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HYBRID FUSION-FISSION SYSTEM BASED ON A COMPACT TOKAMAK DEVICE WITH PROVEN TECHNOLOGIES

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ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

université PARIS-SACLAY

RESEARCH GROUP on HYBRIDS (since 2020)

The research group is based on the collaboration between: **Sapienza University of Rome** (G. Ciocari, A. Gandini, R. Gatto, C. Romagnoli, D. Rotilio), **ENEA Research Centers at Casaccia** (N. Burgio, A. Santagata) and **Frascati** (F. Panza) and **Bologna** (V. Peluso), **Université Paris Saclay, CEA Saclay** (D. Tomatis)

We acknowledge continuous exchange of ideas/information with the authors of next presentation (Dr. Orsitto, et al.) on compact FF hybrids devices
[F.P. Orsitto, M. Romanelli, Prob. At. Sci. and Tech 44 (2021)]

- **Articles:** **(1)** *Subcriticality monitoring in fusion-fission hybrid reactors,* N. Burgio, M, Carta, V. Fabrizio, L. Falconi, A. Gandini, R. Gatto, V. Peluso, E. Santoro, M.B. Sciarretta, Problems of Atomic Science and Technology, ser. Thermonuclear fusion, 44, 2, p. 27 (2021). **(2)** *Novel hybrid pilot experiment proposal for a fusion-fission subcritical coupled system,* M. Ciotti, F. Panza, A. Cardinali, R. Gatto, G. Ramogida, G. Lomonaco, G. Ricco, M. Ripani, M. Osipenko, Problems of Atomic Science and Technology, ser. Thermonuclear fusion, 44 , 2 , p. 57 (2021)*;*

- **Master theses, completed:** **(1)** March 2020: Giulia Porto, *MC+FISPACT calculations for hybrid fusion-fission nuclear systems* (ENEA-Casaccia); **(2)** July 2021: Cristiana Romagnoli, *An MCNP-FISPACT neutronic analysis on a fusion-fission reactor model* (ENEA-Casaccia) **(3)** July 2021: Stefano Murgo, *Studio della fertilizzazione del torio in un sistema ibrido* (ENEA-Casaccia).

- **Master theses, ongoing:** **(1)** July 2022: Gourav Sharma, *A numerical solver for the Bateman equation: application to the Thorium fuel cycle*; **(2)** October 2022: Davide Rotilio, *A compact, high-field tokamak based hybrid fusion-fission system with proven technologies;* **(3)** October 2022: Gianluca Ciocari, *Neutronic optimization studies based on Generalized Perturbation Theory.*

- **Grants:** *We have applied for a two-year research grant by the Italian Ministry of Research in collaboration with University of Padova, University of Genova, ENEA Research Centers at Frascati and Casaccia. Decision expected with the end of 2022.*

HYBRID FUSION-FISSION SYSTEMS

FISSION ENERGY

High power density
Neutron poor
Low-energy neutrons

FUSION ENERGY (D-T)

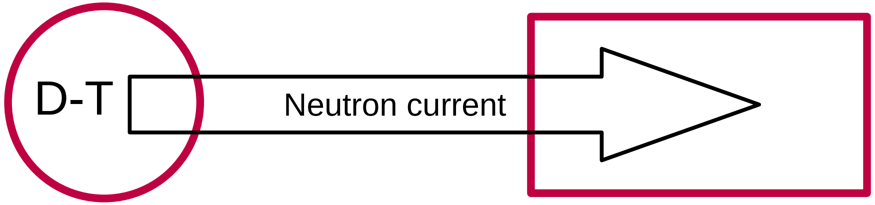
Low power density
Neutron rich
High-energy neutrons

The two hearts of the device

HYBRID FUSION-FISSION SYSTEM ⇒ Nuclear energy sustainability

"Low-performance" fusion plasma

Sub-critical fission core



- Safe & efficient MA fissioning
- Efficient fissile isotope breeding
- Fusion "fission-augmented" energy
- Improved production of tritium

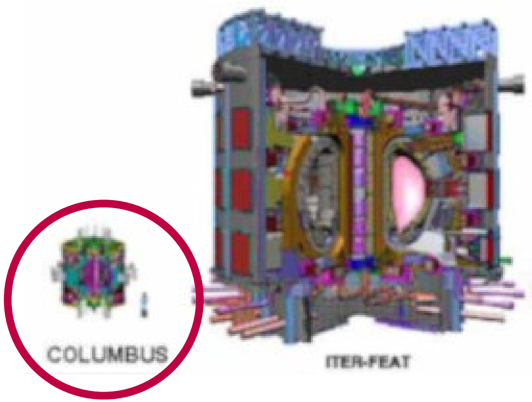
GUIDELINES

Guidelines: arrive to the definition of an hybrid fusion-fission system characterized by the **most compact dimension as possible**, and mostly based on material and technologies already **well-proven** in the nuclear industry

<u>Dimensions:</u>

- *Start from* the Columbus tokamak design [Coppi, Salvetti, 2002]:

