Italian National Agency for New Technologies,
Energy and Sustainable Economic Development

Development of the Advanced D1S for shutdown dose rate calculations in fusion reactors

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Rosaria Villari, Davide Flammini, Fabio Moro and Luigino Petrizzi
ENEA, Department of Fusion and Technology for Nuclear Safety and Security, I-00044 Frascati (Rome) Italy

rosaria.villari@enea.it

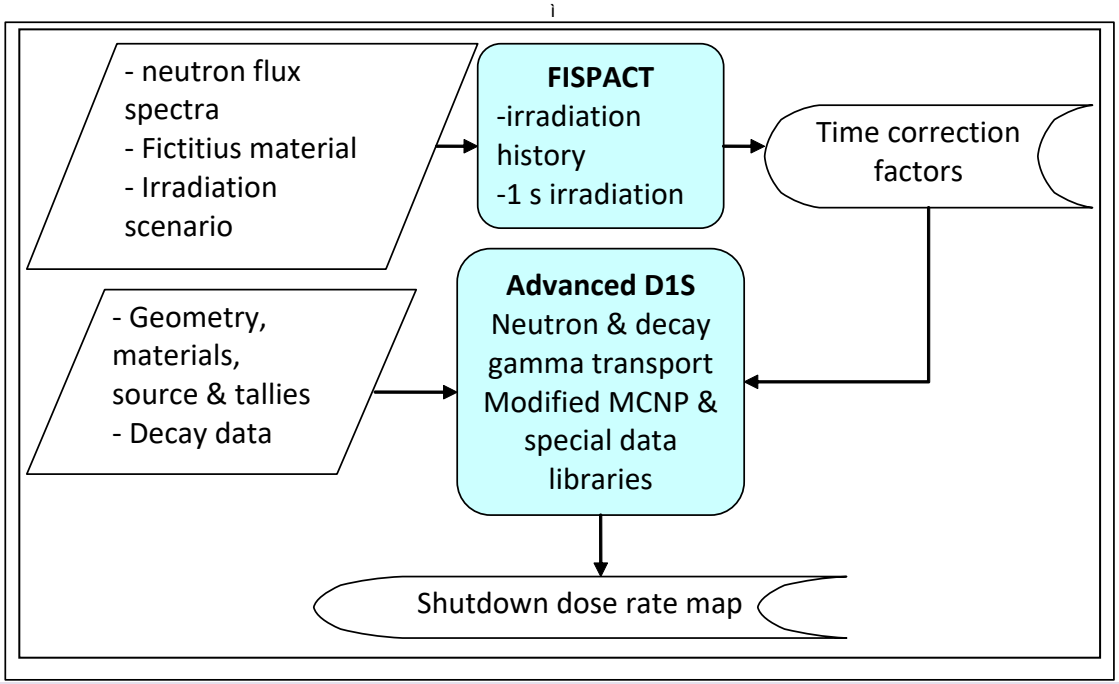
Introduction

- The assessment of the **shutdown dose rate** due to neutron activation is fundamental for **shielding design**, **materials selection, licensing** and **maintenance** operations in high performances fusion devices.
- The shutdown dose rate calculations require the combined use of **radiation transports** and **inventory codes**.
- **Direct One-step (D1S)** is presently one of the most reliable and validated tools for the 3D calculations of the shutdown dose rates in fusion devices.
- It is based on the use of a modified version of the **MCNP** Monte Carlo code with tailored cross-section data.
- The decay gammas of the radioactive nuclides are emitted as prompt → the **n & decay γ are transported in a single Monte Carlo simulation**.
- Time correction factors are applied to take into account the build-up and the decay of the radionuclides considered.
- The original D1S had not mesh tally capability, the time evolution is possible, but it is discrete and complex post-processing is needed.

Advanced D1S

- The “Advanced-D1S” is an improved version of D1S
- In the Advanced D1S the MCNP source code subroutines have been modified to include new features.

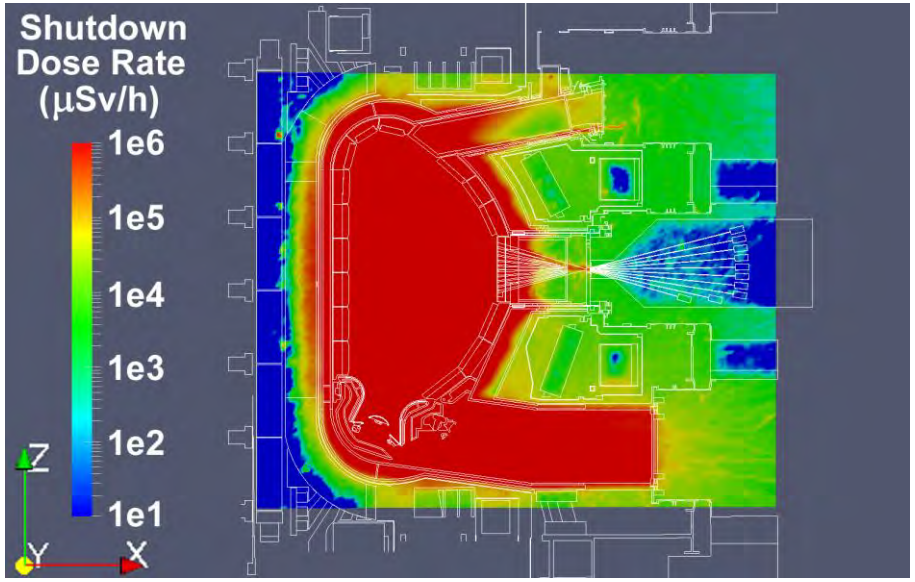
- **Mesh** tally capability
- Automated **time evolution**
- 3D maps neutron and decay γ flux spectra, shutdown dose rate & decay heat in single run

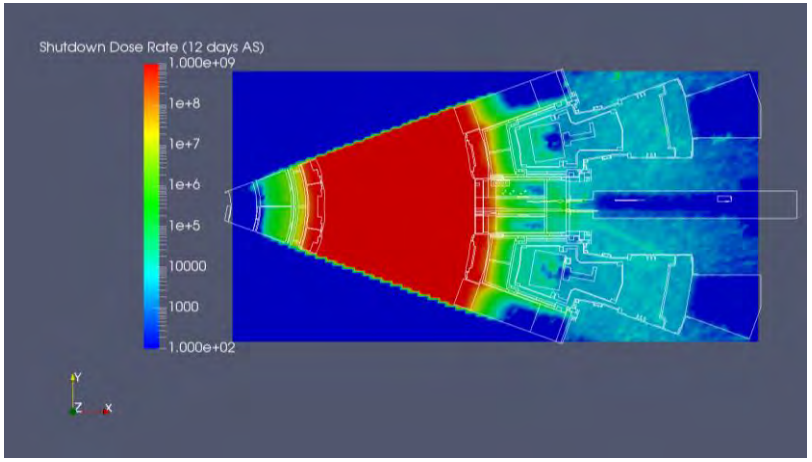


Extensively used for JET & ITER calculations and recently applied to DEMO assessment.

