Karlsruhe Institute of Technology

25^{th} European Fusion Programme Workshop

Advanced systems codes and integrated modelling for DEMO

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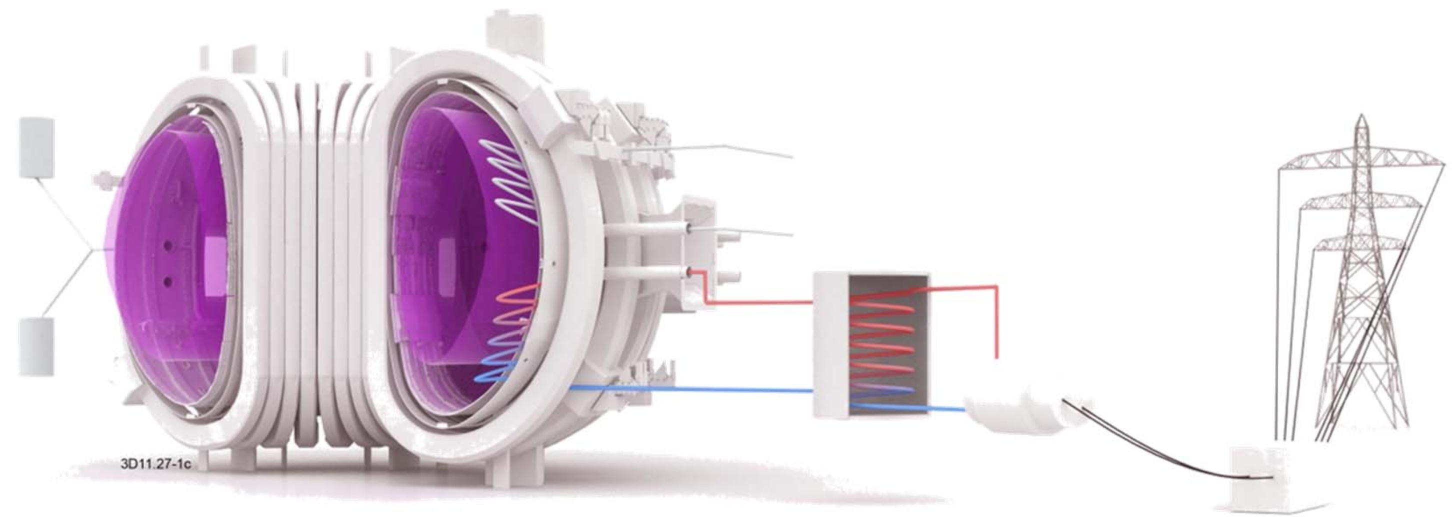
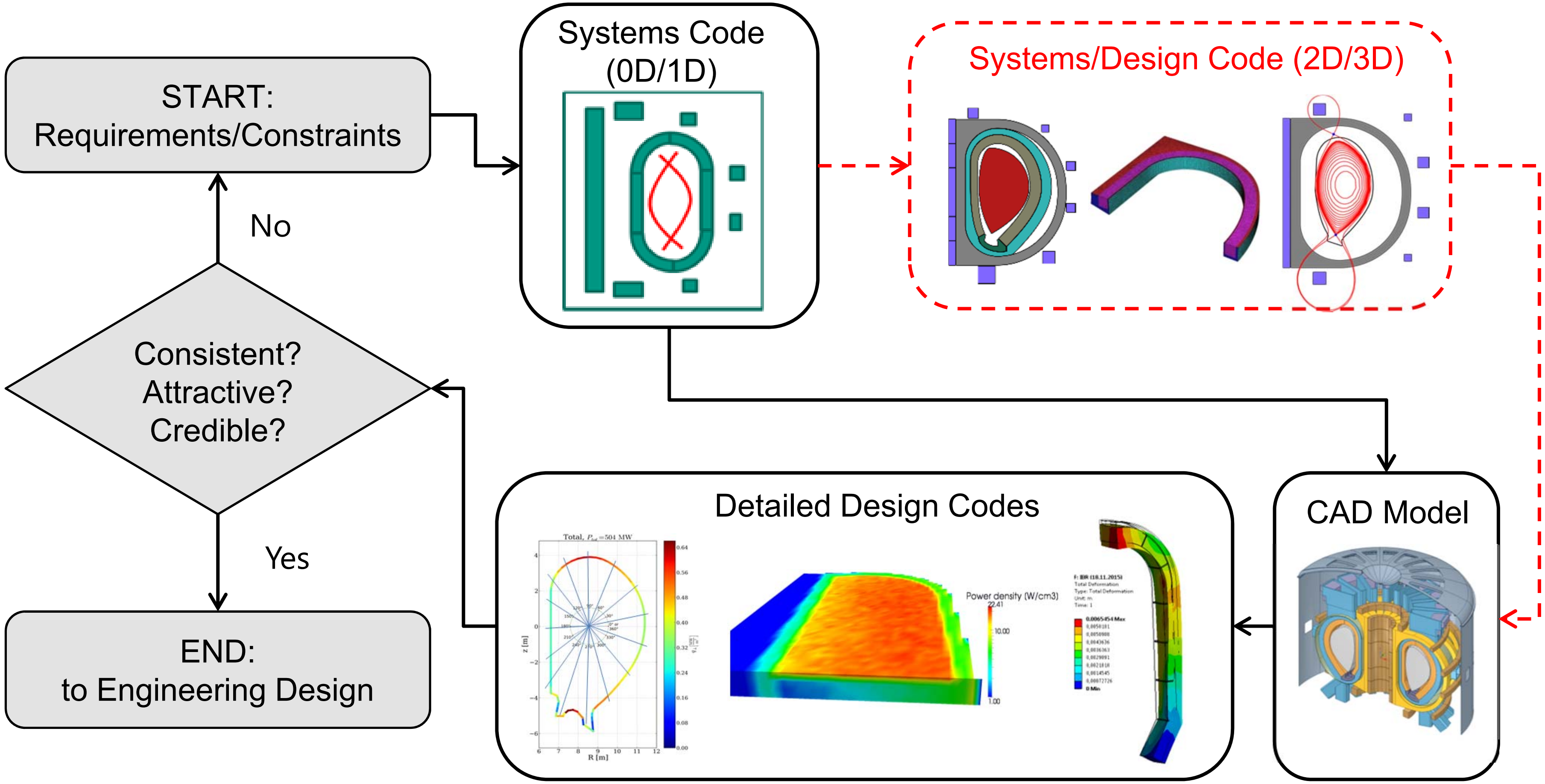
Karlsruhe Institute of Technology (KIT), Institute for Neutron Physics and Reactor Technology (INR), Germany



Motivation to the Work

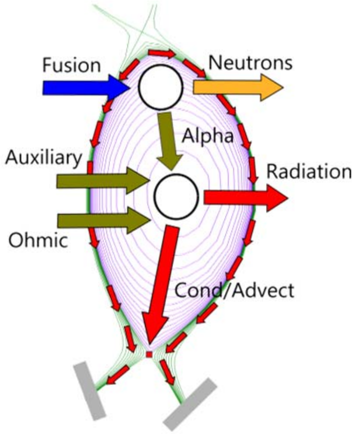
- Development of a System/Design Code at KIT

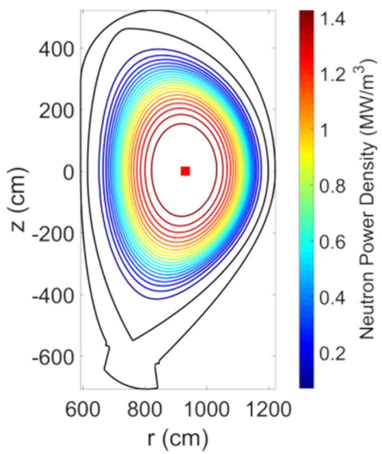
Modular **I**ntegrated **R**eactor **A**nalysis



