MIRA: a Multiphysics Approach to Designing a Fusion Power Plant

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Fusion Reactors‘ System Codes

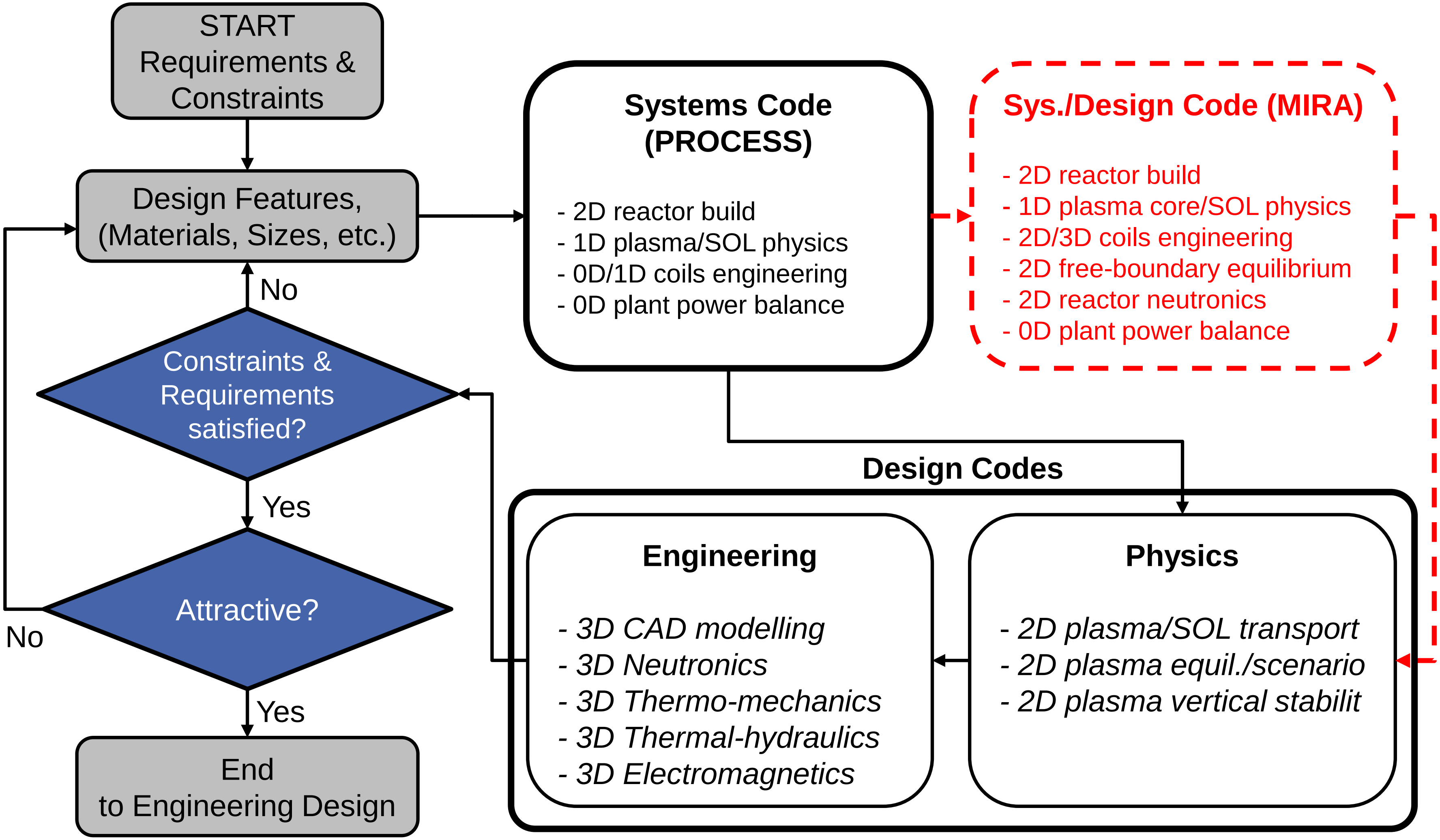
- Major challenges of fusion energy
  - Physics → High confinement and stable plasma operational regime
  - Technology → Plasma heating, blanket, divertor, magnet coils
  - **Integrated Plant Design → System Codes**

- General definition based on existing fusion system codes

  *A tool where all reactor components are simulated by means of simplified models, **often zero dimensional**, aiming to explore all possible configurations and setting the physics and engineering requirements and constraints to be simultaneously met.*

- Presently available system codes (0D/1D)
  - **PROCESS,** SYCOMORE → Reference codes for EU-DEMO analysis
  - ARIES (USA), KSC (Korea), TPC (Japan)

Conceptual Design of the EU-DEMO Reactor



START
Requirements &
Constraints

Design Features,
(Materials, Sizes, etc.)

No

Constraints &
Requirements
satisfied?

Yes

Attractive?

No

Yes

End
to Engineering Design

Systems Code (PROCESS)

- 2D reactor build
- 1D plasma/SOL physics
- 0D/1D coils engineering
- 0D plant power balance

Sys./Design Code (MIRA)

- 2D reactor build
- 1D plasma core/SOL physics
- 2D/3D coils engineering
- 2D free-boundary equilibrium
- 2D reactor neutronics
- 0D plant power balance

Design Codes

Engineering

- *3D CAD modelling*
- *3D Neutronics*
- *3D Thermo-mechanics*
- *3D Thermal-hydraulics*
- *3D Electromagnetics*

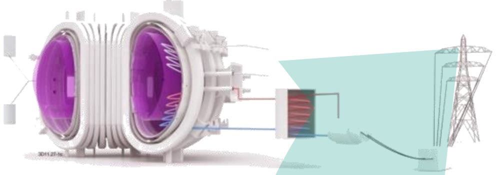
Physics

- *2D plasma/SOL transport*
- *2D plasma equil./scenario*
- *2D plasma vertical stabilit*