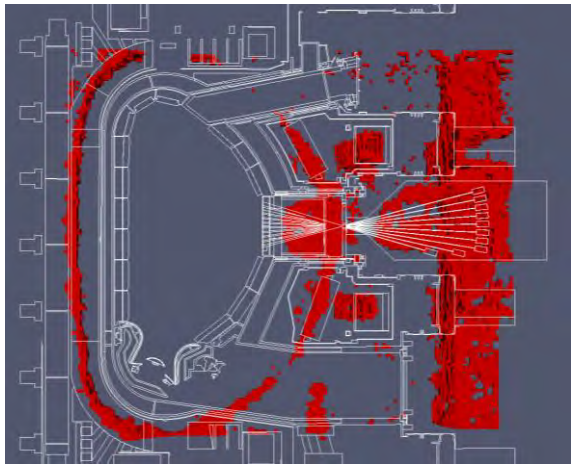
Recent Applications of Advanced D1S to ITER

Global calculation- RNC in ITER C-lite





SDR calculation at **12 days**



- Shutdown dose rate at 12 days after ITER shutdown
- Global calculation
- 24 h 800 cores on CRESCO4 cluster
- good statistical error in the zones of interest

+ decay gamma fluxes maps at different cooling times

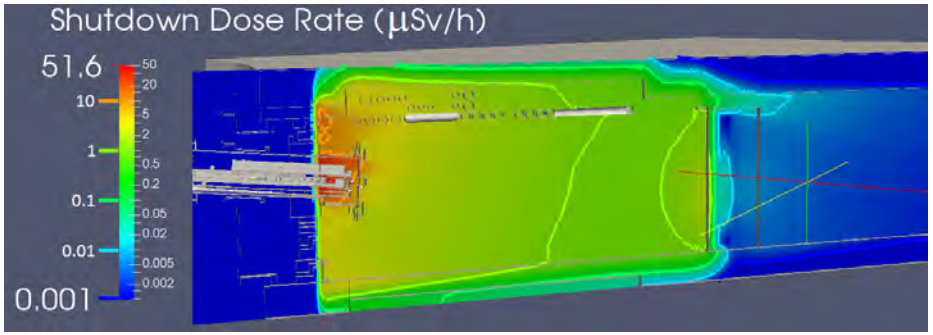
threshold>±15%

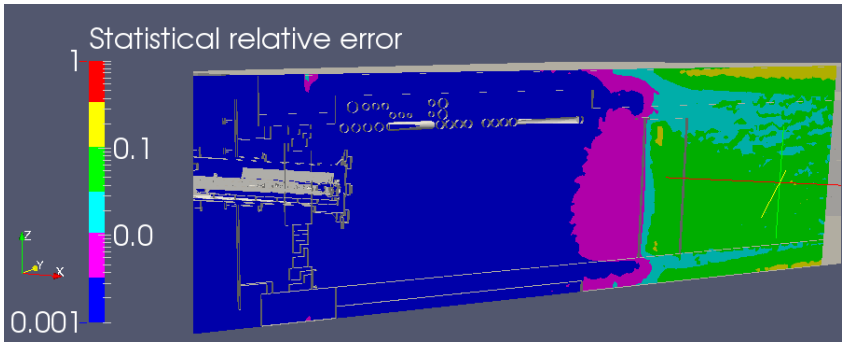
F4E FPA 327

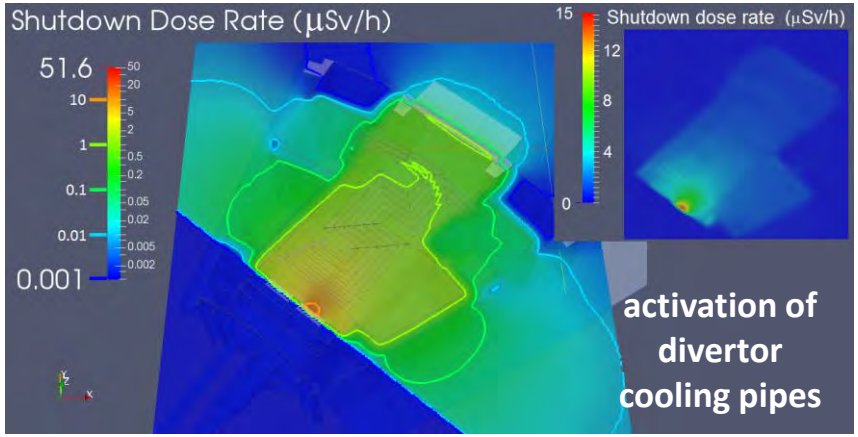
Recent Applications of Advanced D1S to ITER