R_0=1.50 m, a=0.535 m, A=2.8,

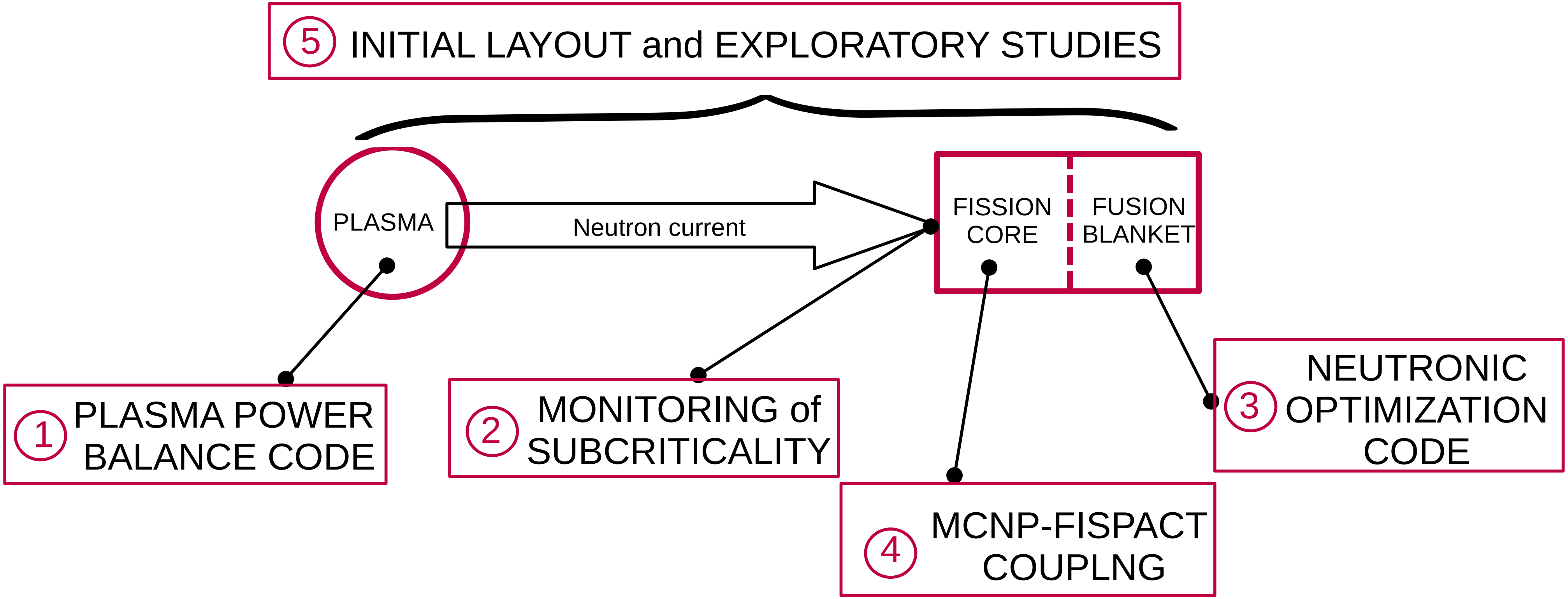


<u>Materials:</u>

- fission core: Thorium-based or MOX fuel
- fusion blanket (D-T case): ceramic Li compounds (γ-$LiAlO_2$, Li_4SiO_4, Li_20)
- multiplier/moderator, reflector: Pb, Be / C, ZrH_2
- structure: Inconel, Copper
- coolant: He

RESEARCH ACTIVITY*

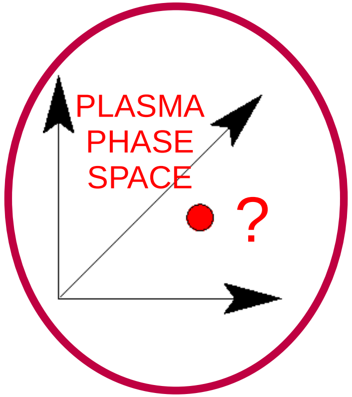
We are working in several areas:



* The authors specify that the goal of the present work consists on a preliminary feasibility study of an hybrid fusion-fission device based on numerical calculation and, at the moment, any experimental activity involving nuclear fuel is not considered.

1 – PLASMA POWER-BALANCE CODE

As a first step in studying the "plasma part" of the device, we are developing a power balance code dedicated to the definition of operational plasma regimes [Stotler, *et al.*, 1994 (ASPECT code). Sheffield, 1985, *See next talk by Dr. Orsitto*]



- The code solves the two coupled equations for the time evolution of the plasma thermal energy *W* and of the α-particle density evolution n_α:

$$\frac{dW(t)}{dt} = \langle P_\alpha \rangle + \langle P_\Omega \rangle + P_{aux} - \langle P_B \rangle - \langle P_{\rm tr} \rangle$$

$$\frac{d\langle n_\alpha \rangle}{dt} = \frac{\langle P_\alpha \rangle}{E_\alpha 2\pi^2 a^2 \kappa R_0} - \frac{\langle n_\alpha \rangle}{\tau_{p,\alpha}}$$

- First equation is recast as a time-evolution equation for the density-averaged electron temperature $\langle T \rangle_n = \langle nT \rangle / \langle n \rangle$, and densities are volume averaged $\langle n \rangle$

1.1 Features

Some features of the code (work in progress):

- Runge-Kutta 4th order numerical solver
- Use radial profiles: code is actually 0.5-D (radial integration at each time step)
- Constraints: charge neutrality and Z_{eff}:

$$n_D + n_T + Z n_Z + 2 n_\alpha = n_e$$

$$(n_D + n_T + Z^2 n_Z + 4 n_\alpha)/n_e = Z_{\text{eff}}$$

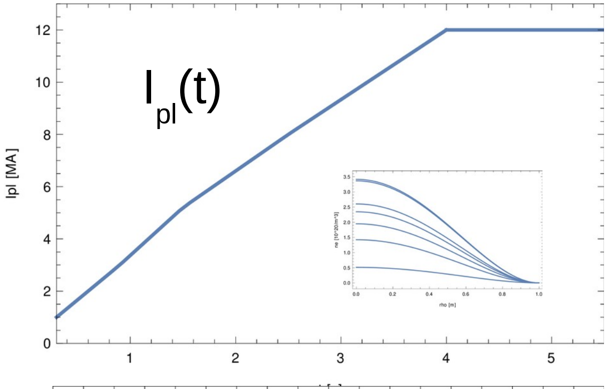
- Several expressions for the energy confinement time [constant value, Neo-Alcator for ohmic discharge, Kaye-All-Complex for L-mode, ITER89-P for L-mode, IBP98(y,2) for H-mode]
- Check stability limits (Greenwald density limit, Troyon beta limit, ...)

