DE LA RECHERCHE À L'INDUSTRIE

NON-OVERLAPPING DOMAIN DECOMPOSITION METHOD AND NON-LINEAR DIFFUSION ACCELERATION IN THE FRAMEWORK OF THE IDT TRANSPORT SOLVER OF THE APOLLO3 CODE

Emiliano Masiello

emiliano.masiello@cea.fr

www.cea.fr

Paris 7/12/2018

OUTLINES

1. IDT with HCC: the Integro-Differential Transport (IDT) solver with Heterogeneous Cartesian Cells (HCC)

2. Spatial integration

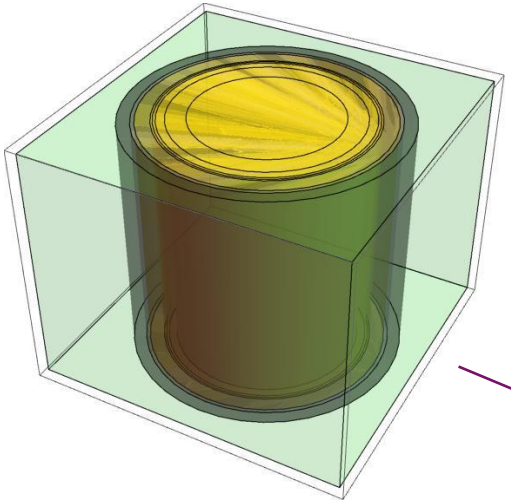
3. Non-linear diffusion iterations & parallelism

4. 3D results on workstation and mid-range HPC (Callisto)

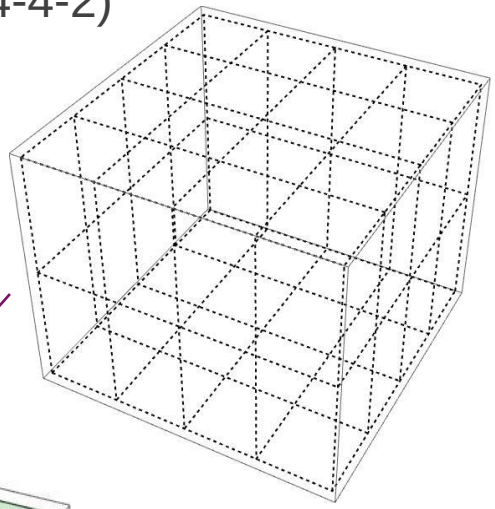
IDT with HCC

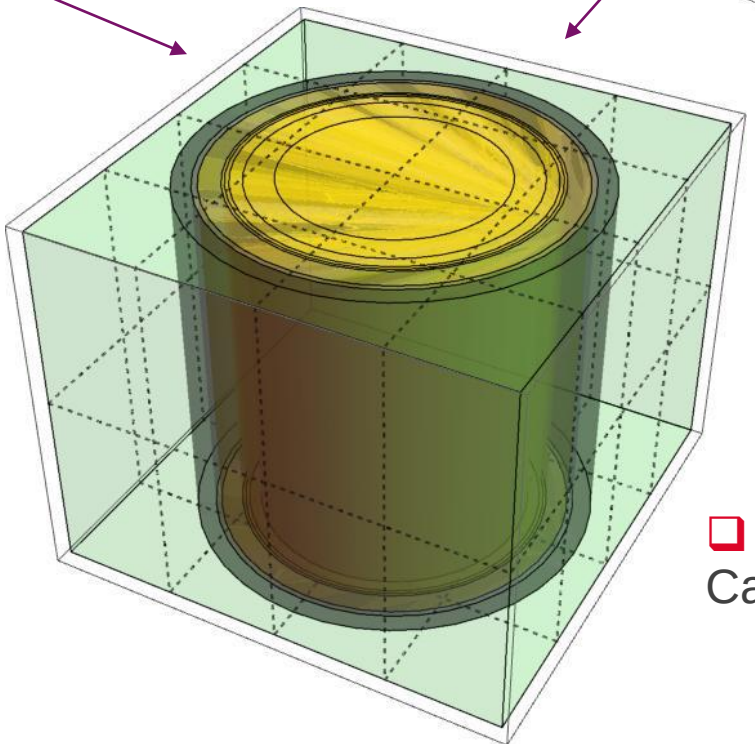
HETEROGENEOUS CARTESIAN CELLS (HCC)

- Volume expansion (z-slice of a pin cell)



- Surface expansion (4-4-2)

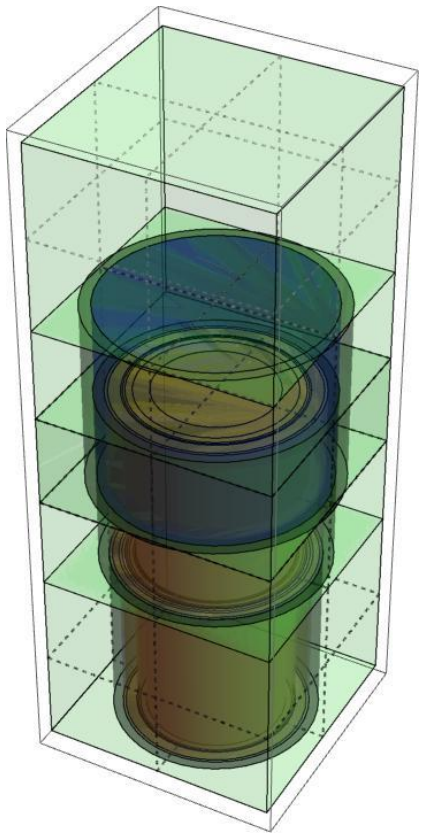


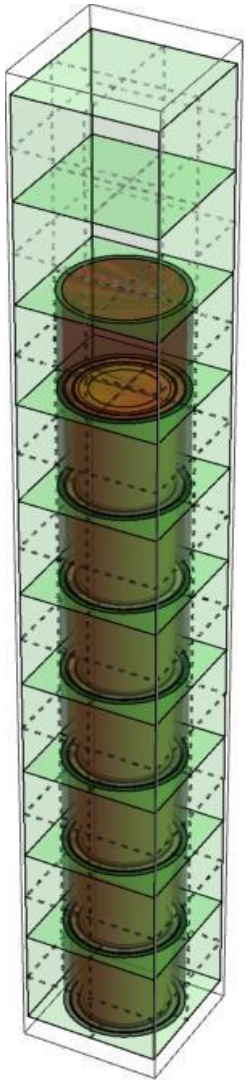


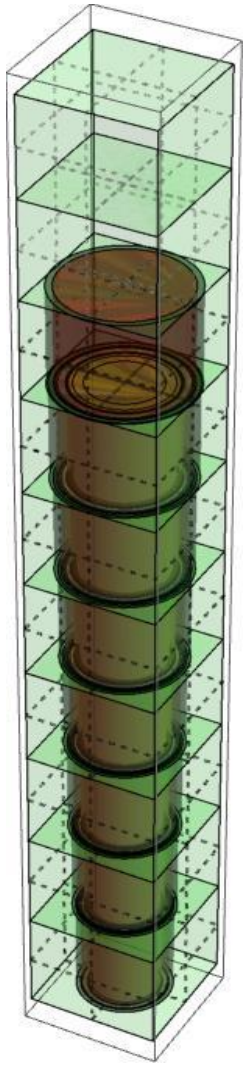
- Heterogeneous Cartesian Cell (HCC)

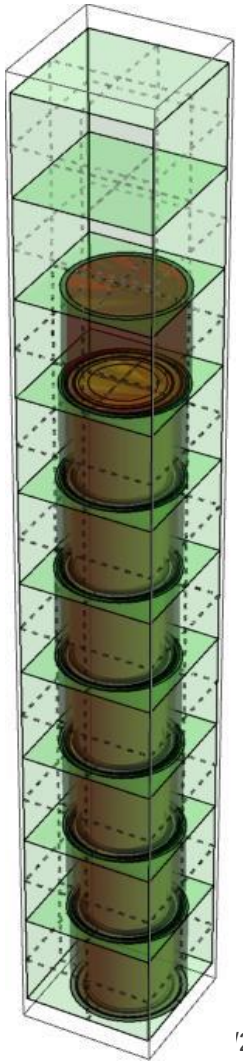
3D MODELIZATION OF THE PIN CELL

- piecewise extruded geometry
- Full 3D pin cell
- Thermo-mechanical deformations (swelling + bowing)



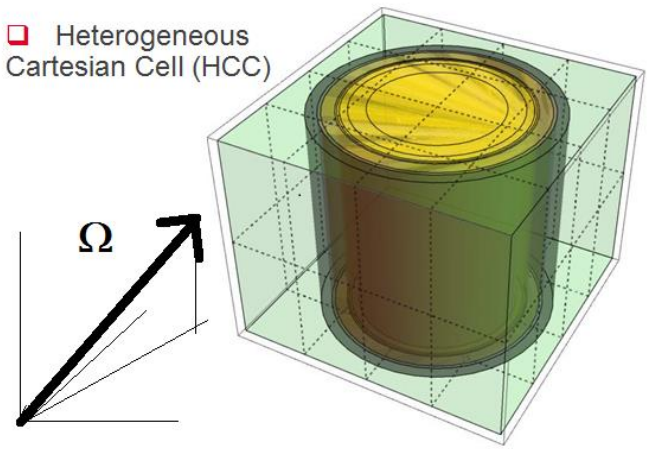






SPATIAL EXPANSION AND SOLUTION

$$\psi(\mathbf{r},\mathbf{\Omega}) = e^{-\tau(0,l)}\psi^{-}(\mathbf{r}^{-},\mathbf{\Omega}) + \int_0^l dx\, e^{-\tau(x,l)} q(\mathbf{r}^{-} + x\mathbf{\Omega},\mathbf{\Omega})$$



- Polynomial expansion for the source (linear)
- Polynomial expansion for the interface angular flux up to the bilinear order

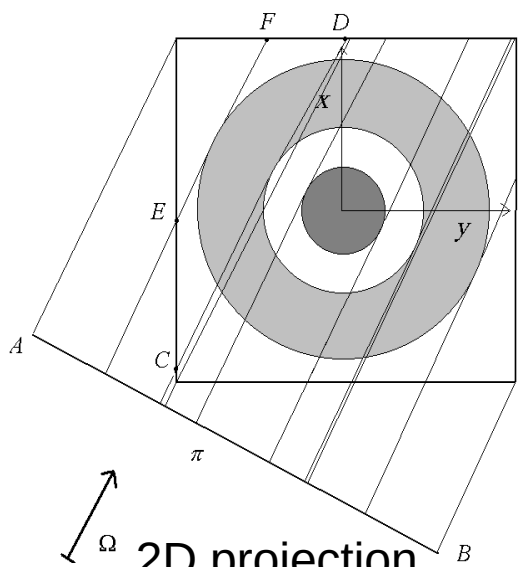
$$V_\alpha \vec{\psi}_\alpha(\mathbf{\Omega}) = \sum_{s' \in x,y,z} I_{\alpha,s'}(\mathbf{\Omega})\vec{\psi}^{-}_{s'}(\mathbf{\Omega}) + \sum_{\beta \in c} C_{\alpha\beta}(\mathbf{\Omega})\vec{q}_\beta(\mathbf{\Omega}),\ \alpha = 1, N_R$$

$$\gamma_s(\mathbf{\Omega})\vec{\psi}^{+}_{s}(\mathbf{\Omega}) = \sum_{s' \in x,y,z} T_{s,s'}(\mathbf{\Omega})\vec{\psi}^{-}_{s'}(\mathbf{\Omega}) + \sum_{\alpha \in c} E_{s,\alpha}(\mathbf{\Omega})\vec{q}_\alpha(\mathbf{\Omega}),\ s \in x, y, z$$

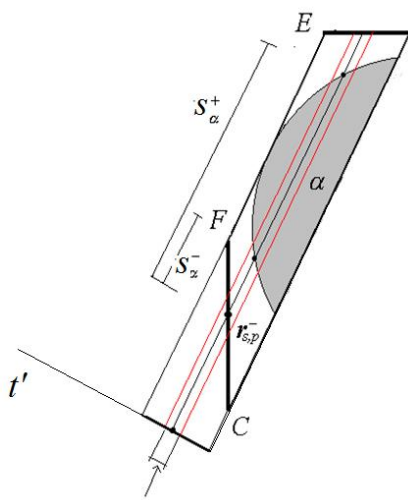
HCC COEFFICIENTS

- The integral transport equation is used to generate the equations for both volume and surface spatial moments. The numerical integration (analytically along the trajectory) based on local projections of the geometrical discontinuities. Trajectories are distributed along each interval using Gauss-Legendre quadrature along each transverse interval.

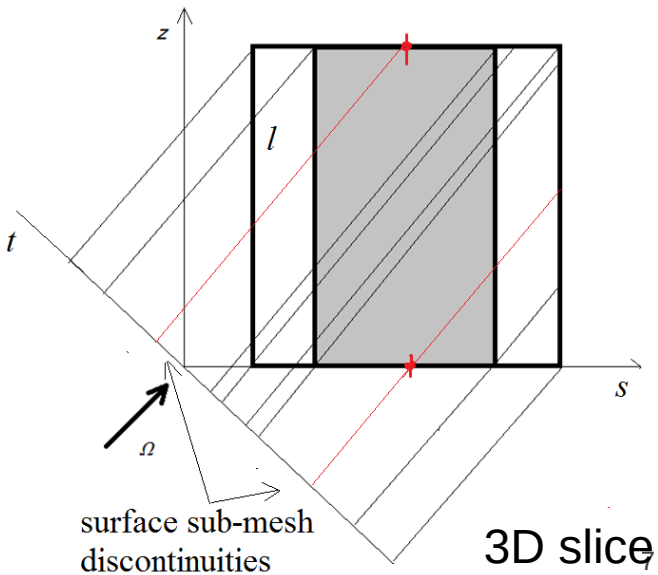
$$\int_{V\alpha} d\mathbf{r}\ f(\mathbf{r}) \simeq \sum_{t'//\mathbf{\Omega}_{xy}\ t'\cap D_{\alpha,xy}} w_{xy,t'} \sum_{t//\mathbf{\Omega}\ t\cap D_{\alpha}} w^{t'}_{sz,t} \int_{l^-_{\alpha,t}}^{l^+_{\alpha,t}} dl\ f(\mathbf{r}_{s,t',t} + l\mathbf{\Omega})$$