Modular Integrated Reactor Analysis (MIRA)

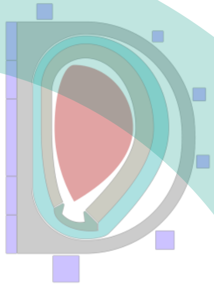
MIRA Multiphysics Approach

Reactor Integration into Plant System



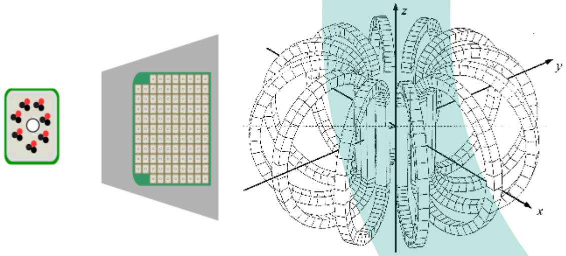
- ☐ Integral plant power balance
- ☐ Reactor pulse characterization

Reactor Architecture



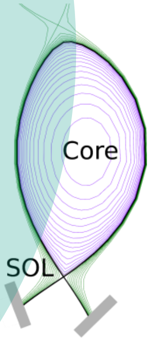
- ☐ 2D geometric construction
- ☐ Blanket material composition
- ☐ Coil cable technology

Reactor Magnetics



- ☐ 3D magnetostatics
  - ☐ Magnetic field, force, energy
  - ☐ Toroidal field ripple
- ☐ Conductor design

Magnetic Equilbrium & Core/SOL Physics



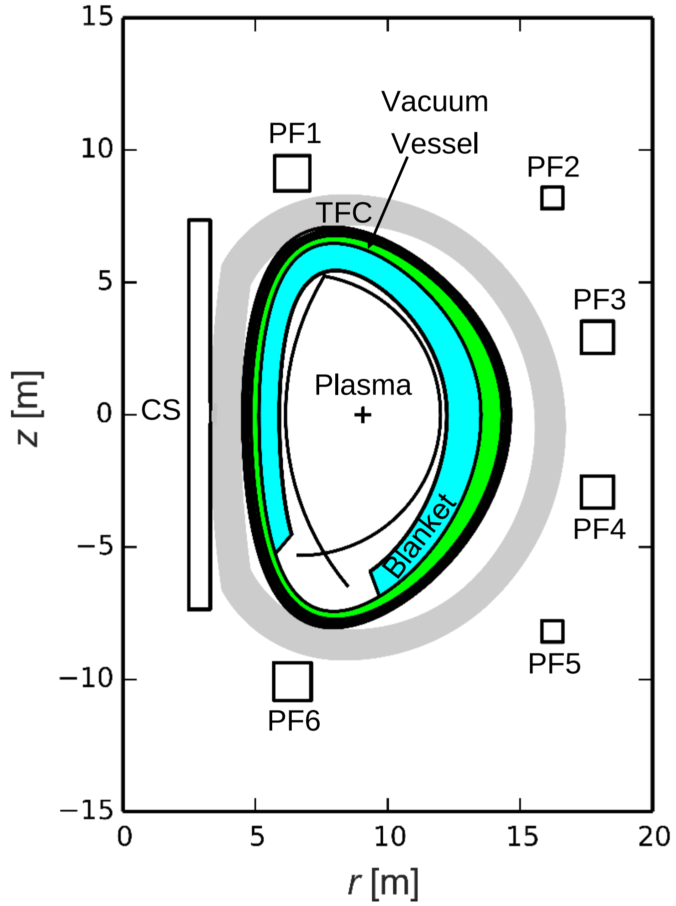
- ☐ 2D free-boundary equilibrium
- ☐ Plasma power, particle, current integral balance

Reactor neutronics

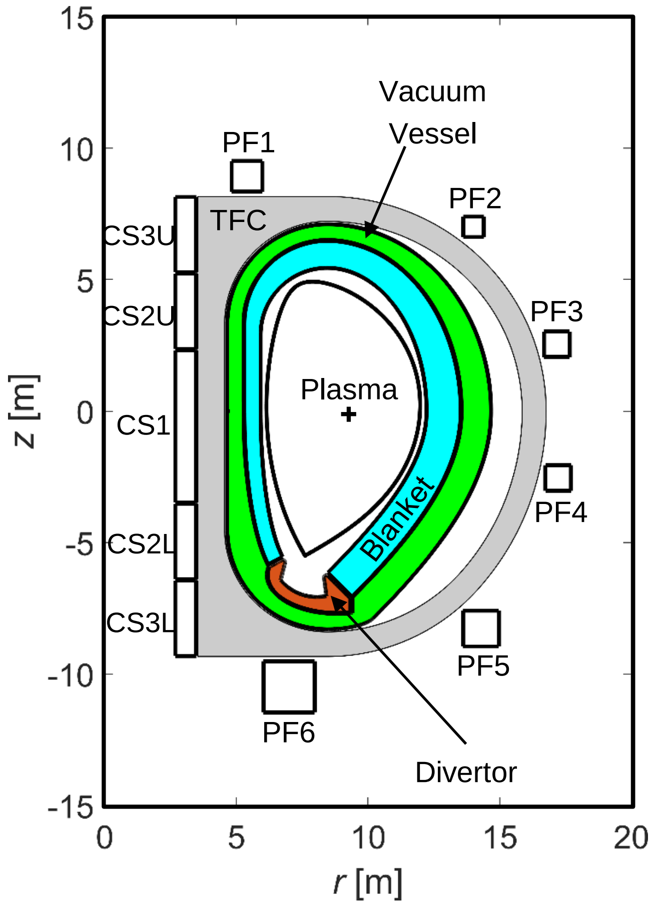
- ☐ 2D n-γ plasma chamber
- ☐ 1D n-γ reactor
- ☐ TBR, nuclear heating
- ☐ Neutron shielding, dpa