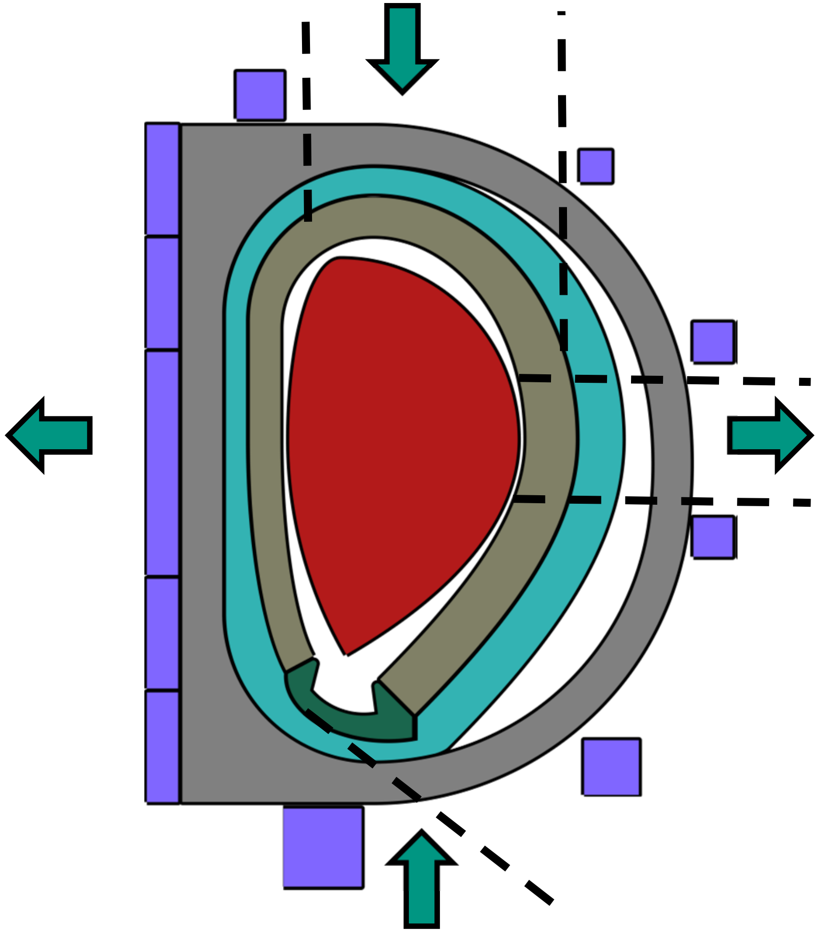
Reactor Architecture

Physics



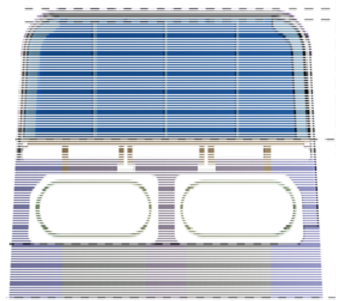


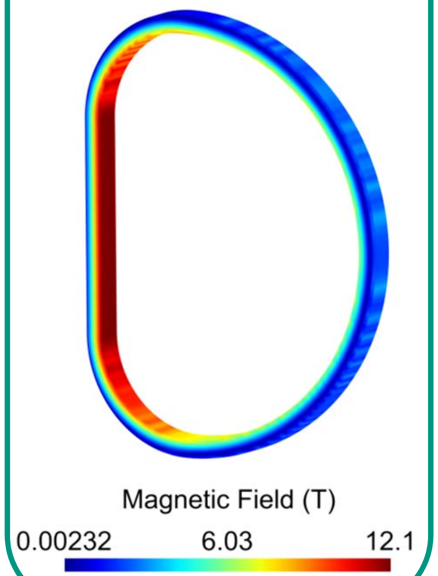
Requirements



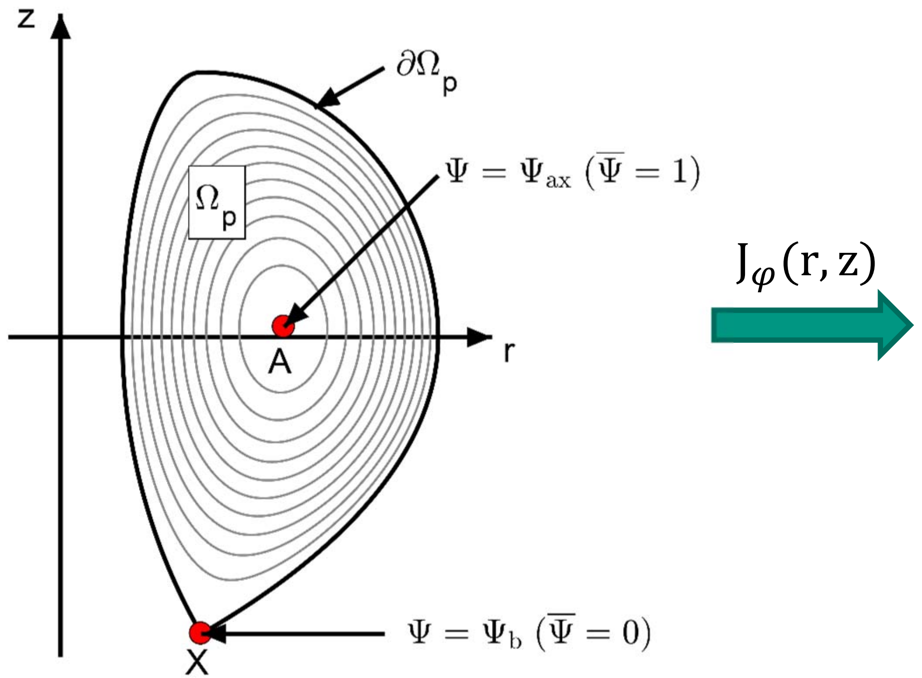
Constraints

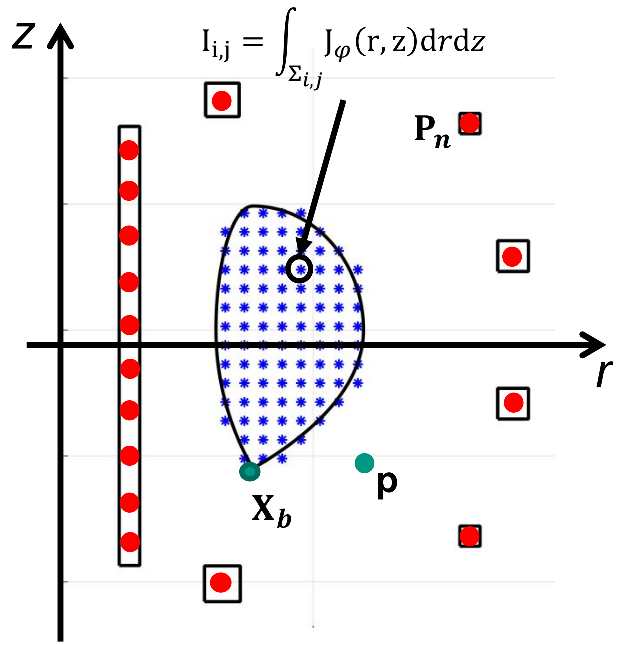
Technology





Magnetic Equilibrium and Confinement





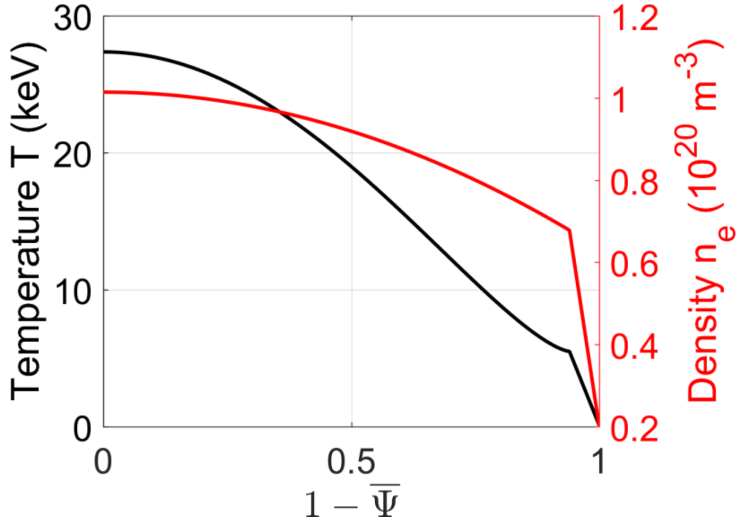
- Plasma parameters $(I_p, \beta_p, l_i, q_{ax})$
- Poloidal magnetic flux $\Psi(r,z)$
  - Solve Grad-Shafranov eq (freefem++)

