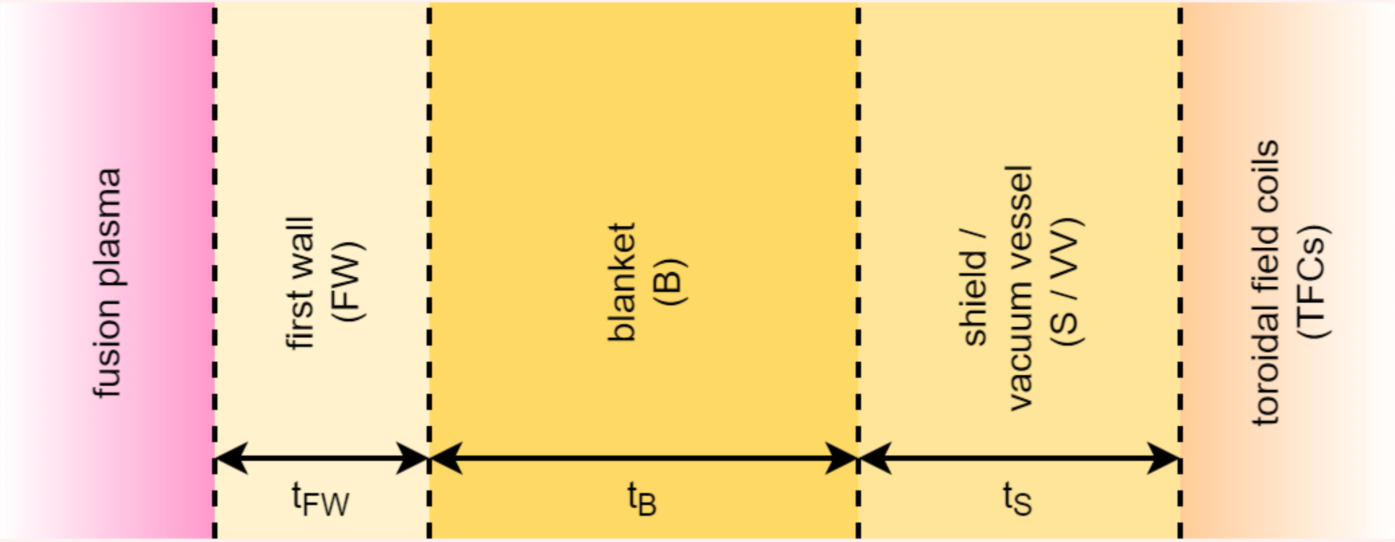


How does the FWBS module affect the output design parameters of sPROCESS?

First Wall, Blanket, Shield

FWBS: protect, extract energy, breed tritium

First **W**all:	reduce damage done to blanket
Blanket:	extract energy, breed tritium (neutron multiplication)
Shield / vacuum vessel:	stop the last neutrons to protect the TFCs



FWBS module in sPROCESS

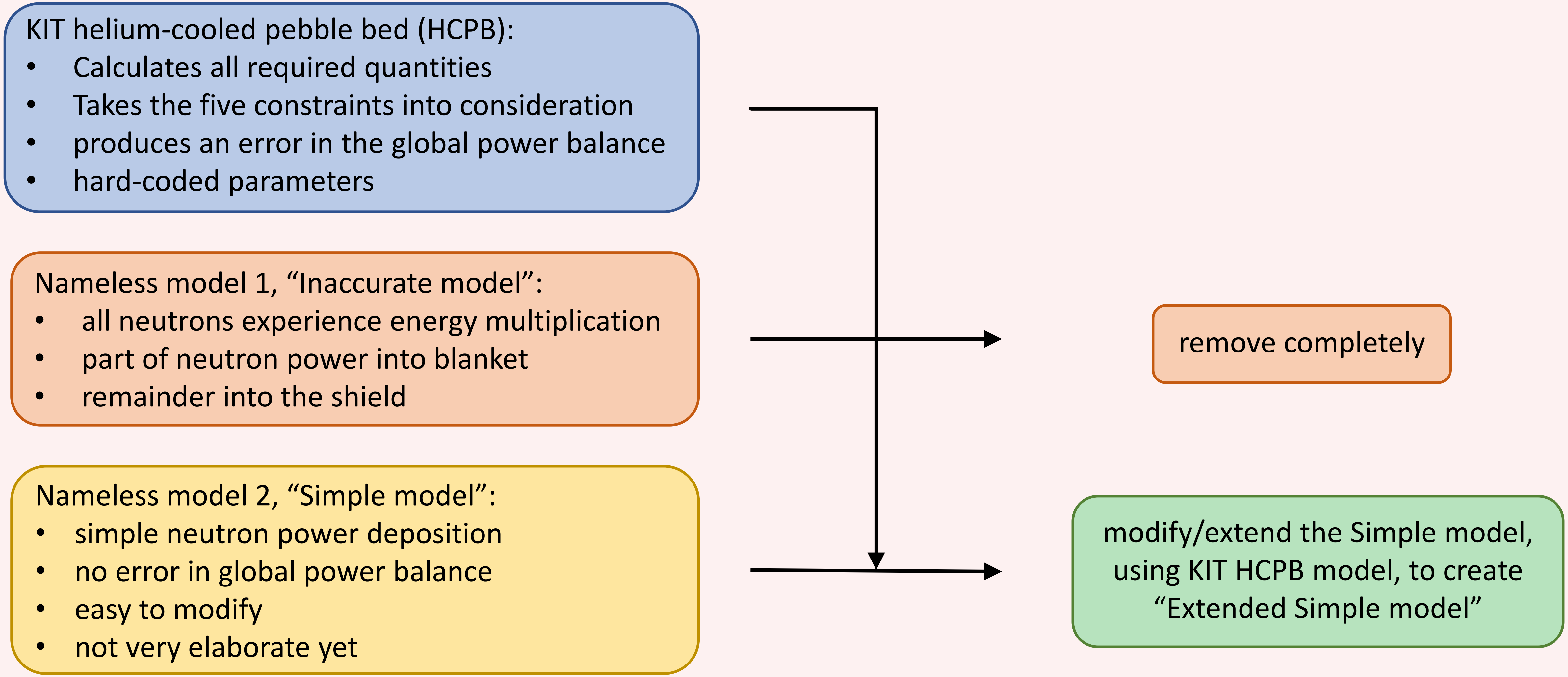
Calculate:

- deposited neutron power
- deposited radiation power
- required pumping power
- energy multiplication in blanket
- blanket lifetime
- weight

Subject to five constraints:

1. consistent radial build
2. lower limit on tritium breeding ratio (TBR)
3. upper limit on neutron power deposited in TFCs
4. upper limit on fast neutron fluence onto TFCs
5. upper limit He-concentration in vacuum vessel

Blanket models in sPROCESS



KIT helium-cooled pebble bed (HCPB):
- Calculates all required quantities
- Takes the five constraints into consideration
- produces an error in the global power balance
- hard-coded parameters

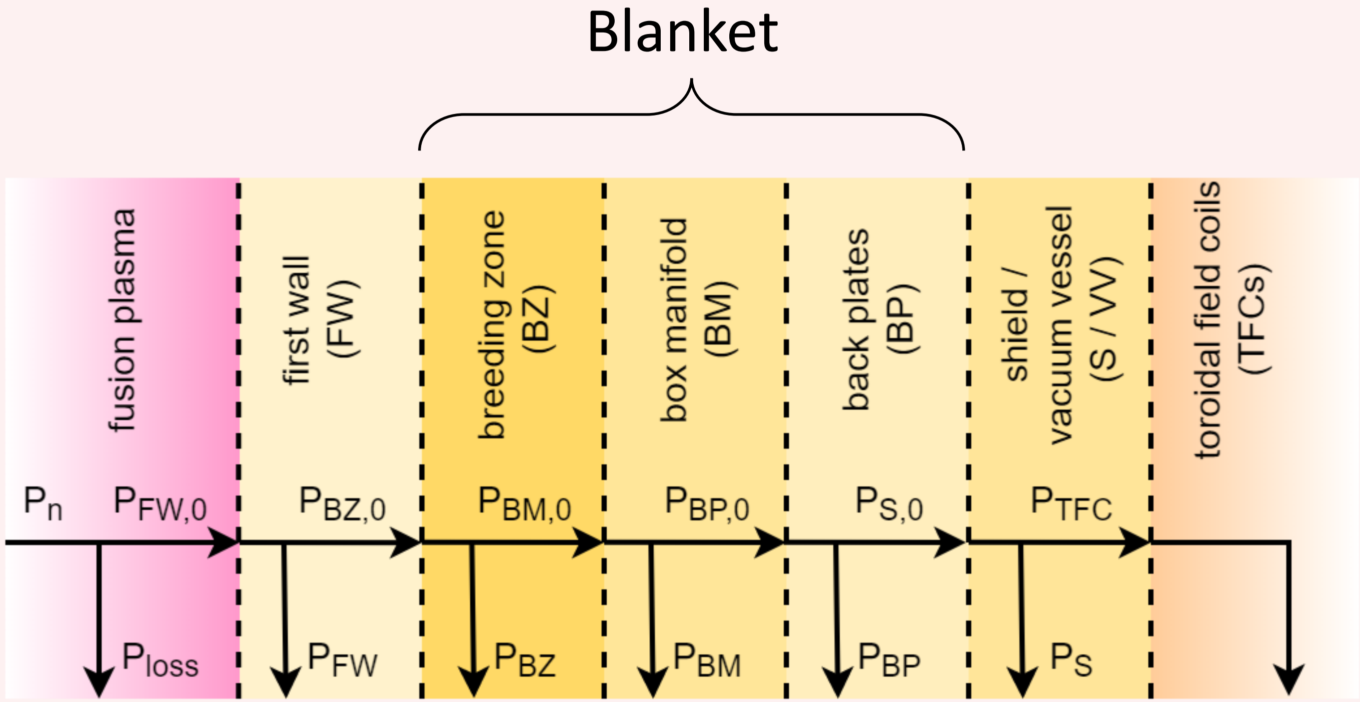
Nameless model 1, “Inaccurate model”:
- all neutrons experience energy multiplication
- part of neutron power into blanket
- remainder into the shield