2D projection



2D slice

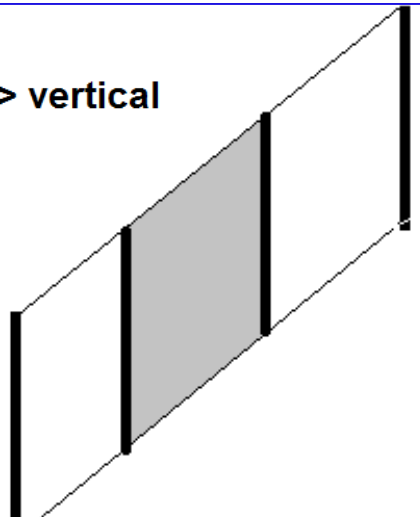


3D slice

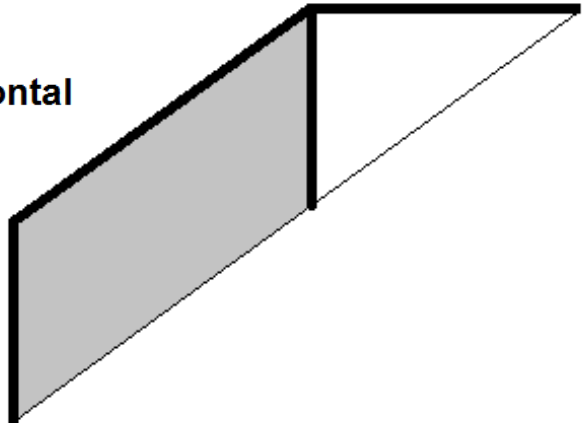
ANALYTICAL INTEGRATION ON THE 3D SLICES

$$\int_{V\alpha} d\mathbf{r}\ f(\mathbf{r}) \simeq \sum_{t'//\mathbf{\Omega}_{xy}\ t'\cap D_{\alpha,xy}} w_{xy,t'} \sum_{\substack{slice(t')//\mathbf{\Omega} \\ slice(t')\in D_\alpha}} \int_{\Delta t(t')} dt \int_{l_\alpha^-(t)}^{l_{\alpha,t}^+(t)} dl\ f(\mathbf{r}_{s,t'}(t) + l\mathbf{\Omega})$$

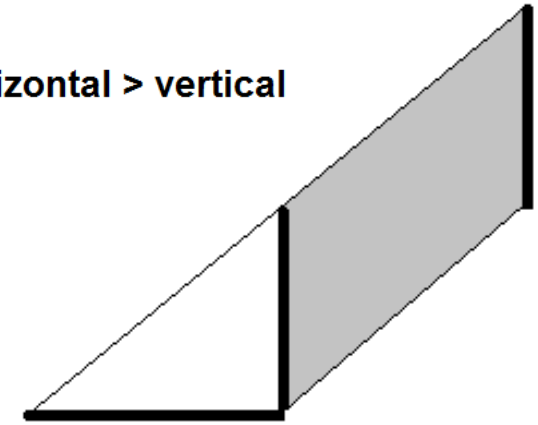
vertical > vertical



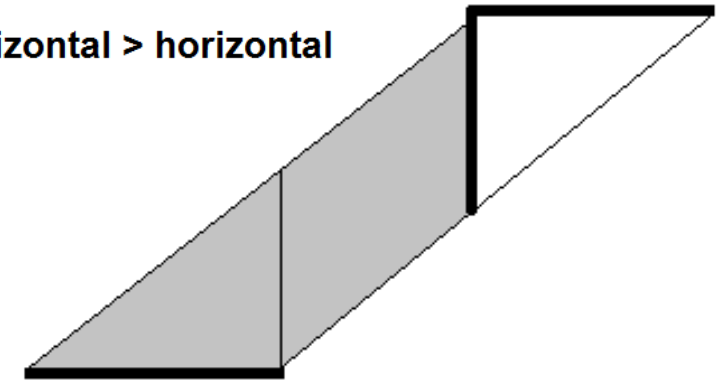
vertical > horizontal



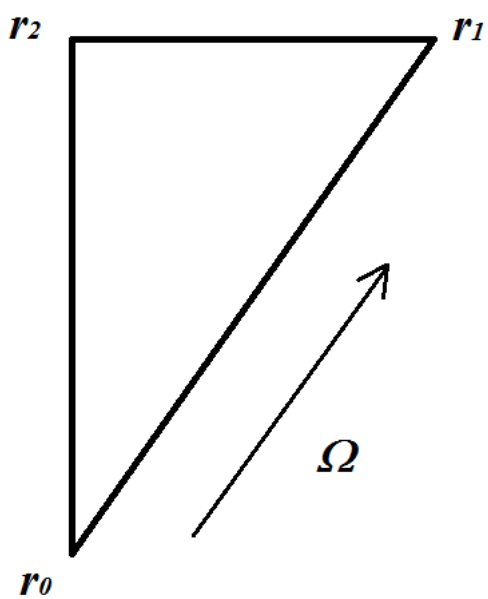
horizontal > vertical



horizontal > horizontal



ISOPARAMETRIC LINEAR TRANSFORMATION



- Linear transformation of the spatial coordinates

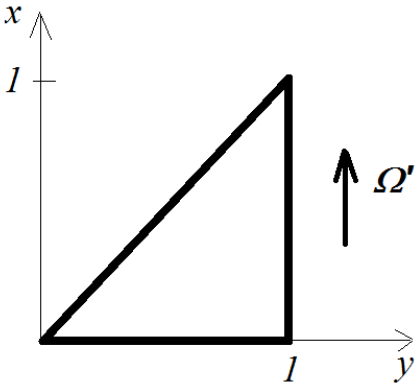
$$\mathbf{r} = \mathbf{r}_0 + [\mathbf{r}_1 - \mathbf{r}_0, \mathbf{r}_2 - \mathbf{r}_1]\ \mathbf{u}$$

- Linear transformation of the base

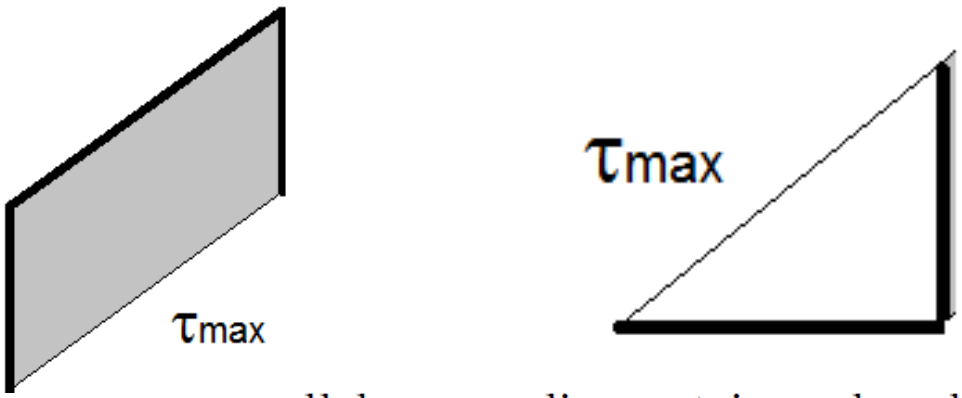
$$\begin{Bmatrix} 1 \\ \mathbf{r} \end{Bmatrix} = \begin{Bmatrix} 1 \\ \mathbf{r}_0 \end{Bmatrix} + \begin{bmatrix} 1 & 0 \\ \mathbf{r}_1 - \mathbf{r}_0 & \mathbf{r}_2 - \mathbf{r}_1 \end{bmatrix} \begin{Bmatrix} 1 \\ \mathbf{u} \end{Bmatrix}$$

$$\mathbf{u} = \{x, y\}$$

$$\begin{aligned} y &= x && \text{for triangle} \\ y &= 1 - x && \text{for inverse triangle} \\ y &= 1 && \text{for slice} \\ x &\in [0, 1] \end{aligned}$$



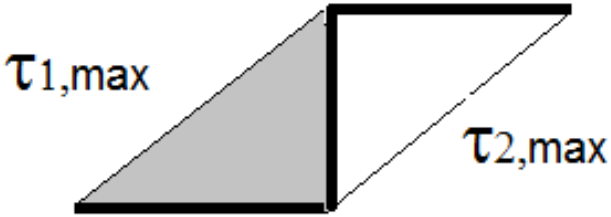
ELEMENTARY SLICE AND EXPONENTIAL INTEGRAL FUNCTIONS



parallelogram slice + triangular slice

- All integrals are decomposed in parallelograms, triangles and double-triangle.

$$K_{i_1,i_2,\ldots i_n}(\tau_{\max}) = \int_0^1 dx_1\ x_1^{i_1} \int_0^{x_1} dx_2\ x_2^{i_2} \ldots \int_0^{x_{n-1}} dx_n\ x_n^{i_n}\ e^{-\tau_{\max} x_n}$$



double-triangle slice

- 2 families of exponential integral functions generate all coefficients

$$L_{i_1,i_2,\ldots i_n}(\tau_{1,\max}, \tau_{2,\max}) = \int_0^1 dx_1\ x_1^{i_1} e^{-\tau_{1,\max} x_1} \int_0^{x_1} dx_2\ x_2^{i_2} \ldots \int_0^{1-x_{n-1}} dx_n\ x_n^{i_n}\ e^{-\tau_{2,\max} x_n}$$

OPTIMIZATION OF COEFFICIENT CALCULATION

- 8 seed functions, 6 for parallelograms and triangles and 2 for double-triangle slice

$$\{K_2(\tau_{\max}),\ K_{0,2}(\tau_{\max}), \ldots,\ K_{0,0,0,0,0,2}(\tau_{\max})\}$$

$$\{L_{1,2}(\tau_{1,\max}, \tau_{2,\max}),\ L_{2,1}(\tau_{1,\max}, \tau_{2,\max})$$

- Linear expansion of transport matrix coefficient

$$\boxed{\frac{d\psi}{d\Sigma}(x,\Sigma) \ = \ -x\psi(x,\Sigma) + \int_0^x dy\ yq(y)e^{-\Sigma(x-y)}}$$

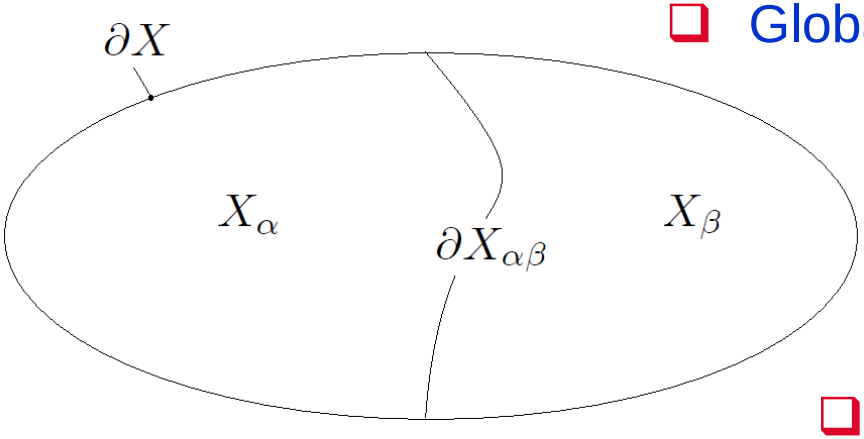
- Linear expansion of the matrix coefficients $\quad \overrightarrow{\Sigma}_{cell} \ = \ \{\Sigma_\gamma\}_{\gamma \in cell}$

$$C_{\alpha,\beta}(\overrightarrow{\Sigma}_{cell}) = C_{\alpha,\beta}(\overrightarrow{\Sigma}_0) + \sum_{\gamma \in cell} \frac{\partial C_{\alpha,\beta}}{\partial \Sigma_\gamma}(\overrightarrow{\Sigma}_0)(\Sigma_\gamma - \Sigma_{\gamma,0}) + o(\Delta\Sigma^2)$$

$$\overrightarrow{\Sigma}_{cell} \in [1-\delta, 1+\delta] \times \overrightarrow{\Sigma}_0 \qquad \boxed{\delta = \sqrt{5\ \mathrm{pcm}} \simeq 0,0071}$$

Domain Decomposition Method (DDM)

NON-OVERLAPPING DDM : ITERATIVE SCHEME



- Global eigenvalue problem : $x \equiv (\mathbf{r}, \mathbf{\Omega}, E) \in X$

$$\begin{aligned} (L-H)\psi(x) &= \frac{1}{\lambda} F\psi(x) \qquad x \in X, \\ \psi^-(x) &= 0 \qquad x \in \partial X^-. \end{aligned}$$

- DD boundary-value problems (PBJ) :

$$\begin{bmatrix} (L-H)_\alpha & 0 \\ 0 & (L-H)_\beta \end{bmatrix} \begin{bmatrix} \psi_\alpha \\ \psi_\beta \end{bmatrix}^{(n+1)} = \begin{bmatrix} q_\alpha \\ q_\beta \end{bmatrix}^{(n)} + \begin{bmatrix} 0 & \delta(x - x^-_{\alpha\leftarrow\beta}) \\ \delta(x - x^-_{\beta\leftarrow\alpha}) & 0 \end{bmatrix} \begin{bmatrix} \psi^+_\alpha \\ \psi^+_\beta \end{bmatrix}^{(n)}$$

Update :

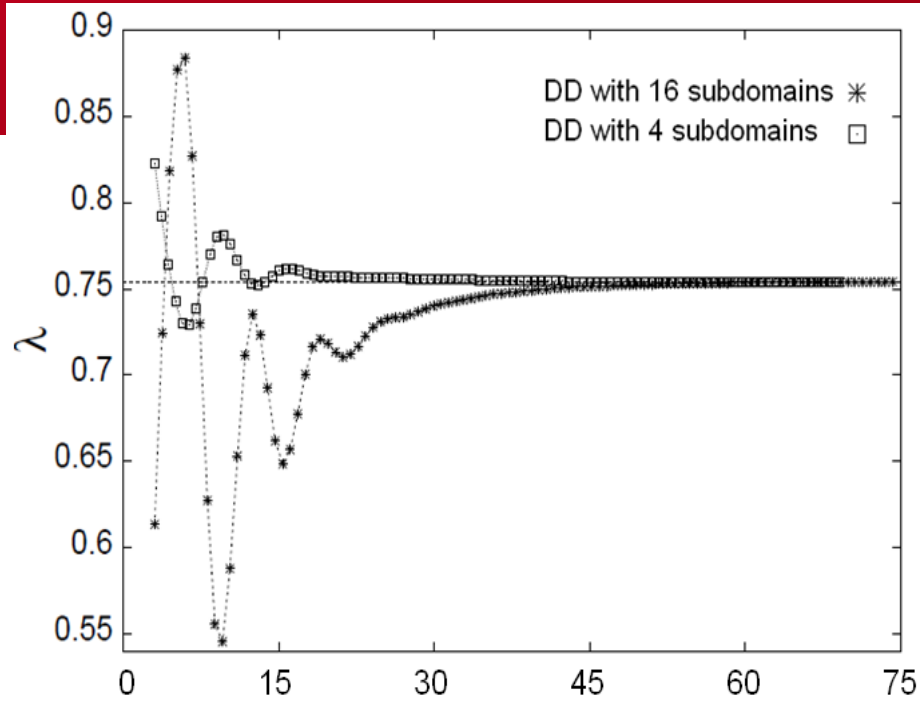
$$\lambda^{(n+1)} = \lambda^{(n)} \frac{\sum_{a=\alpha,\beta} (w, F_a \psi_a^{(n+1)})}{\sum_{a=\alpha,\beta} (w, F_a \psi_a^{(n)})}$$

$$\begin{aligned} q_{f,\alpha}^{(n+1)}(x) &= \frac{F_\alpha \psi_\alpha^{(n+1)}(x)}{\lambda_\alpha^{(n+1)}}, \\ \psi_\alpha^{-,(n+1)}(x) &= \psi_\beta^{+,(n+1)}(x) \qquad x \in \partial X^-_{\beta\alpha}, \\ \psi_\beta^{-,(n+1)}(x) &= \psi_\alpha^{+,(n+1)}(x) \qquad x \in \partial X^-_{\alpha\beta}, \end{aligned}$$

DDM PREFORMACES

- The non-overlapping DDM+PI is less effective than the standard Sn iterative scheme. (Gauss-Jacobi vs. Gauss-Seidel)

- The DDM suffers from oscillatory convergence behavior. The effect is accentuated as the number of subdomains increases.