Port Cell of IVVS system

SDR calculation at **1 day**







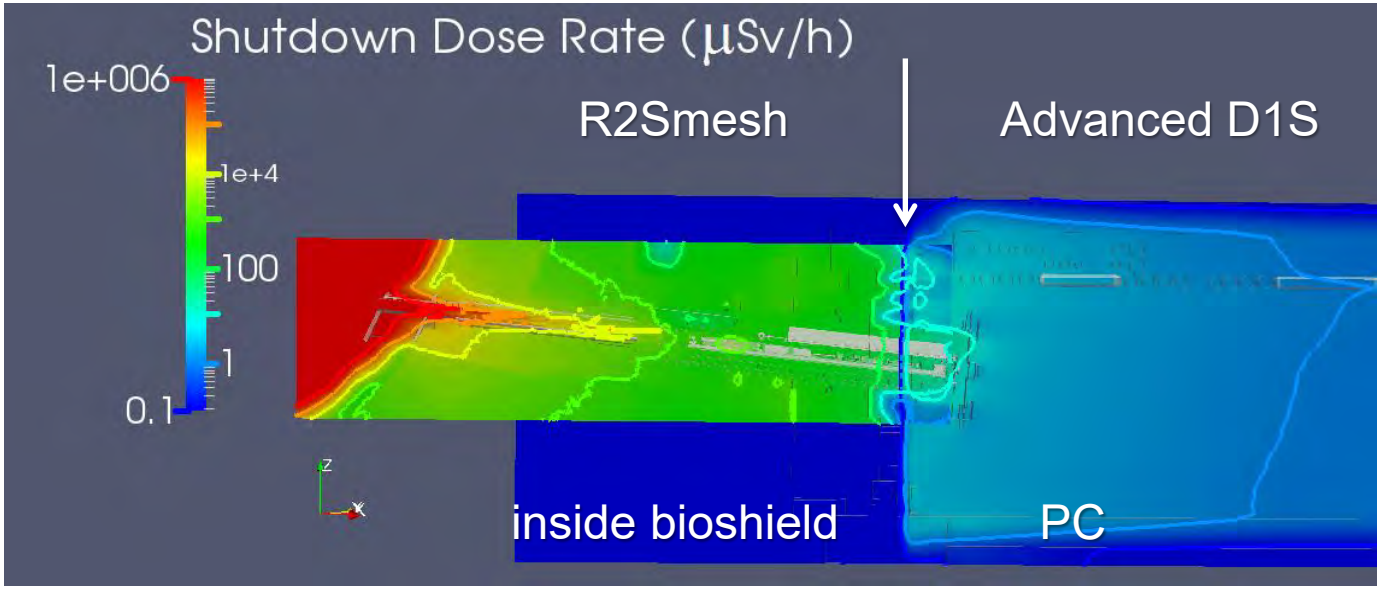
SDR in PC of IVVS

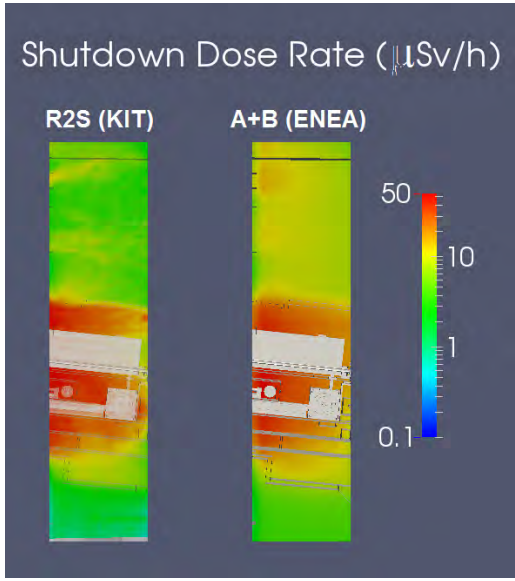
- Contribution due to activation inside the Bioshield (R2Smesh, KIT)
- Activation of PC components (Advanced D1S, ENEA)

The SDR>10 μSv/h only inside the IVVS & in two very localized hotspots close to the Bioshield

Recent Applications of Advanced D1S to ITER

Lower port of IVVS





Interface

Comparison of SDDR from R2Smesh & Advanced D1S at the interface

- Same values in & close to the IVVS penetration
- Above the IVVS, higher dose in PC because of the contribution due to the activated PC components

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Features & Limitations of Advanced D1S

Feature	Implementation
Mesh tally capability (n & γ)	Yes
Automated time evolution of dose rate	Yes (cell tallies)
Propagation of uncertainties	Yes
Selection of activated components	Yes
Computation of radionuclides contribution	Yes
Identification of components contribution	Yes
Change of geometrical config. at shutdown	No
Management of multiple lifetimes	No
Decay gamma source portability	No
Burn-up & Multi-step reactions	No
Handling of libraries in different format	No
MCNP6	No

Advanced D1S dynamic

Development of Advanced D1S dynamic

In progress developments of Advanced D1S dynamic

- Changes of the machine configuration during irradiation and at the shutdown
  - Variation of the geometry operations/shutdown
  - Management of multiple lifetimes
  - Decay gamma source portability
- Handling of libraries in different formats
  - FENDL3-based new library
- Multi-step reactions
  - W-activation in DEMO reactor
- MCNP6

Changes during irradiation & at the shutdown

Assessment of the n flux/shutdown dose rate in a single run when the machine configurations change during irradiation and at the shutdown.

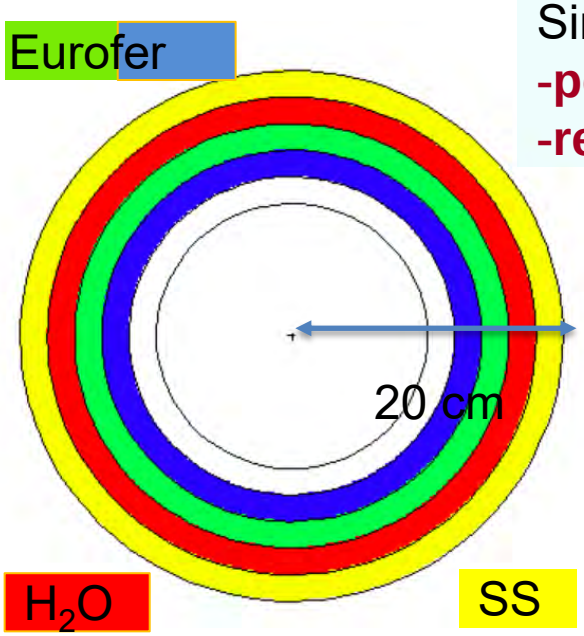
Typical Cases

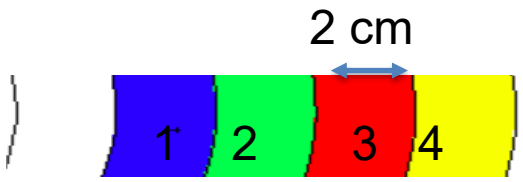
- activated system moved to another site after irradiation (i.e. through cask transfer in hot cell)
- cooling water drained off at the shutdown
- systems present at the shutdown or during irradiation only
- components replaced during machine lifetime

N generation	ON	Source emission
N transport	ON/OFF	Set selective transparencies to n
Decay γ generation	ON/OFF	Activation of selected components- Lifetime management
Decay γ transport	ON/OFF	Set selective transparencies to γ

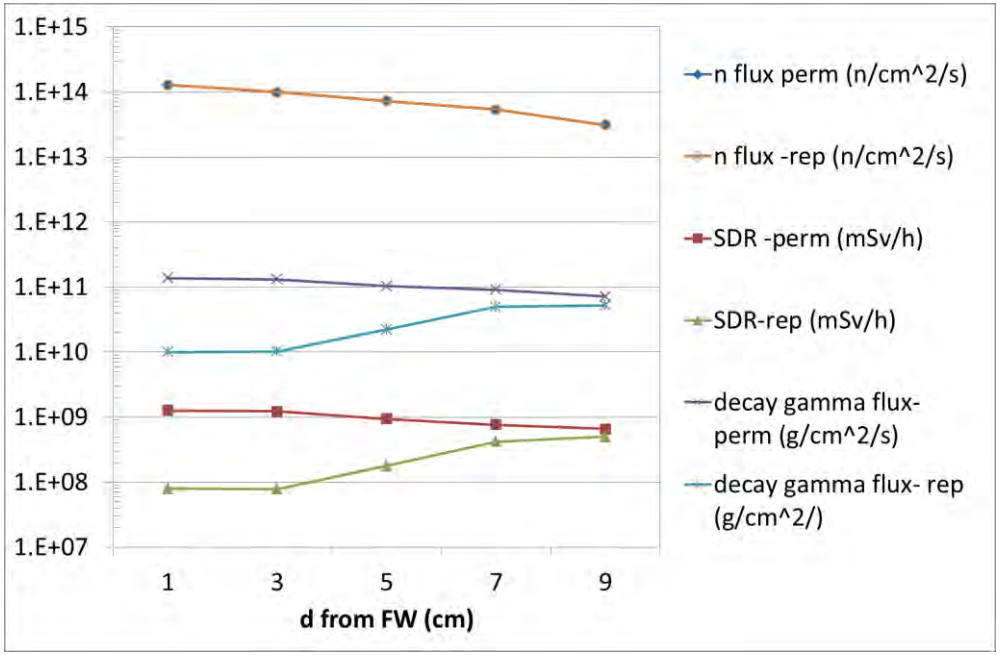
Advanced D1S dynamic: Multiple-lifetime

Management of multiple irradiation histories





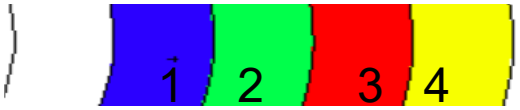
Simple test case
-perm: all permanent
-rep: # 1-2-3 reduced lifetime (replaced) & #4 permanent