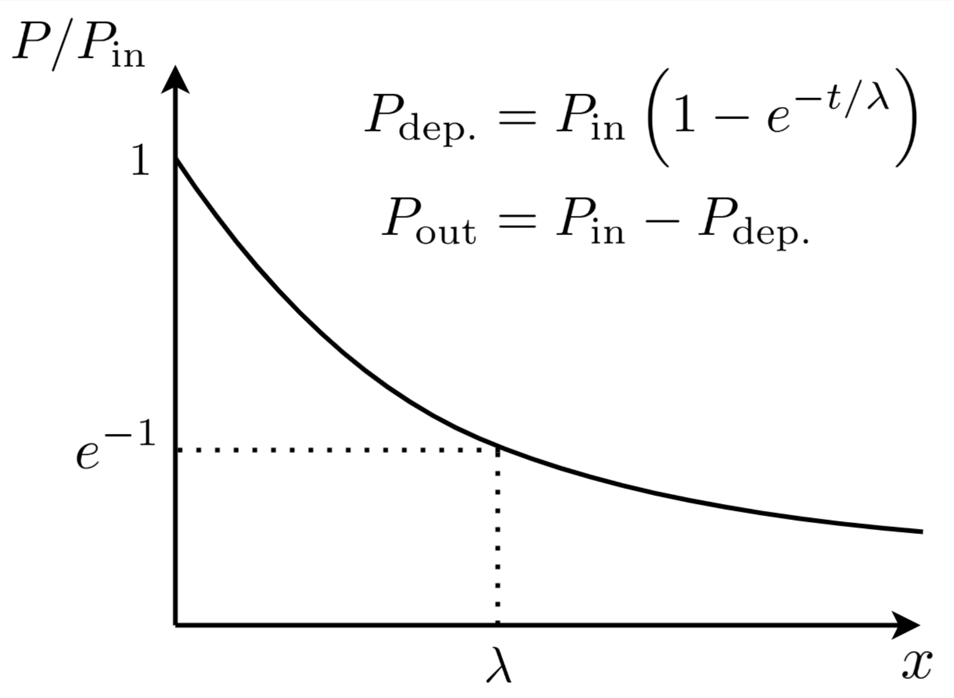
Nameless model 2, “Simple model”:
- simple neutron power deposition
- no error in global power balance
- easy to modify
- not very elaborate yet

remove completely

modify/extend the Simple model, using KIT HCPB model, to create “Extended Simple model”

Neutron power deposition

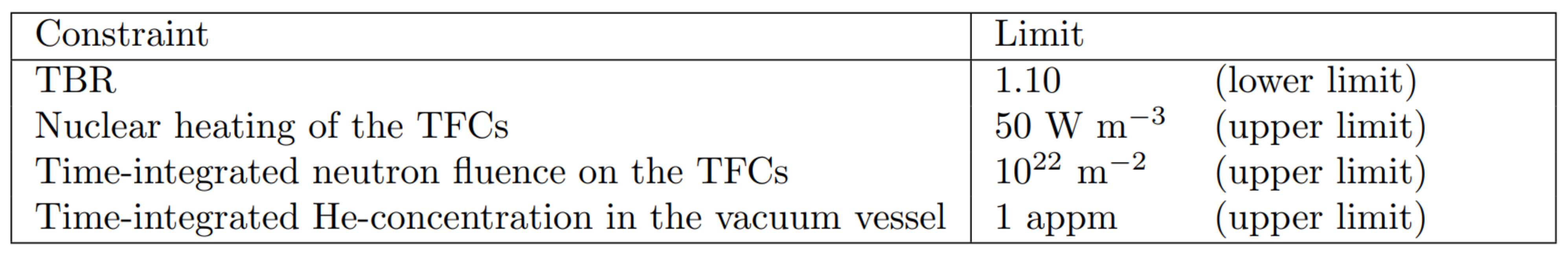




$$P_{\text{dep.}} = P_{\text{in}} \left(1 - e^{-t/\lambda}\right)$$

$$P_{\text{out}} = P_{\text{in}} - P_{\text{dep.}}$$

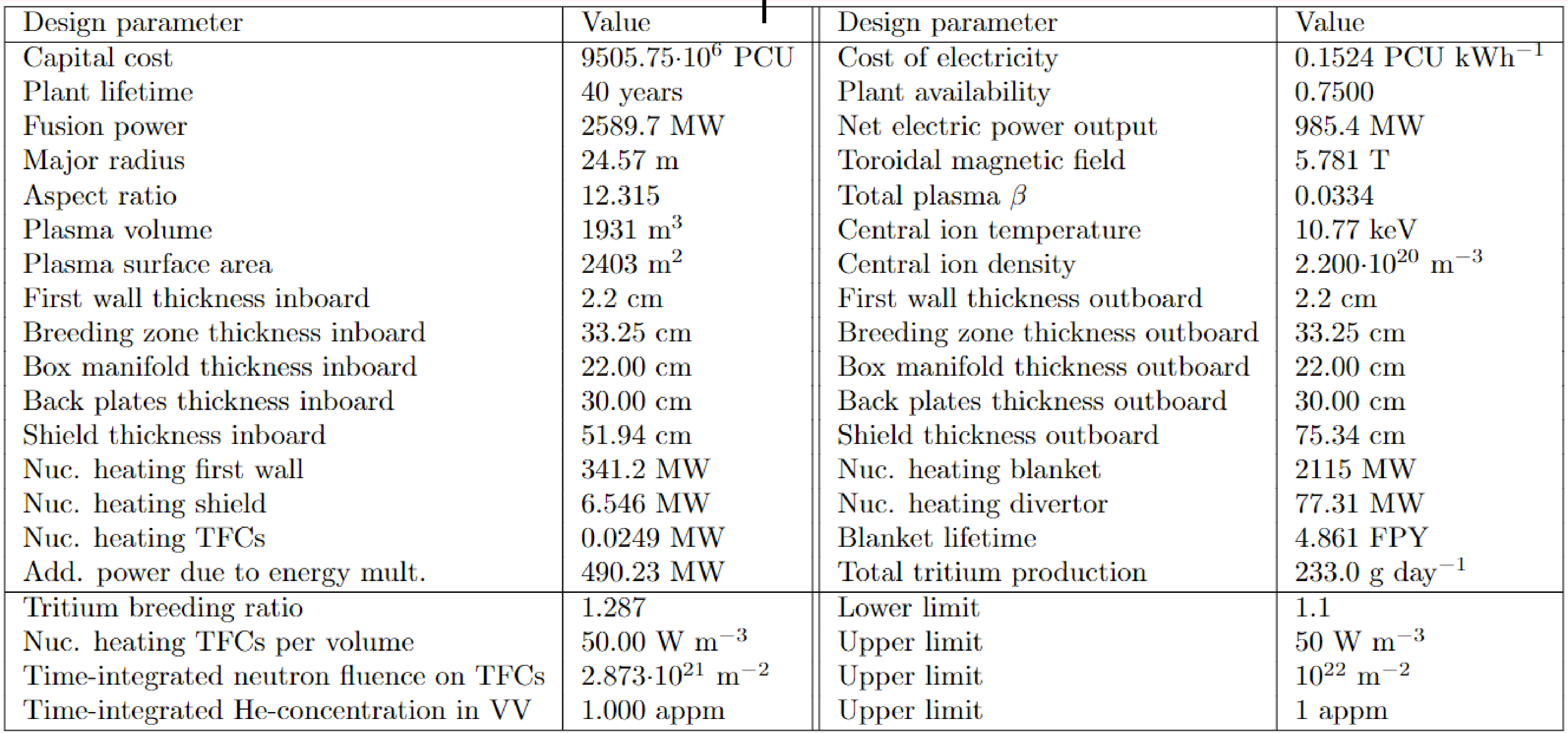
Base design



Constraint	Limit	
TBR	1.10	(lower limit)
Nuclear heating of the TFCs	$50\ \mathrm{W\ m^{-3}}$	(upper limit)
Time-integrated neutron fluence on the TFCs	$10^{22}\ \mathrm{m^{-2}}$	(upper limit)
Time-integrated He-concentration in the vacuum vessel	1 appm	(upper limit)