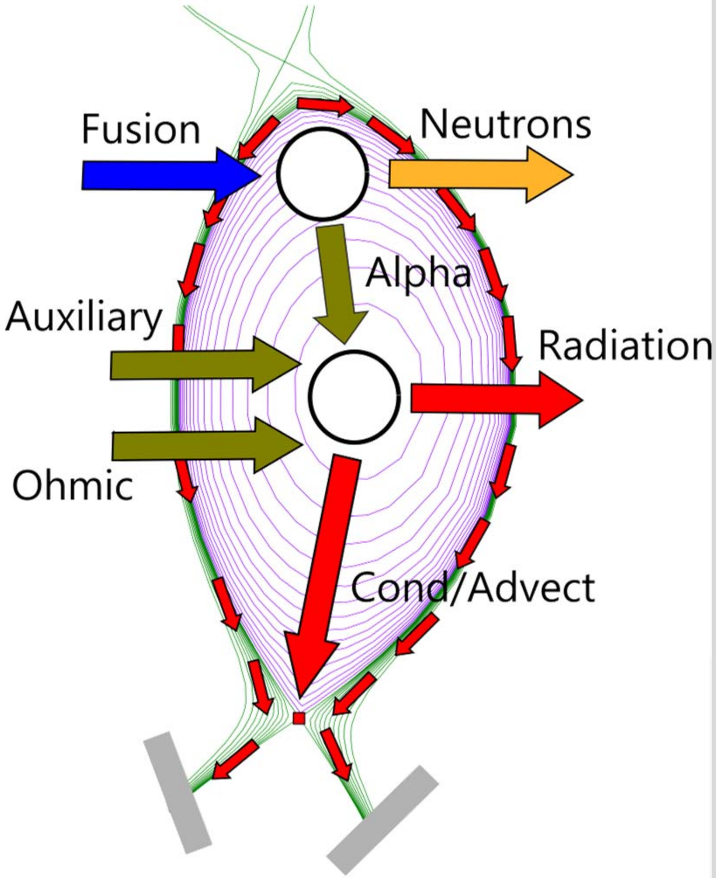
$$\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial\psi}{\partial r}\right) + \frac{\partial^2\psi}{\partial z^2} = -2\pi\mu_0 r J_\varphi(\Psi, I_p, \beta_p, l_i, q_{ax})$$

- $\mathbf{I} = [I_0, I_1, \dots I_h]$ for h+1 PF coils
- Green function (TOKES, KIT)
  - $\sum_{n=0}^{h} G_\psi(\mathbf{p}; \mathbf{P_n}) I_n - \psi_b = 0$
  - $\sum_{n=0}^{h} G_{B,j}(\mathbf{X_b}; \mathbf{P_n}) I_n = 0$, j=r,z

Core Plasma Physics

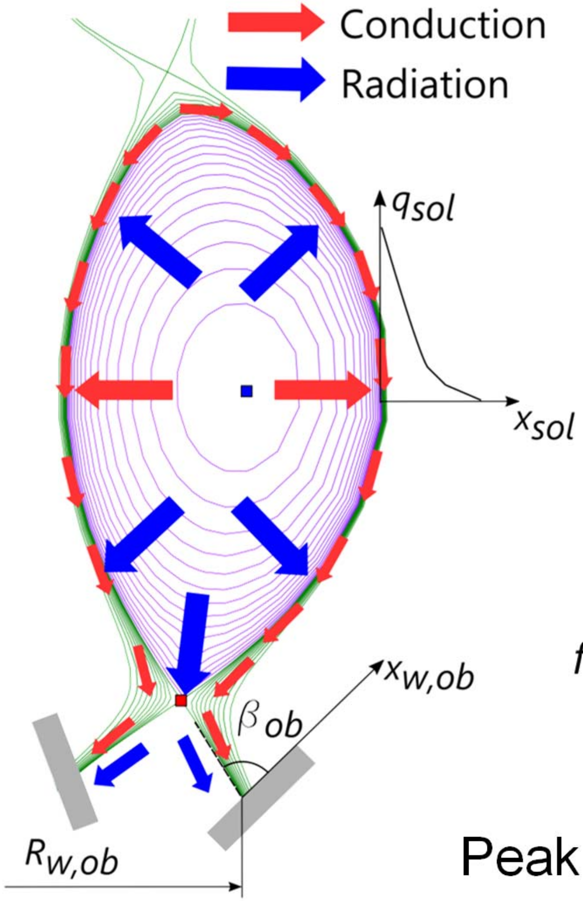
- Power balance: $P_\alpha(n_e, T) + P_{aux}(T) + P_{oh} = P_{rad}(n_e, T) + P_{con}(n_e, T)$
- Particle balance: $n_e = n_{DT} + 2n_{He} + \sum Z_j n_j$
- Current balance: $I_p = I_{BS} + I_{CD} + I_{ind}$
- Plasma Profiles:
  - Pressure $p(\Psi)$ ← Equilibrium model
  - Density $n_e(\Psi)$ ← prescribed (e.g. pedestal)
  - Temperature → $T(\Psi) \propto p(\Psi)/n_e(\Psi)$





Wall Loading: Conduction/Advection

- Peak heat flux on divertor targets



Power balance in plasma core

$$P_\alpha + P_{add} + P_{oh} = P_{rad} + P_{con}$$

Power decay in SOL

$$q_{sol} = q_0 \exp\left(-\frac{x_{sol}}{\lambda_{q,mp}}\right)$$

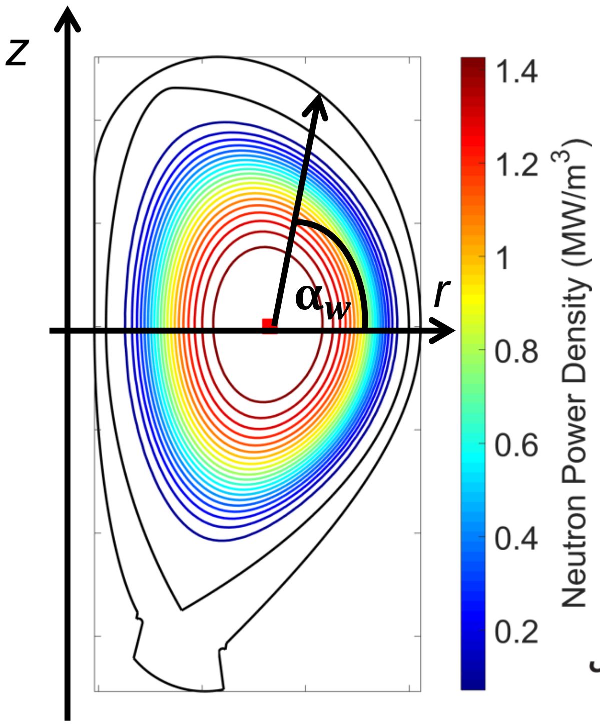
$$\lambda_{d,k} = \lambda_{q,mp}(B_t, q_0, P_{sep}) \cdot \frac{f_{exp,k}}{\sin\beta_k} \qquad k = \mathrm{ib}, \mathrm{ob}$$

$$f_{exp,k} = \frac{R_{mp,k}\, B_{mp,k}}{R_{d,k}\, B_{d,k}}$$ → from magnetic configuration