Basic pattern

C	B	A
C	B	A
C	B	A

4-subdomain DD

C	B	A	C	C	C
C	B	A	B	B	B
C	B	A	A	A	A
A	A	A	A	B	C
B	B	B	A	B	C
C	C	C	A	B	C

16-subdomain DD

C	B	A	C	C	C	C	B	A	C	C	C
C	B	A	B	B	B	C	B	A	B	B	B
C	B	A	A	A	A	C	B	A	A	A	A
A	A	A	A	B	C	A	A	A	A	B	C
B	B	B	A	B	C	B	B	B	A	B	C
C	C	C	A	B	C	C	C	C	A	B	C
C	B	A	C	C	C	C	B	A	C	C	C
C	B	A	B	B	B	C	B	A	B	B	B
C	B	A	A	A	A	C	B	A	A	A	A
A	A	A	A	B	C	A	A	A	A	B	C
B	B	B	A	B	C	B	B	B	A	B	C
C	C	C	A	B	C	C	C	C	A	B	C

PARALLEL BLOCK-JACOBI METHOD (PBJM)

- Spectral radius on the fission integral

$$\rho = \frac{\left| I_{fis}^{(e)} - I_{fis}^{(e-1)} \right|}{\left| I_{fis}^{(e-1)} - I_{fis}^{(e-2)} \right|}, \qquad I_{fis}^{(e)} = \sum_{\forall r} \sum_{is \in r} \sum_{g}^{N_g} \left(\nu \Sigma_f \right)_{is}^{g} \phi_{r,g}^{(e)}(\boldsymbol{r})$$

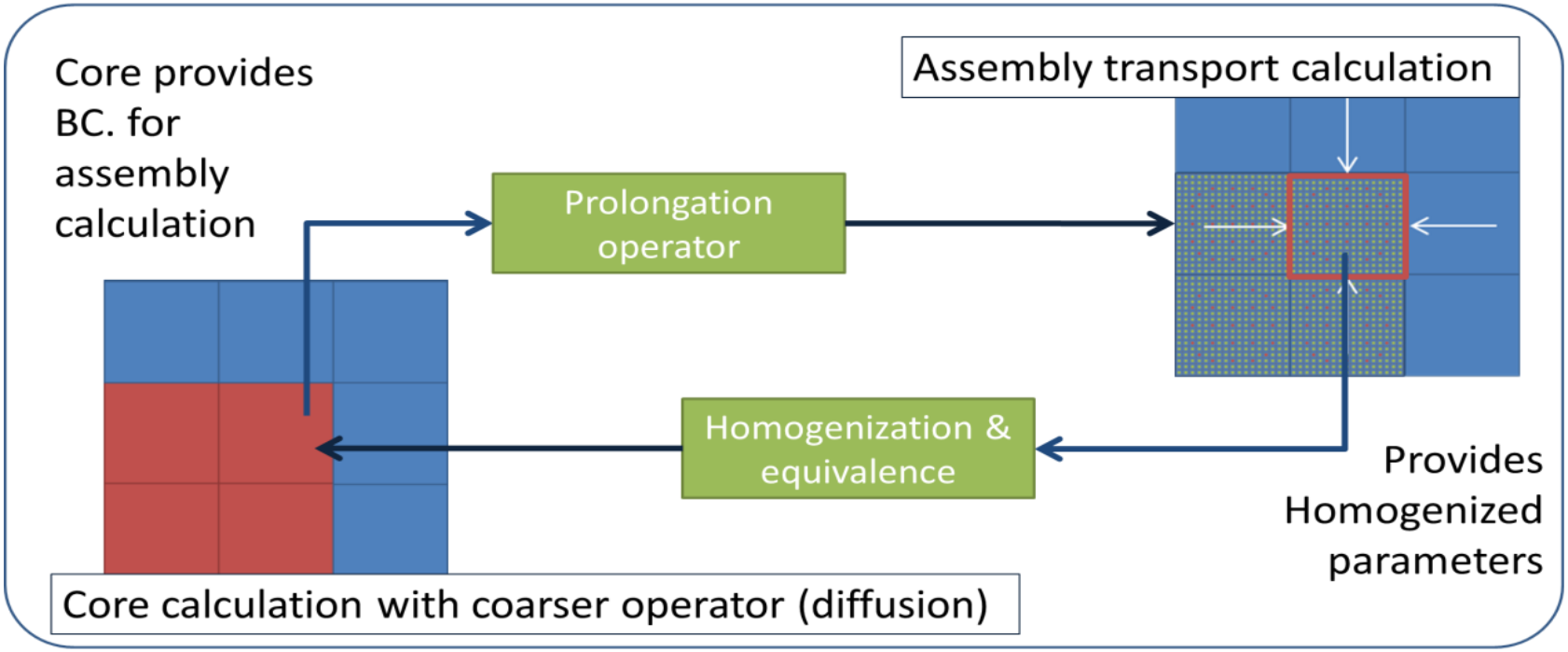
- Number of power iterations $N_e \sim \frac{\ln(\varepsilon)}{\ln(\rho)}$,

Spectral radius vs. n. of subdomains

Algorithm / N. of subdomains	Direct		PBJM	
	ρ	N_e	ρ	N_e
3 x 3	0.818	**58**	0.941	**190**
6 x 6	0.818	**58**	0.946	**208**
9 x 9	0.818	**58**	0.948	**216**

$\Rightarrow$ Ineffective, needs acceleration !

NON-OVERLAPPING DDM + NON-LINEAR DIFFUSION



- Non-linear diffusion: Coarse Mesh Finite Difference (CMFD)

In this case the non-linear operator is an acceleration operator for DDM transport iterations.

NON-OVERLAPPING DDM + NON-LINEAR DIFFUSION

- Coarse phase space: energy, space and angle

$$\boxed{y \equiv \int_y dx \in Y}$$

$$
\begin{aligned}
(\nabla \cdot J + \Sigma_T \phi)(y) &= H_0 \phi(y) + \frac{F\phi(y)}{\lambda}, && \forall\, y \in Y, \\
\text{Modified Fick's Low} \rightarrow \quad J(y) &= -\frac{p}{\Sigma_T} \nabla \phi(y) + \nu_T \phi(y), \\
J(y) &= \beta_T \phi(y), && \forall\, y \in \partial Y.
\end{aligned}
$$

- Equivalence parameter (transport-computed drift velocity)

$$\nu_T(y) = \left[\frac{\int_y dx\, [J_\alpha^{(n+\frac{1}{2})} + \frac{p}{\Sigma_\alpha} \nabla \cdot \phi_\alpha^{(n+\frac{1}{2})}](x)}{\int_y dx\, \phi_\alpha^{(n+\frac{1}{2})}(x)} \right]_T$$

EQUIVALENCE + STABILITY + CORRECTION

- Equivalence

$$\Sigma_T(y) = \left[\frac{\int_y dx\ \Sigma_\alpha(x)\phi_\alpha^{(n+\frac{1}{2})}(x)}{\int_y dx\ \phi_\alpha^{(n+\frac{1}{2})}(x)} \right]_T \qquad \nu_T(y) = \left[\frac{\int_y dx\ [J_\alpha^{(n+\frac{1}{2})} + \frac{p}{\Sigma_\alpha}\nabla\cdot\phi_\alpha^{(n+\frac{1}{2})}](x)}{\int_y dx\ \phi_\alpha^{(n+\frac{1}{2})}(x)} \right]_T$$

$$\beta_T(y) = \left[\frac{\int_y dx\ J_\alpha^{(n+\frac{1}{2})}(x)}{\int_y dx\ \phi_\alpha^{(n+\frac{1}{2})}(x)} \right]_T$$

- Stability parameter

$$\boxed{p = \max_{\forall S\in Y} \left\{ \frac{1}{3}\ ,\ \left[f_S(\phi^{R/L}, c^{R/L}, \tau^{R/L}) \frac{\int_S dx \mu^2 \psi(x)}{\int_S dx \psi(x)} \right]_T \right\}}$$

- Correction :

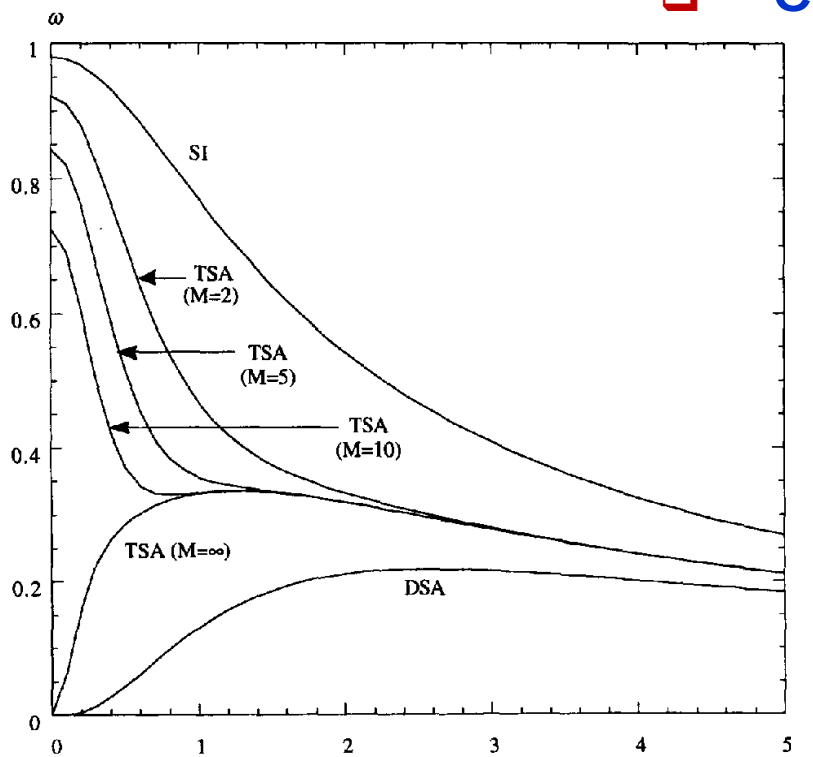
$$\lambda_\alpha^{(n+1)} = \lambda_c$$

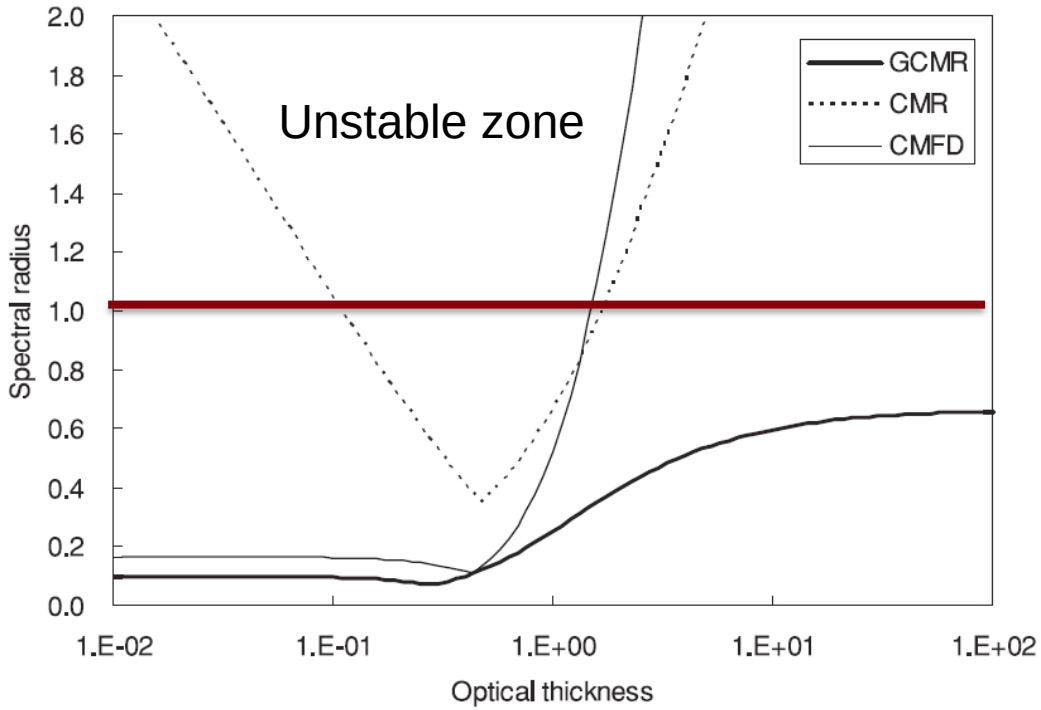
$$\psi_\alpha^{(n+1)}(x) = \psi_\alpha^{(n+\frac{1}{2})}(x) \frac{\phi(y)}{\int_y dx\ \phi_\alpha^{(n+\frac{1}{2})}(x)}, \quad x \in X_\alpha$$

$$\psi_\alpha^{+(n+1)}(x) = \psi_\alpha^{+(n+\frac{1}{2})}(x) \frac{\phi(y)}{\int_y dx\ \phi_\alpha^{(n+\frac{1}{2})}(x)} \quad x \in \partial X_\alpha$$