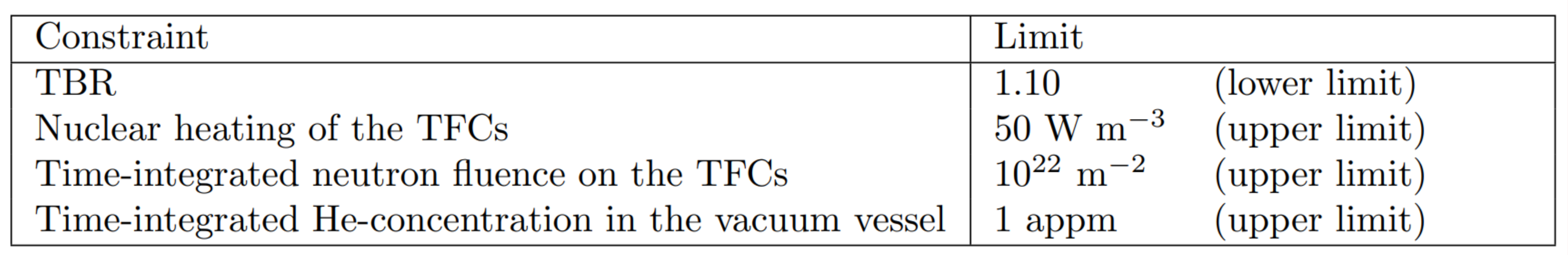
Base design

“PROCESS Cost Unit”, resembles 1990-USD



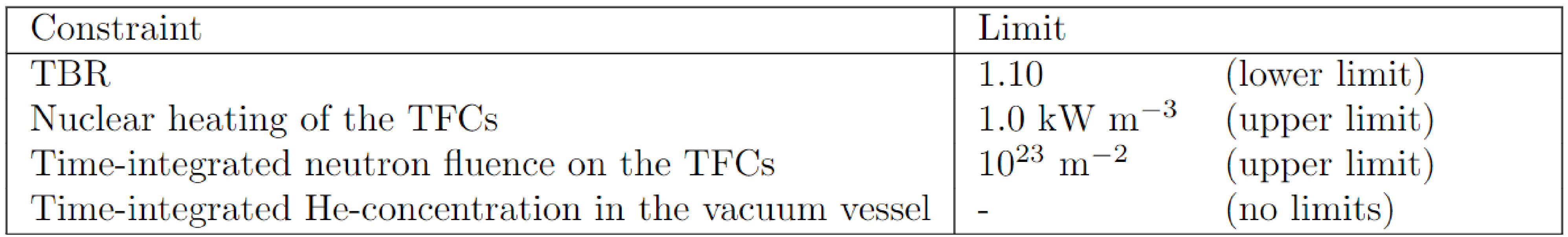
Design parameter	Value	Design parameter	Value
Capital cost	$9505.75 \cdot 10^6$ PCU	Cost of electricity	0.1524 PCU kWh^{-1}
Plant lifetime	40 years	Plant availability	0.7500
Fusion power	2589.7 MW	Net electric power output	985.4 MW
Major radius	24.57 m	Toroidal magnetic field	5.781 T
Aspect ratio	12.315	Total plasma β	0.0334
Plasma volume	1931 m^3	Central ion temperature	10.77 keV
Plasma surface area	2403 m^2	Central ion density	$2.200 \cdot 10^{20}$ m^{-3}
First wall thickness inboard	2.2 cm	First wall thickness outboard	2.2 cm
Breeding zone thickness inboard	33.25 cm	Breeding zone thickness outboard	33.25 cm
Box manifold thickness inboard	22.00 cm	Box manifold thickness outboard	22.00 cm
Back plates thickness inboard	30.00 cm	Back plates thickness outboard	30.00 cm
Shield thickness inboard	51.94 cm	Shield thickness outboard	75.34 cm
Nuc. heating first wall	341.2 MW	Nuc. heating blanket	2115 MW
Nuc. heating shield	6.546 MW	Nuc. heating divertor	77.31 MW
Nuc. heating TFCs	0.0249 MW	Blanket lifetime	4.861 FPY
Add. power due to energy mult.	490.23 MW	Total tritium production	233.0 g day^{-1}
Tritium breeding ratio	1.287	Lower limit	1.1
Nuc. heating TFCs per volume	50.00 W m^{-3}	Upper limit	50 W m^{-3}
Time-integrated neutron fluence on TFCs	$2.873 \cdot 10^{21}$ m^{-2}	Upper limit	10^{22} m^{-2}
Time-integrated He-concentration in VV	1.000 appm	Upper limit	1 appm

Advanced design



Constraint	Limit	
TBR	1.10	(lower limit)
Nuclear heating of the TFCs	50 W m^{-3}	(upper limit)
Time-integrated neutron fluence on the TFCs	10^{22} m^{-2}	(upper limit)
Time-integrated He-concentration in the vacuum vessel	1 appm	(upper limit)

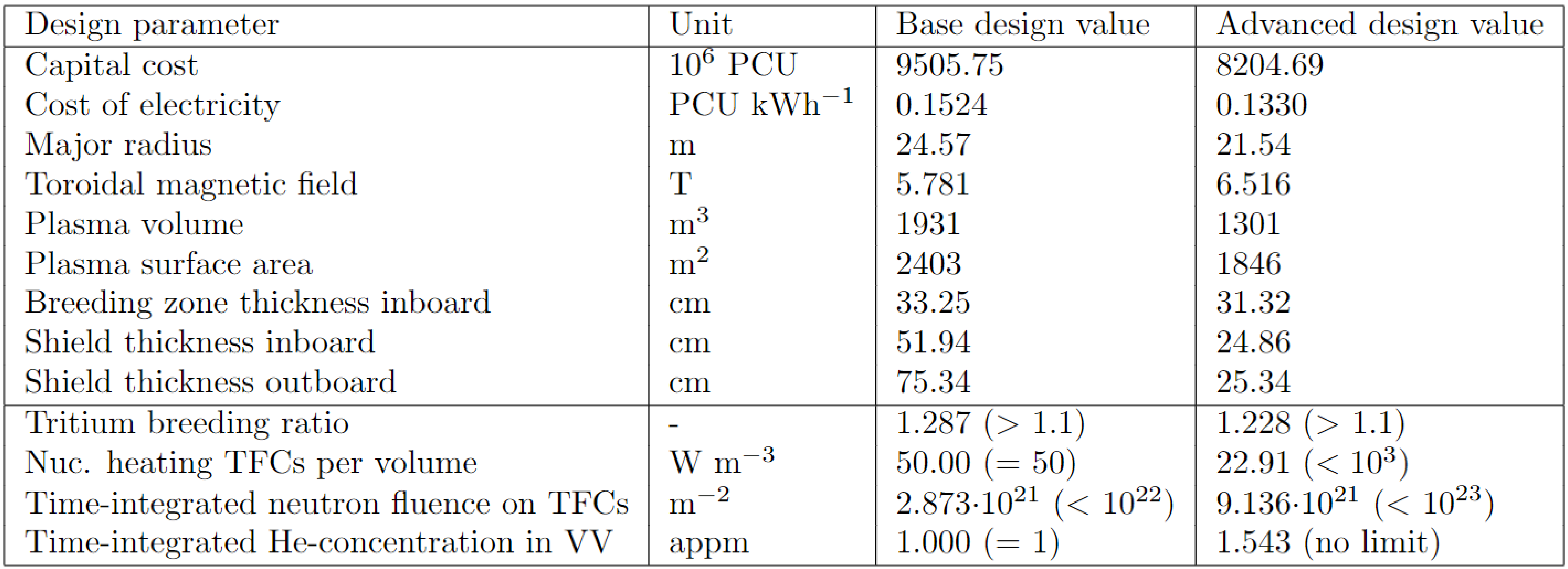
input parameter: max TFC temperature = 4.75 K



Constraint	Limit	
TBR	1.10	(lower limit)
Nuclear heating of the TFCs	1.0 kW m^{-3}	(upper limit)
Time-integrated neutron fluence on the TFCs	10^{23} m^{-2}	(upper limit)
Time-integrated He-concentration in the vacuum vessel	-	(no limits)

input parameter: max TFC temperature = 22 K

Advanced design



Design parameter	Unit	Base design value	Advanced design value
Capital cost	10^6 PCU	9505.75	8204.69
Cost of electricity	PCU kWh^{-1}	0.1524	0.1330
Major radius	m	24.57	21.54
Toroidal magnetic field	T	5.781	6.516
Plasma volume	m^3	1931	1301
Plasma surface area	m^2	2403	1846
Breeding zone thickness inboard	cm	33.25	31.32
Shield thickness inboard	cm	51.94	24.86
Shield thickness outboard	cm	75.34	25.34
Tritium breeding ratio	-	$1.287\ (> 1.1)$	$1.228\ (> 1.1)$
Nuc. heating TFCs per volume	$\mathrm{W\ m}^{-3}$	$50.00\ (= 50)$	$22.91\ (< 10^3)$
Time-integrated neutron fluence on TFCs	m^{-2}	$2.873 \cdot 10^{21}\ (< 10^{22})$	$9.136 \cdot 10^{21}\ (< 10^{23})$
Time-integrated He-concentration in VV	appm	$1.000\ (= 1)$	1.543 (no limit)

Conclusion

- studied the FWBS module in sPROCESS
- three models before: elaborated on the Simple model, based on the KIT HCPB model
- made a structured and elaborate input file
- created three design points (base, advanced, KIT HCPB)

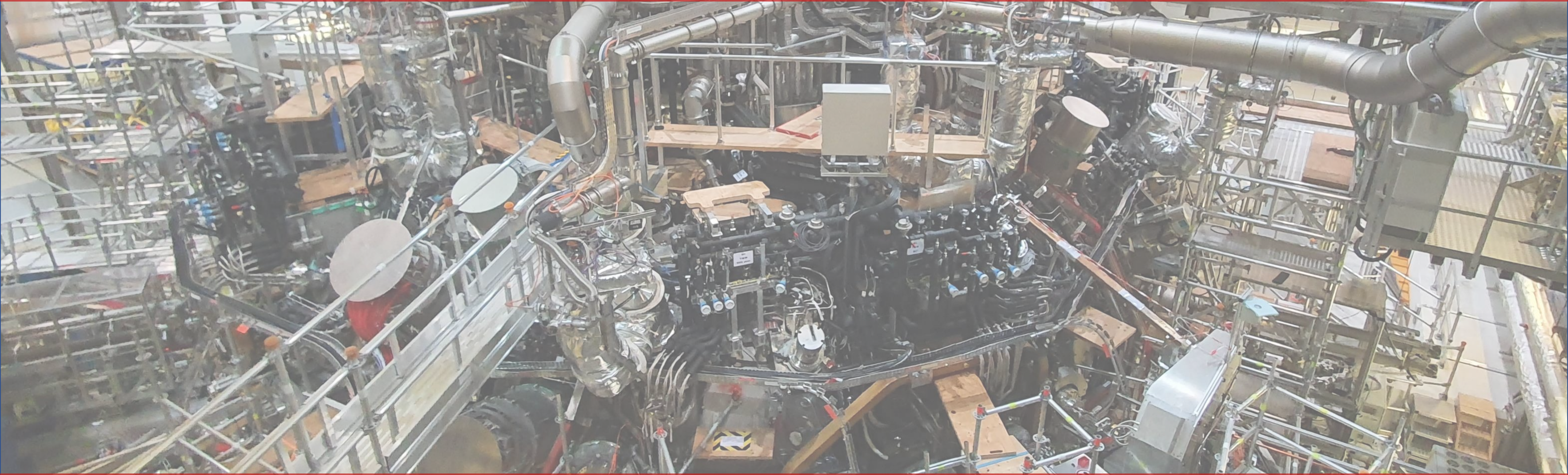
Using “advanced” technology
→ relax FWBS constraints
→ smaller shielding thickness
→ smaller machine
→ cheaper machine (13.69% lower capital cost than the base design)