Peak heat flux → $$q^{peak}_{con,k} = P_{cond,k} \cdot \left(\frac{\sin\beta_k \cdot (1 - f_{rad})}{2\pi \overline{R_{d,k}}\, \lambda_{q,mp}\, f_{exp,k}}\right)$$

Wall Loading: Radiation + Neutrons

- Transport model based on 2D source:
  - Neutron
  - Photon (Bremsstrahlung + Line + Synchrotron)



- Plasma + SOL domain
- Finite element approx. → $\mathcal{T}_h$: $\bigcup_{k=1}^{n_t} \mathcal{T}_k = \Omega_h$
- Discrete ordinate approx. (S_N) $\vec{\boldsymbol{\omega}}_{\boldsymbol{pq}}(\boldsymbol{\xi_p}, \boldsymbol{\mu_{pq}})$
- FEM solution of Boltzmann Eq. in *r,z* geometry

$$\sum_{\tau \in \mathcal{T}_h} \int_\tau \left(-\psi_{pq} \boldsymbol{\omega_{pq}} \cdot \nabla \varphi_{pq}\right) \mathrm{d}\mathbf{r} + \sum_{e \not\subset \partial \mathcal{D}} \int_e \langle \boldsymbol{\omega_{pq}} \psi_{pq} \rangle \, [\![\varphi_{pq}]\!] \mathrm{dS} = \int_{\mathcal{D}} S_{pq}(\mathbf{r}) \varphi_{pq} \mathrm{d}\mathbf{r}$$

$$J_r(r, z) = \sum_{pq}^{M} w_{pq} \mu_{pq} \, \psi_{pq}(r, z)$$

$$J_z(r, z) = \sum_{pq}^{M} w_{pq} \xi_p \, \psi_{pq}(r, z)$$

$$WL|_{A_w} = \frac{\int_{A_w} (n_r J_r + n_z J_z) \, \mathrm{dS}}{\int_{A_w} \mathrm{dS}}$$

Reactor Neutronics

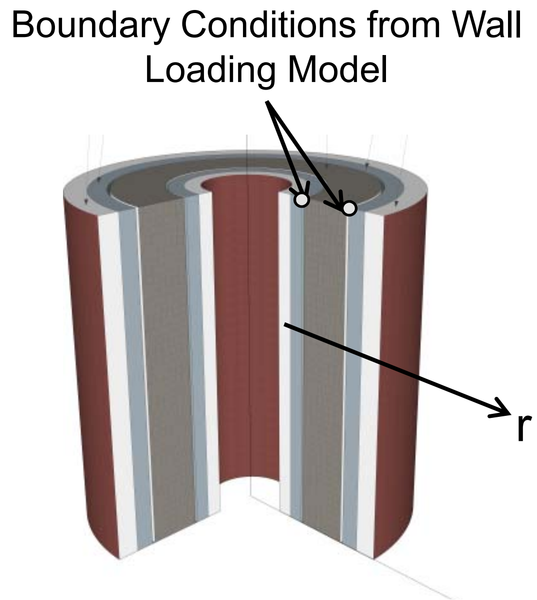
- 1D radial neutron/photon transport

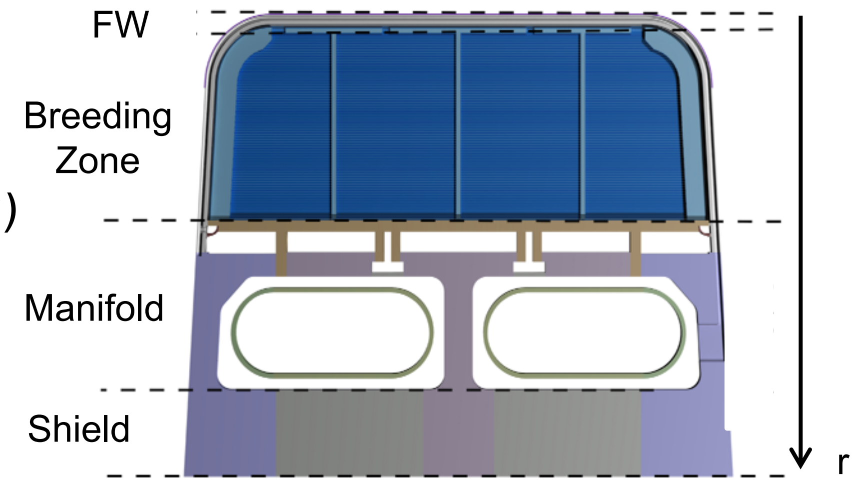
$$\left(\frac{\mu}{r}\frac{\partial}{\partial r}r - \frac{1}{r}\frac{\partial}{\partial \omega}\eta + \sigma\right)\psi(r,\Omega) = q(r,\Omega)$$

- Key parameters
  - Neutron flux distrubution (Shielding)
  - Tritium Breeding Ratio
  - Nuclear Heating power
  - Atomic displacement

- Coupling of external codes:
  - TransX: → Nuclear cross section (σ)
  - ANISN → 1D Transport Code (ψ)