Reactor Architecture

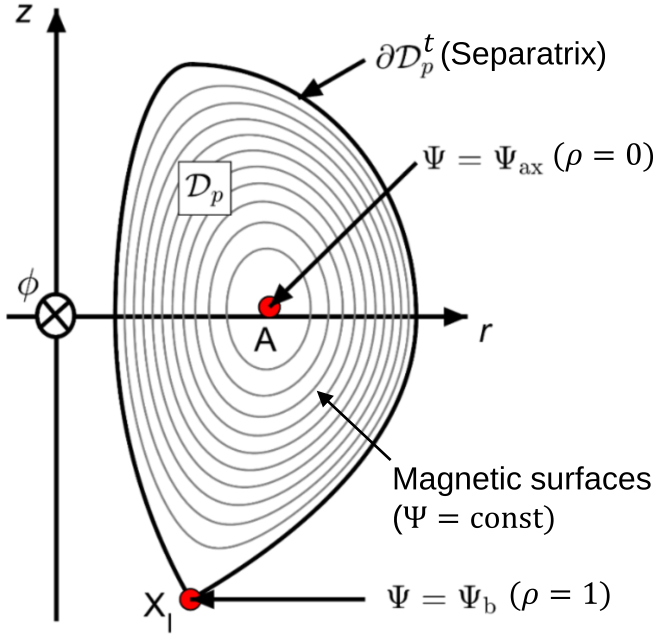
PROCESS, EU-DEMO 2015

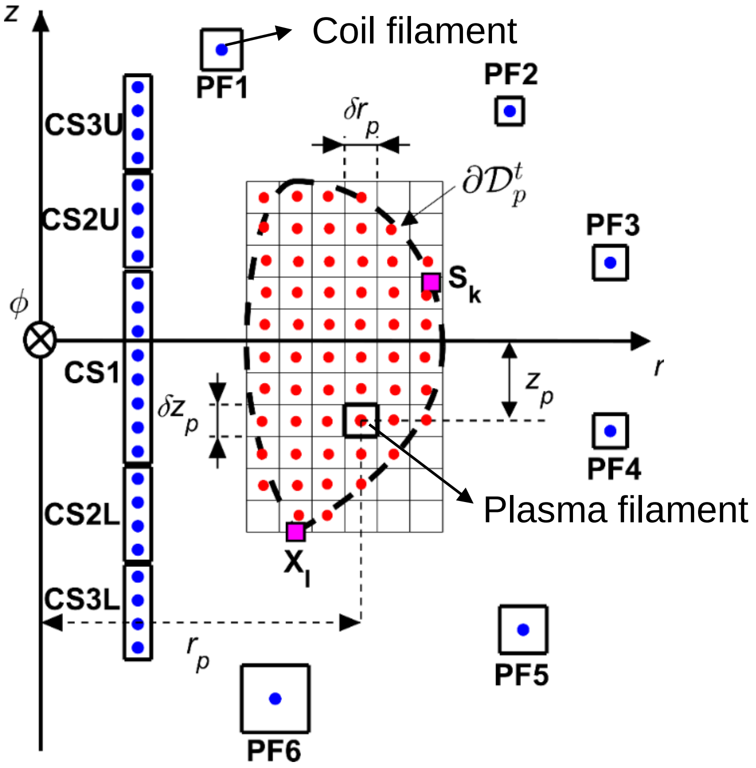


MIRA, EU-DEMO 2015



Free-Boundary Magnetic Equilibrium





Solve Grad-Shafranov Equation

$$\begin{cases} \Delta^*\Psi(r,z) = -2\pi r\mu_0 J_\phi(p, I_p, q, B_t\,) \\ \Psi\Big|_{\partial\mathcal{D}_p^t} = \Psi_b \end{cases}$$

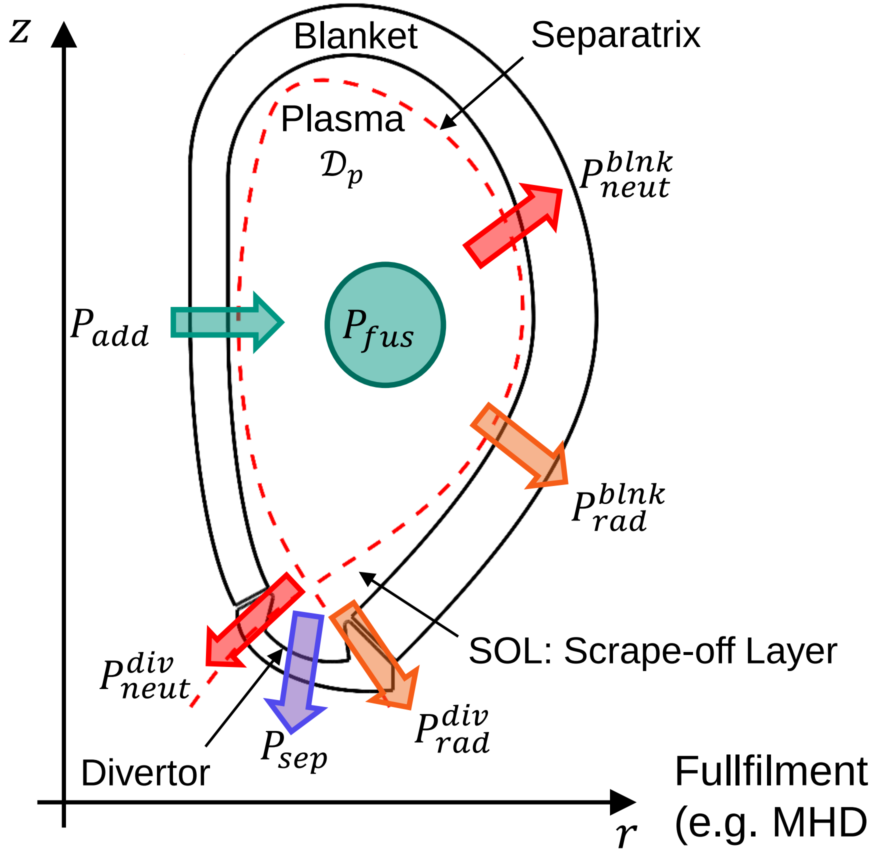
Find PF/CS coils currents s.t.