Lower SDR in front components

Multiple-lifetime check

Photon activities in each cell

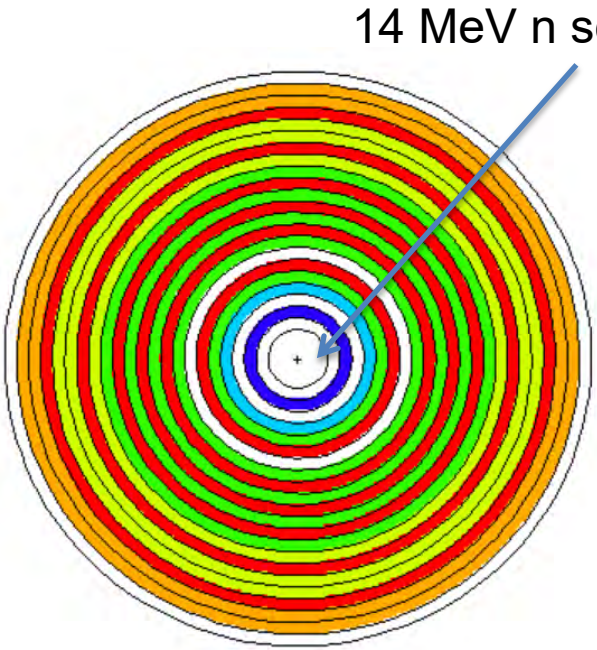


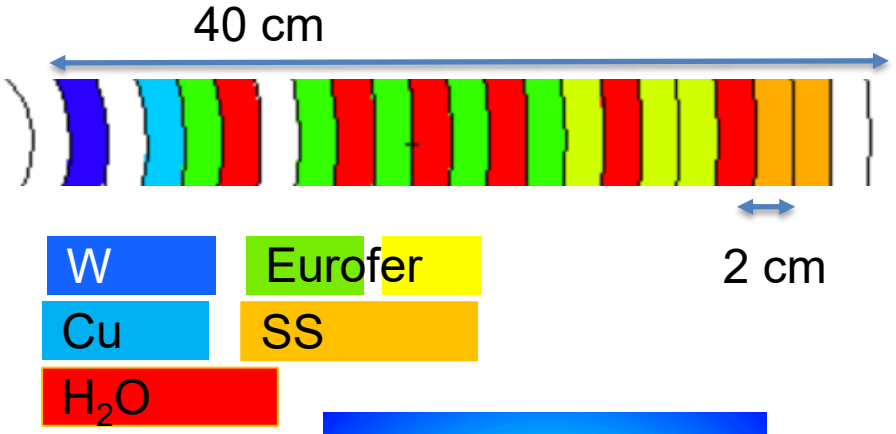
	Permanent	Permanent	Permanent	Permanent		Replaced	Replaced	Replaced	Permanent
cell number	**1**	**2**	**3**	**4**		**1**	**2**	**3**	**4**
external events:									
entering	4.40E+09	5.21E+09	5.98E+09	3.81E+09		6.51E+08	1.86E+09	2.79E+09	1.09E+09
exiting	-5.26E+09	-5.39E+09	-5.97E+09	-6.56E+09		-3.29E+08	-9.00E+08	-2.79E+09	-5.08E+09
	---	---	---	---		---	---	---	---
total	-8.68E+08	-1.79E+08	6.99E+06	-2.75E+09		3.22E+08	9.63E+08	2.94E+06	-3.99E+09
physical events:									
from neutrons	**6.09E+09**	**5.87E+09**	**0.00E+00**	**8.05E+09**		**6.09E+04**	**5.87E+04**	**0.00E+00**	**8.05E+09**
bremsstrahlung	9.58E+08	9.97E+08	2.89E+07	1.09E+09		6.44E+07	1.94E+08	1.57E+07	8.21E+08
capture	-8.31E+09	-9.16E+09	-3.59E+07	-8.13E+09		-5.72E+08	-1.71E+09	-1.87E+07	-6.07E+09
p-annihilation	9.71E+04	1.34E+05	4.83E+04	6.87E+05		6.92E+04	1.23E+05	3.18E+04	6.65E+05
pair production	-4.85E+04	-6.72E+04	-2.41E+04	-3.43E+05		-3.46E+04	-6.13E+04	-1.59E+04	-3.32E+05
flourescence	2.13E+09	2.47E+09	0.00E+00	1.74E+09		1.86E+08	5.53E+08	0.00E+00	1.19E+09
	---	---	---	---		---	---	---	---
total	8.68E+08	1.79E+08	-6.99E+06	2.75E+09		-3.22E+08	-9.63E+08	-2.94E+06	3.99E+09

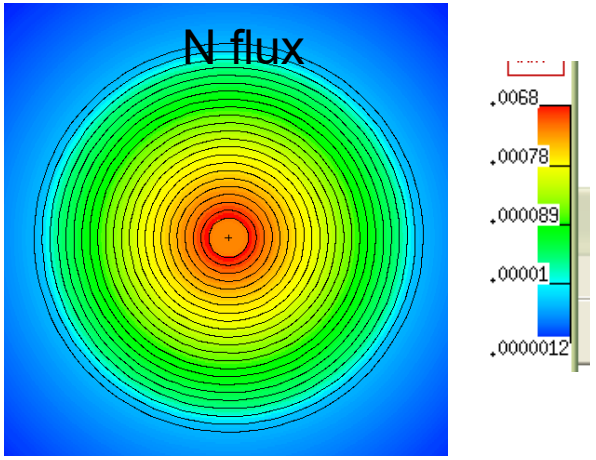
Correct management of multiple lifetimes

AdvanceD1S dynamic: change of configuration during operations/shutdown

Testing case







Standard D1S calculations:

- All permanent
- Same configuration during irradiation & at shutdown

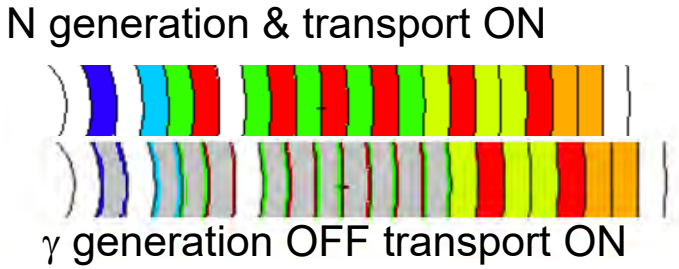
→ N, γ generation & transport ON

- N flux
- Shutdown dose rate
- Decay gamma flux

Test case configurations for Advanced D1S dynamic

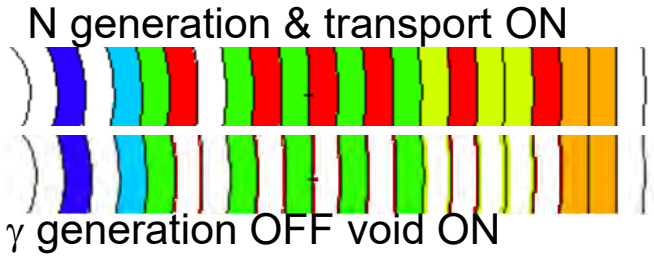
(#1) **Selected activation**

Front components new and not activated



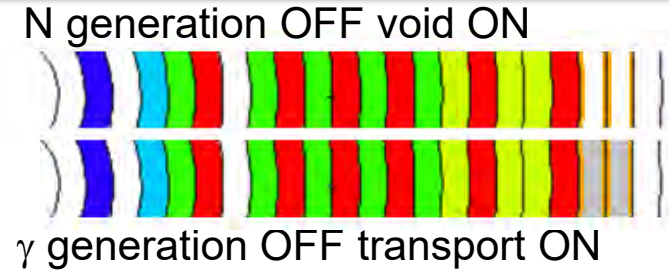
(#2) **Removal of components at the shutdown**

Water & part of shield removed at the shutdown



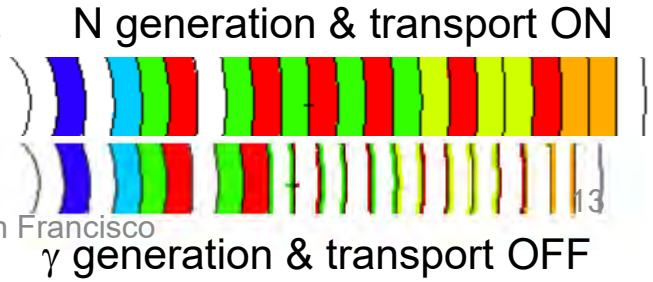
(#3) **Insertion of components at the shutdown**

The rear shield added at the shutdown



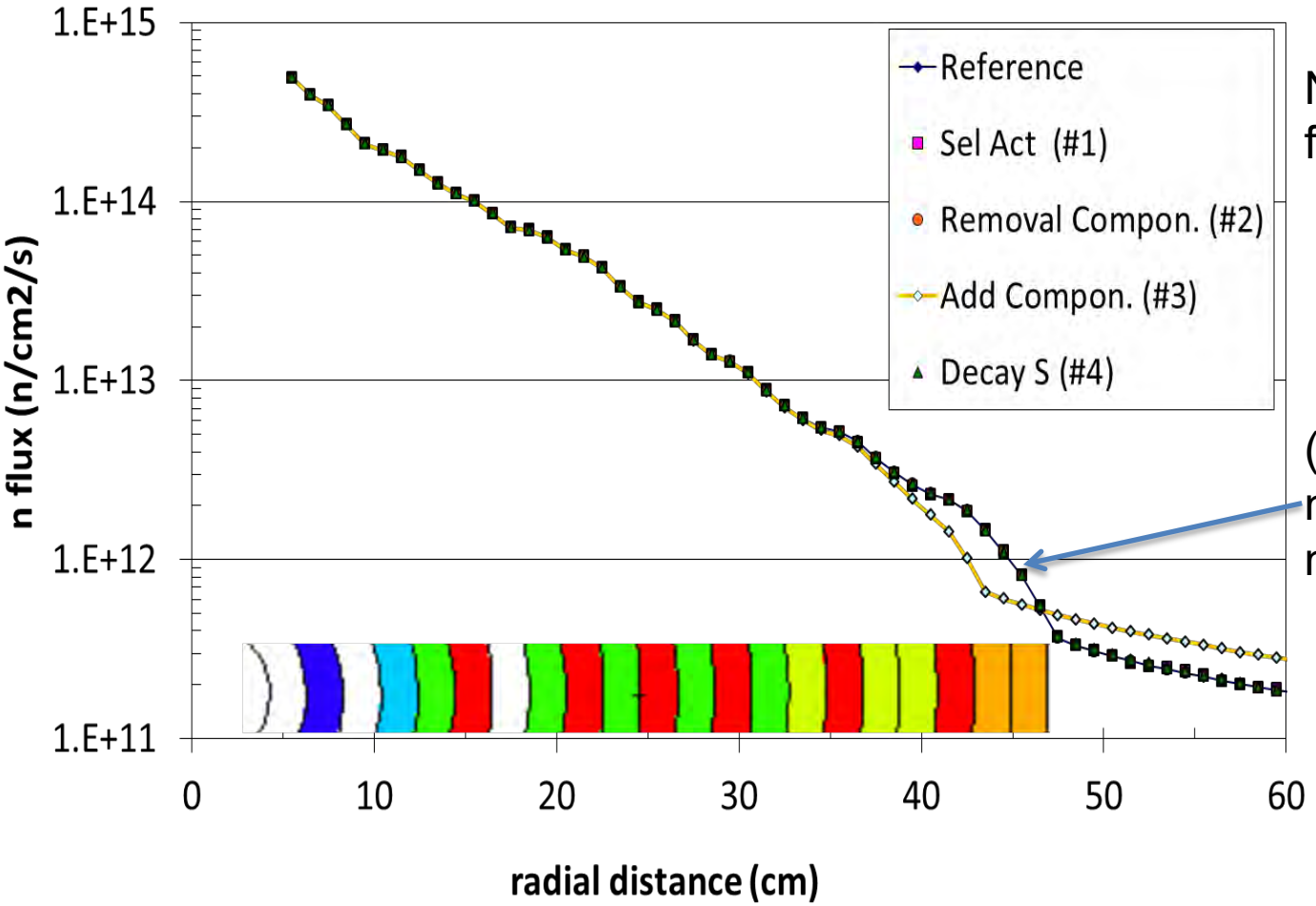
(#4) **Decay gamma from selected components**