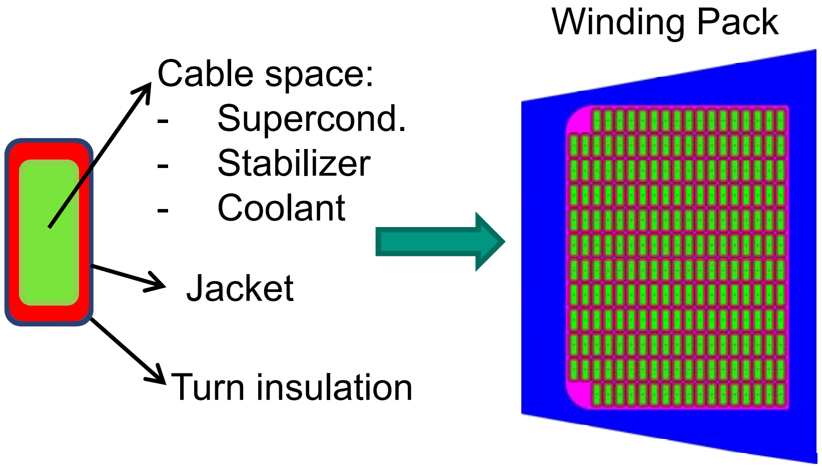
- Nuclear characterization of BB



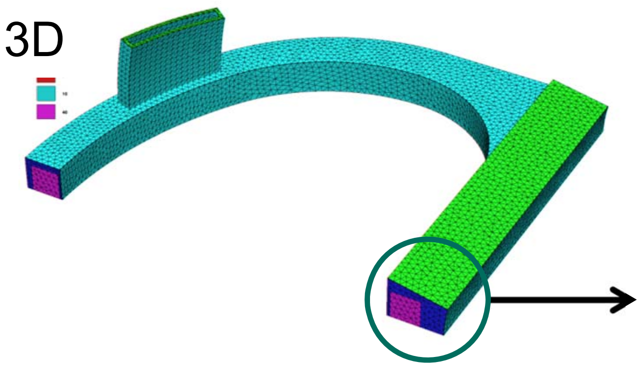


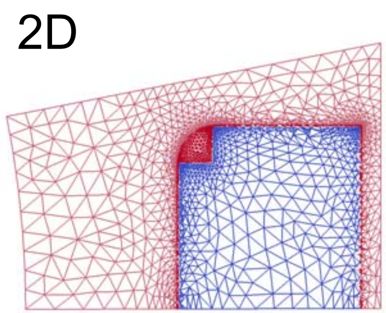
Magnets System

- Conductor technology



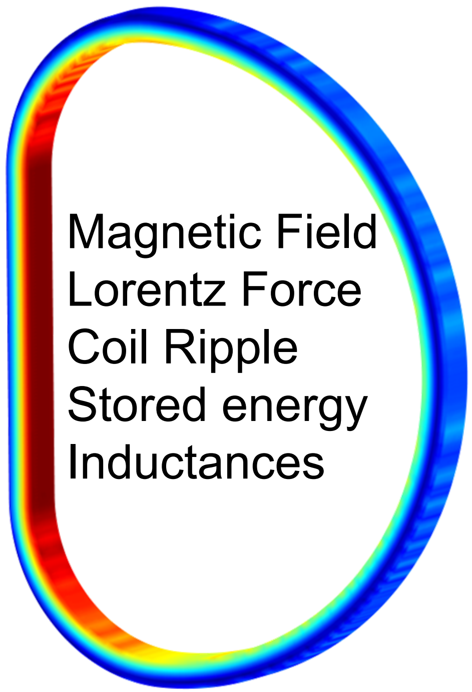
- Structural Mechanics (freefem++)





- 3D Magnetostatics

Biot-Savart solution (EFFI Code)

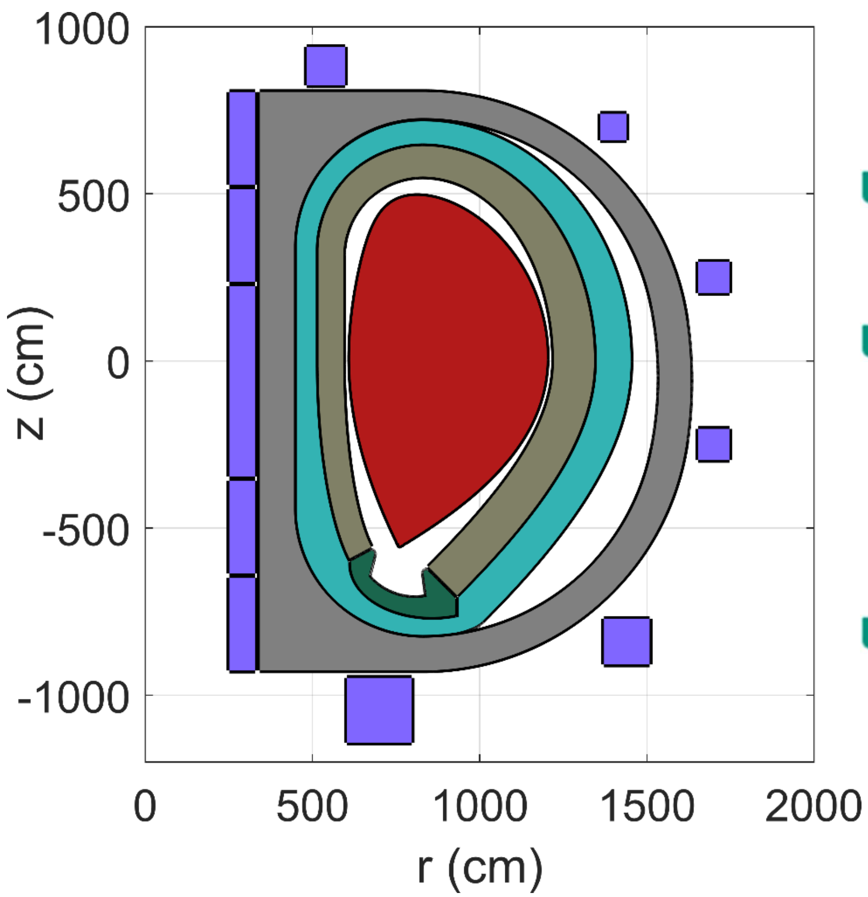


Power Flow

- Steady State system power balance $\sum_i P_{in,i} + \sum_j \dot{q}_{v,j} = \sum_k P_{out,k}$
- Plasma:
  - Core: $P_\alpha + P_{aux} + P_{oh} = P_{rad,Core} + P_{con}$
  - Mantle: $P_{con} = P_{rad,mantle} + P_{sep}$
- Primary heat transfer system $P_{th} = P_{th,bb} + P_{th,div} + P_{th,vv}$
  - Blanket: $P_{th,bb} = P_{nucl,bb} + P_{rad,bb}$
  - Divertor: $P_{th,div} = P_{nucl,div} + P_{rad,div} + P_{sep}$
- Balance of Plant:
  - Gross electric power: $P_{elc,gros} = P_{th} \cdot \eta_{th}$
  - Net electric power: $P_{elc,net} = P_{elc,gros} - P_{aux,elc} - P_{pump,elc} - P_{cryo}$

Application: DEMO Design (2015)

- Set reactor architecture



- Single null plasma
  - R_0 = 9.07
  - A = 3.1
- HCPB blanket
- LT superconductors
  - Nb_3Sn TFC/CS
  - NbTi PF
- Top level requirements
  - $P_{net,elc} \approx 500$ MW
  - $\tau_{flat} \geq 2$ hr
  - TBR ≥ 1.10

Application: DEMO Design (2015) – Plasma

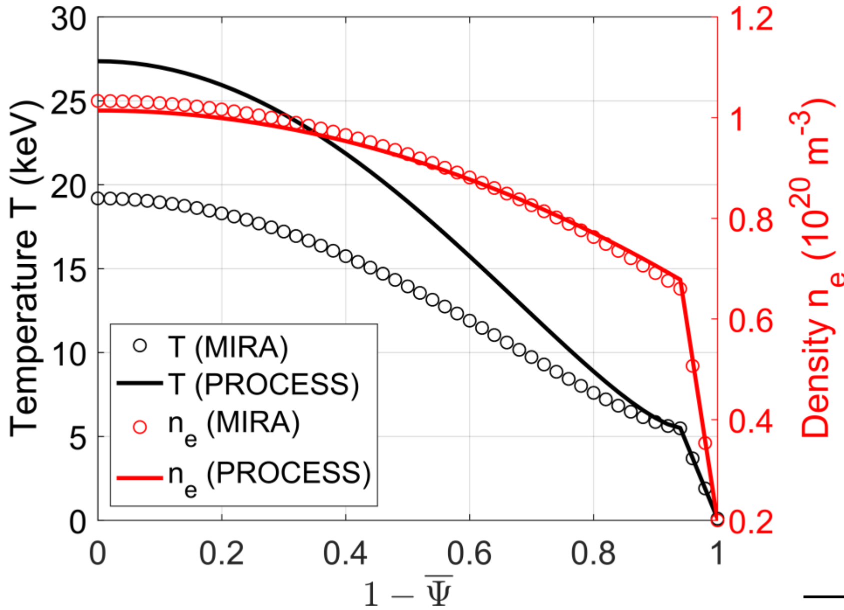
- $\kappa_X = 1.73$, $\delta_X = 0.5$
- Grad-Shafranov equilibrium problem $\Delta^*\psi = -2\pi\mu_0 r J_\varphi(r, \psi, I_p, \beta_p, l_i, q)$
- Power and Current balance
- Set operational limits
  - $q_{95} \geq 3$
  - $P_{sep}/P_{LH} \geq 1.3$
  - $17 \leq P_{sep}/R_0 \leq 20$ MW/m
  - $Q \geq 30$
  - $\beta_N \leq 4l_i$
- Variables
  - Density at magn. axis $n_{e,0}$
  - Xe concentration x_{Xe}
  - W concentration x_W