SPECTRAL RADIUS OF VARIOUS ACCERLERATION METHODS

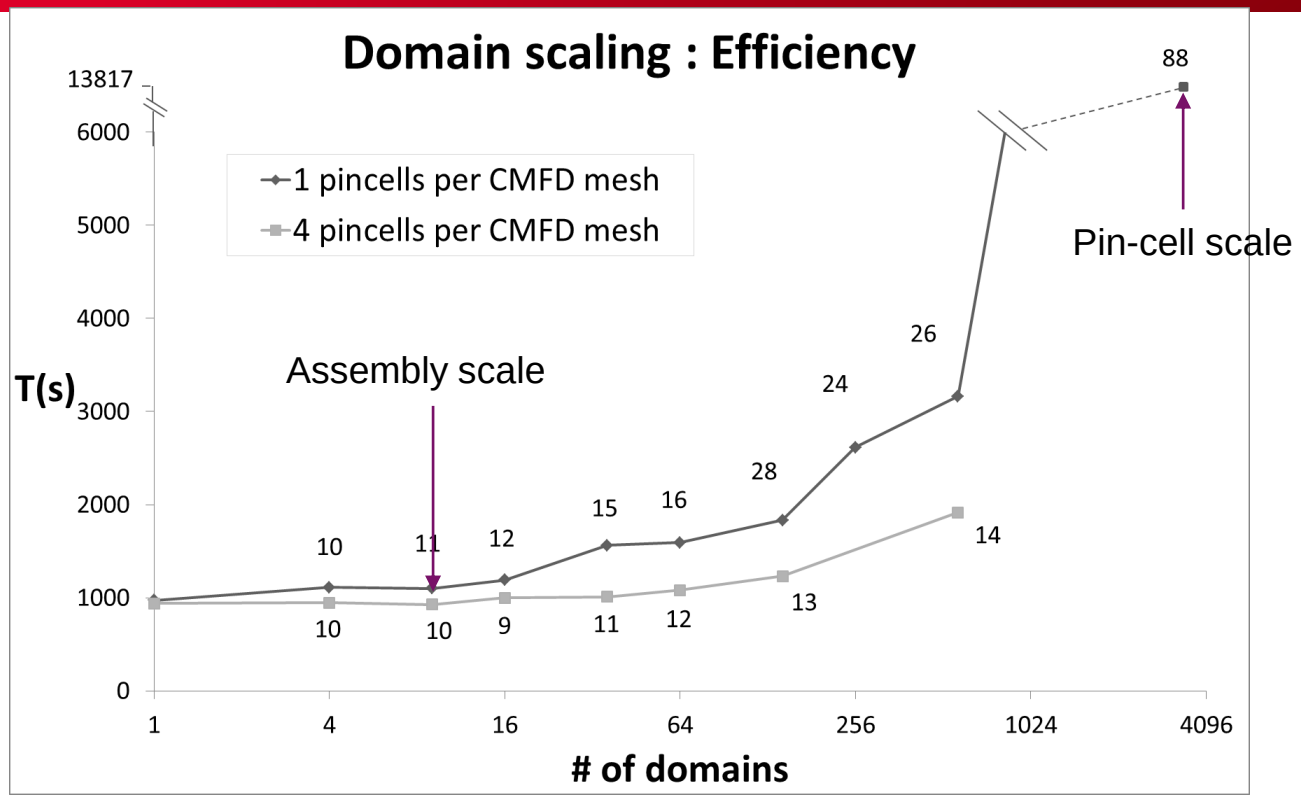
- C = 0.9999





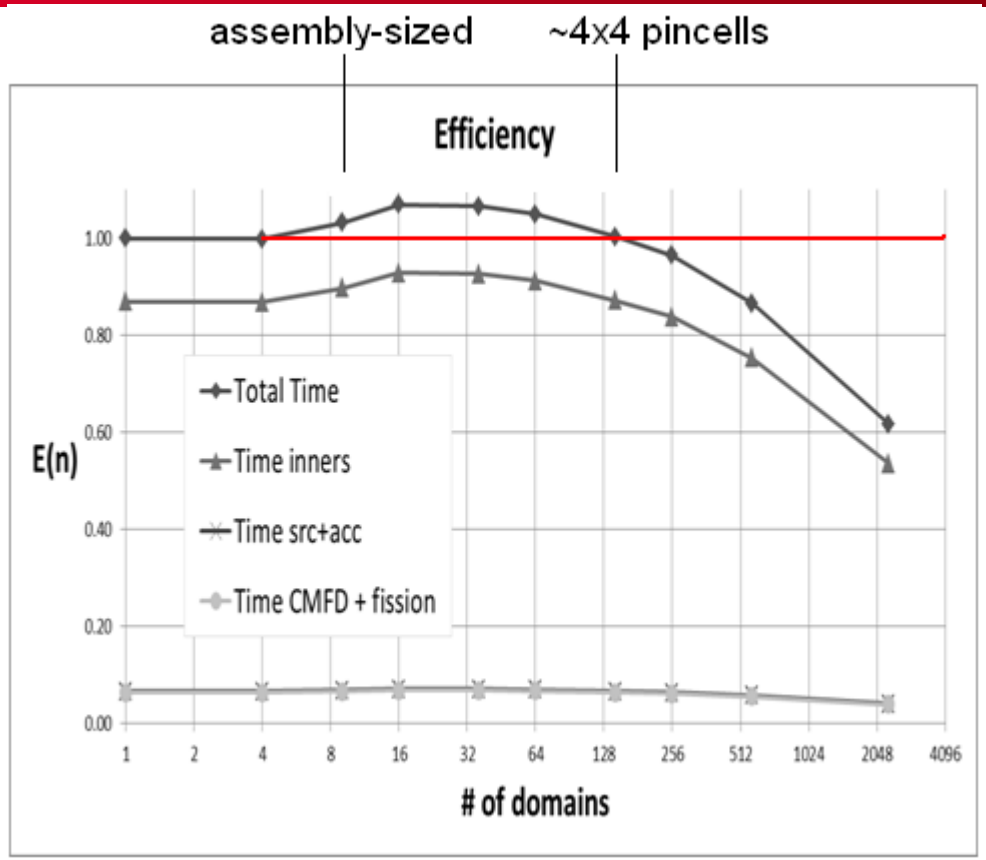
- **The spectral radius source iterations (SI) is bounded by the scattering ratio "*c*", i.e. the ratio among the scattering and total cross sections, (in nuclear reactors c ~ 1)**
- **The CMFD guarantees a huge reduction of the # of DoF for the acceleration operator.**

SINGLE PROCESSOR « STRONG SCALING » TEST (1) : CMFD EFFICIENCY ON THE 3X3 COLORSET



- **The CMFD guarantees a DDM range with no loss in performances w.r.t. the direct calculation!**
- **Limit :** performances deteriorate for subdomains having # of cells < 6x6 pin cells per assembly
- **Advances:** the fuel assembly seems an optimal compromise for the subdomain size.

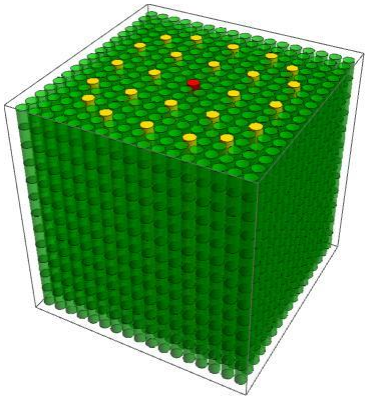
SINGLE PROCESSOR TEST (1) : CACHE EFFECT

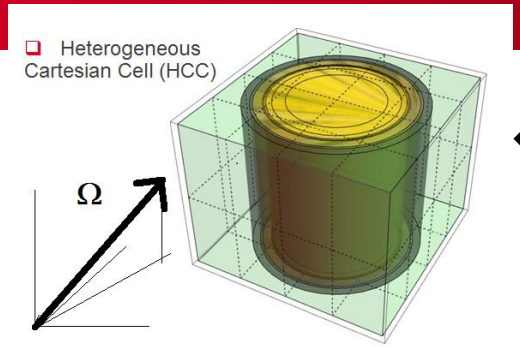


$$S = E = \frac{T(1)}{T(n_{sub})}$$

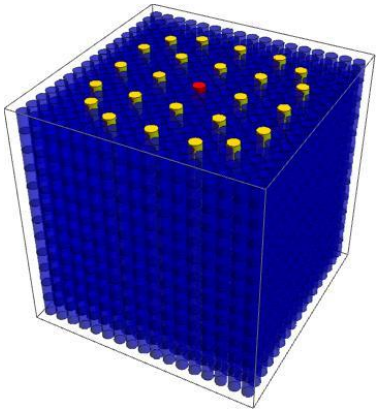
- # of outer iterations = 10
- # of iterations for outer CMFD = 10
- # of inner transport iterations = 10
- # of iterations for inner CMFD= 10

DOMAIN RECONSTRUCTION

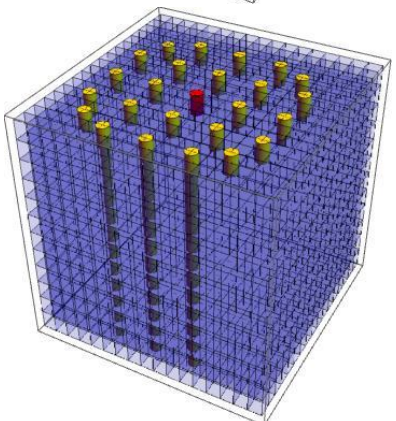


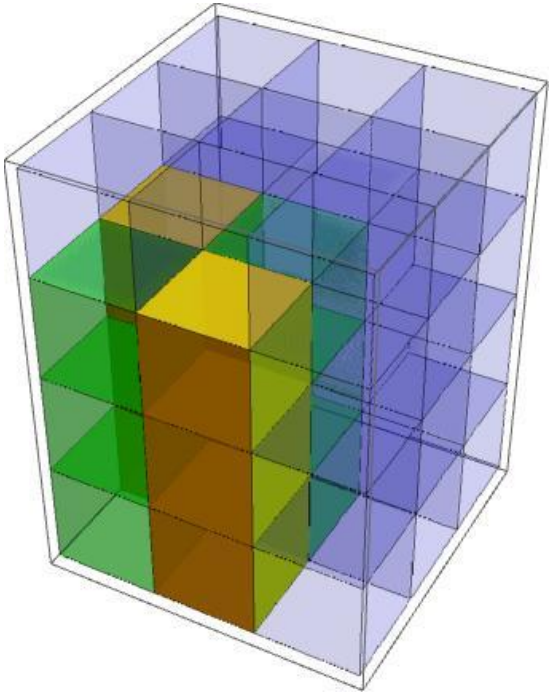


← Hetrogeneous Cartesian cell



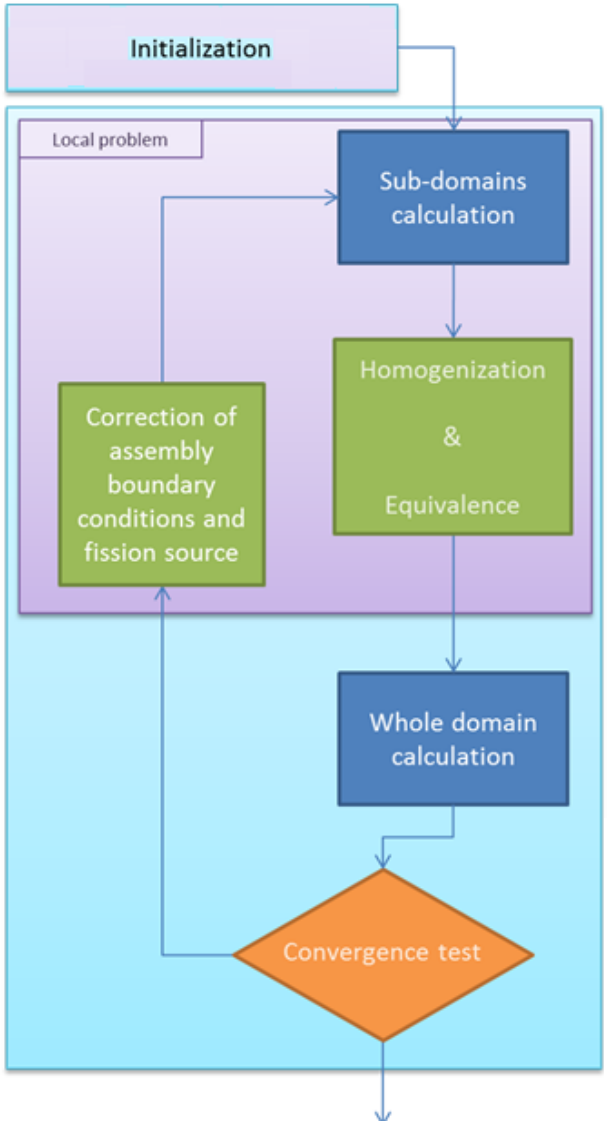
← Generating Calculation Units (GCU) geometries





← PIVOT geometry (ECU) (reactor core)

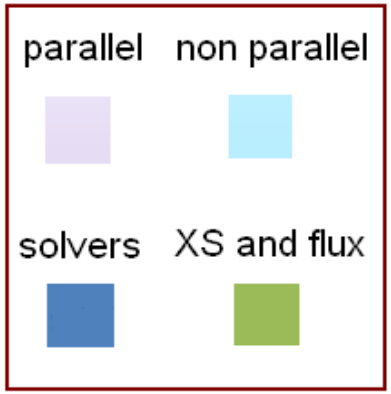
DDM +CMFD IN THE IDT SOLVER



transport solver +
local inner acceleration (CMFD) +
local thermal acceleration
(Rebalancing + CMFD) +
boundary fluxes exchange

CMFD coefficients

FD diffusion solver



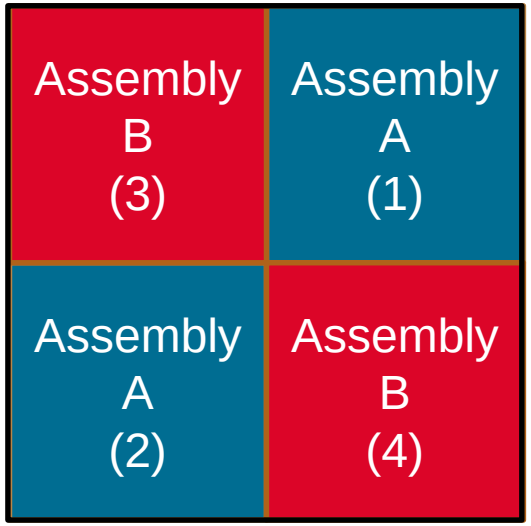
$$\max_{\forall\ x} \left| 1 - \frac{F_\alpha \psi_\alpha^{(n+1)}(x)}{F_\alpha \psi_\alpha^{(n)}(x)} \right| < \epsilon_{fiss},$$

$$\left| 1 - \frac{\lambda^{(n+1)}}{\lambda^{(n)}} \right| < \epsilon_\lambda,$$

$$\max_{\forall\ x \in \partial X_{\alpha -}} \left| 1 - \frac{\int_{2\pi -} d\mathbf{\Omega}\ \ |\mathbf{\Omega} \cdot \mathbf{n}|\, \psi_\alpha^{-(n+1)}(x)}{\int_{2\pi -} d\mathbf{\Omega}\ \ |\mathbf{\Omega} \cdot \mathbf{n}|\, \psi_\alpha^{-(n)}(x)} \right| < \epsilon_J,$$