Systems code: change some inputs/assumptions and monitor the effect on the design

Suggestions for further research

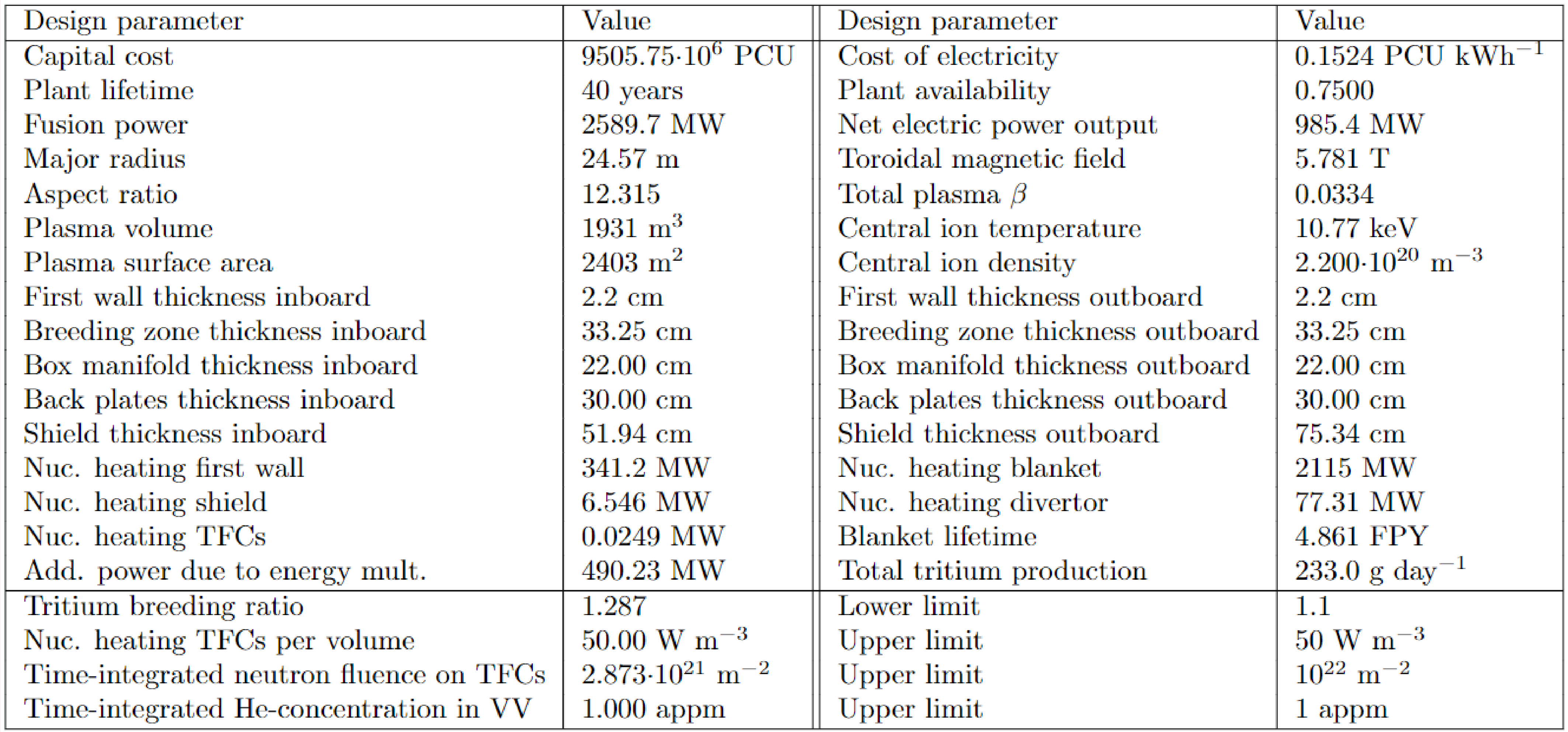
- finish verifying the sources of the input parameters
- edit the code further on a small scale
- investigate the possibility of adding KIT HCLL and CCFE HCPB models to sPROCESS
- research how tokamak studies apply to stellarator FPPs
- research how the distinction between “inboard” and “outboard” applies to stellarators
- try more “advanced technology” designs

Bonus slides



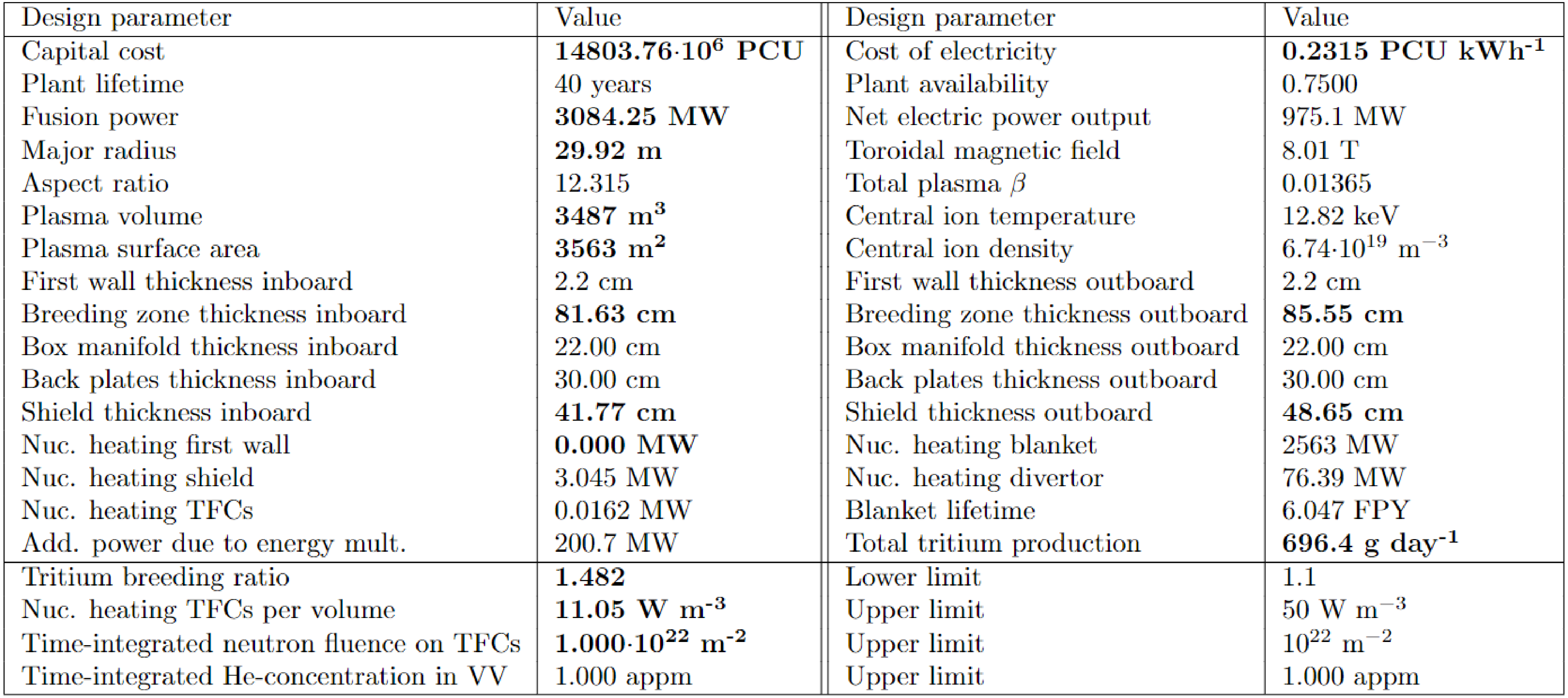
Bonus slides

Base design (repetition of slide 8)