- Shaping requirement $\Psi(\mathbf{S_k}) \rightarrow \Psi_b^t$
- Null field constraint at lower x-point $\mathbf{X_l}$
- Current, field, vertical force coil constraints

Core/SOL Plasma Physics

Steady state core power balance

$$P_{fus} + P_{add} = P_{neut} + P_{rad} + P_{sep}$$

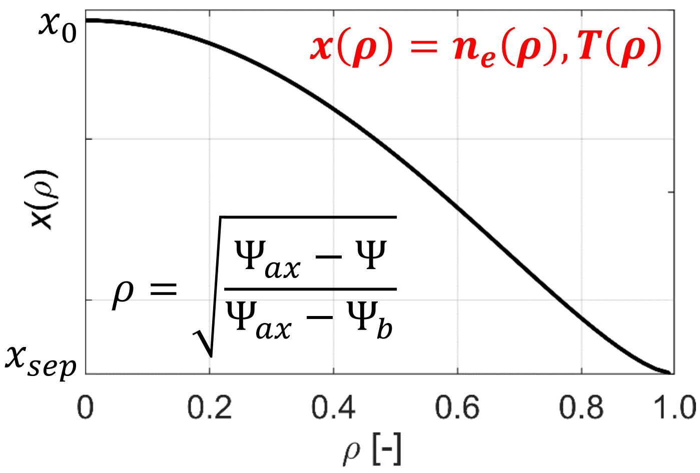


Fusion power

$$P_{fus} = P_{\alpha} + P_{neut} \propto \int_{\mathcal{D}_p} n_e^2(\rho)\langle\sigma v(T(\rho)\rangle \mathrm{d}V$$

Plasma profiles‘ parametrization

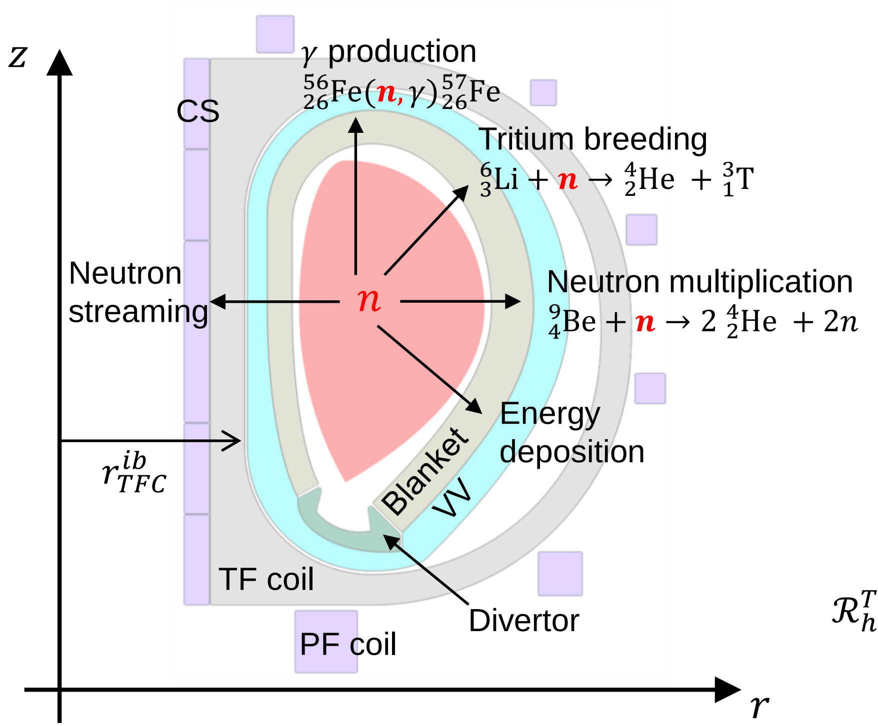
- n_e: Electron density
- T : Temperature



$$\rho = \sqrt{\frac{\Psi_{ax} - \Psi}{\Psi_{ax} - \Psi_b}}$$

Fullfilment of plasma operational limits
(e.g. MHD stability, H-mode operation, divertor protection)

Reactor neutronics



Boltzmann Transport Equation (BTE)

$$\hat{\mathbf{H}}\,\psi(\mathbf{r},\boldsymbol{\Omega},E) = \boxed{q_{neut}(\mathbf{r})} \rightarrow$$ core physics

$$\phi(\mathbf{r},E) = \int \psi(\mathbf{r},\Omega,E)\,\mathrm{d}\boldsymbol{\Omega}$$ → scalar flux density

Tritium Breeding Ratio

$$\mathrm{TBR} \propto \frac{1}{P_{fus}} \iint \Sigma^{\mathrm{Li}}_{n\rightarrow T}\,(\mathbf{r},E)\,\phi(\mathbf{r},E)\,\mathrm{d}E\,\mathrm{d}\mathbf{r} \geq 1.05$$

Neutron shielding

$$\mathcal{R}^{TFC}_{heat,peak} = \int_0^{+\infty} k_{heat}\left(r^{ib}_{TFC},E\right)\phi\left(r^{ib}_{TFC},E\right)\mathrm{d}E \leq 50\ \mathrm{W/m^3}$$