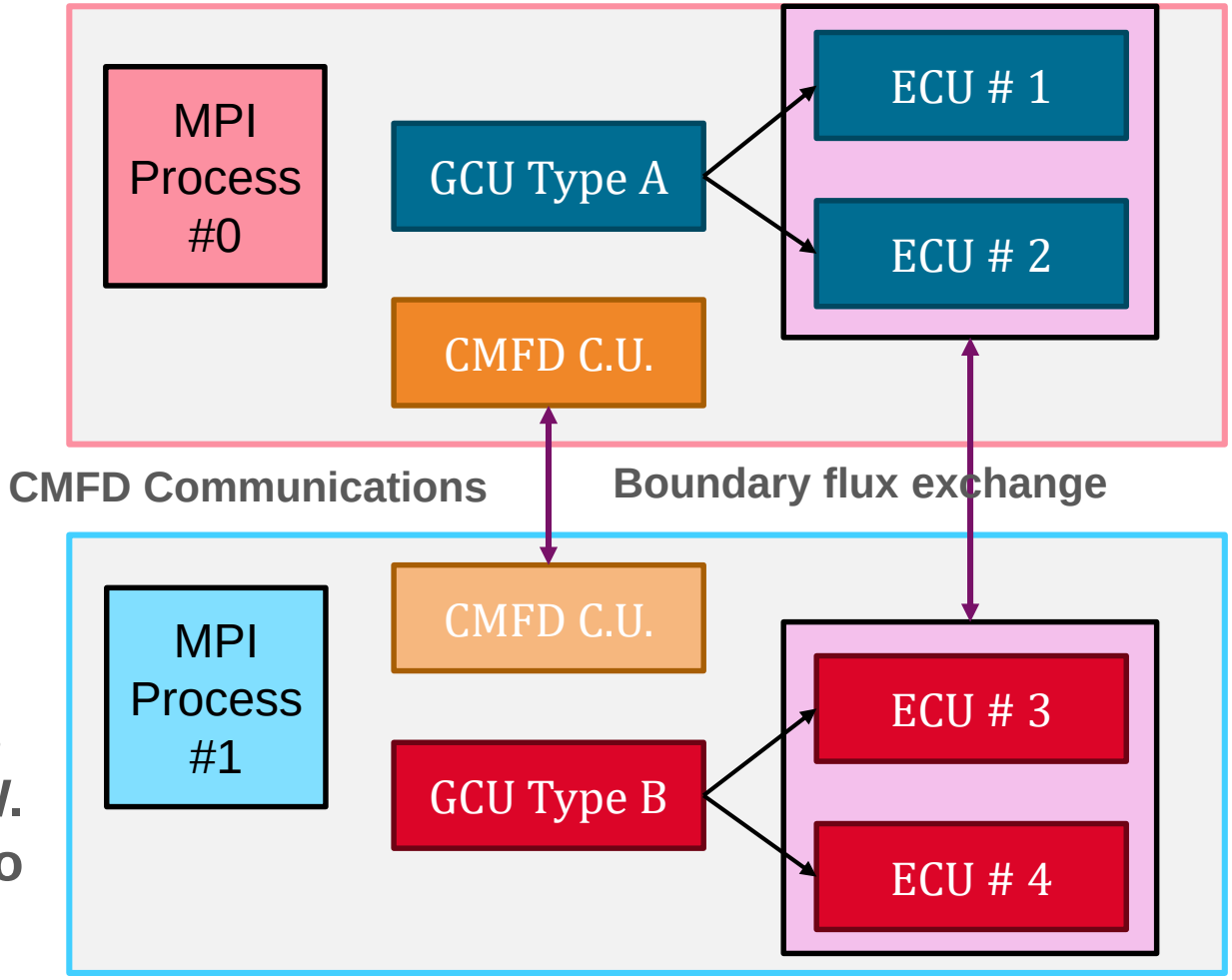
IDT HYBRID PARALLELISM ARCHITECTURE

Distribution of the Subdomains (GCU) on the MPI process



4 subdomains

Present limit: CMFD runs on single MPI process (W. FORD PhD in progress to solve such an issue)



DISTRIBUTED/SHARED-MEMORY PARALLEISM

Initial guess, DO loop, iterate until convergence:

MPI Comm. : update of the interface flux (b.c. for the subdomains)

!OMP PARALLEL

for each $\alpha \in N(MPI)$ **do :**

load incoming flux, compute subdomain α, homogenize

!OMP END PARALLEL

MPI Comm. : gather on 1 single MPI data to feed CMFD

Solve CMFD operator (inner **!OMP PARALLEL**)

MPI Comm. : scatter the CMFD flux and eigenvalue to all processes

!OMP PARALLEL

for each $\alpha \in N(MPI)$ **do :** transport flux update by CMFD acceleration

+ fission source update + eigenvalue (from CMFD)

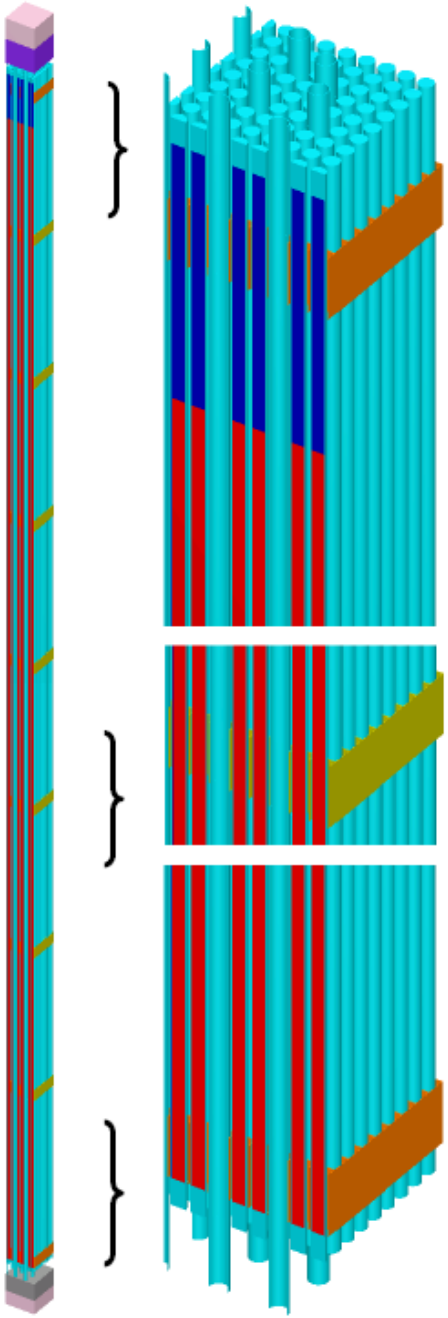
!OMP END PARALLEL

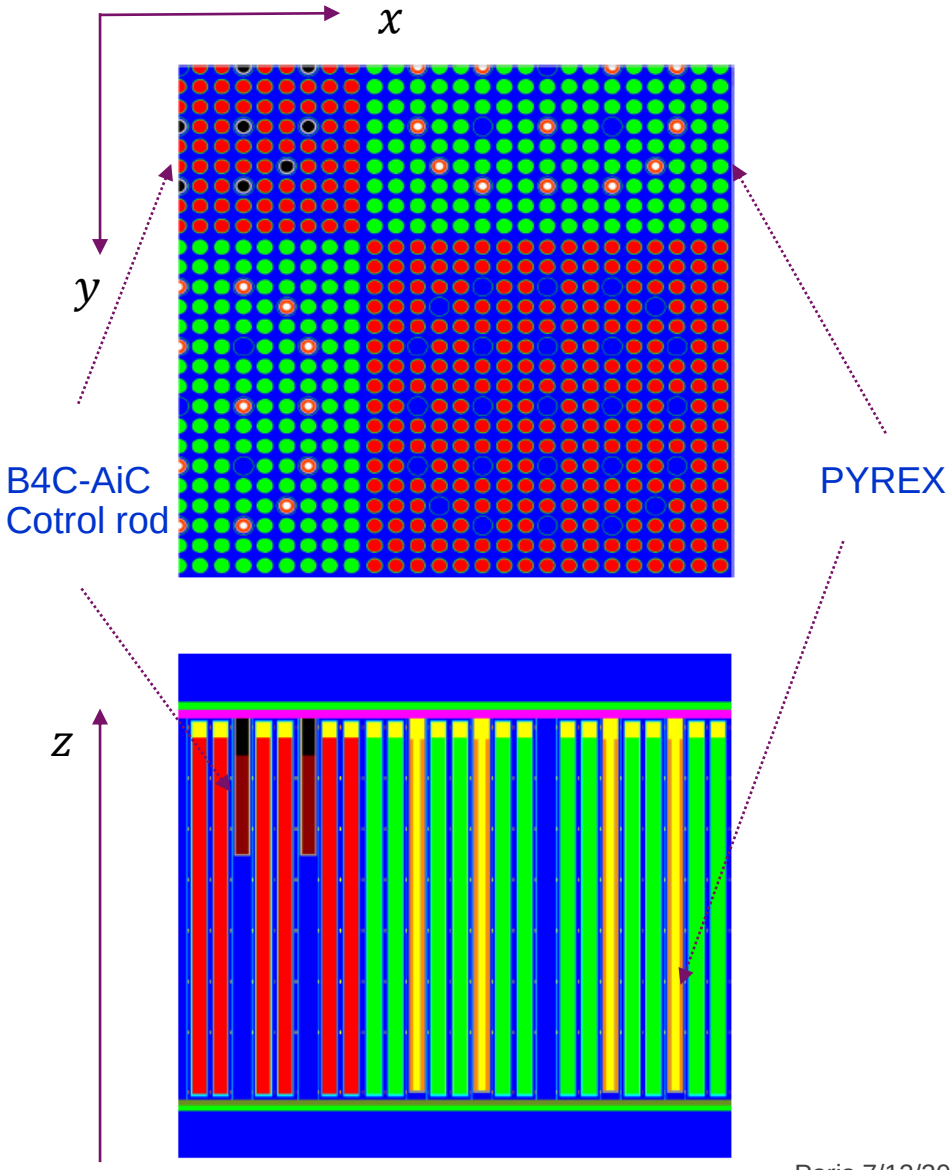
Convergence test: eigenvalue, fission source (isotope-wise), flux angular moments, interface angular flux

End loop

3D Results*

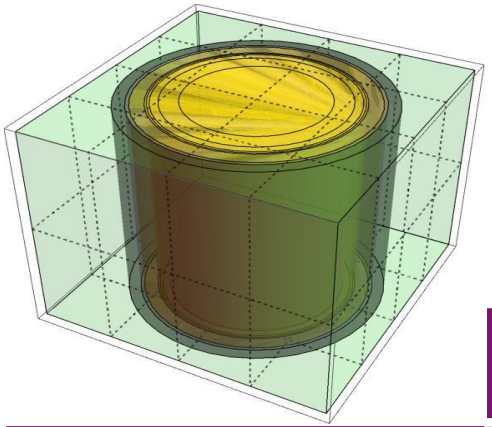
VERA (CASL) BENCHMARK : WATTS BAR UNIT 1 COLORSET





VERA (CASL) BENCHMARK : WATTS BAR UNIT 1 COLORSET

- More than 13000 materials, 47-group P3 XS library
- ~8000 different pins cells (self shielded-depleted materials)
- ½ Million spatial mesh, 160 directions, 16 angular moments, 4 spatial moments (linear Short Characteristics)
- 4-4-2 surface submesh + CMFD at the pin-cell level
- 3 x 3 x 32 = 228 subdomains

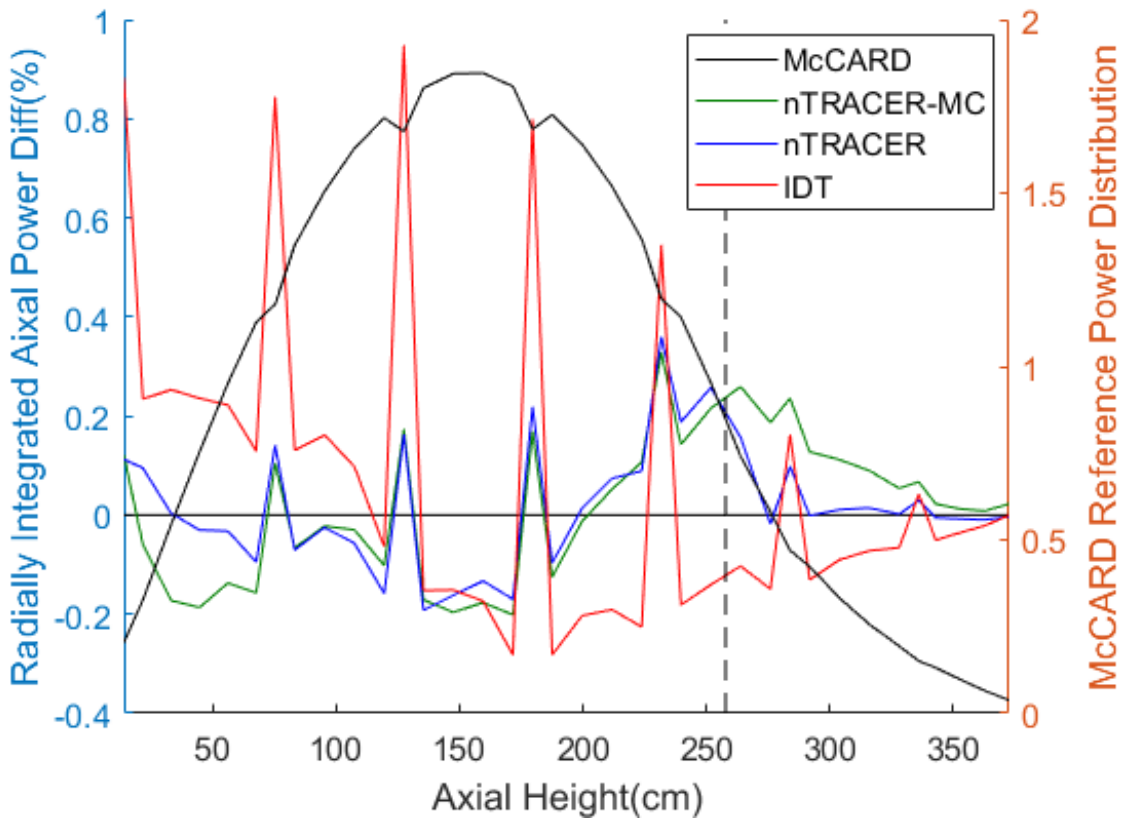


*Young Suk Ban[a], Emiliano Masiello[b], Roland Lenain[b], Han Gyu Joo[a] and Richard Sanchez "***Code-to-code comparisons on spatial solution capabilities and performances between nTRACER and the standalone IDT solver of APOLLO3®"*** Annals of Nuclear Energy **115** (2018) 573–594.