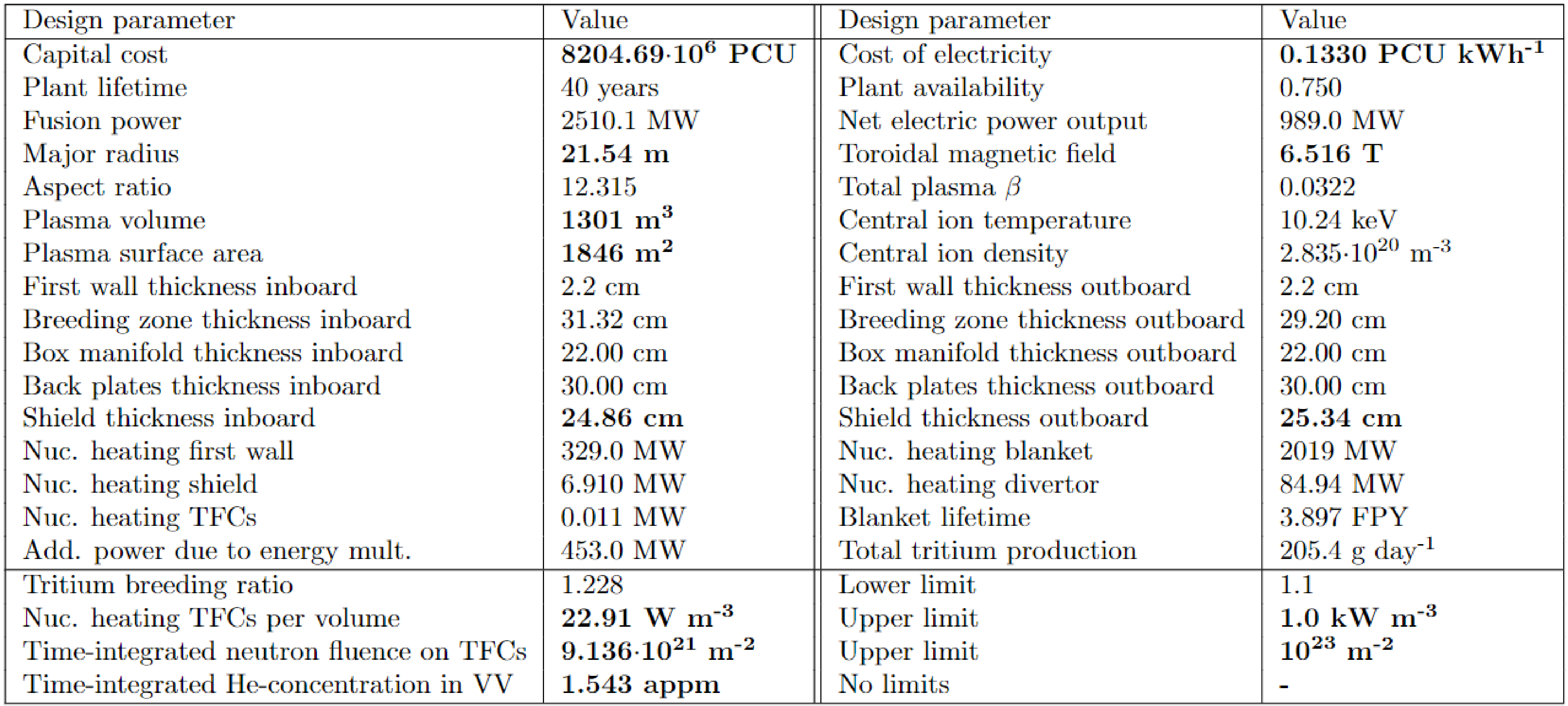
Design parameter	Value	Design parameter	Value
Capital cost	$9505.75 \cdot 10^6$ PCU	Cost of electricity	0.1524 PCU kWh^{-1}
Plant lifetime	40 years	Plant availability	0.7500
Fusion power	2589.7 MW	Net electric power output	985.4 MW
Major radius	24.57 m	Toroidal magnetic field	5.781 T
Aspect ratio	12.315	Total plasma β	0.0334
Plasma volume	1931 m^3	Central ion temperature	10.77 keV
Plasma surface area	2403 m^2	Central ion density	$2.200 \cdot 10^{20}$ m^{-3}
First wall thickness inboard	2.2 cm	First wall thickness outboard	2.2 cm
Breeding zone thickness inboard	33.25 cm	Breeding zone thickness outboard	33.25 cm
Box manifold thickness inboard	22.00 cm	Box manifold thickness outboard	22.00 cm
Back plates thickness inboard	30.00 cm	Back plates thickness outboard	30.00 cm
Shield thickness inboard	51.94 cm	Shield thickness outboard	75.34 cm
Nuc. heating first wall	341.2 MW	Nuc. heating blanket	2115 MW
Nuc. heating shield	6.546 MW	Nuc. heating divertor	77.31 MW
Nuc. heating TFCs	0.0249 MW	Blanket lifetime	4.861 FPY
Add. power due to energy mult.	490.23 MW	Total tritium production	233.0 g day^{-1}
Tritium breeding ratio	1.287	Lower limit	1.1
Nuc. heating TFCs per volume	50.00 W m^{-3}	Upper limit	50 W m^{-3}
Time-integrated neutron fluence on TFCs	$2.873 \cdot 10^{21}$ m^{-2}	Upper limit	10^{22} m^{-2}
Time-integrated He-concentration in VV	1.000 appm	Upper limit	1 appm

KIT HCPB design



Design parameter	Value	Design parameter	Value
Capital cost	**14803.76·10^6 PCU**	Cost of electricity	**0.2315 PCU kWh^{-1}**
Plant lifetime	40 years	Plant availability	0.7500
Fusion power	**3084.25 MW**	Net electric power output	975.1 MW
Major radius	**29.92 m**	Toroidal magnetic field	8.01 T
Aspect ratio	12.315	Total plasma β	0.01365
Plasma volume	**3487 m^3**	Central ion temperature	12.82 keV
Plasma surface area	**3563 m^2**	Central ion density	$6.74 \cdot 10^{19}$ m^{-3}
First wall thickness inboard	2.2 cm	First wall thickness outboard	2.2 cm
Breeding zone thickness inboard	**81.63 cm**	Breeding zone thickness outboard	**85.55 cm**
Box manifold thickness inboard	22.00 cm	Box manifold thickness outboard	22.00 cm
Back plates thickness inboard	30.00 cm	Back plates thickness outboard	30.00 cm
Shield thickness inboard	**41.77 cm**	Shield thickness outboard	**48.65 cm**
Nuc. heating first wall	**0.000 MW**	Nuc. heating blanket	2563 MW
Nuc. heating shield	3.045 MW	Nuc. heating divertor	76.39 MW
Nuc. heating TFCs	0.0162 MW	Blanket lifetime	6.047 FPY
Add. power due to energy mult.	200.7 MW	Total tritium production	**696.4 g day^{-1}**
Tritium breeding ratio	**1.482**	Lower limit	1.1
Nuc. heating TFCs per volume	**11.05 W m^{-3}**	Upper limit	50 W m^{-3}
Time-integrated neutron fluence on TFCs	**$1.000 \cdot 10^{22}$ m^{-2}**	Upper limit	10^{22} m^{-2}
Time-integrated He-concentration in VV	1.000 appm	Upper limit	1.000 appm

Advanced design

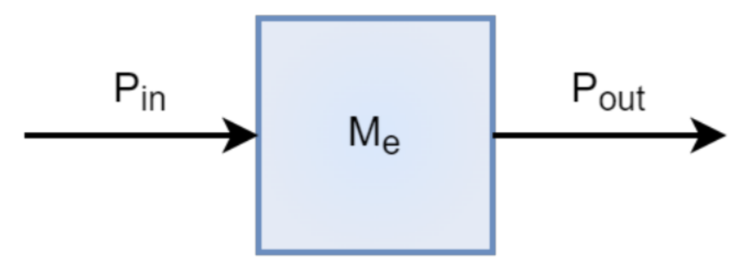


Design parameter	Value	Design parameter	Value
Capital cost	**$8204.69\cdot10^6$ PCU**	Cost of electricity	**0.1330 PCU kWh^{-1}**
Plant lifetime	40 years	Plant availability	0.750
Fusion power	2510.1 MW	Net electric power output	989.0 MW
Major radius	**21.54 m**	Toroidal magnetic field	**6.516 T**
Aspect ratio	12.315	Total plasma β	0.0322
Plasma volume	**1301 m^3**	Central ion temperature	10.24 keV
Plasma surface area	**1846 m^2**	Central ion density	$2.835\cdot10^{20}$ m^{-3}
First wall thickness inboard	2.2 cm	First wall thickness outboard	2.2 cm
Breeding zone thickness inboard	31.32 cm	Breeding zone thickness outboard	29.20 cm
Box manifold thickness inboard	22.00 cm	Box manifold thickness outboard	22.00 cm
Back plates thickness inboard	30.00 cm	Back plates thickness outboard	30.00 cm
Shield thickness inboard	**24.86 cm**	Shield thickness outboard	**25.34 cm**
Nuc. heating first wall	329.0 MW	Nuc. heating blanket	2019 MW
Nuc. heating shield	6.910 MW	Nuc. heating divertor	84.94 MW
Nuc. heating TFCs	0.011 MW	Blanket lifetime	3.897 FPY
Add. power due to energy mult.	453.0 MW	Total tritium production	205.4 g day^{-1}
Tritium breeding ratio	1.228	Lower limit	1.1
Nuc. heating TFCs per volume	**22.91 W m^{-3}**	Upper limit	**1.0 kW m^{-3}**
Time-integrated neutron fluence on TFCs	**$9.136\cdot10^{21}$ m^{-2}**	Upper limit	**10^{23} m^{-2}**
Time-integrated He-concentration in VV	**1.543 appm**	No limits	**-**