Activation of front component only– others removed



Results of test cases for Advanced D1S dynamic

Neutron flux

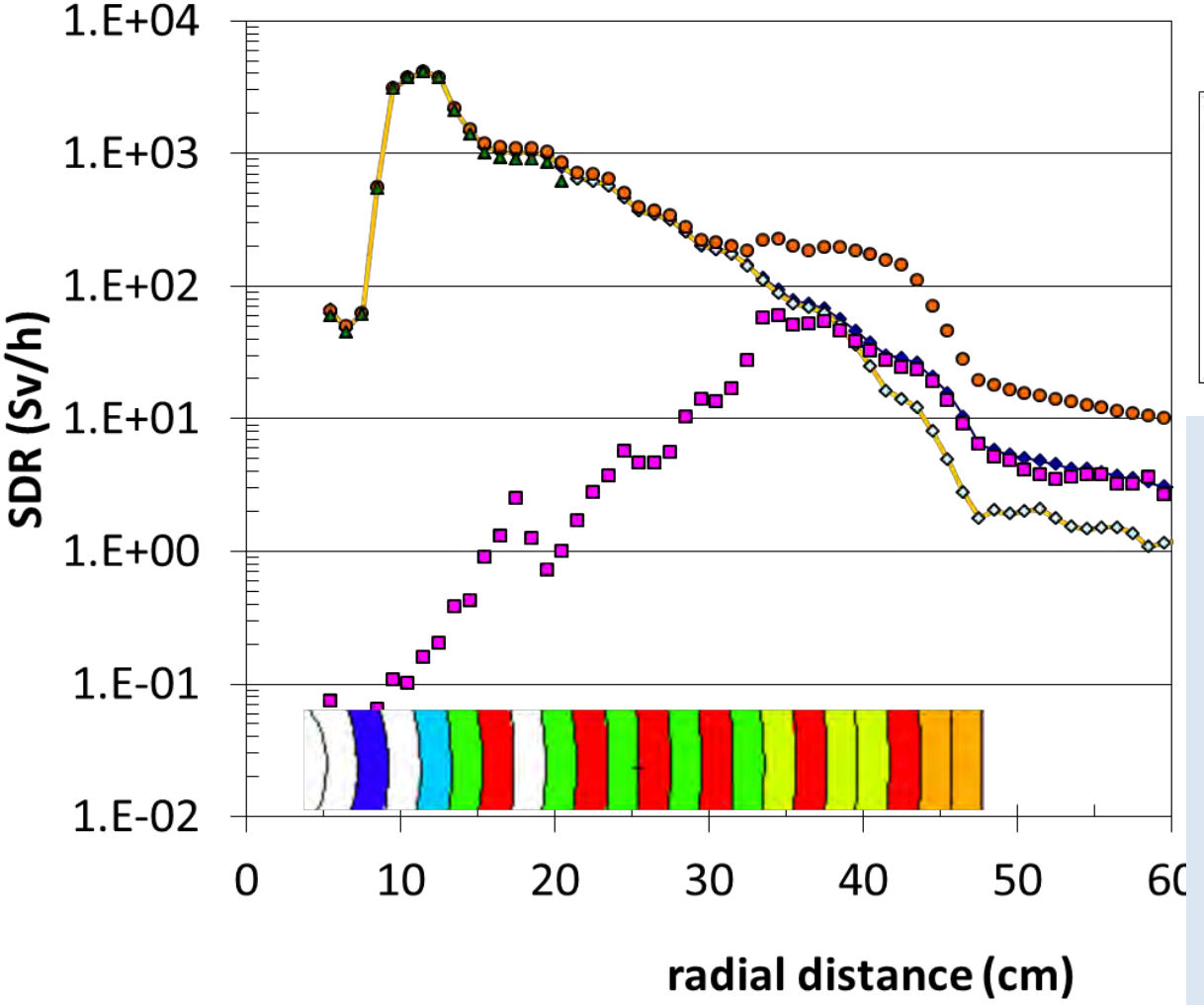


N flux the same for all except (#3)