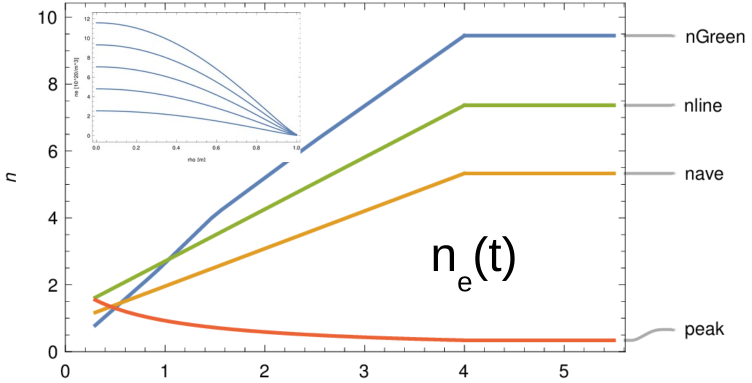
Calculate characteristics of fusion neutron source

1.2 Test case

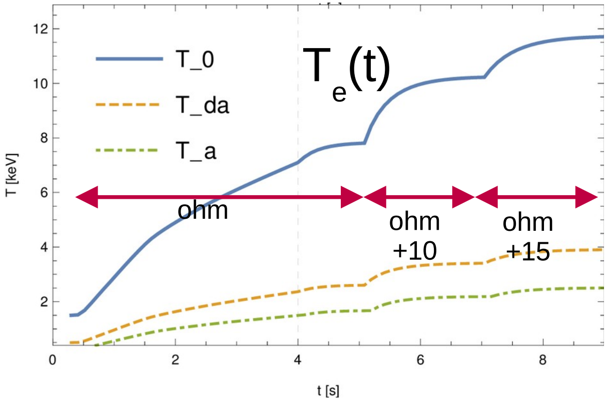
To check the code: ohmic+auxiliary heated discharge in compact, very high magnetic field tokamaks **[Airoldi, Cenacchi, 1997 (Ignitor)]**

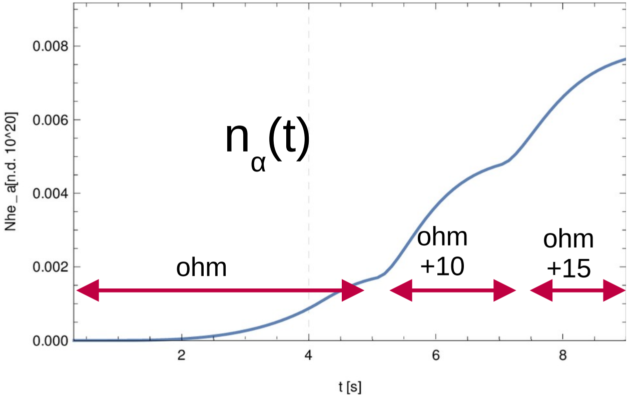
Prescribed evolutions:



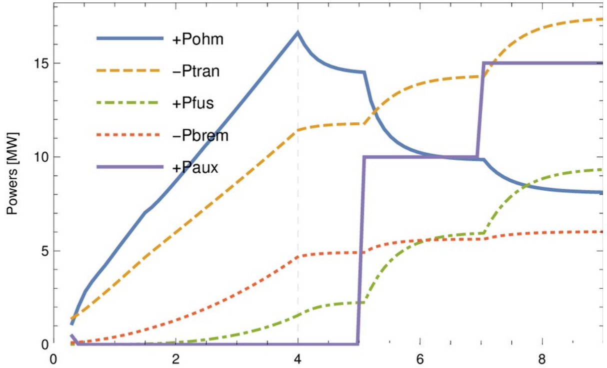


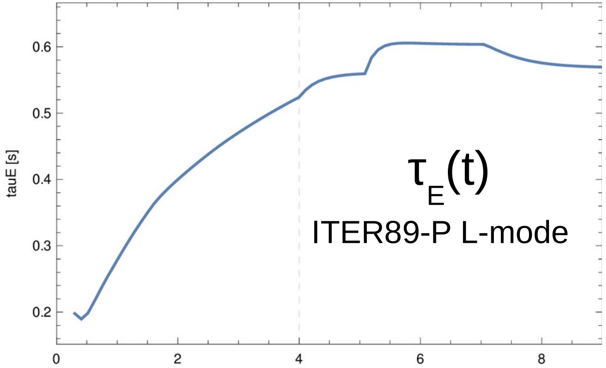
Results:



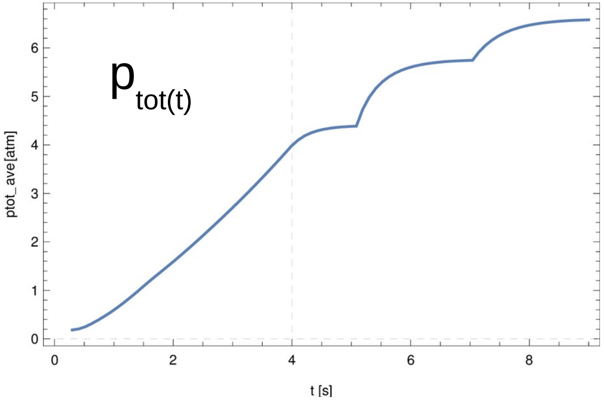


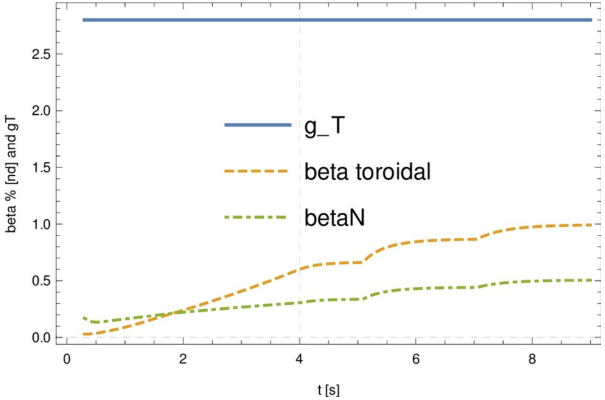
1.3 Test case





$$f_{\mathrm{ign},9} = \frac{P_{\mathrm{fus},\alpha}}{P_{\mathrm{tr}} + P_{\mathrm{br}}} = 0.287$$





$$Q_9 = \frac{(P_{\mathrm{fus,n}} + P_{\mathrm{tr}} + P_{\mathrm{br}}) - P_{\mathrm{aux}}}{P_{\mathrm{aux}}} = 3.658$$