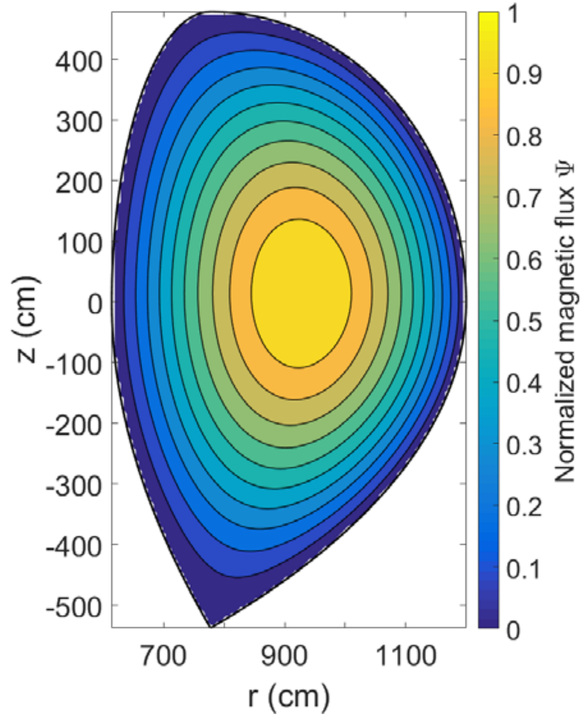
Parameter (unit)	PROCESS	MIRA
Beta poloidal β_p (-)	1.107	1.00*
Internal inductance l_i (-)	1.155	0.80*
Plasma current I_p (MA)	19.6	19.6*
Safety factor q95 (-)	3.24	3.38
Fusion Power P_{fus} (MW)	2037	2161.8
Fusion gain Q (-)	39.86	37.9
CD power P_{CD}(MW)	50	56.3
Radiation power P_{rad} (MW)	305.5	318.9
Transport losses P_{con} (MW)	306.7	295.5
Xe concentration (-)	3.891E-04	2.32E-04
W concentration (-)	5.000E-05	3.275E-05

*Input parameters

Application: DEMO Design (2015) – Plasma

- Impact of integration formula





$$x(\overline{\Psi}) = x_0(1-(1-\overline{\Psi})^2)^{\alpha_x}$$

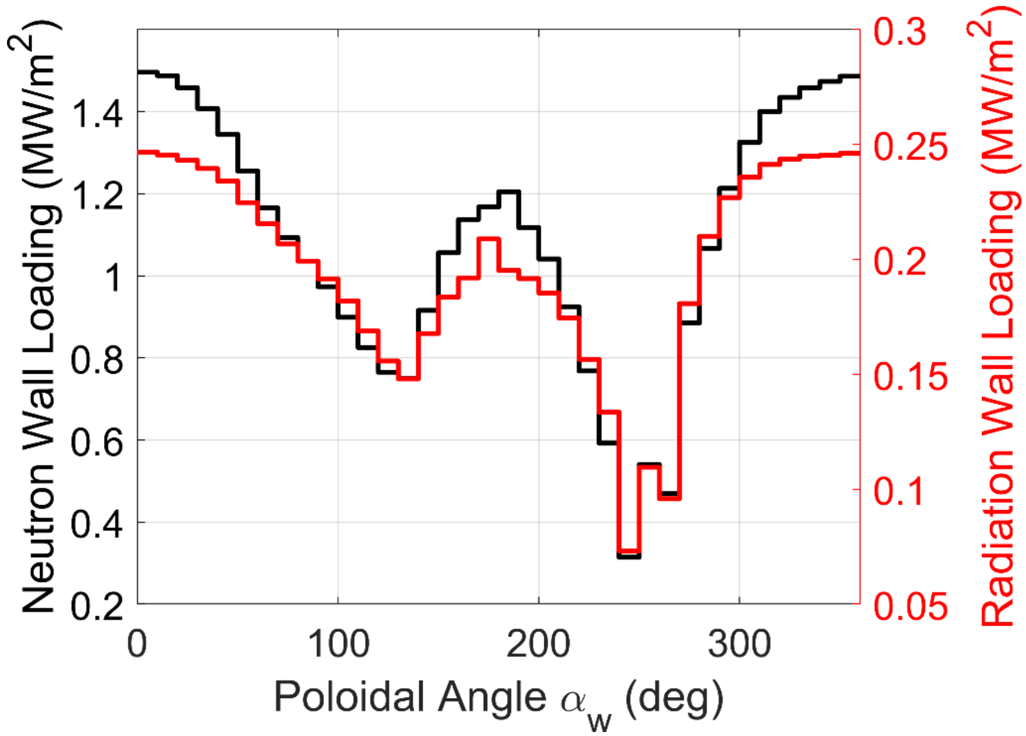
MIRA: $\langle x\rangle = \frac{1}{\mathrm{V}}\int x(\overline{\Psi},\mathrm{r},\mathrm{z})\, 2\pi r dr dz$

PROCESS: $\langle x\rangle = \theta_v \int x(\Psi)\mathrm{d}\,\Psi$

Parameter (Unit)	MIRA	PROCESS
Poloidal beta	0.90	1.107
Fusion power (MW)	2003.6	2037
Volume-averaged n_e (m^{-3})	0.86E+20	0.80E+20
Density-averaged T (keV)	13.37	14.41

Application: DEMO Design (2015) – Wall Loading

- Power loads
  - Neutron (n): 1741 MW
  - Radiation (γ): 319 MW
  - Transport (i+e): 176.4 MW
- Divertor
  - 66.1 MW (n)
  - 13.62 MW (γ)
  - 176.4 MW (i+e)
- Blanket
  - Neutron (n): 1675 MW
  - Radiation (γ): 305 MW



- Peak heat flux
  - Divertor: 18.7 (i+e) + 0.16 (γ) + 0.78 (n) MW/m^2
  - Blanket: 0.24 (γ) + 1.49 (n) MW/m^2

Application: DEMO Design (2015) – Neutronics

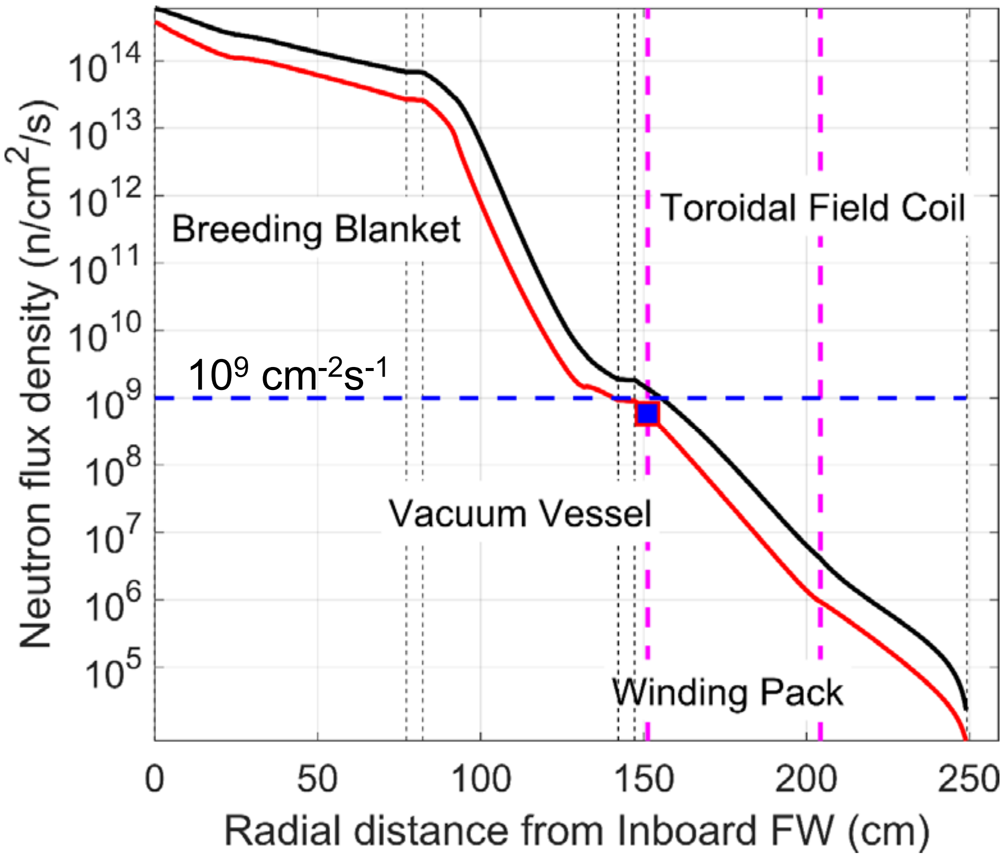
- DEMO 2015 radial build
- Blanket (HCPB 2015, [Hernandez 2016])
  - W armor 0.2/0.2 cm 100 % W
  - FW 2.5/2.5 cm 70/30 % Eurofer/He
  - BZ 23/52 cm 20/12/57/11 % Li_4SiO_4/Eurofer/Be/He
  - BP 8.5/8.5 cm 45/55 % Eurofer/He
  - BSS 43/60 cm 65/35 % Eurofer/He