Reactor neutronics not available in PROCESS → blanket radial build fixed

EU-DEMO 2015 blanket designs

- HCPB: Helium-Cooled Pebble Beds
- WCLL: Water-Cooled Lithium-Lead

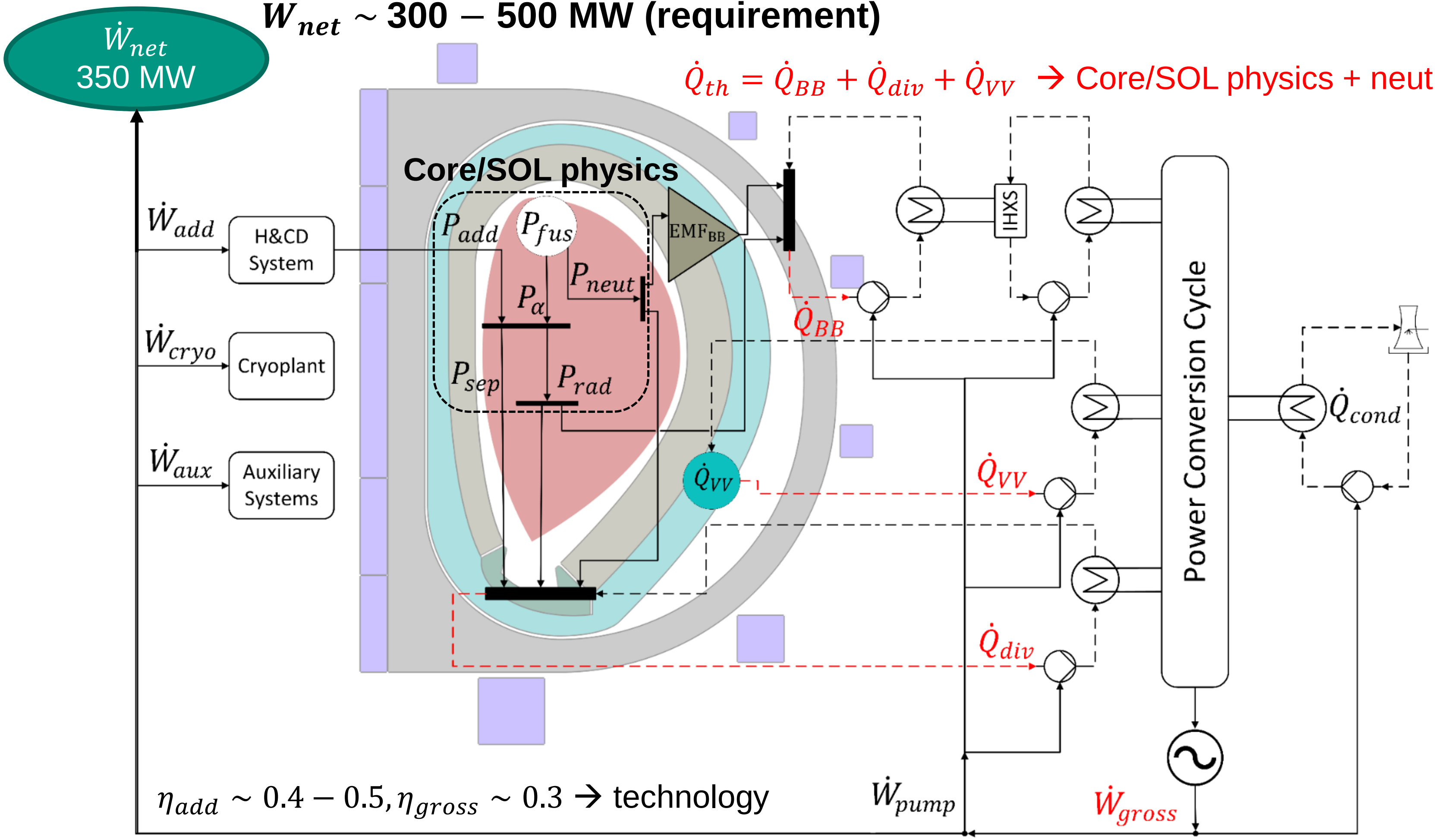
→

	Requirement	MIRA (HCPB)	MIRA (WCLL)
TBR [-]	≥ 1.05	1.20	1.14

Integral Plant Power Balance

$\dot{W}_{net} \sim 300 - 500$ **MW (requirement)**

$\dot{Q}_{th} = \dot{Q}_{BB} + \dot{Q}_{div} + \dot{Q}_{VV}$ → Core/SOL physics + neutronics



$\eta_{add} \sim 0.4 - 0.5, \eta_{gross} \sim 0.3$ → technology

$\dot{W}_{add} = \eta_{add} \cdot P_{add}$ $\quad$ $\dot{W}_{aux} \propto \dot{Q}_{th}$ $\quad$ $\dot{W}_{cryo} \propto \dot{Q}_{th}$ $\quad$ $\dot{W}_{pump} \propto \dot{Q}_{th}^3$ $\quad$ $\dot{W}_{gross} = \eta_{gross} \cdot \dot{Q}_{th}$

Plasma Burn Time

$$\tau_{burn} \approx \tau_{flat} = \frac{\overbrace{\Psi_{BD} - \Psi_{RU}}^{\Psi_{b,SOF}} - \Psi_{b,EOF}}{U_{loop}} \geq 2\ \mathrm{hr}$$

MIRA (2D free-boundary equilibrium)

PROCESS (0D magnetic flux conservation)

- Plasma loop voltage $U_{loop} \sim R_p I_p$ → core plasma physics
- Flux consumed at ramp-up Ψ_{RU} → Ejima scaling