Total number of fusion neutrons at (5,7,9) [s] = (4.0 x 10^{18},9.6x10^{18},1.6 x 10^{19}) [1/s]
Neutron heat load on FW at (5,7,9) [s] = (0.24,0.63, 1.0) [MW/m^2]

2 – SUB-CRITICALITY MONITORING METHOD

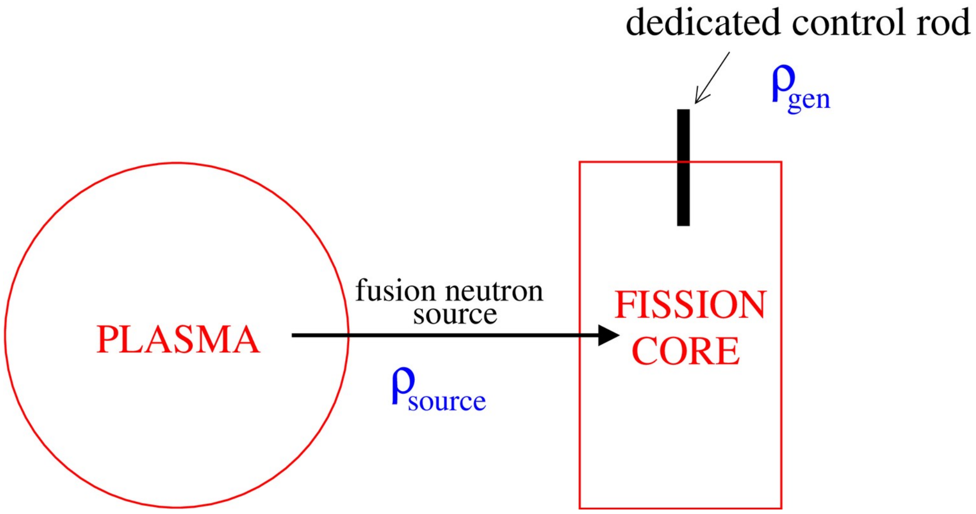
[N. Burgio, *et al.*, 2021]

Of utmost importance in a sub-critical system is the **on-line monitoring of the sub-critical level,** with sufficient *precision* and without significantly *interfering* with the plant normal operation

We consider the "Power control Sub-criticality Monitoring (PCSM)" method **[Gandini, 2002]** based on an extension of the Heuristical Generalized Perturbation Theory to sub-critical reactors **[Gandini, 2001]**

The method consists in compensating slow, small movements of a dedicated control rod with as well slow, small alterations of the "external" neutron source strength, so that the overall fission power is maintained constant:

$$\rho_{gen} + \rho_{source} = 0 \;\; \Rightarrow \;\; k_{sub}$$



2.1 Definitions of multiplication factor *k*

Critical system

$$\left(\underline{\underline{A}} - \frac{1}{k_{\text{eff}}}\underline{\underline{F}}\right)\underline{\Phi} = 0$$

$$\left(\underline{\underline{A}}^{+} - \frac{1}{k_{\text{eff}}}\underline{\underline{F}}^{+}\right)\underline{\Phi}^{+} = 0$$

$$k_{\text{eff}} = \frac{\langle \underline{\Phi}^{+}, \underline{\underline{F}}\,\underline{\Phi}\rangle}{\langle \underline{\Phi}^{+}, \underline{\underline{A}}\,\underline{\Phi}\rangle}$$

Sub-critical system

$$\left(\underline{\underline{A}} - \underline{\underline{F}}\right)\underline{\Phi}_{\text{s}} = \underline{S}_{\text{n}}$$

$$\left(\underline{\underline{A}}^{+} - \underline{\underline{F}}^{+}\right)\underline{\Psi}^{+} = \frac{\gamma}{W_0}\underline{\Sigma_{\text{fis},0}}$$

$$k_{\text{sub}} = \frac{\langle \underline{\Psi}^{+}, \underline{\underline{F}}\,\underline{\Phi}_{\text{s}}\rangle}{\langle \underline{\Psi}^{+}, \underline{S}_{\text{n}}\rangle + \langle \underline{\Psi}^{+}, \underline{\underline{F}}\,\underline{\Phi}_{\text{s}}\rangle}$$

Taking into account both the source flux and the importance function w.r.t. the relevant observable (power level), k_{sub} is an appropriate measure of the level of sub-criticality of the system

2.2 Expression for the reactivities

Point kinetic equations for a sub-critical system, coupling the normalized fission Power $P = W(t)/W_0$, and "effective" precursor density ξ_i [Gandini 2001, 2004]

$$\ell_{\text{eff}} \frac{dP}{dt} = (\rho_{\text{gen}} - \alpha\beta_{\text{eff}})P + \alpha \sum_{i=1}^{M} \lambda_i \xi_i + \zeta(1 - P) + \rho_{\text{source}} \; ,$$

$$\frac{d\xi_i}{dt} = \beta_{\text{eff},i} P - \lambda_i \xi_i$$

where the two reactivities are defined by:

$$\rho_{\text{gen}} = \frac{\langle \underline{\Psi^+}, (\underline{\underline{\delta A}} + \underline{\underline{\hat{\chi}}} \; \underline{\underline{\delta F}}) \; \underline{\Phi} \rangle + (\gamma / W_0) \langle \underline{\underline{\delta \Sigma_{\text{f}}}}, \underline{\Phi} \rangle}{\langle \underline{\Psi^+}, \underline{\underline{\hat{\chi}}} \; \underline{\underline{F}} \; \underline{\Phi} \rangle} \; ,$$

$$\rho_{\text{source}} = \frac{\langle \underline{\Psi^+}, \underline{\delta S_{\text{n}}} \rangle}{\langle \underline{\Psi^+}, \underline{\underline{\hat{\chi}}} \; \underline{\underline{F}} \; \underline{\Phi} \rangle} \; .$$

2.3 Working expression for k_{sub}

From the definition of importance and assuming that the source perturbation corresponds to a measured fractional change of its strength $\delta S_{\mathrm{n}}/S_{\mathrm{n},0}$:

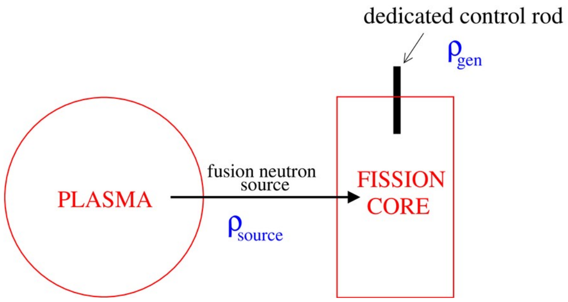
$$\rho_{\mathrm{source}} \rightarrow \frac{\delta S_{\mathrm{n}}}{S_{\mathrm{n},0}} \frac{1-k_{\mathrm{sub}}}{k_{\mathrm{sub}}}$$

Using this expression, the reactivity balance $\rho_{gen} + \rho_{source} = 0$ can be solved for k_{sub}:

$$k_{\mathrm{sub}} = \frac{\delta S_{\mathrm{n}}/S_{\mathrm{n},0}}{\delta S_{\mathrm{n}}/S_{\mathrm{n},0} - \rho_{\mathrm{gen}}}$$

2.4 Results

	Initial system	Right after rod insertion	Final reset system
k_{eff}	0.97	0.96	0.96
P [W]	2.082×10^5	1.814×10^5	2.082×10^5
J_{pl} [$cm^{-2}s^{-1}$]	3.574×10^{12}	3.574×10^{12}	5.128×10^{12}



- Results with **ERANOS code** on a model of an ADS system based on the ENEA-Casaccia TRIGA research reactor [Sciarretta, Master thesis, Sapienza Univ. of Rome, 2018)]:

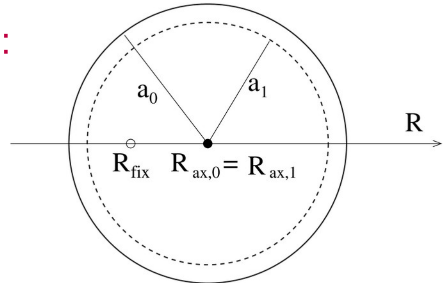
$$|k_{\text{sub}} - k_{\text{eff,i}}|/k_{\text{sub}} = \ \text{0.11\%}$$

the PCSM method allows for an accurate determination of the sub-critical level of a source driven system

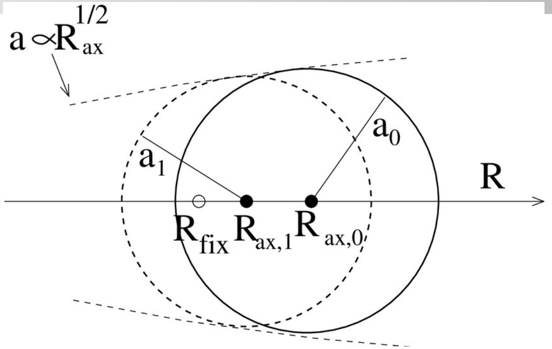
2.5 Fusion power modulation

Fusion power must be increased to reset the reference fission power: we assume the plasma is compressed by varying the confining toroidal and/or vertical magnetic field

Type I compression:



Type II compression:



- Type I compression: $I_{TFC}\uparrow \Rightarrow B_{tor}\uparrow \Rightarrow a\downarrow$ while R_{ax}=const; parallely need $I_{PFC}\uparrow \Rightarrow B_v\uparrow$ to maintain toroidal force balance
  - advantage: no plasma chamber modification required
- Type II compression: $I_{PFC}\uparrow \Rightarrow B_v\uparrow \Rightarrow R_{ax}\downarrow \Rightarrow a\downarrow$ due to $B_{tor} \sim R^{-1}$
  - advantage: no change in I_{TFC} required

2.6 Results

Using scaling laws for magnetic compression [Furth & Yoshikawa, 1970] derived from three basic constraints (number of particles inside magnetic surface, magnetic flux inside magnetic surface, rotational transform):

initial state *final state*

Type I:

$$
\begin{aligned}
a_i &= 120 &\rightarrow\quad a_f &= 112.38 \text{ cm} \\
n_i &= 1.1000 \times 10^{14} &\rightarrow\quad n_f &= 1.2542 \times 10^{14}\ 1/\text{cm}^3 \\
T_i &= 9.000 &\rightarrow\quad T_f &= 9.823 \text{ keV} \\
B_{\text{v,i}} &= 1.786 &\rightarrow\quad B_{\text{v,f}} &= 1.850 \text{ T}
\end{aligned}
$$

Type II:

$$
\begin{aligned}
a_i &= 120 &\rightarrow\quad a_f &= 115.26 \text{ cm} \\
R_{ax,i} &= 350 &\rightarrow\quad R_{ax,f} &= 322.92 \text{ cm} \\
n_i &= 1.1000 \times 10^{14} &\rightarrow\quad n_f &= 1.2922 \times 10^{14}\ 1/\text{cm}^3 \\
T_i &= 9.000 &\rightarrow\quad T_f &= 10.020 \text{ keV} \\
B_{\text{v,i}} &= 1.786 &\rightarrow\quad B_{\text{v,f}} &= 2.121 \text{ T}
\end{aligned}
$$

⇨ Plasma compression studies show for the required changes in the vertical magnetic field to maintain force balance: +3.6% and +18.7%

3 - OPTIMIZATION CODE based on GPT

We are developing ***a deterministic code to perform neutronic optimization studies*** with respect to various functionals of interest (reaction rates, ratio of reaction rates, …), to aid in the definition of the first layout of an hybrid system

- The code solves the 1-D multi-group diffusion equation for systems of any number of homogeneous zones, and it is coupled with a Bateman solver to follow the long time evolution of materials under neutronic irradiation
- The optimization procedure is based on Generalized Perturbation Theory, and in particular on the evaluation of **sensitivity functions**