(#3) Back shield not present during n irradiation

Results of test cases for AdvanceD1S dynamic

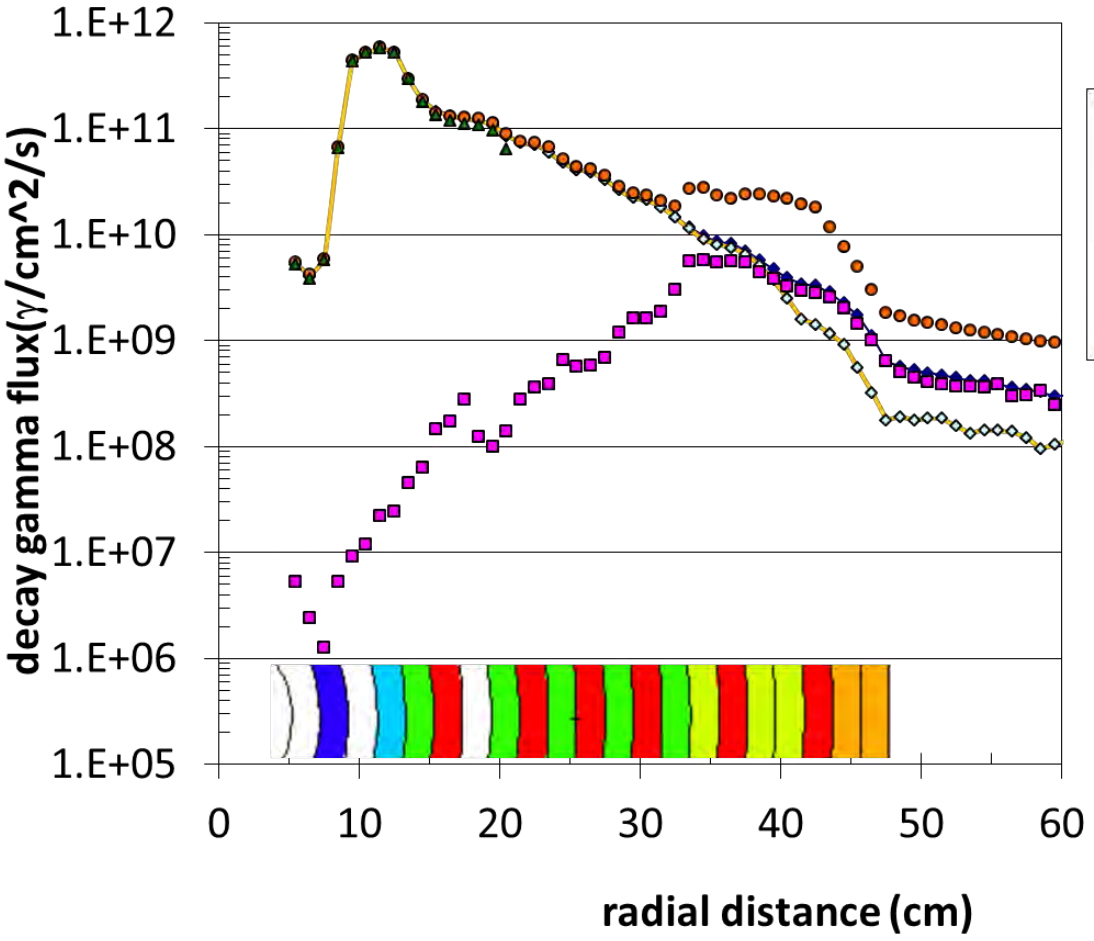
Shutdown dose rate

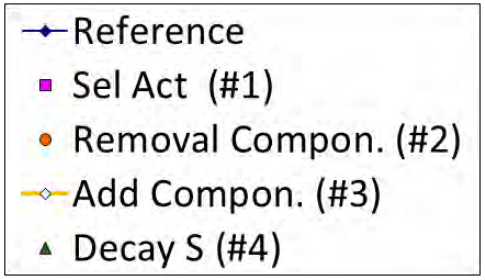


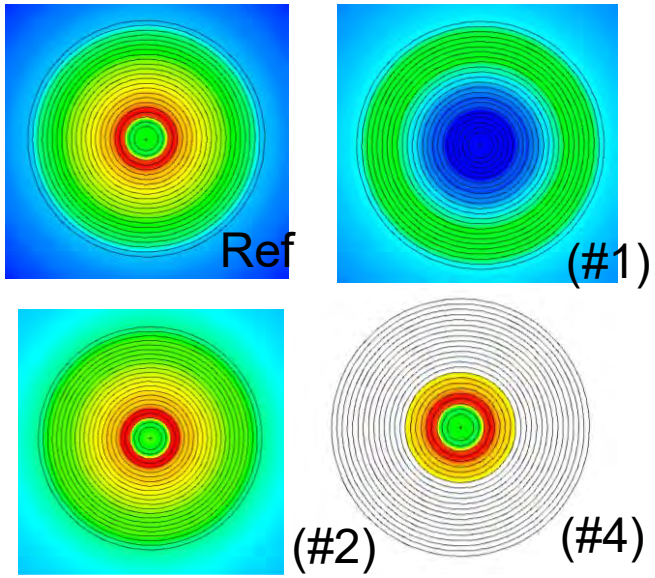
- (#1) no gamma emission from inner components → lower dose in front
- (#2) removal of central components at shutdown → higher dose in back area
- (#3) lack of back shield activation
→lower dose in back area
- (#4) no contribution from back components → slighltly lower dose in front area

Results of test cases for Advanced D1S dynamic

Decay gamma flux







Correct management of multiple changes

Handling of libraries in different format

- Standard D1S uses special libraries in fixed format
  - non-standard libraries
  - mixed data sources
  - Some obsolete cross-sections
  - limited number of nuclides

- Development & testing of FENDL3-based D1S libraries
  - Tool & development of new library- verification (UNED) *In progress*
  - Implementation of D1S modifications to manage new library (ENEA)
  - Validation (ENEA & UNED)

Multi-step reactions

Intrinsic D1S lacks of treatment of burn-up & multistep reactions

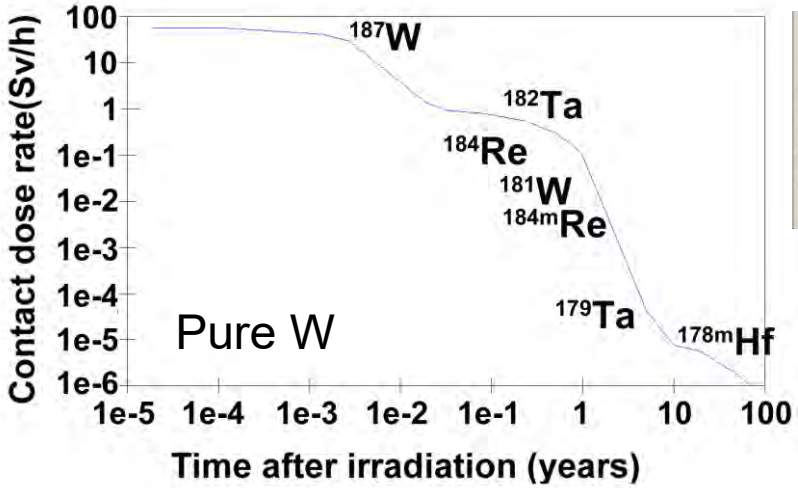
SI_1 (n,R) RI_1 (decay) SI_2 (n, R') RI_2 (decay) → gamma dose

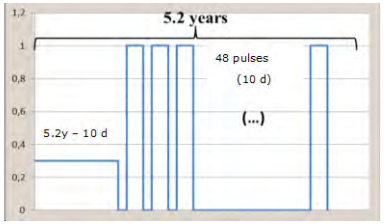
- The parent nuclides change during time
- Shutdown dose due to RI_2 decay cannot be managed by D1S
- No problem for ITER & presently operating machine
- Issue for DEMO & future power plants

Proposed approach to manage multi-step reactions in Advanced D1S dynamic

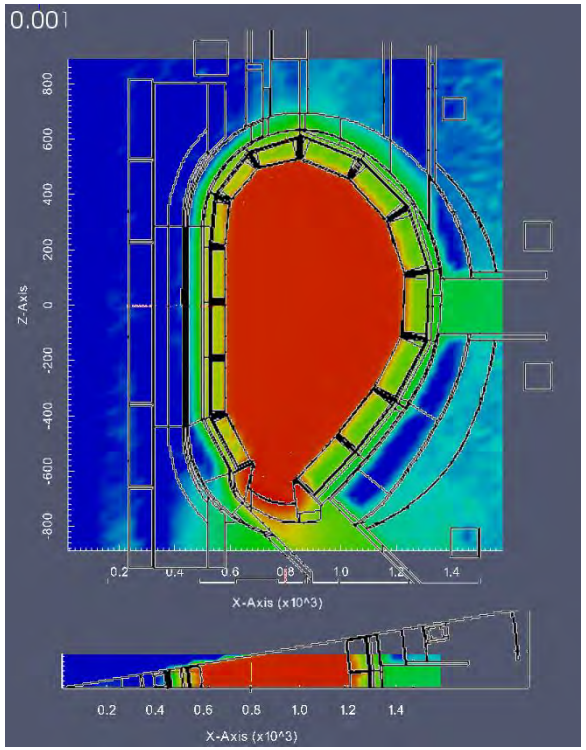
Multi-step approach in Advanced D1S dynamic