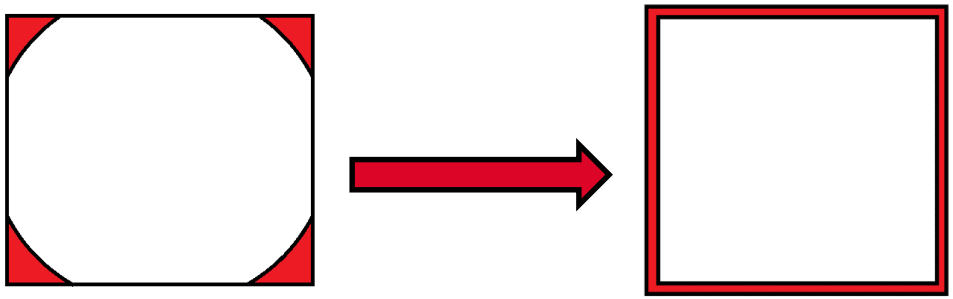
	k-eff	Reactivity error (pcm)	R.M.S. (%)	MAX. (%)
McCARD (Monte Carlo)	0.99956	(ref)	-	-
IDT	0.99871	-85 pcm*	0.25 %	0.99 %

* pcm = pour cent mile

AXIAL POWER ERROR DISTRIBUTION



- The spacer grid has to be improved in IDT

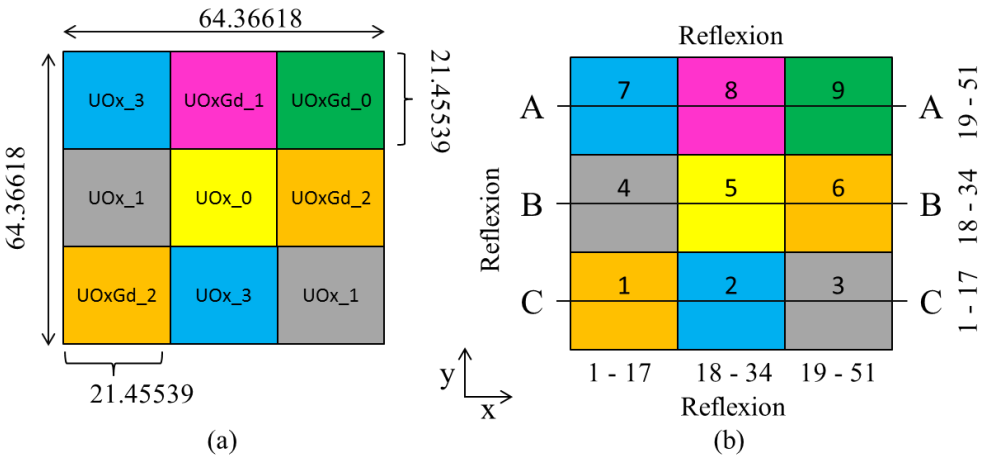


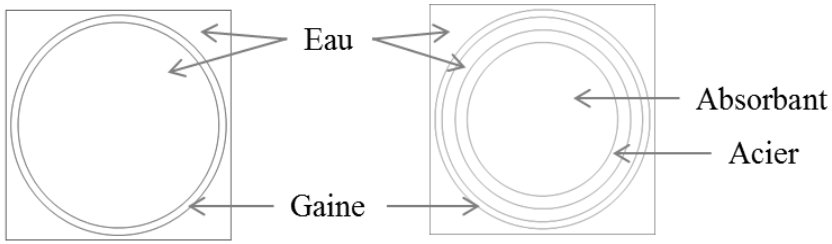
COMPUTATIONAL TIME

Elapsed Time	OpenMP (20 threads)	MPI/OpenMP (20 nodes, 12 threads/node 240 threads)
MOSC	24h (99%) (gfortran) 18h (99%) (Intel)	1h40 (96%) (gfortran)
CMFD	1min (<0.1%)	1min (<1%)
Flux Exchange & misc.	<1min	6min (4%)
Transport + CMFD # of iterations	**8**	**8**
Total	**24h30 / 18h15**	**1h45**

3D 3x3 Colorset
281Gr XS library (P3)

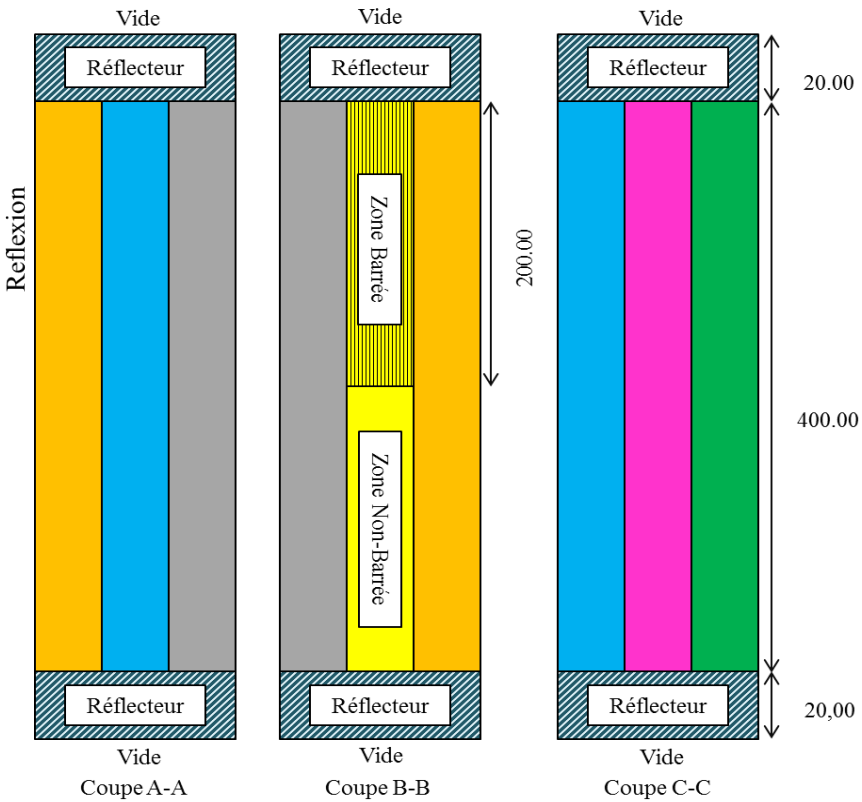
3D COLORSET





(a) Tube guide sans absorbant

(b) Tube guide et absorbant B4C

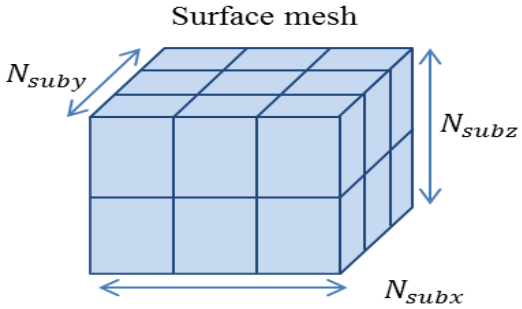


1,535,600 regions (110 Z steps)

281 groups, 16 angular moments (P3)

198 (3x3x22) subdomains

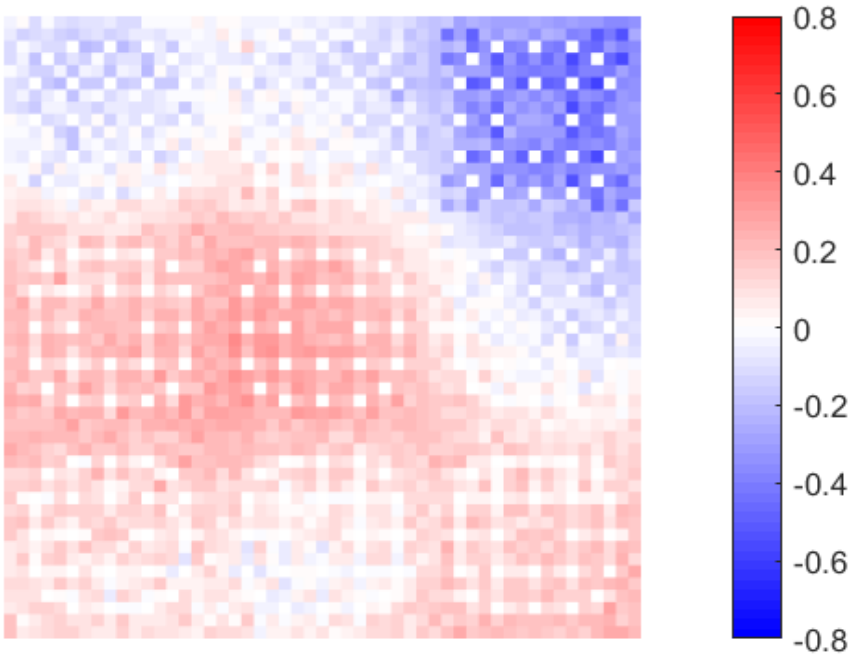
~ 1 Tbyte of DoF

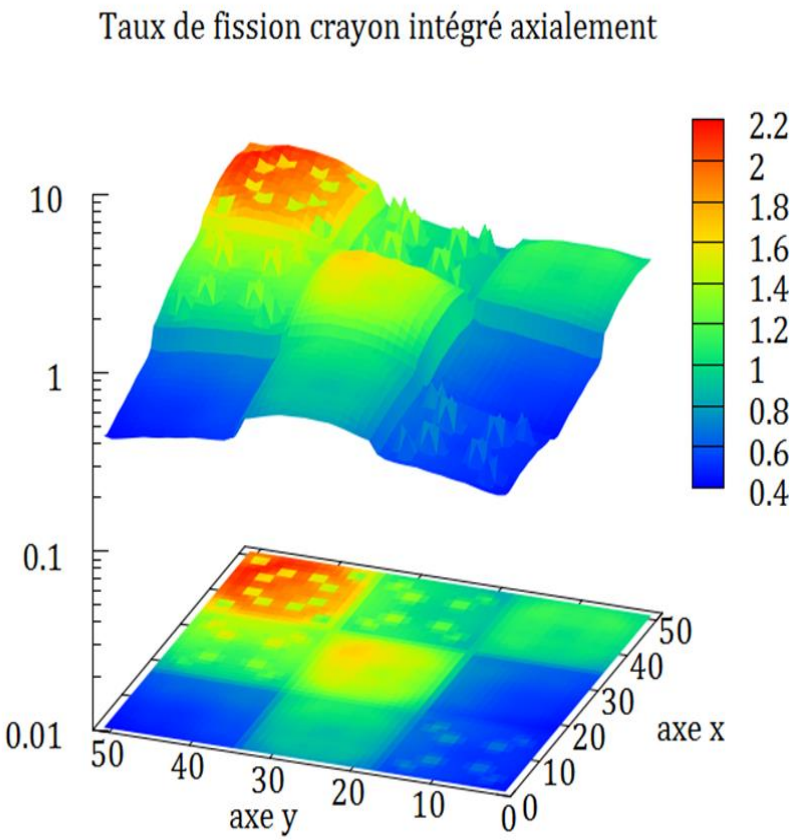


COLORSET 3D : RADIAL POWER DISTRIBUTION

Radial distribution

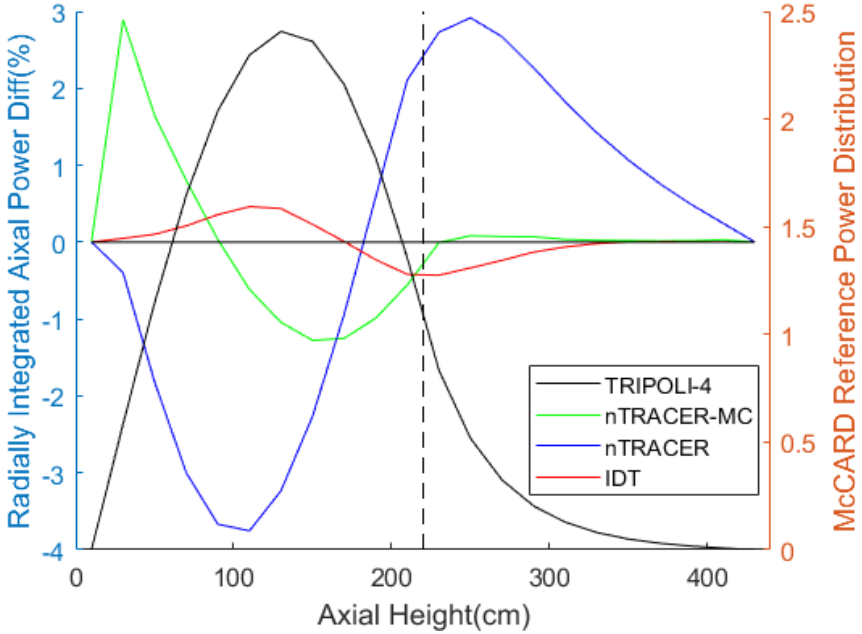
Relative pin power error vs. TRIPOLI4

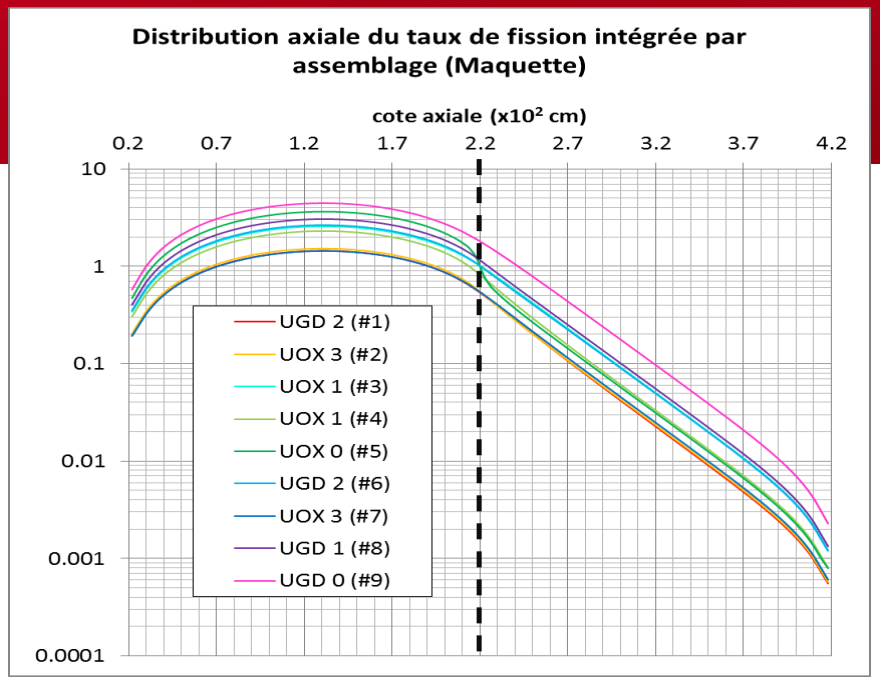


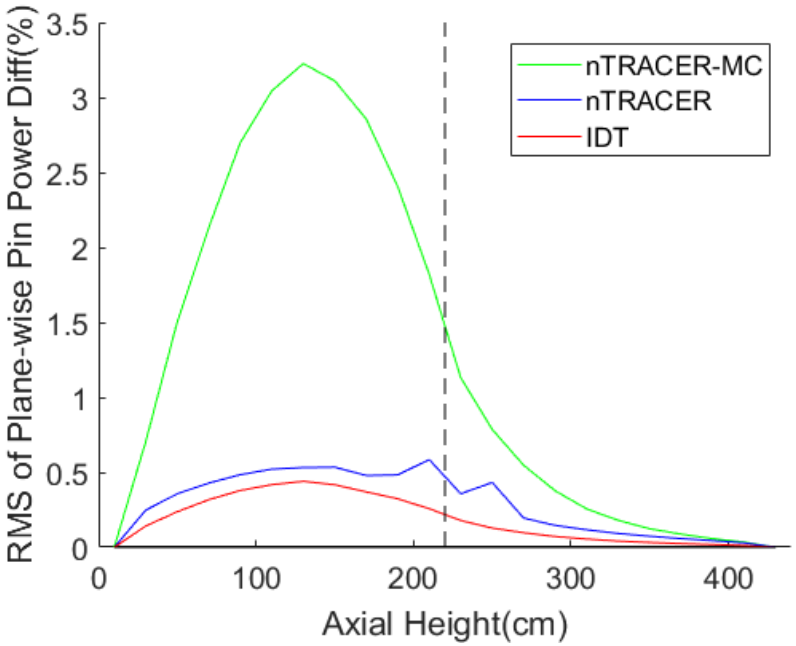


Code-to-code Comparison between nTRACER and the stand-alone IDT solver of APOLLO3
Young Suk Ban*[1)], Emiliano Masiello[2)], Roland Lenain[2)], Han Gyu Joo[1)] and Richard Sanchez[1) 2)],
Nuclear Science and Engineering (to be published).