3.1 Sensitivity function

- The sensitivity function $\mathcal{S}$ describes the functional relationship between the relative change in an integral parameter *R* caused by a fractional change of an input parameter *P*:

$$\mathcal{S} = (\delta R/R)/(\delta P/P)$$

- 1st order result of $\mathcal{S}$ in case of constant source *S*:

$$\mathcal{S} = \frac{P}{R}\left[\left\langle \underline{\phi}, \frac{\delta \underline{S}^{+}}{\delta P} \right\rangle - \left\langle \underline{\psi}^{+}, \frac{\delta \underline{\underline{H}}}{\delta P} \underline{\phi} \right\rangle\right]$$

Where Φ, ψ^{+} are the direct flux and the (adjoint) importance function, and S, S^{+} are the direct and adjoint sources:

$$H\Phi = S \qquad H^{+}\Psi^{+} = S^{+}$$ (reference system)

3.2 Maximizing a reaction rate

- Consider the problem of maximizing a reaction rate: adjoint source $S^+=\Sigma$ reaction rate $R = \langle\langle \phi, \Sigma \rangle\rangle$, and we take P equal to the atomic densities,
  $P \rightarrow N_i$, i=1,…,I

  The functional to be maximized:

$$F(N_1, N_2, \cdots, N_I) = \int d\mathbf{r} \langle \underline{\Sigma}, \underline{\phi} \rangle$$

- Following Greenspan approach [1975]: maximization condition is

$$\delta F = \sum_{i=1}^{I} (\delta F)_i = \sum_{i=1}^{I} \int_V d\mathbf{r} \overbrace{\left[\frac{R(\mathbf{r})}{N_i(\mathbf{r})} \mathcal{S}_{N_i}(\mathbf{r}) \right]}^{E_i(\mathbf{r})} \delta N_i = 0$$

where $E_i(\mathbf{r})$ (Effectiveness Function) gives the *absolute change in the value of F due to a unit change in the density of material i at position r*

3.3 Extremization condition

- Constraint on total volume fraction:

$$\sum_{i=1}^{I} \delta(VF)_i = \sum_{i=1}^{I} \frac{\delta N_i(\mathbf{r})}{N_i^0(\mathbf{r})} = 0 \quad \Rightarrow \quad \delta N_I = -\sum_{i=1}^{I-1} \frac{N_I^0(\mathbf{r})}{N_i^0(\mathbf{r})} \delta N_i$$

- Maximization condition:

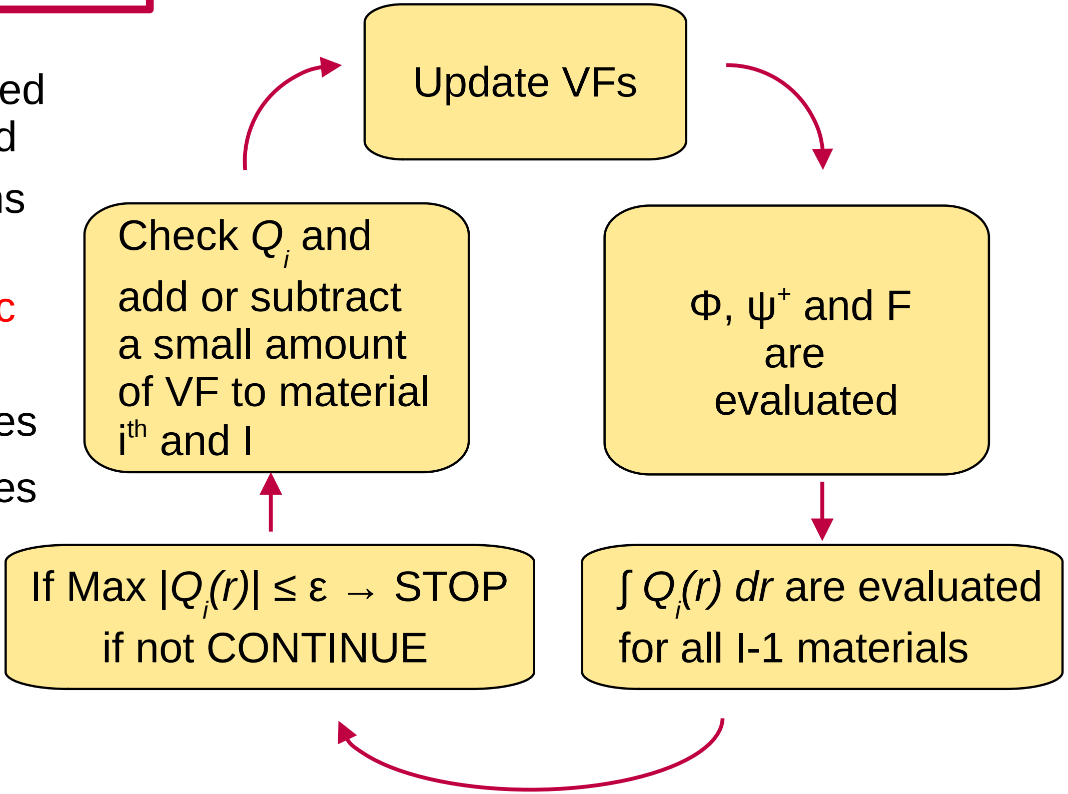
$$\delta F = \sum_{i=1}^{I-1} \int_{V} d\mathbf{r} \overbrace{\left[+E_i(\mathbf{r}) - E_I(\mathbf{r}) \frac{N_I^0(\mathbf{r})}{N_i^0(\mathbf{r})} \right]}^{Q_i(\mathbf{r})} \delta N_i = 0$$

where $Q_i(\mathbf{r})$ *(Substitution Effectiveness Function)* gives the *change in F caused by the substitution at position r of a unit quantity of material I with the same quantity of material i in a zone of the system, whose volume does not change*