MIRA:

- Ψ_{BD} → max value with respect to
  - Breakdown stray field requirements
  - PF/CS coils tech. constraints
- $\Psi_{b,EOF}$ → min value with respect to
  - Plasma shaping requirements
  - PF/CS coils tech. constraints

PROCESS:

- $\Psi_{BD} \sim \pi r_{CS}^2 B_{max,CS}$
- $\Psi_{b,EOF} \sim -\pi r_{CS}^2 B_{max,CS}$

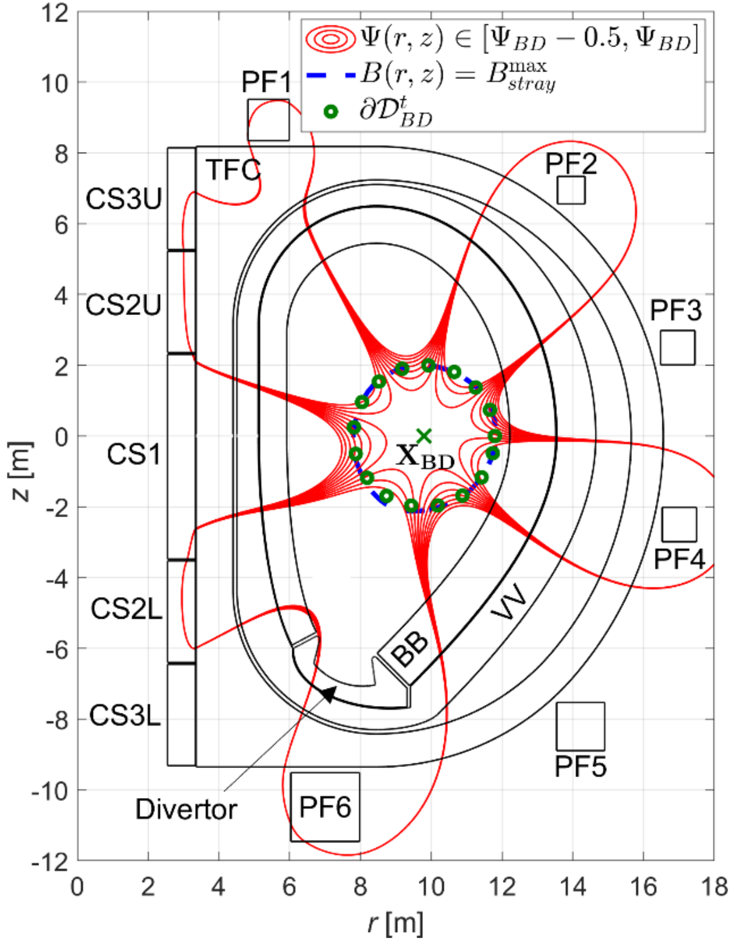
	Requirement	MIRA (2D)	PROCESS (0D)
Burn time τ_{burn} [hr]	≥ 2	**1.81**	2.00

Summary of MIRA analysis - EU-DEMO 2015

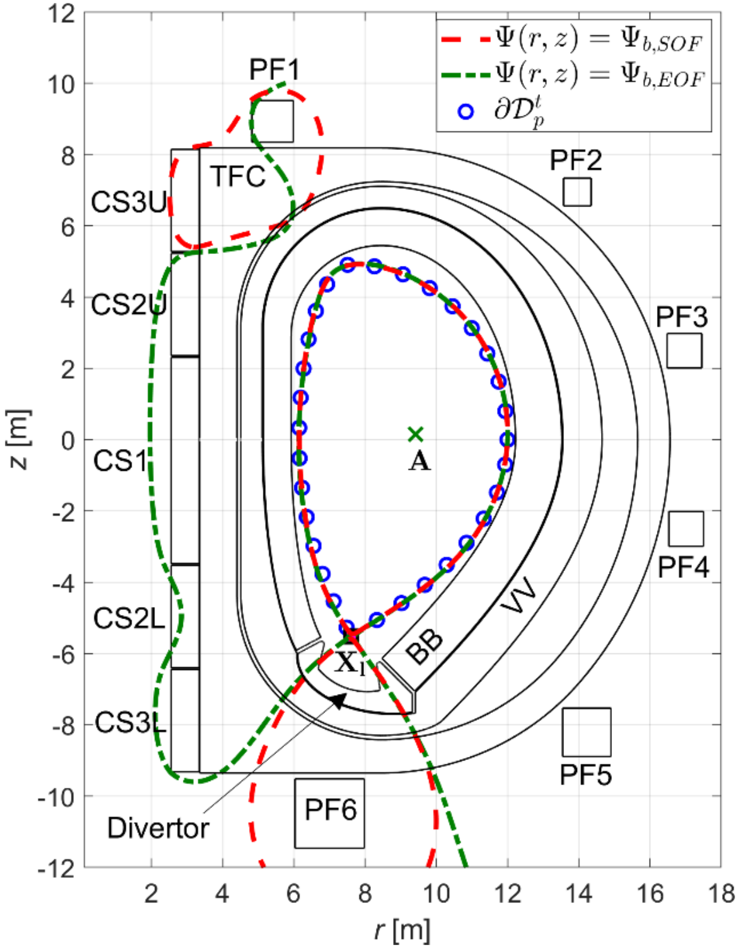
Parameter [unit]	MIRA	PROCESS	Type
Plasma major radius [m]	9.07	9.07	I
Plasma aspect ratio [-]	3.1	3.1	I
Toroidal field at plasma center [T]	5.49	5.67	O
Plasma current [MA]	19.26	19.60	O
Fusion power [MW]	2037	2037	DT $\approx$ 2000
Radiation power [MW]	304.2	305.5	O
Additional heating power [MW]	50	50	DT $\approx$ 50
Transport loss across the separatrix [MW]	154.1	154.2	O
Tritium Breeding Ratio (TBR) (HCPB/WCLL) [-]	**1.20/1.14**	**n.a.**	**DT $\geq$ 1.05**
Total thermal power (HCPB/WCLL) [MW]	2624/2371	2436	O
Net electric power (HCPB/WCLL) [MW]	**365/350**	**500**	**DT $\sim$ 300-500**
Plasma Burn time [hr]	**1.81**	**2.00**	**DT $\geq$ 2 hr**