3D COLORSET : AXIAL POWER







CODE-TO-CODE COMPARISON: NTRACER VS. IDT VS. TRIPOLI4

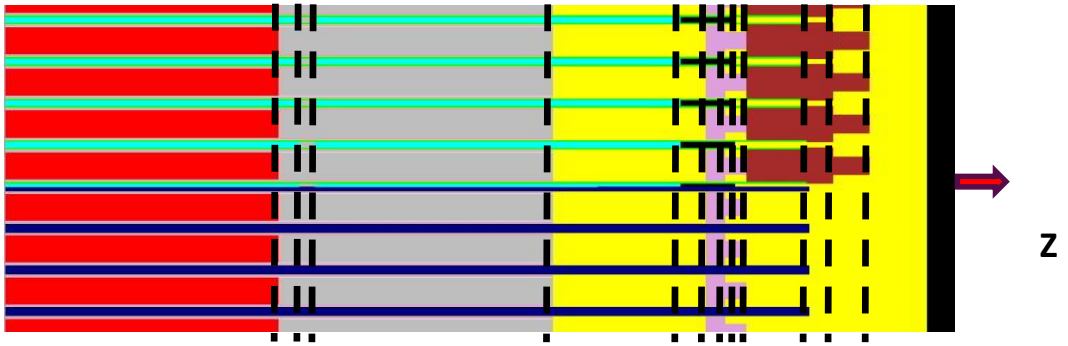
	k-eff	Dr	R.M.S.	MAX.
TRIPOLI-4	1.05575	(reference, std. 0.6 pcm*)		
IDT	1.05437	-138 pcm	0.36 %	1.39 %

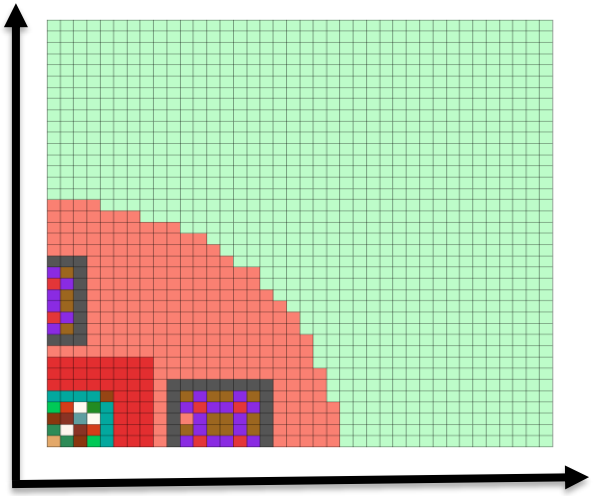
PERFORMANCES

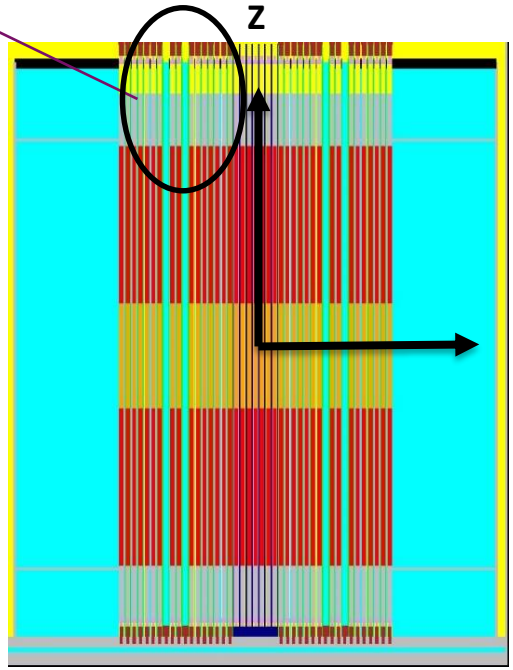
Elapsed Time	OpenMP (20 threads)	MPI/OpenMP (20 nodes, 12 threads/node 240 threads)
	Time	Time
MOSC	24.4h	1.7h
CMFD	0.5h (2%)	0.5h (26%)
Flux Exchange & misc.	6sec. (<1%)	6min. (4%)
Transport + CMFD # of iterations	**18**	**18**
Total	**24.9h**	**2.2h**

3D FULL CORE

EOLE (UH1.2) 3D CORE SIMULATION WITH APOLLO3







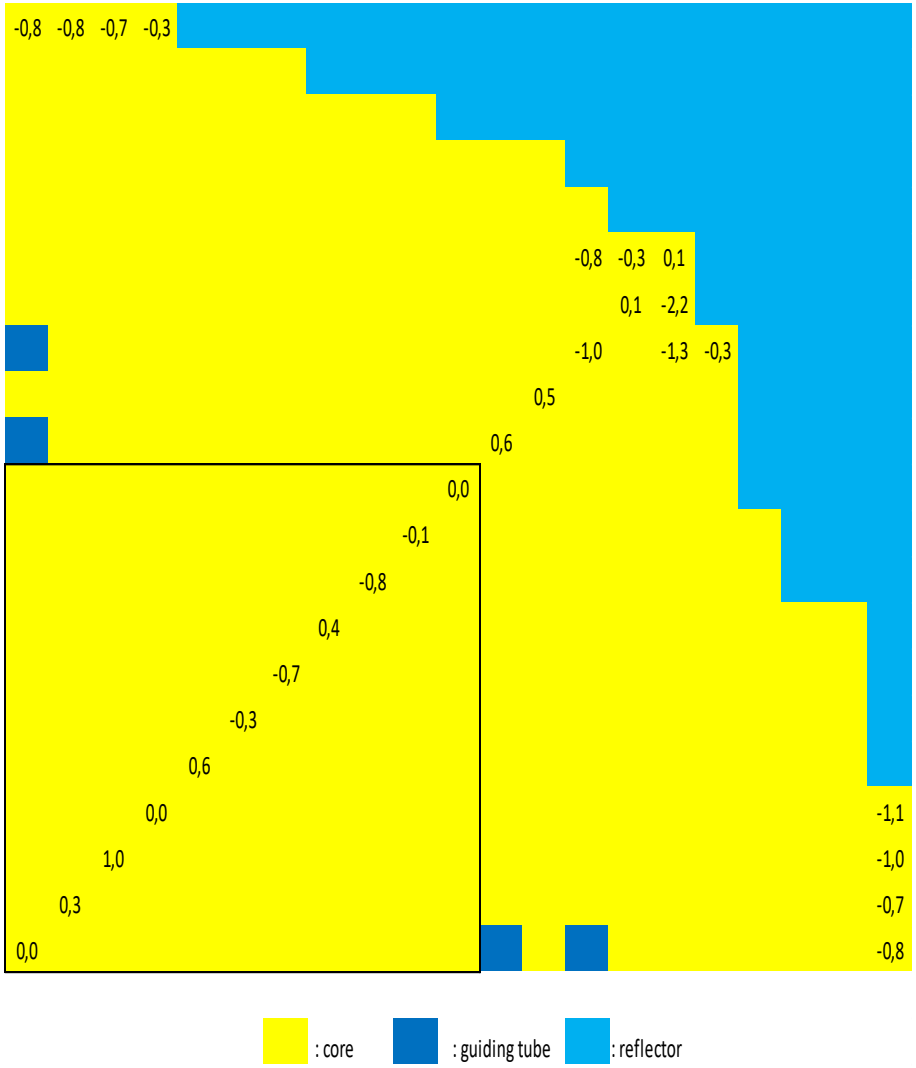
- 164 796 regions
- 62 092 cartesian cells (CMFD mesh)
- S12 C-L quadrature = 288 direction
- 281-group P1 XS library (4 angular moments)
- 3-3-1 surface mesh,
- for a total of 33 GB

Pascal ARCHIER, Bastien FAURE, Jean-Marc PALAU, Jean-François VIDAL, Emiliano MASIELLO ,
DER/SPRC/LEPh 18-221

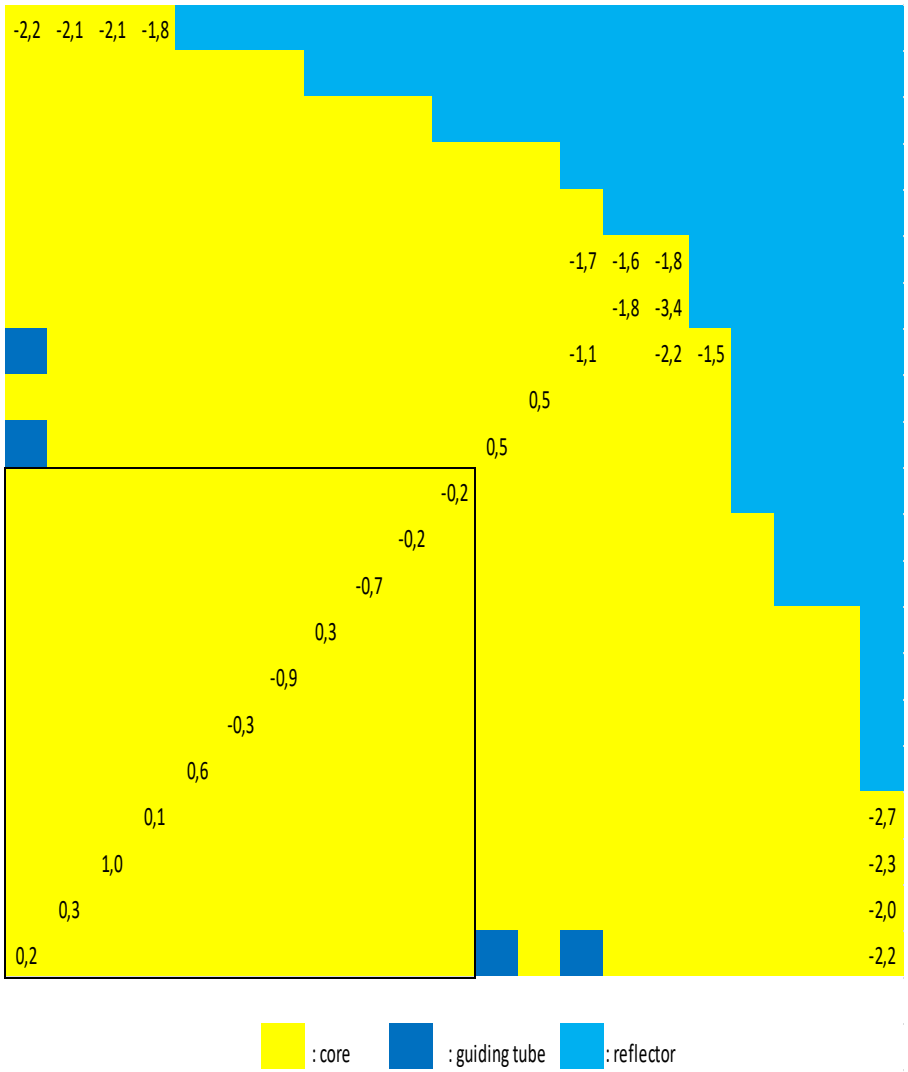
PERFORMANCES

Elapsed Time	OpenMP (24 threads)	MPI/OpenMP (20 nodes, 12 threads/node 240 threads)
	Time	Time
MOSC	14h (85%)	40 min (21%)
CMFD	2h (15%)	2h (71%)
Flux Exchange & misc.	6sec. (25, <1%)	6min. (25, 4%)
Transport + CMFD # of iterations	**15**	**15**
Total	**14.9h**	**2h45**