3.4 Algorithm

δF = 0 is reached when all $Q_i(r)$ are close to zero

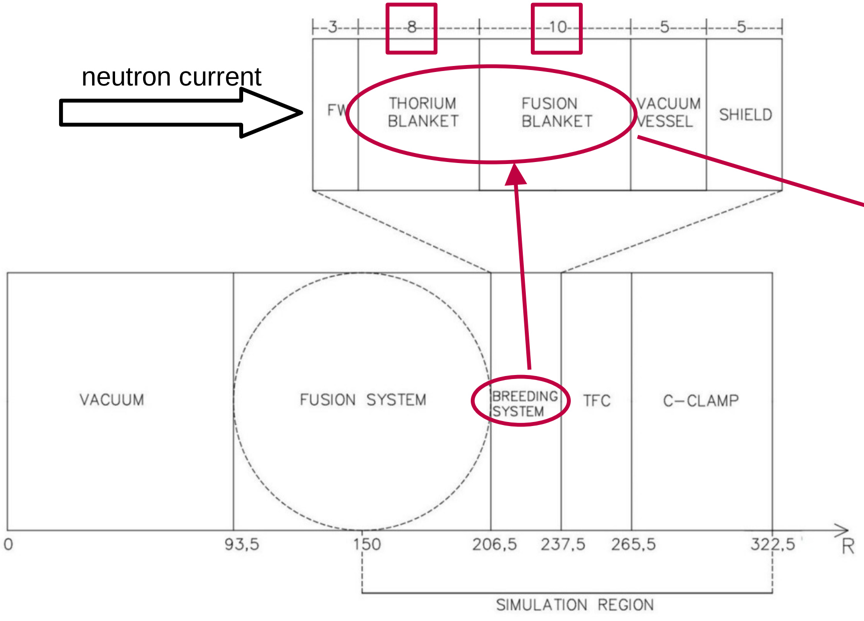
1. VF are initialized, and Φ, ψ and F are evaluated
2. The $\int Q_i(r)\, dr$ of the I-1 materials are evaluated
3. If Max $|Q_i(r)| \leq \varepsilon \rightarrow$ STOP (no further variations of composition are useful)
4. Otherwise code CONTINUES updating atomic densities using $Q_i(r)$ as indicator:
   - If $Q_i(r)>0 \rightarrow VF_i$ increases and VF_I decreases
   - If $Q_i(r)<0 \rightarrow VF_i$ decreases and VF_I increases
5. Back to step 1 and update volume fractions



3.5 Test case: Tritium production

$\Sigma \rightarrow \Sigma_T \neq 0$ in the fusion blanket

Computational tool: 1-D Multi-Group diffusion solver with 6 groups



FISSION CORE		FUSION BLANKET	
Material	VF	Material	VF
ThO_2	0.50	γ-$AlLiO_2$	0.30
Fe	0.25	C	0.10
He	0.25	Pb	0.10
		Fe	0.25
		He	0.25

Objective: maximize T production for fixed amounts of Fe and He

3.6 Test case: Tritium production

The fusion blanket is divided into 6 zones and the optimization code is run for Tritium production maximization:

- No need of multiplier Pb
- No need of moderator C

	1	2	3	4	5	6
γ-$AlLiO_2$	0.30	0.30	0.30	0.30	0.30	0.30
Pb	0.10	0.10	0.10	0.10	0.10	0.10
C	0.10	0.10	0.10	0.10	0.10	0.10

+22.3% Tritium production

	1	2	3	4	5	6
γ-$AlLiO_2$	0.50	0.50	0.50	0.50	0.50	0.50
Pb	0	0	0	0	0	0
C	0	0	0	0	0	0

Possible explanation: the fission core modifies the neutron spectrum so that no multiplication on Pb is possible, and no moderation is required – analysis of the neutron spectrum is needed

4 – COMPUTATIONAL TOOL COUPLING
MCNP and FISPACT

We have developed a simulation chain based on the stochastic method, with the goal of performing neutronic calculations in complex geometries

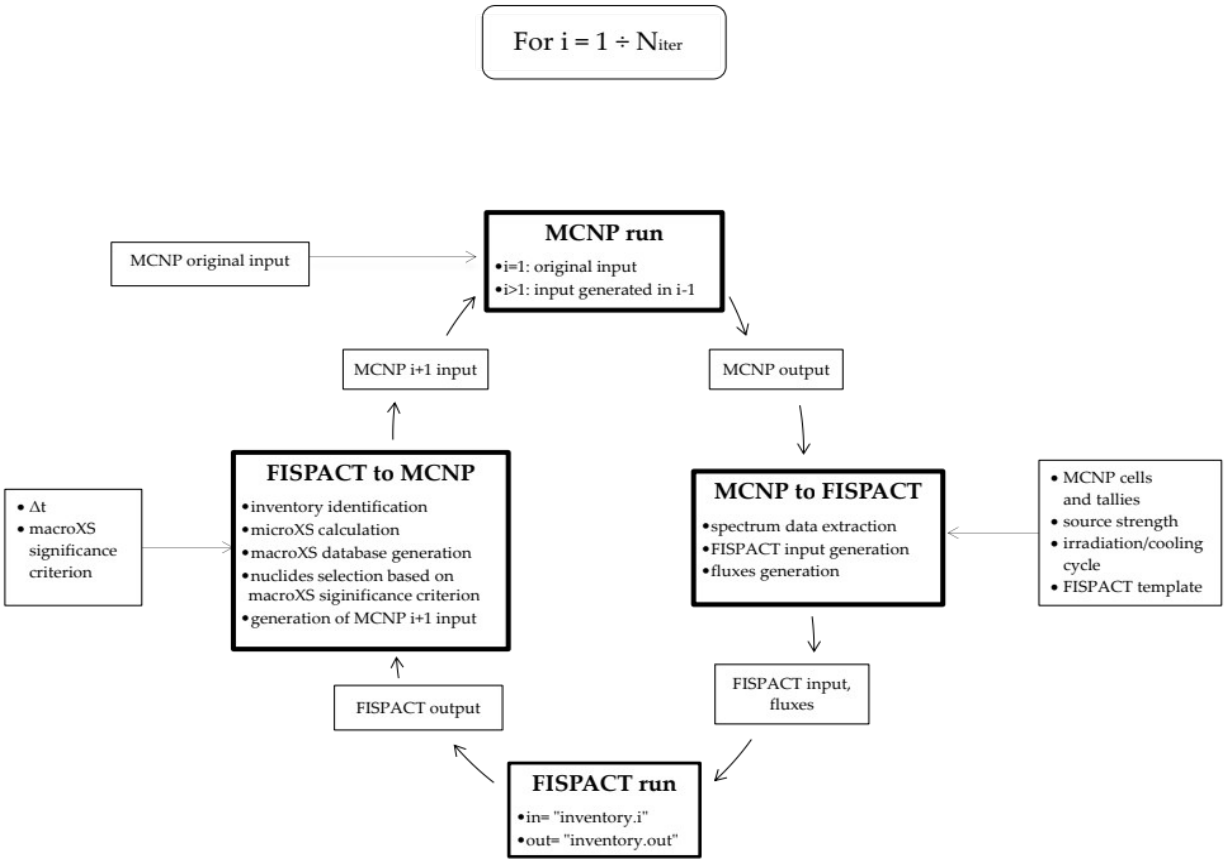
MCNP: stochastic code for particle transport and criticality analysis