Breakdown & Flat-top Magnetic Configurations

Plasma breakdown , $I_p = 0$ MA



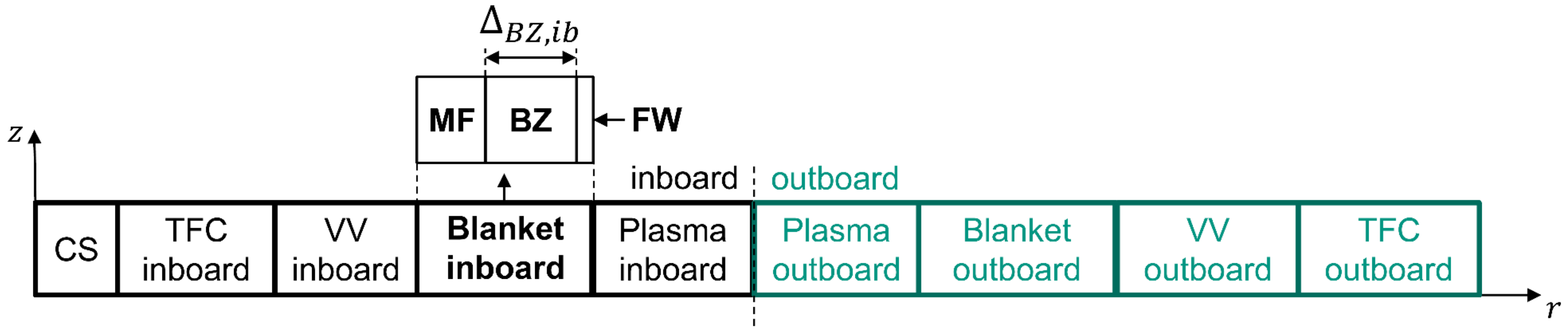
Plasma flat-top, $I_p = 19.26$ MA



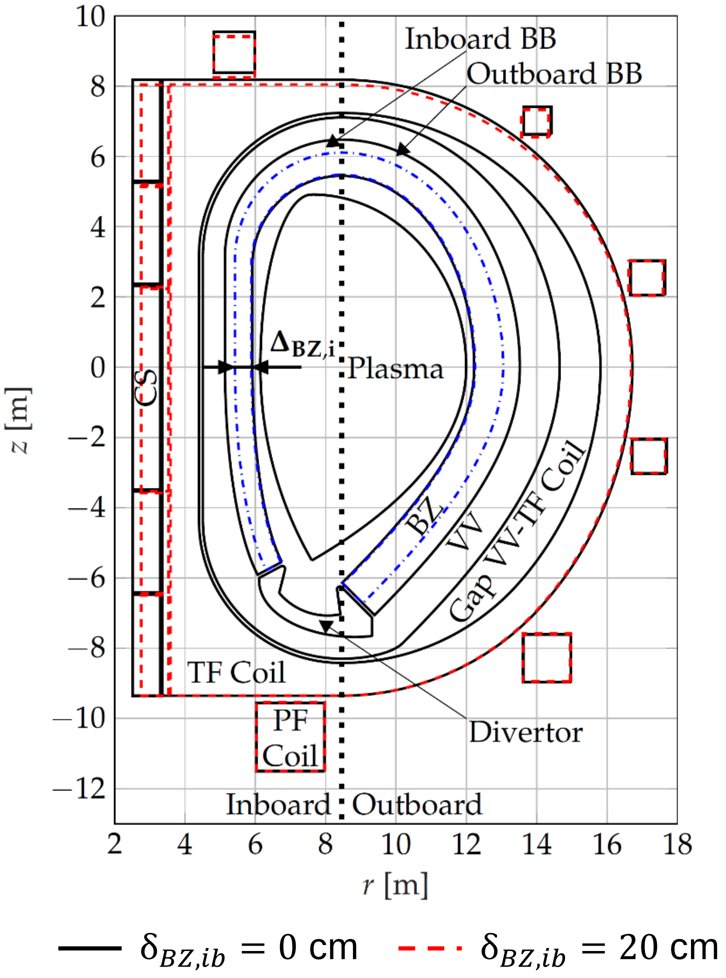
Improvements of EU-DEMO 2015 Baseline

- MIRA analysis of DEMO 2015 baseline issued by PROCESS
  - $\tau_{burn} =$ **1.81 hr** → violation of long pulse requirement ($\tau_{burn} \geq 2$ hr)
  - $\mathrm{TBR} = 1.20$ (HCPB), 1.14 (WCLL) → exploitable margin ($\mathrm{TBR} \geq 1.05$)

- Mitigating strategy: reduction of **inboard blanket thickness**
  - CS closer to plasma → increase of τ_{burn}
  - Reduction of material inventories → cost benefits