A3 VS. T4 VS. EXPERIMENTAL FISSION DISTRIBUTION MESUREMENT

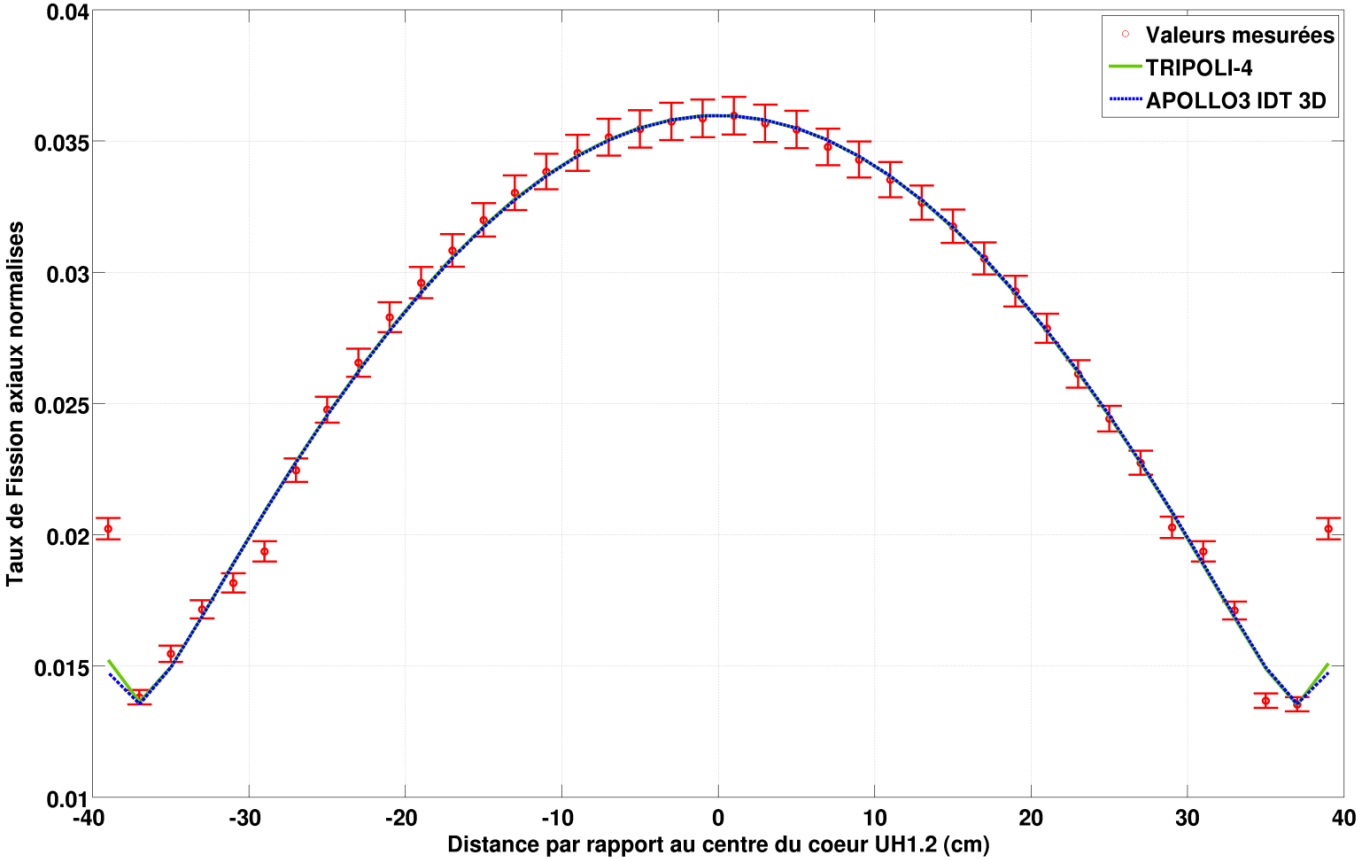


(C/E-1) en % APOLLO3® IDT



(C/E-1) en % TRIPOLI-4

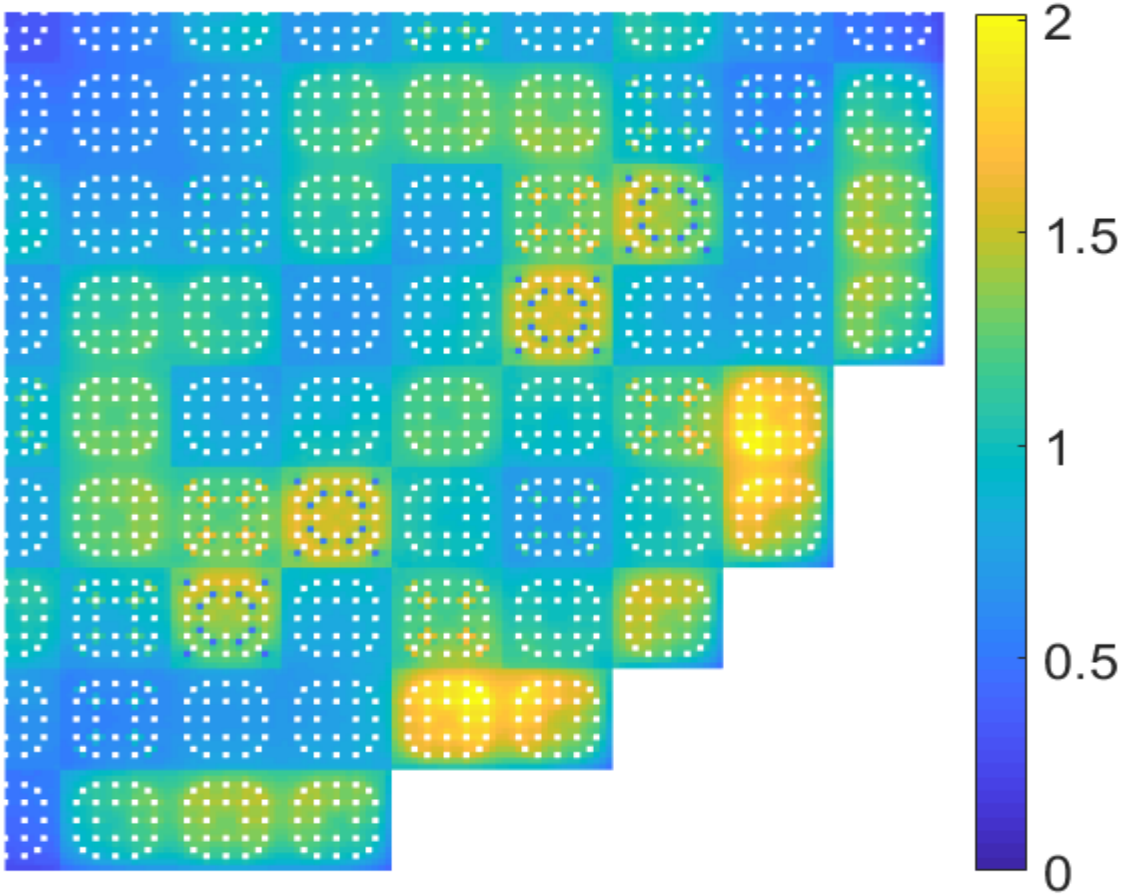
AXIAL POWER DISTRIBUTION AND REACTIVITY



Codes	K-effectif	(C-E) ± δ(C-E) (pcm à 1 σ)
TRIPOLI-4 ± inc. stat. (pcm à 1σ)	1.00421 ± 1.6 pcm	310 ± 300
APOLLO3® IDT 3D hétérogène	1.00485	374 ± 300

3D CORE SIMULATION 26-GROUP XS LIBRARY

RADIAL POWER DISTRIBUTION

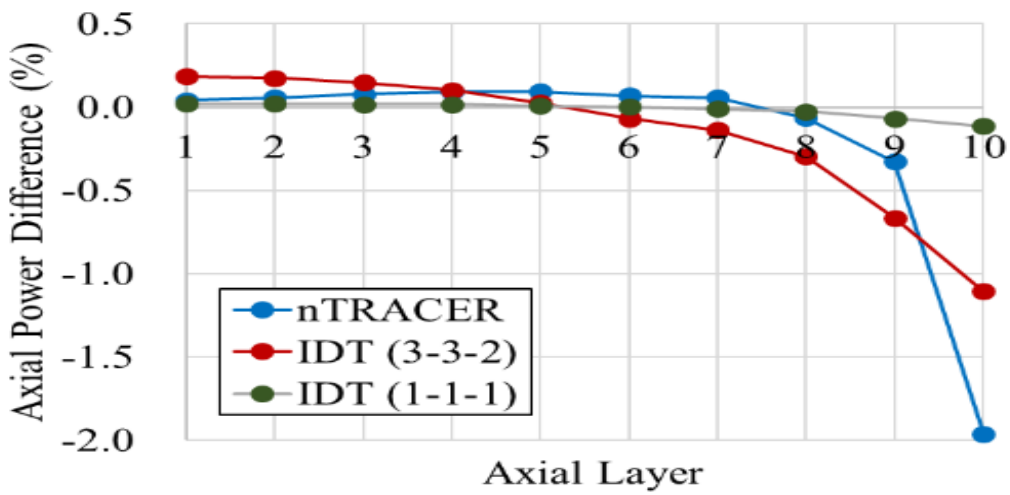


- 19x19 assembly-sized subdomains
- 264 pins/assembly
- 22 axial planes
- about 10 radial regions/pellet
  = ~ 10 Millions of regions
- 26 groups
- P3 (16 angular moments)
- Linear MOSC (4 spatial moments)

= ~ 30 Billions of unknowns

784 GBYTES OF MEMORY:
1% COF, 84% TRA, 16% CMFD
~30 GBYTES/NODE

ACCURACY (NTRACER VS. IDT)



	k-eff	Reactivity error (pcm)	R.M.S. (%)	MAX (%)
nTRACER-MC*	1.01505	-	-	-
nTRACER	1.01527	22	0.66	2.41
IDT(3-3-2)	1.01521	15	1.17	3.61
IDT(1-1-1)	1.01490	-15	0.46	2.40

* nTRACER-MC is a multigroup Monte Carlo solver, with Pn scattering expansion: it is not properly a reference !

PERORMANCES

12/ threads per node * 28 nodes = 336 threads
Xeon L5640 2.26 GHz 36 Go / Node (CALLISTO-PLUTON)
compiler gfortran + mpich

	Time (3-3-2)	Time (1-1-1)
TRANSPORT	55%	37%
CMFD	44%	62%
(Transport + CMFD iterations)	**40**	**24**
Flux Exchange & misc.	<1%	
Total	**5h32**	**2h20**

Thank you!

FIRST CONCLUSION

- **The distributed-memory parallelism is <u>mandatory</u> for high-fidelity 3D full-core transport simulations !**

IDT Short-term updates in APOLLO3:

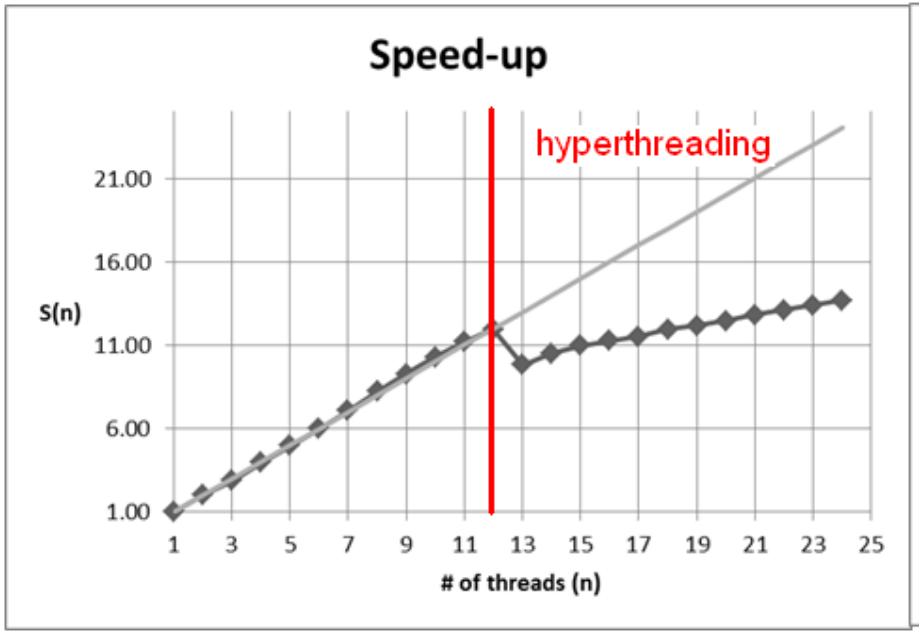
- **Hybrid MPI/Open MP parallelism by the Domain Decomposition Method.***
- **HCC with unstructured volume sub mesh.**
- **Hybrid MPI/Open MP parallelism for the synthetic acceleration (CMFD) ****

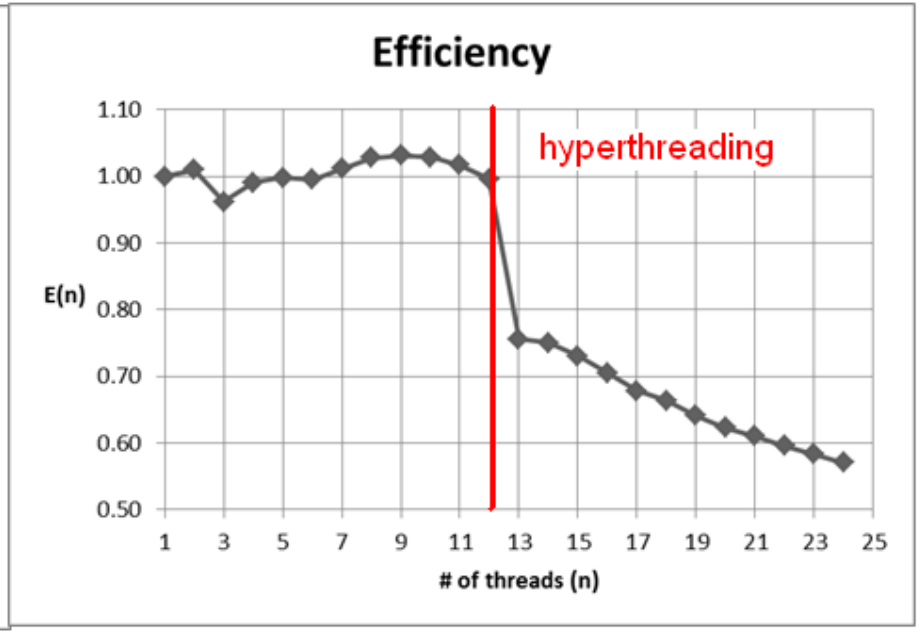
* R.LENAIN, E. MASIELLO, F. DAMIAN, R. SANCHEZ, "Domain Decomposition Method for 2d and 3d Transport Calculations Using Hybrid Mpi/Openmp Parallelism," M&C 2015, Nashville TN

Long-term updates:

- **Triangular and tetrahedral mesh.**

WEAK SCALABILITY





- Assembly-sized subdomains
- 1 to 24 subdomains (and threads)
- Processors run from 1 to 12
- The hyperthreading is switched-on from 13 to 24

$$n_{threads} = n_{sub}$$

$$S = \frac{n_{thread} * T(1)}{T(n_{thread})}$$

$$E = \frac{S}{n_{thread}}$$

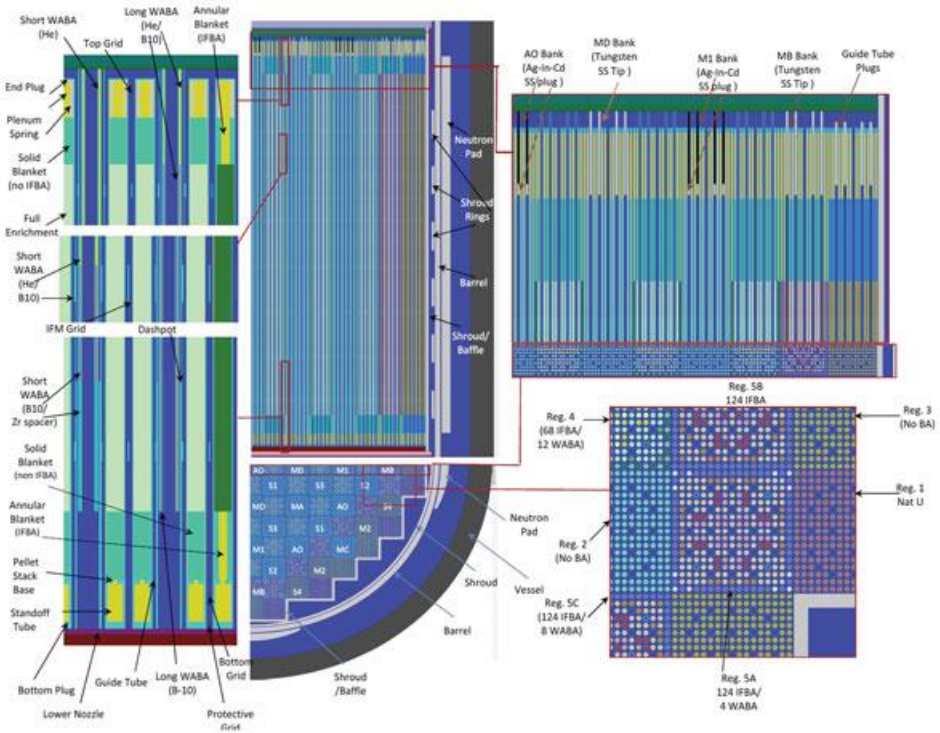
9X9 COLORSET TEST : COERSENING THE CMFD

	9x9 cluster (DDM with 81 assembly-sized subdomains)			
	CMFD (1x1, 281grp)	**CMFD** (4x4, 26grp)	**DDM+CMFD** (4X4, 26grp)	**DDM+CMFD** (4X4, 26grp)
# of subdomains	1	1	81	**81**
# of processors	**1**	**1**	**1**	**12**
Computational time (s)	229398 (63h)	20562 (5h30)	19395 (5h30)	**1735 (29min)**
# of outer iterations	9	11	13	**13**
# of transport iterations	5053	8090	7740	**7740**
# of CMFD outer iterations	98	57	260	**232**

- 81 assemblies, 281 groups, P1 scattering, 40 directions, ~150000 regions, ~ 100000 sets of XS (~ 10Gb.)
- the colorset does not have internal symmetry.

3D Core simulation:

- 193 assemblies
- 264 pins/assembly
- 200 axial pellet/pin
- 10 radial regions/pellet
- 400 nuclides per regions
- 5 reaction per nuclide
- 10 Kbytes/reactions



=~ 2 000 T-bytes of data

HYBRID MPI/OPENMP PARALLELISM

Points	OpenMP	MPI	Hybrid OpenMP/MPI
Available Memory	-	++	++
# of processors	-	++	++
CMFD communications	++	-	+
Load balance	++	-	+
Memory efficiency	++	-	+

⇒ More than 1 subdomains on a single MPI process

⇒ OpenMP paradigms applied to the subdomains sharing the same MPI process.

⇒ **The iterative algorithm remains unchanged !**