Changes to KIT HCPB physics models

- neutron power dep.: also include FW
- added P_{add} calculation
- minor changes to TBR calculation
- include the availability factor for neutron-fluence and He-concentration calculations

$$P_{\mathrm{add.}} = P_{\mathrm{BZ}}(M_e - 1)$$



Changes to KIT HCPB physics models: TBR

$$
\begin{aligned}
\mathrm{TBR} = \mathrm{TBR}_{\mathrm{PPCS}} \cdot & \frac{\left(1-e^{-t_{\mathrm{BZ,in}}/\lambda_{\mathrm{BZ,in}}}\right)}{\left(1-e^{-t_{\mathrm{BZ,in,PPCS}}/\lambda_{\mathrm{BZ,in,PPCS}}}\right)} \frac{\left(1-e^{-t_{\mathrm{BZ,out}}/\lambda_{\mathrm{BZ,out}}}\right)}{\left(1-e^{-t_{\mathrm{BZ,out,PPCS}}/\lambda_{\mathrm{BZ,out,PCCS}}}\right)} \\
& \cdot \frac{\mathrm{CF}}{\mathrm{CF}_{\mathrm{PPCS}}} \cdot \frac{k_1 \ln(e_{\text{Li-6}}[\%]) + k_2}{k_1 \ln(e_{\text{Li-6,PPCS}}[\%]) + k_2} \\
& \cdot (1 - c_{\mathrm{div}} n_{\mathrm{port,div}})(1 - c_{\mathrm{hcd}} n_{\mathrm{port,hcd,in}})(1 - c_{\mathrm{hcd}} n_{\mathrm{port,hcd,out}}).
\end{aligned}
$$

$$
\begin{aligned}
\mathrm{TBR}' = \mathrm{TBR}_{\mathrm{PPCS}} \cdot \frac{1}{2} & \left(\frac{\left(1-e^{-t_{\mathrm{BZ,in}}/\lambda_{\mathrm{BZ,in}}}\right)}{\left(1-e^{-t_{\mathrm{BZ,in,PPCS}}/\lambda_{\mathrm{BZ,in,PPCS}}}\right)} + \frac{\left(1-e^{-t_{\mathrm{BZ,out}}/\lambda_{\mathrm{BZ,out}}}\right)}{\left(1-e^{-t_{\mathrm{BZ,out,PPCS}}/\lambda_{\mathrm{BZ,out,PCCS}}}\right)} \right) \\
& \cdot \frac{\mathrm{CF}}{\mathrm{CF}_{\mathrm{PPCS}}} \cdot \frac{k_1 \ln(e_{\text{Li-6}}[\%]) + k_2}{k_1 \ln(e_{\text{Li-6,PPCS}}[\%]) + k_2} \\
& \cdot (1 - c_{\mathrm{div}} n_{\mathrm{port,div}})(1 - c_{\mathrm{hcd}} (n_{\mathrm{port,hcd,in}} + n_{\mathrm{port,hcd,out}})).
\end{aligned}
$$

Advanced design

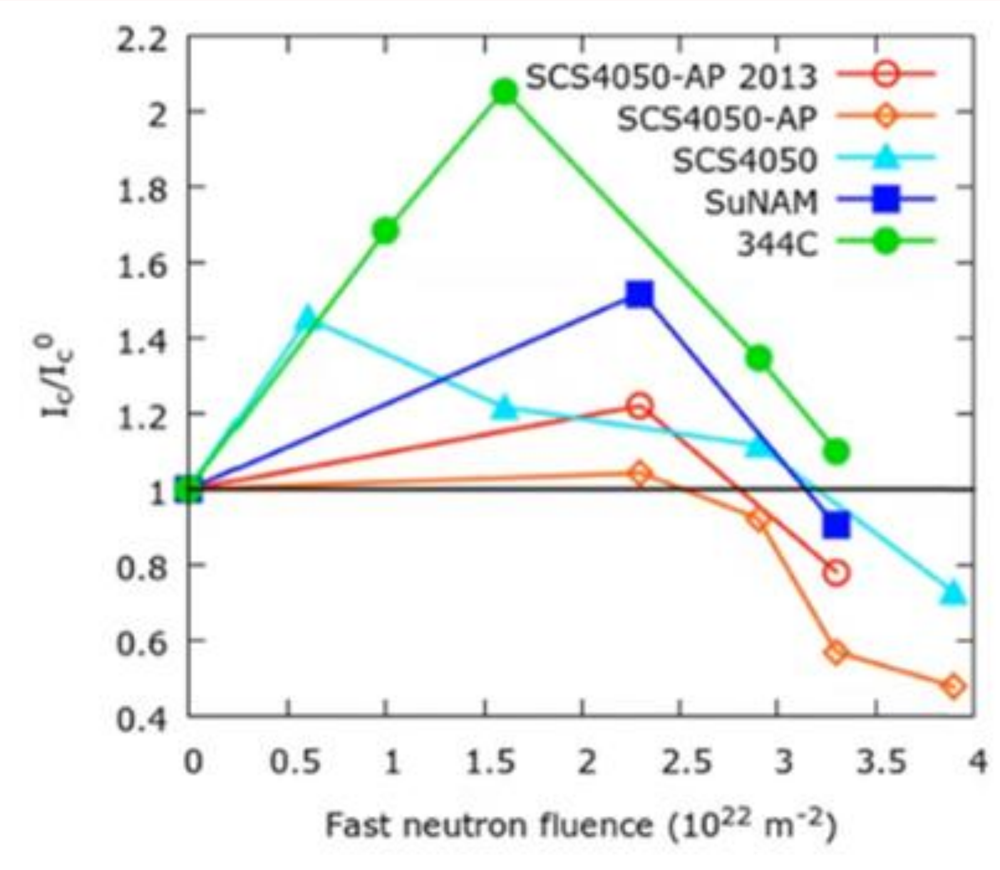
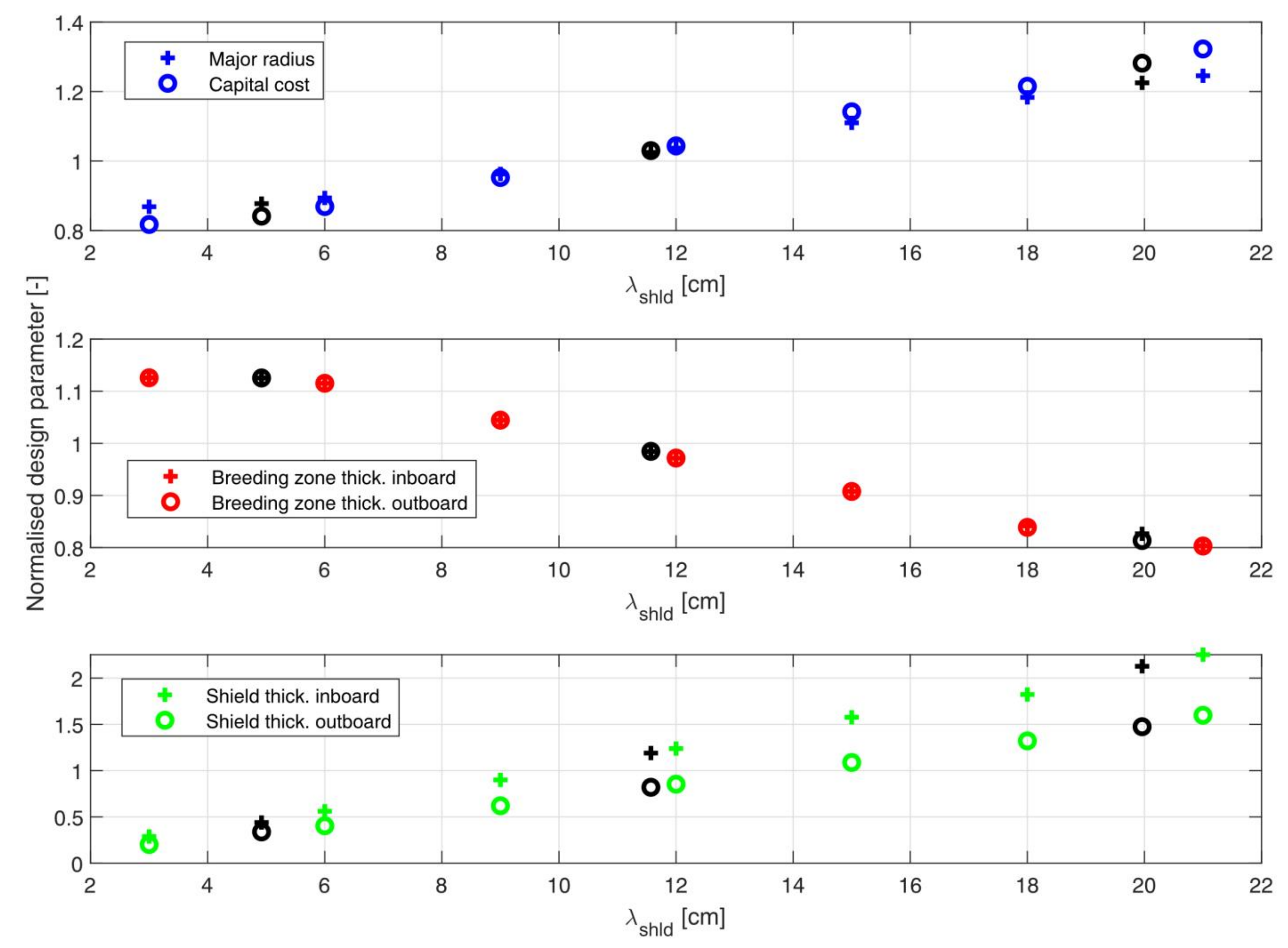
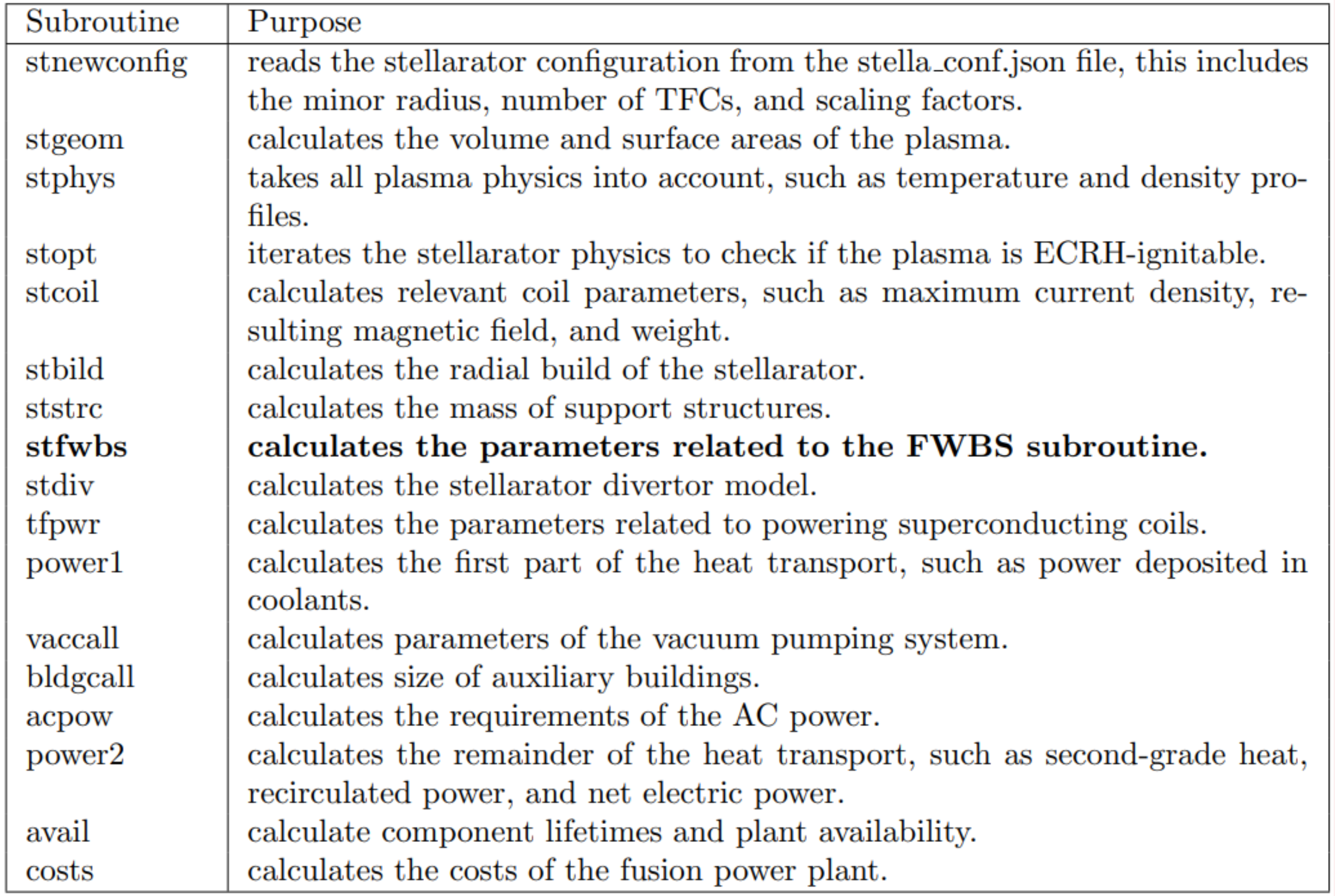