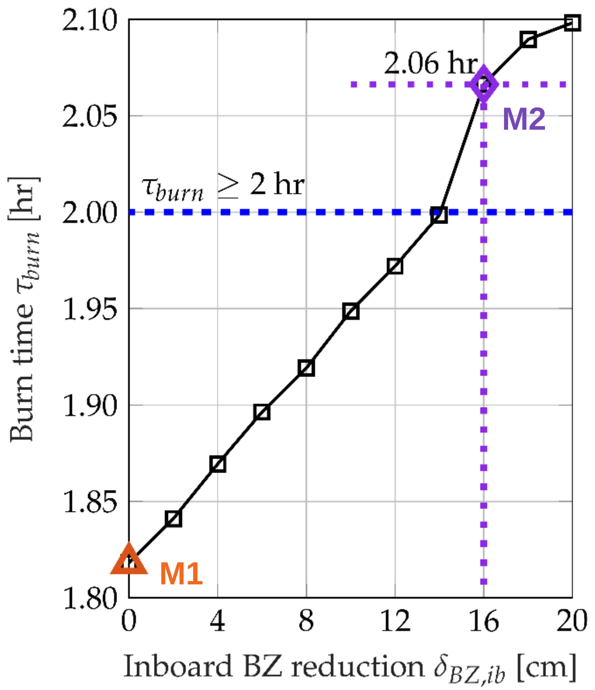
Parametric Scan of Inboard BZ Thickness



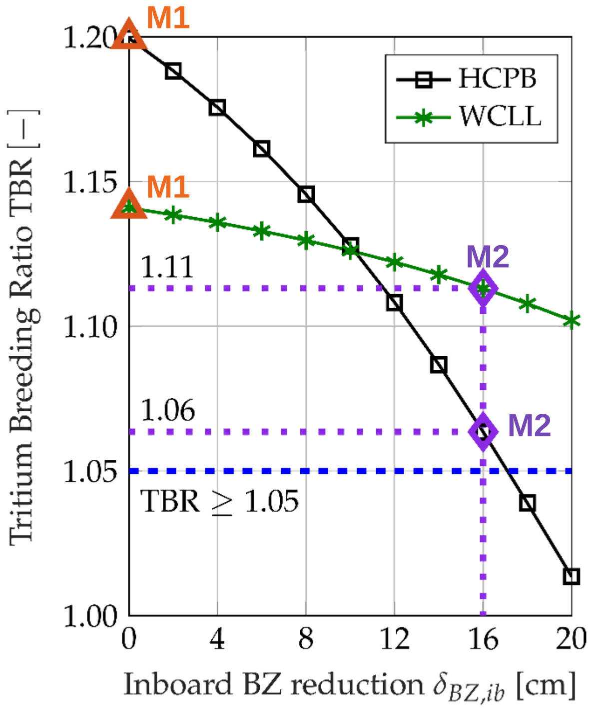
- Reduction of inboard BZ thickness $\Delta_{BZ,ib}$
- EU-DEMO 2015 reference blanket designs
  - HCPB $\Delta^{BL}_{BZ,ib} = 23$ cm, $\mathrm{TBR} = 1.20$
  - WCLL $\Delta^{BL}_{BZ,ib} = 47$ cm, $\mathrm{TBR} = 1.14$
- Relative thickness $\delta_{BZ,ib} = \Delta^{BL}_{BZ,ib} - \Delta_{BZ,ib}$
  - $\delta_{BZ,ib} = [0, 20]$ cm
  - Top thickness → (inboard + outboard) / 2
- Major magnet coils implications
  - Inward shift of CS
  - Inward shift of inboard TF coil leg
  - Breeding, shielding and flux linkage effects

Parametric Scan of Inboard BZ Thickness

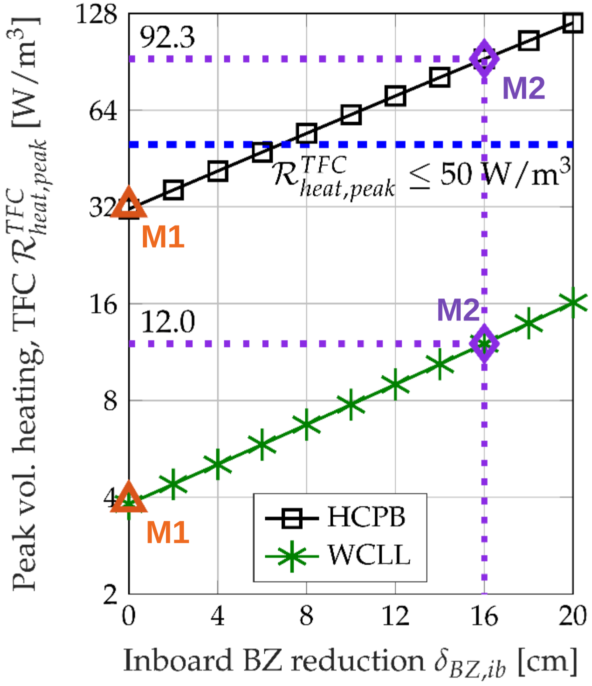
Plasma burn time



Tritium Breeding Ratio



Peak nuclear heating at inboard TFC



△ MIRA DEMO Design Point (M1)
($\delta_{BZ,ib} = 0$ cm)

→

◇ MIRA DEMO Design Point (M2)
($\delta_{BZ,ib} = 16$ cm)

Conclusion & Outlook

- **Achievements**
  - High-fidelity fusion system/design code MIRA
  - Enhanced physics & engineering modelling → from 0D/1D to 2D/3D
  - Refined mathematical representation of key reactor parameters
  - Improved EU-DEMO 2015 reactor design

	Req./ Const.	**DEMO 2015 PROCESS**	**DEMO 2015 MIRA**	**Improved DEMO 2015 MIRA**
Plasma burn time [hr]	≥ 2	**2.00**	**1.81**	**2.04**
Tritium Breeding Ratio [-]	≥ 1.05	**None**	**1.16**	**1.11**

- **Outlook**
  - EUROfusion, TSVV Task 14: *Multi-Fidelity Systems Code for DEMO* Development of BLUEMIRA → BLUEPRINT (CCFE) + MIRA (KIT)
  - Further system modelling and global optimization methods