- Vacuum Vessel
  - Inner 5/5 cm 100 % SS316
  - Mid 45/80 cm 60/40 % SS316/H_2O
  - Outer 5/5 cm 100 % SS316

- Toroidal Field Coils
  - Case in 5/20 cm 100 % SS316L
  - WP: 53/53 cm 18/2.9/7.3/11.7/16.8/43.2 % Epoxy/Nb_3Sn/Bronze/Cu/He/SS316
  - Case out 45/20 cm 100 % SS316L

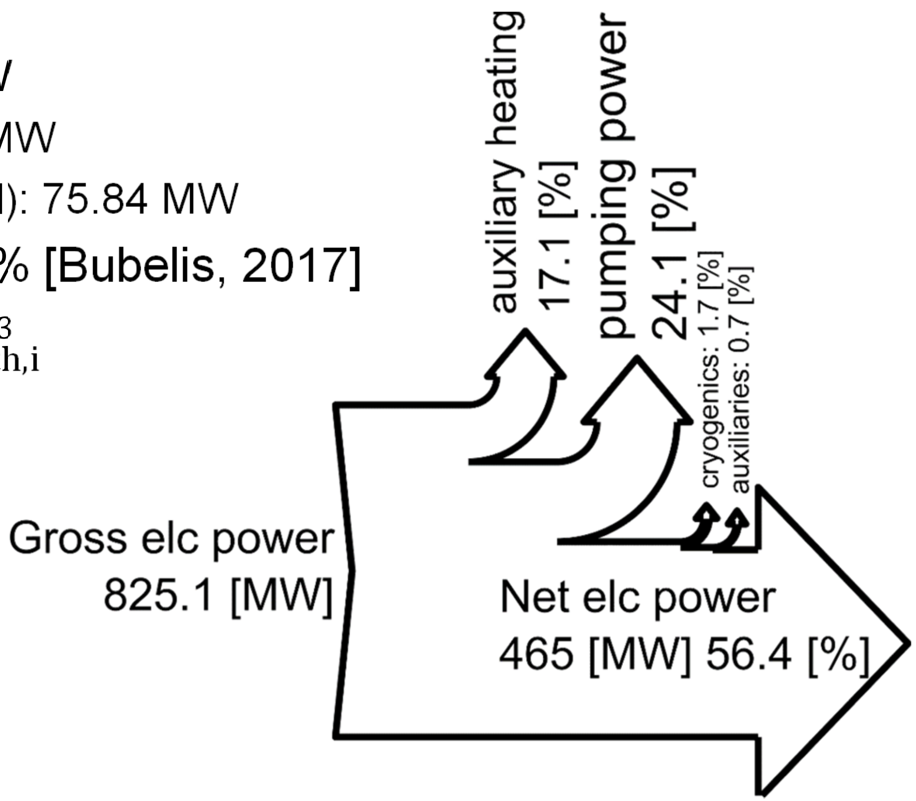
Application: DEMO Design (2015) – Neutronics

- Tritium Breeding Ratio: 1.21 (401.9 g/d)
  - Inboard: 0.302
  - Outboard: 0.608
- Nuclear Heating Power
  - Breeding Blanket: 2054 MW
    - Armor + FW: 279.2 MW
    - BZ: 1616 MW
    - BP/BSS: 158.8 MW
  - Vacuum Vessel: 75.5 MW
  - TFC: 21.38 kW
- Neutron Shielding
  - Peak fast neutron flux on WP: 5.84E8 $cm^{-2}s^{-1}$



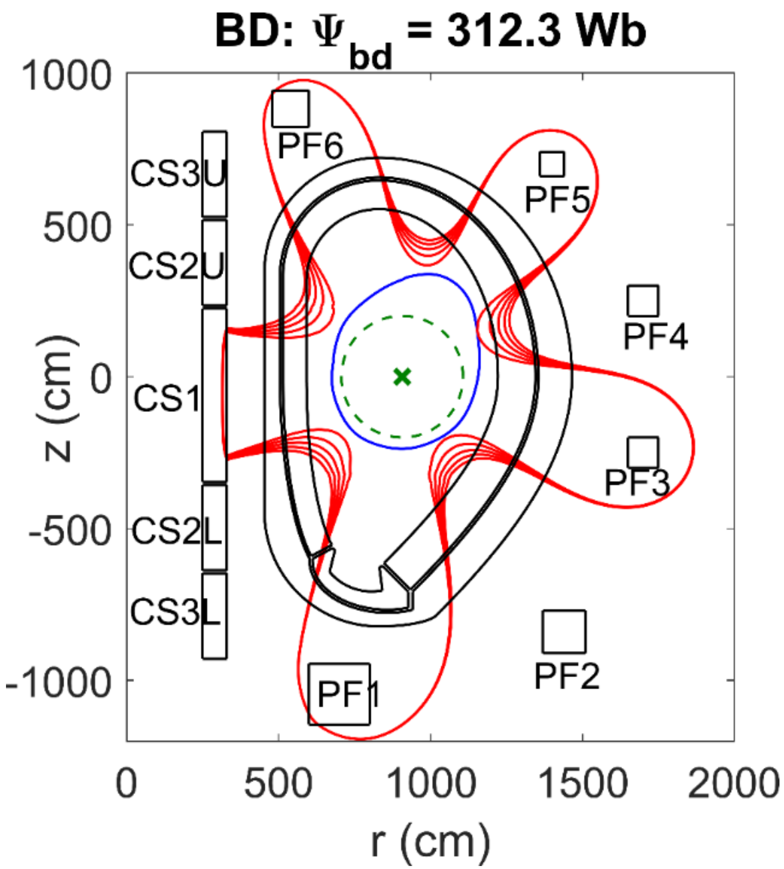
Application: DEMO Design (2015) – Power flow

- Primary Heat Transfer System
  - Power loads:
    - Blanket (He cooled): 2360 MW
    - Divertor (Water cooled): 308 MW
    - Vacuum Vessel (Water cooled): 75.84 MW
  - Rankine cycle efficiency: 28.7 % [Bubelis, 2017]
  - Pumping power $P_{pump,i}^{elc} = g_i \cdot P_{th,i}^{3}$
    - Blanket: 180.3 MW
    - Divertor (PFC): 18.1 MW
- Auxiliary heating (NBI):
  - Wall-plug efficiency η_{add}: 40 %
- Cryogenics system: 17.25 MW
  - $P_{cryo}^{elc} = 0.017 \cdot P_{elc,gross}$ [Duchateau, 2014])