Image source:
D. Fischer, R. Prokopec, J. Emhofer, and M. Eisterer. (2018). “The effect of fast neutron irradiation on the superconducting properties of REBCO coated conductors with and without artificial pinning centers”, Superconductor Science and Technology, Vol. 31, 044006.

Decay lengths



Subroutines of sPROCESS



Subroutine	Purpose
stnewconfig	reads the stellarator configuration from the stella_conf.json file, this includes the minor radius, number of TFCs, and scaling factors.
stgeom	calculates the volume and surface areas of the plasma.
stphys	takes all plasma physics into account, such as temperature and density profiles.
stopt	iterates the stellarator physics to check if the plasma is ECRH-ignitable.
stcoil	calculates relevant coil parameters, such as maximum current density, resulting magnetic field, and weight.
stbild	calculates the radial build of the stellarator.
ststrc	calculates the mass of support structures.
stfwbs	**calculates the parameters related to the FWBS subroutine.**
stdiv	calculates the stellarator divertor model.
tfpwr	calculates the parameters related to powering superconducting coils.
power1	calculates the first part of the heat transport, such as power deposited in coolants.
vaccall	calculates parameters of the vacuum pumping system.
bldgcall	calculates size of auxiliary buildings.
acpow	calculates the requirements of the AC power.
power2	calculates the remainder of the heat transport, such as second-grade heat, recirculated power, and net electric power.
avail	calculate component lifetimes and plant availability.
costs	calculates the costs of the fusion power plant.

Blanket

- shield other components from neutrons
- extract most of the heat (energy multiplication)
- breed new tritium, account for: neutron losses, decay, small storage, new start-up

$$
\begin{aligned}
{}^{6}\mathrm{Li} + \mathrm{n} &\rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He} + 4.8\mathrm{MeV} \\
{}^{7}\mathrm{Li} + \mathrm{n} &\rightarrow {}^{3}\mathrm{H} + {}^{4}\mathrm{He} + \mathrm{n} - 2.8\mathrm{MeV}
\end{aligned}
$$

$$
\begin{aligned}
{}^{9}\mathrm{Be} + \mathrm{n} &\rightarrow 2\alpha + 2\mathrm{n} \\
{}^{208}\mathrm{Pb} + \mathrm{n} &\rightarrow {}^{207}\mathrm{Pb} + 2\mathrm{n}
\end{aligned}
$$