Tungsten (W) activation of plasma facing components of DEMO





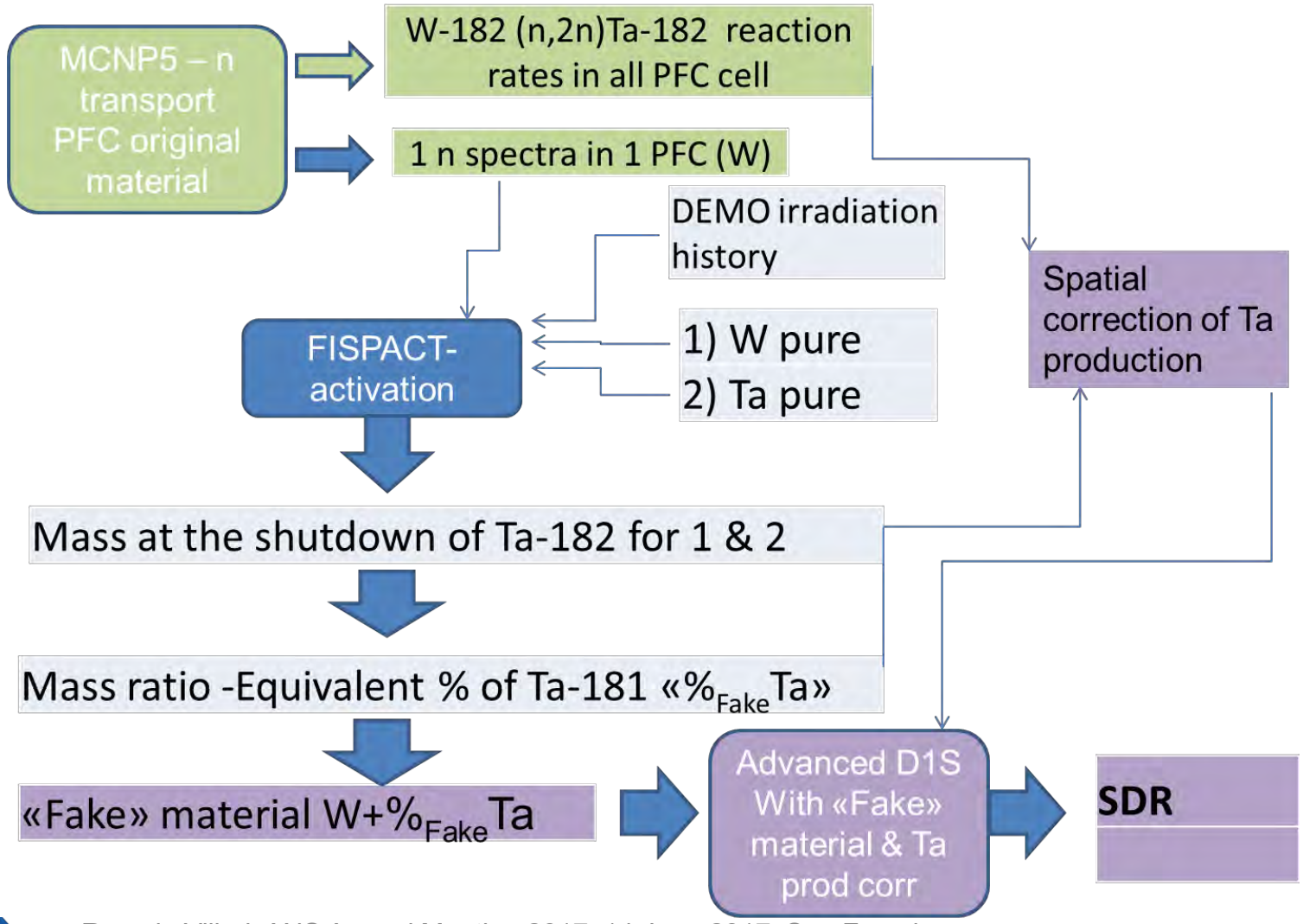
P_{fus} 2037 MW



SDR in W armor
at 12 days after shutdown
mainly due to multi-step reactions

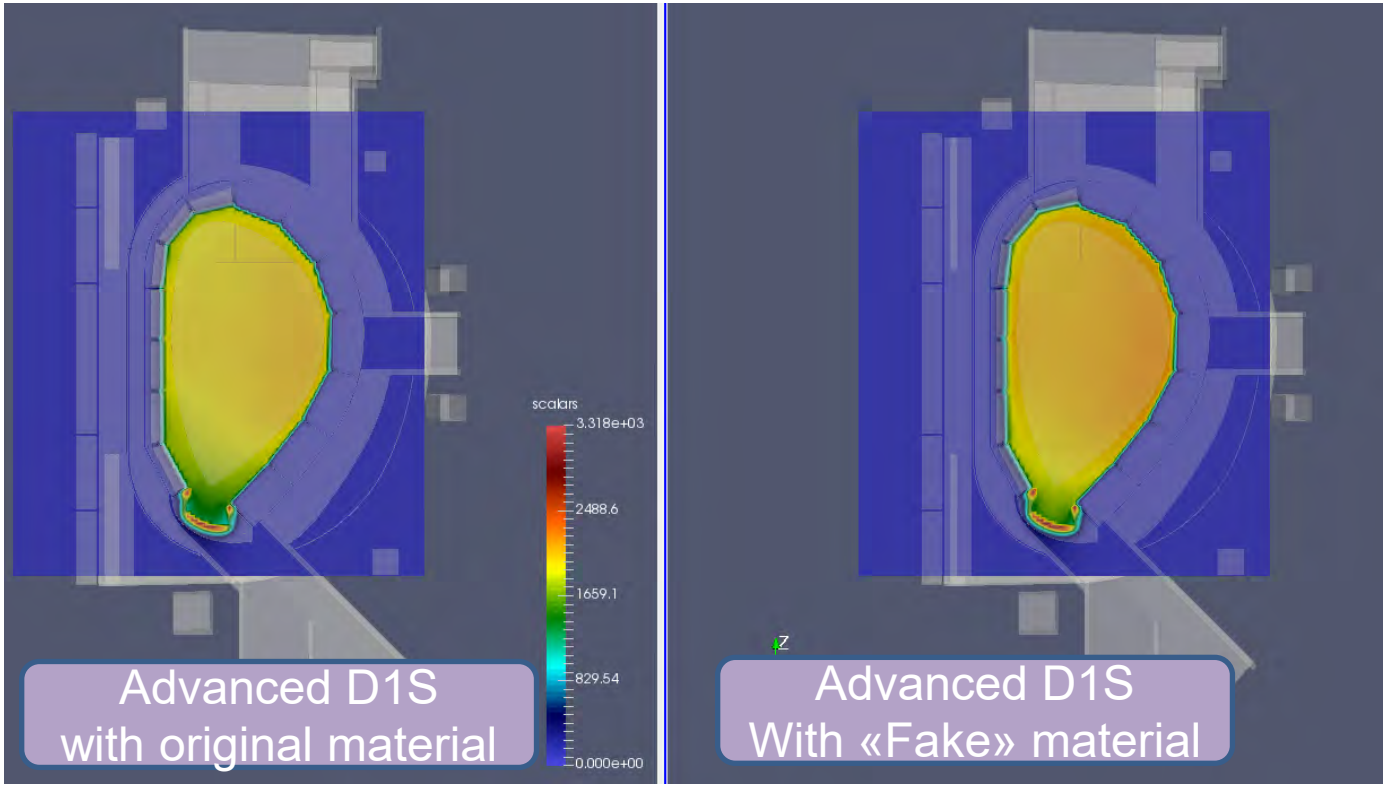
Pathways analysis of dominant nuclides		
Radio Nuclide	**Main Reactions**	**%**
^{187}W	^{186}W (n,γ) ^{187}W	100
^{182}Ta	^{182}W (n,2n) ^{181}W (EC decay)^{181}Ta (n,γ) ^{182}Ta	89.5
	^{182}W (n,p) ^{182}Ta	6.9
^{184}Re	^{184}W (n,γ) ^{185}W (β- decay)^{185}Re (n,2n) ^{184}Re	71.4
	^{186}W(n,2n) ^{185}W (β- decay)^{185}Re (n,2n) ^{184}Re	24.6

Multi-step approach for W in Advanced D1S dynamic



Multi-step approach for W in Advanced D1S dynamic

First result of test cases on DEMO WCLL reactor



- Increase of SDR in plasma chamber due to Ta-182 directly produced from Ta-181
- Interface with spatial correction of Ta-production in progress

Conclusions

- The Advanced D1S is a powerful, reliable and fast tool for shutdown dose rate assessment
- However, it presents some constraints that limit its application to specific problems for ITER, DEMO and future power plant.
- Several code improvements are in progress in Advanced D1S dynamic development to overcome these limitations.
- Preliminary tests on management of multiple lifetimes, change during operations/shutdown and of multistep provided successful results, but extension to more complex geometry is needed to fully extend its range of applications.

Rosaria Villari
Rosaria.villari@enea.it

THANK YOU!