coupling scripts in AWK and OCTAVE

FISPACT: Bateman equation solver for the evolution of the material composition

Run by a global script

4.1 Flow chart



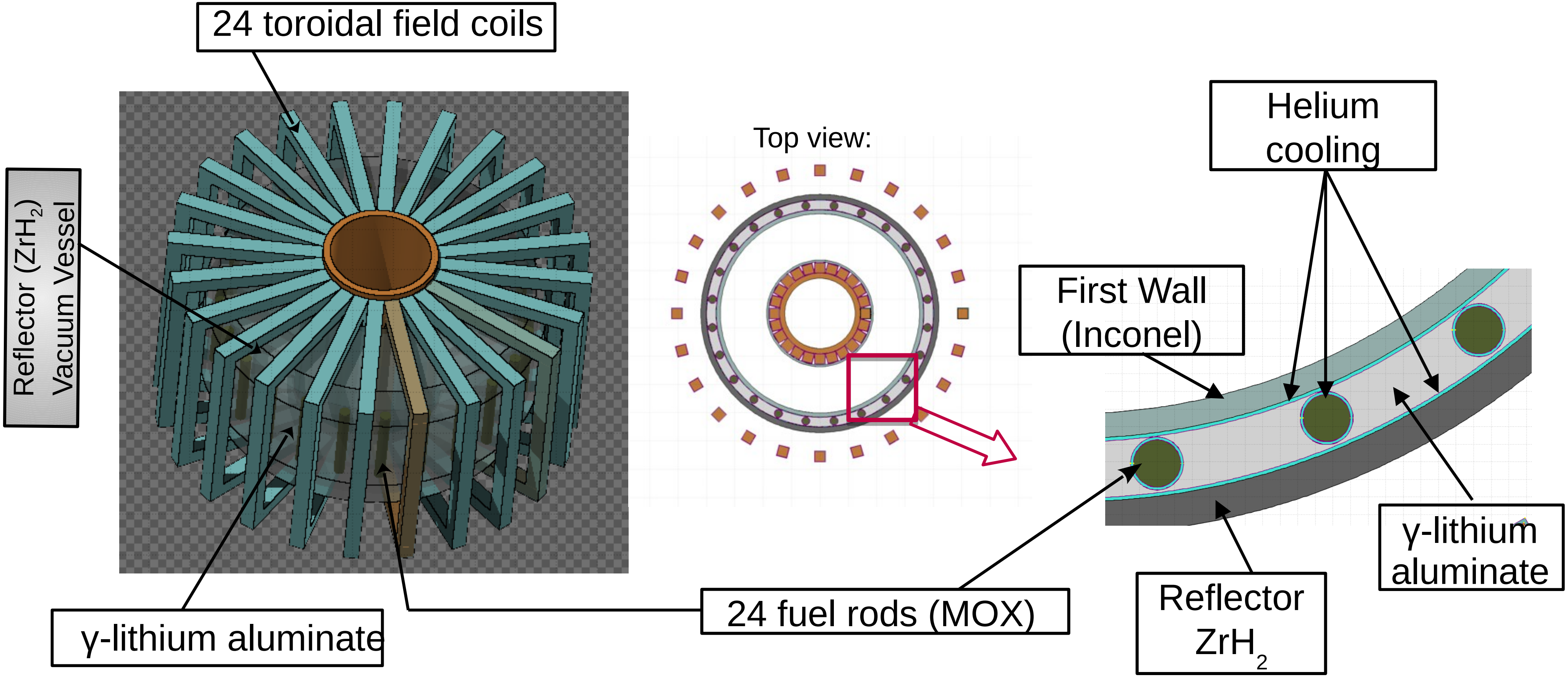
- "Significance criterion": retain in the burn-up calculation only nuclides *i* relevant to the problem at hand.
  For example,

$$R_i = \left(\frac{\sigma_{\text{prod}}}{\sigma_{\text{abs}}}\right)_i \geq R_{\text{thr}}$$

- Different criteria can be implemented

5 – TOWARD THE FF HYBRID SYSTEM

[Coppi, Salvini 2001. Stacey, et al., 2002]



5.1 First studies

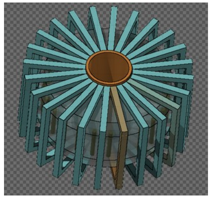
k_{eff}	Standard Deviation	ρ relative to criticality (PCM)
0.75331	0.00023	32747

High level of subcriticality that is very far from $k_{eff} \leq 0.96$. Add another ring of fuel rods and larger volume of aluminate for Tritiuim production

Neutron Flux intensity w/ and w/o Reflector

Elements	With Void Reflector		With ZrH_2 Reflector		%Change (against void)
	n/cm²/s	Er	n/cm²/s	Er	
First Wall	5.63E+14	0.002%	6.93E+14	0.002%	18.87%
γ-alluminate	2.43E+14	0.005%	3.28E+14	0.005%	26.04%
Reflector	1.16E+14	0.011%	3.33E+14	0.011%	65.31%

The reflector increases the flux intensities



Tritium production

Elements	Void Reflector		ZrH_2 Reflector		%Change (against void)
	atom/cm³/s	Er	atom/cm³/s	Er	
aluminate	8.98E+11	0.009%	1.33E+12	0.008%	32.29%

The Reflector increases the Tritium production

Thank you for your attention!

NEW COLLABORATIONS ARE WELCOME!