Application: DEMO Design (2015) – Scenario

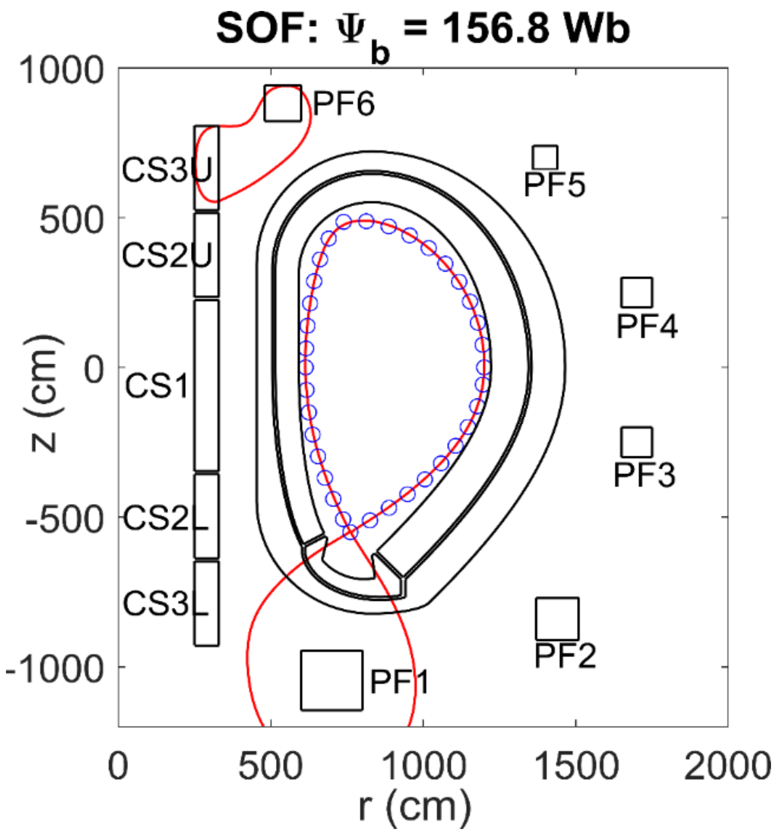
- Plasma Breakdown (BD)

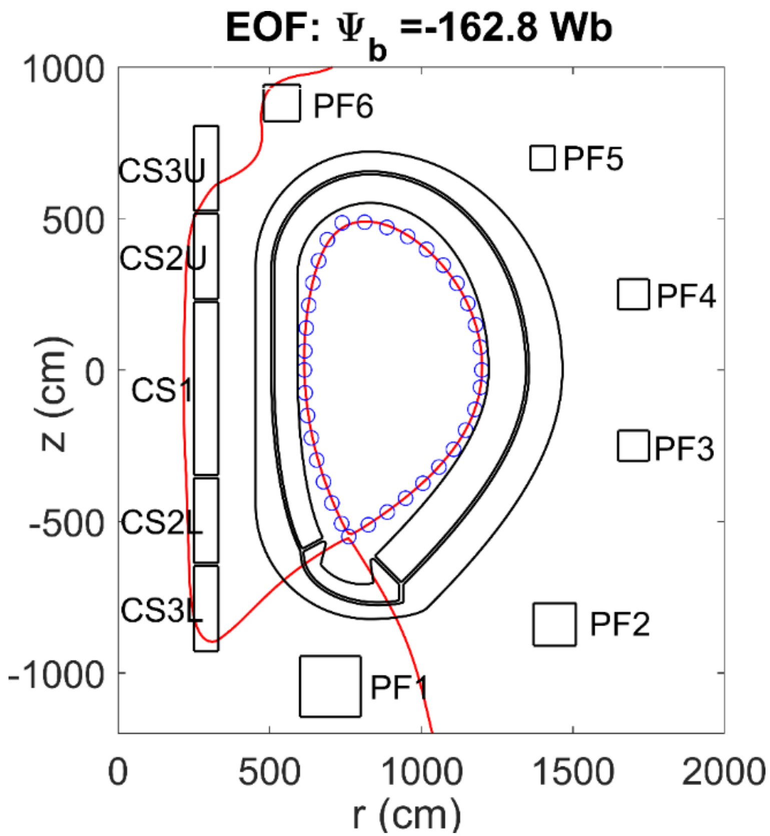


- Coil specifications
  - Fixed position and size (DEMO 2015)
  - Imposed cable design
- „CREATE-like“ approach:
  - Tech. limits on coil current
  - Tech. limits on coil magnetic field
  - Tech. limits on CS separation force
  - Tech. limits on PFC tot vertical force
- Physics constraints
  - Max stray field in BD region: 3 mT
  - Breakdown point (r = 9.8 m, z = 0 m)
  - BD region radius: a = 2 m

Application: DEMO Design (2015) – Scenario

- Plasma Start of Flat-top (SOF) and End of Flat-top (EOF)





$$\Psi_{b,SOF} = \Psi_{BD} - \frac{1}{2}\mu_0 R_0 l_i I_p - c_{Ejima}\mu_0 R_o I_p$$

$$\Psi_{b,EOF} = \min \Psi_b \text{ w.r.t coil limits}$$

Application: DEMO Design (2015) – Scenario

- Main results

Parameter (unit)	BD	SOF	EOF	Tech. Limit
Max current density CS (MA/m^2)	13.63	13.63	-13.63	13.63
Max current density PFC (MA/m^2)	9.3	-7.5	-9.3	9.3
Max magnetic field CS (T)	12.45	9.09	10.8	13.83
Max magnetic field PFC (T)	5.44	4.71	4.6	6.4
Max CS separation force (MN)	92.8	247.9	92.8	350
Max PFC vertical force (MN)	-416.7	159.6	-268.1	450

- Flat-top length

$$U_{loop} = 0.053\ V \longrightarrow \frac{\Psi_{sof} - \Psi_{eof}}{\tau_{flat}} \approx U_{loop} \longrightarrow \boldsymbol{\tau_{flat} = 1.64\ h \leq 2\ h}$$

Application: DEMO Design (2015) – TF Coil

- Turn: LTS ENEA design: $I_{op,max}$ = 81.0 kA, B_{peak} = 12.44
- Physics & Technology constraints
  - $B \leq B_{peak}$
  - Toroidal field ripple ≤ 0.6 %
- Magnetic field (3D Biot-savart EFFI model)
  - Peak magnetic field (T): 12.41 T
  - Max toroidal field ripple (%): **0.81 %→ TFC shape to adjust**
- Lorentz forces (without PF Coil loads)
  - Inward net radial force (MN): -782 MN
  - Vertical separating force (MN): 496 MN
  - Out-of-plane force (MN): -10.08 (BD) -17.1 (SOF) -18.1 (EOF)
- Stored magnetic energy: 151.8 GJ

Application: DEMO Design (2015) – Summary

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- DEMO design as per MIRA simulation (≈ 23 min)

Parameter (unit)	**MIRA**	**PROCESS**
Fusion power (MW)	2152	2037
Poloidal beta (-)	1.00	1.107
Fusion Gain (-)	37.1	39.8
Peak Toroidal field ripple at plasma (%)	0.81	0.6
Thermal power (-)	2887	2699
Net electric power (MW)	465	500
Tritium Breeding Ratio (-)	1.22	n.a.
Pulse length (h)	1.64	2

Plasma + technology operational limits → design drivers

Conclusion and Outlook

- Advanced multidimensional system/design codes
  - Parametrization of reactor components architecture
  - Reduce design iteration
- Modular Integrated Reactor Analysis (MIRA) under development at KIT
  - Reactor architecture
  - Plasma + SOL + Divertor (Core physics + Wall Loading)
  - Plasma magnetic equilibrium
  - Breeding Blanket (Neutronics)
  - Magnets technology (TF + PF Coils)
  - Power flow
- Future work
  - Investigate further DEMO designs
  - Including missing modules (e.g. Fuel cycle, cost estimation)
  - Optimization algorithm

Thank you for your attention!