FPP global power balance

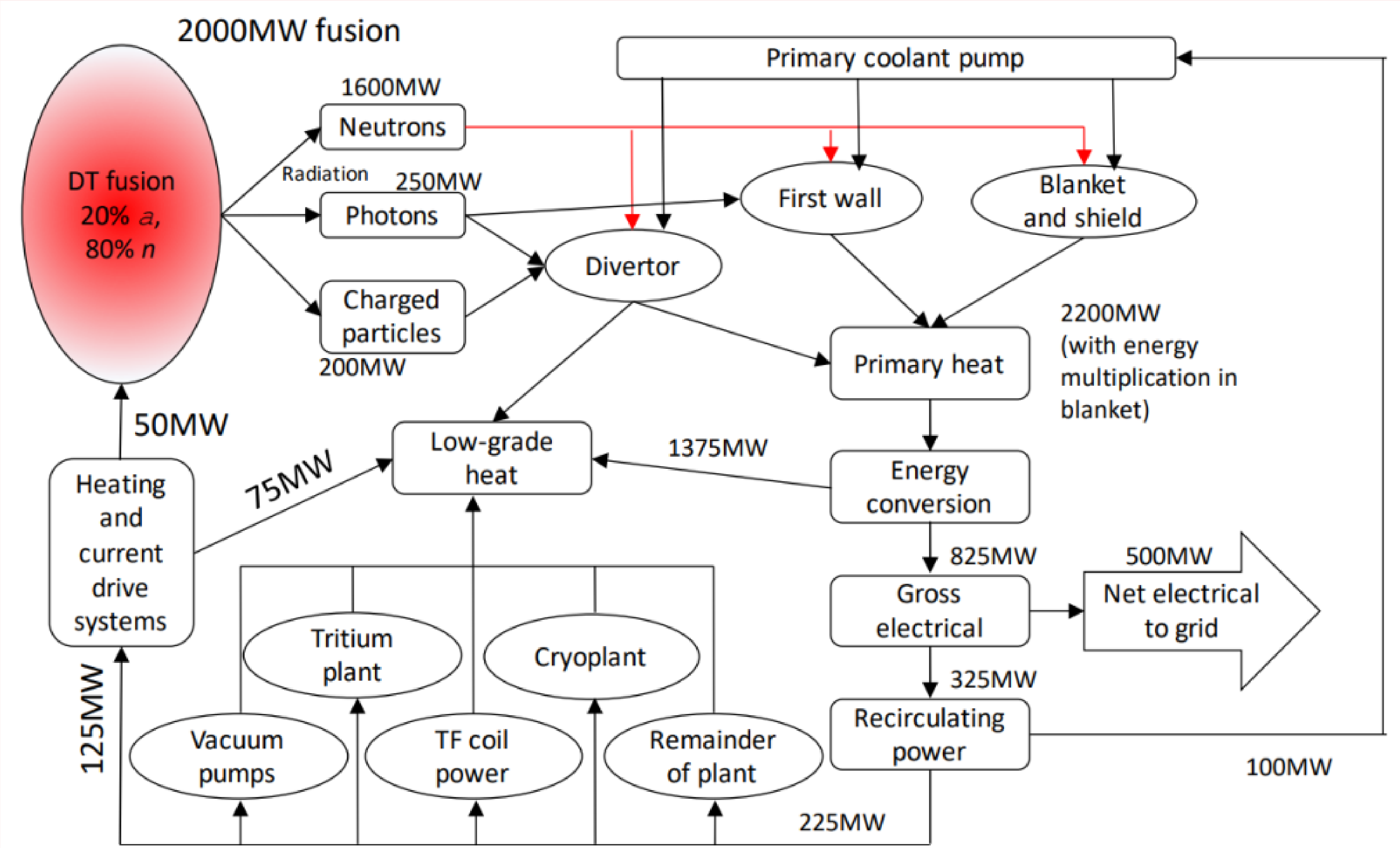
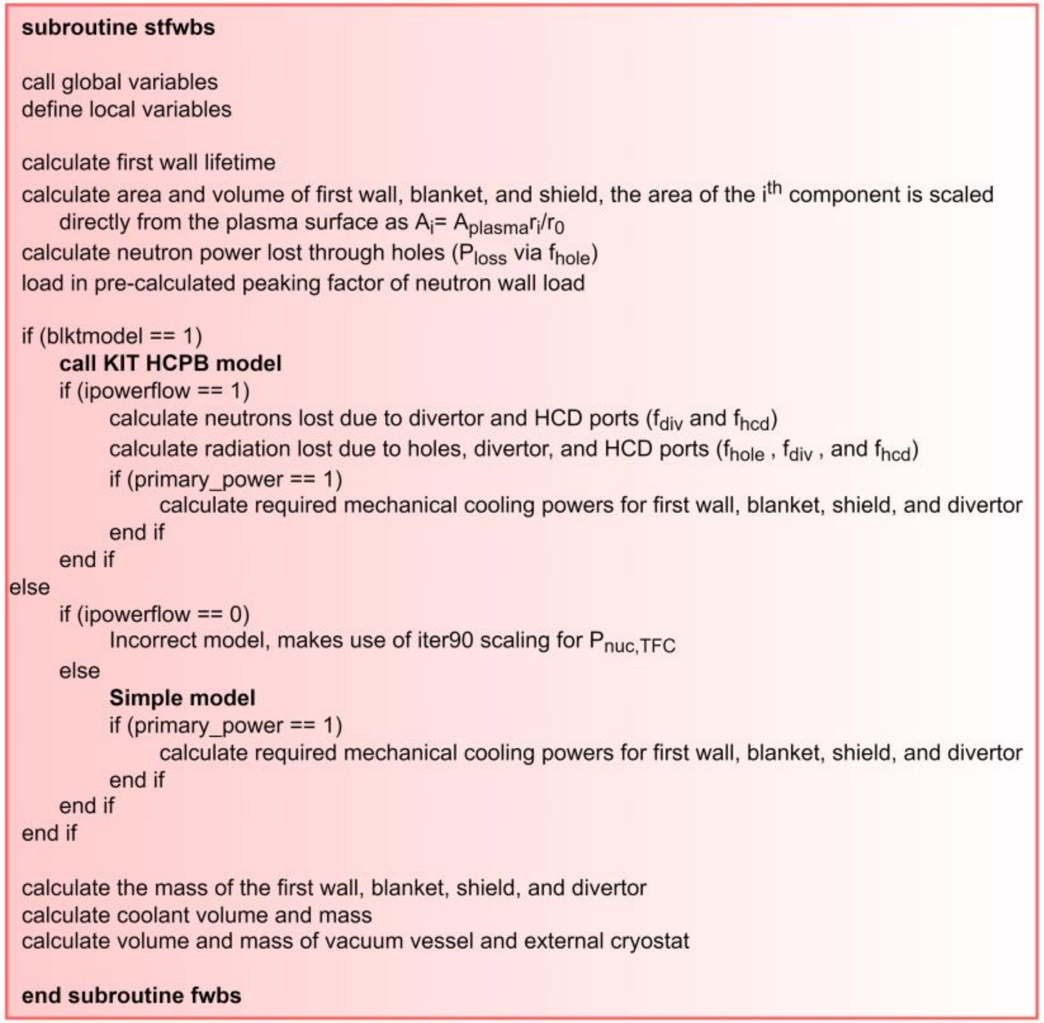
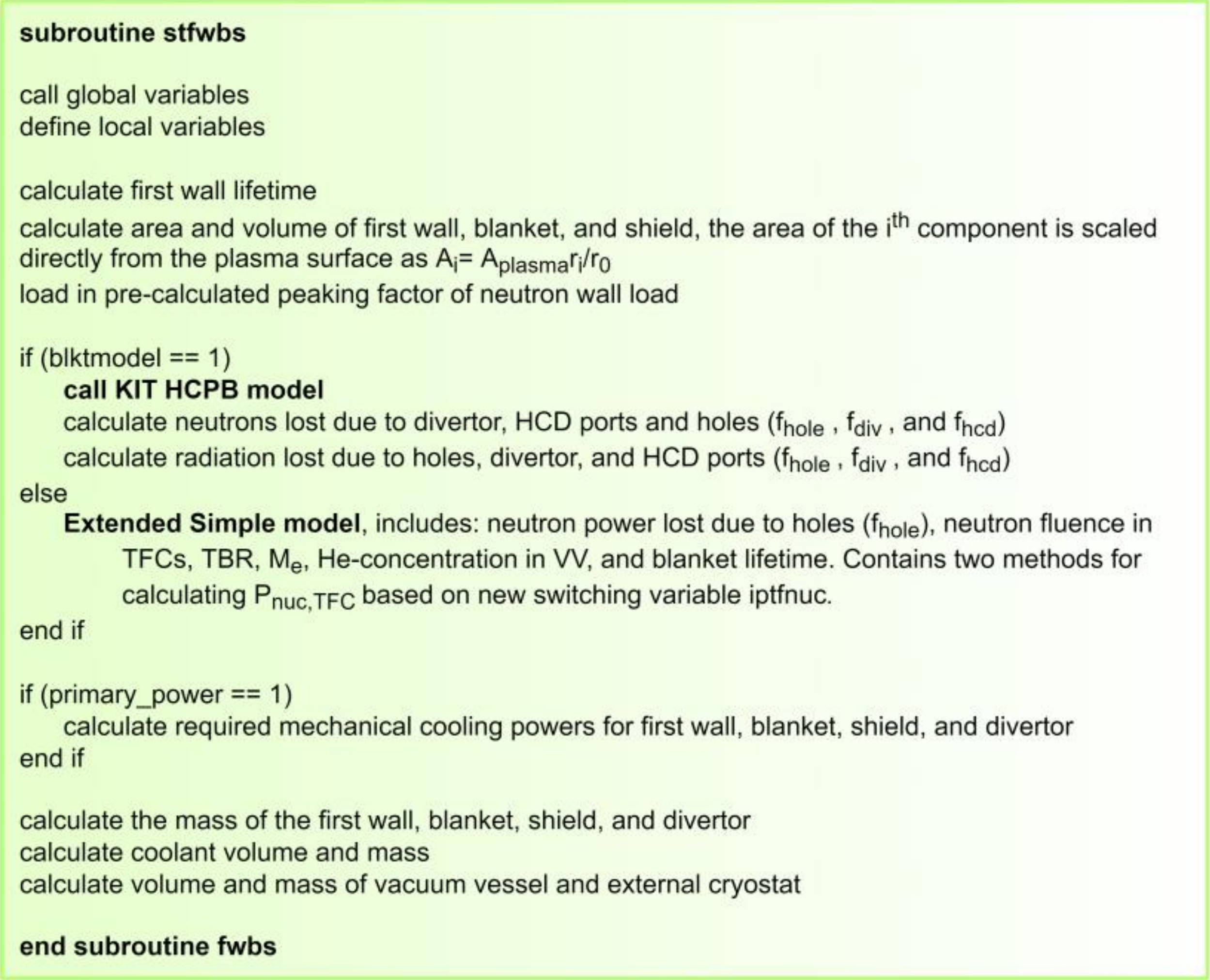


Image source:
R. Kembleton, “Demo design process: Fusion masterclass, April 2021,” lecture given at the Eindhoven University of Technology in April 2021.

stfwbs subroutine: before and after



```
subroutine stfwbs

call global variables
define local variables

calculate first wall lifetime
calculate area and volume of first wall, blanket, and shield, the area of the i$^{th}$ component is scaled
    directly from the plasma surface as $A_i = A_{plasma} r_i / r_0$
calculate neutron power lost through holes ($P_{loss}$ via $f_{hole}$)
load in pre-calculated peaking factor of neutron wall load

if (blktmodel == 1)
    call KIT HCPB model
    if (ipowerflow == 1)
        calculate neutrons lost due to divertor and HCD ports ($f_{div}$ and $f_{hcd}$)
        calculate radiation lost due to holes, divertor, and HCD ports ($f_{hole}$ , $f_{div}$ , and $f_{hcd}$)
        if (primary_power == 1)
            calculate required mechanical cooling powers for first wall, blanket, shield, and divertor
        end if
    end if
else
    if (ipowerflow == 0)
        Incorrect model, makes use of iter90 scaling for $P_{nuc,TFC}$
    else
        Simple model
        if (primary_power == 1)
            calculate required mechanical cooling powers for first wall, blanket, shield, and divertor
        end if
    end if
end if

calculate the mass of the first wall, blanket, shield, and divertor
calculate coolant volume and mass
calculate volume and mass of vacuum vessel and external cryostat

end subroutine fwbs
```



```
subroutine stfwbs

call global variables
define local variables

calculate first wall lifetime
calculate area and volume of first wall, blanket, and shield, the area of the i$^{th}$ component is scaled
directly from the plasma surface as $A_i = A_{plasma} r_i / r_0$
load in pre-calculated peaking factor of neutron wall load

if (blktmodel == 1)
    call KIT HCPB model
    calculate neutrons lost due to divertor, HCD ports and holes ($f_{hole}$ , $f_{div}$ , and $f_{hcd}$)
    calculate radiation lost due to holes, divertor, and HCD ports ($f_{hole}$ , $f_{div}$ , and $f_{hcd}$)
else
    Extended Simple model, includes: neutron power lost due to holes ($f_{hole}$), neutron fluence in
        TFCs, TBR, $M_e$, He-concentration in VV, and blanket lifetime. Contains two methods for
        calculating $P_{nuc,TFC}$ based on new switching variable iptfnuc.
end if

if (primary_power == 1)
    calculate required mechanical cooling powers for first wall, blanket, shield, and divertor
end if

calculate the mass of the first wall, blanket, shield, and divertor
calculate coolant volume and mass
calculate volume and mass of vacuum vessel and external cryostat

end subroutine fwbs
```